

Direct Detection of Self-interacting Dark Matter

Hai-Bo Yu

University of California, Riverside

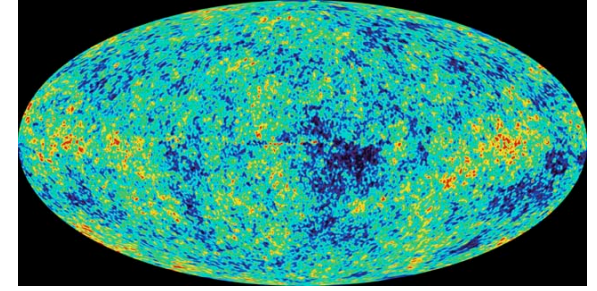
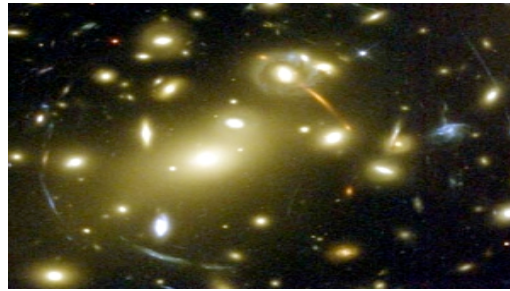
Kaplinghat, Tulin, HBY (1308.0618)+in preparation

TeV Particle Astrophysics 2013
August 26 - 29
Irvine, California, USA

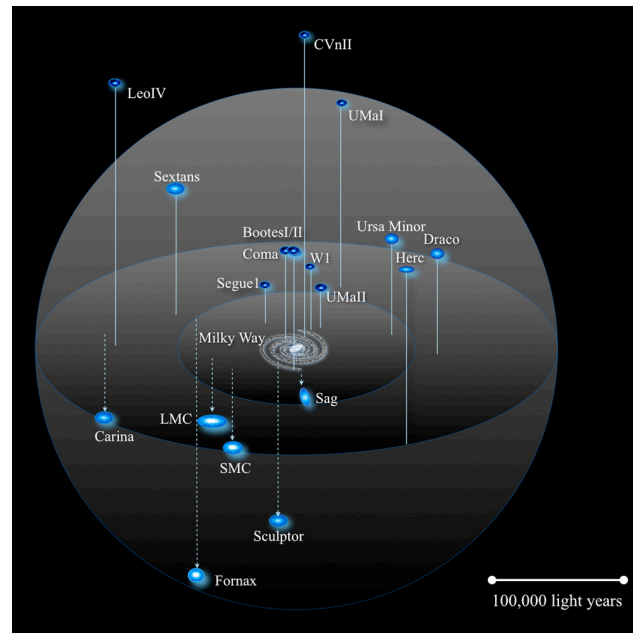


Collisionless Cold Dark Matter

- Large scales: great

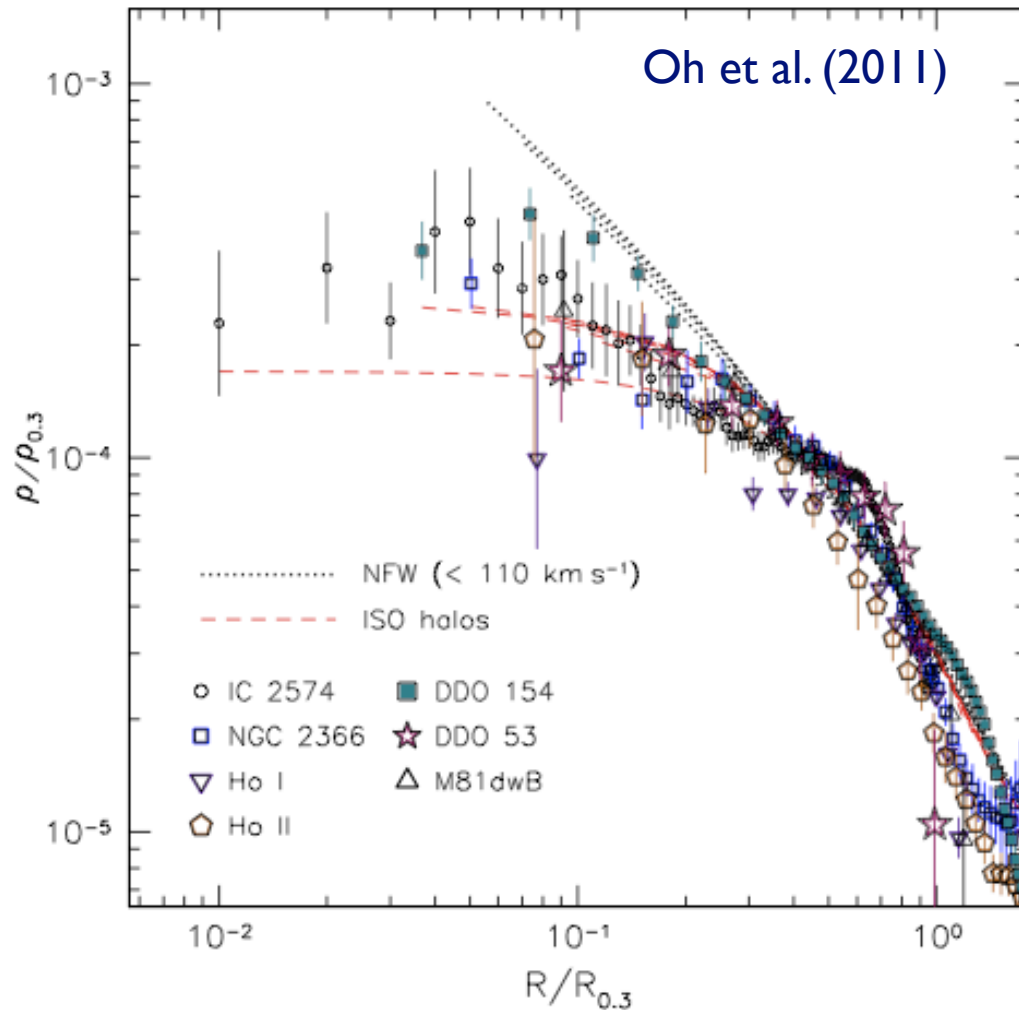


- Small scales (dwarf galaxies, subhalos): ?



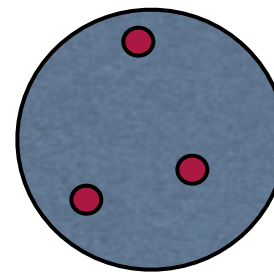
Core VS. Cusp Problem

- THINGS (dwarf galaxy survey)



density profile: $\rho \sim r^\alpha$
 predicted: $\alpha \sim -1$
 observed: $\alpha = -0.29 \pm 0.07$

- Observed central density shows cores
- Collisionless CDM-only simulations predict cusps



$$V \sim \sqrt{\frac{GM_{<}}{r}}$$

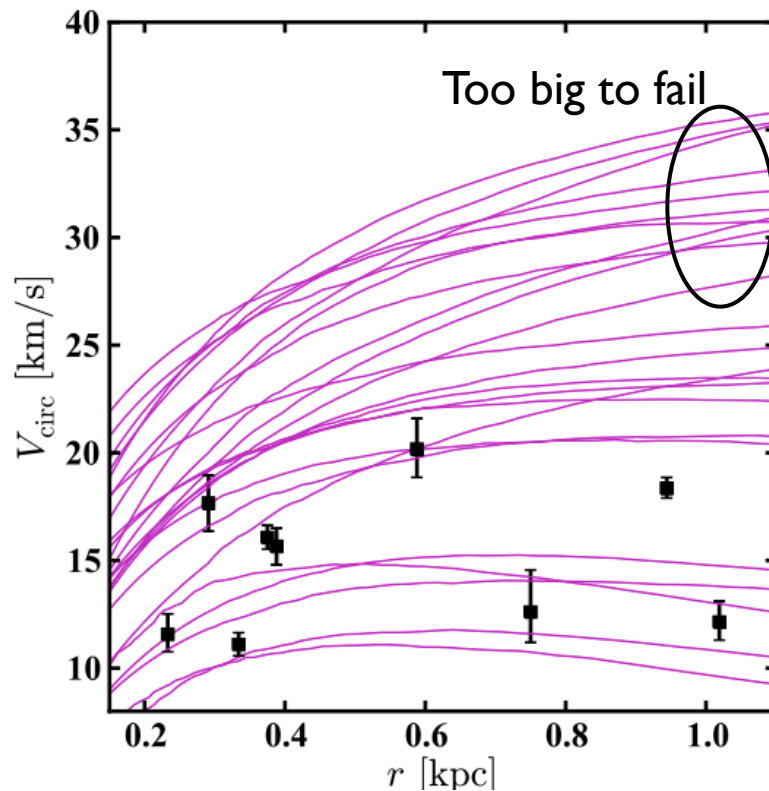
$$M_{<} \sim \int \rho r^2 dr$$

DM cores have been also observed in MW dwarfs and LSB

Too Big to Fail Problem

- Milky Way dwarf galaxies Boylan-Kolchin, Bullock, Kaplinghat (2011)

$$V \sim \sqrt{\frac{GM_{<}}{r}}$$



Biggest predicted satellites
from collisionless CDM
simulations

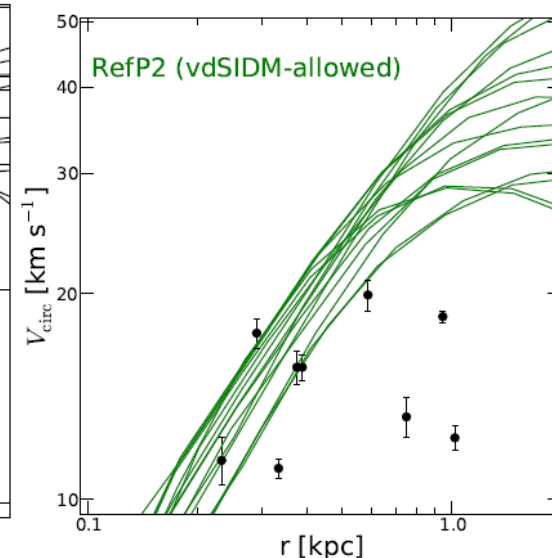
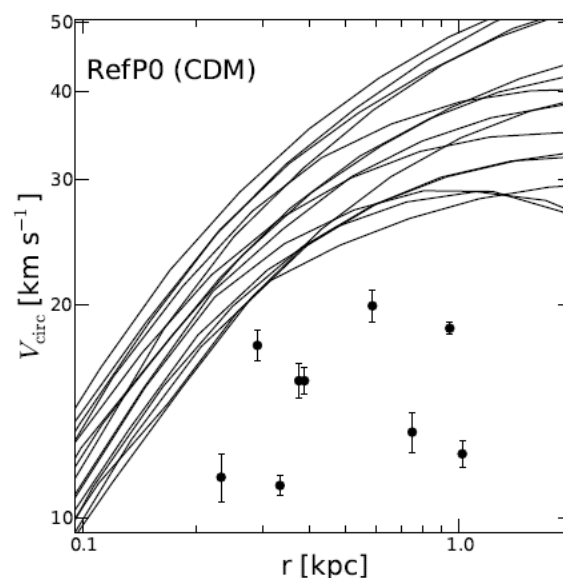
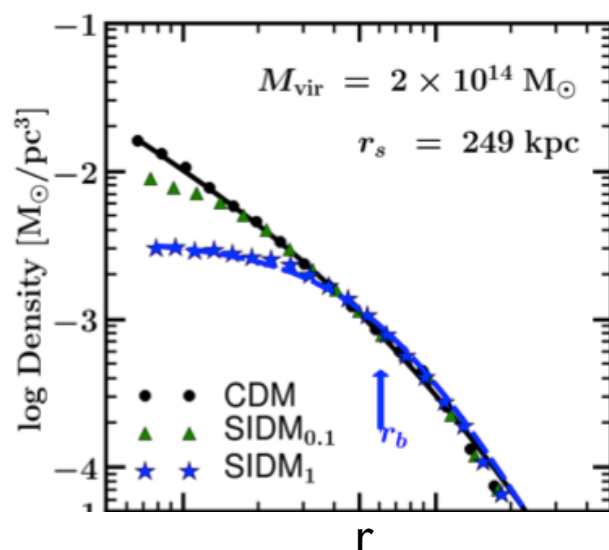
Brightest observed satellites
in the MW

- Most massive subhalos in collisionless CDM simulations are too dense to host observed galaxies in the Milky Way
- On the other hand, it is **easier** for stars to form in massive subhalos

Self-interacting Dark Matter

- These small scale anomalies can be solved if DM is strongly self-interacting

Spergel, Steinhardt (1999)



UCI group: Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas (2012); Peter, Rocha, Bullock, Kaplinghat (2012)

Harvard group: Vogelsberger, Zavala, Loeb (2012); Zavala, Vogelsberger, Walker (2012)

DM self-interactions lead to heat transfer and reduce central densities of DM halos

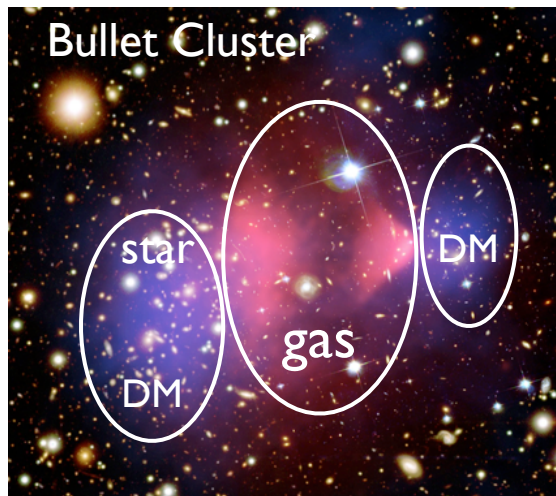
Astrophysics Summary

- Evidence for DM self-interactions on dwarf galaxy scales

$$\sigma/m_X \sim 0.1 - 10 \text{ cm}^2/\text{g} \text{ for } v \sim 10\text{-}30 \text{ km/s}$$

$$\Gamma \simeq n\sigma v = (\rho/m_X)\sigma v \sim H_0$$

- **Constraints:** Bullet Cluster; elliptical halo shapes



$$\sigma/m_X < 1 \text{ cm}^2/\text{g} \text{ for } 3000 \text{ km/s (cluster); } v \sim 300 \text{ km/s (group)}$$

Peter, Rocha, Bullock, Kaplinghat (2012)

Challenges

- A really large scattering cross section! a nuclear-scale cross section

$$\sigma \sim 1 \text{ cm}^2 (m_\chi/\text{g}) \sim 2 \times 10^{-24} \text{ cm}^2 (m_\chi/\text{GeV})$$

$$\text{For a WIMP: } \sigma \sim 10^{-38} \text{ cm}^2 (m_\chi/100 \text{ GeV})$$

SIDM indicates a new mass scale

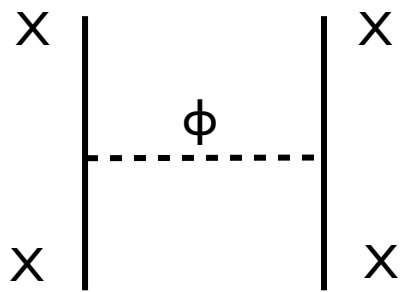
- How to avoid the constraints on large scales?

$$\sigma/m_\chi < 1 \text{ cm}^2/\text{g} \text{ for } v \sim 300 \text{ km/s (group), } 3000 \text{ km/s (cluster)}$$

In particular, if $\sigma \sim \text{constant}$

Spergel, Steinhardt (1999)

Particle Physics of SIDM

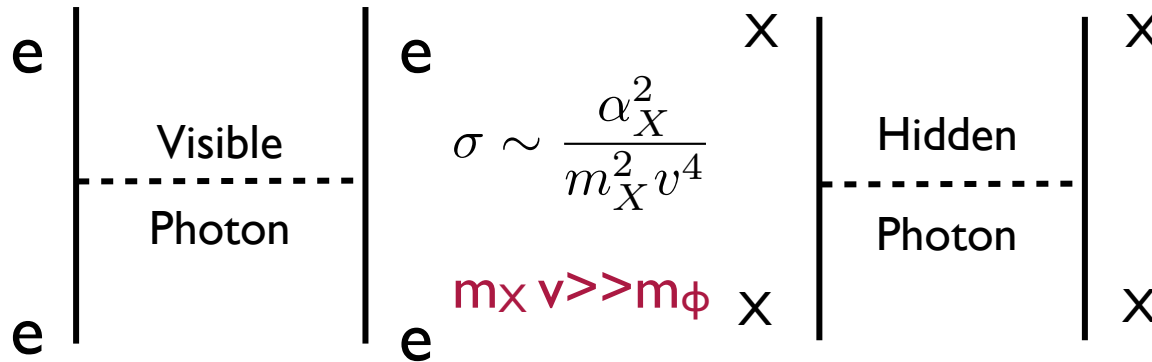


- SIDM indicates light mediators

$$\sigma \approx 5 \times 10^{-23} \text{ cm}^2 \left(\frac{\alpha_X}{0.01} \right)^2 \left(\frac{m_X}{10 \text{ GeV}} \right)^2 \left(\frac{10 \text{ MeV}}{m_\phi} \right)^4$$

in the perturbative and small velocity limit

- With a light mediator, DM self-scattering is velocity-dependent (like Rutherford scattering)

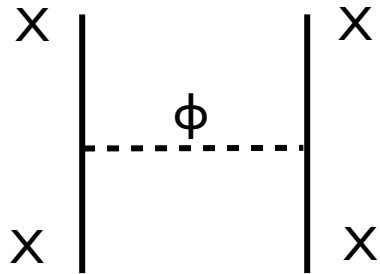


Feng, Kaplinghat, Tu, HBY (2009)
 Feng, Kaplinghat, HBY (2009)
 Buckley, Fox (2009)
 Loeb, Weiner (2010)
 Tulin, HBY, Zurek (2012)(2013)

- DM is self-scattering on small scales ($v \sim 30 \text{ km/s}$)
- DM is collisionless on large scales ($v \sim 3000 \text{ km/s}$)

A Simplified SIDM Model

- DM is a Dirac fermion; Mediator is a vector
- DM self-interactions with a Yukawa potential



$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r} \quad \alpha_X = g_X^2 / (4\pi)$$

$$\sigma_T = \int d\Omega (1 - \cos \theta) \frac{d\sigma}{d\Omega}$$

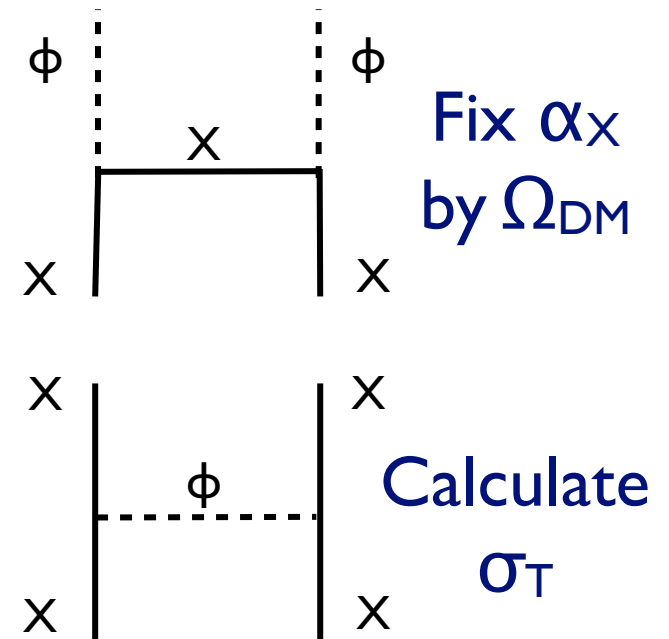
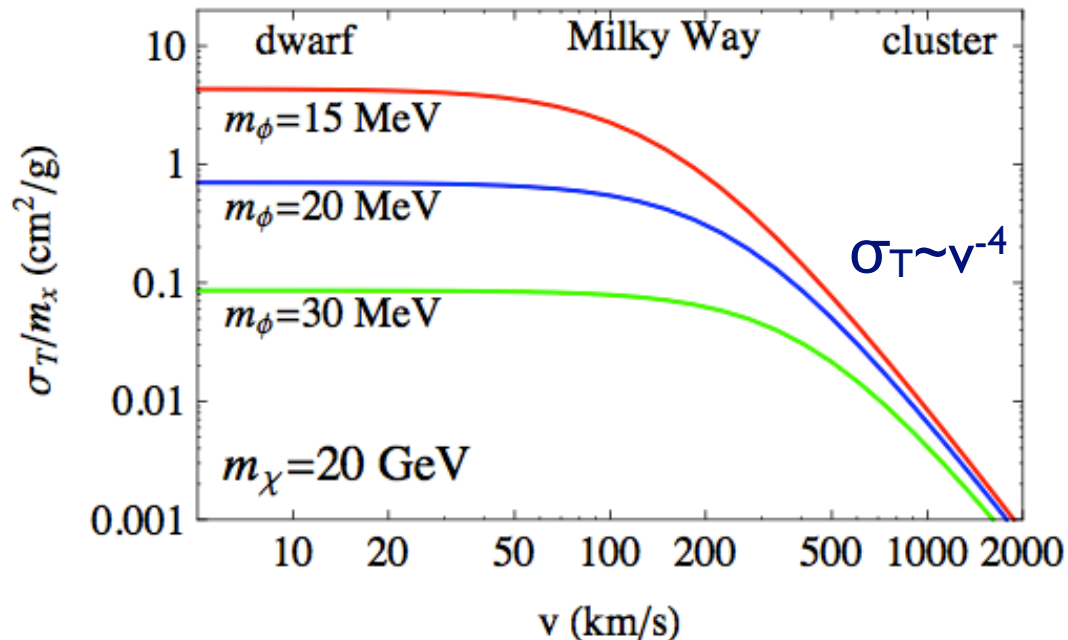
Other possibilities: Bellazzini, Cliche, Tanedo (2013) Boddy's talk

- Map out the parameter space (m_X, m_ϕ, α_X)
 - Solve small scale anomalies
 - Avoid constraints on large scales
 - Get the relic density right

Tulin, HBY, Zurek (2012) (2013)

Velocity-Dependence

- DM self-interactions are typically suppressed on large scales

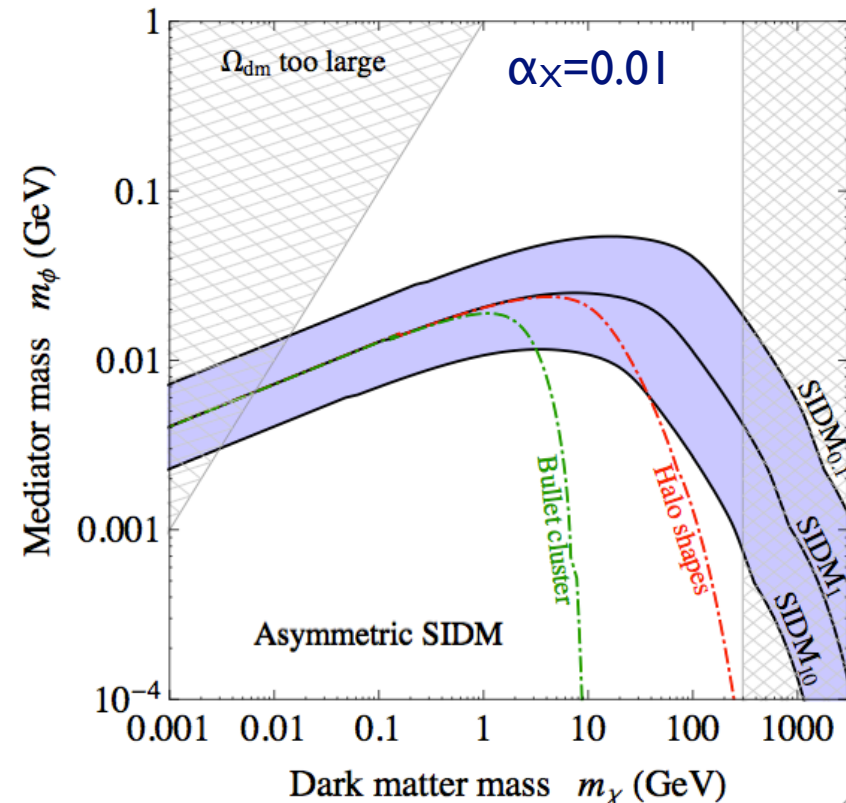
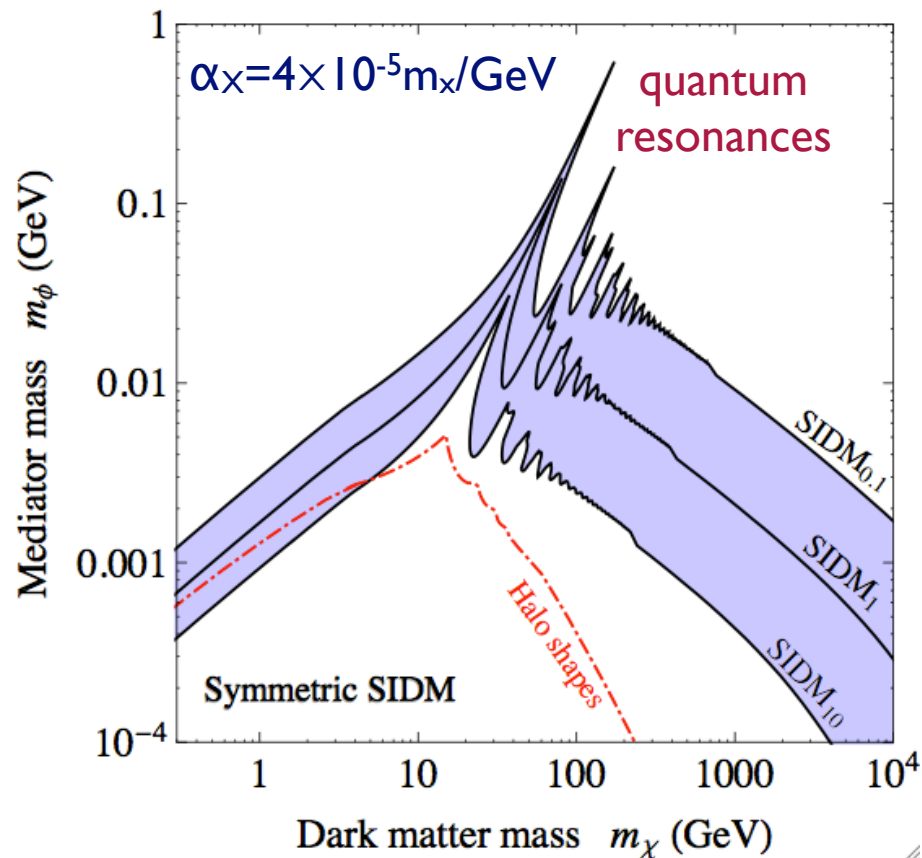


$\sigma/m_\chi \sim 0.1 - 10$ cm²/g for $v \sim 10-30$ km/s

$\sigma/m_\chi < 1$ cm²/g for $v \sim 300$ km/s (group), 3000 km/s (cluster)

SIDM Parameter Space

- Shaded region: Explain small scale anomalies

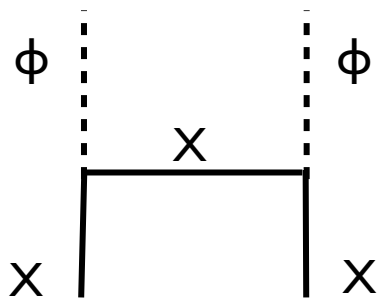
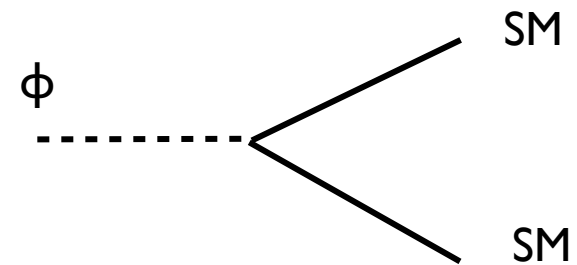


dw: dwarf (30 km/s); halo shapes: (300 km/s); cl: cluster (3000 km/s)

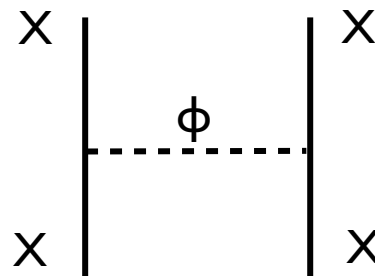
- SIDM predicts a **1-100 MeV** light force carrier
- Halo shape and Bullet Cluster constraints are sensitive to **light** SIDM

Light Mediators in Dark Sector

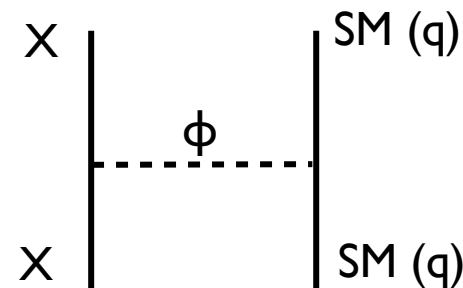
- The mediator may dominate the energy density of the Universe
 - Decays to SM particles
 - Decays to dark “neutrinos”
 - Make hidden sector very cold (Boddy’s talk)
 - The mediator decays before BBN
 - Maximal life for ϕ is ~ 1 second
 - **Minimal** coupling between the dark sector and the SM
 - A **lower** bound on direct detection cross section
- A super model!**



DM relic density



DM self-scattering



DM direct detection

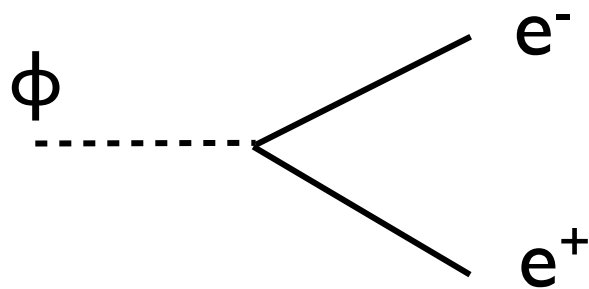
Portals to the Dark Sector

- Vector mediator $\phi \cdots \cdots X \cdots \cdots \gamma (Z)$

- Focus on kinetic mixing case

$$\frac{\epsilon_\gamma}{2} \phi_{\mu\nu} F^{\mu\nu} \quad \text{Holdom (1986)}$$

- The mediator only decays to electron/positron pairs



$$m_\phi \sim 1-100 \text{ MeV}$$

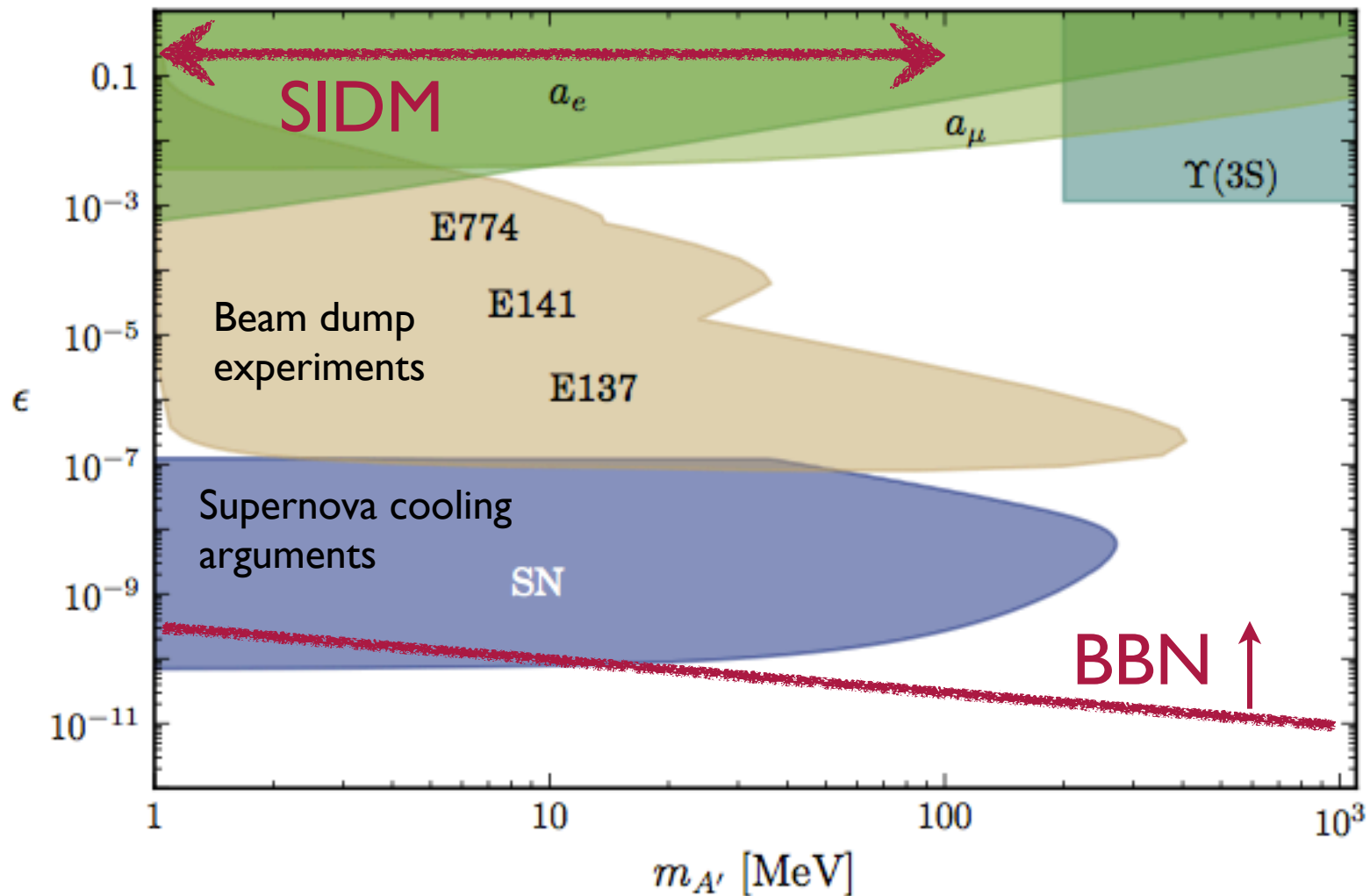
lifetime less than ~ 1 second

$$\epsilon \gtrsim 10^{-10} \sqrt{10 \text{ MeV} / m_\phi}$$

DD cross section:

- suppressed by the tiny coupling
- enhanced by the small mediator mass

Constraints on Kinetic Mixing

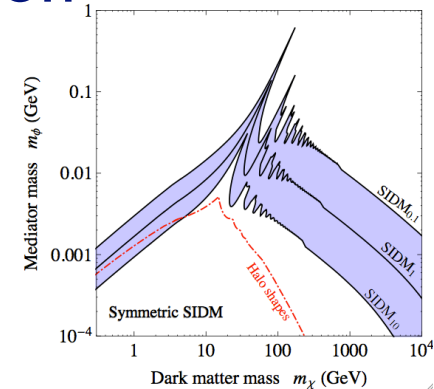
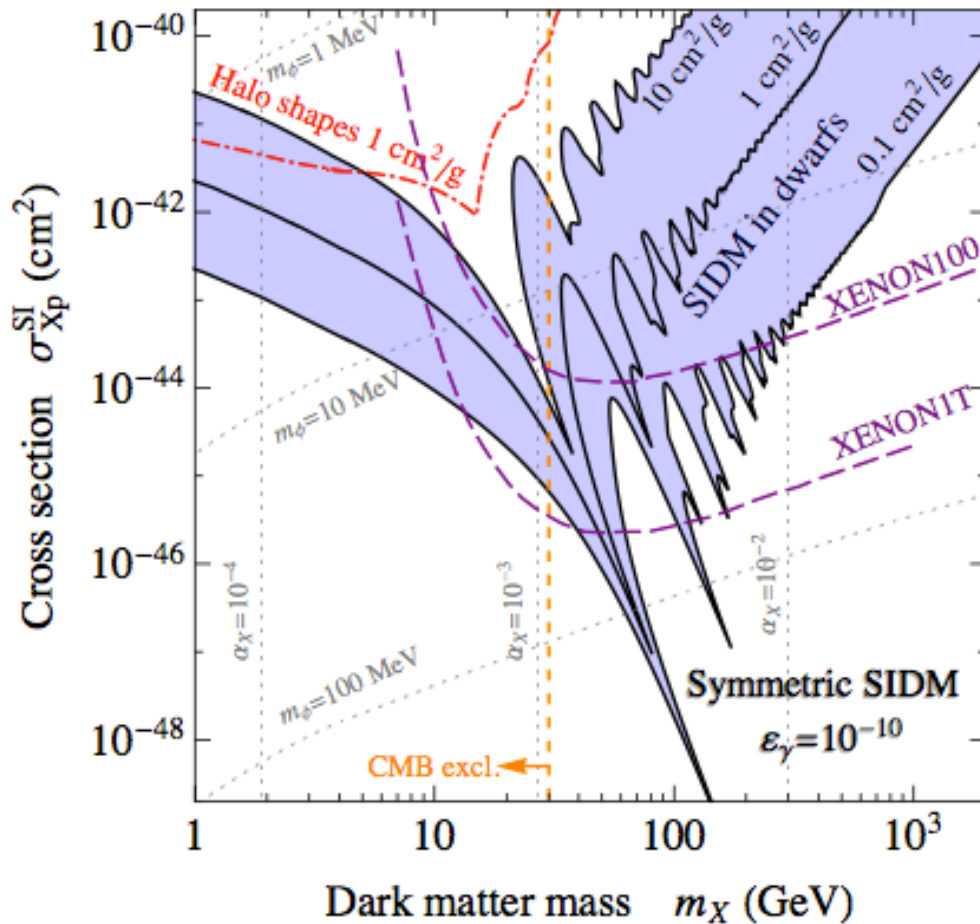


Bjorken, Essig, Schuster, Toro (2009)

Dent, Ferrer, Krauss (2012)

Direct Detection of SIDM

- The lower limit of direct detection cross section



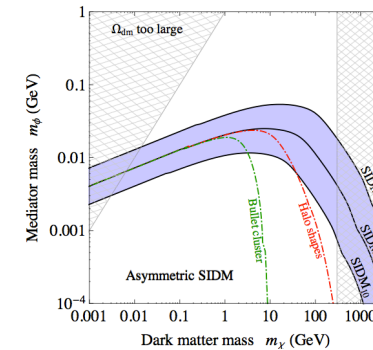
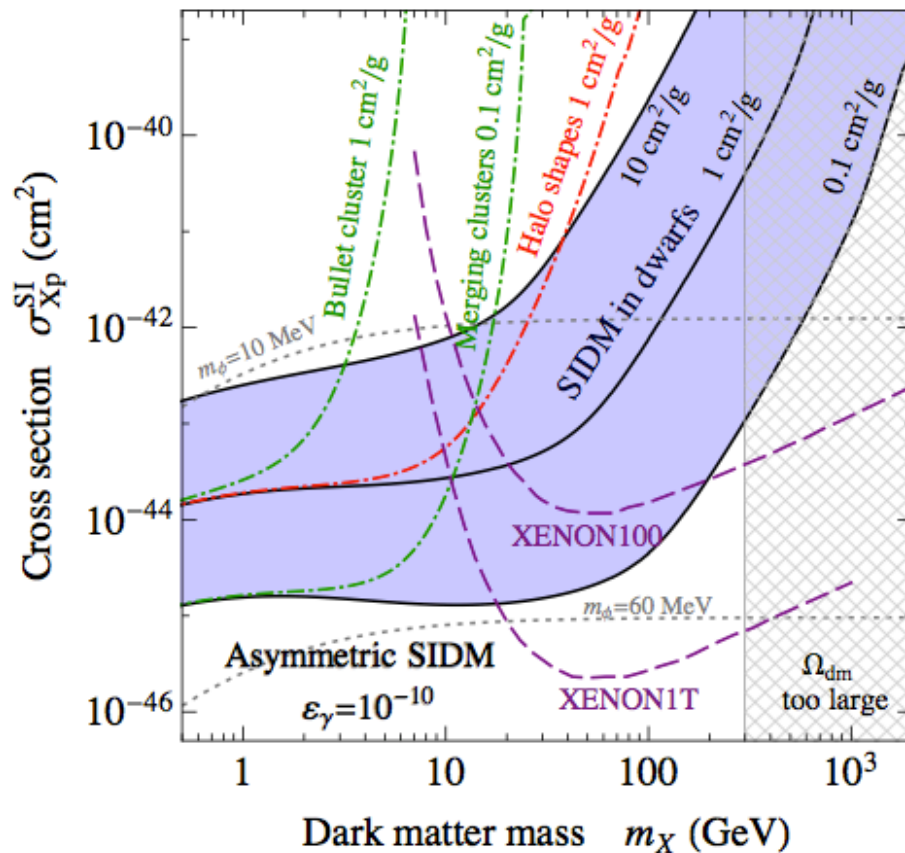
- XENON100 excludes SIDM with a mass **larger** than 300 GeV
- Astrophysical constraints are sensitive to **light** SIDM
- They **complement** each other

Future XENONIT, SuperCDMS, LUX, PandaX can reach ~5 GeV SIDM

$$\sigma_{Xp}^{\text{SI}} \approx 1.5 \times 10^{-24} \text{ cm}^2 \times \varepsilon_{\gamma}^2 \times \left(\frac{\alpha_X}{10^{-2}} \right) \left(\frac{m_{\phi}}{30 \text{ MeV}} \right)^{-4}$$

Direct Detection of SIDM

- The lower limit of direct detection cross section



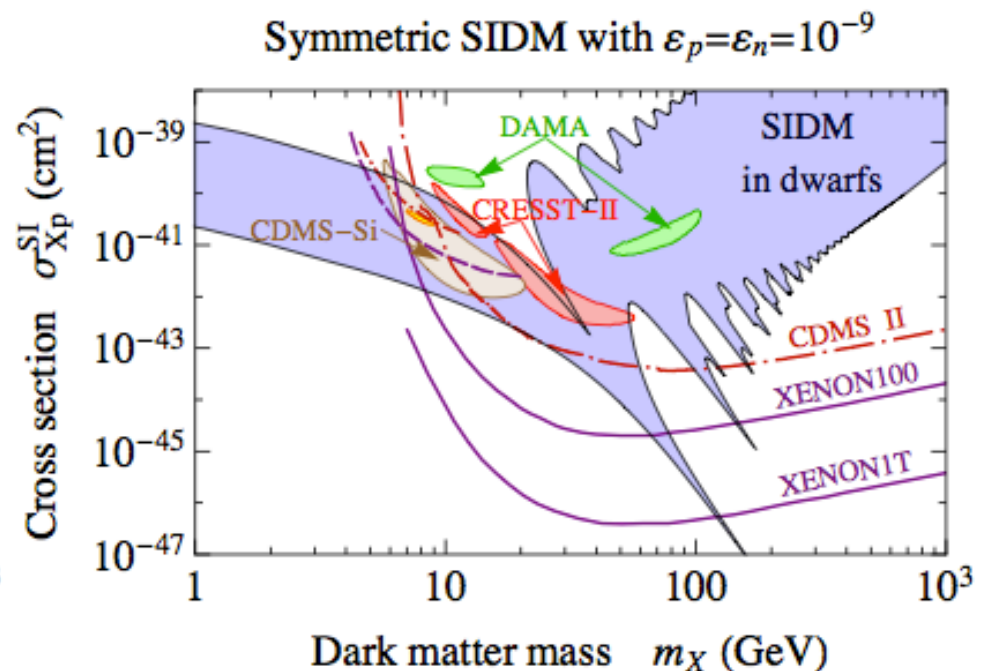
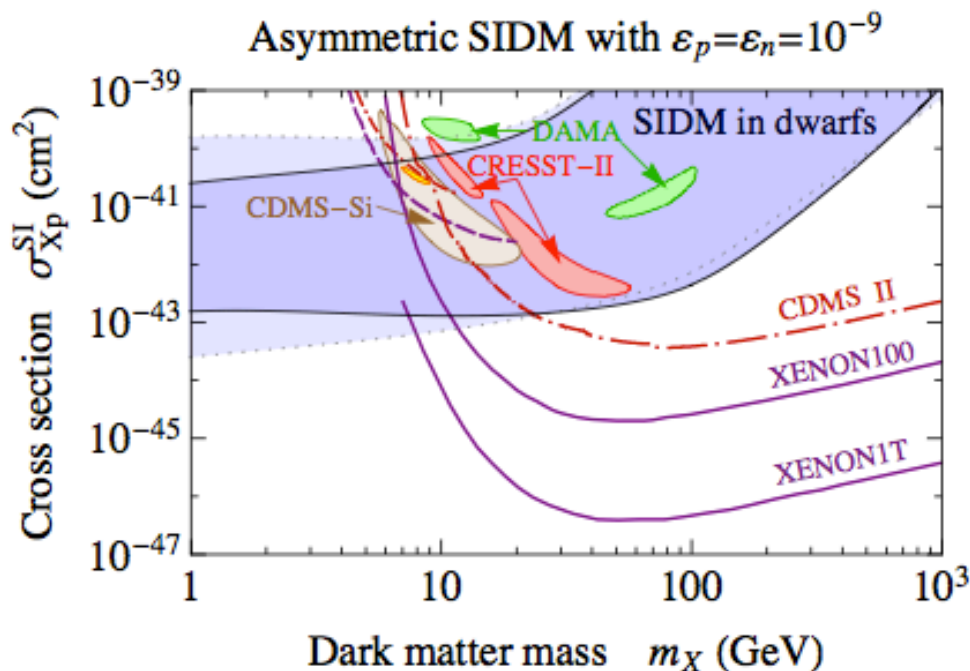
- XENON100 excludes SIDM with a mass larger than 200 GeV
- No CMB constraints

Direct detection experiments provide **complementary** searches for SIDM candidates

$$\sigma_{Xp}^{\text{SI}} \approx 1.5 \times 10^{-24} \text{ cm}^2 \times \varepsilon_\gamma^2 \times \left(\frac{\alpha_X}{10^{-2}} \right) \left(\frac{m_\phi}{30 \text{ MeV}} \right)^{-4}$$

Direct Detection of SIDM

- Explain signals?

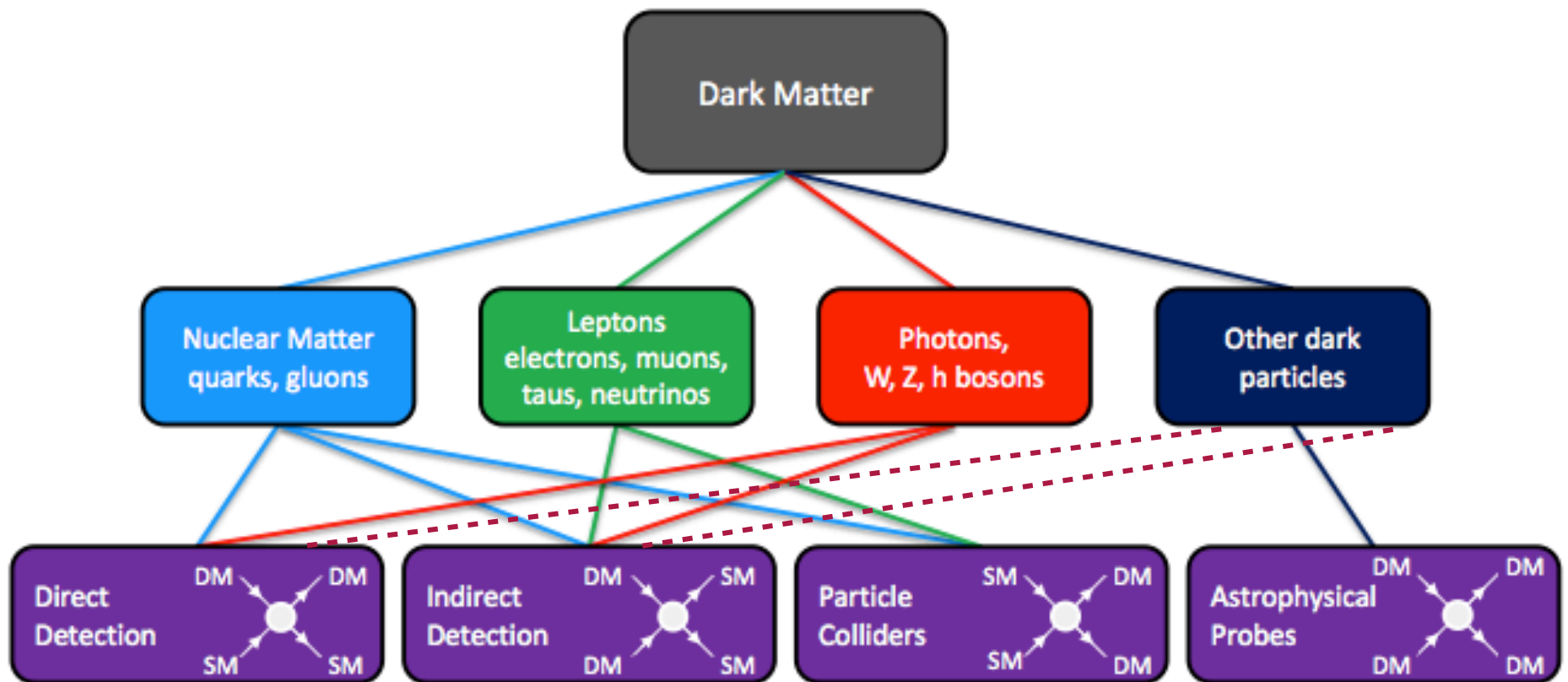


Kaplinghat, Tulin, HBY in preparation

Conclusions

- SIDM predicts the existence of a 1-100 MeV mediator
- Current and future direct detection experiments are exploring the “BBN parameter space”
- Astrophysical observations (halo shapes, the Bullet Cluster) probe light SIDM
- Direct detection experiments are more sensitive to heavy SIDM
- They are complement each other in the search for SIDM candidates

Complementarity



Snowmass report I305.I605