Exploiting experimental data to constrain exotic dark matter scenarios

Suchita Kulkarni

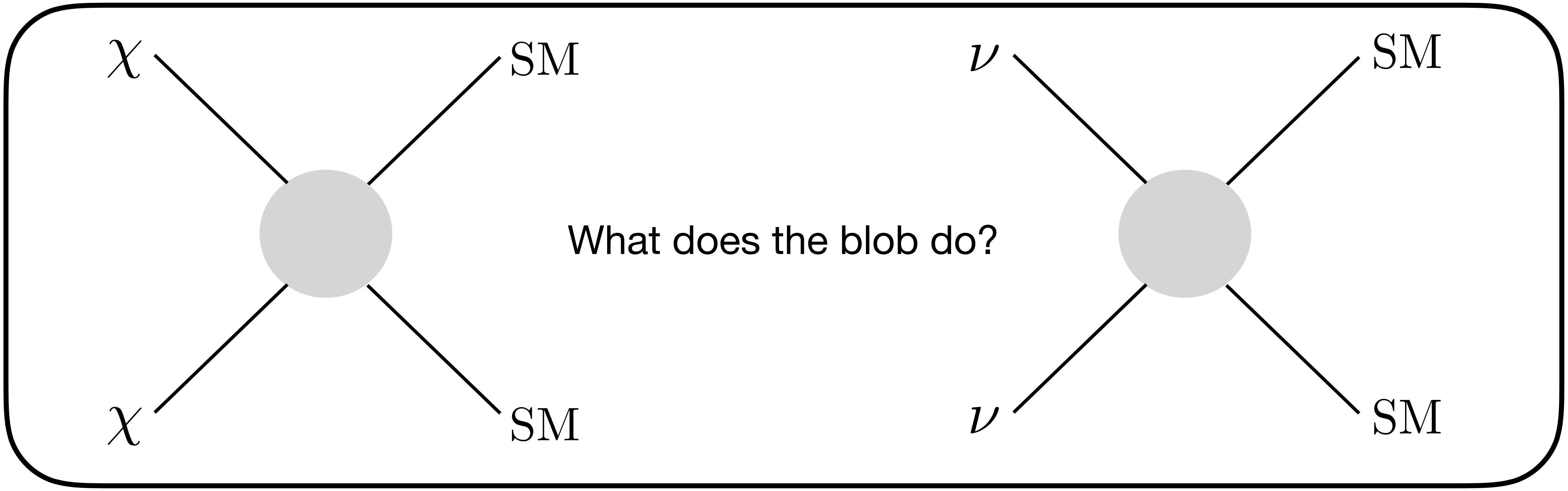
Don't shoot for the stars, we already know what's in there. Shoot for the space in between because that's where the real mystery lies.

- Vera Rubin

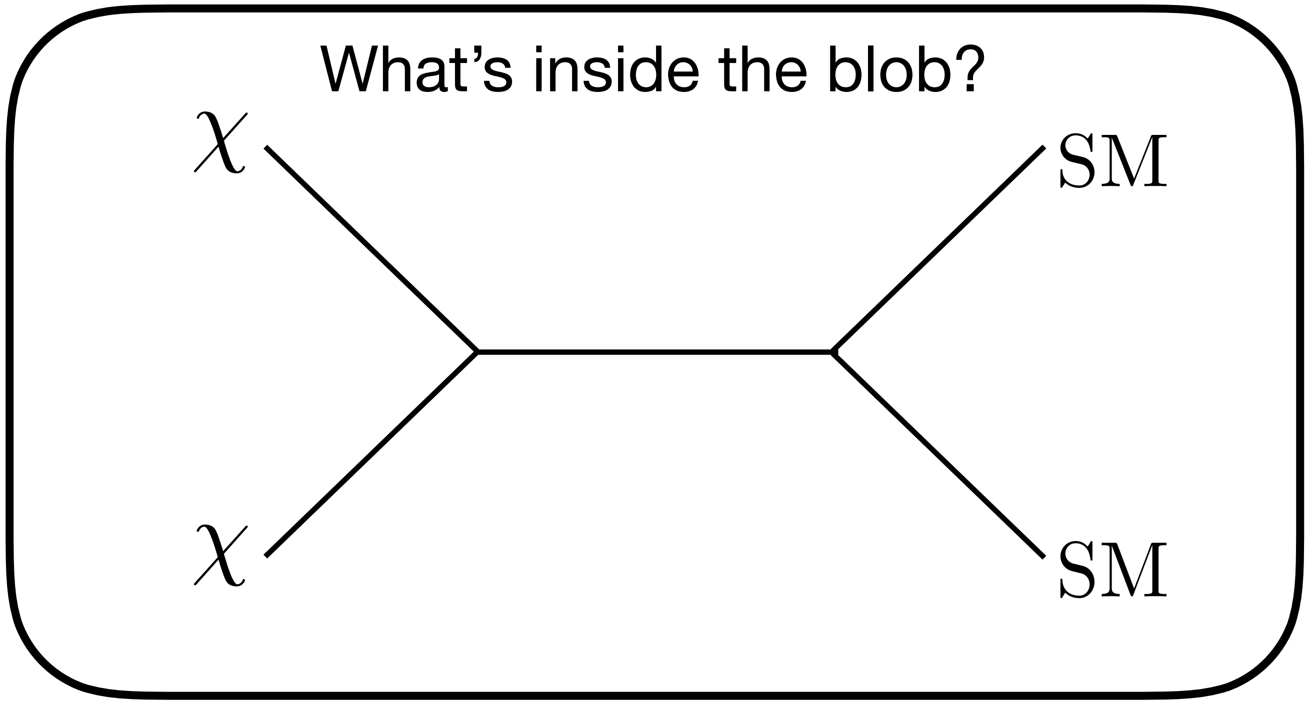
HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

ÖAW
ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

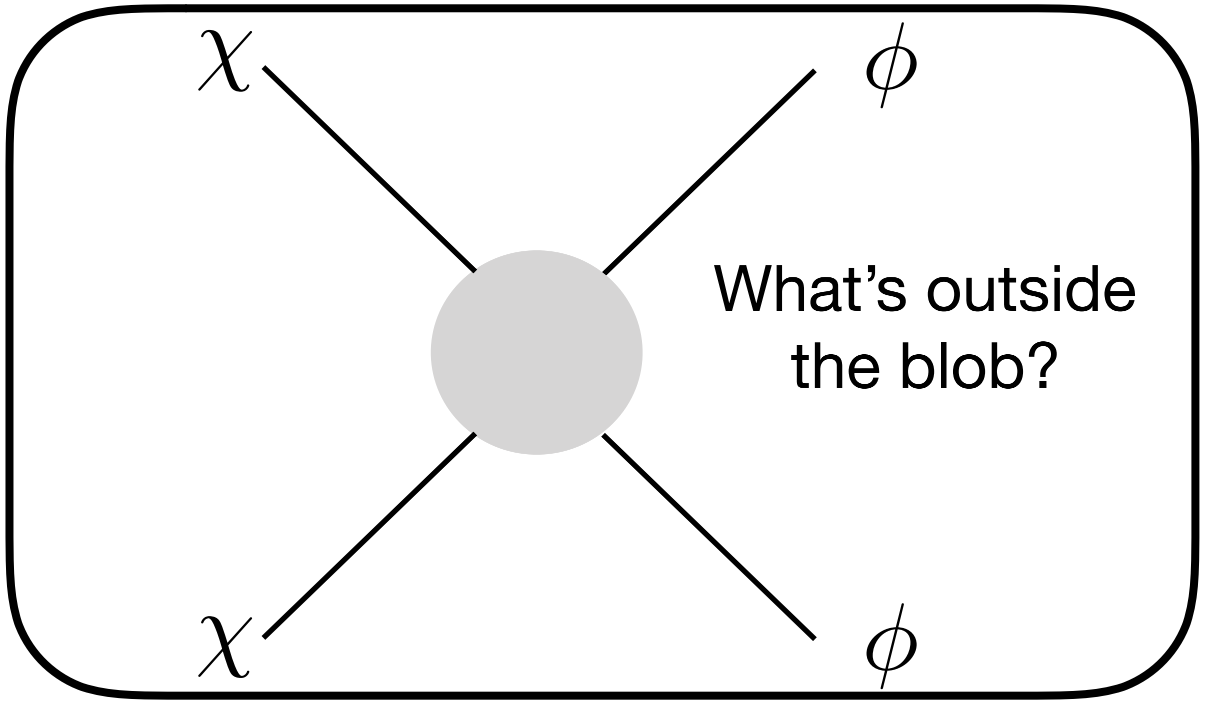
Dark matter - exotic interactions



What does the blob do?



What’s inside the blob?



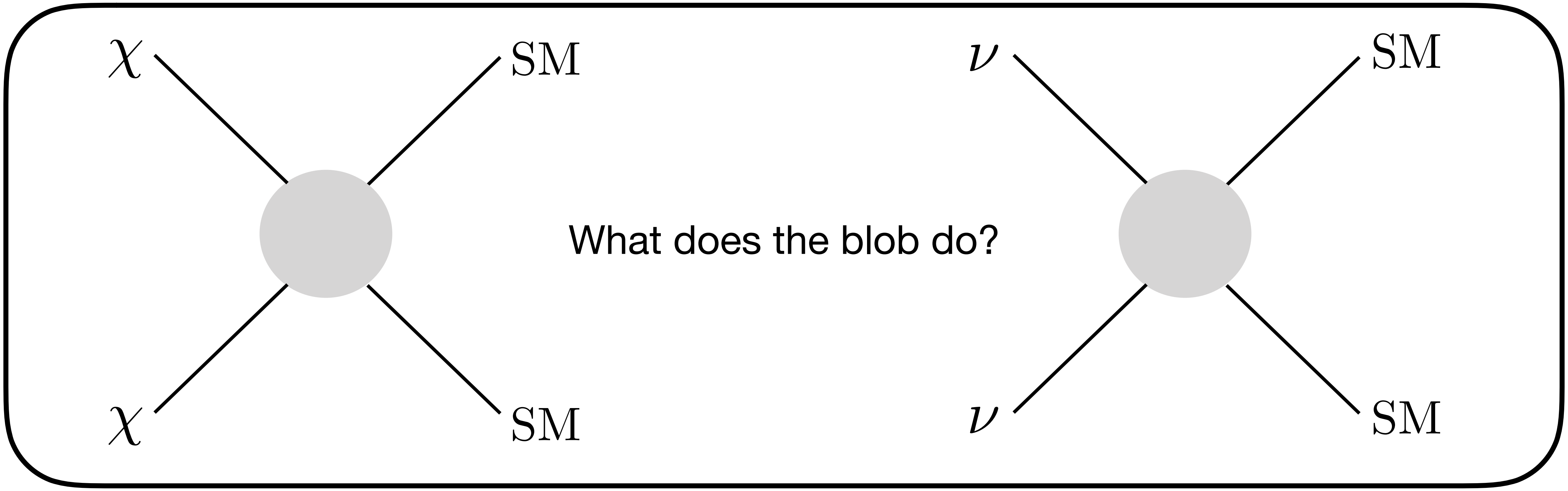
What’s outside the blob?

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

Additional interactions due to blob

Be model independent



What does the blob do?

Kulkarni et. al. JHEP 1704 (2017) 073

DM, neutrinos at direct detection

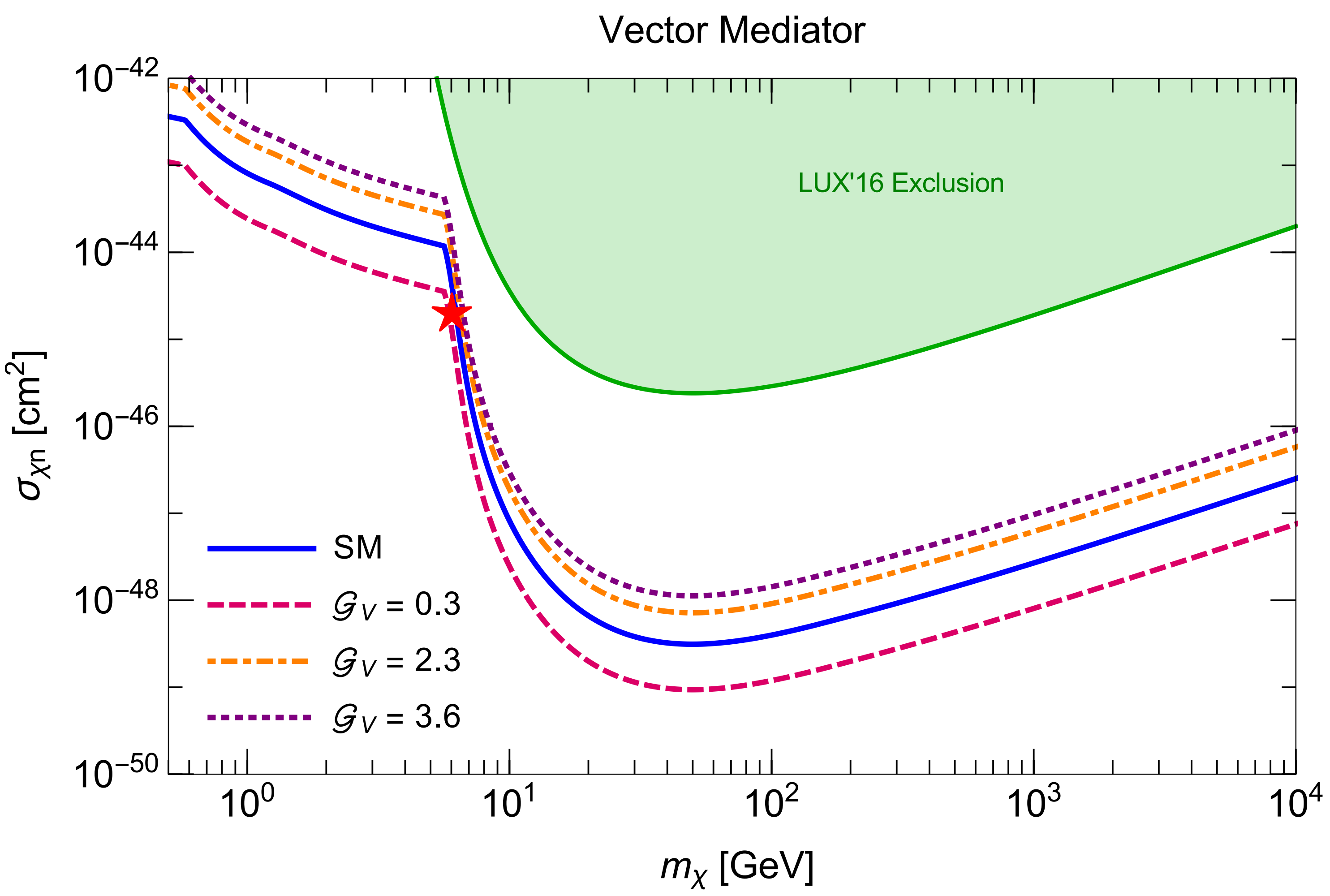
- Dark matter event rate at direct detection experiments

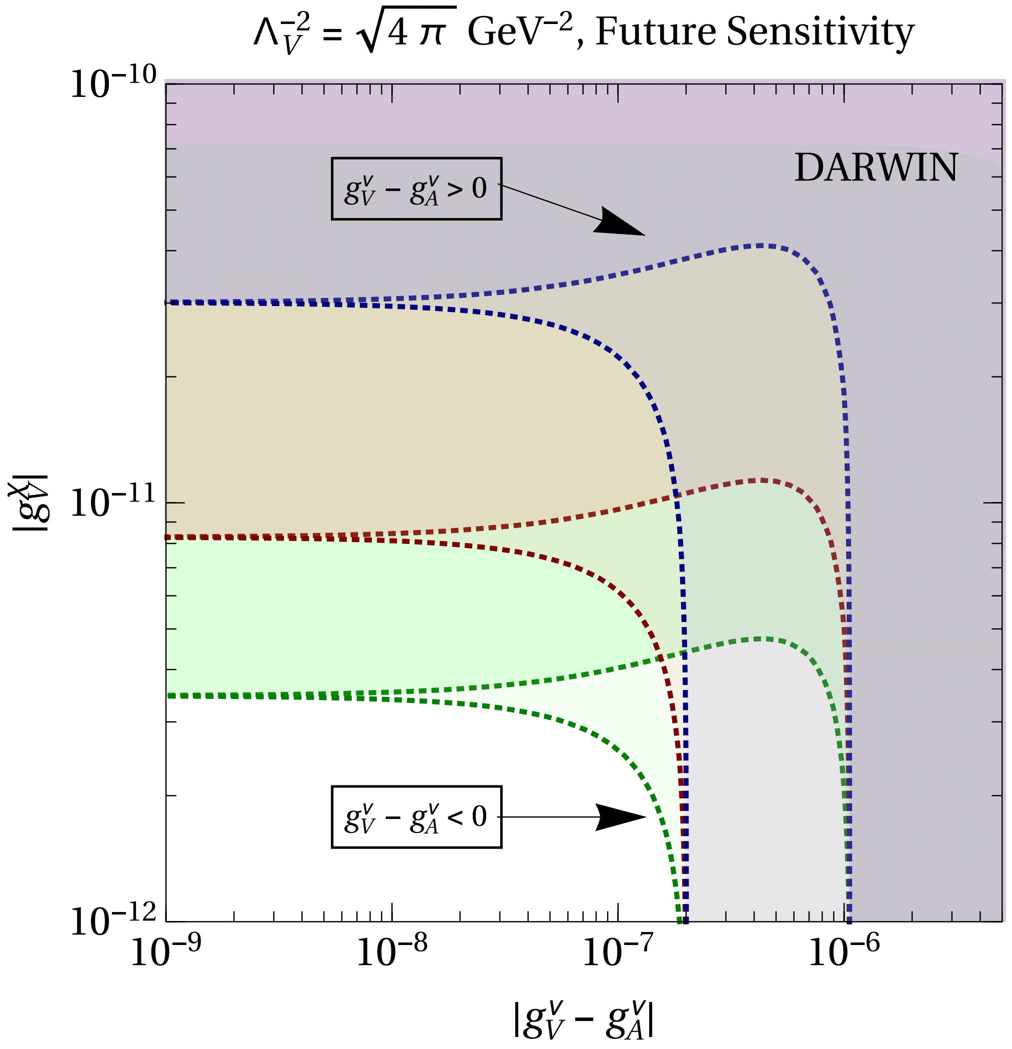
$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}} = \frac{\rho_0}{m_\mathrm{DM}}\,\eta(v_\mathrm{min}(E_\mathrm{R}))\,\frac{g^2\,F_T^2(E_\mathrm{R})}{2\pi\,m_\mathrm{med}^4}$$

- Neutrino event rate at direct detection experiments

$$\frac{dR}{dE_r} = \mathcal{N} \times \int_{E_\nu^\mathrm{min}} \frac{dN}{dE_\nu} \times \frac{d\sigma(E_\nu, E_r)}{dE_r} dE_\nu$$

Preparing for the end game





- Exotic neutrino interaction can lead to measurable effects at the direct detection experiments

- Next generation direct detection experiments can put constraints on combined DM - SM and neutrino SM interactions

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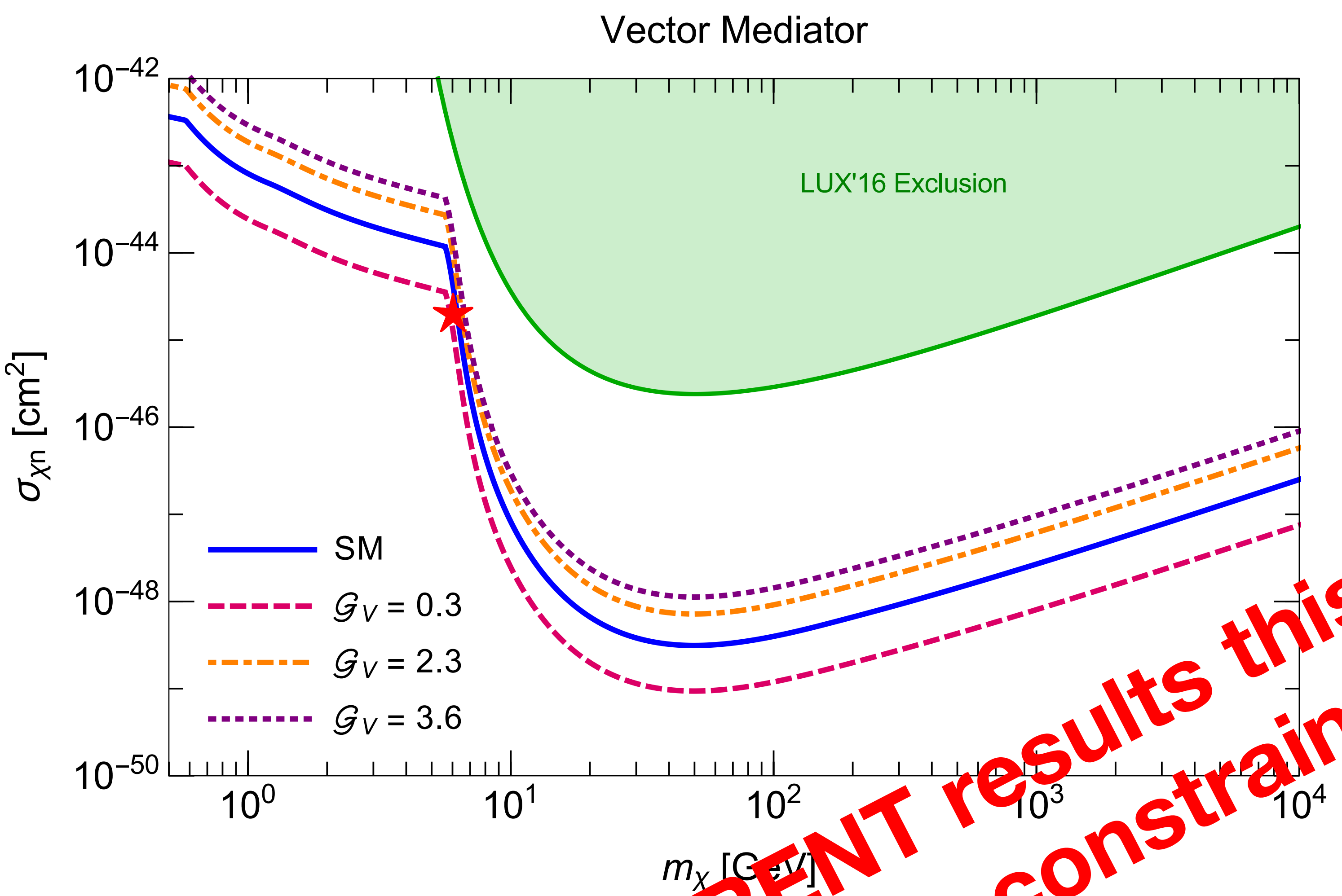
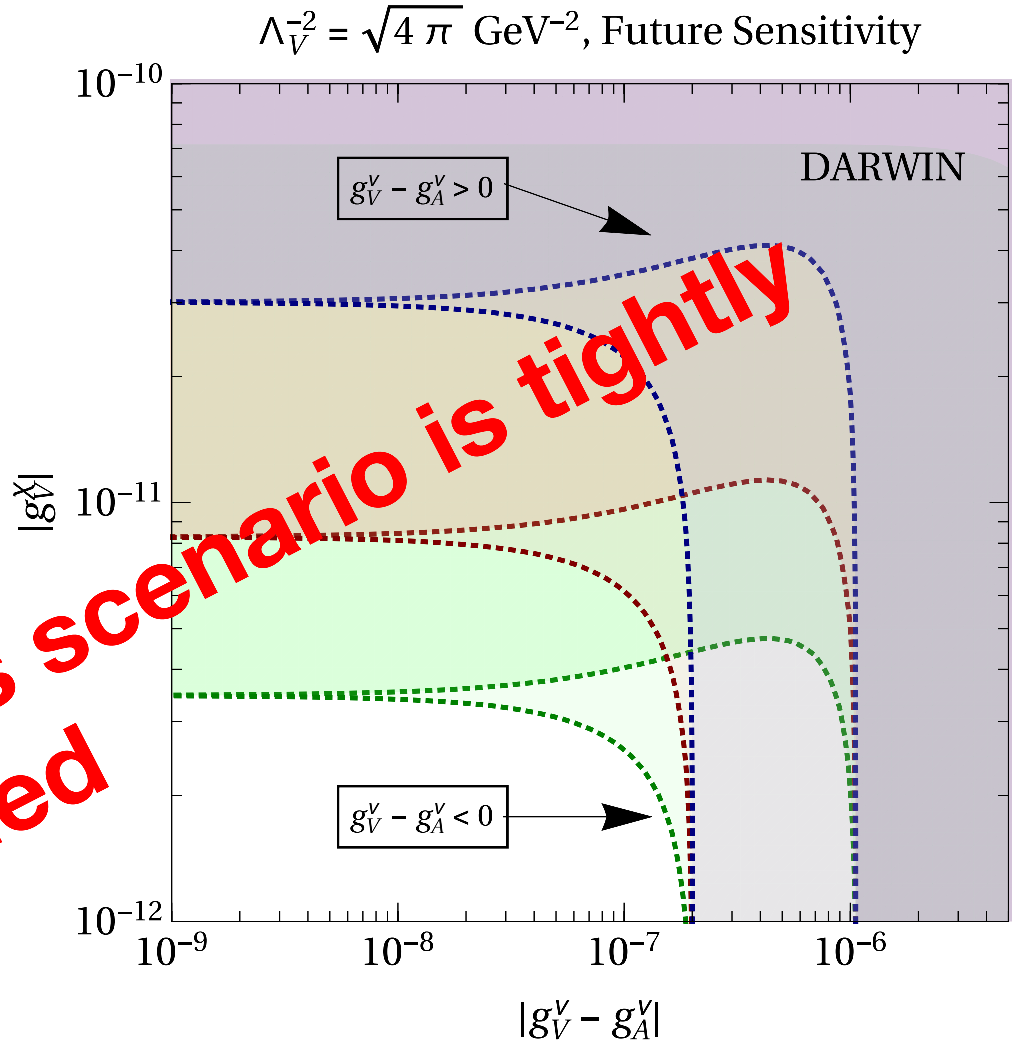




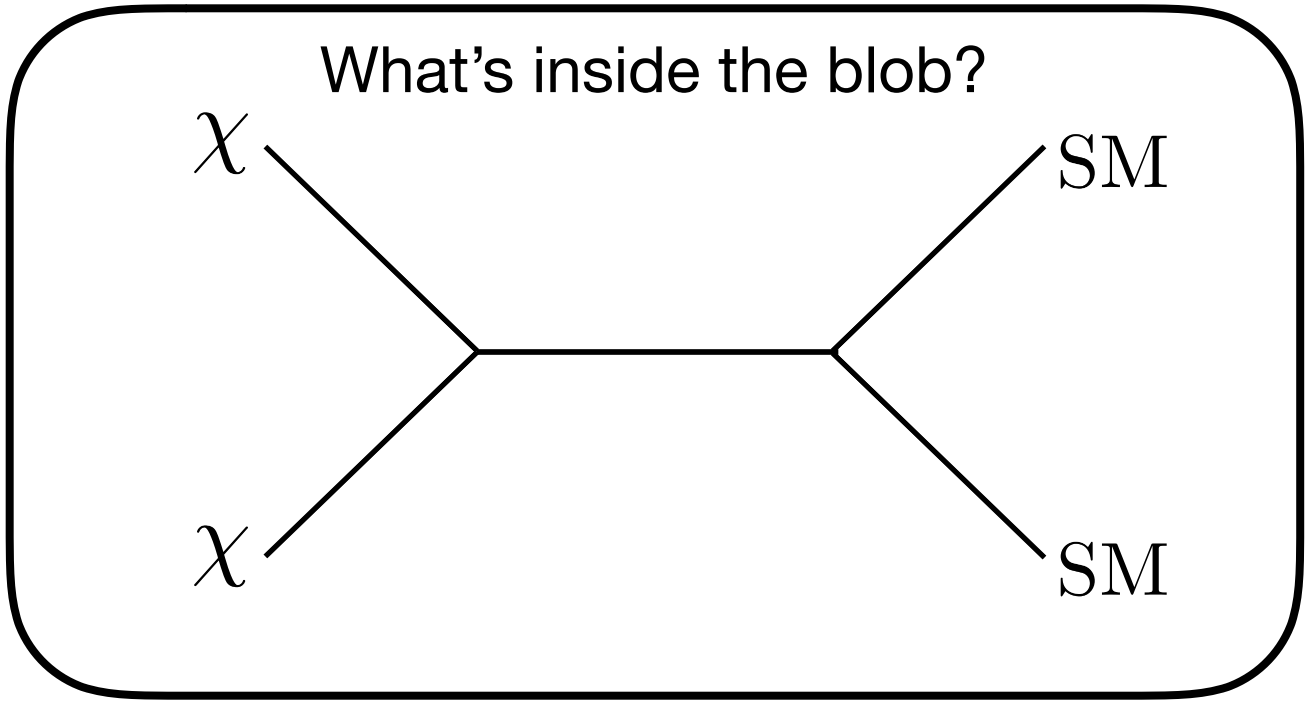
Post COHERENT results this scenario is tightly constrained

- Exotic neutrino interaction can lead to measurable effects at the direct detection experiments

- Next generation direct detection experiments can put constraints on combined DM - SM and neutrino SM interactions

Looking inside the blob

Be model independent



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

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

Light mediators at direct detection

- Event rate at direct detection experiment for light mediators

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

- Measuring the signal event rate also needs accurate knowledge of shape and normalisation of backgrounds

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Nuclear response function
depends on coupling to
protons and neutrons

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Light mediators at direct detection

- Event rate at direct detection experiment for light mediators

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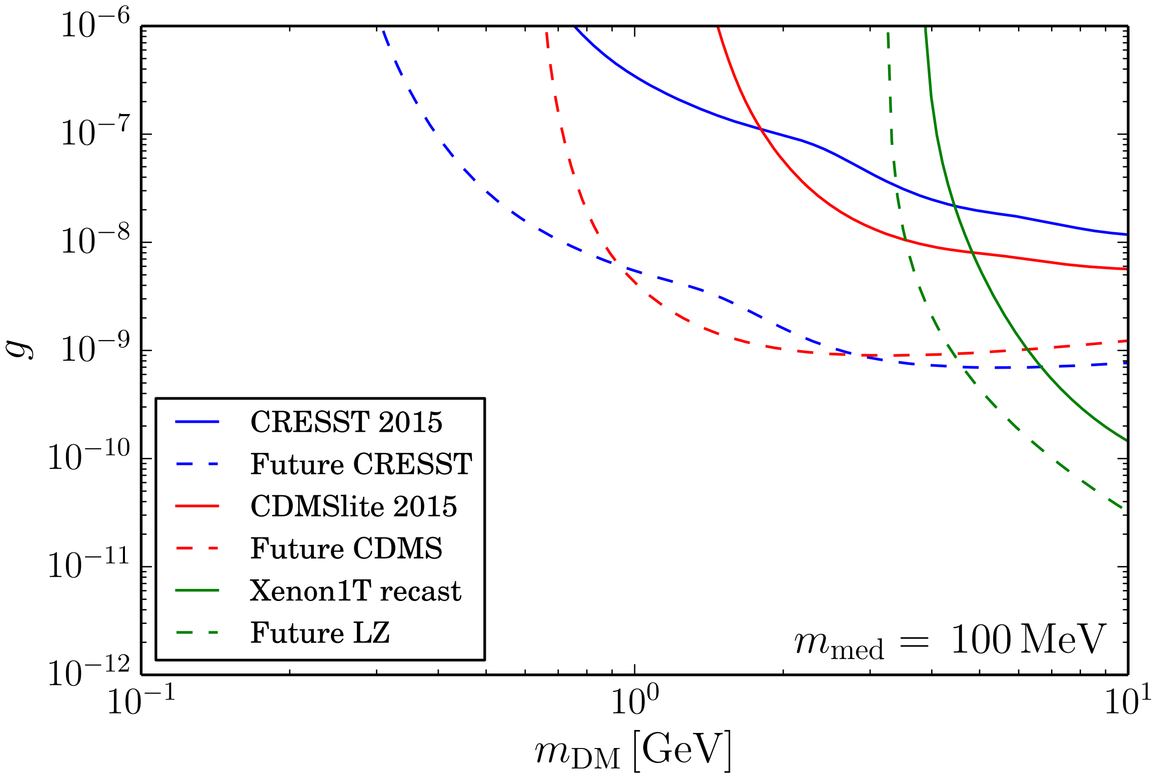
Velocity distribution source of astrophysical uncertainty

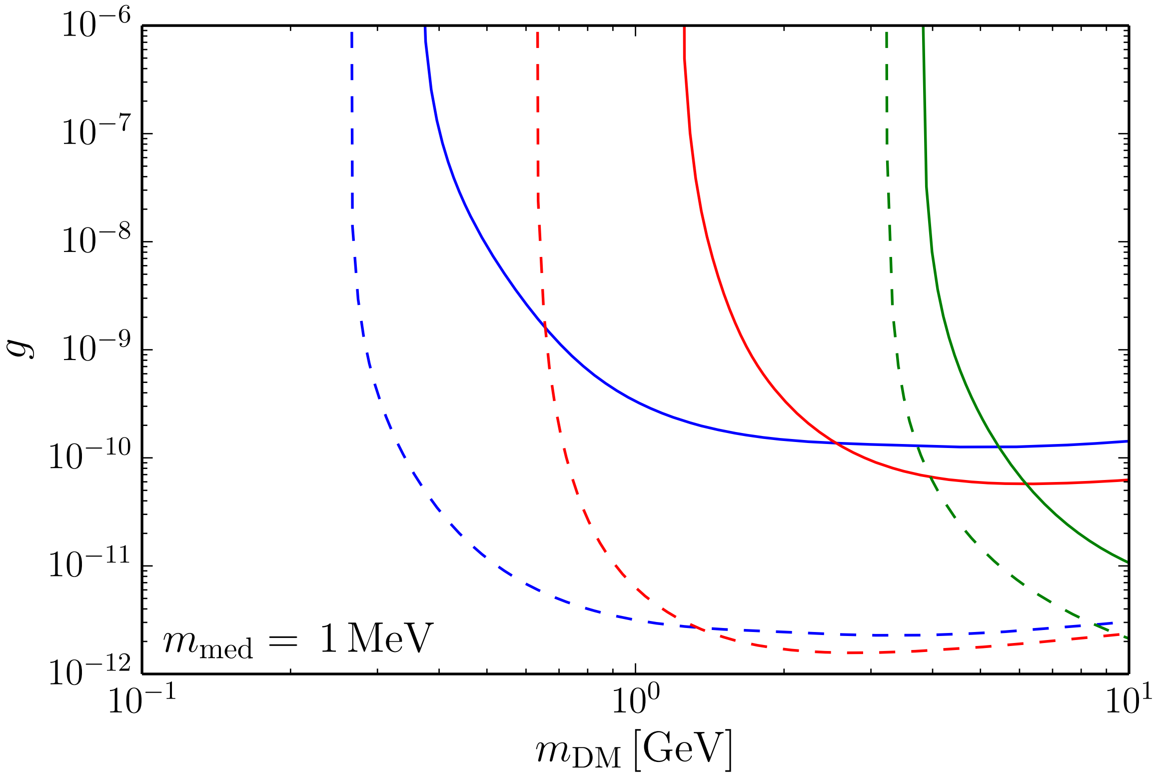
- Measuring the signal event rate also needs accurate knowledge of shape and normalisation of backgrounds

Contact interactions vs. light mediators

Traditional limits on DM space

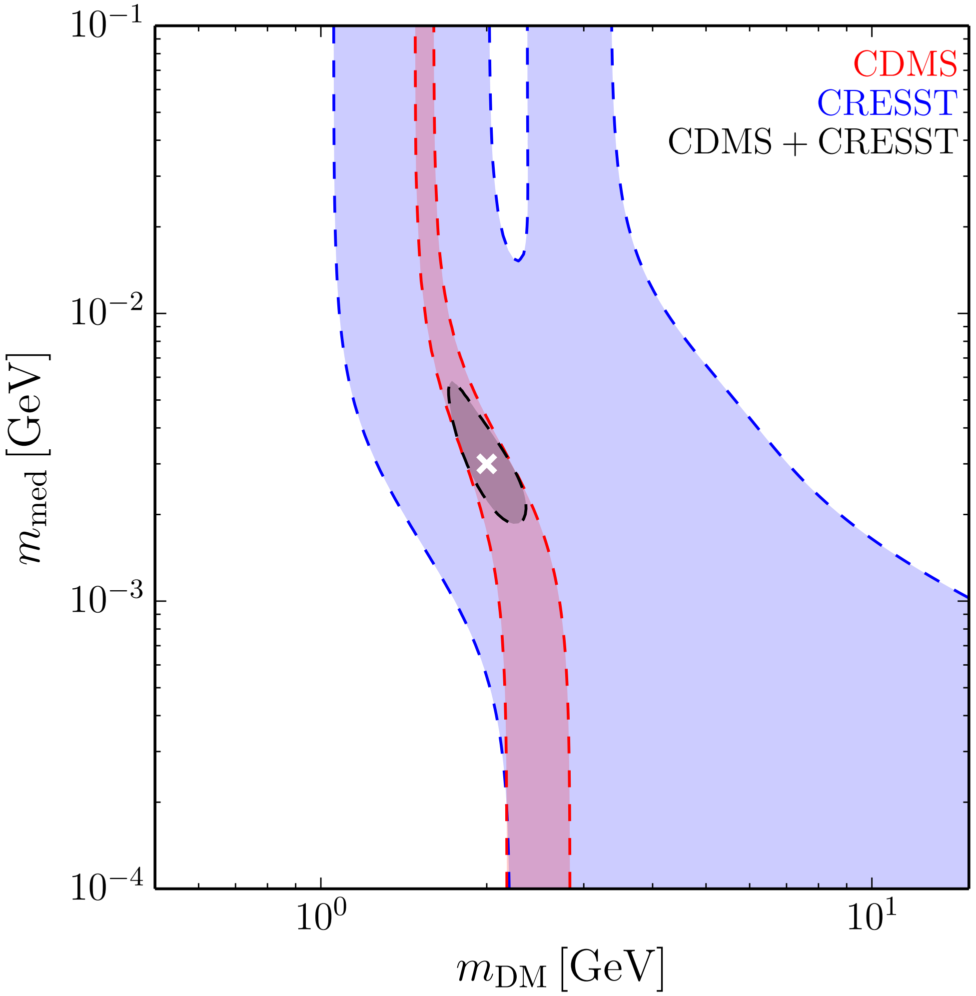


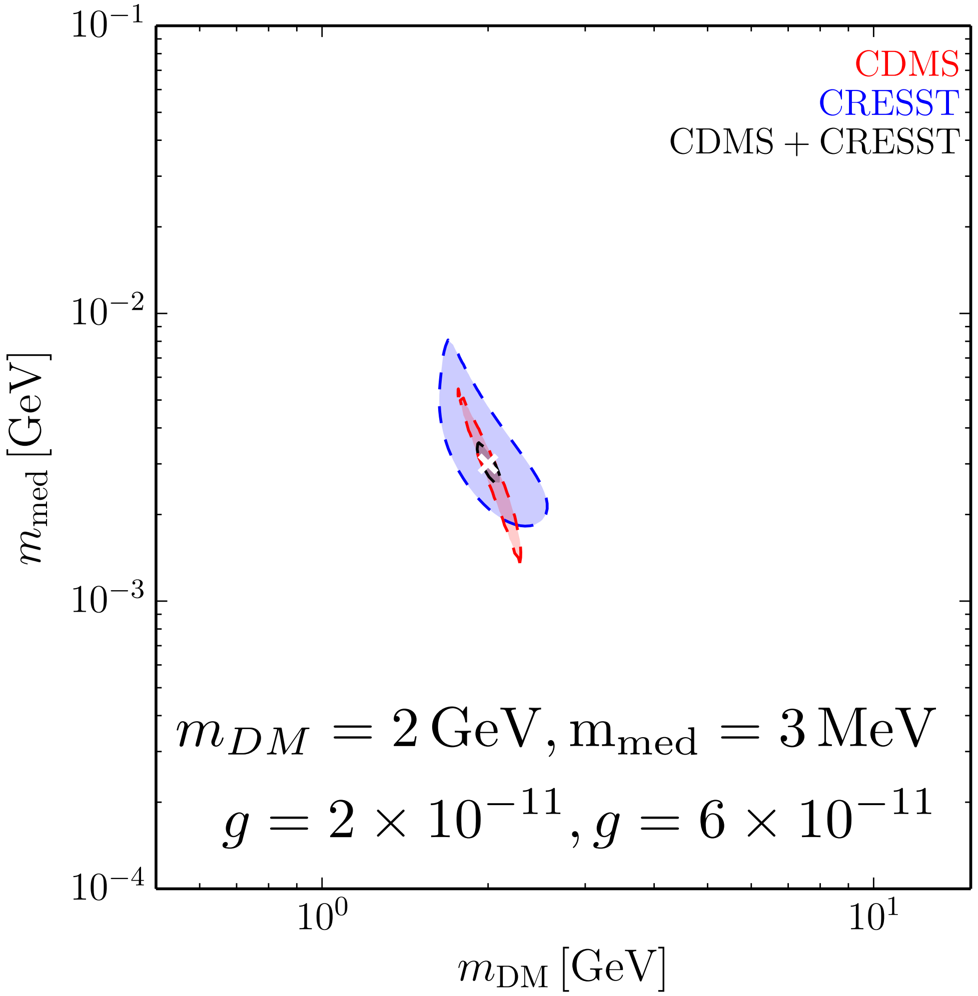
Limits on models with light mediators



- 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!!

Let’s be optimistic

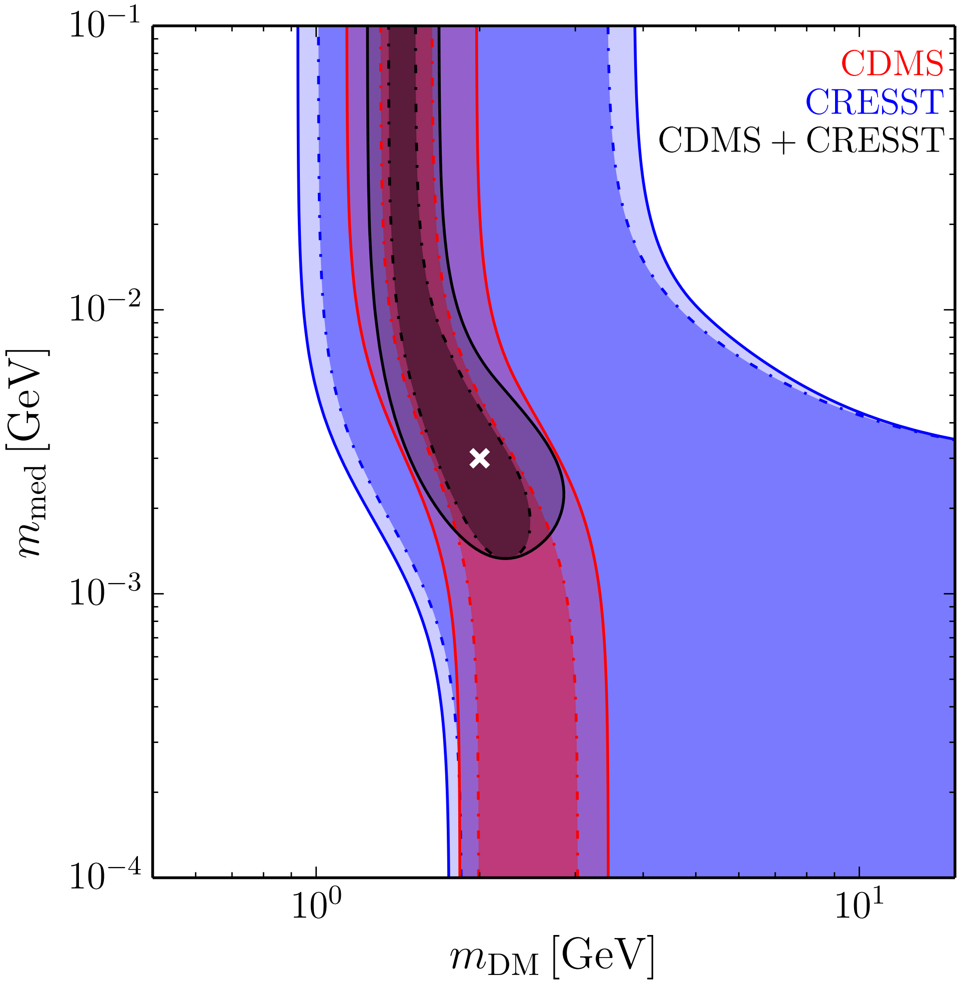

Low statistics (~900 events)


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 treated as nuisance parameter for reconstruction (fixed at max likelihood)

Let’s be realistic

Low statistics (~900 events)



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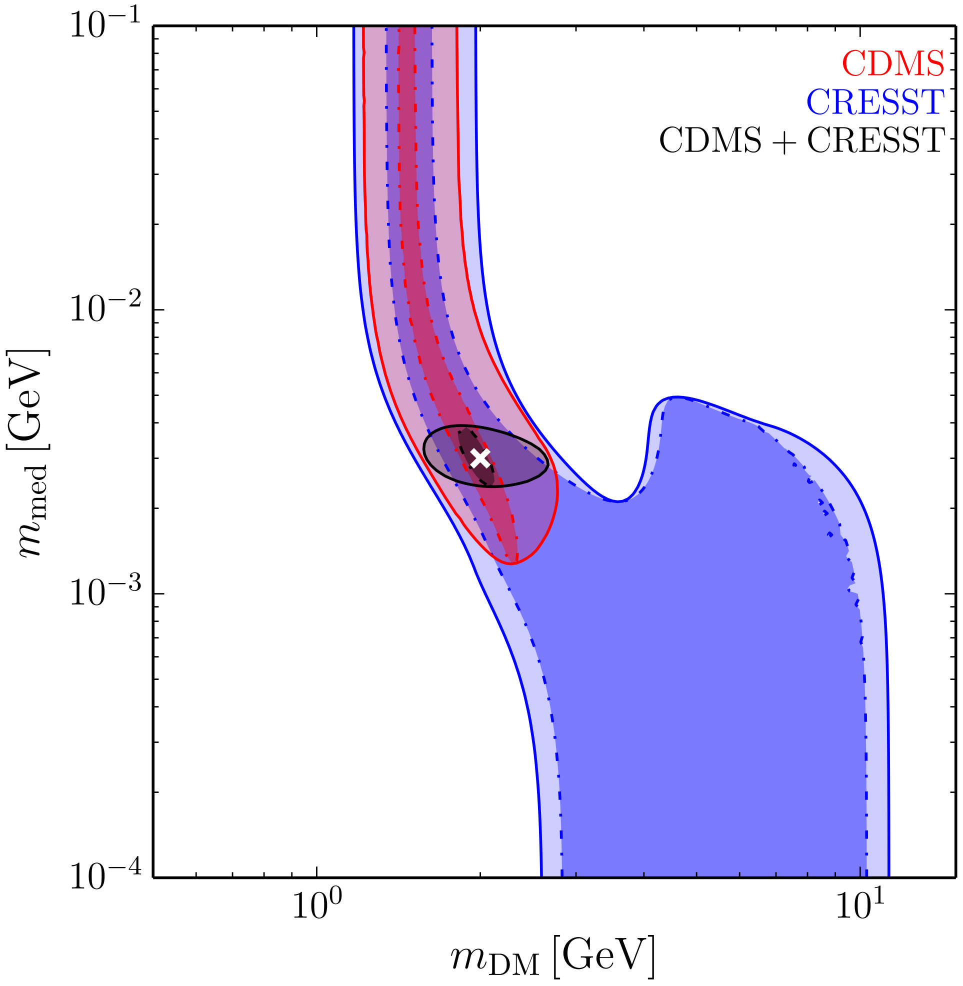
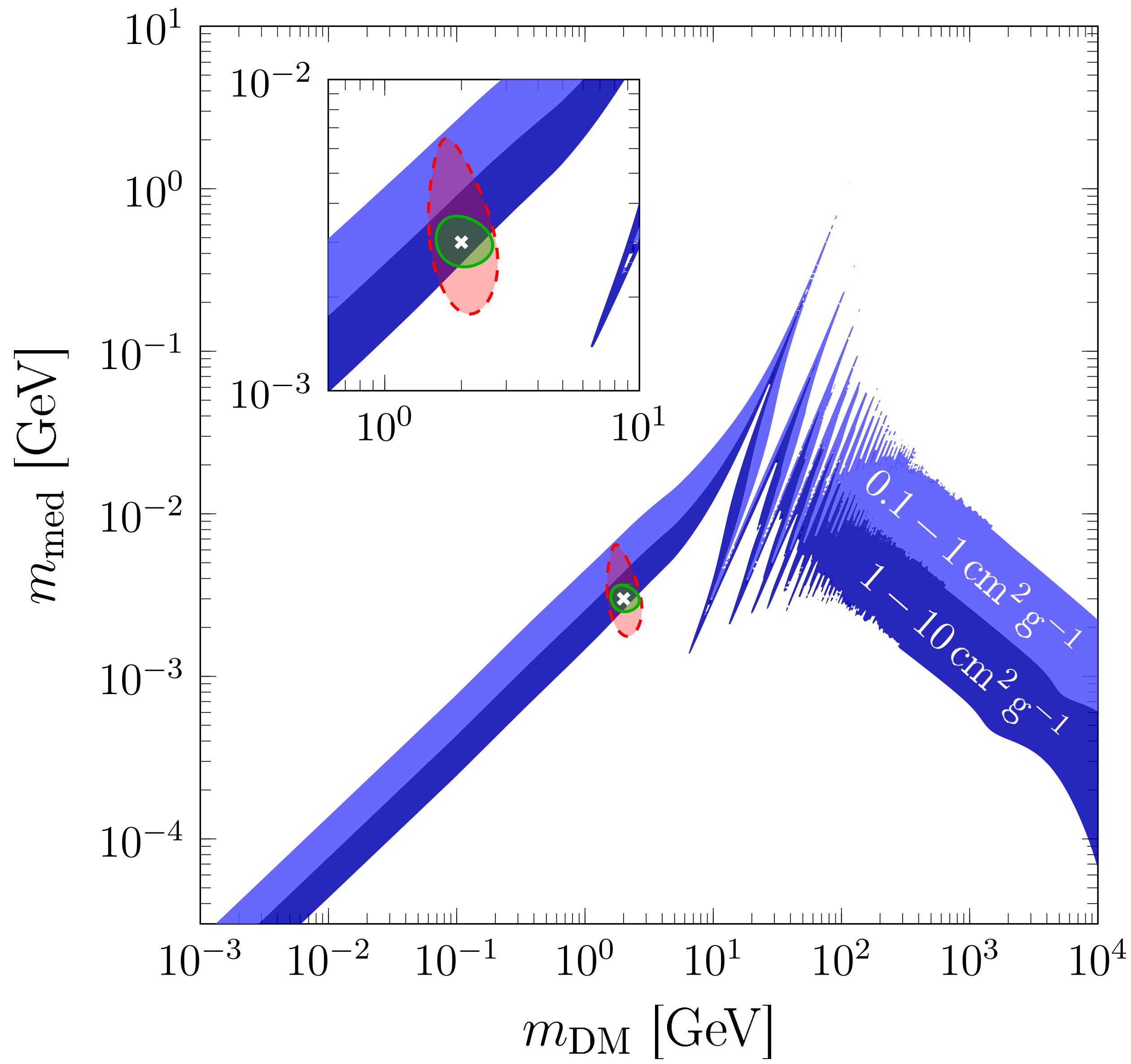


- Include astrophysical uncertainty
- Maxwell-Boltzmann distribution only
- Even when including the astrophysical uncertainty, the reconstruction is possible

Solid curve =
astrophysical uncertainties

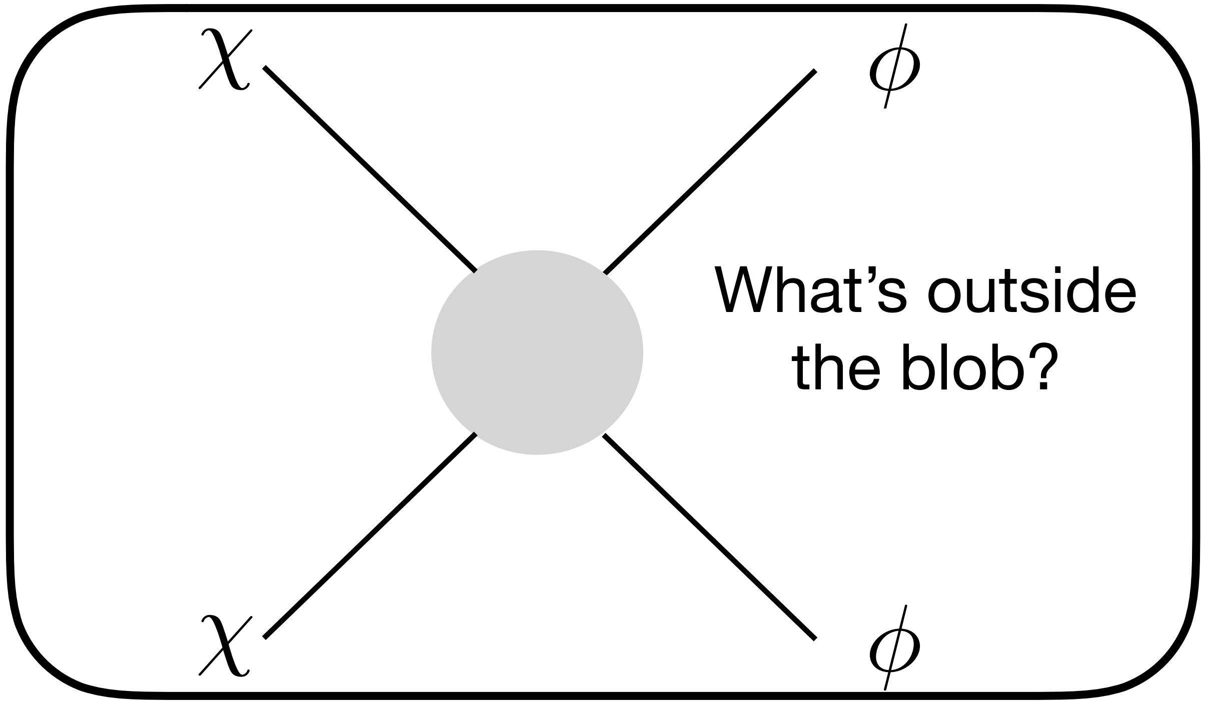
Self-interacting DM



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

Looking at the other side of blob

Be model independent

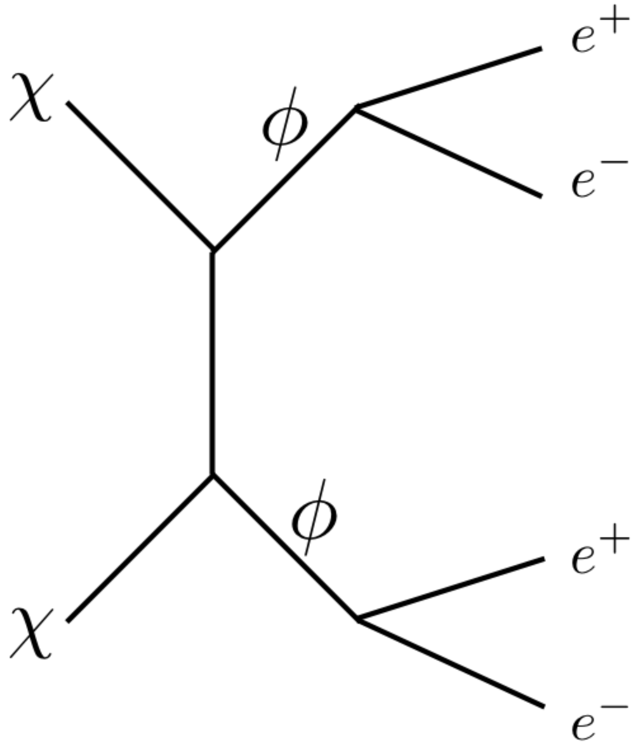


What's outside the blob?

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

DM with long lived mediator

Kulkarni et al

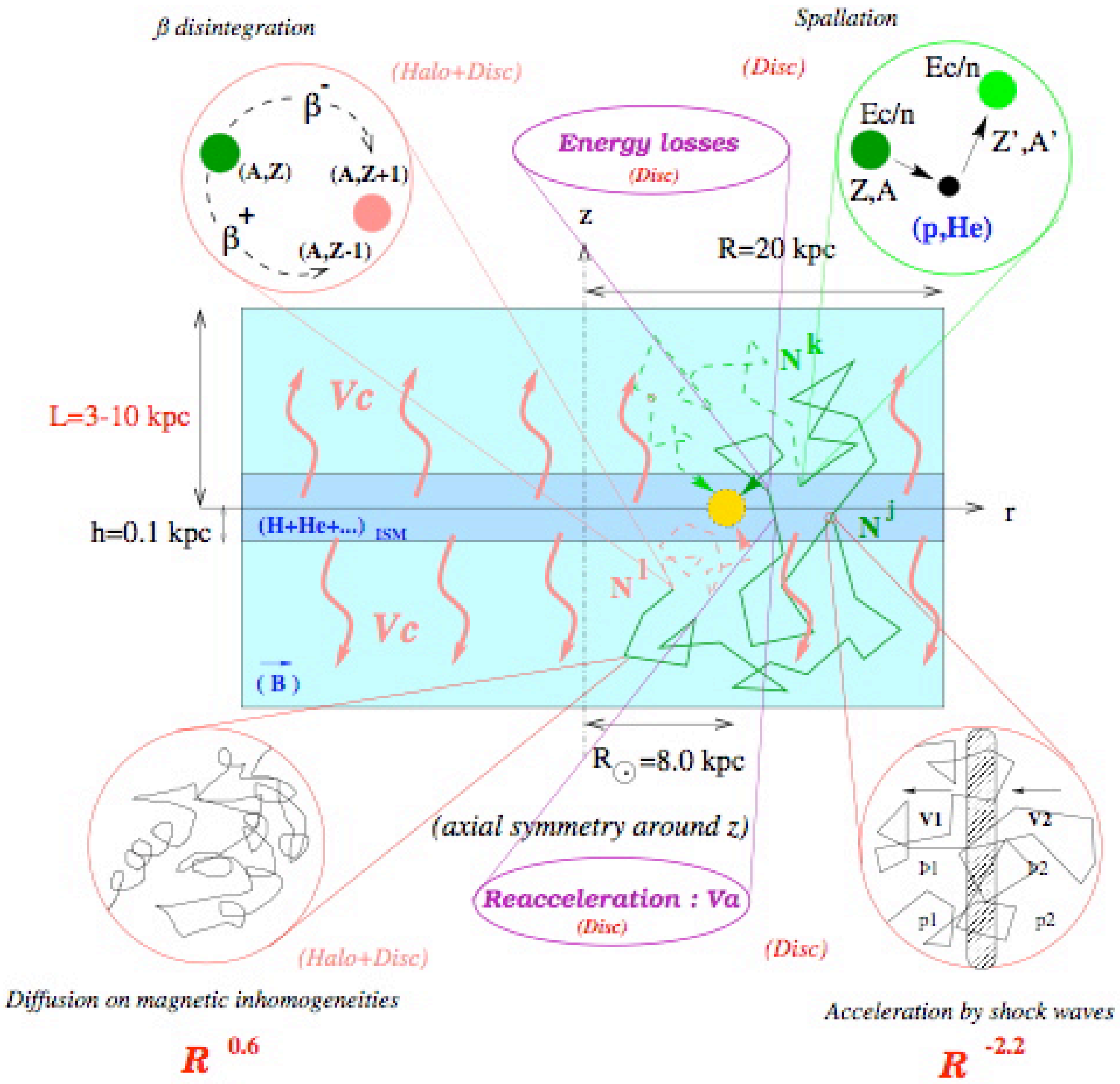


- DM particle undergo annihilation into mediator, which is long lived

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

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

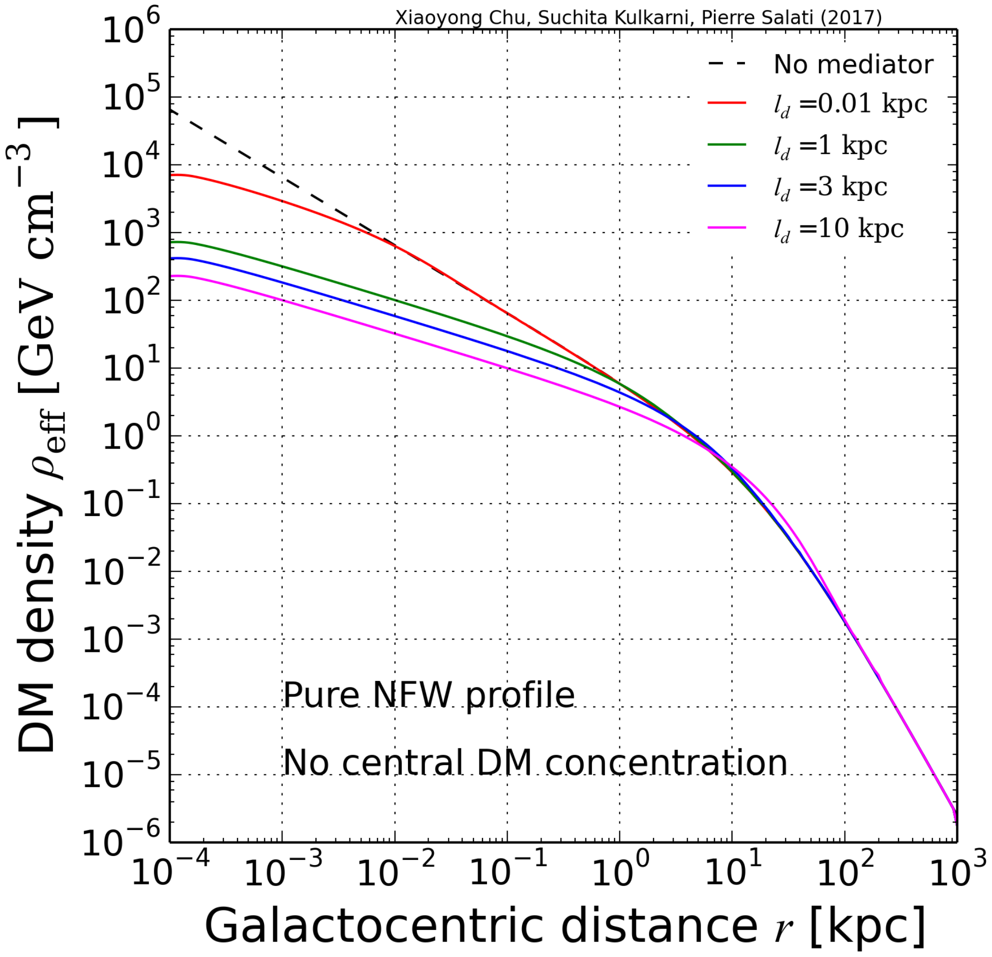
Cosmic rays



- From the point of production cosmic rays travel up to a certain distance ballistically
- After the ‘ballistic’/‘last scattering’ sphere, they promptly loose energy due to diffusive effects
- What are the effects if the cosmic rays produced due to DM annihilation enter this ballistic regime?

- Consider DM annihilation at the centre of our galaxy, the mediators travel a distance and decay within the positron ballistic sphere around the earth

Smeared mediator density profile



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

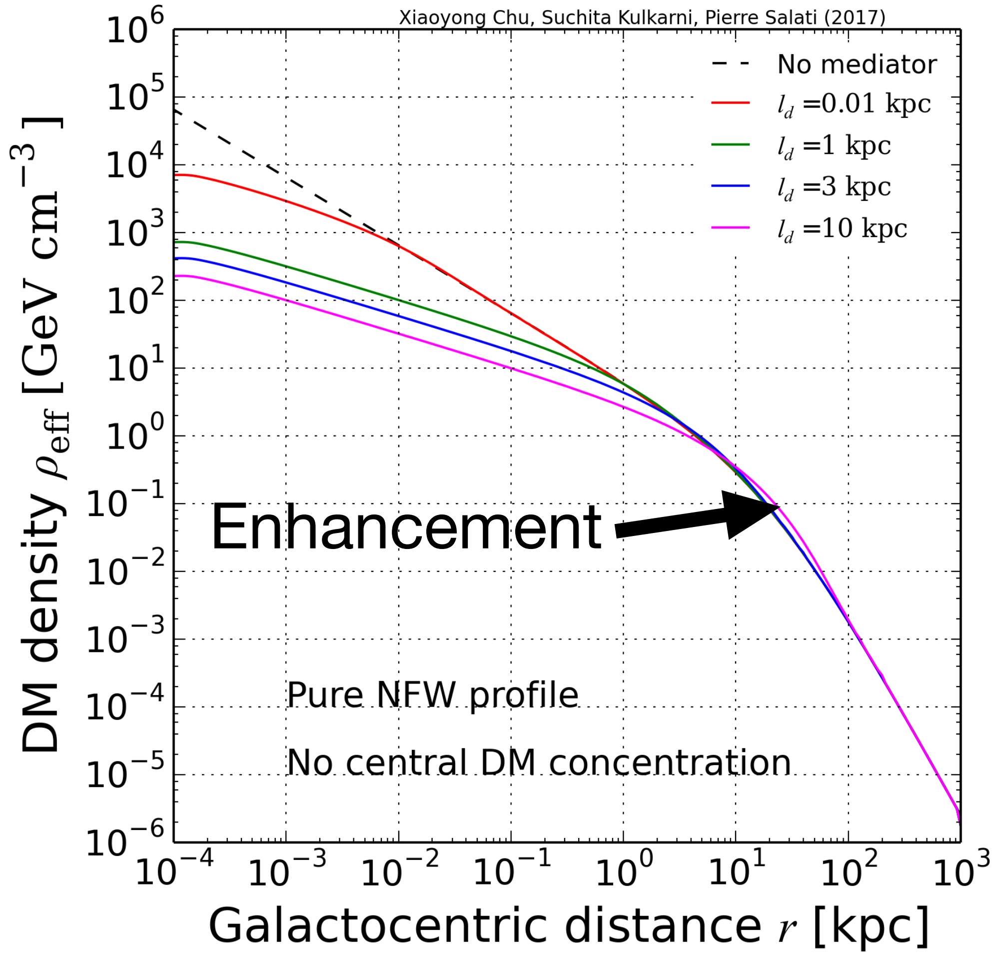
$$q_{\rm SM}(\vec{r}_B) = a \int d^3\vec{l} \cdot \frac{\rho^2(\vec{r}_A)}{m_\chi^2} \langle \sigma_{\rm ann} v \rangle \cdot \frac{P(l)}{4\,\pi\,l^2} \, .$$

Source term for SM particles

Convolution with standard density profile

- Effective dark matter density gets smeared
- Enhancement in the effective DM density around the Earth
- No strong signals associated with DM annihilations

Smeared mediator density profile



Enhancement

Pure NFW profile

No central DM concentration

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

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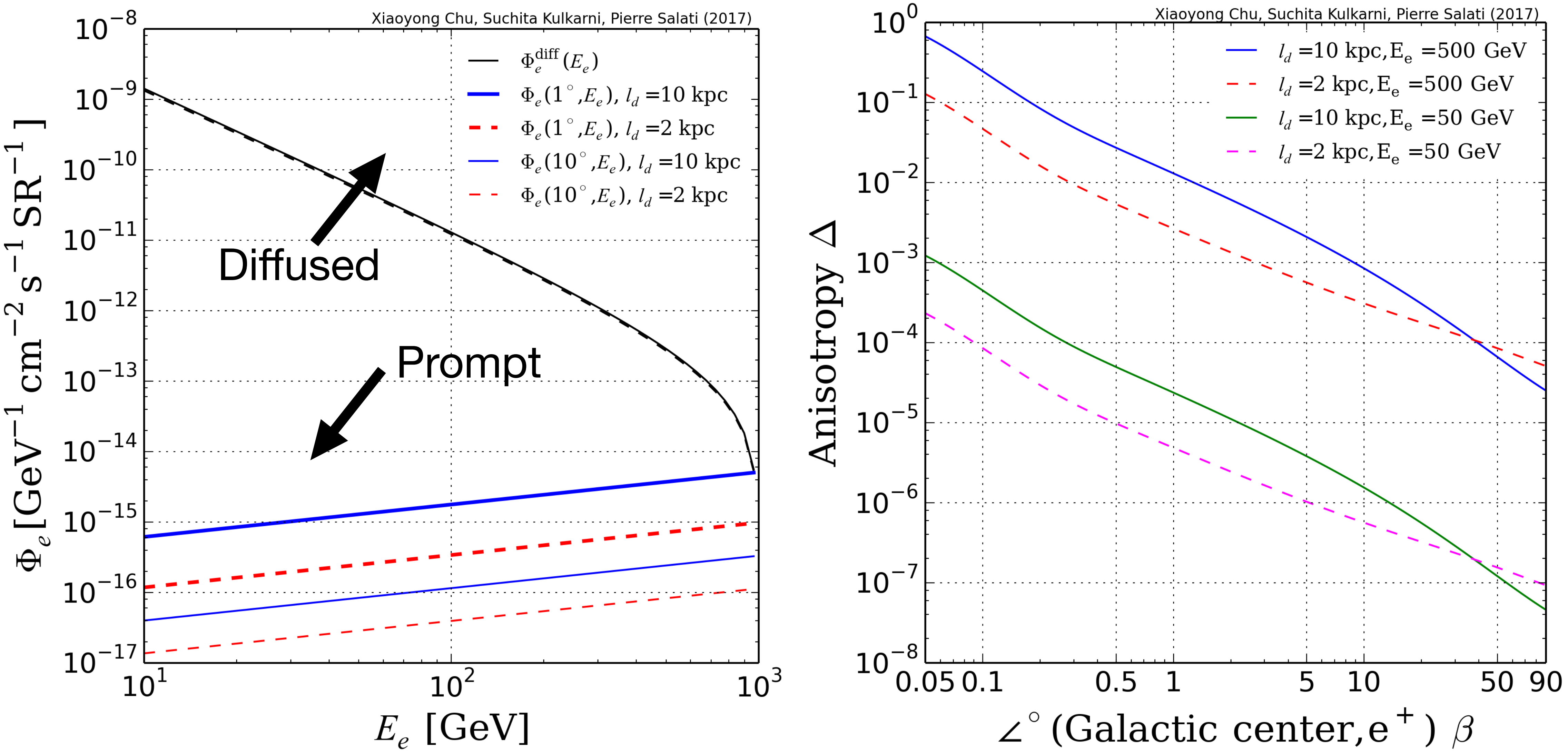
Two body decay of mediator



- 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

Conclusions

- Identification and realistic evaluation of exotic dark matter interactions at experiments is a crucial task for next generation dark matter experiments
- Plenty of parameter space is still unexplored and next gen program will shed some light on this
- Exotic interactions in dark matter and neutrino sector can be simultaneously probed and should be considered for the ultimate direct detection experiments
- It is possible to constrain both dark matter and mediator mass at direct detection experiments if the mediator is reasonably light
- If the mediator is ultra-long lived, then indirect detection experiments can be hopeful
- Asymmetry in cosmic rays can be generated, for light mediator lifetimes of O(years)

Backup

Light dark matter - detectors

- CRESST III
  - 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
  - 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
- Can lead to thousands of DM events in the future

Technical details

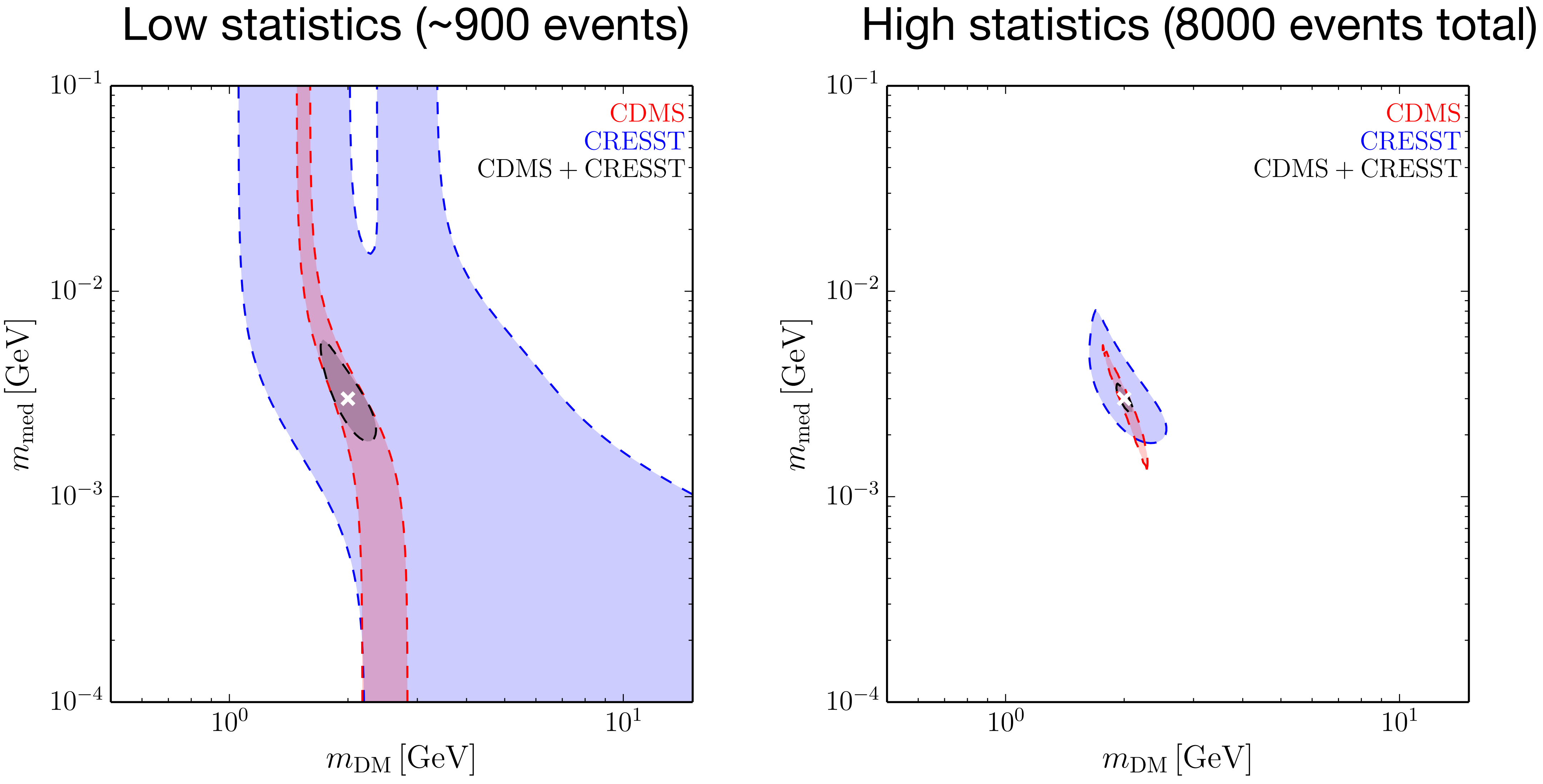
- Generate mock data and attempt reconstruction
- Likelihood function

$$-2\log\mathcal{L}^{\alpha}(\mathbf{x},\mathbf{y}) = 2\sum_i\left[\underbrace{R_i^{\alpha}(\overbrace{\mathbf{x},\mathbf{y}}^{\text{Particle physics parameters}})}_{\text{Predicted signal events}} + \underbrace{B_i^{\alpha}(\overbrace{\mathbf{y}}^{\text{Nuisance parameters}})}_{\text{Predicted background events}} - \underbrace{N_i^{\alpha}}_{\text{Observed events}} + N_i^{\alpha}\log\frac{N_i^{\alpha}}{R_i^{\alpha}(\mathbf{x},\mathbf{y})+B_i^{\alpha}(\mathbf{y})}\right]$$

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

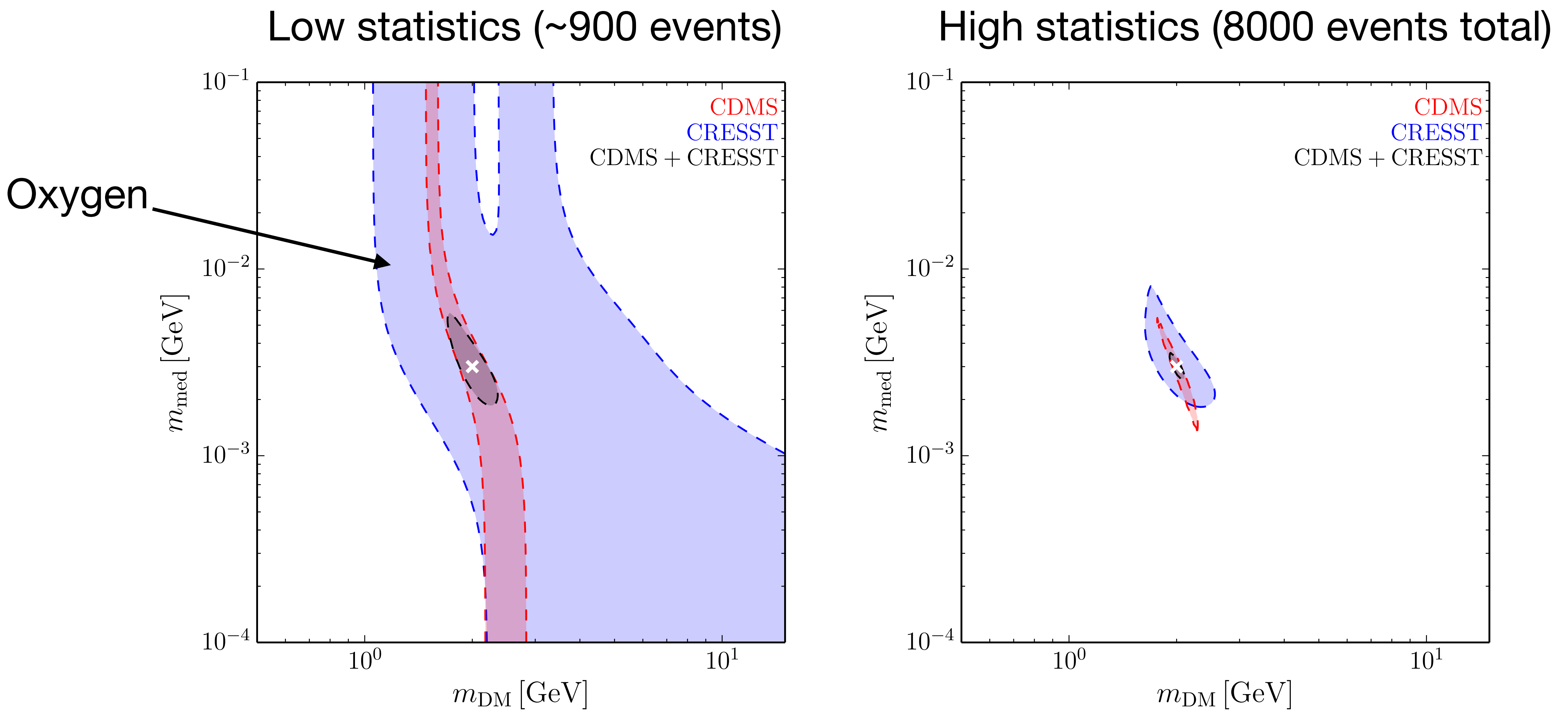
$$-2\log\mathcal{R} < 5.99$$

Let’s be optimistic



- 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



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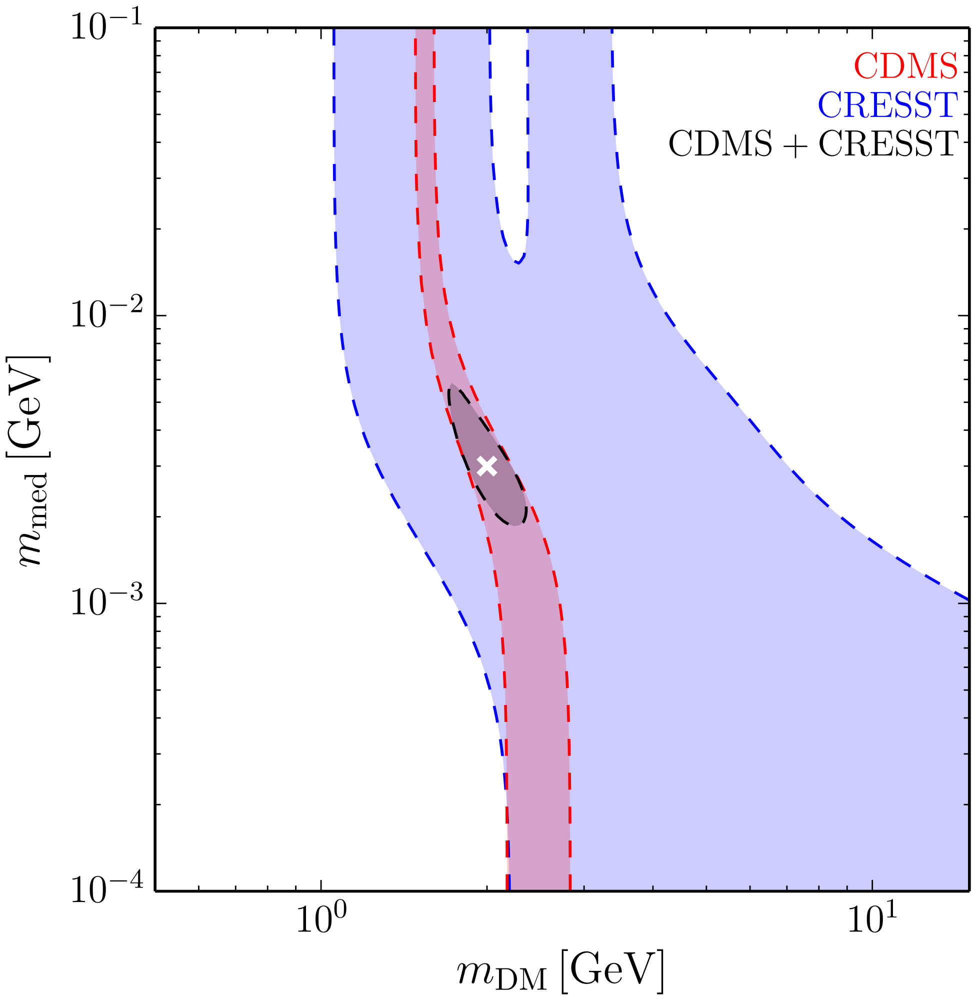

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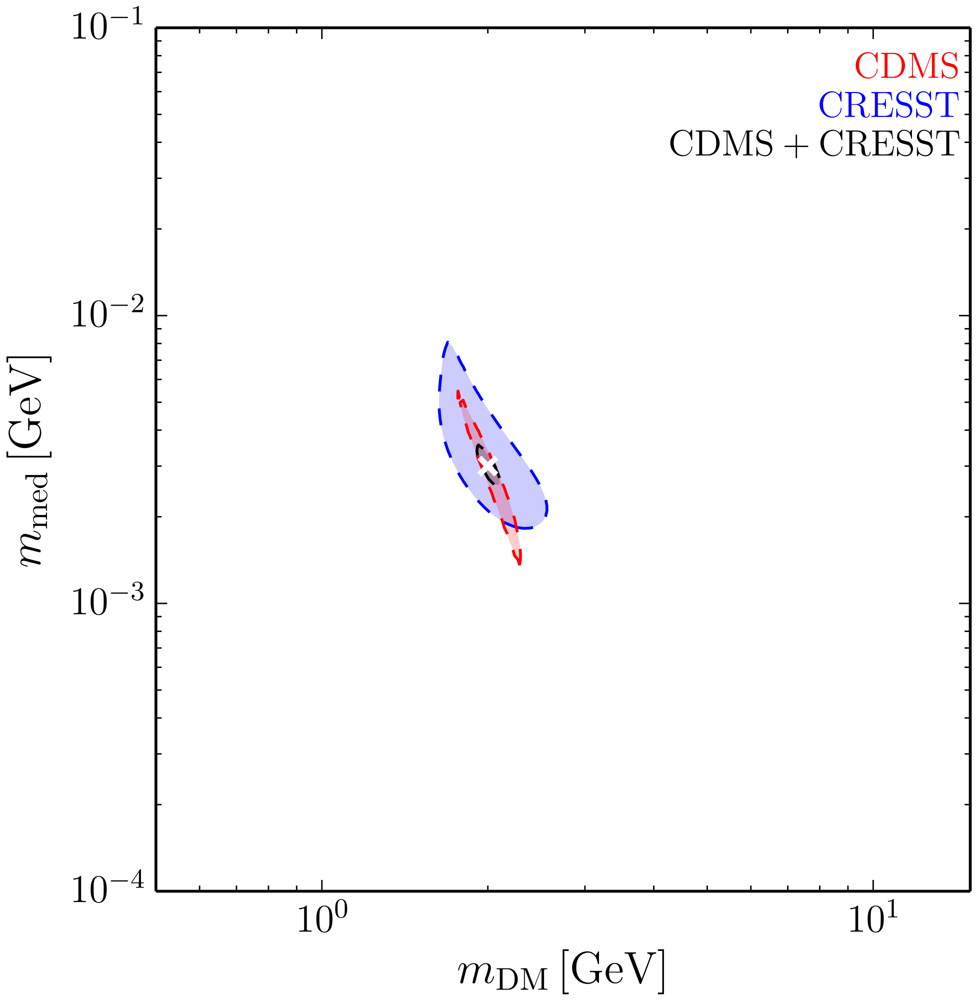

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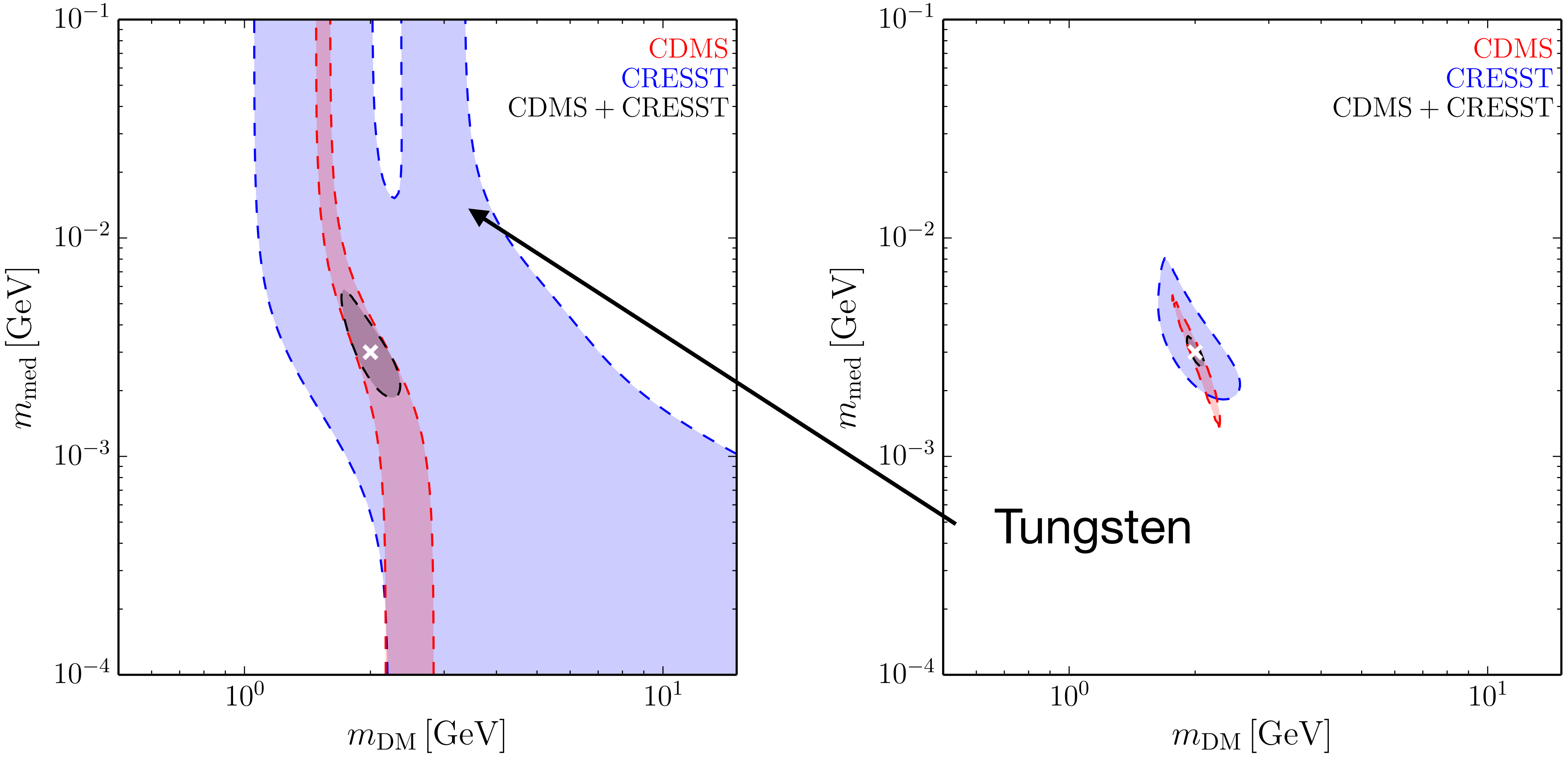

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Tungsten

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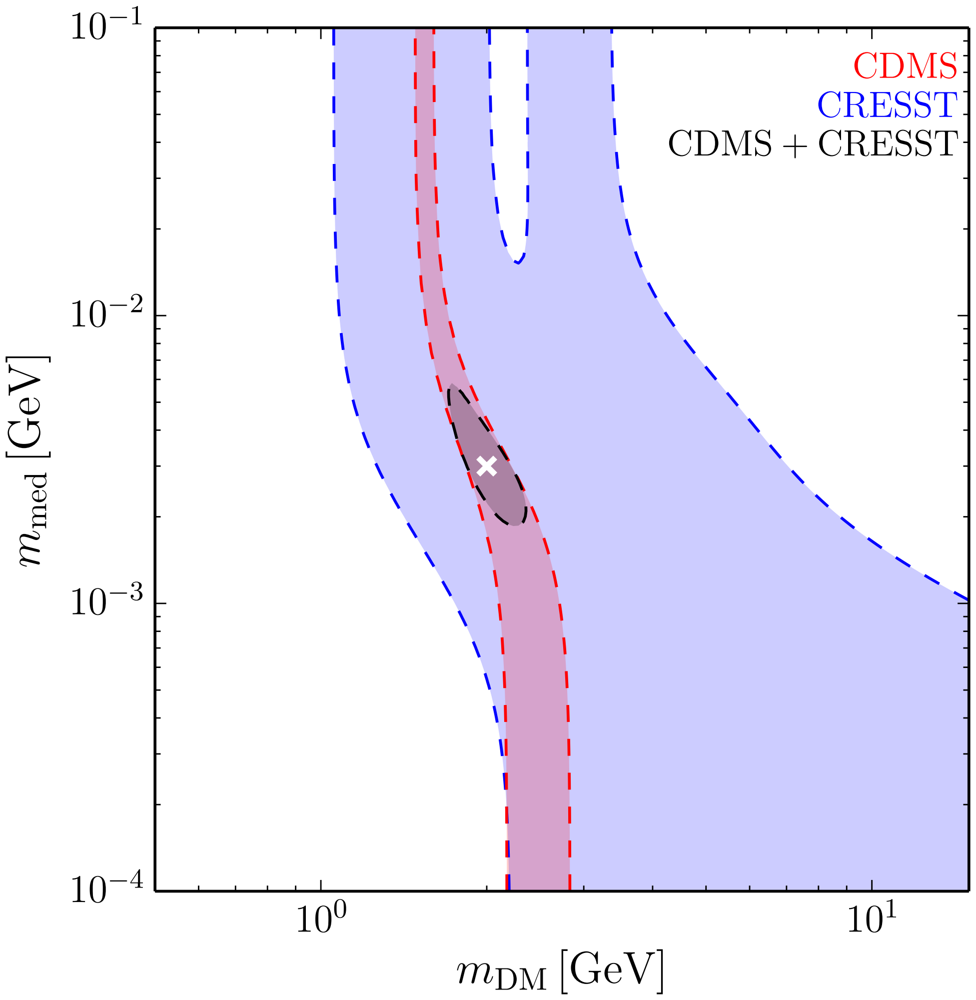

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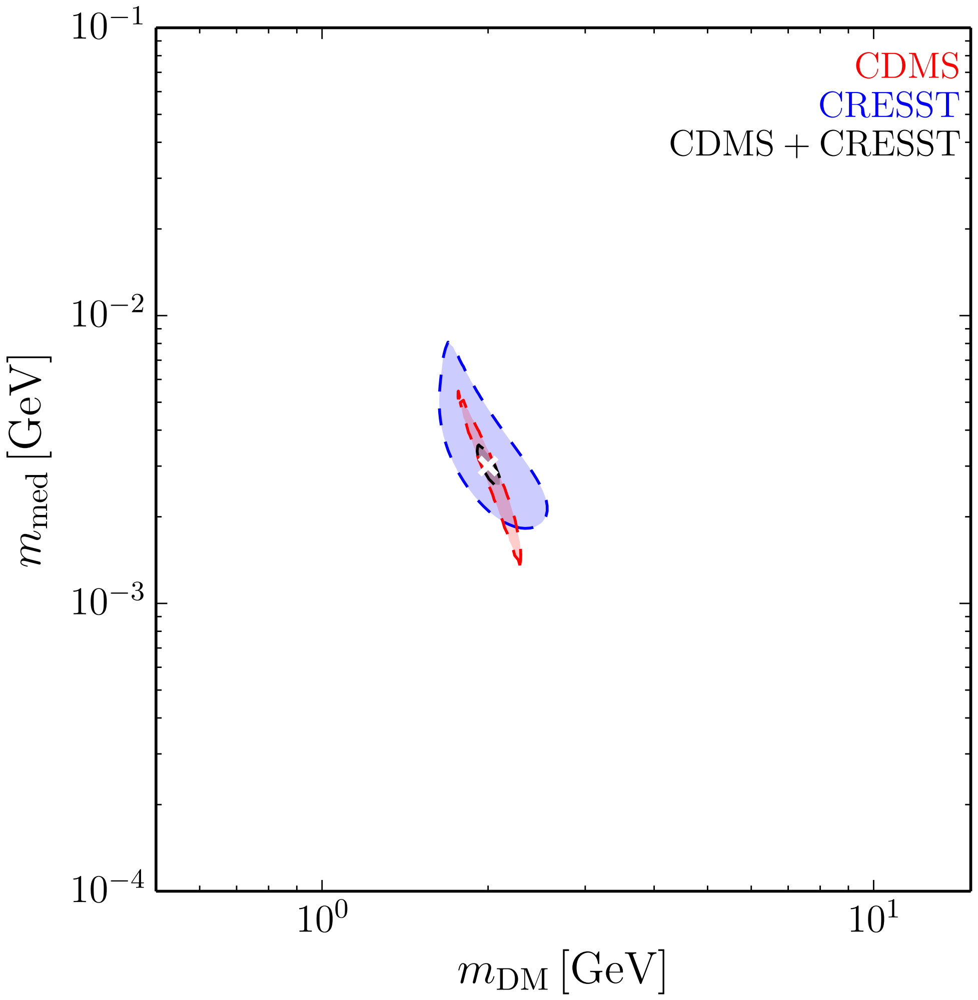

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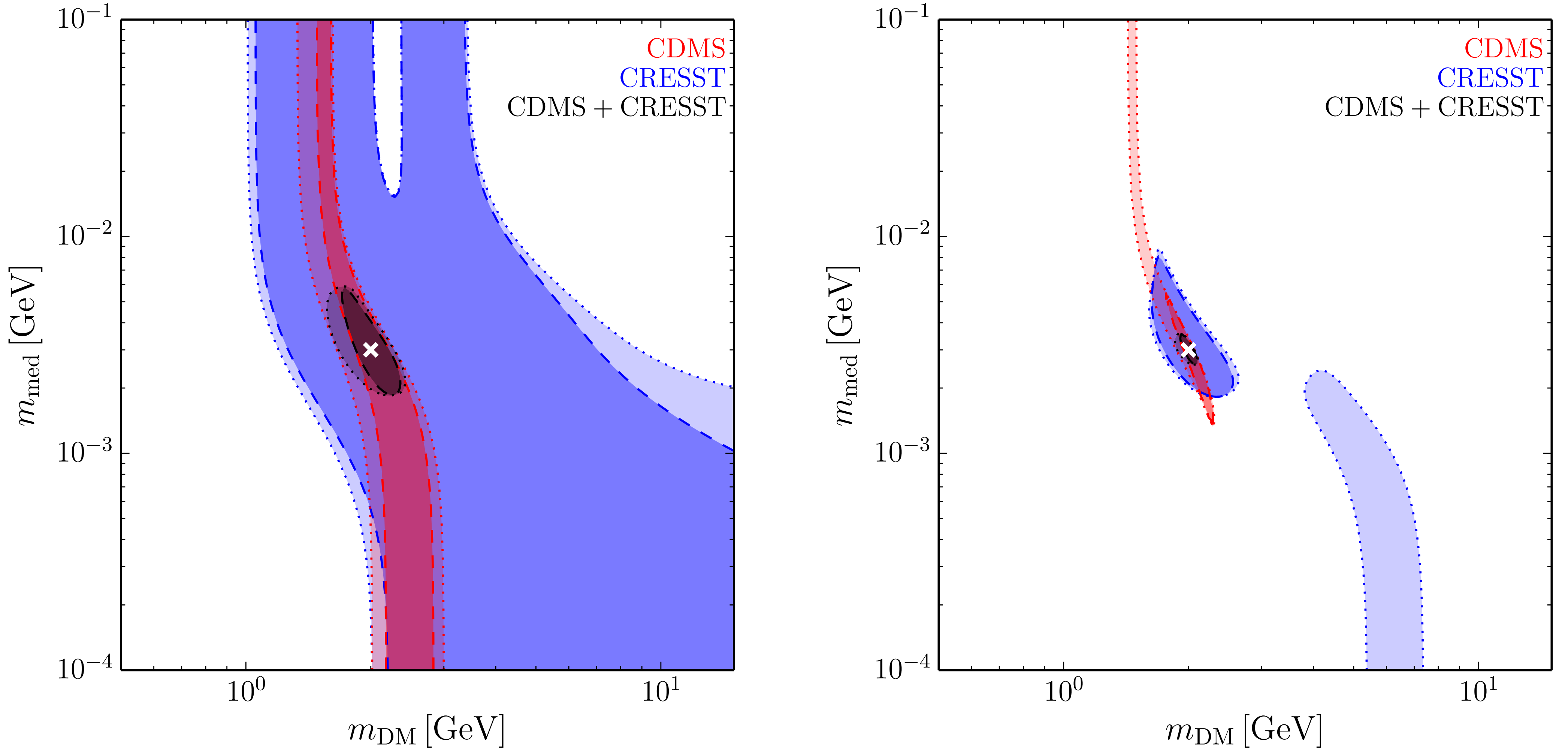
Let’s be realistic

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

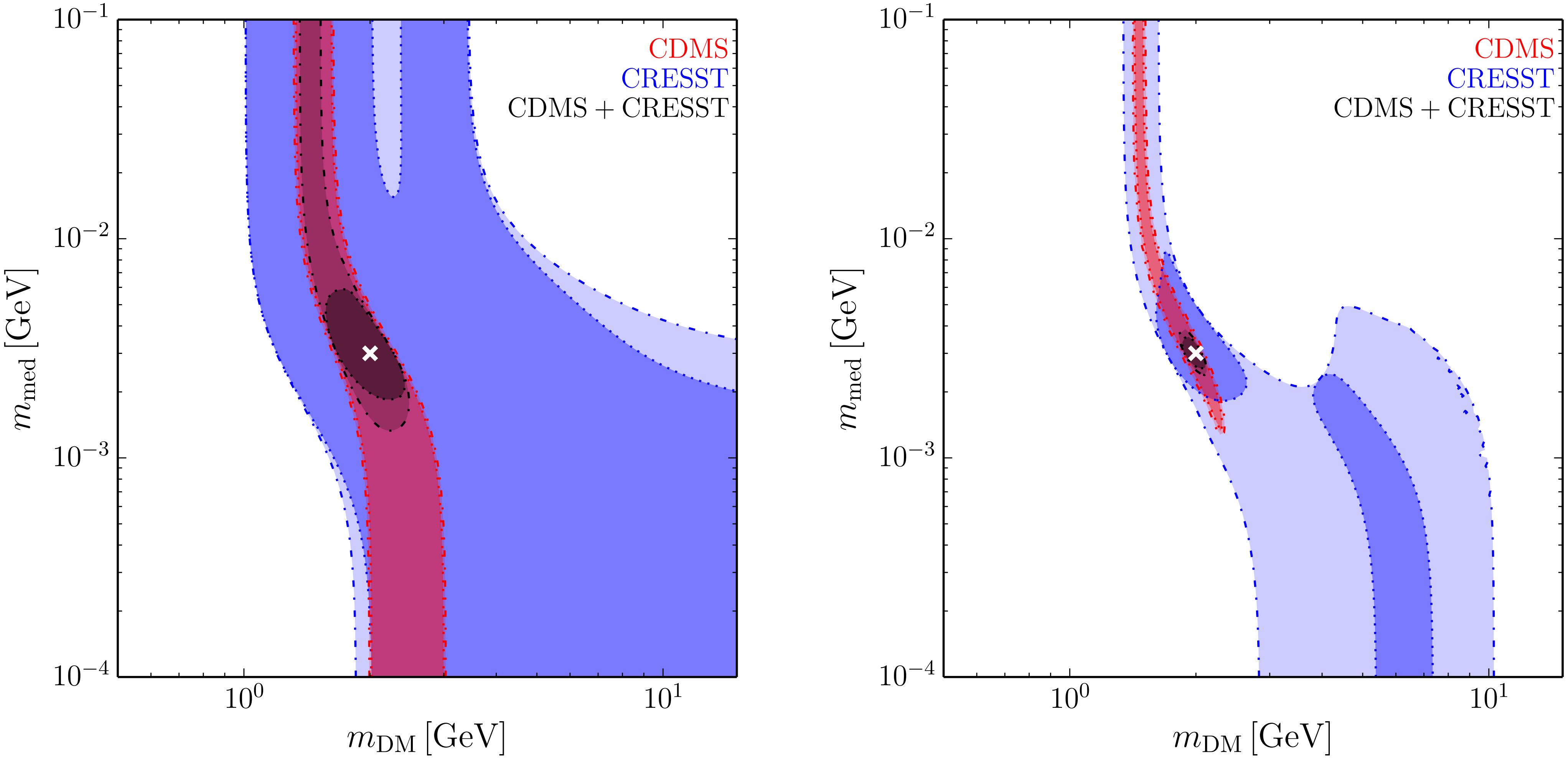


- Characteristic tilt: light mediators needed for heavier masses and vice versa
- Nuisance parameter for background normalisation: shape known, normalisation unknown
- Degeneracy between DM mass, coupling and mediator mass removed by combination of data - accurate reconstruction

Let’s be realistic

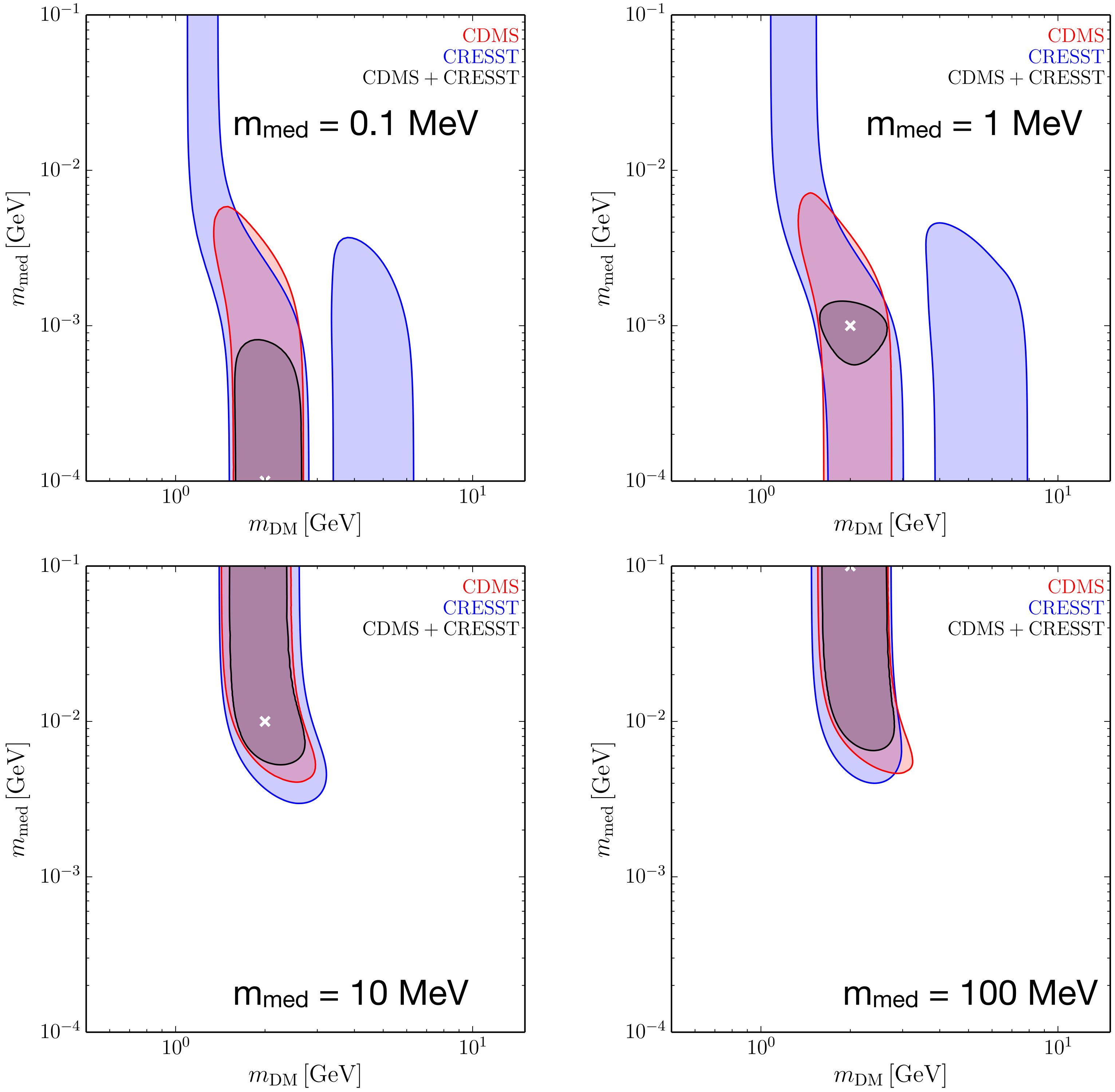
Low statistics (~900 events)

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

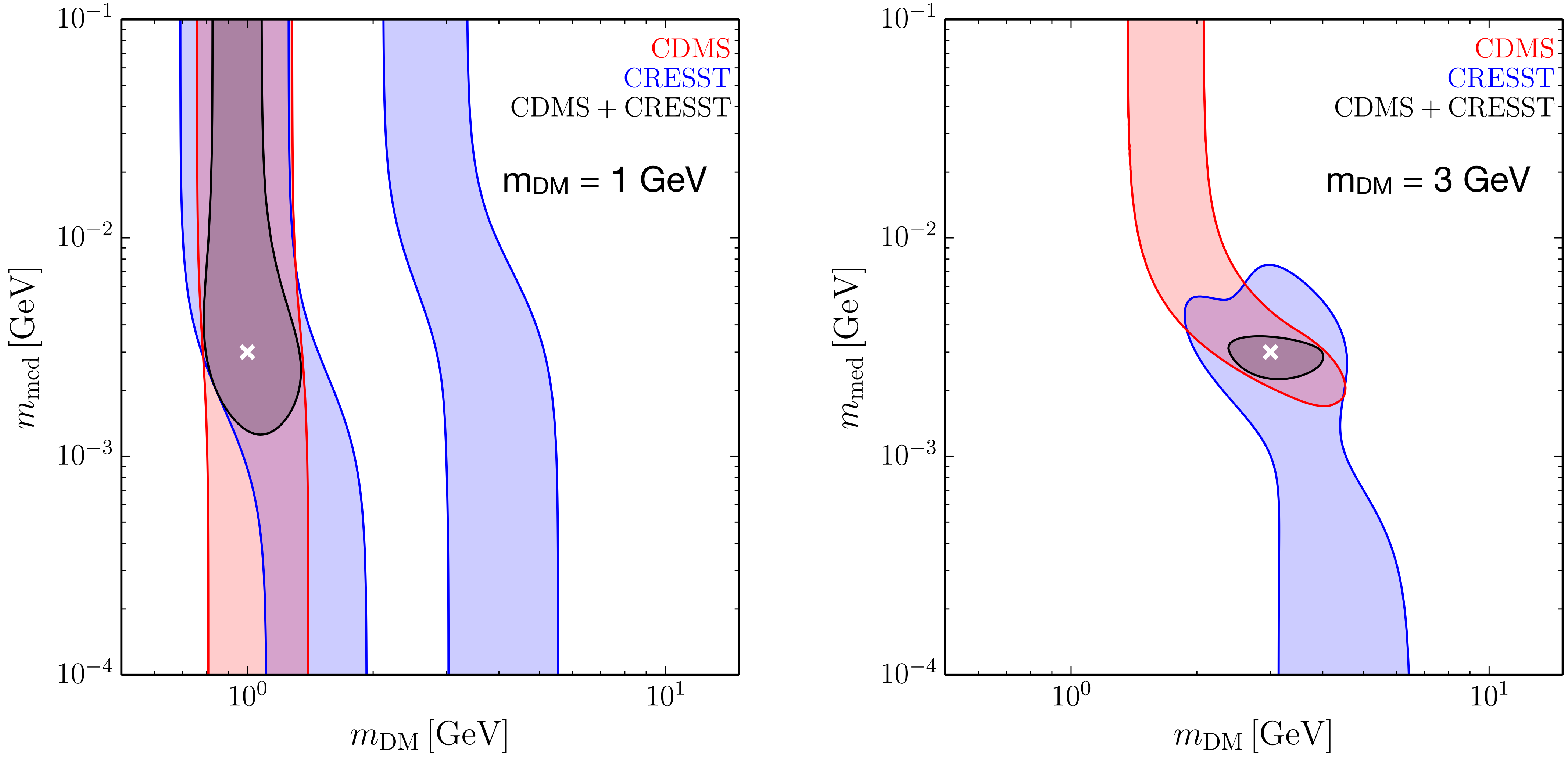
Alternative benchmarks



- 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

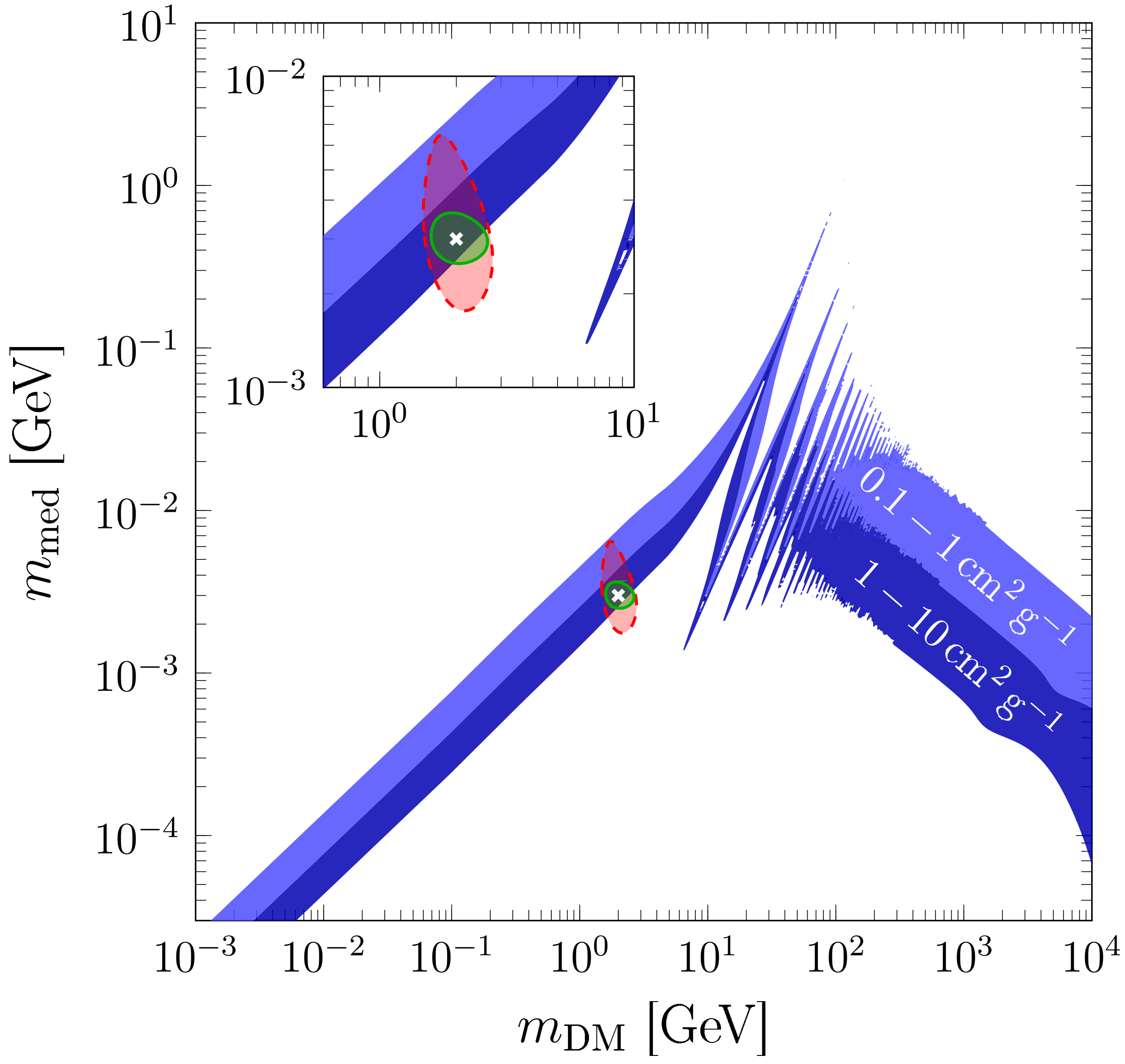
Alternative benchmarks



- 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



Low statistics

High statistics

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DM with long lived mediator

Kim et. al. arXiv:1702.02944

- 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 $\rho_\phi \times \mathrm{BR}(\phi \to \gamma\gamma)$ or $\rho_\phi \times \mathrm{BR}(\phi \to e^\pm e^\pm)$
- For $\rho_\phi \sim 10^{-2} - 10^{-5} \times \rho_{DM}$, $\tau_\phi \lesssim 10^6 - 10^8$ seconds by BBN constraints
- If $\rho_\phi \sim 10^{-5}$ - $10^{-11} \times \rho_{DM}$, 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