‘Spåtind’ conference, Skeikampen, 2-7 Jan 2020

Searching for Dark Matter

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UiO : University of Oslo

Outline

Sunday (5 Jan)

- Introduction — ***Sokolenko*** ***(Oslo Winter school)***
  - Evidence
  - Candidates & Tools — ***Ruchayskiy***
- [Collider searches] — ***Bjørke, Corrigan, Hansen, Vadla, …*** [For an intro see also the nice review Kahlhoefer, IJMP '17]
- Direct searches
  - 'reverse' direct detection
- Indirect searches — ***Koskinen***
  - Gamma rays

Monday (6 Jan)

  - Charged cosmic rays — ***Tjemsland***
- Other astrophysical probes
  - The matter power spectrum
  - Self-interacting dark matter — ***Sokolenko***
  - ETHOS
- Complementarity
  - Example: Light scalar mediators

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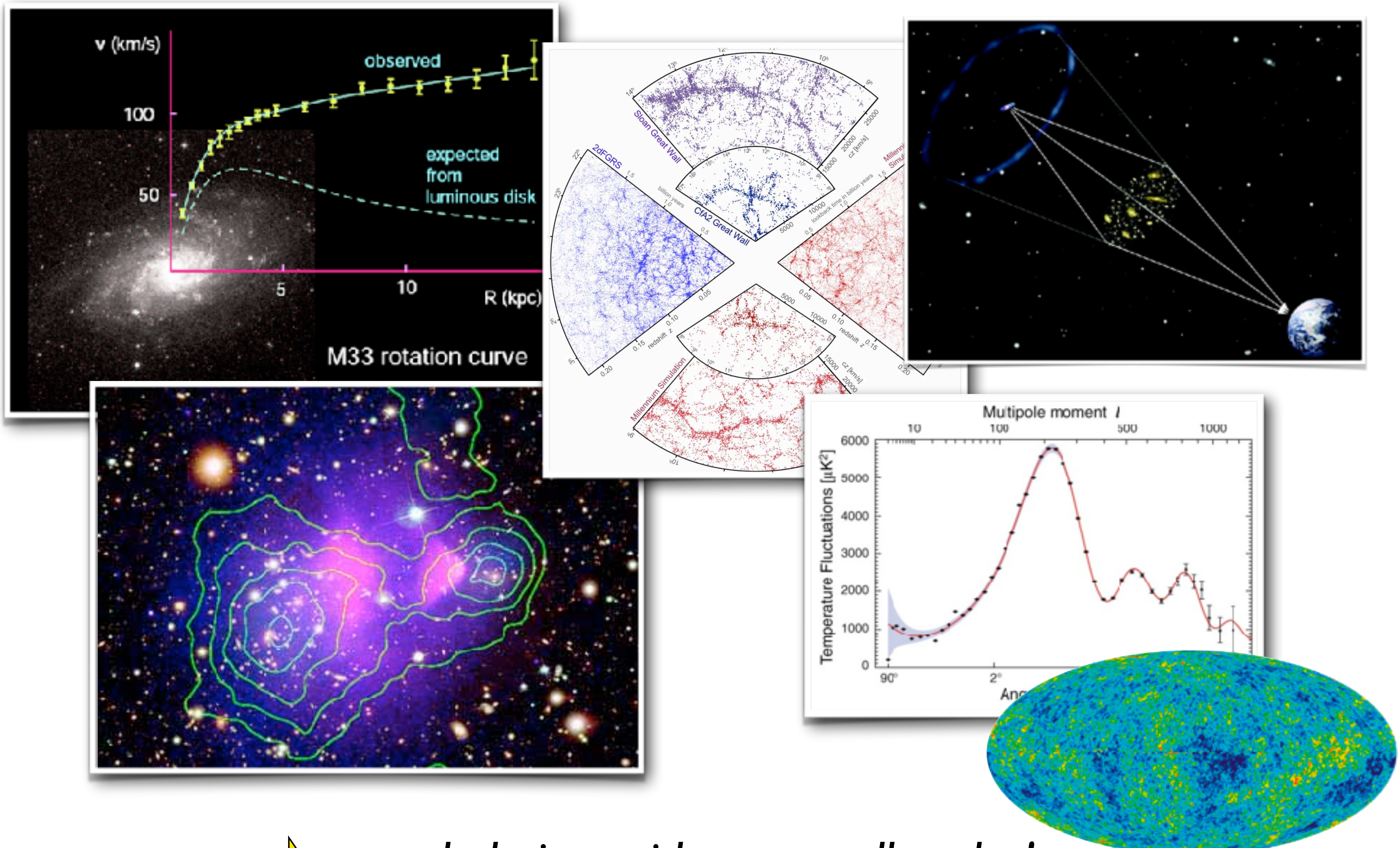
Dark matter all around



➡ *overwhelming evidence on* ***all*** *scales!*

Cosmology without dark matter ?

- **Fails miserably** already at linear level:
  1. Observation: $\Delta T/T_{\rm CMB} \sim \delta \equiv |\rho - \bar\rho|/\bar\rho \sim 10^{-5}$
  2. $T > T_{\rm CMB} : \delta_\gamma = \delta_b$
  3. Observation: $T_{\rm CMB} \sim 2.7\,K \rightsquigarrow a_{\rm CMB}/a_0 \sim 10^{-3}$
  4. (Linear gravity) $T < T_{\rm CMB} : \delta_\gamma \sim const, \quad \delta_b \propto a(t)$

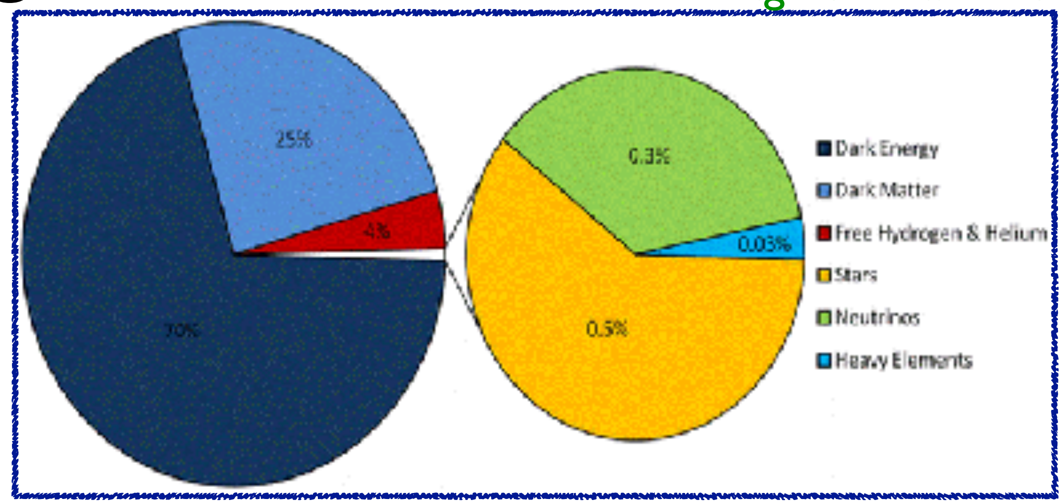
  ⇒ **Expect $\delta \sim 10^{-2}$ today:**
  ***No* galaxies, stars, planets, …life !**

- DM is a crucial ingredient of cosmological SM!
  - constant co-moving energy density
  - only gravitational interactions
  - cold + dissipation-less

  ⇒ $\boxed{\Omega_{\rm CDM}h^2 = 0.1188 \pm 0.0010}$ **Percent-level measurements of a single parameter!**

  Ade+ [Planck Coll.], A&A '16

Image credit: KIAS



- DM conversion into (in)visible energy?
  - E.g. decays, late-time annihilation, coalescing PBHs, …

  ⇒ $\Omega_{\rm CDM}$ decrease of up to 10% possible during matter domination!

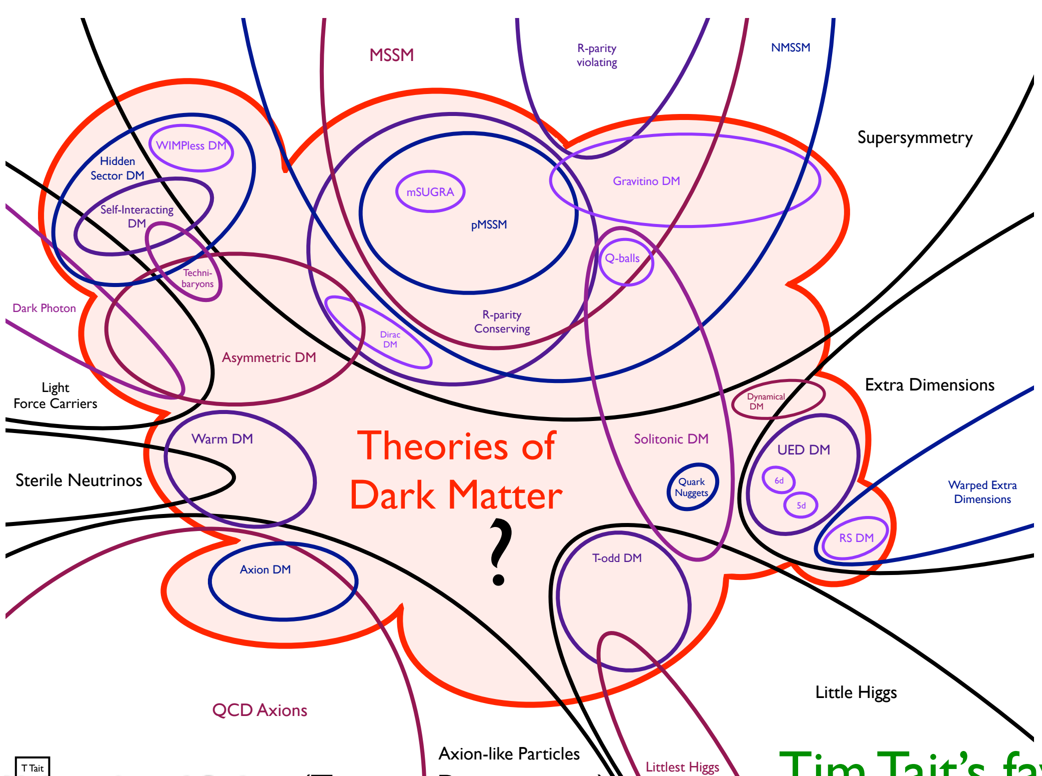
  (*model-independent*; but much more allowed during RD)

  TB, Kahlhoefer, Schmidt-Hoberg & Walia, PRD '18

Candidates

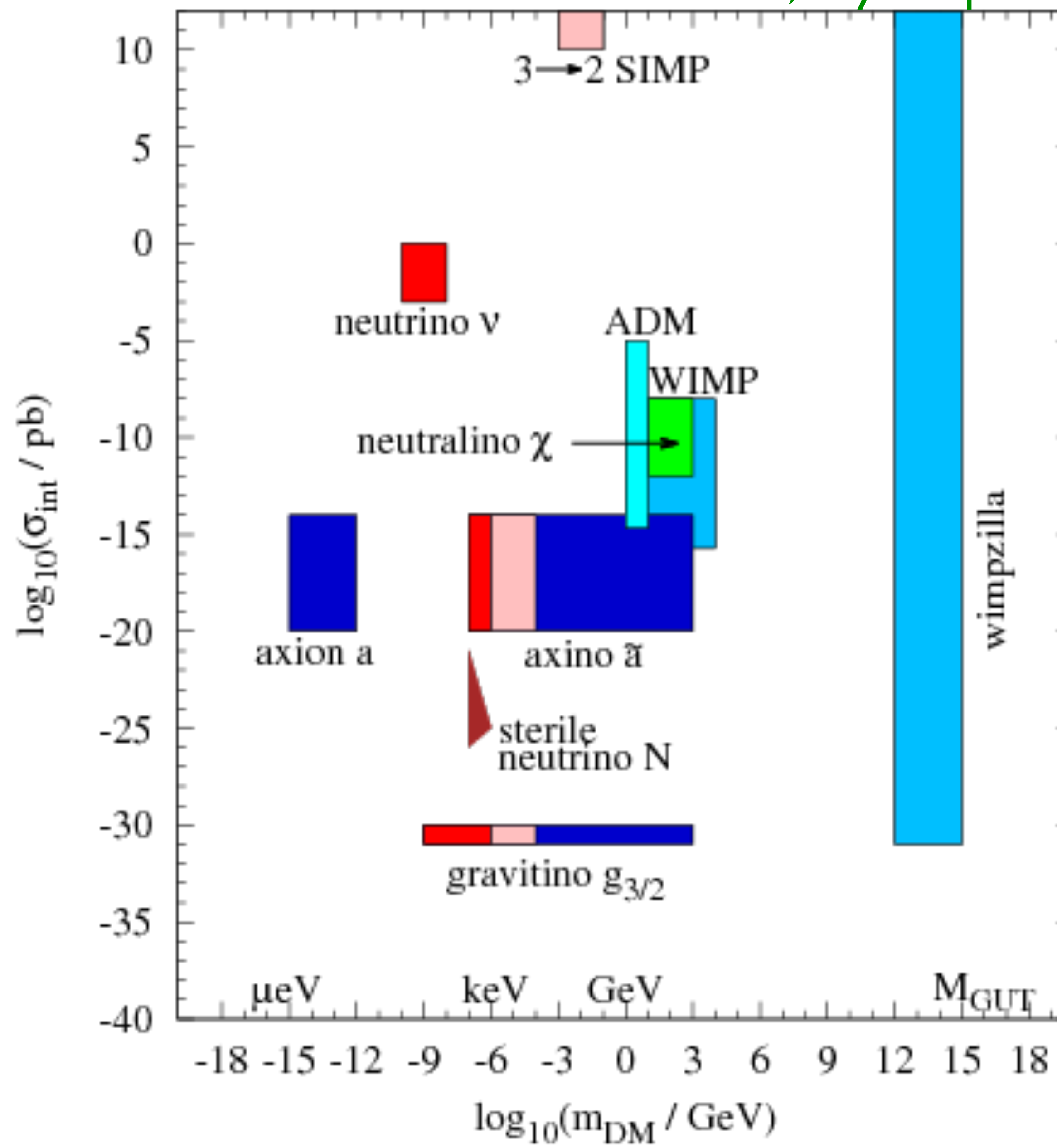
- Existence of (particle) DM = evidence for BSM physics!
  - + rather good handle on what it is ***not***
- Unfortunately, this still leaves too many options…

Oleg's favourites



Tim Tait's favourites

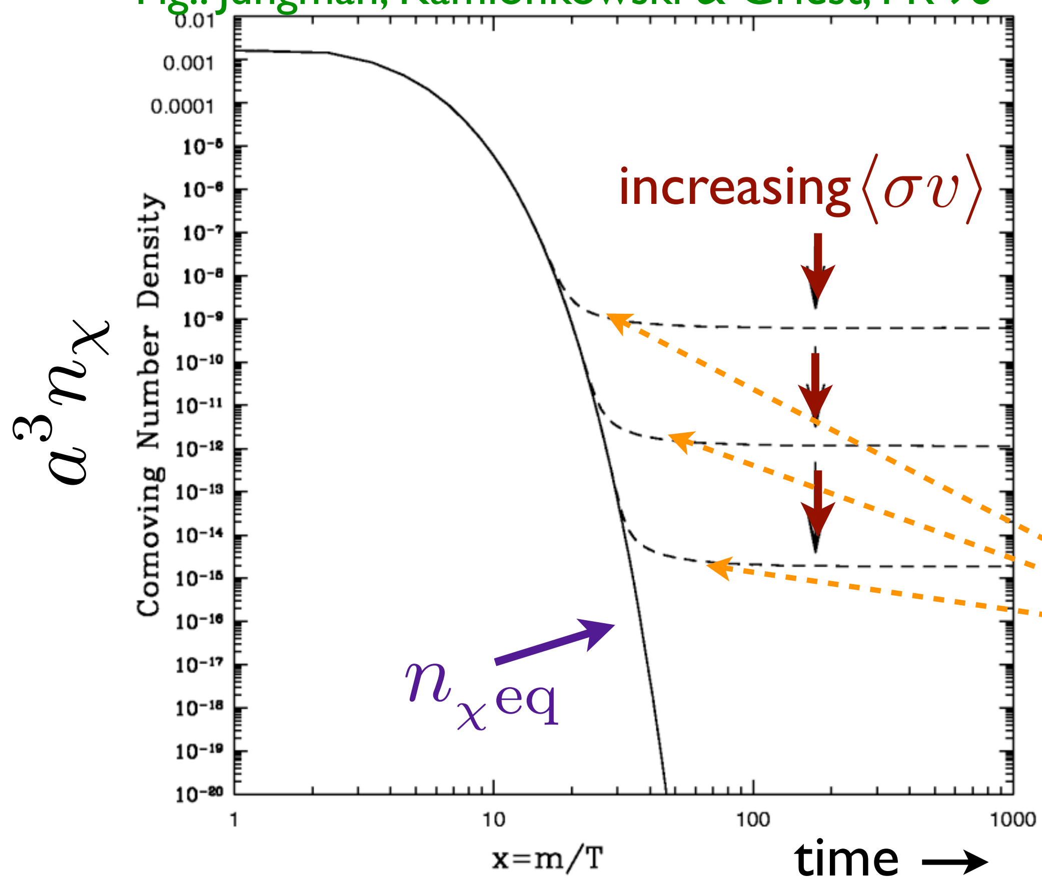
Baer+, Phys.Rep.'15



Weakly Interacting Massive Particles

- well-motivated from particle physics [SUSY, EDs, …]
- thermal production in early universe:

Fig.: Jungman, Kamionkowski & Griest, PR'96



$$\boxed{\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)}$$

$\langle\sigma v\rangle$: $\chi\chi \to \mathrm{SM\ SM}$

(thermal average)

"Freeze-out" when annihilation rate falls behind expansion rate

$\Rightarrow$ Relic density (today): $\Omega_\chi h^2 \sim \dfrac{3\cdot 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle} \sim \mathcal{O}(0.1)$

for weak-scale interactions!

= a 'miracle' ?

- WIMP DM is seriously pressured, but not (yet) 'dead' !

Arcadi+, EPJC '18
Athron+, EPJC '19
(+ many more)

Dead or alive ?

Forbes Billionaires Innovation Leadership Money Business Small Business Lifestyle Lists Advisor Featured Breaking More

52,696 views | Feb 22, 2019, 02:00am

The 'WIMP Miracle' Hope For Dark Matter Is Dead

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science

The Universe is out there, waiting for you to discover it.

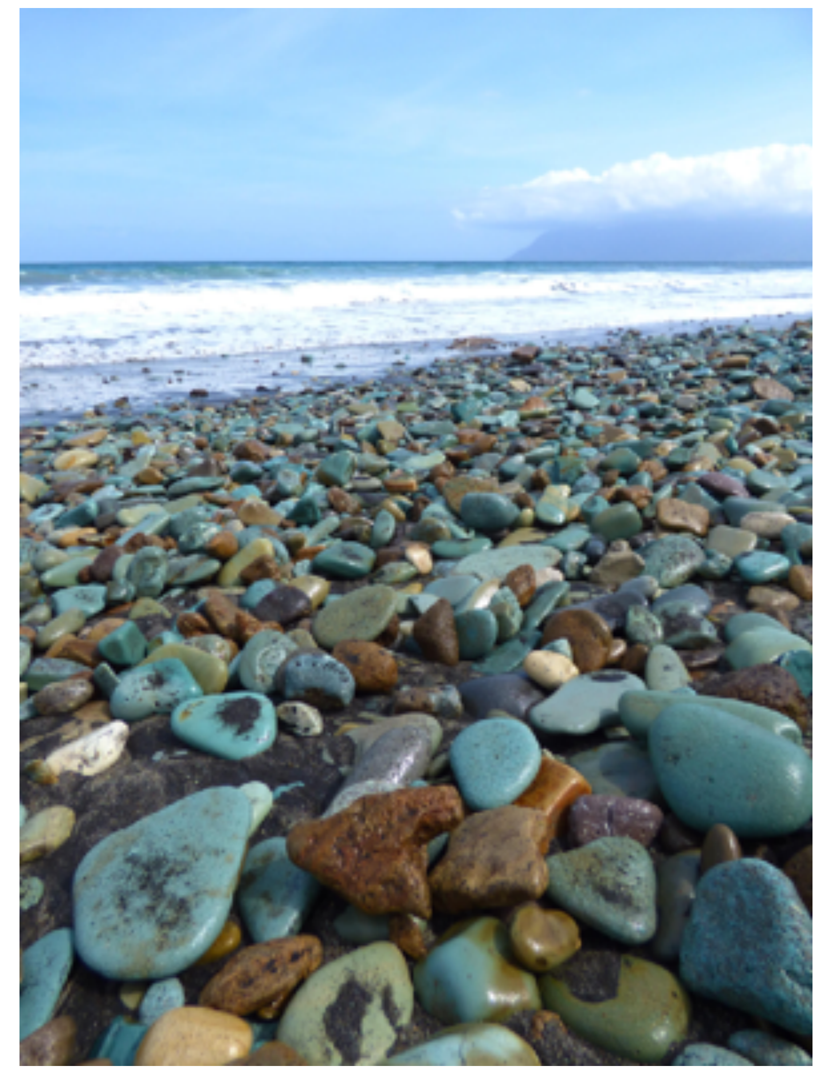
Dan Hooper @DanHooperAstro Follow

While I agree that direct detection experiments and the LHC have put some strain on the WIMP hypothesis, there are still plenty of WIMP models that have not been ruled out. WIMPs may have looked better in the past, but they are still very much alive. #DarkMatter

• • •

Where next?

- If fine-tuning isn't a good guiding principle, what about the alternatives?
  - quite hard to 'automatically' get the DM relic density right, even for 'nice' models!



- Or should we give up on theoretical guiding principles, leaving 'no stone unturned'?

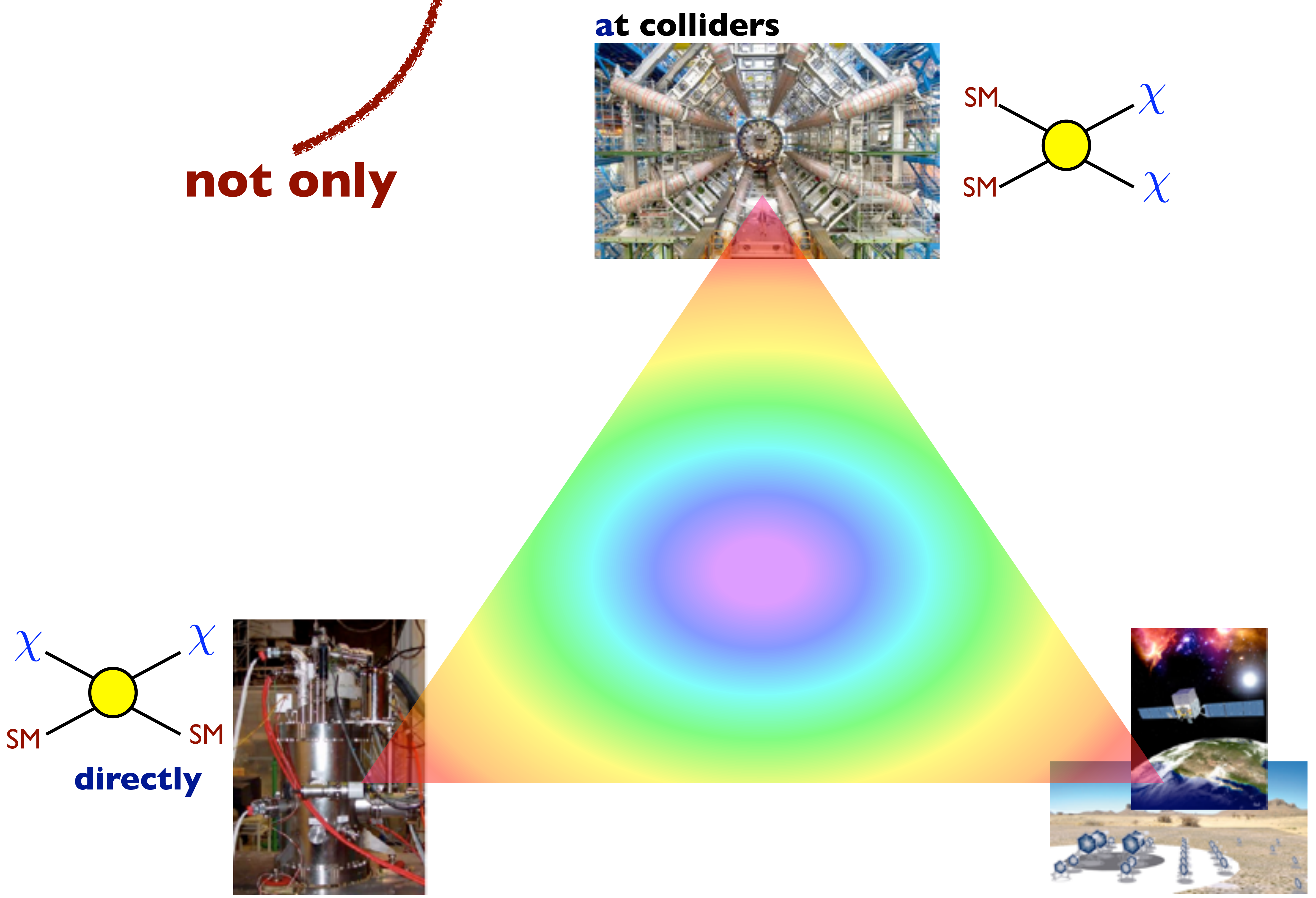
  Bertone & Tait, Nature '18

  - Problem: there might be quite a few of them (not even counting those that cannot be unturned)...

⇨ *Challenge for the field: Stay open-minded yet focussed !*

Strategies for WIMP searches

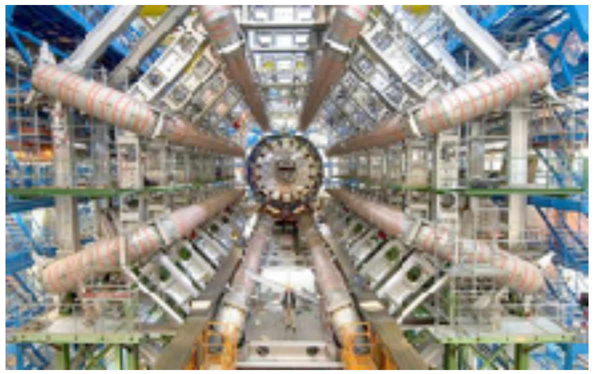
not only



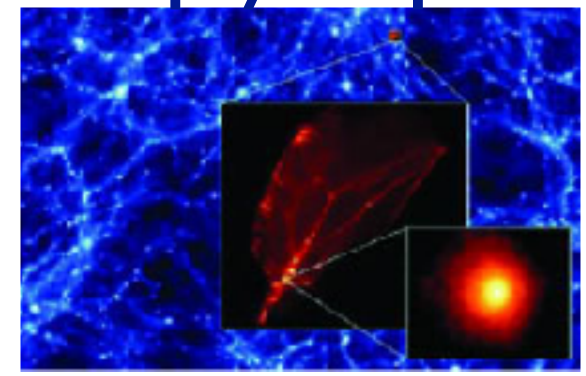
➡ *all complementary !*

Strategies for dark matter searches

at colliders

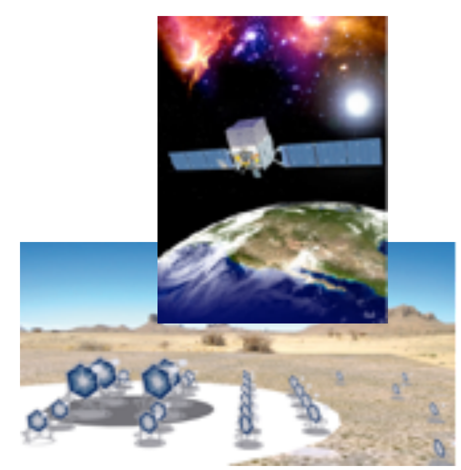


astrophysical probes



of matter distribution

directly



indirectly

DarkSUSY

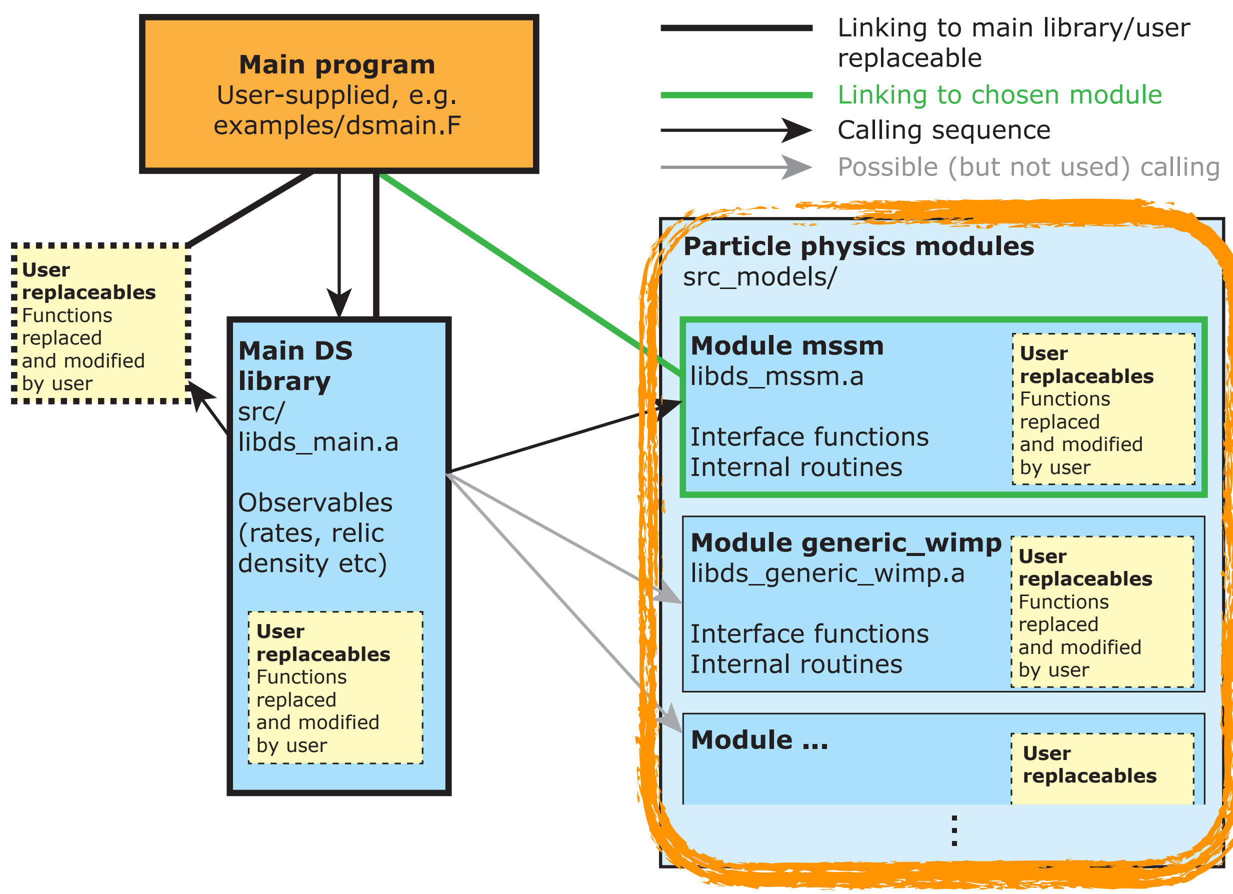
;)

TB, Edsjö, Gondolo,
Ullio & Bergström,
JCAP '18

http://darksusy.hepforge.org

Since version 6: no longer restricted to supersymmetric DM !

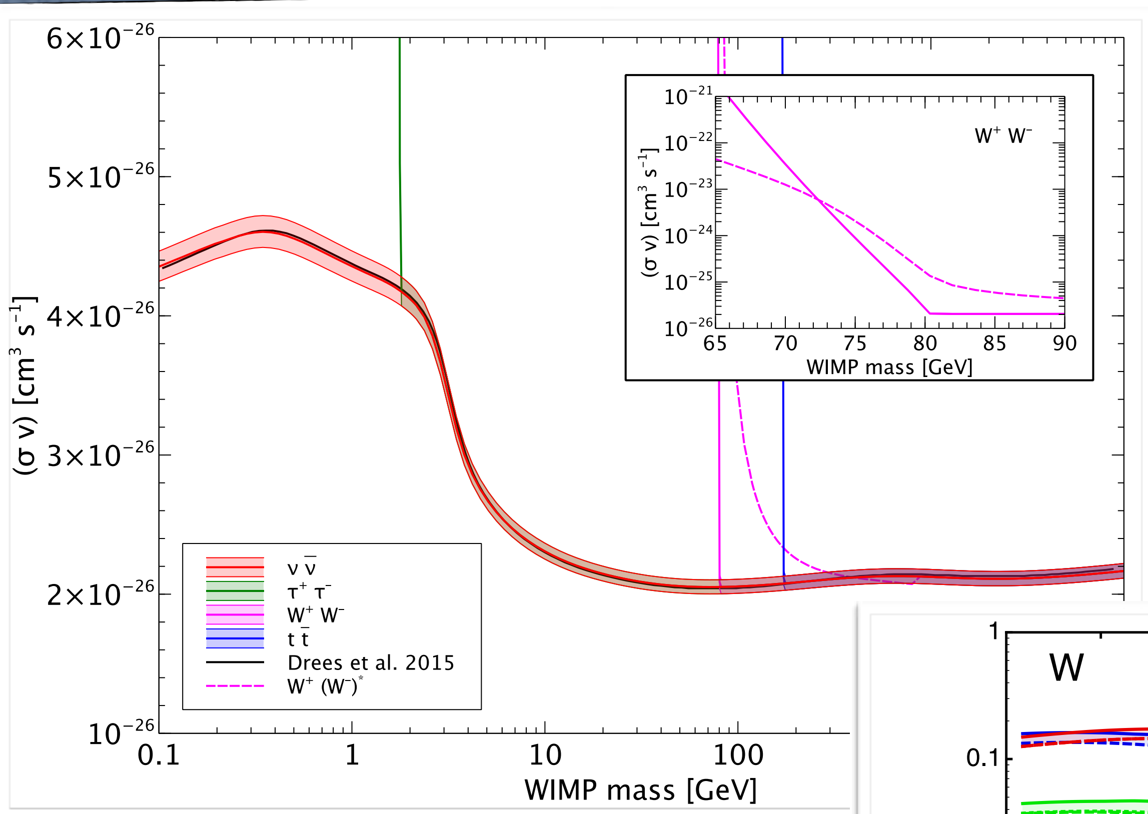
- Numerical package to calculate 'all' DM related quantities:
  - *relic density + kinetic decoupling* **(also for $T_{\rm dark} \neq T_{\rm photon}$)**
  - *generic SUSY models + laboratory constraints implemented*
  - *cosmic ray propagation*
  - particle yields for generic DM annihilation or decay
  - *indirect detection rates: gammas, positrons, antiprotons, neutrinos*
  - *direct detection rates*
  - …



since 6.1: DM self-interactions

since 6.2: 'reverse' direct detection (see later)

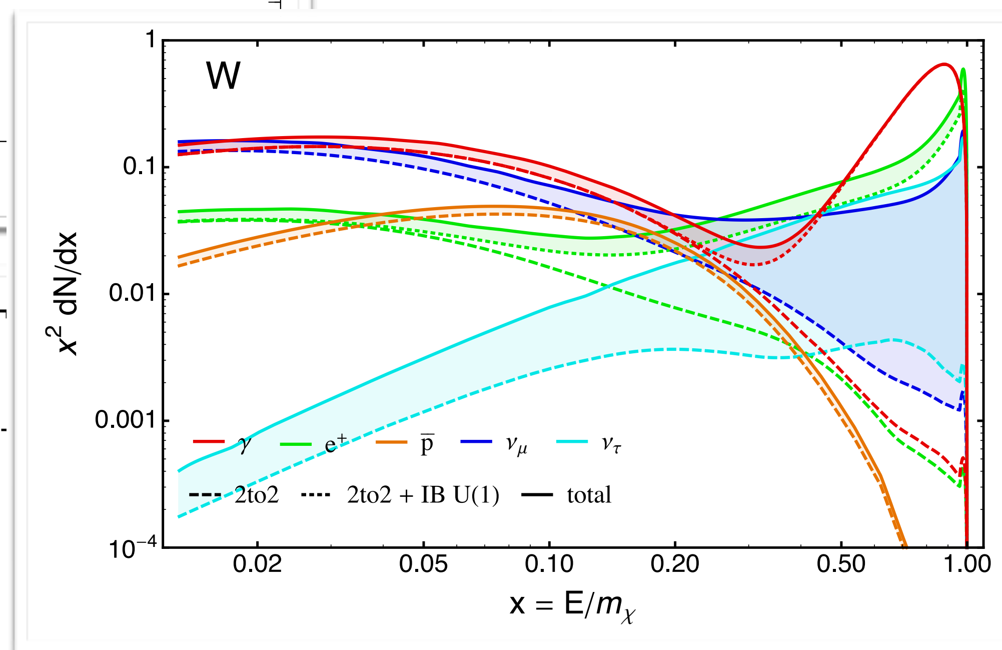
DarkSUSY — selected applications



- precision calculations of 'thermal' cross section

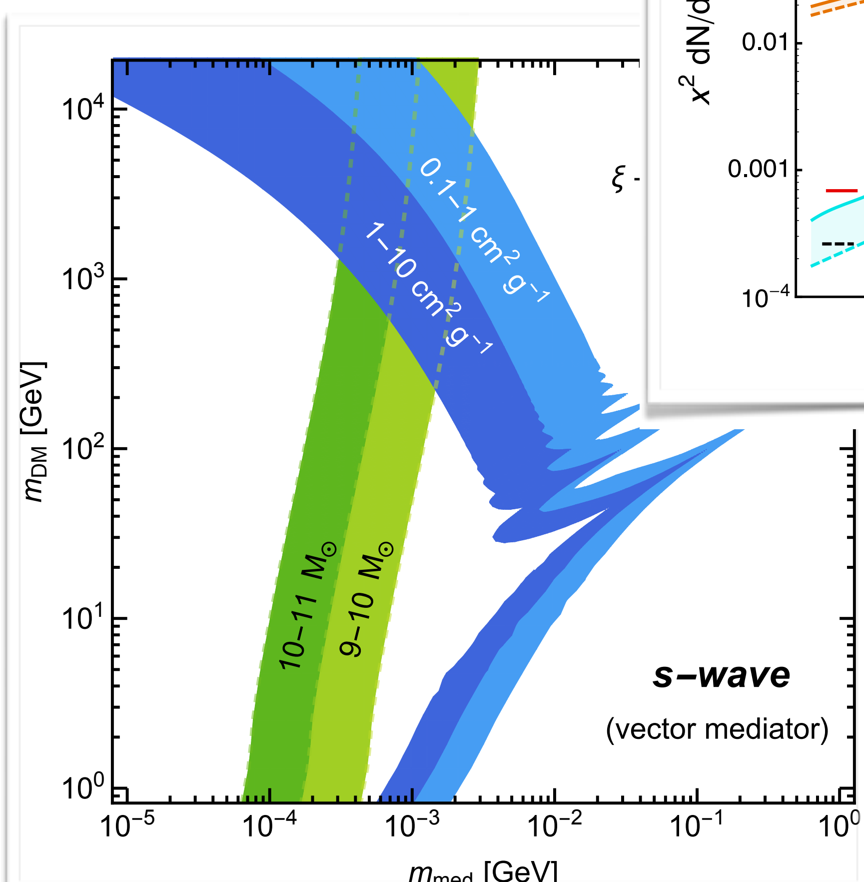
  code: examples/aux/generic_wimp_oh2.f

  ➡ **update to Steigman+, PRD '12**



- particle yields including *U(1)*, *SU(2)* and *SU(3)* corrections

  TB, Calore, Galea & Garny, JHEP '17



- Dark sector observables, including Sommerfeld enhancement

  code: examples/aux/vdSIDM_RD.f

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org   EPJC **77** (2017) 784   arXiv:1705.07908

- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source
- Fast definition of new datasets and theories
- Plug and play scanning, physics and likelihood packages

Members of:
ATLAS, Belle-II, CLiC, CMS, CTA, *Fermi*-LAT, DARWIN, IceCube, LHCb, SHiP, XENON
Authors of:
DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, IsaTols, nulike, PolyChord, Rivet, SoftSUSY, SuperISO, SUSY-AI, WIMPSim

Recent collaborators:
Peter Athron, Csaba Balázs, Ankit Beniwal, Sanjay Bloor, Torsten Bringmann, Andy Buckley, José Eliel Camargo-Molina, Marcin Chrząszcz, Jonathan Cornell, Matthias Danninger, Joakim Edsjö, Ben Farmer, Andrew Fowlie, Tomás E. Gonzalo, Will Handley, Sebastian Hoof, Selim Hotinli, Felix Kahlhoefer, Anders Kvellestad, Julia Harz, Paul Jackson, Farvah Mahmoudi, Greg Martinez, Are Raklev, Janina Renk, Chris Rogan, Roberto Ruiz de Austri, Pat Scott, Patrick Stöcker, Aaron Vincent, Christoph Weniger, Martin White, Yang Zhang

40+ participants in 11 experiments and 14 major theory codes

(slide stolen form Pat Scott)

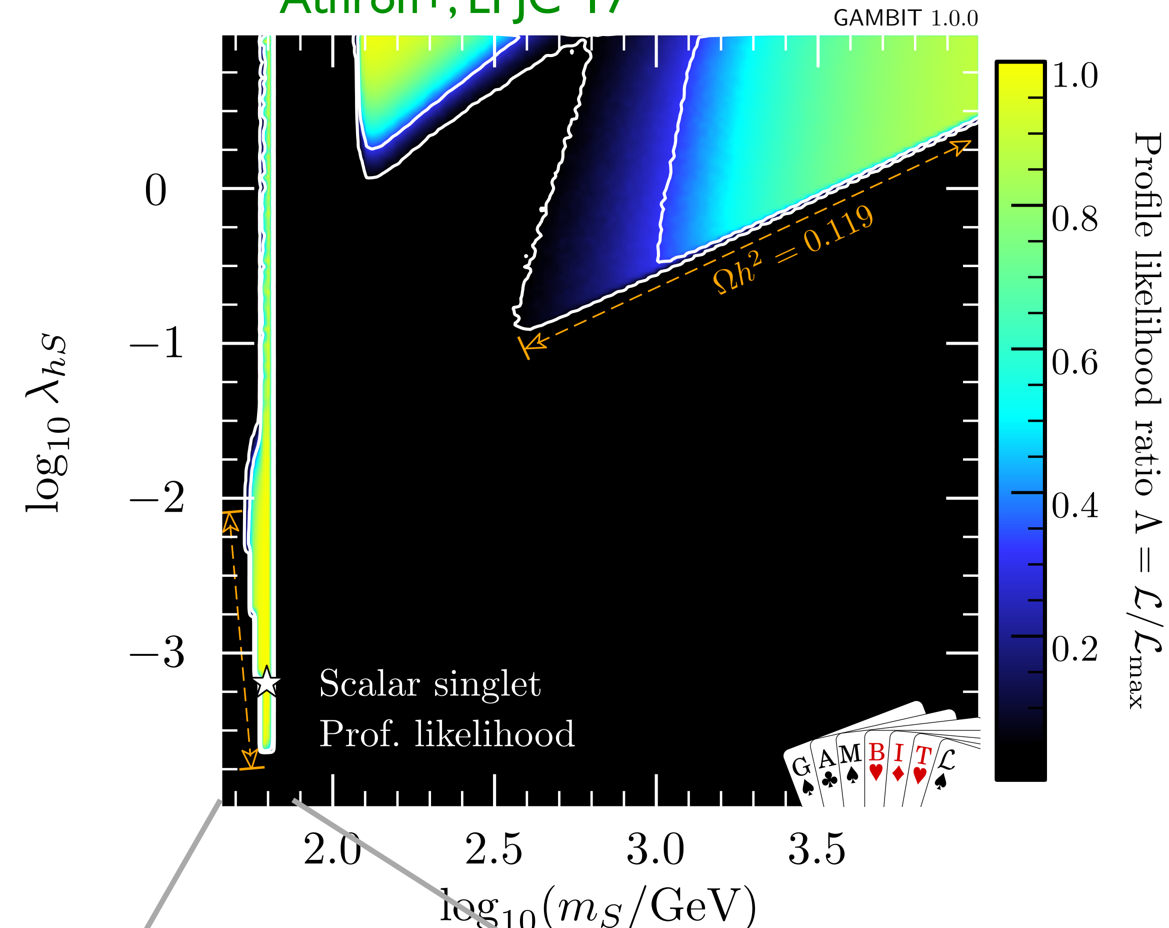
Dark matter with GAMBIT

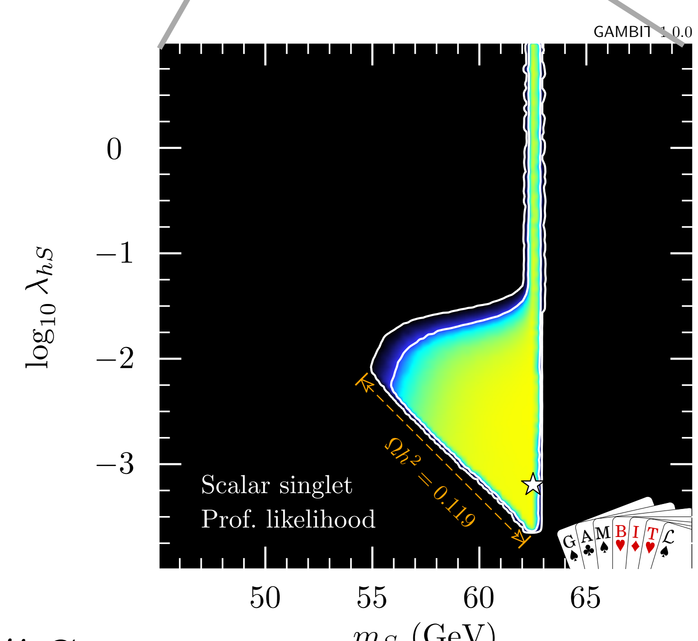
- **DarkBit** TB+, EPJC '17
  - takes input (DM observables) from 'backended' codes like DarkSUSY, micrOMEGAs, DDCalc, nuLike, gamLike…
  - adds fully 'native' observables (e.g. astrophysical axion limits)
  - returns likelihoods for a plethora of experimental data
- **GAMBIT**
  - adds likelihoods from other 'Bits' (Collider, Flavour, …)
  - performs global scan over model parameters
- **Example: The Scalar Singlet**

$$\mathcal{L} = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 |H|^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\partial_\mu S \partial^\mu S$$

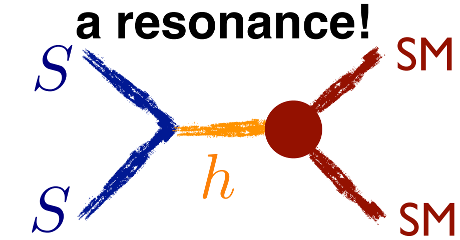
Silveira & Zee, PLB '85

Athron+, EPJC '17





<u>But</u> do not (blindly) trust relic density calculations very close to a resonance!



Binder, TB, Gustafsson & Hryczuk, PRD '17

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Direct searches

- Look for dark matter collisions with atomic nuclei

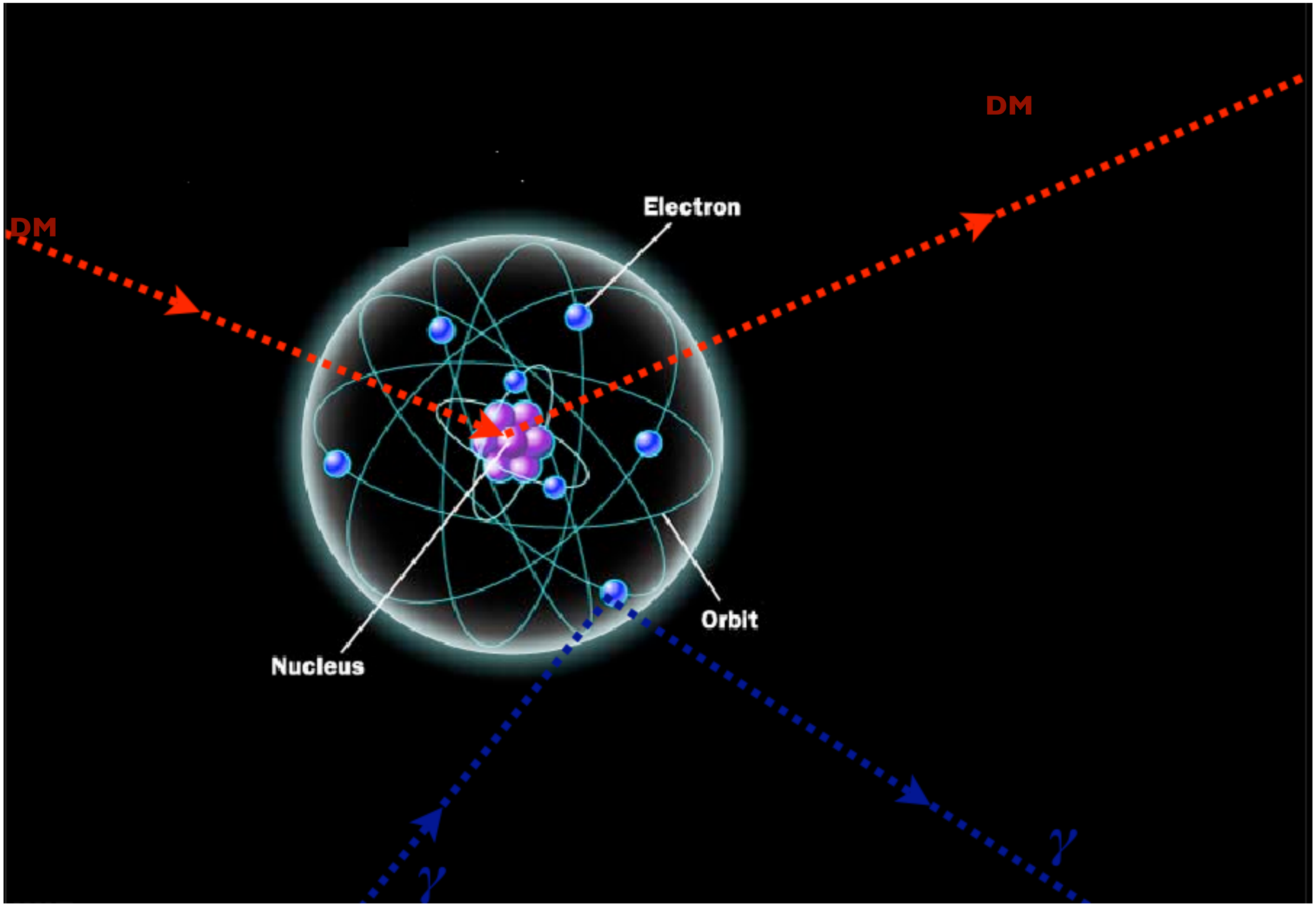


Fig.: Queiroz, 1605.08788

Experiments typically aim at 'background-free' setting !

Elastic scattering cross section

- Spin-independent interactions couple to nuclear ***mass***
  (from scalar, vector and tensor couplings)

$$\sigma_N^{\rm SI} \sim \sigma_p^{\rm SI} \left(\frac{\mu_{\chi N}}{\mu_{\chi p}}\right)^2 [Z f_p + (A-Z) f_n]^2 \xrightarrow{f_p = f_n} \boxed{\sigma_N^{\rm SI} = \sigma_\chi^{\rm SI} A^2 \left(\frac{m_N(m_\chi + m_p)}{m_p(m_\chi + m_N)}\right)^2}$$

per **nucleus** (measured)

per **nucleon** (reported limit)

⇨ coherent enhancement of A^2 to A^4 !

- Spin-dependent interactions couple to nuclear ***spin***
  (from axial-vector couplings)

$$\boxed{\sigma_N^{\rm SD} \sim \mu_{\chi N}^2 G_F^2 \frac{S_N + 1}{S_N} [a_p \langle S_p \rangle + a_n \langle S_n \rangle]^2}$$

- Form-factor *(or spin-structure function)* suppression for large momentum transfer

$$\boxed{\sigma_N \to \sigma_N^{q=0} \times G_N(q^2)}$$

The dark matter halo

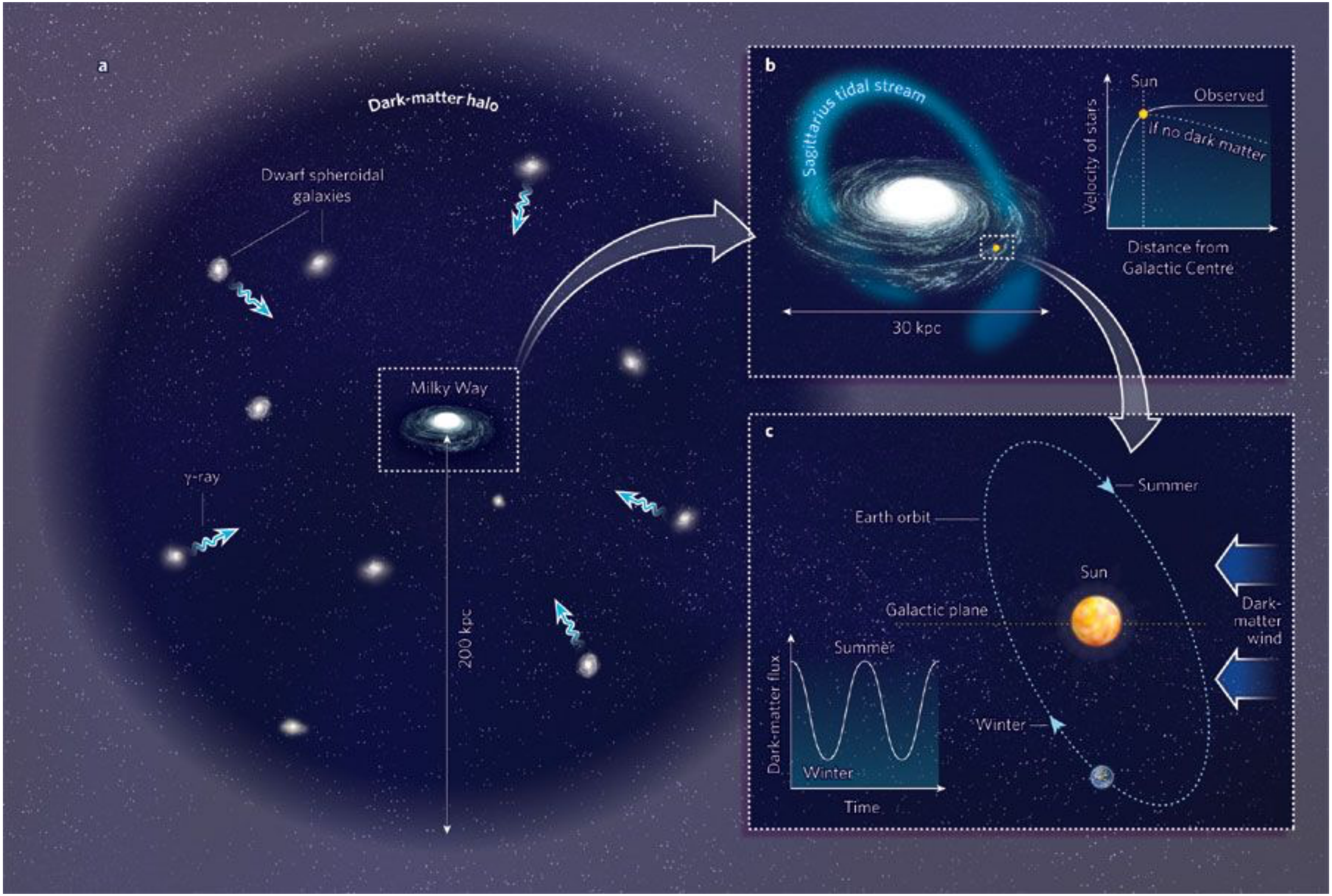


Fig.: Caldwell & Kamionkowski, Nature '09

Recoil rate [per unit detector mass]

$$\boxed{\frac{dR}{dE_R} = \frac{\rho_\odot^\chi}{m_\chi m_N} \int_{v_{\min}}^{v_{\max}} \frac{d\sigma_{\chi N}}{dE_R} v f(v) dv}$$

- Astrophysical input
  - $\rho_\odot^\chi \sim 0.4\,\mathrm{GeV cm}^{-3}$ — *average DM density at Sun's distance to Galactic center relatively well measured*
  - $f(v) \sim (\pi v_0^2)^{-\frac{3}{2}} e^{-\frac{\mathbf{v}^2}{v_0^2}}$ — *standard halo model (SHM) in galactic* frame *rests on isothermal density profile*

    $\boxed{v_0 \sim 220\,\mathrm{km/s}}$

    [from $\rho_\odot^\chi$]

    $\rightsquigarrow$ *NB: exact form only roughly corresponds to what is seen in simulations*
  - $v_{\max} \sim 544\,\mathrm{km/s}$ — *galactic escape velocity, well measured*

- Recoil energy

$$E_R = \frac{Q^2}{2m_N} = \frac{4m_\chi m_N T_\chi}{(m_\chi + m_N)^2} \frac{1 - \cos\theta_{\mathrm{cm}}}{2} \Rightarrow \boxed{v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}}$$

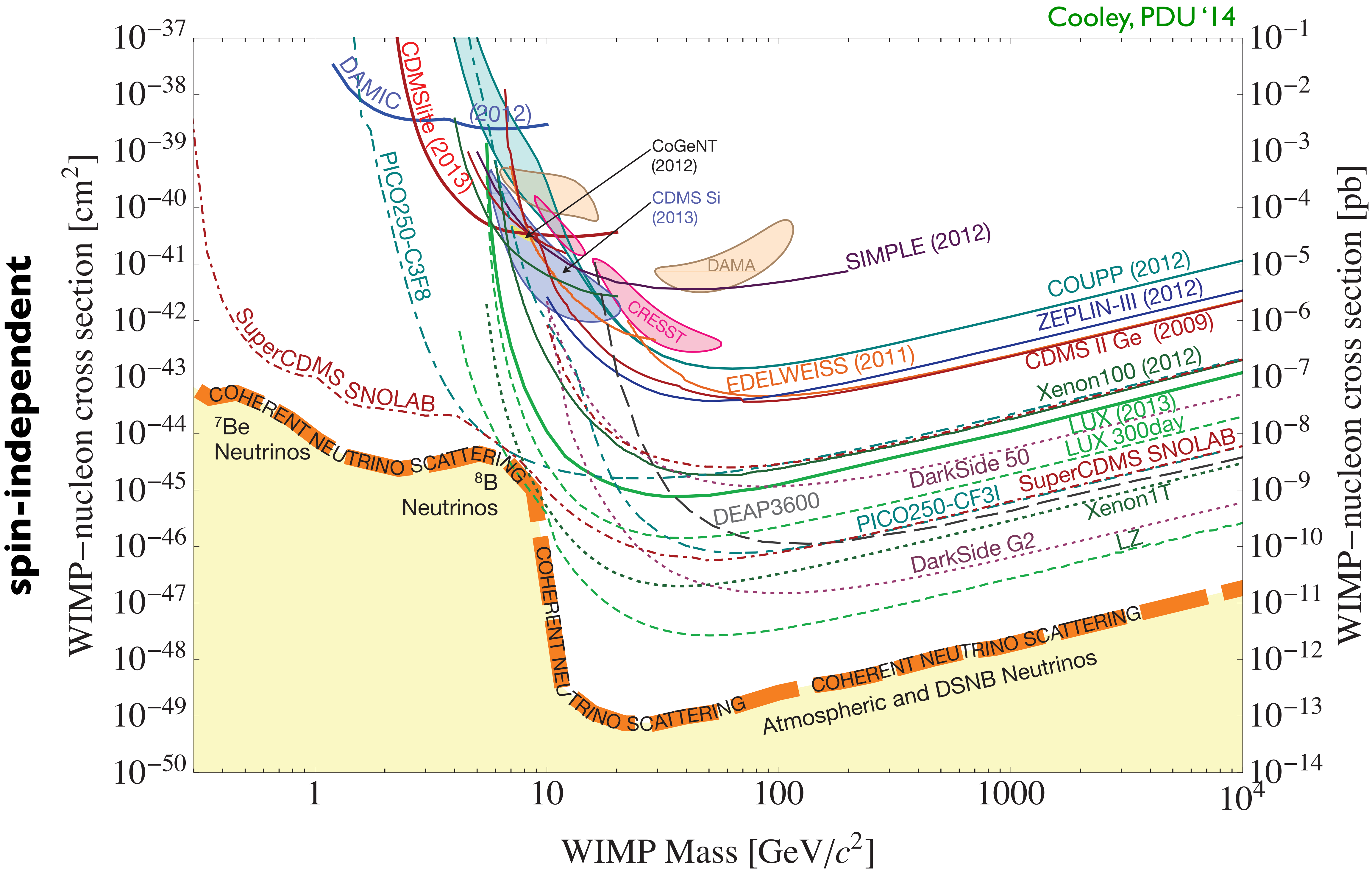
$m_\chi \gg m_N$: $\rightarrow 21.2 \, \frac{\mathrm{km}}{\mathrm{s}} \times \left(\frac{E_R}{\mathrm{keV}}\right)^{\frac{1}{2}} \left(\frac{m_N}{100\,\mathrm{GeV}}\right)^{-\frac{1}{2}}$

$\ll v_0 \rightsquigarrow$ *sample full* $f(v)$

$m_\chi \ll m_N$: $\rightarrow 2120 \, \frac{\mathrm{km}}{\mathrm{s}} \times \left(\frac{m_\chi}{\mathrm{GeV}}\right)^{-1} \left(\frac{E_R}{\mathrm{keV}}\right)^{\frac{1}{2}} \left(\frac{m_N}{100\,\mathrm{GeV}}\right)^{\frac{1}{2}}$

$\gg v_0 \rightsquigarrow f(v)$ *exp. suppressed*

A vast experimental effort



Need lower threshold

$v_{\rm min} \gg v_0$

(rate exponentially suppressed)

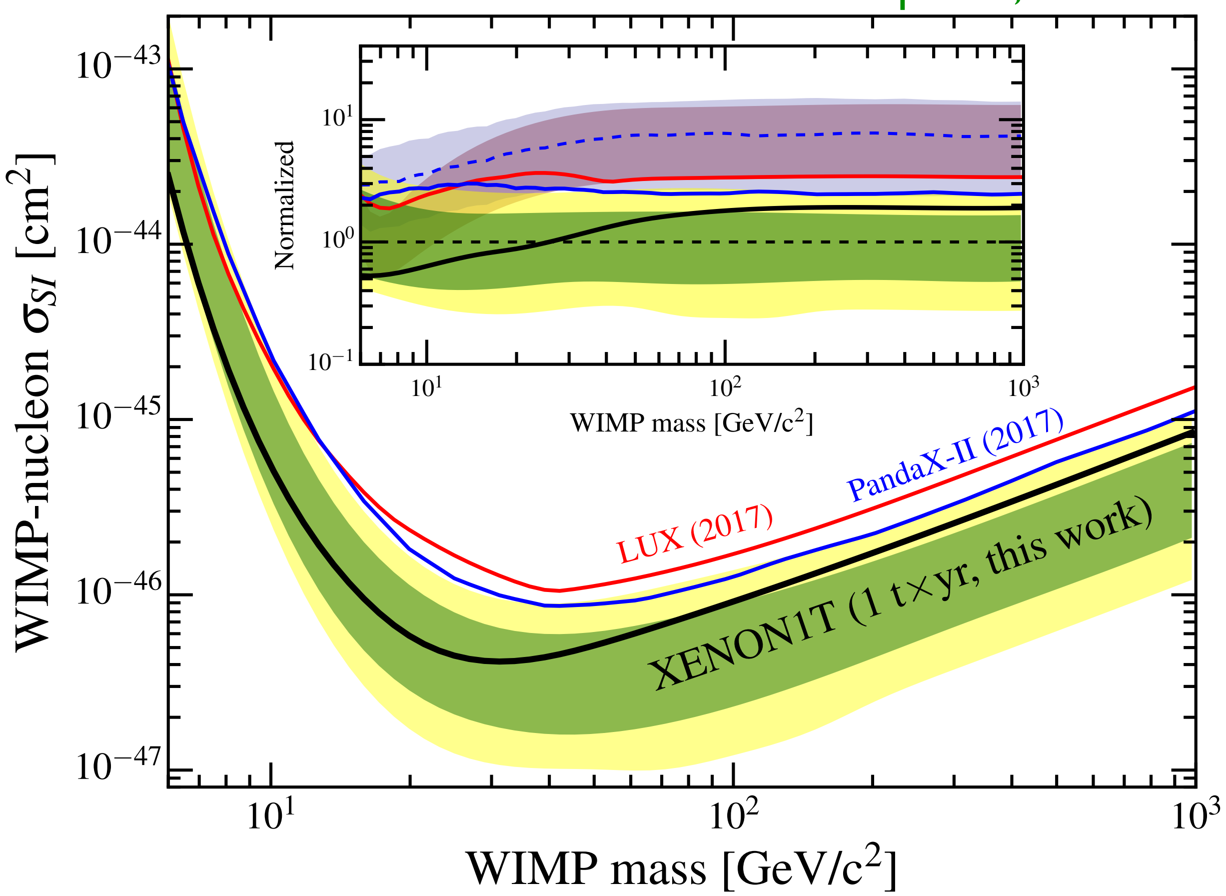
$v_{\rm min} \ll v_0$

(rate $\propto n_\chi \propto m_\chi^{-1}$)

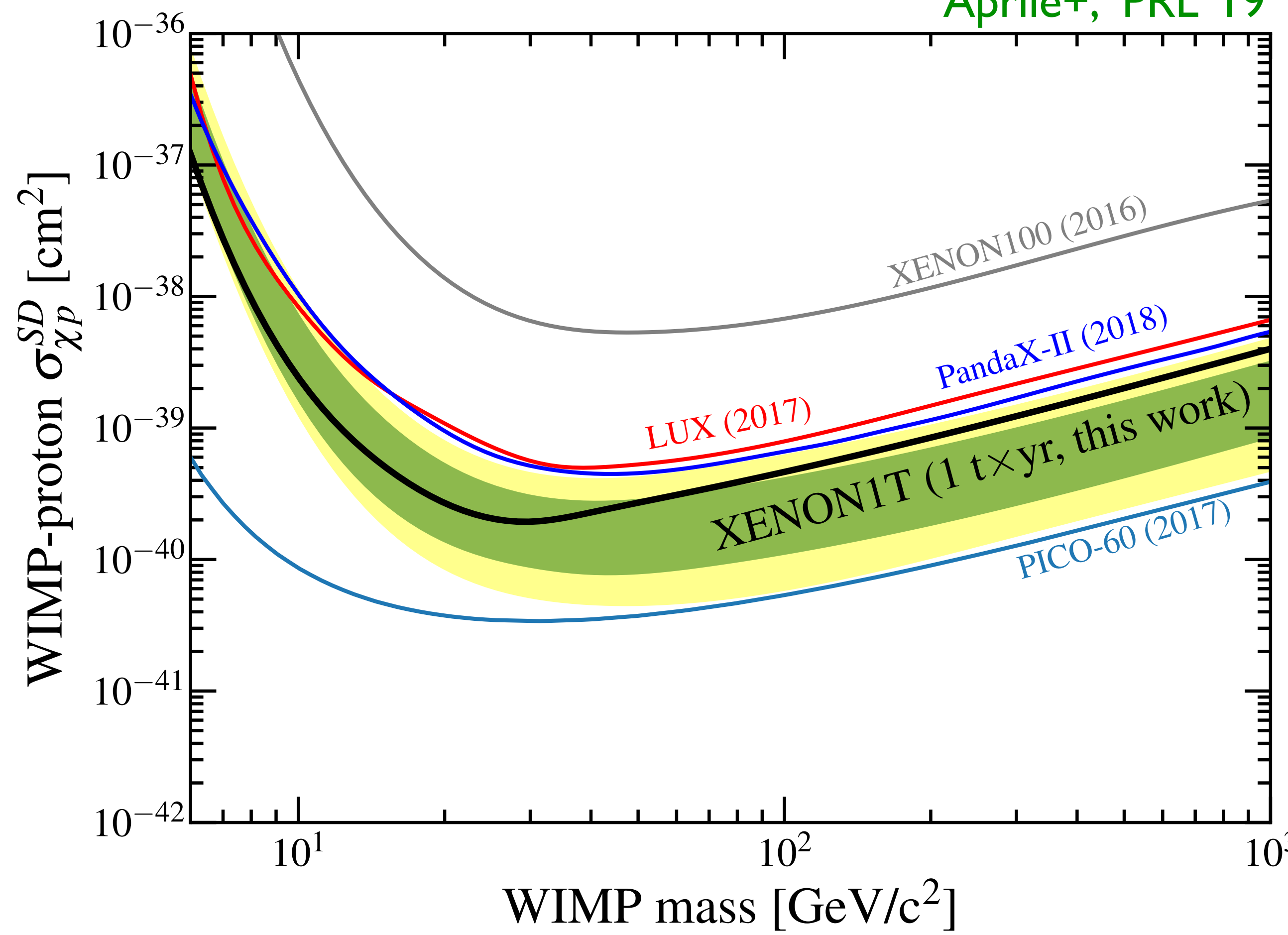
Need higher exposure (mass)

Current limits

Aprile+, PRL '18



Aprile+, PRL '19



- Limits highly relevant for popular WIMP models
  - E.g. rule out previous best-fit points in simple SUSY models

Athron+, EPJC '17 a,b

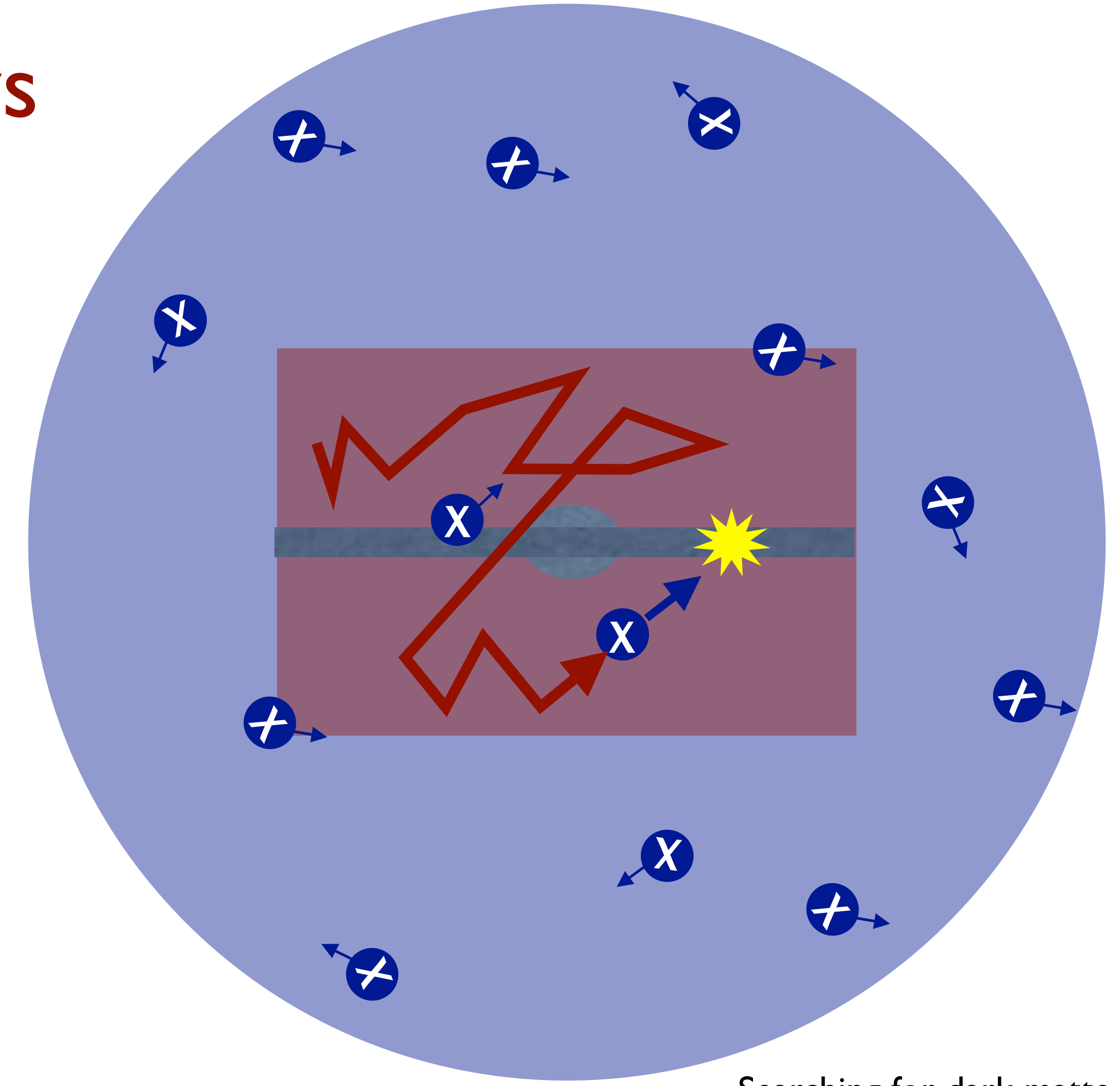
- As expected, spin-dependent limits are a factor of ~ 10^7 less stringent

(no coherent enhancement!)

Reverse direct detection

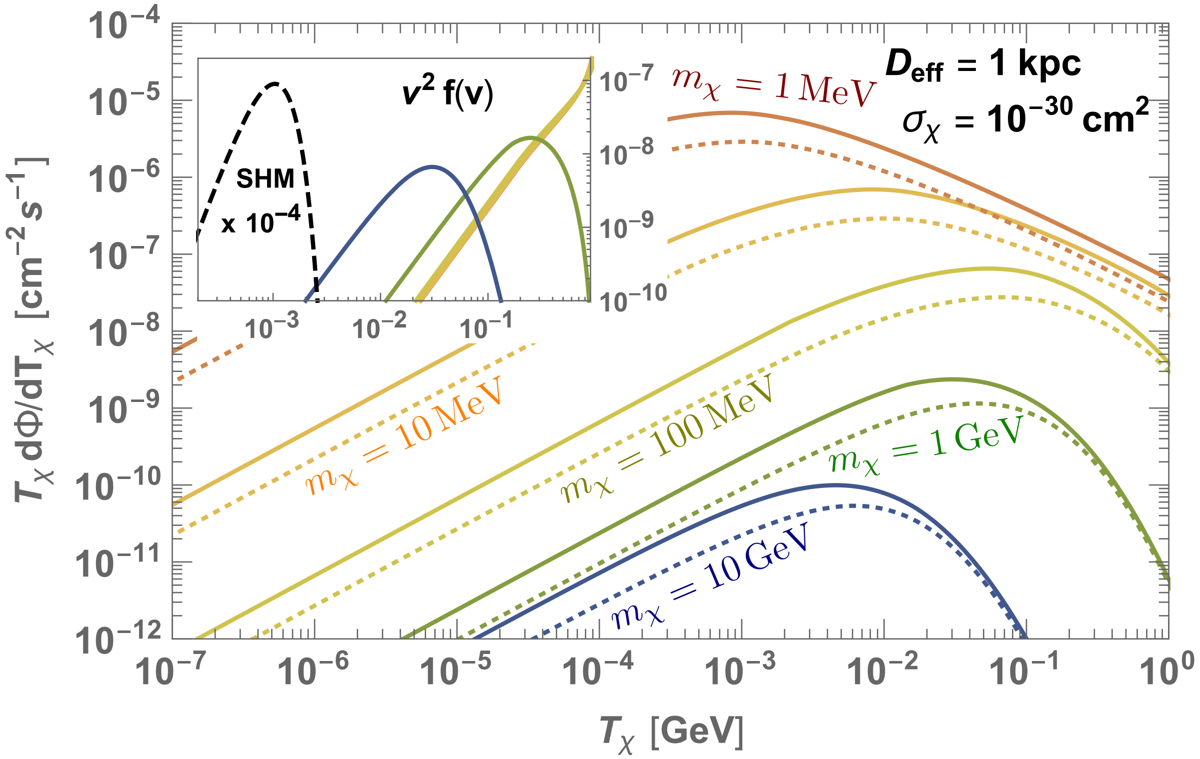
- Light DM really only accessible with lower thresholds?
- Not if part of the DM distribution moves fast!
  - 'Boosted DM' from decays — Agashe, Cui, Necib & Thaler, JCAP '14
  - DM accelerated in the sun — Kouvaris, PRD '15; An, Pospelov, Pradler & Ritz, PRL '18; Emken, Kouvaris & Nielsen, PRD '18
- *New idea:* high-energy cosmic rays should up-scatter DM initially (almost) at rest! — TB & Pospelov, PRL '19

Cappiello, Ng & Beacom, PRD '19
Ema, Salo & Sato, PRL '19
Dent, Dutta, Newstead & Shoemaker, 1907.03782
Bondarenko+, 1909.08632
…



Cosmic-ray up-scattered DM

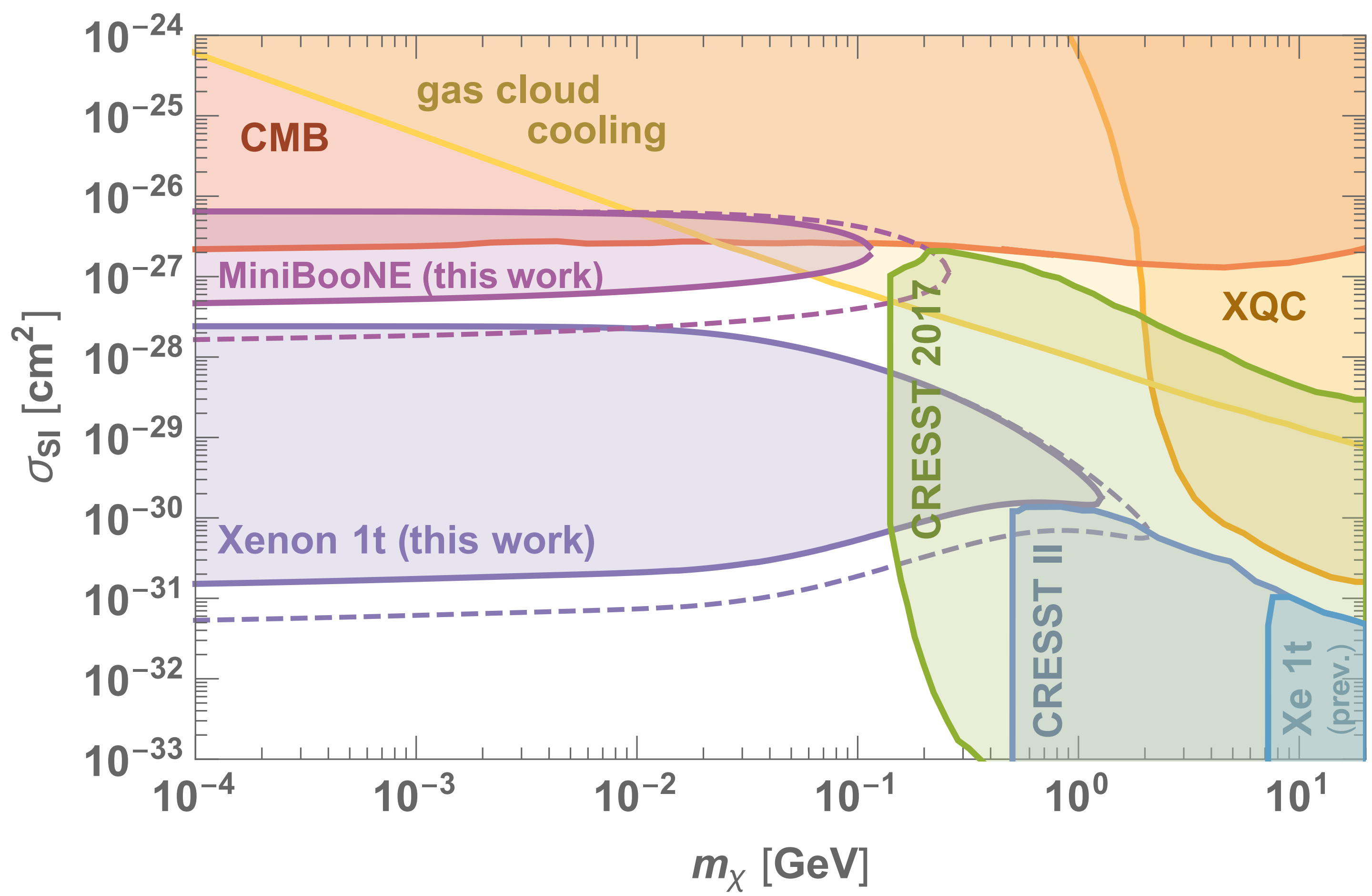
TB & Pospelov, PRL '19



- Isotropic CRDM flux
  - highly energetic
  - highly subdominant

- Re-interpreting Xenon 1t results leads to **significantly improved limits** at low DM masses!
  - even neutrino detectors (MiniBooNE, Borexino, …) can now be used for DM searches!

see also Cappiello & Beacom, 1906.11283



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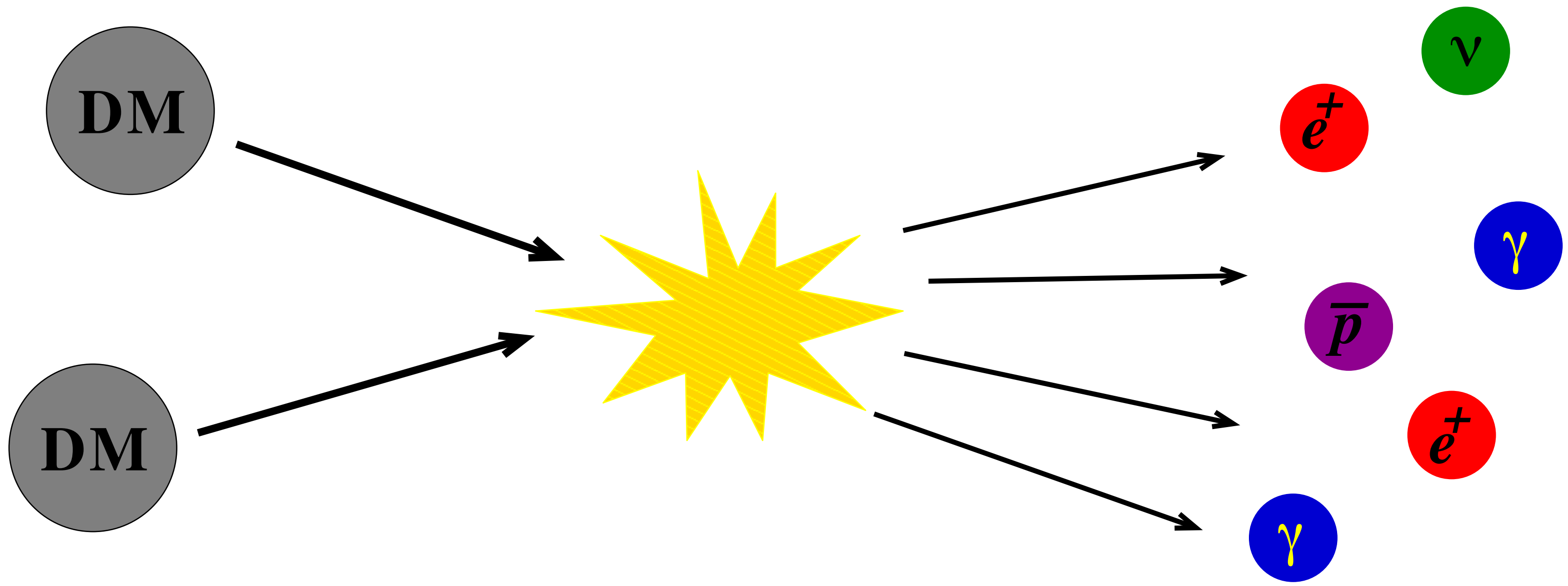
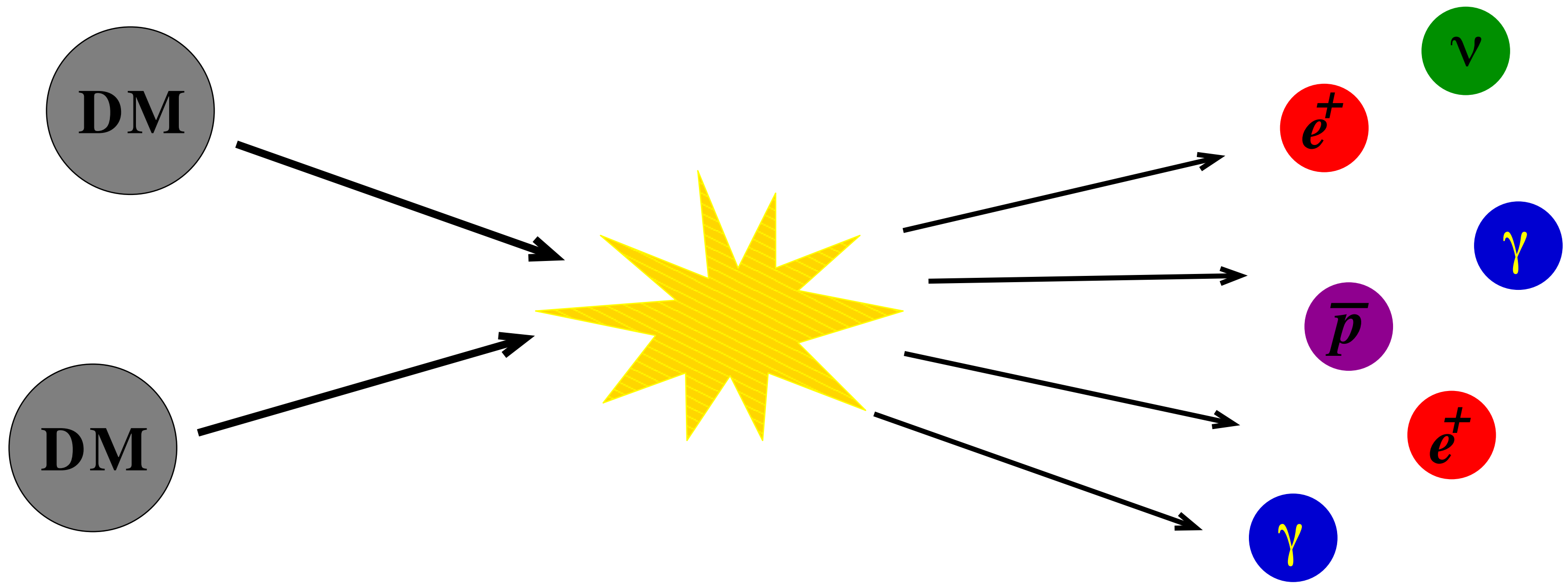
Indirect dark matter searches



- DM has to be (quasi-)stable against decay...
- … but can usually pair-annihilate into SM particles
- Try to spot those in cosmic rays of various kinds

- The challenge: i) absolute rates
  $\rightsquigarrow$ regions of high DM density
  ii) discrimination against other sources
  low background; clear signatures

Indirect dark matter searches



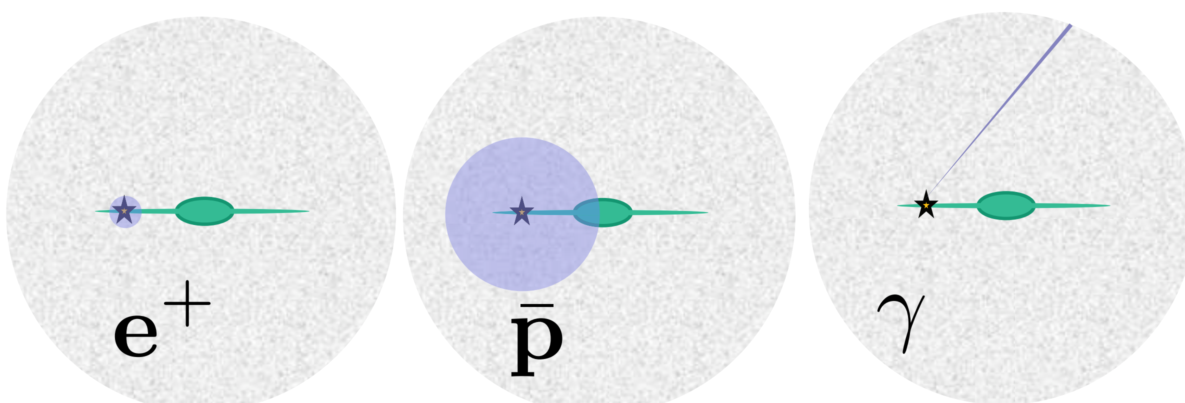


Fig.: Bergström, NJP '09

Total flux:

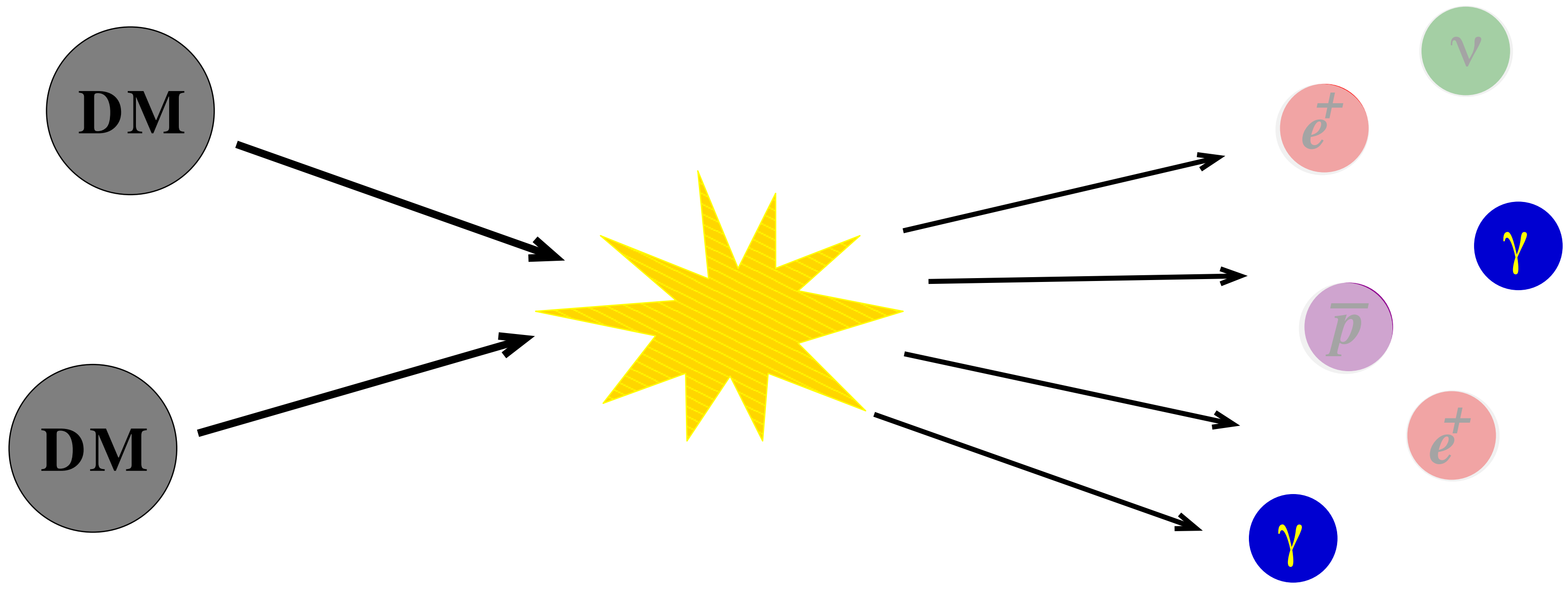
$$\Phi_{\rm SM} \propto \langle \rho_\chi^2 \rangle = (1 + {\rm BF}) \langle \rho_\chi \rangle^2$$

- "Boost factor"
  - each decade in $M_{\rm subhalo}$ contributes very roughly the same
    e.g. Diemand, Kuhlen & Madau, ApJ '07
  - depends on uncertain form of microhalo profile ($c_{\rm v}$ ...) and dN/dM
    (large extrapolations necessary!)

⇨ *(still) important to include realistic value for* $M_{\rm cut}$ *!*

The ‘golden’ channel

Review: TB & Weniger, PDU ‘12



Gamma rays:

- Rather high rates
- No attenuation when propagating through halo
- No assumptions about diffuse halo necessary
- Point directly to the sources: clear spatial signatures
- Clear spectral signatures to look for

Gamma-ray flux

The expected gamma-ray flux [GeV^{-1}cm^{-2}s^{-1}sr^{-1}] from a source with DM density ρ is given by

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\psi) = \underbrace{\int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{\mathrm{l.o.s}} d\ell(\psi)\rho^2(\mathbf{r})}_{\text{astrophysics}} \; \underbrace{\frac{\langle\sigma v\rangle_{\mathrm{ann}}}{8\pi m_\chi^2 S_\chi}\sum_f B_f\frac{dN_\gamma^f}{dE_\gamma}}_{\text{particle physics}}$$

for point-like sources:
$\simeq (D^2\Delta\psi)^{-1}\int d^3r\,\rho^2(\mathbf{r})$

$\Delta\psi$: angular res. of detector
D : distance to source

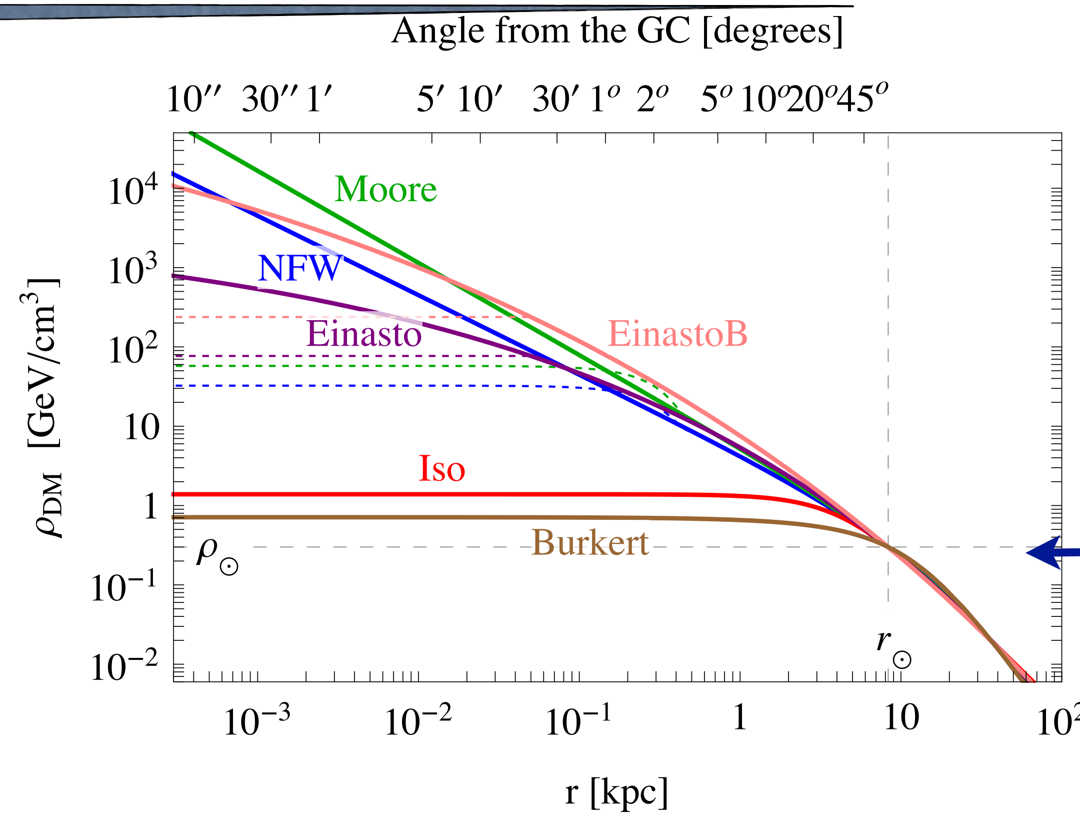
$\langle\sigma v\rangle_{\mathrm{ann}}$: total annihilation cross section
m_χ : DM mass
B_f : branching ratio into channel f
N_γ^f : number of photons per ann.
S_χ : 1 for $\chi=\bar\chi$ (2 otherwise)

↓ angular information
+ rather uncertain normalization

↓ high accuracy
spectral information

Dark matter distribution

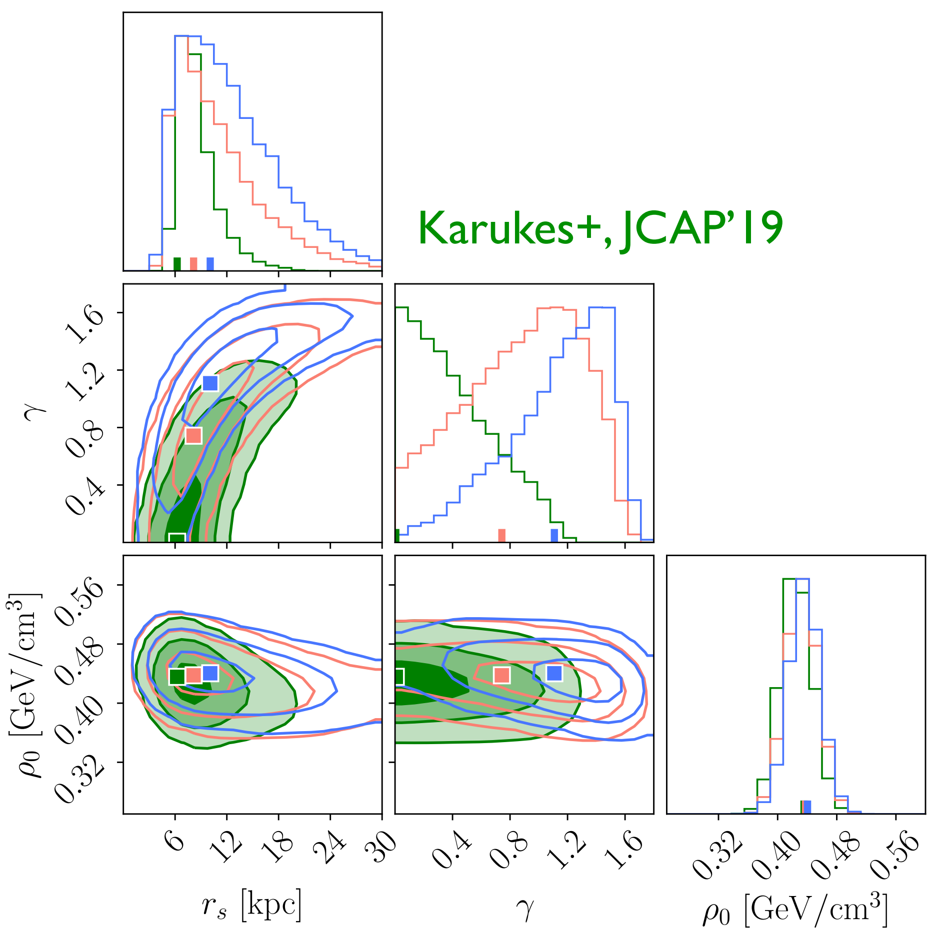
- Large uncertainties "only" in the very central region.



Cirelli+, JCAP'11

local DM density:

$\rho_\odot \sim 0.4\,\mathrm{GeV/cm^3}$



Karukes+, JCAP'19

- Difference in annihilation flux from galactic center 1-2 orders of magnitude

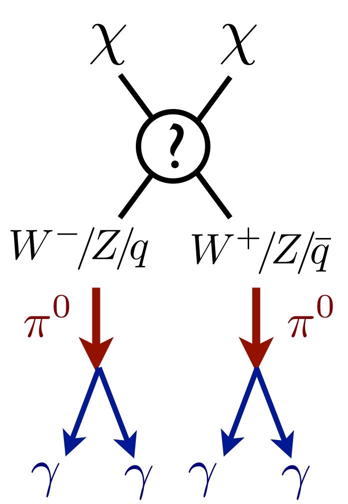
Benito+, JCAP'19

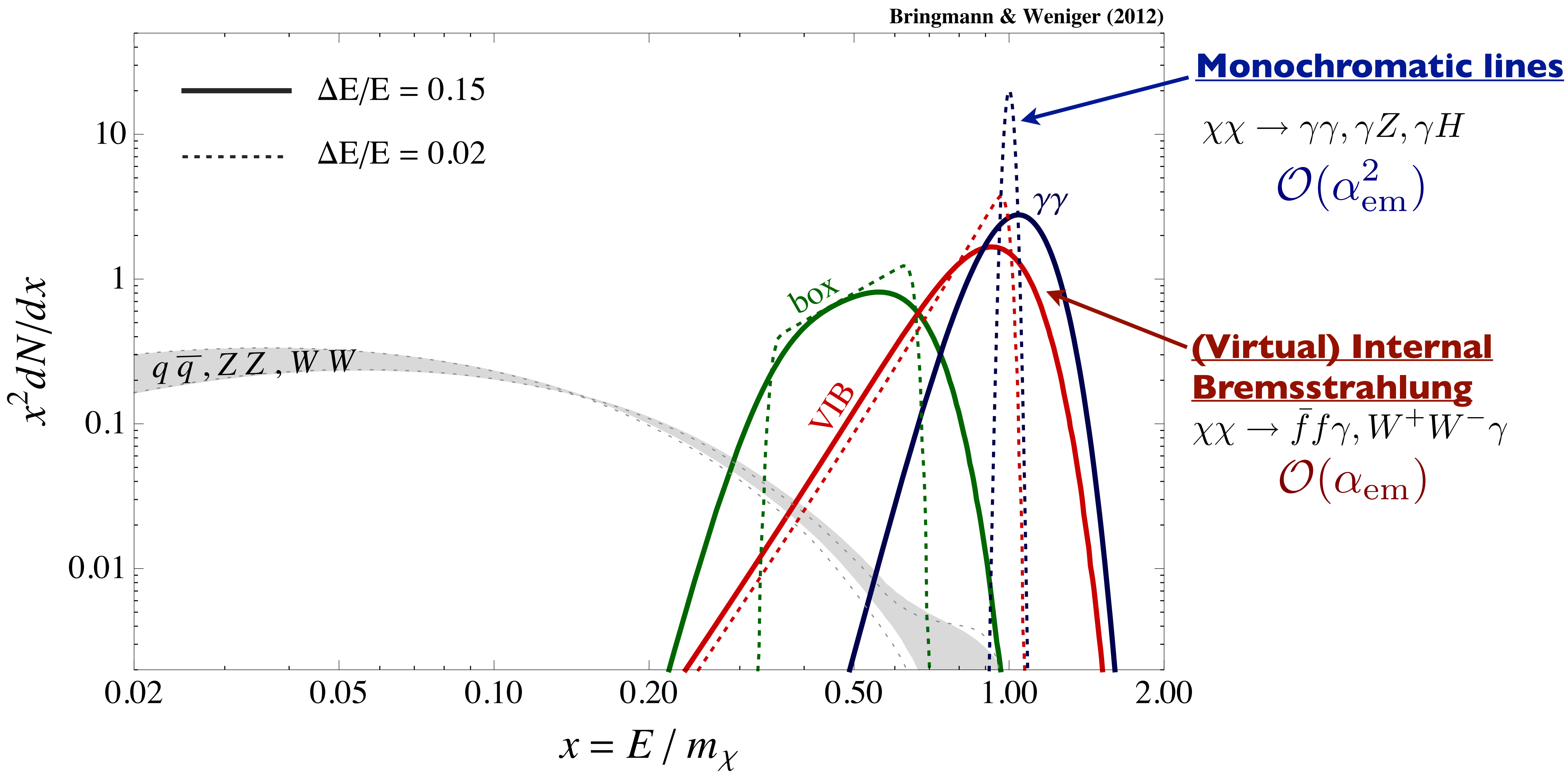
  - For large FoV $(40^\circ \times 40^\circ)$, fixed 3-param profile
  - Some dependence on assumed baryonic profile
  - *Only kinematic data for* $r \gtrsim 1\,\mathrm{kpc}$ *included !*

    ➡ *Higher densities for* $r \ll 1\,\mathrm{kpc}$ *(baryonic contract., black hole!) would further increase flux!*

- Situation much better for e.g. dwarf galaxies E.g. Bonnivard+, MNRAS '15

Annihilation spectra





- Secondary photons
  - *many* photons but
  - featureless & model-independent
  - difficult to distinguish from astro BG

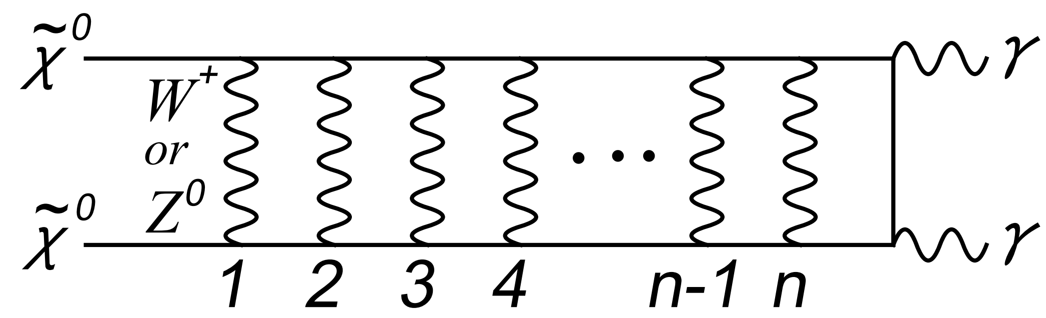
  ⇨ *good constraining potential*

- Primary photons
  - direct annihilation to photons
  - model-dependent 'smoking gun' spectral features near $E_\gamma = m_\chi$

  ⇨ *discovery potential*

More particle physics input

- ## Sommerfeld effect
  - strong enhancement of annihilation rates for light mediators / heavy DM
  - (particularly relevant for line signals)
  - related effect: bound state formation



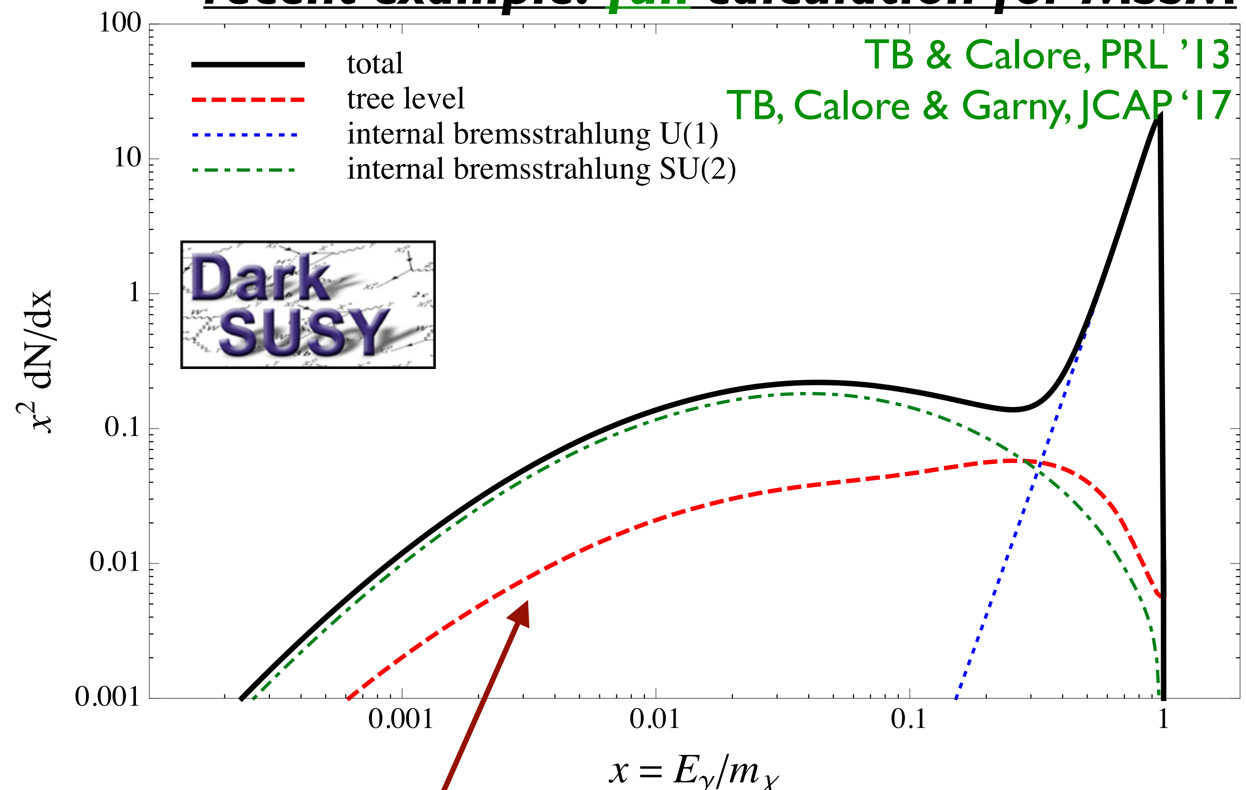
Hisano, Matsumoto, Nojiri, Saito, … '03 - '06

- ## Radiative corrections
  - strong enhancement possible (in particular if tree-level rates are suppressed)
  - electromagnetic IB: line-like spectral signatures or sharp steps
  - electroweak IB: enhancement of continuum part; can change composition of final stable particles

[disclaimer: list of relevant papers would fill the whole slide…]

recent example: full calculation for MSSM

TB & Calore, PRL '13
TB, Calore & Garny, JCAP '17



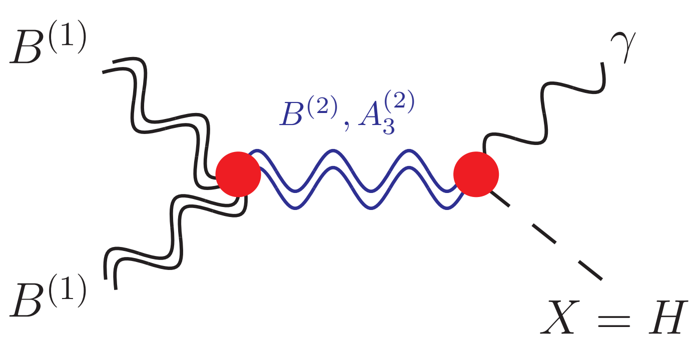
also ~same for "model-independent" SU(2) corrections!
[as implemented e.g. in PPPC 4 DM ID (Cirelli+, JCAP '11)]

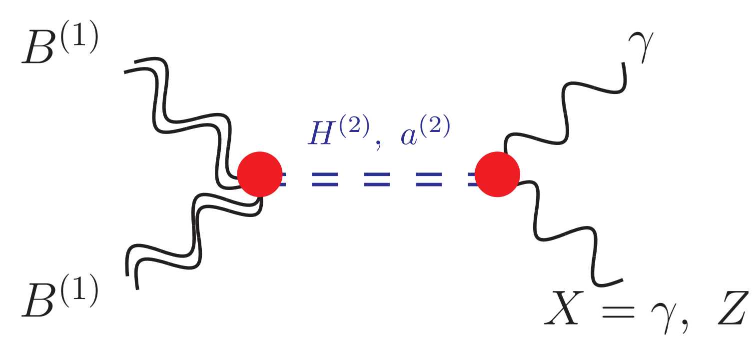
➡ *These contributions are highly model-dependent!*

More fancy signatures?

Arina, TB, Silk & Vollmann, PRD '14

- Resonances can single out spectral features
  - counter example for "flux = particle factor x astrophysical factor" !
  - particularly relevant for extra-dimensional scenarios
  - example: universal extra dimensions (Appelquist, Cheng & Dobrescu, PRD '01)



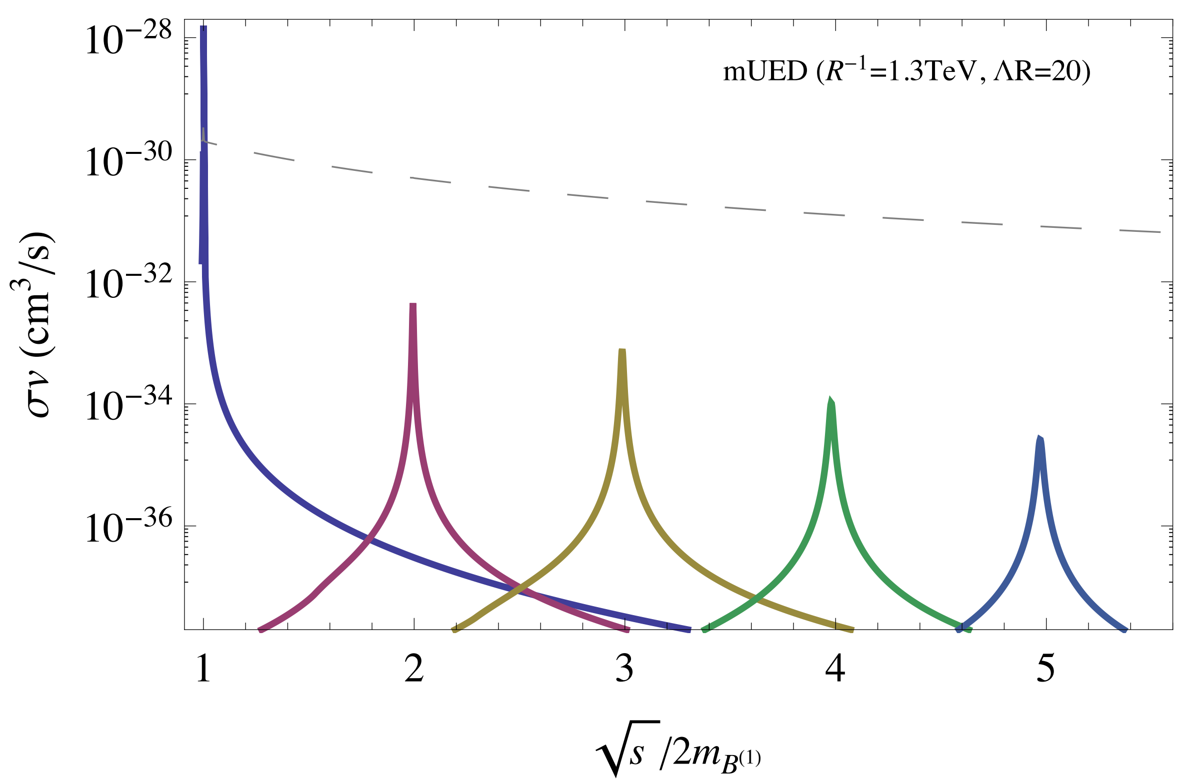


NB: $X^{(2)}$ decay is loop-suppressed!

- (Kerr) Black holes can accelerate DM particles to $\sqrt{s} \gg 2m_{\mathrm{DM}}$

  Banados, Silk & West, PRL '09
  - but beware of many caveats: ongoing discussion…

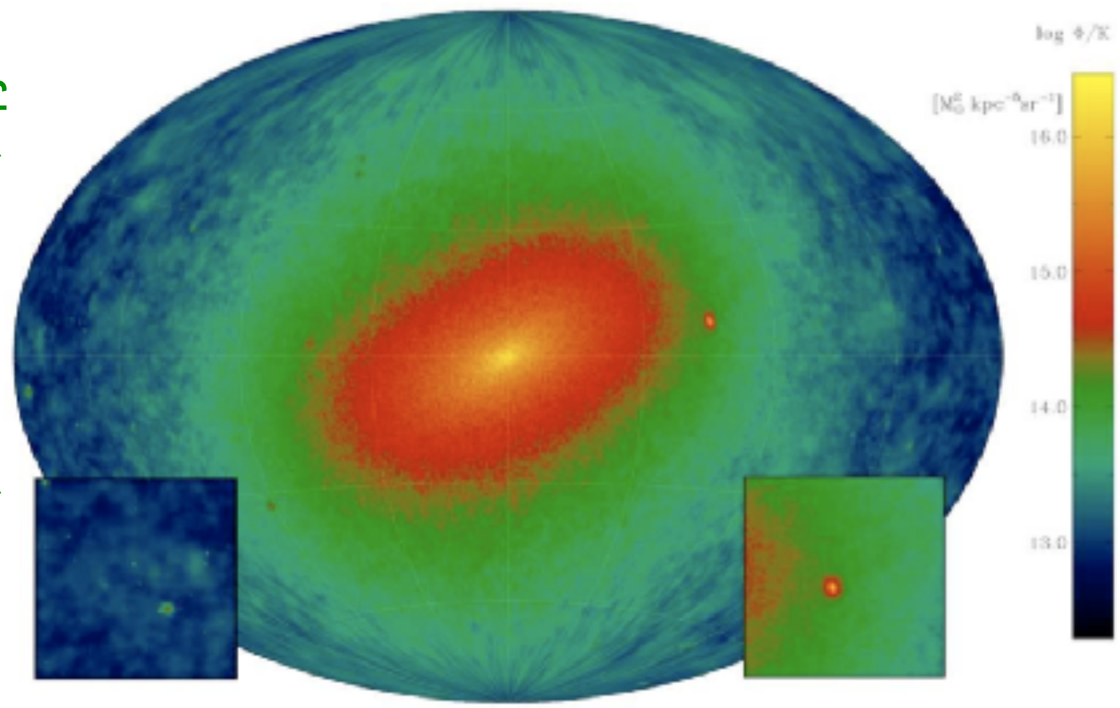
➡ *Potential smoking gun signature for extra-dimensional origin of DM: equidistant line signals!*

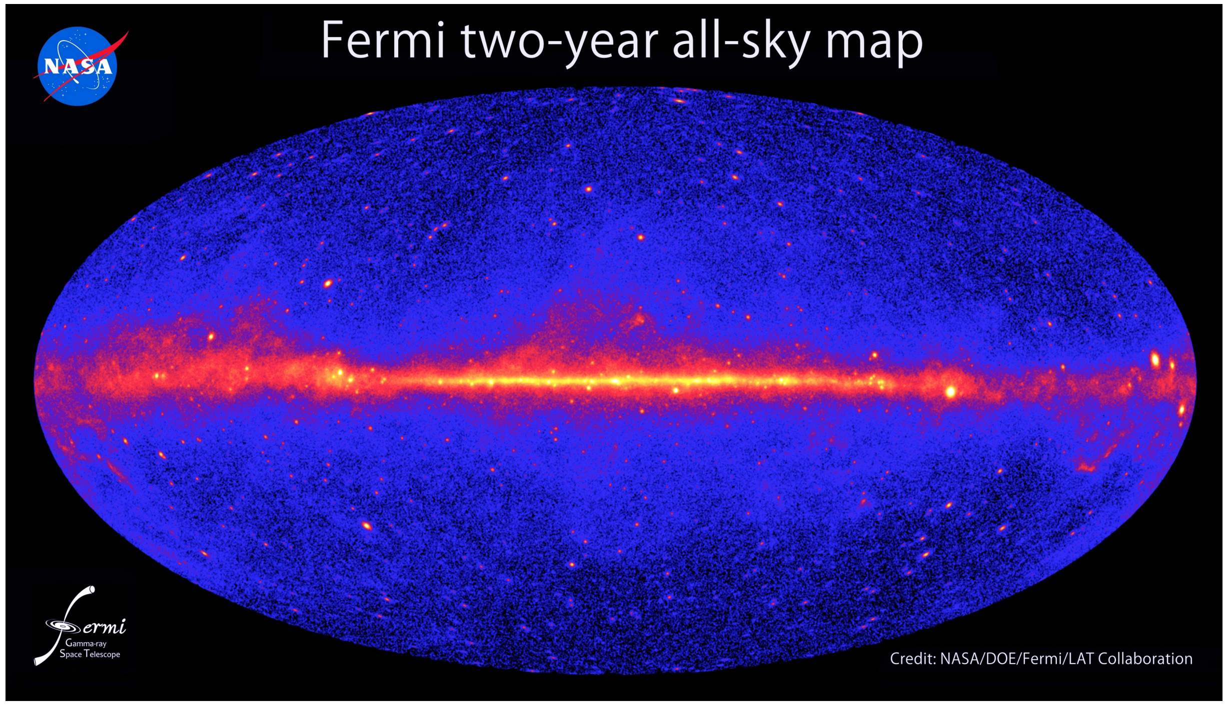


Signal versus Background

- Astrophysical processes present significant backgrounds:

Diemand, Kuhlen & Madau, ApJ '07





- Possible targets include
  - The Galactic center: brightest source in sky, but large backgrounds
  - Dwarf galaxies: DM dominated, M/L~1000; still smaller fluxes (distance!)
  - The Galactic halo: good statistics, angular information; significant backgrounds
  - DM clumps: easy discrimination (once found); bright enough?
  - Galaxy clusters: large substructure boost; good discovery potential, limits model-dependent
  - Extragalactic background: cosmological signal; hard to model, potentially very constraining