Dark Matter

Jim Cline, McGill U.

Nordic Winter School, Jan., 2015

Outline

- Observations/constraints (in historical perspective)
- Cosmological origin
- Direct detection
- Indirect detection
- Theoretical models
- Production at colliders

The earliest observation?

Jan Oort observed in 1932 that there is more mass near the solar system than accounted for by visible matter, by analyzing motions of stars perpendicular to the galactic plane. He speaks of "invisible mass".

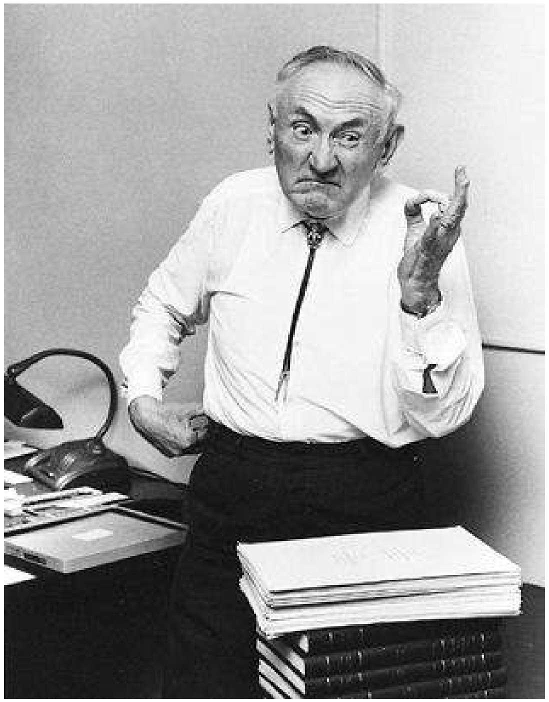
> **11.** It is found that the total density of matter near the sun is equal to $6{\cdot}3.10^{-24}$ g/cm³ or ·092 solar masses per cubic parsec. The observed total mass of the stars down to $+13{\cdot}5$ visual absolute magnitude is found to be ·038 solar masses per ps³ (Table 34). It is probable that this value would still be greatly increased if we could have taken the next 5 absolute magnitudes into account, so that the total mass of meteors and nebular material is probably small in comparison with that of the stars. There is an indication that the invisible mass is more strongly concentrated to the galactic plane than that of the visible stars (Table 33).

Oort had actually discovered dark baryons, not dark matter!

Oort made further relevant contributions to dark matter evidence later in his career.

Fritz Zwicky, father of dark matter

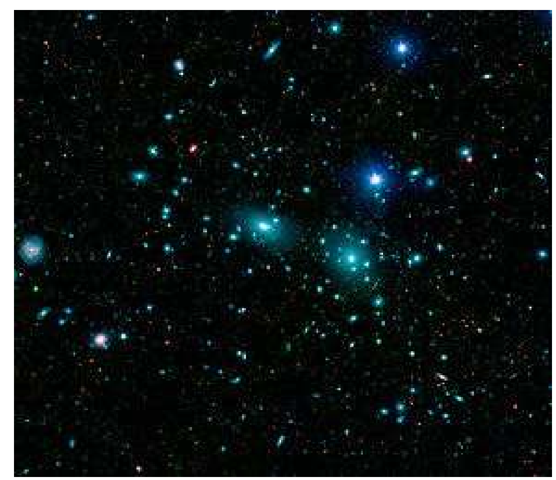
Gravitational pull is how he inferred existence of dark matter



Fritz Zwicky, 1898-1974
Astrophysicist
Caltech, Pasadena

Called astronomers “spherical bastards,” explaining “You’re a bastard every way I look at you."

1933, studied motions of galaxies around each other in Coma cluster. They were moving too fast!



Zwicky's 1933 paper

appeared in Helvetica Physica Acta, vol 6, 1933, p.110-127

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

"The redshifts of extragalactic nebulae"

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Dark matter

400 times more prevalent
than visible matter

400 was an overestimate (error in distance to Coma cluster), but the conclusion was correct

Zwicky's argument (1937)

(Ap.J. 86, p.217, in English)

Virial theorem says

$$\frac{GM^2}{R} = M\langle v^2 \rangle$$

for cluster of mass M and size R.

His measurement of $\langle v^2 \rangle^{1/2} = 1200$ km/s was good, and $R = 2 \times 10^6$ light-years right order of magnitude.

He deduces mass $M > 5 \times 10^{13} M_\odot$, and mass-to-light ratio 170 times bigger than for stars.

Cluster must be dominated by nonluminous matter

Impact of Zwicky's 1933 paper

Did it cause a sudden revolution?

from S. van den Bergh,
astro-ph/0005314

Table 1: Citations of Zwicky (1933)

Year	No. citations
1955-59	2
1960-64	6
1965-69	5
1970-74	2
1975-89	63[a]
1990-99	71

[a] There is a clustering of eight references that cite the wrong page number for Zwicky's article. Apparently seven of these authors copied the reference from Bahcall (1977), which contains a typographical error, without actually reading the original paper.

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Maybe this is why Zwicky thought his colleagues were bastards?

Too much mass in galaxies

Most astronomers became convinced of dark matter around 1973-74, by measurements of speeds of stars orbiting in galaxies.

Stars move too fast for only the visible matter to be pulling on them.

So, the first evidence of this kind must have come in the mid-1970's?

Babcock’s 1939 measurement

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BY

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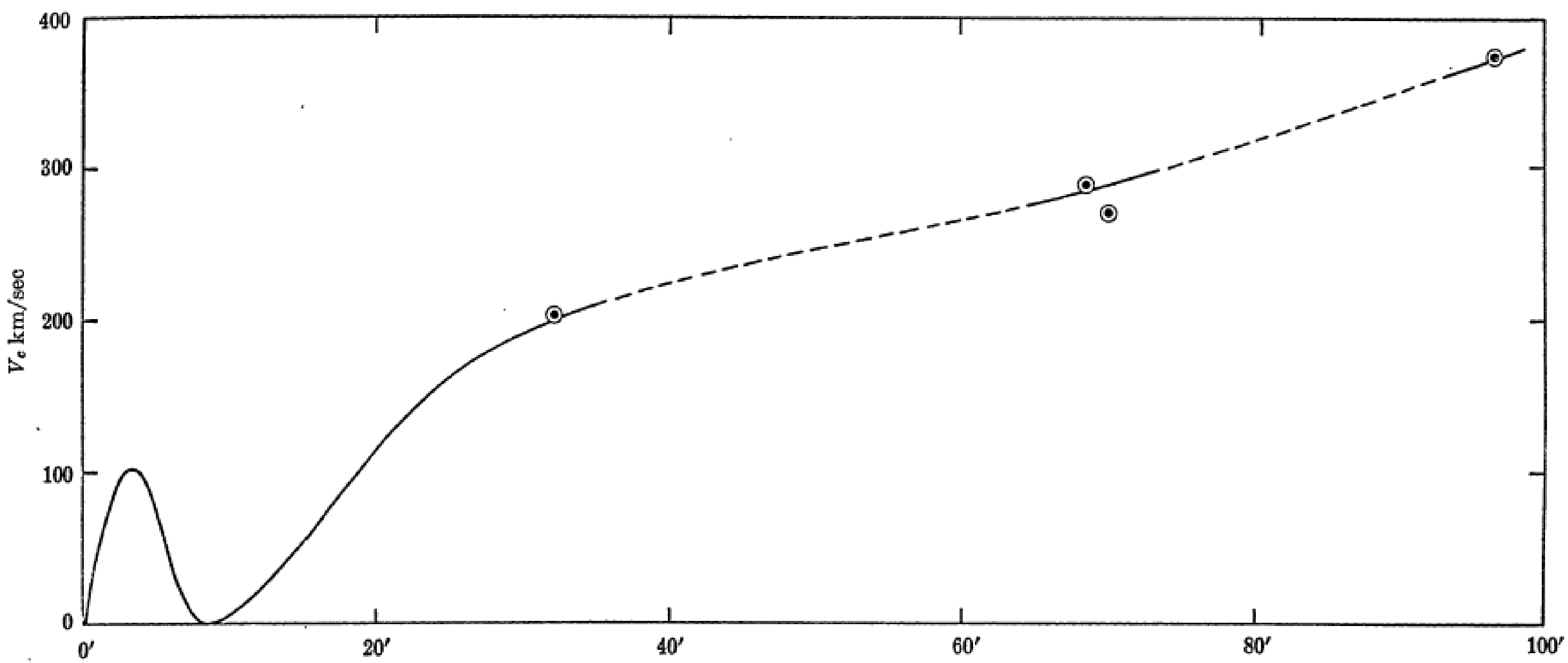
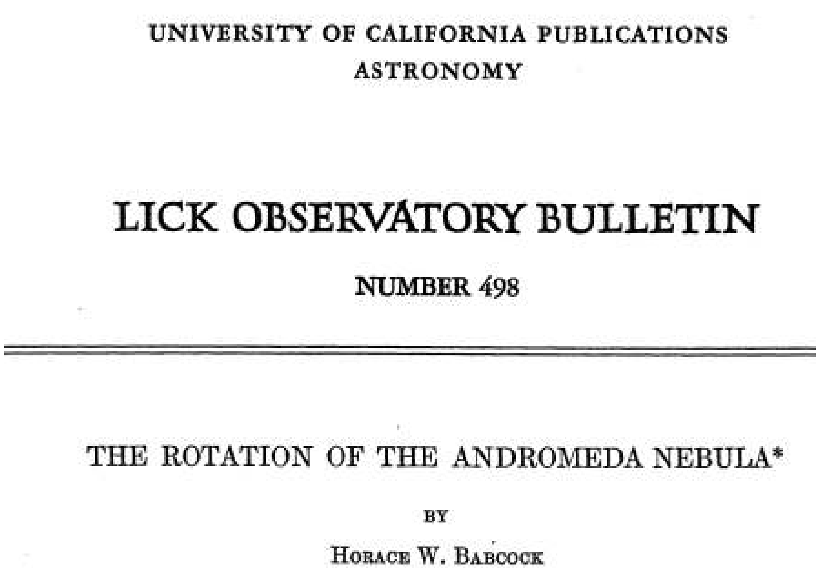


Fig. 4. Mean velocities of rotation in the plane of the spiral.

Rotation speed stays too high



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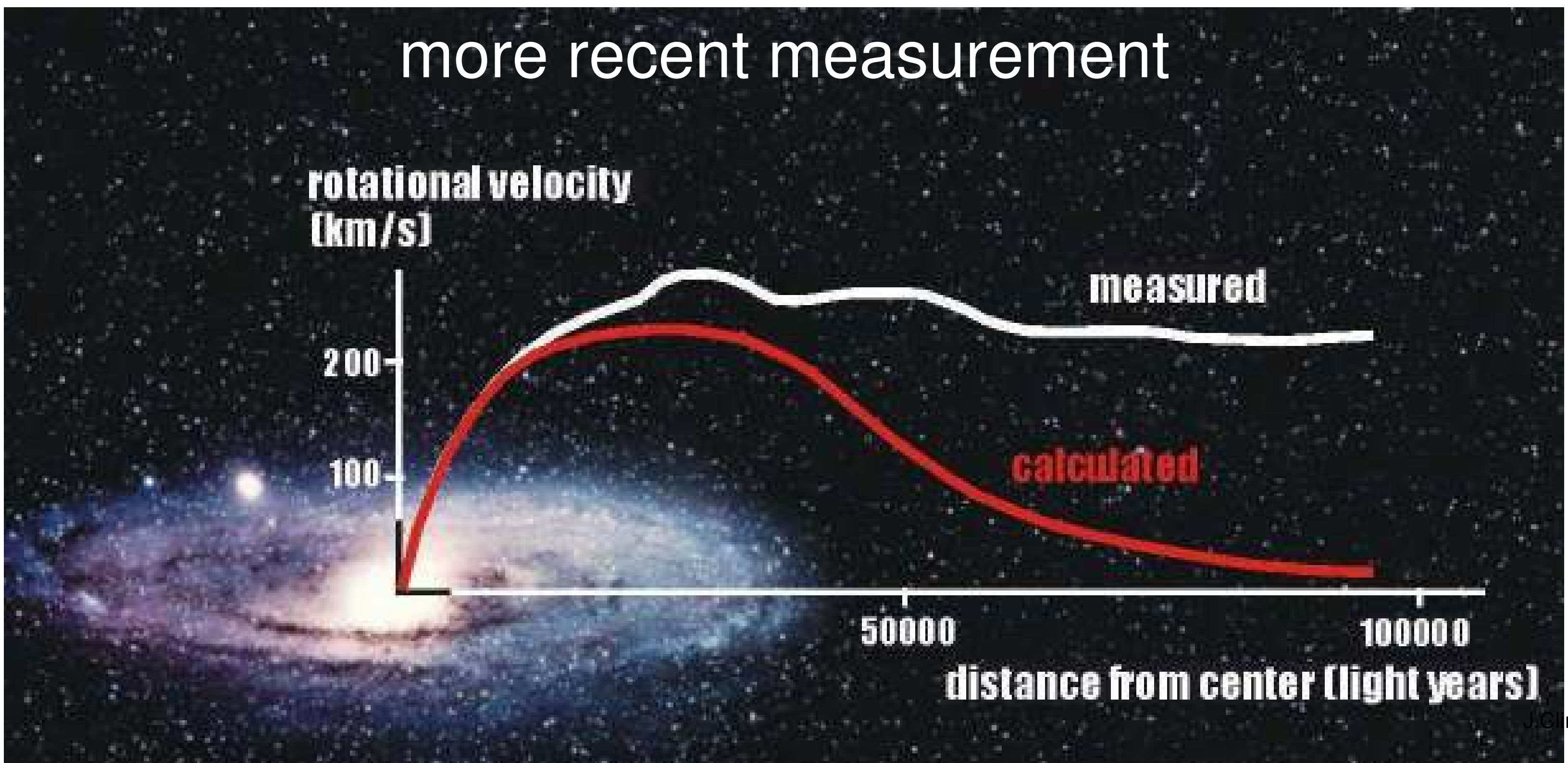


Babcock's inferences

model used in the preceding section, is 1.04×10^{11} cubic parsecs, and the calculated mass is 1.02×10^{11} ⊙. It follows that the mean luminosity density, in absolute visual magnitudes, is 8.85 per cubic parsec, and that the average mass per cubic parsec is 0.98⊙. The total luminosity of M31 is found to be 2.1×10^{9} times the luminosity of the sun, and the ratio of mass to luminosity, in solar units, is about 50. This last coefficient is much greater than that for the same relation in the vicinity of the sun. The difference can be attributed mainly to the very great mass calculated in the preceding section for the outer parts of the spiral on the basis of the unexpectedly large circular velocities of these parts.

He computes mass of Andromeda from Newton's Law: $v^2 = GM(r)/r$ where $M(r)$ is the mass enclosed within r

Then mass-to-light ratio

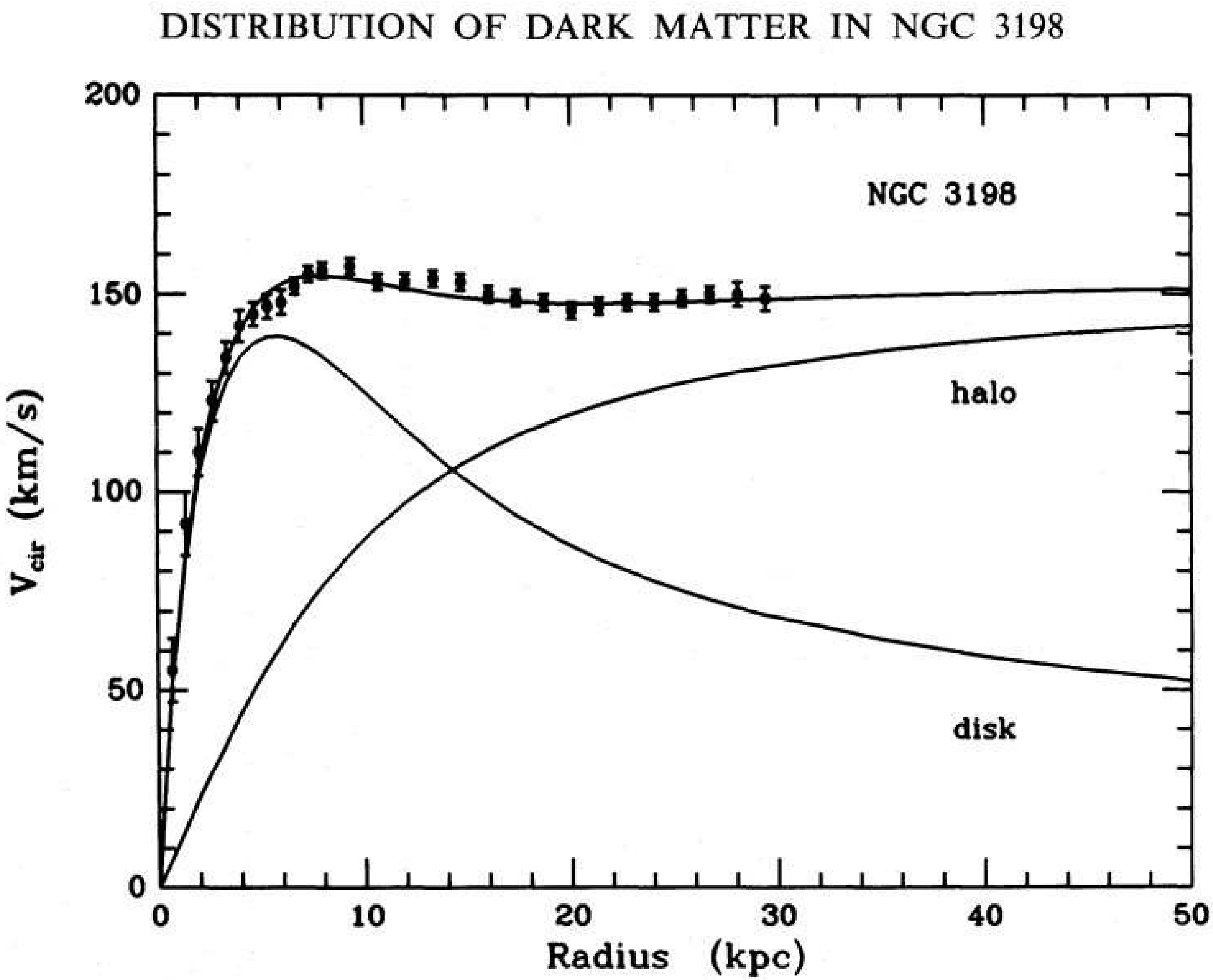
Notes that it is surprisingly large due to surprisingly high velocities at large radii

Now there are similar measurements for hundreds of galaxies indicating the same flat curves at large radii

Galaxy rotation curves

A typical rotation curve, showing expected contributions to $v = (GM(r)/r)^{1/2}$ from baryons (disk) and dark matter (halo)

(Albada *et al.*, Ap.J. 295,305 (1985))



Would not be flat without the dark matter!

Larger scales: clusters again

More modern observations of galaxy clusters confirm Zwicky's basic finding. Galaxy clusters are so large, their baryon fraction should approach that of the whole universe,

$$f_b = \frac{M_b}{M_{\rm tot}} \to \frac{\Omega_b}{\Omega_m}$$

where $M_b = M_{\rm gas} + M_{\rm stars}$.

Can estimate $M_{\rm gas}$ using X-ray surface brightness, $M_{\rm stars}$ using visible luminosity, and $M_{\rm tot}$ using velocity dispersion. (Improves on Zwicky by measuring $M_{\rm gas}$.)

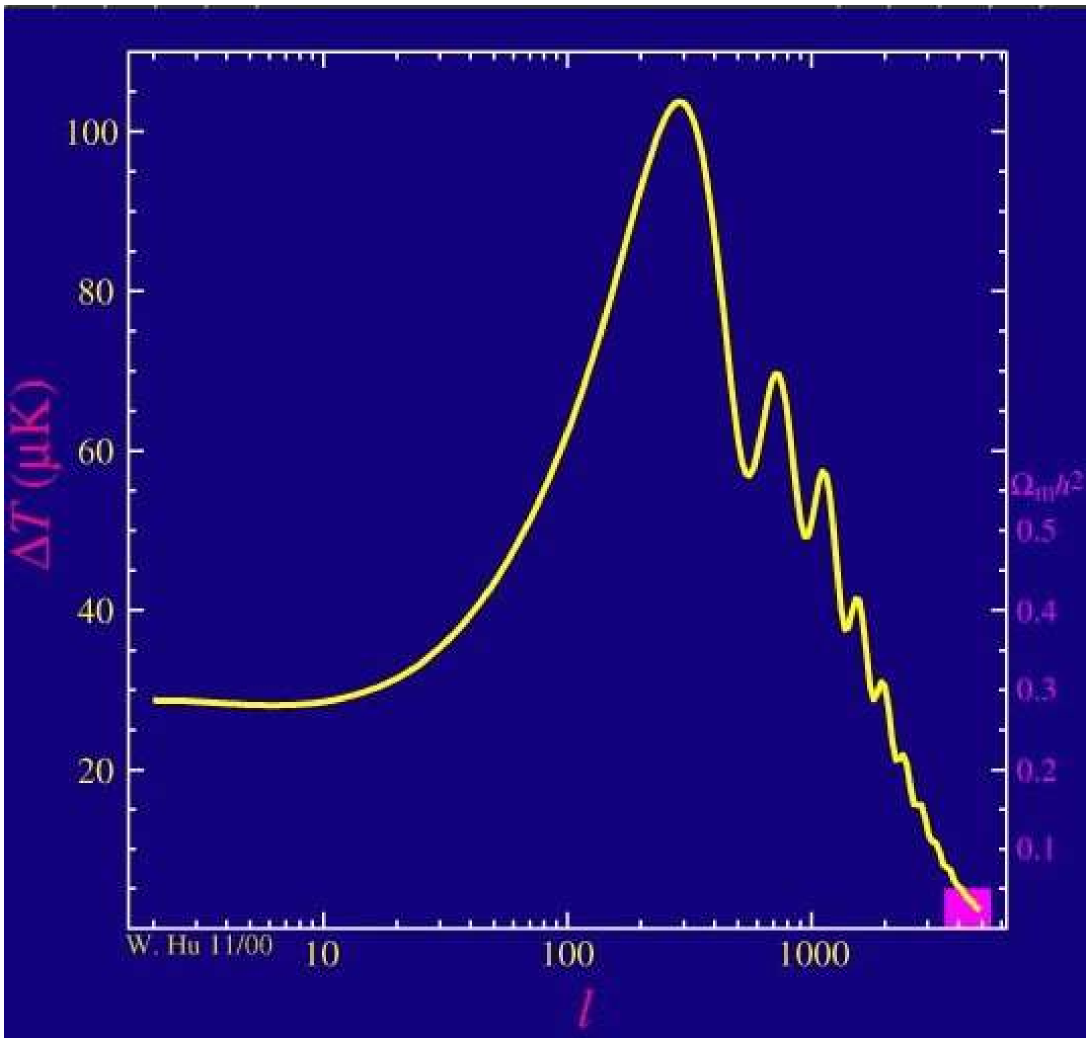
S.White *et al.*, Nature 366, 429 (1983) reanalyzed Coma cluster to find

$$f_b \cong 0.1$$

Most of the matter is dark! (Even a bit too dark in clusters; cosmologically $f_b = 0.16$: "missing baryons" problem)

Cosmological scales: the CMB

Fluctuations of the Cosmic Microwave Background are very sensitive to the amount of dark matter in the early universe. Shows that DM must be 27% of energy density of universe!



Position of first peak depends on $\Omega_\Lambda + \Omega_m$

Ratio of heights of 2nd to 1st peak is sensitive to Ω_b

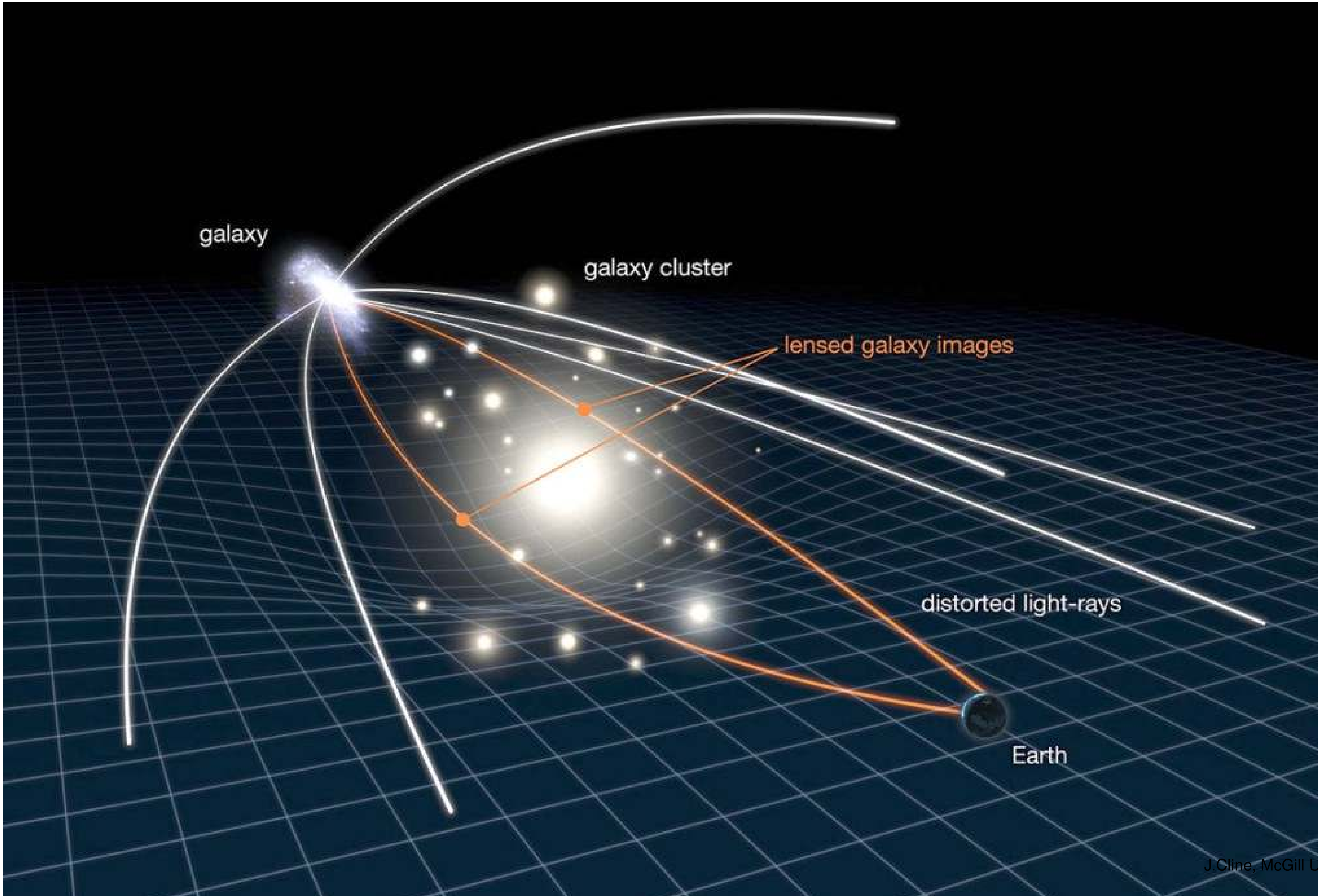
Third peak has additional dependence on Ω_m

$$\begin{aligned} \Omega_\Lambda &= \;\; 0.685 \pm 0.017, \\ \Omega_b &= \;\; 0.050 \pm 0.002, \\ \Omega_{\rm cdm} &= 0.265 \pm 0.011 \end{aligned}$$

W. Hu, http://background.uchicago.edu/∼whu/metaanim.html

Other evidence: gravitational lensing

Gravity of dark matter bends the light of objects from behind it



Suggested by Zwicky in 1937!

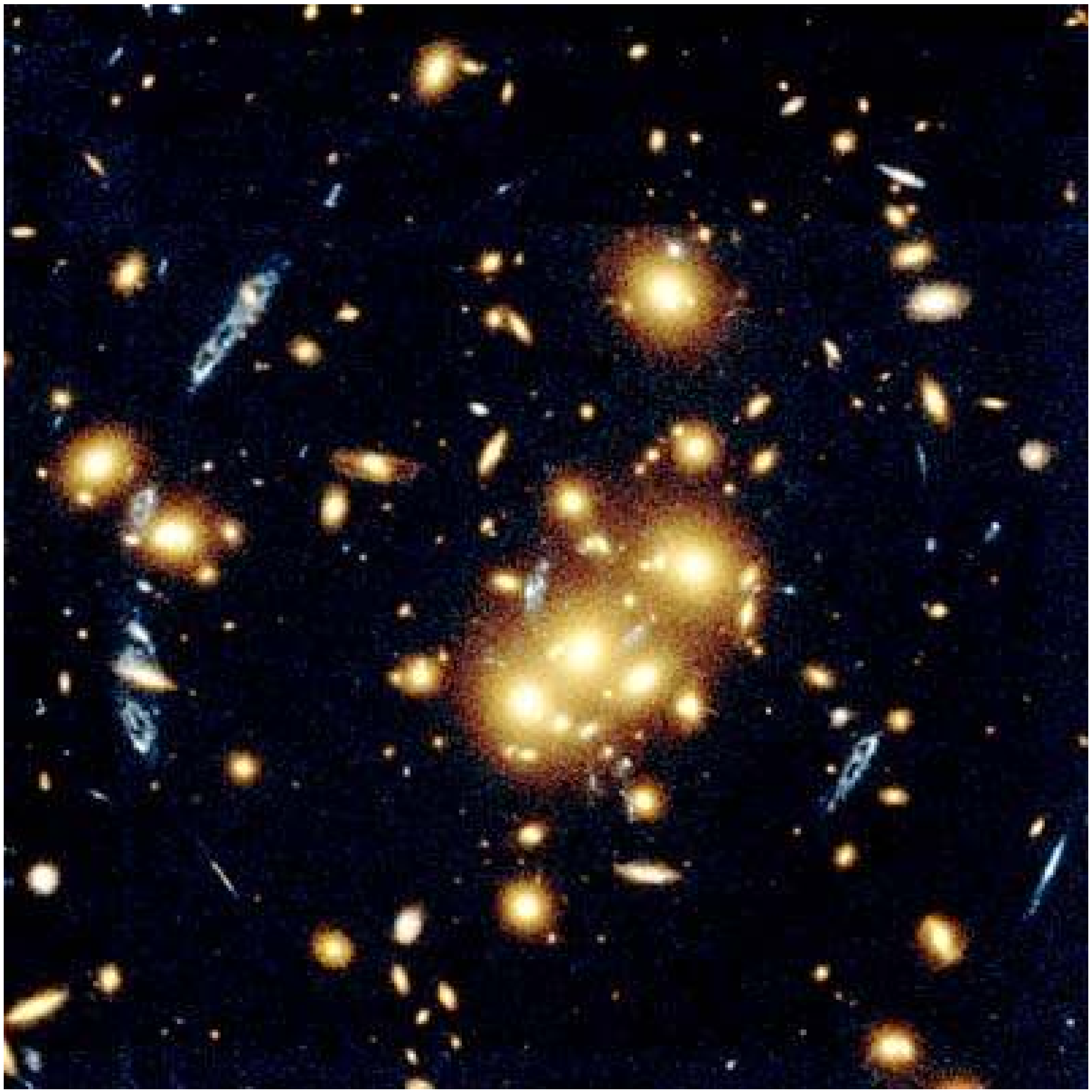
Zwicky suggested use of gravitational lensing to "see" dark matter in his 1937 paper continuing his earlier work:

IV. NEBULAE AS GRAVITATIONAL LENSES

As I have shown previously,[6] the probability of the overlapping of images of nebulae is considerable. The gravitational fields of a number of "foreground" nebulae may therefore be expected to deflect the light coming to us from certain background nebulae. The observation of such gravitational lens effects promises to furnish us with the simplest and most accurate determination of nebular masses. No

Strong gravitational lensing

Galaxy lensed by foreground cluster looks like this (Hubble Space Telescope):

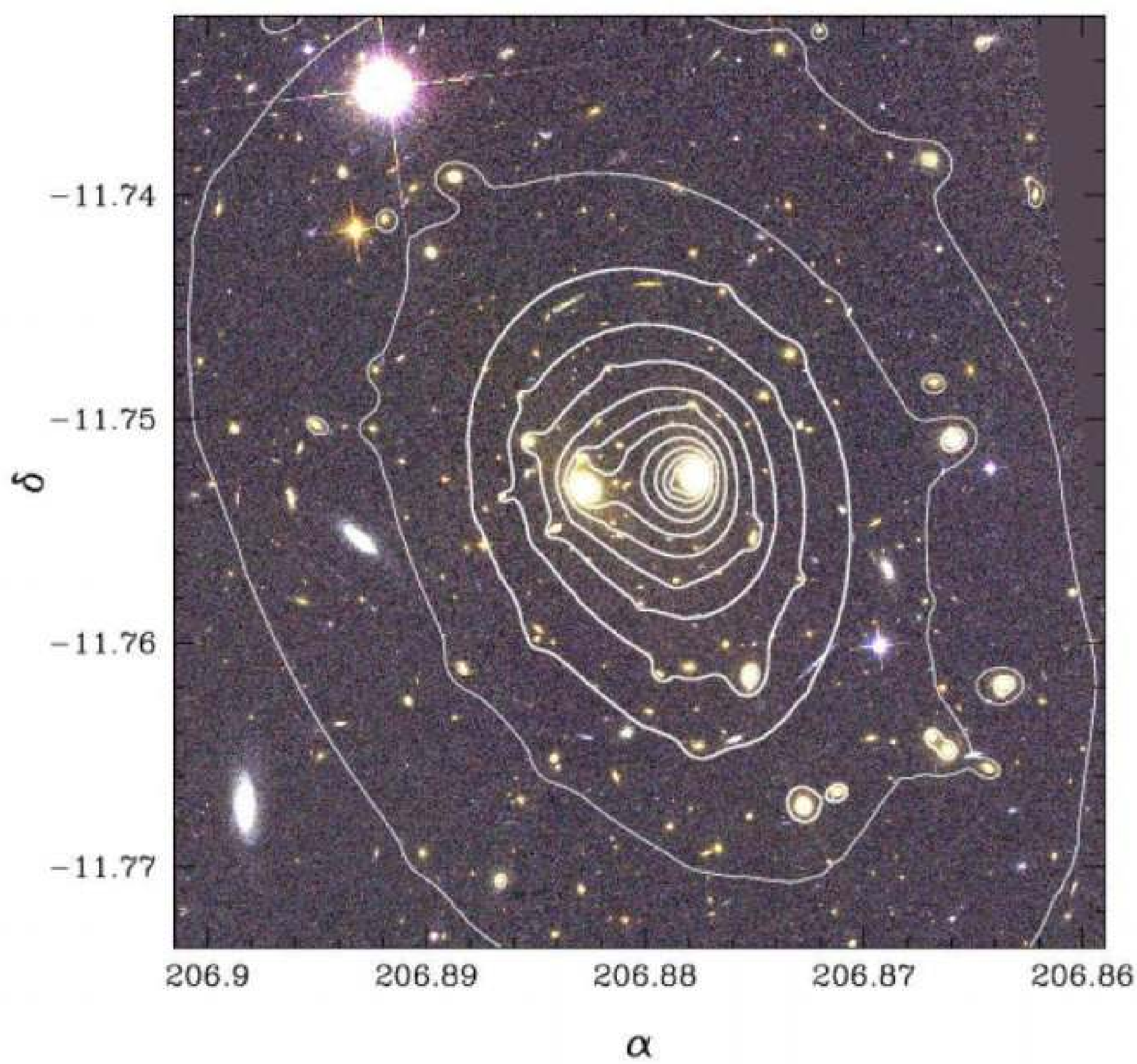


Dark matter distribution of cluster can be fit by predicting the lensed images of the background galaxy

Strong lensing DM map

Example of cluster RX J1347-1145

(Halkola *et al.*, 0801.0795)

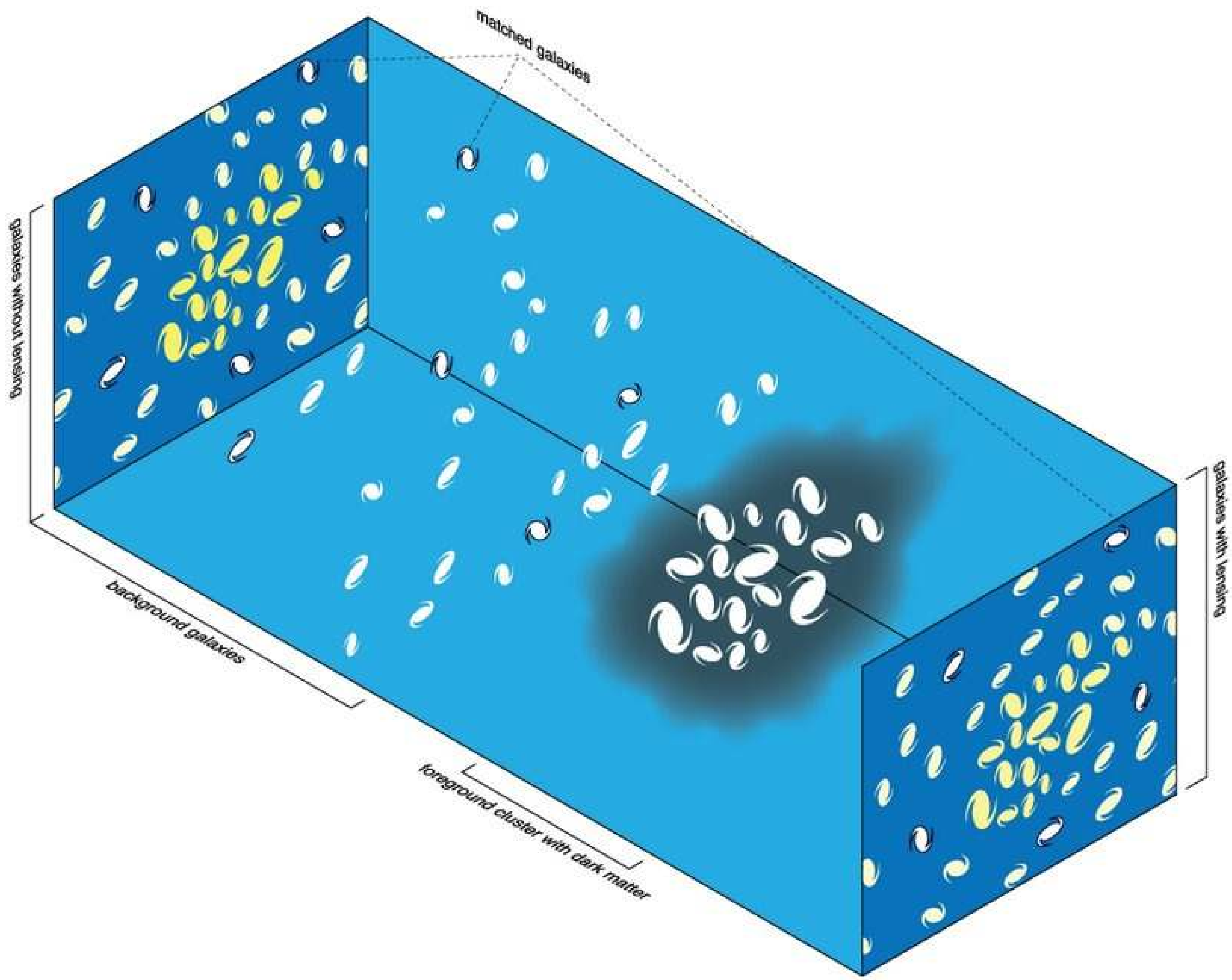


Contours of mass density deduced from strong lensing

DM-only contours would be smooth; blips are due to individual galaxies

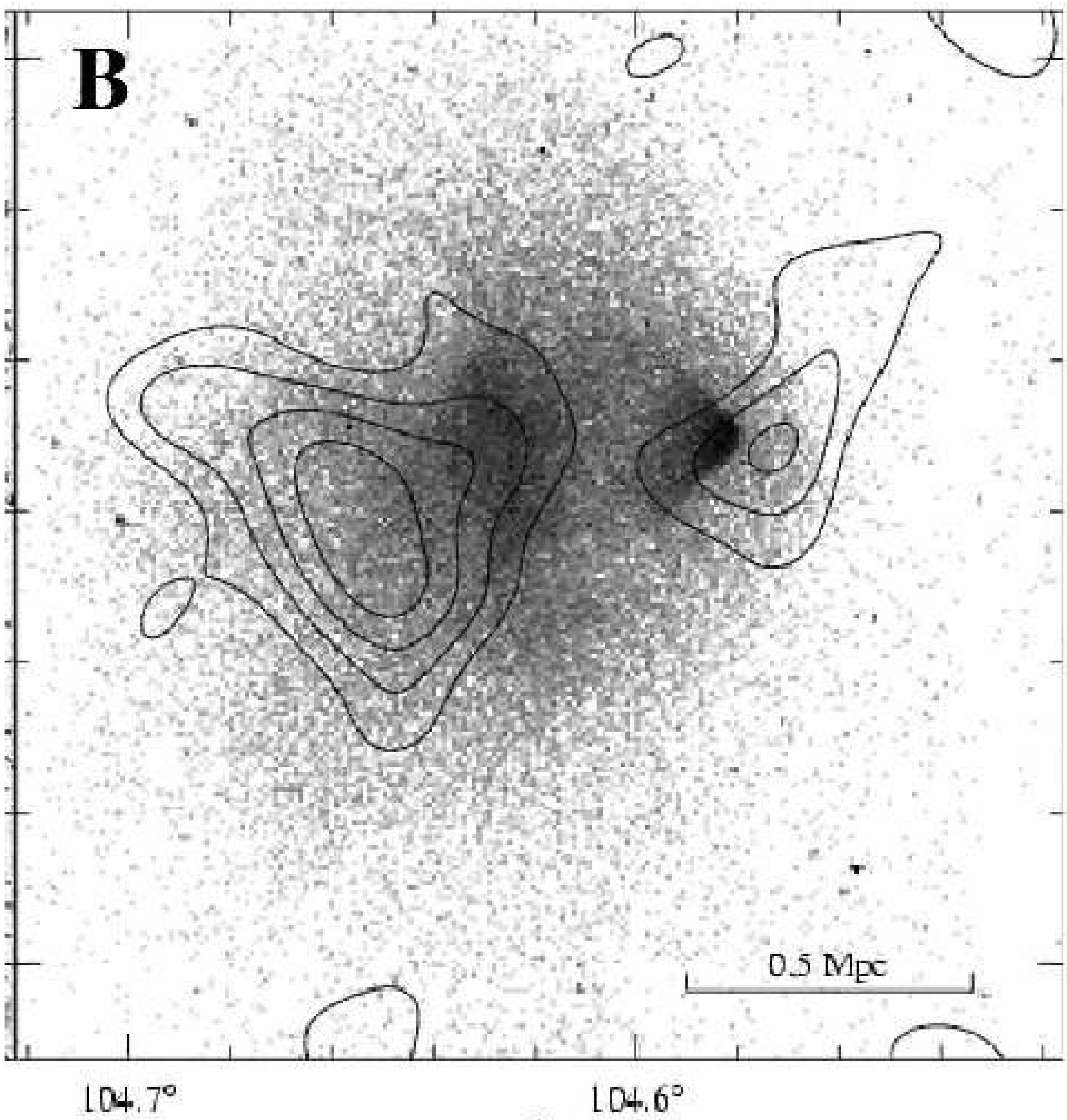
Weak gravitational lensing

More commonly, background galaxy images undergo shearing rather than being multiply imaged. Statistics of shearing can be used to infer DM distribution of foreground cluster.



Weak lensing: the Bullet Cluster

Clowe *et al.*, astro-ph/0312273

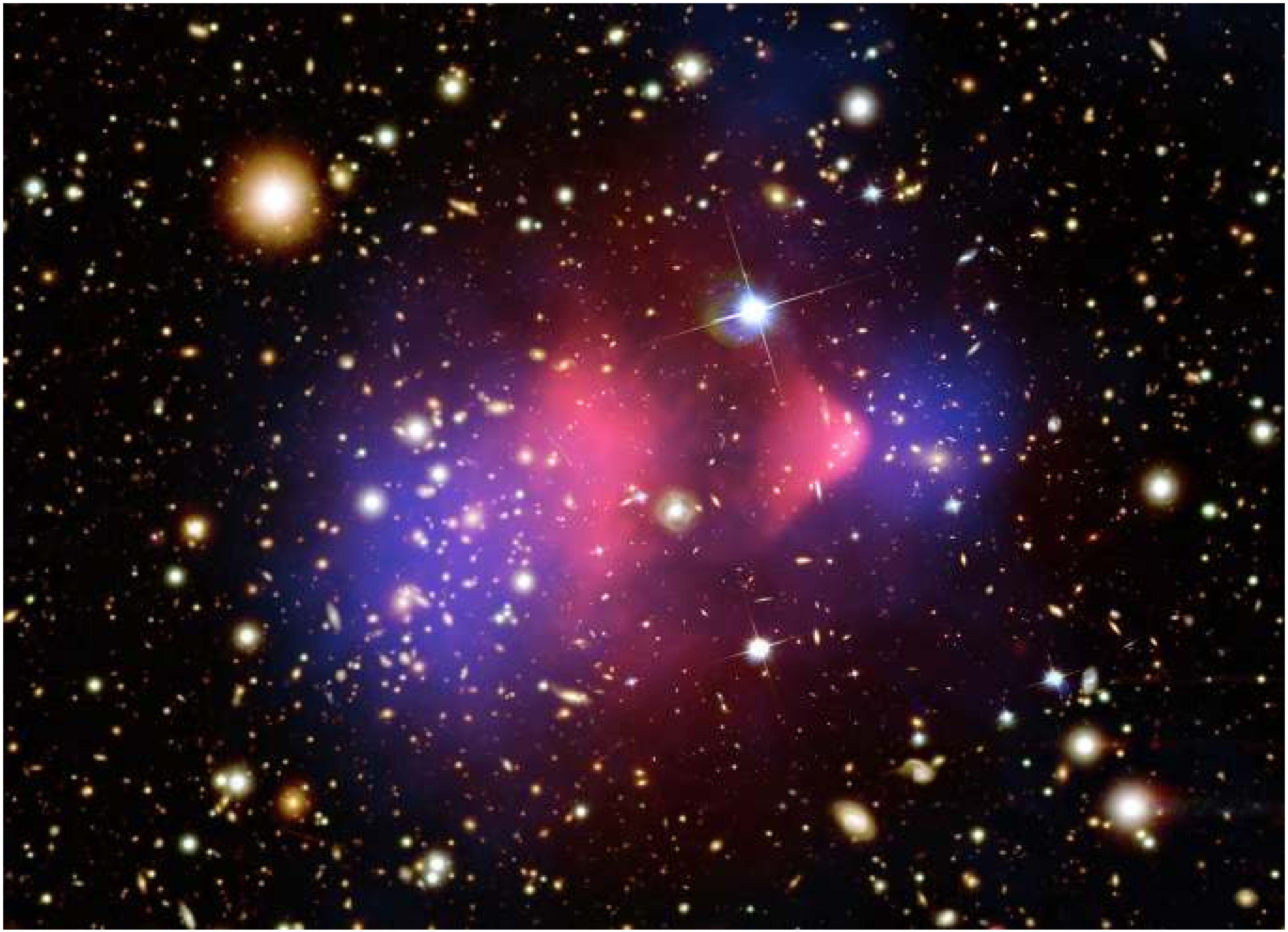


Two colliding clusters reveal offset between the hot gas barycenters and those of the dark matter; contours mapped by weak lensing.

DM components passed through each other without interacting; baryons in the hot gas got hung up in the middle.

The Bullet Cluster

The pretty version



Are there alternatives to DM?

Dark matter simulations don't automatically give flat galaxy rotation curves (or Tully-Fisher relation, luminosity $\propto$ rotation velocity in spiral galaxies.).

MOND (Modified Newtonian Dynamics, Milgrom, 1983) explains flat rotation curves in galaxies by altering Newton's law at low acceleration:

$$F = \begin{cases} ma, & a \gg a_0 \\ m\frac{a^2}{a_0}, & a \ll a_0 \end{cases}$$

with $a_0 = 1.2 \times 10^{-10}\mathrm{m/s^2}$ to fit rotation curve data. MOND also explains Tully-Fisher relation.

Better thought of as a modification to gravity. What does it look like in this form?

Bekenstein, astro-ph/0403694 formulates tensor-vector-scalar theory, TeVeS, that reduces to MOND.

TeVeS (Bekenstein, 2004)

TeVeS has usual Einstein-Hilbert action for gravity, plus two scalar fields (one nondynamical), with action

$$S_s = -\frac{1}{2}\int \left[\sigma^2 h^{\alpha\beta}\phi_{,\alpha}\phi_{,\beta} + \frac{1}{2}G\ell^{-2}\sigma^4 F(kG\sigma^2)\right](-g)^{1/2}d^4x,$$

where $h^{\alpha\beta} = g^{\alpha\beta} - \mathfrak{U}^\alpha\mathfrak{U}^\beta$, and a timelike vector $\mathfrak{U}_\alpha$ such that $\mathfrak{U}_\alpha\mathfrak{U}^\alpha = -1$, with action

$$S_v = -\frac{K}{32\pi G}\int \left[g^{\alpha\beta}g^{\mu\nu}\mathfrak{U}_{[\alpha,\mu]}\mathfrak{U}_{[\beta,\nu]} - 2(\lambda/K)(g^{\mu\nu}\mathfrak{U}_\mu\mathfrak{U}_\nu + 1)\right](-g)^{1/2}d^4x,$$

The function $F(\mu)$ must have certain features to reproduce MOND,

$$F = \frac{3}{8}\,\frac{\mu\,\left(4 + 2\,\mu - 4\,\mu^2 + \mu^3\right) + 2\,\ln[(1-\mu)^2]}{\mu^2}$$

making the theory nonlocal.

Problems with TeVeS

It needs some extra source like dark matter in addition to get the current Hubble constant right (Skordis, 0903.3602)

To explain Bullet Cluster, vector field must give rise to weak lensing (Dal *et al.*, 0806.4319). Same for growth of large scale structure of the universe (Dodelson, Ligouri, astro-ph/0608602). So we have just replaced DM by something more complicated.

Does not get CMB acoustic peaks right unless massive neutrinos with $m_\nu = 2\ \mathrm{eV}$ each are added (Skordis *et al.,* astro-ph/0505519). Not clear whether this would still work with current CMB data.

Compare to Lagrangian for fermionic or scalar DM:

$$\bar{\psi}(i\partial\!\!\!/ - m)\psi \quad \text{or} \quad \tfrac{1}{2}\left((\partial\phi)^2 - m^2\phi^2\right)$$

Do we really gain enough to justify the loss of simplicity? DM $+$ baryons may be sufficient for galactic dynamics.

Cold vs. warm vs. hot DM

Dark matter temperature refers to time when matter domination and growth of large scale structure begins

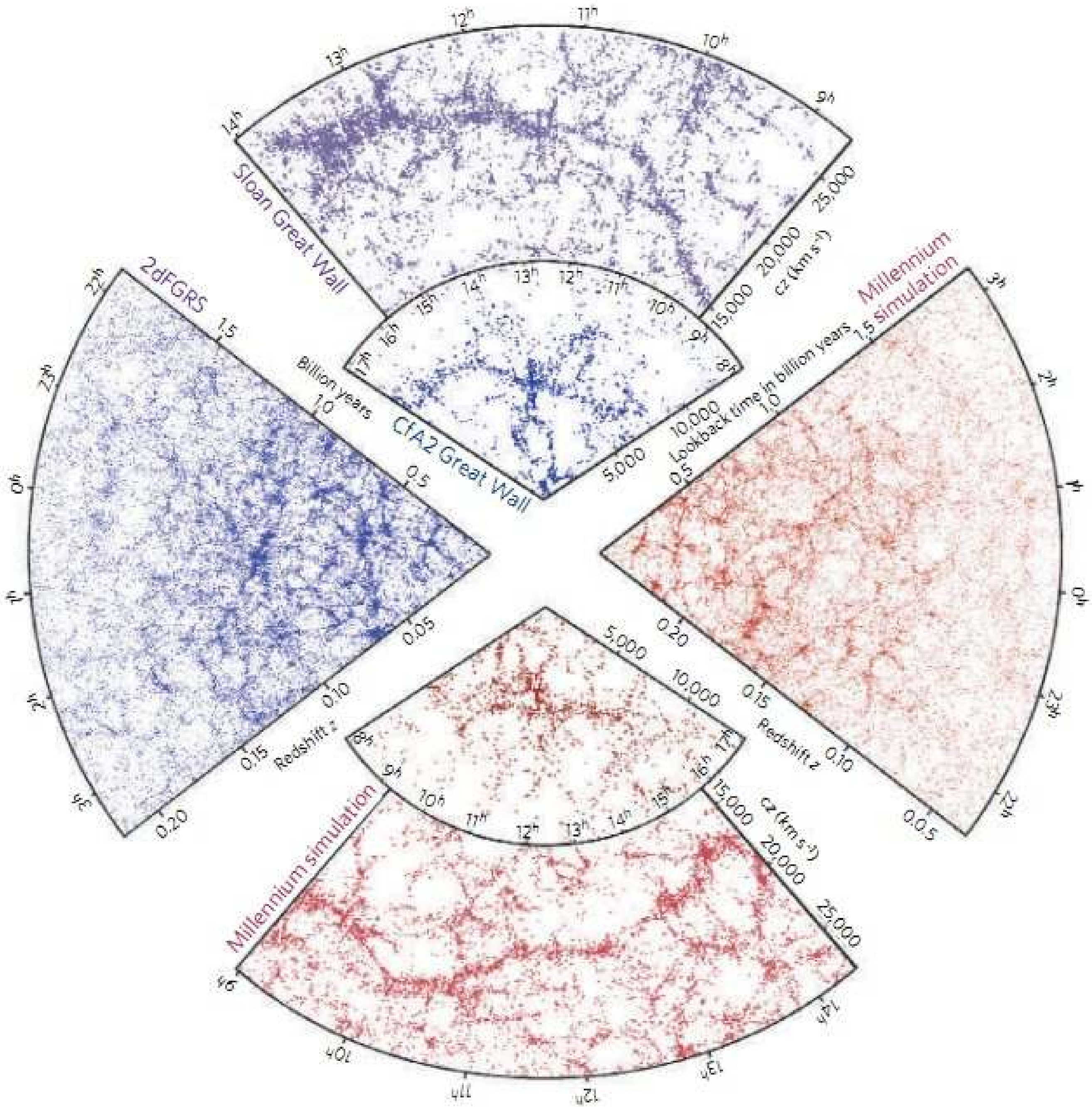
Cold DM was nonrelativistic at freeze-out; structure can form at all relevant scales

Hot DM (*e.g.,* neutrinos) was relativistic; structures at small scales get wiped out by free-streaming over comoving length scale $\sim 3\ \mathrm{Mpc}$

Warm DM has mass $\sim$ temperature of universe at time of matter-radiation equality, $\sim 1\ \mathrm{keV}$.

Numerical simulations of large scale structure show agreement with observations for CDM but not HDM.

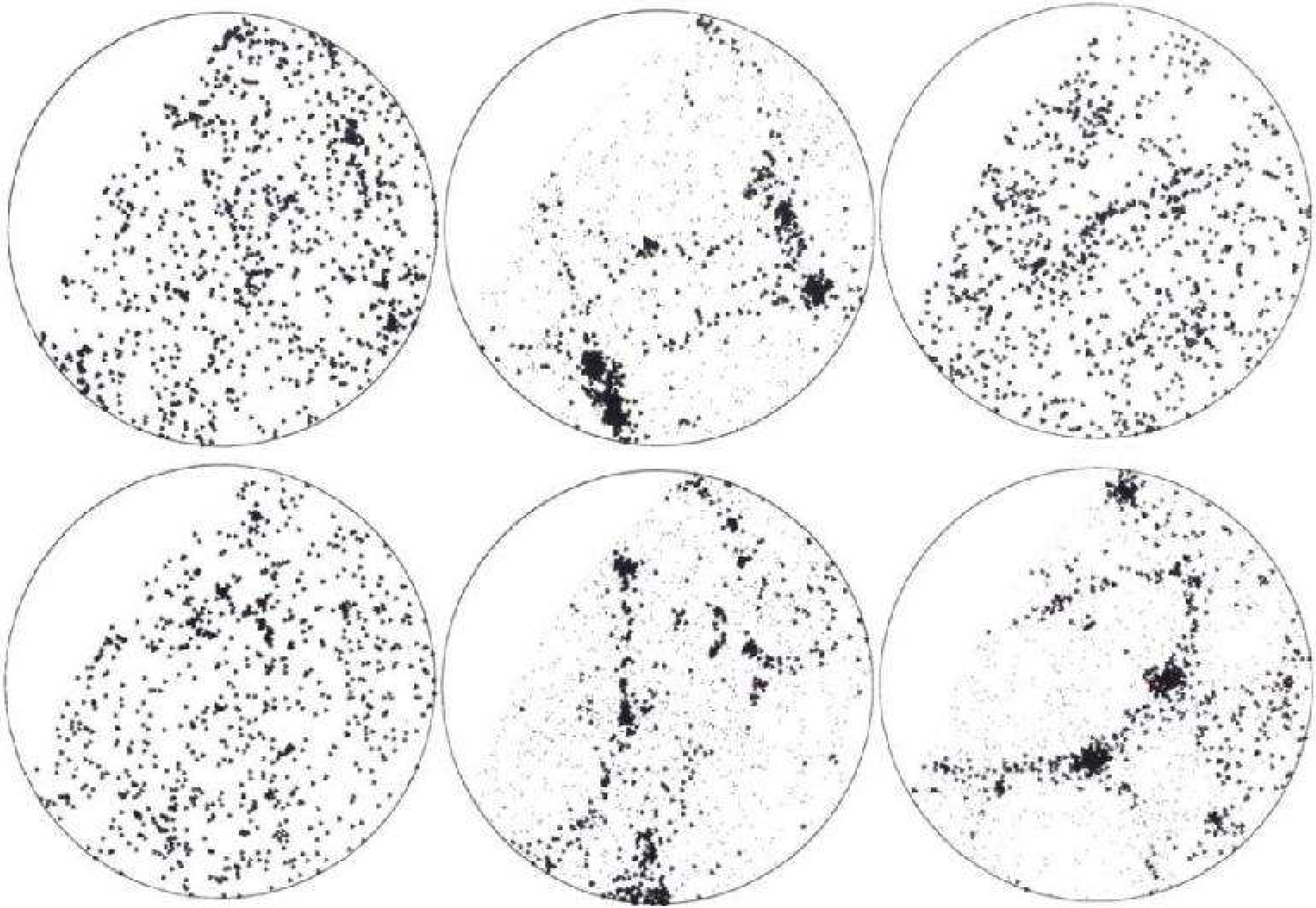
Cold DM agrees with observations



Simulations versus Sloan Digital Sky Survey data

Springel, Frenk & White, Nature **440**, 1137 (2006)

Hot DM doesn't



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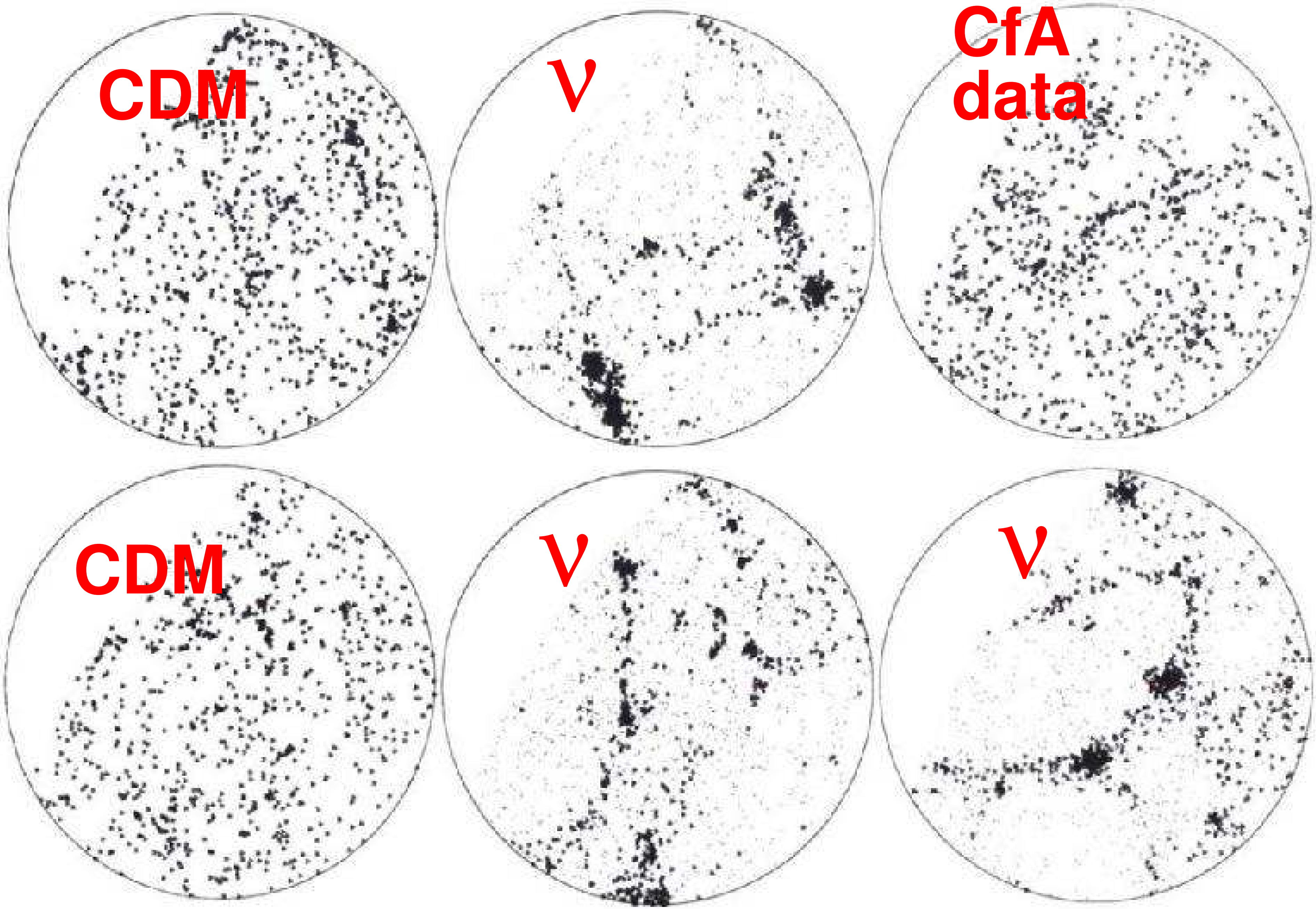


Frenk & White, arXiv:1210.0544

Must cold DM be heavy?

Usually CDM has $m \gg 1\ \mathrm{keV}$, HDM has $m \ll 1\ \mathrm{keV}$.

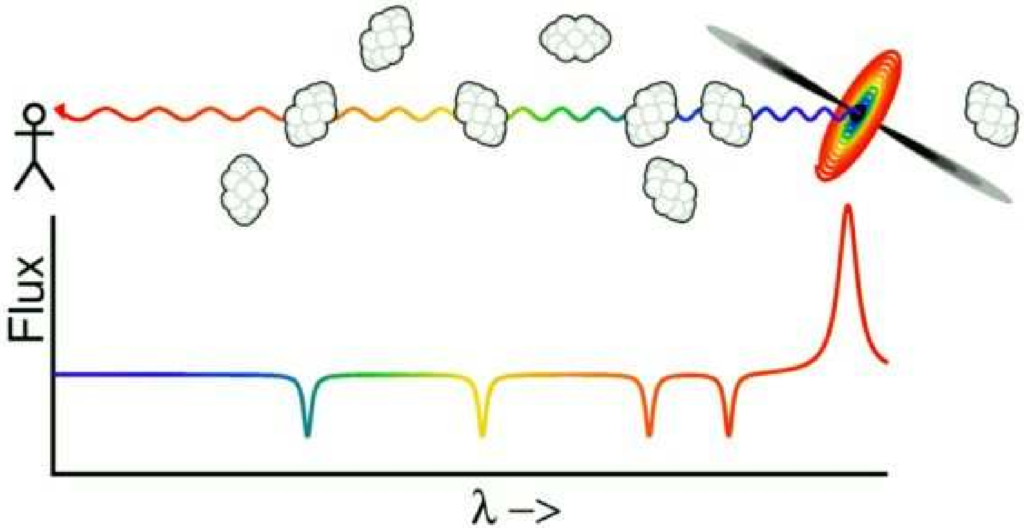
But axions with $m < 10^{-3}\ \mathrm{eV}$ are still CDM.

They went out of equilibrium long before matter-radiation equality, so their temperature redshifts to values much lower than $1\ \mathrm{keV}$ at that time.

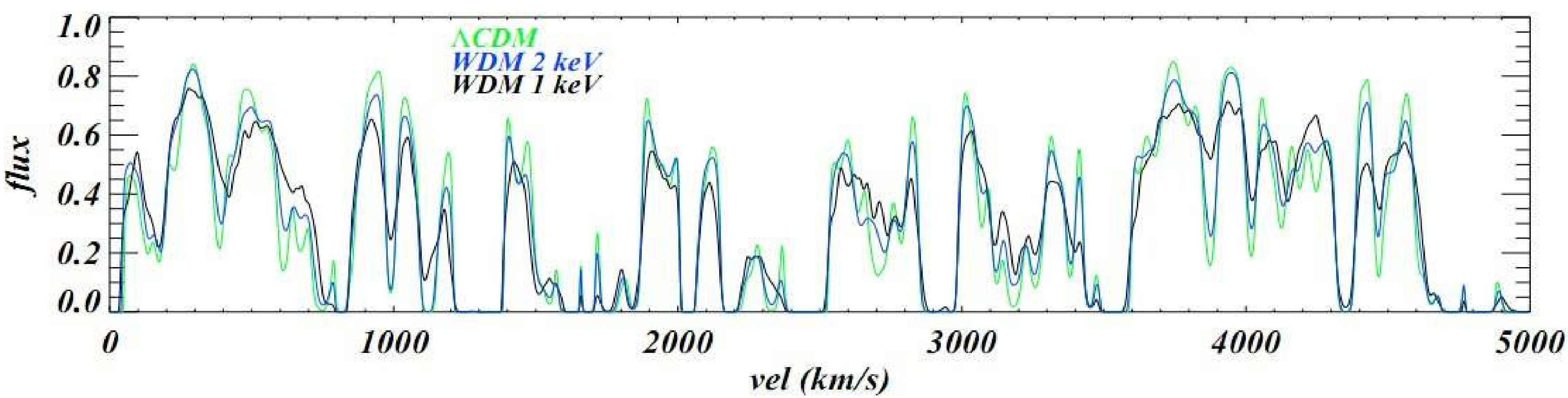
Temperature of a dark matter candidate depends upon its thermal history.

Lyman-α constraint on WDM

Warm dark matter, if too warm, suppresses power in structures at scales probed by Lyman-α forest measurements



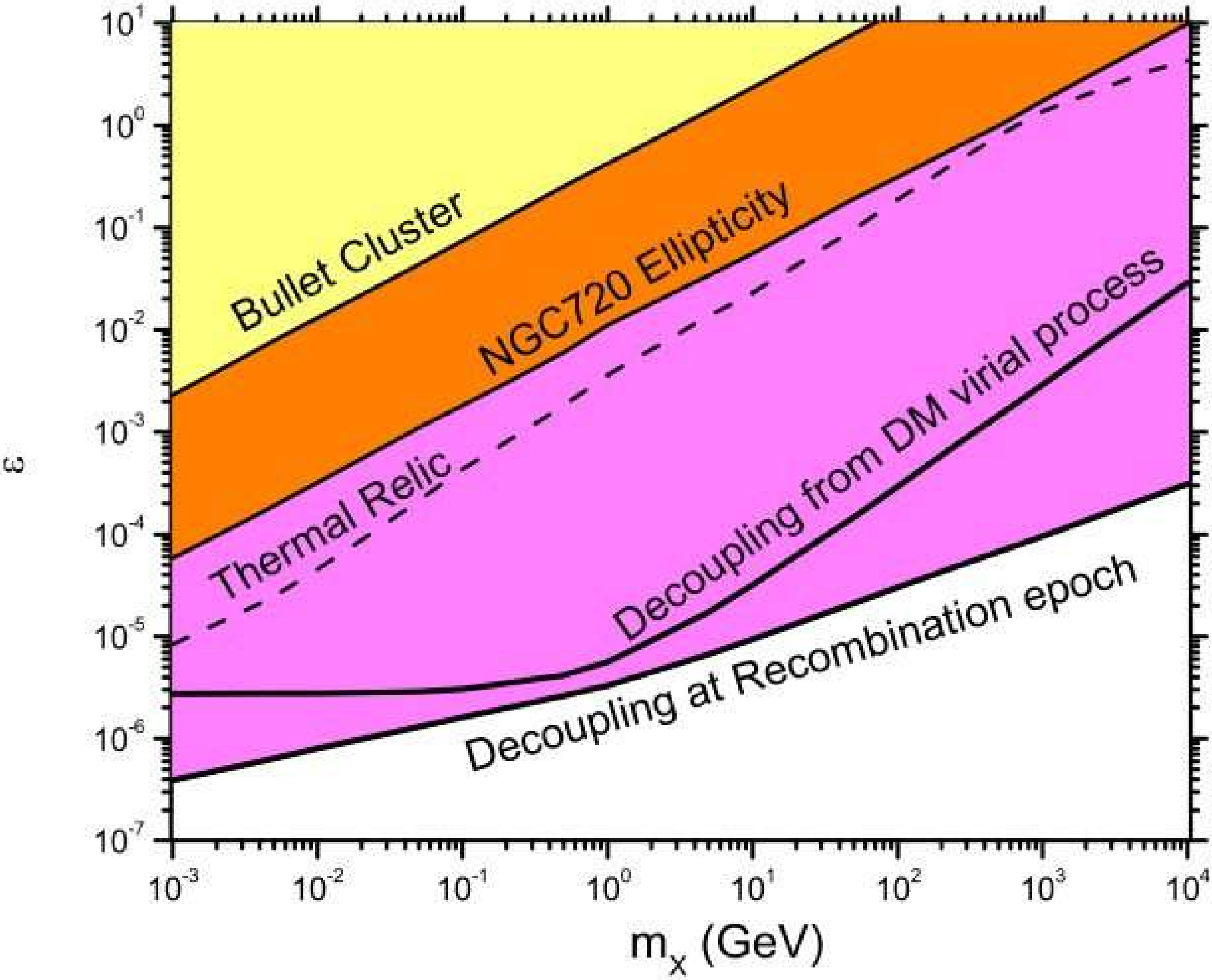
Viel *et al.* (1306.2314) compare simulations to observations



Find $m > 3.3\ \mathrm{keV}$ at 95% c.l.

How Dark must DM be?

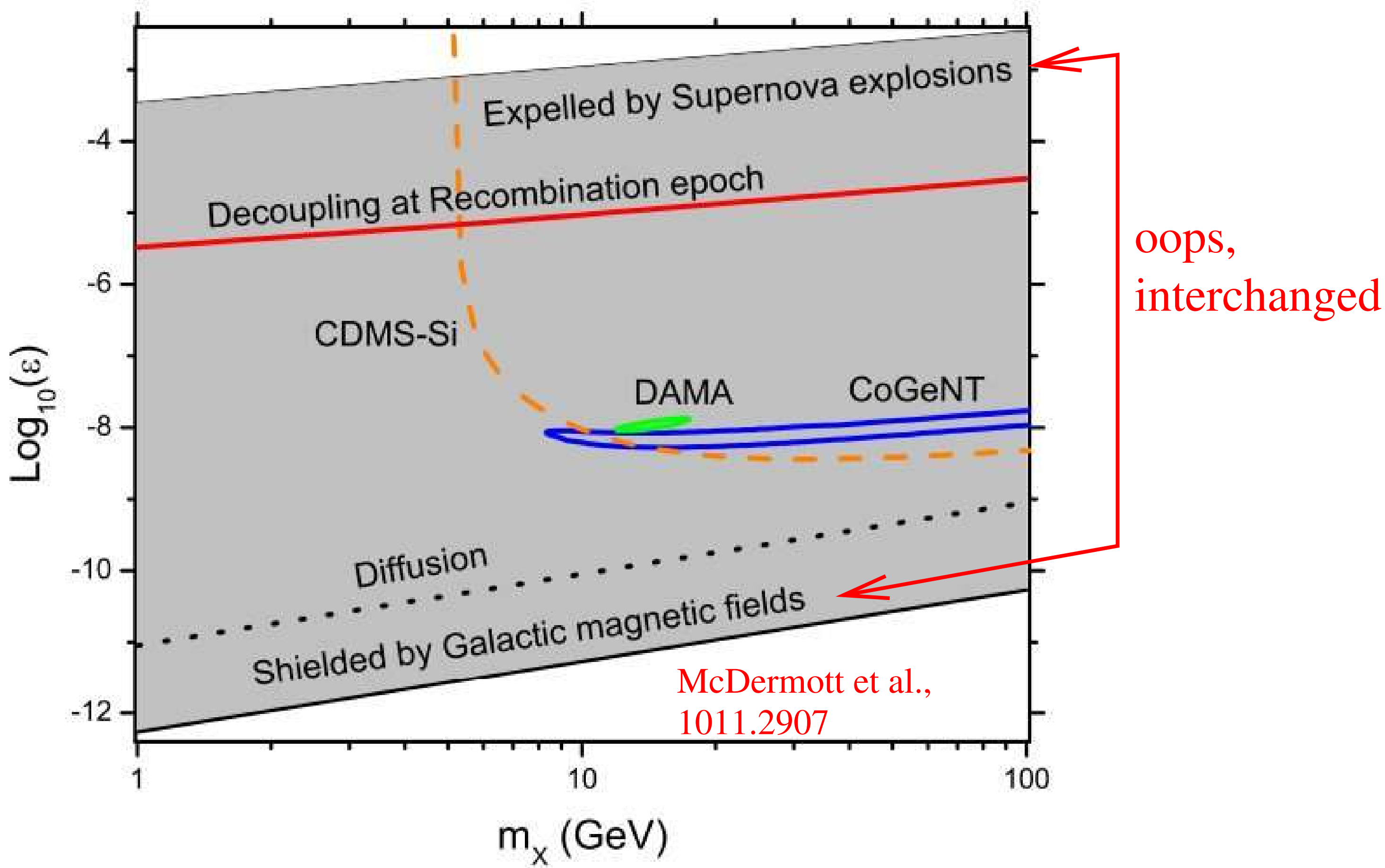
Suppose it has small electric charge ϵe. McDermott *et al.* (1011.2907) find various constraints on ϵ versus DM mass



How Dark must DM be?

These constraints can be relaxed by charged dark matter being expelled from the galaxy by supernova shock waves

(Chuzhoy and Kolb, 0809.0463)



But then there will be no direct detection signal (CDMS, DAMA, CoGeNT)

Can DM be self-interacting?

Bullet cluster can tolerate a certain level of DM self interactions, Randall *et al.,* (0704.0261),

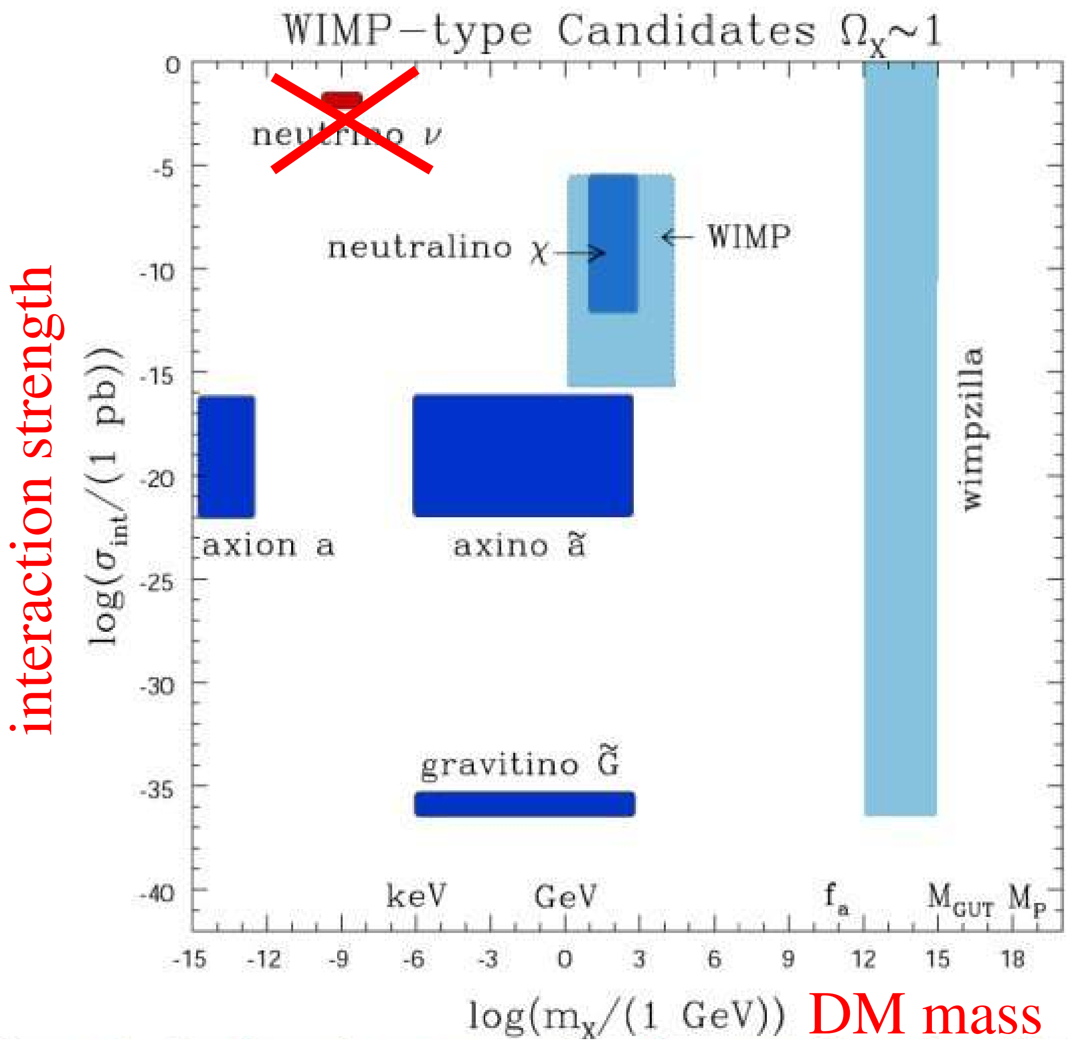
$$\frac{\sigma}{m} \lesssim 0.7 \text{ b/GeV}$$

(recall $1 \text{ b} = 10^{-24} \text{ cm}^2$).

A similar limit arises from cosmological simulations of galaxy structure (Rocha *et al.,* 1208.3025 & 1208.3026)

Saturating this limit could solve claimed problems for DM: cuspy versus cored halos, lack of large satelllite galaxies predicted by simulations (Weinberg *et al.,* 1306.0913)

Expectations for DM mass / interactions



L. Roszkowski
hep−ph/0404052

(WIMP = weakly interacting massive particle)

A priori we haven’t a clue, but historically the supersymmetric neutralino was a highly motivated candidate, subject to direct detection

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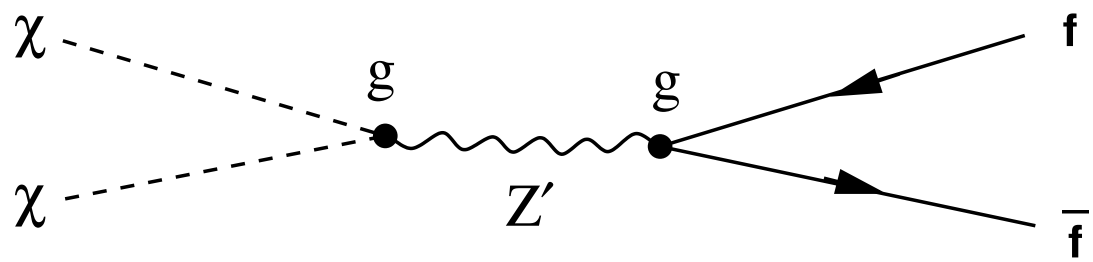
Cosmological Origin of Dark Matter

How did DM come to have its present relic density?
There are three main ideas:

- Thermal freeze-out: symmetric DM
  (DM is its own antiparticle)
- A dark genesis mechanism: asymmetric DM
  (DM has a conserved number)
- Thermal "freeze-in:" extremely weakly interacting DM

Freeze-out

Imagine DM interactions with standard model were in equilibrium at very high temperatures, *e.g.,* annihilation via heavy Z' boson.



If $m_{Z'} \gg m_\chi$, and χ is nonrelativistic, rate goes like

$$\Gamma = n_\chi \langle \sigma v \rangle_{\rm ann} \sim (m_\chi T)^{3/2} e^{-m_\chi/T} \left(\frac{g^4 m_\chi^2}{m_{Z'}^4} \right).$$

Goes out of equilibrium when $\Gamma = H \sim T_f^2/M_p$; freeze-out temperature is

$$T_f \sim \frac{m_\chi}{\ln(\sigma M_p m_\chi^{3/2}/T_f^{1/2})} \sim \frac{m_\chi}{\ln(\sigma M_p m_\chi)}$$

What is the final abundance of χ?

Relic density estimate

We can estimate $n_\chi \sim \Gamma/\sigma \sim H(T_f)/\sigma \sim T_f^2/M_p\,\sigma$.
Then DM-to-photon abundance is

$$y_\chi \;=\; \frac{n_\chi}{n_\gamma} \;\sim\; \frac{1}{T_f M_p\,\sigma} \;\sim\; \frac{\ln(\sigma M_p m_\chi)}{m_\chi M_p\,\sigma}$$

and DM fraction of critical energy density of universe is

$$\Omega_\chi = \frac{\rho_\chi}{\rho_c} = \frac{m_\chi y_\chi n_\gamma}{\rho_c} \;\sim\; \frac{10^7 \ln(\sigma M_p m_\chi)}{\text{GeV}\;M_p\,\sigma} \;\cong\; 0.265 \text{ (Planck)}$$

Depends only weakly on m_χ, and requires (for $m_\chi \sim 100$ GeV)

$$\sigma \sim 10^{-10}\,\text{GeV}^{-2} \sim G_F^2$$

a weak-interaction-scale cross section! (note, $\log(\sigma M_p m_\chi) \sim 27$)

This is the WIMP (Weakly Interacting Massive Particle) "miracle" — or is it just a coincidence?

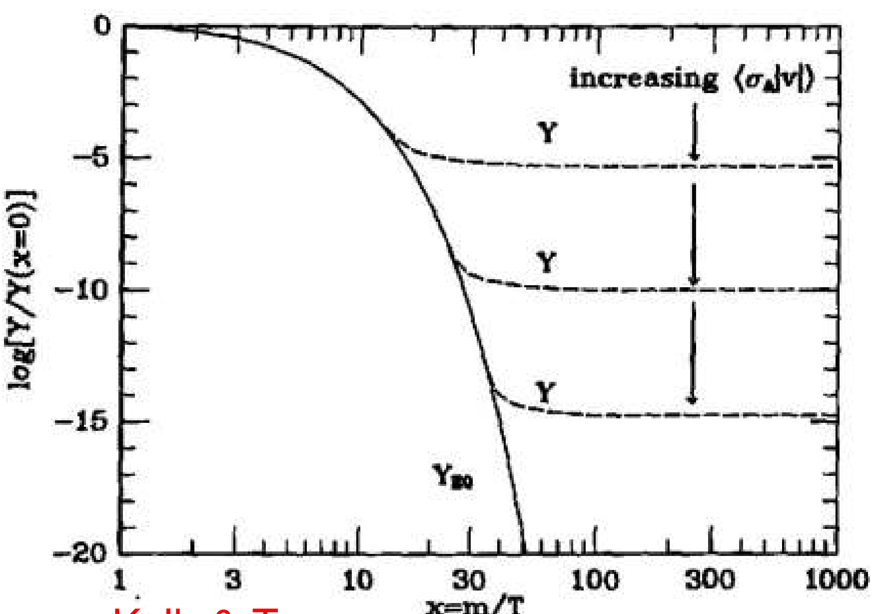
More quantitative: Boltzmann eq.

(Lee & Weinberg, PRL **39**, 165 (1977); Kolb & Turner, *The Early Universe*)

To more accurately determine relic density, we must solve the Boltzmann (Lee-Weinberg) equation,

$$\frac{dY}{dx} = -\frac{x\, s\langle\sigma v\rangle_{\rm ann}}{H(m_\chi)}\left(Y^2 - Y_{\rm eq}^2\right)$$

where $Y = n_\chi/s$, $\quad x = m_\chi/T$ plays role of time, entropy density $s = (2\pi^2/45)g_{*s}T^3 \sim x^{-3}$, and Hubble rate $H(m_\chi)$ is evaluated at $T = m_\chi$.



Kolb & Turner

Y tracks equilibrium density,

$$Y_{\rm eq} \cong 0.145\,\frac{g}{g_{*s}}\,x^{3/2}\,e^{-x}$$

at early times, then freezes out at

$$T = T_f \sim \frac{m_\chi}{\ln(\sigma m_\chi M_p)}$$

Thermal averaging

$\langle \sigma v \rangle$ is averaged with the thermal distribution functions. In Maxwell-Boltzmann approximation (Gondolo, Gelmini, Nucl. Phys. B360, 145 (1991))

$$\langle \sigma v_{\text{Møl}} \rangle = \frac{1}{8m^4 T K_2^2(m/T)} \int_{4m^2}^{\infty} \sigma(s - 4m^2)\sqrt{s}\, K_1(\sqrt{s}/T)\, ds$$

where $s =$ Mandelstam invariant.

Often (if annihilation is s-wave into light particles) it is sufficient to simply evaluate σv at kinematic threshold, $s = 4m_\chi^2$:

$$\langle \sigma v \rangle \cong \lim_{v \to 0} \sigma v = \frac{|\mathcal{M}|^2}{32\pi\, m_\chi^2}$$ (PDG, eq. (46.32))

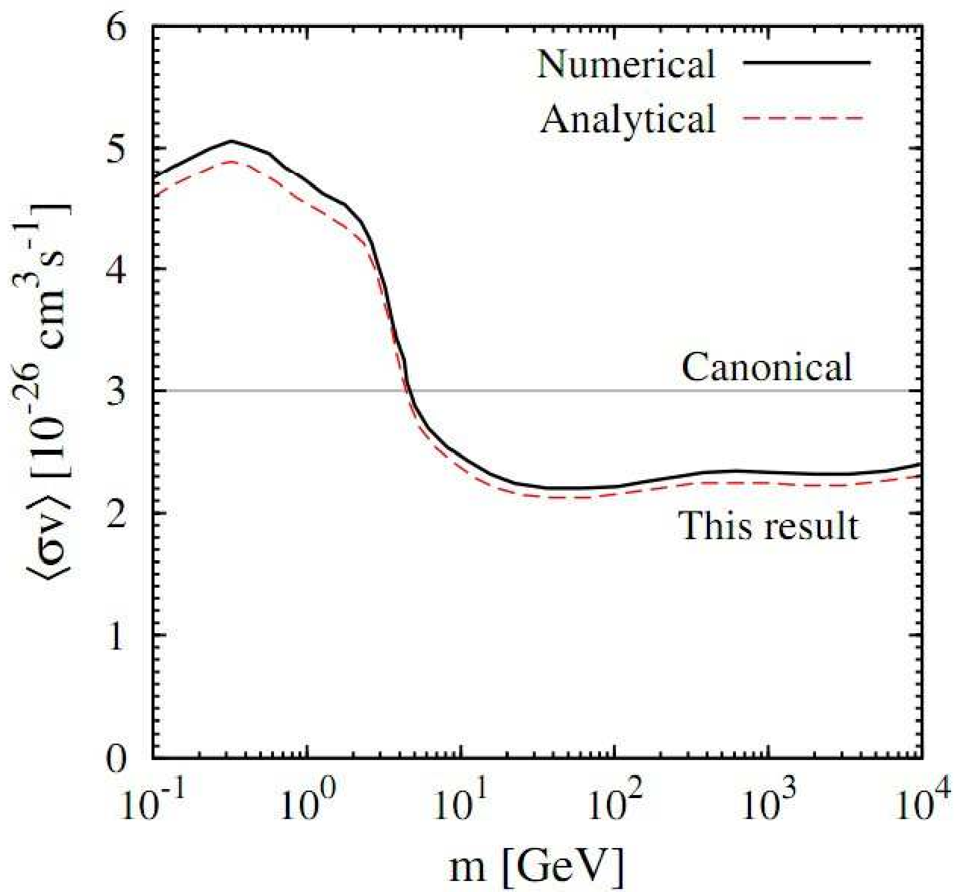
But if $\sigma \sim v^2$ (p-wave suppressed) or if there is a nearly on-shell resonance, $\sigma \sim 1/|s - m^2 + 2i\Gamma m|^2$ with $m \sim m_\chi/2$, then more exact thermal averaging is important. (s can move closer to or farther from the pole in the integration, relative to threshold approximation $s \cong 4m_\chi^2$.)

Relic density short-cuts

Recall that $\Omega_\chi \sim 1/\sigma$ with weak dependence on m_χ. In the simple s-wave annihilation case, one can use the "canonical" estimate

$$\langle \sigma v \rangle \cong 3 \times 10^{-26}\,\mathrm{cm}^3/s$$

To be more exact, use this m_χ-dependent result:



This is for Majorana or real scalar DM. For Dirac or complex scalar, must double the cross section to suppress density, since antiparticles contribute equally

Steigman, Dasgupta, Beacom, 1204.3622.

Semianalytic solution of Boltzmann eq.

Approximation schemes allow quantitative solution of Boltzmann eq. without full numerical integration.

Method described by Kolb and Turner has been improved (1204.3622 & 1306.4710.) Change variables, $Y = (1+\delta)Y_{\rm eq}$. Then $d\delta/dx$ remains $\ll \delta$ even to freeze-out and can be ignored; Boltzmann eq. becomes algebraic!

Suppose $\delta = \delta_f$ at freeze-out. Can solve for x_f analytically in terms of δ_f. Then at freeze-out,

$$Y_f = (1+\delta_f)\,Y_{\rm eq}(x_f)$$

Integrate Boltzmann eq. from x_f to ∞ neglecting $Y_{\rm eq}^2$ term — can do analytically up to an integral:

$$Y_{\rm today} = \frac{Y_f}{(1+Y_f A_f)}, \quad A_f = \sqrt{\frac{\pi}{45}}\, m_\chi M_p \int_{x_f}^\infty dx\, \frac{\sqrt{g_{*s}(x)}\langle\sigma v\rangle(x)}{x^2}^{\;*}$$

Choose $\delta_f \sim 1$; result is insensitive at level of $< 1\%$ for $\delta_f = 1 \pm 0.5$

*note: integral $\cong \sqrt{g_{*s}}\langle\sigma v\rangle/x_f$

Asymmetric DM

Suppose DM is a Dirac fermion or charged scalar, with a conserved particle number.

$\chi \neq \bar{\chi}$: DM particles and antiparticles are distinct.

If $\chi\bar{\chi}$ annihilation cross section is large, then symmetric contribution to relic density can be neglected.

Need a χ-$\bar{\chi}$ asymmetry, analogous to the baryon asymmetry.

If $n_\chi = n_{\bar{\chi}}$ in early universe, need a DM-genesis mechanism, similar to baryogenesis.

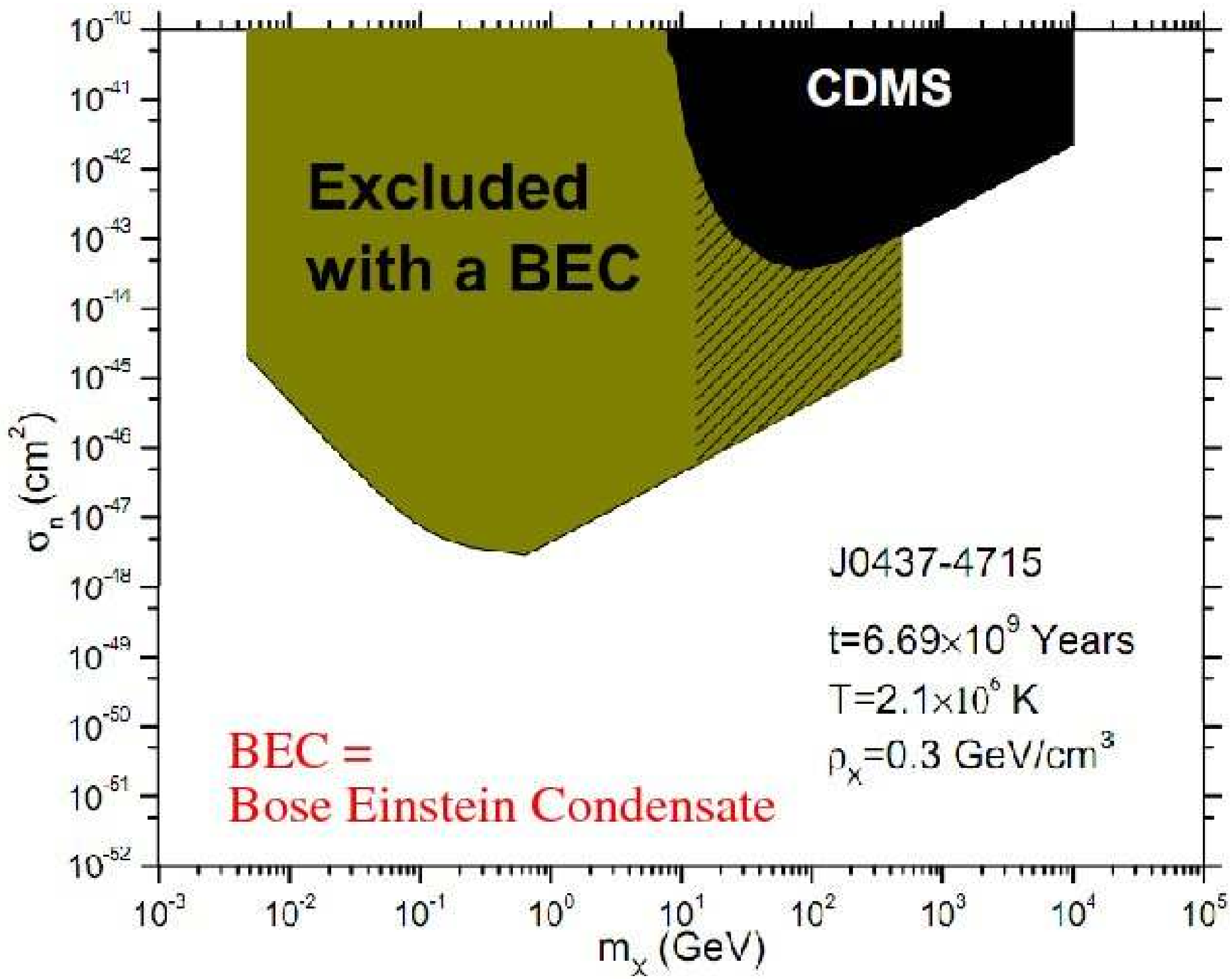
Perhaps DM genesis and baryogenesis are related? Could explain the coincidence $\Omega_\chi = 5.3\,\Omega_b$, especially if $m_\chi \sim 5\,m_p$

Sounds simple, but unfortunately concrete realizations seem to be quite complicated.

Asymmetric DM features

Zurek, 1308.0338

Constraints from indirect detection can be much weaker since $\chi\chi \to f\bar{f}$ is greatly suppressed (symmetric component of DM density is small)



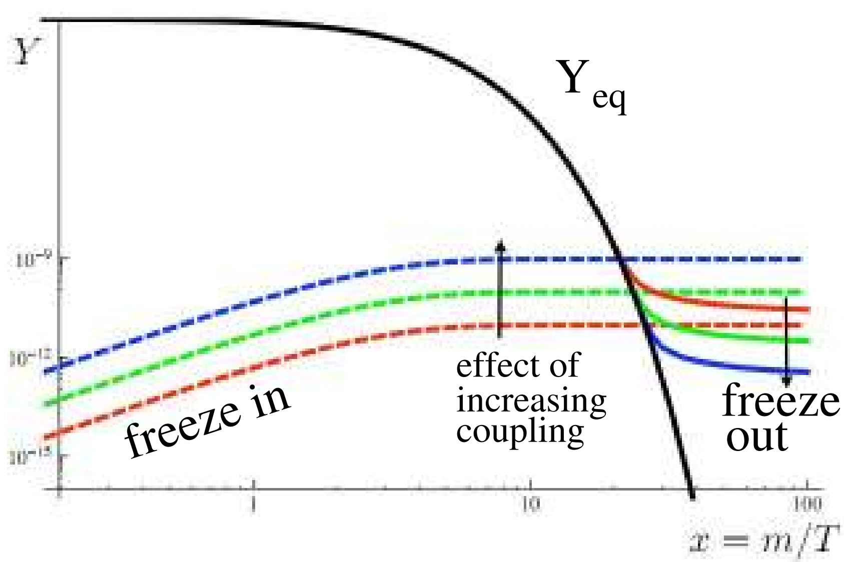
Constraints on χ-nucleon scattering from neutron stars can be much stronger if χ is bosonic, because it accumulates inside the star and can cause gravitational collapse (fermi pressure prevents this for fermionic χ)

Freeze-in mechanism

In freeze-out, DM interactions start out strong and Y_χ reaches $Y_{\rm eq}$ from above.

Suppose DM interactions with SM are so weak they were never in equilibrium, and $Y_\chi \ll Y_{\rm eq}$.

Then Y_χ can slowly grow and "freeze in" to some constant value (Hall *et al.*, 0712.2312)



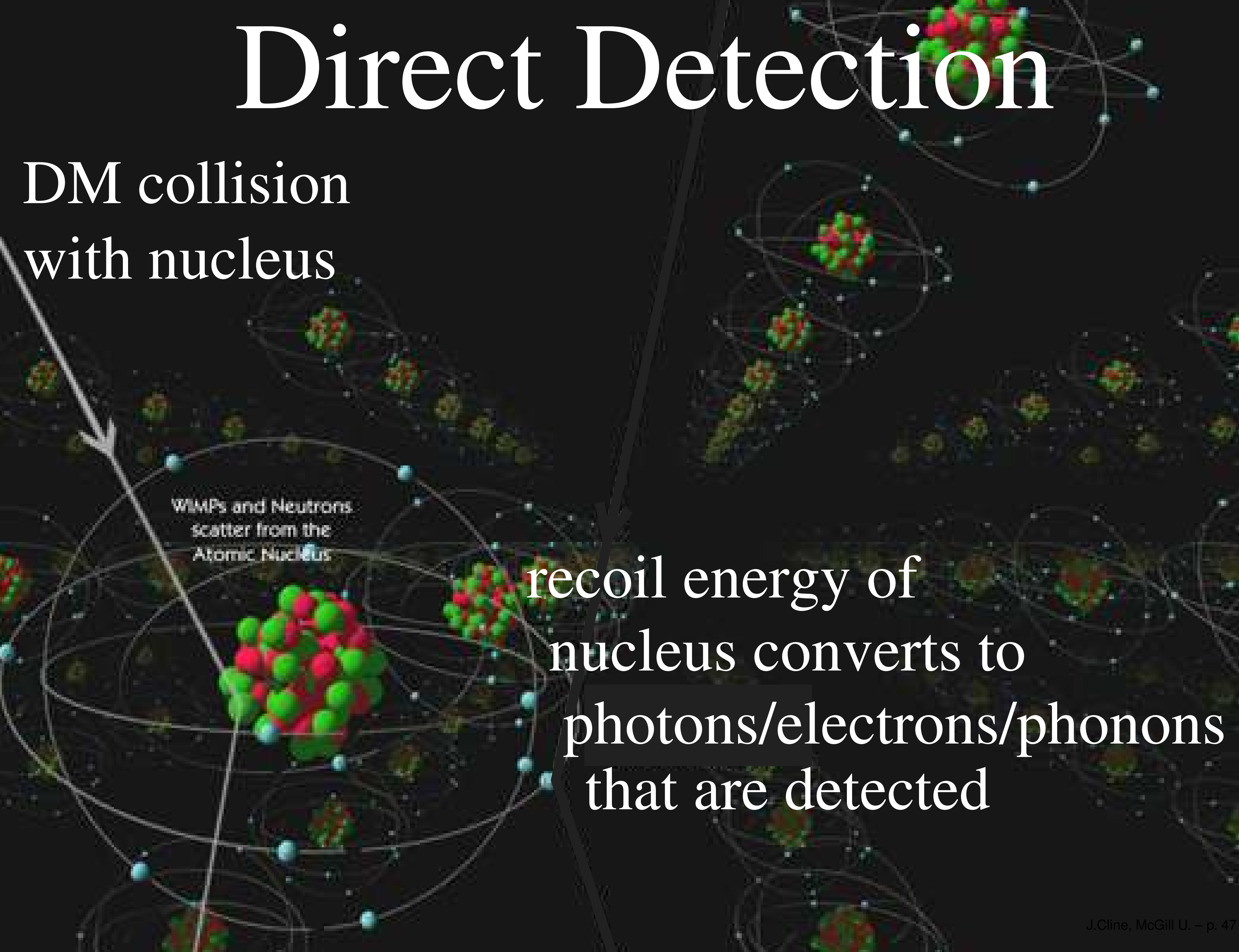
With dimensionless coupling λ, relic abundance goes like

$$Y \sim \lambda^2 \frac{M_p}{m_\chi}$$

instead of $1/(\sigma M_p m_\chi)$. Need $\lambda \sim 10^{-11} - 10^{-12}$ for correct relic density.

Direct Detection

DM collision
with nucleus

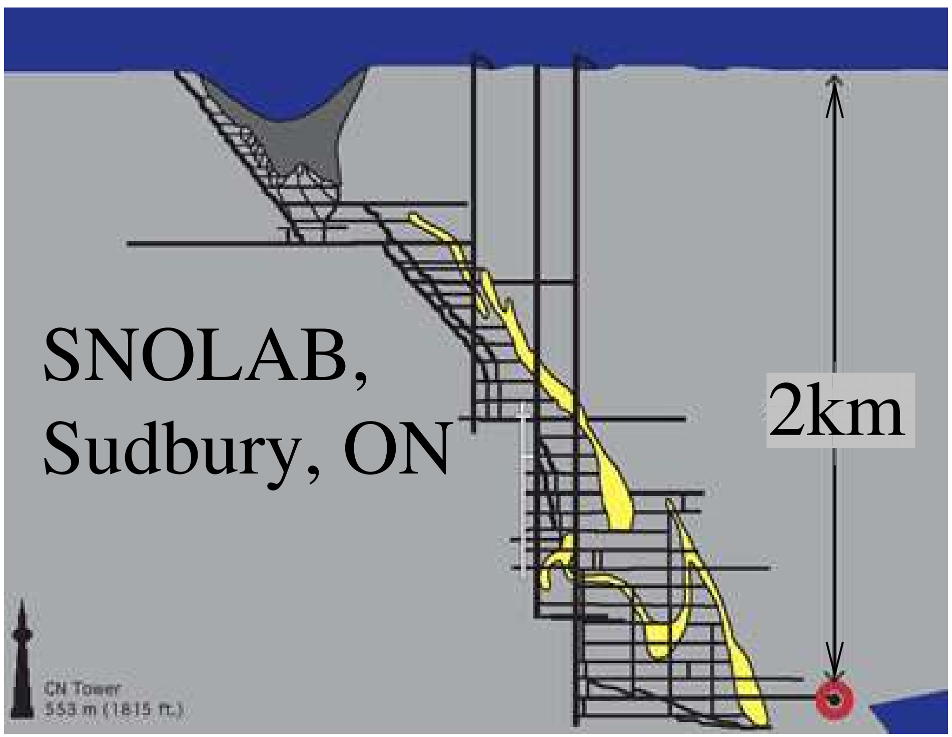


recoil energy of
nucleus converts to
photons/electrons/phonons
that are detected

A challenging undertaking

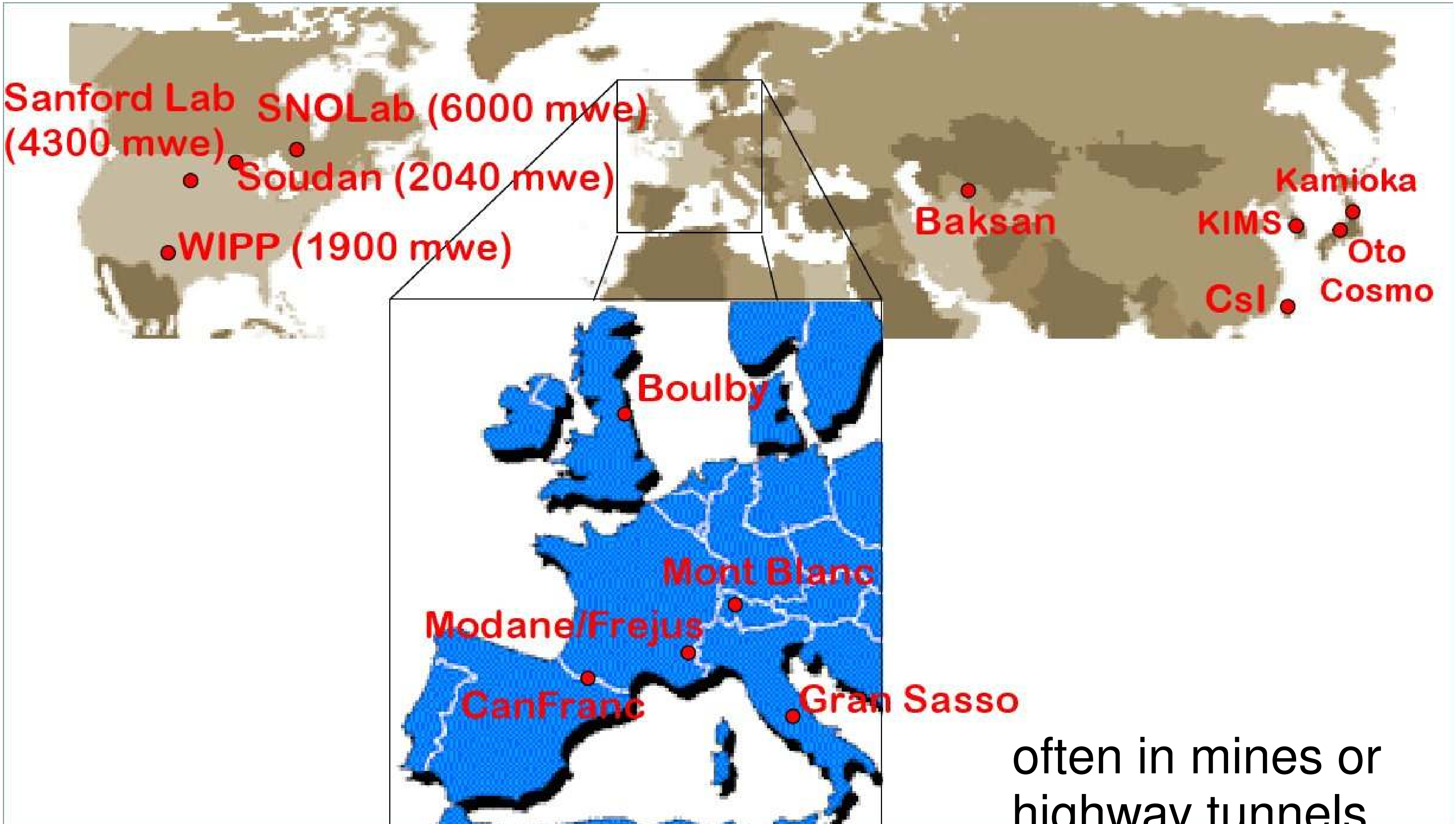
DM interacts with normal matter very weakly, if at all

Need big and well-shielded targets to maximize signal and minimize cosmic ray backgrounds



A worldwide effort

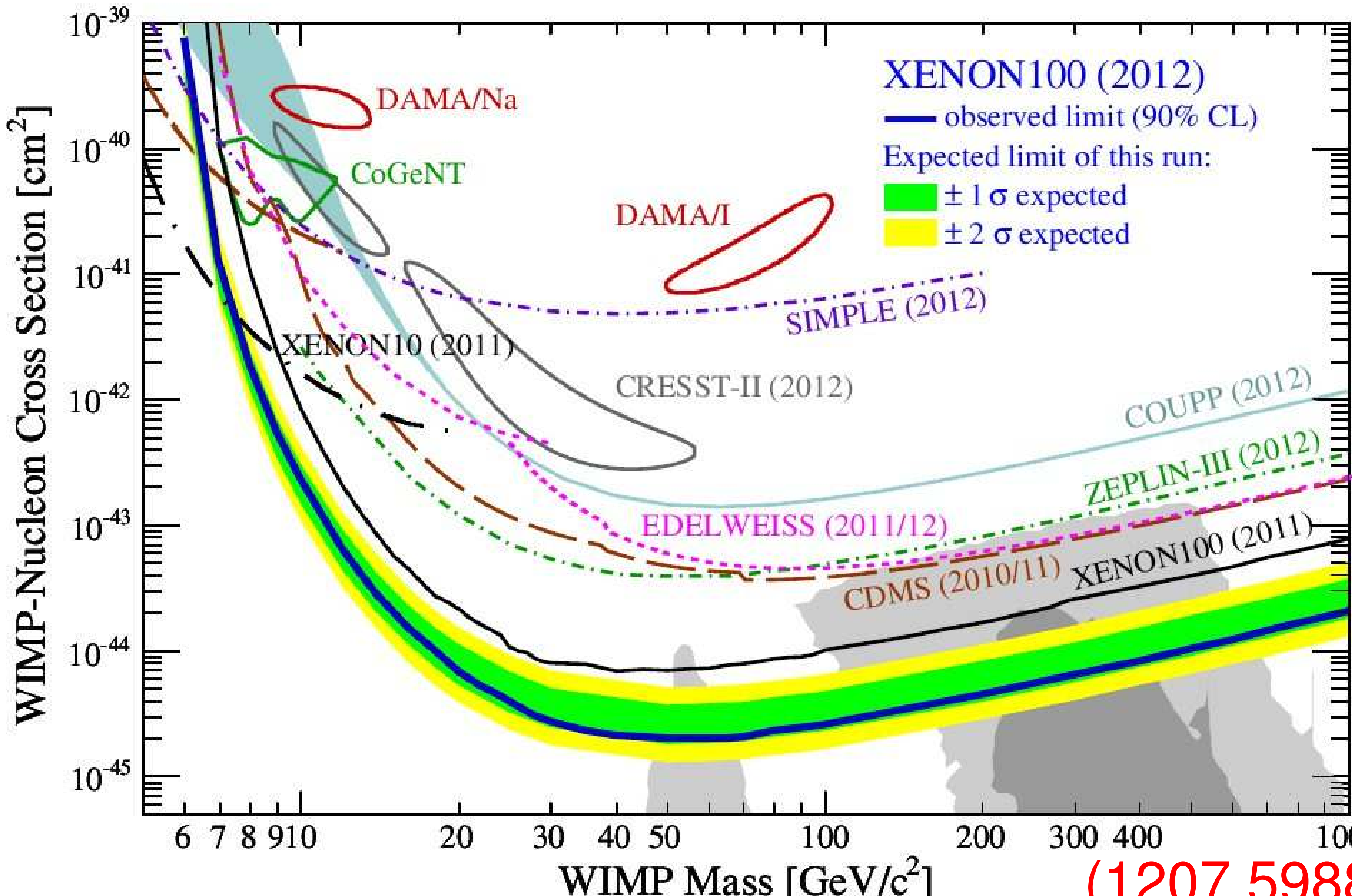
Underground laboratories



often in mines or
highway tunnels

2012 limits on DM-nucleon scattering

XENON100 formerly had strongest limit on DM-nucleon scattering cross section, $\sigma \lesssim 10^{-45}\mathrm{cm}^2$ for $m_\chi \gtrsim 20$ GeV

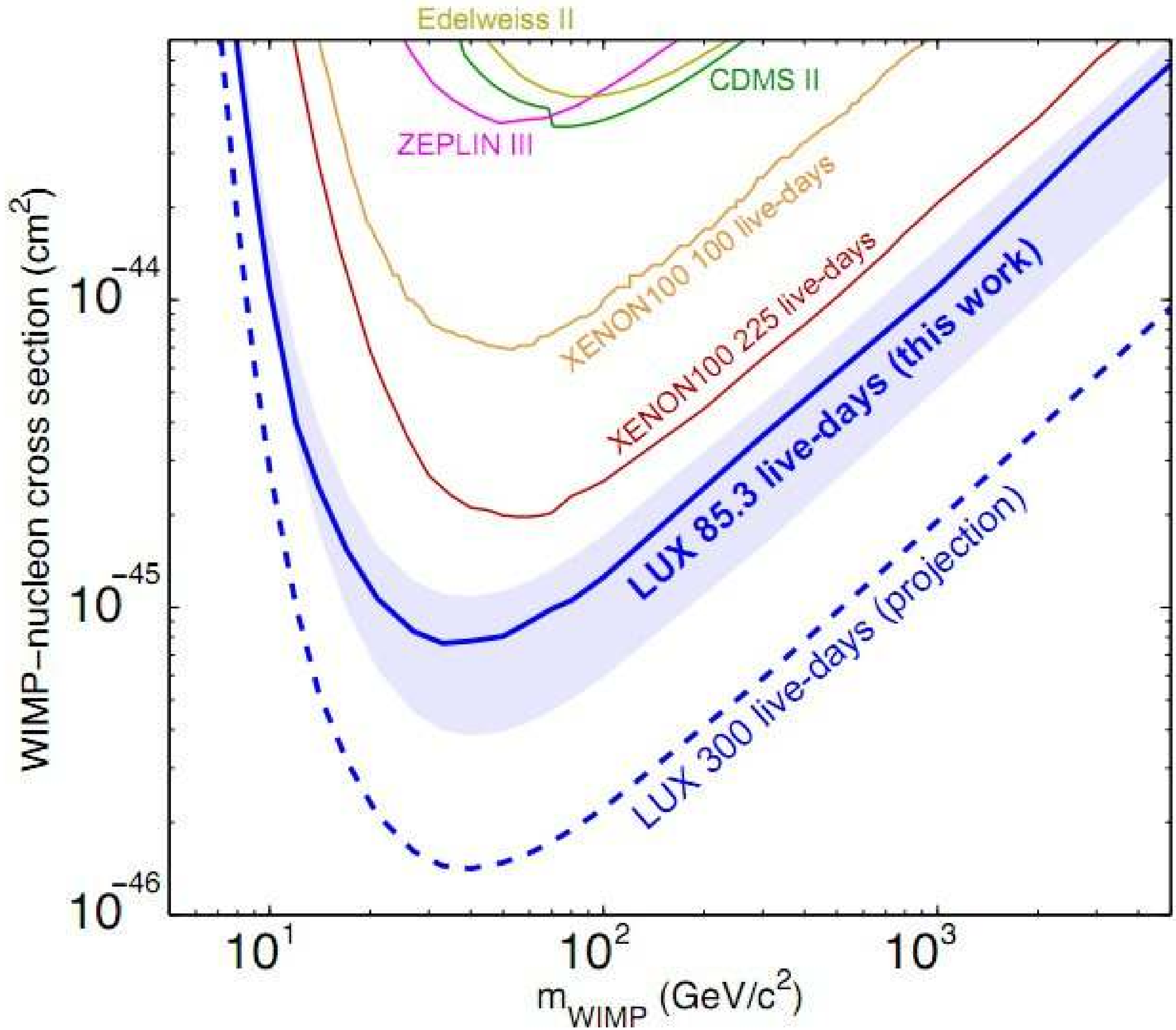


(1207.5988)

Compare to the size of a proton: $10^{-26}\mathrm{cm}^2$!

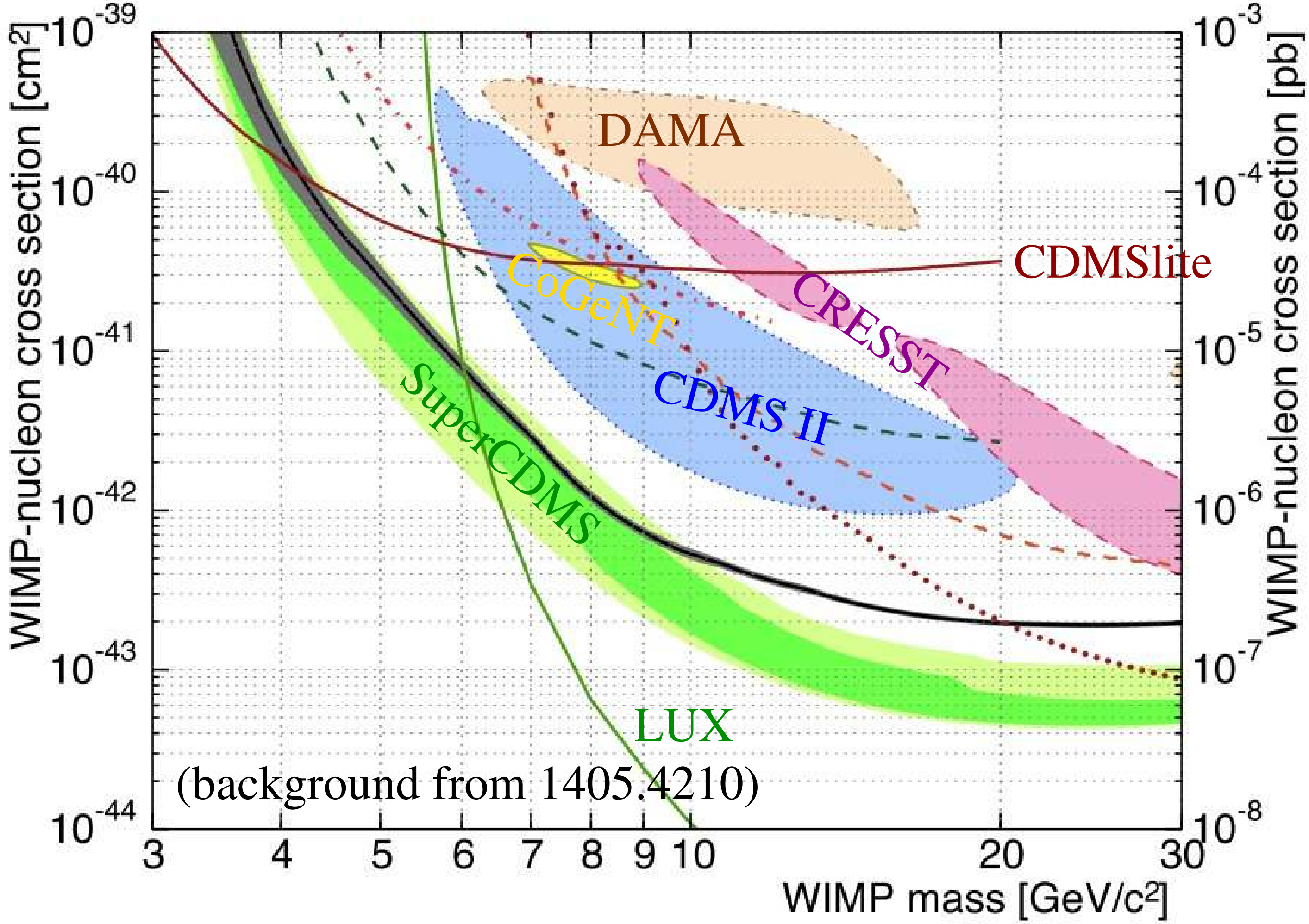
LUX limit on DM-nucleon scattering

At high DM masses, LUX (also liquid xenon) now sets the limit (1405.5906)



Hints of direct detection at low mass

DAMA, CoGeNT, CRESST and CDMSII had excess events that might have been DM. But simplest models are excluded by other experiments.



Spin-dependent scattering limits

If DM interacts only with nucleon spin, limits are much weaker

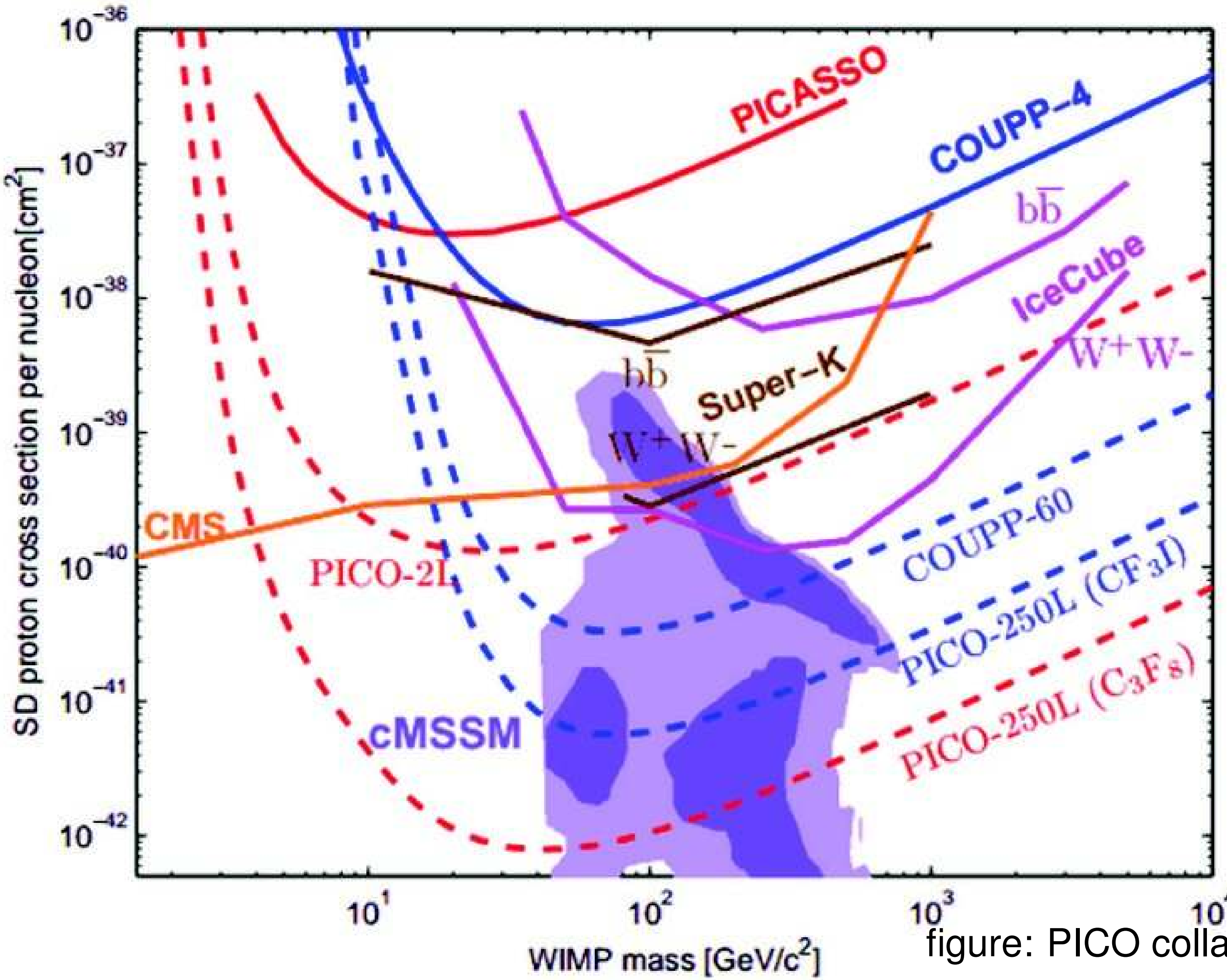


figure: PICO collaboration

PICO collaboration at SNOLAB will push limits (2017)

Direct detection event rate

Basic eq. for scattering rate on particles with density n:

$$\Gamma = n\langle\sigma v\rangle = n\int d^3v\, v\, f(v)\sigma$$

For DM detection, we want differential rate R w.r.t. nuclear recoil energy $E_{\rm nr}$, per mass m_N of target nucleus:

$$\frac{dR}{dE_{\rm nr}} = \frac{\rho_\odot}{m_\chi\, m_N}\,\epsilon_{\rm eff}(E_{\rm nr})\int_{v_{\rm min}}^{\infty} d^3v\, v\, f(v)\frac{d\sigma_N}{dE_{\rm nr}}$$

$\epsilon_{\rm eff}$ is detector efficiency. DM density in solar neighborhood: $\rho_\odot = (0.3-0.4){\rm GeV/cm}^3$ (Green, 1112.0254). In c.m. frame,

$$E_{\rm nr} = \mu_N^2 v^2(1-\cos\theta)/m_N$$

with $\mu_N = m_\chi m_N/(m_\chi + m_N)$, hence minimum DM velocity is

$$v_{\rm min} = \left(m_N E_{\rm nr}/2\mu_N^2\right)^{1/2}$$

DM phase space distribution

Detection rate has important astrophysical uncertainties. Velocity distribution in galactic rest frame is typically taken as

$$f(v) = N\left(e^{-v^2/v_c^2} - e^{-v_{\rm esc}^2/v_c^2}\right)\Theta(v_{\rm esc} - v)$$

with circular velocity $v_c = 220 \pm 20\ (279 \pm 33?)^*\ \mathrm{km/s}$ and escape velocity $544 \pm 64^\dagger\ (490 - 730?)^\#\ \mathrm{km/s}$. But in earth rest frame, $v \to |\vec v + \vec v_E|$, with

$$v_E = v_c + 12\ \mathrm{km/s} + (26\ \mathrm{km/s})\cos(2\pi(t - t_p)/1\,\mathrm{y})$$

with $t_p = \mathrm{June}\ 2 \pm 1.3\ \mathrm{d}$. Leads to annual modulation of signal.

Most experiments assume central values of v_c and $v_{\rm esc}$ to calculate limits. Later we will discuss ways of factoring out these uncertainties in comparing different experiments.

* (0907.4685) † (astro-ph/0611671) $^\#$ (1003.0014)

Spin-independent scattering

Jungman *et al.*, (hep-ph/9506380)

In many models, DM couples to proton or neutron number with relative strengths f_p, f_n. Let σ_n be cross section for $\chi n \to \chi n$ scattering on a free proton. Then

$$\frac{d\sigma_{N,SI}}{dE_{\rm nr}} = \frac{m_N}{2v^2}\,\frac{\sigma_{p,SI}}{\mu_p^2}\,\left[Z + (f_n/f_p)(A-Z)\right]^2\,F^2(E_R)$$

with $\mu_p = m_p m_\chi/(m_p+m_\chi)$, $Z, A =$ atomic number and weight, $v =$ DM velocity, $F =$ Helm (Woods-Saxon) nuclear form factor $\cong 0.9 - 1$,

$$F = \left(\frac{3j_1(qR_1)}{qR_1}\right)^2 e^{-q^2 s^2}$$

depending on momentum transfer $q = \sqrt{2m_N E_{\rm nr}}$, $s \cong 1$ fm and size of nucleus is $R_1 \cong \sqrt{1.44\, A^{2/3}\ {\rm fm}^2 - s^2}$.

$[Z + \cdots]^2$ reflects coherence of scattering, F quantifies structure of nucleus. Coherence boosts $\sigma_{N,SI}$ by $\sim A^2$ for large nuclei.

SI-scattering details

σ_p ($p =$ proton) is defined in limit of zero momentum transfer:

$$\sigma_{N,SI}(0) = \sigma_{p,SI}\left(\frac{\mu_N}{\mu_p}\right)^2 \left[Z + (f_n/f_p)(A-Z)\right]^2$$

Here

$$\left(\frac{\mu_N}{\mu_p}\right)^2 = \left(\frac{m_p}{m_N}\right)^2 \left(\frac{m_N + m_\chi}{m_p + m_\chi}\right)^2$$

The two factors come from

$$\sigma_i \sim g^4 \frac{|\bar{u}_i X u_i|^2}{16\pi s} \sim \frac{g^4}{16\pi}\frac{m_i^2}{(m_i + m_\chi)^2}$$

(where $i = n$ or N) not counting the coherence effect. From kinematics,

$$\frac{d\sigma_N}{dE_{\rm nr}} = \frac{m_N}{2\mu_N^2 v^2}\,\sigma_N(0)$$

Spin-dependent scattering Tovey *et al.*, (0005041)

If interaction is mediated by axial vector or pseudoscalar, there is a γ_5 in the nucleon vertex, giving coupling to nucleon spin ($\propto$ total J of nucleus),

$$\bar{N}\gamma_5 N \to -\frac{\vec{q}}{2m_N}\cdot N^\dagger\vec{\sigma}N, \quad \bar{N}\gamma_\mu\gamma_5 N \to \left(\frac{\vec{p}}{2m_N}\cdot N^\dagger\vec{\sigma}N,\ N^\dagger\vec{\sigma}N\right)$$

in nonrelativistic limit. Nucleon spins are paired up to one odd one, so there is no coherence, no A^2 or even J^2 enhancement (Engel & Vogel, PRD **40**, 3132 (1989)). Limits on SD cross section are weaker. Then

$$\sigma_{N,SD}(0) = \sigma_{p,SD}\cdot\frac{4}{3}\frac{J+1}{J}\left(\frac{\mu_N}{\mu_n}\right)^2\left[\langle S_p\rangle + (a_n/a_p)\langle S_n\rangle\right]^2$$

where $\langle S_{n,p}\rangle$ is nuclear matrix element of neutron/proton spins, and $a_{n,p}$ is DM coupling to single neutron/proton spin.

$\sigma_{N,SD} = 0$ unless N has odd number of nucleons.

SD-scattering details

Unlike SI case where typically $f_p = f_n$, for SD the ratio a_p/a_n (even the sign) depends strongly on DM model; experiments must make some assumption to report a SD limit.

To be general, experiments should report limits on both σ_n with $(a_p, a_n) = (0, 1)$ and on σ_p with $(a_p, a_n) = (1, 0)$.

Theorists can then constrain their favorite model using

$$\left(a_p \sqrt{\frac{\sigma_p}{\sigma_{p,\lim}}} + a_n \sqrt{\frac{\sigma_n}{\sigma_{n,\lim}}} \right)^2 < |a_p|^2 + |a_n|^2$$

Form factor is no longer Helm/Woods-Saxon, rather spin-dependent function $F^2(q) = S(q)/S(0)$ (Tovey, 0005041),

$$S(q) = a_p^2\, S_{pp}(q) + a_p\, a_n\, S_{pn}(q) + a_n^2\, S_{nn}(q)$$

requiring nuclear physics calculation.

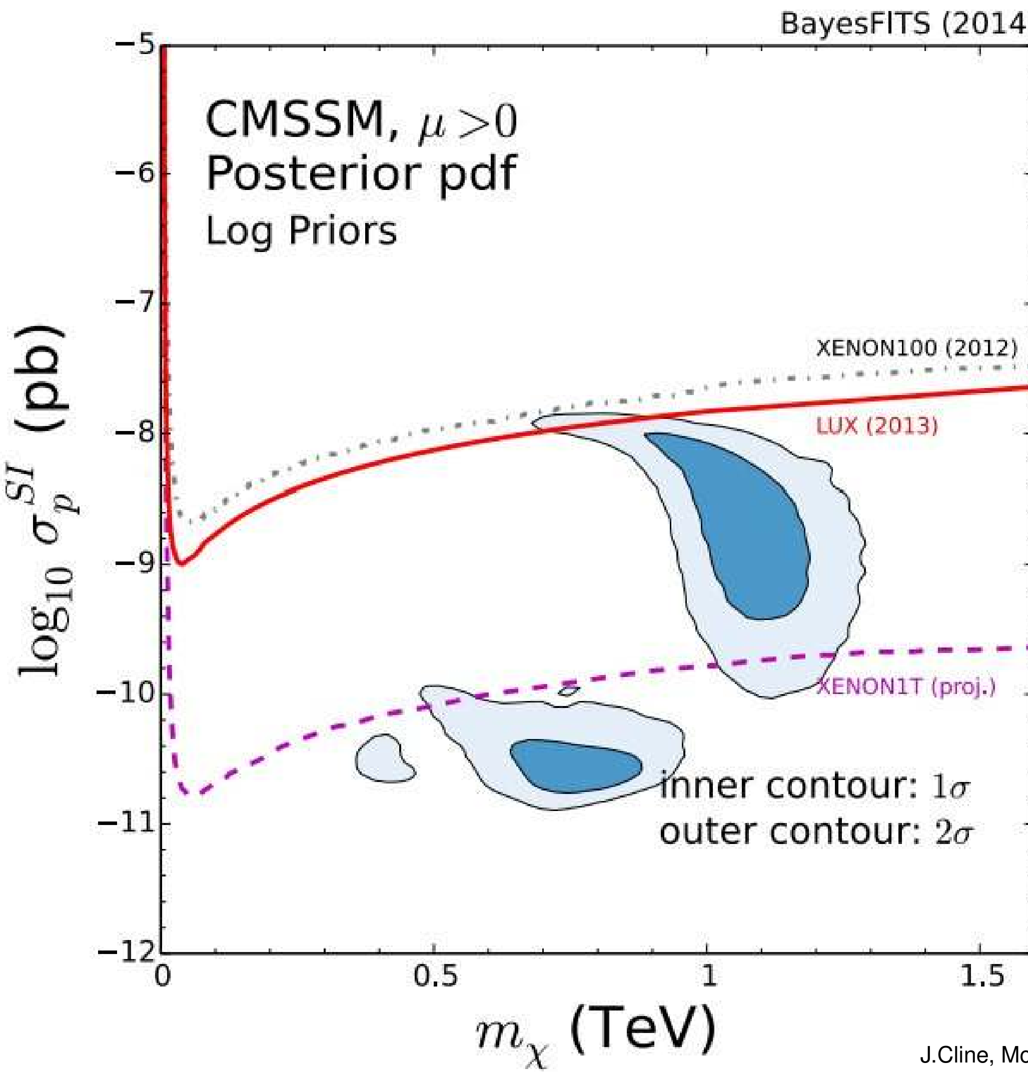
Example: the CMSSM

Roszkowski *et al.*, (1405.4289)

Lightest superpartner (neutralino) in Minimal Supersymmetric Standard Model (MSSM) is famous candidate for DM. MSSM has 128 parameters, but constrained (simplified) version has only 6 (plus $\mathrm{sign}(\mu)$).

Blue regions have correct relic density

XENON 1T will reach dashed curve by 2017

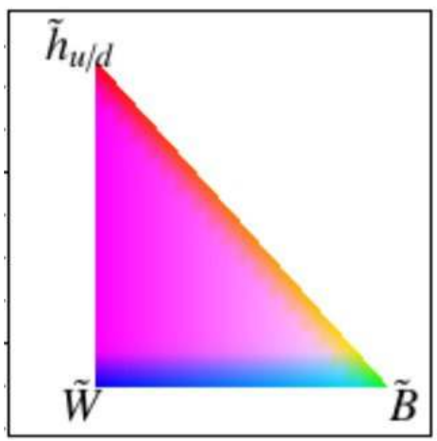


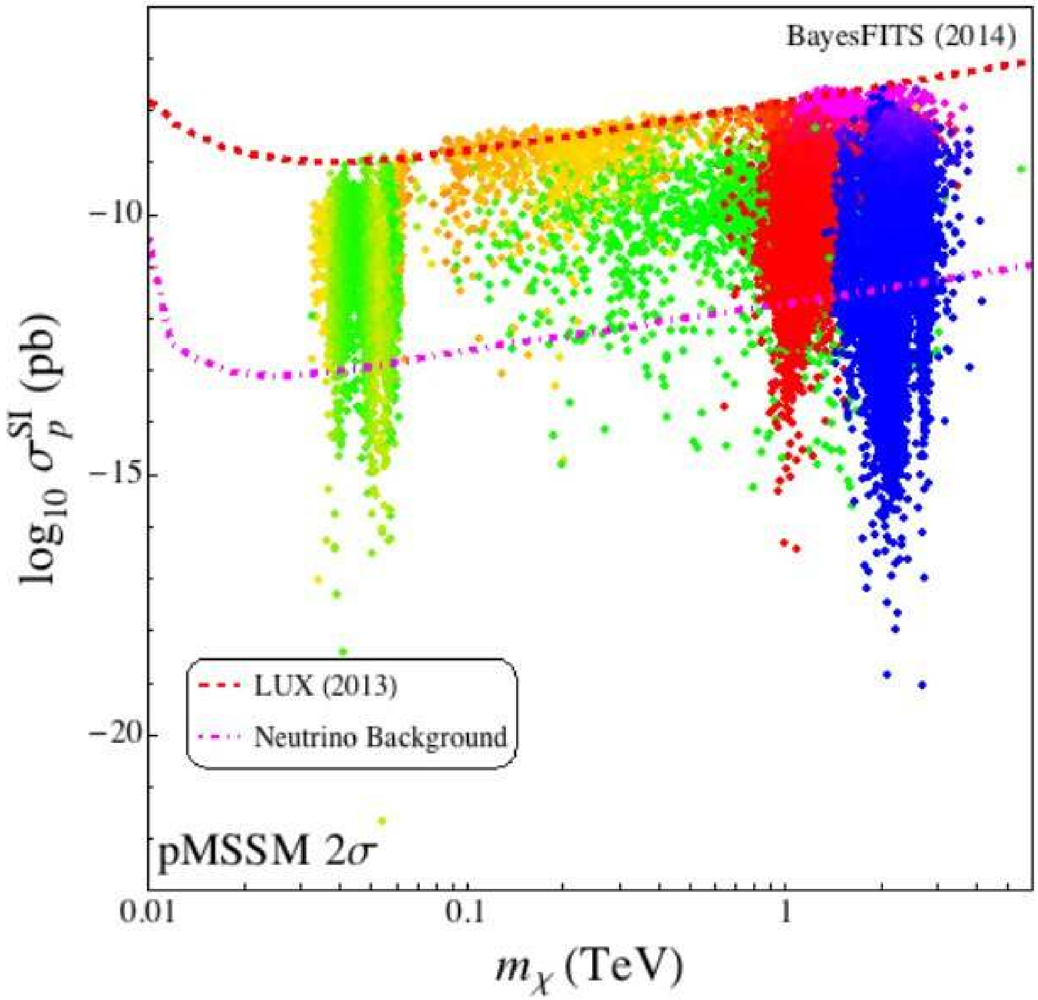
Example: the pMSSM

Roszkowski *et al.*, (1411.5214)

A less simplified version of MSSM with 19 parameters

Regions of correct relic density; color indicates Wino/Bino/higgsino content of neutralino

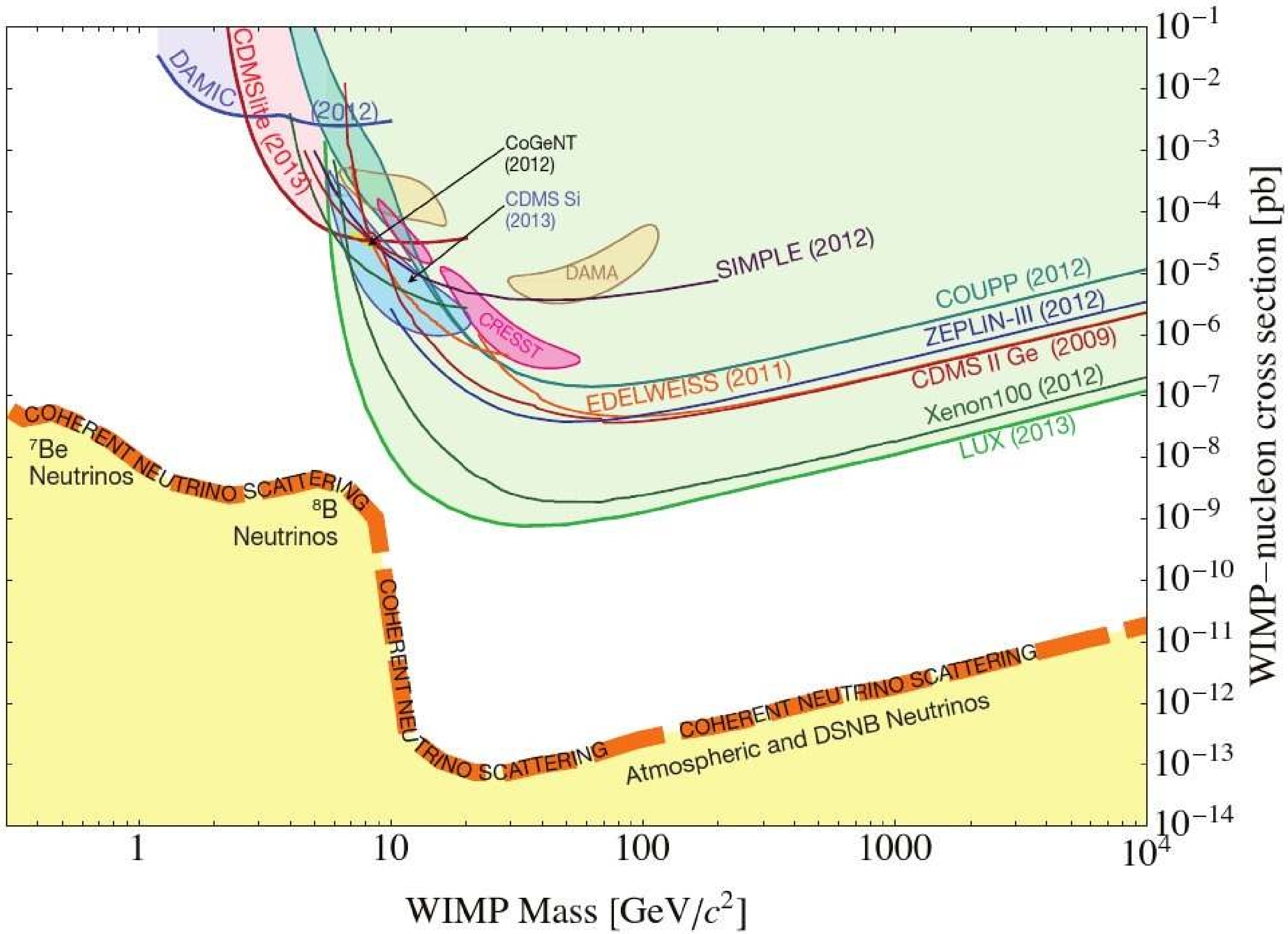




Notice the irreducible neutrino background!

The neutrino background

Even if direct detection sensitivity continues to improve, it will be difficult to discover DM this way if the neutrino background is reached (Billard *et al.*, 1307.5458)



Gets contributions from sun, atmosphere and supernovae

Beyond SI and SD

In general, interactions with nuclei can have extra dependences on v (DM velocity) or q (momentum transfer) (see, *e.g.*, 1007.5325, 1107.0715, 1207.3039) giving extra form factor for the DM vertex. $\Longrightarrow$

More complicated models might reconcile conflicting signals from different experiments

Experimentalists do not analyze these more complicated models; how to constrain them?

Get data from the experiment and repeat their statistical analysis on your model

Or use a simpler analysis, *e.g.,* maximum gap method (S. Yellin, Phys.Rev. D66 (2002) 032005) requiring no knowledge of background for upper limit

Example: magnetic dipole DM

DM could have a magnetic dipole moment,

$$\frac{\lambda_\chi}{2}\bar{\chi}\sigma_{\mu\nu}F^{\mu\nu}\chi$$

leading to differential cross section (Gelmini, 1411.0787)

$$\begin{aligned}\frac{d\sigma_T}{dE_R} &= \alpha\lambda_\chi^2\left\{Z_T^2\frac{m_T}{2\mu_T^2}\left[\frac{1}{\mathrm{v}_{min}^2}-\frac{1}{\mathrm{v}^2}\left(1-\frac{\mu_T^2}{m^2}\right)\right]\right.\\ &\times\ F_{\mathrm{SI},T}^2(E_R(\mathrm{v}_{min}))\\ &+\left.\frac{\hat{\lambda}_T^2}{\mathrm{v}^2}\frac{m_T}{m_p^2}\left(\frac{S_T+1}{3S_T}\right)F_{\mathrm{M},T}^2(E_R(\mathrm{v}_{min}))\right\}.\end{aligned}$$

where T refers to target nucleus. v dependence is more complicated than for generic models (with simple $1/v^2$ dependence), and nuclear magnetic form factor is present.

Beyond SI and SD

In general, interactions with nuclei can have extra dependences on v (DM velocity) or q (momentum transfer) (see, *e.g.*, 1007.5325, 1107.0715, 1207.3039) giving extra form factor for the DM vertex.

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Maximum gap method

(S. Yellin, Phys.Rev. D66 (2002) 032005)

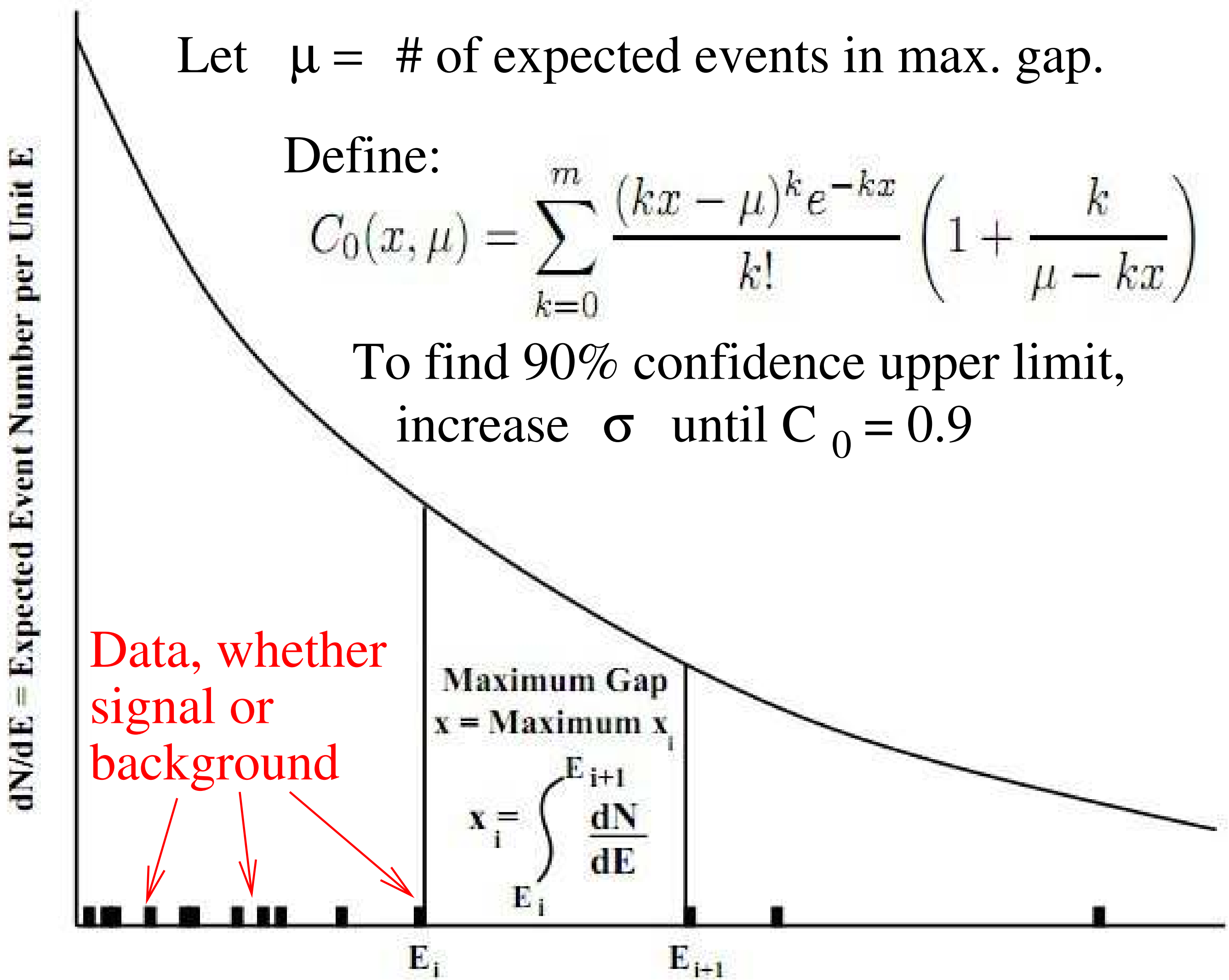
Find maximum energy gap x between any two events. The fact that no event is seen in that interval gives strongest constraint, using Poisson statistics.

Let $\mu =$ # of expected events in max. gap.

Define:

$$C_0(x,\mu) = \sum_{k=0}^{m} \frac{(kx-\mu)^k e^{-kx}}{k!}\left(1+\frac{k}{\mu-kx}\right)$$

To find 90% confidence upper limit, increase σ until $C_0 = 0.9$



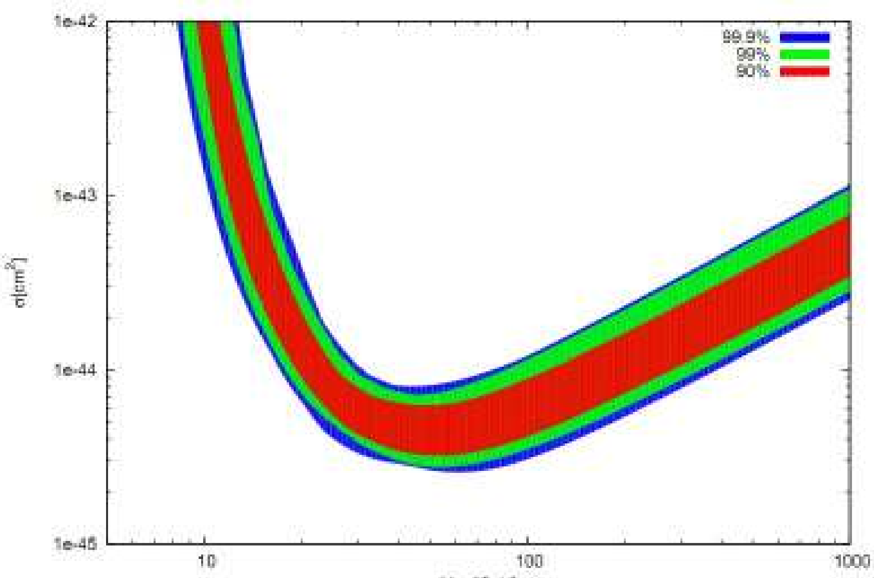
Dependence on DM halo

For a review of determinations and uncertainties of local DM distribution, see A. Green, 1112.0524.

$f(\vec{v})$ need not be isotropic (radial and tangential velocities can differ): non-Maxwellian

There may be tidal streams, DM debris that is not smoothly distributed (Kuhlen *et al.*, 1202.0007)

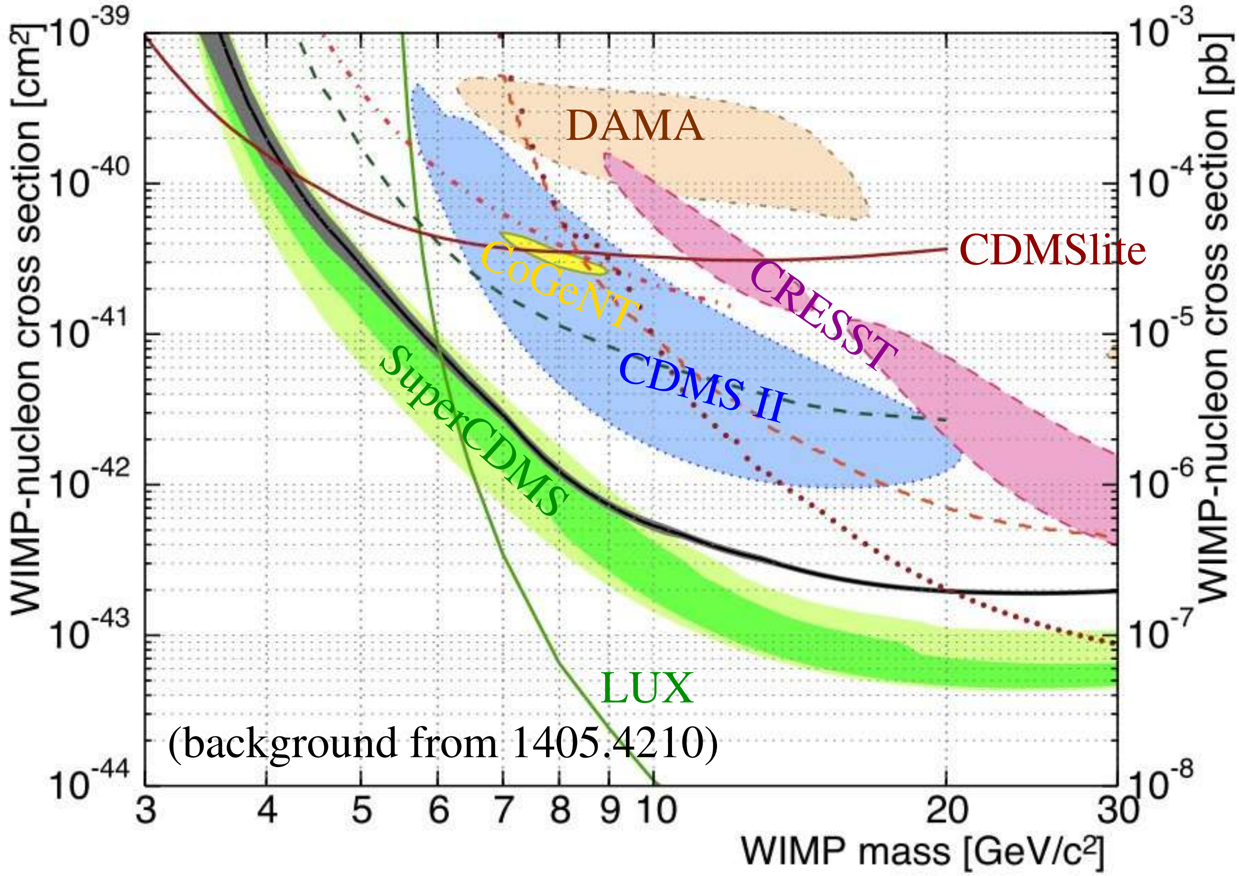
There may be a dark disk in addition to the spherical (or triaxial) halo (Read *et al.*, 0803.2714; Fan *et al.*, 1303.1521)



Astrophysical uncertainty in limit on σ can be a factor of 10 (Fairbairn *et al.*, 1206.2693)

Dependence on DM halo

Several experiments get conflicting results. Could they be reconciled by varying the halo parameters?



DM velocity (including tidal streams) can affect relative sensitivity of different experiments

Halo independent methods

Can determine whether two experiments are compatible with one model independently of DM halo properties.
(Fox *et al.*, 1011.1915; see 1411.0787 for recent review)

For elastic scattering, differential rate $dR/dE_{\rm nr}$ is proportional to

$$g(v_{\rm min}) = \int_{v_{\rm min}}^{\infty} dv\, \frac{f(v)}{v}$$

(recall $v_{\rm min}^2 = m_N E_{\rm nr}/2\mu_N^2$).

Fix m_χ to some value of interest. Each experiment gives limit on

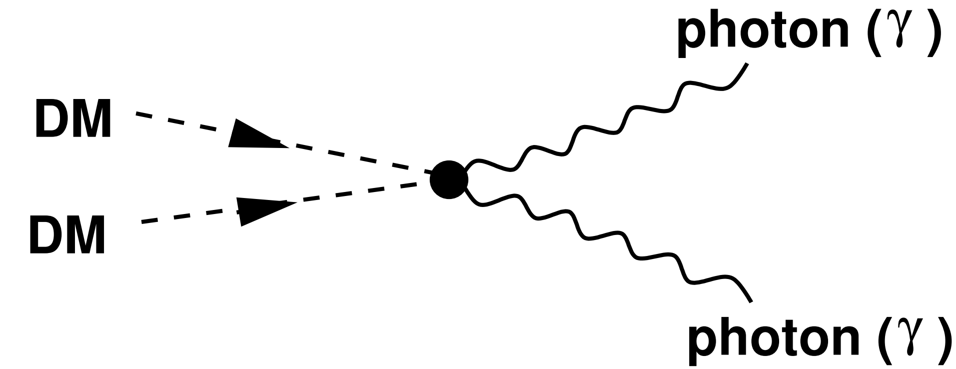
$$\frac{dR}{dE_{\rm nr}}(E_{\rm nr}) \sim \frac{\rho_\odot}{m_\chi}\sigma_n\, g(v_{\rm min})$$

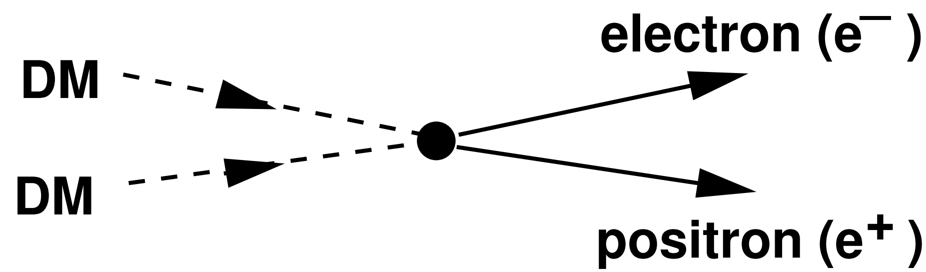
as function of $v_{\rm min}$, that does not depend (explicitly) on halo properties.

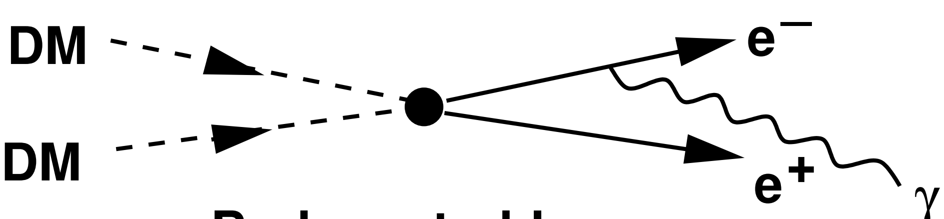
Can also expand $g(v) = g_0(v) + g_1(v)\cos\omega t$ to constrain annual modulation.

Indirect detection of DM

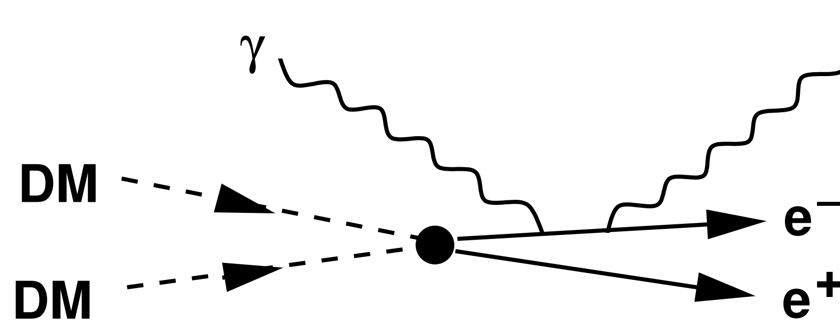
DM annihilation in galaxies could create cosmic rays (e^+, e^- or photons)



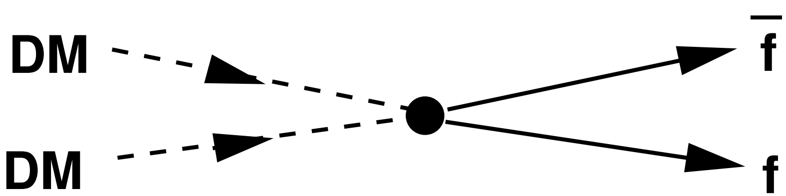




Brehmsstrahlung



Inverse compton scattering on CMB or starlight

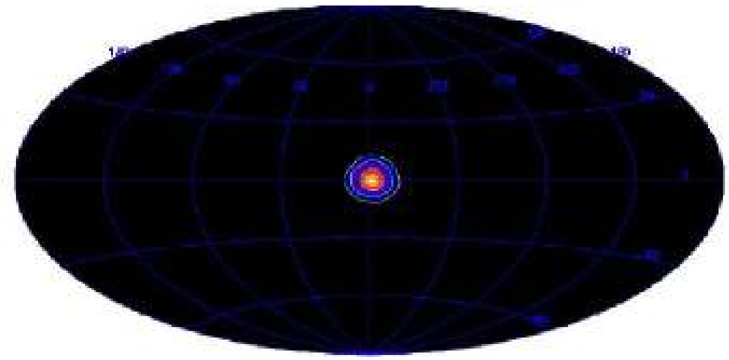


annihilation into SM particles (f), followed by decays into electrons + photons

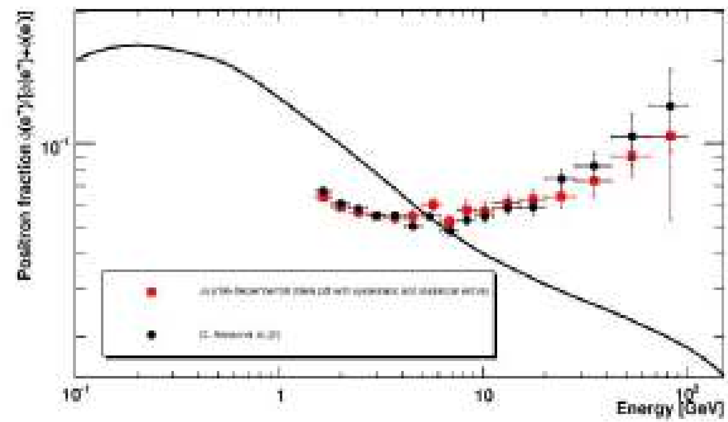
Various cosmic ray anomalies hint at a dark matter origin . . .

Some cosmic ray anomalies . . .

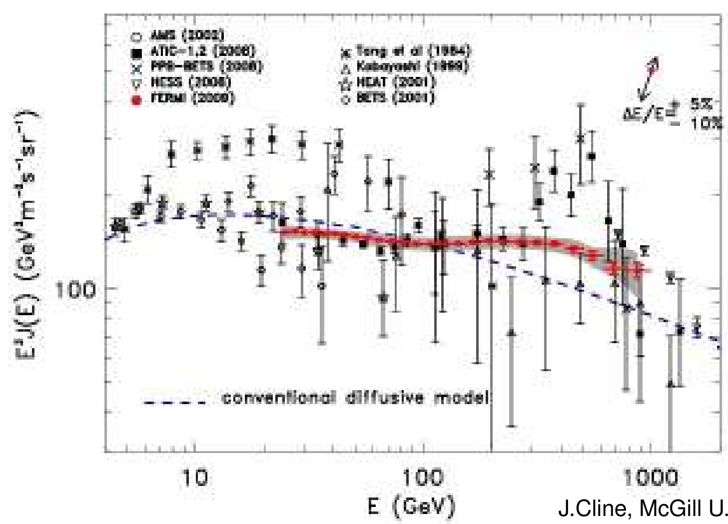
- Excess 511 keV γ's from galactic center, observed by INTEGRAL/SPI (astro-ph/0702621)



- PAMELA positron excess at 10$-$100 GeV (0810.4995)

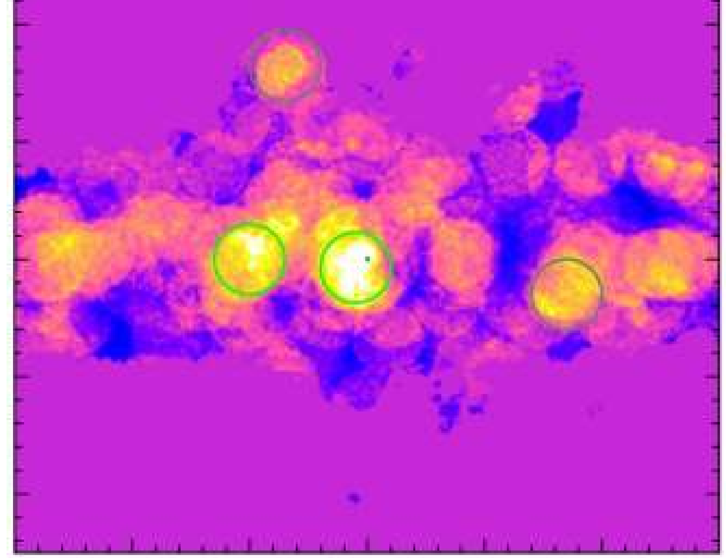


- Fermi/LAT (Large Area Telescope) $e^{\pm}$ excess at 100$-$1000 GeV (0905.0025)

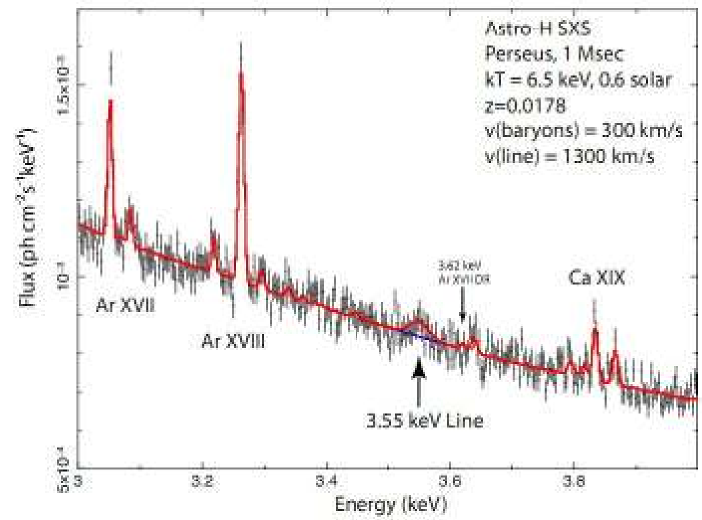


. . . and some more

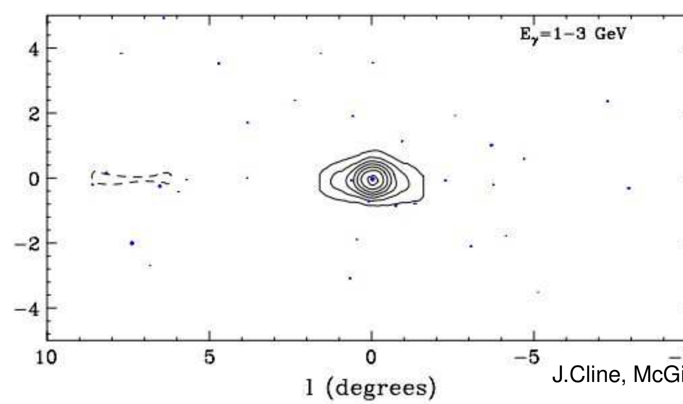
- 130 GeV γ-rays from galactic center, observed by Fermi/LAT (1205.1045)



- 3.55 keV X-ray line in XMM-Newton data (1402.2301, 1402.4119)



- Fermi/LAT continuum excess gamma rays from galactic center (1010.2752, 1207.6047, 1402.6703)

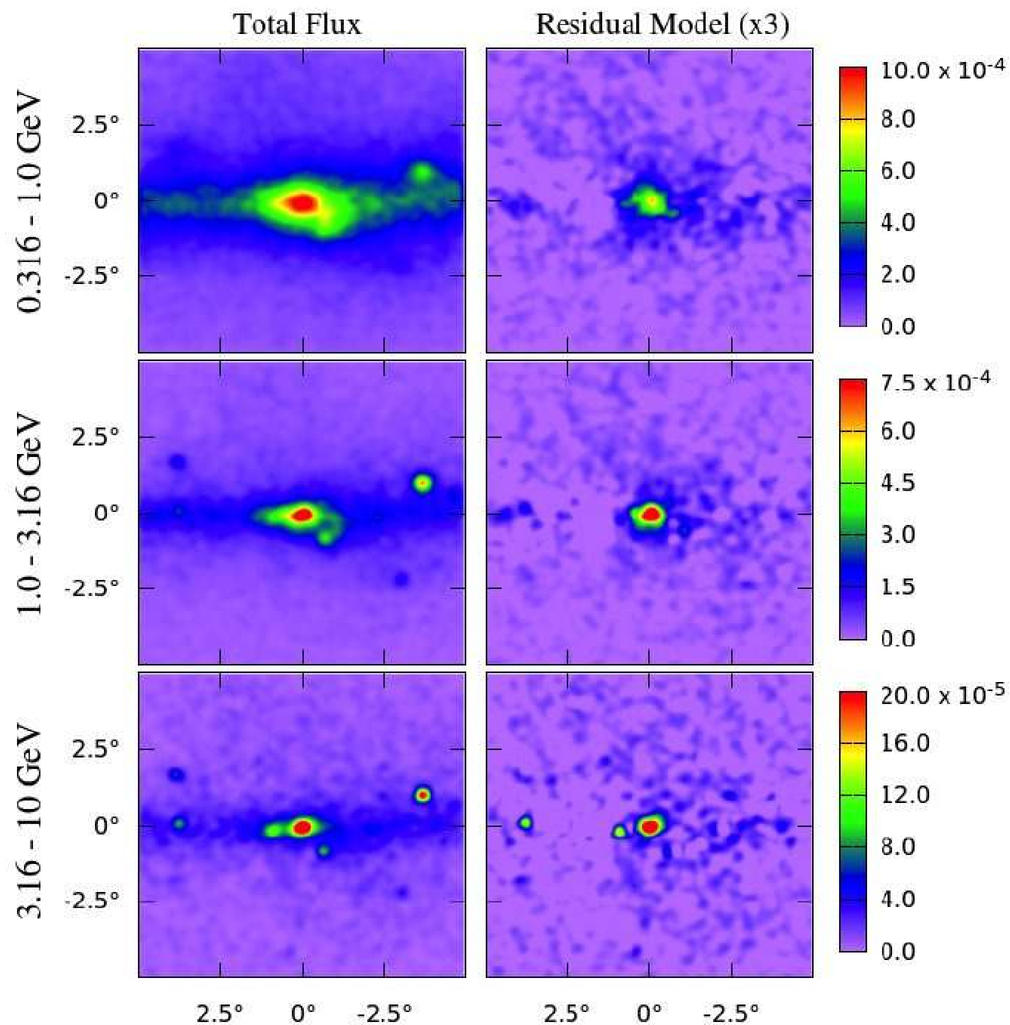


Galactic center γ-ray excess

Hooper *et al.* continue to find evidence for excess 0.3-10 GeV γ-rays in inner 10° of galaxy.

raw maps

includes point sources, diffuse emission, isotropic template, sources associated with 20 cm synchrotron emission...



residual maps

excess is 30% of raw signal

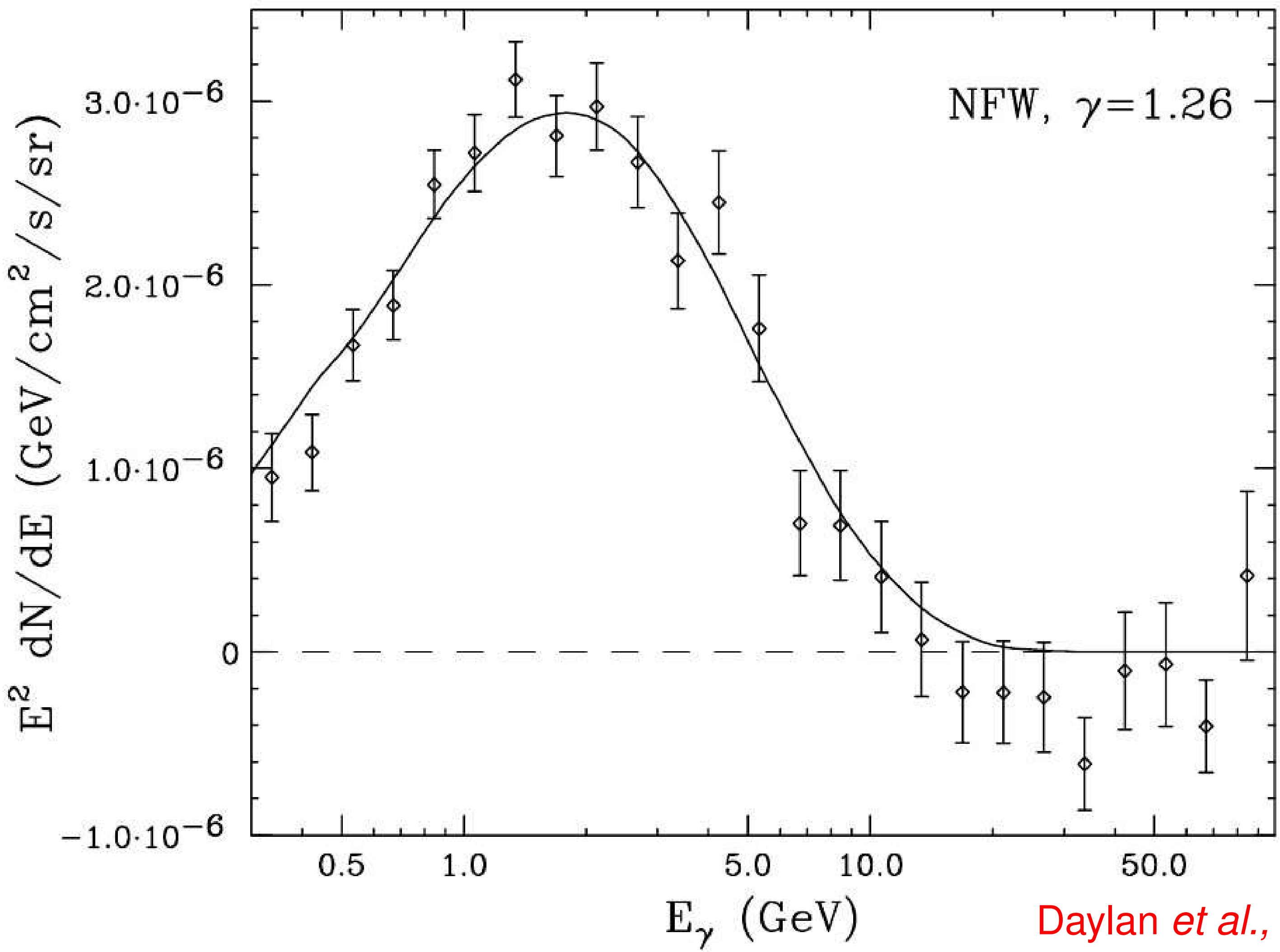
NFW profile fits shape well

Daylan et al., 1402.6783

Confirmed by other groups (Abazajian, 1207.6047, Calore, 1409.0042)

GC excess spectrum

Spectrum fits 35 GeV DM annihilating to $b\bar{b}$ with $\langle\sigma v\rangle = 1.7 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$ (80% of relic density value)

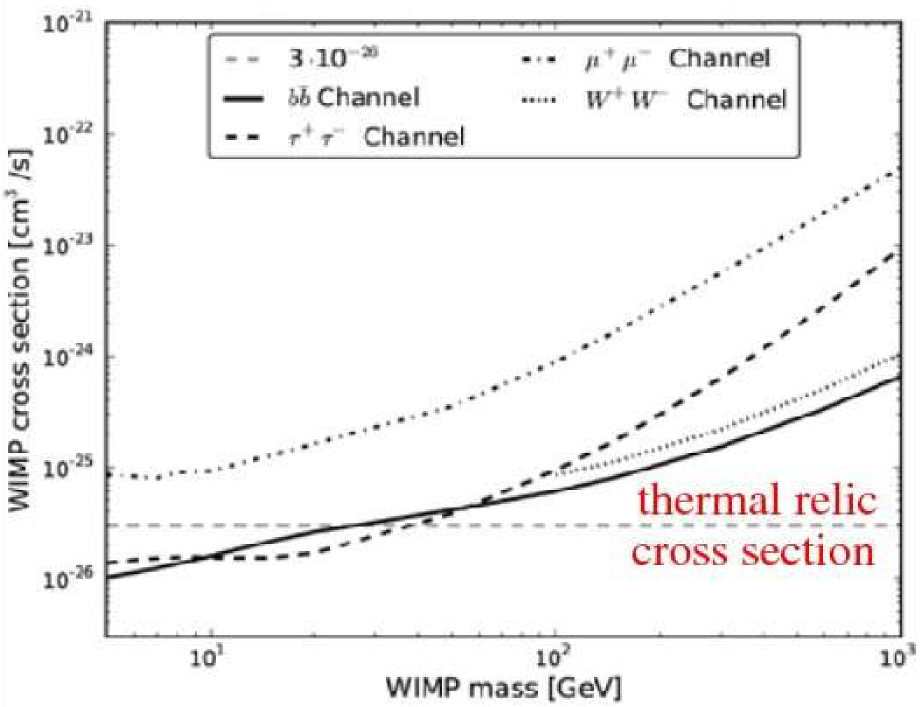


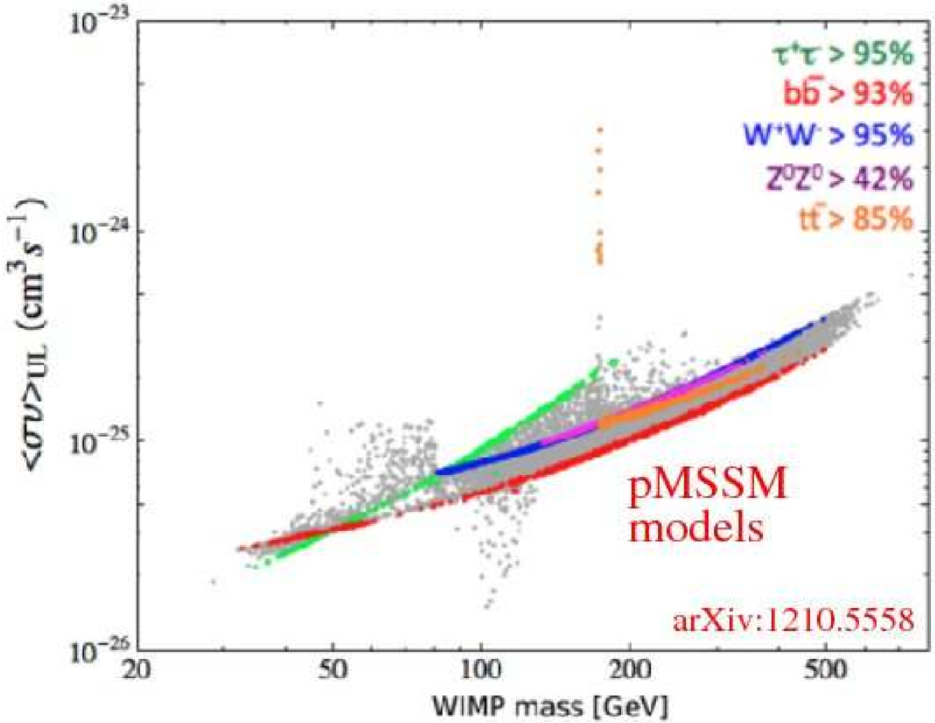
Daylan *et al.*, 1402.6703

Morphology consistent with DM annihilations with generalized NFW profile

Limits on DM annihilation in dwarfs

Fermi puts upper limits on $\langle\sigma v\rangle_{\rm ann}$ into various channels, looking at dwarf spheroidal satellites of our galaxy



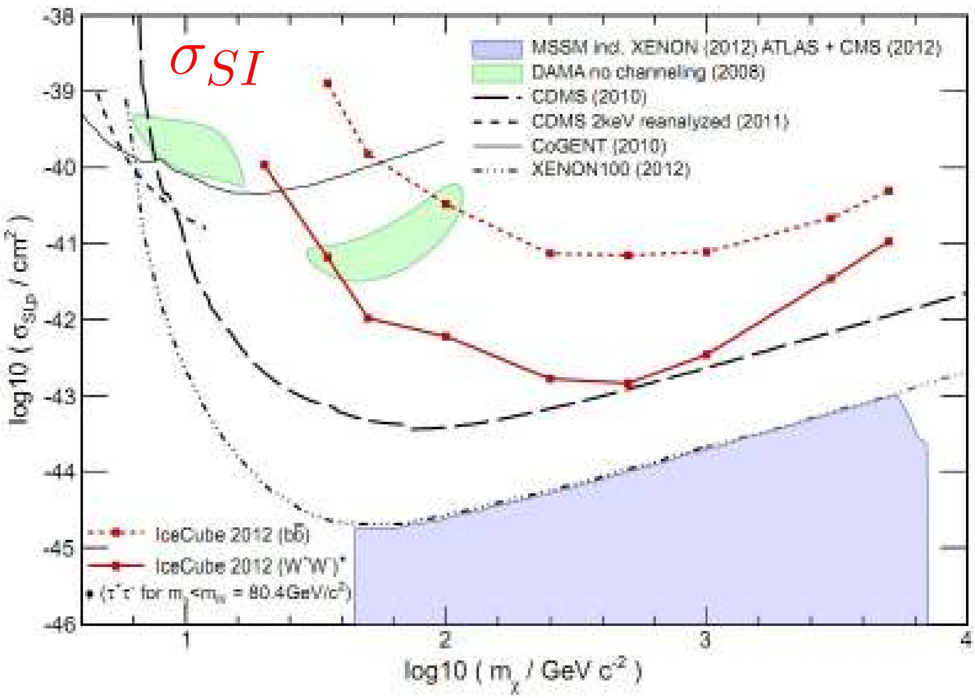


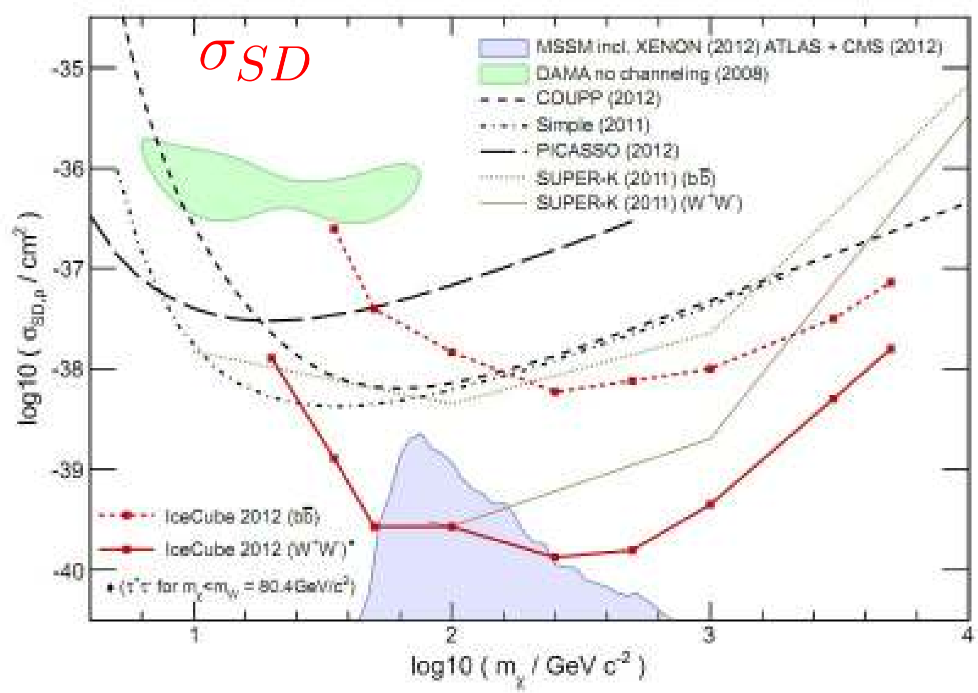
E.g., DM achieving thermal relic density via $\chi\chi\to b\bar b$ should have $m_\chi > 30$ GeV.

Limits on DM annihilation in the sun

Neutrino telescopes might detect ν's from $\chi\chi \to \nu\nu$ in the sun. Scattering on nuclei allows DM to collect in sun, then annihilate. Since hydrogen is main target, spin-dependent scattering can be important (Wikström & Edsjö, 0903.2986).

Limits on σ_{SD} can be better than from direct detection

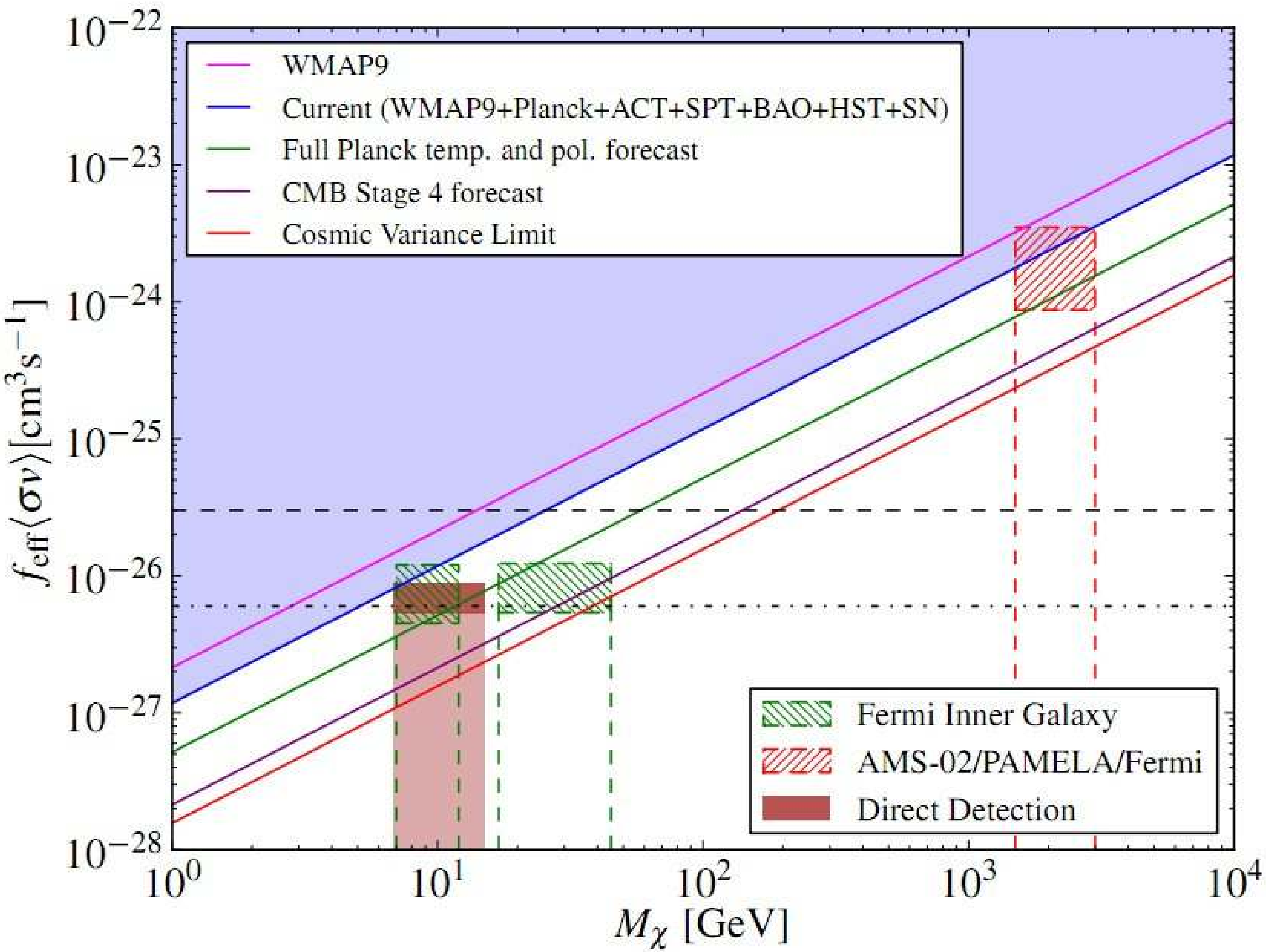




IceCube collaboration, 1212.4097

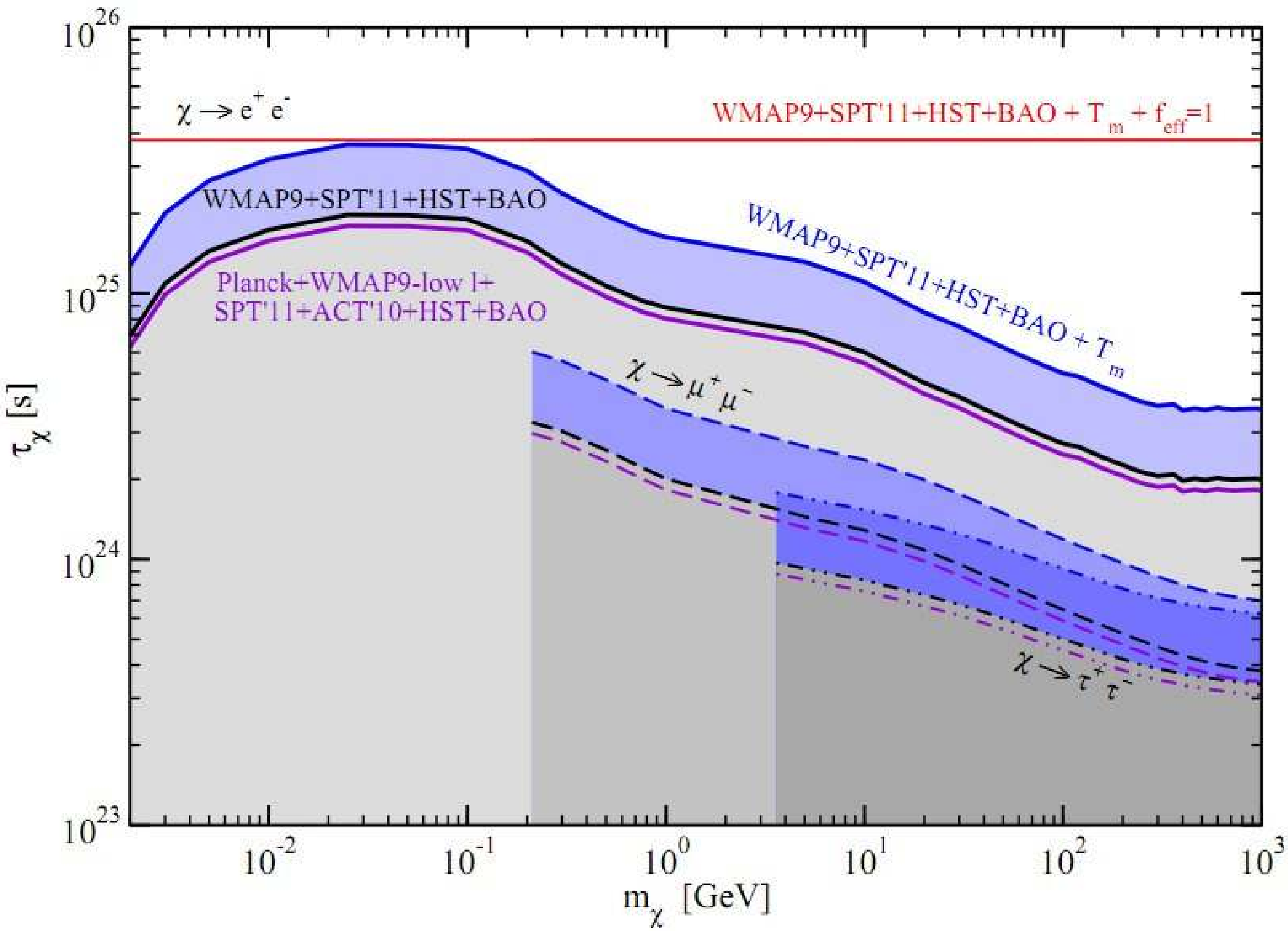
CMB annihilation limits

Injection of ionizing radiation at redshifts $z \sim 100 - 1100$ affects CMB multipoles, constrains $\langle \sigma v \rangle_{\rm ann}$ into SM particles, up to an efficiency factor $f_{\rm eff} \sim 0.3 - 0.85$ depending on final states and m_χ (Madhavacheril *et al.*, 1310.3815)



CMB limits on decaying DM

Lower limit on lifetime τ due to decays into various final states (Diamanti *et al.*, 1308.2578)



If only a fraction of DM mass decays, limit is relaxed proportionally.

Instruments for indirect detection

- Fermi Large Area Telescope: γ rays, $e^{\pm}$
- XMM-Newton, Chandra, Suzaku: X-rays
- PAMELA, AMS-02: electrons, positrons, antiprotons $\dots$
- H.E.S.S., VERITAS, CTA: Cherenkov light from cosmic ray showers in atmosphere
- Super-Kamiokande, ANTARES, IceCube: neutrinos from DM annihilation in the sun or in galaxies
- WMAP and Planck give constraints on (χ or $\chi\chi$) $\to \gamma +$ charged particles, via distortion of CMB
- future radio arrays (LOFAR, MWA, SKA $\dots$) detecting 21 cm emission will improve on CMB constraints

Principles of indirect detection

First consider decays or annihilations of DM into γ or ν. The flux is

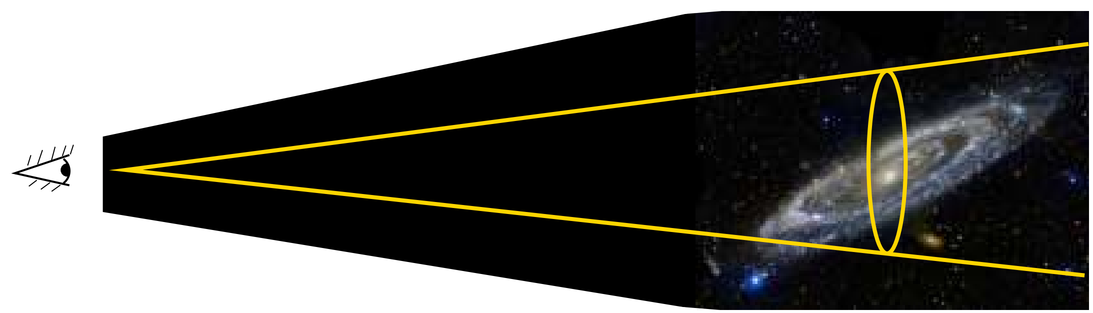
$$F = \frac{\Gamma}{m_\chi}\int \frac{d^3x}{4\pi\, x^2}\,\rho \quad (\mathrm{counts/cm^2/s})$$

for decays, or

$$F = \frac{\langle\sigma v\rangle}{m_\chi^2}\int \frac{d^3x}{4\pi\, x^2}\,\rho^2$$

for annihilations. Note $\rho/m_\chi =$ DM number density, flux = photons/area/time

Integral is over conical field of view (FOV).



The purely geometrical integrals are known as J-factors.

We need to know $\rho(r)$ for the object of interest (typically galaxy or galaxy cluster)

NFW profile

Numerical simulations of galaxy formation found empirical evidence for the NFW profile (Navarro *et al.*, astro-ph/0311231)

$$\rho_{\rm NFW} = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

where ρ_s and r_s vary from galaxy to galaxy, but shape is universal. For Milky Way, $r_s \cong 20 \pm 7\ \mathrm{kpc}$ (Read, 1304.5127; Nesti & Salucci, 1304.5127)

Note that $\int d^3x\,\rho$ does not converge! Instead, ρ merges smoothly onto the cosmic average value at some large radius.

Halo size can be characterized by virial radius, *e.g.*, R_{200} = radius such that average density inside R_{200} is 200 times critical density:

$$\frac{4\pi \int_0^{R_{200}} dr\, r^2 \rho}{\frac{4\pi}{3} R_{200}^3} = \frac{M_{200}}{\frac{4\pi}{3} R_{200}^3} = 3\,\frac{\rho_s}{c^3}\left(\ln(1+c) - \frac{c}{1+c}\right) = 200\,\rho_{\rm crit}$$

Here $c = c_{200} = R_{200}/r_s$ is called the concentration of the halo; M_{200} is the virial mass.

Cusp or core?

J factor for annihilation is very sensitive to behavior near $r = 0$. Does ρ really go like $1/r$ (cusp)? Numerical simulations do not resolve very short distances.

Some authors argue for a cored profile (Nesti & Salucci, 1304.5127)

$$\rho \to \text{const. for } r < r_{\text{core}}$$

Original simulations do not include complex effects of baryons. They can make halo more (Tissera *et al.*, 0911.2316, Schaller *et al.*, 1409.8617) or less (Martizzi *et al.*, 1211.2648) cuspy.

Different ansätze for halo profile have been developed to cover the possibilities, *e.g.*, generalized NFW profile,

$$\rho = \frac{\rho_s}{(r/r_s)^\gamma (1 + r/r_s)^{2-\gamma}}$$

(Morphology of GC GeV excess suggests $\gamma \cong 1.2$)

DM halo profiles

Besides NFW, Einasto and Moore have been used to fit galaxy profiles from simulations, while cored Burkert is based on observations suggesting that dwarf galaxies are cored

$$\text{NFW}: \quad \rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2} \quad \text{cuspy}$$

$$\text{Einasto}: \quad \rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\} \quad \text{variable}$$

$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2} \quad \text{cored}$$

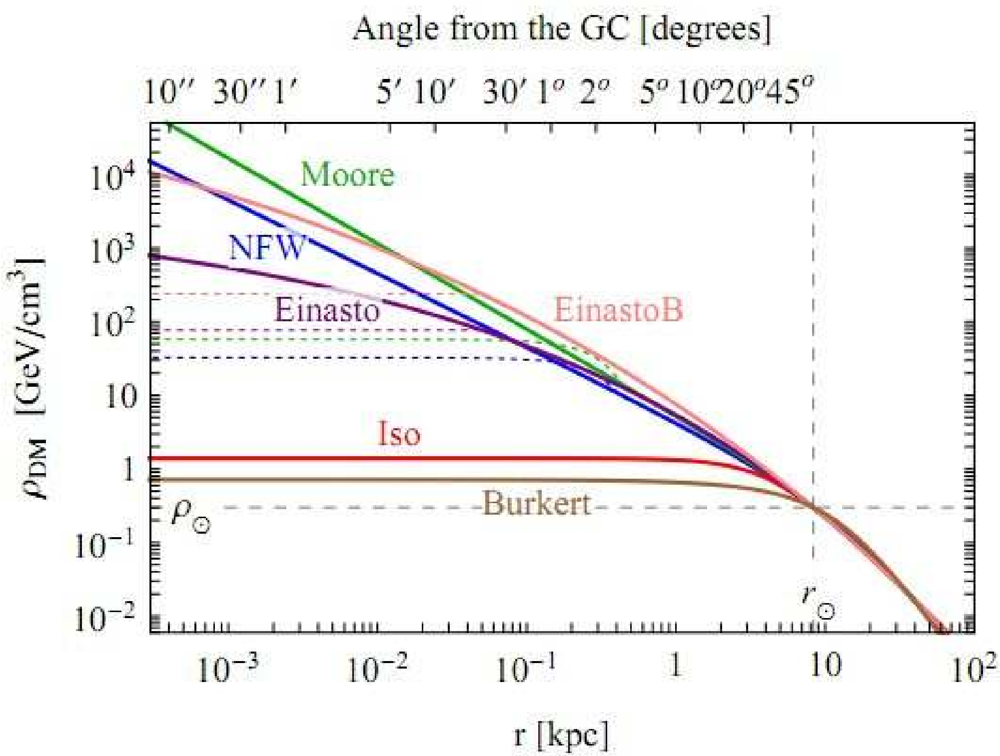
$$\text{Burkert}: \quad \rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)} \quad \text{cored}$$

$$\text{Moore}: \quad \rho_{\rm Moo}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84} \quad \text{cuspy}$$

$\alpha = 0.17$, $r_s \cong 28\ \mathrm{kpc}$ are standard Einsato parameters for MW-like galaxies without baryons. With baryons, $\alpha \to\sim 0.1$ (Tissera *et al.*, 0911.2316)

Comparison of MW profiles

From Cirelli *et al.*, 1012.4515



DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105

We must rely upon theory of structure formation to predict behavior for $r < r_\odot$

(Unless we really think we are seeing DM annihilations from the MW center!)

Predicting particle spectra

If DM $\to$ photons directly, spectrum is a line at $E_\gamma = m_\chi$ (annihilations) or $E_\gamma = m_\chi/2$ (decays).

differential flux = counts/energy/area/time from solid angle $\Delta\Omega$:

$$\frac{d\Phi_\gamma}{dE}(E_\gamma) = \frac{r_\odot}{4\pi} \begin{cases} \frac{1}{2}\left(\frac{\rho_\odot}{M_{\rm DM}}\right)^2 \bar{J}\,\Delta\Omega \sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE_\gamma} & \text{(annihilation)} \\ \frac{\rho_\odot}{M_{\rm DM}} \bar{J}\,\Delta\Omega \sum_f \Gamma_f \frac{dN_\gamma^f}{dE_\gamma} & \text{(decay)} \end{cases}$$

where

$$\bar{J} = \frac{J}{\Delta} = \frac{1}{\Delta\Omega}\int_{\rm l.o.s.} \frac{ds}{r_\odot}\left(\frac{\rho(r(s,\theta))}{\rho_\odot}\right)^n$$

is integral along line of sight (same as $\int d^3x/4\pi x^2$ over conical field of view) and $n = 1(2)$ for decay (annihilation)

Predicting particle spectra (2)

If DM $\to$ other SM particles $f\bar{f}$, γ-ray or other spectra of interest are complicated!

1. Use Monte Carlo generator (PYTHIA) to predict showering of f into final states of interest ($e^{\pm}$, γ, $\bar{p}$, $\bar{d}$, ν). Bremsstrahlung is included here.

2. Prompt photons (or ν's) from step 1 have morphology from J-factor.

3. Propagate charged particles in galactic magnetic field: must solve diffusion equation.

4. Find inverse Compton (and possibly synchrotron) contribution to γ-ray spectra from propagated electrons.

Propagation of cosmic rays

Phase space density $f(t, \vec{x}, E)$ obeys diffusion equation due to random walk in galactic magnetic field (see *e.g.* 1012.4515)

$$\frac{\partial f}{\partial t} - \nabla\left(\mathcal{K}(E, \vec{x})\nabla f\right) - \frac{\partial}{\partial E}\left(b(E, \vec{x}) f\right) = Q(E, \vec{x})$$

$\mathcal{K} = \mathcal{K}_0 (E/\mathrm{GeV})^\delta$ is diffusion coefficient, with empirically determined parameters and x-dependence neglected for simplicity; in reality it should follow B field shape,

$$B(\rho, z) \approx (5-10)\,\mu\mathrm{G}\exp\left(-\frac{\rho}{10\ \mathrm{kpc}} - \frac{|z|}{2\ \mathrm{kpc}}\right)$$

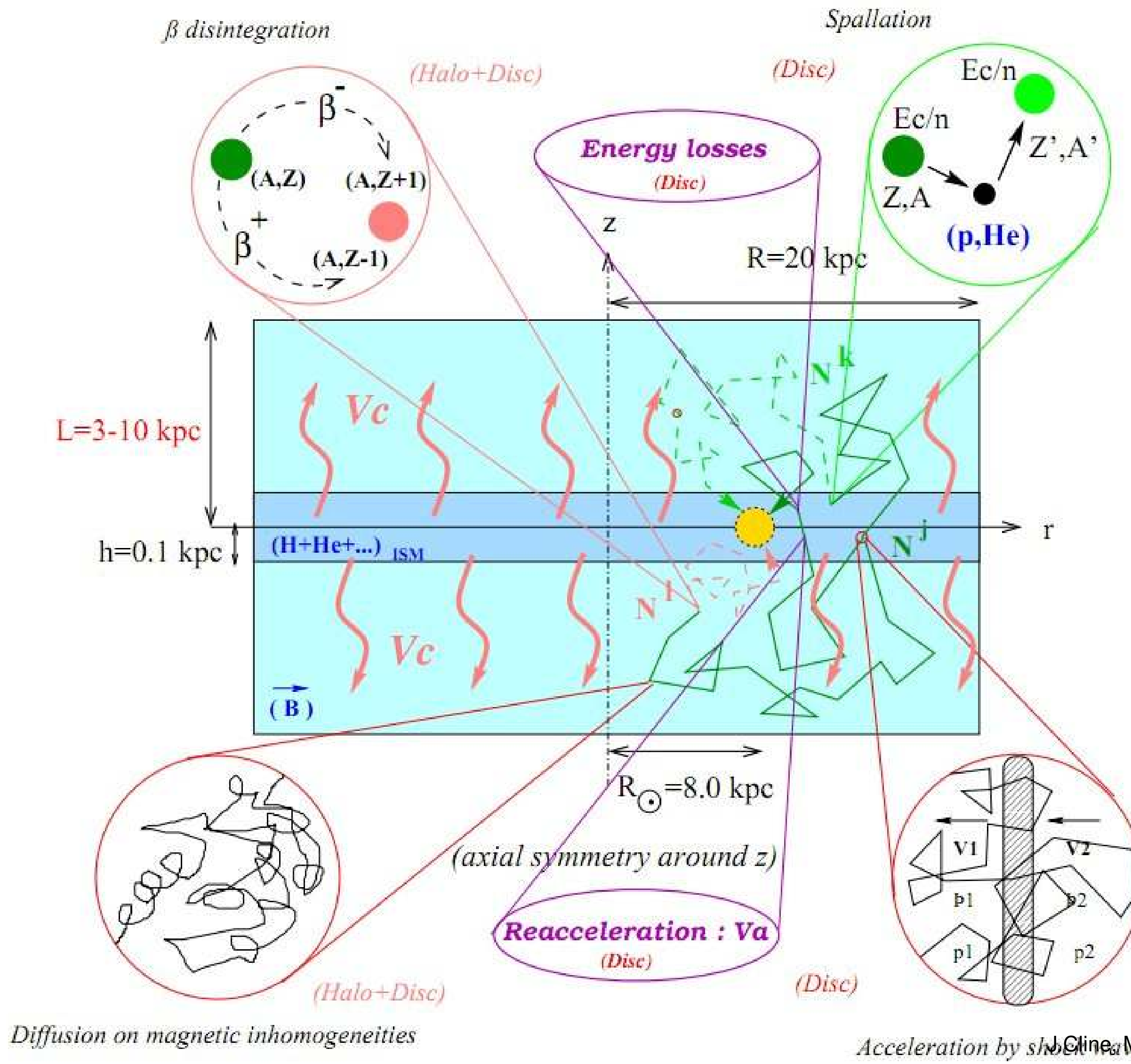
b is energy loss coefficient due to synchrotron and inverse Compton scattering,

$$b = \frac{4\sigma_T}{3m_e^2} E^2 \left(u_B(x) + \sum_{\substack{i=\mathrm{CMB} \\ \mathrm{IR,\ starlight}}} u_i(\vec{x})\, R_i(E) \right)$$

u_i are energy densities of B-field or photons;
$Q \propto \rho^2(x)$ or $\rho(x)$ is source term from DM annihilation or decay.

Propagation of cosmic rays (2)

Even assuming steady-state $df/dt = 0$, diffusion equation is hard to solve. Fully numerical package GALPROP solves it in cylinder of radius $20\ \mathrm{kpc}$ and height $\pm L$.



Maurin *et al.*, astro-ph/0212111

Propagation of cosmic rays (3)

Uncertainties in parameters are encompassed by several standard choices, all compatible with measured boron/carbon abundances (from spallation process):

	Electrons or positrons		Antiprotons (and antideuterons)			
Model	δ	$\mathcal{K}_0$ [kpc^2/Myr]	δ	$\mathcal{K}_0$ [kpc^2/Myr]	$V_{\rm conv}$ [km/s]	L [kpc]
MIN	0.55	0.00595	0.85	0.0016	13.5	1
MED	0.70	0.0112	0.70	0.0112	12	4
MAX	0.46	0.0765	0.46	0.0765	5	15

(MIN, MED, MAX refer to size of predicted antiproton flux)

Must include convective term in diffusion equation for $\bar{p}$ and $\bar{d}$ (of interest for PAMELA or AMS-02)

Inverse Compton Scattering

(Cirelli & Panci, 0904.3830)

Differential flux from electron of energy $E = m\gamma$:

$$\frac{d\Phi}{d\epsilon_1} = \frac{1}{\epsilon_1}\int_{\Delta\Omega} d\Omega \int_{\rm line-of-sight} ds\, \frac{j(\epsilon_1, r(s))}{4\pi}$$

with ϵ_1 (ϵ) = final (initial) photon energy,

$$j(\epsilon_1, r) = 2\int_{m_e}^{M_{\rm DM}} dE\, \mathcal{P}(\epsilon_1, E, r)\, n_e(r, E)$$

$$\mathcal{P}(\epsilon_1, E, r) =$$

$$\frac{3\sigma_{\rm T}}{4\gamma^2}\epsilon_1 \int_{1/4\gamma^2}^{1} dq \left(1 - \frac{1}{4q\gamma^2(1-\tilde\epsilon_1)}\right) \frac{n\big(\epsilon(q), r\big)}{q} \left[2q\ln q + q + 1 - 2q^2 + \frac{1}{2}\frac{\tilde\epsilon_1^2}{1-\tilde\epsilon_1}(1-q)\right]$$

where $\Gamma_\epsilon = 4\epsilon/E$, $\tilde\epsilon_1 = \epsilon_1/E$, $q = \tilde\epsilon_1/(\Gamma_\epsilon(1-\tilde\epsilon_1))$,

$n(\epsilon, r)$ = photon distribution function,

σ_T = Thomson cross section

Poor Particle Physicist Cookbook

(Cirelli *et al.,* 1012.4515)

These authors provide Mathematica code to predict indirect signals (γ, $e^\pm$, $\nu_{e,\mu,\tau}$, $\bar{p}$, $\bar{d}$) for DM from $m_\chi = 5$ GeV to 100 TeV decaying or annihilating into a variety of final states,

$$
\begin{array}{ll}
e_L^+e_L^-,\ e_R^+e_R^-,\ \mu_L^+\mu_L^-,\ \mu_R^+\mu_R^-,\ \tau_L^+\tau_L^-,\ \tau_R^+\tau_R^-, & hh, \\
q\bar{q},\ c\bar{c},\ b\bar{b},\ t\bar{t},\ \gamma\gamma,\ gg, & \nu_e\bar{\nu}_e,\ \nu_\mu\bar{\nu}_\mu,\ \nu_\tau\bar{\nu}_\tau, \\
W_L^+W_L^-,\ W_T^+W_T^-,\ Z_LZ_L,\ Z_TZ_T, & VV\to 4e,\ VV\to 4\mu,\ VV\to 4\tau.
\end{array}
$$

You choose m_χ, propagation parameters (MAX, MED, MIN), DM halo profile (see p. 84) and lifetime τ or cross section $\langle\sigma v\rangle$.

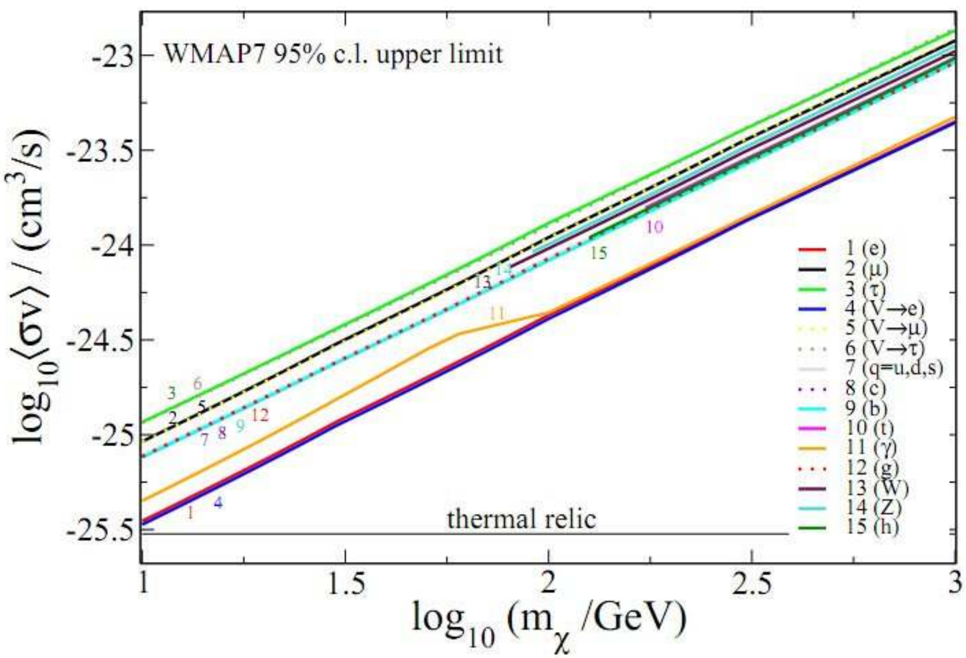
No need to repeat PYTHIA, GALPROP, the many integrals, *etc.*

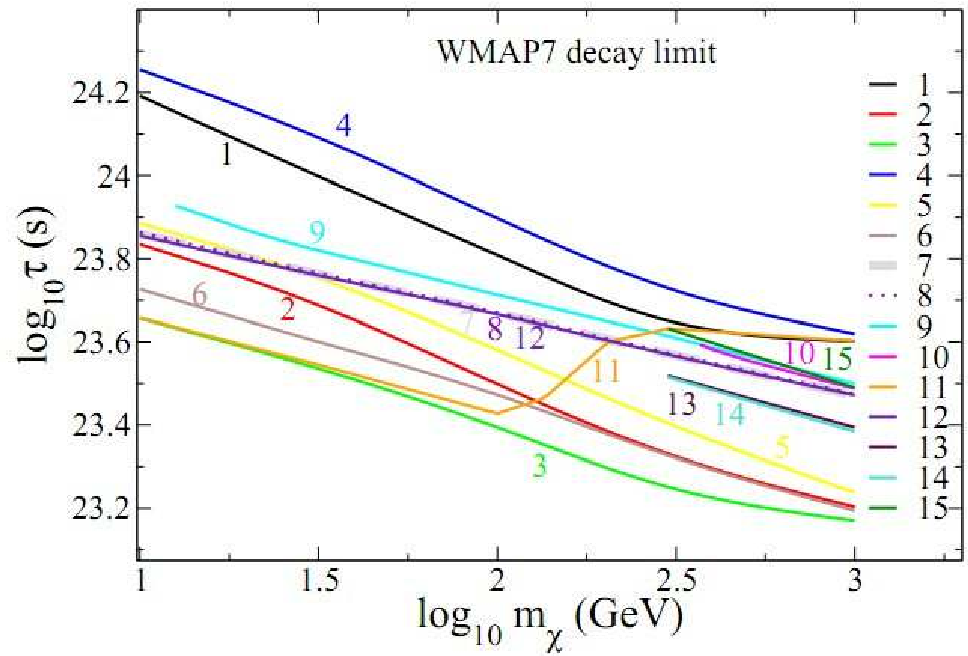
Analogous cookbook provided for neutrinos from annihilation in the sun, Baratella *et al.,* 1312.6408.

PPPC at work: CMB constraints

(Cline & Scott, 1301.5908)

We used results from PPPC to derive CMB constraints on wide range of final states for annihilating and decaying DM





Limits on γ final states strengthen as universe becomes opaque to photons above $\sim 50\ \mathrm{GeV}$

Theoretical Models

Lightest superpartner (LSP), neutralino of MSSM was historically favored DM candidate

Hidden sector models became popular in recent years: dark sector could be complex, with multicomponent or composite dark matter, dark atoms, Higgs fields, gauge interactions . . .

Models can be classified according to portals: mediator that connects DM to the standard model

We might discover the mediator (*e.g.,* dark photon) before the dark matter itself

Simplest DM model: singlet scalar

Neutralino dark matter

The neutralino mass matrix in basis of Bino $\tilde{B}$, Wino $\tilde{W}$ and Higgsinos $\tilde{h}_u$, $\tilde{h}_d$ is

$$\begin{pmatrix} M_1 & 0 & m_Z s_W s_b & -m_Z s_W c_b \\ 0 & M_2 & -m_Z c_W s_b & m_Z c_W c_b \\ m_Z s_W s_b & -m_Z s_W s_b & 0 & -\mu \\ -m_Z s_W c_b & -m_Z c_W c_b & -\mu & 0 \end{pmatrix}$$

with $s_b/c_b = \tan\beta = \langle h_u \rangle / \langle h_d \rangle$. LSP (dark matter candidate) is the state with smallest eigenvalue.

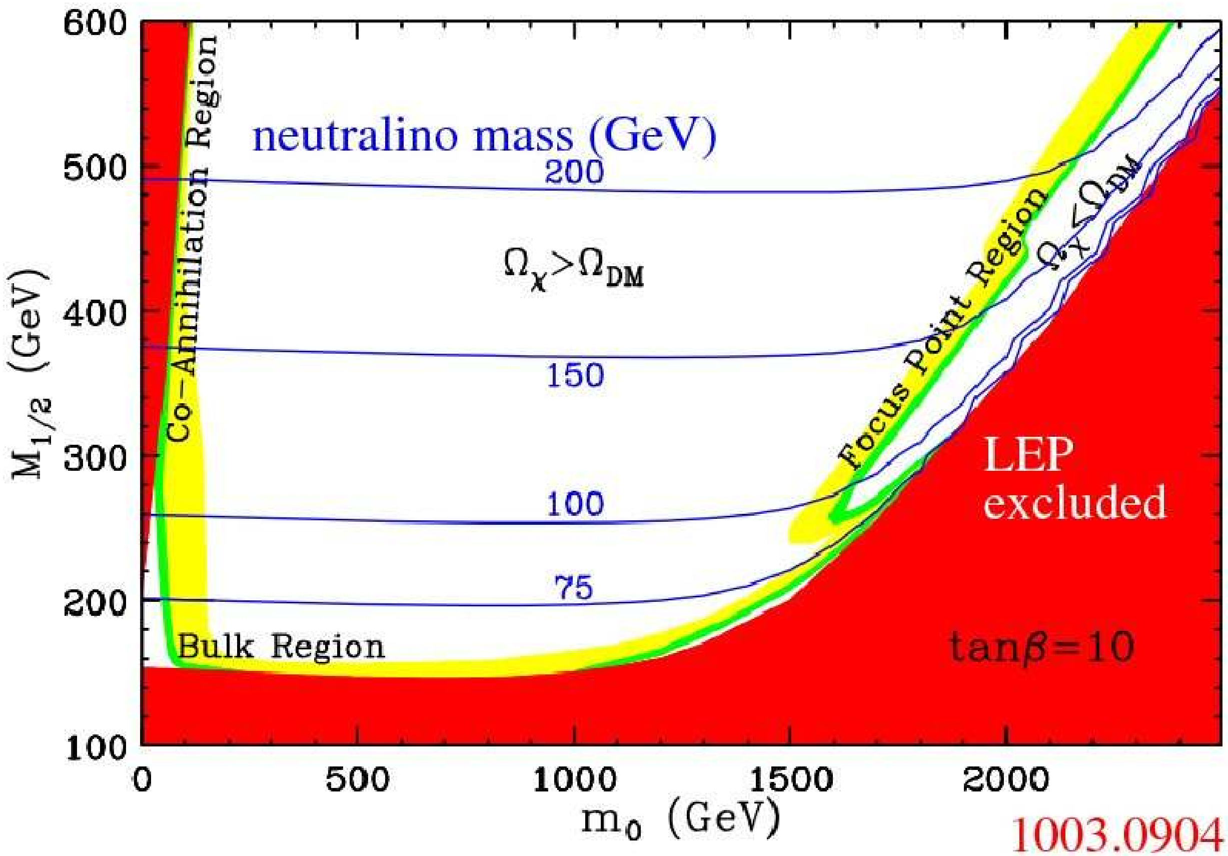
In minimal supergravity (mSUGRA, same as CMSSM), squarks have common mass m_0, as do gauginos: $M_1 = M_2 = M_{1/2}$. μ is determined up to sign by Higgs VEV.

Parameters are m_0, $M_{1/2}$, A_0, $\tan\beta$, $\mathrm{sign}(\mu)$.

Neutralinos before the LHC

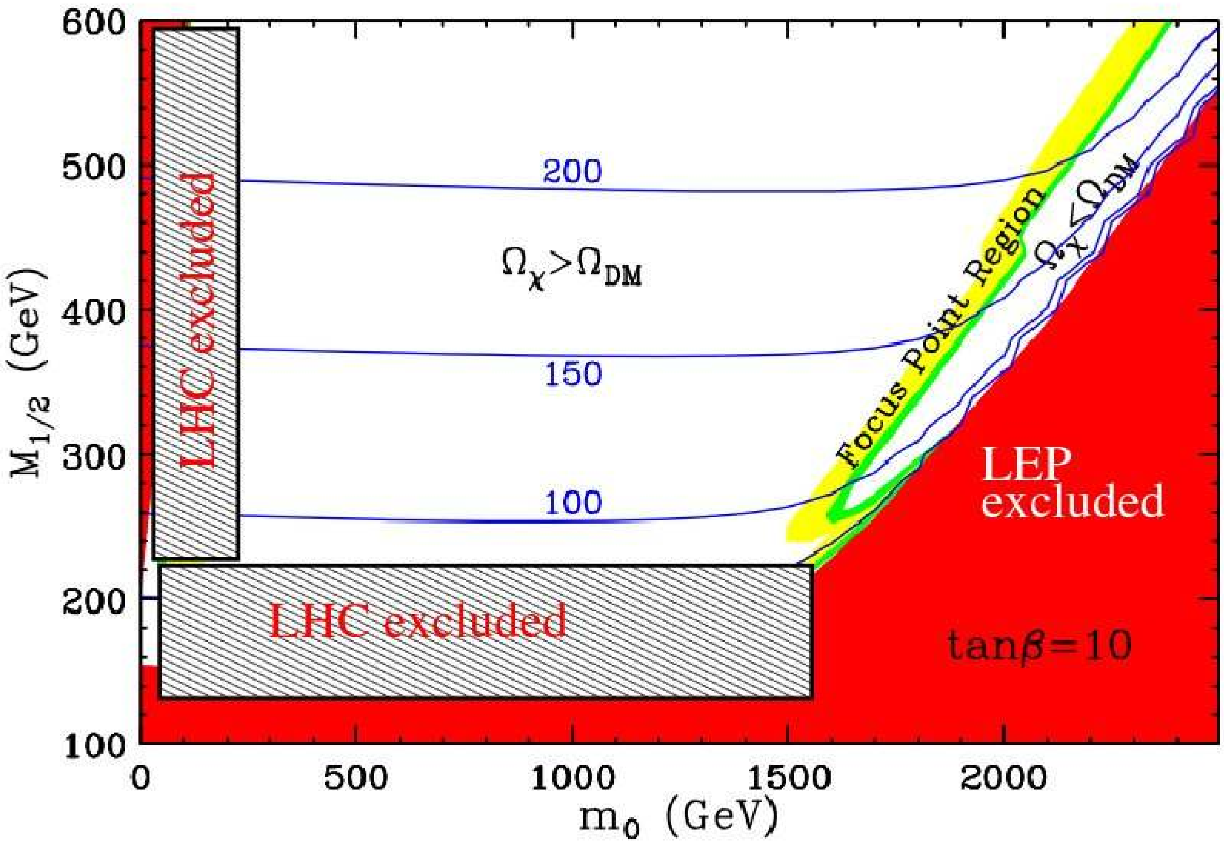
Even before LHC, WMAP-allowed regions of parameter space were small (Feng, 1003.0904)

- Coannihilation: $\chi_0\tilde{\tau} \to \tau\gamma,\, \tau Z,\, \tau h$
- Bulk: resonant $\chi_0\chi_0$ annihilation via h with $2m_{\chi_0} \cong m_h$
- Focus point: higgsino-like $\chi_0\chi_0 \to WW,\, ZZ,\, Zh$



Neutralinos after LHC start

Early LHC searches for squarks and gluons removed “bulk” region and most of coannihilation region (Baer *et al.*, 1202.4038)

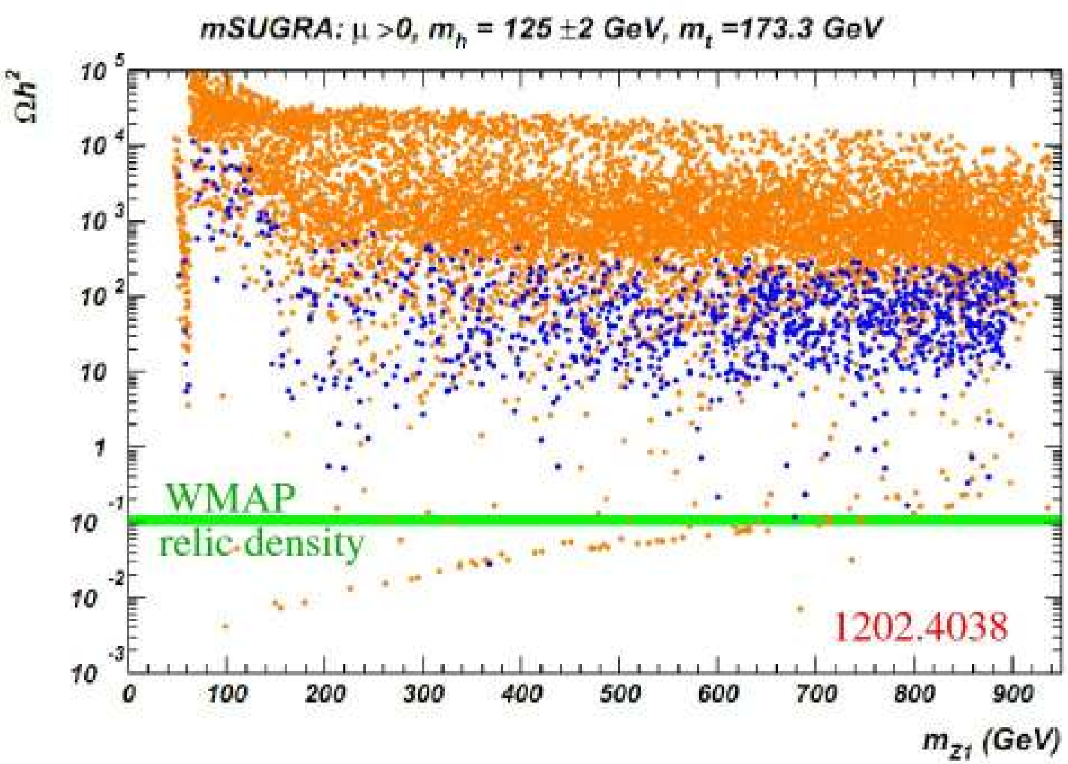


Discovery of $125\ \mathrm{GeV}$ Higgs removes remaining focus point region for $m_0 < 5\ \mathrm{TeV}\ldots$

Neutralino dark matter today

In Minimal Supergravity (mSUGRA, CMSSM), the WIMP "miracle" requires exchange of light $(30 - 80\ \mathrm{GeV})$ sleptons to get the right relic density; these are ruled out by LEP (Baer *et al.,* 1202.4038)

Must go to fine-tuned regions of parameter space to get large enough annihilation cross section



Blue points: common squark mass $m_0 < 5\ \mathrm{TeV}$; orange: $5\ \mathrm{TeV} < m_0 < 20\ \mathrm{TeV}$

Heavy squarks are much more likely for satisfying relic density constraint.

Nonminimal versions of MSSM may fare better

Hidden sectors

“Hidden Valley” models were first proposed as alternative to MSSM for LHC searches (Strassler & Zurek, hep-ph/0604261)

They have dark gauge sector $G \times U(1)_h$ where SM particles are neutral under G, and $U(1)_h$ mixes with SM hypercharge

Mixing allows decays of HV hadrons into SM particles. Hidden sector could be SUSY, with separate LSPs in HV and SM and unstable $\chi_{\rm SM}$,

$$\chi_{\rm SM} \to \chi_{\rm HV} + \text{ HV hadrons} \to \chi_{\rm HV} + \text{ SM particles}$$

Can be realized in string-theoretic versions of the SM (Cvetic *et al.*, 1210.5245)

Portals connecting SM to hidden sector

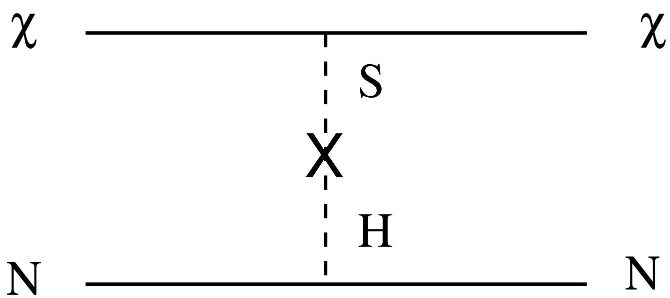
$\lambda |H|^2 S^2$

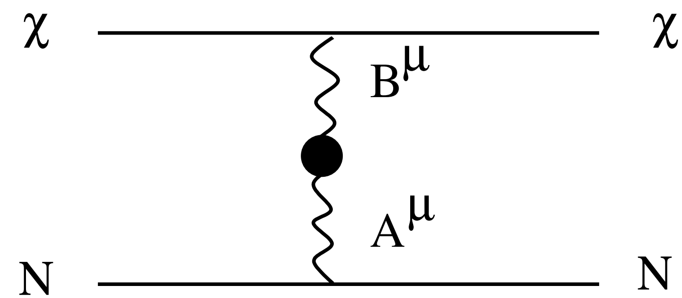
Higgs portal

$\epsilon Y_{\mu\nu} B^{\mu\nu}$

gauge kinetic mixing portal

($Y_{\mu\nu}$ is SM hypercharge field strength.)
B. Holdom, PLB 166 (1986) 196





Interactions with SM are suppressed by small parameter,

$$\lambda \frac{v\langle s\rangle}{m_h^2 - m_s^2} \quad \text{(Higgs portal)}, \qquad \epsilon \quad \text{(gauge kinetic mixing)}$$

Kinetic mixing portal

If B_μ has mass m_B, mixing is removed by transformation

$$A_\mu = \tilde{A}_\mu - \epsilon\cos\theta_W \tilde{B}_\mu + O(\epsilon^2)$$

$$B_\mu = \tilde{B}_\mu + \epsilon\sin\theta_W \tilde{Z}_\mu + O(\epsilon^2)$$

$$Z_\mu = \tilde{Z}_\mu - \epsilon\sin\theta_W \frac{m_B^2}{m_z^2}\tilde{B}_\mu + O(\epsilon^2)$$

$\tilde{A}_\mu$, $\tilde{B}_\mu$, $\tilde{Z}_\mu$ are mass eigenstates. Dark matter does not couple to photon.

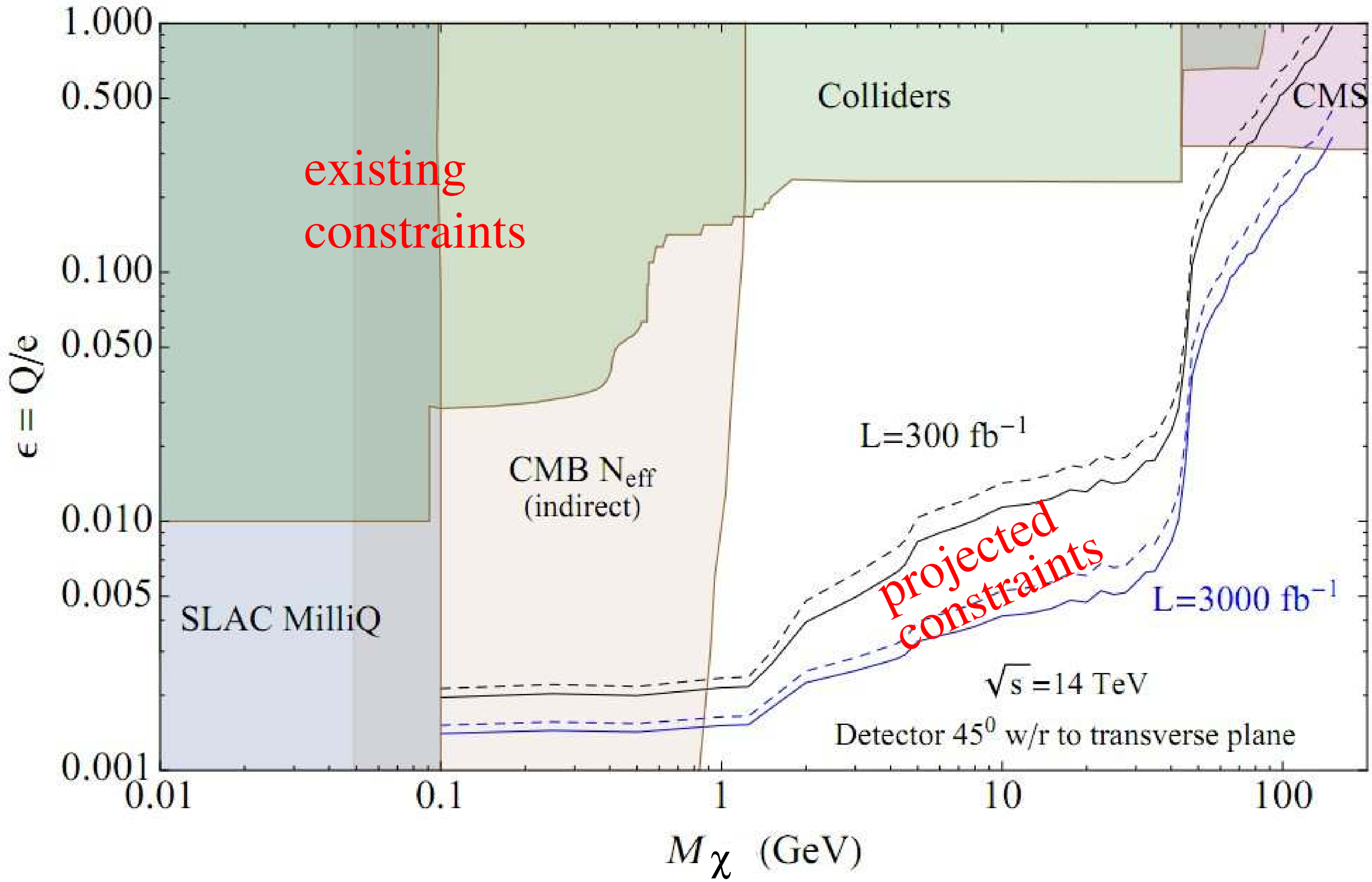
But if dark photon is massless, mixing $\epsilon B_{\mu\nu}F^{\mu\nu}$ is removed by

$$B_\mu \cong \tilde{B}_\mu + \epsilon A_\mu$$

Dark matter gets millicharge ϵe !

Constraints on millicharged particles

Haas *et al.*, (1410.6816) propose new experiment at LHC to improve constraints on millicharged particles

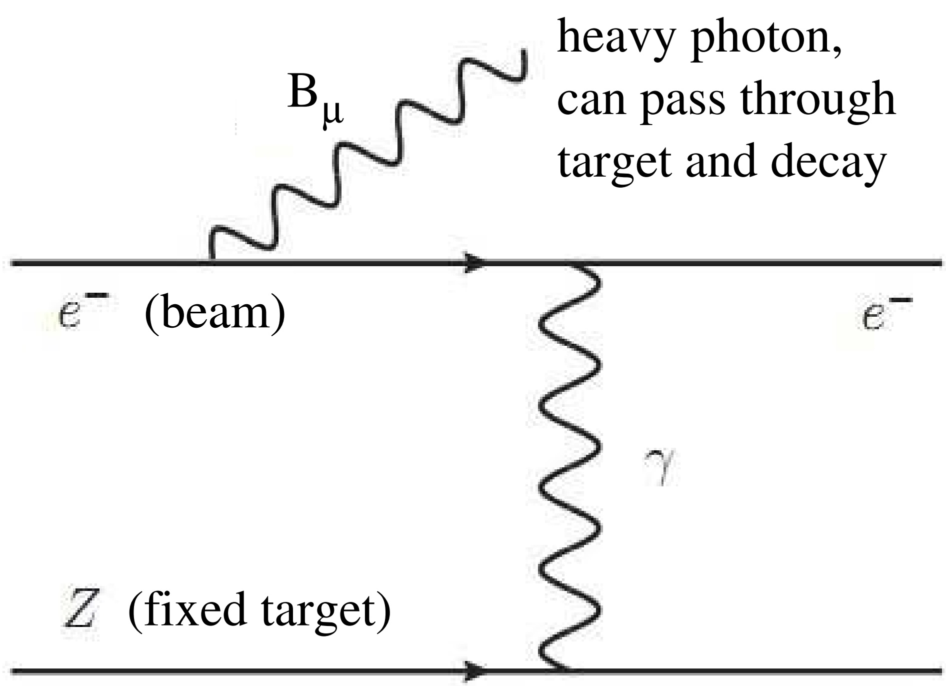


MCPs escape ATLAS/CMS detectors, produce ionization in new external scintillator

Heavy photon searches

Many applications to indirect detection prefer dark photon B_μ to be light, $m_B \lesssim \text{GeV}$ (but not massless).

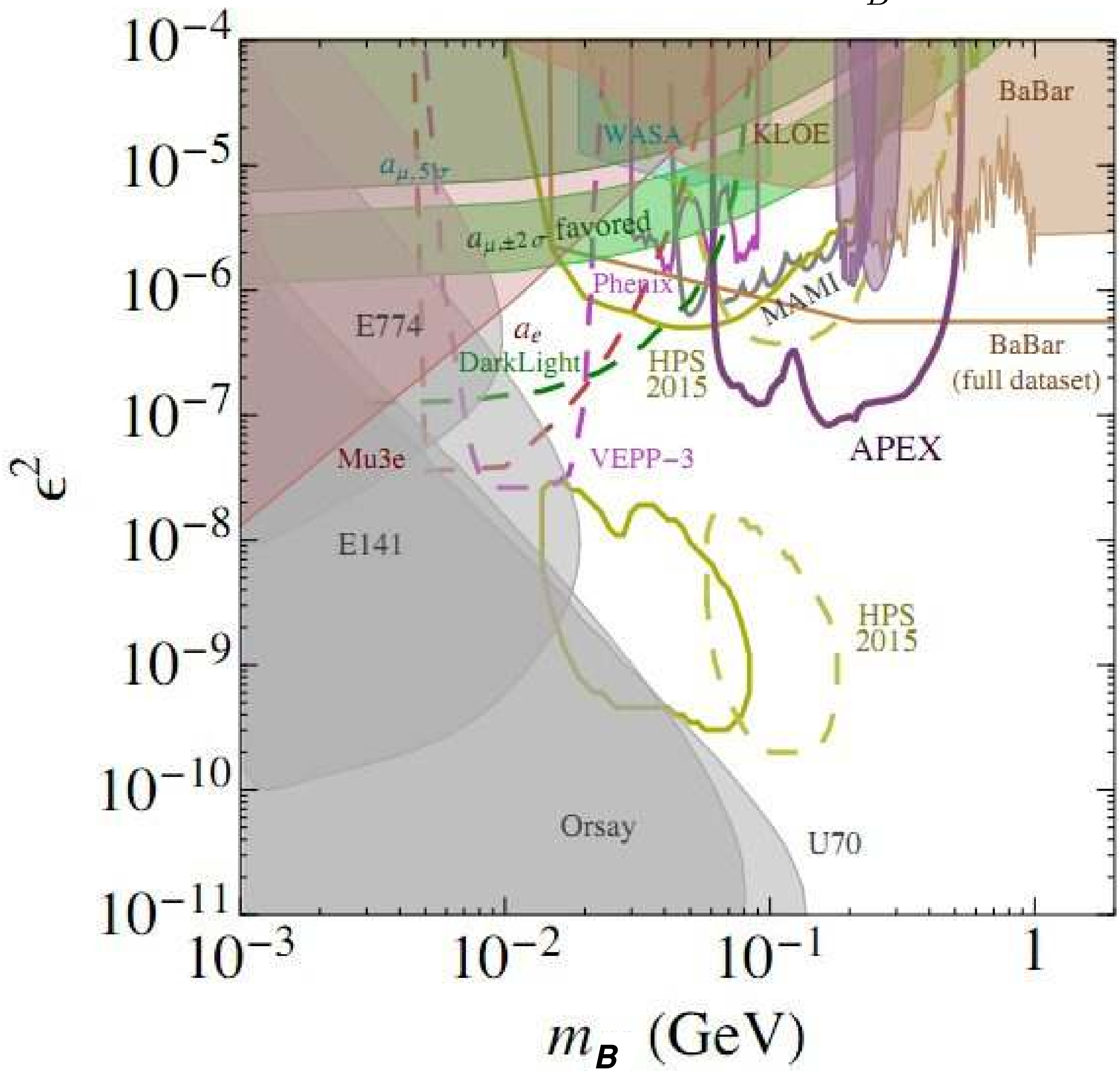
Low-energy, high-intensity electron beams can produce B_μ and look for its decays into e^+e^-.



Current experiments: APEX, DarkLight, HPS (Heavy Photon Search) at Jefferson Lab, or MAMI (Mainz Microtron)

Constraints on kinetic mixing

For $1\ \mathrm{MeV} < m_B < 1\ \mathrm{GeV}$:

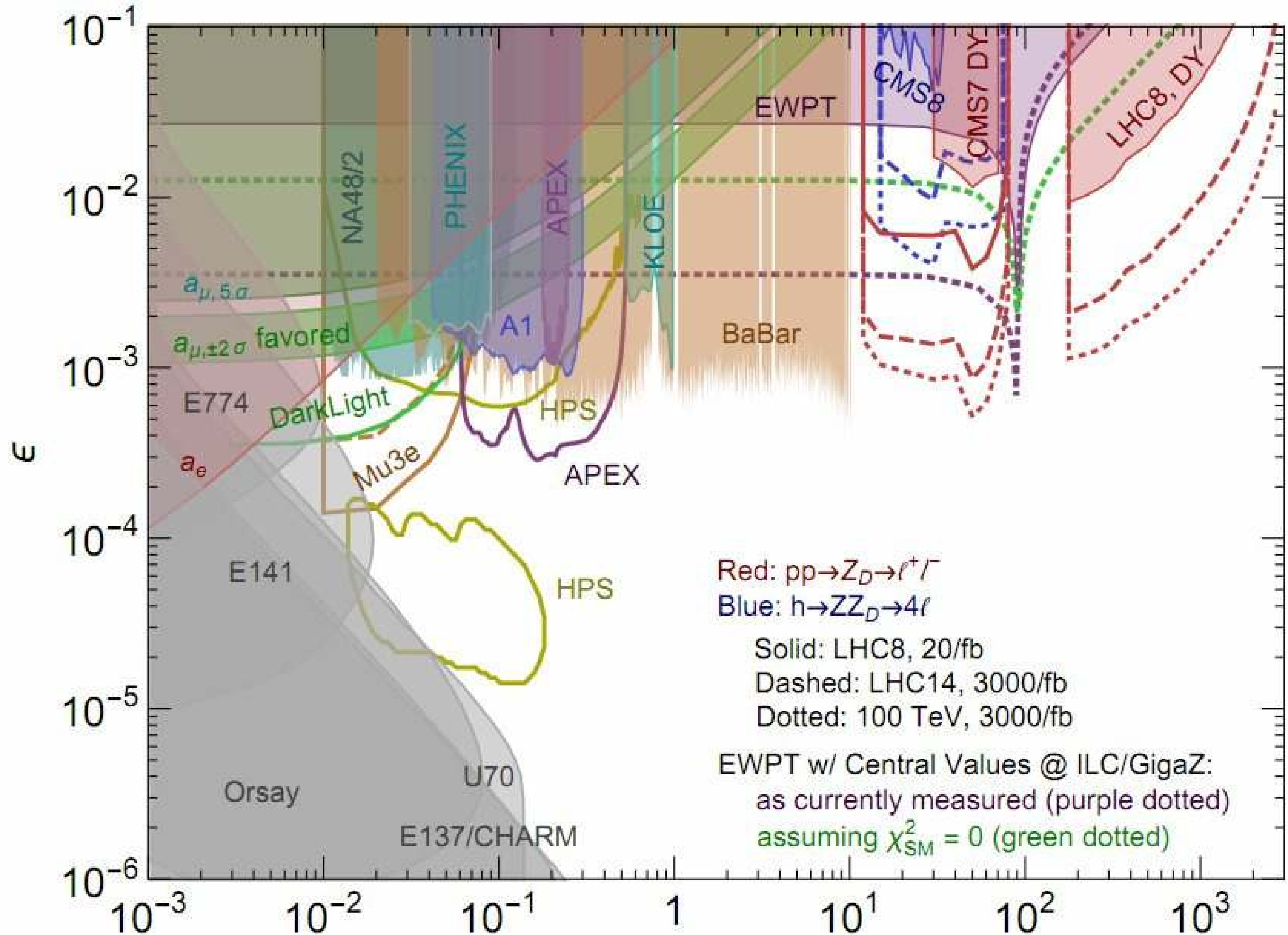


MAMI, HPS, APEX and DarkLight will cover part of unexcluded regions in near future

http://hallaweb.jlab.org/experiment/APEX/collab2014/Rouven-Essig-APEX-Overview.pdf

Constraints on kinetic mixing (2)

At higher m_B constraints are weak



Curtin *et al.*, (1412.0018) propose LHC searches for $pp \to B \to \ell\bar{\ell}$ and $h \to ZB \to 4\ell$ to extend the limits

Higgs portal $\left(\frac{1}{2}\lambda|H|^2S^2\right)$

If singlet scalar S gets VEV s, Higgs mass matrix is

$$\begin{pmatrix} m_h^2 & \lambda v s \\ \lambda v s & m_s^2 \end{pmatrix}$$

Mixing angle given by $\tan 2\theta = \lambda v s/(m_h^2 - m_s^2)$.

Singlet interacts with SM fermions like Higgs, but with $\sin\theta$-suppressed couplings.

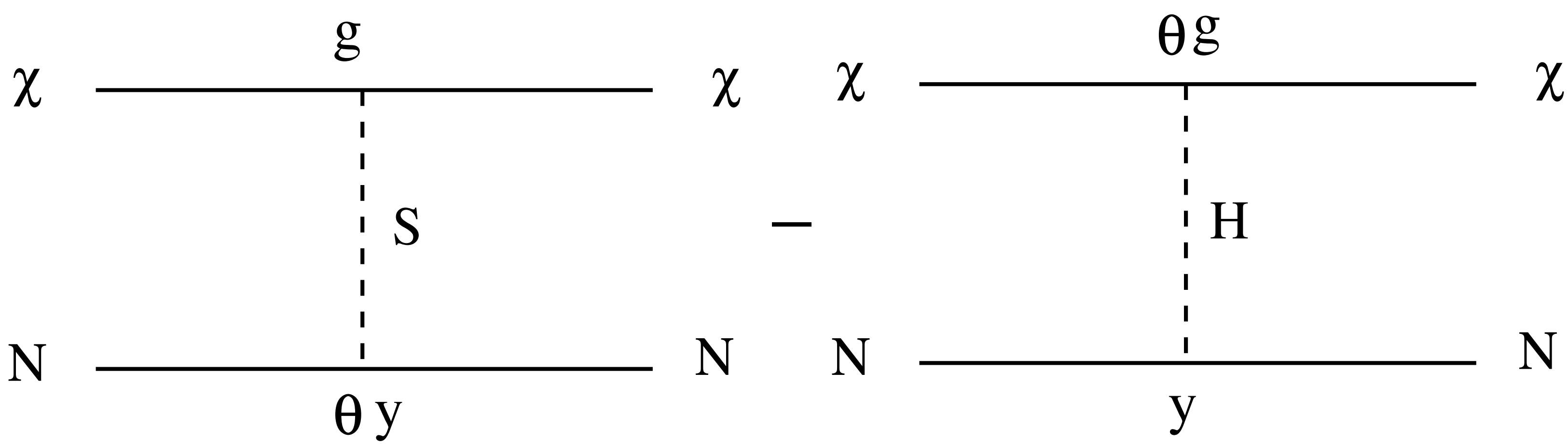
Similarly, if S couples to DM $(gS\bar{\chi}\chi)$, Higgs acquires θ-suppressed coupling to χ, $\mathcal{L} \sim \theta g h \bar{\chi}\chi$

If $m_\chi < m_h/2$, then invisible decays $h \to \chi\bar{\chi}$ constrain θg:
$\Gamma_{\rm inv} = \theta^2 g^2 m_h (1 - 4m_\chi^2/m_h^2)^{3/2}/16\pi < 0.19 \times 4.1\ \mathrm{MeV}$ (1306.2941)

$$\Rightarrow \theta g \lesssim 0.02$$

Direct detection via Higgs portal

Direct detection ($N\chi \to N\chi$ by scalar exchange) also constrains θg. Interference is destructive,



Cross section for scattering on nucleon is

$$\sigma_p = \frac{(g\theta y)^2}{\pi}\,\mu_{\chi p}^2 (m_s^{-2} - m_h^{-2})^2$$

Higgs-nucleon coupling is $y \cong 0.35\, m_p/v \cong 1.3 \times 10^{-3}$ (1306.4710). *E.g.*, if $m_s = 2\, m_h$ and $m_\chi = 100$ GeV, LUX limit gives

$$\theta g \lesssim 0.05$$

Other portals

The portal need not be a renormalizable operator. For example the neutrino portal $\mathcal{O}_{\rm dark} H L$ (Falkowski *et al.*, 0908.1790). Explicit example:

$$\mathcal{L}_{\rm int} = \frac{1}{\Lambda^2}\chi^a \sigma^{\mu\nu} G^a_{\mu\nu} H L$$

with a hidden SU(N) gauge symmetry. DM is an unstable "glueballino" (bound state of χ^a and dark gluons) that decays (very slowly) into SM neutrino plus Higgs.

Charged lepton portal (Bai & Berger, 1402.6696, Chang *et al.*, 1402.7358)

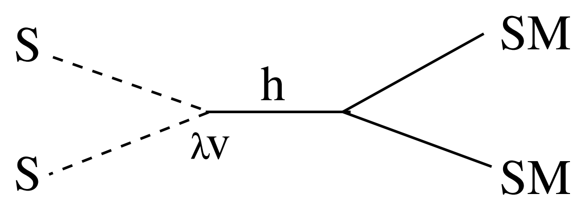
A renormalizable interaction involving fermionic or scalar DM plus a new charged scalar (ϕ) or fermion (ψ):

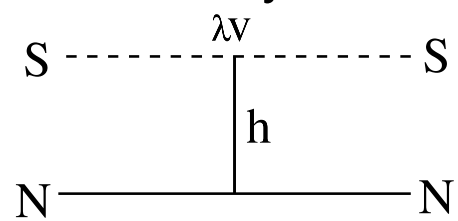
$$\phi \bar\chi_L e_R \qquad \text{or} \qquad \chi \bar\psi_L e_R$$

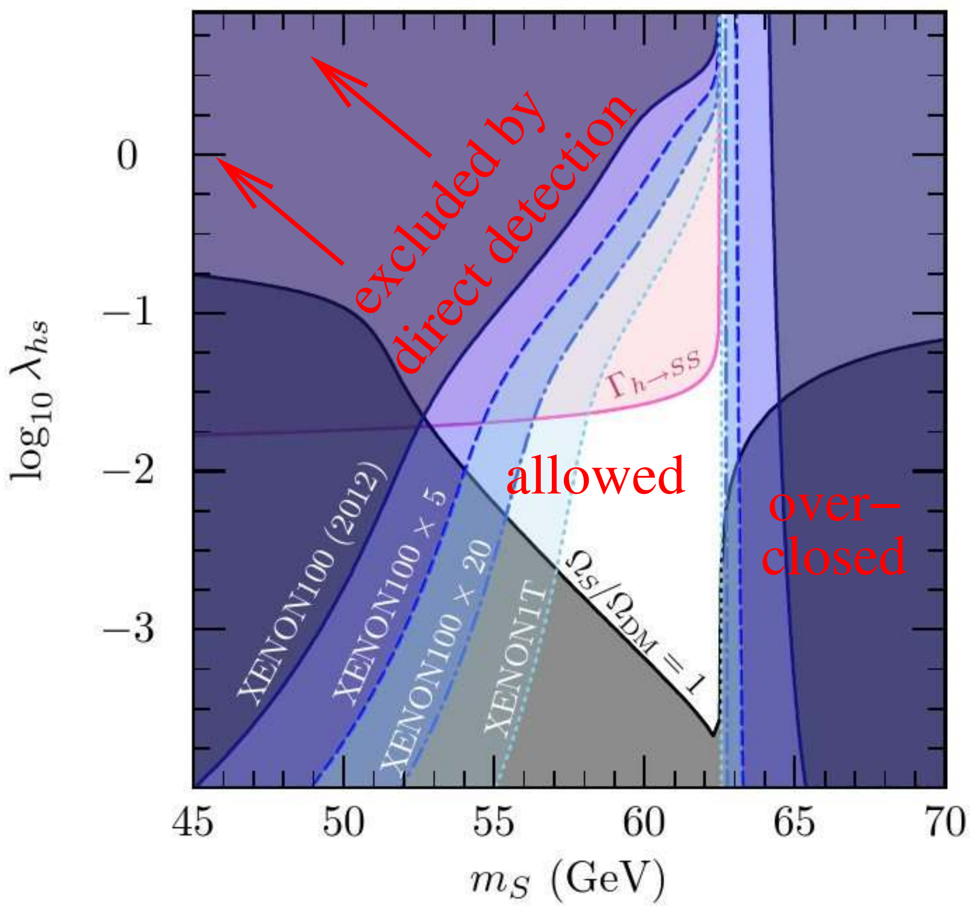
Could be discovered at LHC (see p. 114)

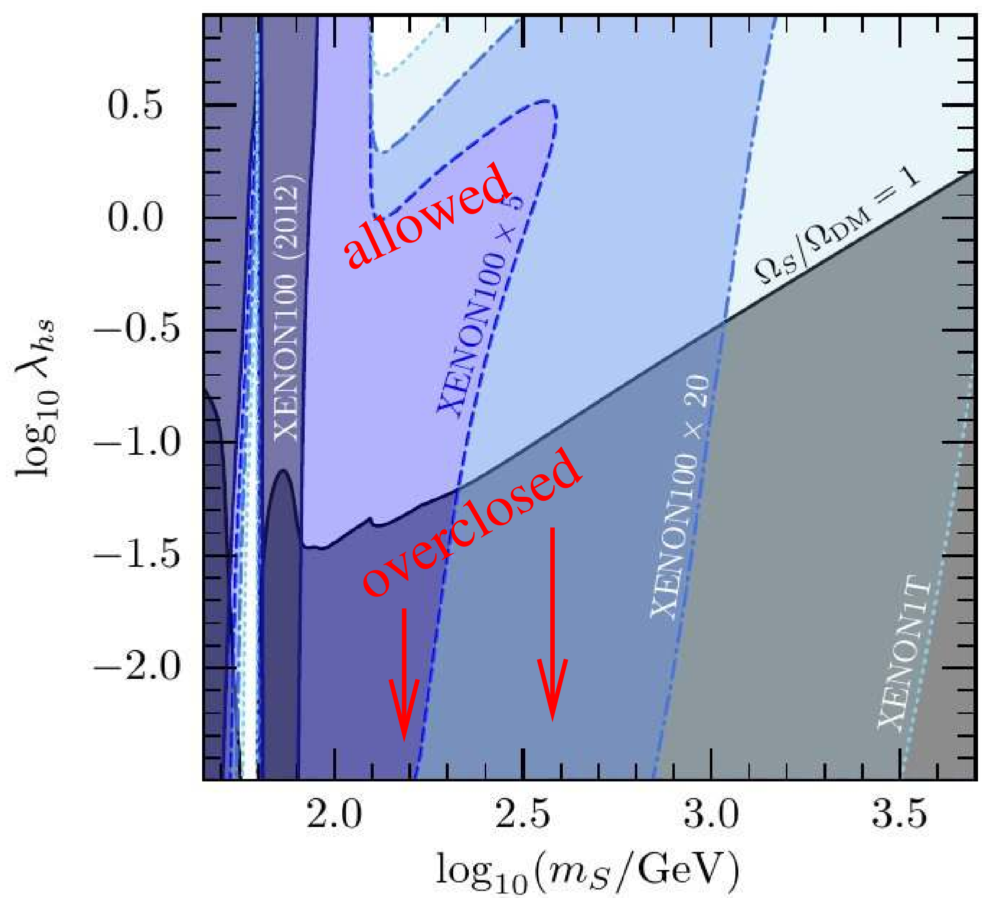
Simplest DM model: singlet scalar

If S does not get a VEV, then it does not mix with Higgs and is stable: can be the dark matter itself. λ controls both relic density and direct detection,







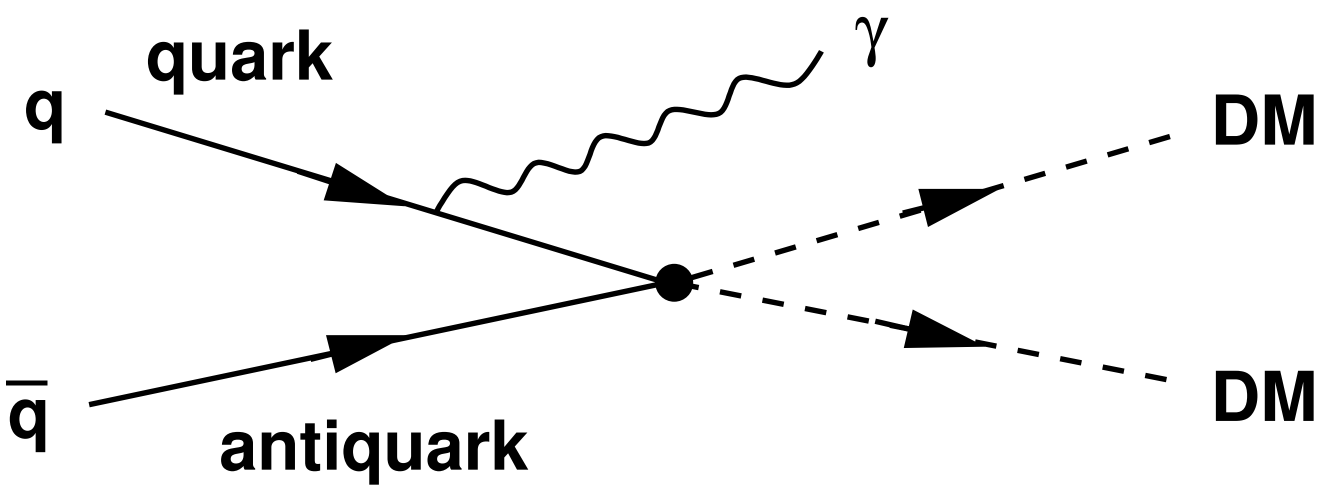


JC, K. Kainulainen, P. Scott, C. Weniger (1306.4710)

Creation of DM in the lab

Dark matter would look like *missing transverse energy* in a high-energy collision

Particle experimentalists are used to looking for $\not{E}_T$

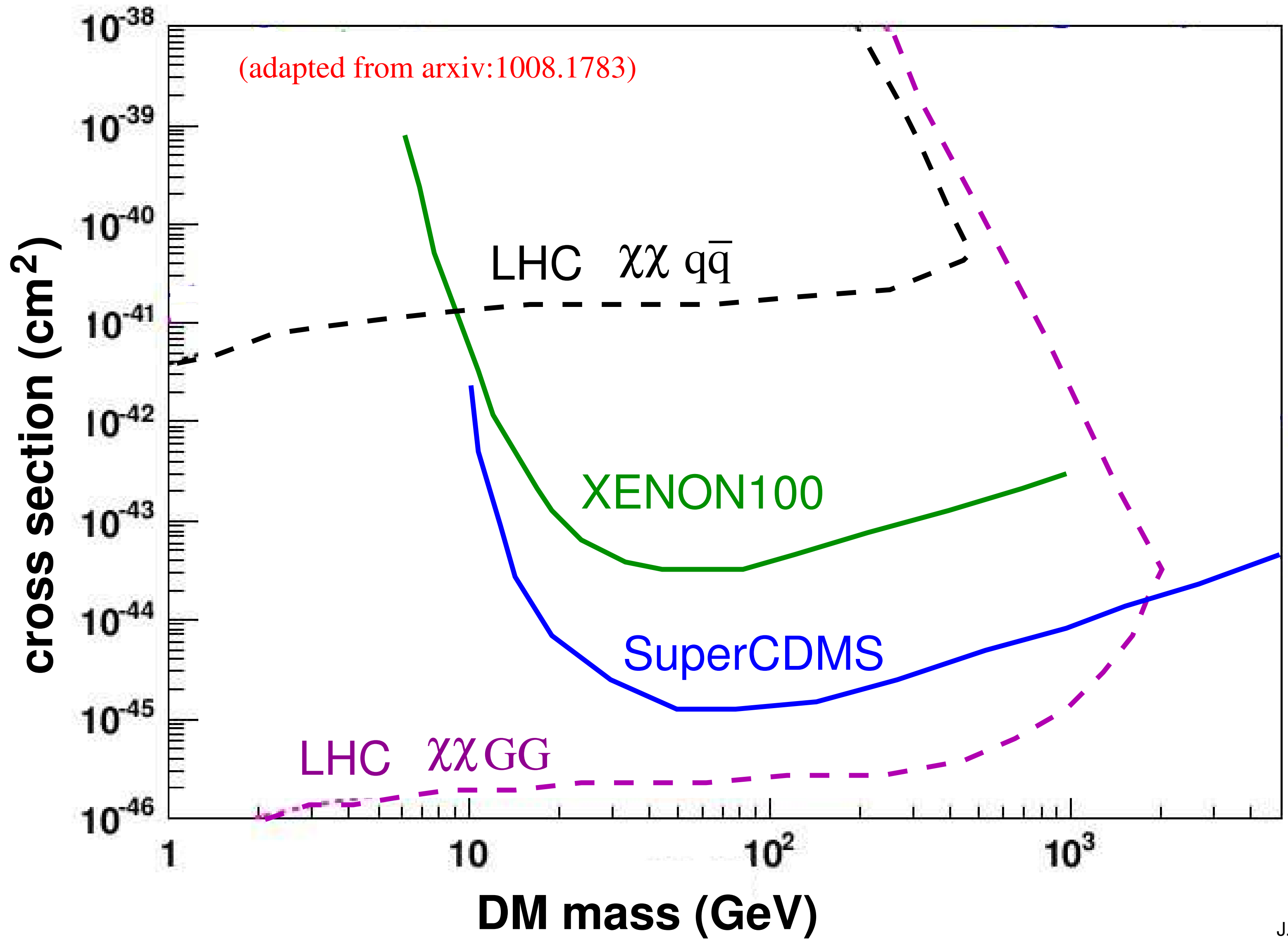


Momentum of photon (or hadronic jet) must be balanced by *something*

Monophotons/monojets would be evidence for DM in the lab

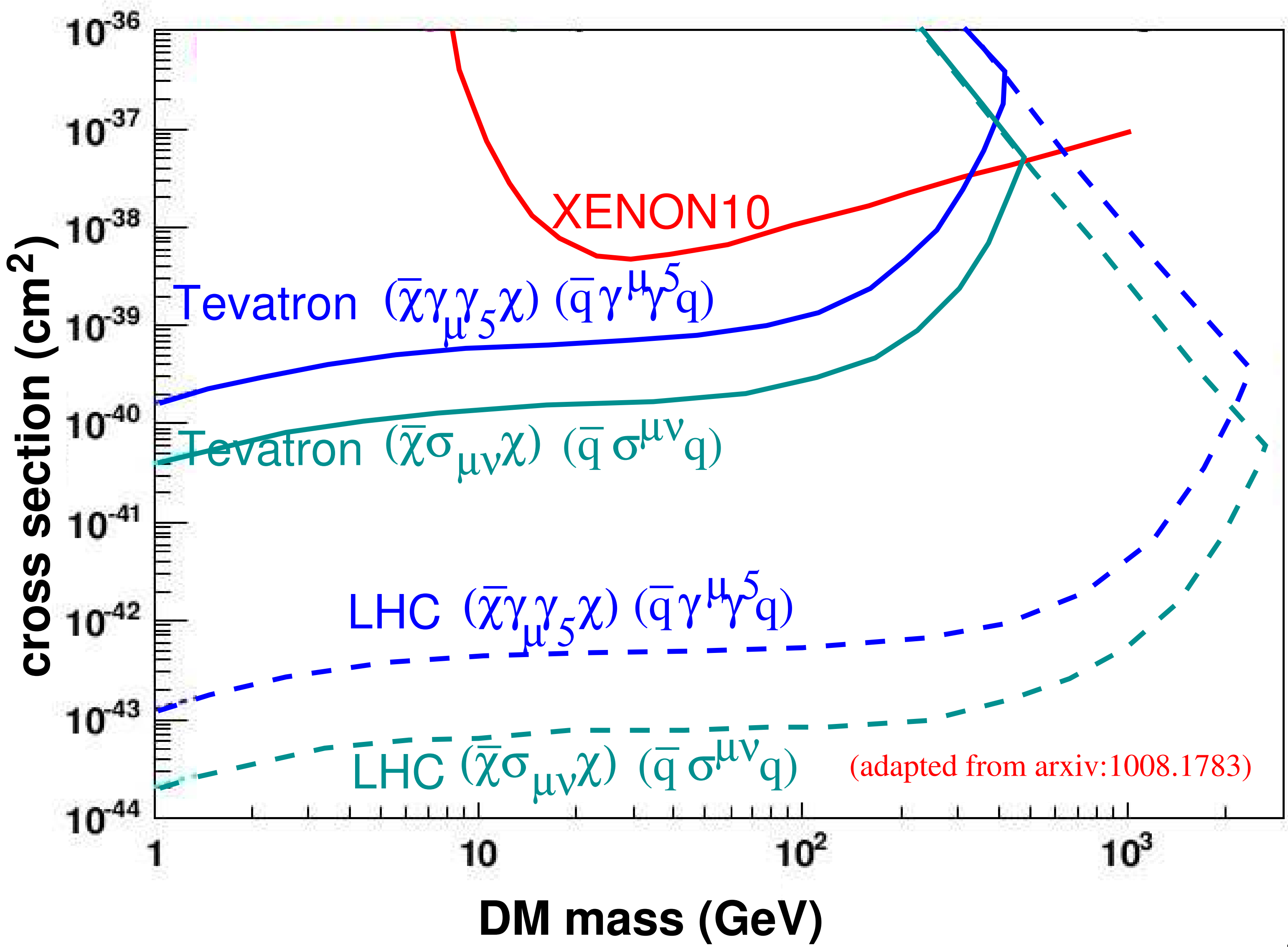
LHC sensitivity to DM

LHC could be more sensitive or less so than direct searches, depending on exactly how DM interacts with quarks.



LHC sensitivity to DM

For spin-dependent scattering, LHC and Tevatron are more sensitive than direct detectors



Limitations of effective operators

Previous limits depend on how DM interacts with SM. If mediators are heavy ($\gg$ TeV), can use effective operator approach to avoid model dependence.

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Effective operators from Goodman *et al.*, (1008.1783)

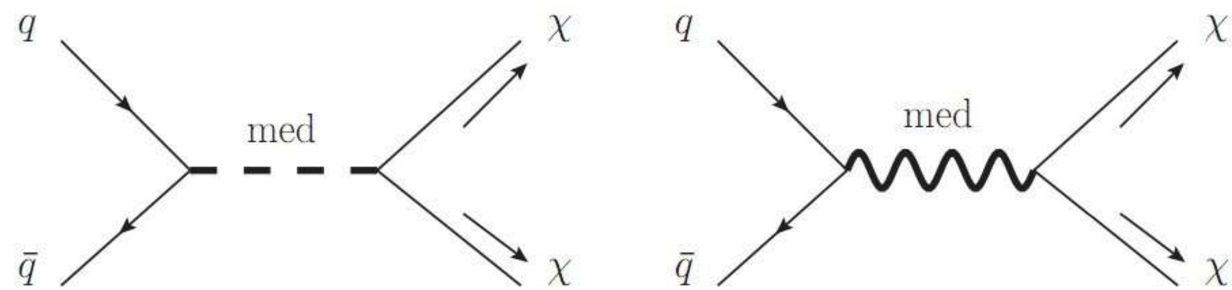
D: Dirac DM
C: Complex scalar DM
R: Real scalar DM

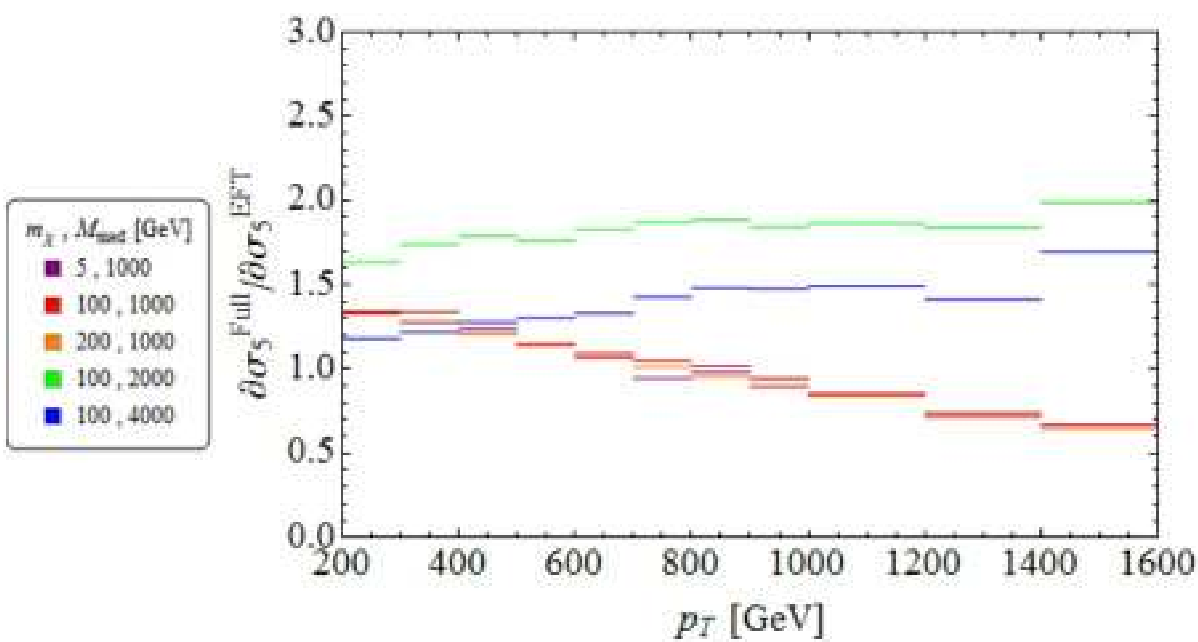
But if mediator is light, effective operator approach is invalid: *e.g.*, $1/M_*^2 \to g^2/(s - m_*^2)$

Simplified Models

Abdallah *et al.*, (1409.2893)

To go beyond EFT, study the simplest models that UV-complete the EFT. *E.g.*, $\bar\chi\chi\,\bar q q$ ($\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q$) is generated by exchange of scalar (vector) mediator

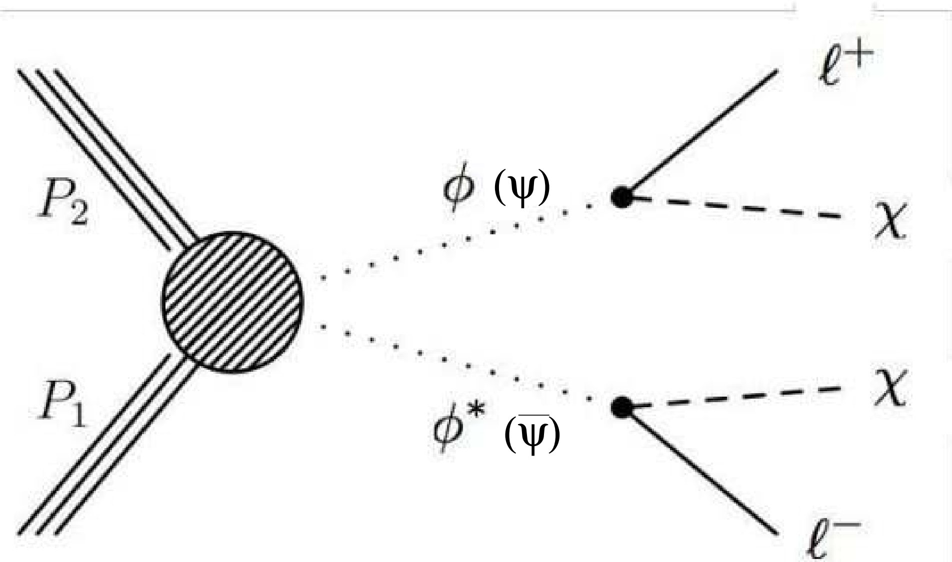




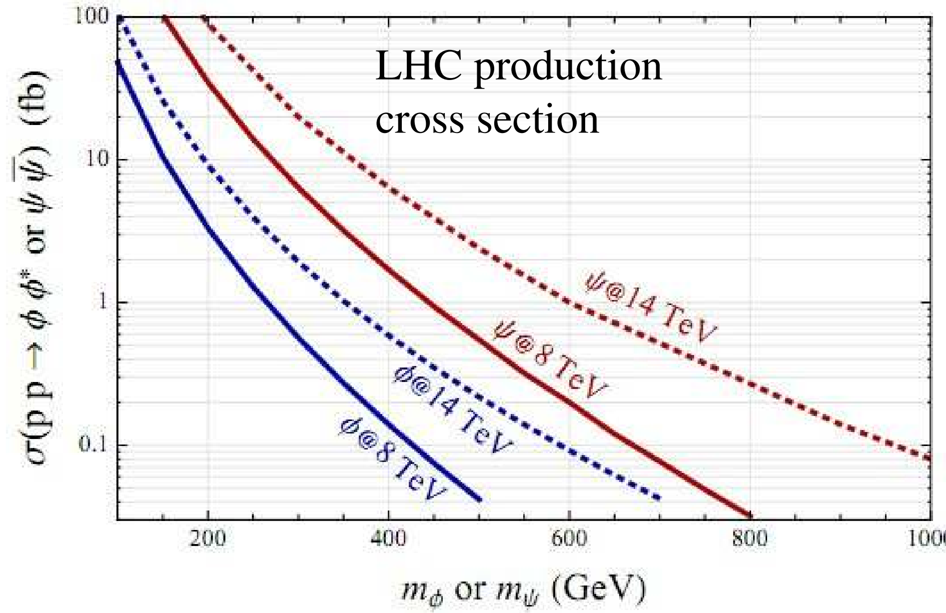
Ratio of true σ to $\sigma_{\rm EFT}$ versus transverse momentum of monojet, for vector mediator

Specific models: lepton portal

Specific DM models can have novel signatures beyond $\not{E}_T$.
E.g., lepton portal DM gives lepton pairs plus $\not{E}_T$:



Bai & Berger, 1402.6696

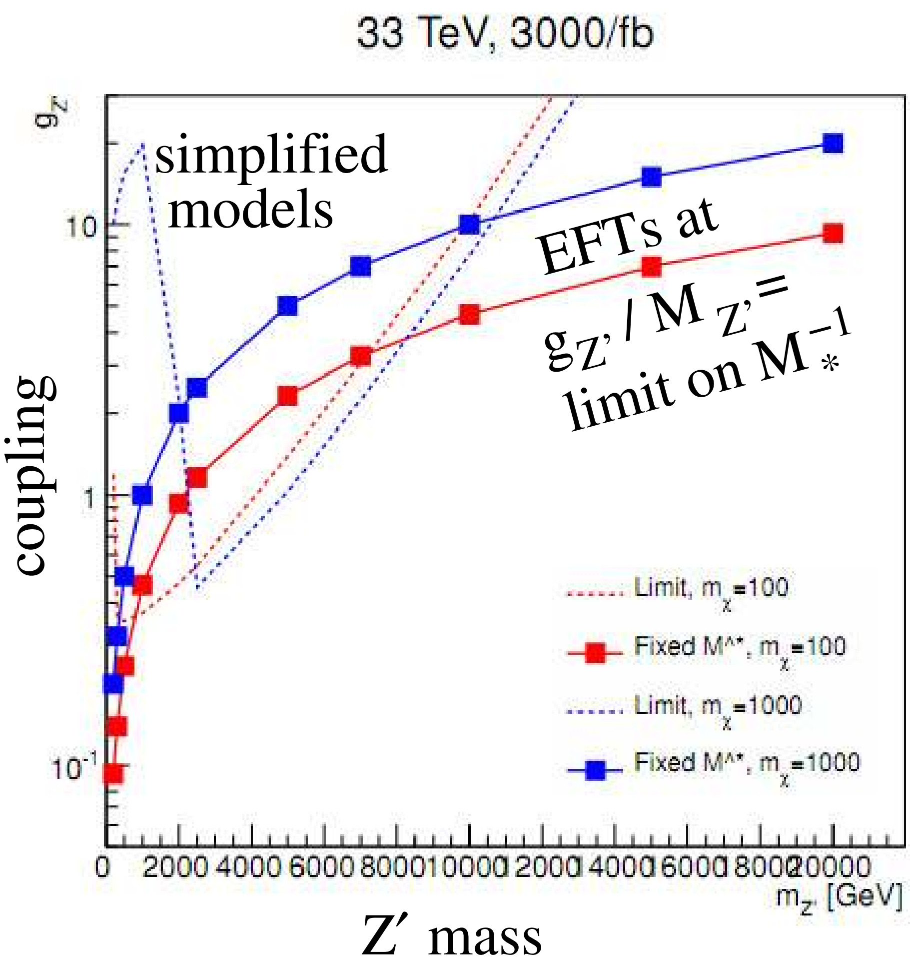


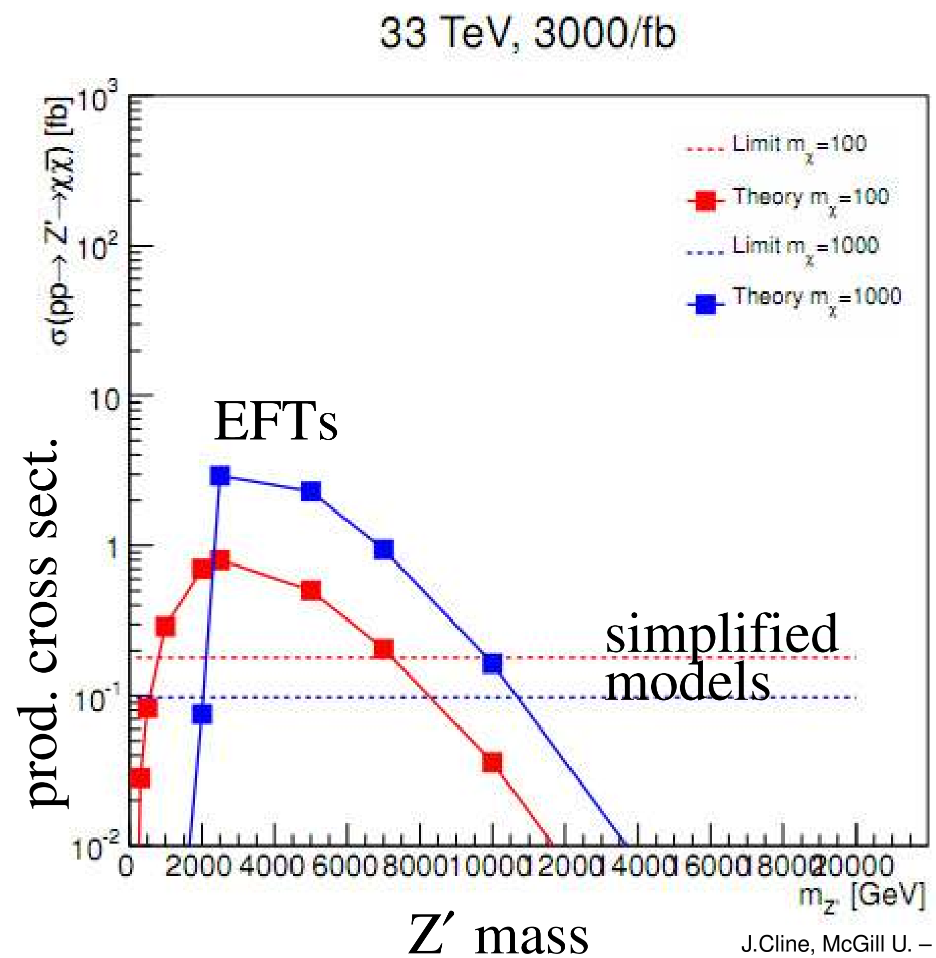
Similar to lepton-slepton-higgsino coupling in SUSY.

Specific models: Z' mediation

An extra U(1) with heavy gauge boson Z' is a simple way to extend the SM. Suppose Z' couples to χ and to quarks with strength $g_{Z'}$.
EFT interaction would be $M_*^{-2}\,\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q$ with $M_* = m_{Z'}/g_{Z'}$

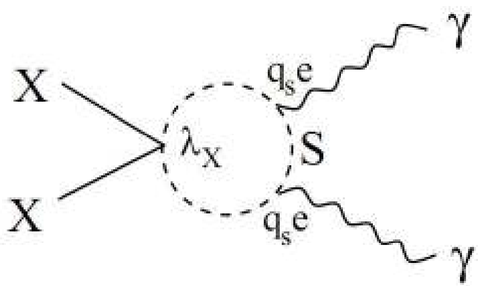
Projected limits at 33 TeV collider (Zhou *et al.*, 1307.5327):



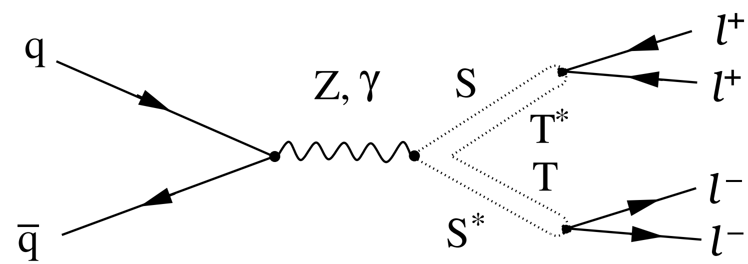


Specific models: dilepton pairs

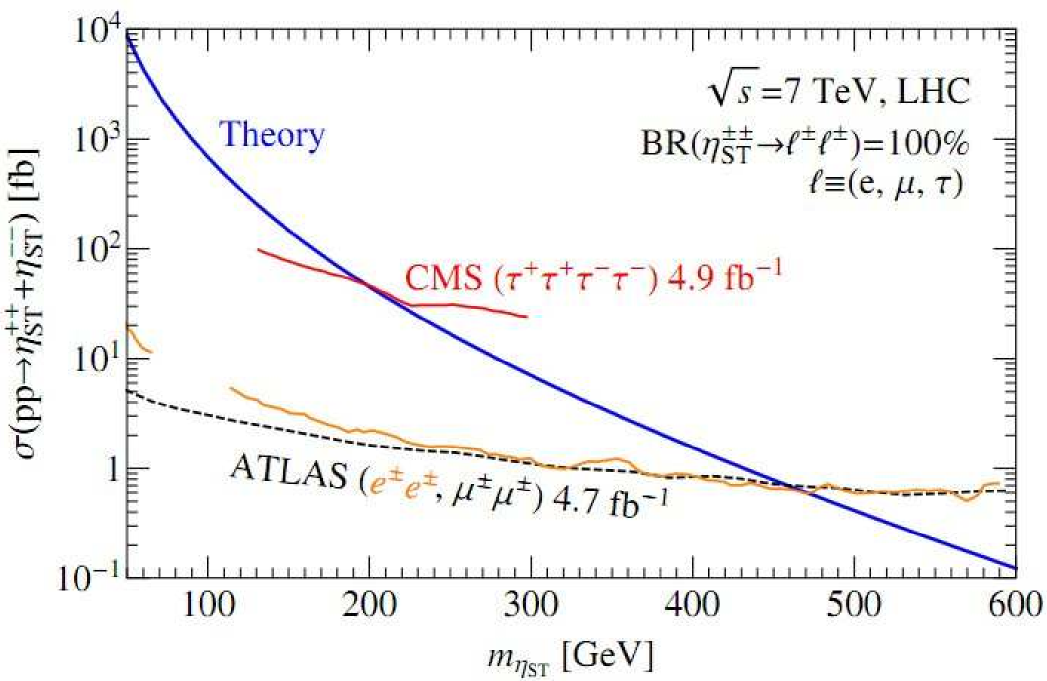
Hints of 130 GeV γ-ray excess from Fermi telescope motivated models of DM annihilating to photons (J. Cline,1205.2688). Model with charged scalar mediators predicts same-sign dileptons at LHC:



DM annihilation to photons via strongly interacting charged scalar



Same−sign dilepton production from decays of bound states of charged and neutral scalars



ATLAS and CMS constrain minimum mass of exotic ST^* bound state

J. Cline, G. Dupuis, Z. Liu, 1306.3217

Conclusions

We believe that DM must exist. It seems unlikely that its interactions are only gravitational. We should be able to discover it!

Indirect detection bounds on $\langle\sigma v\rangle_{\rm ann}$ are close to thermal relic value $\sim 3\times 10^{-26}{\rm cm}^3/{\rm s}$ for some DM masses. Discovery could be near—especially if galactic center γ-ray excess holds up.

End of an era for direct detection approaches: either we see DM scattering on nuclei, or we hit the neutrino background wall.

If we are lucky, missing energy signals at LHC will show that DM has been produced in the laboratory.