Self-Destructing Dark Matter

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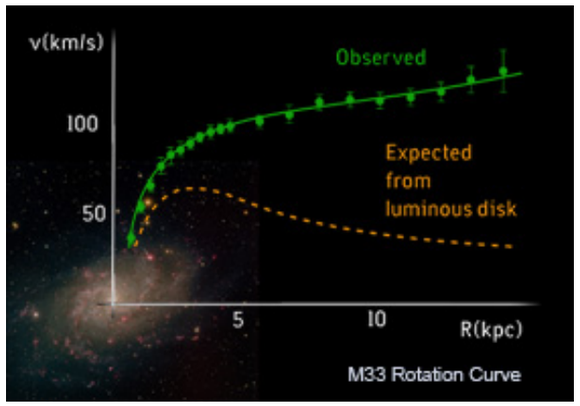
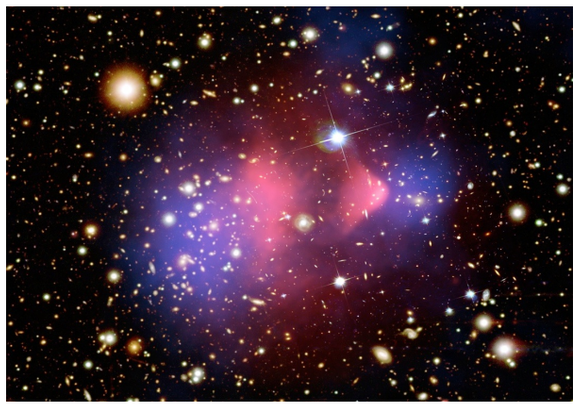
Northwestern & Fermilab

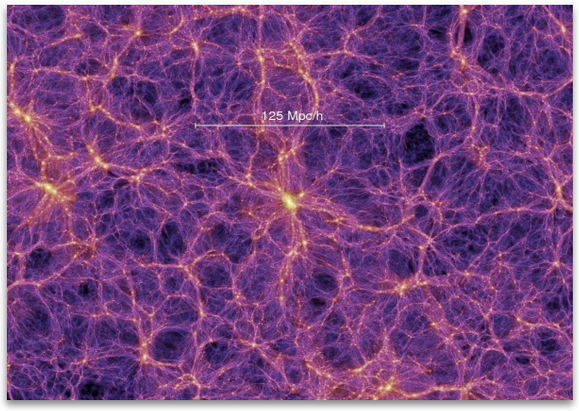
KICP Dark Matter Workshop
University of Chicago, April 12, 2018

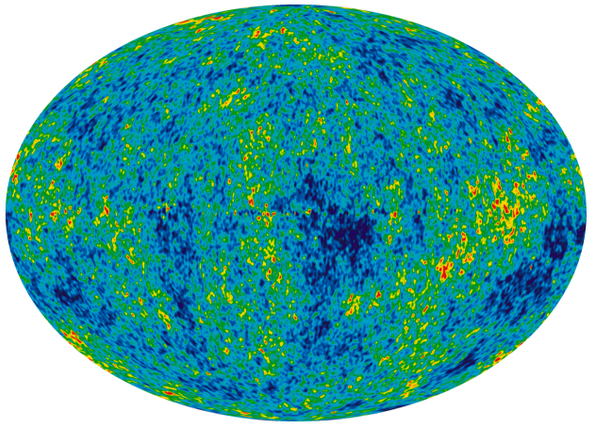
Dark Matter Exists In Nature

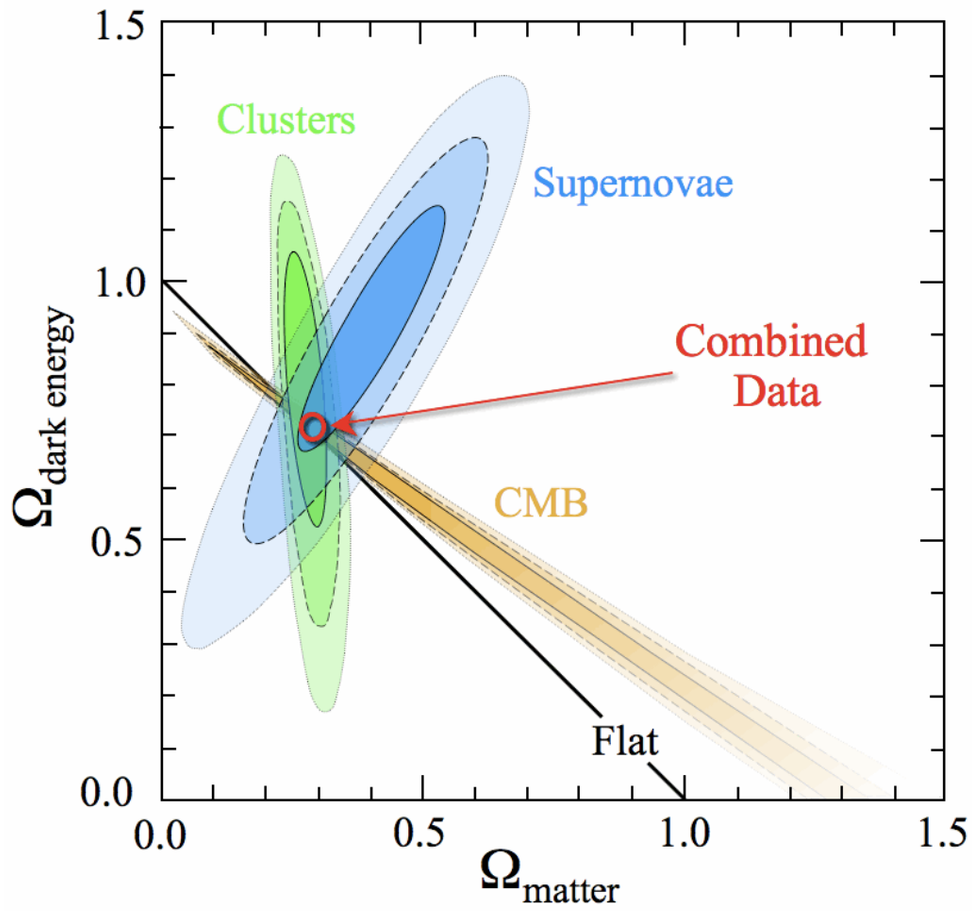
Overwhelming evidence from cosmological data.











Is it a particle? Can it be detected like the other known particles?

Dark Matter Candidates

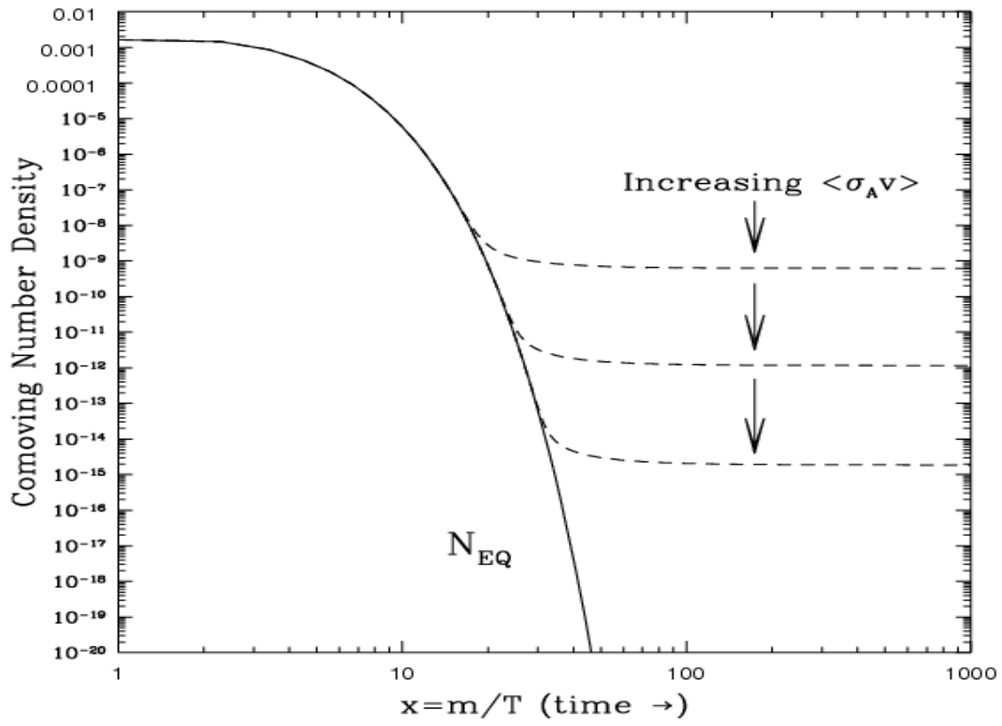
To name a few:

- Black holes ($m_{\mathrm{LIGO}} \sim 30$ solar mass)
- Axion, or light bosons ($m > 10^{-22}$ eV)
- Sterile neutrino, or light fermions ($m > 500$ eV)

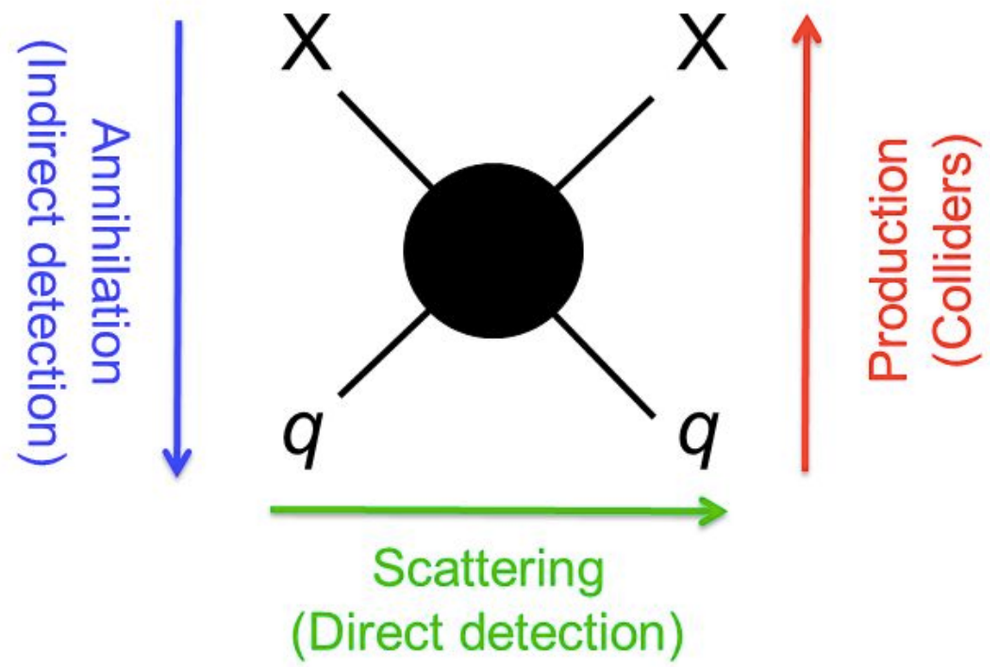
- WIMP
- Dark sector

+ many other ways to classify …

WIMP Has A Paradigm

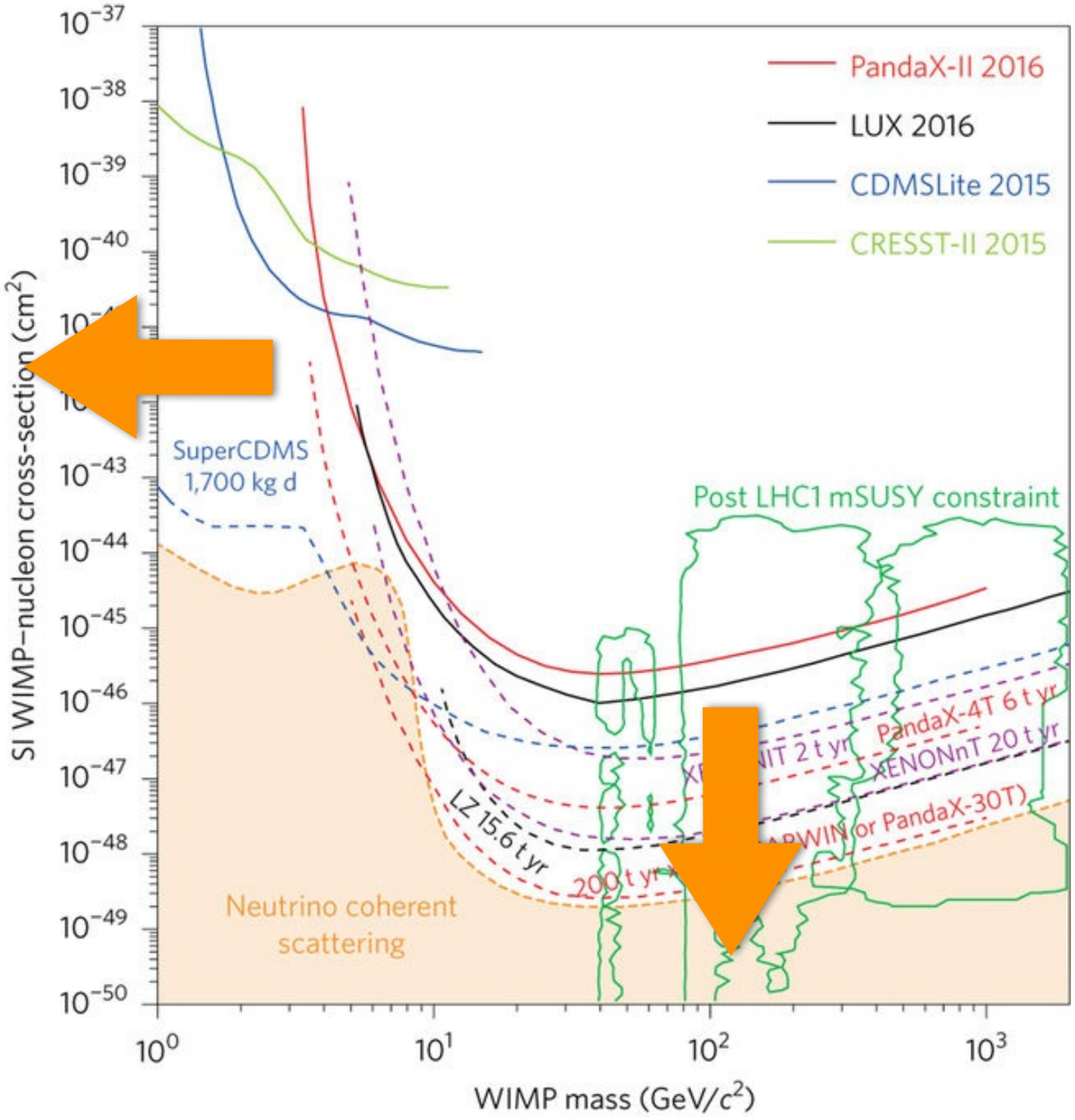


Dynamical generation of relic abundance & familiar scale



Close connection among various searches

A Drought of Discovery



Which is THE theory?

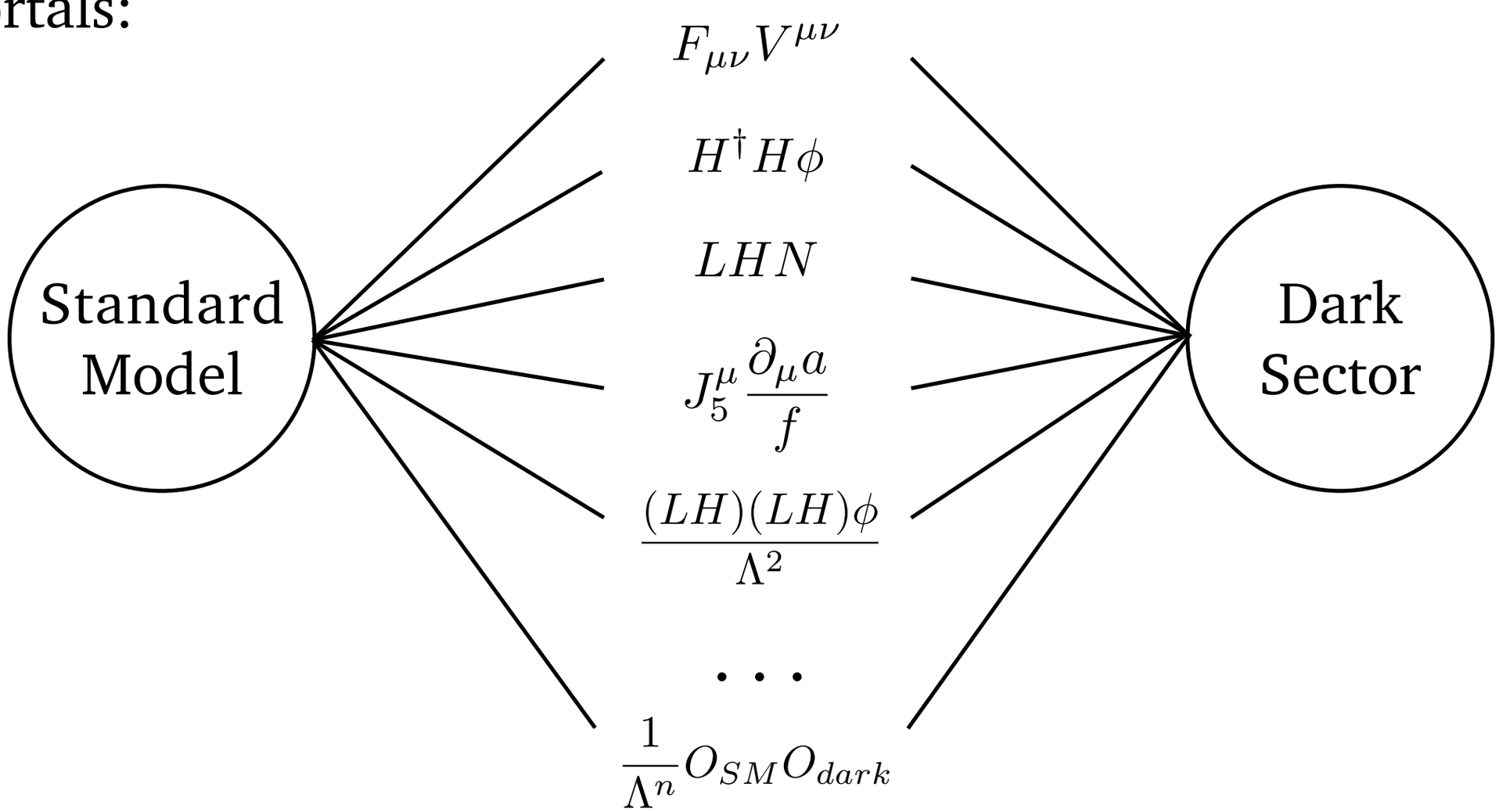
- stay put
- weakly coupled
- light, or both

We need (new) signals

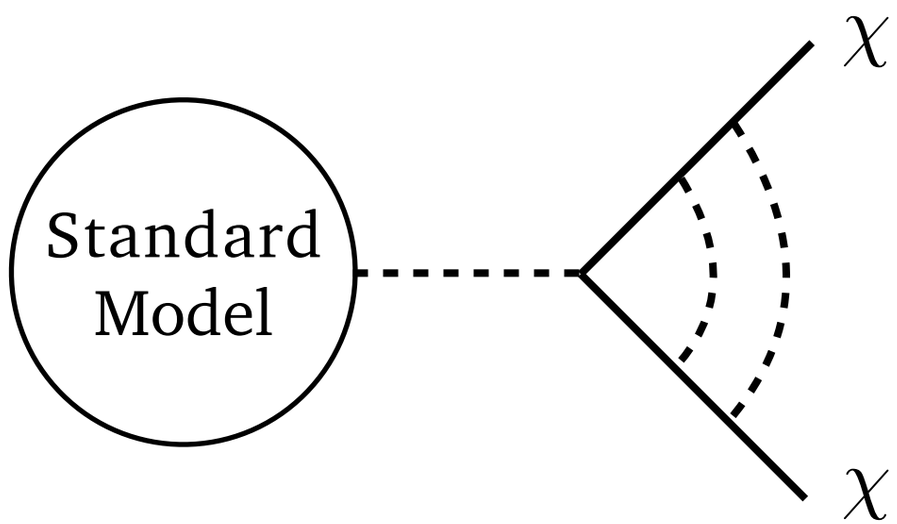
Dark Matter From Dark Sector

Dark sector particles are all SM singlets. SM particles are also singlets under possible dark gauge interactions.

Portals:



Sketch of A Simple Dark Sector



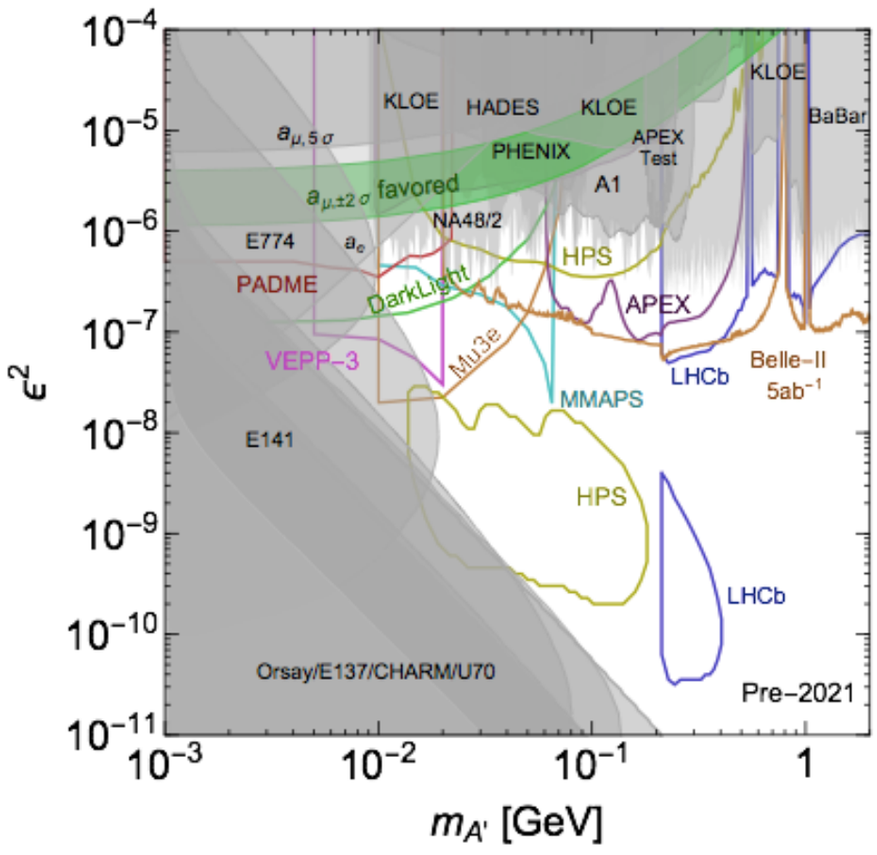
Assumption throughout this talk: light mediators & dark forces

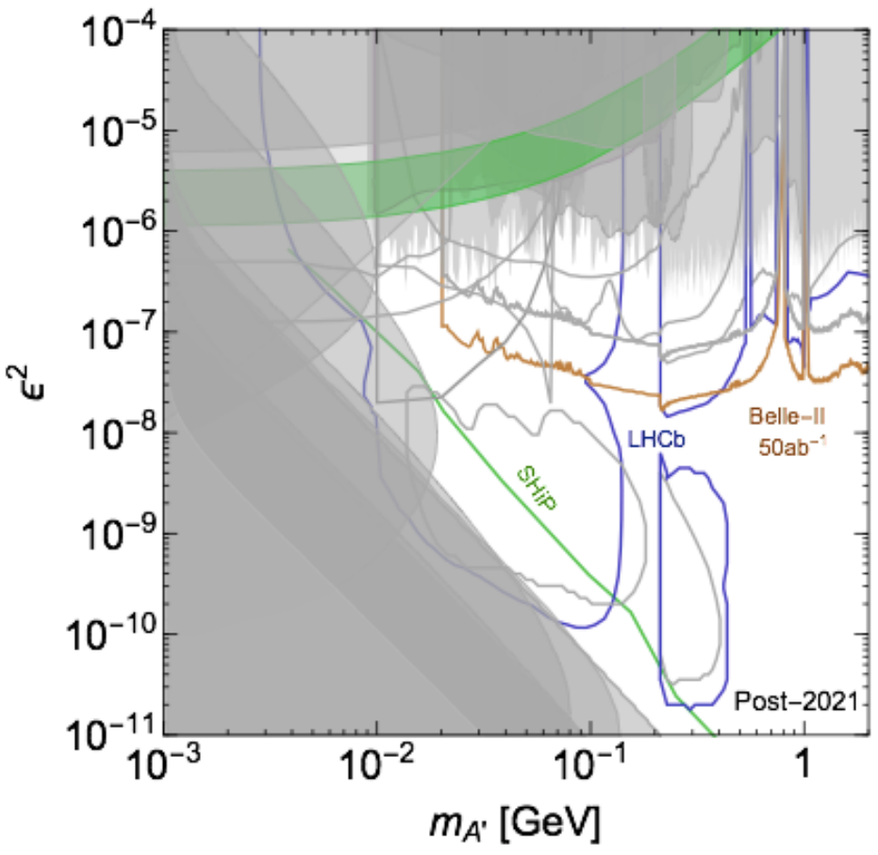
Historically, such models were considered for understanding experimental results that WIMP cannot explain

- PAMELA … Sommerfeld enhancements
- DAMA… light DM relic density (maybe asymmetric)
- Small scale structure: core/cusp problem? etc.

New Ingredients

New light particles. Search for the mediator itself is an exciting endeavor. A' decays visibly ($m_{A'}<m_\chi$), prompt or long lived.

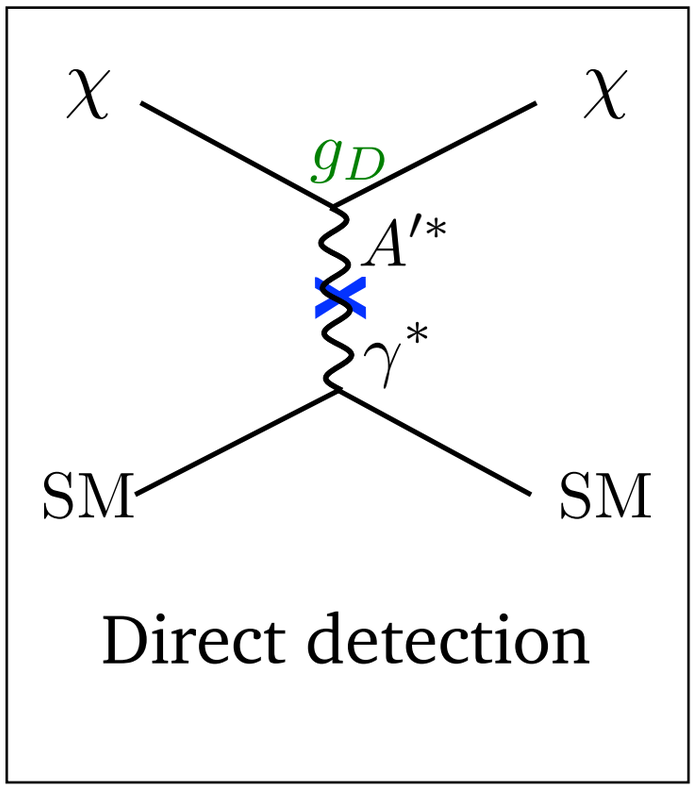




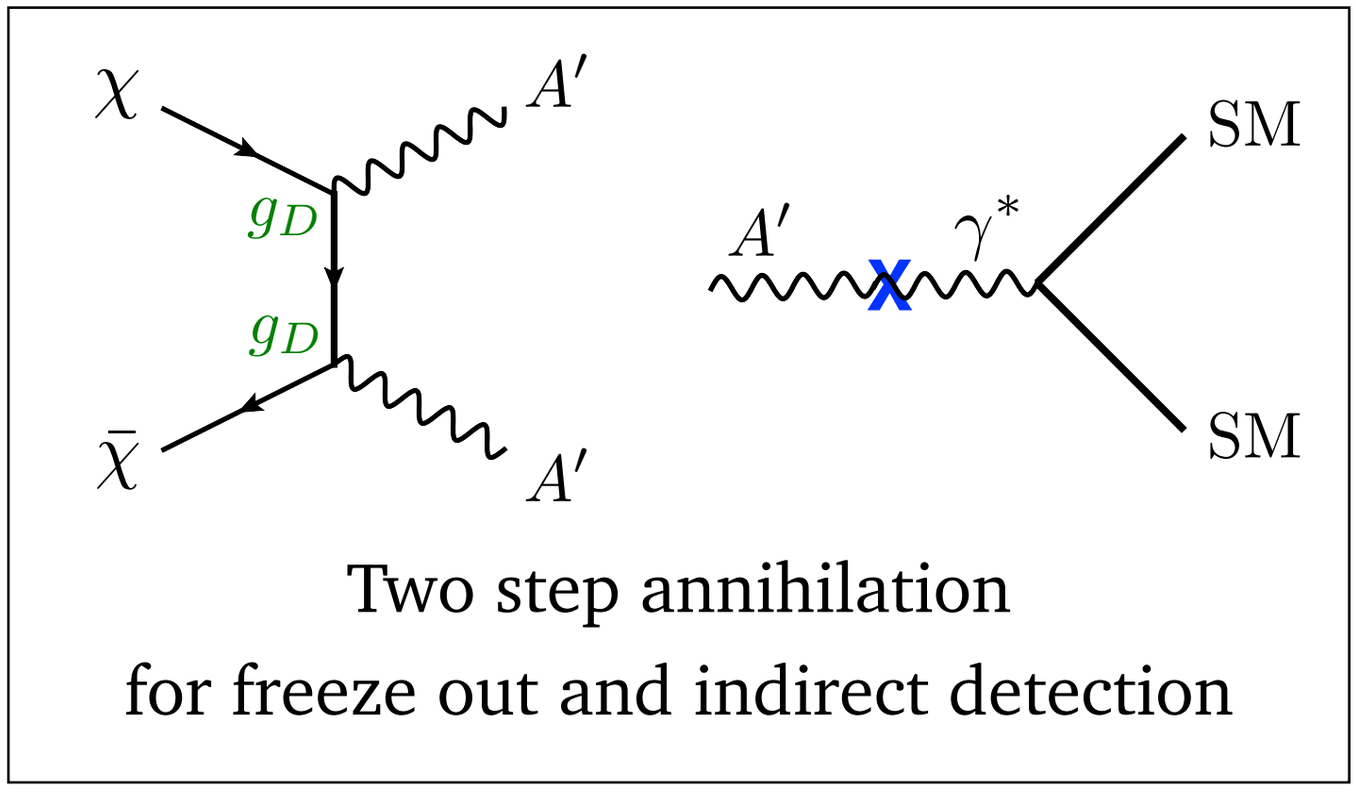
Dark Sectors Community Report (1608.08632)

New Ingredients

New interplays. Time scale for each detection process to occur can be quite different.



Direct detection



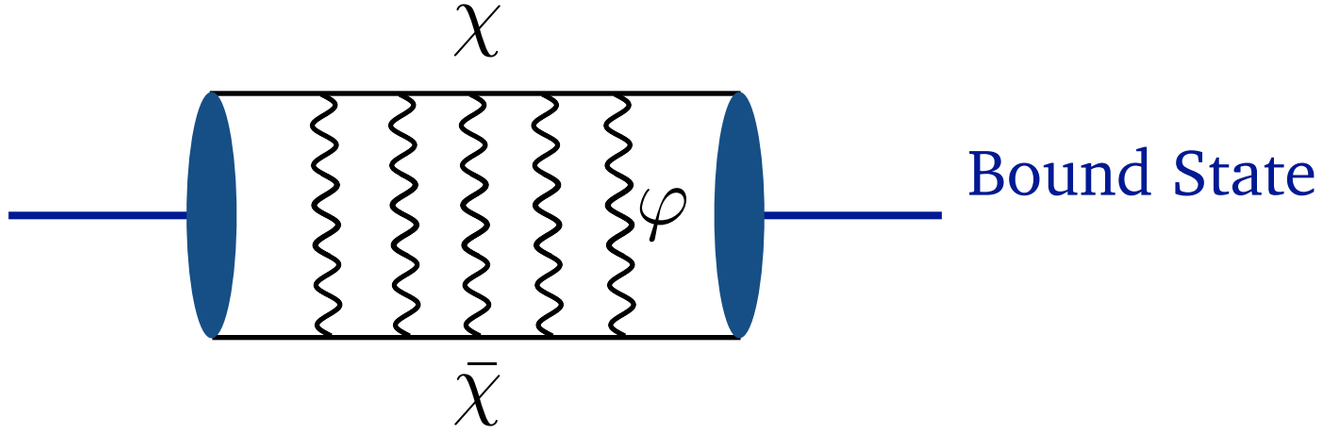
Two step annihilation
for freeze out and indirect detection

secluded DM $m_{A'} < m_\chi$

Dark Matter Bound States

New dark matter signals. Dark force makes bound states.

This talk will only consider two-body ($\chi\bar{\chi}$) bound states. Models discussed here are inspired by what occurs in the SM.

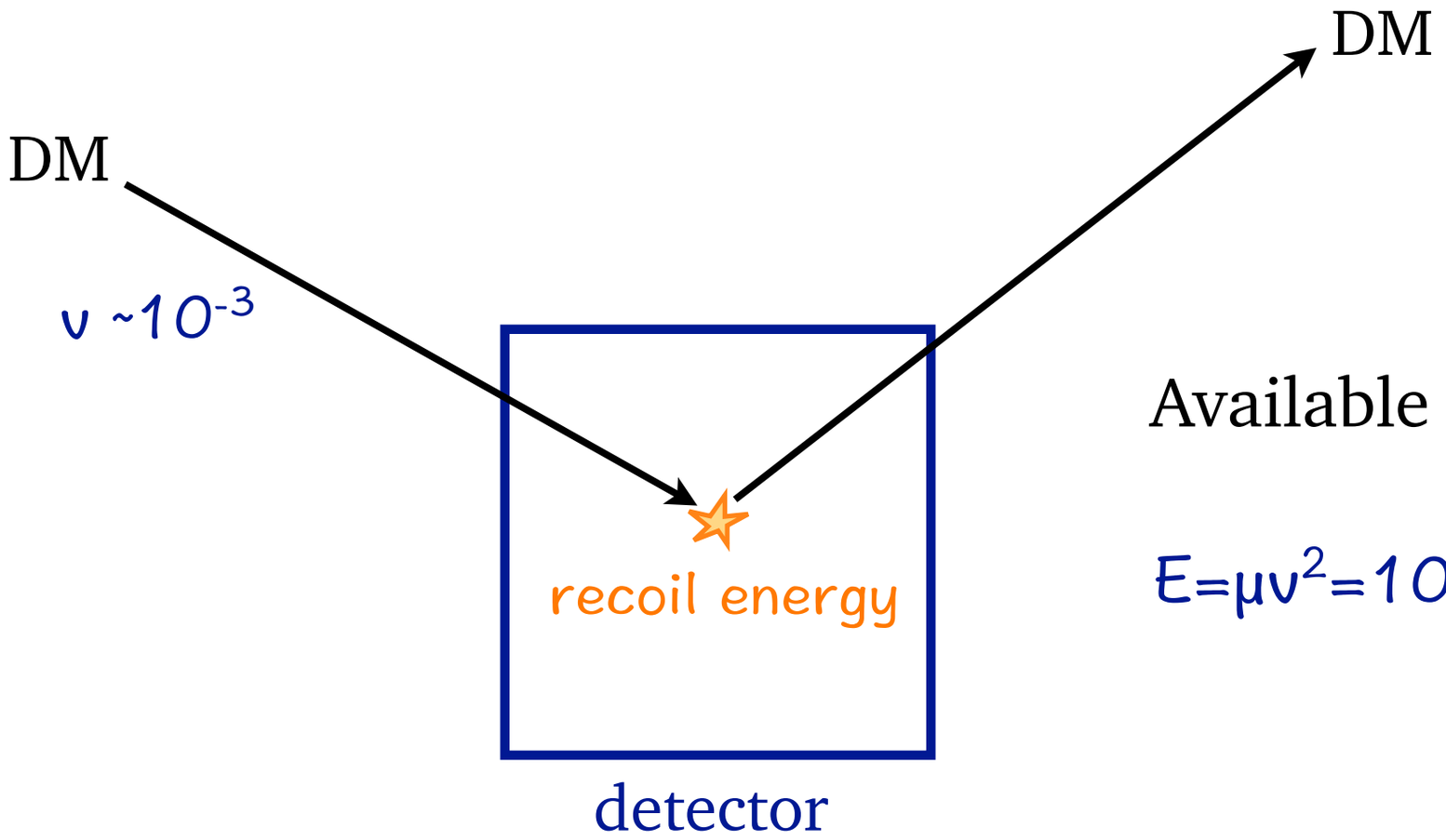


$(\alpha_D m_\chi)^{-1} \lesssim m_\varphi^{-1}$ (Bohr radius < Size of potential well)

New Direct Detection Signal

New signals in the direct detection of DM bound states?

First, the usual story (scattering):



Available recoil energy

$E=\mu v^2=10^{-6}\mu \lesssim 100$ keV

Need to build a clean detector, go deep underground, and wait.

Underground Lab

2.4 km

deep down here

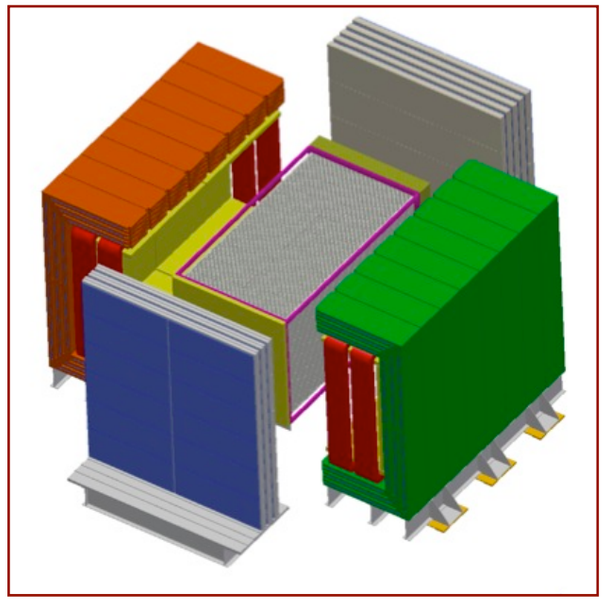
LUX (~1 ton target, keV threshold)

Underground Lab

2.4 km

deep down here

LUX (~1 ton target, keV threshold)



DUNE (tens of kiloton target, MeV threshold)

A New Way Of Direct Detection

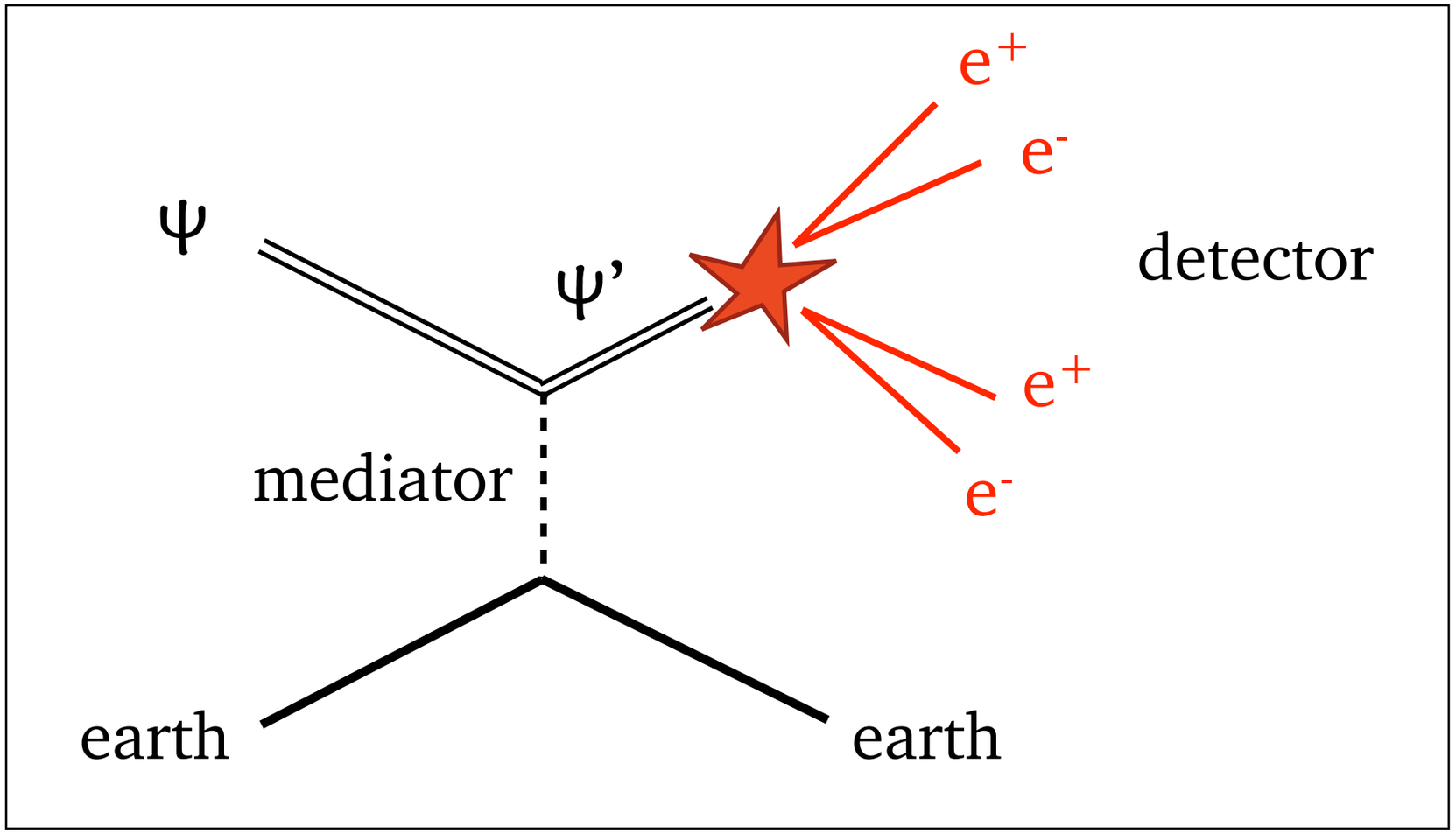
Broaden the theory considerations and detector purposes: release more than only the kinetic energy.

I will discuss a scenario where

- All the DM mass turns into visible energy after scattering.
- DM as light as MeV still means substantial energy release.
- Such DM candidates are best searched for in neutrino detectors.

Grossman, Telem, Harnik, **YZ** (1712.00455)

Self-Destructing Dark Matter



Self destruction does not occur to SDDM in vacuum; only triggered by a scattering.

Grossman, Telem, Harnik, **YZ** (1712.00455)

A Back-of-Envelope Estimate

DM has lived in the galaxy (not empty) for a long time, why would self destruction still occur at the earth today?

Place	Time spent, Δt	Density of stuff, n
Galactic Halo	10^{17} sec	~ 1 cm^{-3} (DM@1GeV)
Earth	10 sec	~ 10^{23} cm^{-3}

There is room for our Earth to be special

A Viable Model

We have to separate the roles of dark force and mediator.

A light dark force φ for binding χ and $\overline{\chi}$ in together.

$$\alpha_D^2 m_\chi/4 < m_\varphi < \alpha_D m_\chi/(2n)$$

Rydberg Bohr radius

A heavier (above MeV) mediator V for talking to SM : $\kappa F_{\mu\nu} V^{\mu\nu}$

$$\chi\overline{\chi} \to VV, \quad V \to e^+e^-$$

Mass range of V : $\alpha_D m_\chi/2 < m_V < m_\chi$

Stabilization With High ℓ

Higher angular momentum states are (much) more stable.

- Direct annihilation into V or φ.

$$\Gamma(\Psi_{n,\ell} \to VV) \sim (\alpha_D/n)^{2\ell+3}\ \alpha_D^2\ m_\chi$$

- De-excitation by radiating SM particles (3γ or 2ν) via V* strongly suppressed (Δbinding energy $\ll 2m_e$).

If α_D=0.01, m_χ=1GeV, the $n=10$, $\ell=9$ state very long-lived

$$\tau(\Psi_{10,9}) > 10^{40}\ \text{sec}$$

Scattering and Transition

With a 3-momentum transfer, $\Psi_{10,q} + (A,Z) \rightarrow \Psi_{1,0} + (A,Z)$

$$\sigma \sim g_D^2 \kappa^2 e^2 Z^2 \left(\frac{\alpha_D}{v}\right)\left(\frac{\mu^2}{m_V^4}\right) F(q)^2$$

α_D/v enhancement when $\alpha_D \gg v$. Exothermic: binding energy release enlarges phase space of scattering

$$|\vec{q}| \sim m_\chi \alpha_D + m_\chi v \cos\vartheta$$

Form factor for dark bound state transition

$$F_n(q) = \int dV \, \Psi_{10,q}^*(x) \, \Psi_{n,0}(x) \left(e^{iq\cdot x} - e^{-iq\cdot x} \right)$$

The Dark Form Factor

$$F_n(q) = \int dV\, \Psi_{10,q}^{*}(x)\, \Psi_{n,0}(x)\, \left(e^{iq\cdot x} - e^{-iq\cdot x} \right)$$

If $\alpha_D \ll v$, momentum transfer too large — dissociate bound state — not of our interest, will focus on $\alpha_D > v$ next:

Big change in angular momentum, here $\Delta\ell = 9$. Need to expand exponential $(q\cdot x)^9$, suppressed if $q\cdot x < 1$.

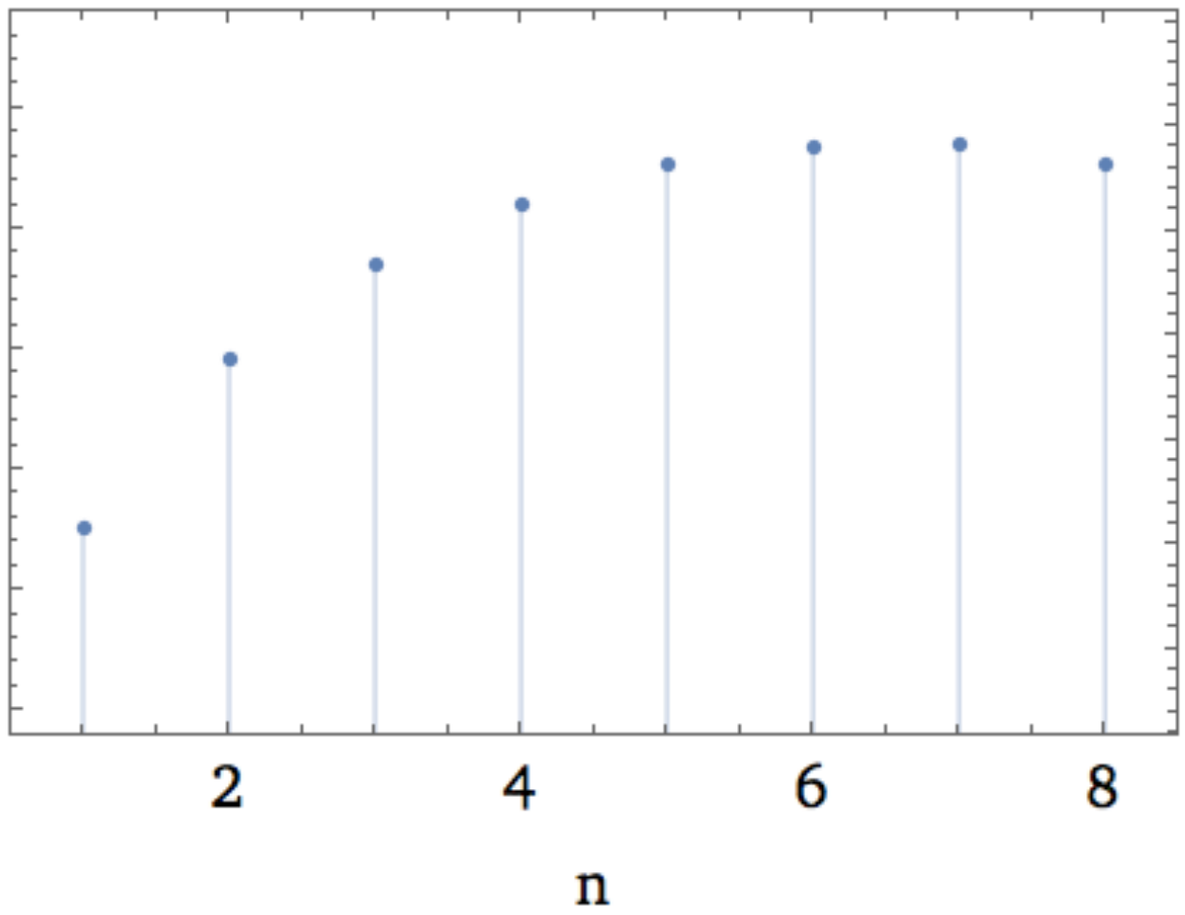
Power counting for bound state ($n < 10$),

$$x \sim n/(m_\chi \alpha_D), \quad q \sim m_\chi v$$

For generic $\alpha_D > v$, always exist an *S*-wave state with $n \sim \alpha_D/v$ (may not be the ground state), whose form factor is not suppressed.

The Dark Form Factor

$\sigma_{(10,9)\to(n,0)}$ $\alpha_D = \alpha_{\mathrm{EM}}$



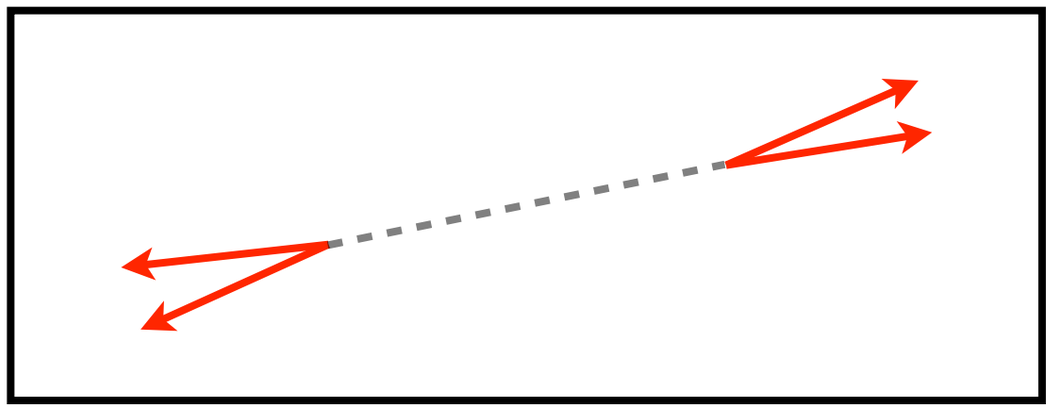
Self Destruction and Signals

Self destruction: final $\Psi_{1,0}$ state decays promptly into V's

$$\tau(\Psi_{n,0}) = (\alpha_D^5 m_\chi/2n^3)^{-1} \sim 2\times10^{-14}\text{sec}\left(\frac{\alpha_D}{0.01}\right)^{-5}\left(\frac{m_\chi}{1\text{GeV}}\right)^{-1} n^3$$

$\Psi_{n,0}\to VV\to 2(e^+e^-)$ produces two pairs of e^+e^-. Each pair carries energy dictated by m_χ. Invariant mass equal to m_V.

V decay length $\lesssim$ *10 meter*, observe both pairs, back to back.

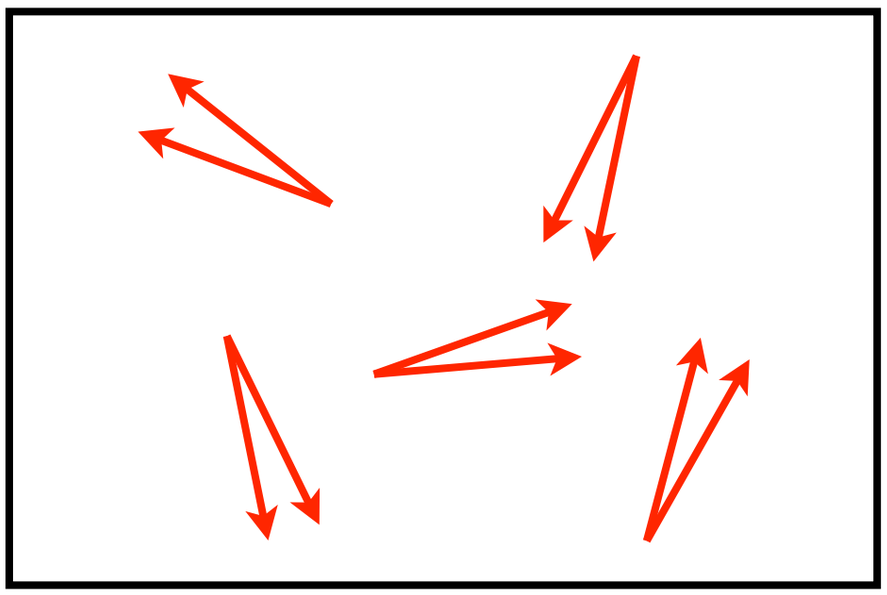


detector

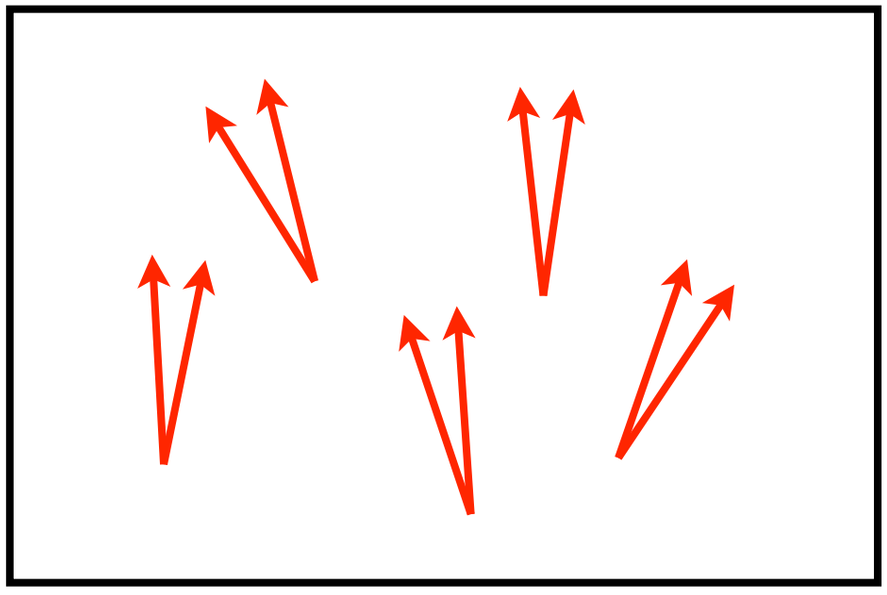
Directionality

Dark photon V could be long lived, $c\tau \gtrsim 10$ m. Scattering on earth, only one V travels to detector — see single pair.

- $c\tau \lesssim$ km: isotropic
- $c\tau >$ km: most pairs up-going

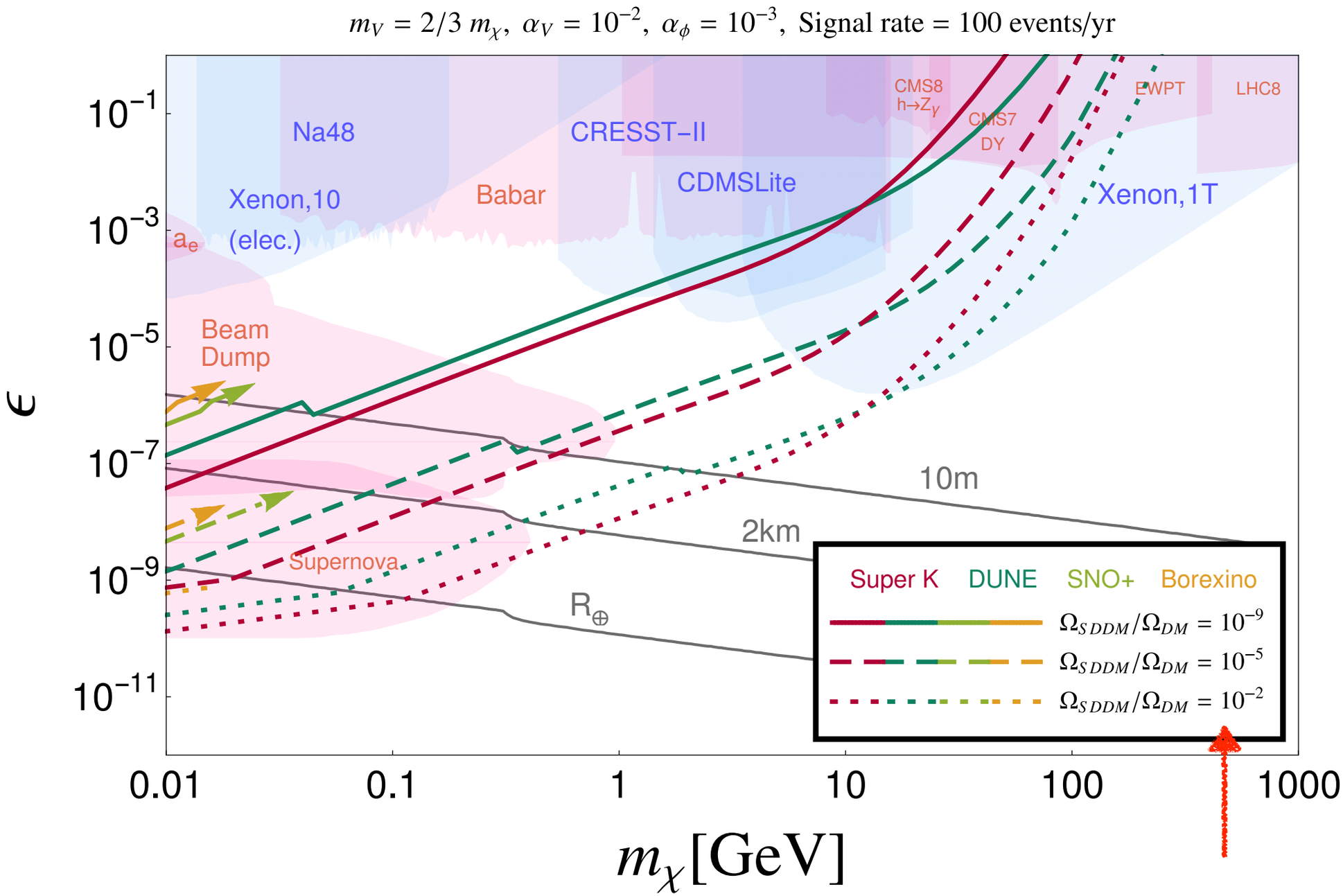


detector



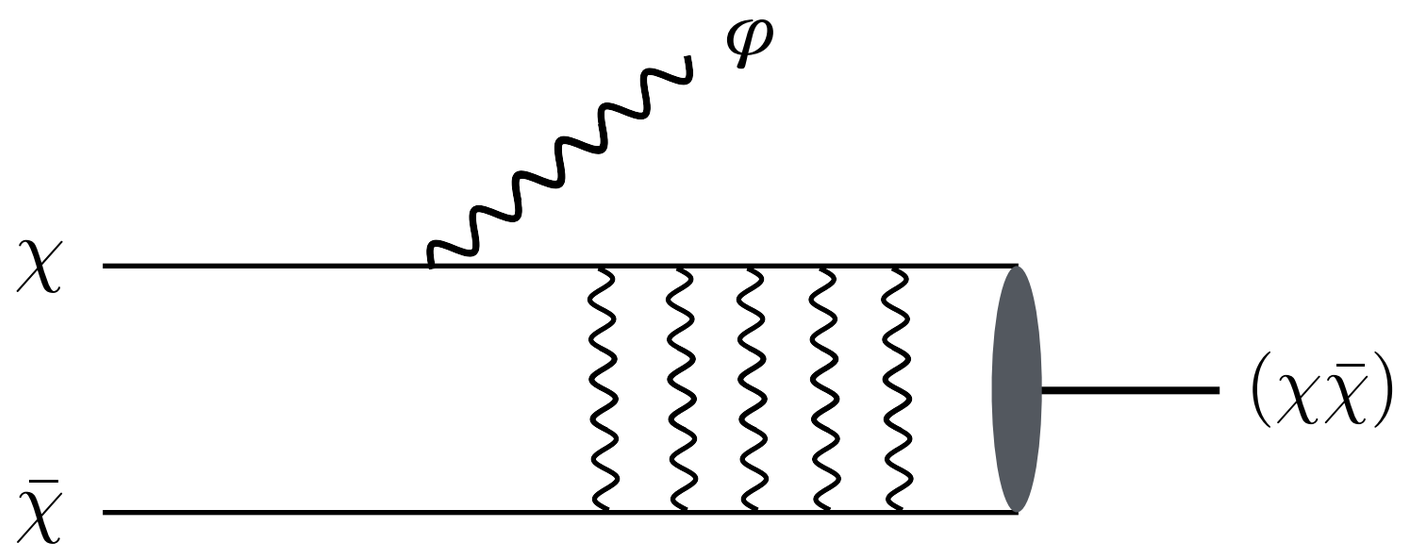
detector

New Constraints



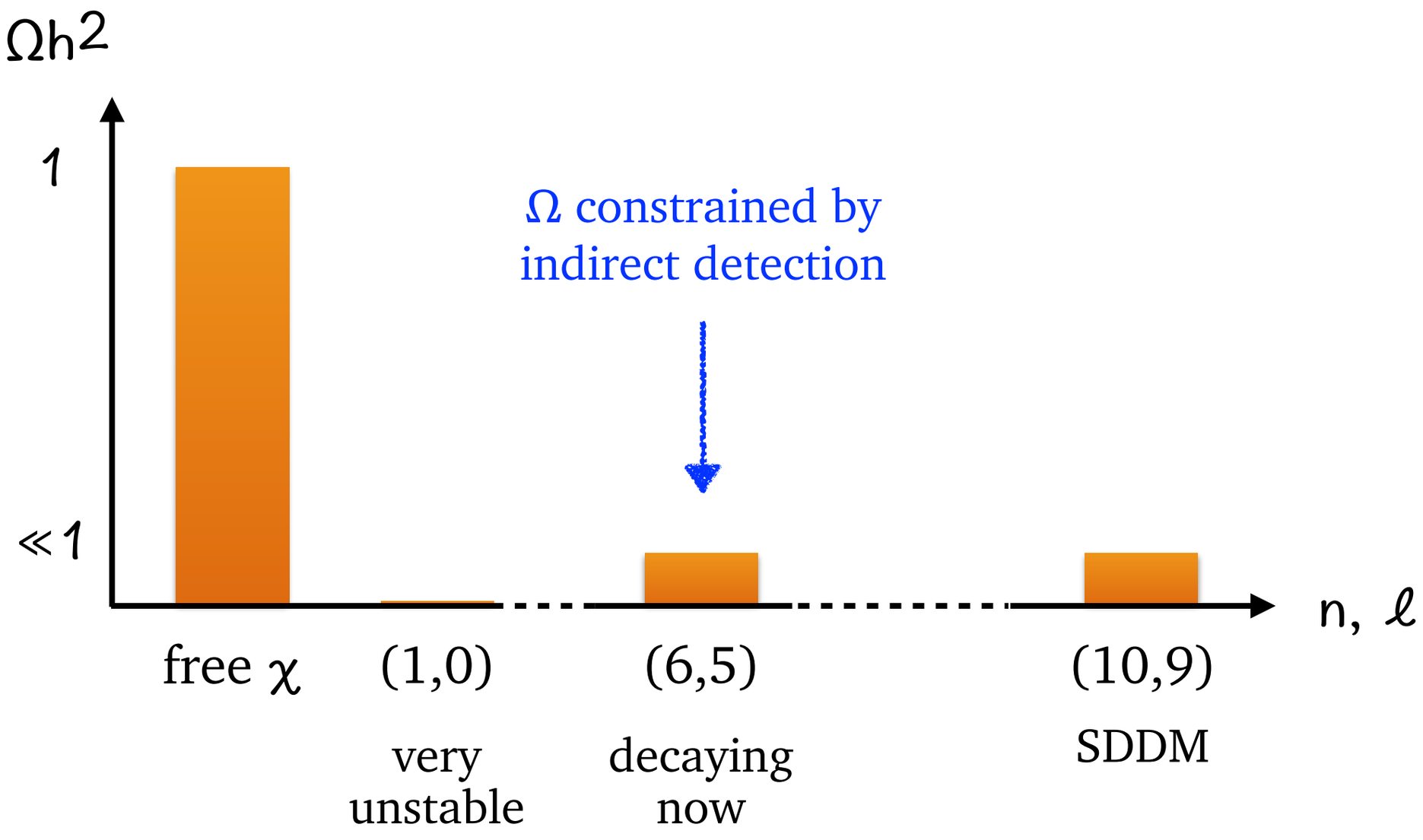
Grossman, Telem, Harnik, **YZ** (1712.00455)

A Challenge for Early Universe



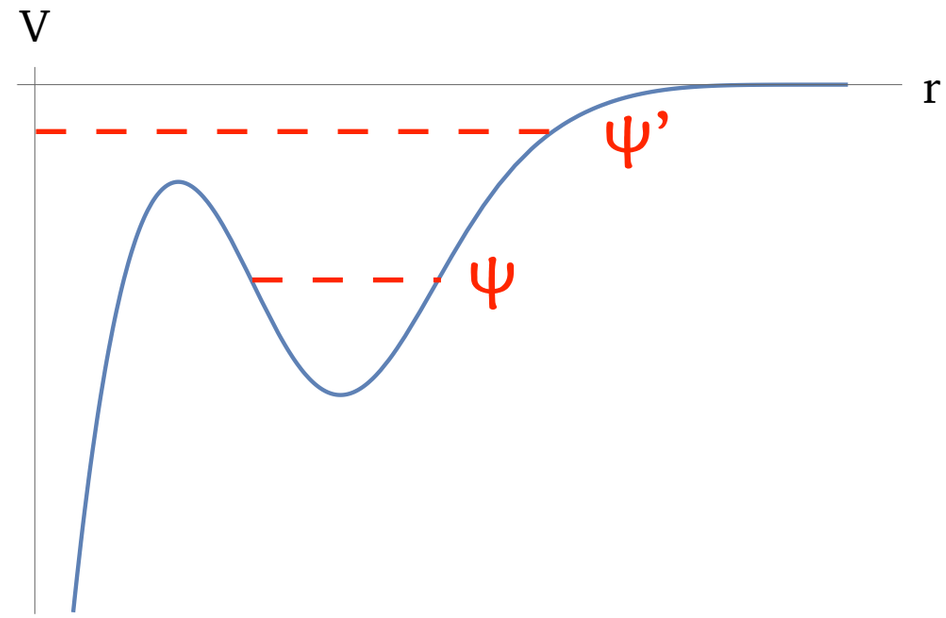
- For SDDM stability: $m_\varphi >$ Rydberg (binding energy).
- Inverse process (dissociation) always fast even φ at rest.
  [Similar to the deuterium bottleneck in BBN.]
- Must suppress φ number density in non-thermal ways.
- Or another possibility: quirks.

Distribution of Relic Abundances



Other SDDM Models

Tunneling stabilization:



- Ground state wavefunction exponentially suppressed at origin.
- Unsuppressed for excited state.
- Analogy to D_2 molecule → ^4He (plus a confining potential).

Symmetry stabilization: χ carries baryon number

- $(\chi\chi)$ and $(\chi\bar{\chi})$ are bounded by an SU(2) confining dark force.
- $(\chi\chi) + (A,Z) \rightarrow (\chi\bar{\chi}) + (A\text{-}1,Z)$, remove a neutron.

Conclusion

Exploring the dark sector means more than re-analyzing WIMP-like processes.

Self-Destructing Dark Matter: all the DM mass turns into energy after a scattering.

Neutrino detectors are the leading places to search for such DM candidates.

New limits for DM mass down to MeV scale.

Strong impact even with a small faction of relic density.

Conclusion

"The hardest thing of all is to find a black cat in a dark room, especially if there is no cat." Confucius (551 BC — 479 BC)

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Be open-minded

Prepare for surprises

Exciting discoveries awaiting us!

Bonus

More Bound State Effects on Dark Matter

Intriguing exercise: apply our knowledge of bound state physics to various aspects of dark matter.

- Direct detection

  Laha, Braaten (1311.6386); Laha (1505.02772)

- Indirect detection

  March-Russell, West (0812.0559); An, Wise, YZ (1604.01776, 1606.02305); Cirelli, Panci, Petraki, Sala, Taoso (1612.07295)

- At colliders (dark resonances)

  Shepherd, Tait, Zaharijas (0901.2125); An, Echenard, Pospelov, YZ (1510.05020); Bi, Kang, Ko, Li, Li (1602.08816); Krovi, Low, YZ (in progress)

- Early universe (normal freeze out…or maybe, nuggets)

  Wise, YZ (1407.4121, 1411.1772); Gresham, Lou, Zurek (1707.02313, 1707.02316)