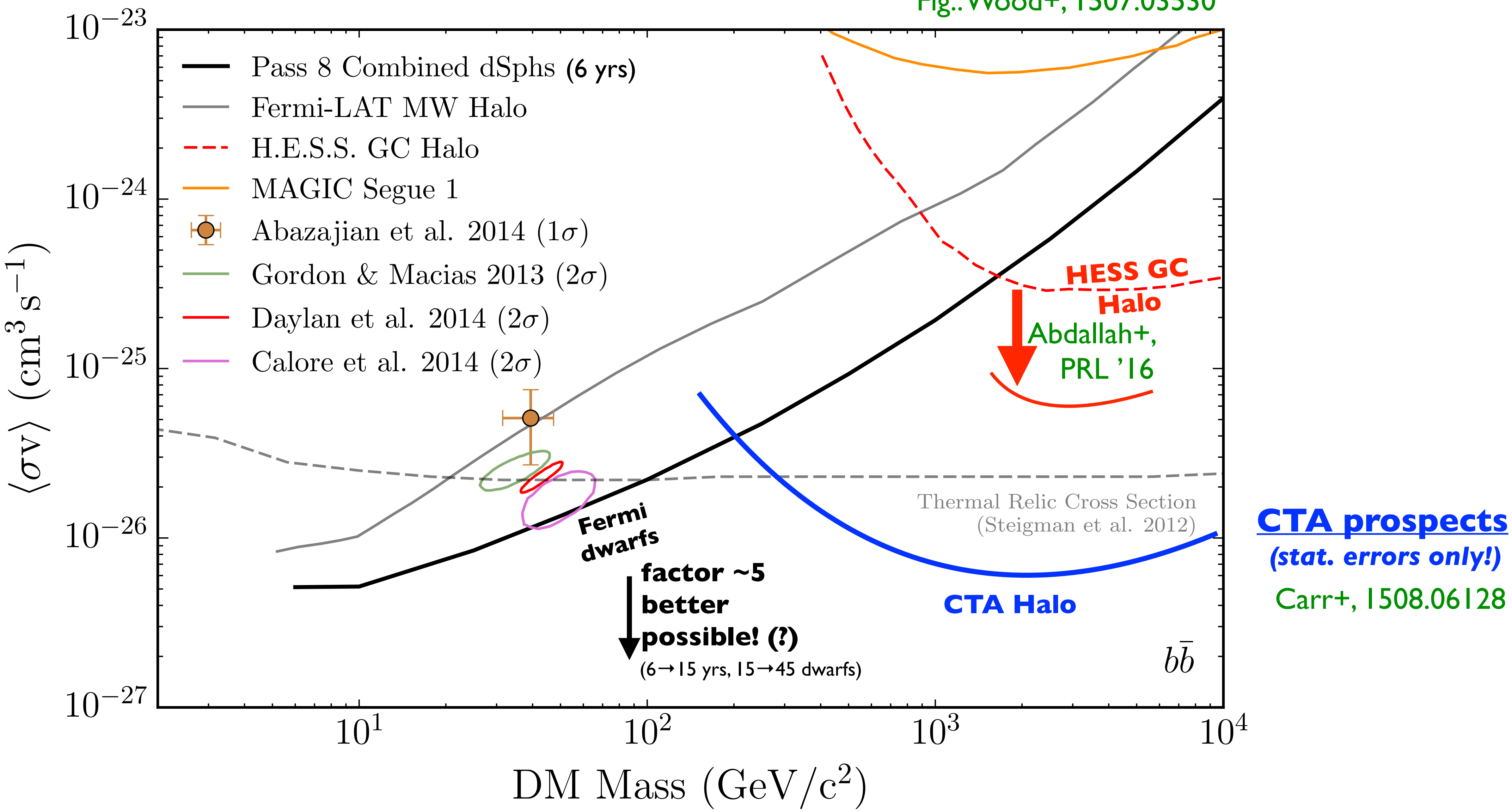
Limits: Status and prospects

- Look for secondary photons from DM

[typical assumption: 100% annihilation into $\bar{b}b$]

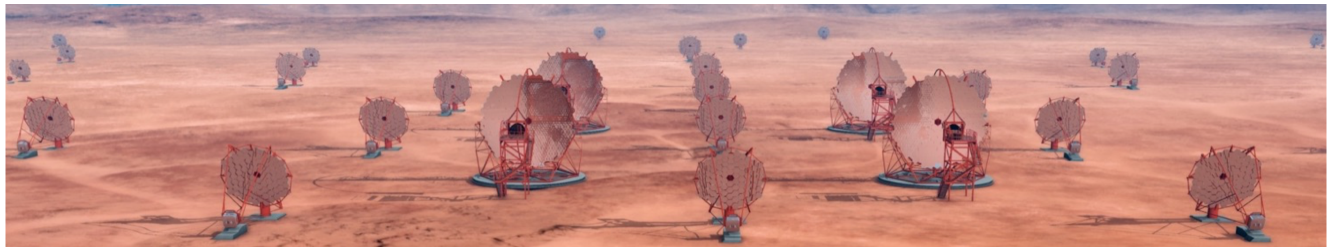
Fig.: Wood+, 1507.03530



⇨ Indirect searches ever more competitive!

CTA prospects

- The next-generation ground-based gamma-ray observatory
  - Two sites (Chile & Canary Islands)
  - Large arrays of differently sized telescopes ⇝ energy range ~10 GeV — ~300 TeV
  - unprecedented sensitivity + survey mode: ideal for DM observations



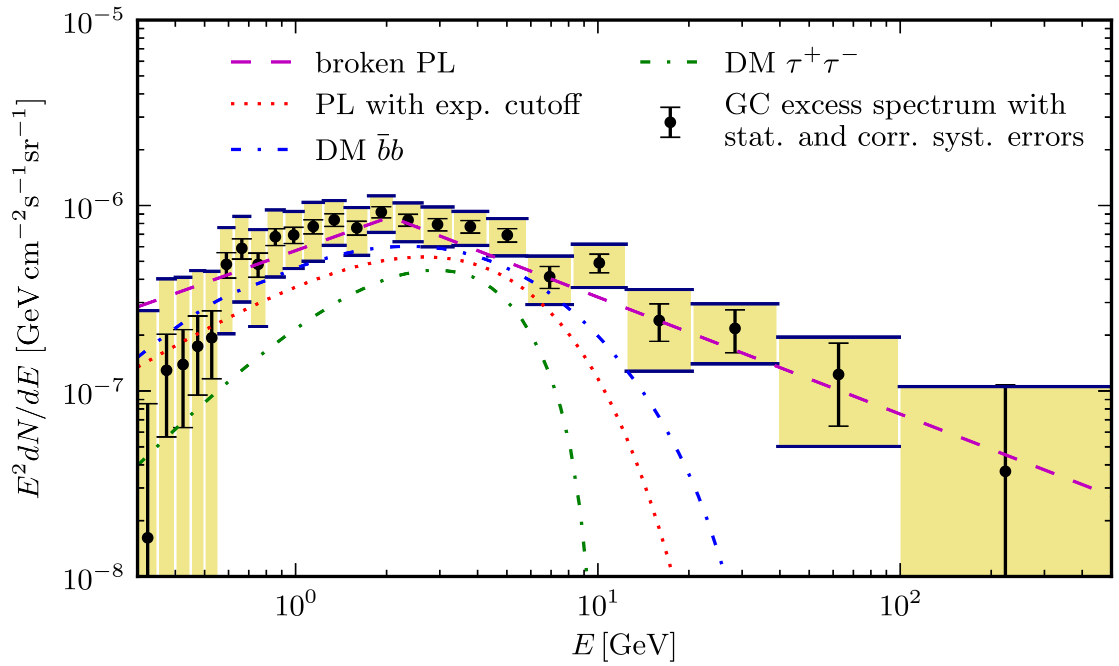
- Detailed sensitivity study for GC observations
  - template analysis (DM, CRs + all relevant astro BGs)
  - fully include systematic uncertainty

For the CTA collaboration:
TB, Eckner, Sokolenko, Yang, Zaharijas

A *signal* from the galactic center?

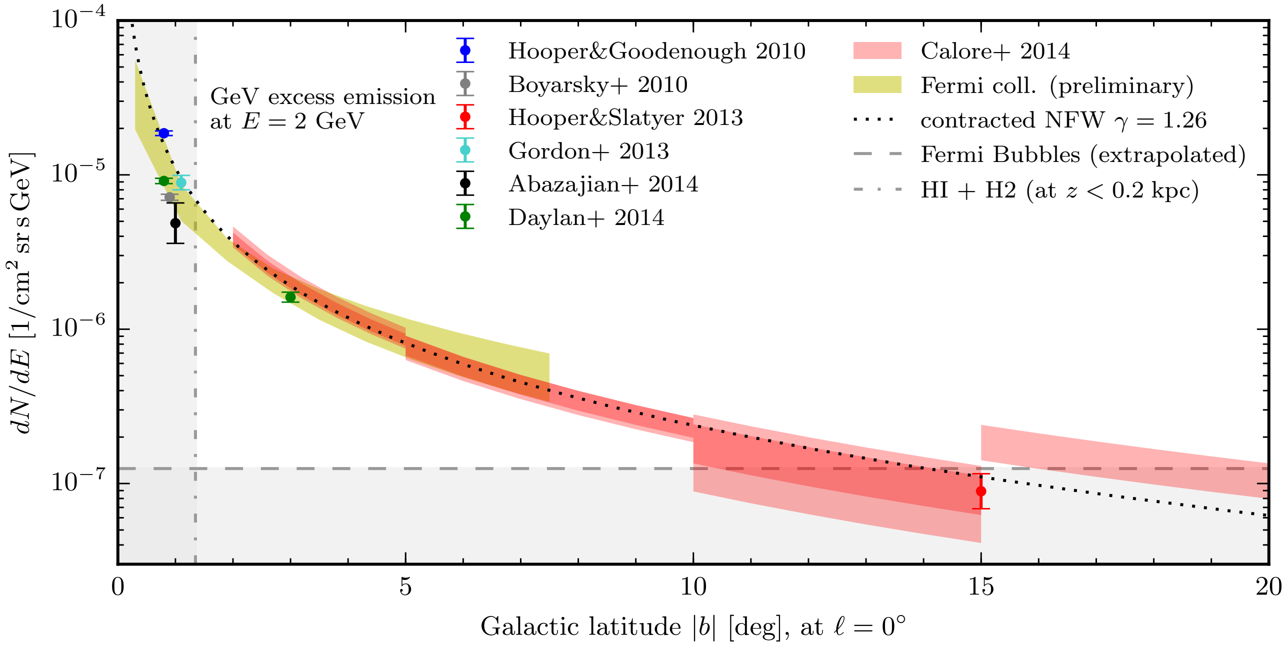
- **Excess emission** in inner Galaxy and Galactic center region:
  - extremely high statistical evidence
  - relatively sharp peak around 1-3 GeV
  - rotationally symmetric
  - roughly $r^{-2.5}$ emission profile
  - extends at least from ~10pc to ~1kpc

Goodenough & Hooper, 0910.2998
Hooper & Goodenough, PLB '11
Hooper & Linden, PRD '11
Abazajian & Kaplinghat, PRD '12
Macias & Gordon, PRD '14
Hooper, PDU '13
Hooper & Slatyer, PDU '13
Huang, Urbano & Xue, 1307.6862
Abazajian, Canac, Horiuchi & Kaplinghat, PRD 14
Daylan *et al.*, PDU '16
and *then* the list fully explodes…



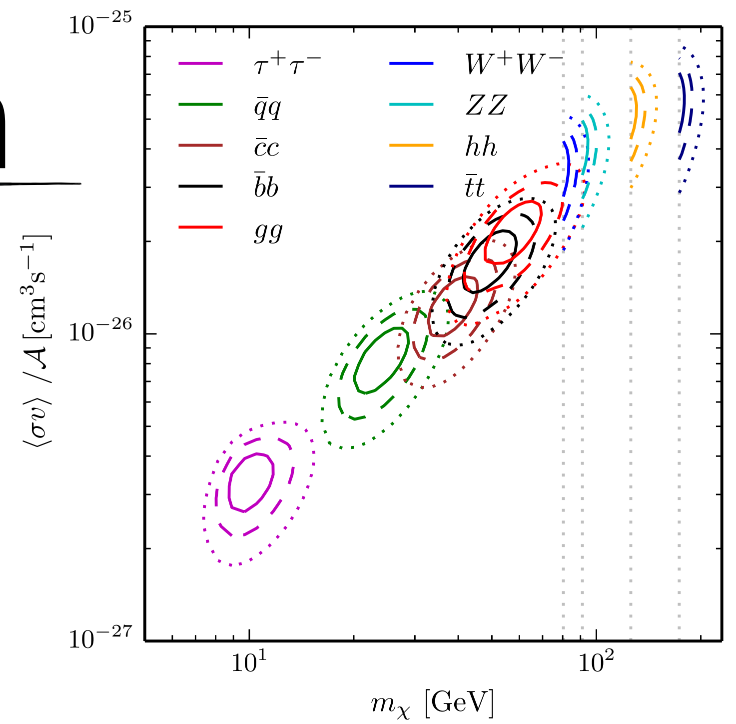
Calore, Cholis & Weniger, JCAP '15

(excess equally consistent with DM signal and broken PL)



Calore, Cholis, McCabe & Weniger, PRD '15

Dark matter interpretation



Calore+, PRD '15

- Constraints
  - collider & direct detection experiments lead to highly model-dependent constraints — Alves+, PRD '14; Berlin, Hooper & McDermott, PRD '14; Izaguirre, Krnjaic & Shuve, PRD '14; Kong & Park, NPB '14 ...
  - indirect searches: model-independent constraints
    - tension with Milky Way $\bar{p}, e^+$& radio — TB, Vollmann & Weniger, PRD '14
      (**NB**: astrophysical uncertainties smaller than typical because DM profile is ~fixed!)
    - (just) OK with Fermi dwarf limits — Albert+, ApJ '17

- Astrophysical explanations (start to become) more likely:
  - milli-second pulsars: need large population — Hooper+, PRD '13; Calore, Di Mauro & Donato, ApJ '14
  - But strong evidence (> 4σ) for unresolved point sources — Bartels, Krishnamurthy & Weniger, PRL '16; Lee+, PRL '16
  - MSPs also consistent bulge+disk component — Bartels+, Nature Ast. '18; MNRAS '18; Eckner+, ApJ '18

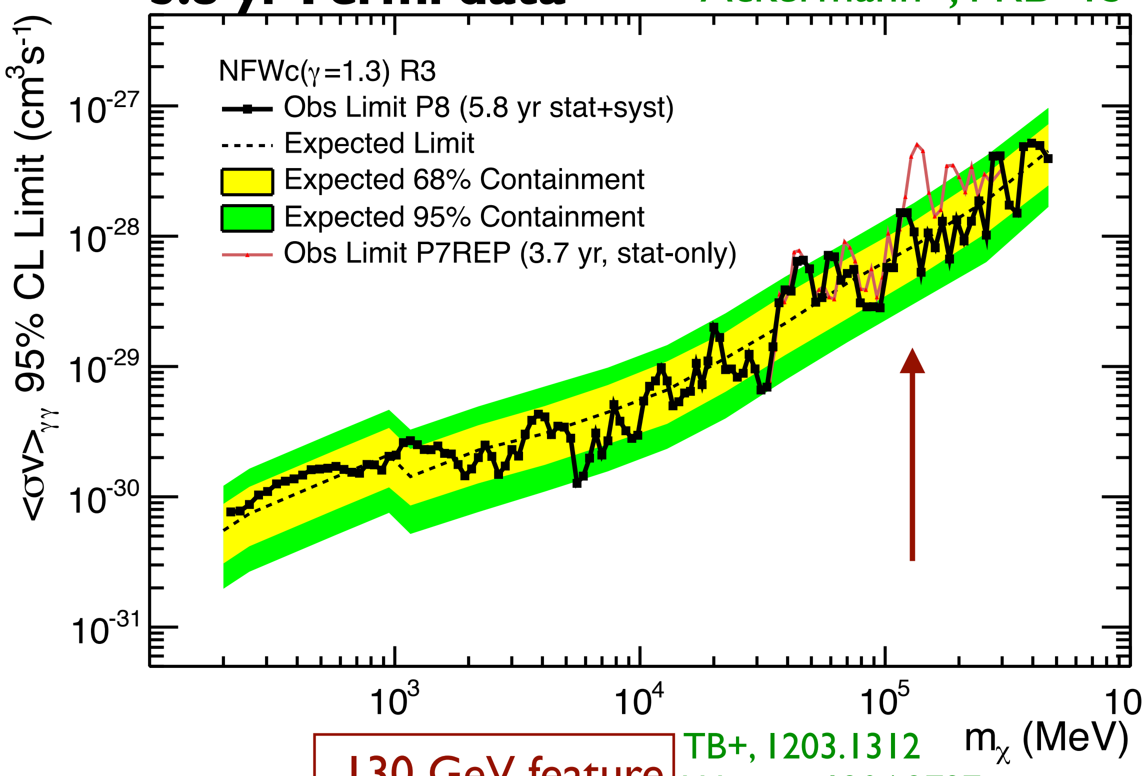
⇨ *targeted radio observations (MeerKAT, SKA) will conclusively test the MSP hypothesis!*

  - Further options: "recent" bursts injecting high-*E*; high-*E* tail of Fermi bubbles; molecular clouds; … — Petrovic, Serpico & Zaharijas, JCAP '14; Carlson & Profumo, PRD '14; Linden+, PRD '16; Dogiel+, ApJ '18

Also no gamma-ray *lines*…

- Clear spectral features allow to place much stronger limits:

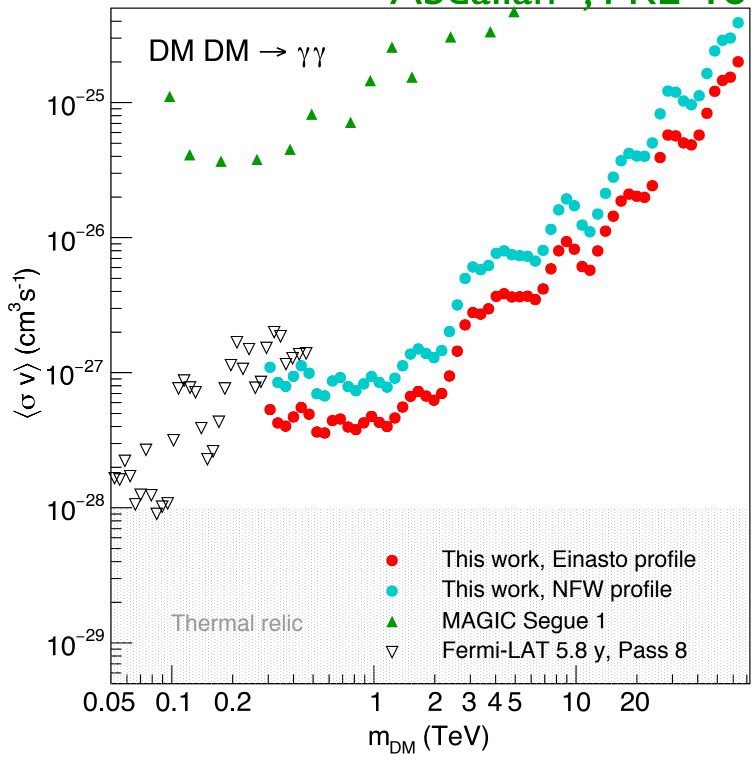
5.8 yr Fermi data Ackermann+, PRD '15



130 GeV feature

TB+, 1203.1312
Weniger, 1204.2797
Tempel, Hektor & Raidal, 1205.1045
Su & Finkbeiner, 1206.1616

Abdallah+, PRL '18 **254 *h* HESS data**

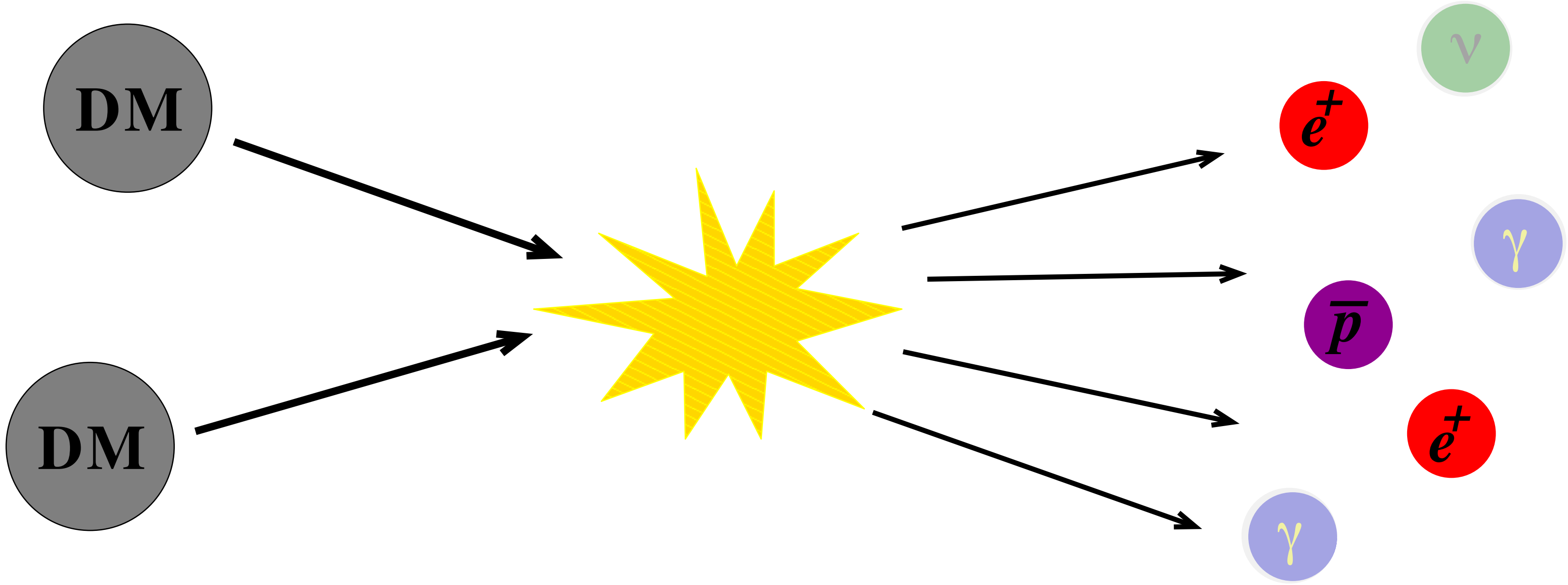


- Huge potential to improve limits:
  - CTA, Gamma-400, CALET, DAMPE, …

- And: the 3.5 *keV* X-ray line is still there…!

Bulbul+, ApJ '14
Boyarski, Ruchayskiy,
Iakubovskyi & Franse, PRL '14

Charged cosmic rays



- GCRs are confined by galactic magnetic fields
- Random distribution of field inhomogeneities
  ⇝ propagation well described by diffusion equation
- After propagation, no directional information is left
- Also the spectral information tends to get washed out
- Equal amounts of matter and antimatter
  ⇨ focus on antimatter (low backgrounds!)

Analytical vs. numerical

How to solve the diffusion equation?

- Numerically
  - ⊕ 3D possible
  - ⊕ any magnetic field model
  - ⊕ realistic gas distribution, full energy losses
  - ⊖ computations time-consuming
  - ⊖ "black box" (for inexperienced users)

e.g. GALPROP

Strong, Moskalenko, …

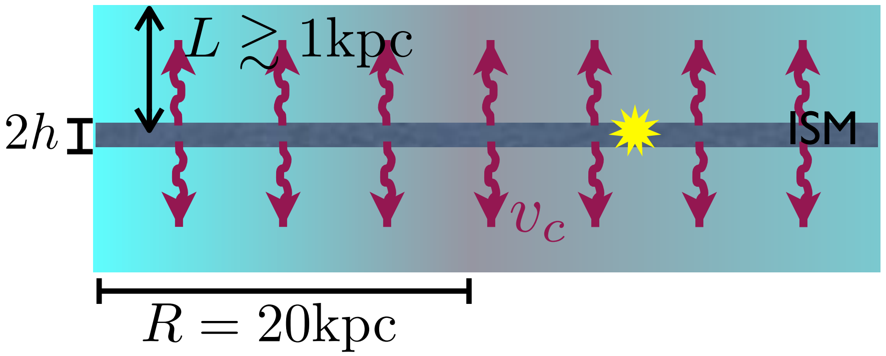
DRAGON

Evoli, Gaggero, Grasso & Maccione

DarkSUSY

- (Semi-)analytically
  - ⊕ Physical insight from analytic solutions
  - ⊕ fast computations allow to sample full parameter space
  - ⊖ only 2D possible
  - ⊖ simplified gas distribution, energy losses

e.g. Donato, Maurin, Salati, Taillet, ...



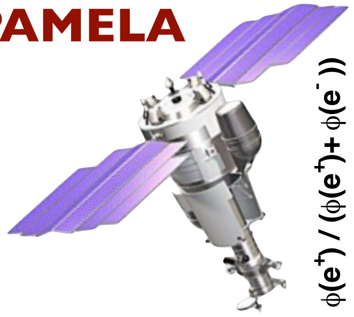
General concern: data start to become better than models!

⇨ *loss of predictivity ?*

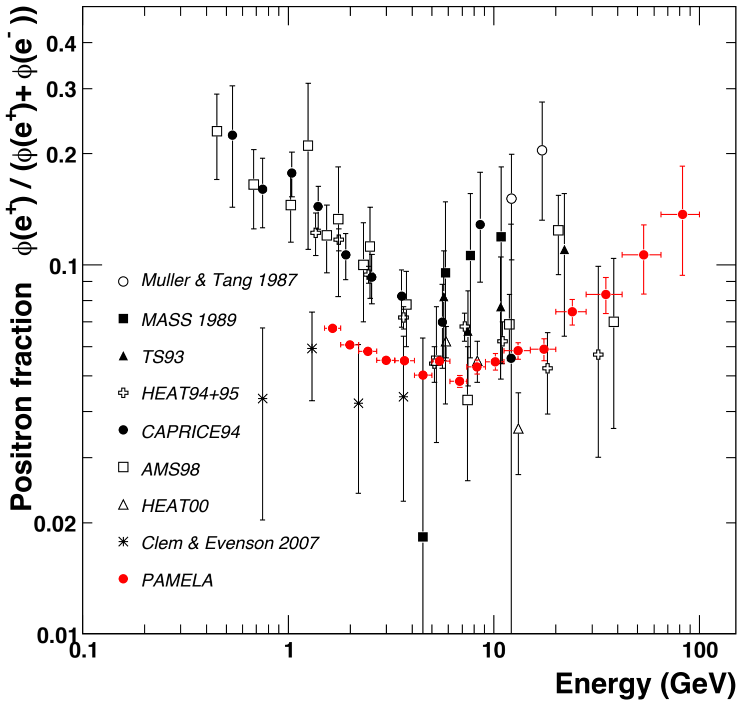
Positrons

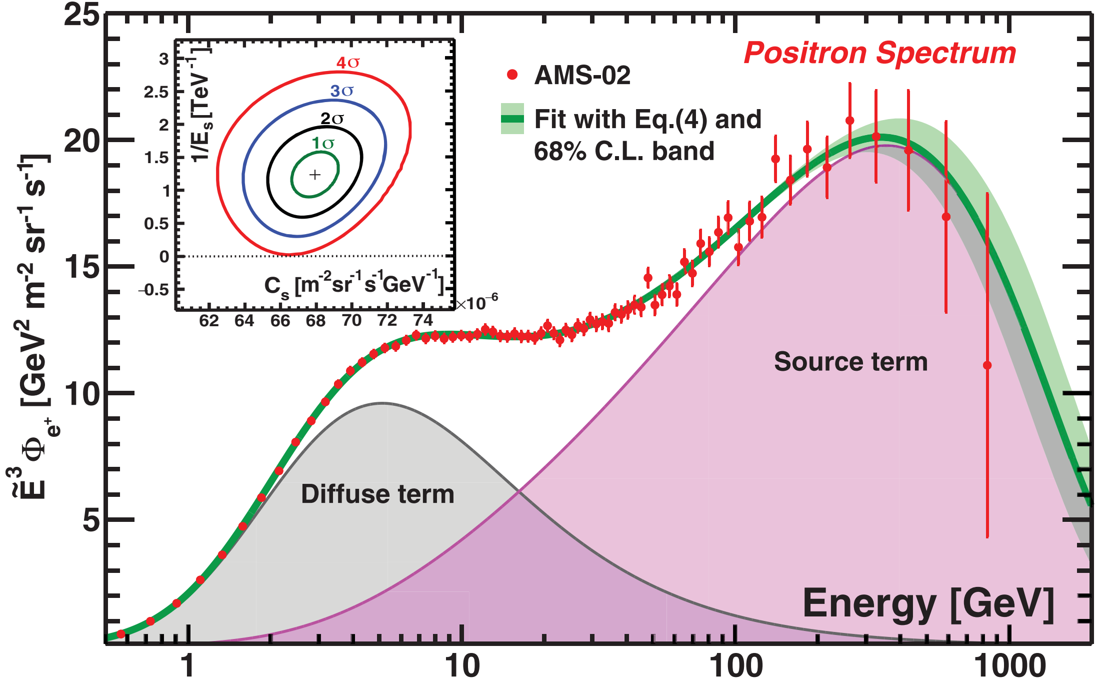
- Excess in high-energy cosmic ray positron data

PAMELA



Adriani+, Nature '09





AMS

Aguilar+, PRL '19

- Standard production through cosmic-ray collisions
  - mostly CR p on ISM gas

- At high energies, an additional component is required
  - Efficient energy losses (IC, synchrotron) ⇨ source must be local (few kpc)
  - Single power law with exponential cutoff provides a good fit

⇨ *Astrophysical (PWN, SNRs) or dark matter ?* [loooong discussion…]

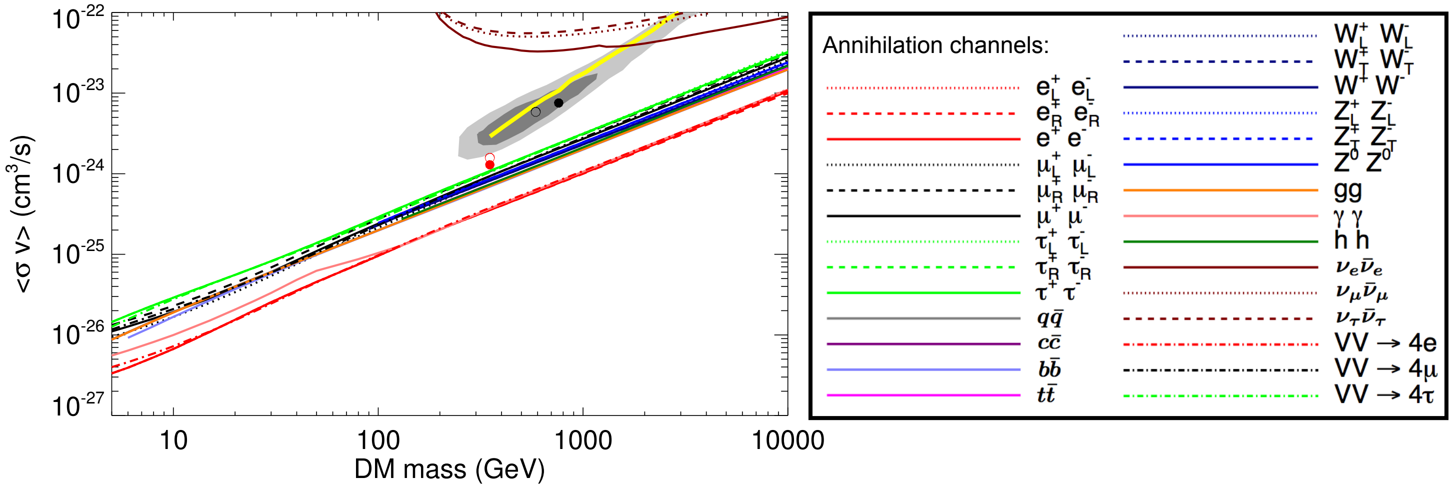
DM signal ? DM limits !

- Dark matter interpretation requires
  - leptophilic DM (lack of excess in antiprotons)
  - TeV masses
  - annihilation cross section ~ 10^3 x ‘thermal’ value

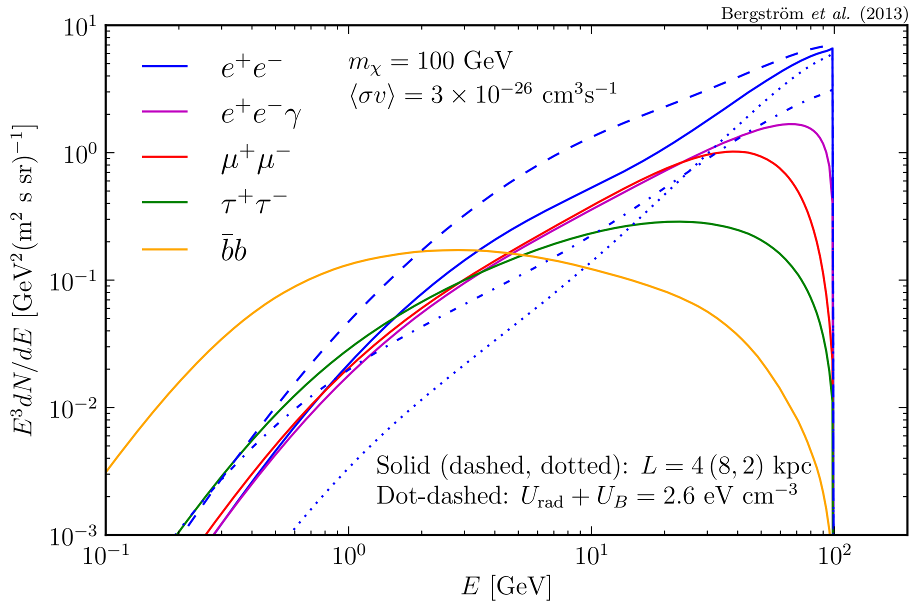
  … and is (now) in clear tension with CMB data

e.g. Cirelli, Kadastik, Raidal & Strumia, NPB ’09, ’13
Bergström, Edsjö & Zaharijas, PRL ‘09

Slatyer, PRD ‘16

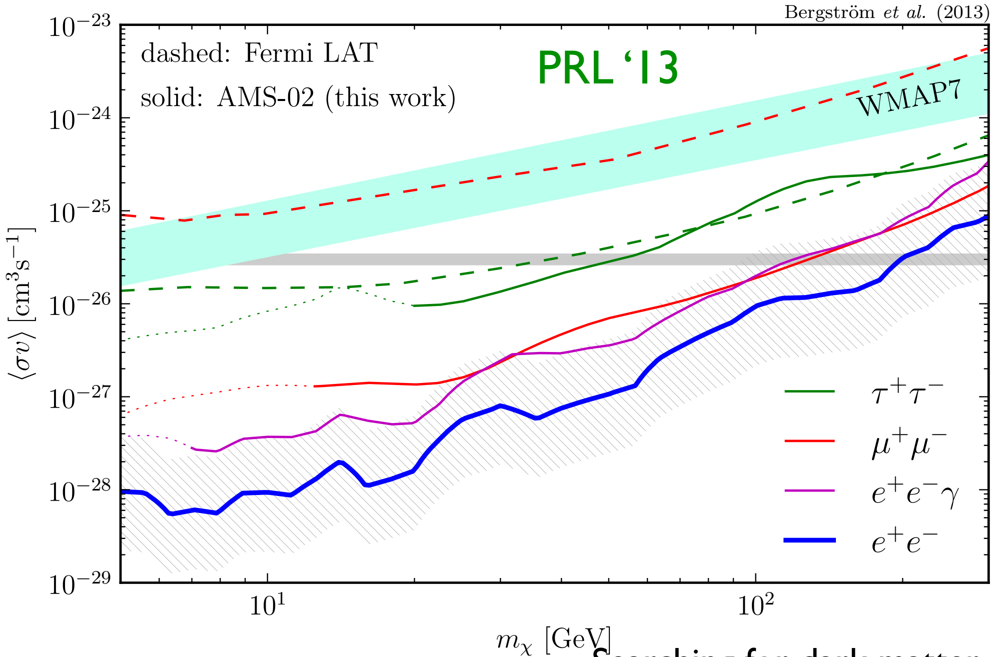


- But *sharp* spectral features actually survive propagation



data well described by *smooth* BG model

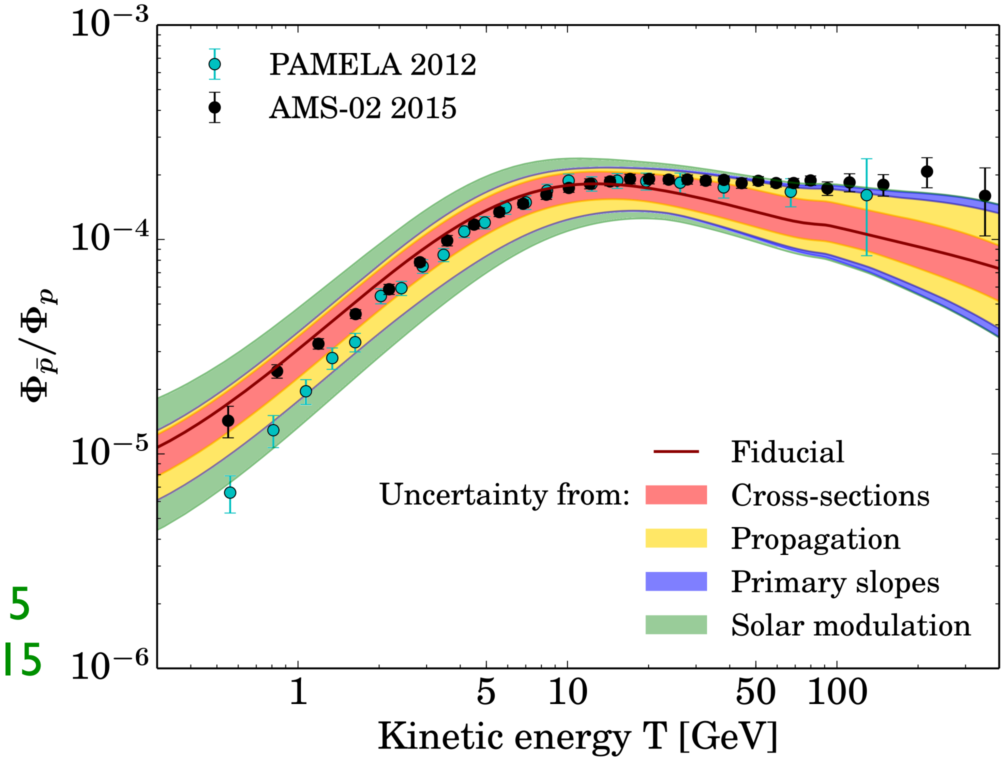
- Very stringent (and robust!) limits on leptonic final states



Antiprotons

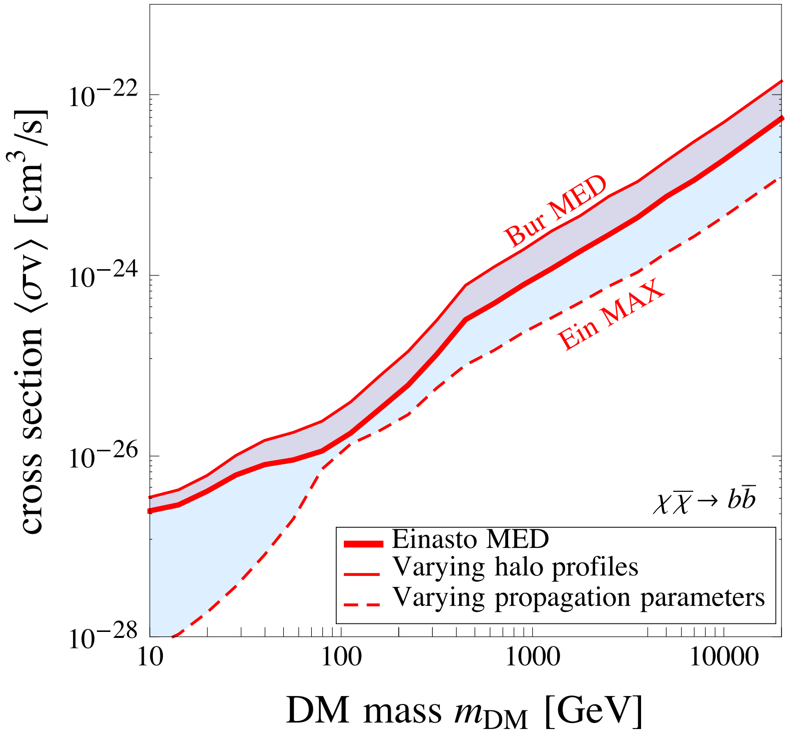
- Cosmic-ray antiprotons
  - are also produced as secondary particles
  - suffer from less energy losses

    ⇨ diffuse much further
  - do not show any (obvious) high-E excess

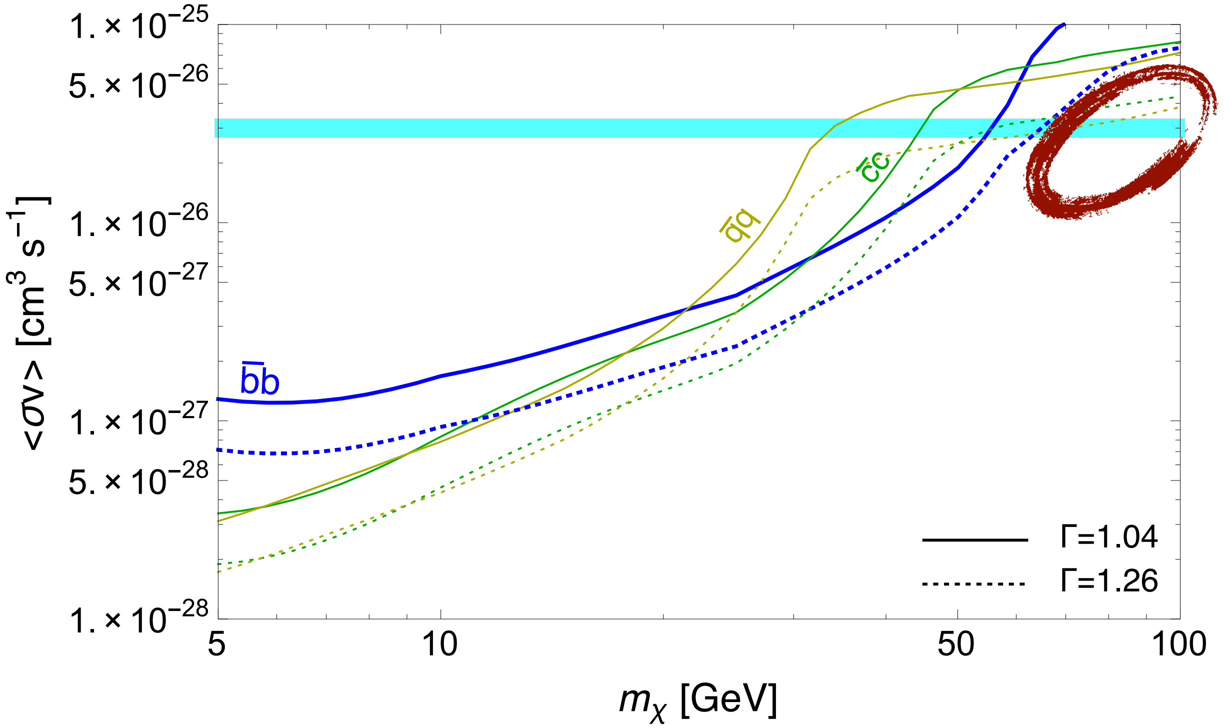


Giesen+, JCAP '15
Evoli, Gaggero & Grasso, JCAP '15
Kappl, Reinert & Winkler, JCAP '15

- Stringent constraints on hadronic annihilation channels



Giesen+, JCAP '15

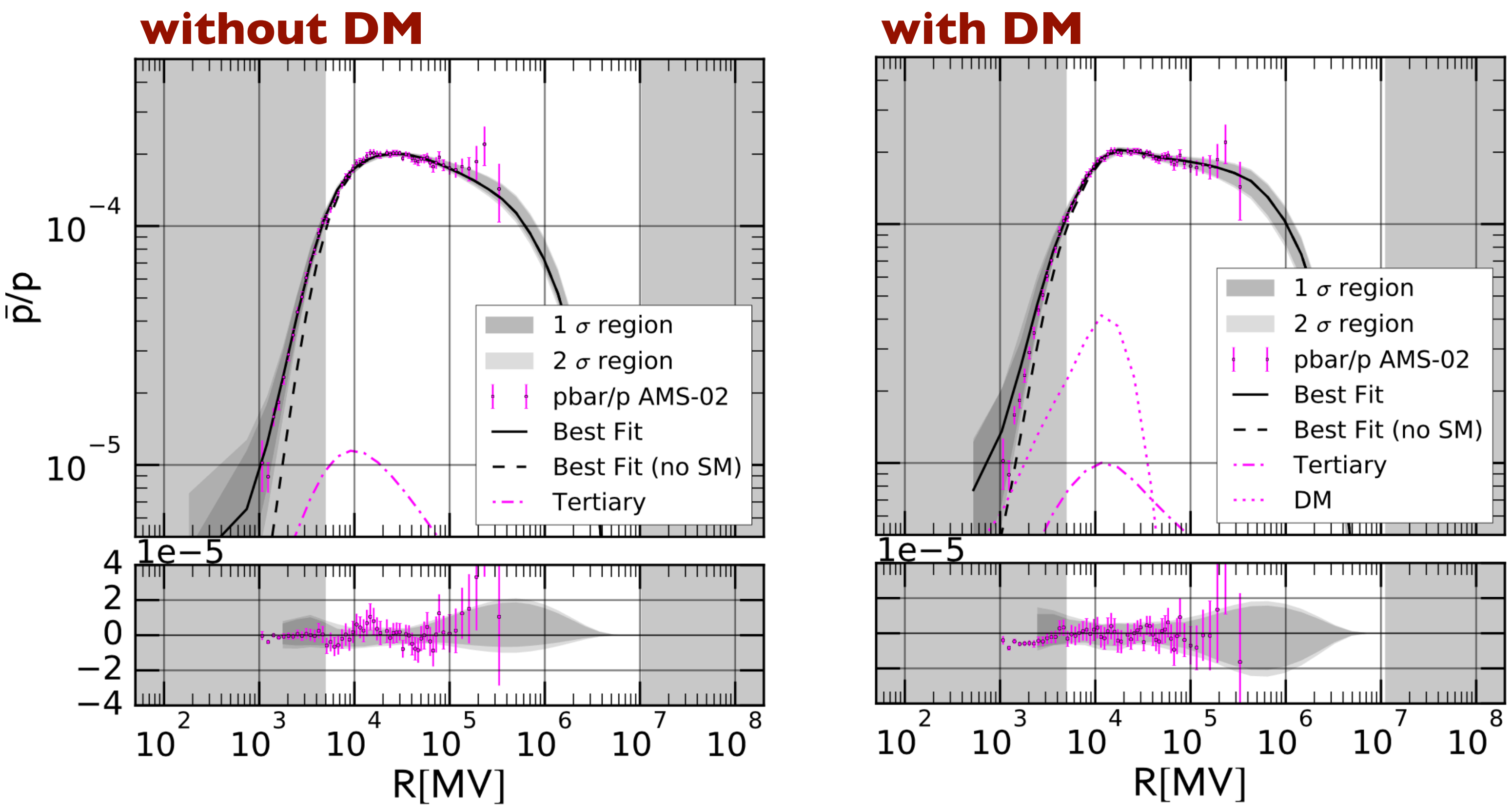


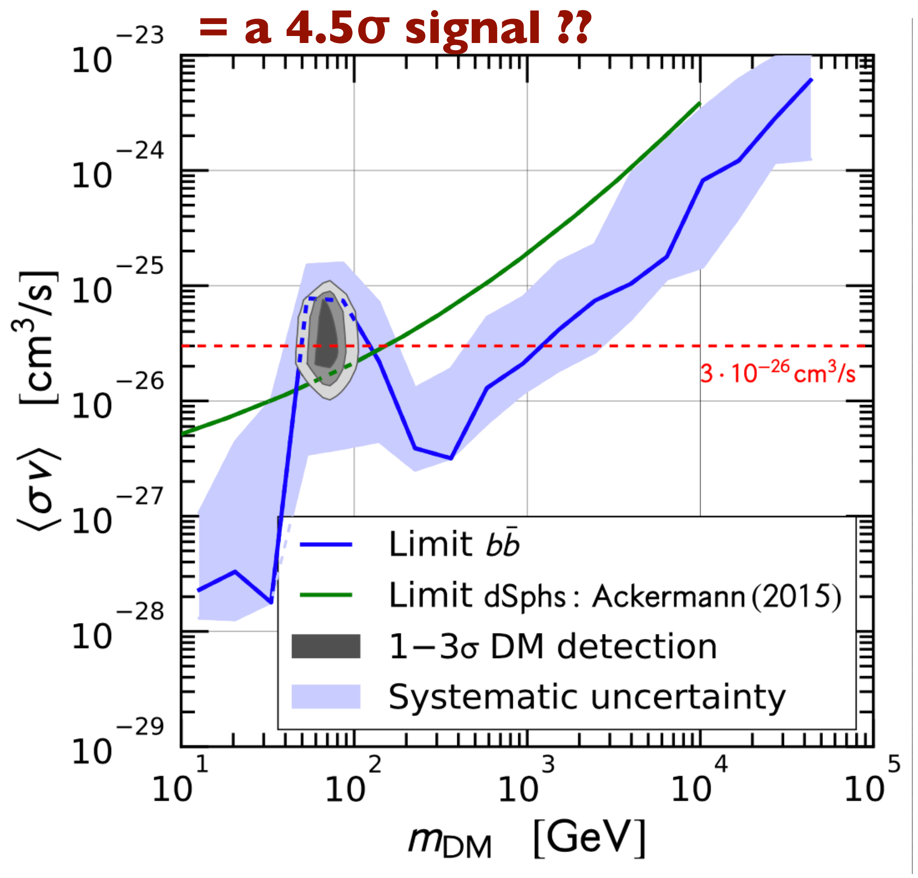
TB, Vollmann & Weniger, PRD '14

Details in the analysis do matter…

Another GeV excess ?

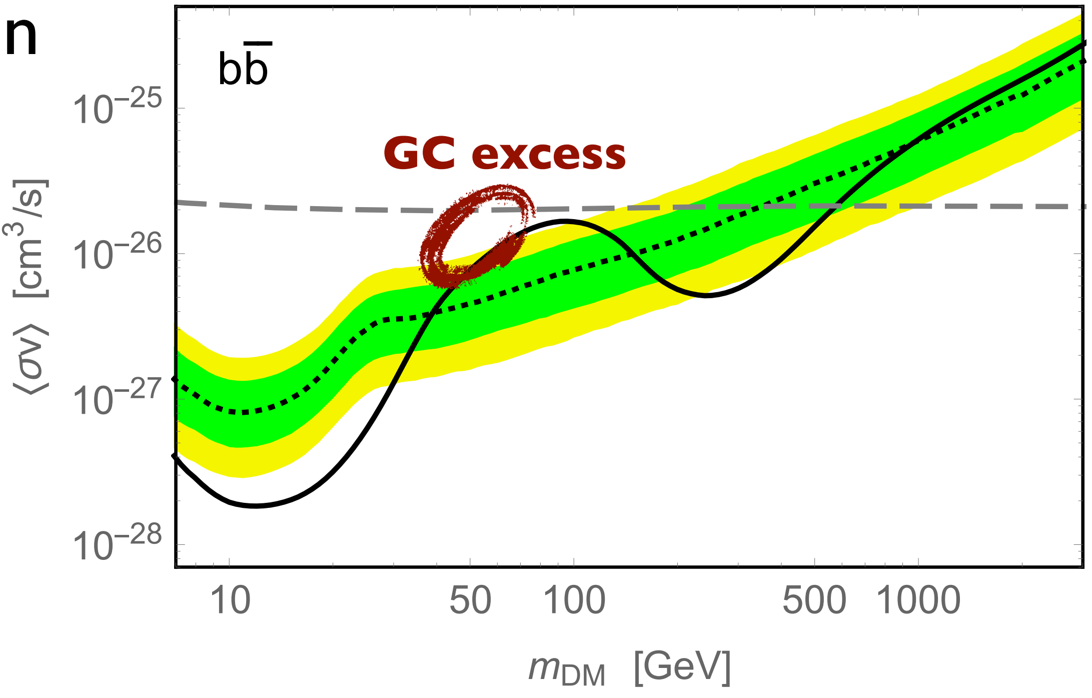
Cuoco, Krämer & Korsmeier, PRL '17





- **Various worries**
  - propagation setup inconsistent with B/C
  - strong dependence on choice of analysis region
- **Various similar claims**

Cui, Yuan, Tsai & Fang, PRL '17
Huang+, PRD '17
Feng& Zhang, ApJ '18
Cuoco, Heisig, Krämer& Korsmeier, JCAP '17



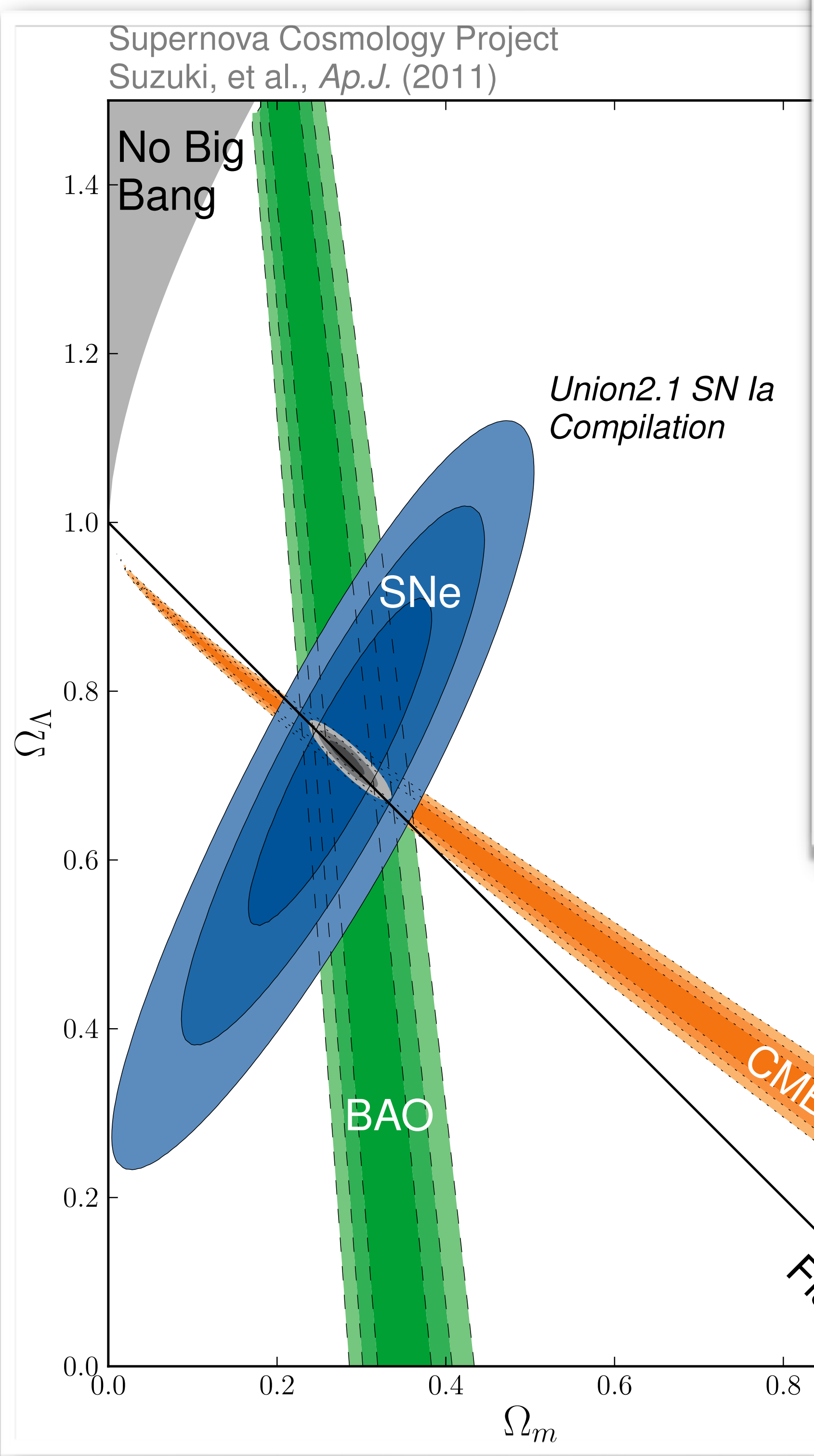
- **Significance likely exaggerated**
  - dominant effect: cross-section uncertainty
  - add low-E data, updated propagation params

Reinert & Winkler, JCAP '18

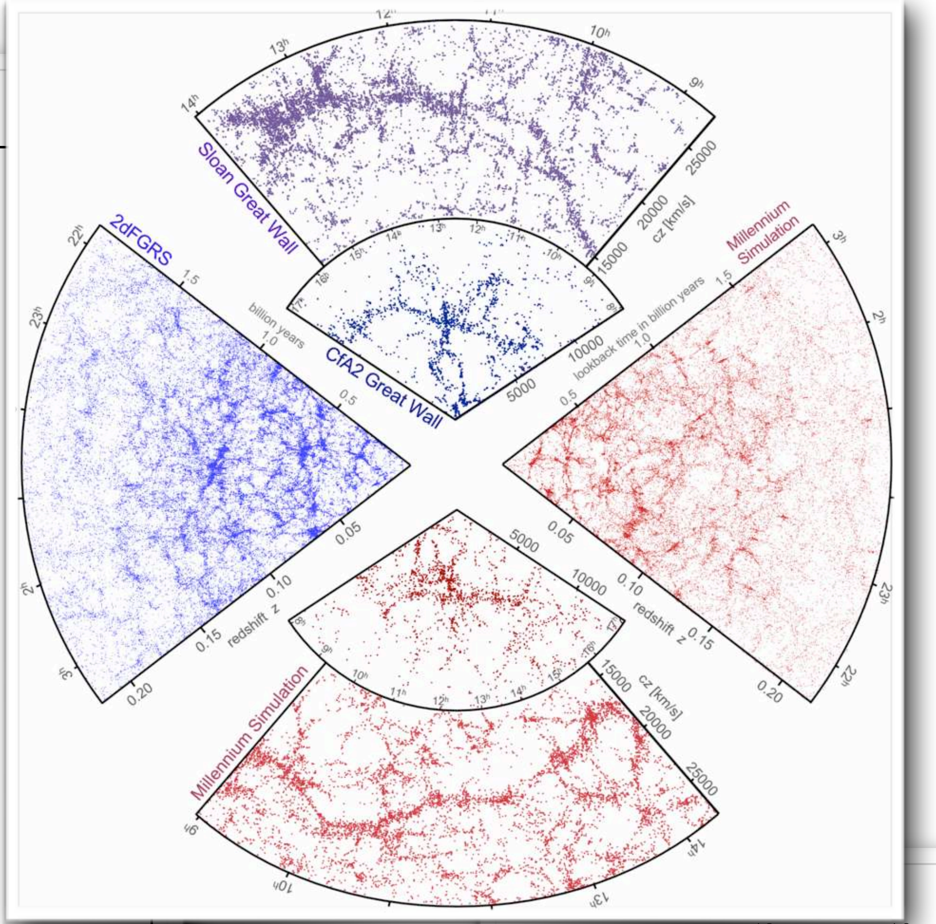
Outline

- Introduction
  - Evidence
  - Candidates & Tools
- [Collider searches]
- Direct searches
  - ‘reverse’ direct detection
- Indirect searches
  - Gamma rays
  - Charged cosmic rays
- Other astrophysical probes
  - The matter power spectrum
  - Self-interacting dark matter
  - ETHOS
- Complementarity
  - Example: Light scalar mediators

ΛCDM cosmology



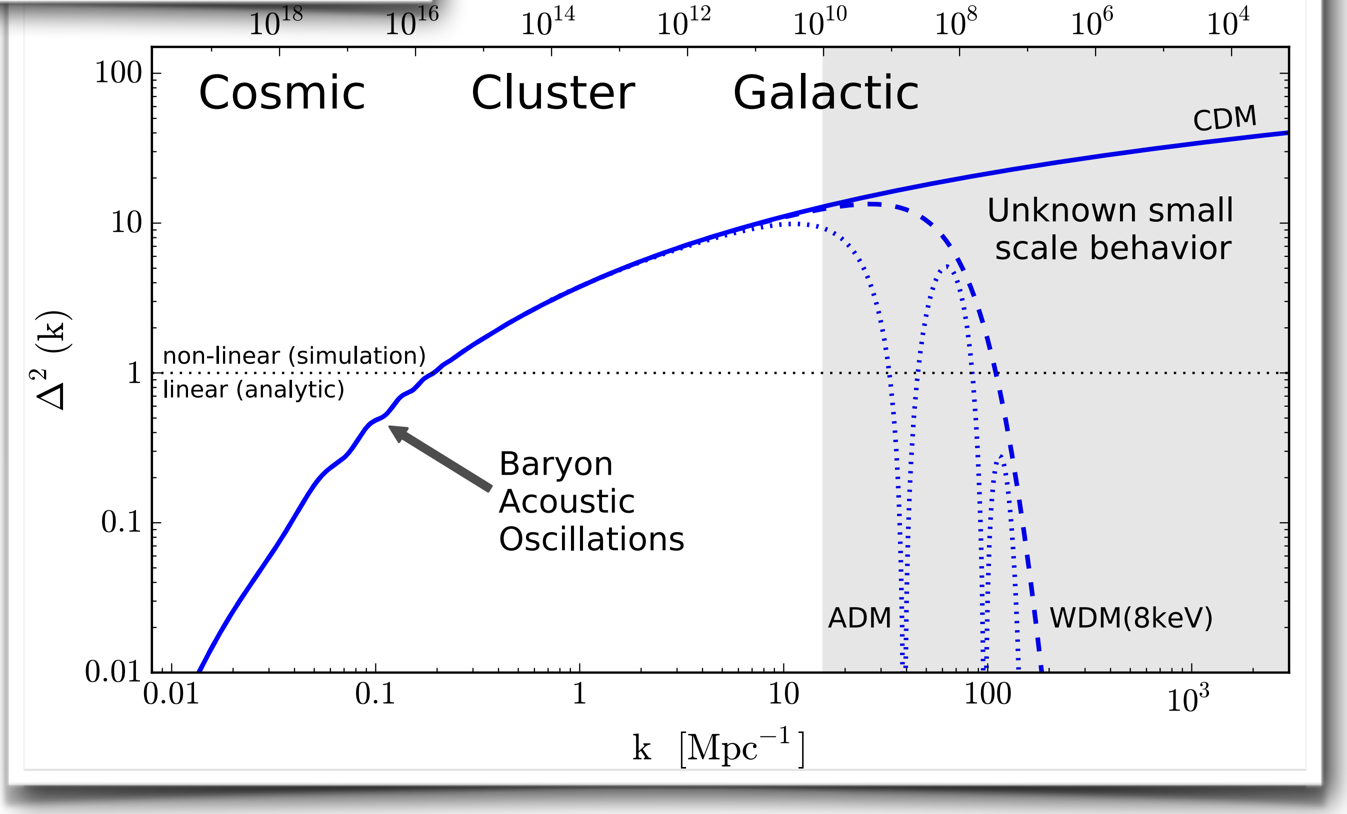
Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)



Springel, Frenk & White, Nature '06

A great success
on large scales...

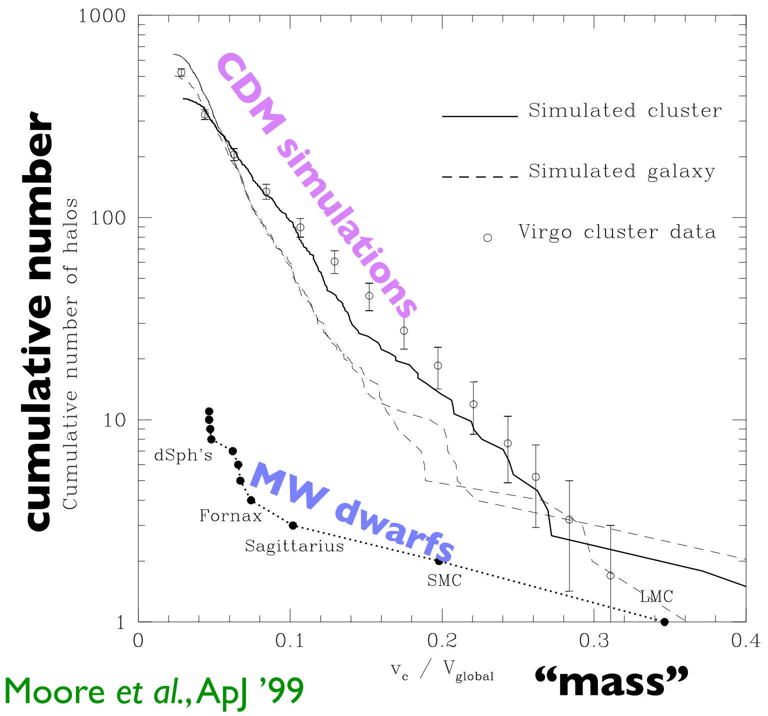
Kuhlen, Vogelsberger & Angulo, PDU '12



Small-scale problems?

Potential observables!

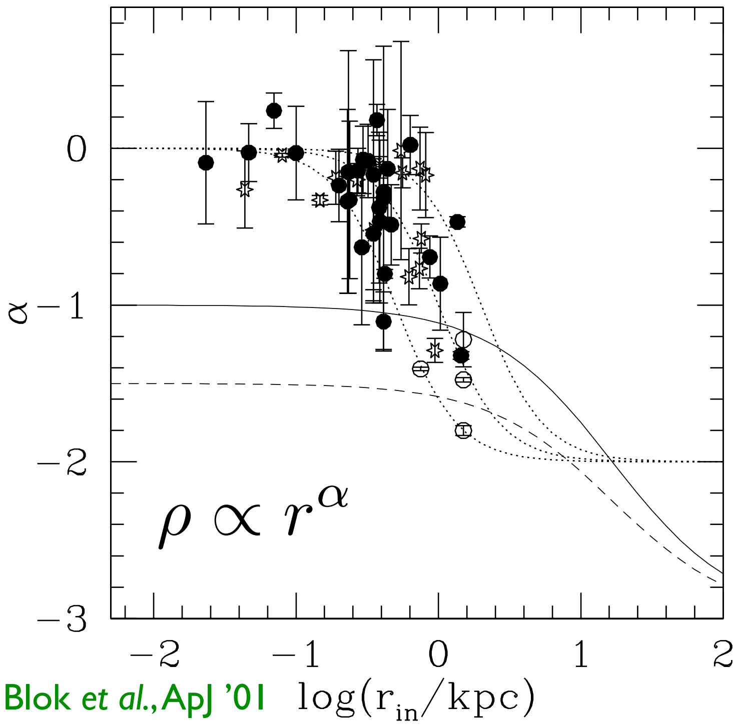
1. Missing satellites?



Moore *et al.*, ApJ ’99

More satellites in simulations of MW-like galaxies than observed

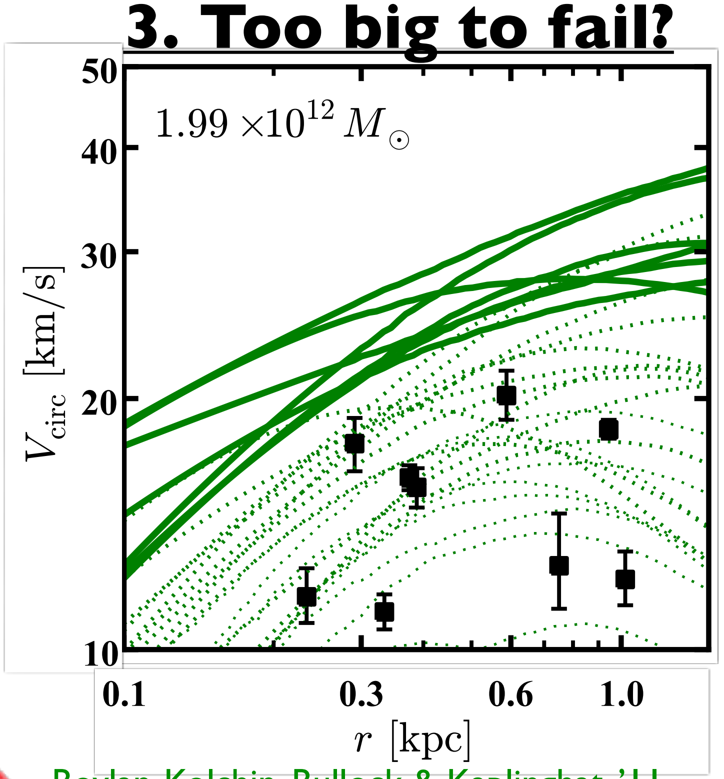
2. Cusps or cores?



Blok *et al.*, ApJ ’01

Cuspy inner density profiles predicted by simulations not found in (all) observations

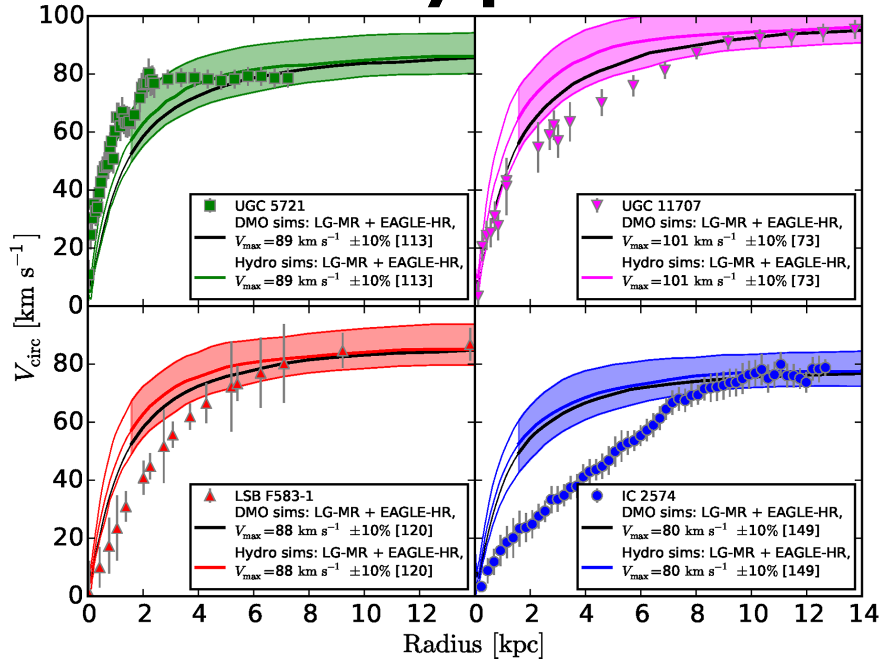
3. Too big to fail?



Boylan-Kolchin, Bullock & Kaplinghat, ’11

Most massive simulated sub-halos too dense to form observed brightest dwarf galaxies

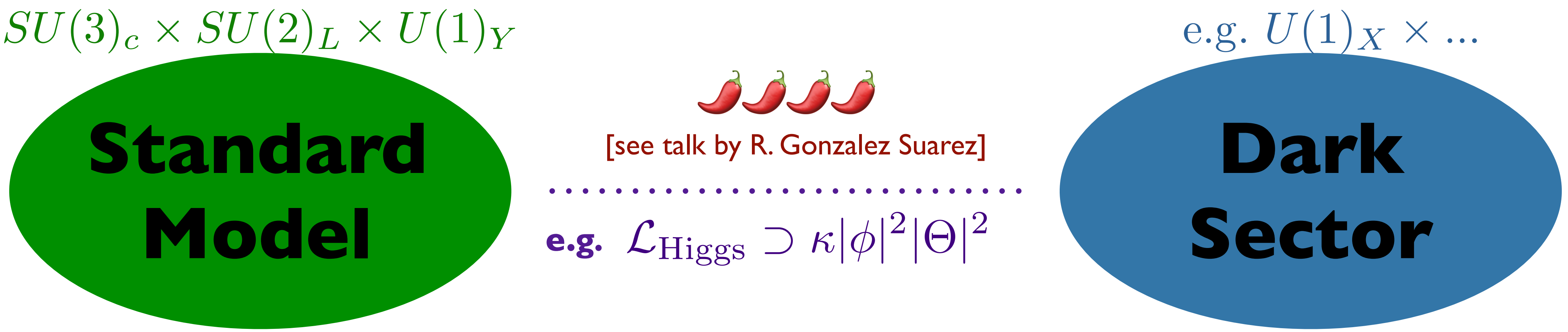
4. Diversity problem?



Oman+, MNRAS ‘15

Real rotation curves vary more than in simulations with(!) baryons

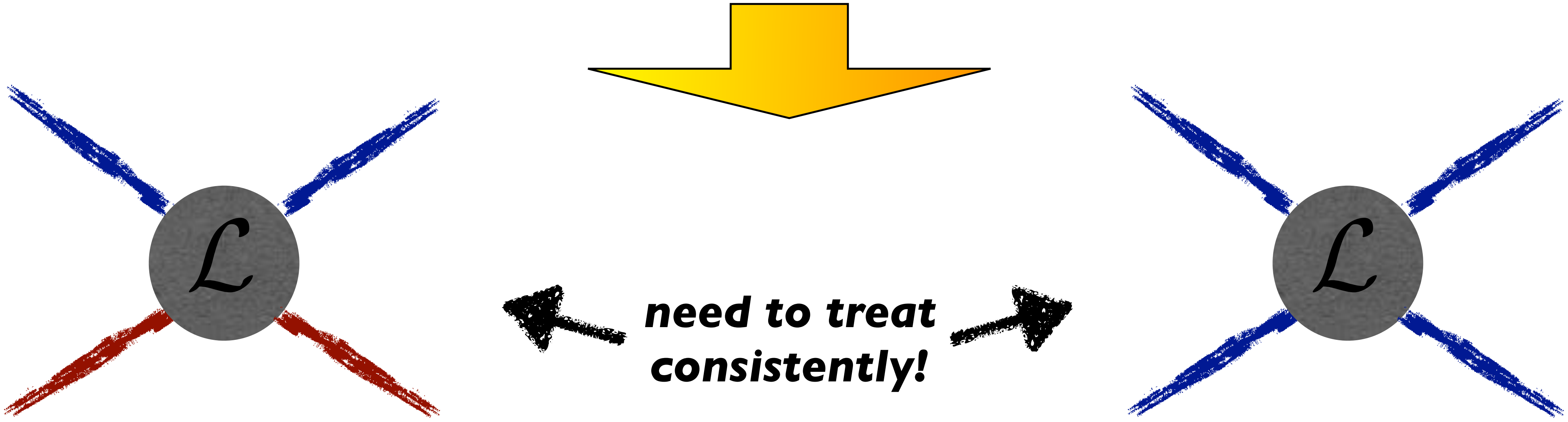
Generic dark sector models



- SM particles

- Dark matter
- Dark radiation
  (‘sterile neutrinos’, ‘dark photons’, …)

- A ‘portal’ typically still ensures thermalisation at high temperatures
  - Separate entropy conservation after decoupling $\rightsquigarrow T_{\mathrm{photon}} \neq T_{\mathrm{dark}}$



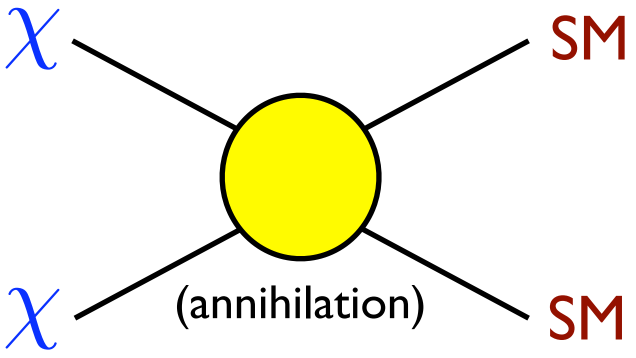
need to treat consistently!

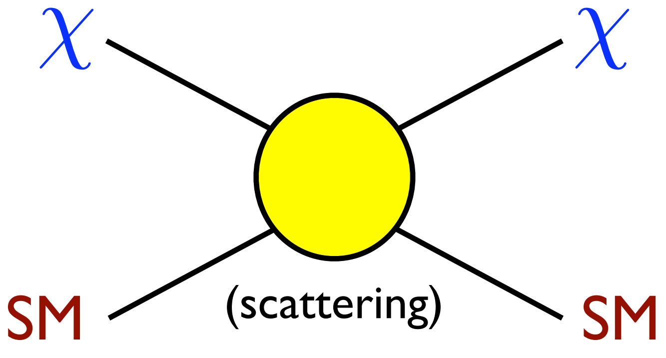
- imprints on linear $\mathcal{P}(k)$

- imprints on inner (sub-)halo structure

Freeze-out ≠ decoupling !

- Expect WIMPs (and similar DM particles) to stay much longer in kinetic than in chemical equilibrium:





- Boltzmann equation in FRW spacetime: $\boxed{E(\partial_t - H\mathbf{p}\cdot\nabla_\mathbf{p})f_\chi = C[f_\chi]}$
  - $\int d^3p$ recovers familiar $\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\text{eq}}^2\right)$
  - Now consider 2nd moment, introducing

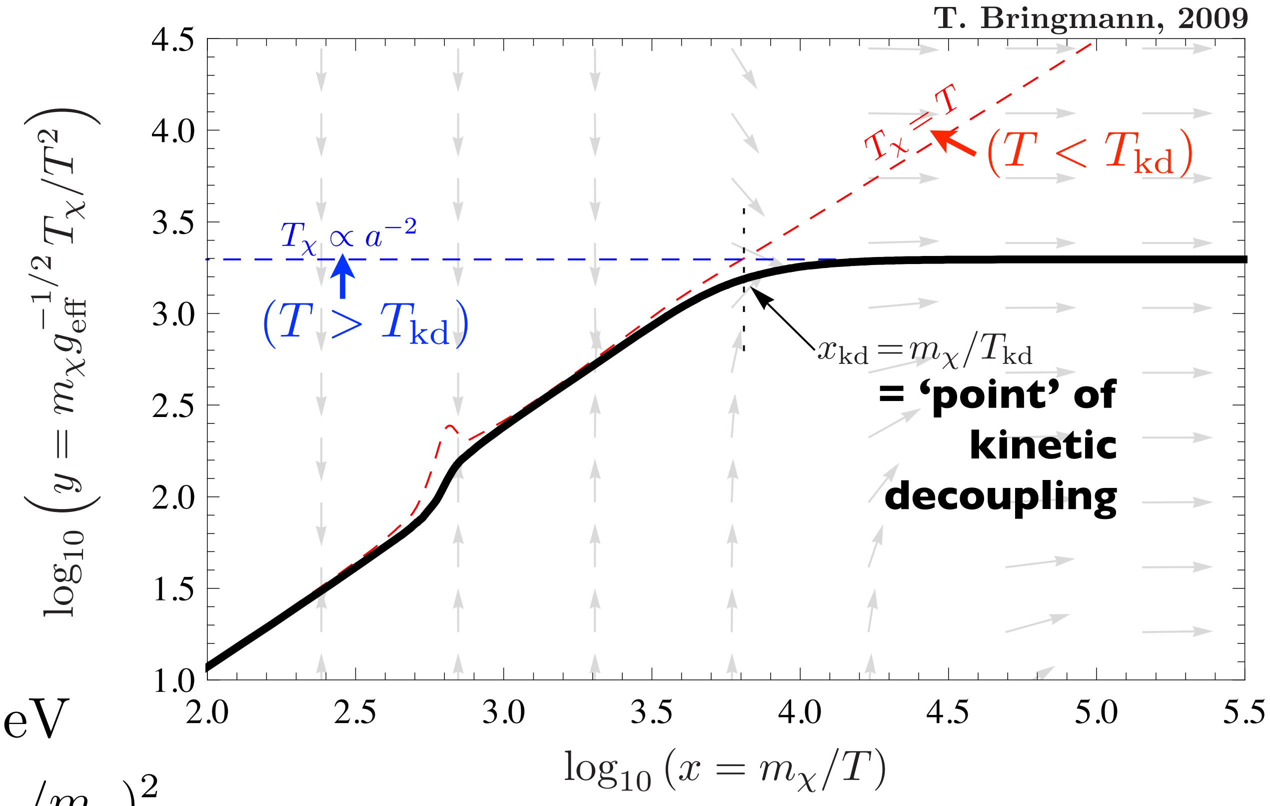
$$\boxed{T_\chi n_\chi \equiv \int \frac{d^3p}{(2\pi)^3}\frac{\mathbf{p}^2}{3m_\chi}f(\mathbf{p})}$$

Bertschinger, PRD '06
TB & Hofmann, JCAP '07
TB, NJP '09

solve resulting ODE for T_χ

[See also Binder, TB, Gustafsson & Hryczuk, PRD '18 for detailed treatment]

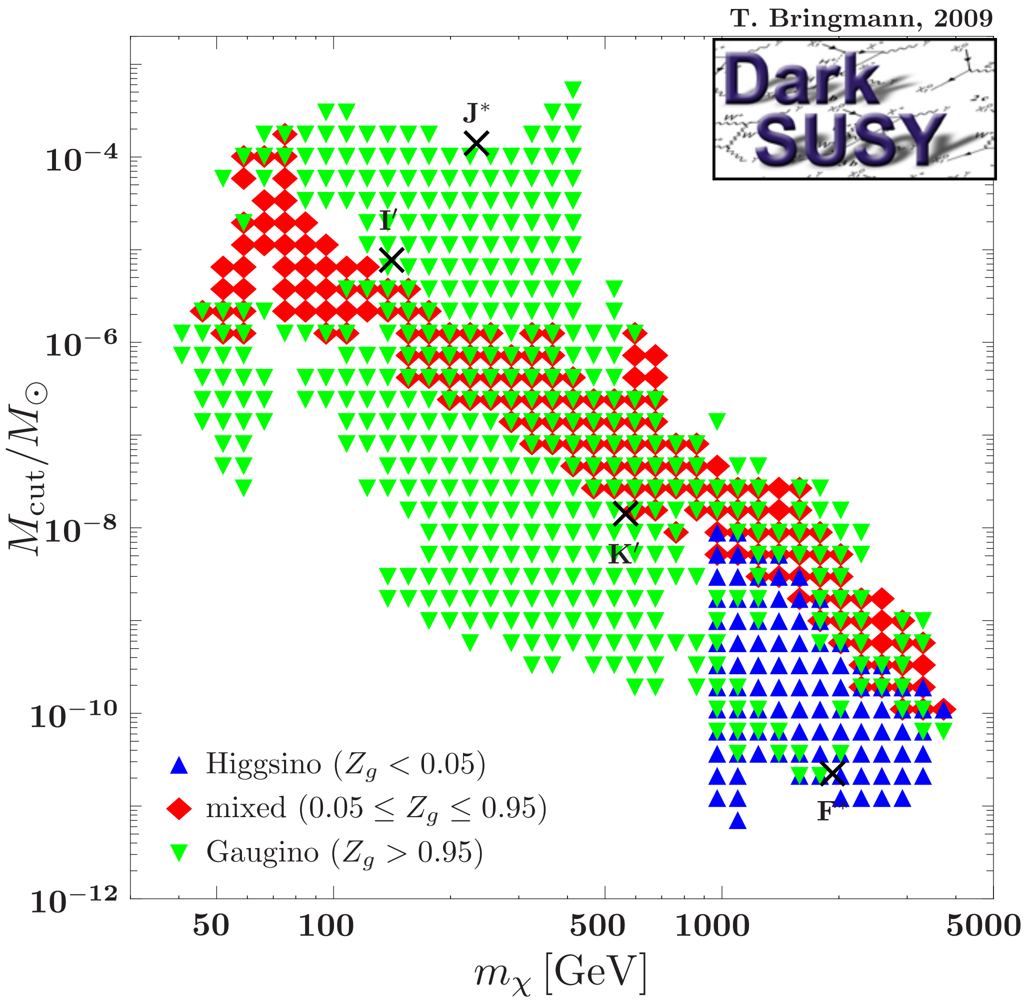
Example:
$m_\chi = 100\,\mathrm{GeV}$
$|\mathcal{M}|^2 \sim g_Y^4 (E_\chi/m_\chi)^2$


T. Bringmann, 2009

The smallest protohalos

- In kinetic equilibrium, density contrasts in DM component immediately erased

- Around and after decoupling, two effects suppress the growth of overdensities:
  - free-streaming e.g. Green, Hofmann & Schwarz, JCAP '05
  - baryonic ('dark') acoustic oscillations Loeb & Zaldarriaga, PRD '05;Bertschinger, PRD '06



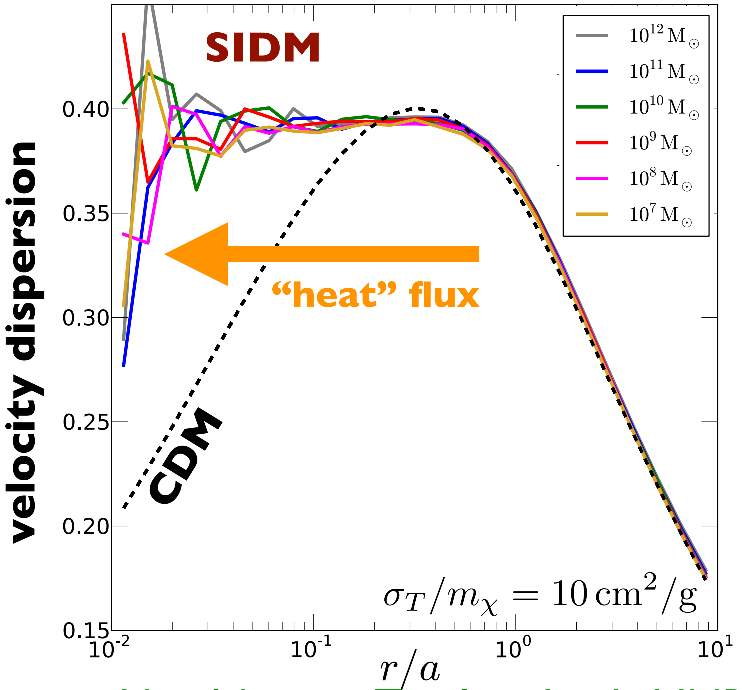
- Resulting small-scale cutoff in power spectrum corresponds to mass of smallest gravitationally bound structures
  - Not 'earth-mass' but strongly model-dependent!

- Much later kinetic decoupling (i.e. larger cutoffs) possible for scattering with dark radiation, e.g. with light mediators
  - way to address the missing satellite 'problem'

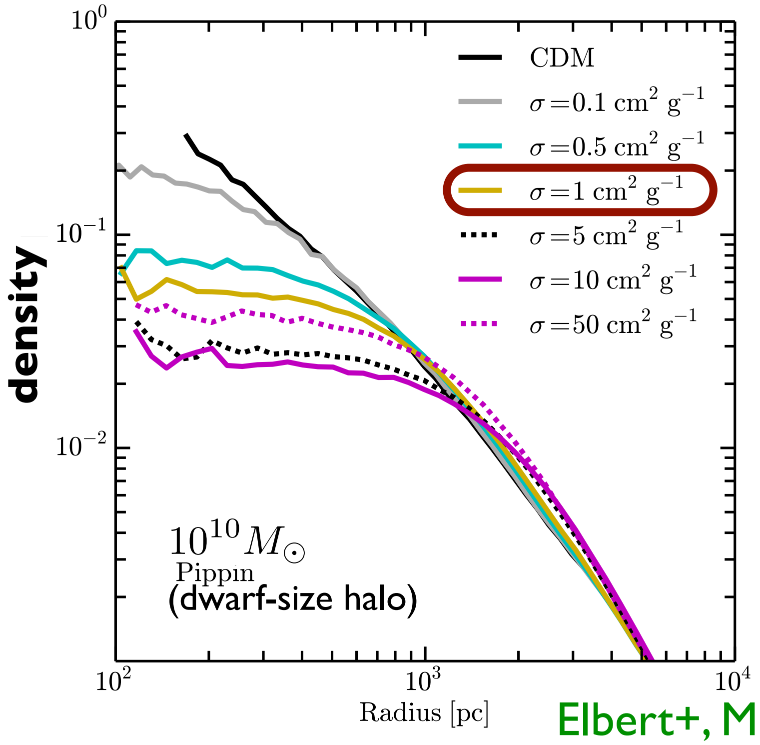
TB, Ihle, Kersten & Walia, PRD '16
[full simplified model classification]

Self-interacting DM (SIDM)

- DM-DM scatterings Spergel & Steinhardt, PRL '99
  - do not affect linear perturbations (number densities!)
  - but isotropise DM distribution in inner parts of halo:
    - ⇨ core formation once $\mathcal{O}(1)$ scatters per dynamical time



Vogelsberger, Zavala & Loeb, MNRAS '12



roughly
needed for
cusp/core

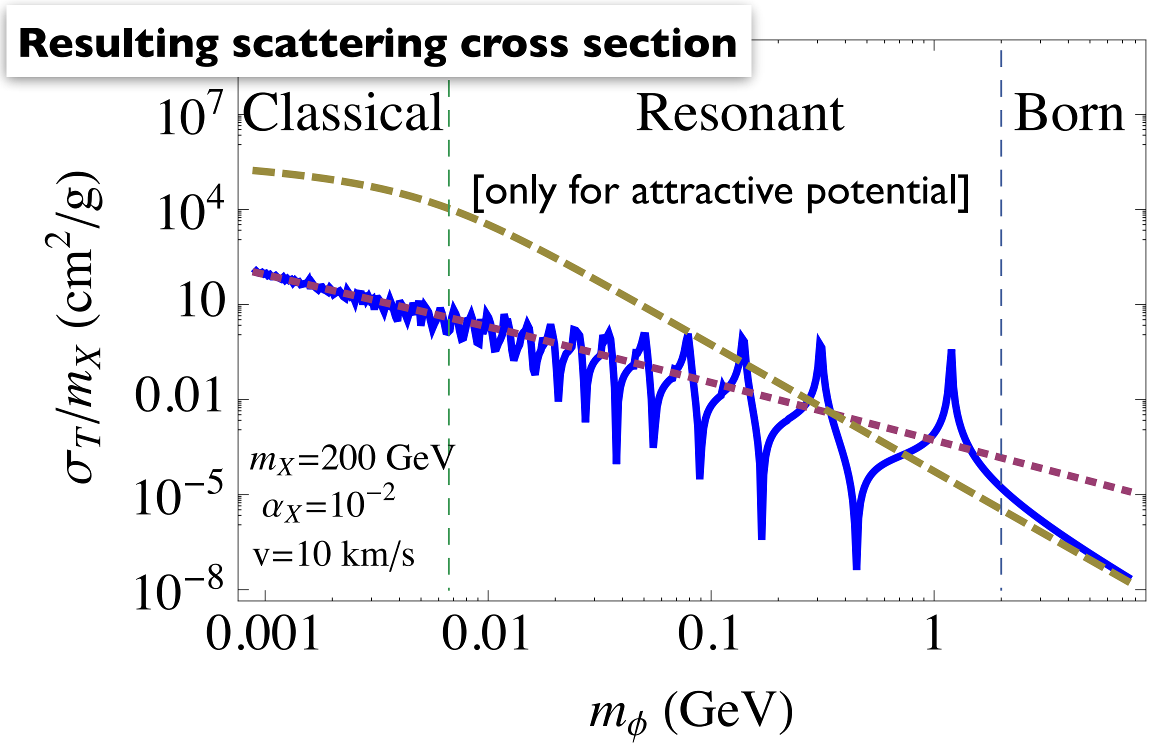
Elbert+, MNRAS '15

- Simple analytic models to predict core radius from $\sigma_{\rm SIDM}$
  - reproduce CDM simulation results for $\rho_\chi(r)$ remarkably well Kaplinghat, Tulin & Yu, PRL '15
  - but underlying (microphysics) assumptions not really satisfied Sokolenko+, JCAP '18
    - ⇨ *Use caution when applied to systems including baryons!* ⚠

Velocity dependence

- Massive mediators induce a Yukawa potential between DM particles.

$$\left(-\frac{\nabla^2}{m_\chi}+V\right)\psi(r)=m_\chi v^2\,\psi(r)$$

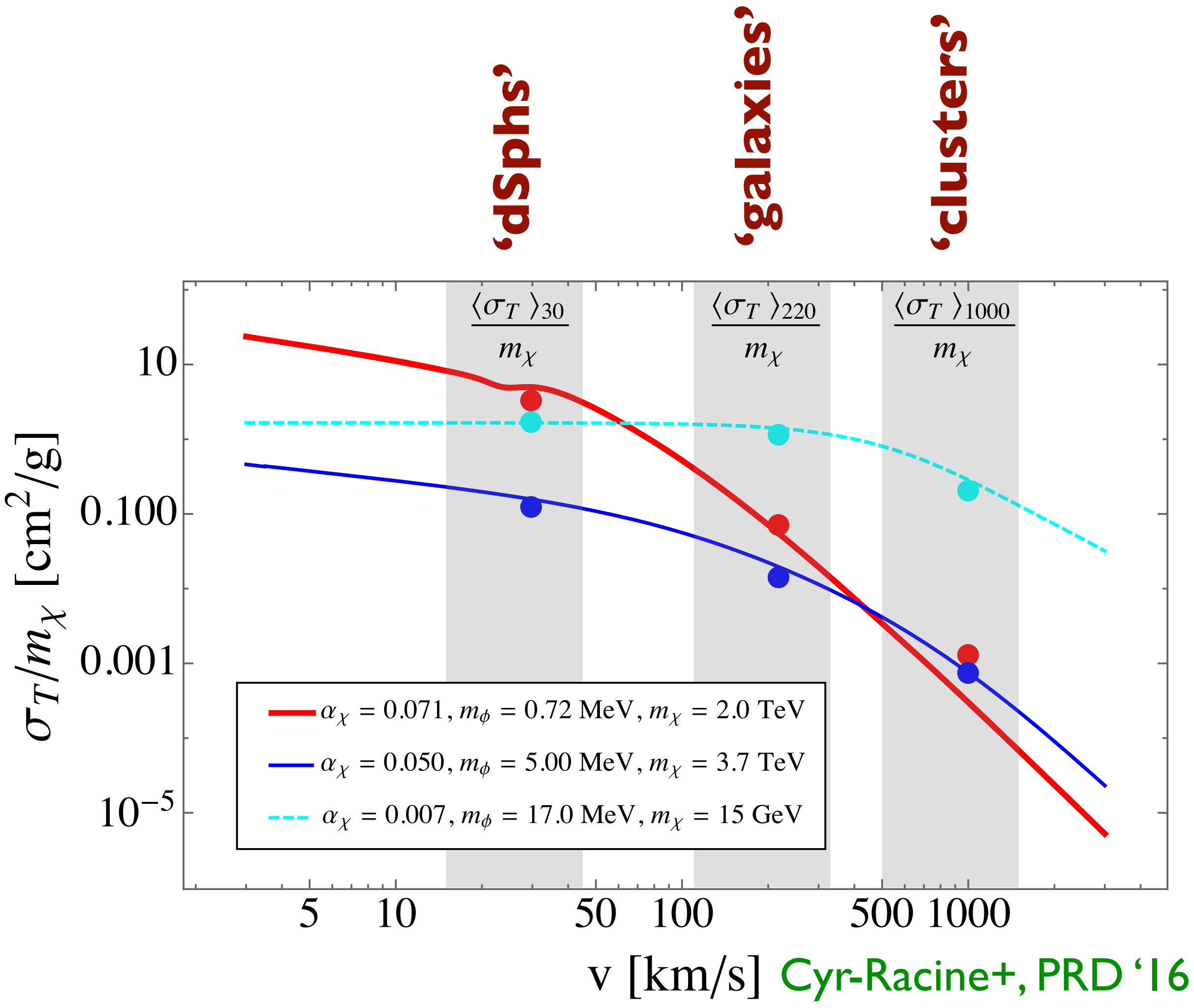

Resulting scattering cross section

$$\sigma_T \equiv \int d\Omega(1-\cos\theta)\frac{d\sigma}{d\Omega}$$

see e.g. Tulin, Yu & Zurek, PRD '13

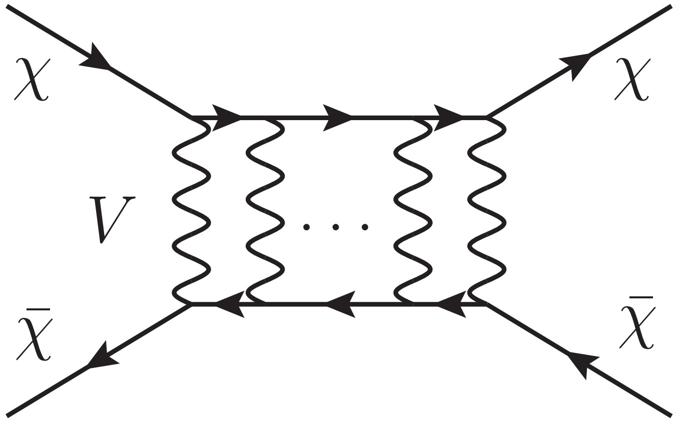
- Phenomenologically important: characteristic velocity dependence

[*not only for Yukawa potentials!* Chu, Garcia-Cely & Murayama, PRL '19]



Cyr-Racine+, PRD '16

Effective Theory of Structure Formation



particle model

input:
masses, spins,
coupling constants

task 1

cosmological simulations

input:
consistent initial conditions, non-gravitational forces between "particles"

task 2

astrophysical observables

input
(for interpretation of data):
output from simulations

- The first task can be demanding,
  the second in addition computationally very expensive
- But expect large degeneracies, so very inefficient…
- **Idea of ETHOS**: identify effective parameters and provide maps for each of those steps ($\rightsquigarrow$ no need to re-compute each model!)

Cyr-Racine+, PRD'16; Vogelsberger+, MNRAS '16

Details: Cyr-Racine+, PRD ‘16

Linear perturbations - setup

- Fundamentally, have to solve coupled Boltzmann equations:

$$\frac{df_\chi}{d\lambda} = C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_\chi, f_{\rm DR}], \qquad \frac{df_{\rm DR}}{d\lambda} = C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_{\rm DR}, f_\chi] + C_{\tilde{\gamma}\tilde{\gamma}\leftrightarrow\tilde{\gamma}\tilde{\gamma}}[f_{\rm DR}]$$

  - rewrite as differential equations for DM density, velocity and ‘temperature’:

$$\boxed{n_\chi} \equiv \eta_\chi \int \frac{d^3p}{(2\pi)^3} f_\chi(\mathbf{p}) \quad \boxed{\vec{v}_\chi} \equiv \frac{\eta_\chi}{n_\chi} \int \frac{d^3p}{(2\pi)^3} f_\chi(\mathbf{p}) \frac{p\,\hat{\mathbf{p}}}{E} \quad \boxed{T_\chi} \equiv \frac{\eta_\chi}{3n_\chi^{(0)}} \int \frac{d^3p}{(2\pi)^3} \frac{\mathbf{p}^2}{m_\chi} f_\chi^{(0)}(p)$$

  - keep terms up to first order in perturbations

- Take advantage of various simplifications
  - Neglect (subdominant) DR-DR iterations
  - Assume DR close to EQ: $f_{\rm DR}(\mathbf{x}, \mathbf{q}, \tau) = f_{\rm DR}^{(0)}(q, \tau)[1 + \Theta_{\rm DR}(\mathbf{x}, \mathbf{q}, \tau)]$
  - Momentum transfer in DM-DR scatterings must be small!

- Derive hierarchy of Boltzmann moments

$$\boxed{\mu \equiv \hat{q} \cdot \hat{k}}$$

  - Expand in Legendre polynomials: $\Theta_{\rm DR}(k, \hat{q}, q, \tau) = \sum_{l=0}^{\infty} (-i)^l (2l+1) F_l(k, q, \tau) P_l(\mu)$

$$\left(\frac{1}{\eta_\chi \eta_{\rm DR}} \sum_{\rm states} |\mathcal{M}|^2 \right) \Bigg|_{\substack{t = 2p_1^2(\tilde{\mu}-1) \\ s = m_\chi^2 + 2p_1 m_\chi}} = \sum_{n=0}^{\infty} (2n+1) A_n(p_1) P_n(\tilde{\mu})$$

  - Integrate BEs on both sides with $\frac{1}{2(-i)^l} \int_{-1}^{1} d\mu P_l(\mu)$

Linear perturbations - summary

- Summary (1st order equations):

DM:

$$\boxed{\begin{array}{c} \dot\delta_\chi + \theta_\chi - 3\dot\phi = 0, \\ \dot\theta_\chi - c_\chi^2 k^2\delta_\chi + \mathcal{H}\theta_\chi - k^2\psi = \dot\kappa_\chi\left[\theta_\chi - \theta_{\rm DR}\right] \end{array}}$$

Only way that (non-gravitational) DM physics enters !

'ETHOS'

$\delta \equiv (\rho - \bar\rho)/\bar\rho$

$\theta_j \equiv i\,\mathbf{k}\cdot\mathbf{v}_j$

$\phi, \psi :$ metric perturb. in conformal Newtonian gauge

DR:

$$\boxed{\dot\Pi_{{\rm DR},l} + \frac{k}{2l+1}\left((l+1)\Pi_{{\rm DR},l+1} - l\Pi_{{\rm DR},l-1}\right) = (\alpha_l \underbrace{\dot\kappa_{\rm DR-DM}}_{\sim\,\kappa_\chi} + \beta_l \underbrace{\dot\kappa_{\rm DR-DR}}_{\sim\,0})\ \Pi_{{\rm DR},l}}$$

$$\Pi_{{\rm DR},l}(k,\tau) = \frac{\int dq\, q^3 f^{(0)}_{\rm DR}(q,\tau) F_l(k,q,\tau)}{\int dq\, q^3 f^{(0)}_{\rm DR}(q,\tau)}$$

$\delta \sim \Pi_0 \qquad \theta \sim \Pi_1$

- Step-by-step procedure:
  - calculate κ, α_l from $A_l(p) = \frac{1}{2}\int_{-1}^{1} d\tilde\mu\, P_l(\tilde\mu)\left(\frac{1}{\eta_\chi\eta_{\rm DR}}\sum_{\rm states}|\mathcal{M}|^2\right)\Bigg|_{\substack{t=2p^2(\tilde\mu-1)\\ s=m_\chi^2+2pm_\chi}}$ **Details**: Cyr-Racine+, PRD '16
  - calculate $c_\chi^2 = \frac{T_\chi}{m_\chi}\left(1 - \frac{\dot T_\chi}{3\mathcal{H}T_\chi}\right)$ from $\frac{dT_\chi}{d\tau} = -2\mathcal{H}T_\chi + \Gamma_{\rm heat}(T_{\rm DR})\,(T_{\rm DR} - T_\chi)$ **Details**: TB, NJP '09, TB+, PRD '16

    aka **'momentum exchange rate'** γ

Linear perturbations - results

- ETHOS comes with a dedicated Boltzmann solver:

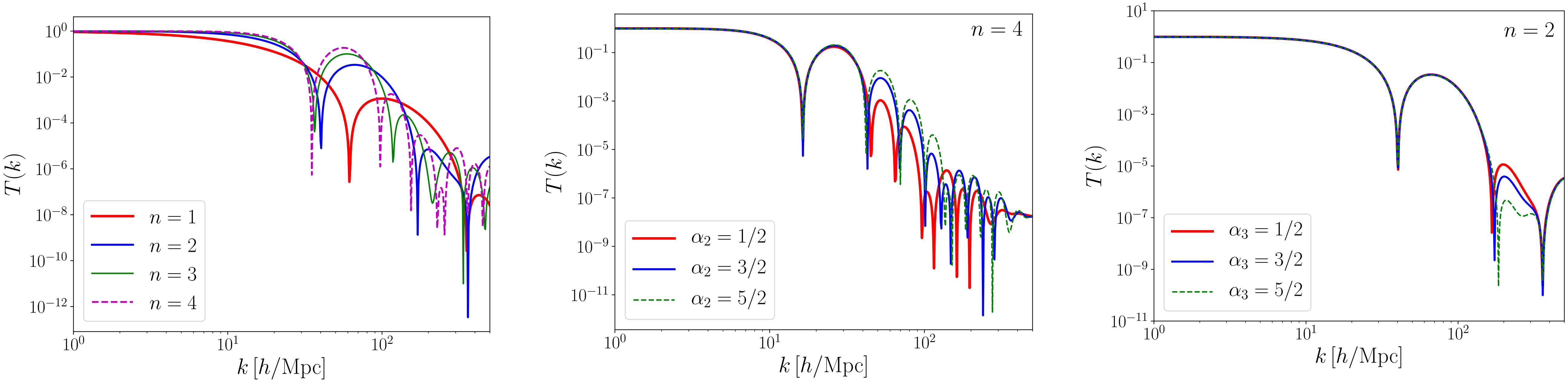
  https://bitbucket.org/franyancr/ethos_camb

  - modified version of CAMB Lewis & Bridle, PRD ‘02
  - Actual implementation based on phenomenological power-law ansatzes:

$$\kappa \sim \sum_n a_n \left(\frac{1+z}{1+z_\mathrm{D}}\right)^n \qquad \Gamma_\mathrm{heat} \sim \sum_n d_n \frac{(1+z)^{n+1}}{(1+z_\mathrm{D})^n} \qquad \text{etc}$$

  - detailed examples for calculating a_n, d_n from given model $\left(|\mathcal{M}|^2\right)$ Cyr-Racine+, PRD ‘16 TB+, PRD ‘16

- Example spectra:



⇨ ‘Dark acoustic oscillations’

(Physics very similar to CMB photons scattering on electrons around decoupling!)

Implementation

- Translate power spectrum to initial particle distribution
  - use MUSIC code Hahn & Abel, MNRAS '11 [see also Dolag+, '08]
- Probabilistic method to account for elastic scattering

Vogelsberger, Zavala & Loeb, MNRAS '12

  - isotropic scattering of macroscopic 'particles' with mass m_i

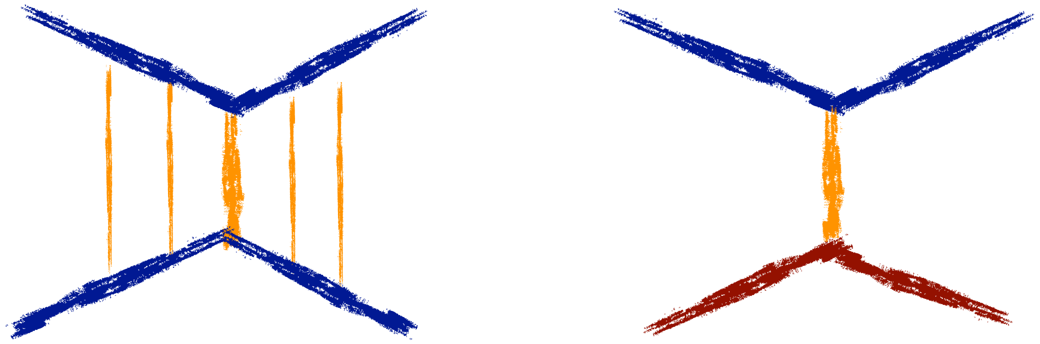
$$P_{ij} = \frac{m_i}{m_\chi} W(r_{ij}, h_i)\, \sigma_{\mathrm{T}}(v_{ij}) v_{ij}\, \Delta t_i$$

smoothing function to weight nearest neighbour highest

- Cosmological simulation with $m_i \sim 10^8 M_\odot$ $(\epsilon \sim 3\,\mathrm{kpc})$, zoom-in of MW-like halos down to $m_i \sim 3 \times 10^4 M_\odot$ $(\epsilon \sim 70\,\mathrm{pc})$

- First ETHOS example:
  - TeV-scale DM particle
  - MeV-scale vector mediator
  - massless (sterile) neutrino-like fermion

van den Aarssen, TB & Pfrommer, PRL '12
TB, Hasenkamp & Kersten, JCAP '14



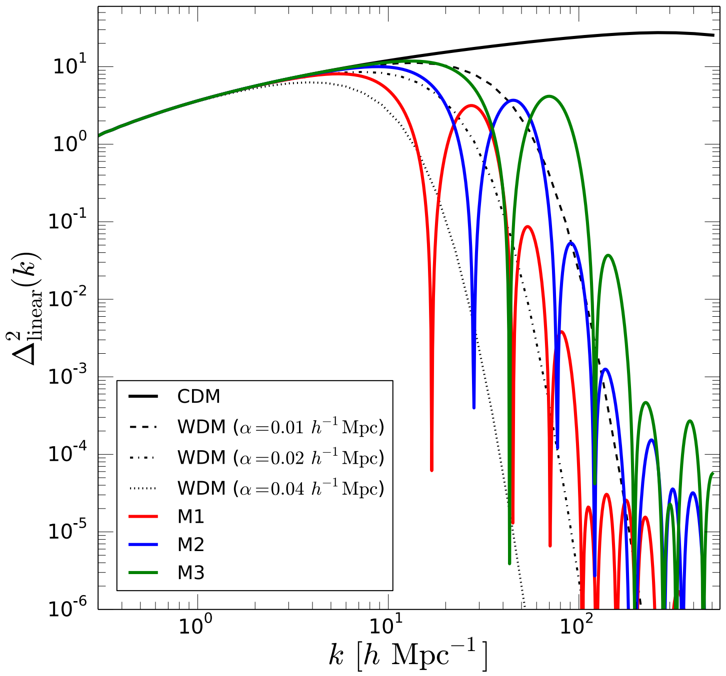
$$\{m_\chi, m_\phi, g_\chi, g_\nu, \eta_\chi, \eta_\nu, \xi\}$$

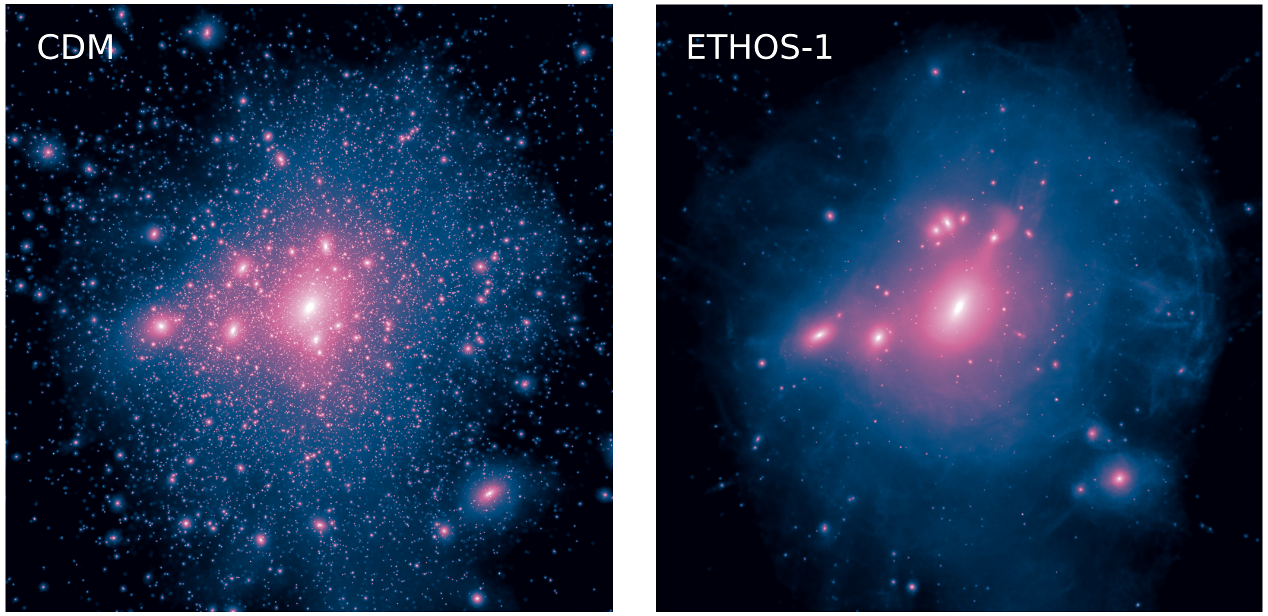
task I

$$\left\{\omega_{\mathrm{DR}}, a_4, \alpha_{l\geq 2} = \frac{3}{2}, \frac{\langle\sigma_T\rangle_{30}}{m_\chi}, \frac{\langle\sigma_T\rangle_{220}}{m_\chi}, \frac{\langle\sigma_T\rangle_{1000}}{m_\chi}\right\}$$

Late kinetic decoupling

- Select four benchmarks: Vogelsberger+, MNRAS'16





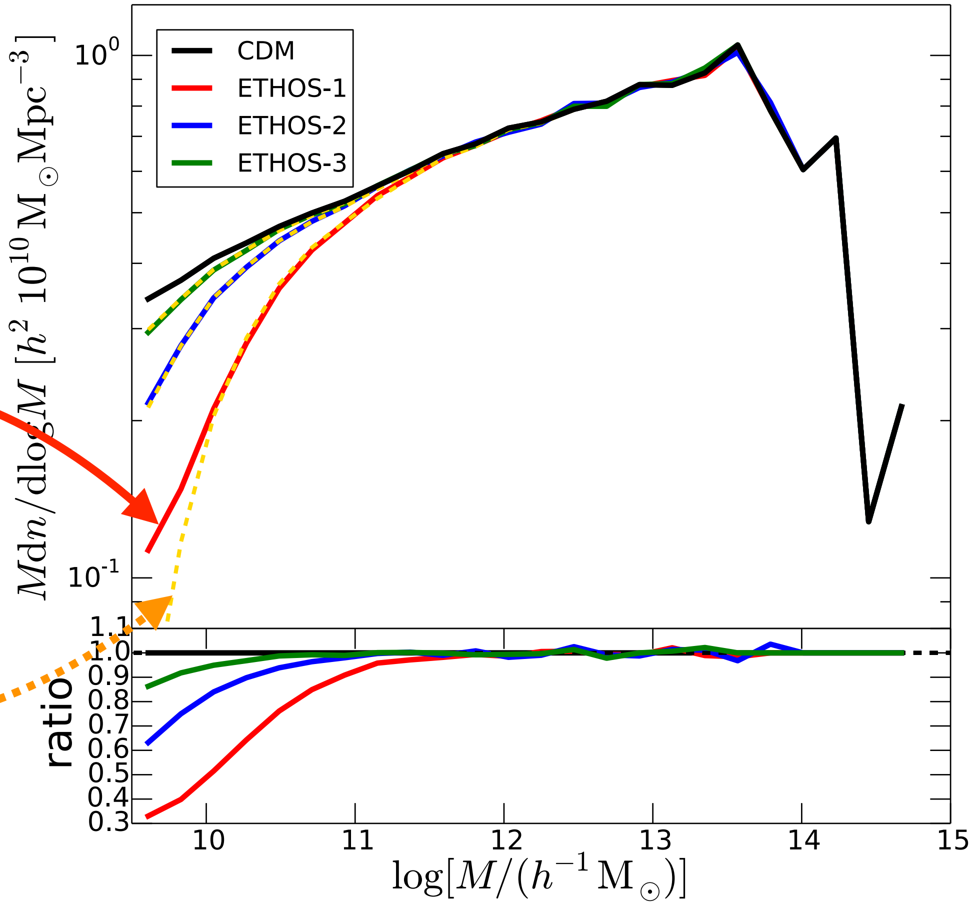
- Almost identical suppression of halo mass function as for WDM cosmology:

$$M_{\rm cut,kd} = 5\cdot 10^{10}\left(\frac{T_{\rm kd}}{100\,{\rm eV}}\right)^{-3} h^{-1}\,M_\odot$$

[solid lines; NB: up to factor ~2 same as analytic estimate!**]**

$$M_{\rm cut,WDM} = 10^{11}\left(\frac{m_{\rm WDM}}{\rm keV}\right)^{-4} h^{-1}\,M_\odot$$

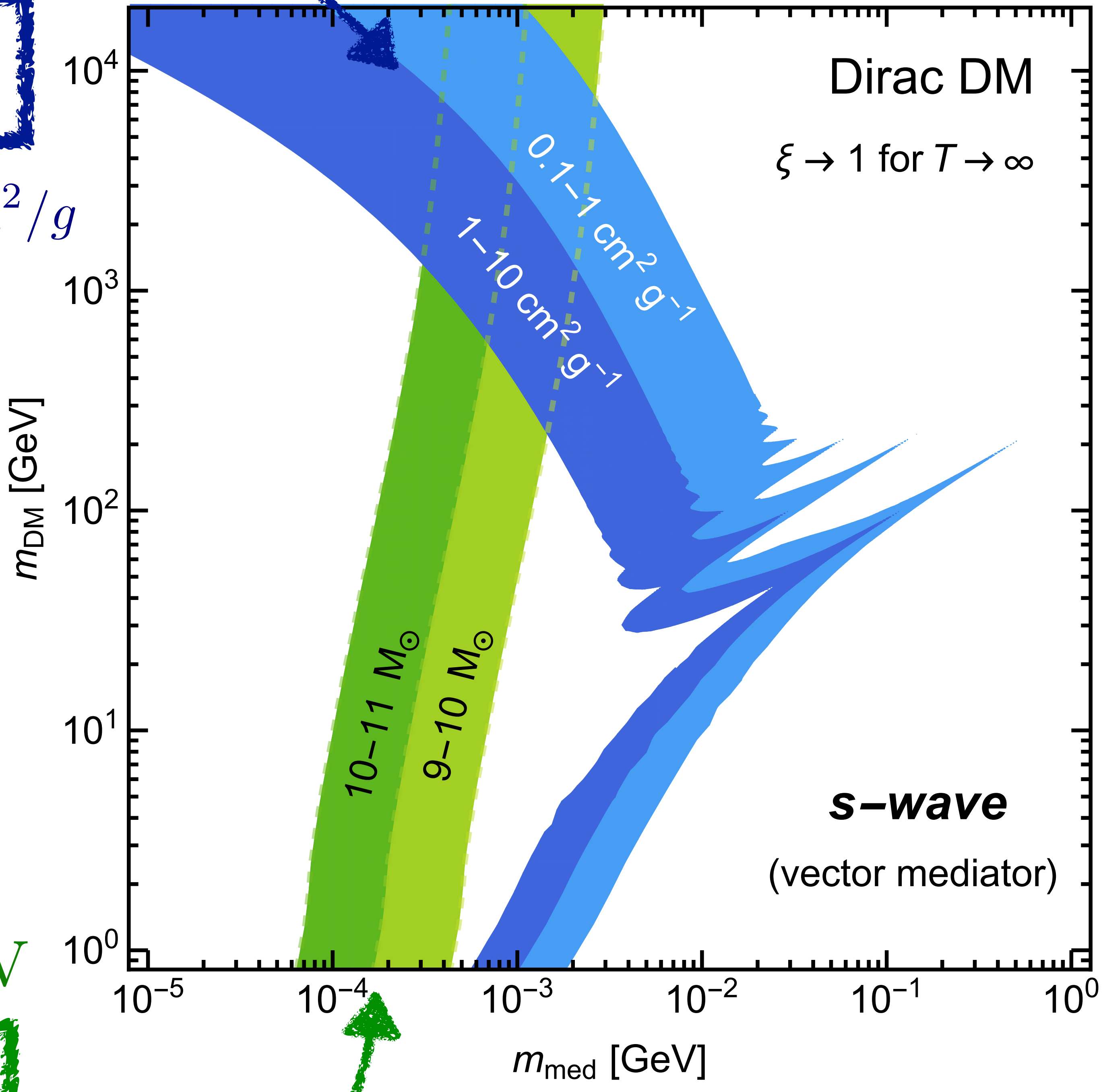
[dashed lines; would-be result from WDM free-streaming**]**



Full parameter scan

affect core/ cusp + TBTF

$\langle\sigma_T\rangle/m_\chi \sim 1\,\mathrm{cm}^2/g$

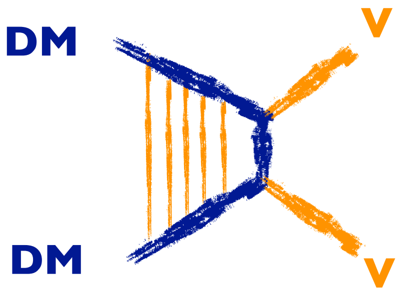


TB, Edsjö, Gondolo, Ullio & Bergström, JCAP '18

- NEW since v6.1:
  - SIDM
  - Sommerfeld
  - handle varying

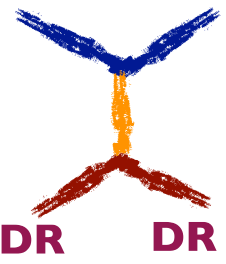
$\xi \equiv T_{\rm dark}/T_{\rm photon}$

coupling fixed by thermal relic density



$T_{\rm kd} \sim 0.1\,\mathrm{keV}$

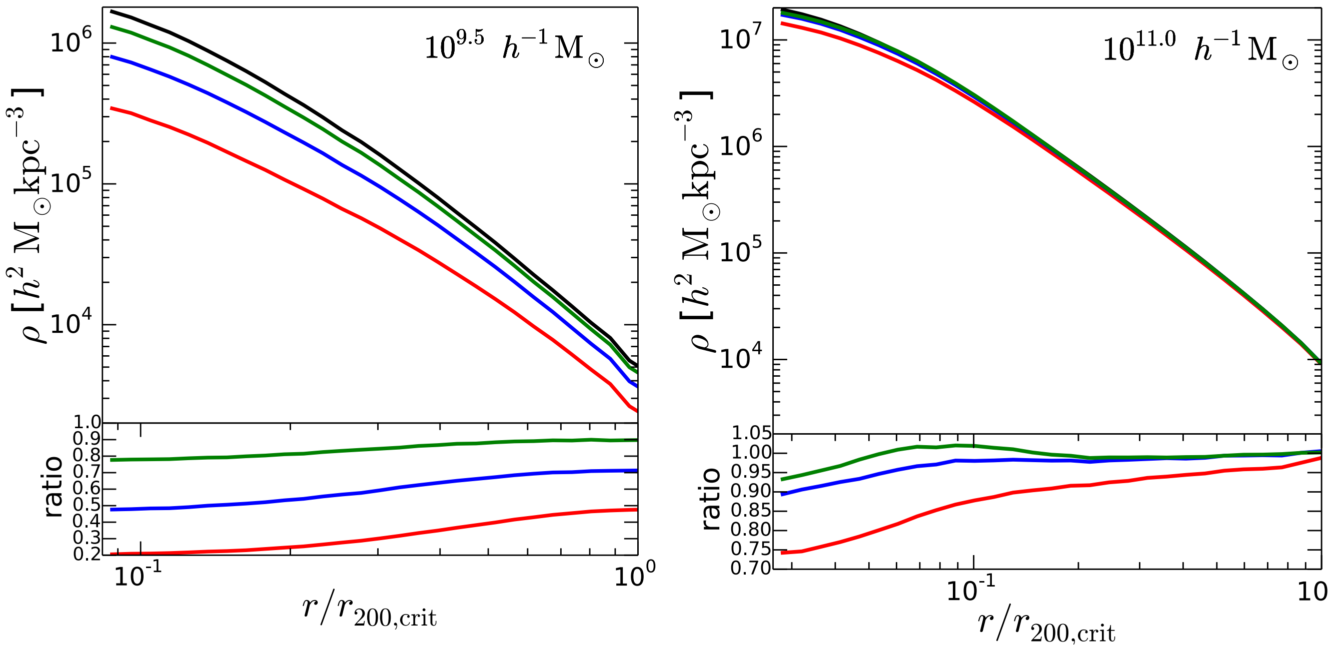
address missing satellites ?



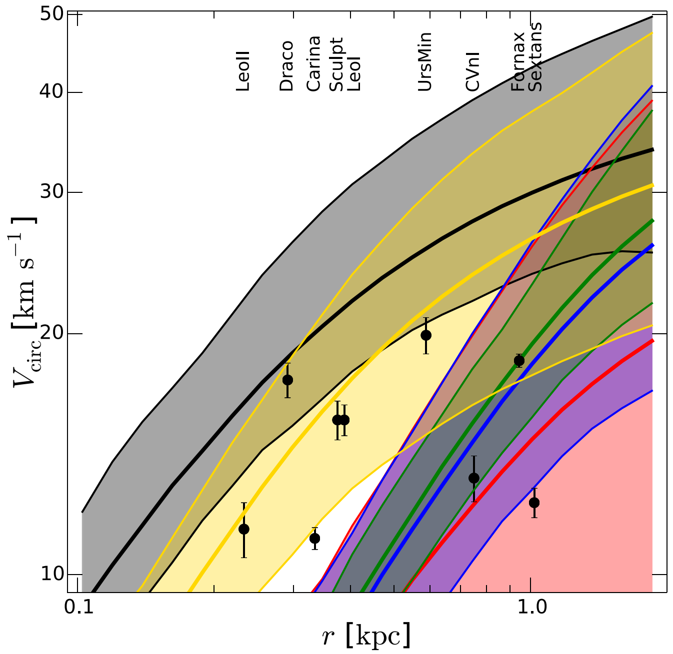
Inner halo structure

Vogelsberger+, MNRAS'16

- Closer look: can indeed address CDM abundance and structural 'problems' simultaneously, in a consistent particle framework:



central (sub)halo densities reduced
(→ core/cusp)



most massive subhalos less dense
(→ too-big-to-fail)

- NB: Non-trivial interplay between modified power spectrum and self-interactions

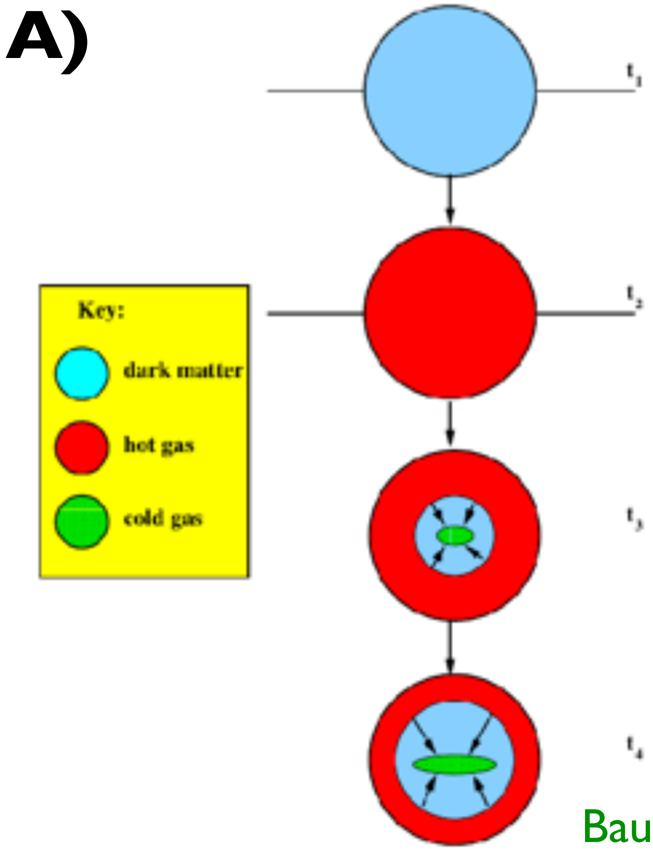
  ➡ *Details more complicated than the usual 'need ~1 cm²/g' !*

- Also, this is still without baryonic physics…
  [though dSphs highly DM dominated]

Adding Baryons

- Simplest picture: two competing effects

A)

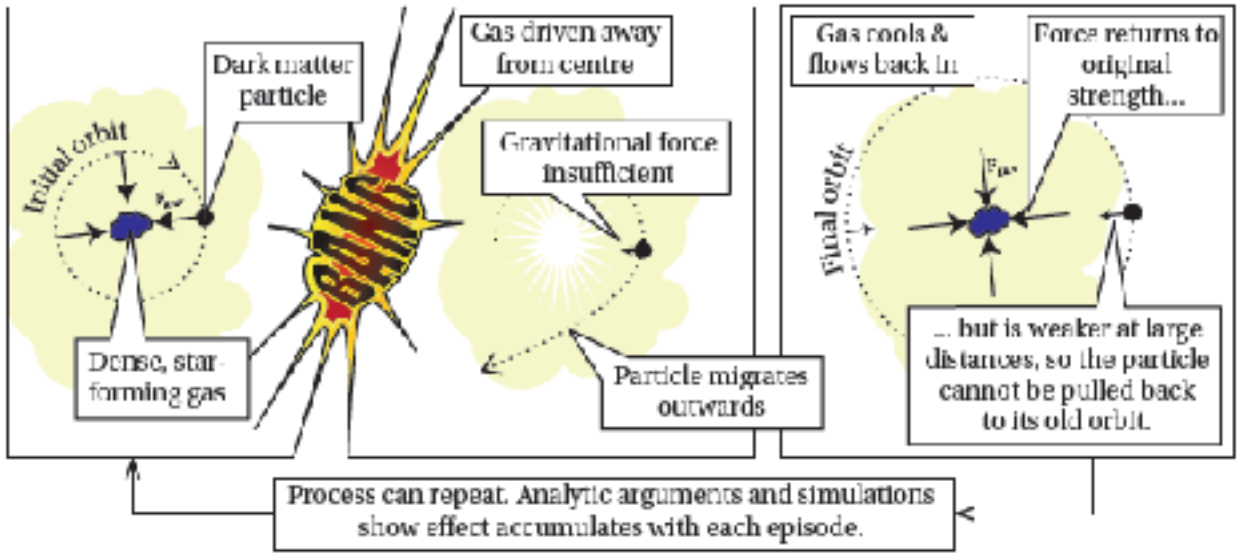


Baugh, RPP '06

Adiabatic contraction due to disk assembly

increase
of inner DM density

B)



Pontzen & Governato, Nature '14

gas and DM heating due to supernova feedback

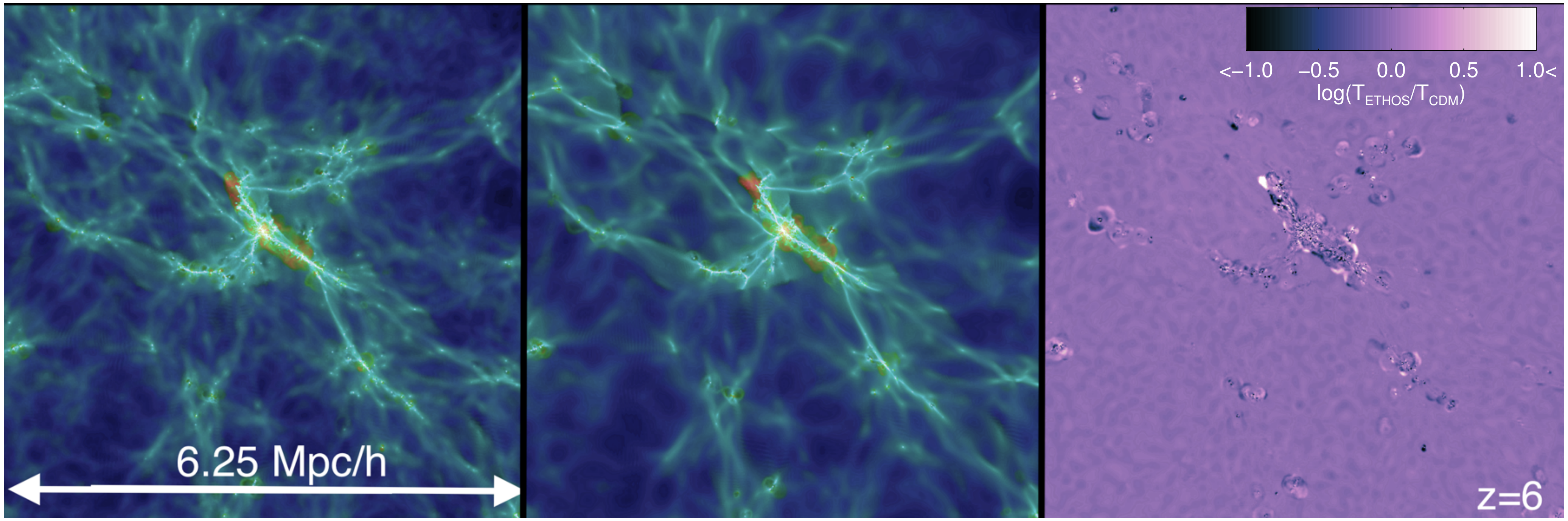
decrease
of inner DM density

- SIDM + A) may lead to core collapse Elbert+, ApJ '18

  ⇝ *A way to address the diversity problem?* Creasey+, MNRAS '17
  Kamada+, PRL '17
  …

Re-ionization history

- Lack of small halos should delay onset of structure formation



IGM gas temperature

Lovell+, MNRAS '18

- Hydrodynamical simulations: Indeed — but effect on reionisation history is surprisingly small **[similar to WDM!]**
  - Suppression of high-z, low-mass galaxies: maybe visible with JWST
  - Brighter starbursts in these galaxies compensate effect on optical depth

- Follow-up: halo collapse comparison on individual basis
  - Virial masses of ETHOS halos are suppressed, but not stellar mass
  - Promising way to test/constrain ETHOS: large populations of very old stars $(z > 17)$

Lovell, Vogelsberger & Zavala, MNRAS '19

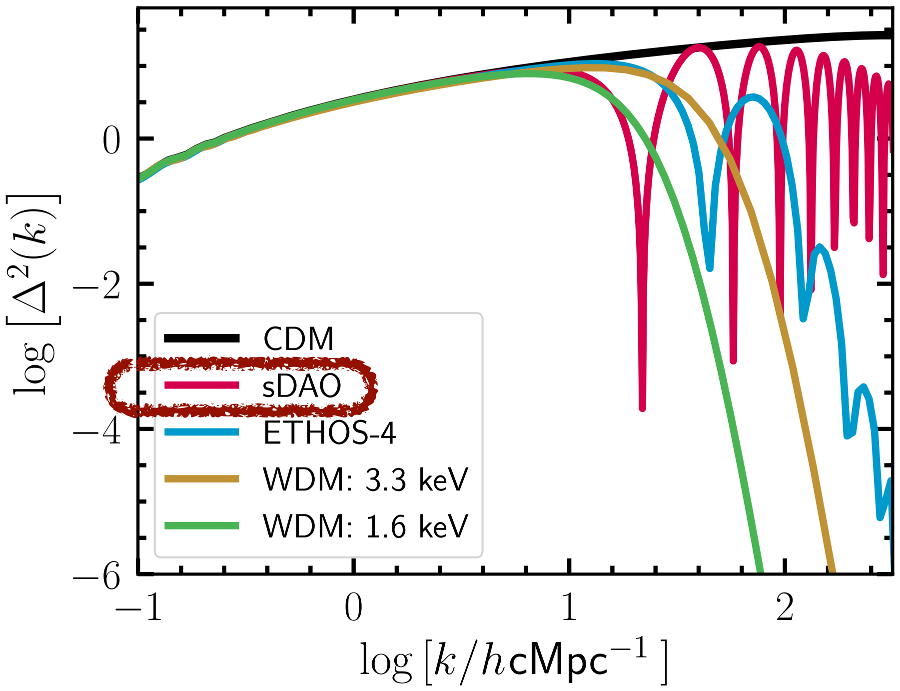
Imprint on Lyman alpha spectra ?

- Need strong features in linear $\Delta^2(k)$ to survive in non-linear regime
  - use atomic DM benchmark (sDAO)

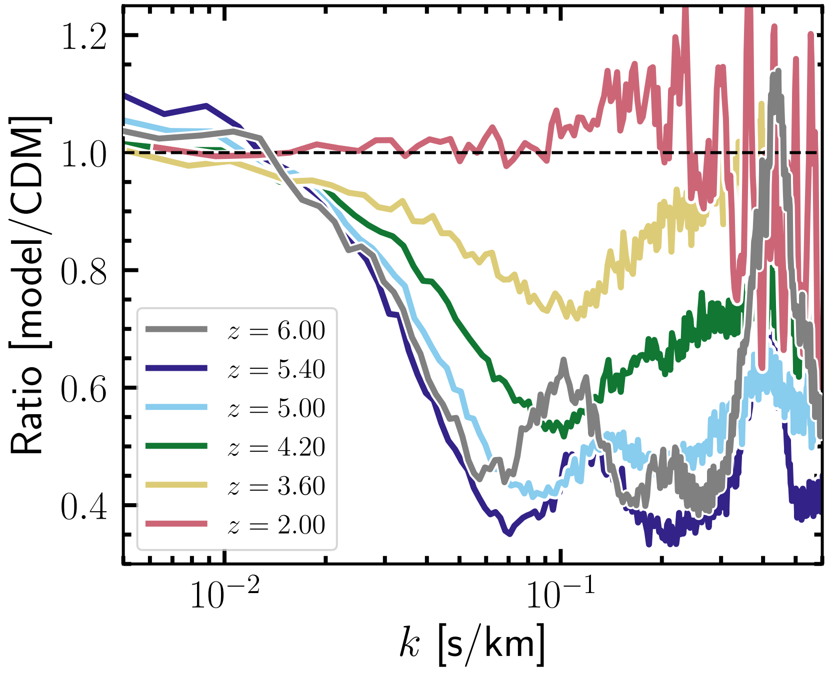
    Kaplan+, JCAP '10
    Cyr-Racine & Sigurdson, PRD '13
  - galaxy formation model as in IllustrisTNG

    Marinacci+, MNRAS '18; …

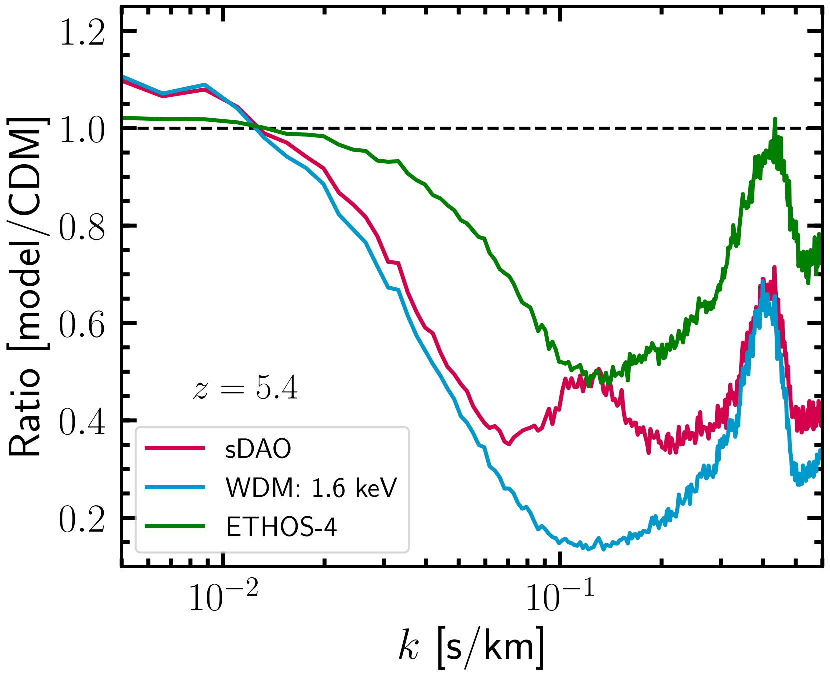
Bose+, MNRAS '19



- DAO bump visible in 1D Ly-α flux spectra only for $z \gtrsim 5$



NB: bump at ~0.4 s/km set by numerical resolution!



⇨ *In principle, this allows to disentangle WDM from sDAO!*

Outline

- Introduction
  - Evidence
  - Candidates & Tools
- [Collider searches]
- Direct searches
  - ‘reverse’ direct detection
- Indirect searches
  - Gamma rays
  - Charged cosmic rays
- Other astrophysical probes
  - The matter power spectrum
  - Self-interacting dark matter
  - ETHOS
- Complementarity
  - Example: Light scalar mediators

Light DM with portal couplings

- Light DM evades DD constraints
  - need light mediators to evade (EFT-type) collider constraints
  - Light DM annihilation to even lighter vector mediators *generically* completely ruled out by CMB

Ade+, AA '16
TB, Kahlhoefer, Schmidt-Hoberg & Walia, PRL '17

- Annihilation to scalar mediators is *p*-wave
  - no CMB limits

- Simplest model consistent with all SM symmetries:

$$\boxed{\mathcal{L}_{S/\chi} = \frac{1}{2}\partial_\mu S \partial^\mu S + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - g_\chi S \bar{\chi}\chi - V(S,H)}$$

$$V(S,H) = \left(A_{hs}S + \lambda_{hs}S^2\right) H^\dagger H + \mu_h^2 H^\dagger H + \lambda_h (H^\dagger H)^2 + V(S)$$

DM + particle (accelerator) pheno

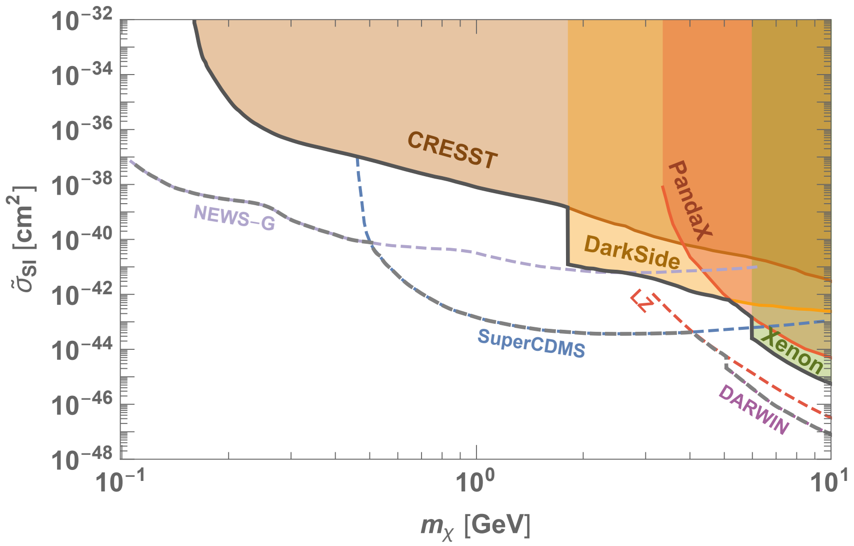
$$\Rightarrow \boxed{\mathcal{L} \supset -\sin\theta \frac{m_f}{v} S \bar{f} f - \sin\theta g_\chi h \bar{\chi}\chi}$$

→ **invisible Higgs width**

Constraints

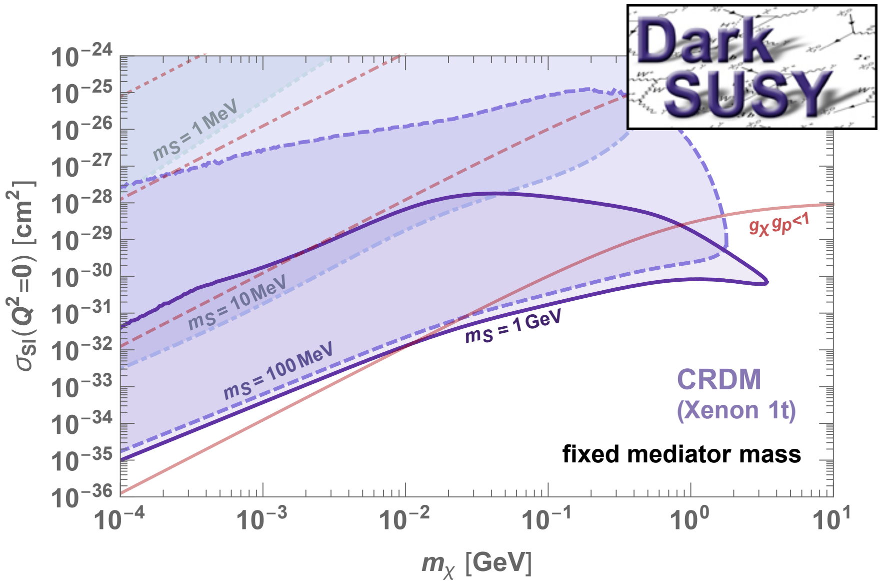
Bondarenko, Boyarsky, TB, Hufnagel, Schmidt-Hoberg & Sokolenko, 1909.08632

- Direct detection

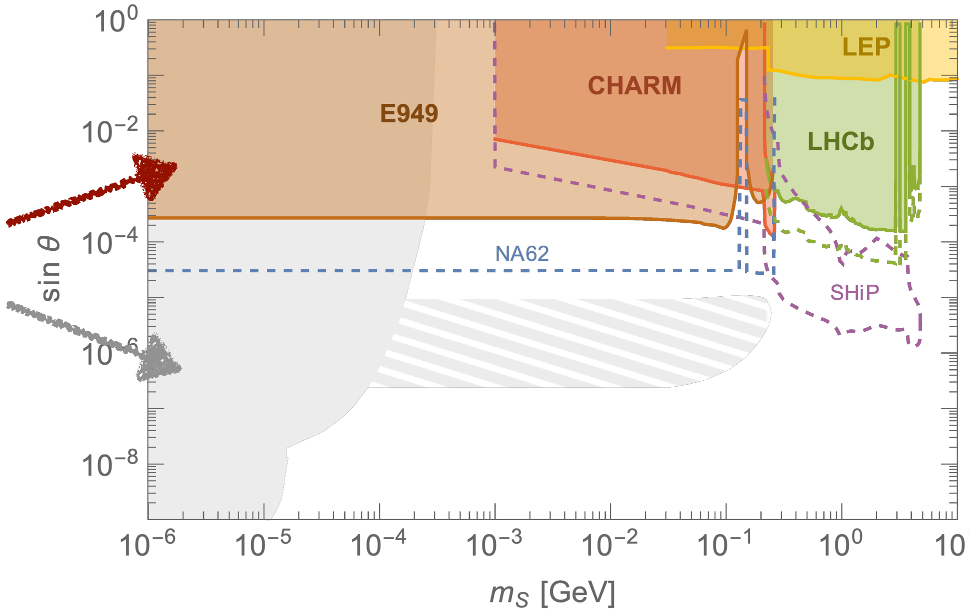


Q²-dependent scattering

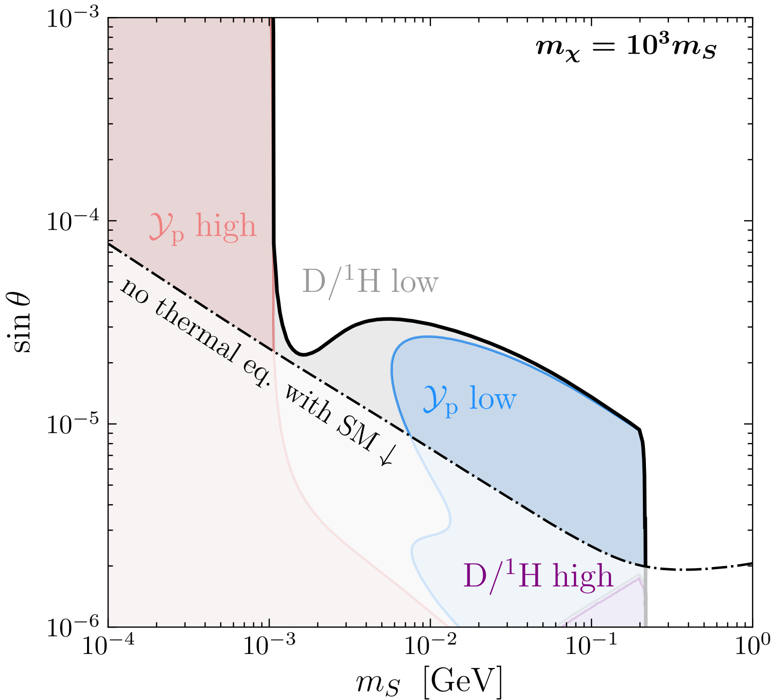
- rescale standard limits!
- new code for CRDM absorption



- Bounds on $\sin\theta$
  - accelerator searches
  - energy loss in stars/SN



- Invisible *h* decay
- Cosmology
  - follow $T_\chi(T_\gamma)$ after decoupling of sectors
  - run dedicated BBN code
  - SIDM beyond *s*-wave (anti-resonances!)

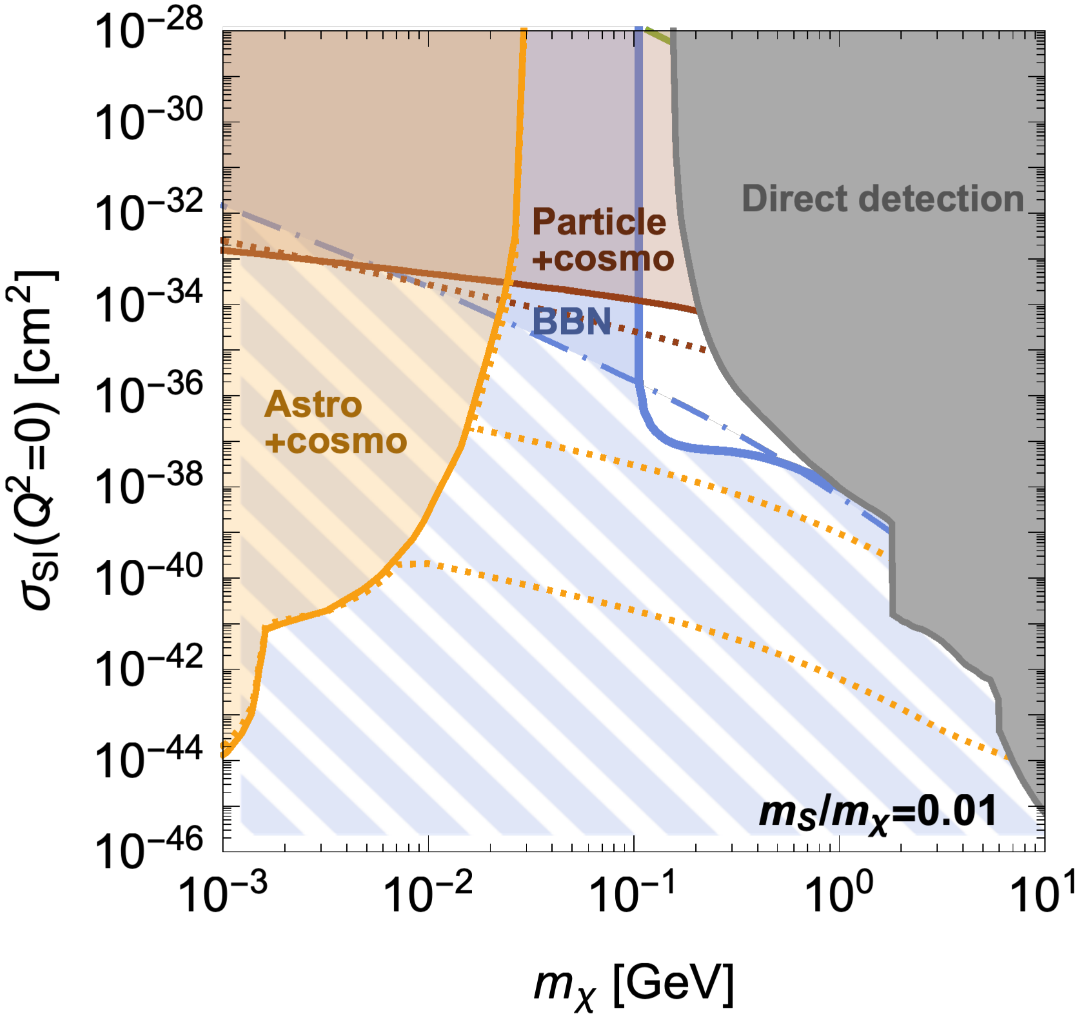


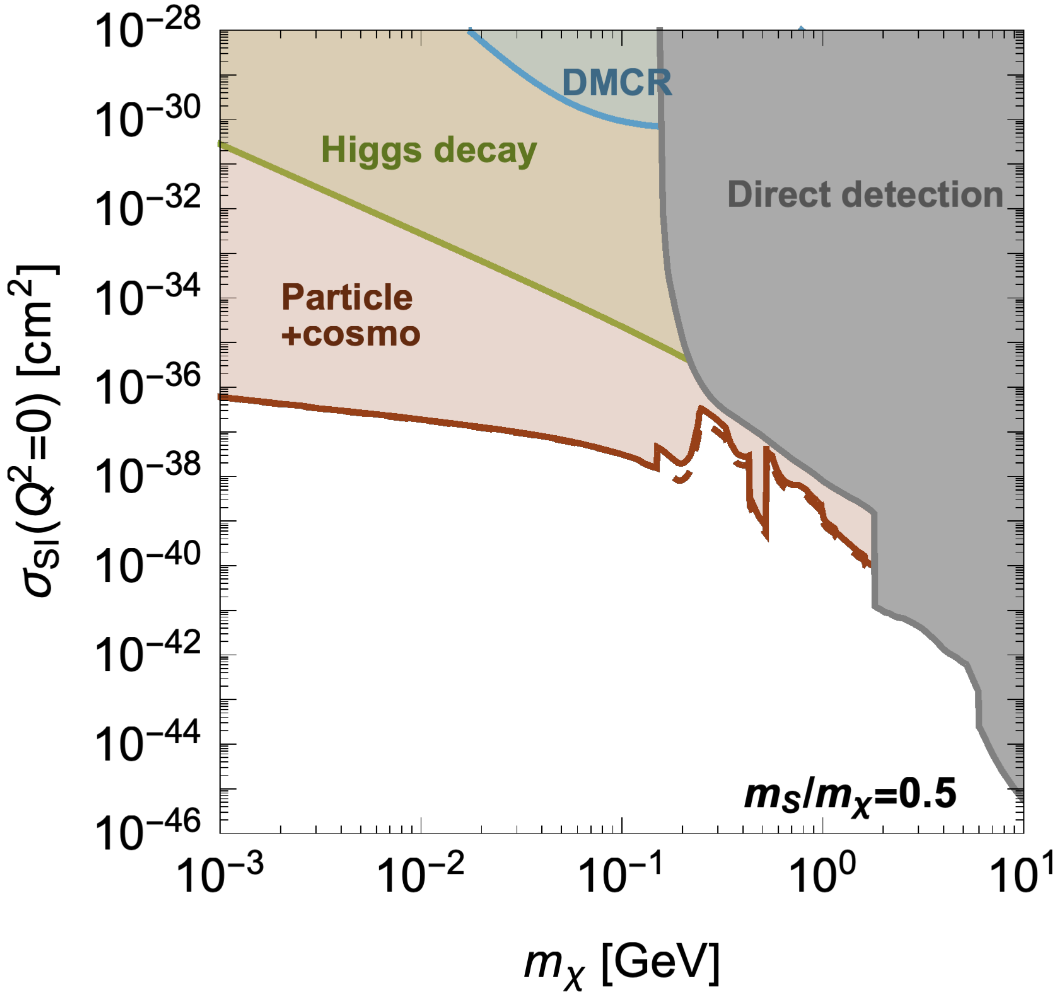
Need to go beyond 'vanilla constraints':
Model-specific details, fully consistent cosmology!

Results

Bondarenko, Boyarsky, TB, Hufnagel, Schmidt-Hoberg & Sokolenko, 1909.08632

- Need cosmology to translate particle limits to DD plane!
  - relic density *optionally* included
  - SIDM *alone* typically gives comparable constraints





Complementarity clearly visible this way.

Helps to prioritise design of novel DD experiments…?

Conclusions

- Impossible to find DM without first installing DarkSUSY ;)
- The cosmos *might* be the only laboratory to test the *particle* DM hypothesis

  (though of course it would be *nicer* to detect DM in multiple experiments)
- We have not yet detected DM, other than gravitationally
- The field is at the crossroad — which implies interesting times ahead!

Decreasing level of personal bias

Thanks for your attention!