Prospects for Ultra Heavy Dark Matter Phenomenology

Gopolang (Gopi) Mohlabeng

+ Hooman Davoudiasl

based on

Phys.Rev. D98 (2018) no.11, 115035

&

JHEP 04 (2020) 177

BSM PANDEMIC Seminar

04 September 2020

BROOKHAVEN NATIONAL LABORATORY → Queen's UNIVERSITY

Thank you to all frontline workers

unitedway.org/blog/8-ways-to-thank-frontline-workers

Who Risk their lives to ensure society runs smoothly during 2020

2020 has been a rough year, but on a positive note…

In the past decade particle physics, astrophysics & cosmology have had amazing achievements:

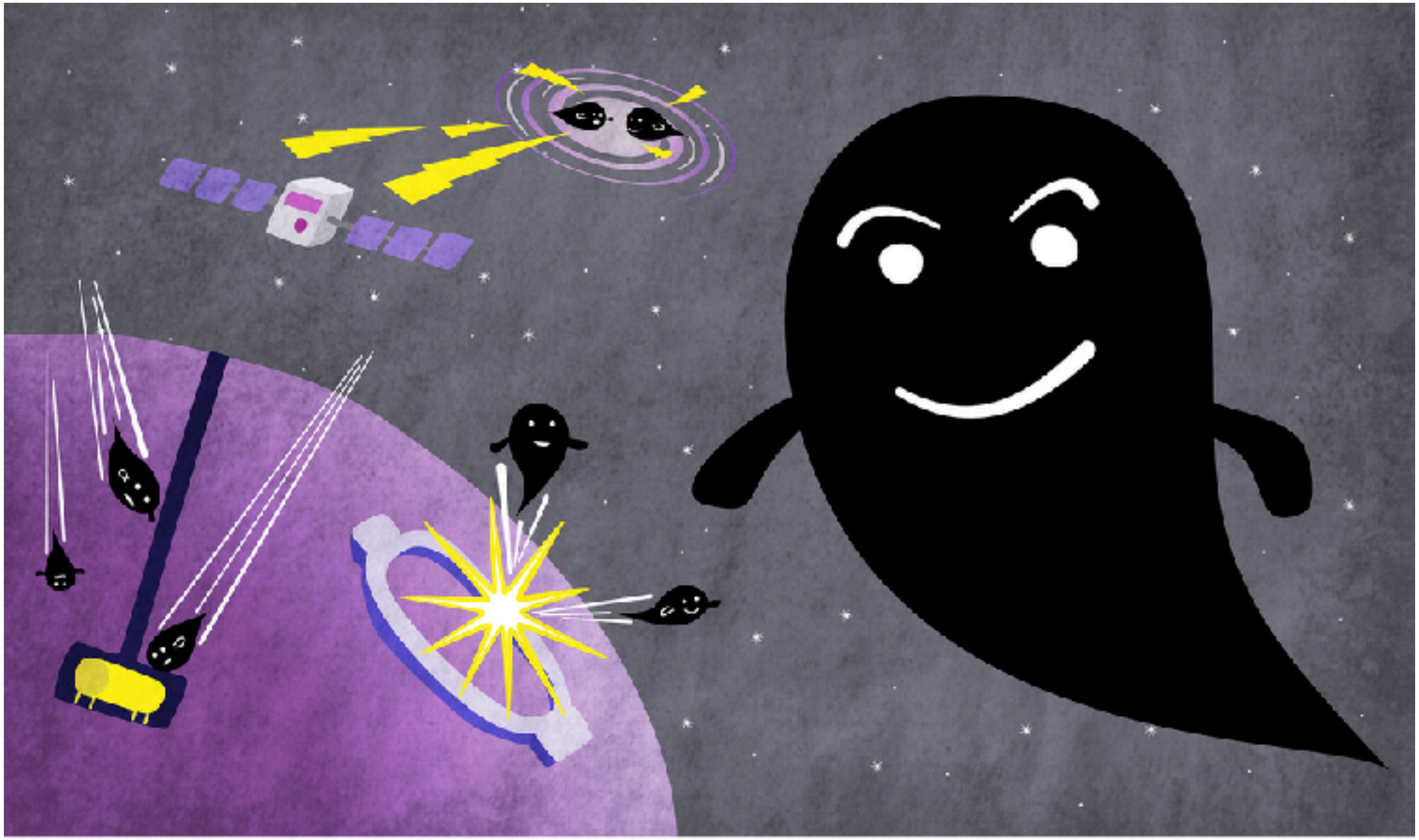
- Nobel Prize for discovery accelerating expansion of the universe - 2011
- Discovery of the Higgs & completion of SM - 2012

  Nobel Prize - 2013
- Nobel prize for discovery of neutrino oscillations - 2015
- Observations of Gravitational waves - 2016

  Nobel Prize - 2017
- First Image of Black-hole - 2019

  Breakthrough Prize - 2020

Hopefully the next decade will offer more discoveries and insights



worldofwierdthings.com

Especially in answering the question:

What is the nature of Dark Matter?

Outline

1. Current status of searches: super-brief overview.

2. GeV - scale messengers of GUT/Planck - scale DM

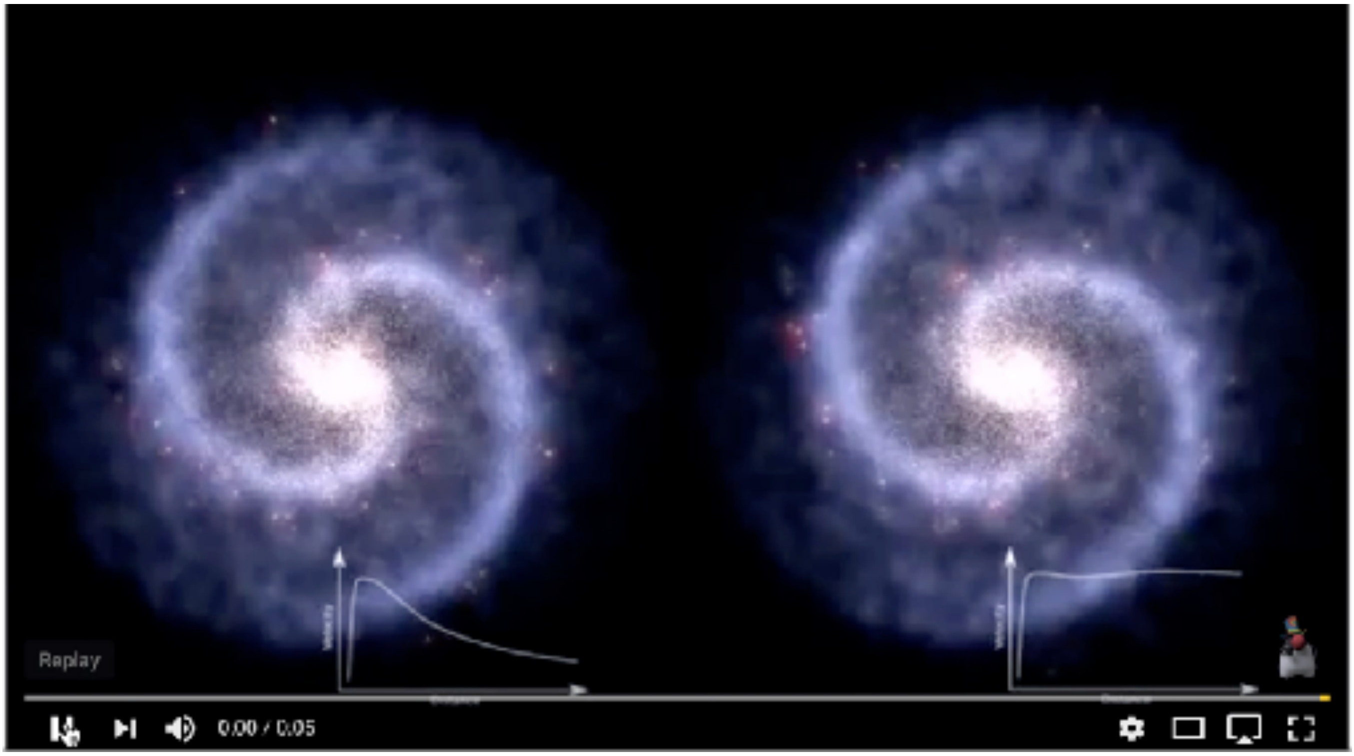
   - Model for ultra-heavy DM motivated by possible multi-scatter signals in direct detection experiments

3. How to get a THUMP from a WIMP

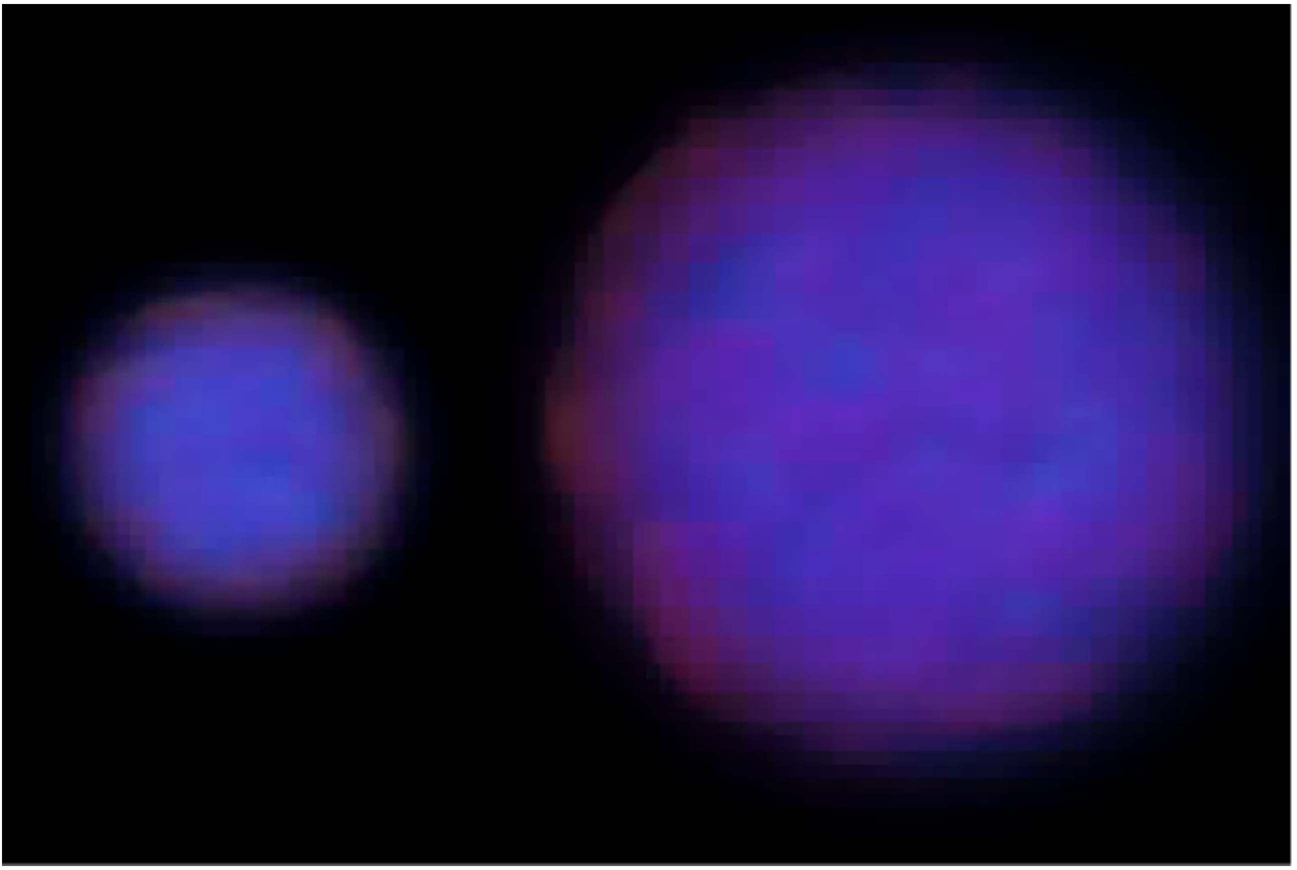
   - Thermal production in the early universe.

4. Conclude

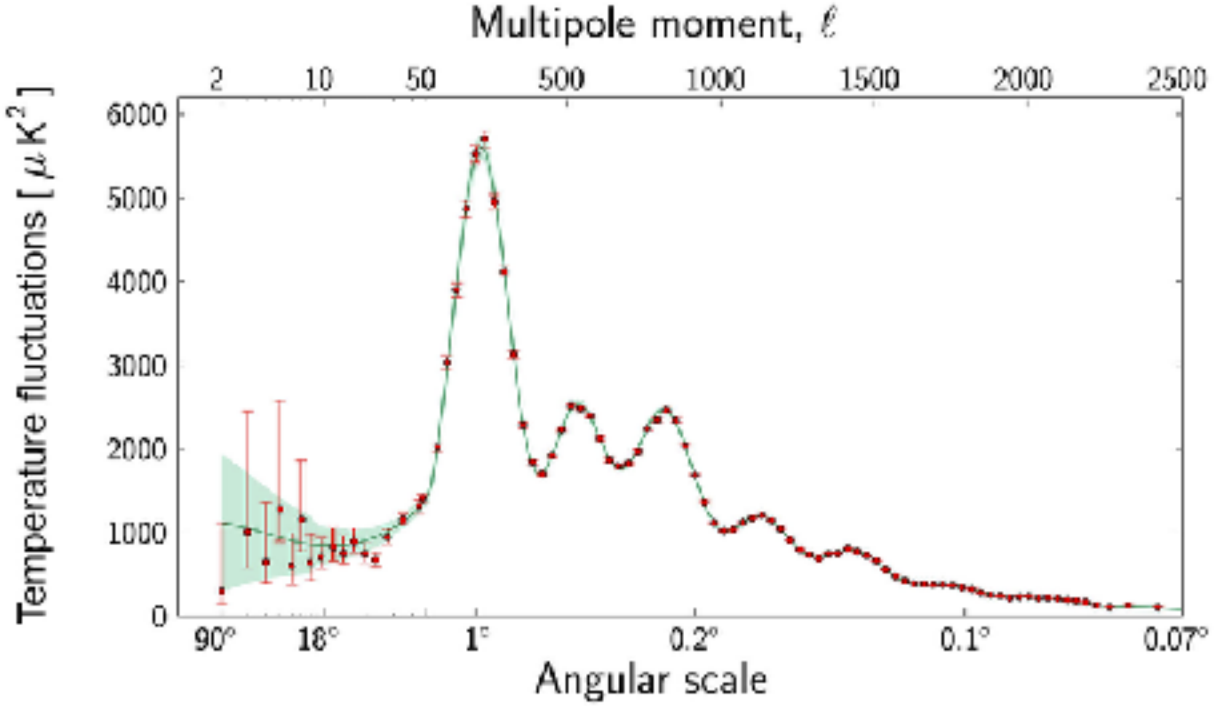
Undeniable evidence that dark matter exists



Rotational velocities of Galaxies



Gravitational Lensing



Cosmic Microwave Background

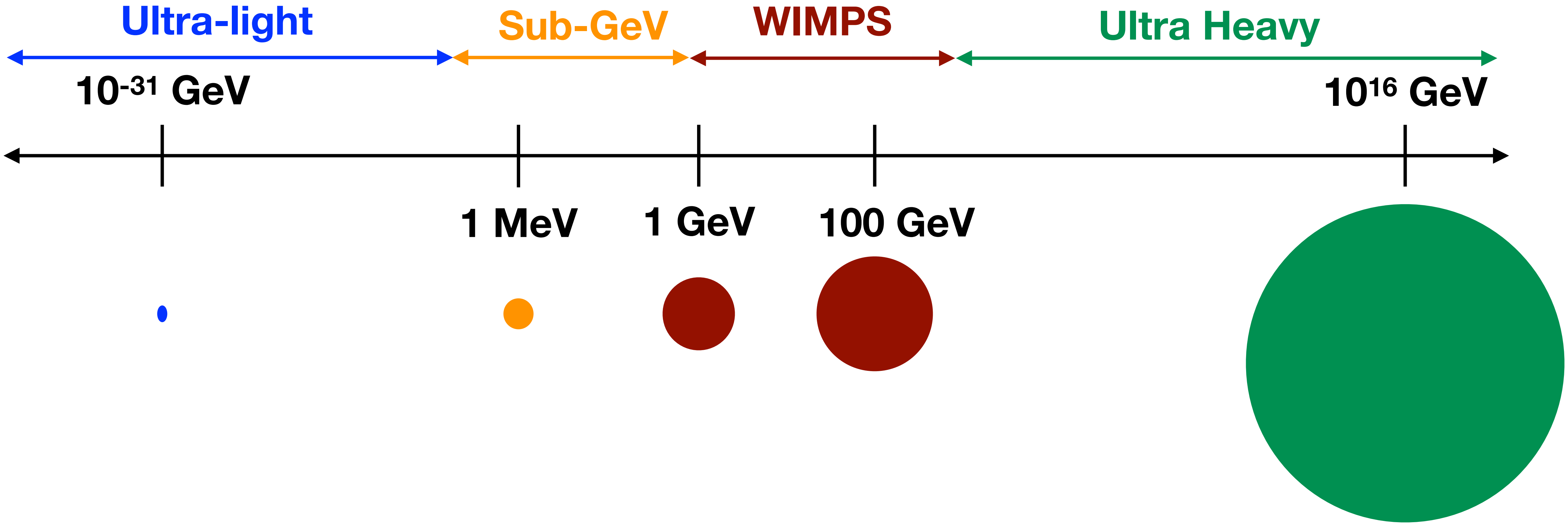
The (Inconvenient) Truth about Dark Matter

If **a new particle…**

1. Mass = ???
2. Spin = ???
3. Decays = ???
4. Interactions = ***Gravity***, ???
5. Elementary = ???
6. …

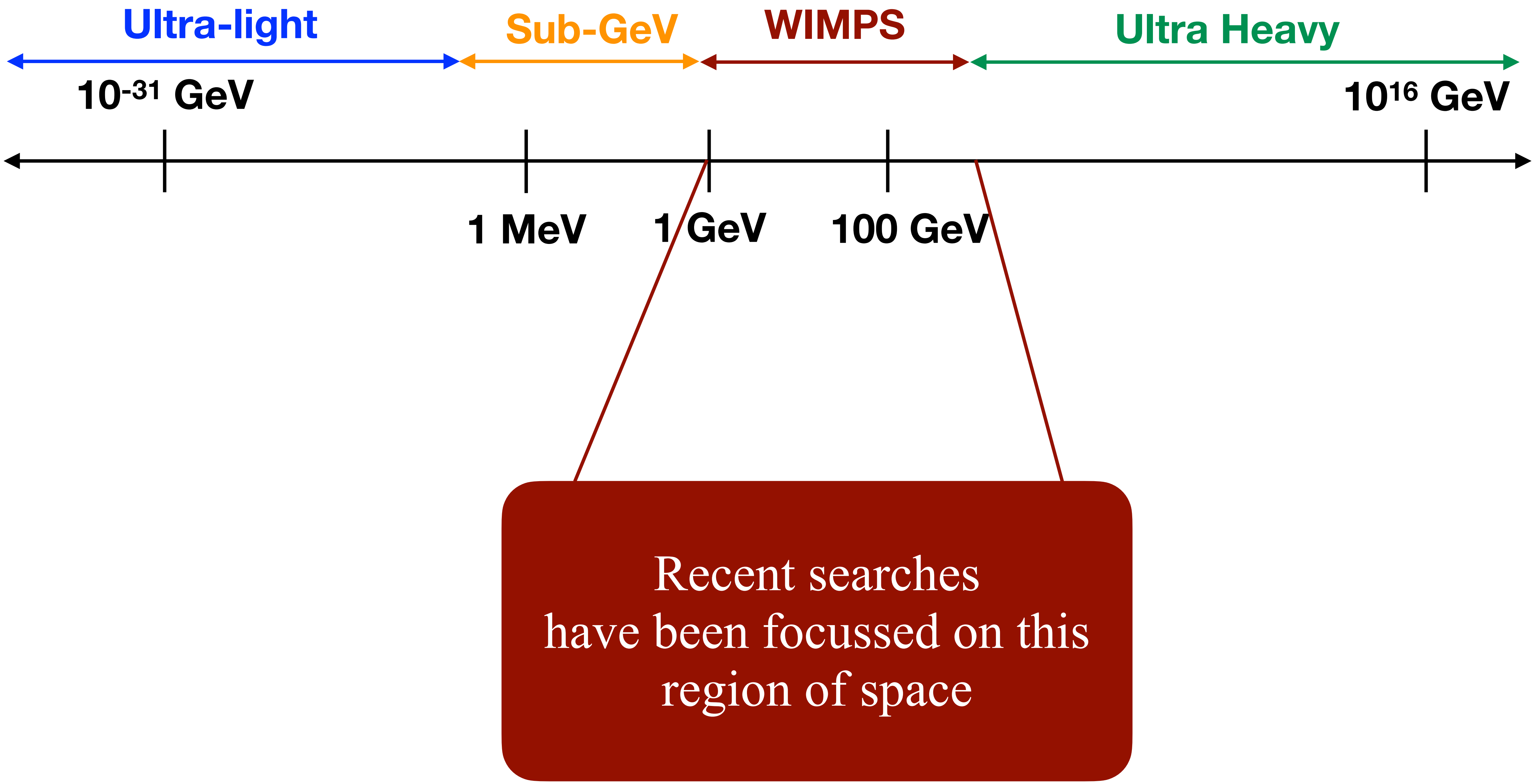
To have any hope of directly probing it, we look for its non-gravitational interactions with the SM

Range of possibilities is VAST

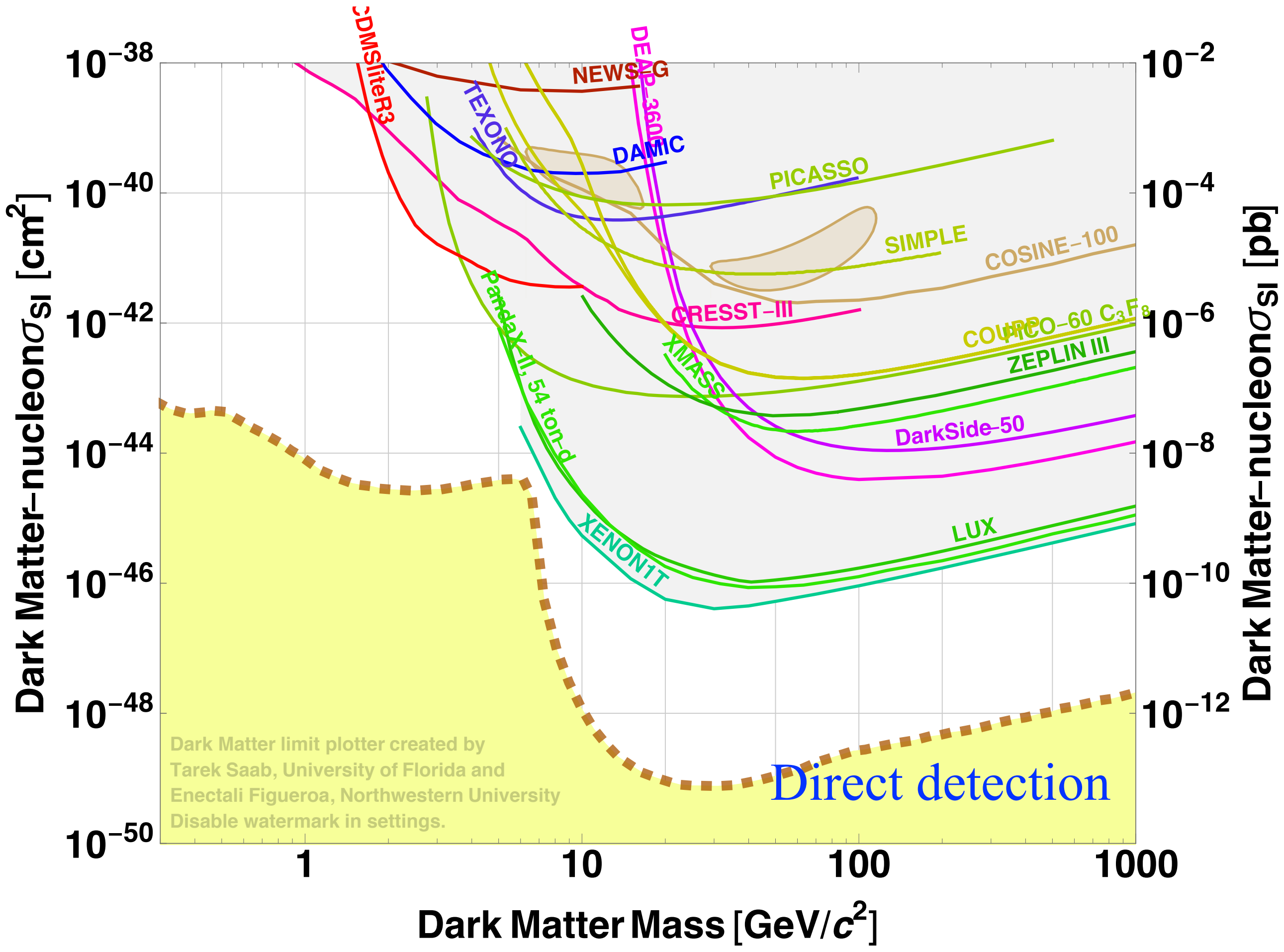


Or even a Primordial Black Hole

Range of possibilities is VAST

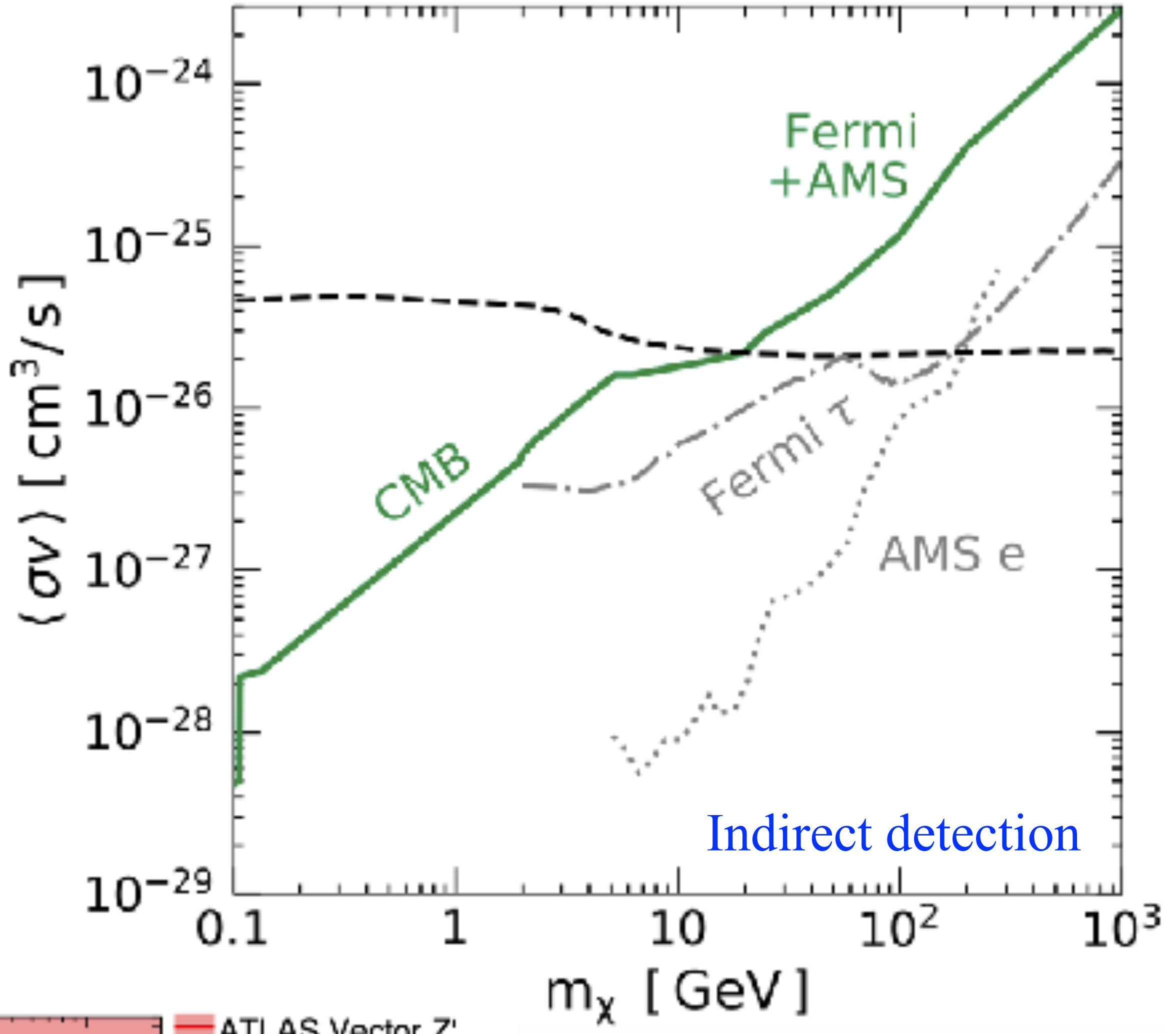


Recent searches have been focussed on this region of space



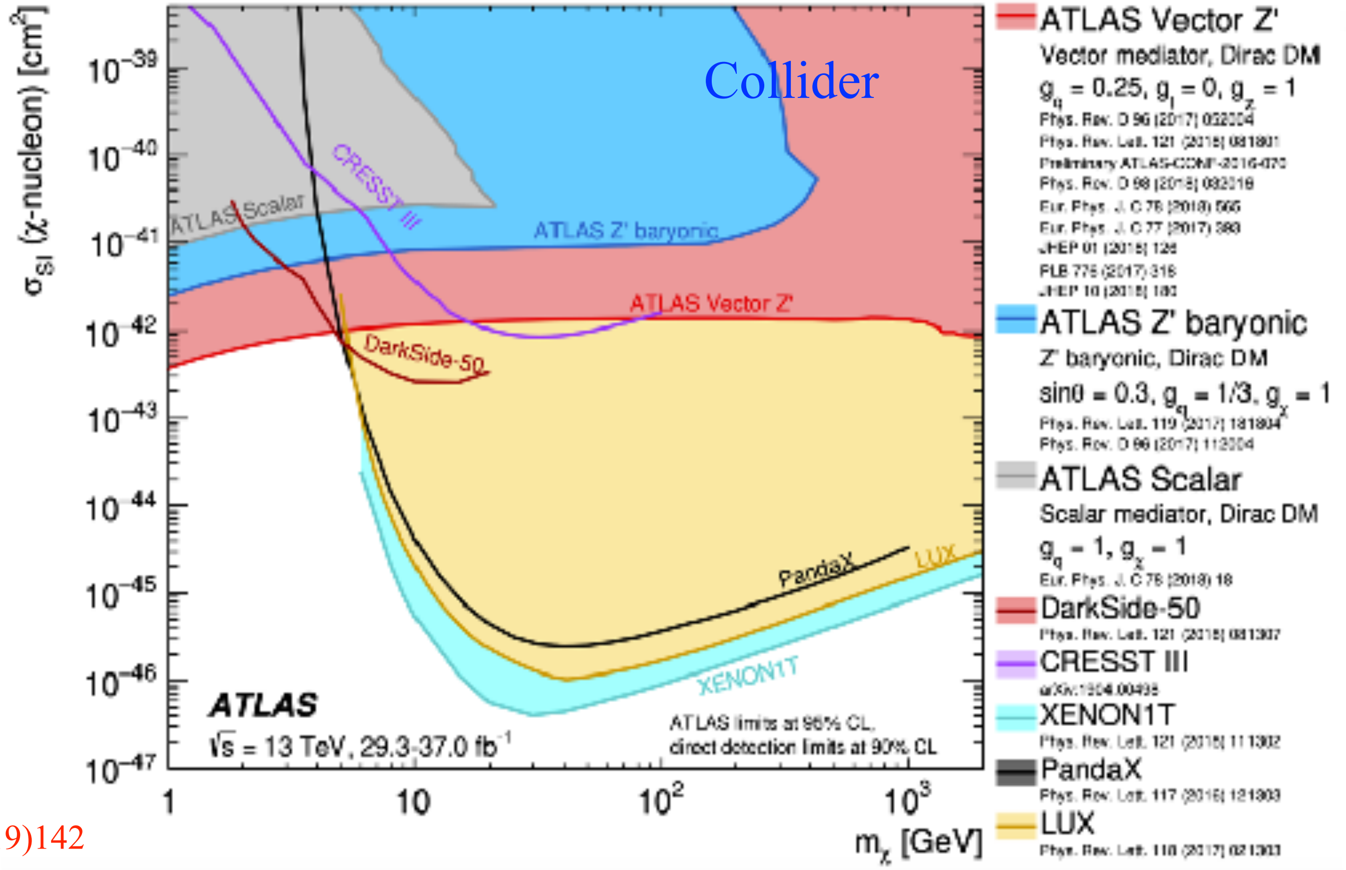
Direct detection

supercdms.slac.stanford.edu/dark-matter-limit-plotter



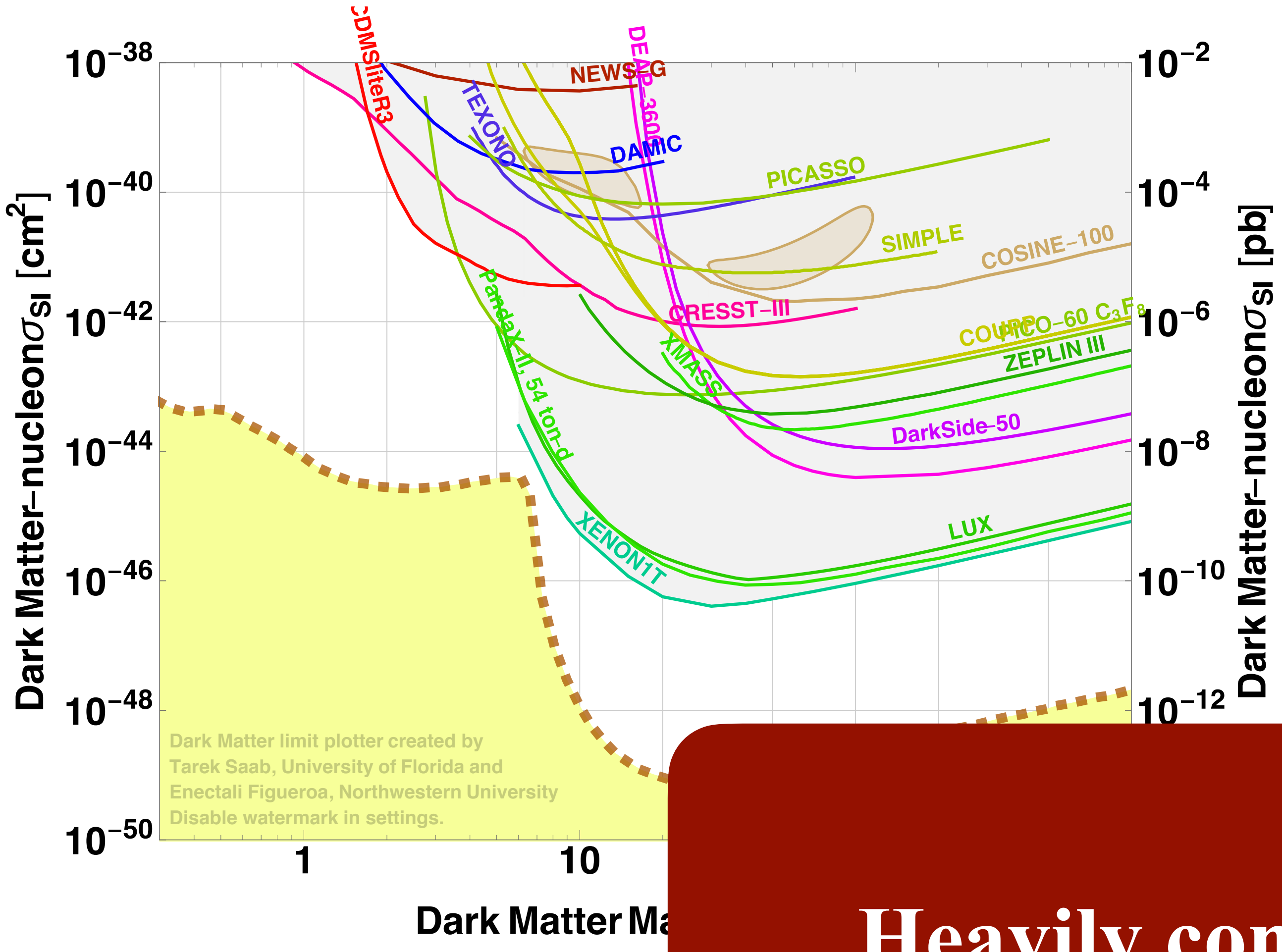
Indirect detection

Leane et al, Phys.Rev.D 98 (2018) 2



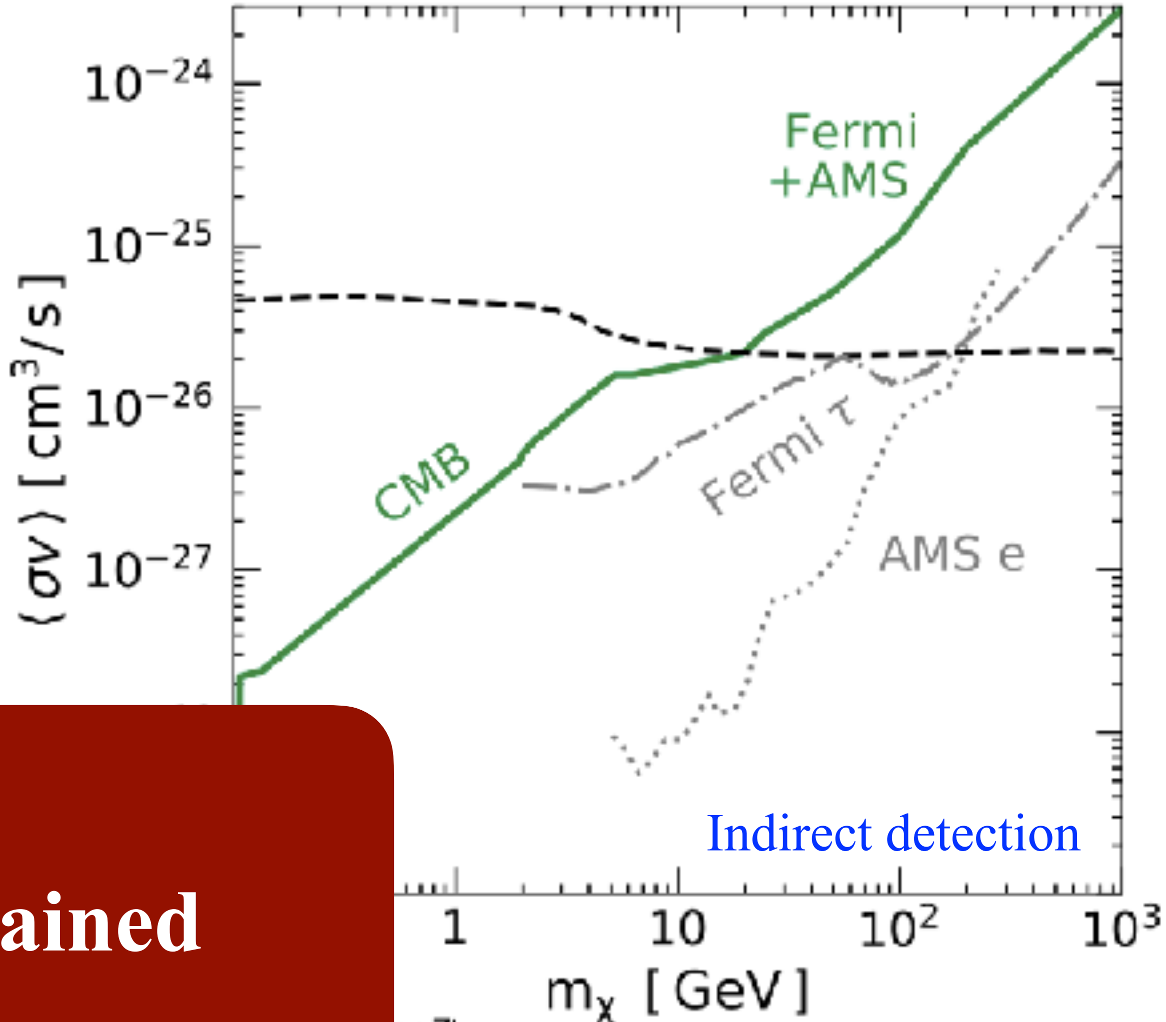
Collider

ATLAS Collaboration JHEP05(2019)142



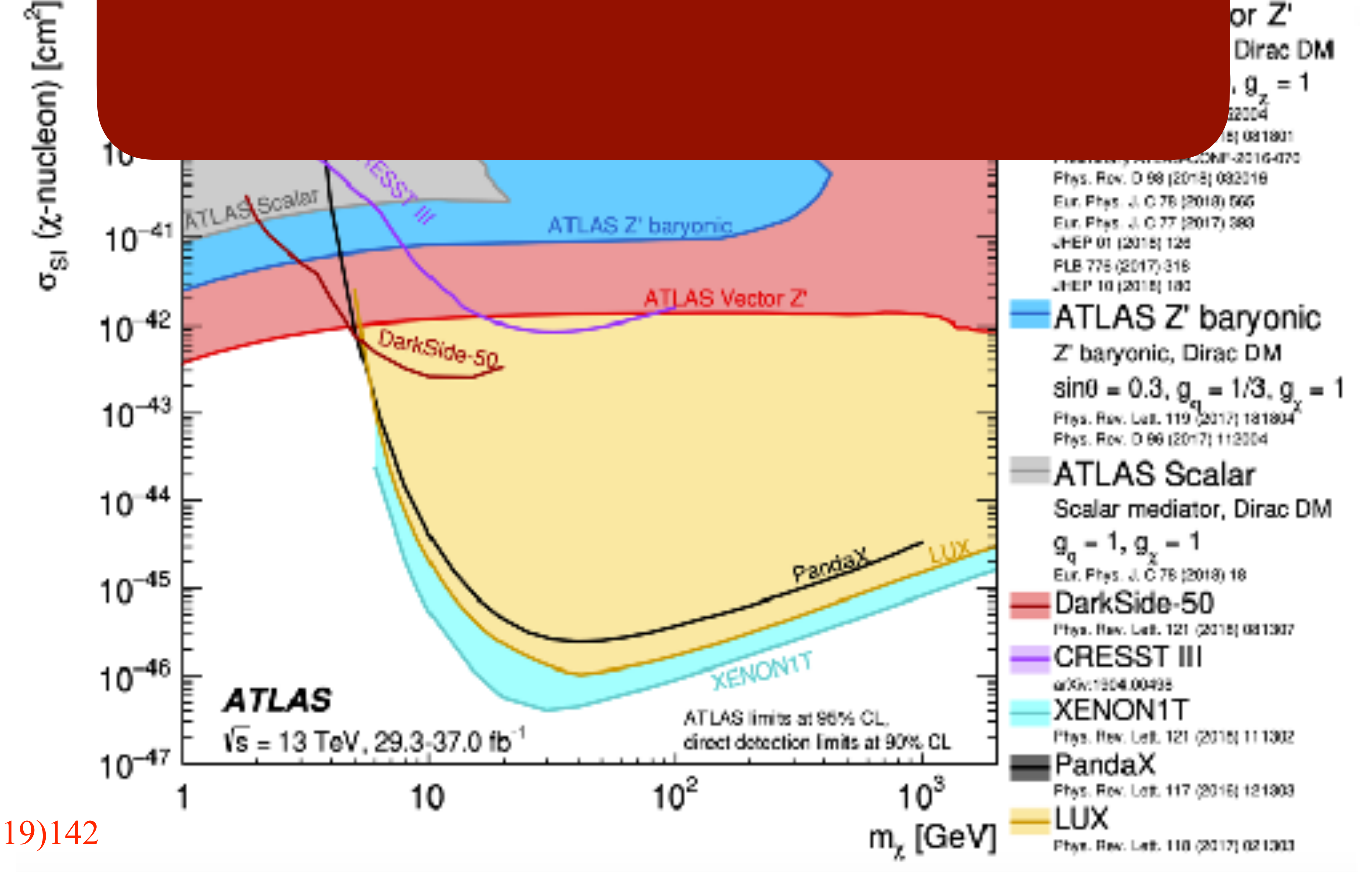
supercdms.slac.stanford.edu/dark-matter-li

Heavily constrained



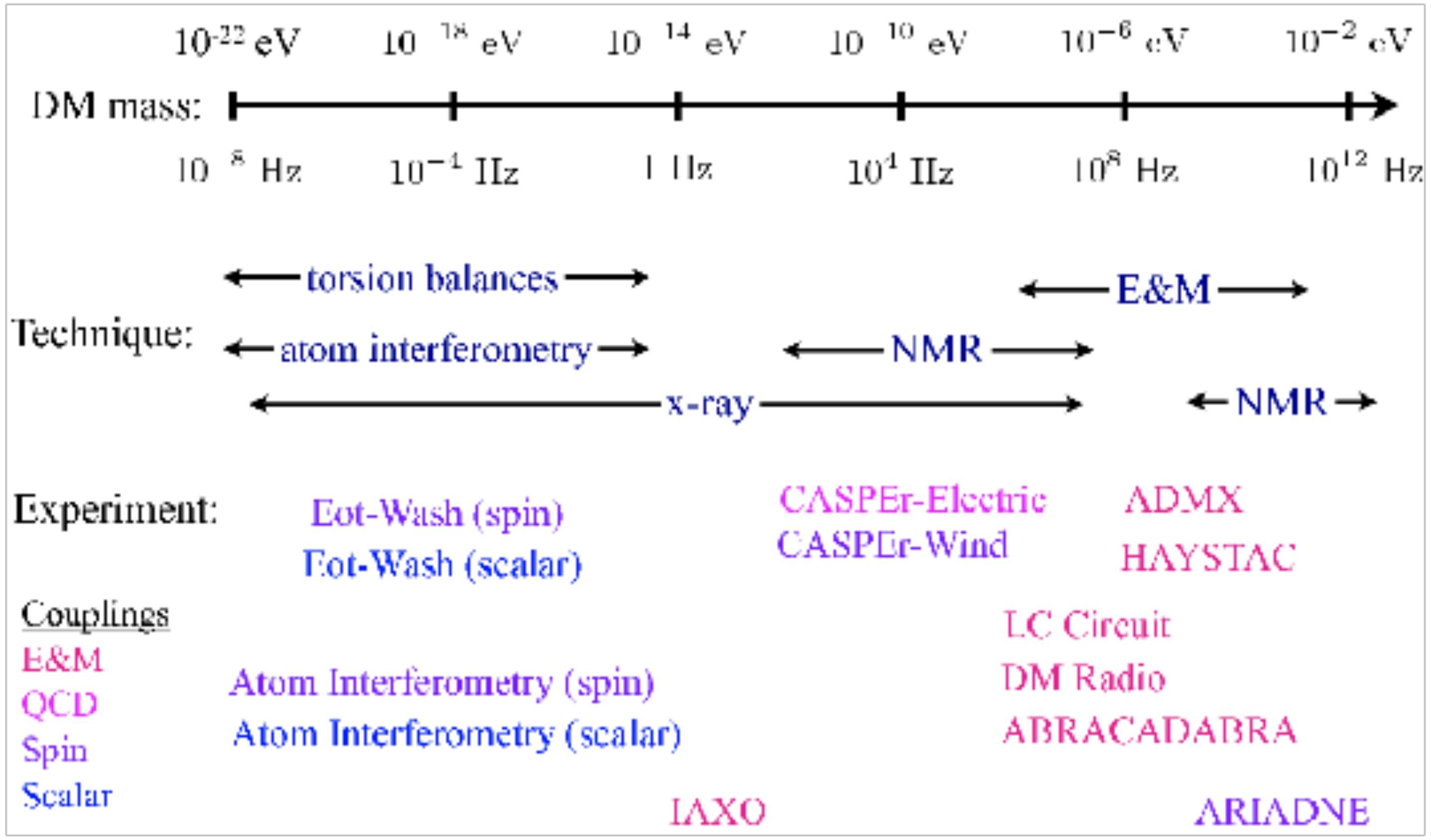
Indirect detection

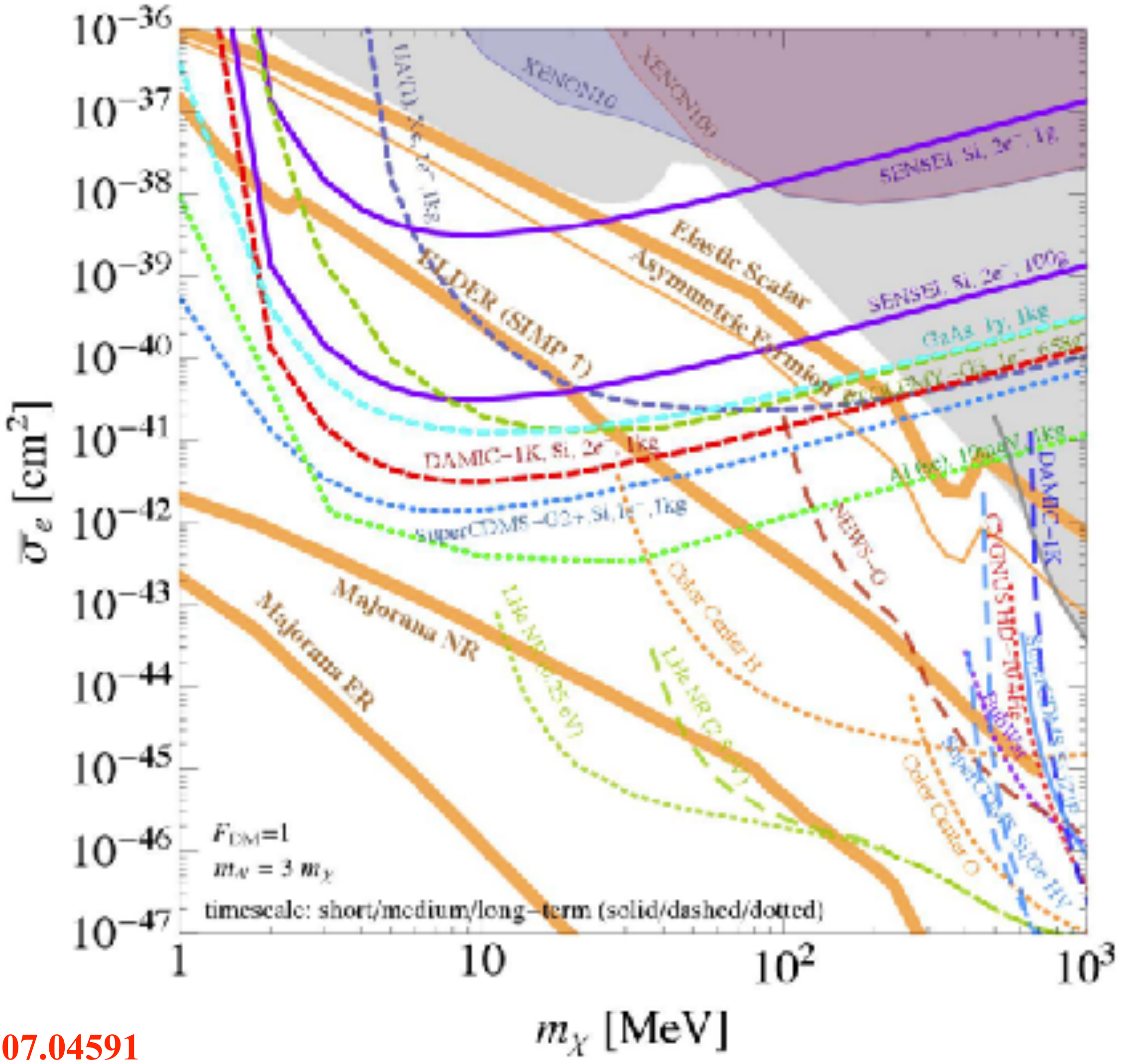
Leane et al, Phys.Rev.D 98 (2018) 2



ATLAS Collaboration JHEP05(2019)142

Motivated searches away from the WIMP scale, mainly towards lower masses





US Cosmic Visions Report: **arXiv:1707.04591**

+ Many other great ideas

See previous PANDEMIC talks + FIPs 2020 workshop talks

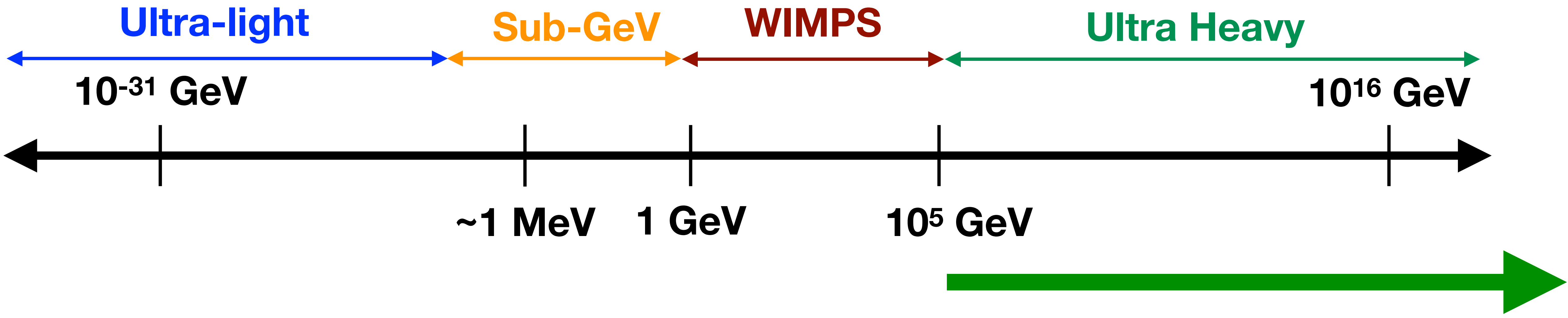
https://indico.cern.ch/event/864648/

Can dark matter be heavier than WIMPs?

How heavy is heavy?

- Planck Mass
- Scale of quantum gravity
- GUT scale

reasonable targets



How can we detect Ultra heavy dark matter?

Indirect detection?

- Flux for annihilating particles: $\Phi \sim \dfrac{1}{M_{DM}^2}$ heavier DM, lower flux

★ DM could decay at late times to Ultra high energy cosmic rays/neutrinos

Colliders?

- Cannot produce particles at any collider

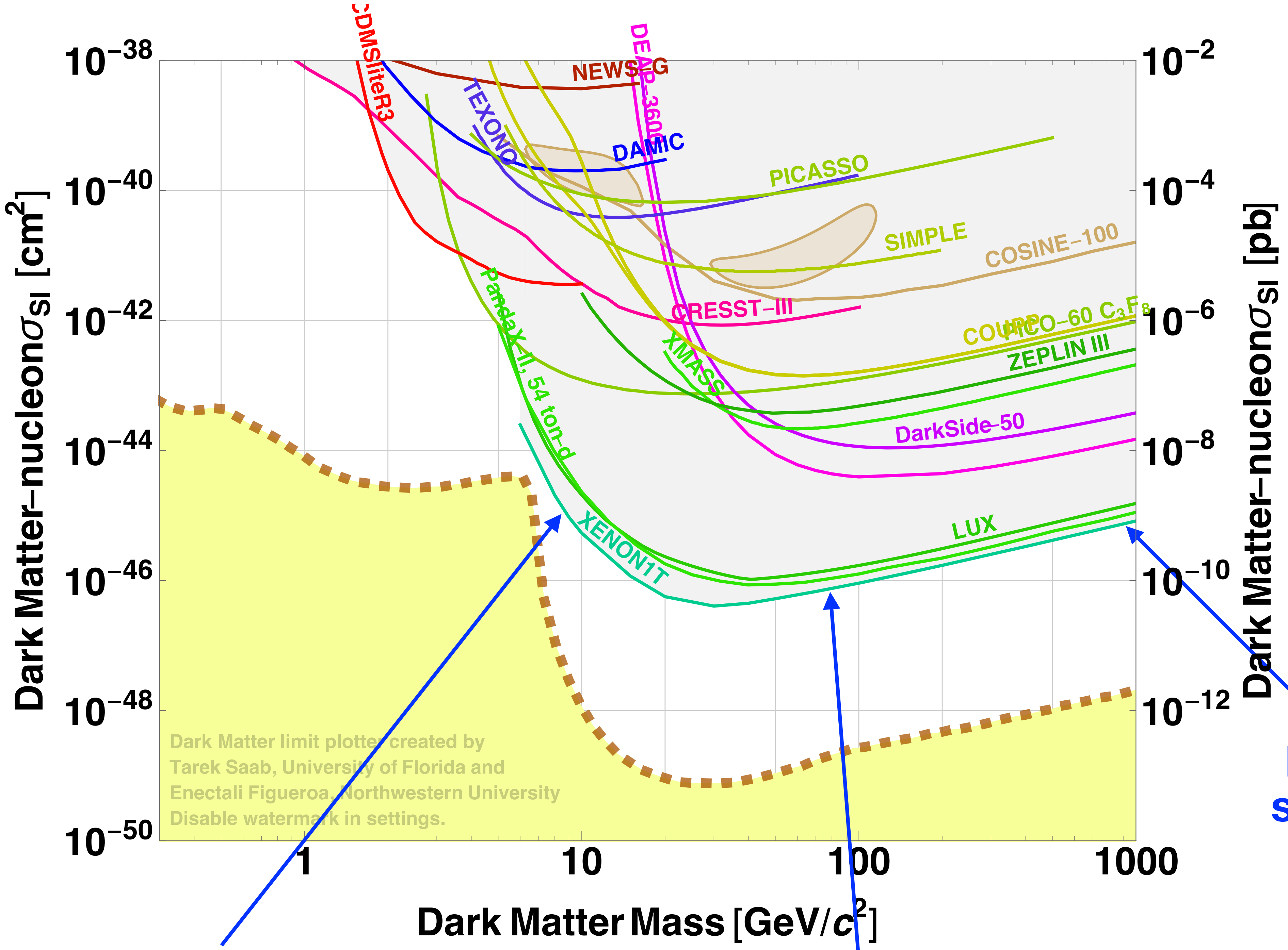
unless collider larger than size of solar system

Direct Detection?

✤ Number density/flux for heavier particles is smaller: $n_{DM} \sim \dfrac{1}{M_{DM}}$

Disadvantage? Lets explore this

Direct detection limits



$$\rho_{DM} \sim 0.3\ \mathrm{GeV.cm}^{-3}$$

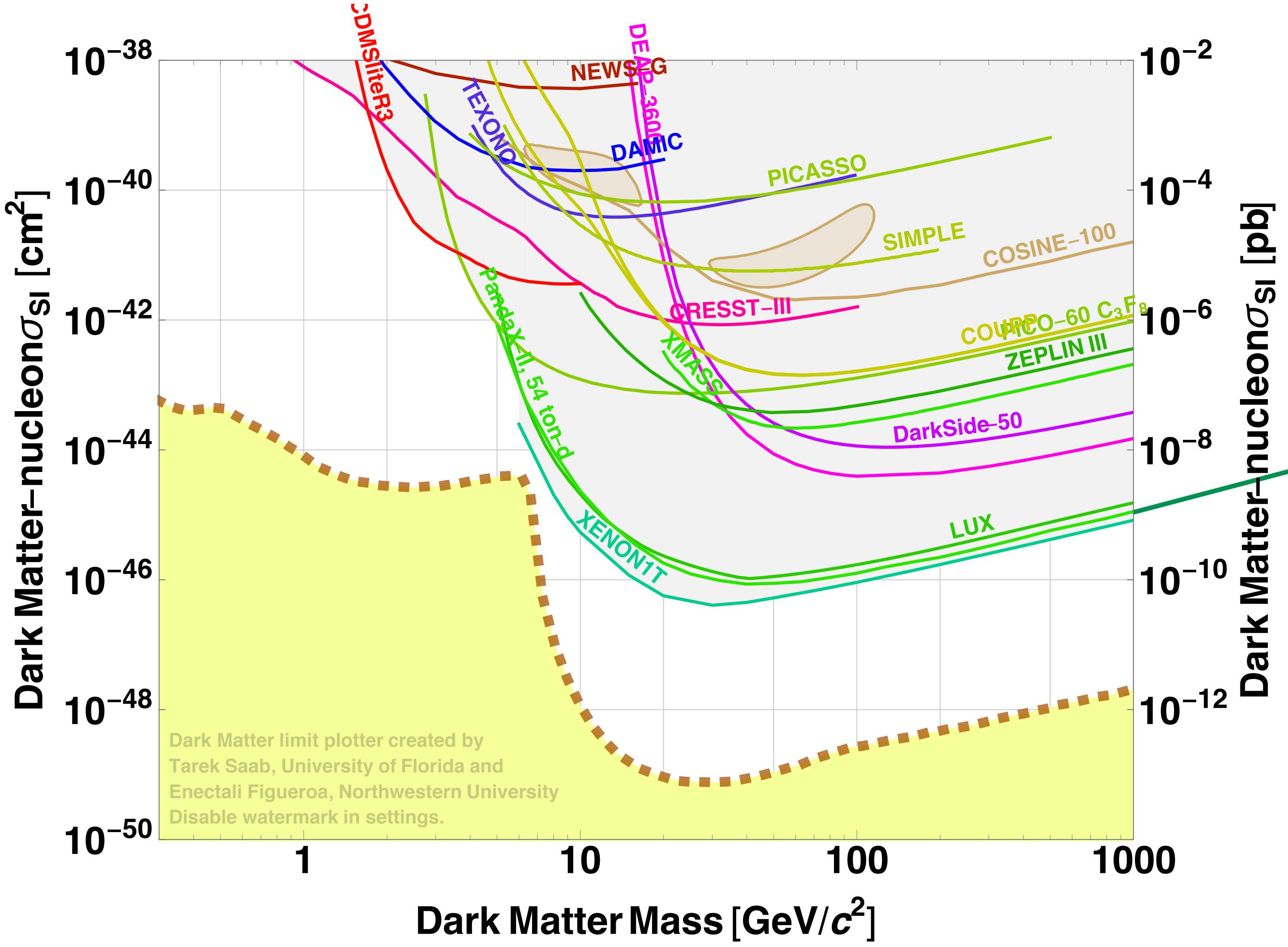
$$n_{DM} \sim \frac{\rho_{DM}}{m_{DM}}$$

Number of particles gets smaller ⟹ less recoils

Dark Matter mass is too low to provide sizable recoils

Most sensitive best recoil possibility

Is it really a disadvantage?



If we keep going higher ⇒ less & less recoils

current experiments not sensitive to ultra heavy dark matter

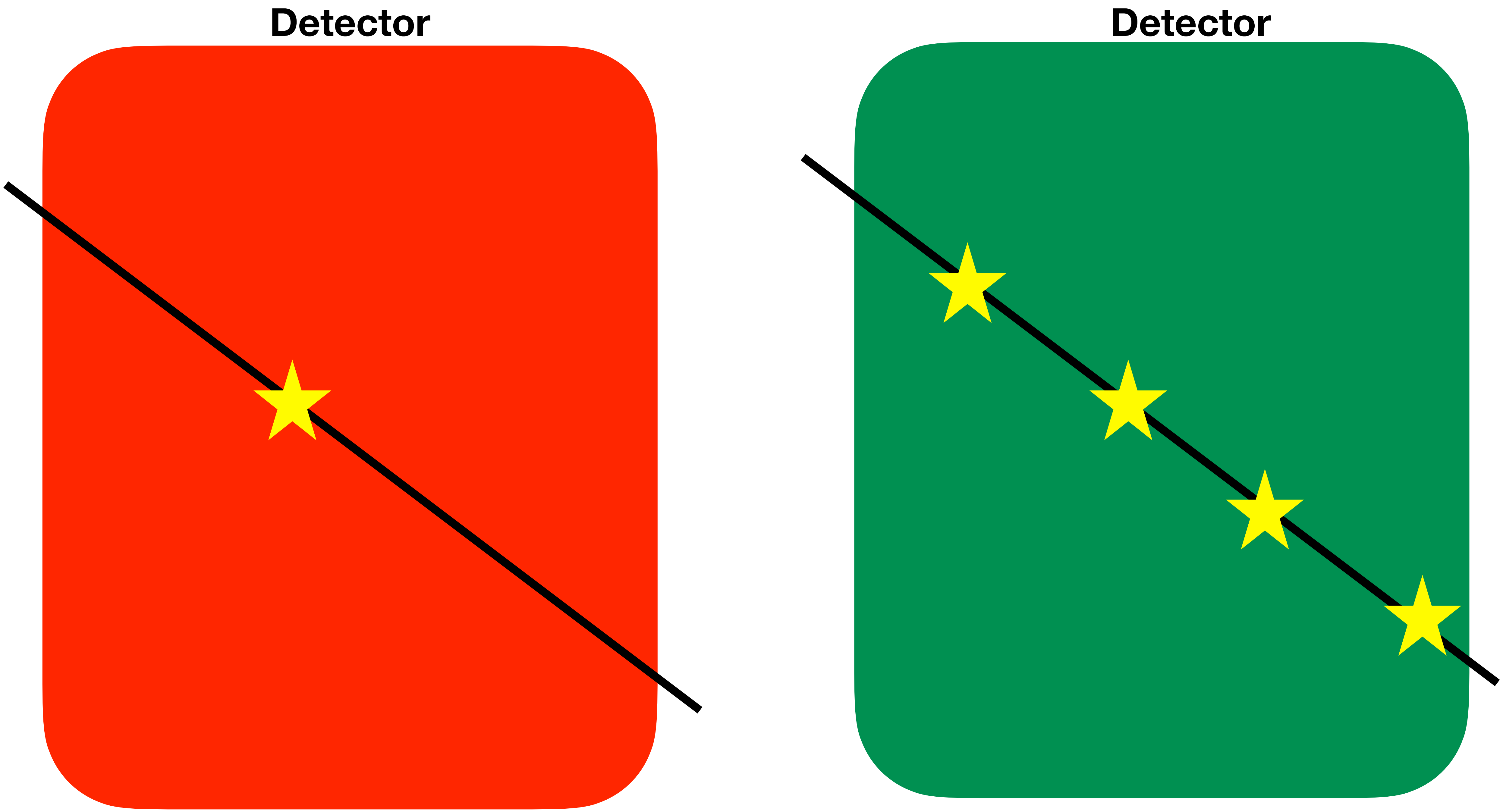
implying

Ultra heavy dark matter can interact stronger with protons than weak scale dark matter

May scatter multiple times in detector

Bramante, Broerman, Lang & Raj: **Phys.Rev. D98 (2018) no.8, 083516**

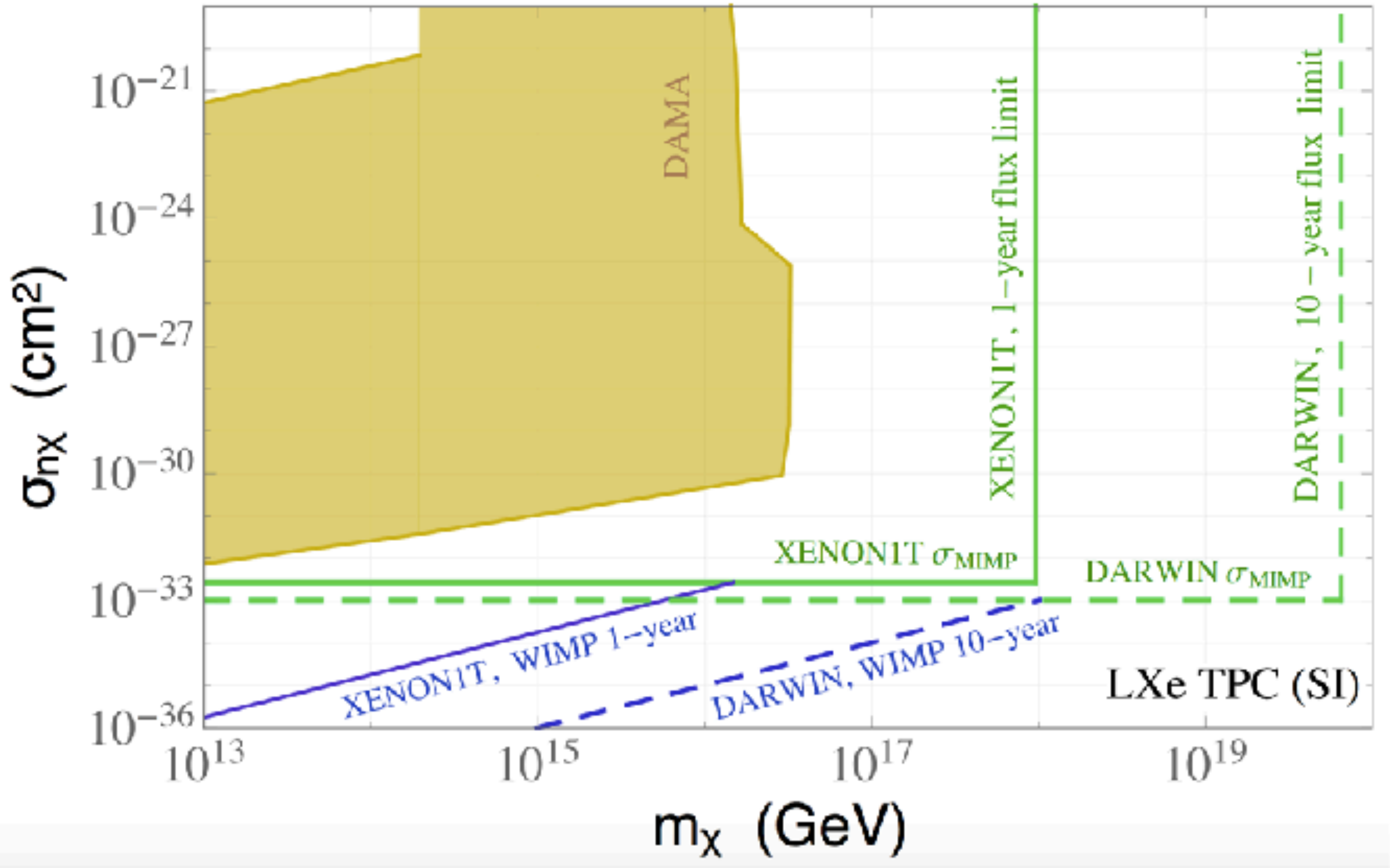
Current detectors can search for multi-scatter events



Single Scatter

Multiple Scatter

Multiple scattering signature would be a clear DM signal



Direct Detection limits extrapolated to include Multi-Scattering and Single Scattering

Cross-sections of order

> 10^{-33} cm^2

for XENON1T & DARWIN

Bramante, Broerman, Lang & Raj: **Phys.Rev. D98 (2018) no.8, 083516**

Bramante, Broerman, Kumar, Lang, Pospelov & Raj: **Phys.Rev. D99 (2019) no.8, 083010**

Also see Nirmal's PANDEMIC talk from 01 July

What kind of physics can give these kind of cross-sections?

- Simplest possibility is to consider light mediators between these very large scales and the SM

- Vector bosons associated with gauge symmetries well motivated

- To keep vector light compared to Planck scale, need resilient gauge symmetry, not easily broken

Simplest gauge group $U(1)$ enjoys this property

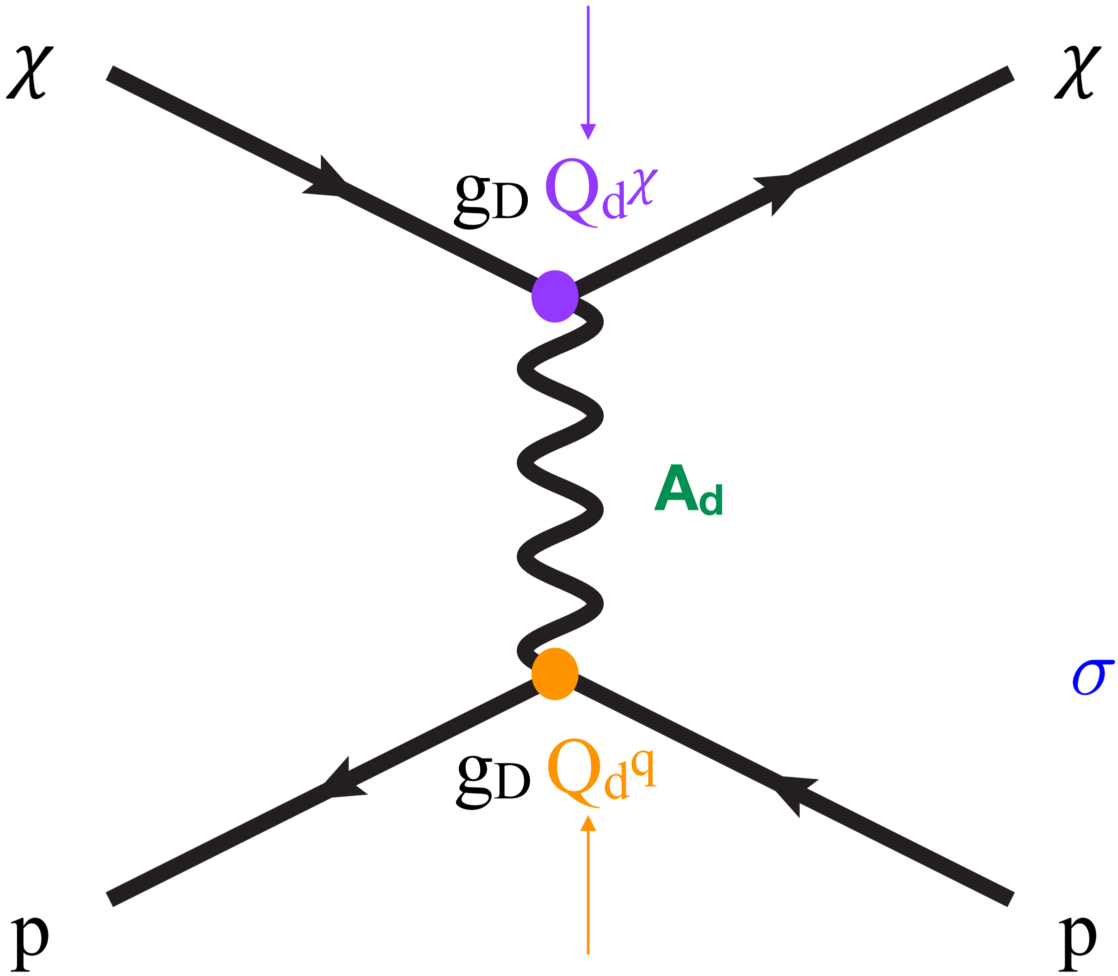
Halverson & Langacker: **arXiv:1801.03503**

We proposed a “dark” gauge group $U(1)_d$ which has vector A_d

e.g. $U(1)_d \Rightarrow$ gauged baryon number

$$\mathcal{L} \supset g_d(Q_d^q \bar{q}\gamma_\mu q + Q_d^\chi \bar{\chi}\gamma_\mu \chi)A_d^\mu + \epsilon.e(\bar{q}\gamma_\mu q + \bar{l}\gamma_\mu l)A_d^\mu$$

Detection of Ultra heavy dark matter through a light messenger



Baryon charge of dark matter ~1/2

Baryon charge of nucleon ~ 1

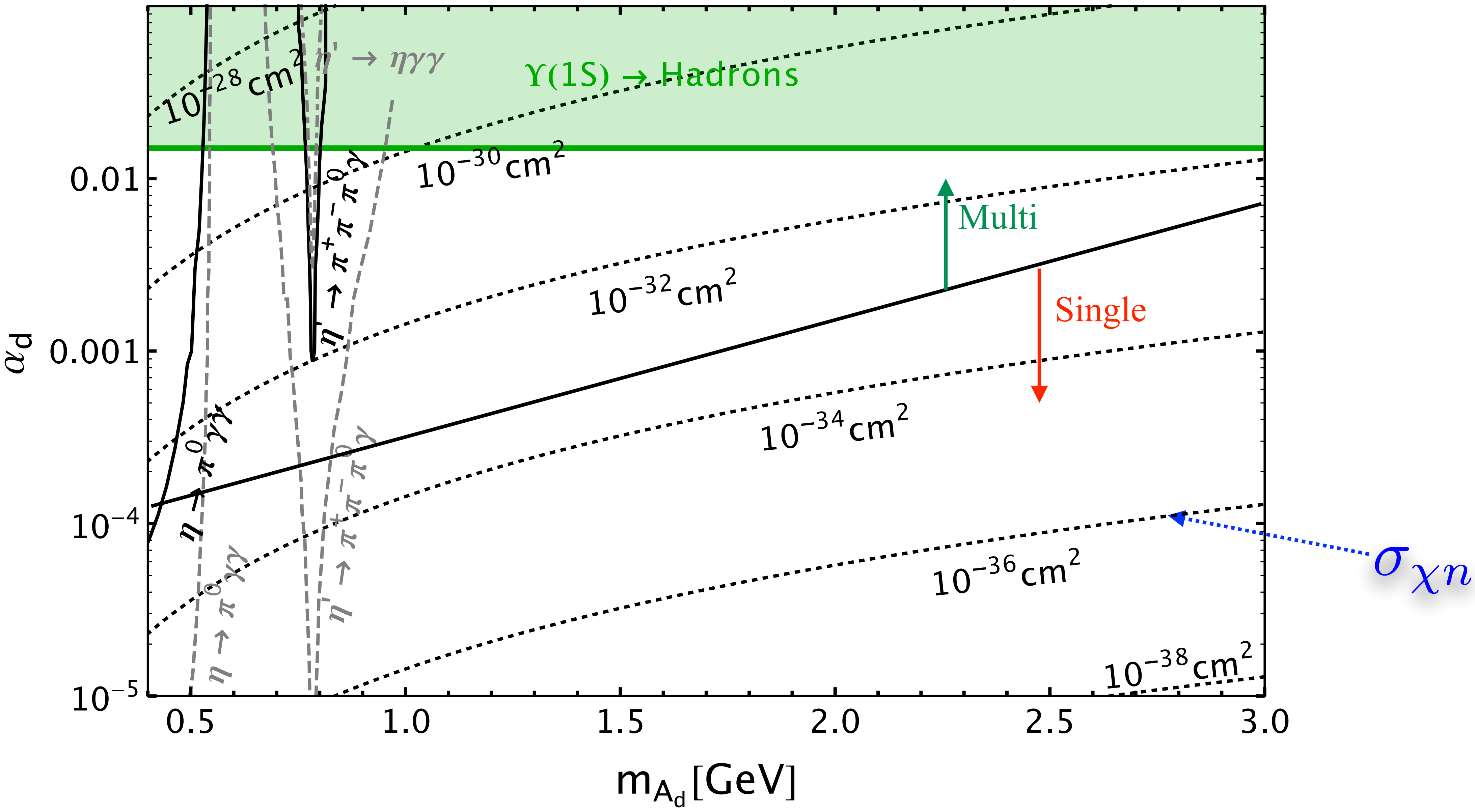
Spin Independent DM-nucleon cross-section

$$\sigma_{\chi n} \sim \frac{16\pi \mu_{\chi n}^2 (Q_d^n Q_d^\chi)^2 \alpha_d^2}{m_{A_d}^4}$$

e.g. $> 10^{-33}\ \mathrm{cm}^2$

dark matter much heavier than mediator

Davoudiasl & Mohlabeng **Phys.Rev. D98 (2018) no.11, 115035**



Davoudiasl & Mohlabeng **Phys.Rev. D98 (2018) no.11, 115035**

Ultra heavy dark matter can be searched for at current direct detection experiments

Messenger particle can be searched for at low energy accelerators

How is this Dark Matter produced?

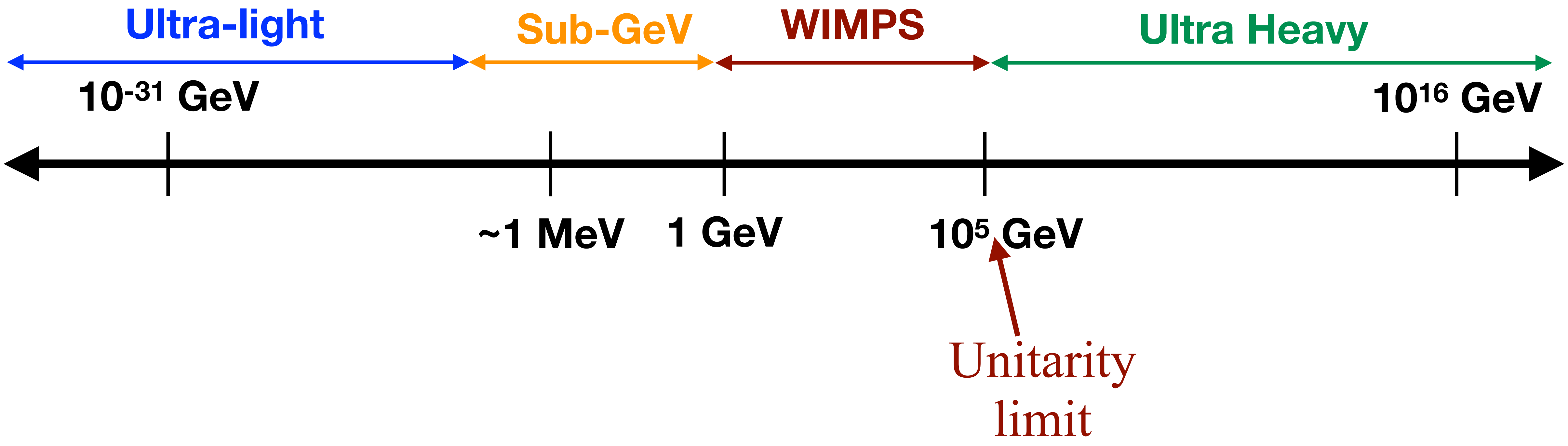
Well motivated: Thermal Freeze-out

- Thermal equilibrium requires large couplings to the SM

- Large couplings are useful for detection at present times

Problem

✤ Elementary dark matter heavier than **100 TeV** leads to over-closure of universe, if produced in thermal equilibrium with SM in early universe



Ultra-light
Sub-GeV
WIMPS
Ultra Heavy
10^{-31} GeV
10^{16} GeV
~1 MeV
1 GeV
10^{5} GeV
Unitarity limit

Getting around the Unitarity Limit

Creative ways of getting around this, for example …

- **Superheavy dark matter from thermal inflation**

  Hui & Stewart, **Phys. Rev. D 60 (1999) 023518**

- **Thermal DM from decoupled sector**

  Berlin, Hooper & Krnjaic, **Phys. Lett. B 760 (2016) 106-111**

- **Coannihilation with lighter unstable species**

  Berlin, **Phys. Rev. Lett 119 (2017) 121801**

- **Filtered Dark Matter**

  Baker, Kopp & Long, **arXiv:1912.02830** Chway, Jung & Shin, **arXiv:1912.04238**

- **+ many other theoretical possibilities**

  Kim & Kuflik, **Phys. Rev. Lett 123 (2019) 191801**

  Kramer et al, **arXiv:2003.04900**

- **THUMPs**

  Davoudiasl & Mohlabeng, **JHEP 04 (2020) 177**

THermal **U**ltra **M**assive **P**articles

Basic idea:

- Dark matter is light before freeze-out, i.e. WIMP

- Require it to over-annihilate so that number density of DM particles after freeze-out is very small

- DM obtains large mass after freeze-out which sets the right relic density

- Over-annihilation sets small number density for heavy DM, expected at present times

Concrete example

$$\mathcal{L} \supset (\underset{\underset{m_\chi^f}{\uparrow}}{\lambda\phi} + m_\chi^i)\bar{\chi}\chi + i g_D Q_D \underset{\underset{\text{dark photon}}{\uparrow}}{A'_\mu}\bar{\chi}\gamma^\mu\chi + \varepsilon . e A'_\mu \underset{\underset{\text{SM fermions}}{\uparrow}}{\bar{f}}\gamma^\mu f - \frac{1}{2}m_\phi^2(\underset{\underset{\text{ultra-light scalar}}{\nwarrow}}{\phi} - \phi_0)^2$$

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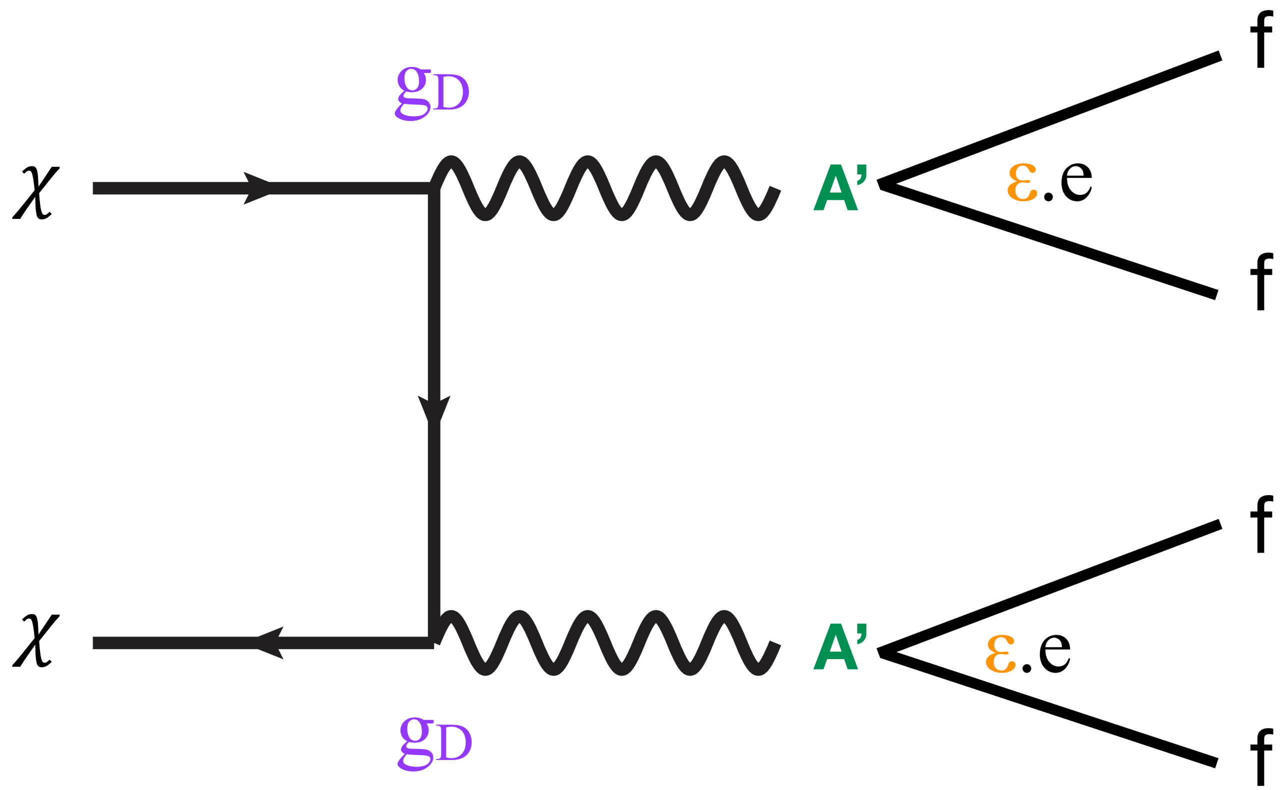
Before freeze-out DM over-annihilates

if $m_\chi^i \gtrsim m_{A'}$ then dominant annihilation process is



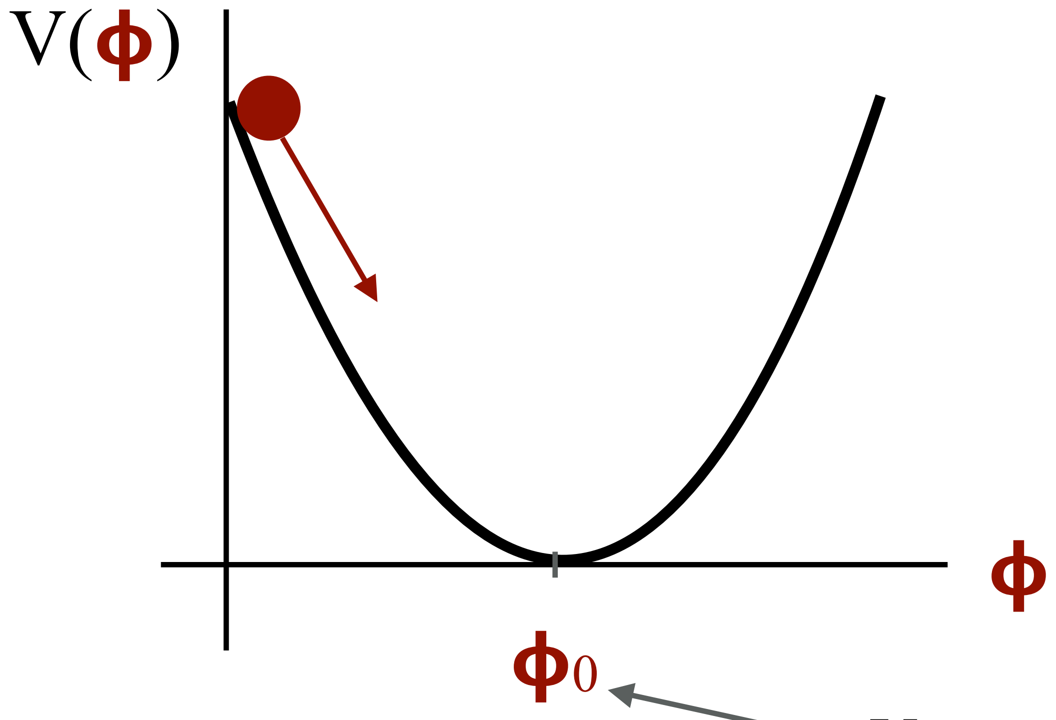
Thermal annihilation process

Large number ~ 1, ensures DM annihilates efficiently

$$\langle \sigma v \rangle \approx \frac{g_D^4}{16\pi {m_\chi^i}^2} \sqrt{1 - \left(\frac{m_{A'}}{m_\chi^i} \right)^2}$$

Davoudiasl & Mohlabeng, **JHEP 04 (2020) 177**

- After freeze-out, ultra-light scalar rolls in its potential



$$V(\phi) = \frac{1}{2} m_\phi^2 (\phi - \phi_0)^2$$

Vacuum expectation value

- When scalar reaches minimum, gives large mass to dark matter after freeze-out

$$\mathcal{L}_m \supset (m_\chi^i + \lambda\phi)\bar{\chi}\chi \qquad\qquad m_\chi^f \to m_\chi^i + \lambda\phi_0$$

Some benchmark numbers

λ	m_ϕ	ϕ_0
10^{-6}	10^{-14} eV	10^{15} GeV

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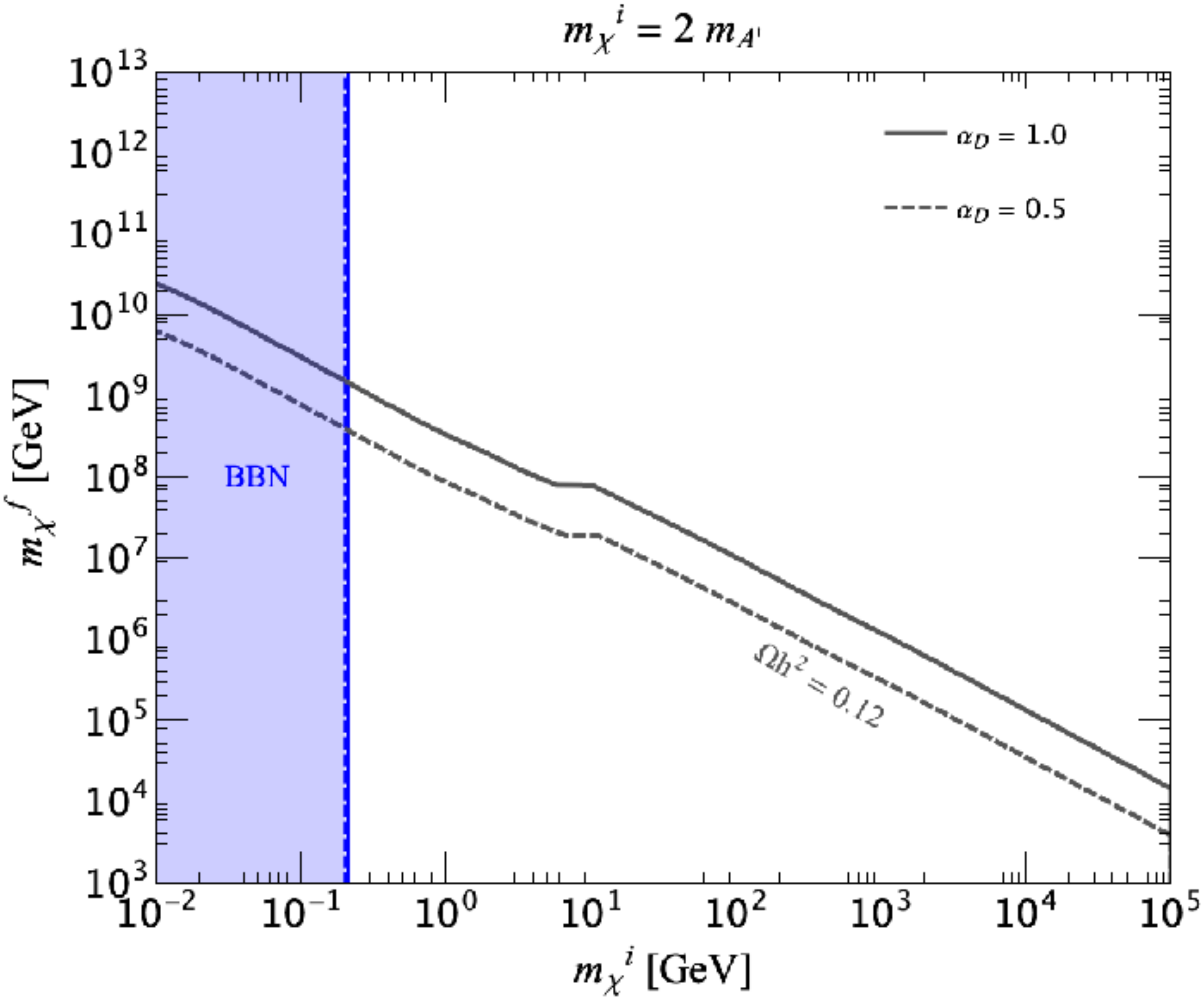
Relic density $\Omega_\chi h^2 \sim n_\chi(m_\chi^i)\; m_\chi^f$



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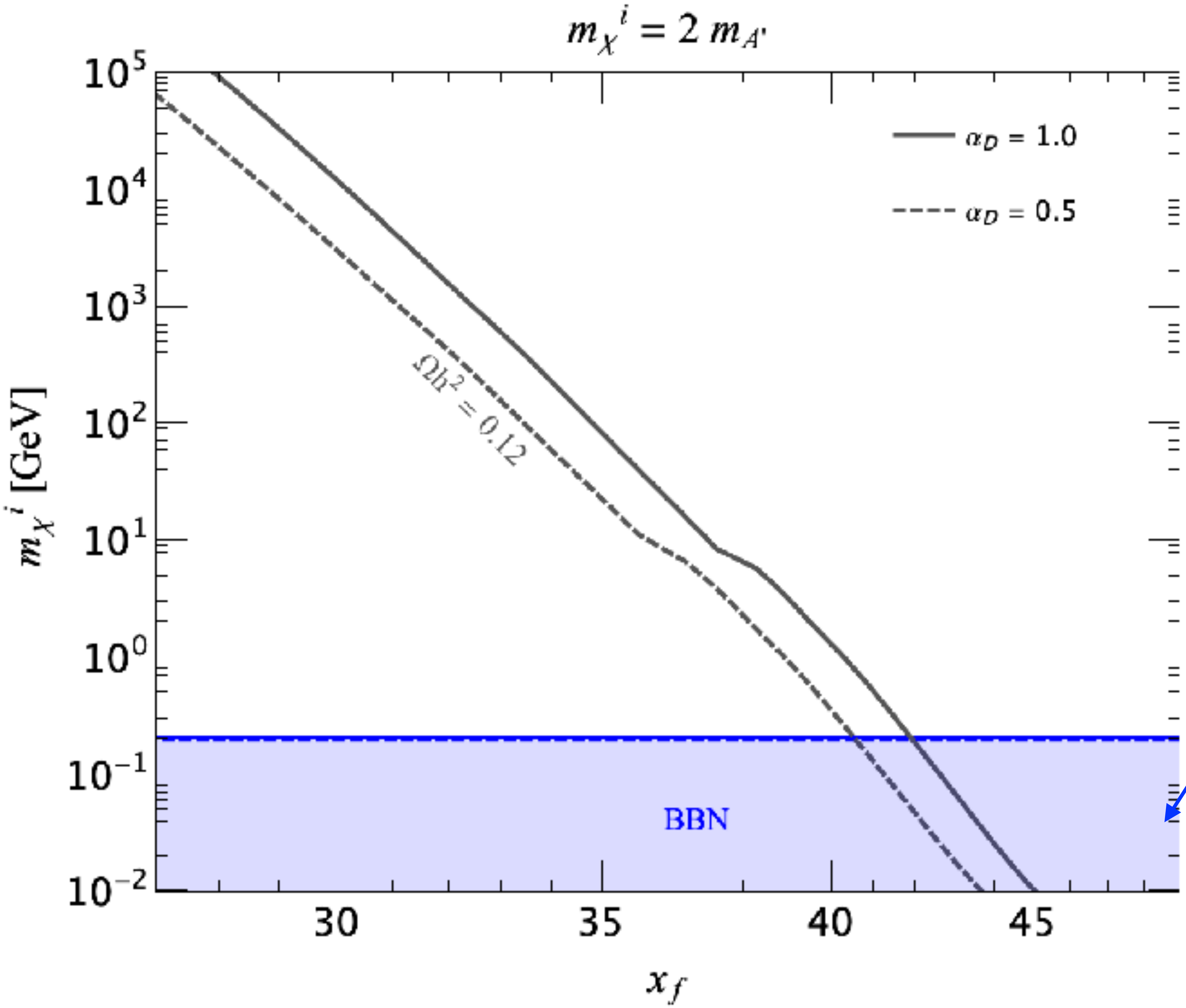
Relic density

$$\Omega_\chi h^2 \sim n_\chi(m_\chi^i)\ m_\chi^f$$



DM annihilates during BBN & disrupts elemental abundances

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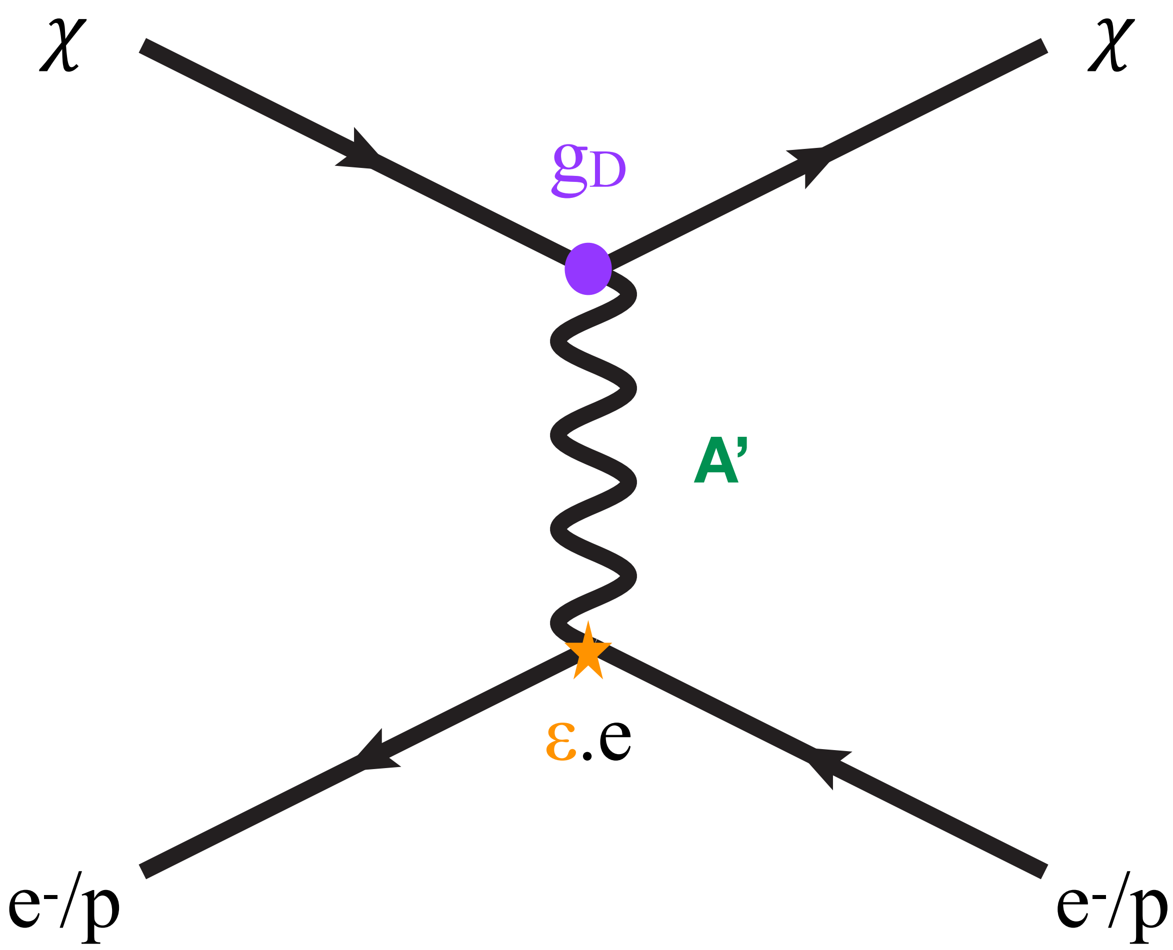
Direct Detection of THUMP Dark Matter

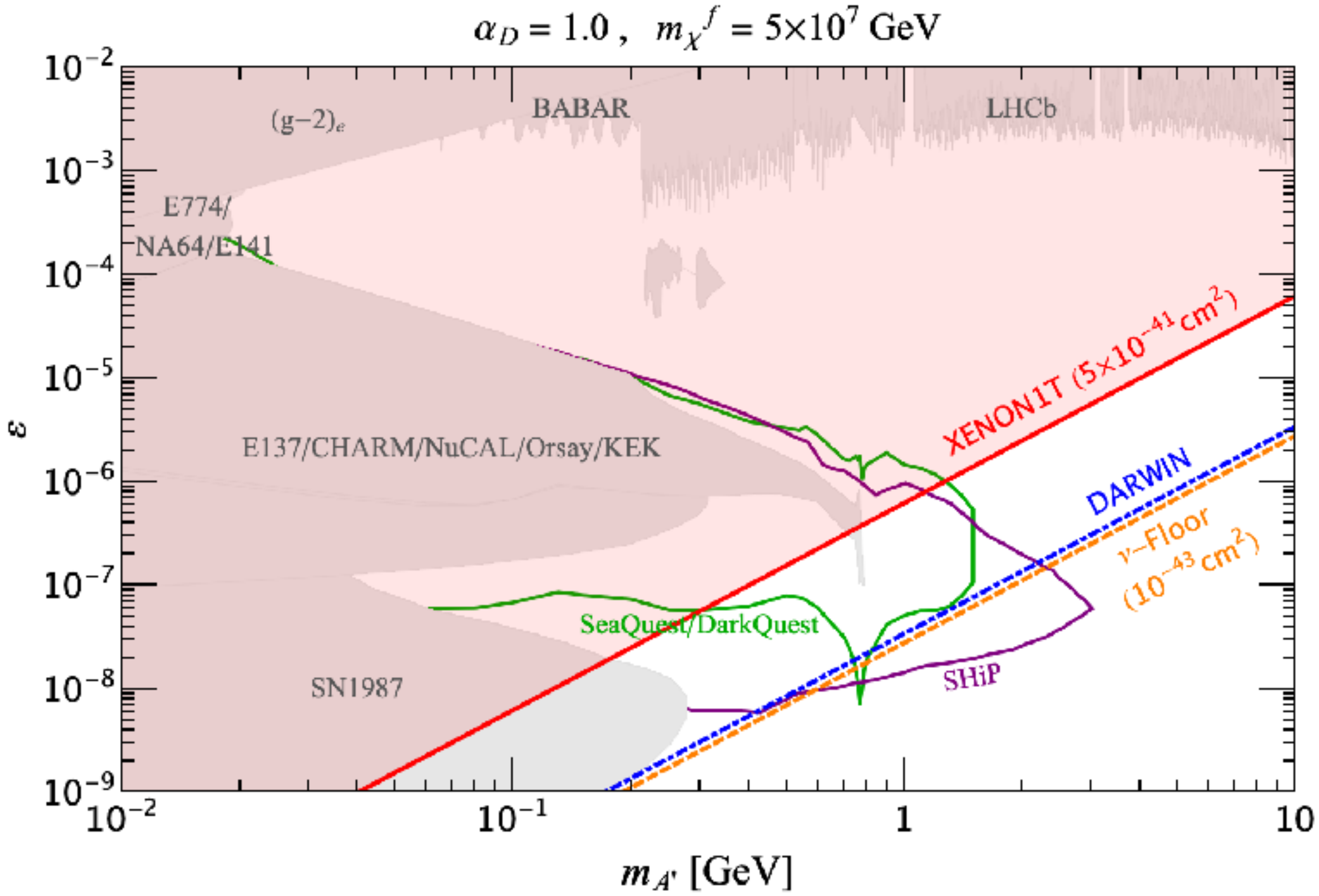


$$\sigma_{\chi n} \sim \frac{16\pi\mu_{n\chi}^2\epsilon^2\alpha\alpha_D}{m_{A'}^4}$$

Independent of m_χ^f

Lower the mediator mass, larger the direct detection cross-section

Complementarity of direct detection and low energy accelerators



- Low energy experiments search for mediator
- Direct Detection experiments search for THUMP

Davoudiasl & Mohlabeng, **JHEP 04 (2020) 177**

Take away

- We need to look at many avenues in our search for Dark Matter.

Ultra-heavy dark matter is one possibility

- I discussed a possible model for multi-scattering in direct detection experiments.

- Disussed a viable scenario for early universe thermal production, called THUMPs.

- Possible complementarity between direct detection of UHDM & accelerator searches for low mass mediator.

In light of recent social events

In memory of:

Trayvon Martin
Eric Garner
George Floyd
Breonna Taylor
Atatiana Jefferson
Aura Rosser
Stephon Clarke

Alton Sterling
Michelle Cusseaux
Freddie Gray
Janisha Fonville
Gabriela Nevares
Tamir Rice
Mike Brown

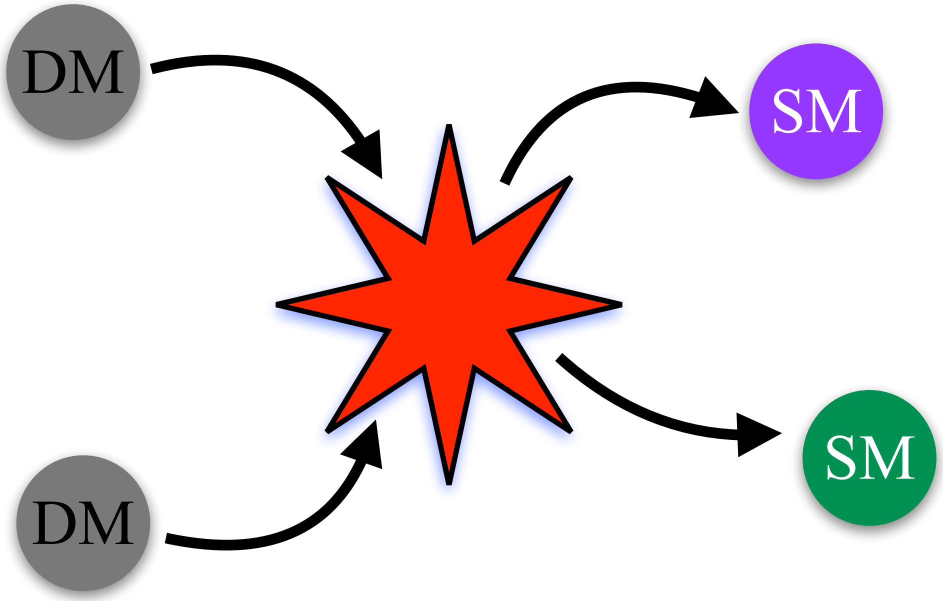
Nathaniel Julius
Sibusiso Amos
Petrus Miggels
Adane Emmanuel
Jason Pero
Paul Castaway
Collins Khoza

Preston Bell
Frank Joey Half Jr.
Justin Howell
Sean Monterrosa
Corey Kanosh
Zachary Bearheels
Philando Castille

+ many many many others

Back up

Unitarity / Griest-Kamionkowski bound



The thermal annihilation cross-section: $\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$

Relic density: $\boxed{\Omega h^2 \sim \frac{0.1 \text{ pb}}{\langle \sigma v \rangle}}$

If ***M_{DM} > 100 TeV*** then thermal relic density is very large, i.e. produce too much DM, over-close universe

If g_D is too large, i.e. above **perturbative unitarity,** calculation is unreliable

K. Griest & M. Kamionkowski, **Phys. Rev. Lett 64, 615 (1990)**

$U(1)_B$ is anomalous, i.e. not a consistent gauge theory

Anomaly cancelation requires heavy fermions that are:

- Vector-like under SM
- Chiral under dark sector

Heavy fermions would get mass from U(1) breaking by dark Higgs

Scale of symmetry breaking ≳ 100 GeV

Dobrescu & Frugiuele, **Phys. Rev. Lett. 113, 061801 (2014)**

$$m_{A_d} \sim g_d Q_d^{\Phi} < \Phi >$$

$$m_F \sim y < \Phi >$$

$$\mathcal{L} \supset y \bar{F}_L F_R \Phi$$

If $< \Phi > \quad \lesssim \; 100 \text{ GeV}$ Fermions F would have been seen at LEP/LHC

$$\Rightarrow 100 \text{ GeV} \lesssim \; < \Phi >$$

For $\; m_{A_d} \sim 1 \text{ GeV} \quad \Rightarrow \quad Q_d^{\Phi} << 1$

$$\Rightarrow \quad Q_d^{F} << 1$$

Many fermions at TeV scale to cancel anomalies

Breaking $U(1)_B$ & preserving EWS results in non-zero Wess-Zumino terms

Giving non-decoupling longitudinal mode of vector showing up in low energy processes

Dror, Lasenby & Pospelov, Phys. Rev. Lett. 119, 141803 (2017)

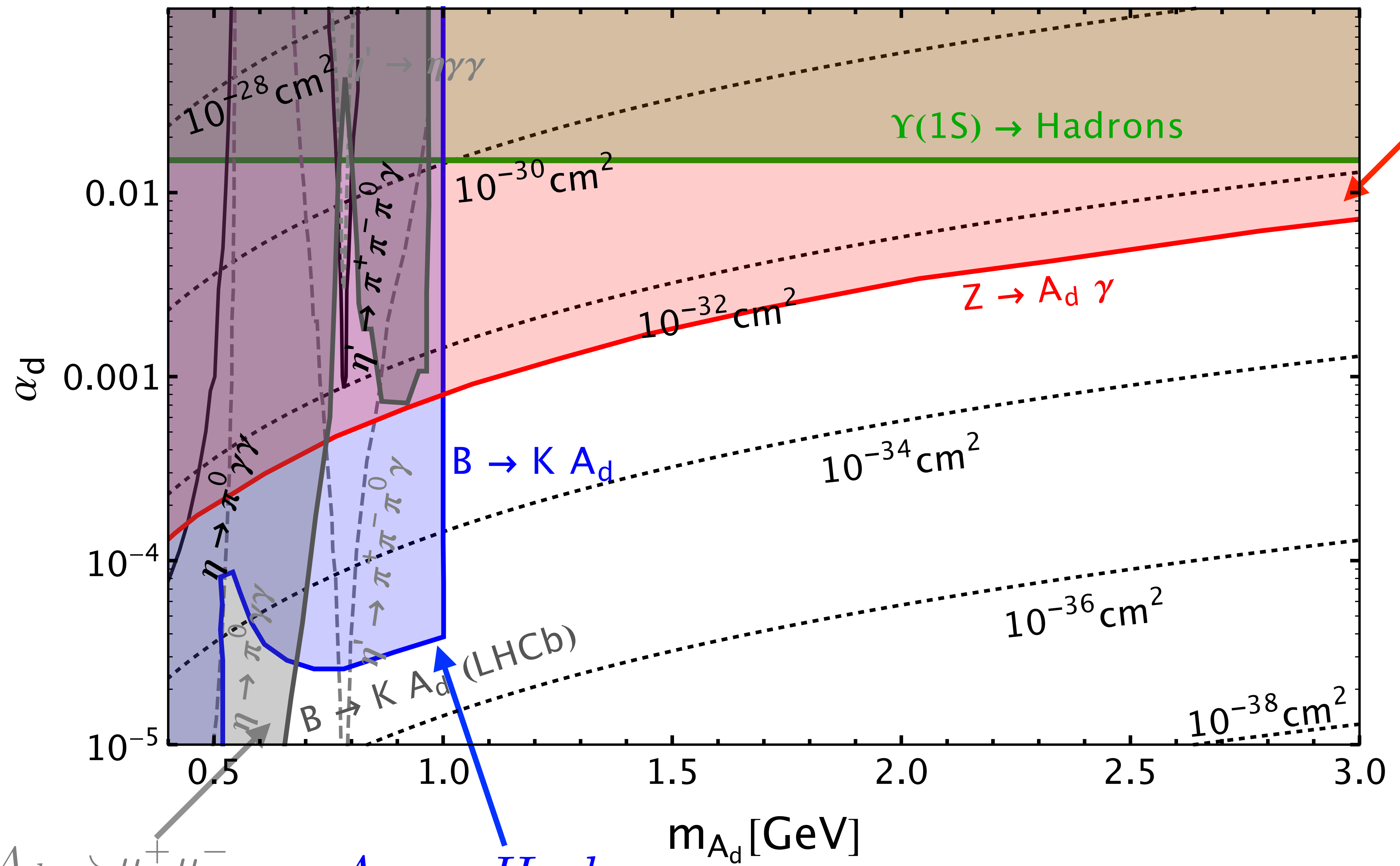
Effects show up in:
- B-meson decays
- Z-boson decays

If $U(1)_B$ breaking is different i.e. not EWS preserving

No longitudinal mode effects

Including longitudinal mode enhancements

Were made assuming: $\epsilon = \frac{e g_d}{(4\pi)^2}$



$A_d \to l^+l^-$

$A_d \to \mu^+\mu^-$

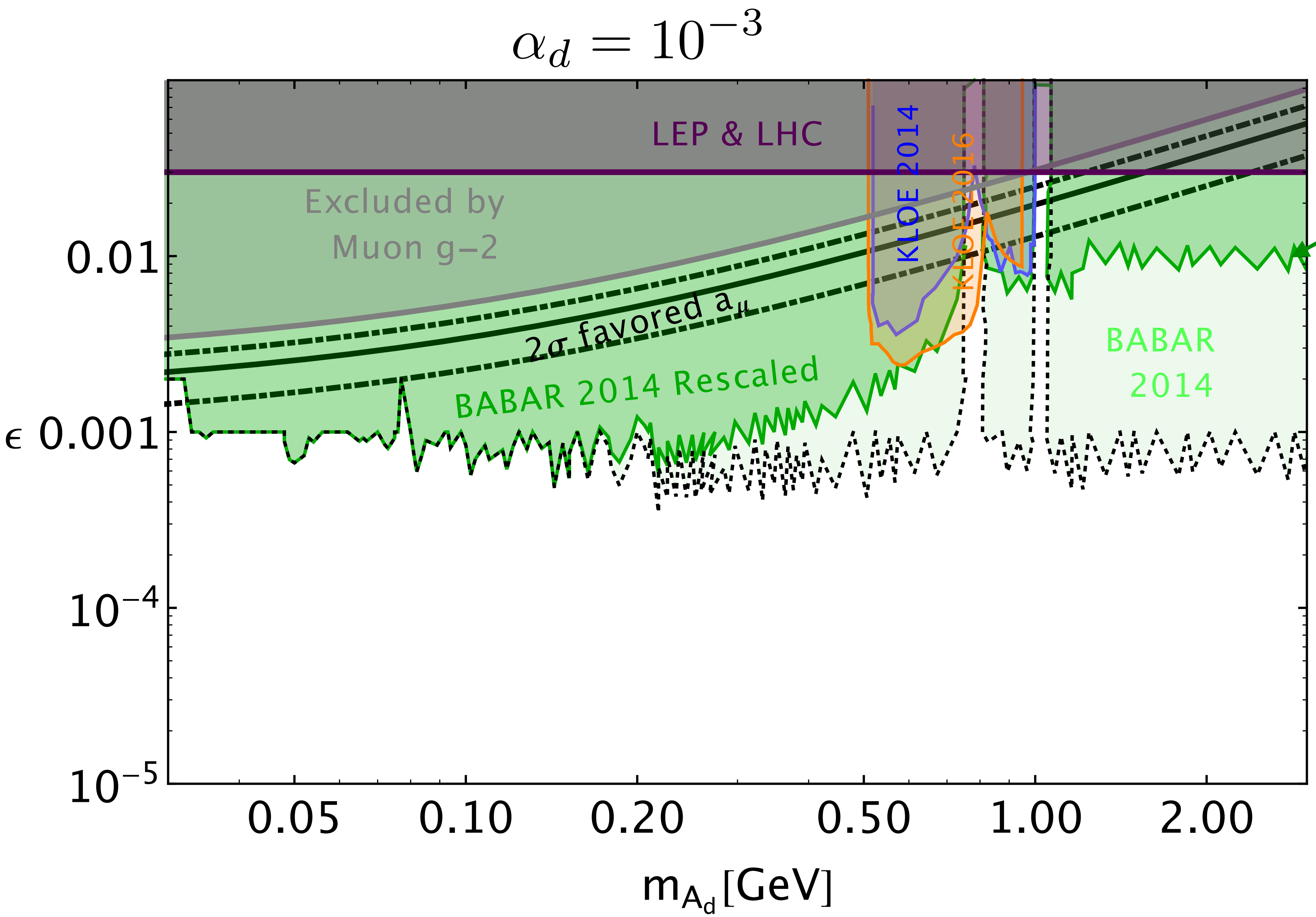
$A_d \to Hadrons$

can still get: $\sigma_{\chi n} \sim 10^{-33} - 10^{-38}\mathrm{cm}^2$

We can recast the BaBar visible decay limit using

$$N_{A_d} = \sigma_{A_d\gamma} BR(A_d \to l^+ l^-)\mathcal{L}$$

Assuming $N_{A_d} \approx N_{BaBar}$

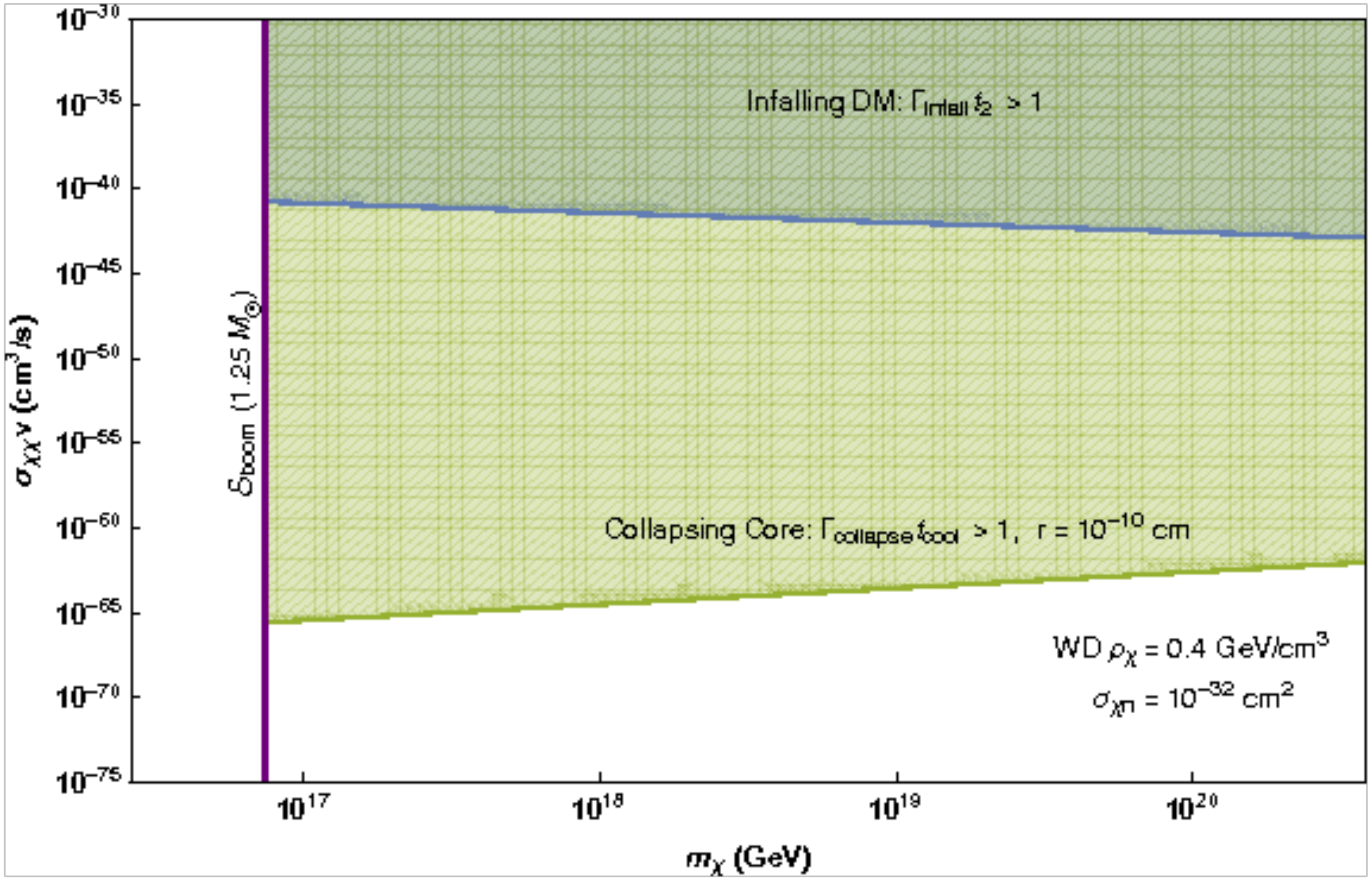


Rescaled BaBar
limit

Davoudiasl & Mohlabeng: **Phys.Rev. D98 (2018) no.11, 115035**

Further constraints

White Dwarf constraints on PSDM



$$\sigma_{\chi\chi} v_\chi \sim \frac{4\pi\alpha_d^2}{m_\chi^2}$$

$$\sim 10^{-54}\mathrm{cm}^3/\mathrm{s}$$

for $m_\chi \sim 10^{17}\mathrm{GeV}$

& $\alpha_D \sim 10^{-2}$

Graham, Janish, Narayan, Rajendran & Riggins, arXiv:1805.07381

What ensures that scalar only rolls after Freeze-out?

During thermal equilibrium, plasma is relativistic

- Thermal effects of DM on ϕ mass: $m_\phi^2(T) \sim m_\phi^2 + \lambda^2 T^2$
- minimizing ϕ potential gives $\phi(T) \sim \dfrac{m_\phi^2 \phi_0}{m_\phi^2 + \lambda^2 T^2}$

$\Longrightarrow$ at large T, before freeze-out, $\phi(T) \to 0$

e.g.

λ	m_ϕ	ϕ_0	T
10^{-6}	10^{-14} eV	10^{15} GeV	10 MeV

$$\phi(T) \sim 10^{-30}\phi_0$$

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At or after freeze-out, DM is non-relativistic

$$\mathcal{L} \supset \lambda\phi\bar{\chi}\chi - \frac{1}{2}m_\phi^2(\phi^2 - \phi_0)^2$$

Lorenz invariance allows $\bar{\psi}\psi \to n_\psi\langle\sqrt{1-v^2}\rangle$

Tadpole term $\lambda\phi\bar{\chi}\chi \to \lambda n_\chi$

Solving equation of motion gives

$$\phi(T) \sim \frac{\lambda n_\chi(T)}{m_\phi^2} + \phi_0$$

As Universe expands, DM density gets diluted $\phi(T) \to \phi_0$

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$$\mathcal{L} \supset \lambda\phi\bar{\chi}\chi - \frac{1}{2}m_\phi^2(\phi^2 - \phi_0)^2$$

Lorenz invariance allows $\bar{\psi}\psi \to n_\psi\langle\sqrt{1-v^2}\rangle$

Tadpole term $\lambda\phi\bar{\chi}\chi \to \lambda n_\chi$

Solving equation of motion gives $\phi(T) \sim \dfrac{m_\phi^2\phi_0}{m_\phi^2 + \omega_x^2(T)}$

$\omega_\chi^2(T) \sim \dfrac{\lambda^2 n_\chi(T)}{m_\chi^i}$ Plasma Frequency

Davoudiasl & Mohlabeng, **JHEP 04 (2020) 177**