GSSI Seminar
L'Aquila, 6 March 2019

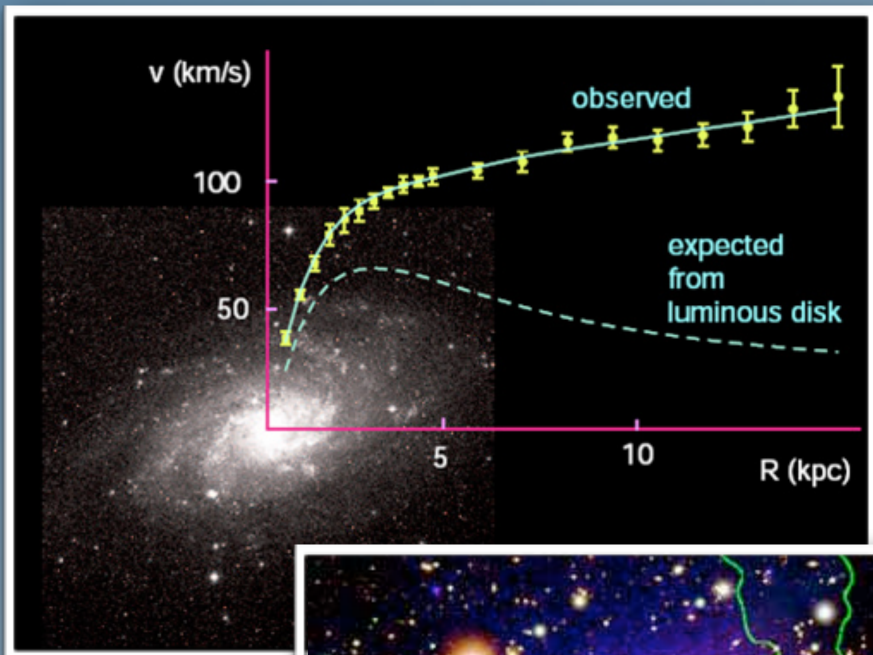
Searching for sub-GeV dark matter in current underground laboratories

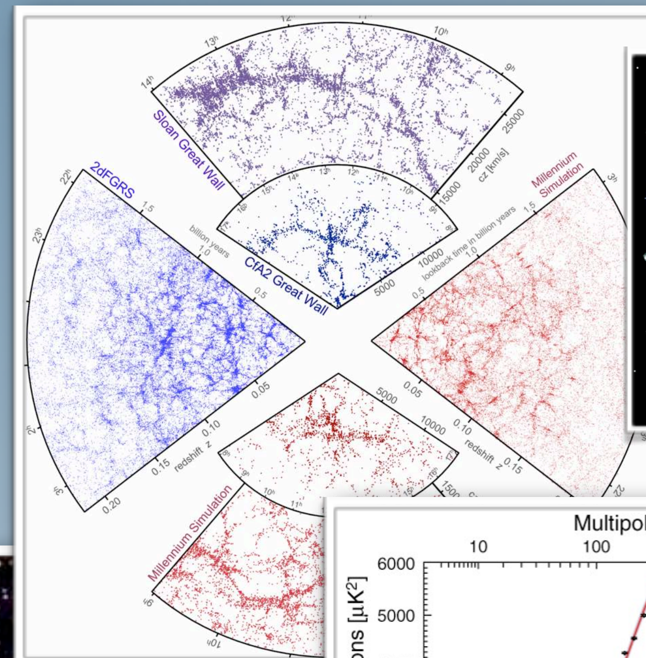
(Mostly) based on: TB & Pospelov, 1810.10543

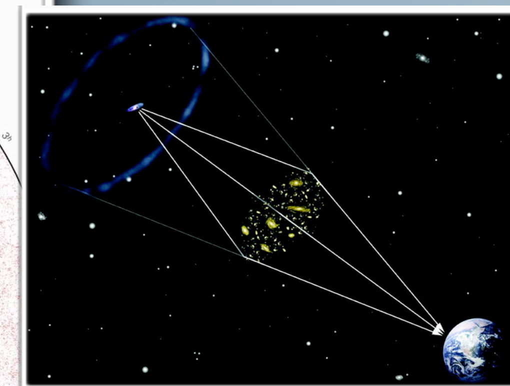
Torsten Bringmann

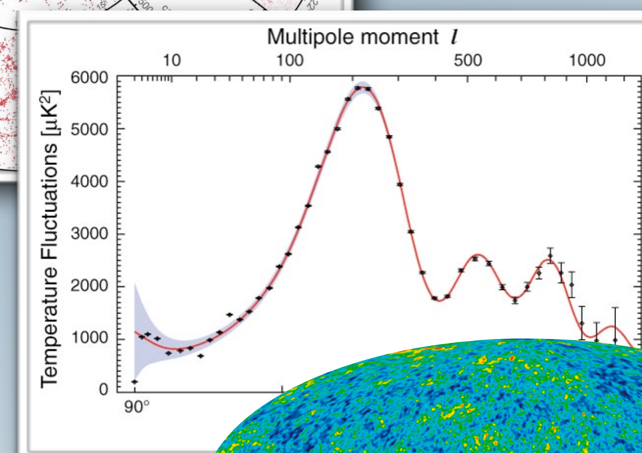
UiO : University of Oslo

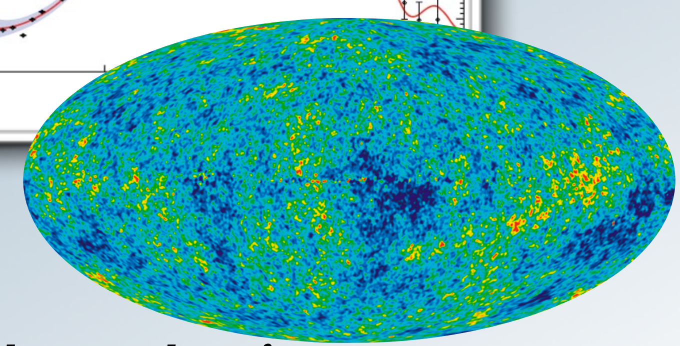
Dark matter all around











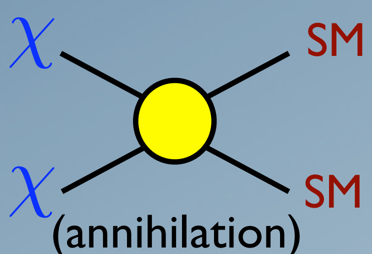
➩ *overwhelming evidence on all scales!*

Candidates?

→ strong evidence for… modified gravity

BSM physics
⇝ many good(!) options

- WIMP "miracle"

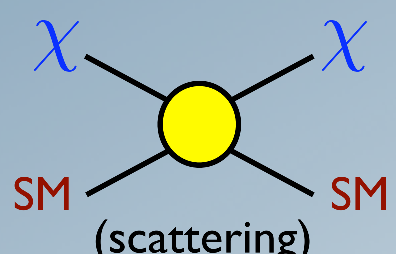


→ $T_{\rm cd} \sim m_\chi/25$
chemical decoupling
("freeze-out")
→ Ω_χ

relic density

~observed RD for weak-scale interactions

- Freeze-out ≠ decoupling



→ $T_{\rm kd} \sim m_\chi/(10^2..10^5)$
kinetic decoupling
→ $M_{\rm cut}$

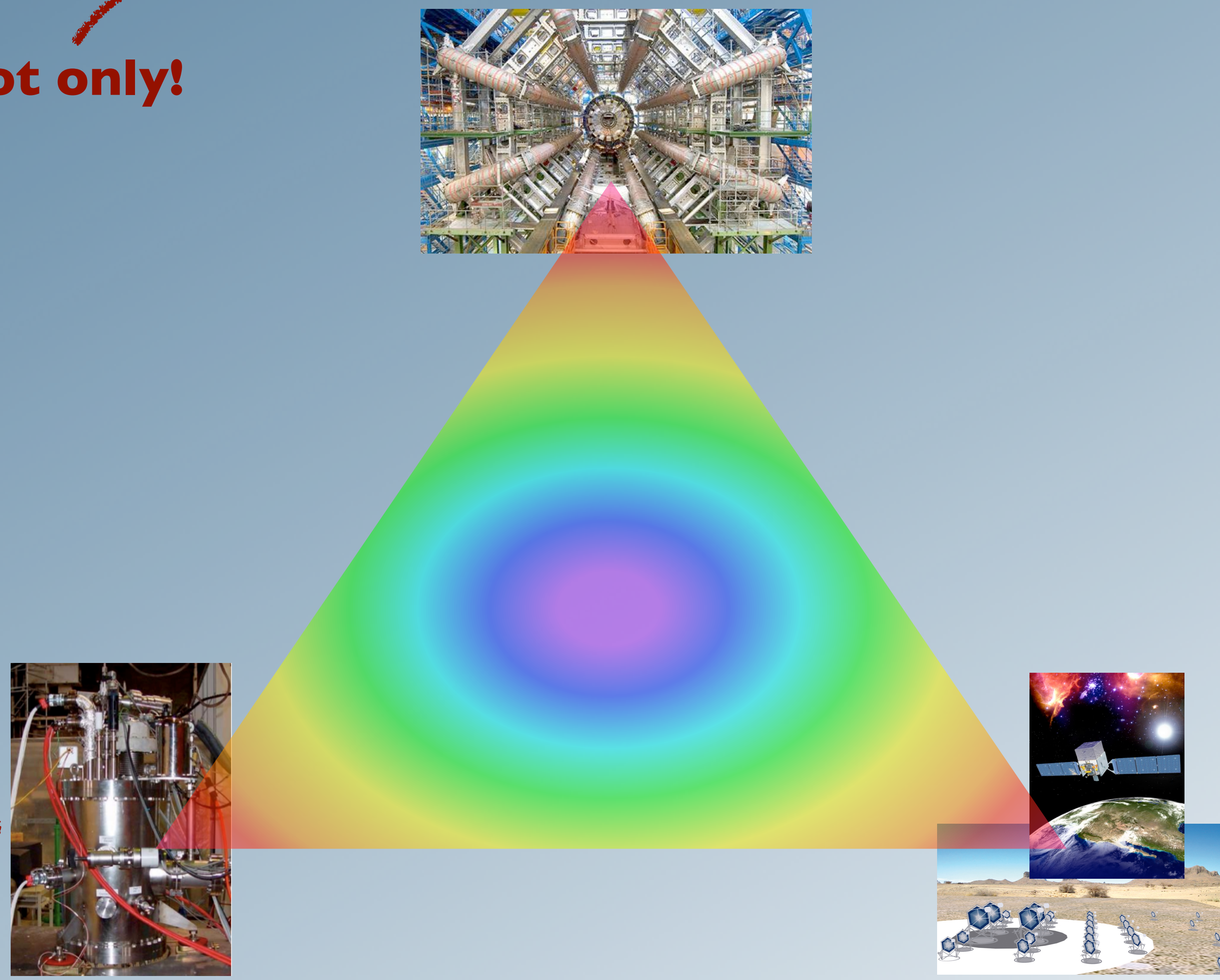
strongly model-dependent!

~size of smallest subhalos

review: TB, NJP '09

Strategies for WIMP DM searches

not only!



DarkSUSY

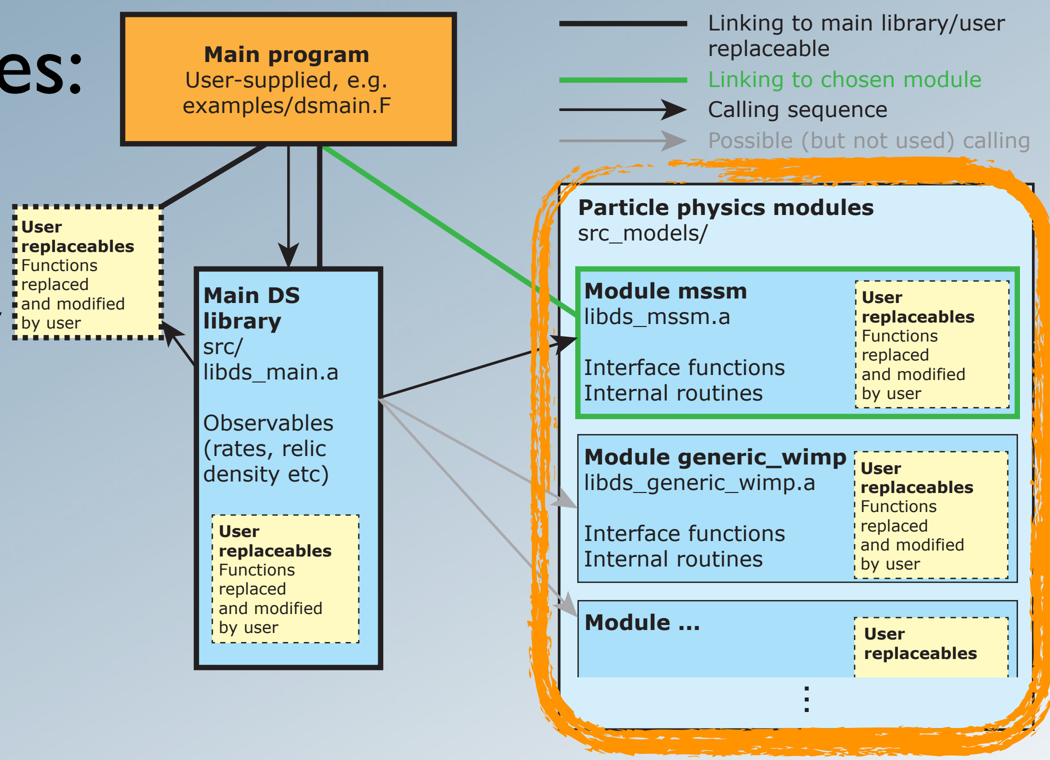
FREE DOWNLOAD ;)

TB, Edsjö, Gondolo, Ullio & Bergström, 1802.03399 (JCAP)

http://darksusy.org

Significantly revised version 6 last year!

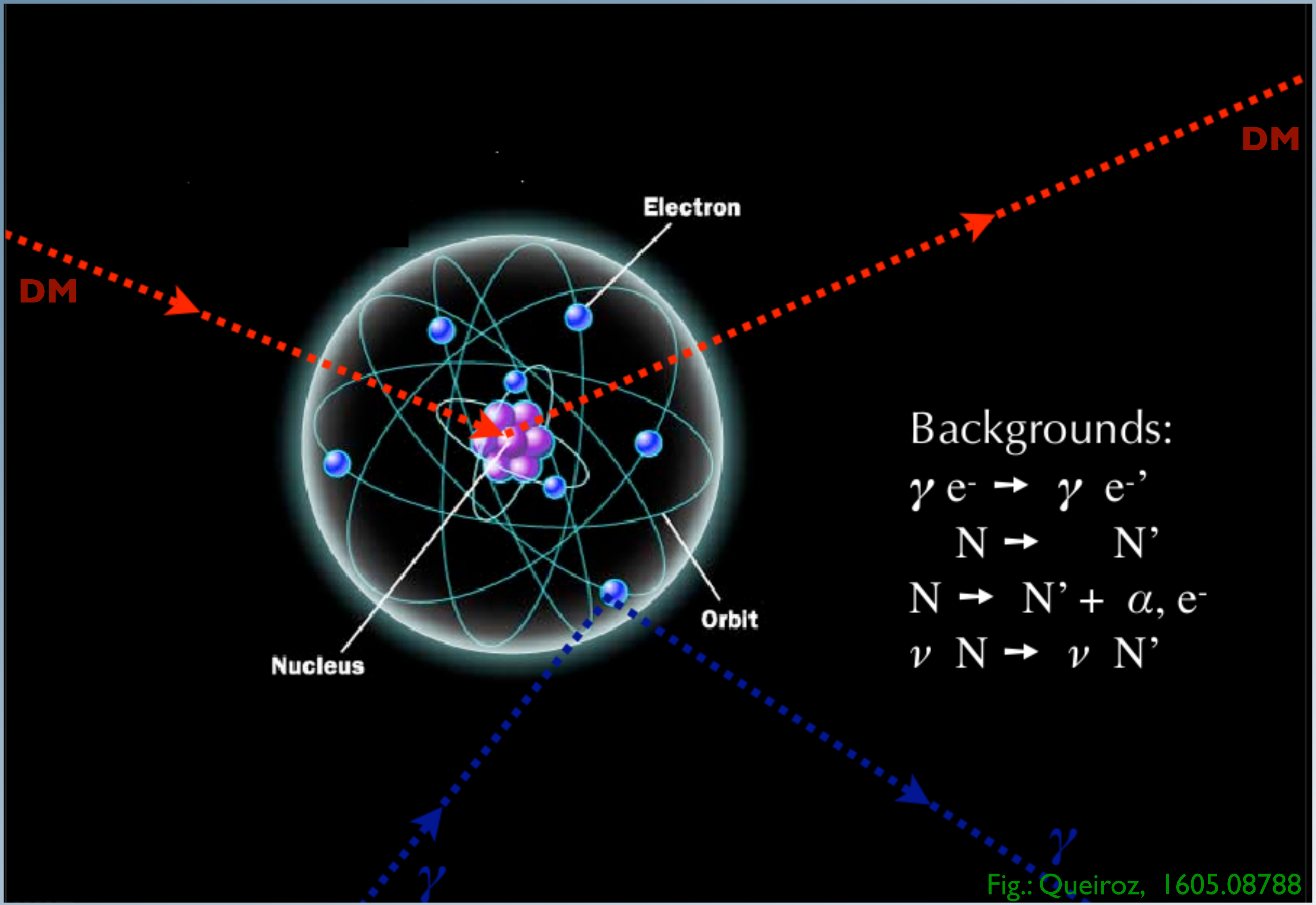
- Fortran package to calculate "all" DM related quantities:
  - *relic density + kinetic decoupling* **(also for $T_{\rm dark} \neq T_{\rm photon}$)**
  - *generic SUSY models + laboratory constraints implemented*
  - *cosmic ray propagation*
  - *indirect detection rates: gammas, positrons, antiprotons,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



since 6.1: DM self-interactions
since 6.2: CRDM (this talk)

Direct detection

- Look for dark matter collisions with atomic nuclei



Experiments typically aim at '*background-free*' setting !

Elastic scattering cross section

- **Spin-independent** interactions couple to nuclear *mass*

  (from scalar, vector and tensor couplings)

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

  per **nucleon**

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

- **Spin-dependent** interactions couple to nuclear *spin*

  (from axial-vector couplings)

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

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

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

The dark matter halo

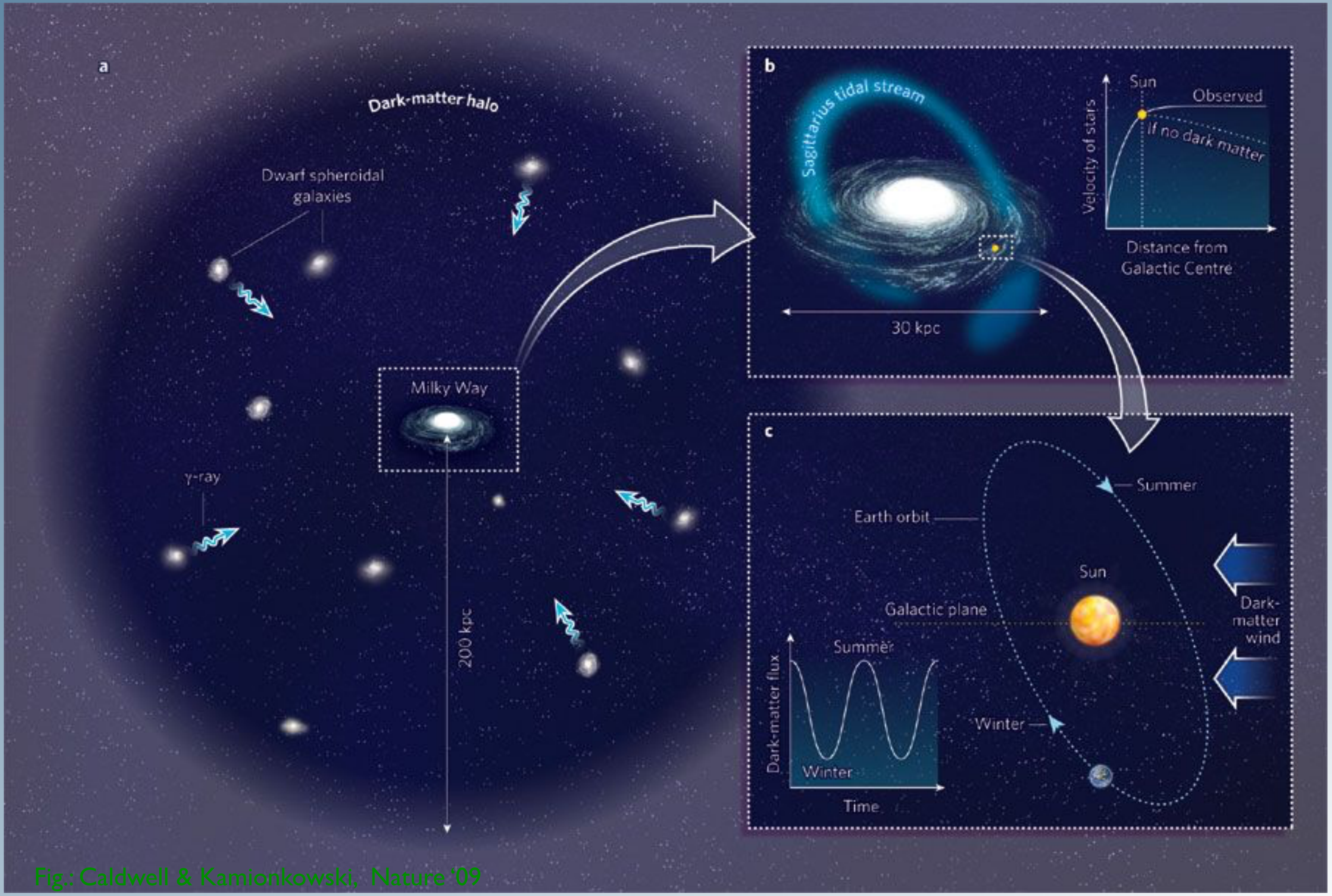


Fig.: Caldwell & Kamionkowski, Nature '09

Recoil rate

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

- 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*

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

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

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

    to be discussed !

Recoil rate

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

- Astrophysical input
- Recoil energy

$$E_R = \frac{Q^2}{2m_N} \overset{\textbf{NR!}}{=} \frac{4 m_\chi m_N T_\chi}{(m_\chi + m_N)^2} \frac{1-\cos\theta_{\rm cm}}{2}$$

$$\Rightarrow \quad v_{\rm min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

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

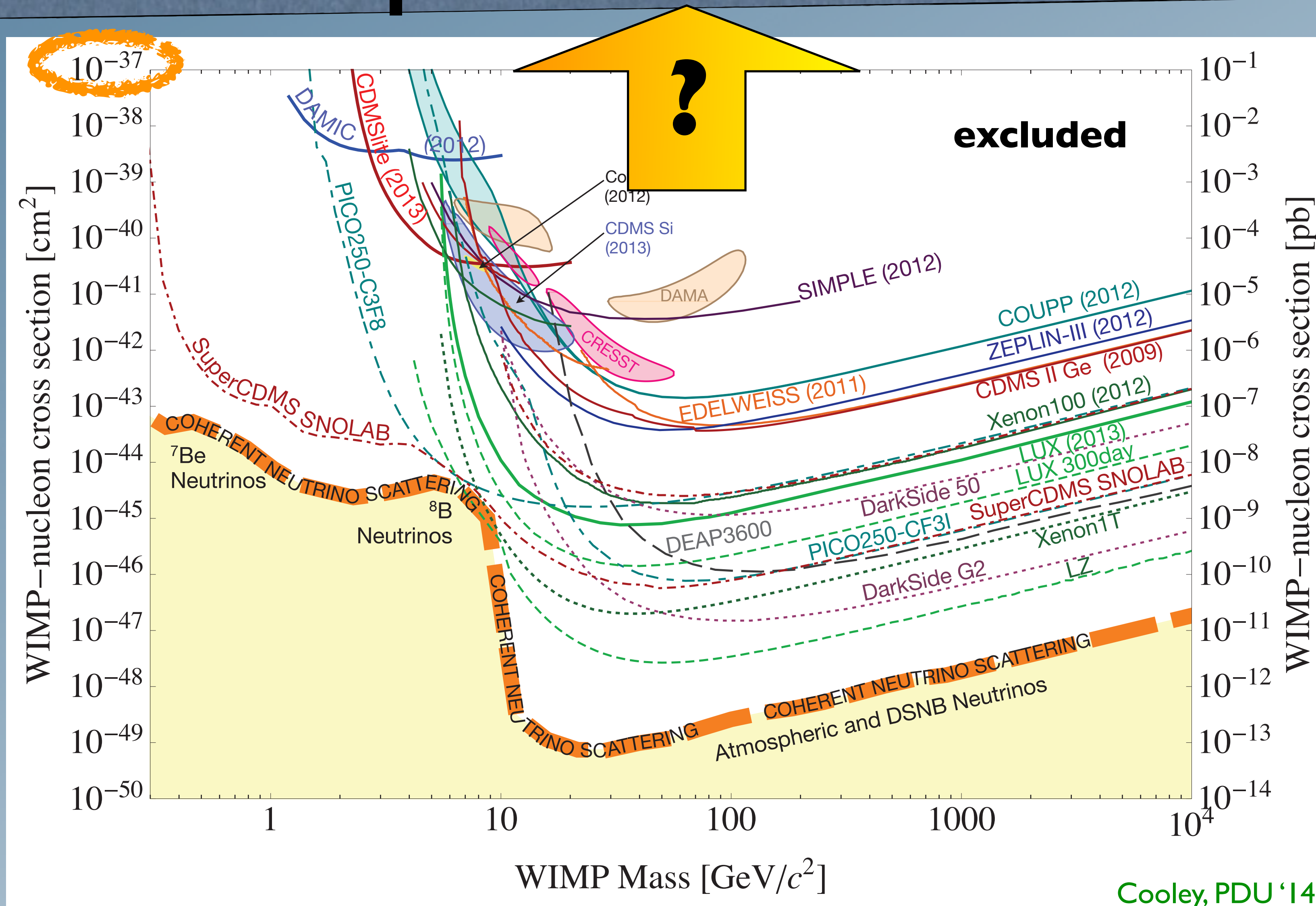
$\ll v_0$ **independent of DM mass!**

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

$\gg v_0$

A vast experimental effort…

spin-independent



$v_{\rm min} \gg v_0$

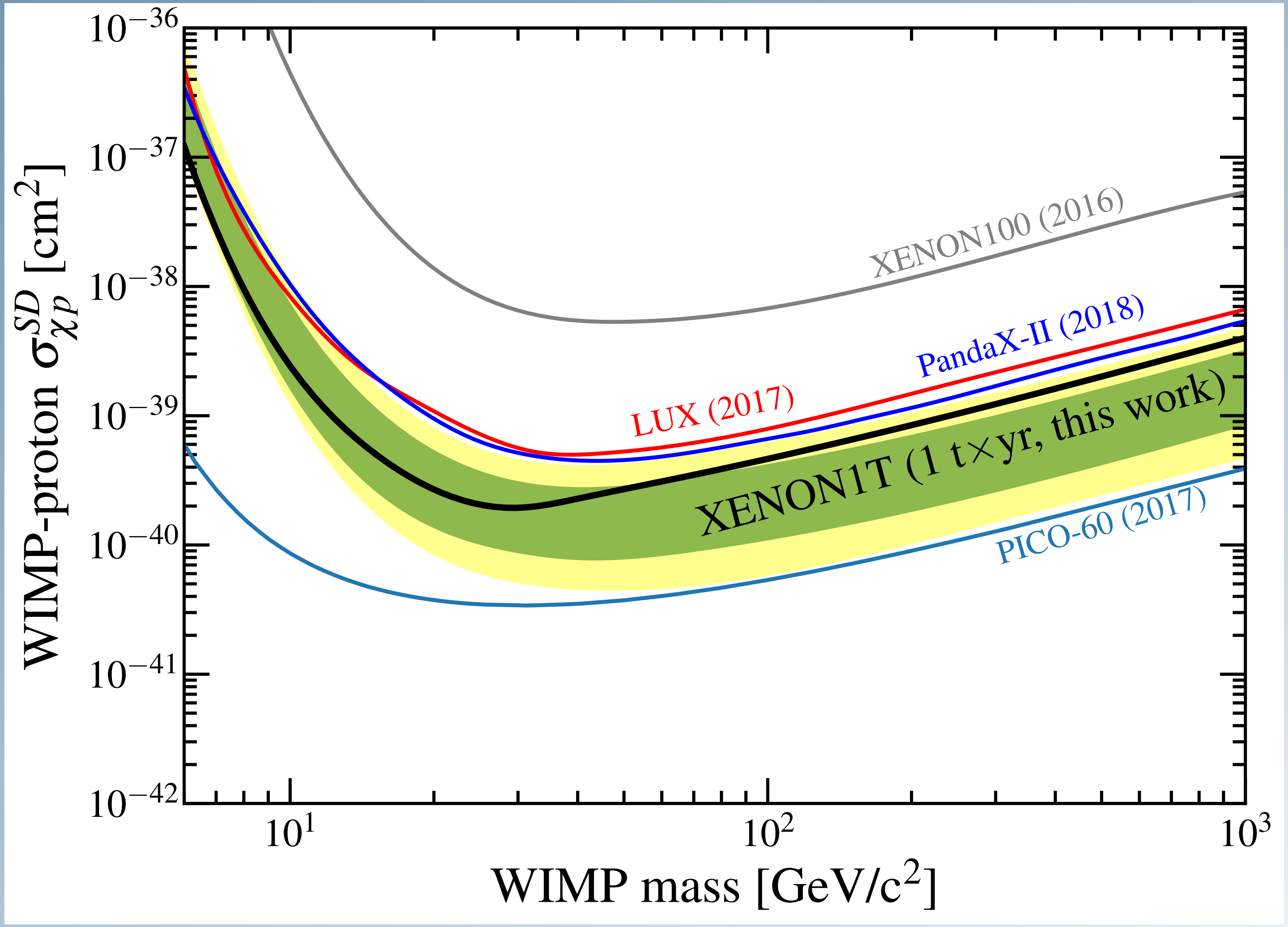
(rate exponentially suppressed)

$v_{\rm min} \ll v_0$

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

Spin-dependent scattering

- Similar behaviour of general limits
- As expected, factor of ~ 10^7 less stringent
  (no coherent enhancement!)



Aprile+, 1902.03234

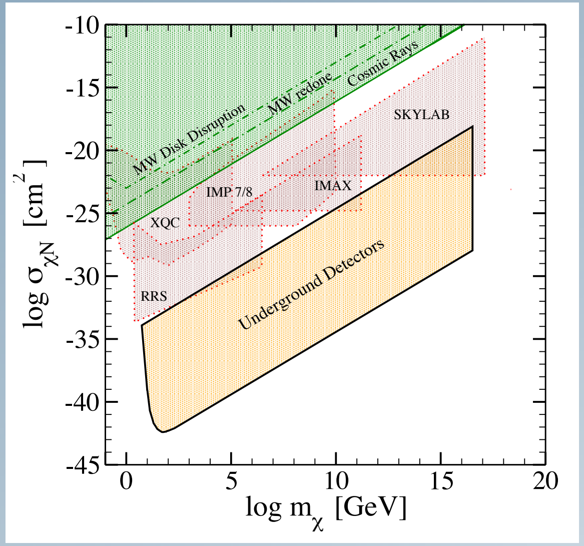
Strongly interacting DM?

- Dark matter scattering too efficiently with nucleons would not reach the detector!

  Starkman, Gould, Esmailzadeh & Dimopoulos, PRD '90

  - *Possibility of unconstrained window of strongly interacting dark matter*

    Zaharijas & Farrar, PRD '05
    Mack, Beacpm & Bertone, PRD '07
    ...



- Simplest approach: model continuous loss of *average* energy down to detector location

$$\frac{dT_{DM}}{dx} = -\sum_N n_N \int_0^{T_r^{\max}} \frac{d\sigma_{\chi N}}{dT_r} T_r dT_r$$

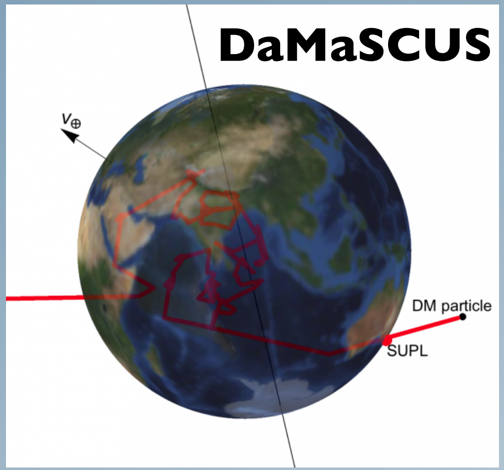
⇨ Exponential suppression, with mean free path $\ell \sim \left(\sum_N n_N \sigma_{\chi N}\right)^{-1}$

Simulations

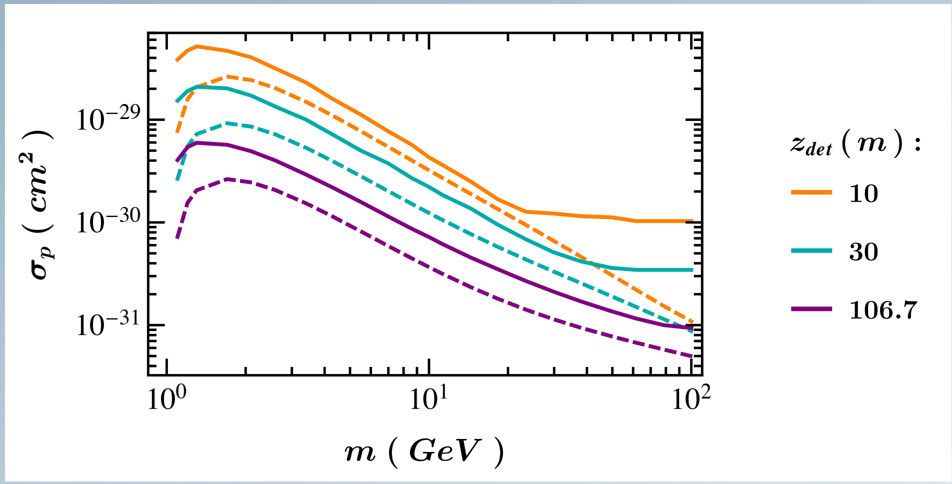
- Analytic approach simplistic:
  - *particles do not only arrive from azimuthal direction*
  - *multiple scatterings in overburden*
  - *high-energy tail has higher penetration power*
  - …

E.g. Emken & Kouvaris, PRD '18

- Full simulations needed:



Emken & Kouvaris, JCAP '17

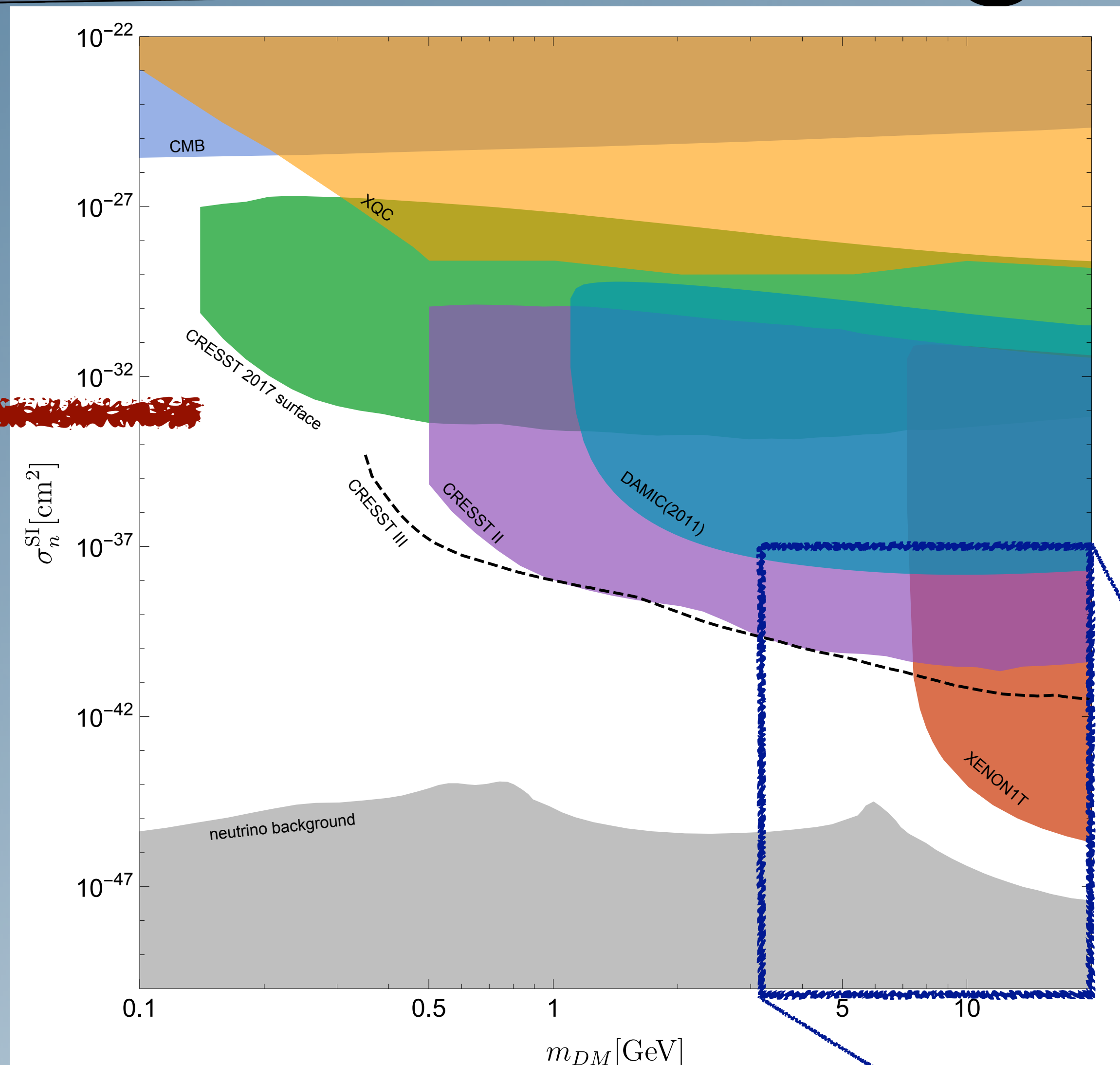


Mahdawi & Farrar, 1712.01170

➡ ***Simple analytical approach overestimates stopping power***

(upper limit on $\sigma_{\chi N}$ too conservative by factor of ~few)

Status at low *m* / high σ



Rocket-based **X-ray Quantum Calorimeter**

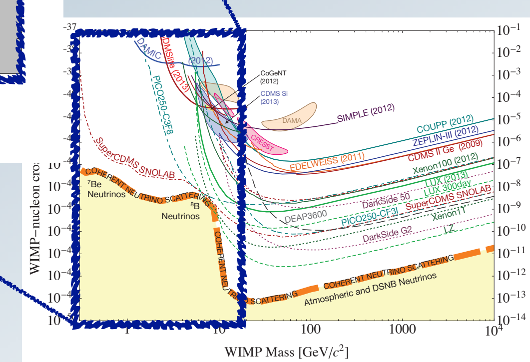
Erickcek, Steinhardt, McCammon & McGuire, PRD '07

DaMaSCUS

+ CRESST / Xenon

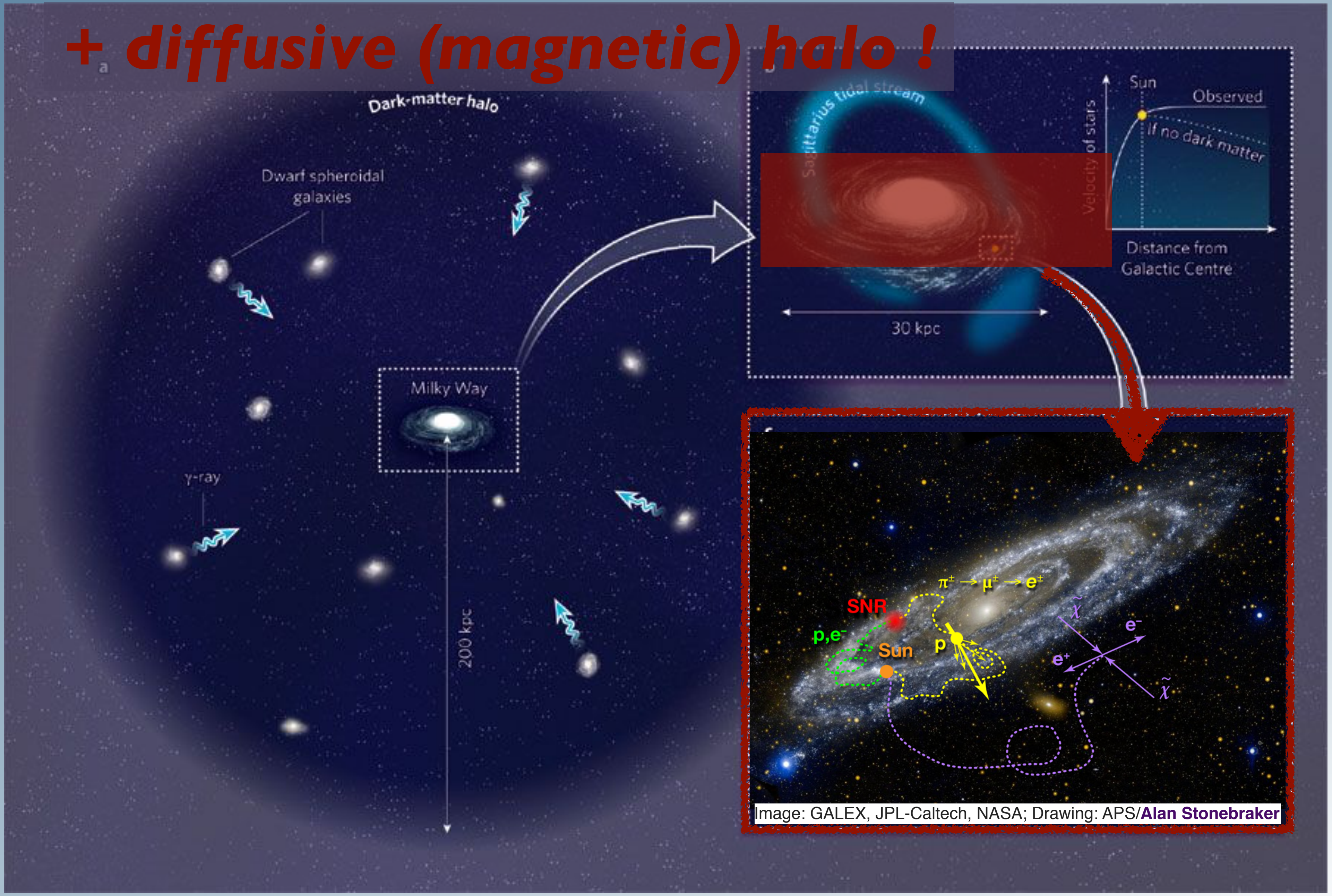
Emken & Kouvaris, PRD '18

would need larger DM momenta to probe this region!



The dark matter halo

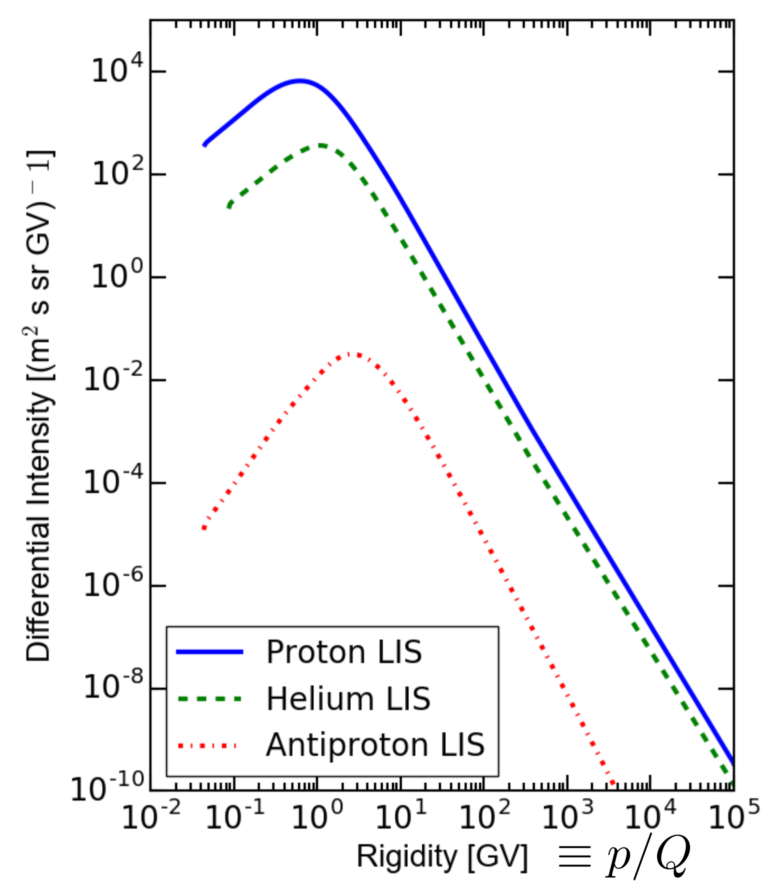
+ diffusive (magnetic) halo !



Cosmic rays

- Local interstellar(!) flux well constrained by Voyager and PAMELA, AMS, …

Image: www. helmod.org



- Further out: confined by galactic magnetic fields for $E \lesssim 10^3\,\mathrm{TeV}$
- Propagation well described by diffusion equation

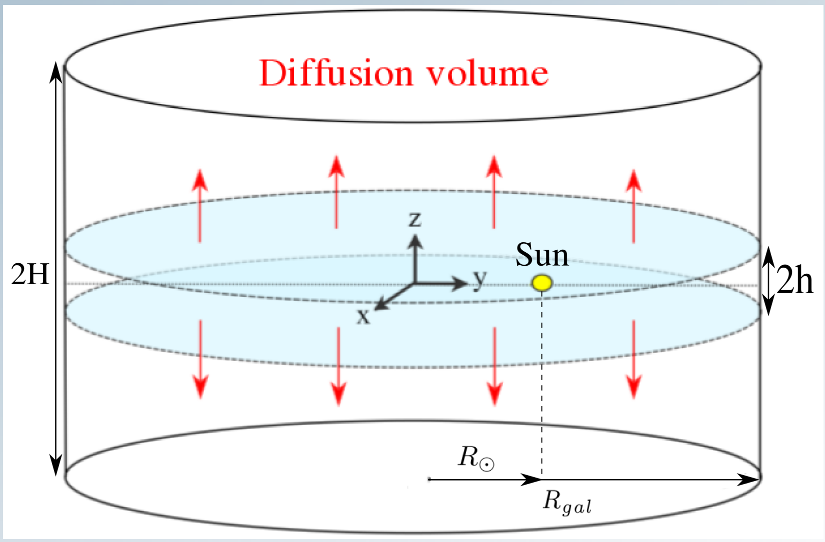
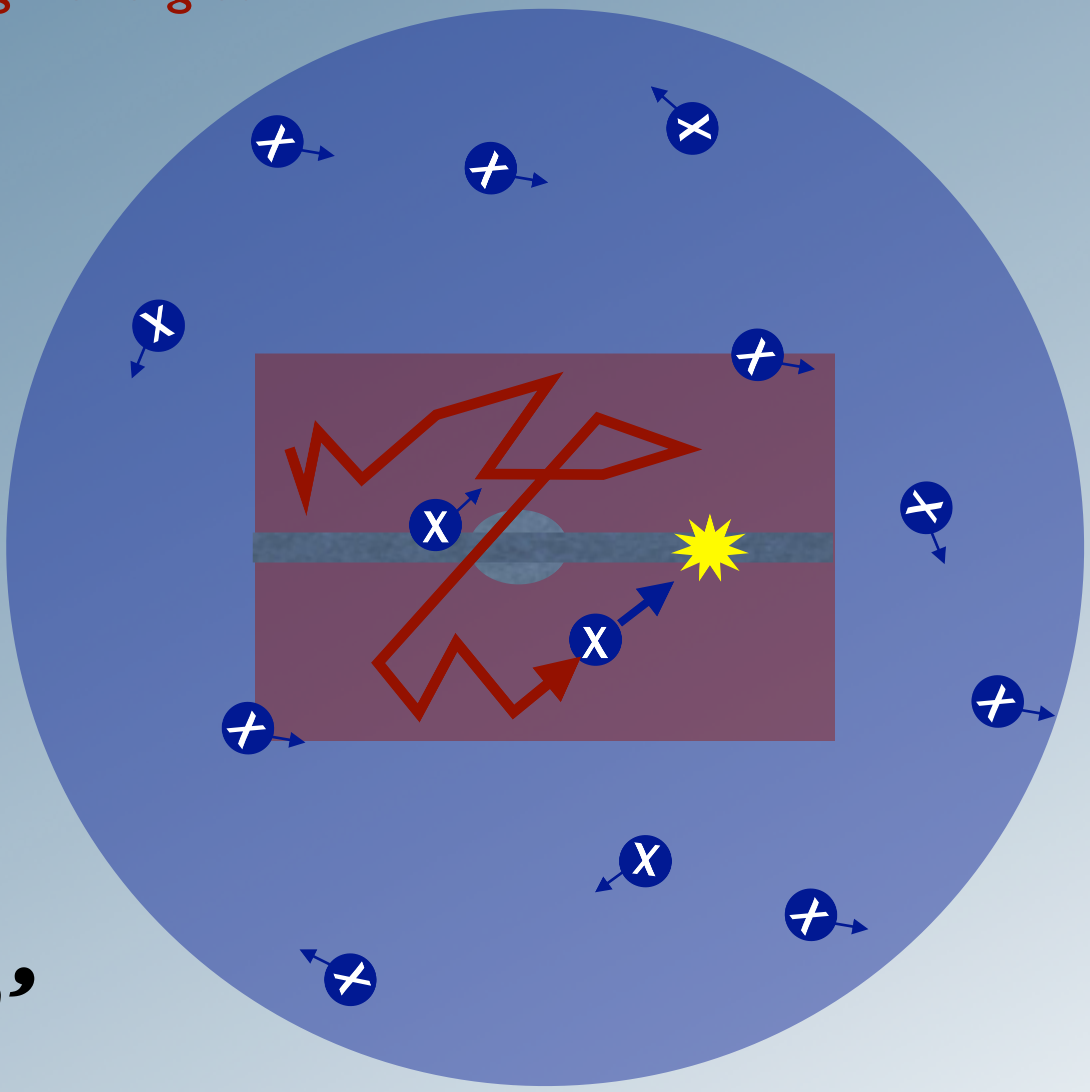


Fig: Y. Genolini , ICRC'15

Cosmic rays → dark matter

- An inevitable **CRDM** component:
  - *extends to high energies*
  - ~ *isotropic*



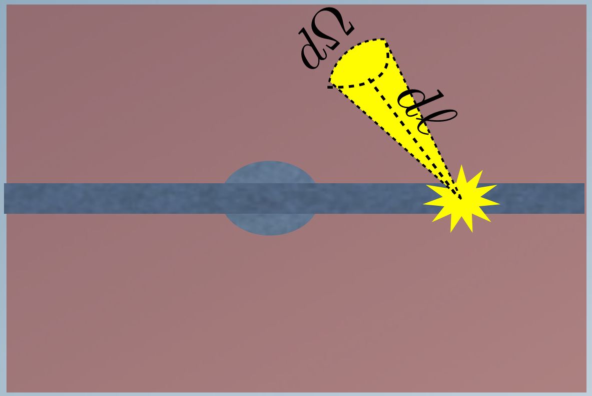
'reverse direct detection'

CRDM flux

- Differential CRDM flux wrt CR energy T_i:

$$\frac{d\Phi_\chi}{dT_i} = \int \frac{d\Omega}{4\pi} \int_{l.o.s.} d\ell \, \sigma_{\chi i} \frac{\rho_\chi}{m_\chi} \frac{d\Phi_i}{dT_i} \equiv \sigma_{\chi i} \frac{\rho_\chi^{\rm local}}{m_\chi} \frac{d\Phi_i^{LIS}}{dT_i} D_{\rm eff}$$

same as for direct detection!



- Astrophysical uncertainties:
  - local *DM density relatively well measured, small anisotropy*
  - local *CR flux relatively well measured, tiny anisotropy*
  - *but how far out is this valid ?*

➡ ***Parameterize by effective distance*** $D_{\rm eff}$

highly conservative *choice:* $D_{\rm eff} \approx 1\,{\rm kpc}$ [e.g. from integrating NFW out to **1** kpc, constant CR density]

more realistic *choice:* $D_{\rm eff} \approx 8\,{\rm kpc}$ [e.g. from integrating NFW out to **10** kpc, constant CR density]

CRDM flux (2)

- Recoil energy of DM particle initially at 'rest':

$$T_\chi = T_\chi^{\max}\frac{1-\cos\theta_{\rm cm}}{2},\quad T_\chi^{\max} = \frac{T_i^2 + 2m_iT_i}{T_i + (m_i+m_\chi)^2/(2m_\chi)}$$

Additional terms compared to corresponding (non-rel.) DD expression

$\rightsquigarrow\ T_i^{\min}(T_\chi)\ \widehat{=}\ v_{\min}(E_R)$ in standard DD

- For isotropic scattering (in CMS):

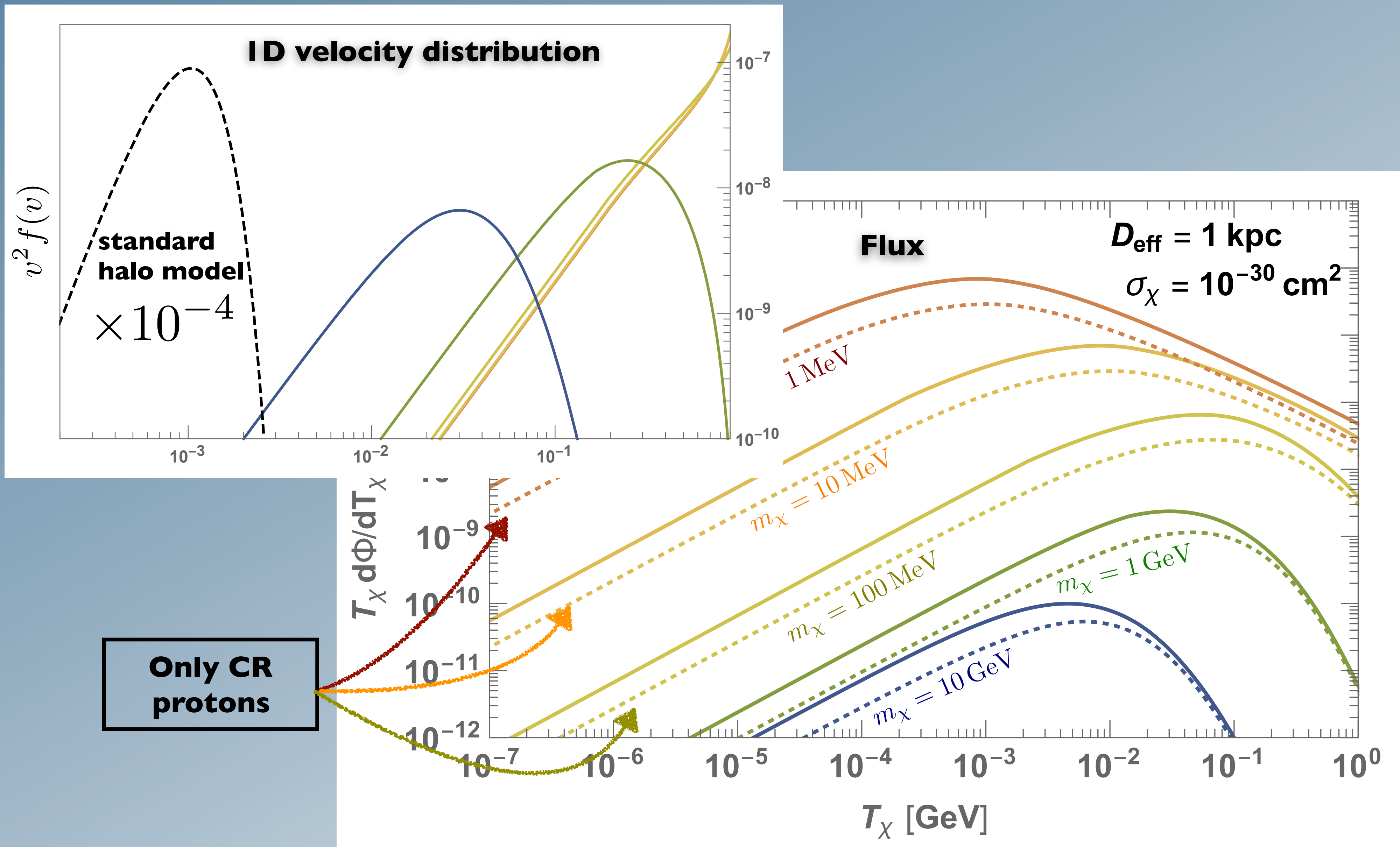
$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff}\frac{\rho_\chi^{\rm local}}{m_\chi}\sum_i \sigma_{\chi i}^0\, G_i^2(2m_\chi T_\chi)\int_{T_i^{\min}}^\infty dT_i\,\frac{d\Phi_i^{LIS}/dT_i}{T_\chi^{\max}(T_i)}$$

$\{p,\ ^4\mathrm{He}\}$

Form factor suppression

[Choose simple dipole form, $G_i(Q^2) = 1/(1+Q^2/\Lambda_i^2)^2$]

CRDM flux — results



Attenuation in overburden

- Follow simple approach $\frac{dT_{DM}}{dx} = -\sum_N n_N \int_0^{T_r^{\max}} \frac{d\sigma_{\chi N}}{dT_r} T_r dT_r$
- But extend to fully relativistic treatment

$$\frac{d\Phi_\chi}{dT_\chi^z} = \left(\frac{dT_\chi}{dT_\chi^z}\right) \frac{d\Phi_\chi}{dT_\chi} = \frac{4m_\chi^2 e^{z/\ell}}{\left(2m_\chi + T_\chi^z - T_\chi^z e^{z/\ell}\right)^2} \frac{d\Phi_\chi}{dT_\chi}$$

(for $m_\chi \ll m_N$)

- Mean free path

$$\ell^{-1} \equiv \sum_N n_N \sigma_{\chi N} \frac{2m_N m_\chi}{(m_N + m_\chi)^2}$$

$$\sigma_{\chi N} = \sigma_\chi^{\rm SI} A^2 \left(\frac{m_N(m_\chi + m_p)}{m_p(m_\chi + m_N)}\right)^2$$

DarkSUSY

Sum over 11 most abundant elements, averaging Earth's mass density profile down to detector location

$\rho_N(r)$ based on McDonough, Geochemistry '03

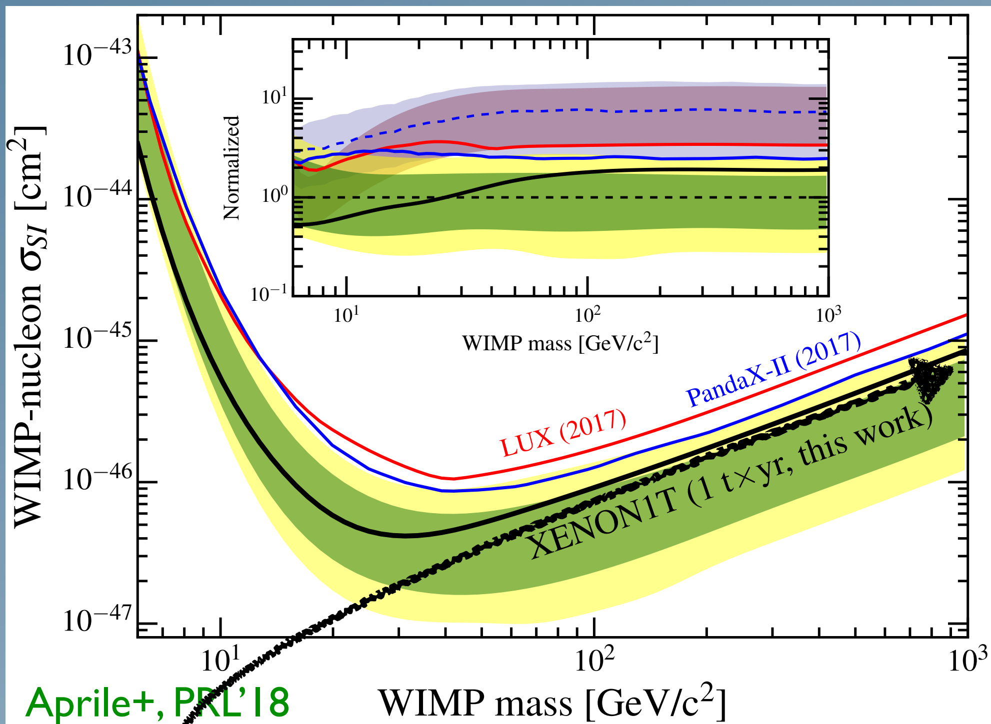
Rate in detector

- CRDM scattering in (underground or near-surface) detector like ordinary direct detection
  - *But need to use fully relativistic kinematics, as for CR → DM*
- Final result: differential recoil rate per target nucleus

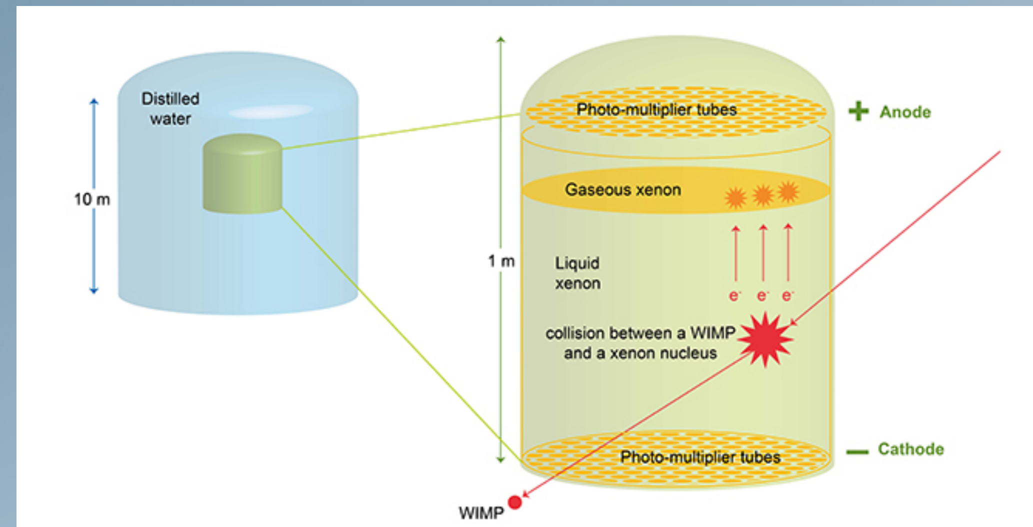
$$\frac{d\Gamma_N}{dT_N} = \sigma^0_{\chi N} G_N^2(2m_N T_N) \int_{T_\chi(T_\chi^{z,\min})}^{\infty} \frac{dT_\chi}{T_{r,N}^{\max}} \frac{d\Phi_\chi}{dT_\chi}$$

➡
- *Integrate over experimentally accessible window of nuclear recoil energies T_N*
- ***NB**: form factor only depends on Q^2, and hence not on T_χ !*

Re-interpreting Xenon limits



Aprile+, PRL'18



- Limits derived from window $T_{\mathrm{Xe}} \in [4.9, 40.9]\,\mathrm{keV}$

- Expected rate for very high masses:

$$\Gamma = \int dT_{\mathrm{Xe}} \left(\frac{d\Gamma}{dT_{\mathrm{Xe}}} = \frac{\rho_\odot^\chi}{m_\chi m_N} \int_{v_{\min}}^{v_{\max}} \frac{d\sigma_{\chi N}}{dT_{\mathrm{Xe}}} v f(v) dv \right) \xrightarrow[m_{\mathrm{DM}} \gg m_N]{} \kappa \frac{\sigma_{\chi N}^{\mathrm{DM}}}{m_{\mathrm{DM}}} \left(\bar{v}\, \rho_{\mathrm{DM}}\right)^{\mathrm{local}}$$

NB:
- $\kappa \sim 0.23 \sim$ *fraction of DM particles to give recoils inside window*
- $\sigma_{\chi N}^{\mathrm{DM}} = A^4 \sigma_\chi^{\mathrm{SI}}$ *(high-mass limit!)*

Results

- Testing uncharted territory at small masses!

TB & Pospelov, 1810.10543

- $m_\chi \to 0$?
  - *in detector:*

    $$T_{\rm Xe}^{\rm max} \to \frac{2T_\chi^2}{m_{\rm Xe}}$$

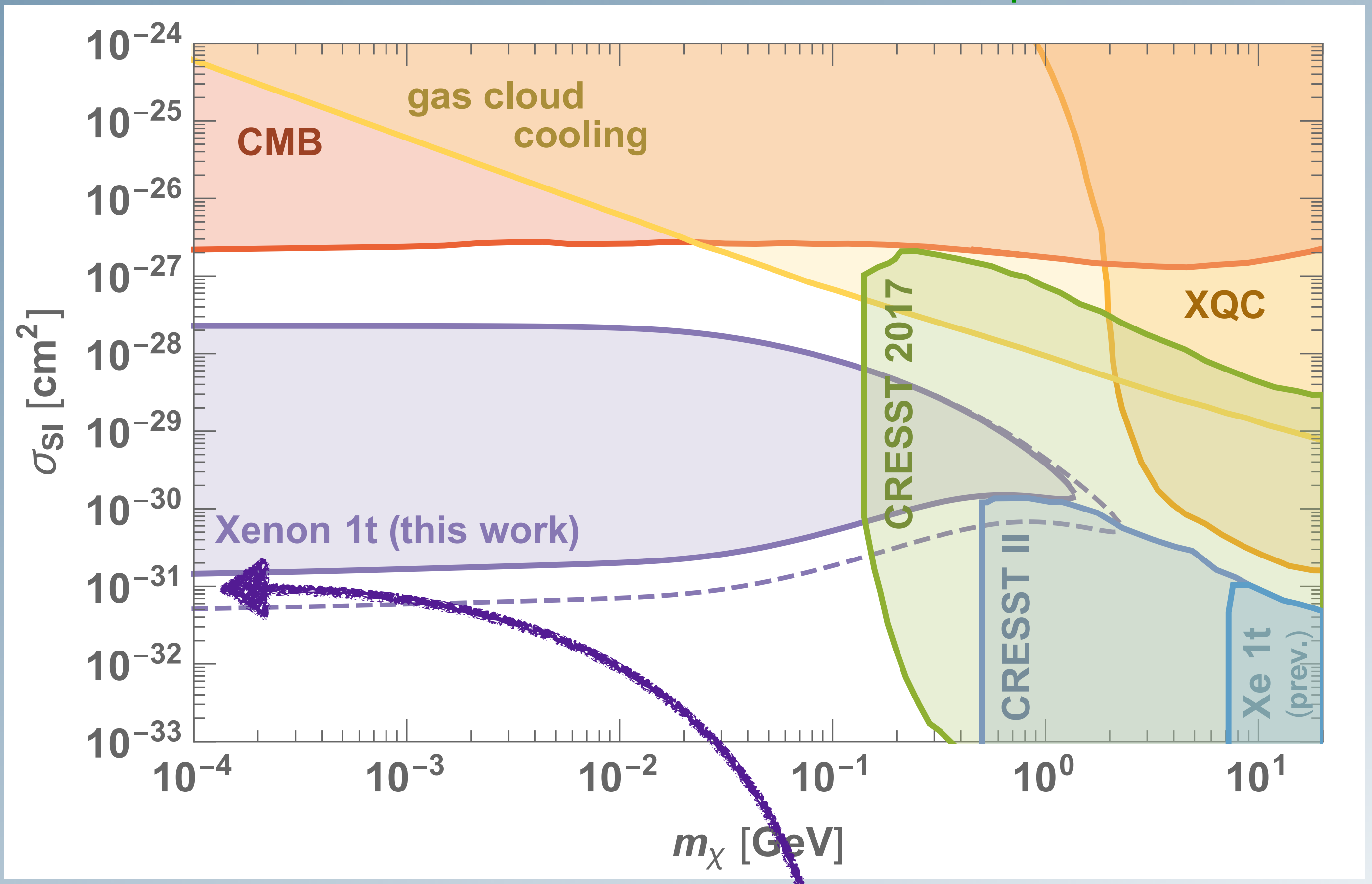
    $$\rightsquigarrow \boxed{T_\chi \gtrsim 10\,\mathrm{GeV}}$$

    (independent of m_χ)
  - *DM flux:*

    $$\frac{d\phi_\chi}{dT_\chi} \propto \frac{1}{m_\chi}\int_{T_i^{\rm min}}^{\infty} dT_i \frac{1}{T_\chi^{\rm max}} \frac{d\phi_i}{dT_i}$$

    $T_i^{\rm min}$: $\propto m_\chi^{-1/2}$; $\frac{1}{T_\chi^{\rm max}}$: $\propto m_\chi^{-1} T_i^{-2}$; $\frac{d\phi_i}{dT_i}$: $\propto T_i^{-\gamma}$

    $$\rightsquigarrow \boxed{\frac{d\phi_\chi}{dT_\chi} \propto m_\chi^{-\frac{3-\gamma}{2}}}$$



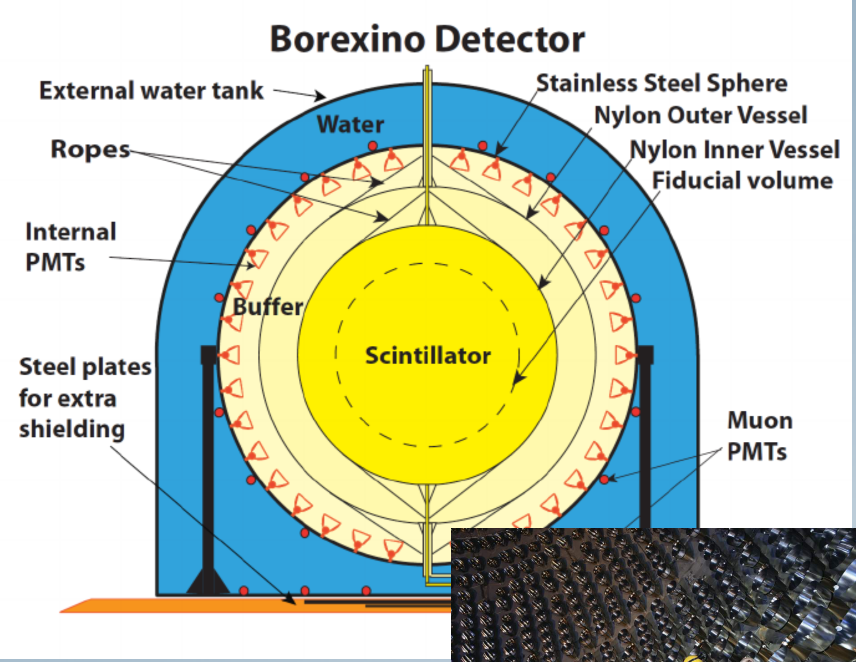
$$\Rightarrow \sigma^{\rm lim} \propto m_\chi^{\frac{3-\gamma}{4}} \sim m_\chi^{0.075}$$

Neutrino detectors I

- Deep underground detectors looking for $\nu - p$ scattering
  - *E.g. Borexino: no events for* $T_p \gg \mathrm{MeV}$
  - *Similar: Kamland, SNO+*

➡ ***Neutrino detectors can be used to search for CRDM !***

[But recoil energy way too high for ordinary DM]



- Borexino analysis
  - *Constraints stated in terms of equivalent electron recoil energy*

$$\Gamma_p^{\mathrm{Borexino}}(T_e > 12.5\,\mathrm{MeV}) = \frac{S_{lim}}{\epsilon\, N_p\, T} < 1.9 \times 10^{-39}\,\mathrm{s}^{-1}$$

Bellini+, PRD '13

  - *Use Birk's law to convert to proton recoil energy in liquid scintillator*

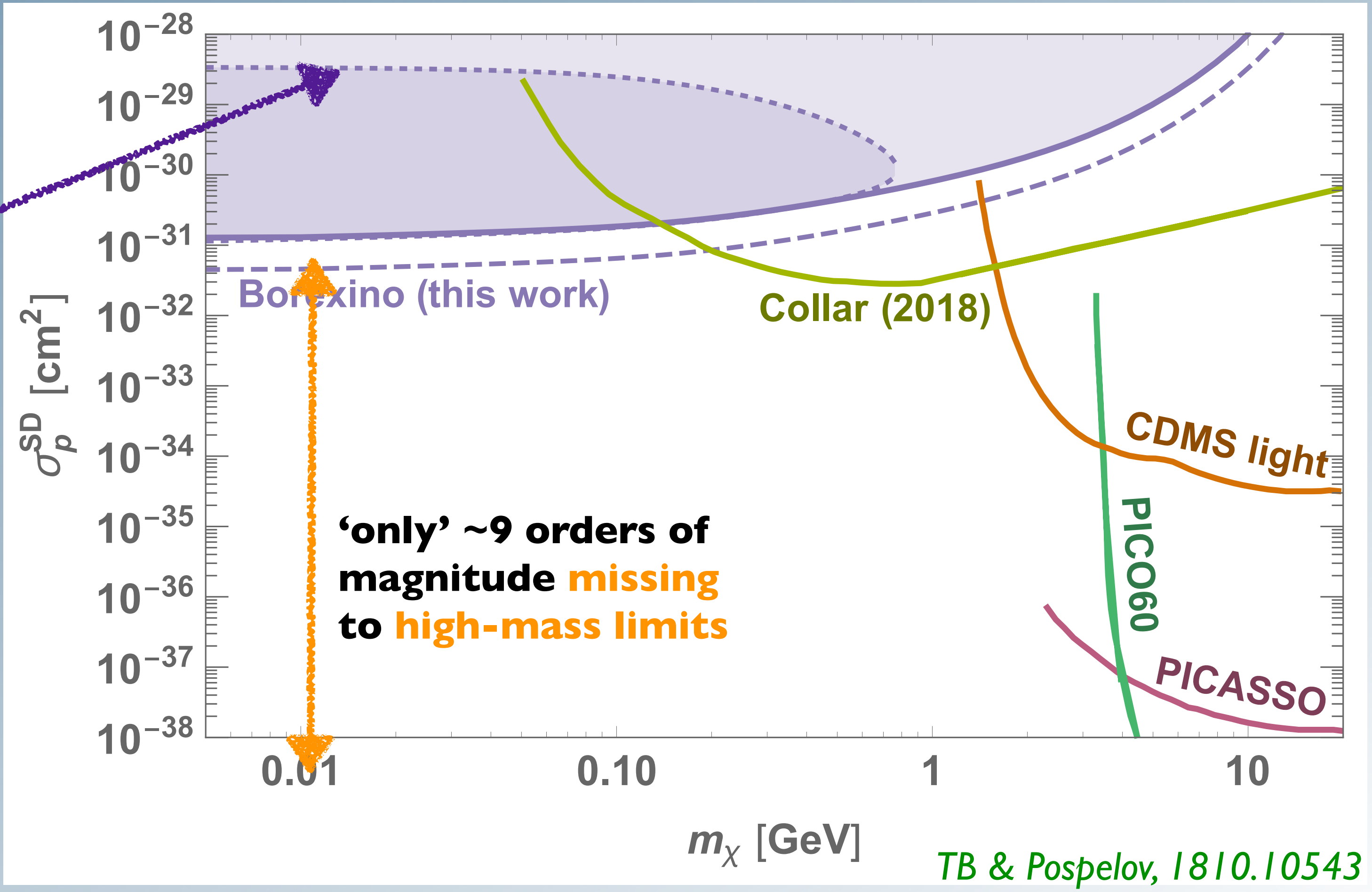
e.g. Dasgupta & Beacom, PRD '11

$$T_e(T_N) = \int_0^{T_N} \frac{dT_N}{1 + k_B \langle dT_N/dx \rangle}$$

PSTAR tables for stopping of protons in pseudocumene from http://physics.nist.gov

Borexino limits

- This leads to low-mass limits comparable to those from the re-analysis of Xenon 1t results
- Even more relevant: comparison to spin-dependent limits !



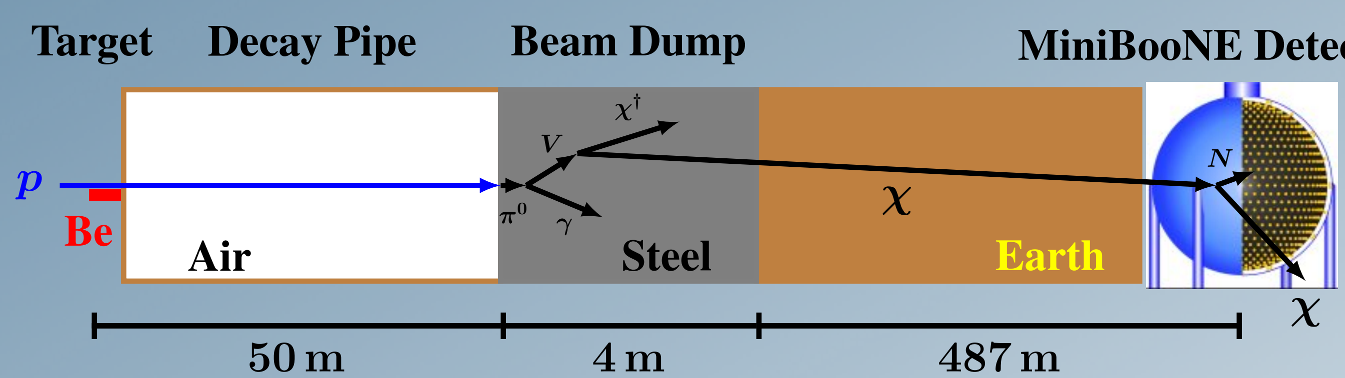
stopping power like for spin-independent scattering
(just for comparison)

TB & Pospelov, 1810.10543

Neutrino detectors II

- Near surface detectors looking for $\nu - p$ scattering
  - *Large backgrounds*
  - *Still useful for constraining very large cross sections*
- Re-analyse MiniBooNE dark matter search

Aguilar-Arevalo+, PRL '17



- *No excess seen*

$$\Gamma_p^{\mathrm{MiniBooNE}}(T_p > 35\,\mathrm{MeV}) = \frac{S_{\mathrm{lim}}}{\epsilon\, N_p\, \Delta t\, (POT/N_{p,\mathrm{bunch}})}$$

~800 beam-unrelated BG events [from Aguilar-Arevalo+, PRD '15]

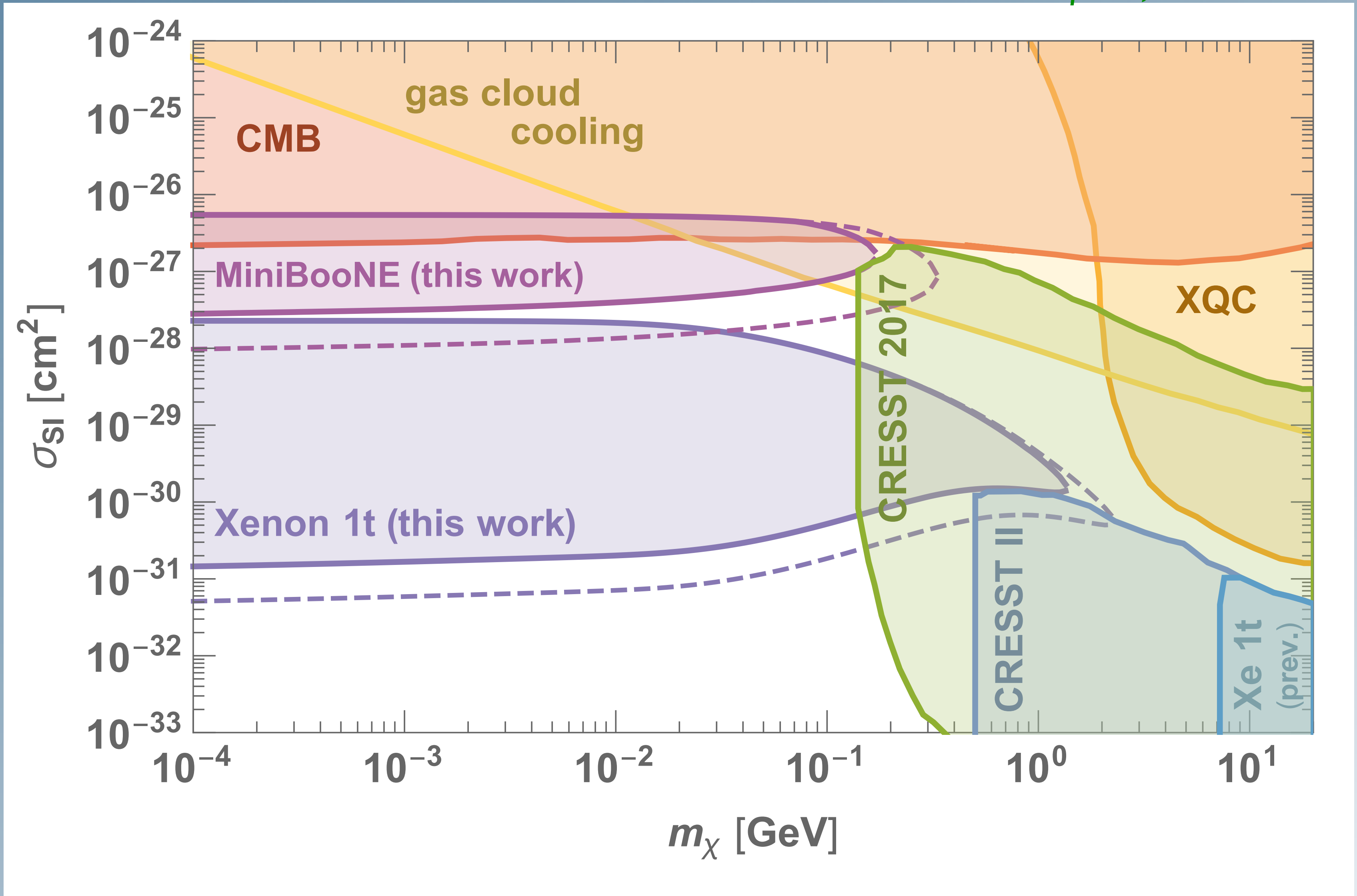
~900s effective running time

$$\Gamma_p^{\mathrm{MiniBooNE}}(T_p > 35\,\mathrm{MeV}) < 1.5 \times 10^{-32}\,\mathrm{s}^{-1}$$

NB: quite conservative because no BG subtraction!

Results for SI scattering

TB & Pospelov, 1810.10543



➡ ***(Almost) no window of large cross sections left!***

Conclusions

- If dark matter can elastically scatter with nuclei, there is an inevitable high-energy component in DM flux
- Can use conventional DD and neutrino detectors to probe dark matter *much* lighter than ~GeV
- Improved constraints by 4-5 orders of magnitude!
  - *but still* much *weaker than at high masses (in particular for SI scattering)…*
- Only outlined main principle — much to be refined :
  - *more detailed investigation of (effective) source volume*
  - *multiple scatterings in overburden*
  - *revisit instrumental responses (high recoil energies!)*
  - *specific DM models, e.g. inelastic or non-trivial energy dependence*
  - …

Thanks for your attention!

Backup slides

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"

e.g. GALPROP

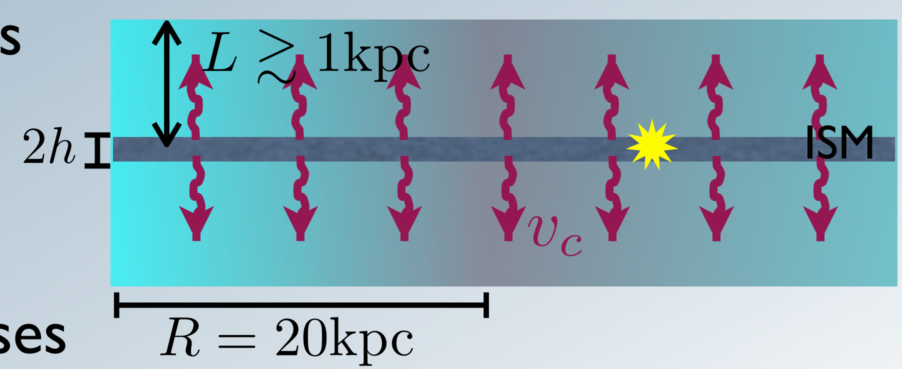
Strong, Moskalenko, …

DRAGON

Evoli, Gaggero, Grasso & Maccione

- (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, Fornengo, Maurin, Salati, Taillet, ...



Galactic cosmic ray composition

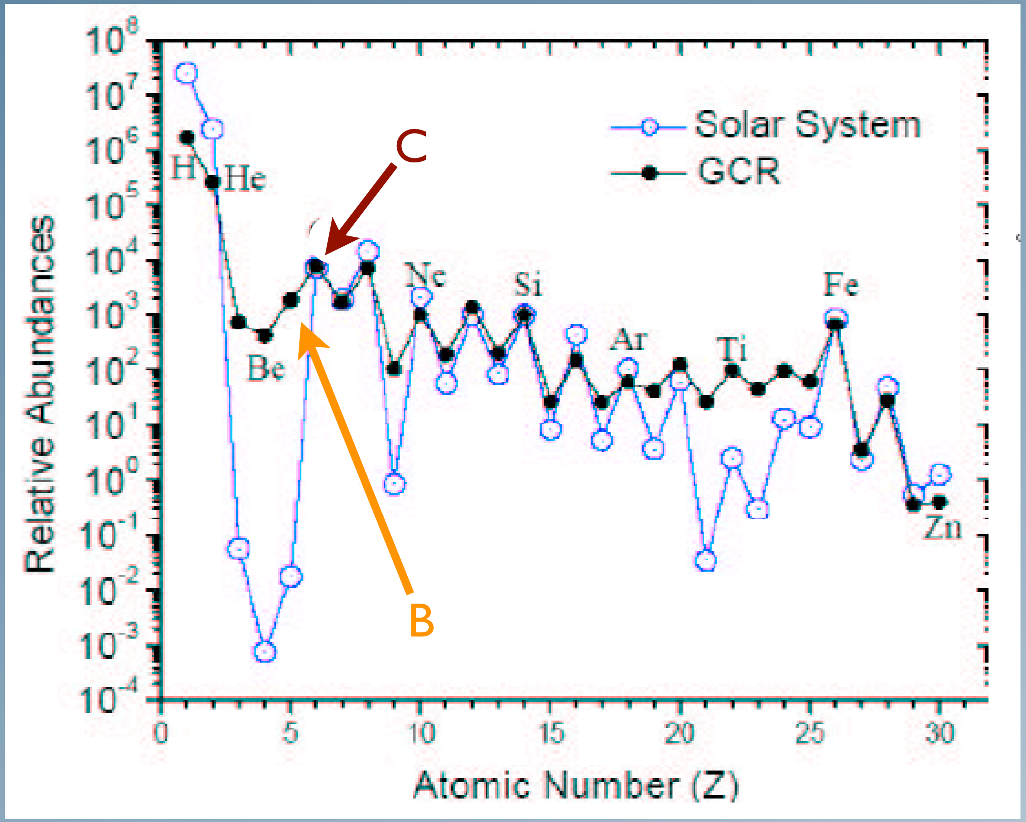


Fig. from D. Maurin

- Primary species
  - present in sources
  - element distribution following stellar nucleosynthesis
  - accelerated in SN shockwaves
- Secondary species
  - much larger relative abundance than in stellar environments
  - produced by interaction of primary CRs with ISM

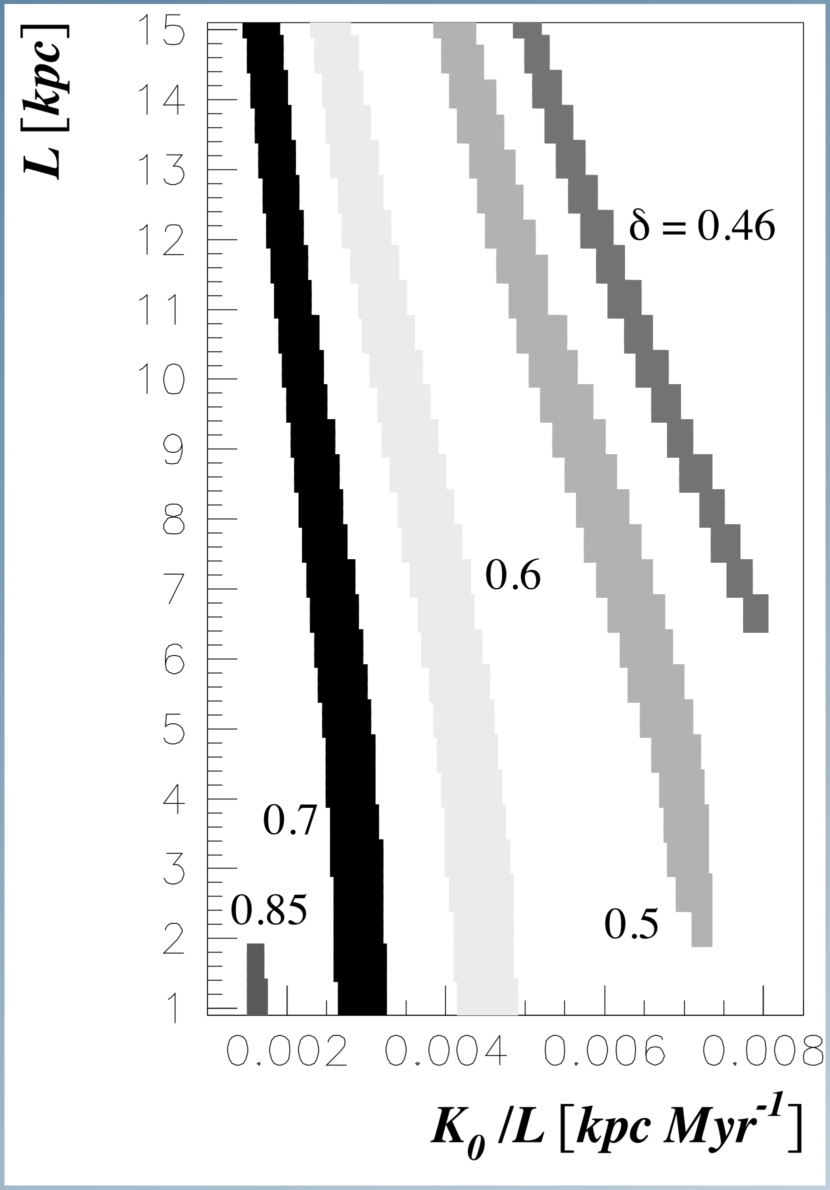
- Propagation parameters $(K_0, \delta, L, v_a, v_c)$ of two-zone diffusion model strongly constrained by B/C

Maurin, Donato, Taillet & Salati, ApJ '01

➡ ***Test model by successfully predicting other CR fluxes!***

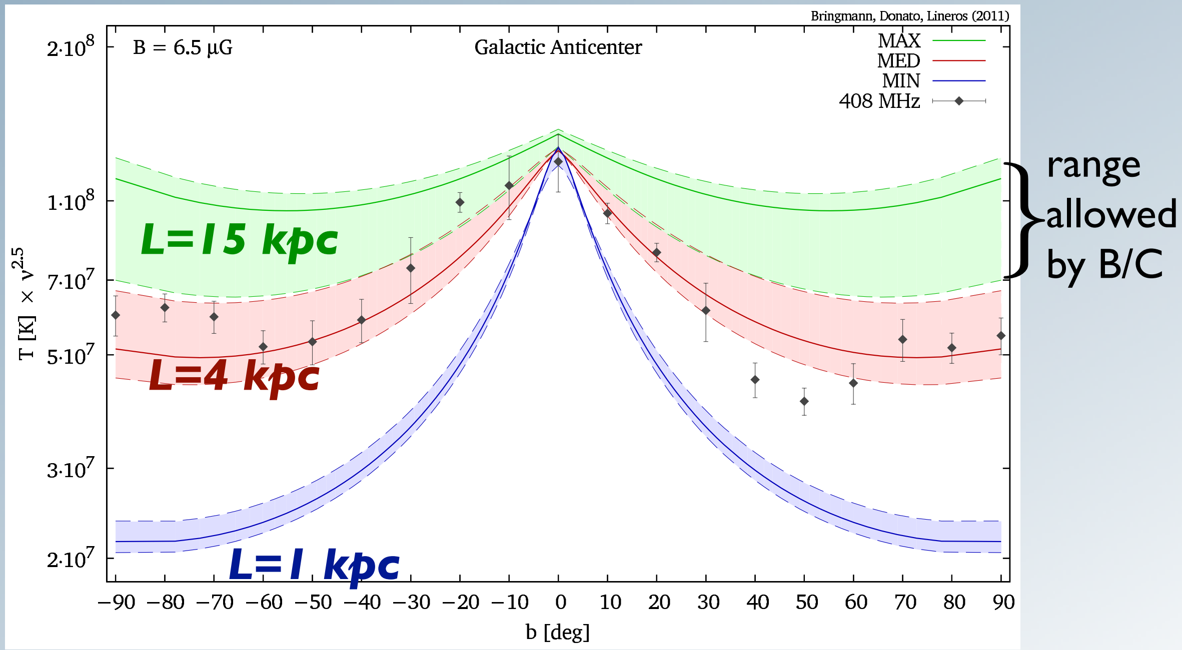
E.g. TB & Salati, PRD '07

Degeneracies



Maurin, Donato, Taillet & Salati, ApJ '01

- B/C analysis leaves large degeneracies, in particular on size L of diffuse halo
- Complementary information e.g. from radio observations



TB, F. Donato & R. Lineros, JCAP '12