Self-Destructing Dark Matter

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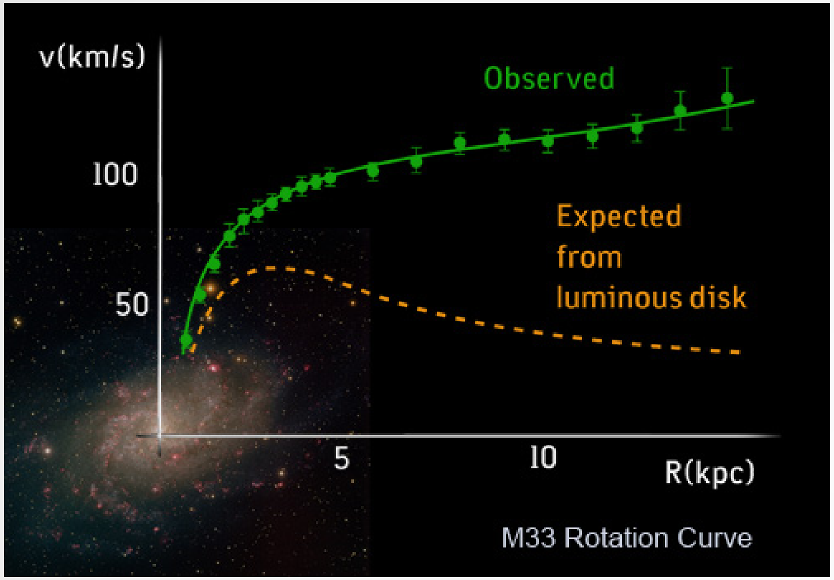
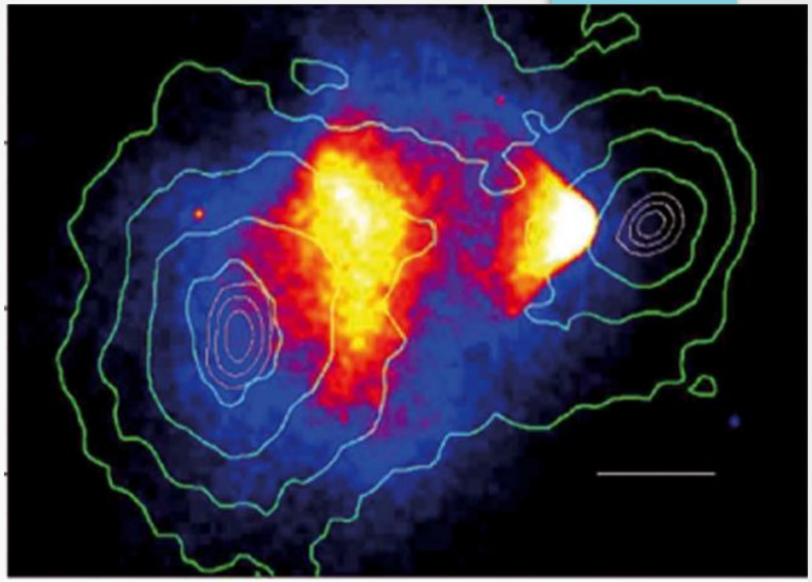
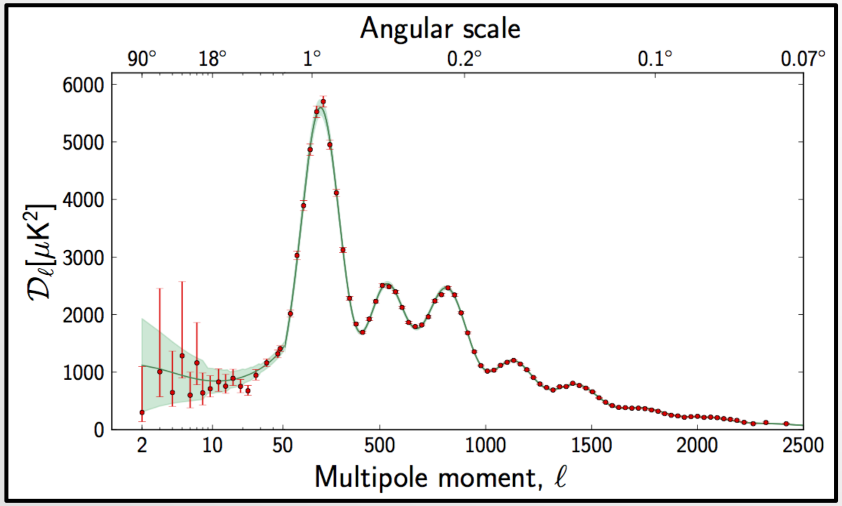
Phenomenology 2018

arXiv:1712.00455 with Yuval Grossman, Roni Harnik and Yue Zhang

We know that it's out there



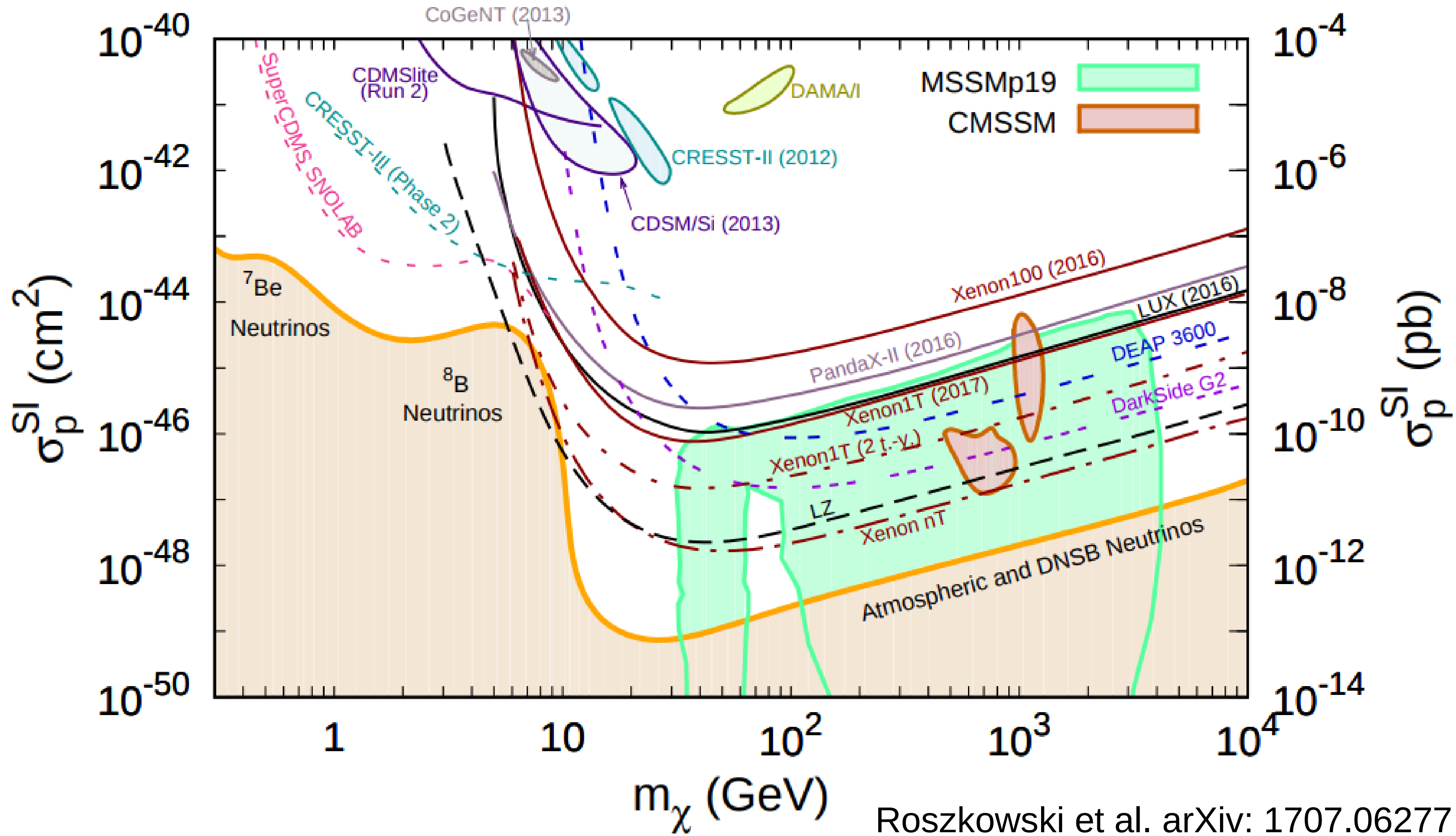




Evidence for cold Dark Matter from vastly different scales:

- Galaxies
- Clusters
- CMB

Direct Detection



Roszkowski et al. arXiv: 1707.06277

Why the loss of sensitivity at low masses?
- Nuclear recoil energy below threshold!

The light DM frontier

New detection concepts

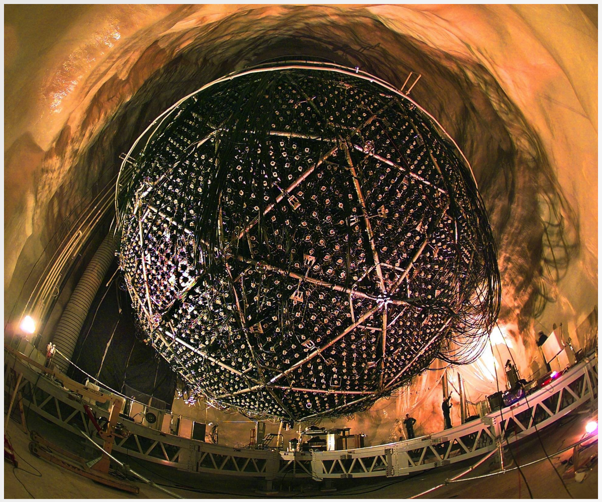
- Semiconductors
  Essig et al. 2015
- Supercondutors
  Hochberg et al. 2016
- Superfluids
  Schutz & Zurek 2016
- Color centers
  Budnik et al. 2017
- Single electron CCD - Sensei
  Tiffenberg et al. 2017
- ...

Non minimal Dark Sectors

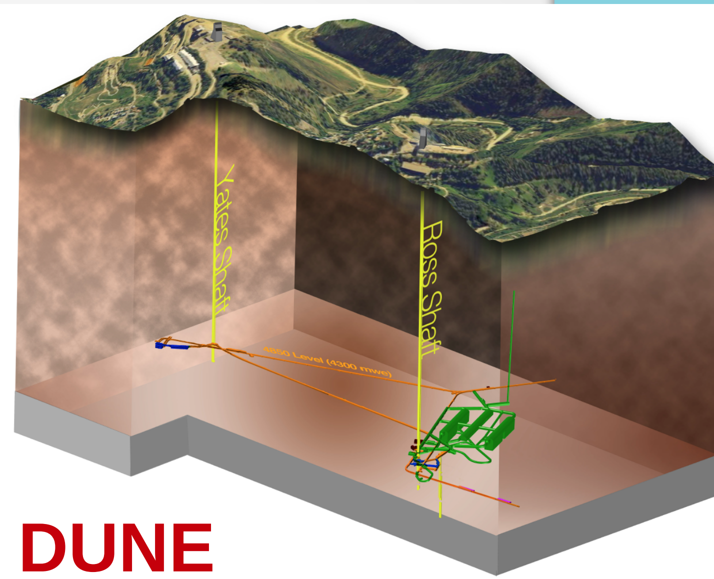
- Asymmetric DM 1308.0338, 1111.0293
- Freeze-in 0911.1120
- WIMPless 0803.4196
- SIMP 1402.5143, 1411.3727
- ELDER 1706.05381
- Atomic DM 1609.03592, 1311.6468
- Co-decaying 1607.03110
- Cannibal 1607.03108, 1602.04219
- Vector DM 1105.2812, 1504.02102
- ...

What about direct detection @ neutrino detectors?

Neutrino detectors

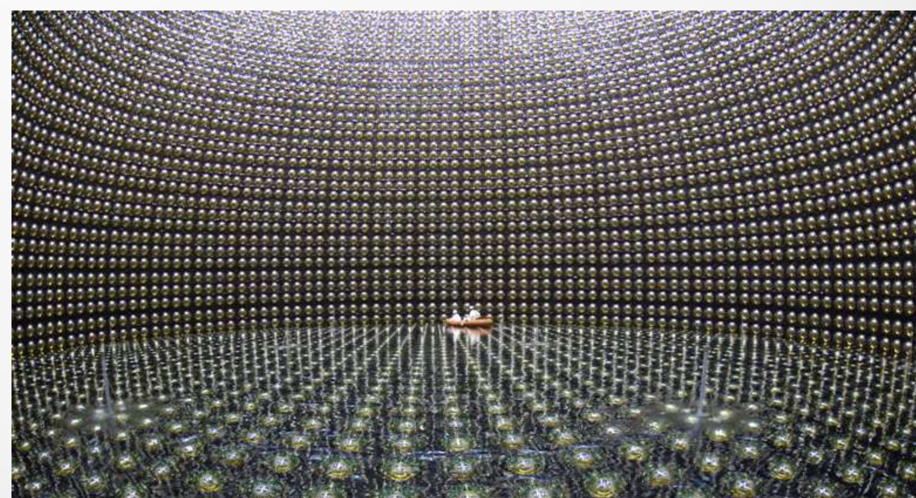


SNO+



DUNE

Borexino



Super-K

Neutrino detectors

	Material	Density	Volume	Threshold	Purpose
Super-K	$H2O$	1 gr/cc	13×10^4 m^3	5.5 MeV	solar, atmospheric, SN, θ_{13} (T2K), ...
Borexino	PC + PPO	0.9 gr/cc	3×10^2 m^3	250-665 keV	solar, SN, ...
SNO+	^{130}Te + LAB	5.7 gr/cc 0.9 gr/cc	9×10^2 m^3	~1 MeV	ν-less β, pep, ...
DUNE	LAr	1.4 gr/cc	1×10^4 m^3	5 MeV	ν hierarchy, δ_{CP},...

Low densities, large volumes, high thresholds.
How are we going to look for DM with these ?!

See also Agashe et al., arXiv:1405.7370, 2014
Berger et al., arXiv:1410.2246, 2015
also J. Berger's talk on boosted DM this afternoon

What if the DM leaves more than just its kinetic energy?

See also Graham et al., arXiv:1004.0937, 2010
Pospelov et al. arXiv:1312.1363, 2014

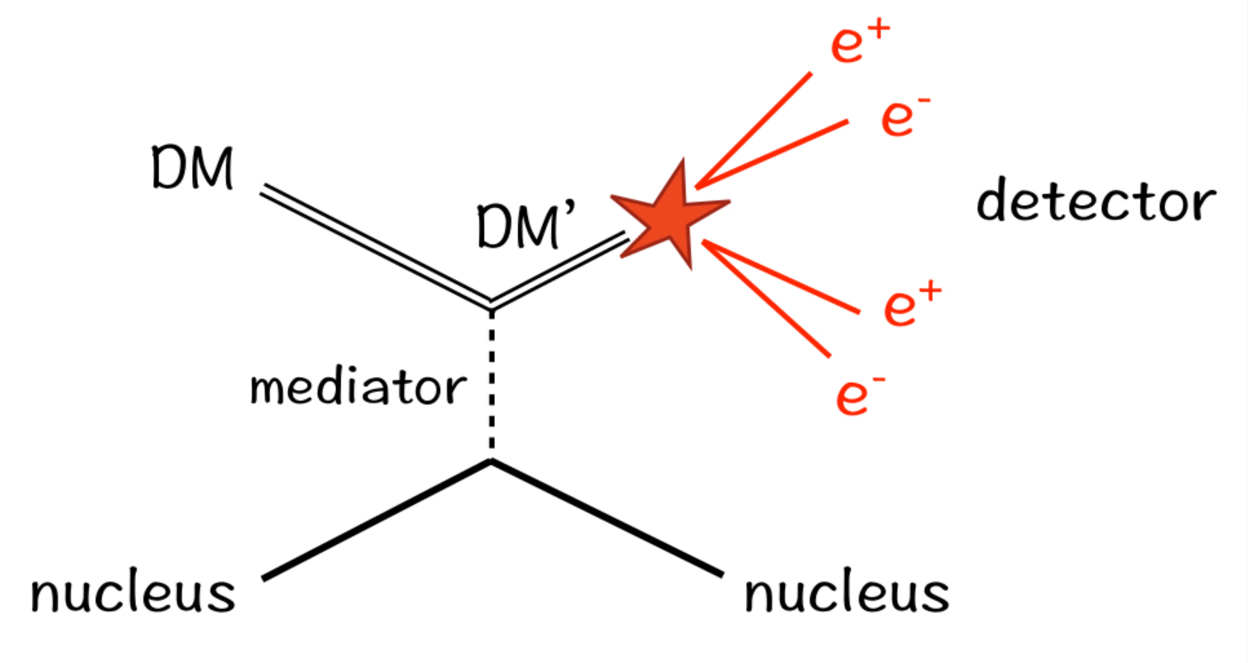
What if the DM ~~leaves more than just its kinetic energy?~~

converts all of its rest mass to signal

↓

Self-Destructing Dark Matter

Self-destructing DM (SDDM)

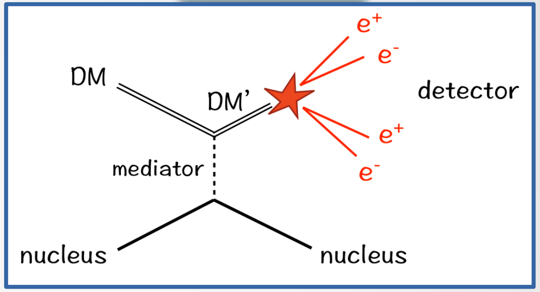


DM – cosmologically stable bound state
DM' – unstable bound state (“positronium”)

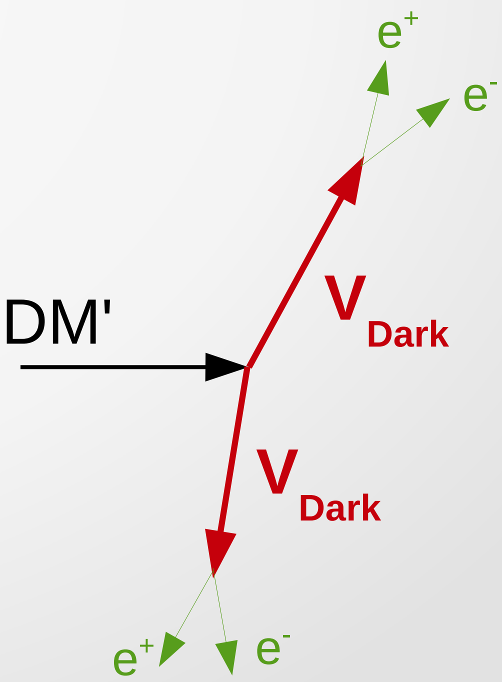
1. DM + N → DM' + N
2. DM' self-annihilates into 2 dark photons V
3. Each dark photon V → SM e+e- pairs

The novelty in SDDM detection

All of the DM rest mass gets converted to detectable signal!

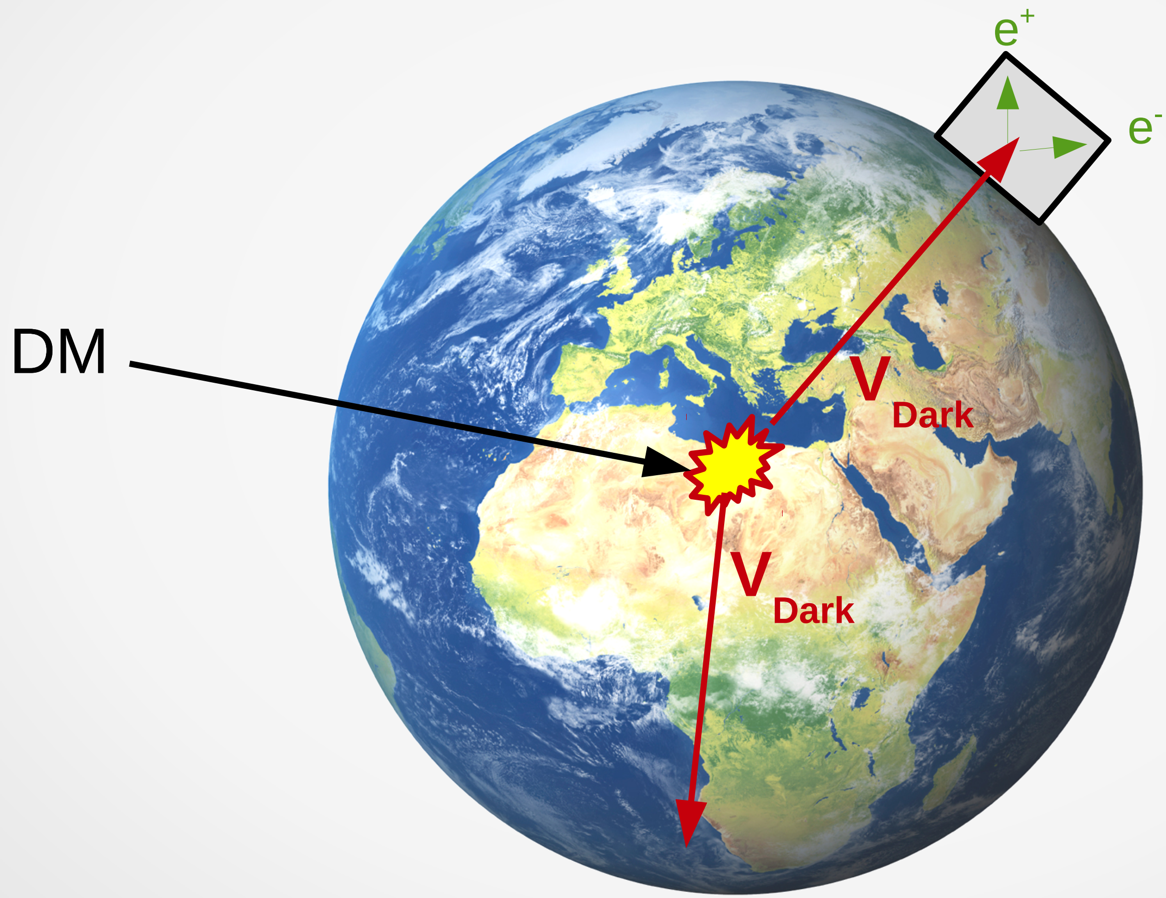


- Can search for 10 MeV DM with a 5 MeV detector threshold
- Neutrino detectors have major reach - even if SDDM is a tiny subcomponent of DM
- If the SDDM decays in the detector: 2 back to back boosted e+e- pairs
- SDDM can decay outside the detector if dark photon decay length macroscopic



Earth as a detector

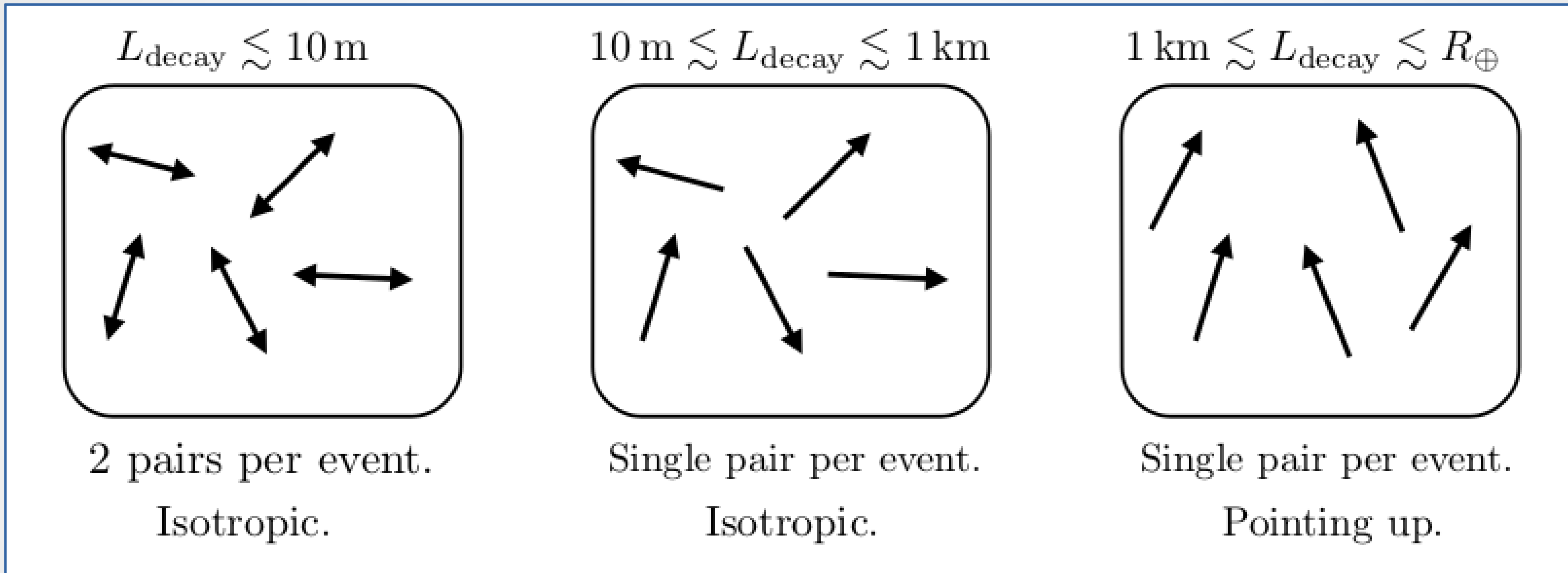
If the dark photon decay length is long enough:



Only the detector volume and threshold matter!

Three SDDM detection regions

For different dark photon decay lengths:



$$E_{\mathrm{pair}} = \frac{m_{\mathrm{SDDM}}}{2} \qquad L_{\mathrm{V_{dark}}} = c\tau_{\mathrm{V_{dark}}} \sqrt{\frac{E^2_{V_{\mathrm{dark}}}}{m^2_{V_{\mathrm{dark}}}} - 1}$$

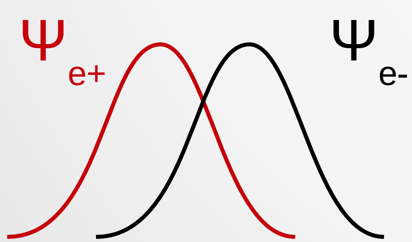
$$m_{\mathrm{pair}} = m_{V_{\mathrm{dark}}} \qquad \cos\theta_{\ell^+\ell^-} \sim 1 - \frac{8m^2_{V_{\mathrm{dark}}}}{m^2_{SDDM}}$$

Models for SDDM

Models for SDDM have bound states $\chi\bar{\chi}$ that can self-annihilate into two mediators (e.g. dark photon)

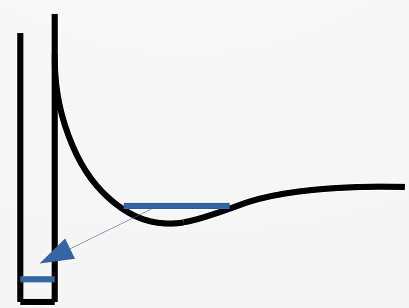
- Some bound states have lifetime > 10^{28} s
- Other bound states have lifetime << 10 s (Earth crossing time)

Can we find examples in **Nature?** *Yes!*



Positronium decay

This talk



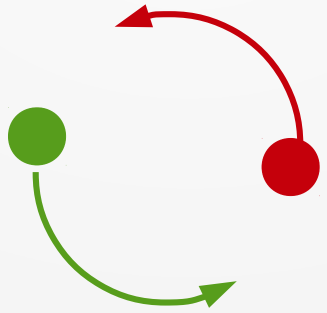
Coulomb barrier for fusion

p $\tau_p > 10^{35}$ s

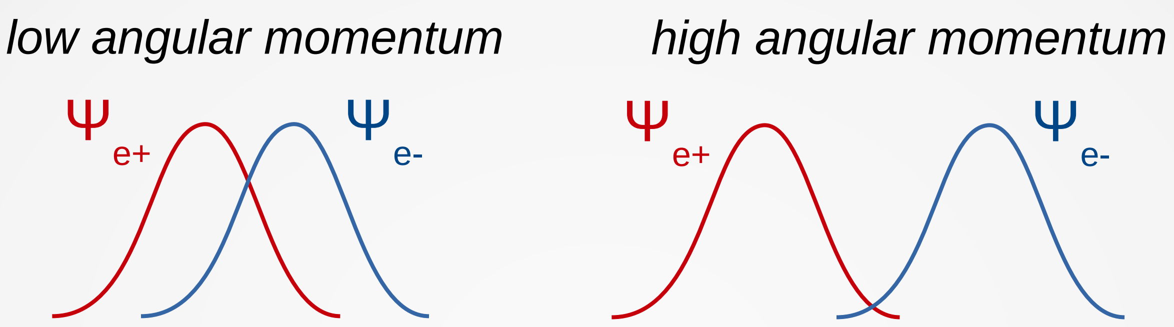
n $\tau_n \sim 15$ min

Proton stability

A model for SDDM:
Angular momentum stabilization



Inspiration from positronium decay



$$\Gamma_{\text{positronium}} \sim \left|\Psi^{(l)}(r=0)\right|^2 \sim \left(\frac{\alpha}{n}\right)^{2l+3}$$

High angular momentum dark positronium - hierarchically long lifetime for self-annihilation

In reality – can first transition to l=0 positronium and then self annihilate

Angular momentum stabilization

How do we prevent a high l state from transitioning to the ground state?

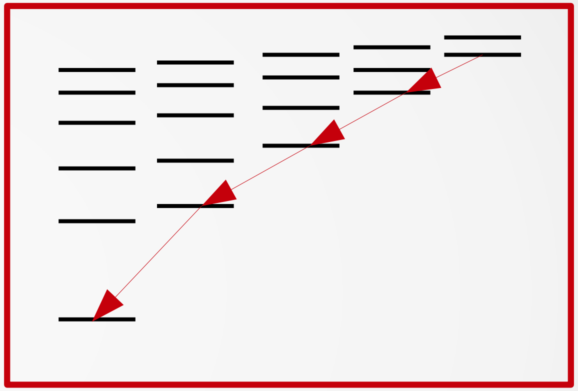
In Nature:

Δl=1 selection rule & phase space, e.g.

$\tau(4p \rightarrow 1s) \sim 14.7$ ns

$\tau(4f \rightarrow 3d \rightarrow 2p \rightarrow 1s) \sim 90$ ns

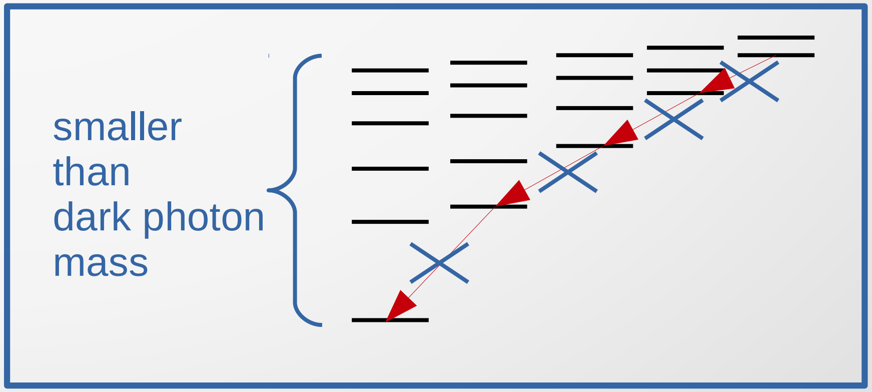
not enough for cosmology...



Rydberg states in Hydrogen

For our dark positronium:

make the dark photon
heavier than ΔE



Our dark positronium

Angular momentum stabilization - the model

$$\mathcal{L} = \underbrace{\bar{\chi} i \not{D} \chi - m_\chi \bar{\chi}\chi}_{\text{Dark Fermion}} \underbrace{- \frac{1}{4}\phi^{\mu\nu}\phi_{\mu\nu} + \frac{1}{2}m_\phi^2 \phi_\mu \phi^\mu}_{\text{light mediator – i.e., vector}}$$

$$\underbrace{-\frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\epsilon}{2}V_{\mu\nu}F^{\mu\nu}}_{\text{heavy dark photon}}$$

If the mediator is light enough, χ and $\bar{\chi}$ form positronium-like bound states ($\chi\bar{\chi}$)

Angular momentum stabilization - the model

We take the mass ranges to be:

To allow for the n_*th bound state, its radius must be smaller than the range of the mediator interaction.

$$\frac{1}{4}\alpha_\phi^2 m_\chi < m_\phi < \frac{1}{2n_*}\alpha_\phi m_\chi$$

To prevent spontaneous emission to the ground state, the mediator has to be heavier than the Rydberg energy.

$$2m_e,\ \frac{1}{2}\alpha_\phi m_\chi < m_V \lesssim m_\chi$$

To allow the decays $(\chi\bar{\chi}) \to VV \quad V \to e^+e^-$ and prevent spontaneous emission

The rate for self-annihilation

The self annihilation rate for the (n,l) bound state is:

$$\Gamma_{n,\ell\to V's} \sim \left(\frac{\alpha_\phi}{n}\right)^{2\ell+3} \alpha_V^{N_V} m_\chi$$

The α_φ^{2l} suppression is the same as in regular positronium

For $N_V=2$, $\alpha_\varphi = \alpha_V = 10^{-2}$ and $m_\chi = 1$ GeV, we have

$\tau_{n=10,l=9} = 10^{42}$ s cosmologically stable

$\tau_{n=7,l=6} = 10^{22}$ s problem with BBN?- not if tiny subcomponent

$\tau_{n=2,l=1} = 10^{-9}$ s prompt

$\boxed{\text{angular momentum stabilization!}}$

Viable SDDM

A small fraction < 10^{-2} of DM is in ($\chi\bar{\chi}$) bound states

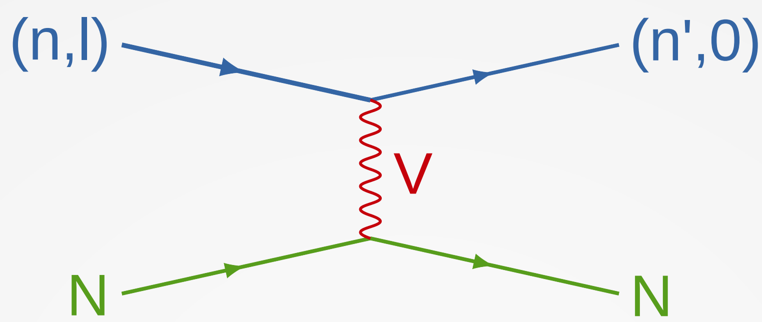
The (n~10, l~9) bound states are cosmologically stable, and their lifetime for self-annihilation/de-excitation is > 10^{41} s

when the bound states hit Earth, they can scatter through the V portal into (n~1,l~0) bound states, with lifetime << 10 s to go to VV

This is a realization of SDDM.

We will now estimate the scattering cross section $\langle\sigma v\rangle_{scat}$

(n,l)+N → (n',0)+N scattering rate



$$\frac{d\sigma_{\rm scatter}}{d|\vec{q}\,|^2} \simeq \frac{g_V^2 \epsilon^2 e^2}{4\pi v^2(|\vec{q}|^2 + m_V^2)^2} \times \underbrace{|F_D(|\vec{q}\,|)|^2}_{\text{DM form factor}} \times Z^2 \underbrace{F^2(|\vec{q}|)}_{\text{Woods-Saxon nuclear form factor}}$$

$$F_D(|\vec{q}\,|) = \int d^3\vec{x}\, \underbrace{\Psi^*(\vec{x})_{n'0}\Psi(\vec{x})_{nl}}_{\text{Hydrogenic wavefunctions}} \underbrace{\left[e^{i\vec{q}\cdot\vec{x}/2} - e^{-i\vec{q}\cdot\vec{x}/2}\right]}_{\text{V plane wave}}$$

(n,l)+N → (n',0)+N scattering rate

The momentum transfer for $\alpha_\varphi > v$ is sharply peaked around

$$|q| \sim \sqrt{2\mu\,\left(m_{(n,l)} - m_{(n',0)}\right)} \sim 2\alpha_\phi m_\chi \ll m_V$$

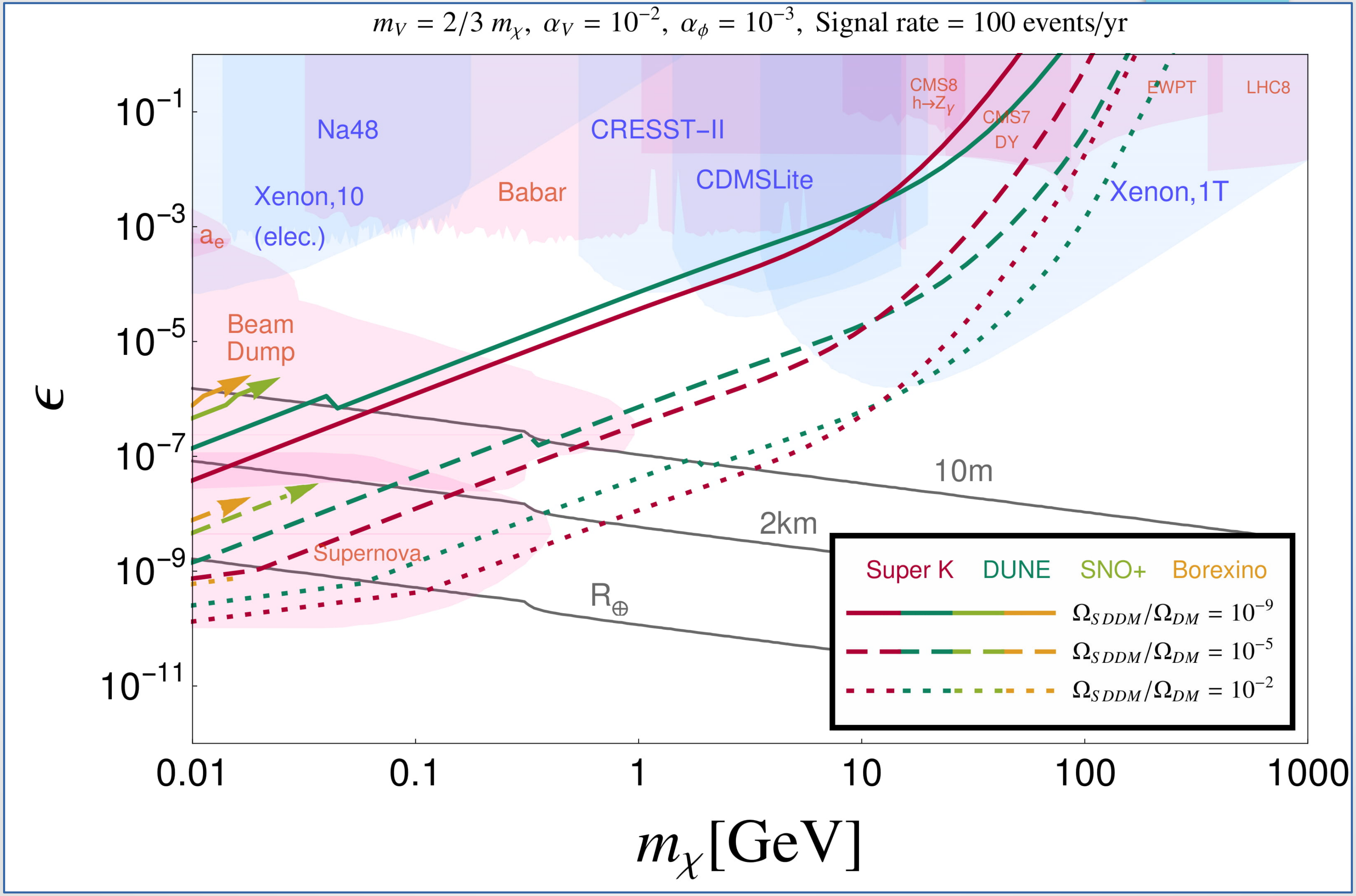
and the cross section simplifies to

$$\sigma_{\rm scatter} \simeq \frac{64\pi\epsilon^2\alpha_{\rm EM}\alpha_V\alpha_\phi m_\chi^2}{\pi v m_V^4} \times \left|F_D(2\alpha_\phi m_V^2)\right|^2 \times Z^2F^2(2\alpha_\phi m_V)$$

we can now calculate the 100 events/year discovery reach for neutrino detectors:

$$\boxed{\epsilon^2_{100} = \frac{100 \text{ events}}{T_{\rm year} \times nV \times n_{\chi\bar{\chi}}\,\langle\sigma v\rangle^{(\epsilon=1)}_{\rm scatter} \times {\rm Br}\,(V \to l^+l^-)}}$$

Discovery reach for angular momentum stabilization



Conclusions

SDDM is a new class of dark matter models in which the scattering of DM with the Earth induces its decay to SM.

The novelty in SDDM detection is that all of the DM rest mass gets converted to detectable signal.

We can search for 10 MeV SDDM in Neutrino detectors with a 5 MeV threshold, even when it's a tiny subcomponent.

Thank you!