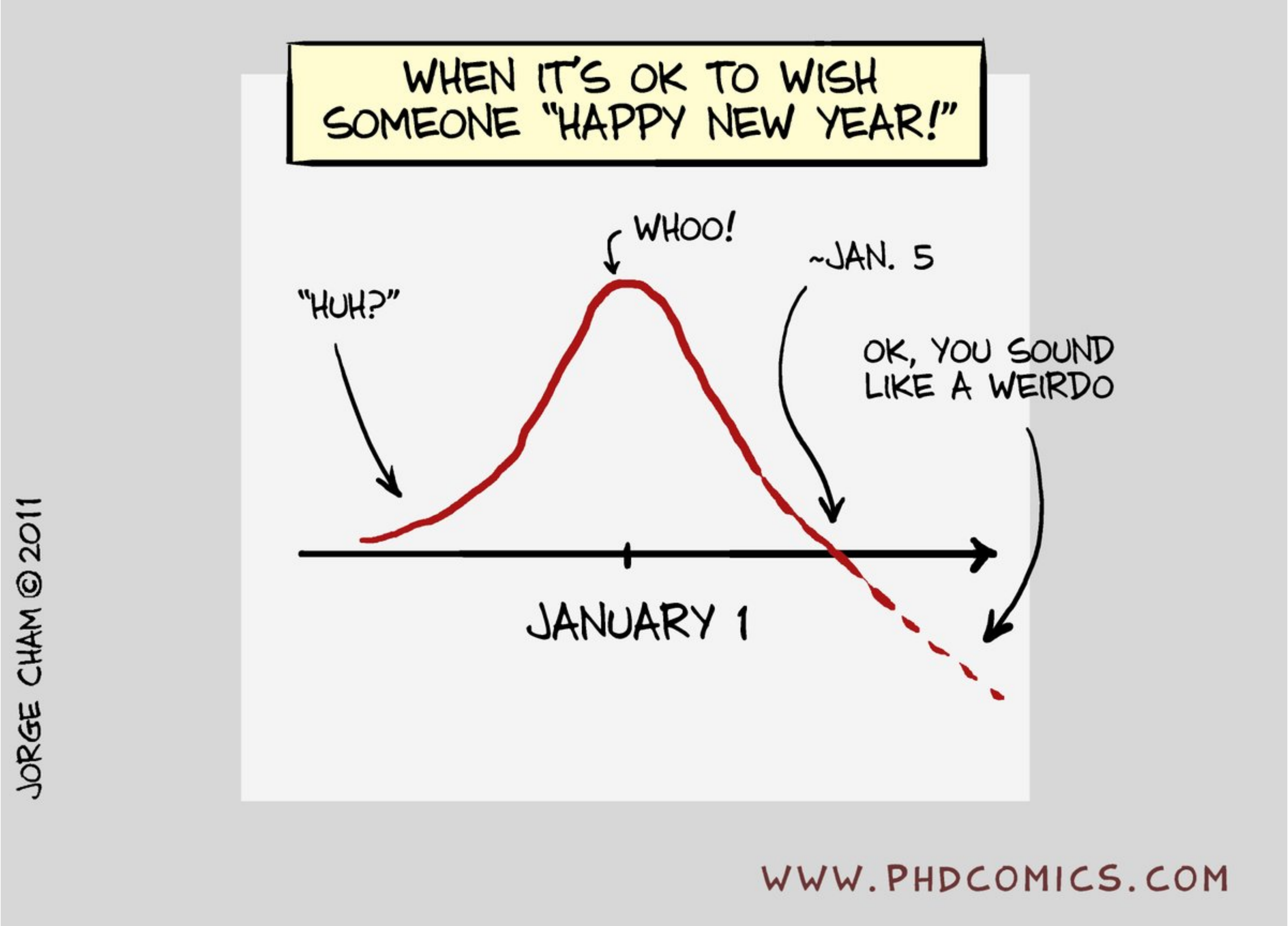

Happy new year!
2018

Direct/indirect detection prospects for dark matter scenarios involving light, long lived mediators

Suchita Kulkarni
@suchi_kulkarni

Based on:
1. F. Kahlhoefer, S. Kulkarni, S. Wild, JCAP 1711 (2017) no.11, 016
2. X. Chu, S. Kulkarni, P. Salati, JCAP 1711 (2017) no.11, 023
3. + works in progress

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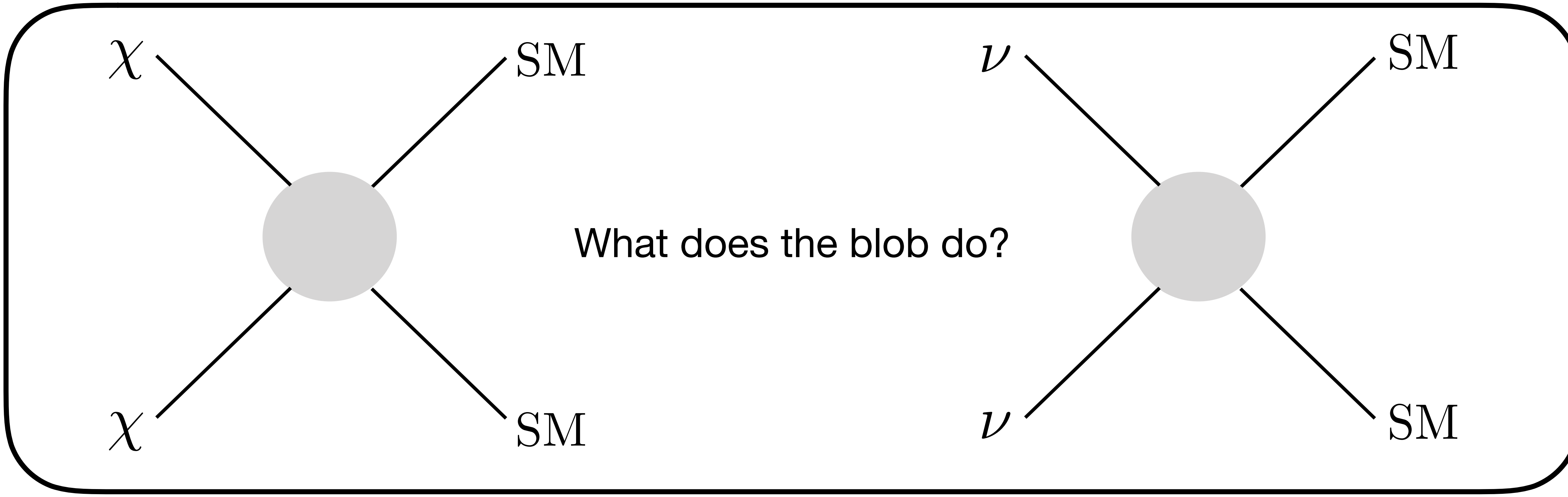
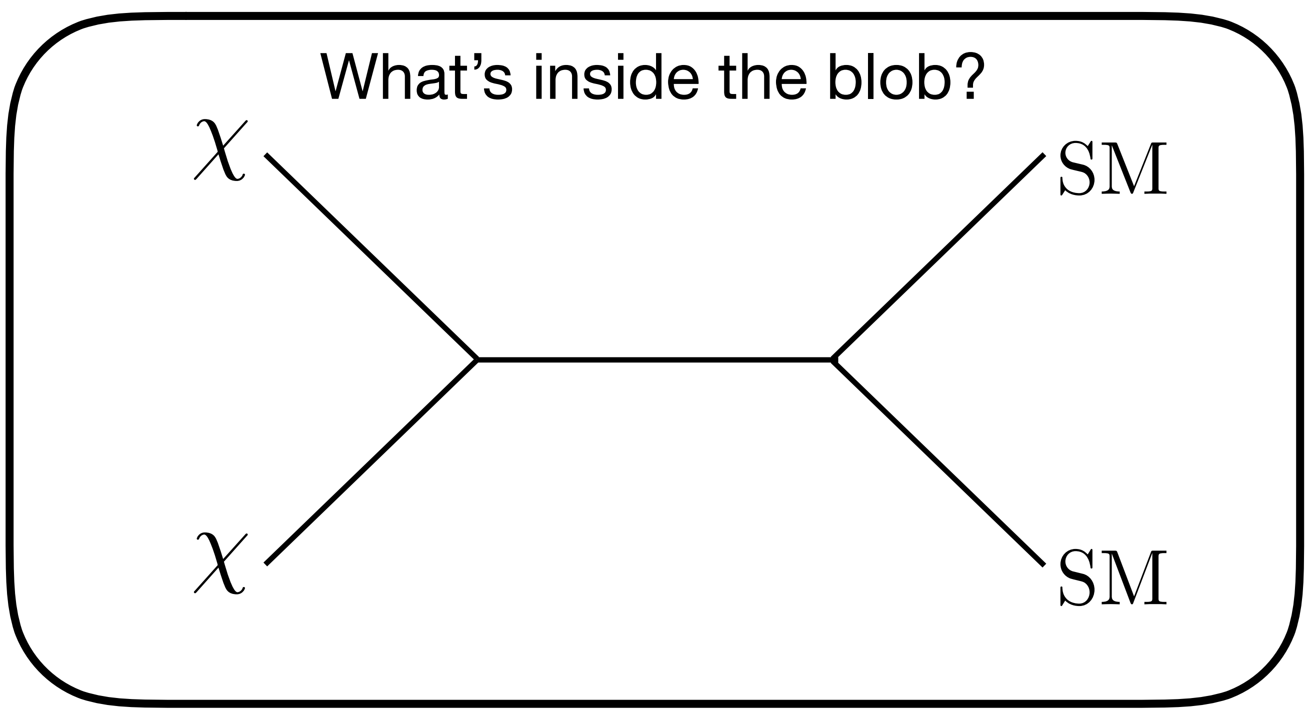
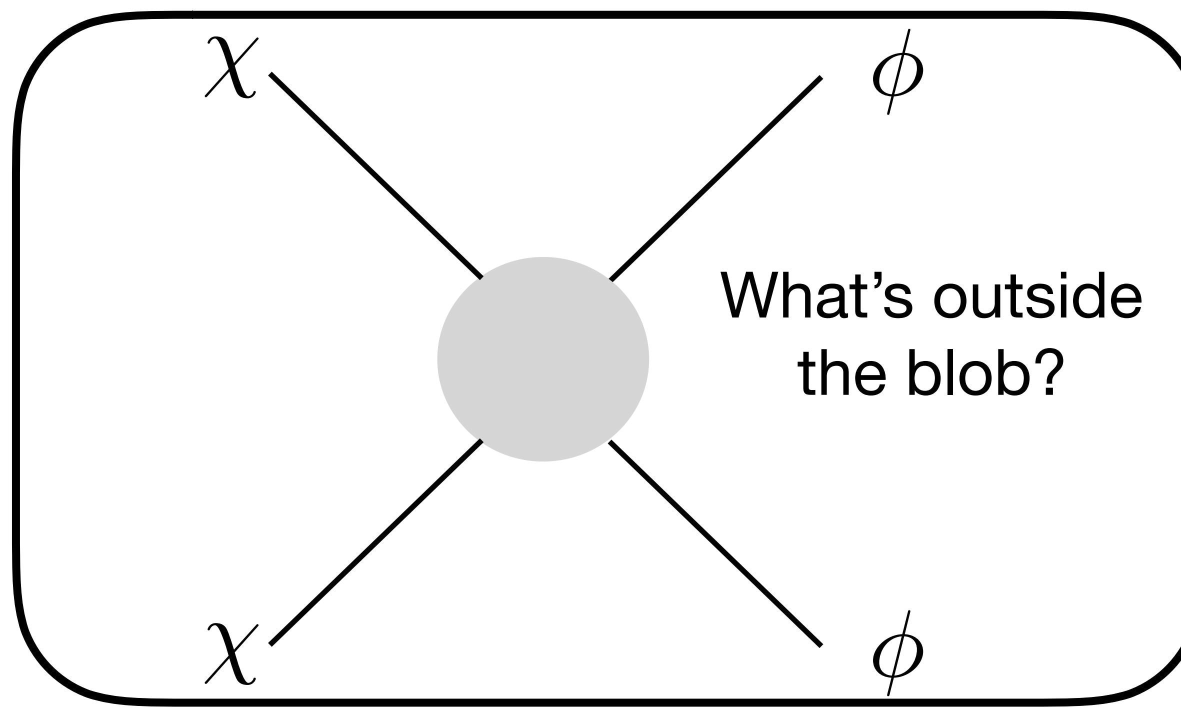
ÖAW
ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Dark matter interactions





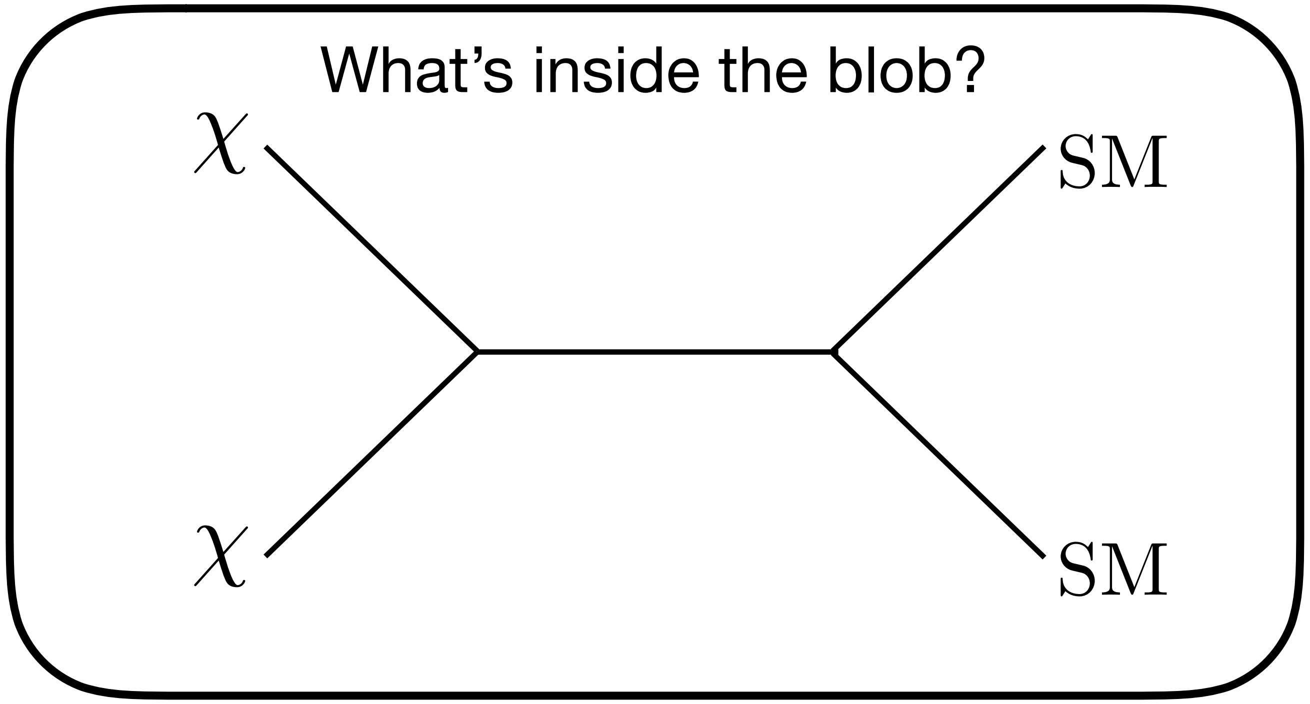


Detection avenues

- Direct and indirect detection of dark matter are crucial avenues to search for dark matter
- Go beyond and complement direct searches for dark matter at the LHC
- Question: how can we maximally exploit the potential of current experiments to constrain exotic interactions in dark matter sector?
- Both direct and indirect detection search strategies are prone to uncertainties in astrophysical environment
- Identification of new effects and realistic evaluation both matters

Looking inside the blob

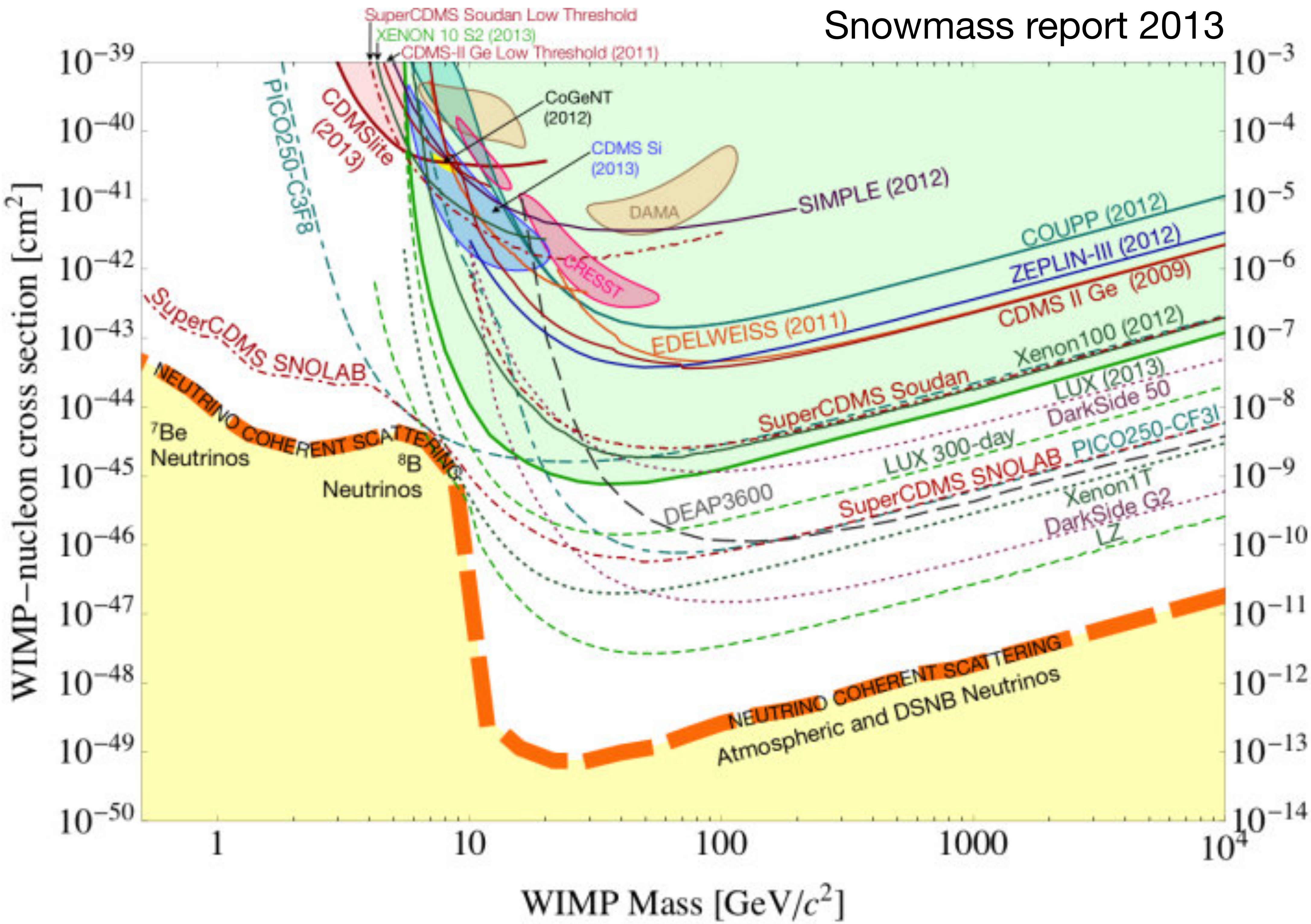
Be model independent



Kulkarni et. al. JCAP 1711 (2017) no.11, 016

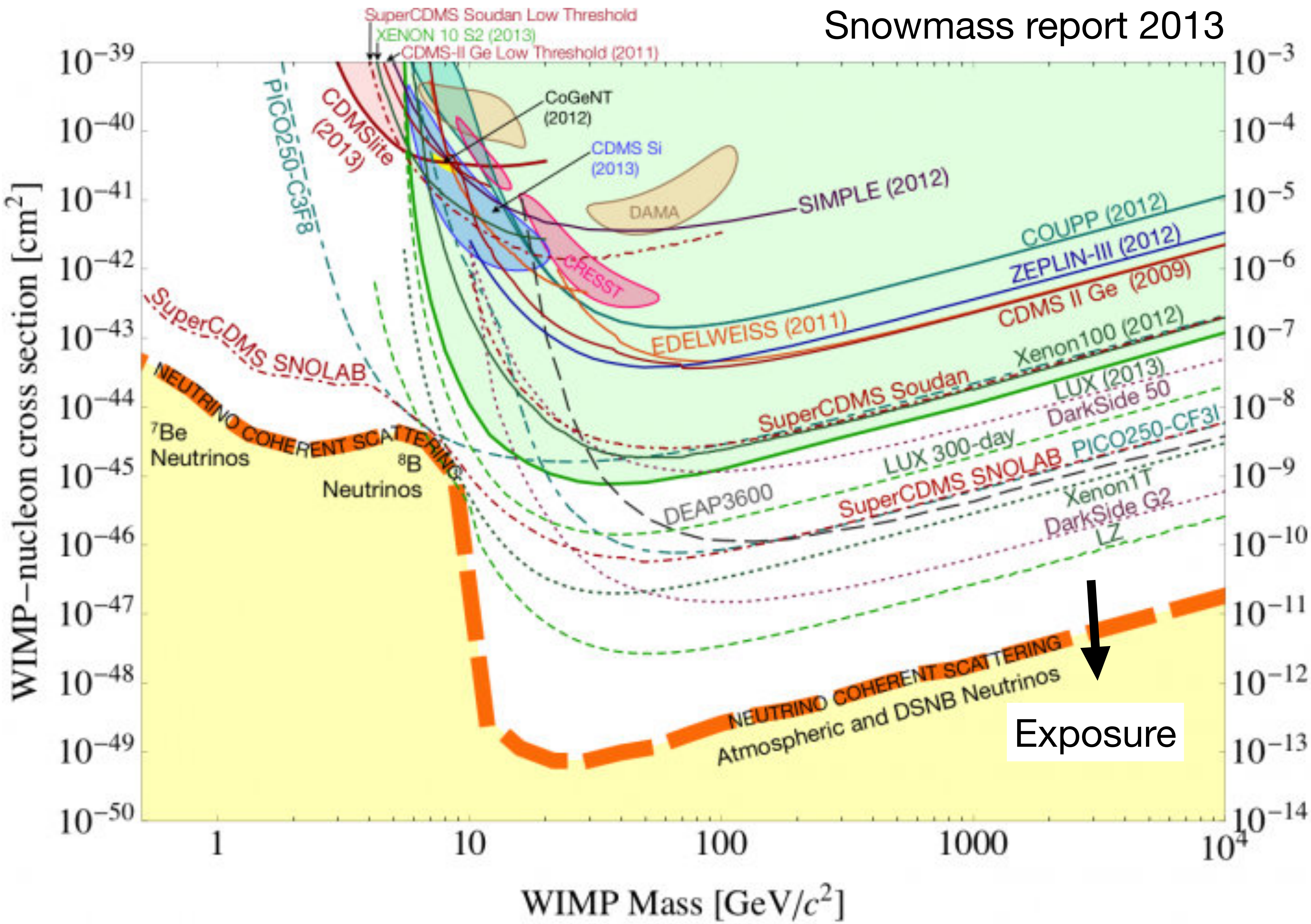
DM direct detection

Snowmass report 2013



DM direct detection

Snowmass report 2013



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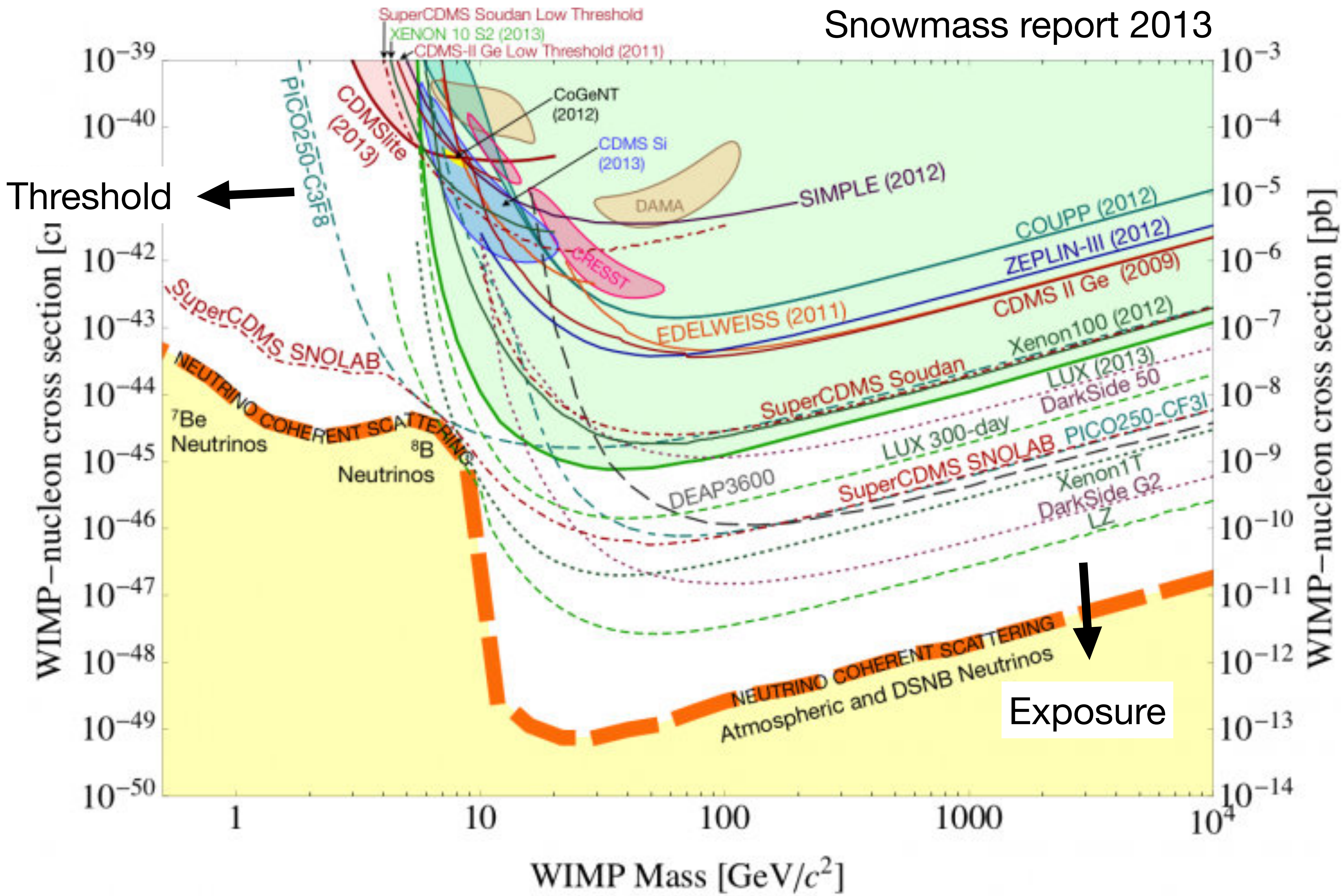
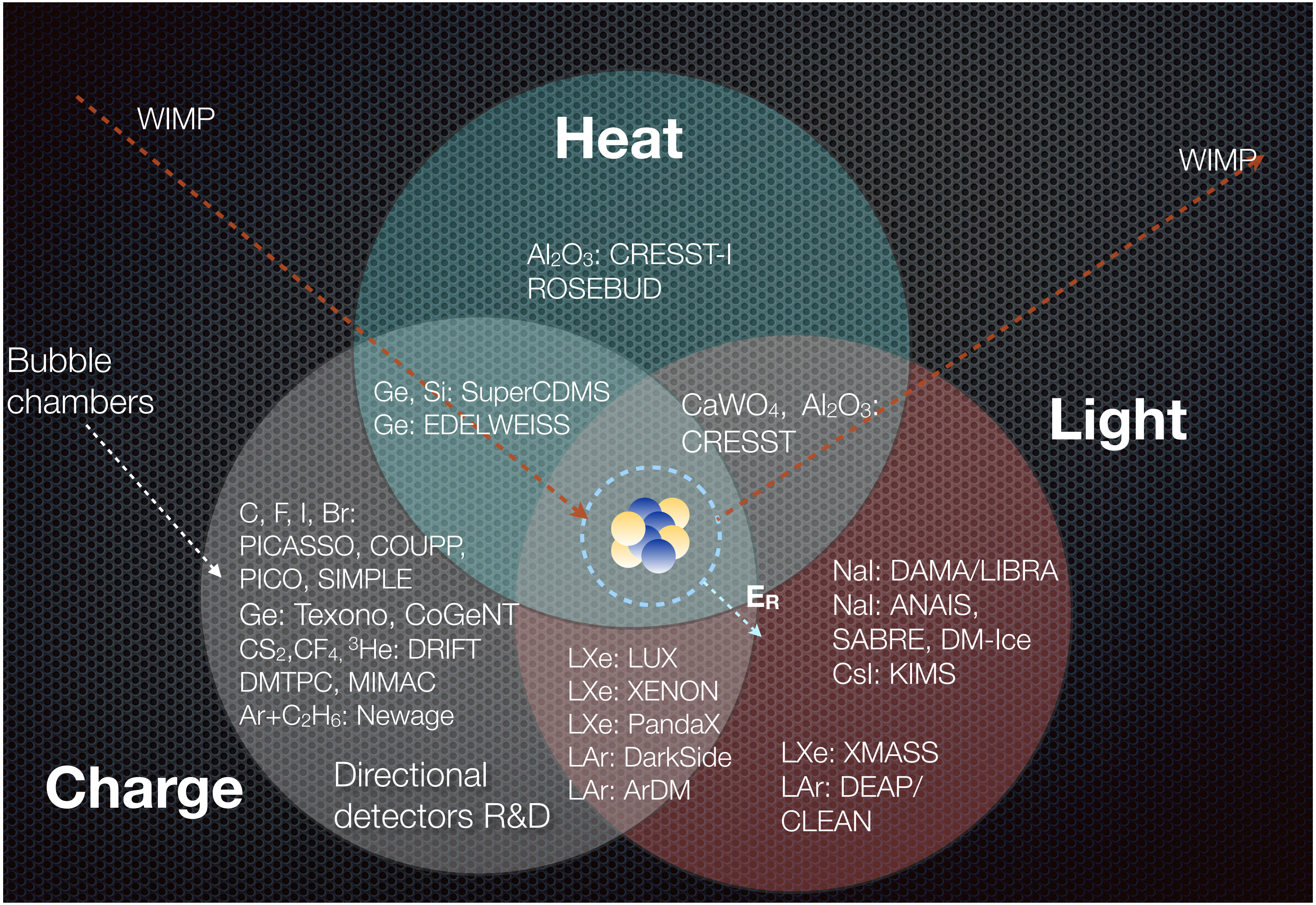
DM direct detection



S. Kulkarni

DM direct detection

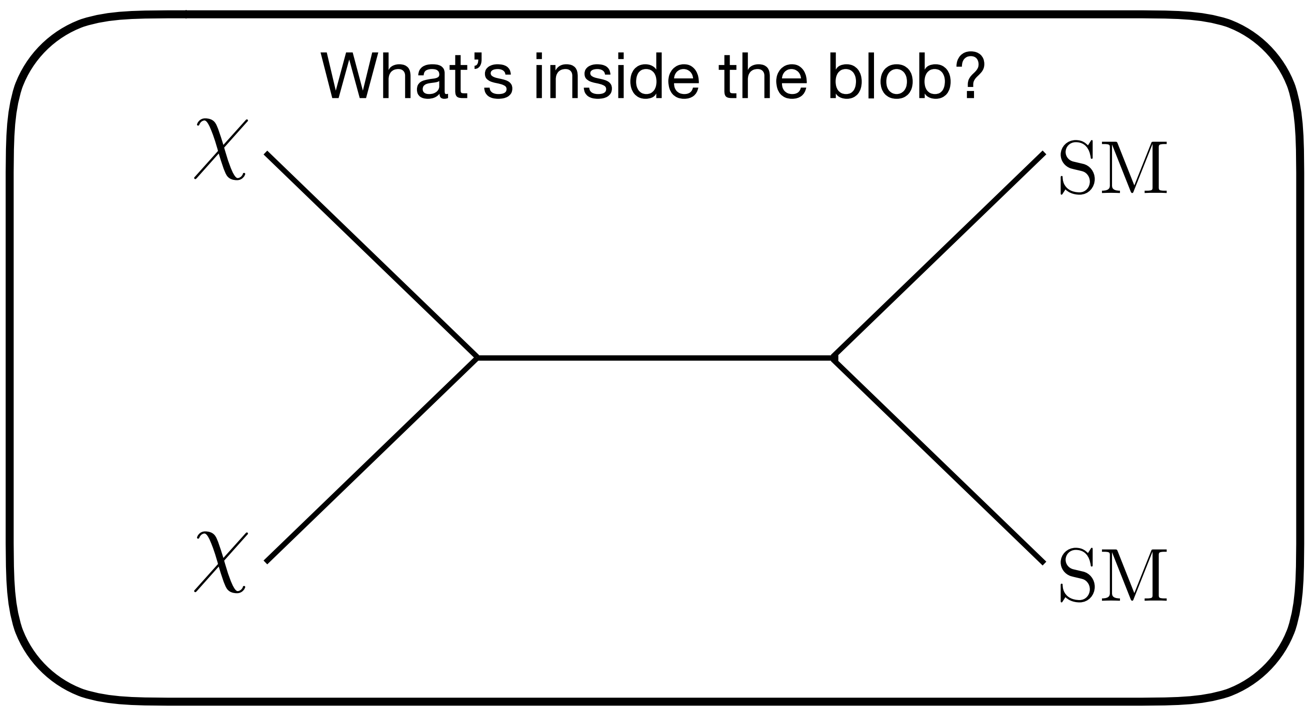


Shamelessly stolen from talk by L. Baudis

Looking inside the blob

Kulkarni et. al. JCAP 1711 (2017) no.11, 016

Be model independent



- Focus only on dark matter nucleus scattering

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Light mediators at direct detection

- Dark matter event rate at direct detection experiment for heavy mediators

$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}} = \frac{\rho_0}{m_\mathrm{DM}}\,\eta(v_\mathrm{min}(E_\mathrm{R}))\,\frac{g^2\,F_T^2(E_\mathrm{R})}{2\pi\,m_\mathrm{med}^4}$$

- Dark matter event rate at direct detection experiment for light mediators

$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}} = \frac{\rho_0\,\xi_T}{2\pi\,m_\mathrm{DM}}\,\frac{g^2\,F_T^2(E_\mathrm{R})}{\left(2\,m_T\,E_\mathrm{R} + m_\mathrm{med}^2\right)^2}\,\eta(v_\mathrm{min}(E_\mathrm{R}))$$

- Shape of differential event rate changes as soon as mediator mass is comparable to momentum transfer

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Light mediators at direct detection

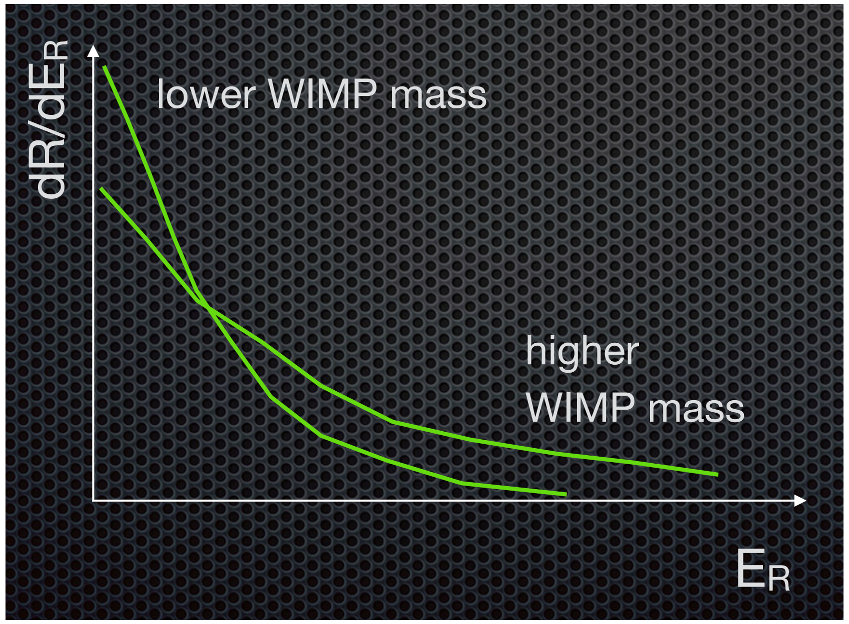
- Sharply falling recoil spectrum: need of very low threshold

See An et al. arxiv: 1412.8378 (PLB)

- Recoil spectrum shape important: need good energy resolution

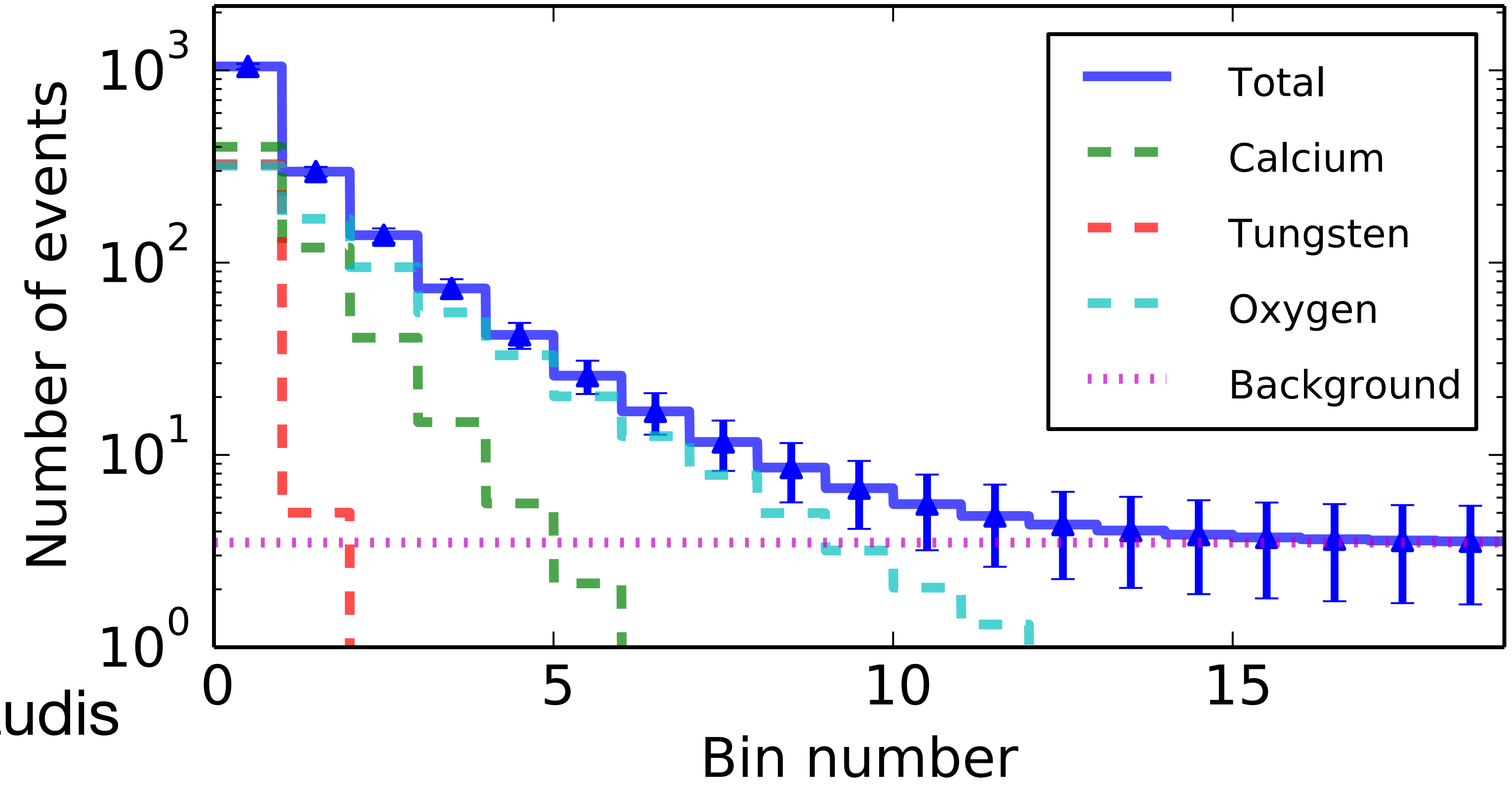
See Gelmini et al. arxiv:1612.09137

- Cryogenic detectors are ideal for this!



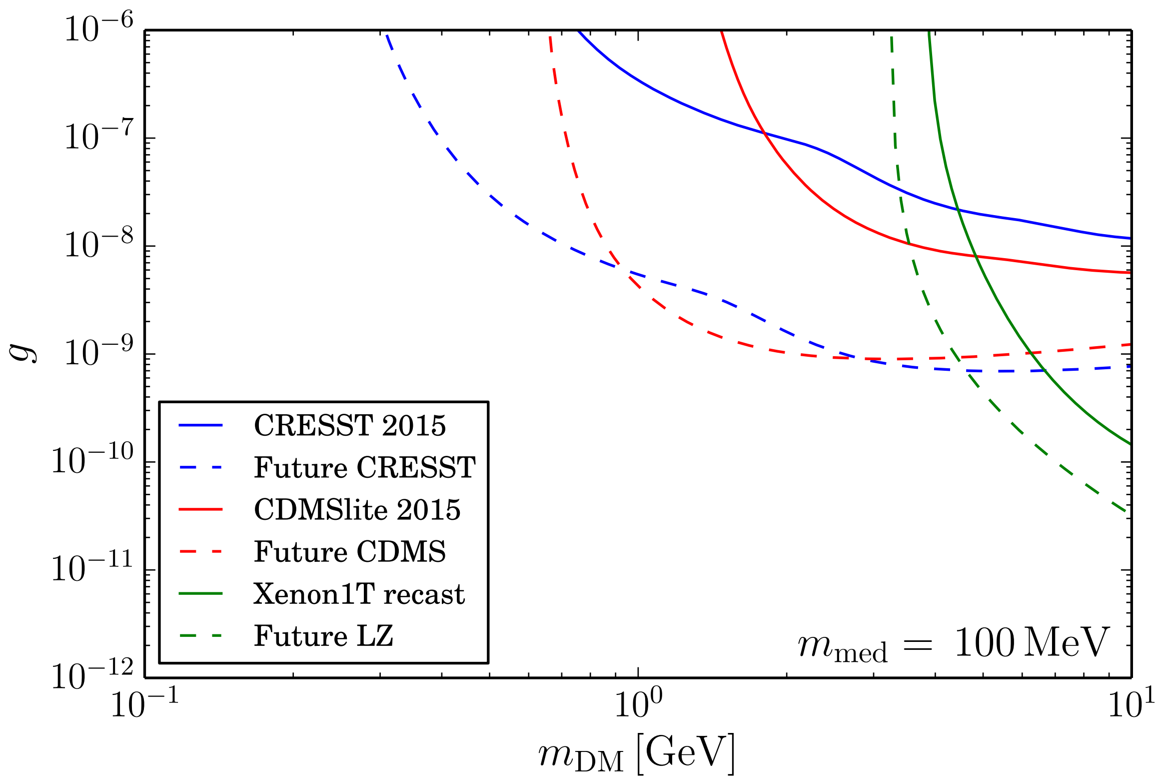
Shamelessly stolen from talk by L. Baudis

CRESST parameters

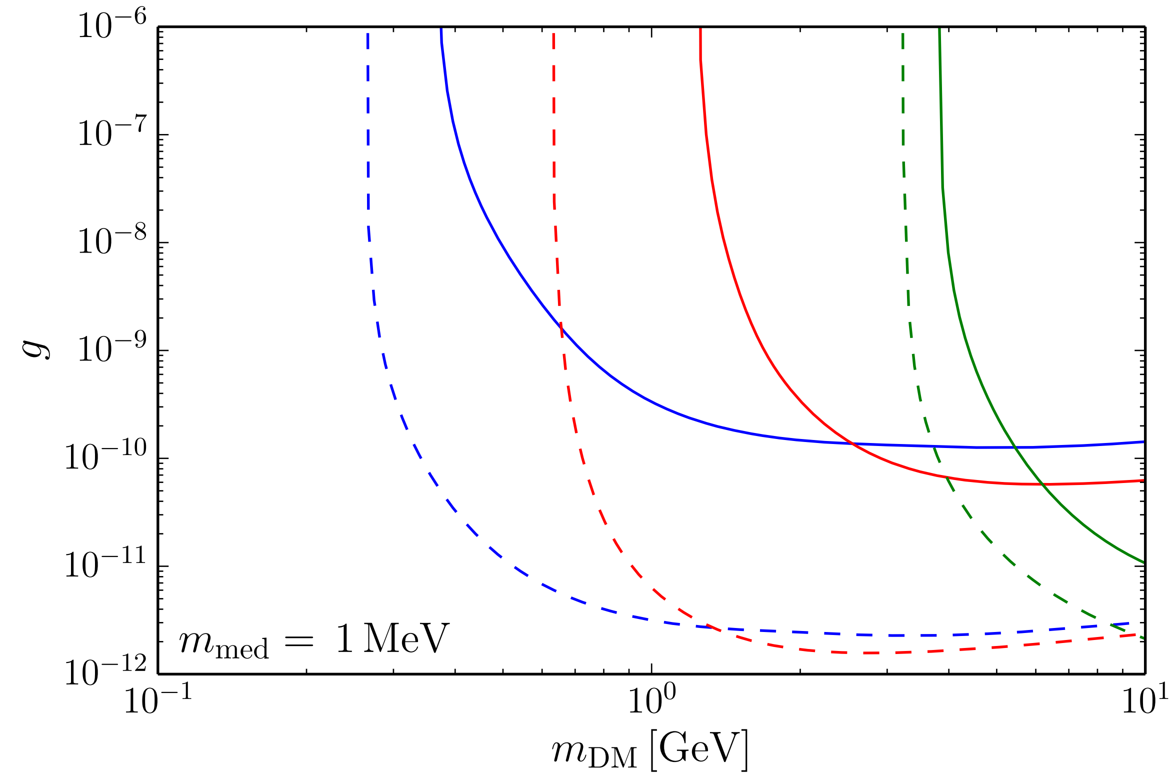


Contact interactions vs. light mediators

Traditional limits on DM space



Limits on models with light mediators



- g = product of SM - mediator and DM - mediator coupling
- Best sensitivity of cryogenic experiments for DM masses with light mediators ~ 10 GeV
- Two orders of magnitude improvement for effective coupling g, corresponds to up to four orders of magnitude in terms of the scattering rate.
- Thousands of events can be observed!!

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Upgrade plans - parameters

- CRESST III

See CRESST arXiv:1503.08065.

  - Molecular experiment: target $CaWO_4$, exposure: 1000 kg days
  - Energy threshold: 100 eV
  - Background level: 3.5 x 10^{-2} keV^{-1} kg^{-1} day^{-1} = 3.5 events each bin
  - Flat efficiency and Gaussian energy resolution of 20 eV

- SuperCDMS

See SuperCDM arXiv:1610.00006

  - High voltage Germanium, exposure 1.6 x 10^4 kg days
  - Energy threshold 100 eV (conservative)
  - Background level: 10 keV^{-1} kg^{-1} $year^{-1}$
  - Flat signal efficiency, energy resolution of 10 eV

Technical details

- Generate mock data and attempt reconstruction
- Likelihood function

$$-2\log\mathcal{L}^{\alpha}(\mathbf{x},\mathbf{y}) = 2\sum_i \left[R_i^{\alpha}(\mathbf{x},\mathbf{y}) + B_i^{\alpha}(\mathbf{y}) - N_i^{\alpha} + N_i^{\alpha}\log\frac{N_i^{\alpha}}{R_i^{\alpha}(\mathbf{x},\mathbf{y}) + B_i^{\alpha}(\mathbf{y})}\right]$$

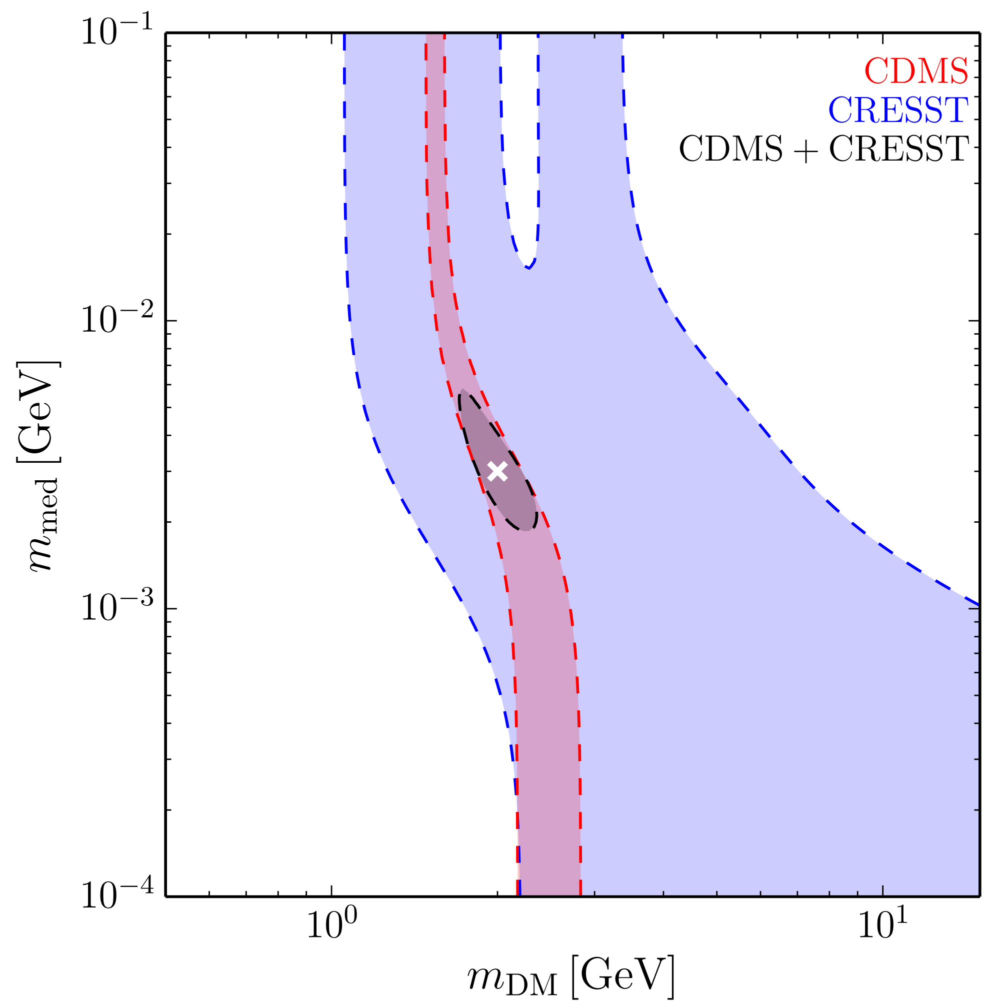
Particle physics parameters
Nuisance parameters
Predicted signal events
Predicted background events
Observed events

- Construct likelihood ratio (R), log likelihood follows a chi-square
- Exclude parameters, for two free parameter model if:

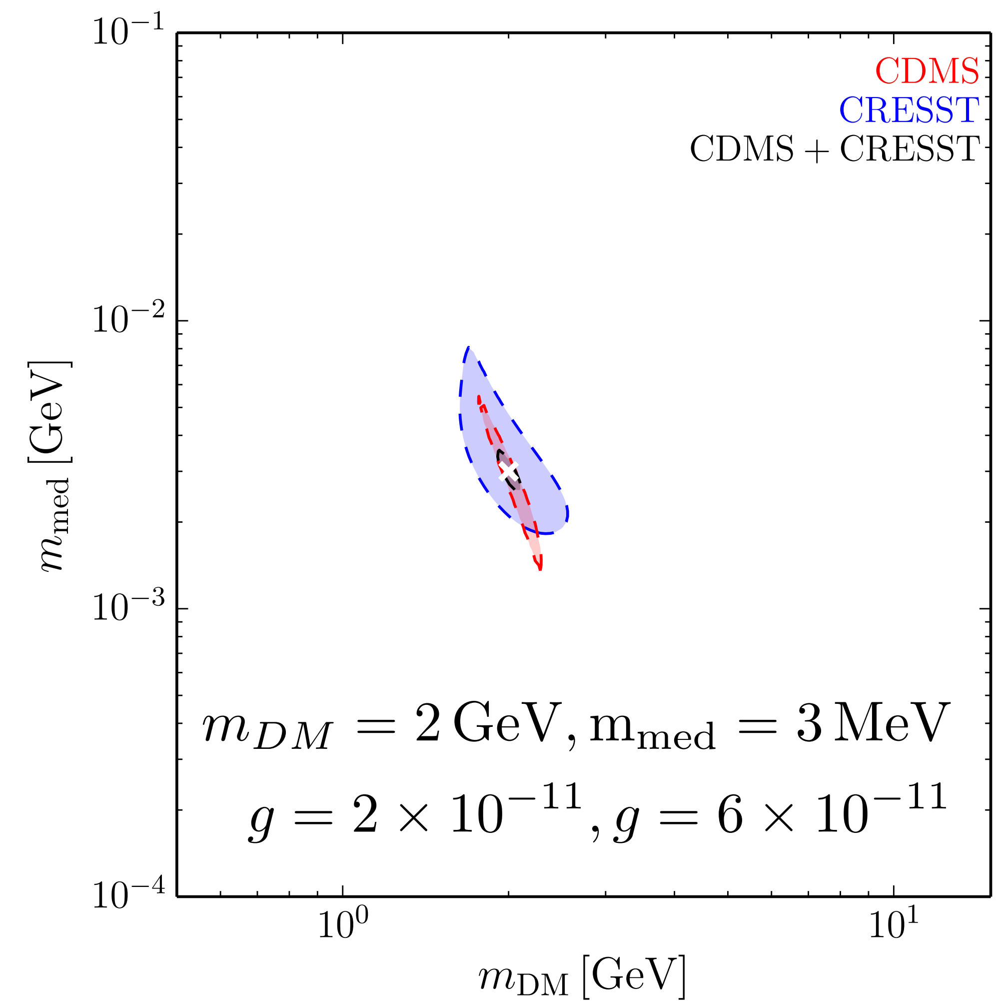
$$-2\log\mathcal{R} < 5.99$$

Let's be optimistic

Low statistics (~900 events)



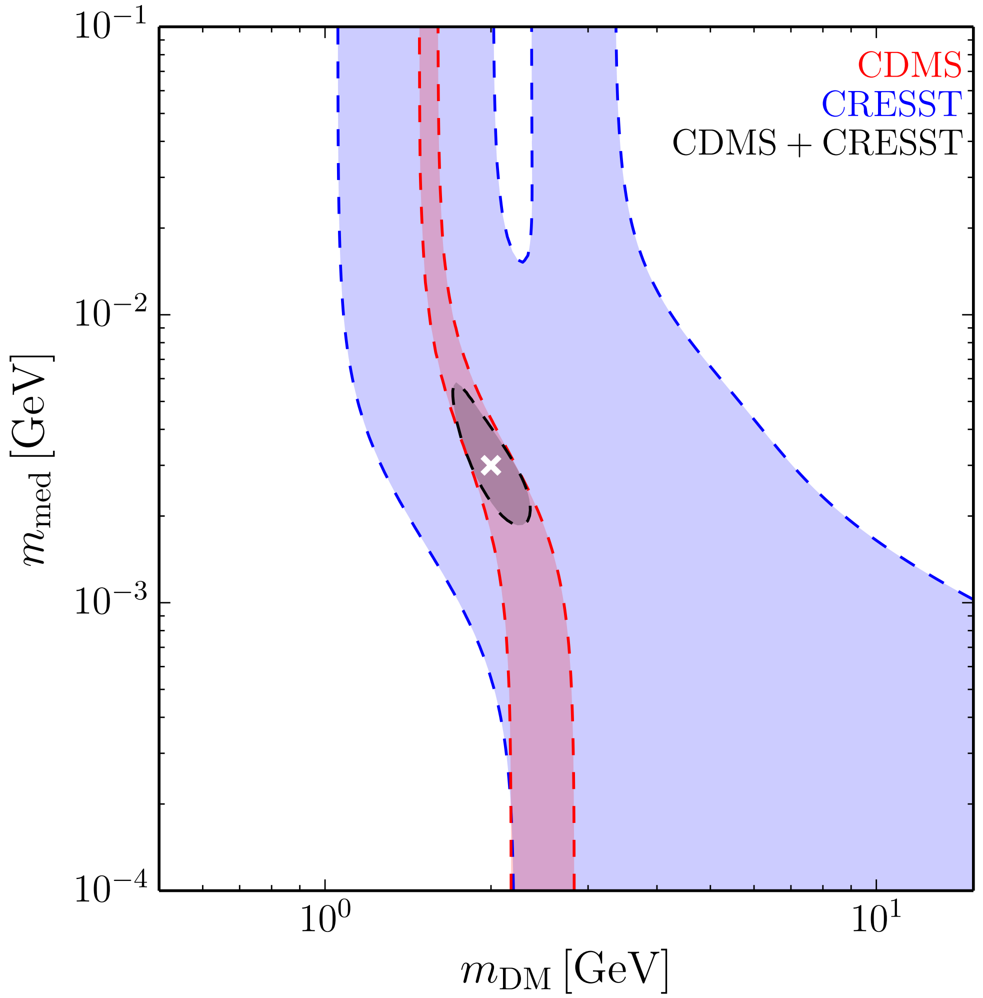
High statistics (8000 events total)



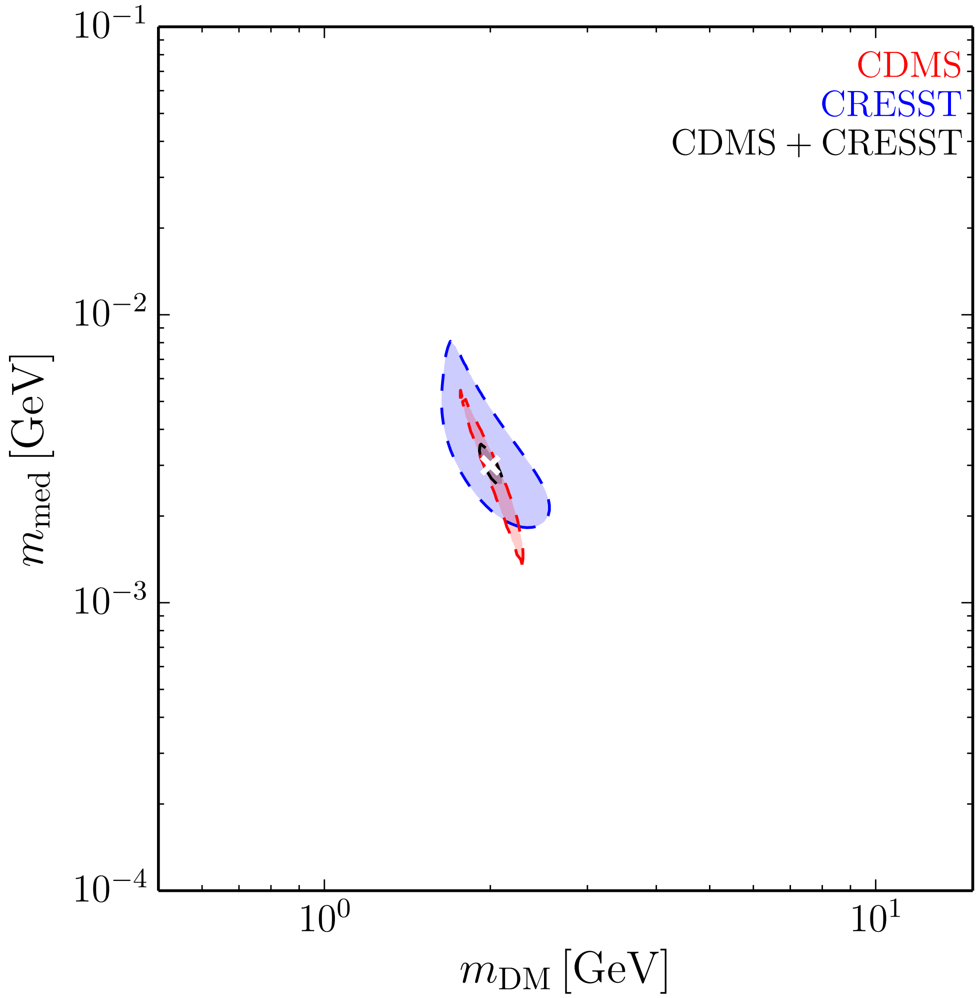
- Let us assume, we know the backgrounds, there are no astrophysical uncertainties, also let's assume DM couples to protons only
- Realistic treatment including detector resolution and background events
- Coupling g a nuisance parameter for reconstruction (fixed at max likelihood)

Let's be optimistic

Low statistics (~900 events)



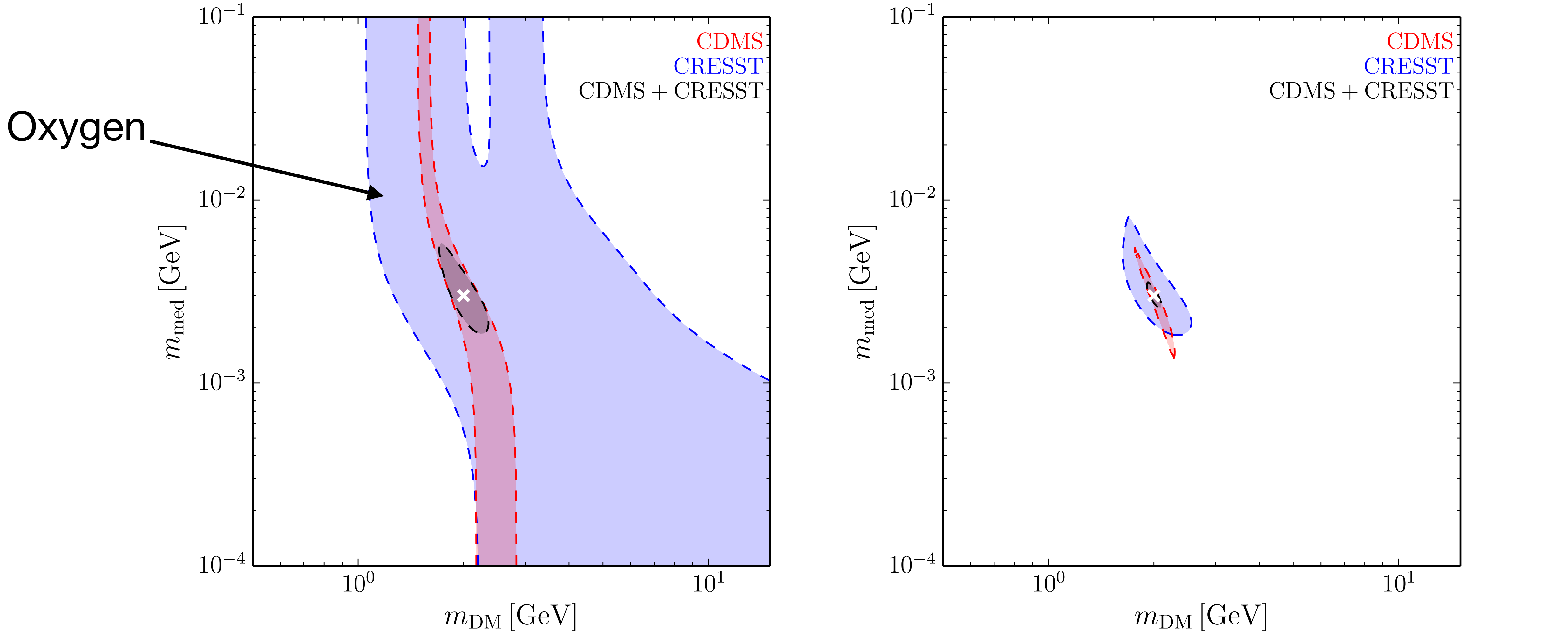
High statistics (8000 events total)



- Several target elements contribute to CRESST parameter reconstruction
  - For low masses oxygen contributes for high masses tungsten
- Very accurate reconstruction once SuperCDMS data is included
  - Four times more number of events at SuperCDMS

Let's be optimistic

Low statistics (~900 events) High statistics (8000 events total)



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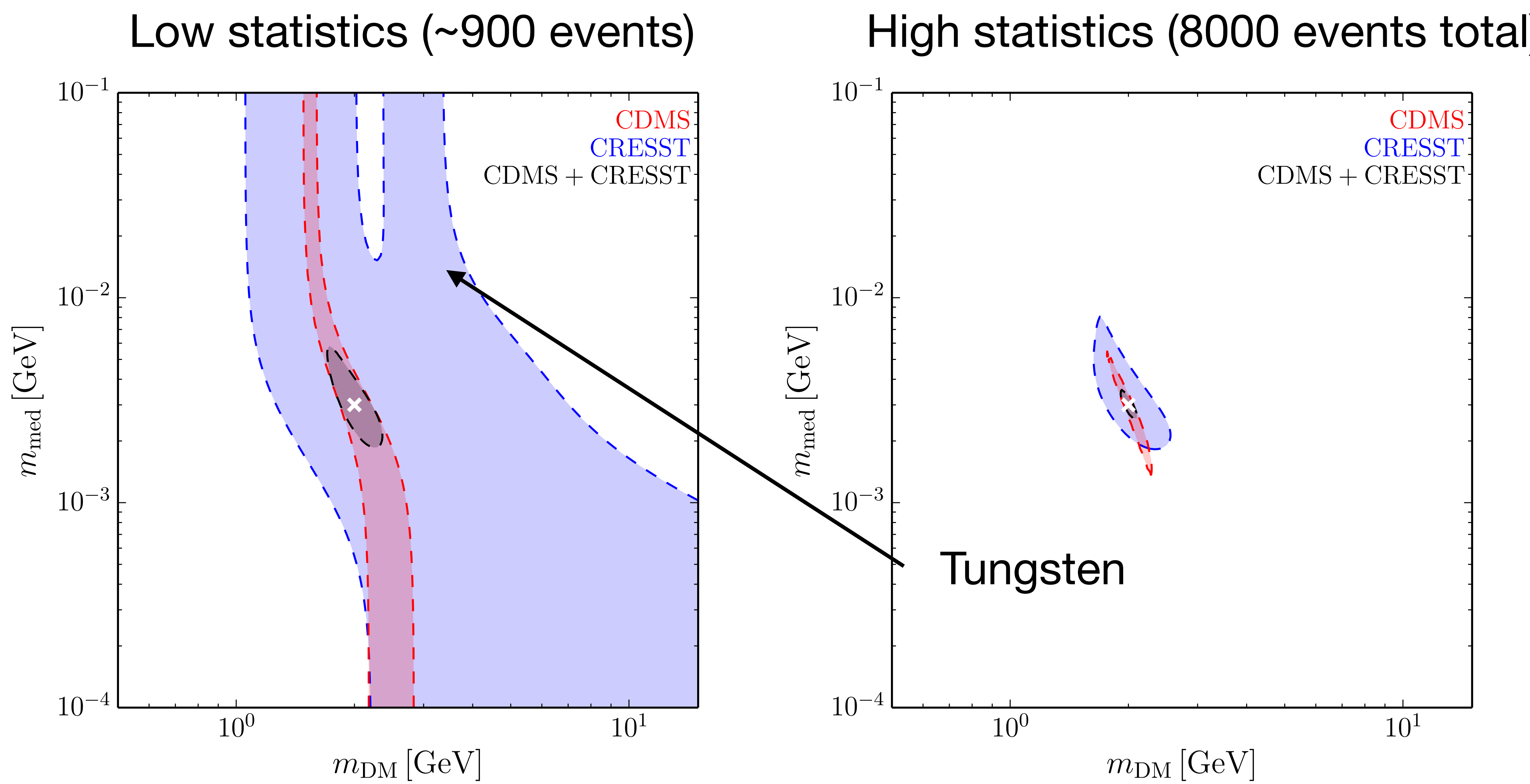
Let's be optimistic



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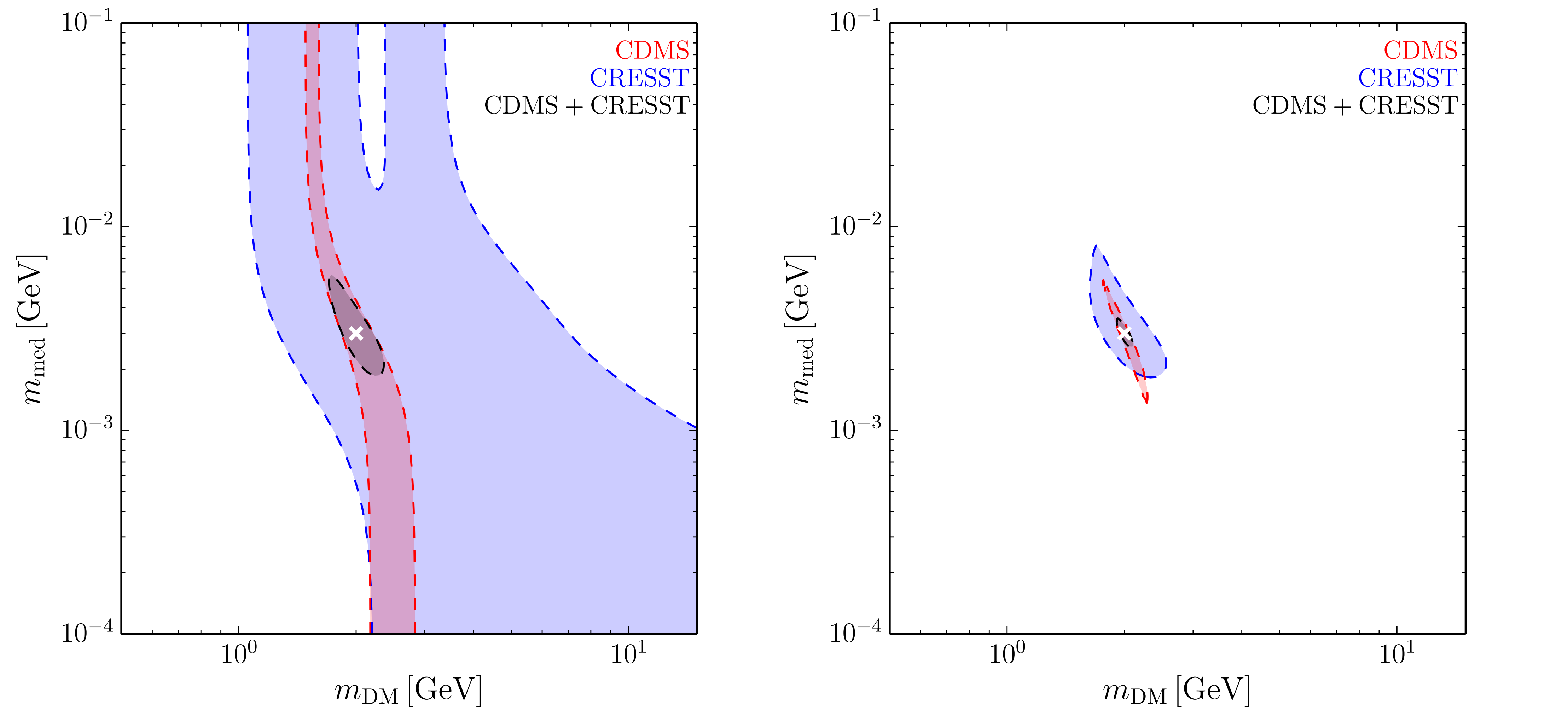

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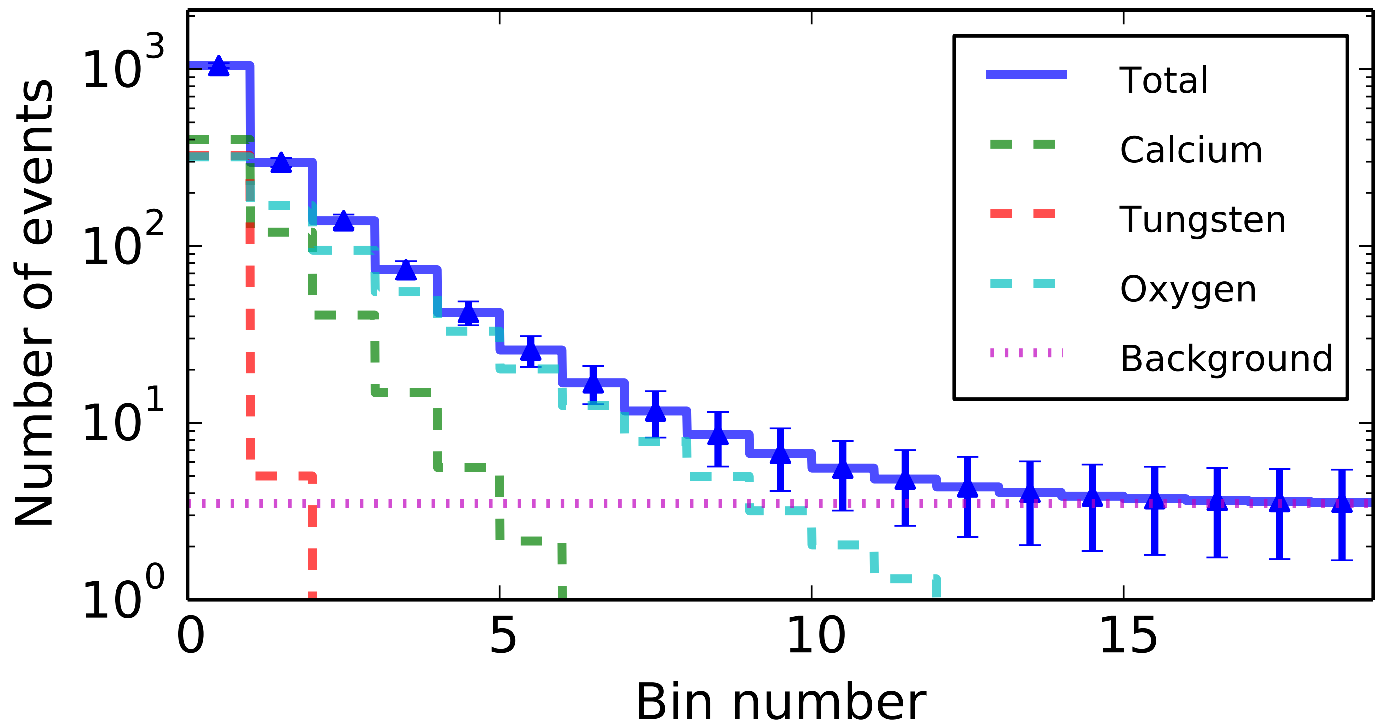
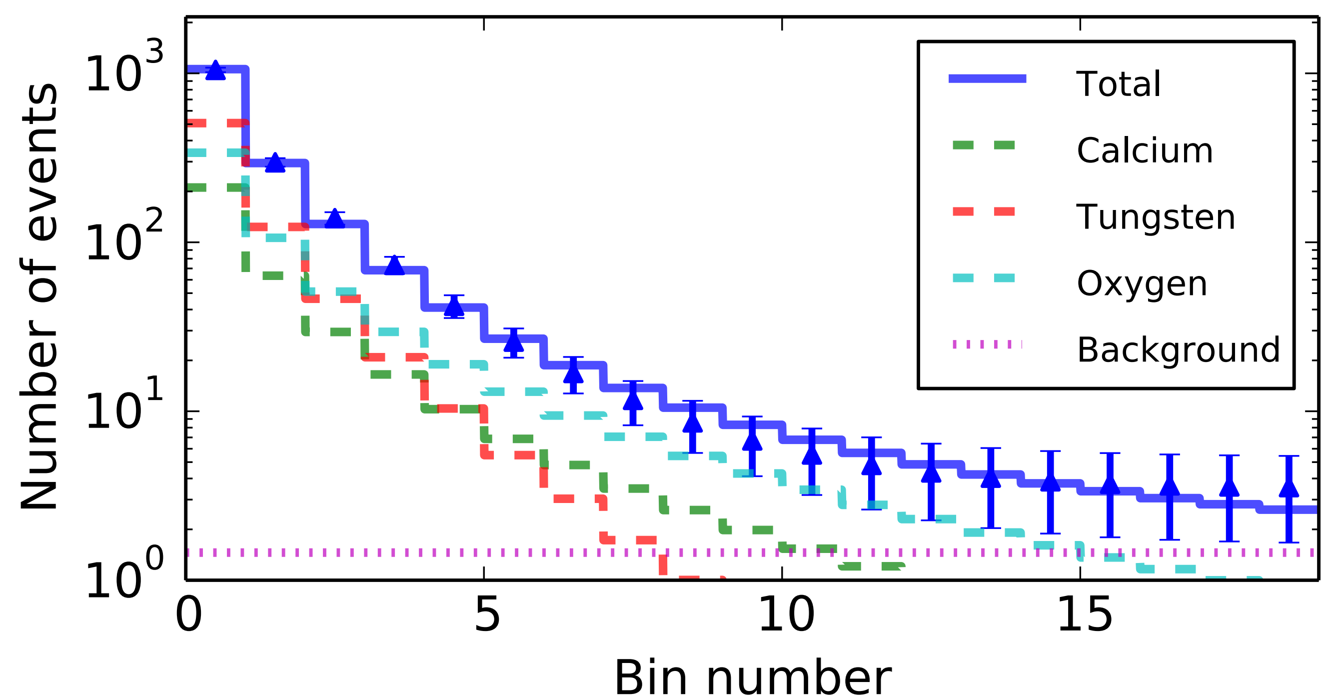
    - For low masses oxygen contributes for high masses tungsten
- Very accurate reconstruction once SuperCDMS data is included
    - Four times more number of events at SuperCDMS

Tungsten contribution



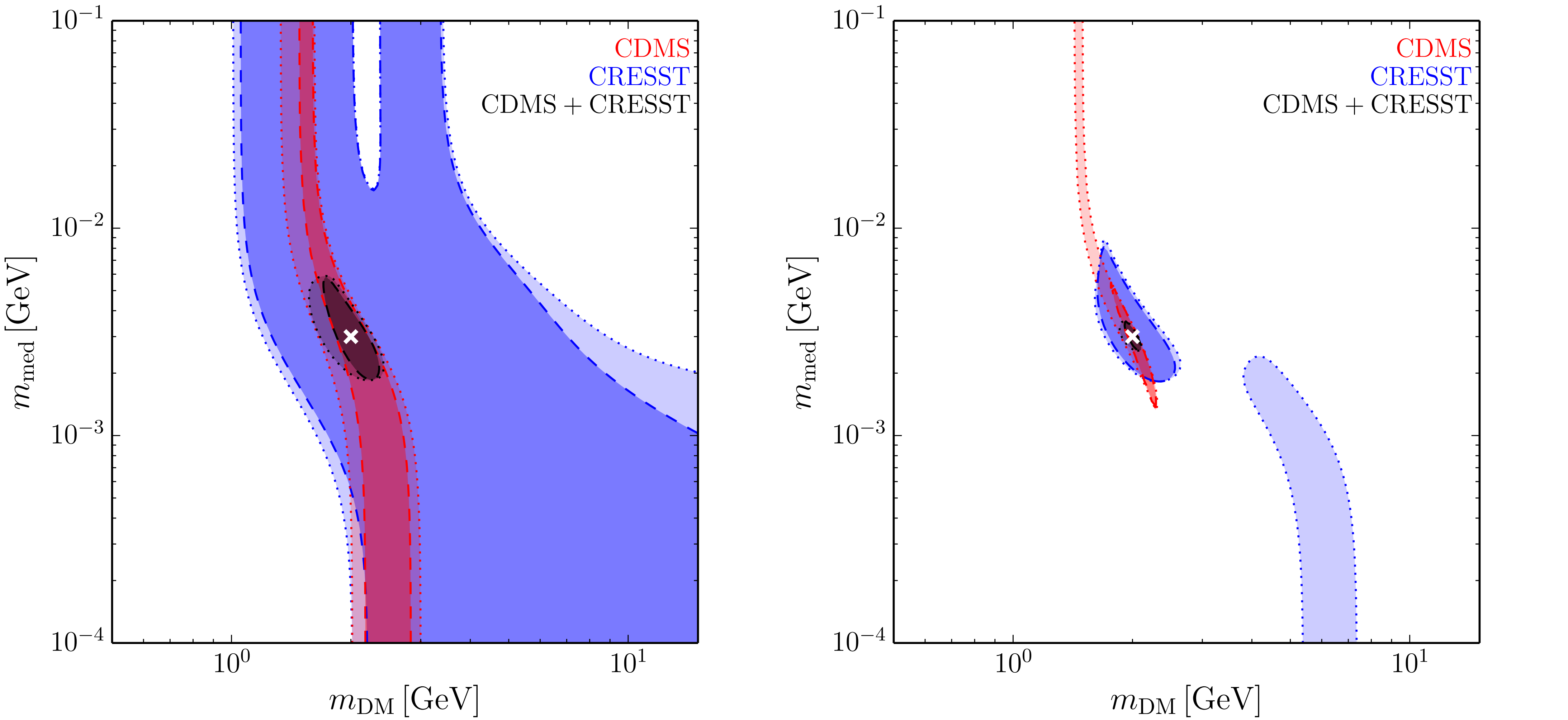
- True parameters

- False parameters



Let's be realistic

Low statistics (~900 events) High statistics (8000 events total)

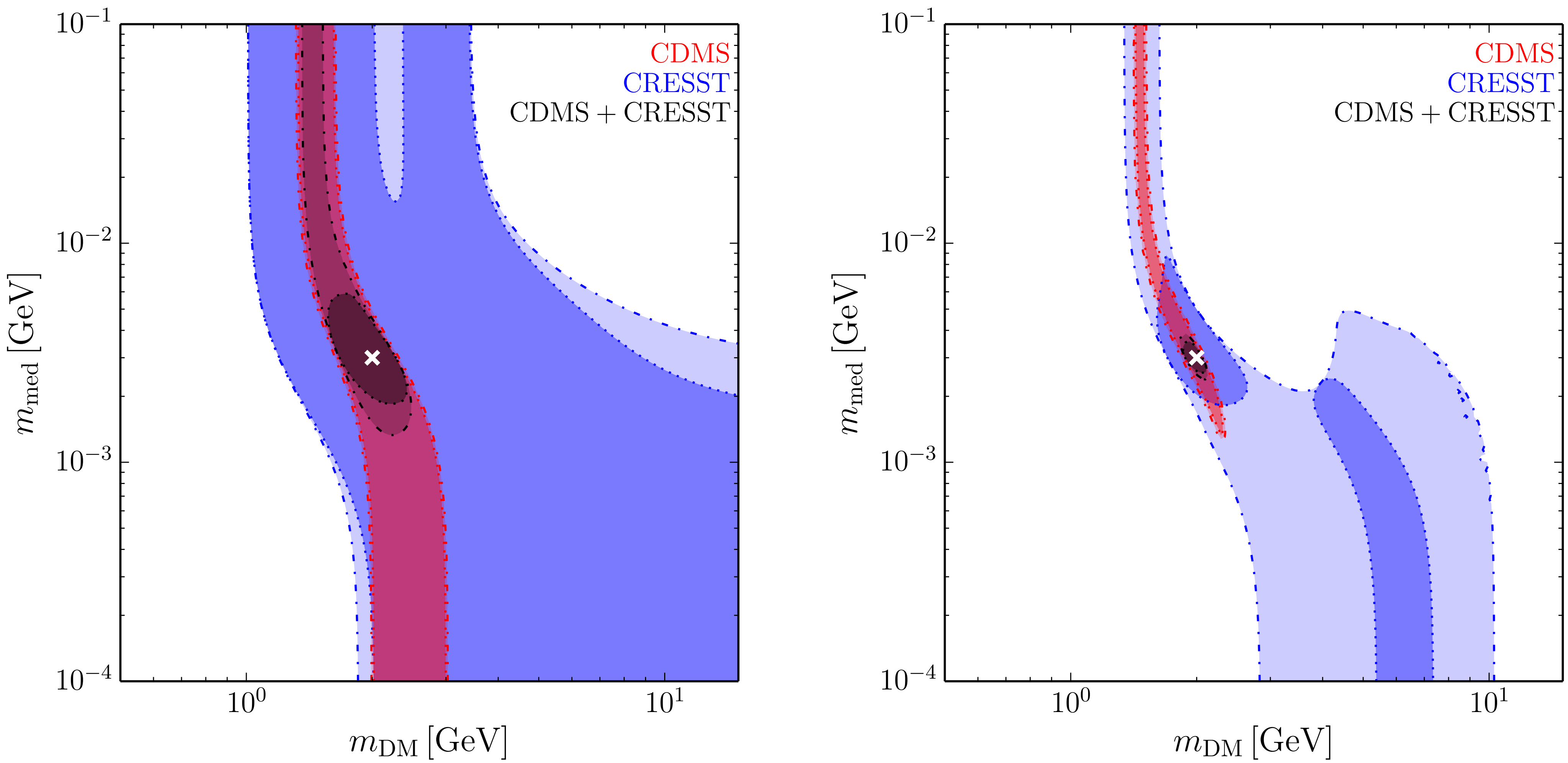


- Characteristic tilt: light mediators needed for heavier masses and vice versa
- Nuisance parameter for background normalisation: shape known, normalisation unknown
- Degeneracy between DM mass, coupling and mediator mass removed by combination of data - accurate reconstruction

Let’s be realistic

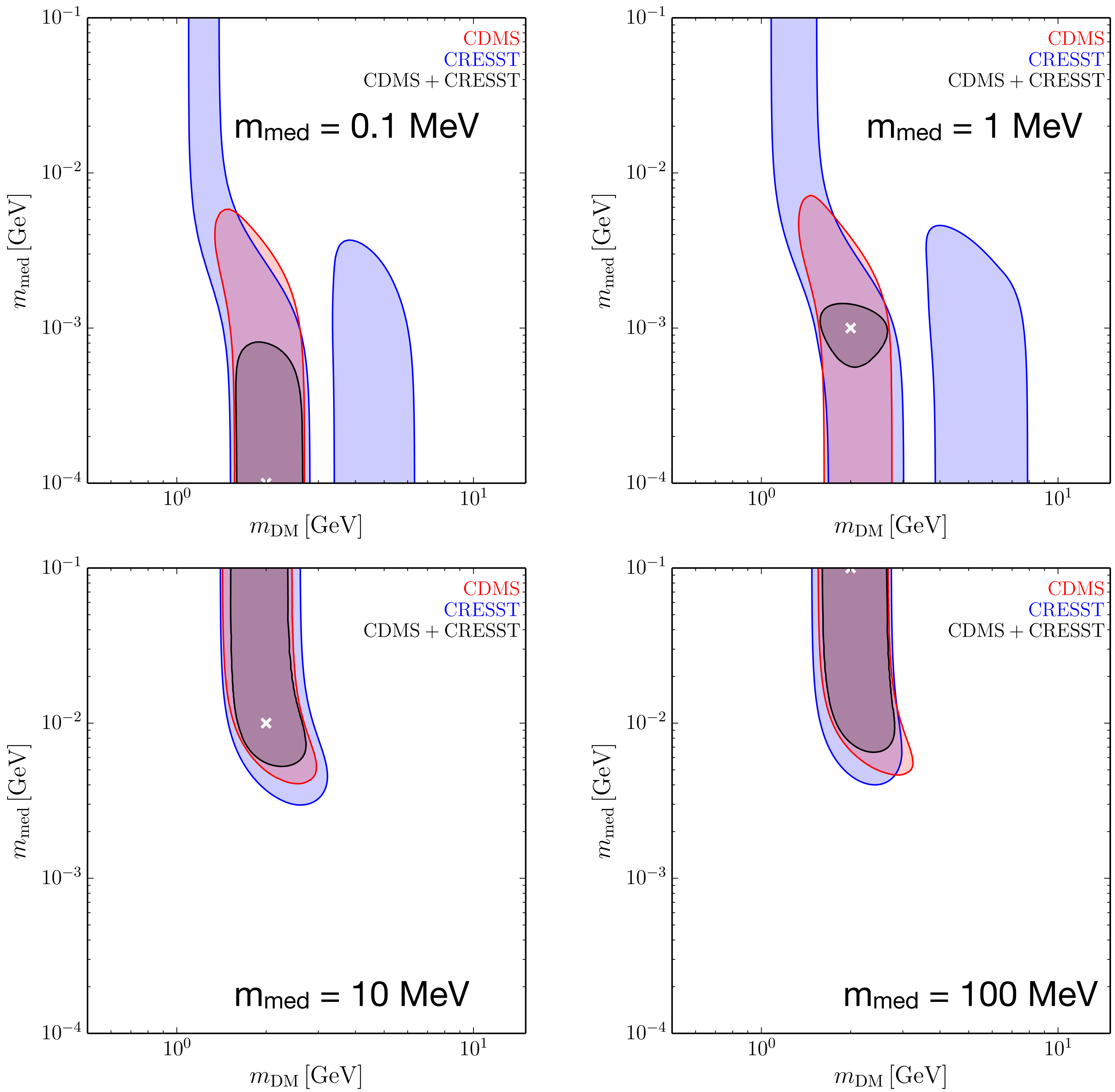
Low statistics (~900 events)

High statistics (8000 events total)



- Nuisance parameter for unknown ratio of proton to neutron coupling
- Ability of CRESST to reconstruct parameters significantly reduced when coupling let vary

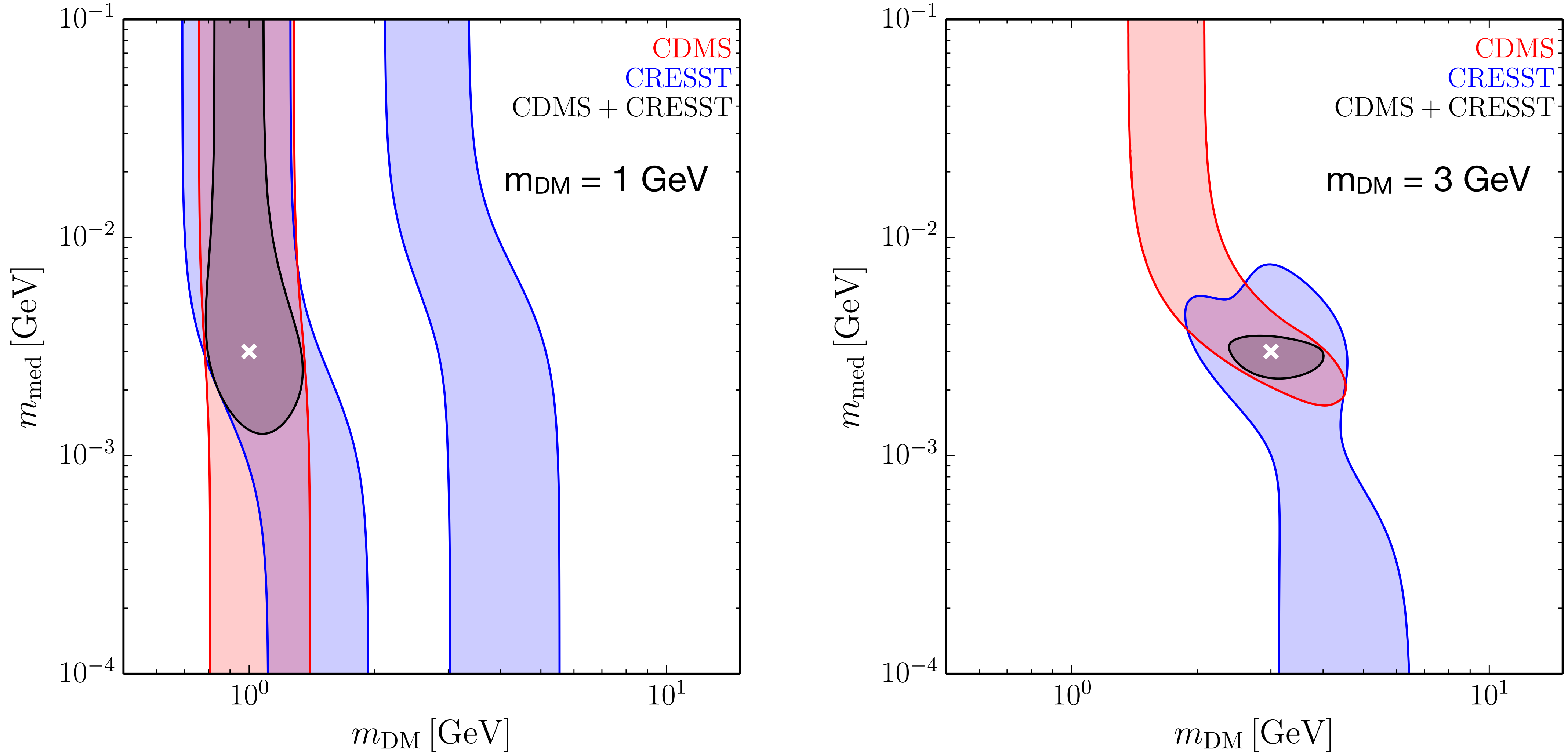
Alternative benchmarks



- Works for limited ranges
- In each case it is possible to rule out contact interaction or light mediators

Fixed m_{DM} = 2 GeV
High statistics case

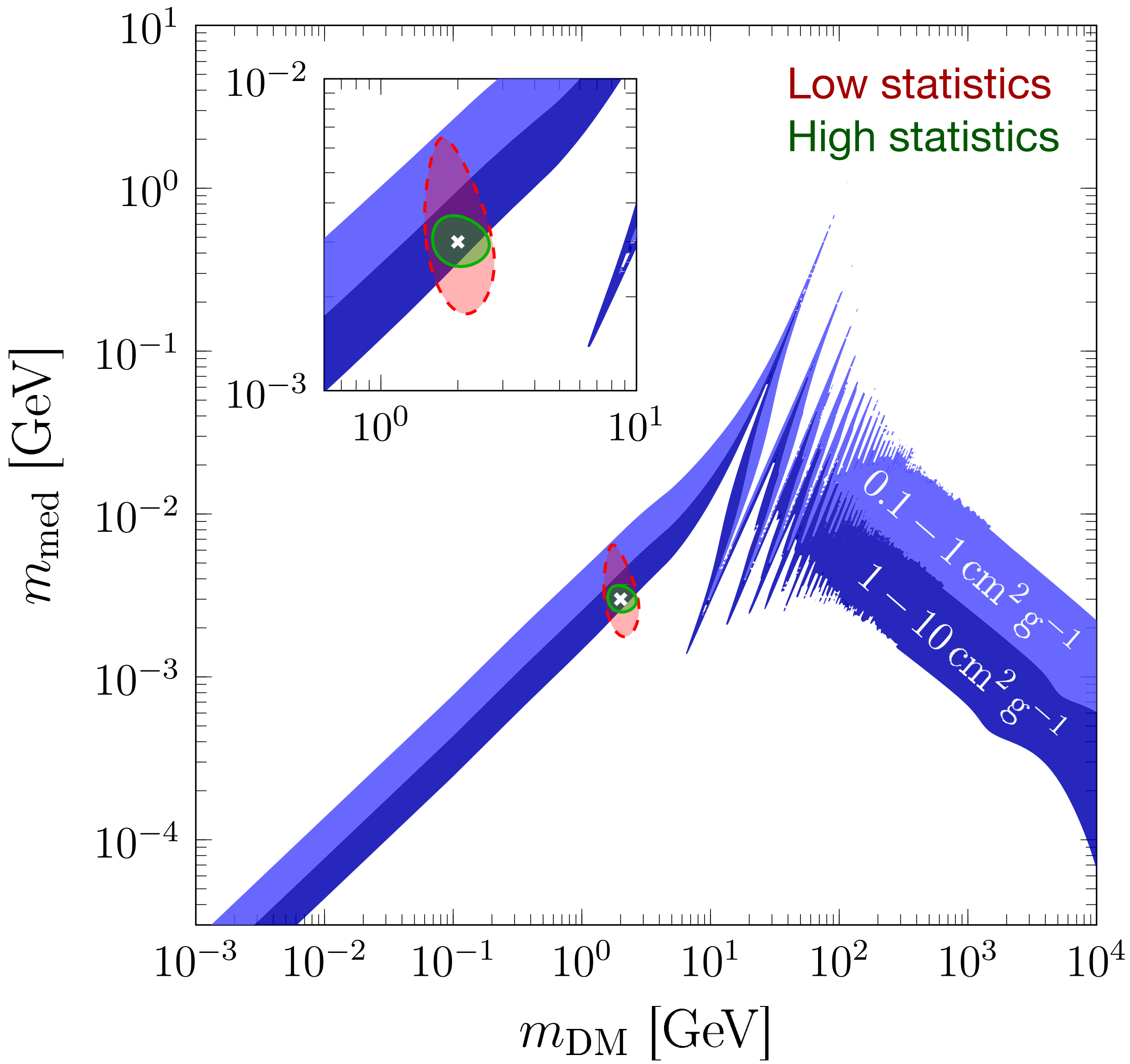
Alternative benchmarks



- Qualitatively similar results
- Decreasing mass -> loss in sensitivity
  - Less statistics, worse reconstruction
  - Oxygen, Tungsten degeneracy

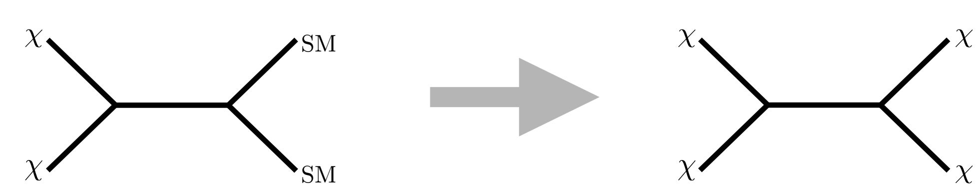
m_{med} = 3 MeV
g = 6 x 10^{-11}

Self-interacting DM



See also
Vogelsberger et al. arXiv:1211.1377
Chen et al. arXiv:1505.03781
Del Nobile et al. arXiv:1507.04007

For plot:
Tulin et. al. arXiv:1302.3898



- Within **specific model** (not a general conclusion)
- Fermionic DM, scalar mediator
  - Relic via dark sector freeze out and mediator decay via Higgs mixing

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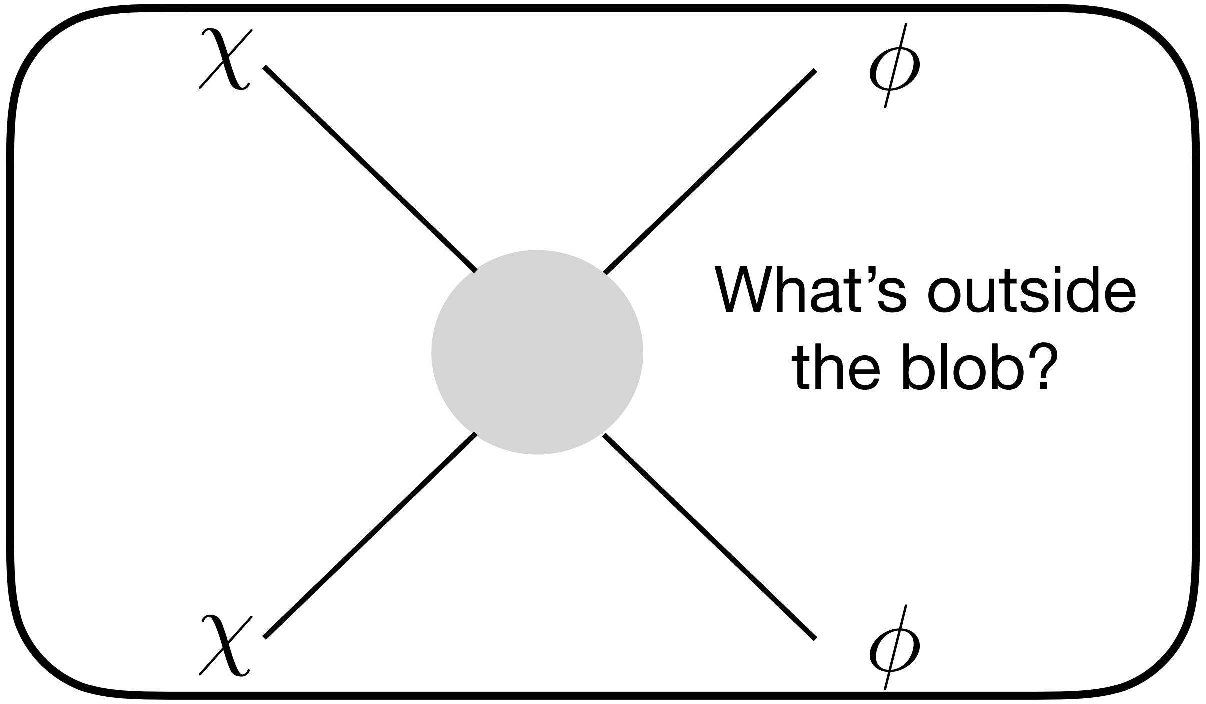
Looking at the other side of blob

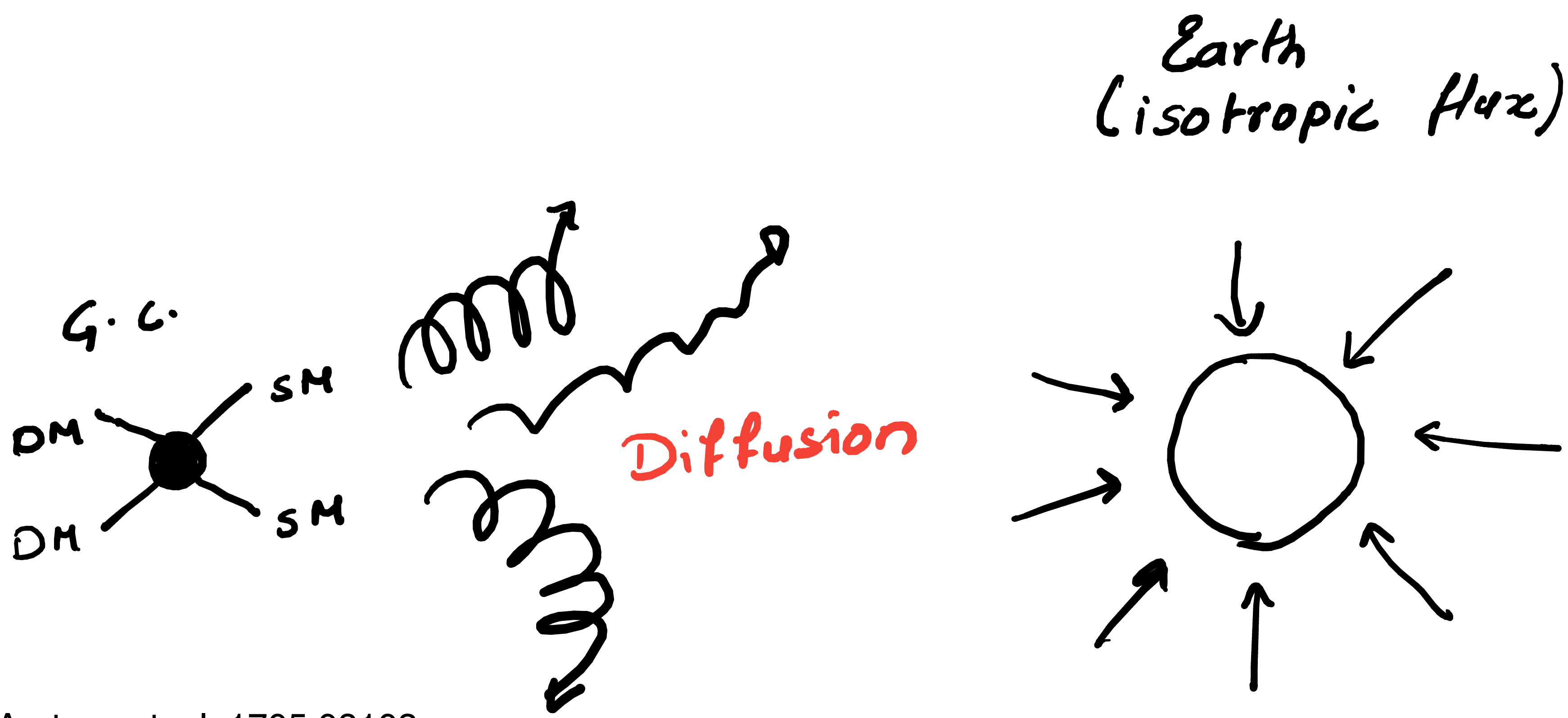
Be model independent



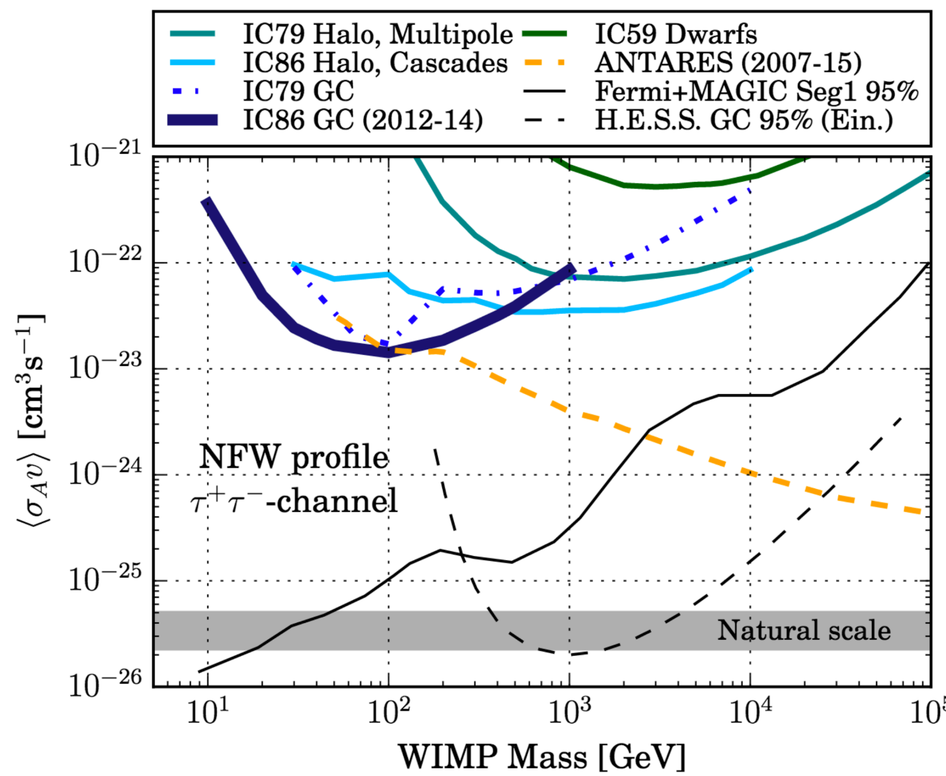
Kulkarni et. al. JCAP 1711 (2017) no.11, 023

Indirect detection

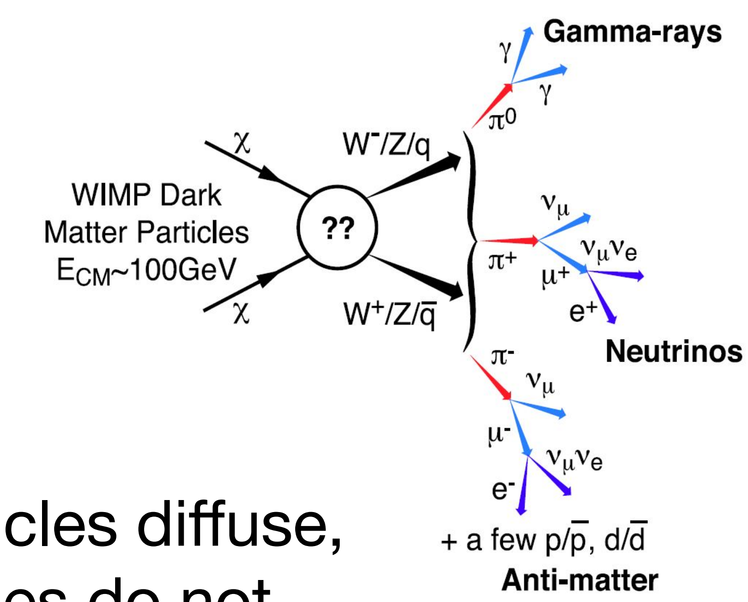
Top view



Aartsen et. al. 1705.08103

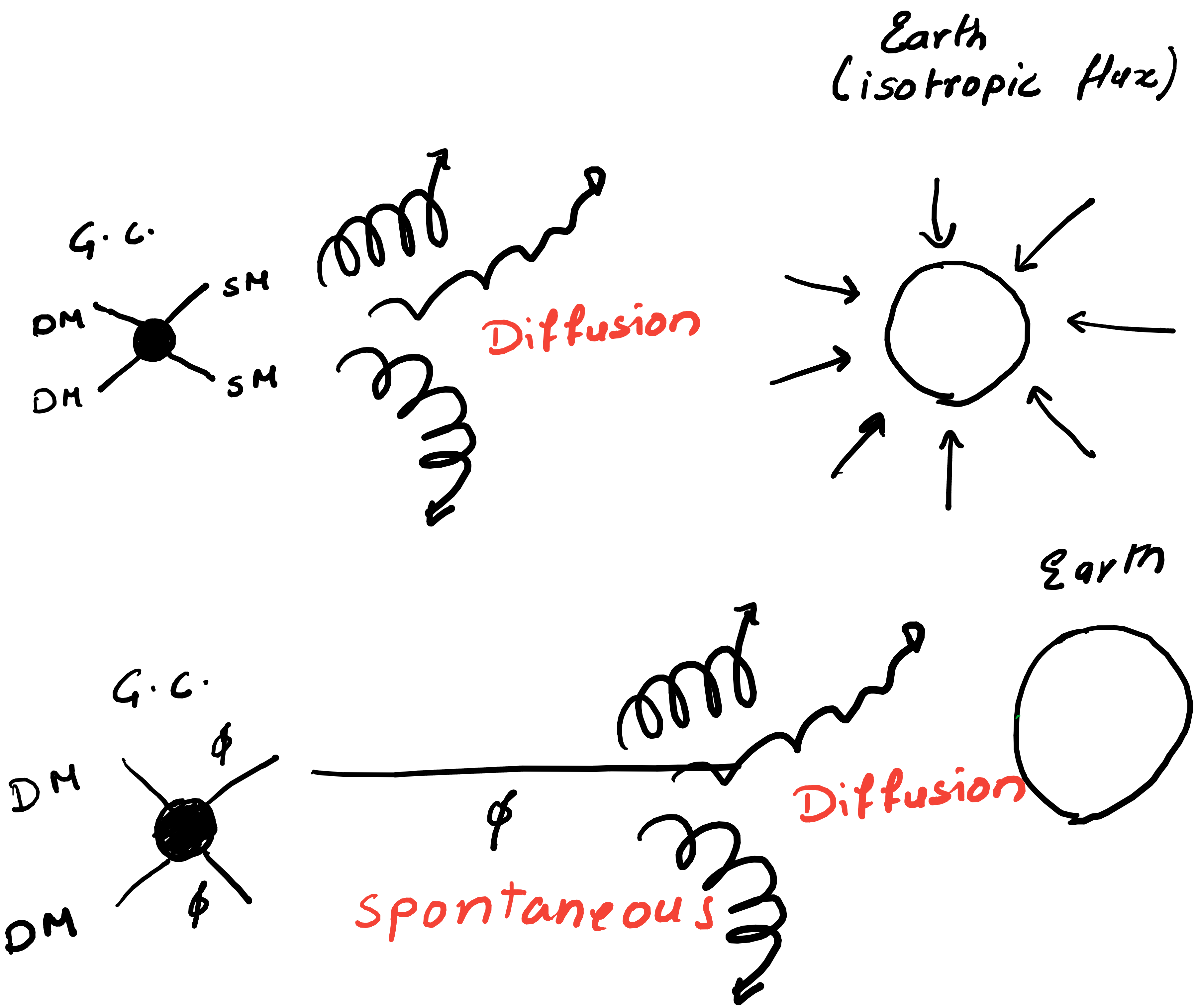


Charged particles diffuse, neutral particles do not



Indirect detection

Top view



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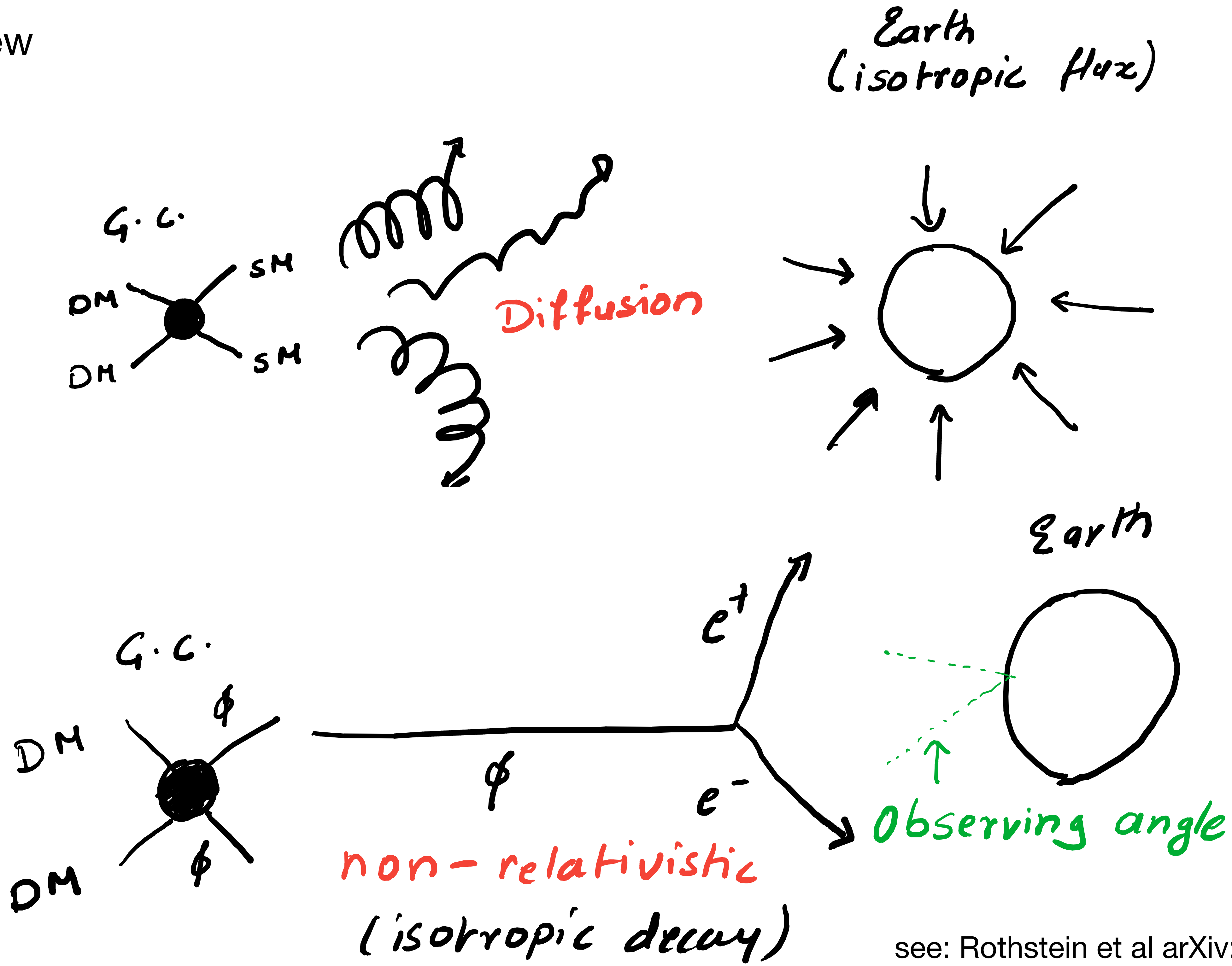
Indirect detection

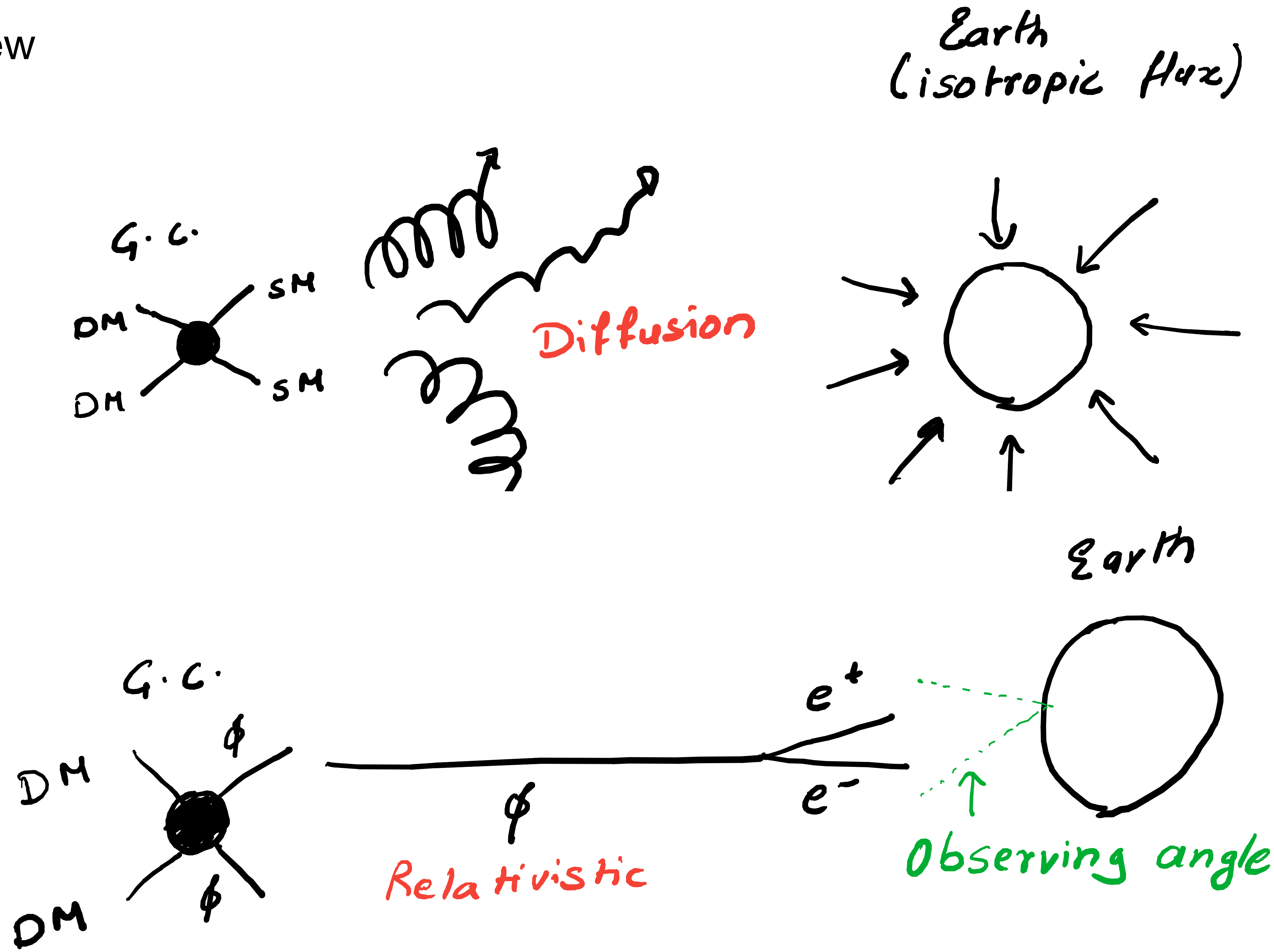
Top view



see: Rothstein et al arXiv: 0903.3116

Indirect detection

Top view



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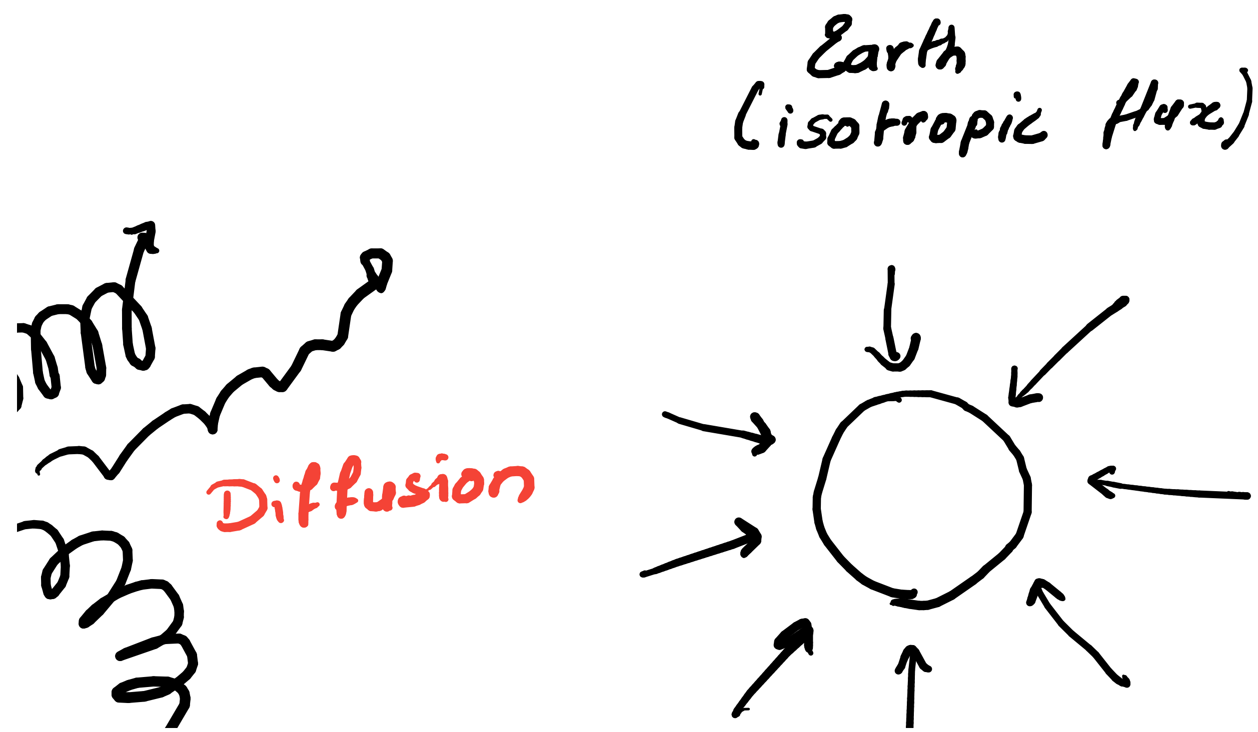
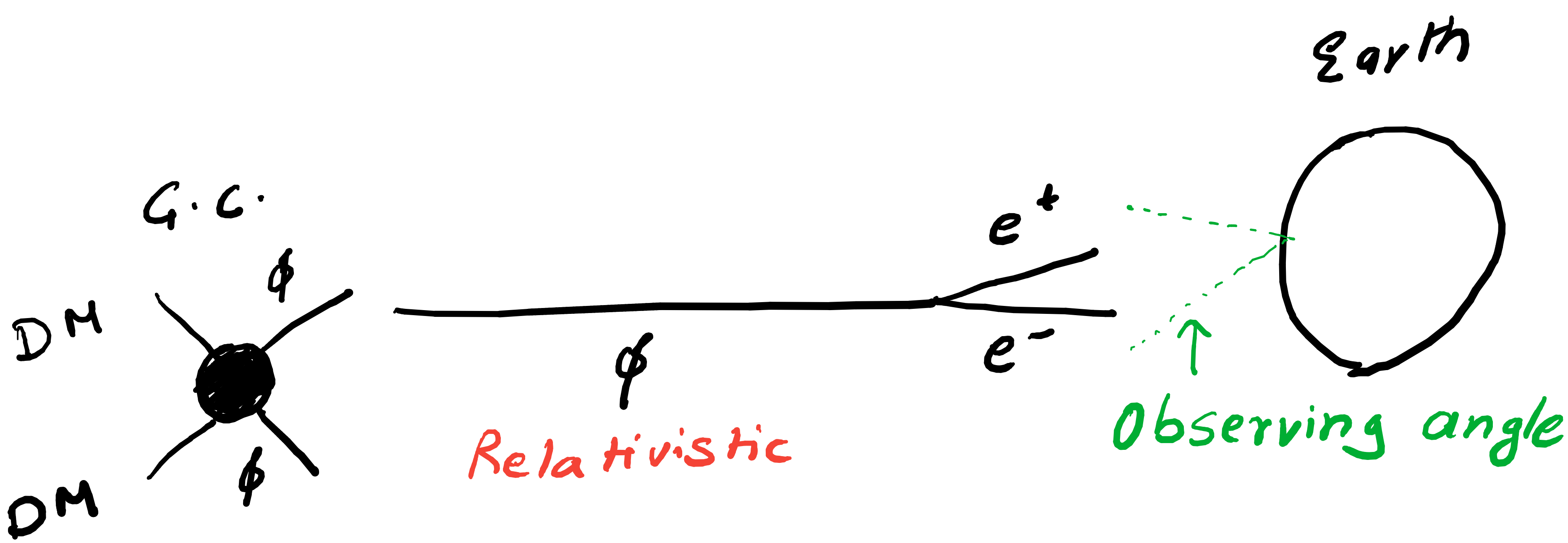
Indirect detection

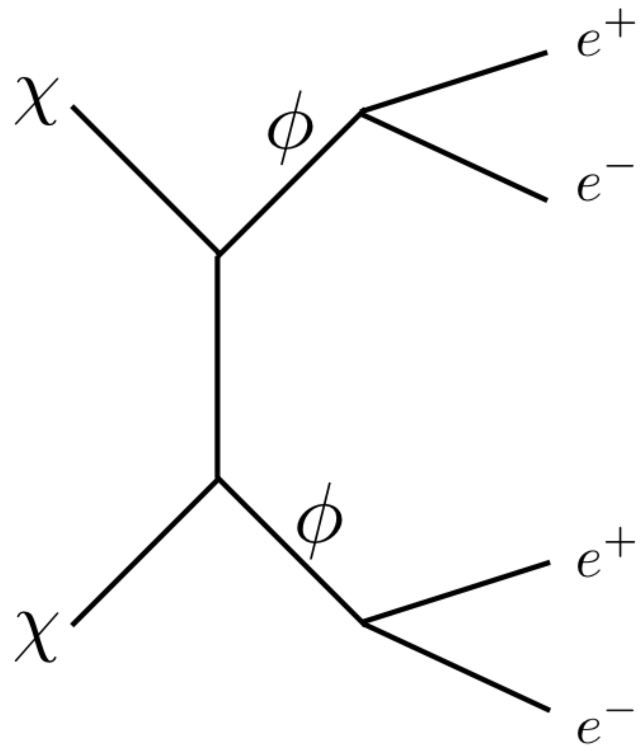
Top view

Fun fact: Drawing such funny cartoons on flight leads to a scicomm opportunity





DM with long lived mediator



For non-relativistic mediator propagation see: Rothstein et al arXiv: 0903.3116
For complementary detection techniques from Sun see: Batell et al. arXiv:0910.1567

- DM particle undergo annihilation into mediator, which is long lived

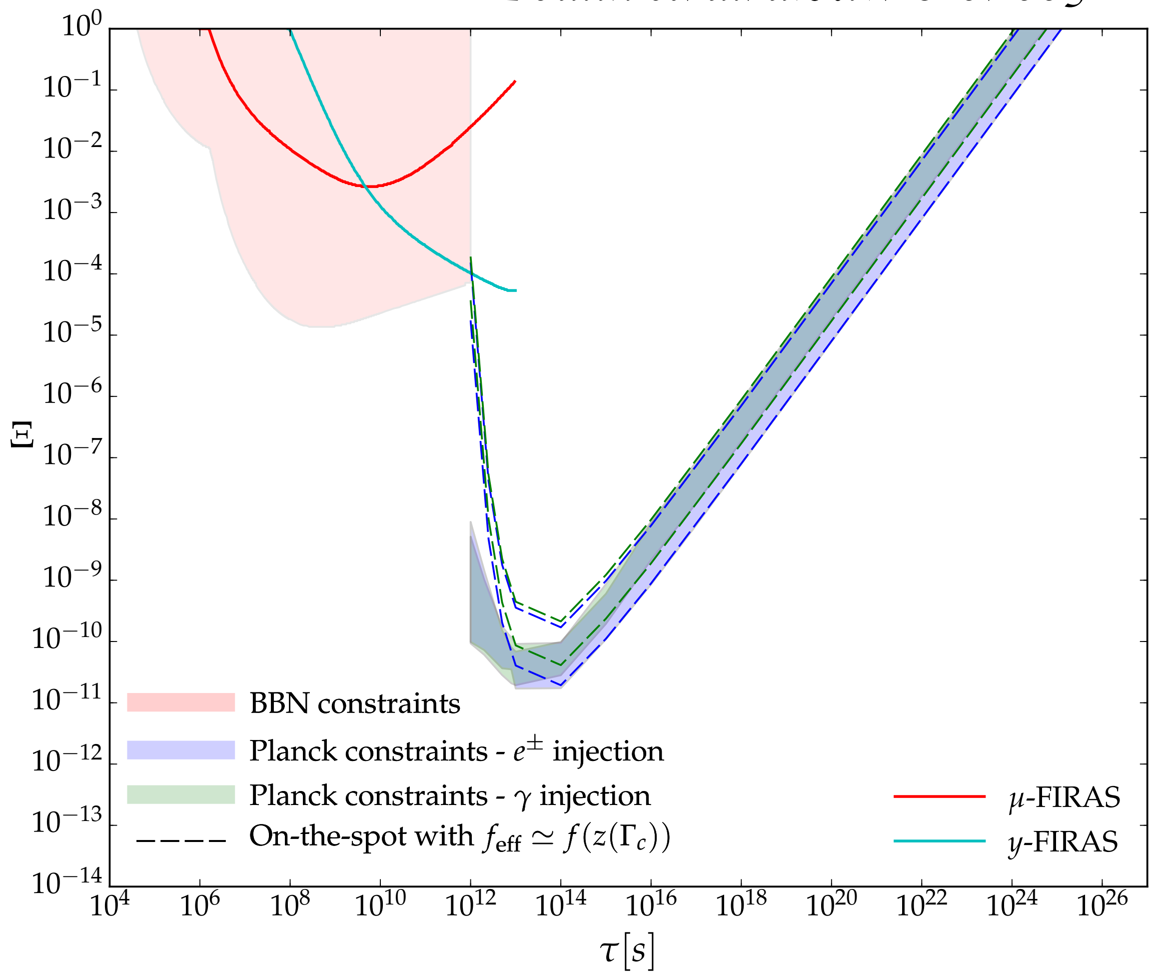
$$m_\chi \gg m_\phi \gg m_e$$

- Mediator is highly boosted and decays to SM particles
- Ideal observatory, our Universe

DM with long lived mediator

- τ_ϕ lifetime > a few 10^5 seconds in order for ϕ produced around the GC to travel close to the Earth
- The constraints from BBN and CMB depend on ρ_ϕ X BR($\phi \rightarrow \gamma\ \gamma$) or ρ_ϕ X BR($\phi \rightarrow e^\pm\ e^\pm$)
- For $\rho_\phi \sim 10^{-2} - 10^{-5}$ X ρ_{DM}, $\tau_\phi \lesssim 10^6 - 10^8$ seconds by BBN constraints
- If $\rho_\phi \sim 10^{-5}$ - 10^{-11} X ρ_{DM}, the existence of ϕ is constrained not by BBN but by CMB, requiring $\tau_\phi \lesssim 10^{12}$ seconds
- For $\rho_\phi \sim 10^{-11} \cdot \rho_{DM}$ there are no constraints even from the CMB observation

Poulin et. al. arXiv:1610.10051



Kim et. al. arXiv:1702.02944

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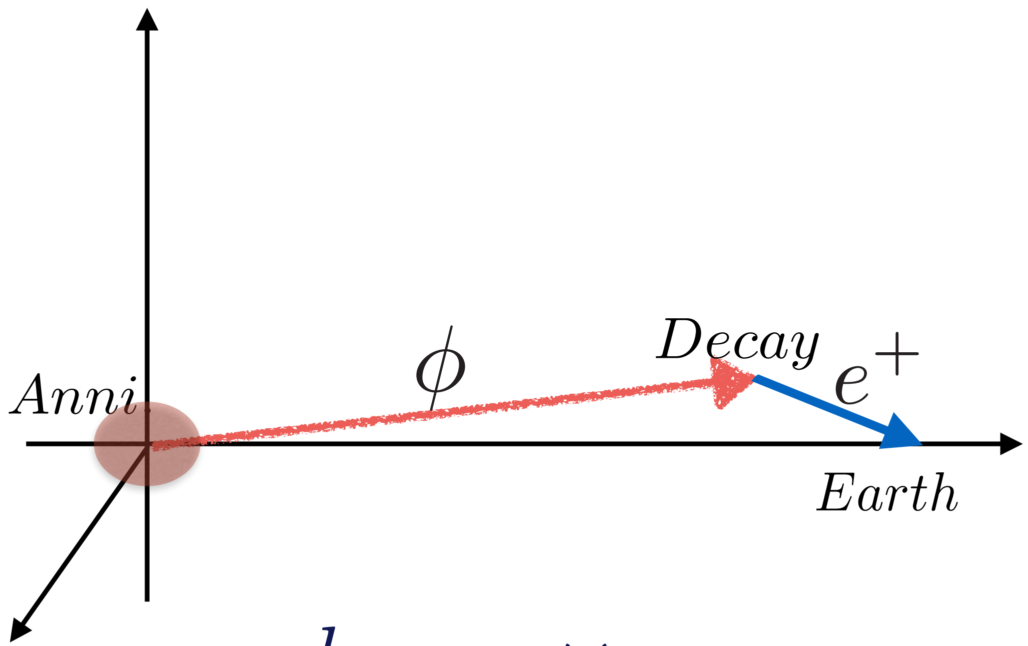
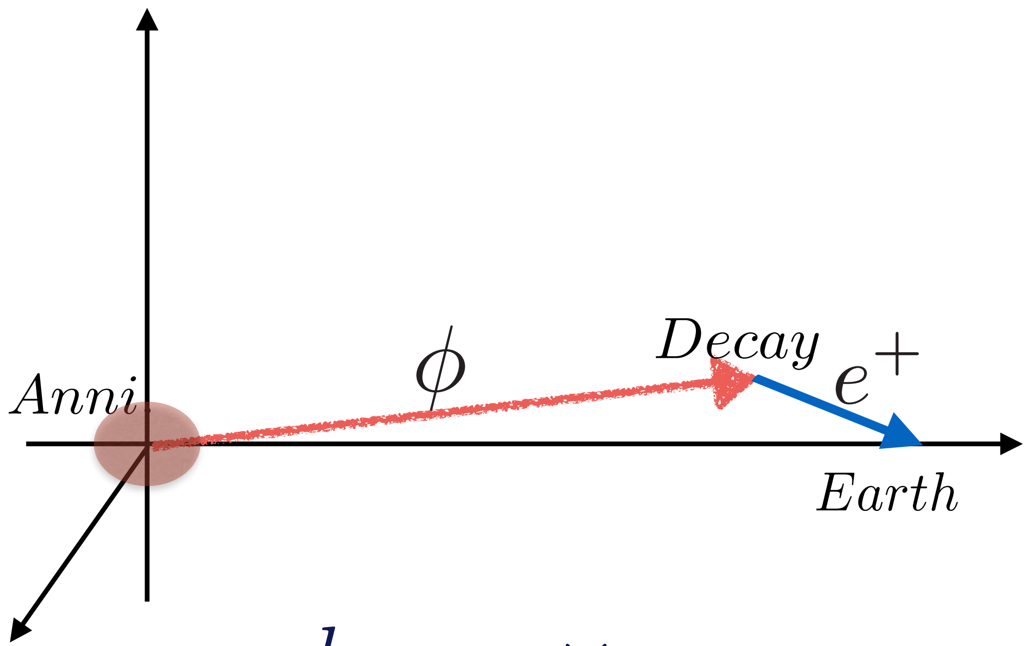
Flux computation



$$l_d = v \times \tau_\phi$$

$$\frac{d\Phi_{e^\pm}}{dE}(E,\vec{x}) = \frac{v_{e^\pm}}{4\pi\, b(E,\vec{x})} \begin{cases} \frac{1}{2}\left(\frac{\rho(\vec{x})}{M_{\rm DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \int_E^{M_{\rm DM}} dE_{\rm s}\, \frac{dN^f_{e^\pm}}{dE}(E_{\rm s})\, I(E,E_{\rm s},\vec{x}) & \text{(annihilation)} \\ \left(\frac{\rho(\vec{x})}{M_{\rm DM}}\right) \sum_f \Gamma_f \int_E^{M_{\rm DM}/2} dE_{\rm s}\, \frac{dN^f_{e^\pm}}{dE}(E_{\rm s})\, I(E,E_{\rm s},\vec{x}) & \text{(decay)} \end{cases}$$

Flux computation

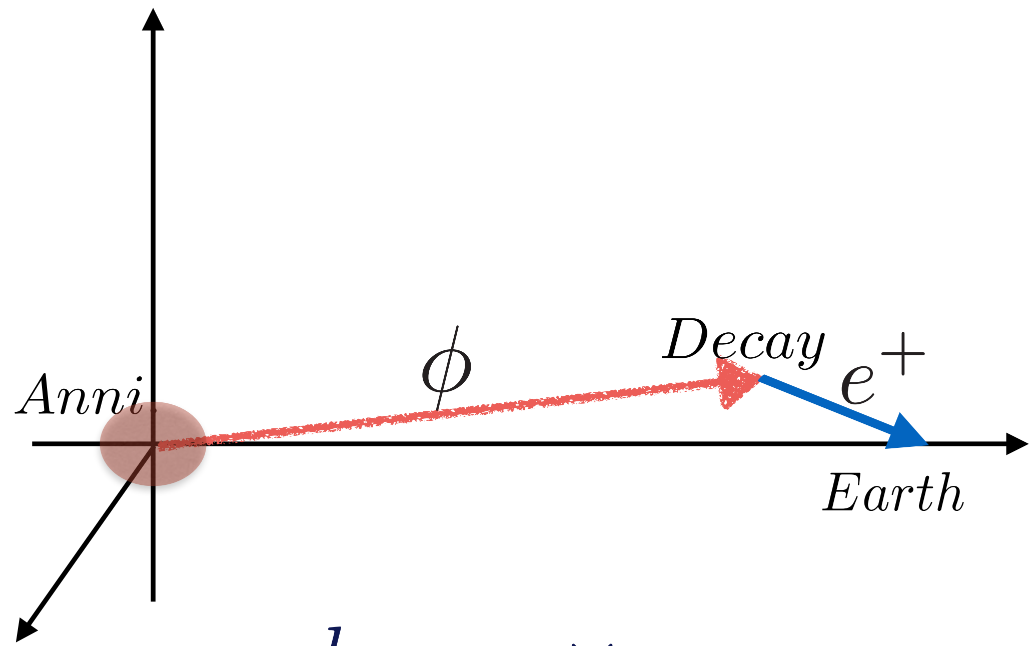


$$l_d = v \times \tau_\phi$$

Green's function from source to observation

$$\frac{d\Phi_{e^\pm}}{dE}(E,\vec{x}) = \frac{v_{e^\pm}}{4\pi\, b(E,\vec{x})} \begin{cases} \frac{1}{2}\left(\frac{\rho(\vec{x})}{M_{\rm DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \int_E^{M_{\rm DM}} dE_{\rm s}\, \frac{dN^f_{e^\pm}}{dE}(E_{\rm s})\, I(E, E_{\rm s}, \vec{x}) & \text{(annihilation)} \\ \left(\frac{\rho(\vec{x})}{M_{\rm DM}}\right) \sum_f \Gamma_f \int_E^{M_{\rm DM}/2} dE_{\rm s}\, \frac{dN^f_{e^\pm}}{dE}(E_{\rm s})\, I(E, E_{\rm s}, \vec{x}) & \text{(decay)} \end{cases}$$

Flux computation

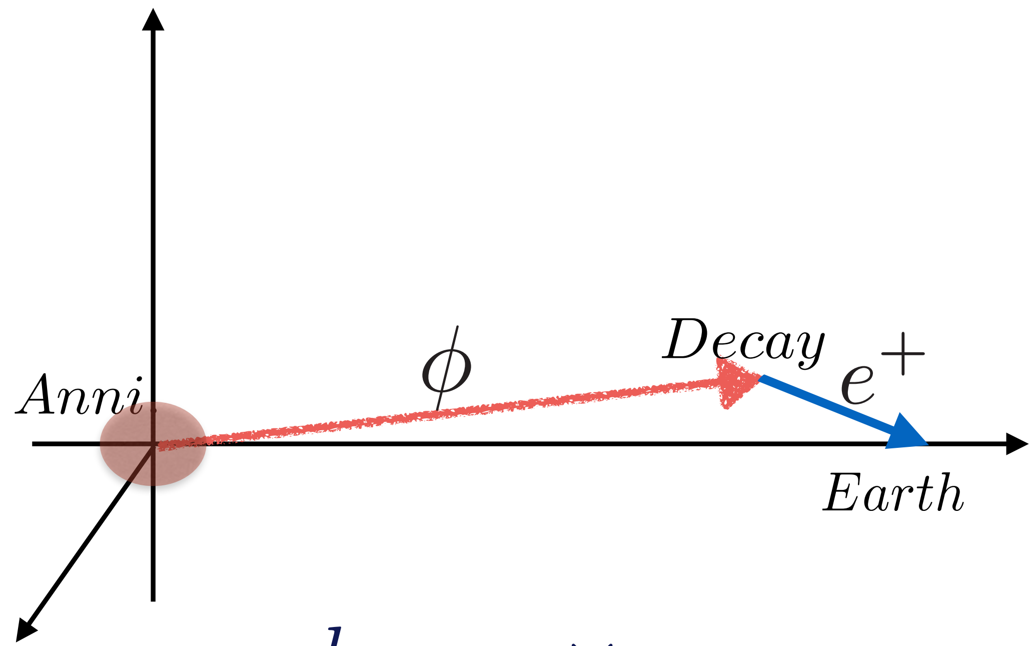


$$l_d = v \times \tau_\phi$$

Injection spectra, depends on decay kinematics

$$\frac{d\Phi_{e^\pm}}{dE}(E,\vec{x}) = \frac{v_{e^\pm}}{4\pi\, b(E,\vec{x})} \begin{cases} \frac{1}{2}\left(\frac{\rho(\vec{x})}{M_{\rm DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \int_E^{M_{\rm DM}} dE_{\rm s}\, \frac{dN^f_{e^\pm}}{dE}(E_{\rm s})\, I(E,E_{\rm s},\vec{x}) & \text{(annihilation)} \\ \left(\frac{\rho(\vec{x})}{M_{\rm DM}}\right) \sum_f \Gamma_f \int_E^{M_{\rm DM}/2} dE_{\rm s}\, \frac{dN^f_{e^\pm}}{dE}(E_{\rm s})\, I(E,E_{\rm s},\vec{x}) & \text{(decay)} \end{cases}$$

Flux computation



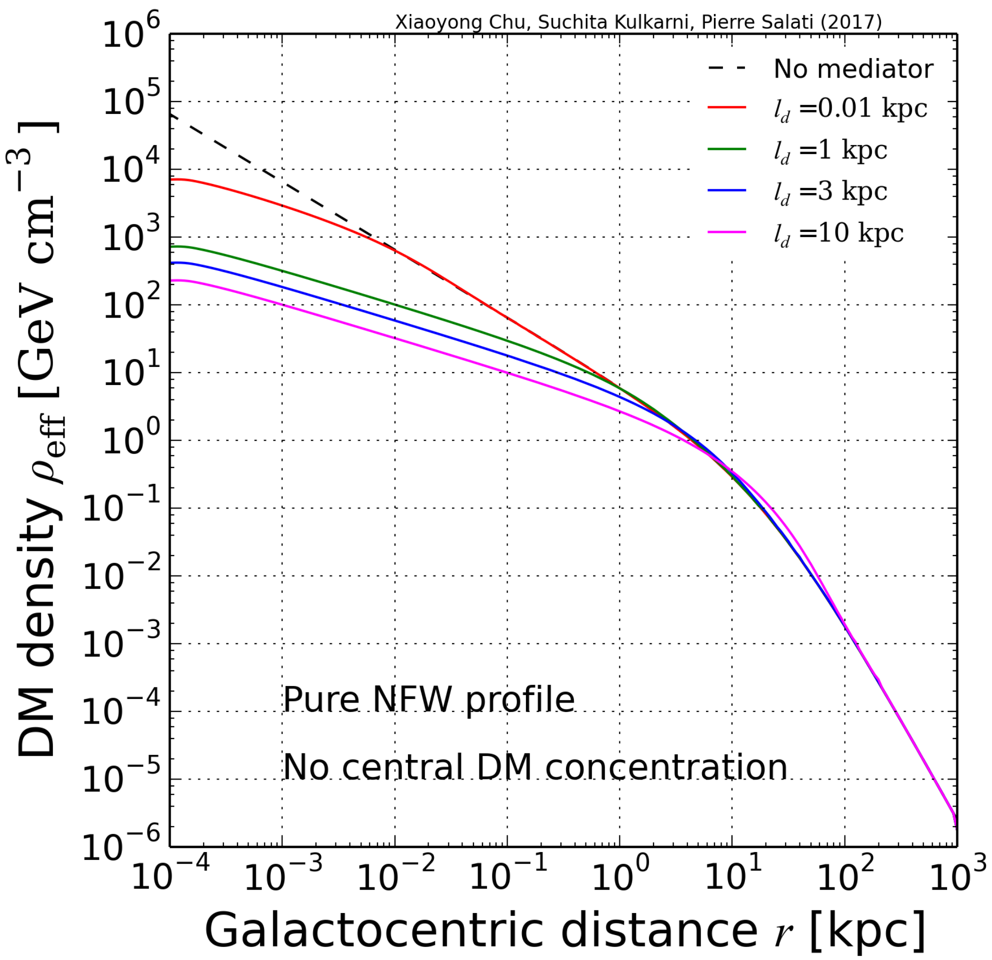
$$l_d = v \times \tau_\phi$$

Density of DM where e± injection takes place

$$\frac{d\Phi_{e^\pm}}{dE}(E,\vec{x}) = \frac{v_{e^\pm}}{4\pi\, b(E,\vec{x})} \begin{cases} \frac{1}{2}\left(\frac{\rho(\vec{x})}{M_{\rm DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \int_E^{M_{\rm DM}} dE_{\rm s}\, \frac{dN^f_{e^\pm}}{dE}(E_{\rm s})\, I(E,E_{\rm s},\vec{x}) & \text{(annihilation)} \\ \left(\frac{\rho(\vec{x})}{M_{\rm DM}}\right) \sum_f \Gamma_f \int_E^{M_{\rm DM}/2} dE_{\rm s}\, \frac{dN^f_{e^\pm}}{dE}(E_{\rm s})\, I(E,E_{\rm s},\vec{x}) & \text{(decay)} \end{cases}$$

Smeared mediator density profile

see also : Rothstein et al arXiv: 0903.3116



$$P(l) = \frac{1}{l_d}\exp(-l/l_d).$$ Mediator probability distribution

$$\rho^2_{\rm eff}(\vec{x}) = \int d^3\vec{x}_S \, \rho^2_\chi(\vec{x}_S) \times \frac{e^{-r/l_{\rm d}}}{4\,\pi\, l_{\rm d}\, r^2}, \quad \text{where } r = |\vec{x} - \vec{x}_S|$$

- Effective dark matter density gets smeared
- Does not depend on the masses involved, only on decay length
- Enhancement in the effective DM density around the Earth
- No strong signals associated with DM annihilations

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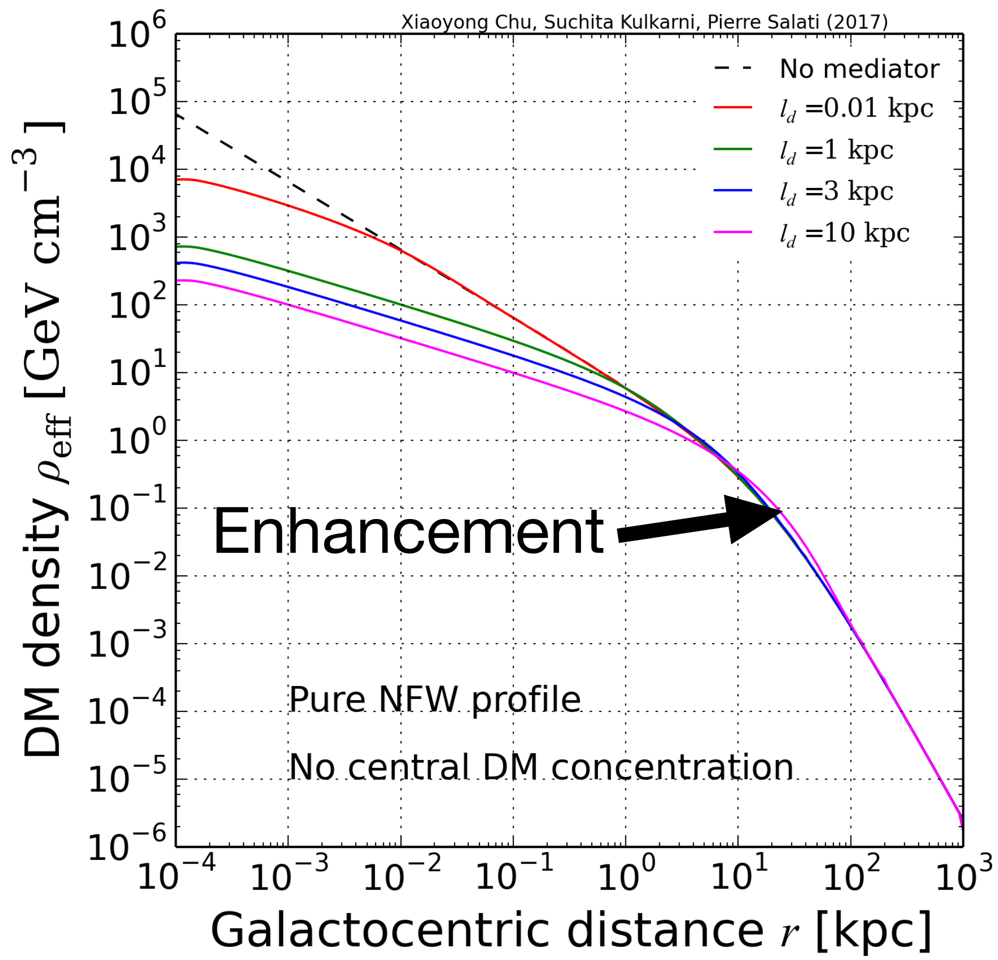

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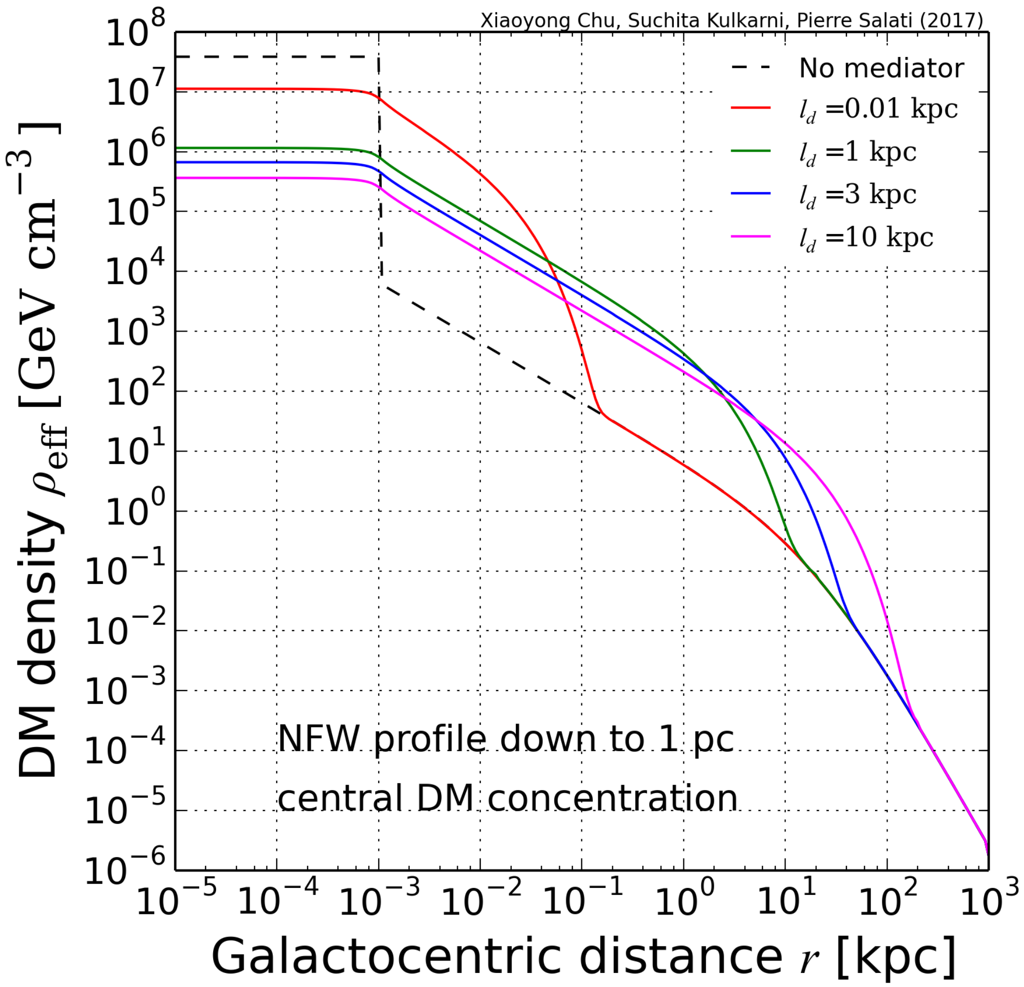

NFW profile + central core

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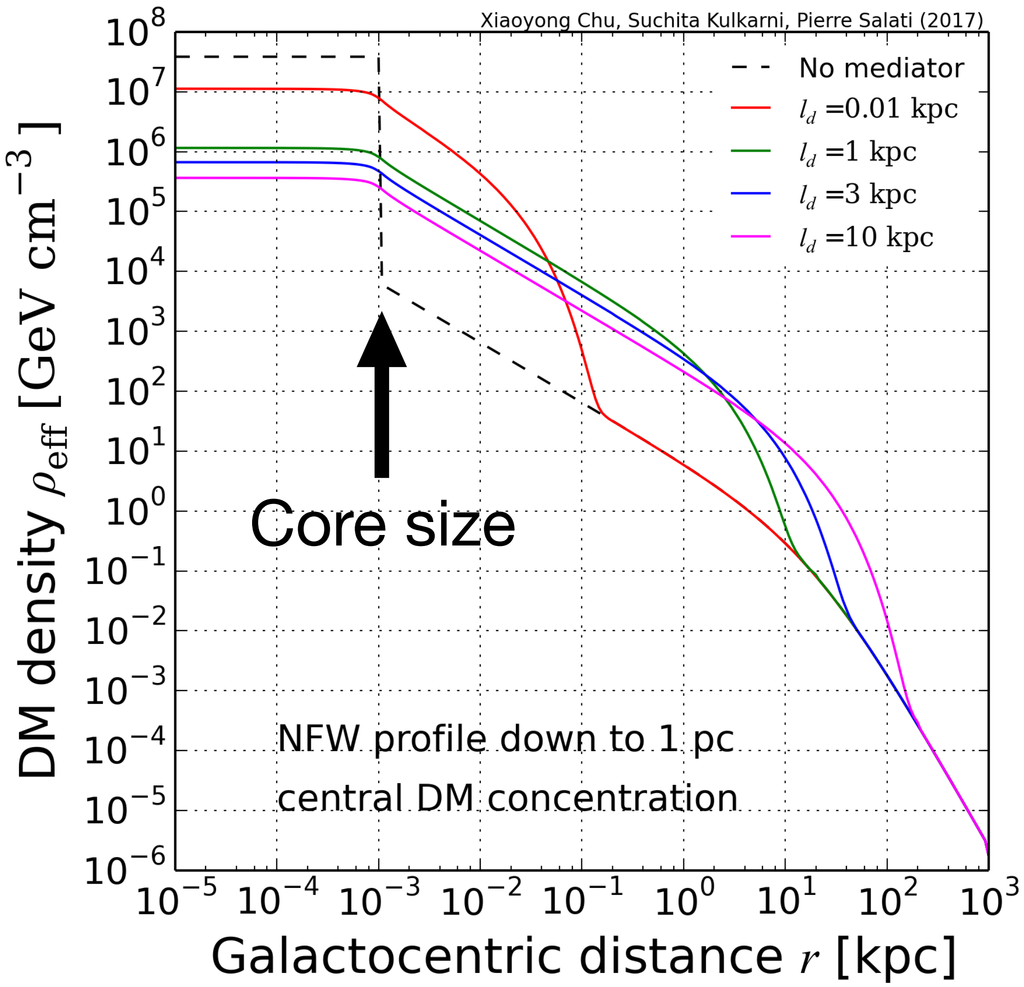

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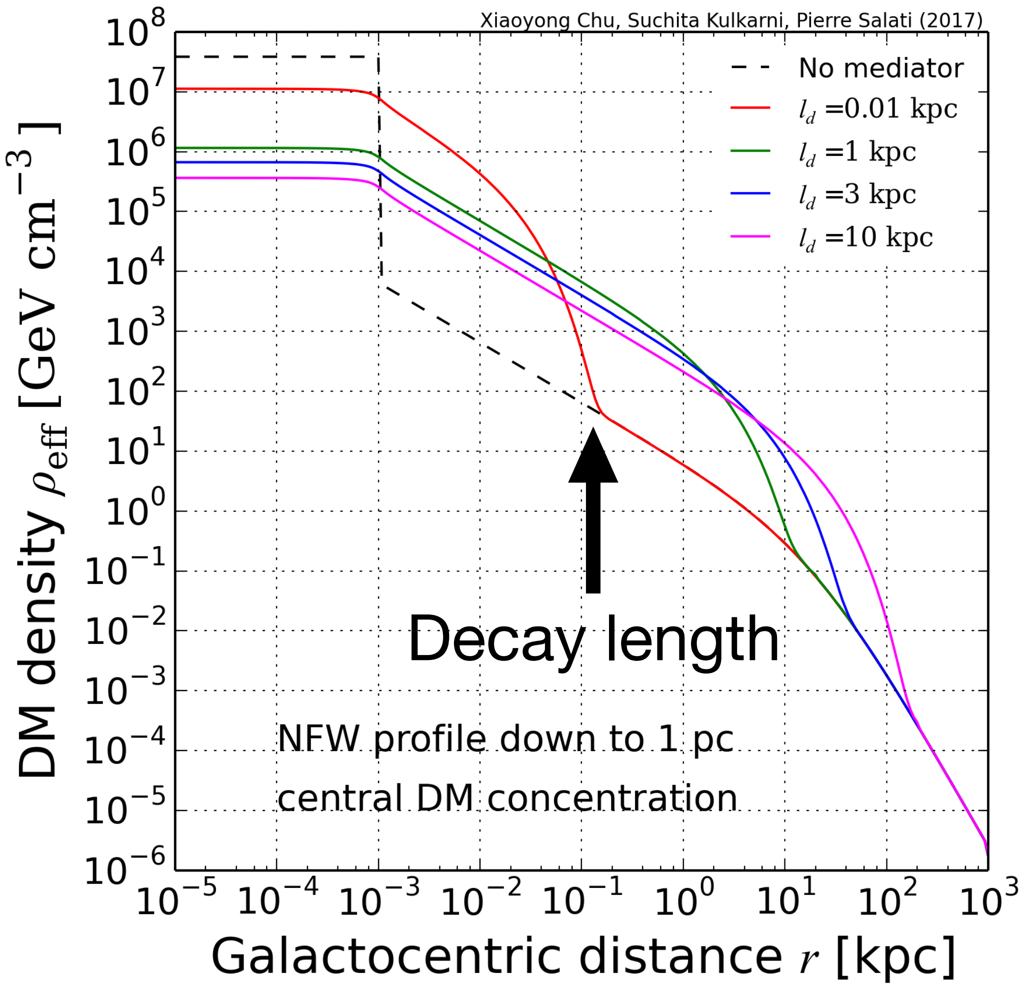

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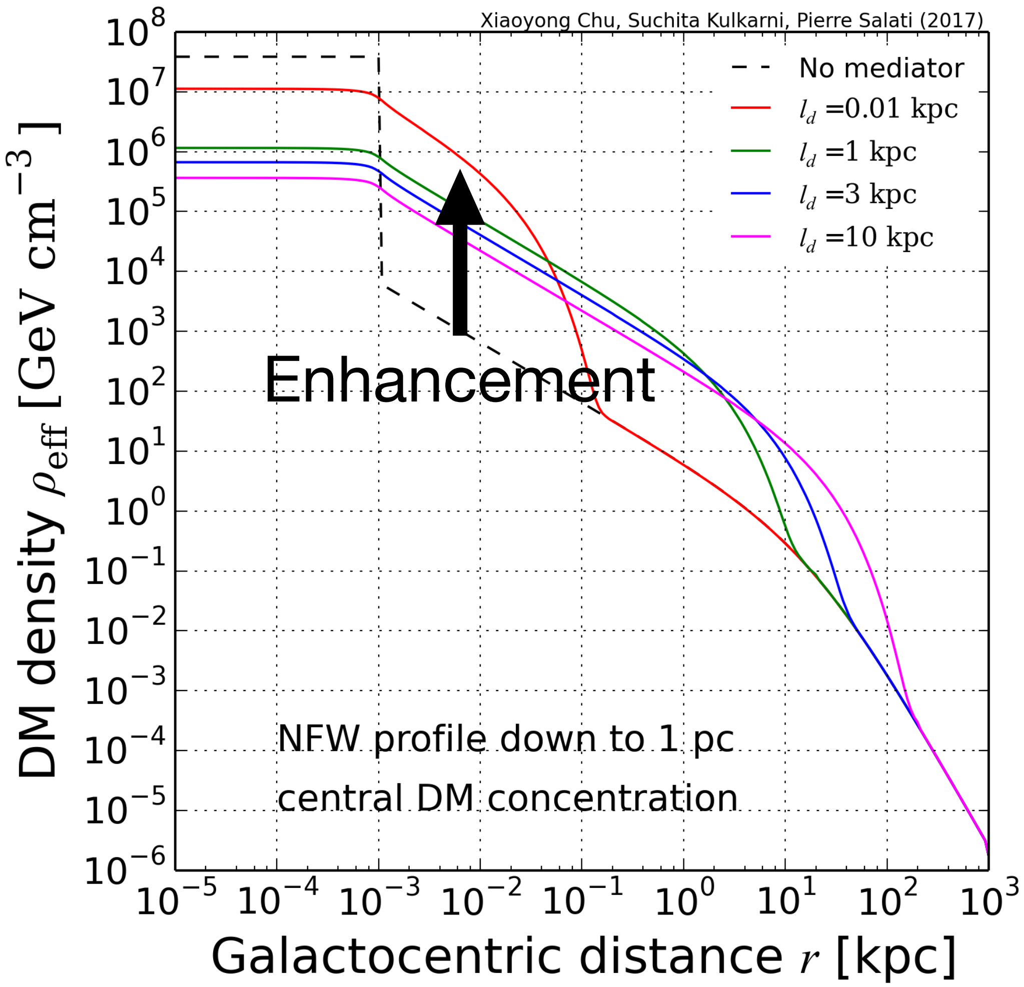

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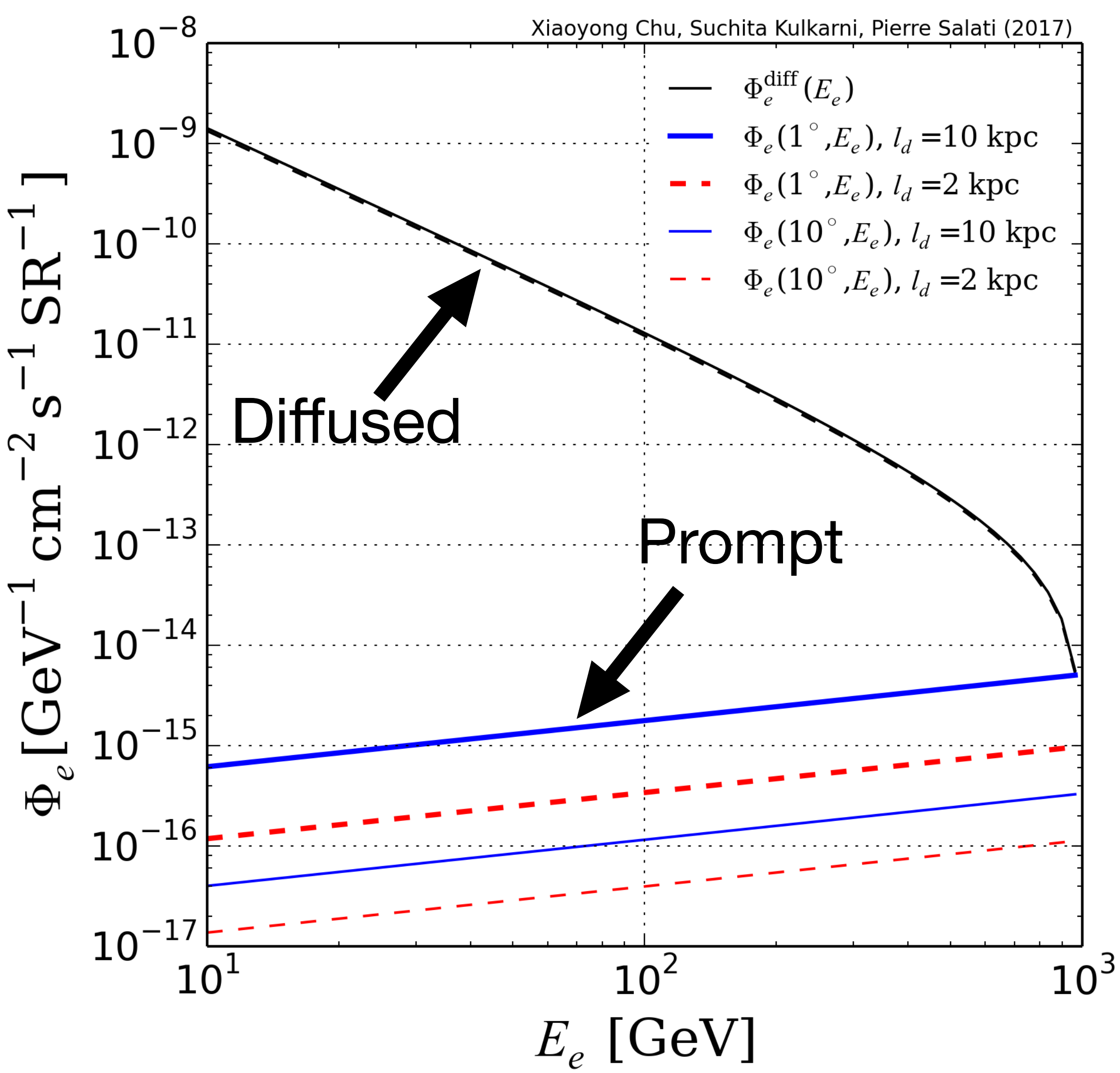
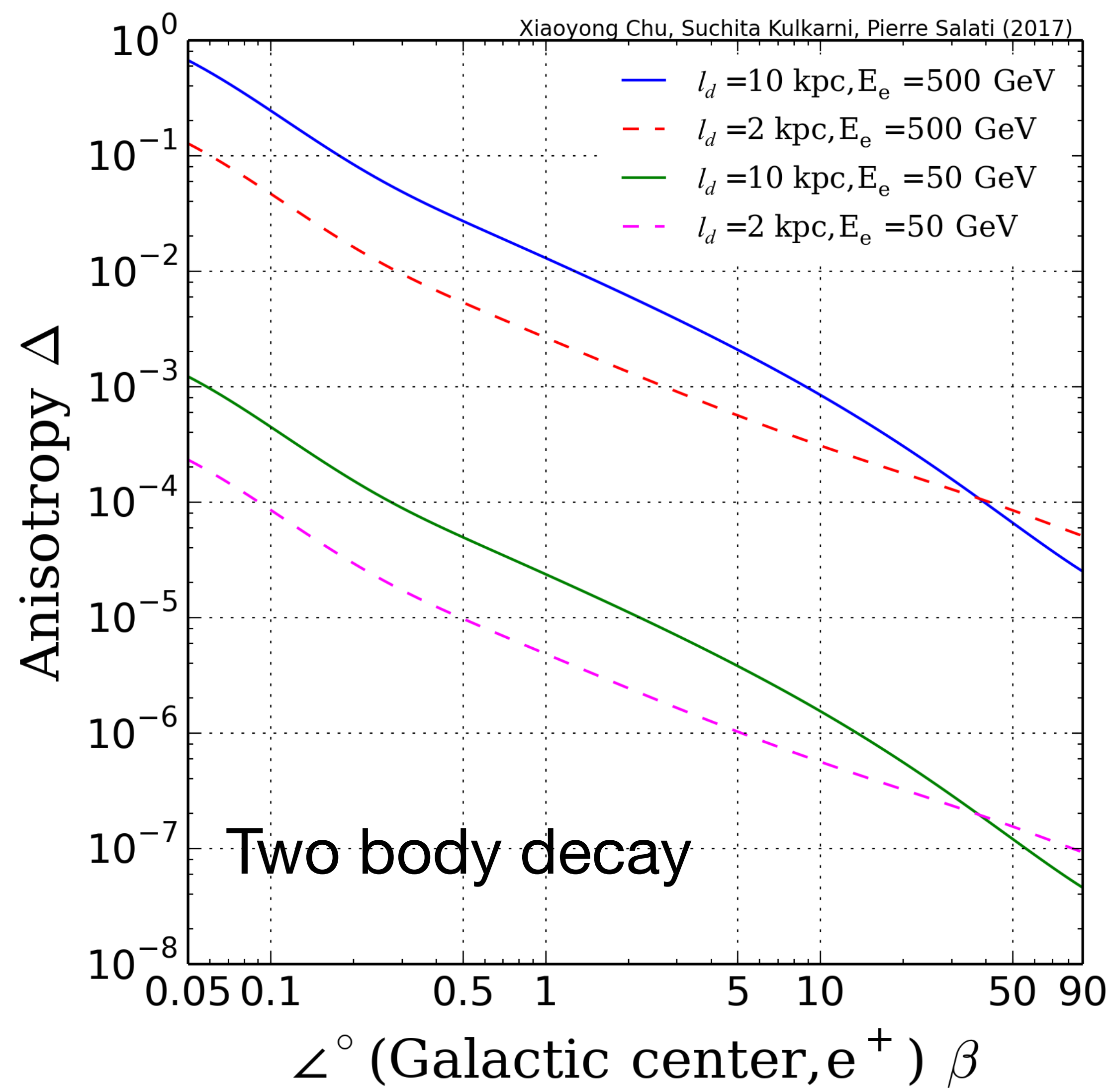
Anisotropies

- Two components:
  - Diffused flux: proportional to effective DM density
  - Non-diffused flux: originates due to mediators decaying inside the mean-free-path sphere (much below pc)
- Define anisotropy: information on the directionality of the positrons

$$\Delta(\vec{w}, E_e) \sim \frac{\Phi_e^{\rm non}(\vec{w}, E_e)}{\Phi_e^{\rm non}(\vec{w}, E_e) + \Phi_e^{\rm diff}(E_e)}$$

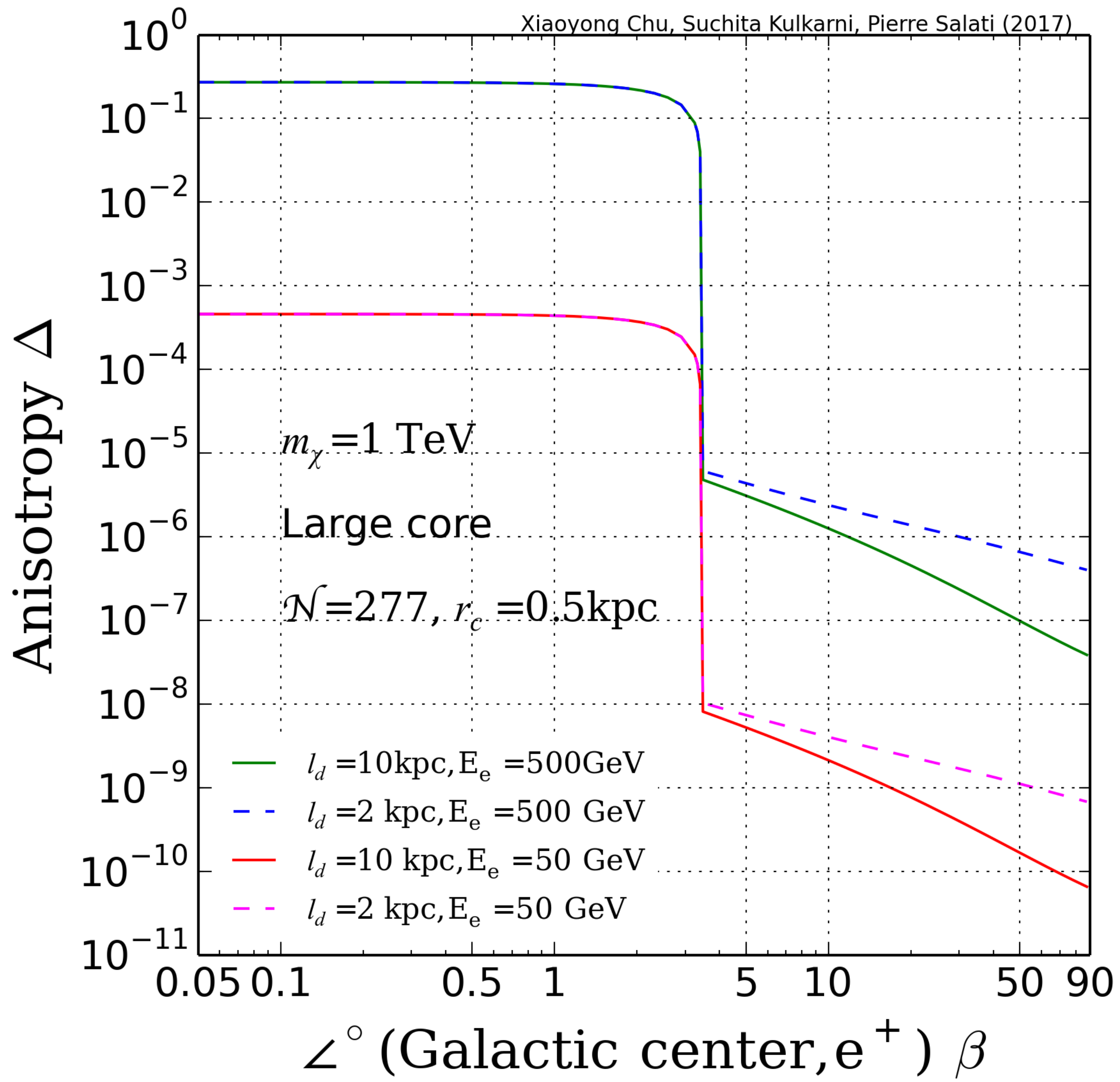
Two body decay of mediator





- Diffused component does not depend on the decay length
- Prompt flux depends on decay length and increases with observed energy, because increasing observed energy increases the diffusion length

Three body decay of mediator



- With a very good angular resolution we might be able to "see" the core in the sky

$$\mathcal{A}(E_e) \equiv \frac{3}{\sqrt{4\pi}} \times \sqrt{\frac{\sum_m |a_{1m}^2|}{3}} = 3 \times \frac{\left|\int_{-1}^{1} d\cos\beta\, \Phi_e^{\text{total}}(\vec{w}, E_e)\cos\beta\right|}{\int_{-1}^{1} d\cos\beta\, \Phi_e^{\text{total}}(\vec{w}, E_e)}$$

1 TeV DM	E_e = 50 GeV	E_e = 500 GeV
small core (1 pc)	8.45×10^{-7}	5.37×10^{-4}
large core (0.5 kpc)	8.44×10^{-7}	5.36×10^{-4}

- Not within experimental sensitivity yet

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Conclusions

- Identification and realistic evaluation of exotic dark matter interactions at experiments is a crucial task for next generation dark matter experiments
- Next generation program will probe new regions of unexplored parameter space
- Exploiting low threshold cryogenic detectors:
    - It is possible to constrain both dark matter and mediator mass at direct detection experiments if the mediator is reasonably light
    - Taking into account various uncertainties does not drastically affect the results
    - Further improvement might be possible by taking into account the discrimination in recoil spectra
- Phenomenology of long lived relativistic mediators
    - Annihilating dark matter behaves as decaying for detection purposes
    - Asymmetry in cosmic rays can be generated, for light mediator lifetimes of O(years). Albeit currently out of reach possibility to have sensitivity in future
    - A wide phenomenology program is possible

Thank you!

Suchita Kulkarni
@suchi_kulkarni

If you come to Max Planck institute for nuclear physics, Heidelberg for a seminar, you get your own plate of cookies! #seminartrivia

2:22 PM - 8 Jan 2018

7 Likes

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