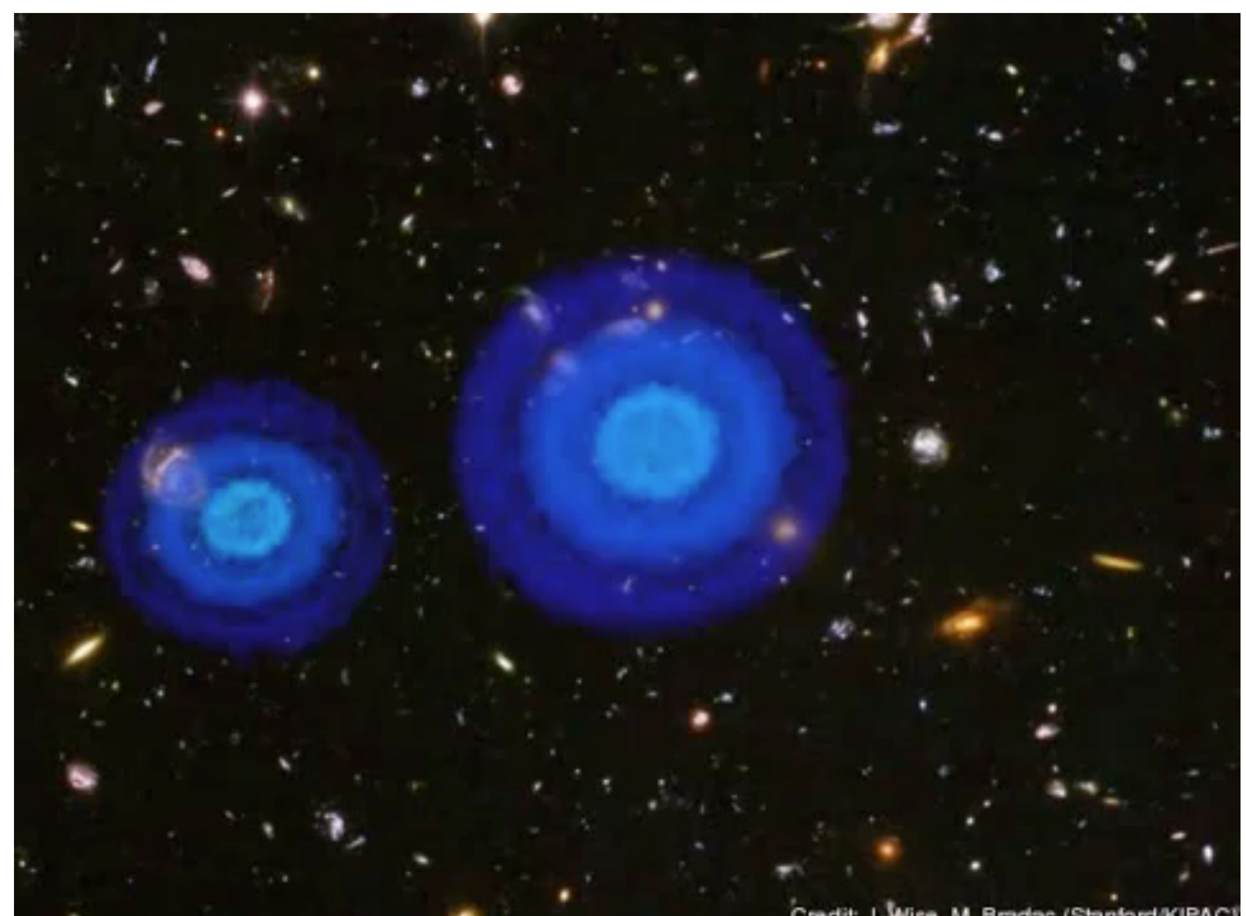
Dark Matter Below the Higgs Scale

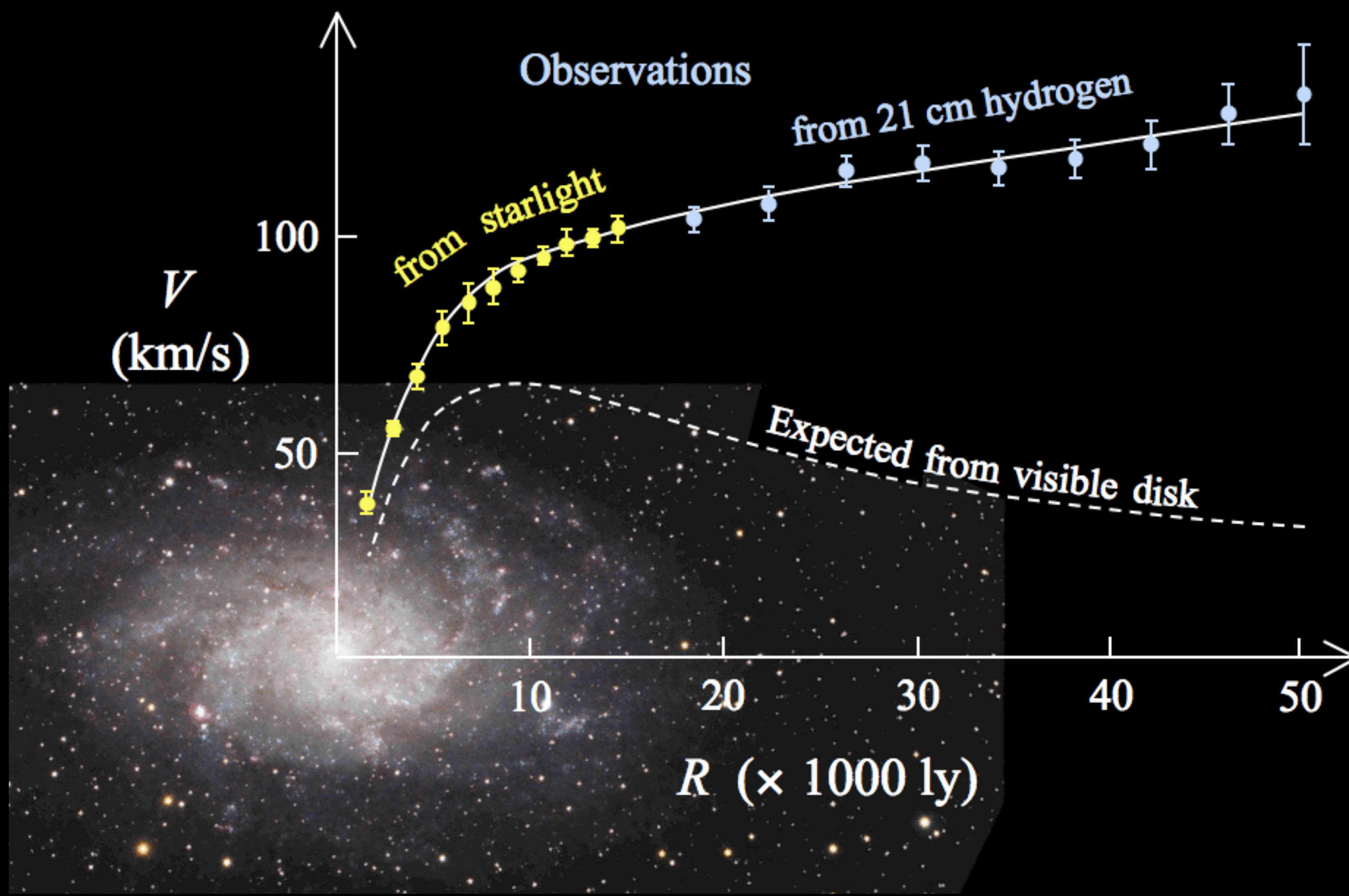
Josh Ruderman
(NYU, CERN)

@DESY, 4/4/2018



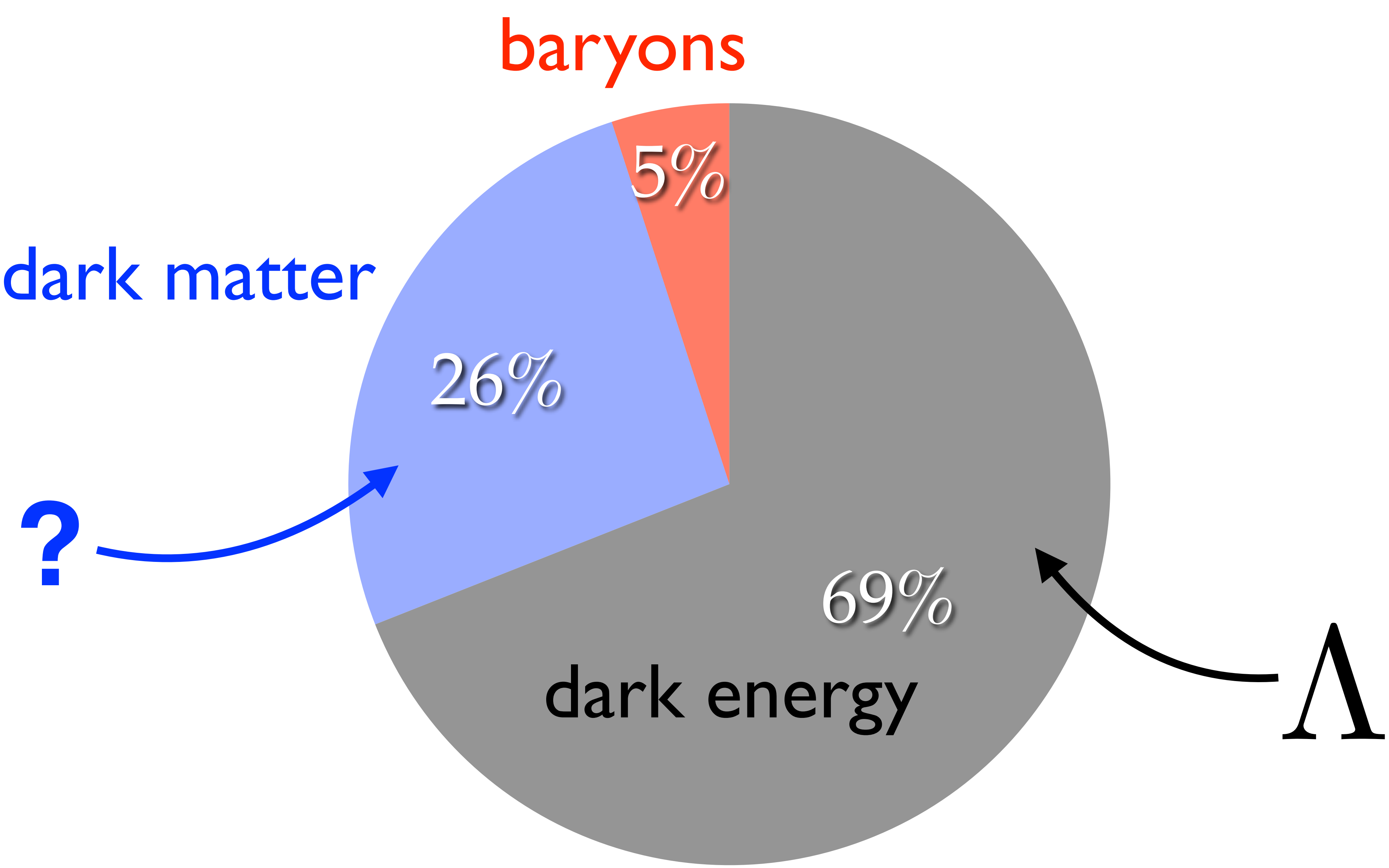
Galactic Rotation Curves

M33

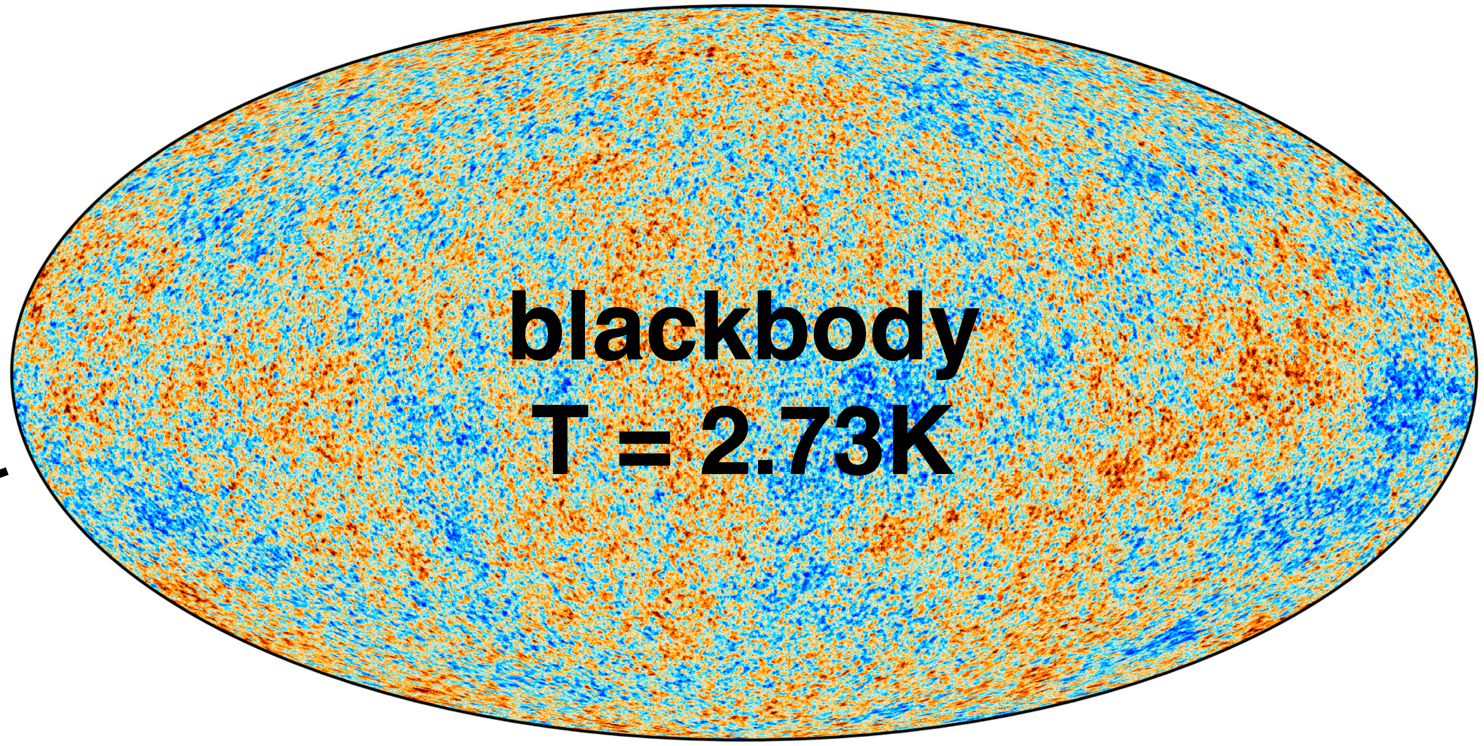


- Corbelli, Salucci, MNRAS **311**, 411 (2000).

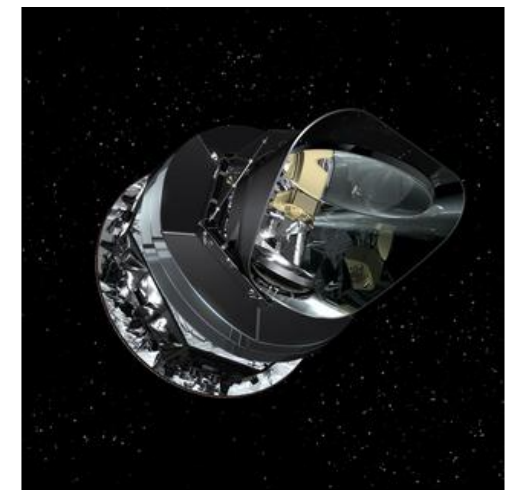
Energy Budget of our Universe



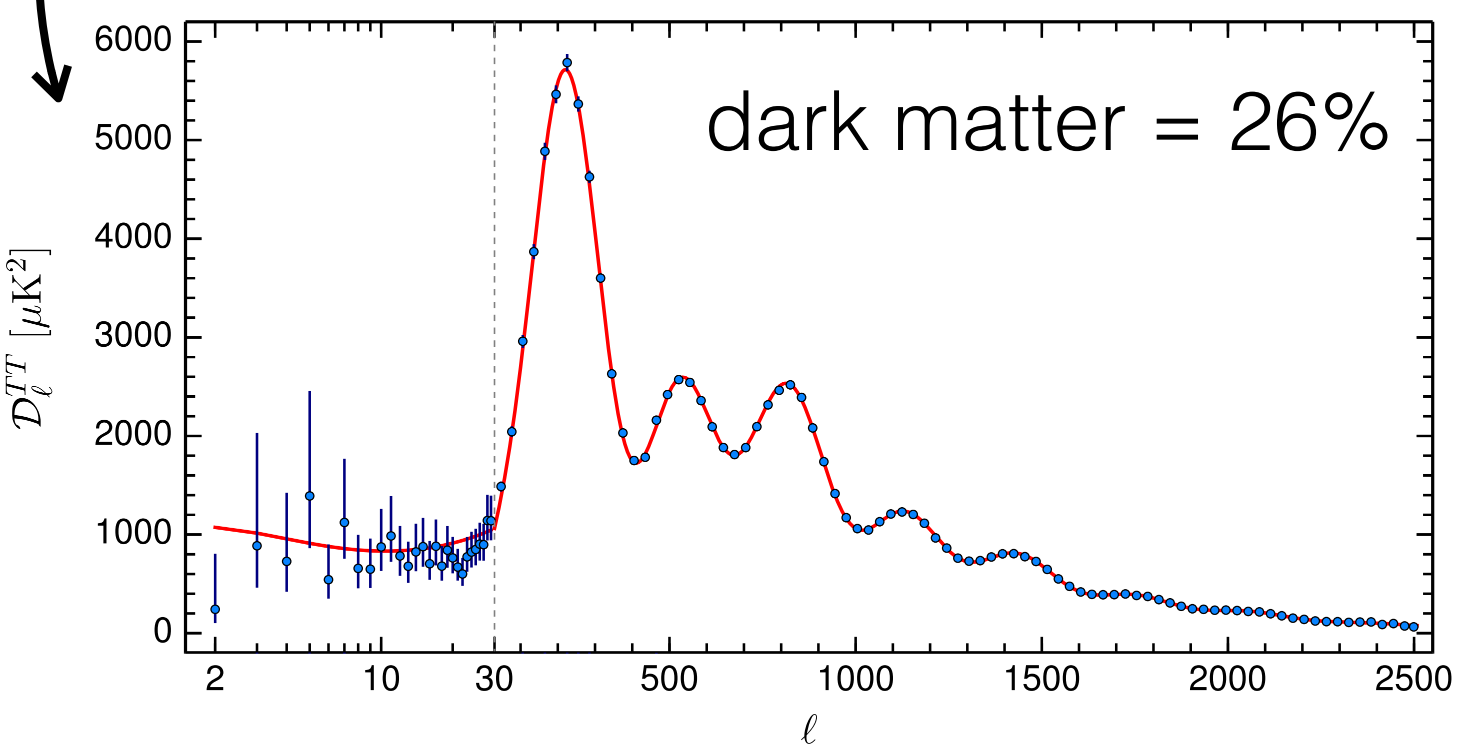
Cosmic Microwave Background

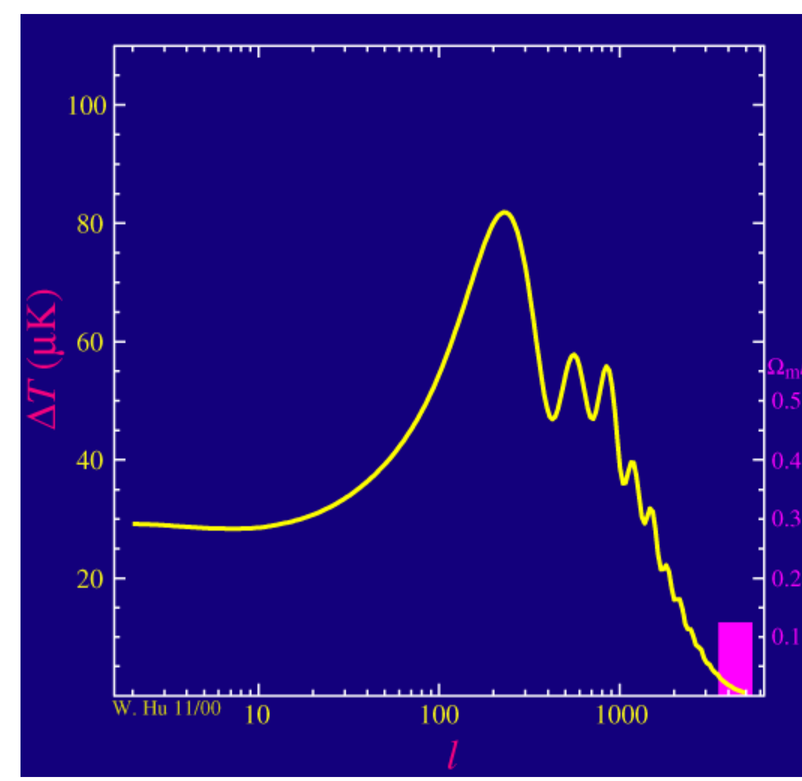


Planck Satellite



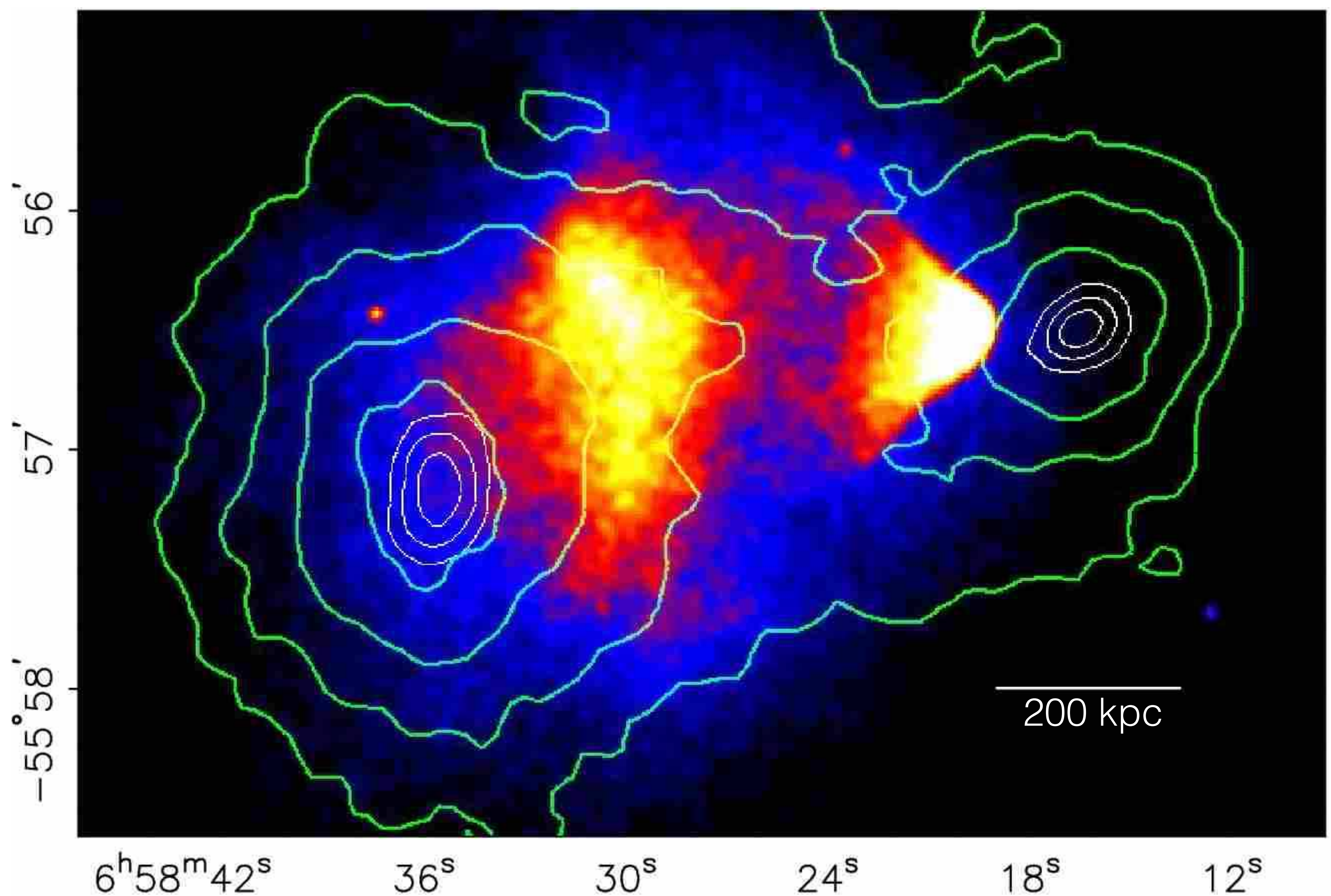
power spectrum





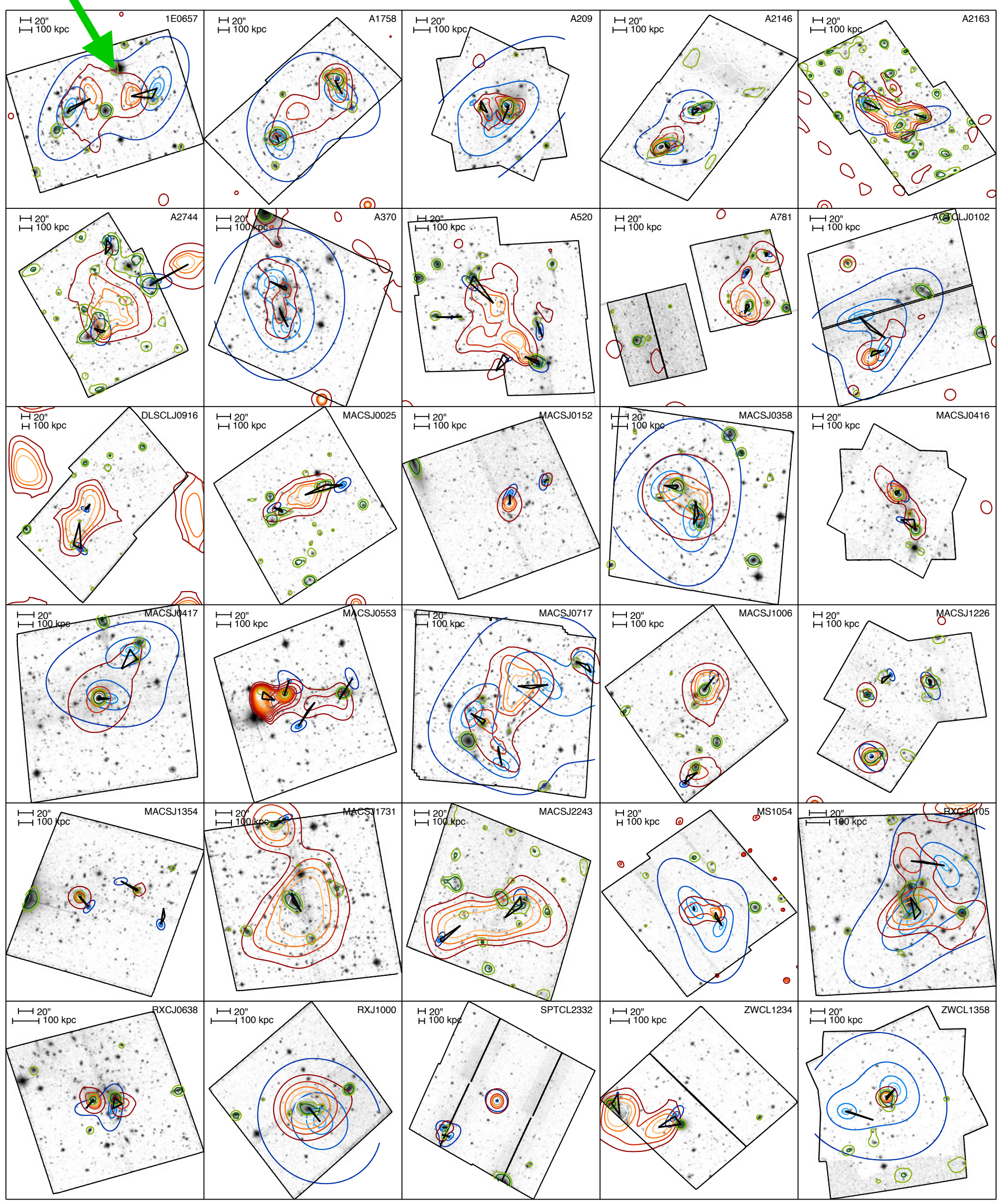
Wayne Hu

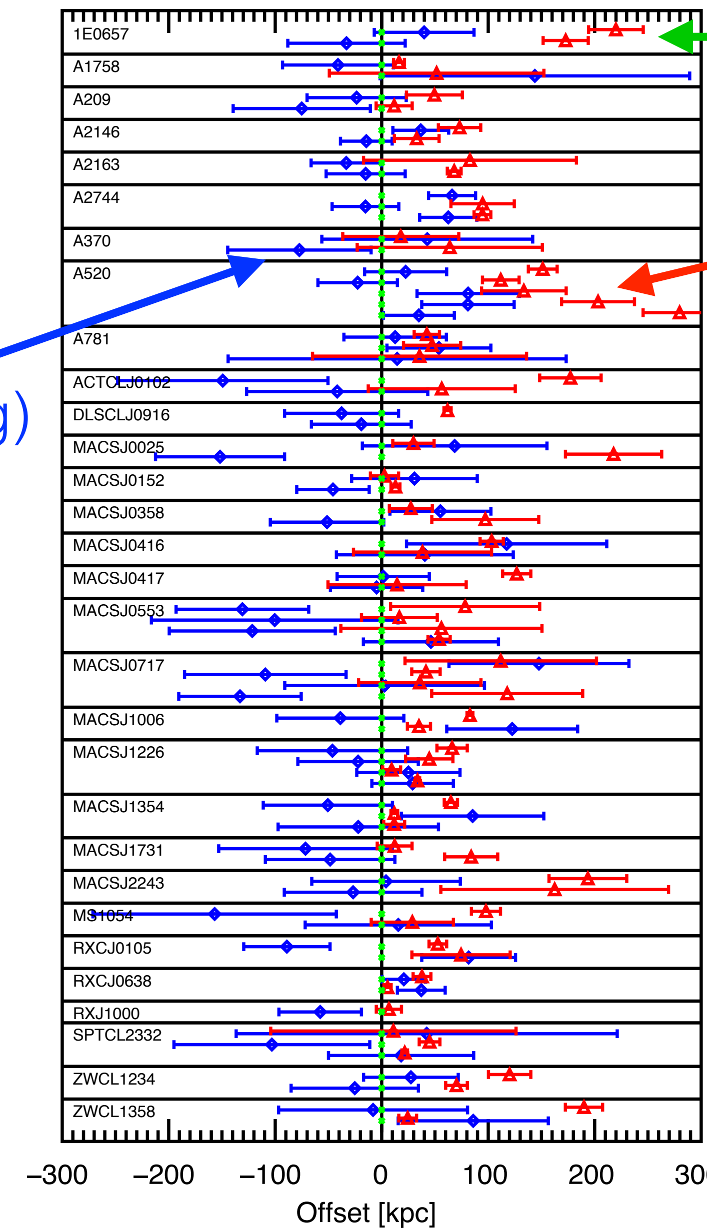
Bullet Cluster



- Clowe *et al.*, Astrophys. J. **648**, L109 (2006).

Cluster Merger Zoo

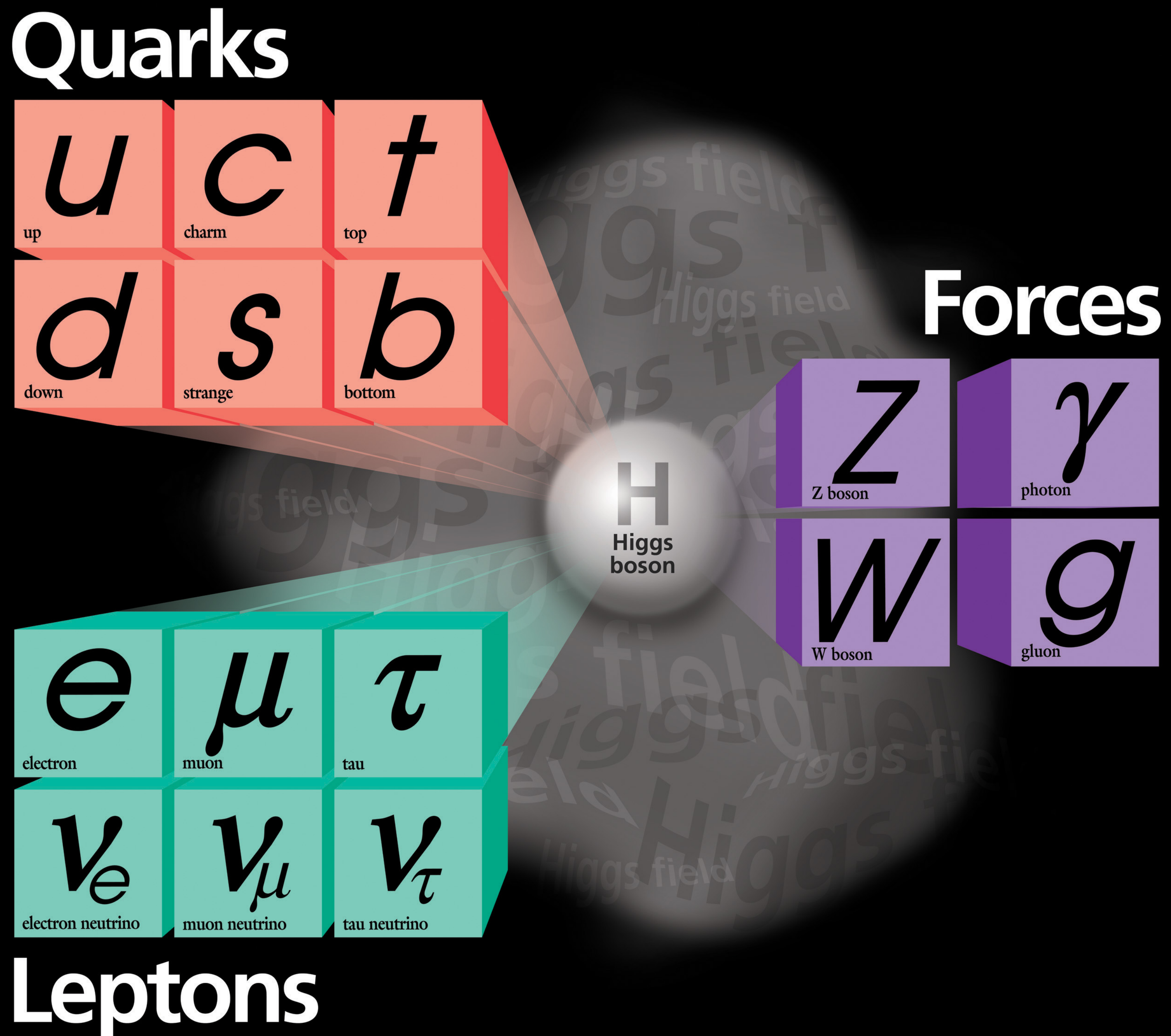




dark matter: 7.6σ

- Harvey *et al.*, Science **347**, 1462 (2015).

Standard Model



Particle Dark Matter

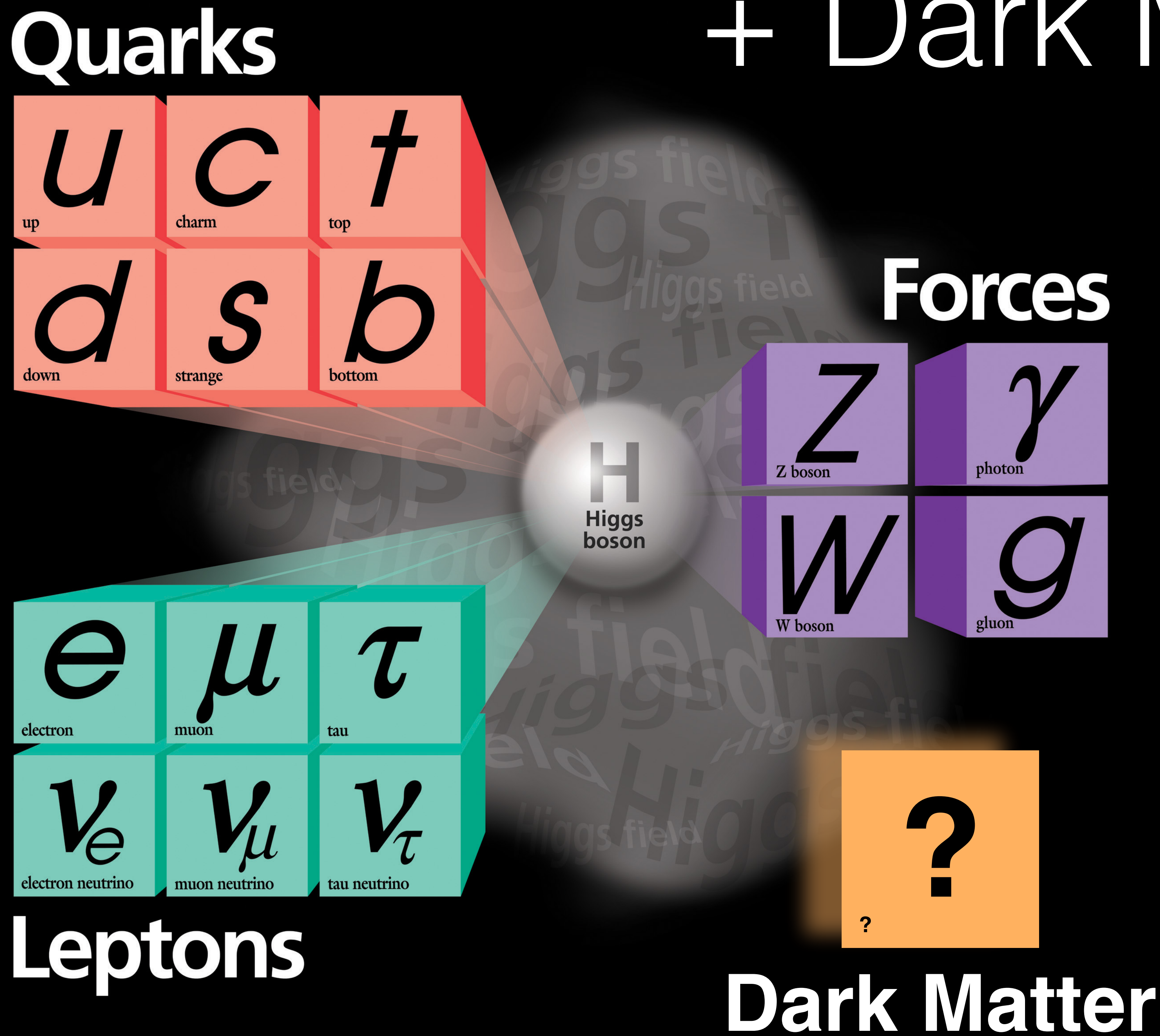
- DM could be made of particles that are:

    1) stable (cosmologically)
    2) electrically neutral
    3) non-relativistic when galaxies form

- DM is not a SM particle*

*maybe a collection of SM particles, like primordial black holes

Standard Model
+ Dark Matter



Mass of Particle Dark Matter

10^{-22} eV

10^{19} GeV

m_{DM}

de Broglie wavelength = 1 kpc

black holes

50 decades!

plan

1. Dark Matter at the Higgs Scale

h DM

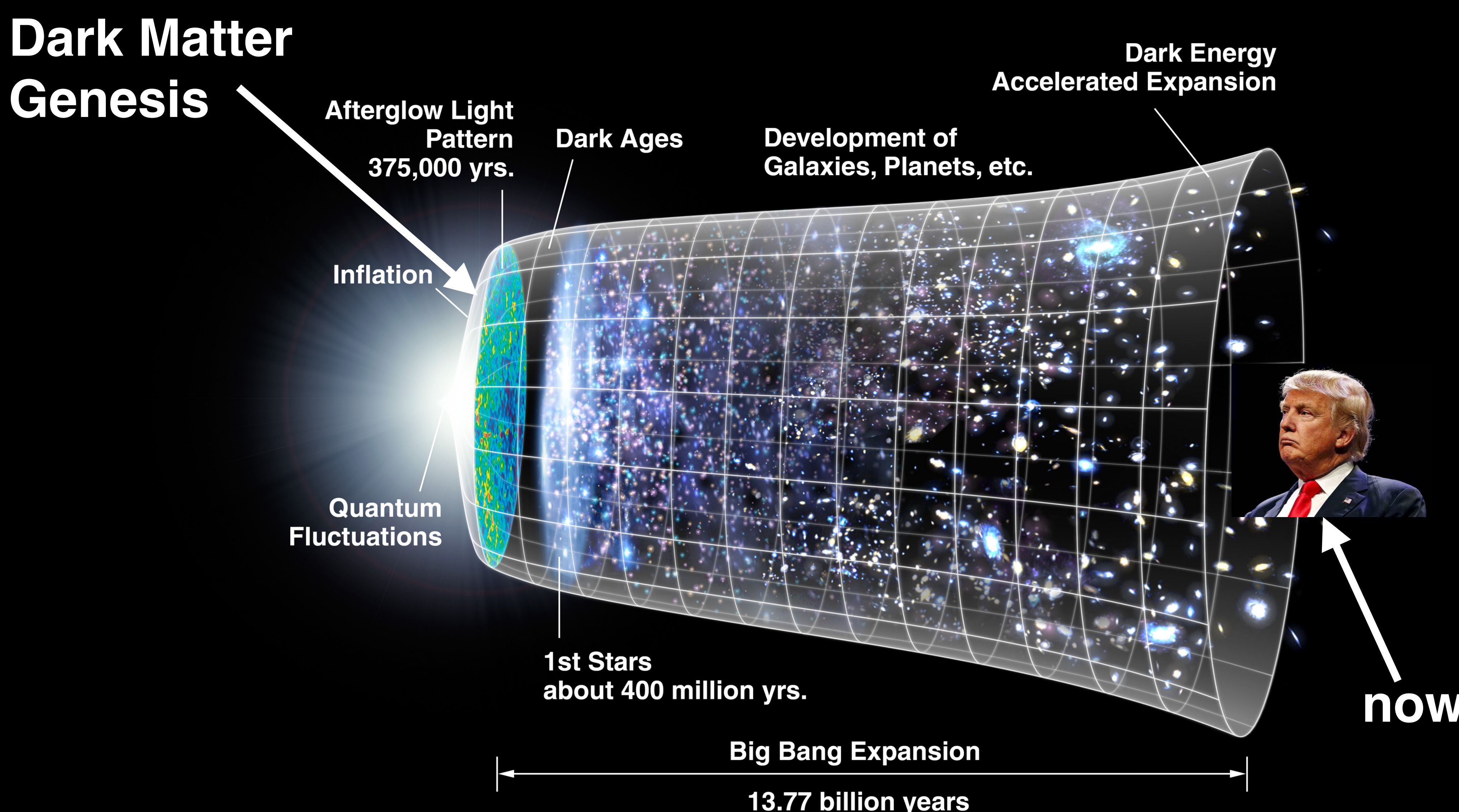
2. Experiment vs. Dark Matter

3. Dark Matter Below the Higgs Scale

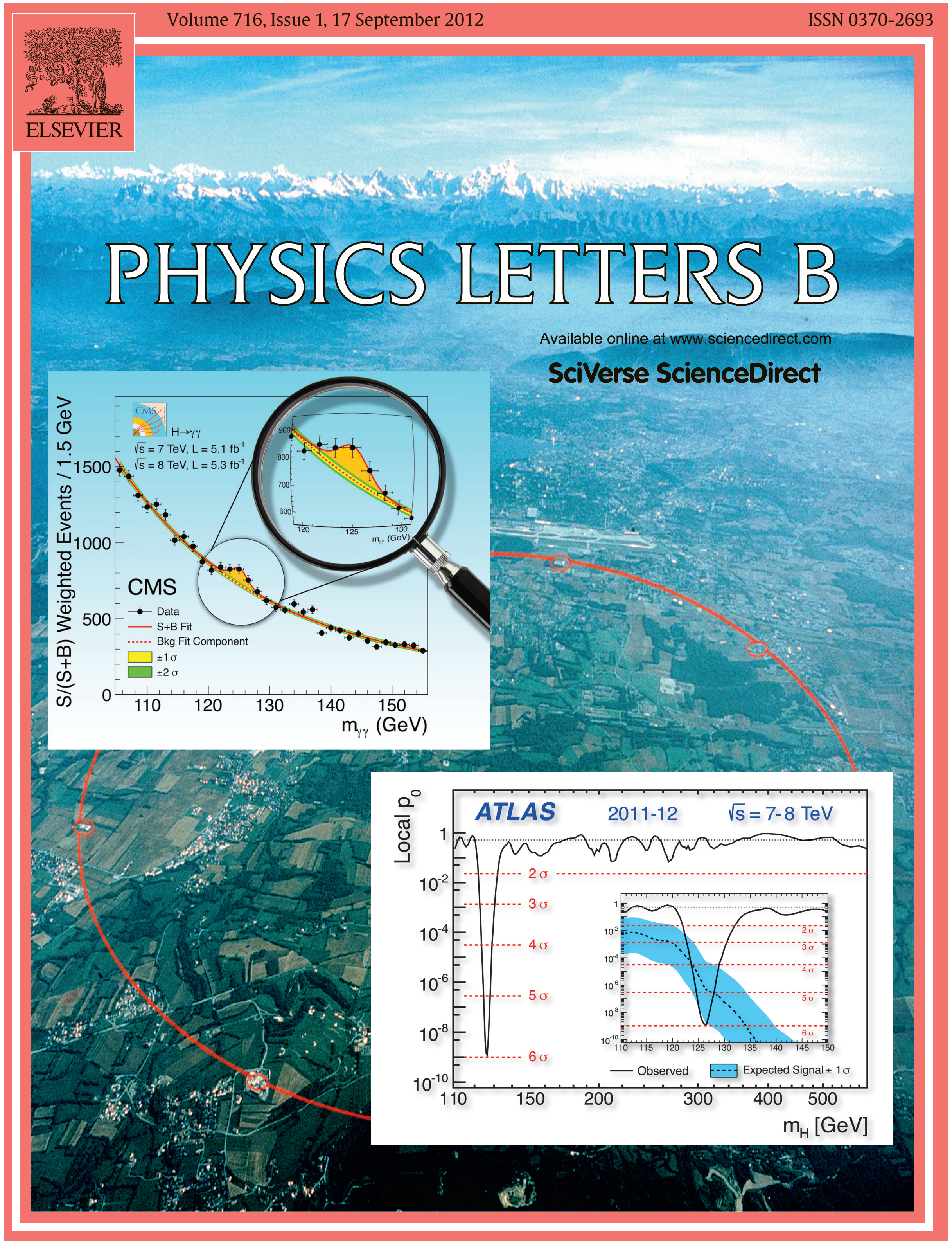
h

DM

1. Dark Matter at the Higgs Scale

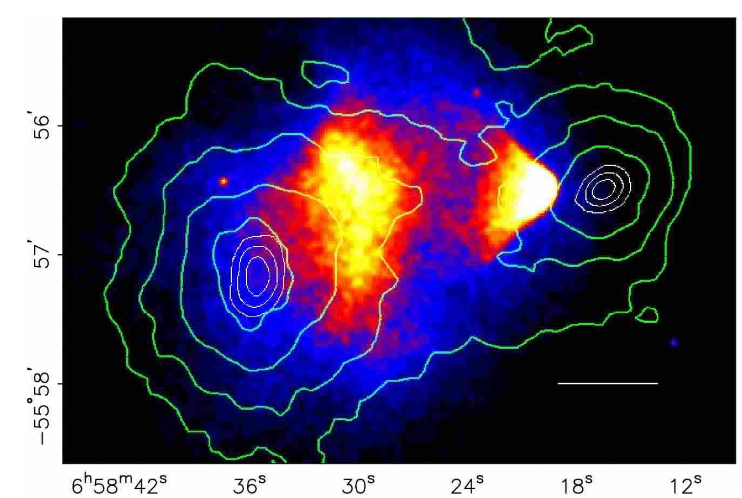


The Higgs Boson



$$m_h \approx 125 \text{ GeV}$$

is this mass scale related to dark matter?



- ATLAS Collaboration, Phys. Lett. B **716**, 1 (2012).
- CMS Collaboration, Phys. Lett. B **716**, 30 (2012).

Thermal Relic Dark Matter

- SM particles had a high temperature in the early Universe

$$T_\gamma \gg 1 \ \mathrm{MeV}$$

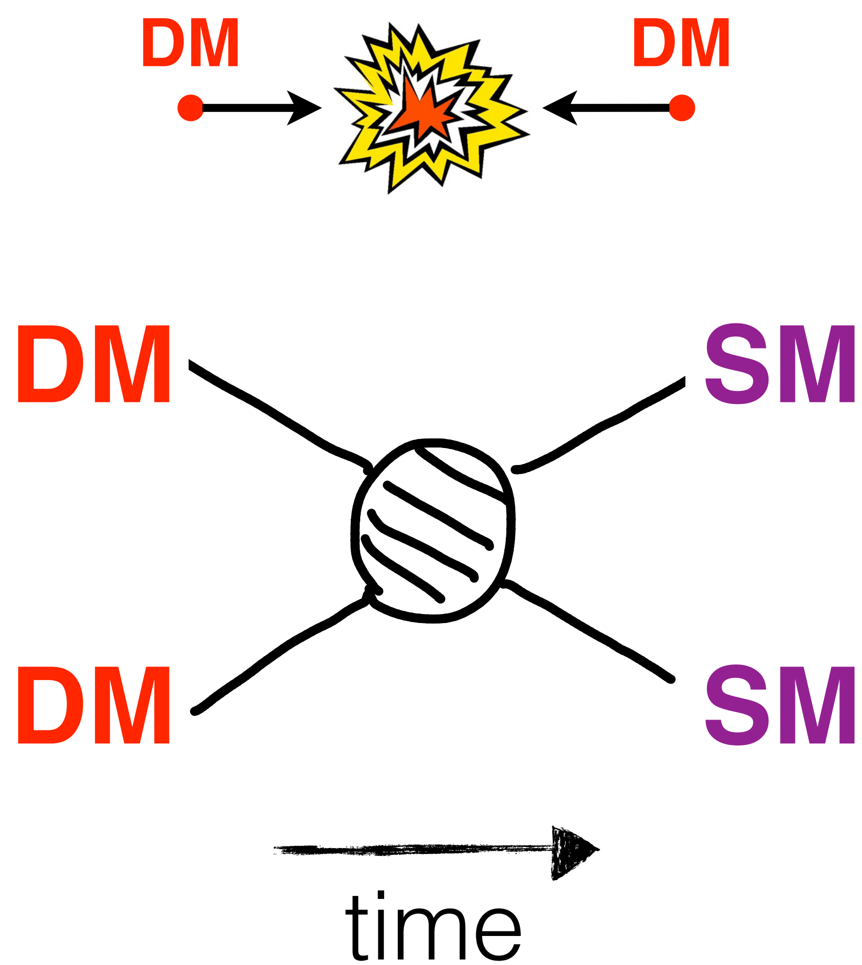
- maybe dark matter also had a high temperature*

$$T_{DM} \gtrsim m_{DM}$$

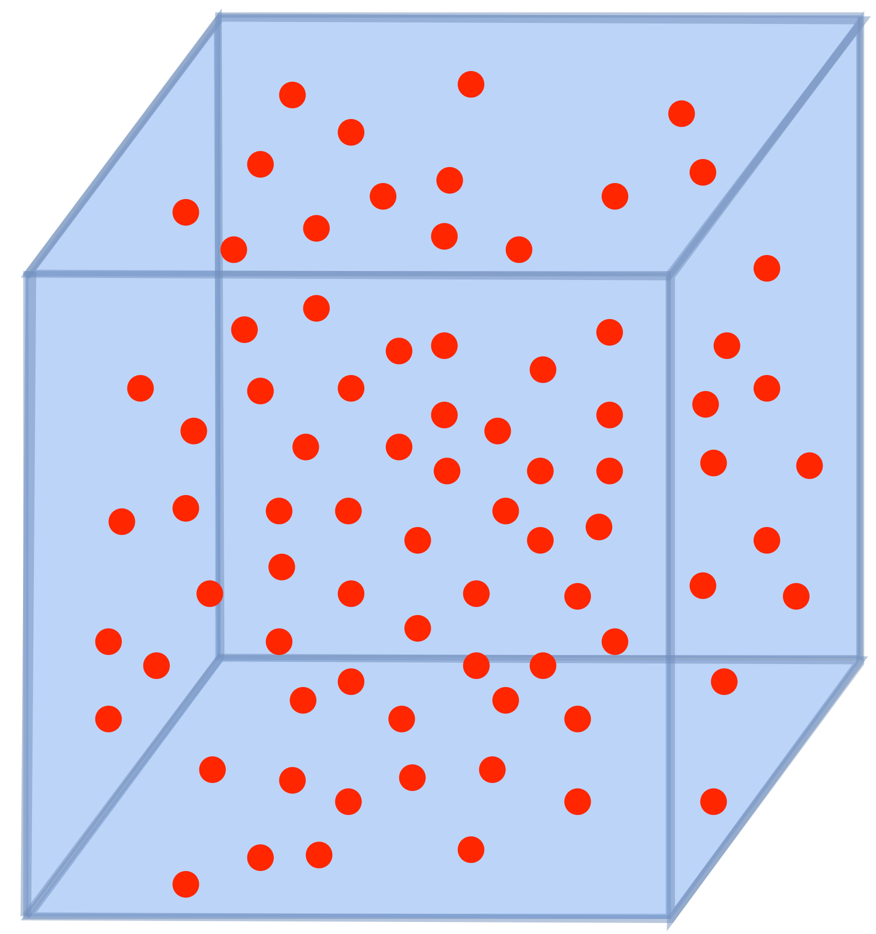
"thermal relic"

*there are also non-thermal candidates: axion, WISP, etc…

Dark Matter Freezeout



$T = m_{DM}$

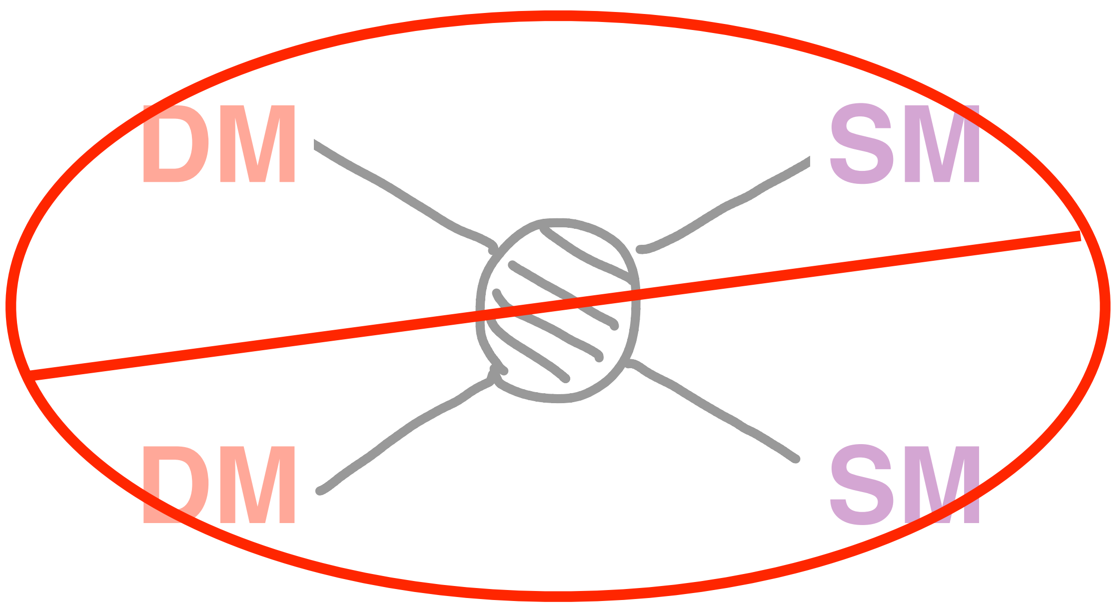


comoving volume: $V \propto T^{-3}$

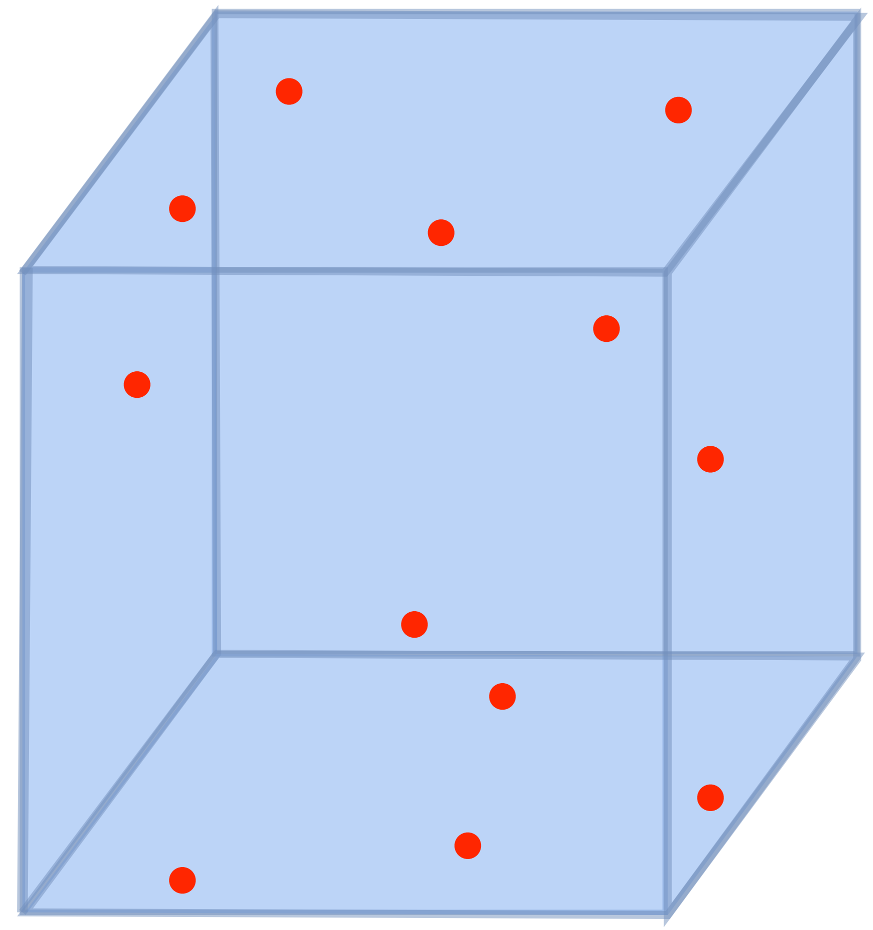
- Lee, Weinberg, Phys. Rev. Lett. **39**, 165 (1977).

Dark Matter Freezeout

annihilations “freezeout”



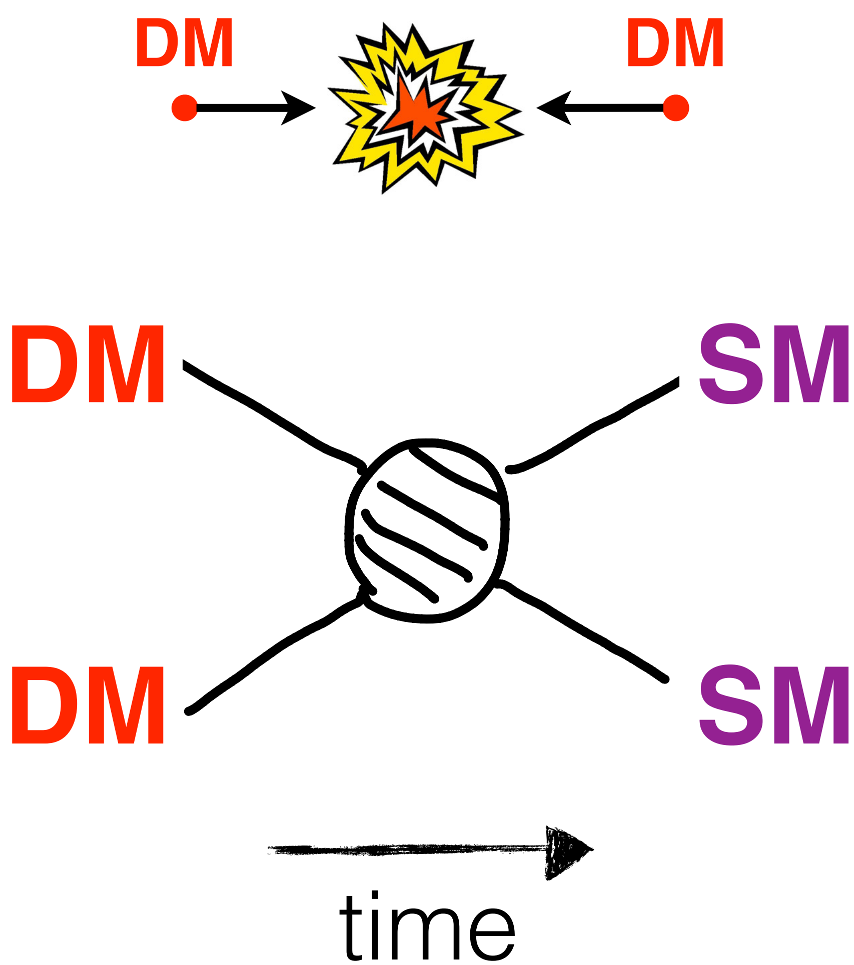
$T = T_{FO}$

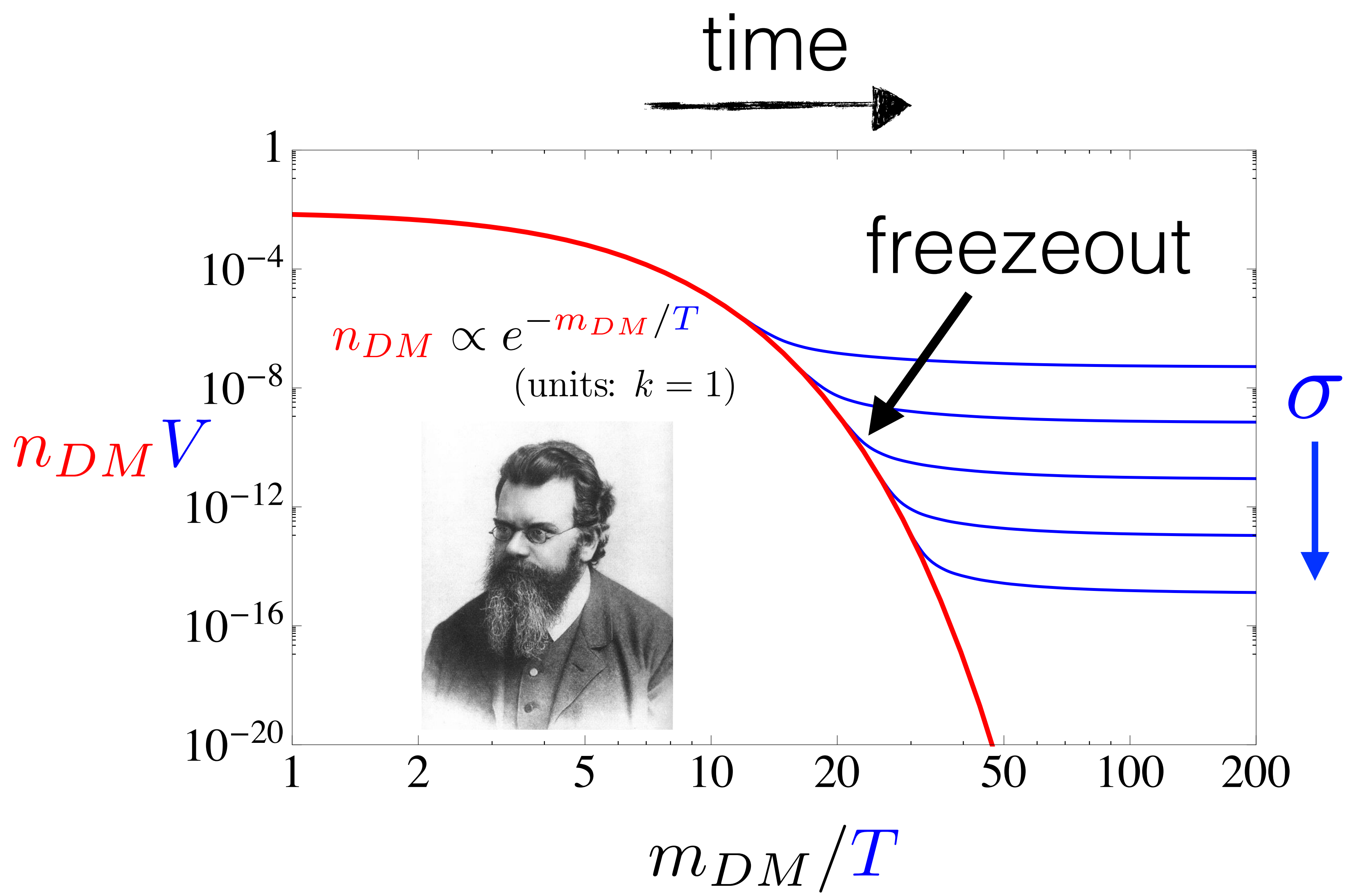


comoving volume: $V \propto T^{-3}$

- Lee, Weinberg, Phys. Rev. Lett. **39**, 165 (1977).

Dark Matter Freezeout

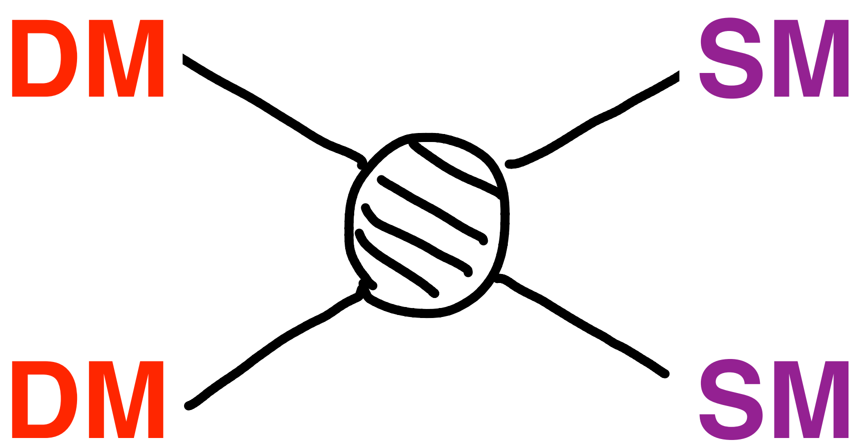




- Lee, Weinberg, Phys. Rev. Lett. **39**, 165 (1977).

WIMP "Miracle"

Weakly **I**nteracting **M**assive **P**article



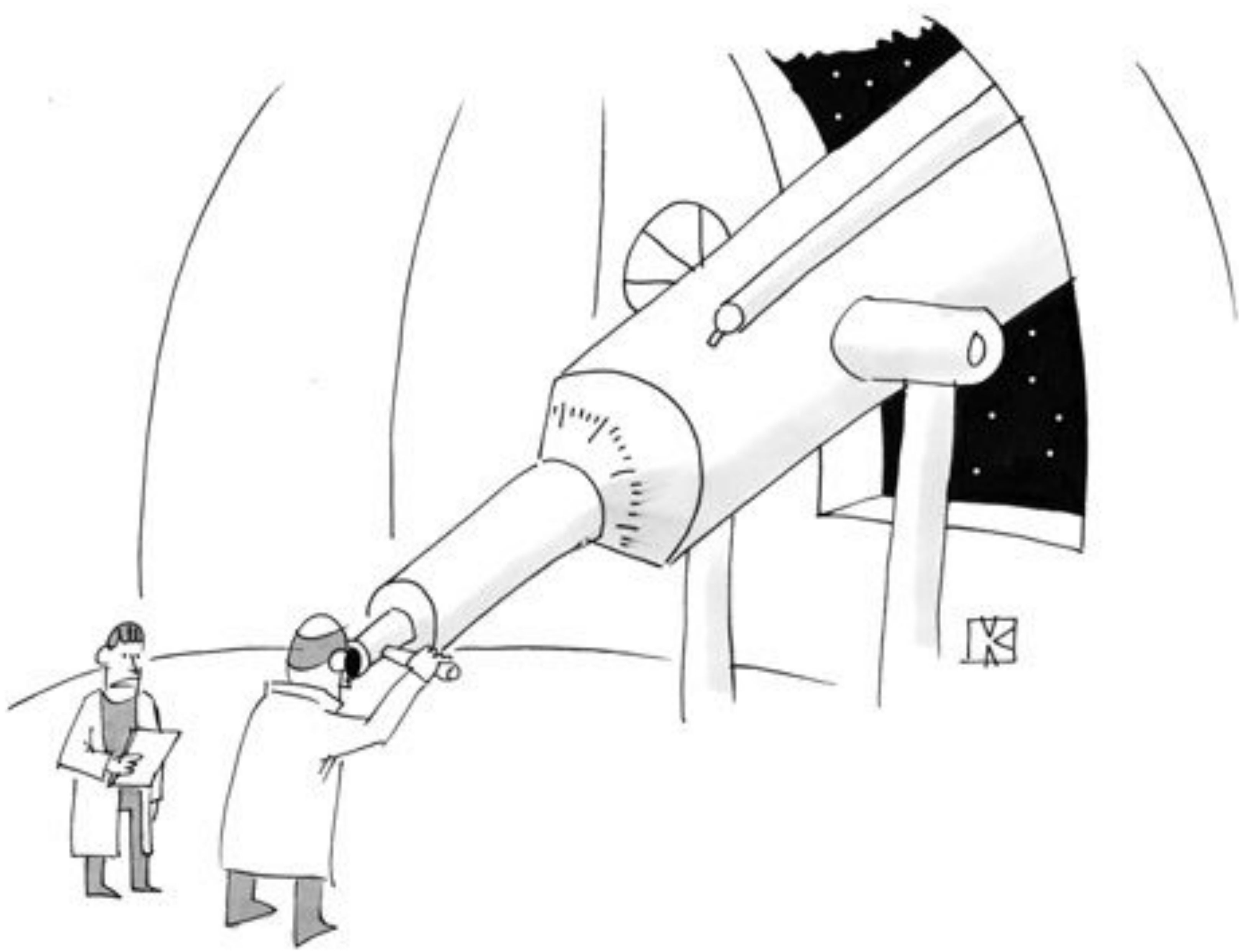
$$\sigma v = 3 \times 10^{26}\ \mathrm{cm}^3/\mathrm{s}$$

$$\sigma v \approx \frac{\alpha_{EM}^2}{(200\ \mathrm{GeV})^2} \qquad \alpha_{EM} \approx \frac{1}{137}$$

$$m_h \approx 125\ \mathrm{GeV}$$

$$m_{DM} \sim m_h \ \textbf{?}$$

2. Experiment vs. Dark Matter

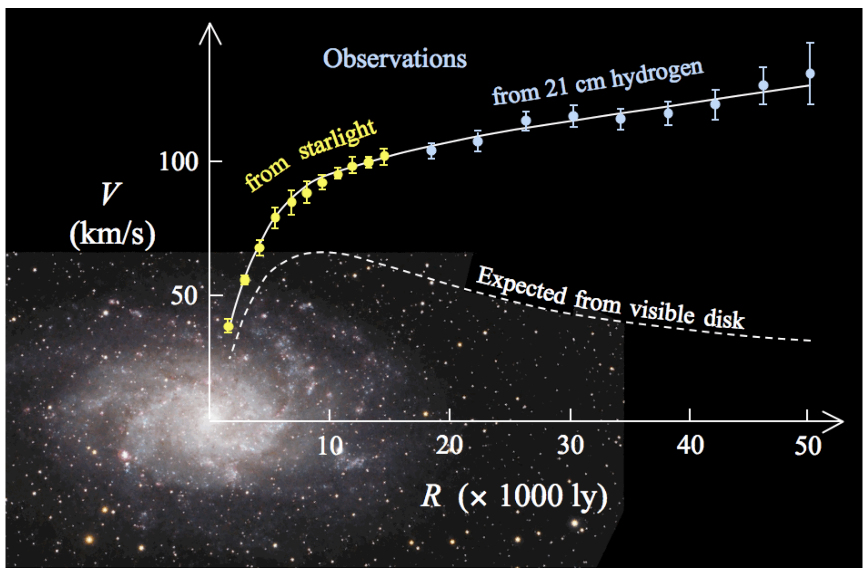


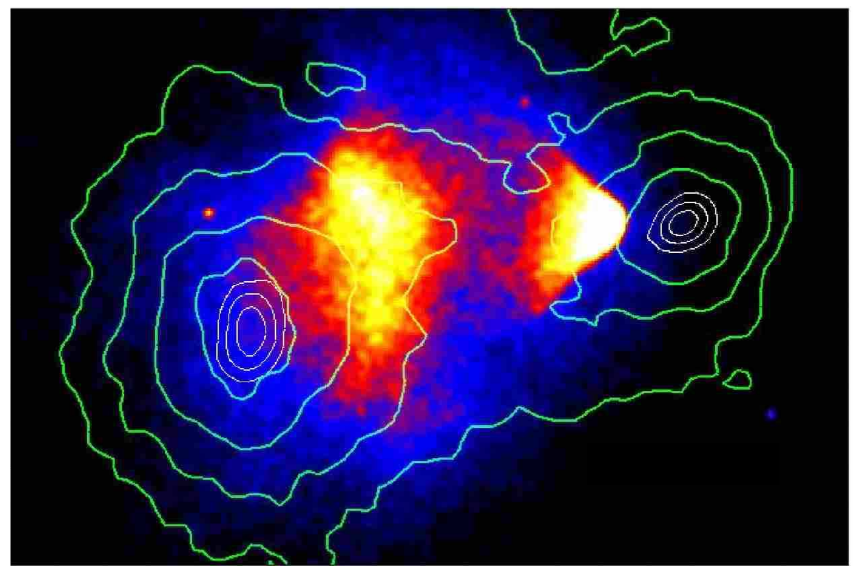
"That isn't dark matter, sir—you just forgot to take off the lens cap."

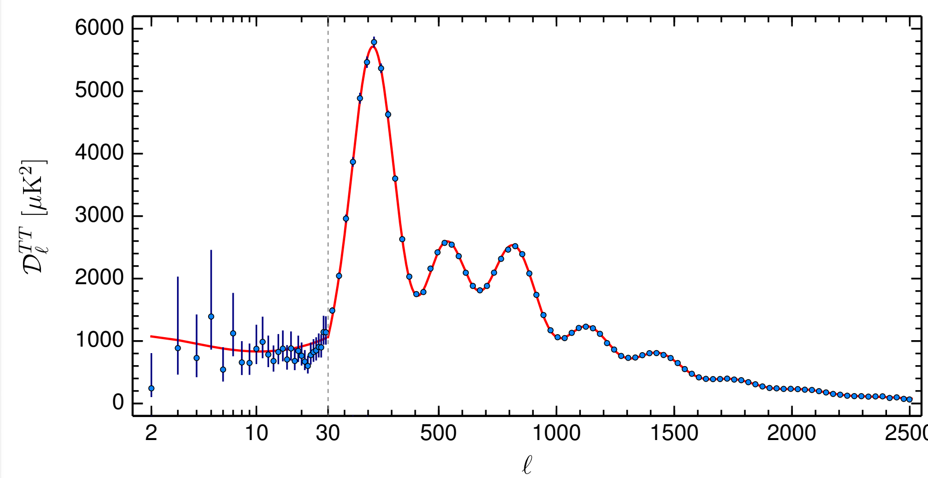
Gregory Kogan.

2. Experiment vs. Dark Matter

- evidence for Dark Matter relies on gravity

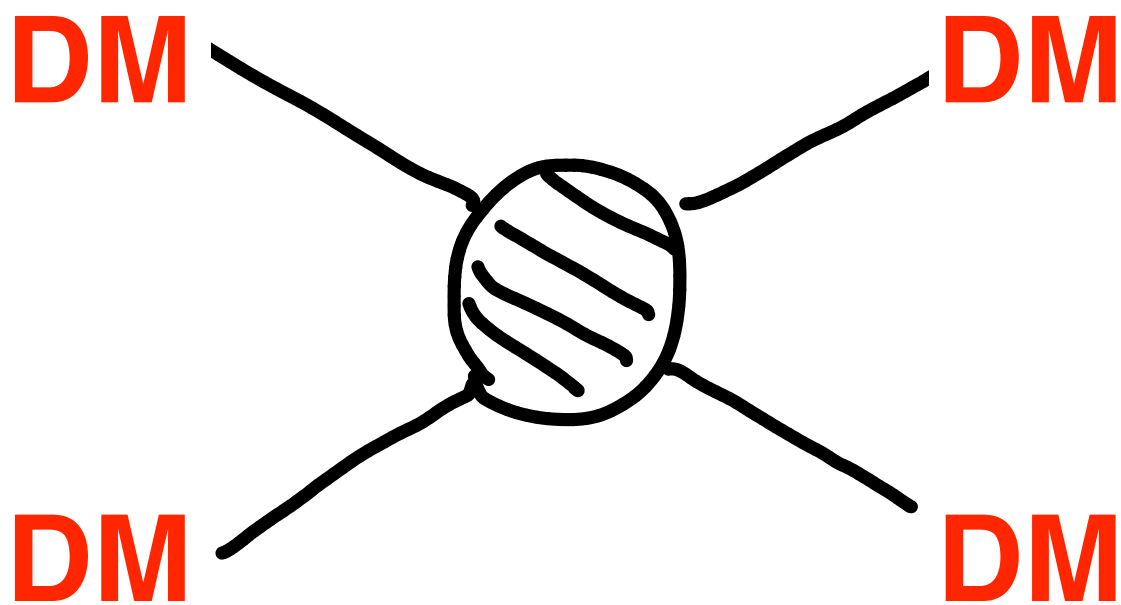


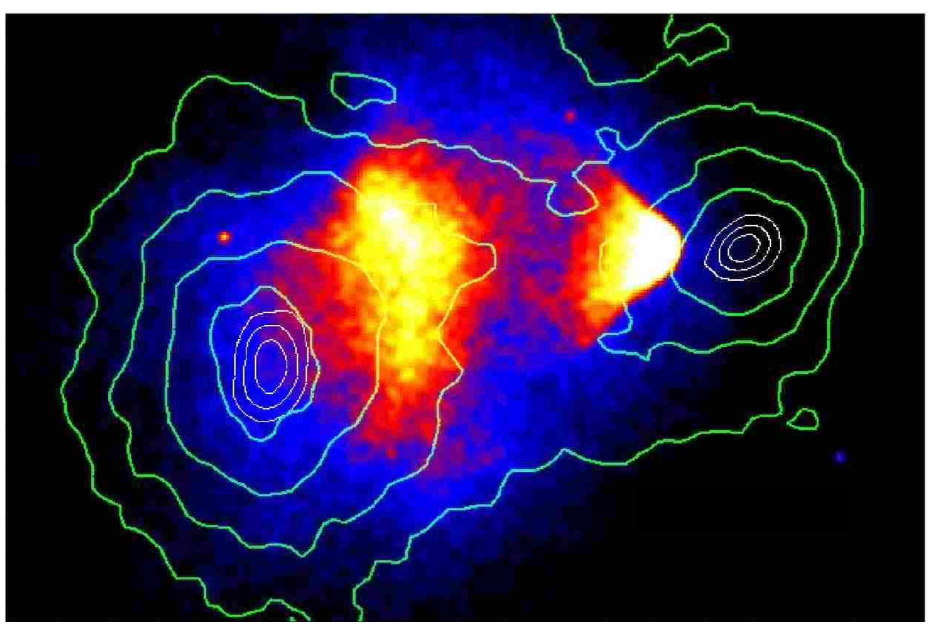




- Dark Matter Holy Grail: non-gravitational interactions

Dark Matter Self-Interactions



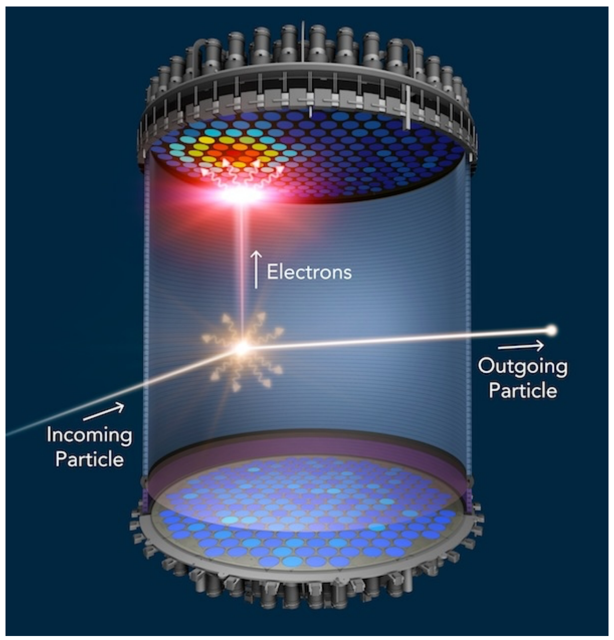


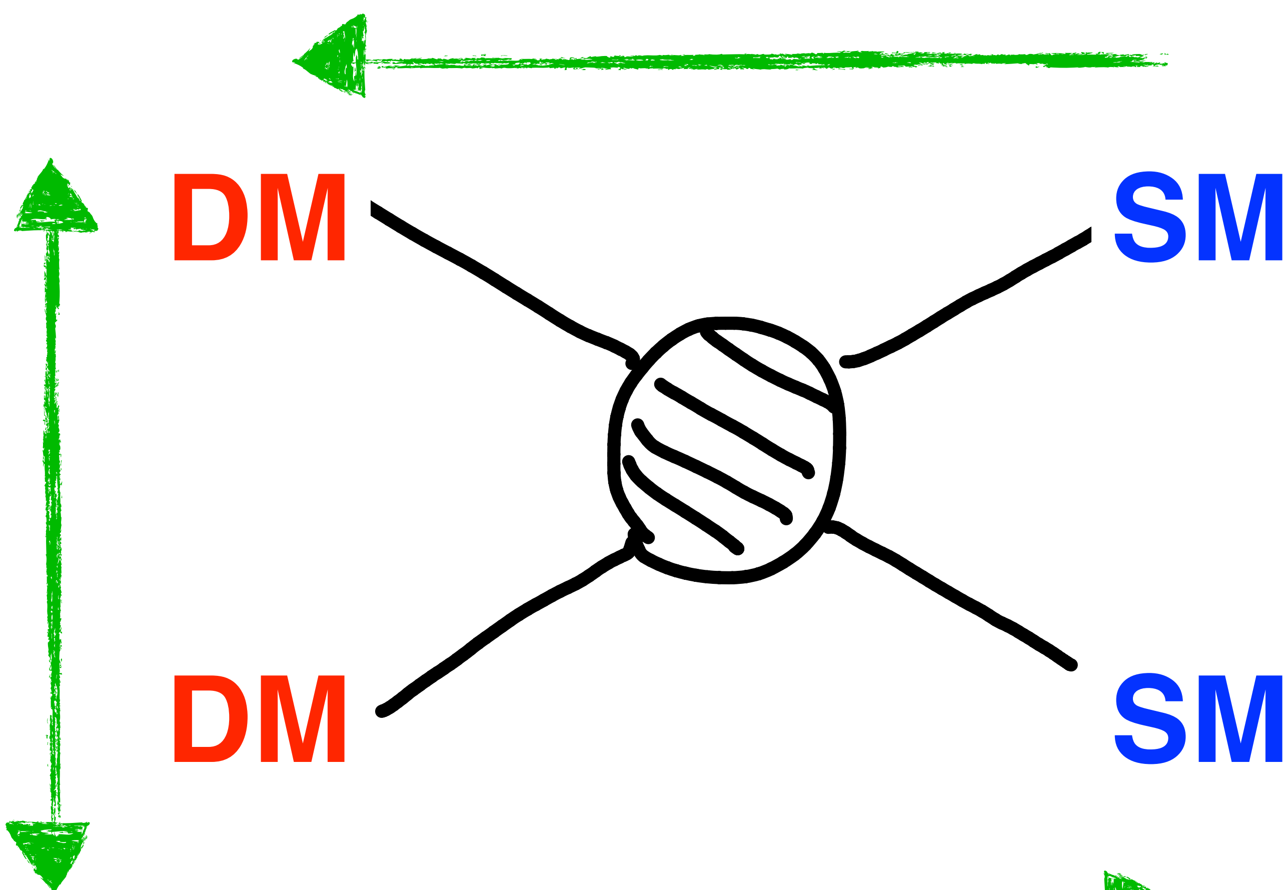
$$\frac{\sigma_{SI}}{m_{DM}} \lesssim 1\ \mathrm{cm}^2/\mathrm{g}$$

$$\sim 2\ \mathrm{barn}/\mathrm{GeV}$$

How to test if Dark Matter couples to the Standard Model

collider production of DM



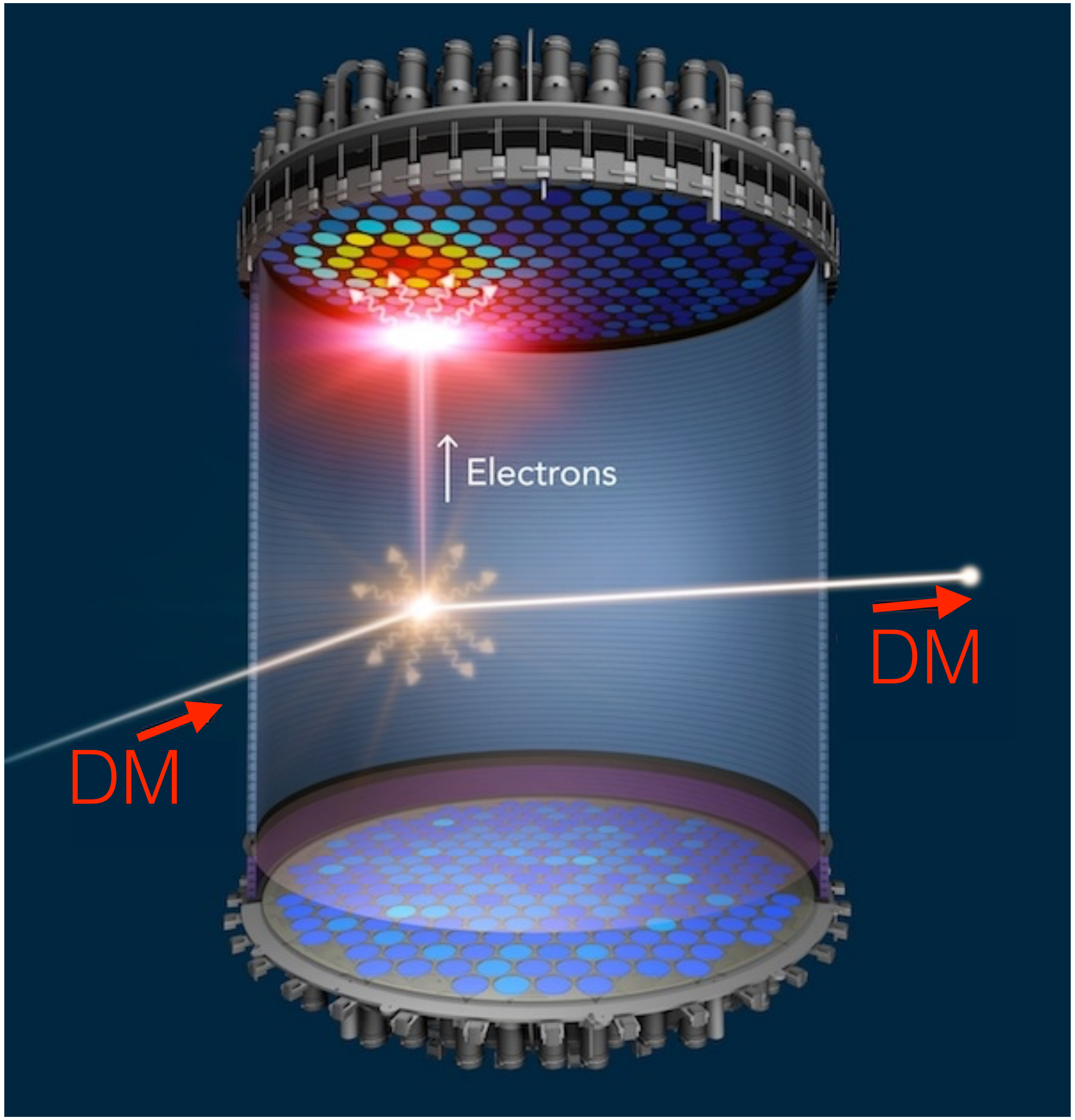


direct detection

time

indirect detection
(DM annihilations)

Direct Detection

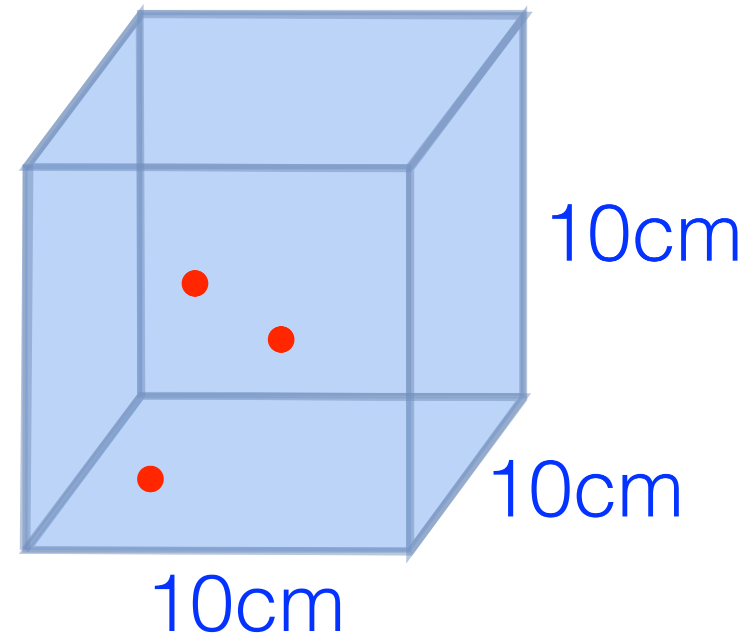


Some Dark Numbers

- local DM density:

$$\rho_{DM} \approx 0.3 \text{ GeV/cm}^3$$

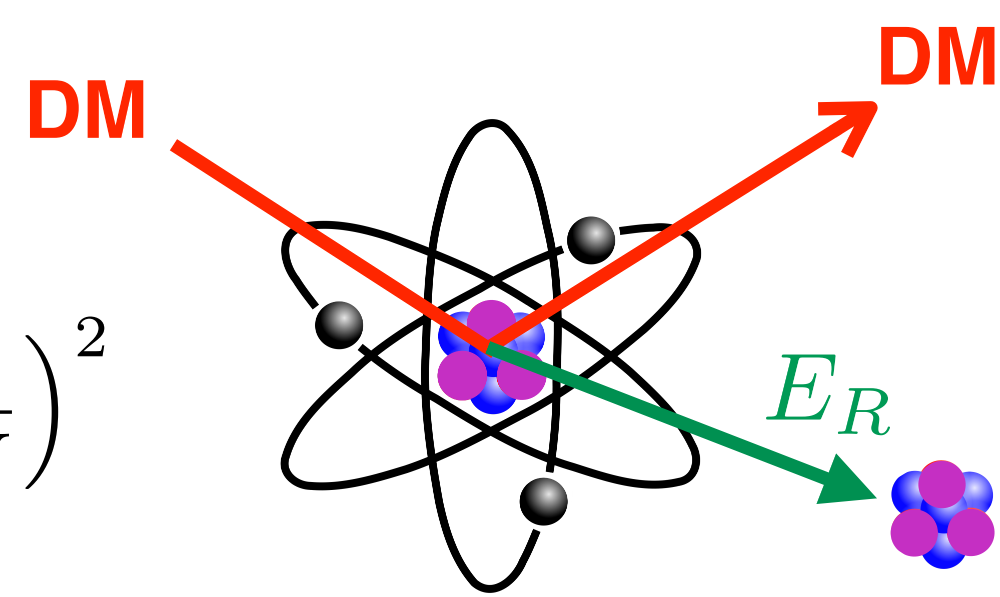
$$m_{DM} = 100 \text{ GeV}$$



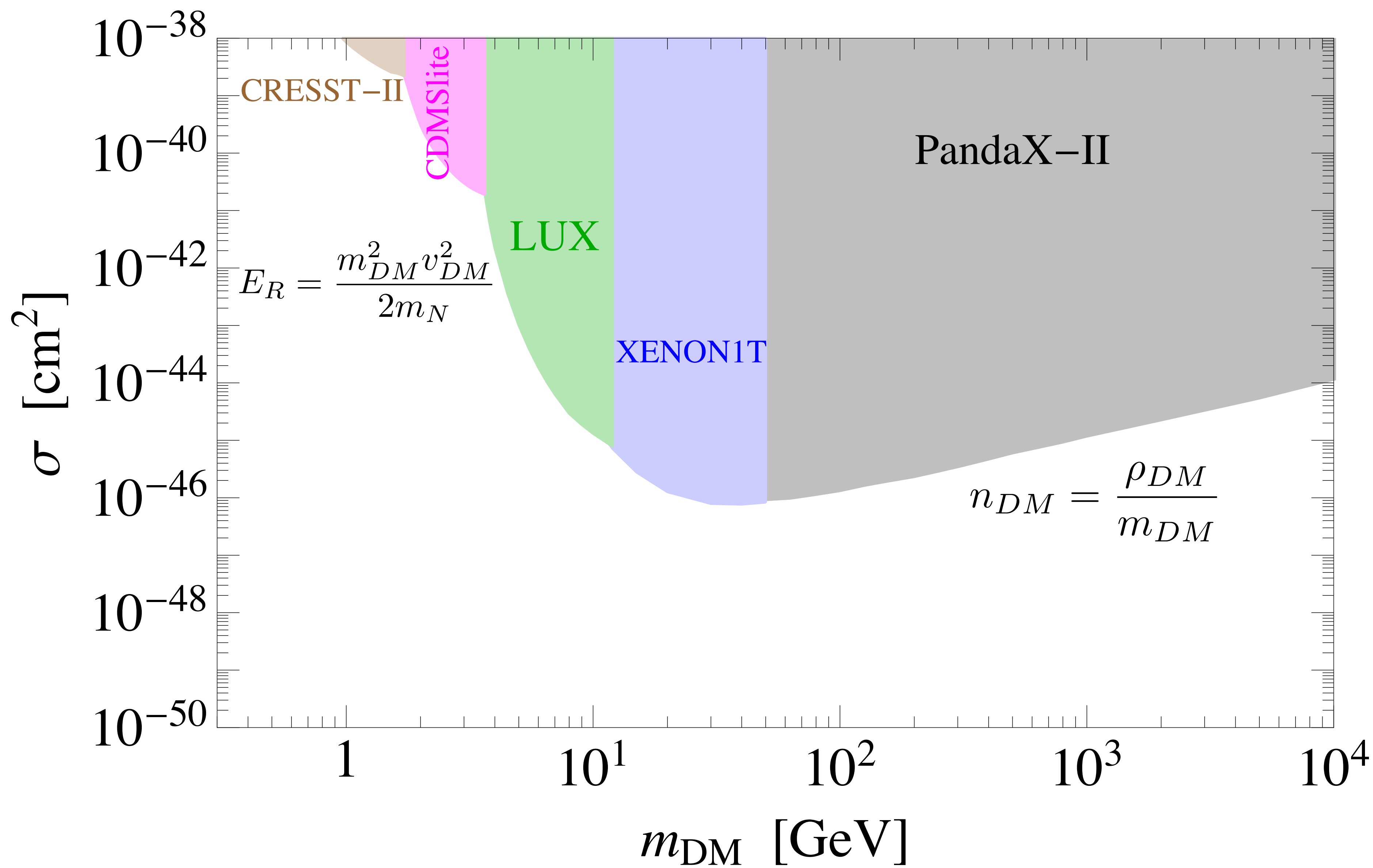
- dark matter velocity: $v_{DM} \sim 200 \text{ km/s} \sim 10^{-3}c$

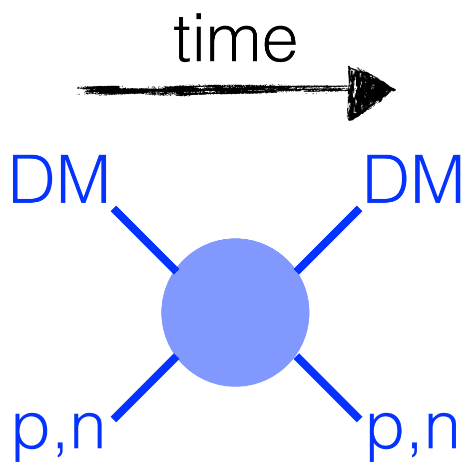
- nuclear recoil energy:

$$E_R = \frac{m_{DM}^2 v_{DM}^2}{2m_N} \sim 50 \text{ keV} \times \left(\frac{m_{DM}}{100 \text{ GeV}}\right)^2$$



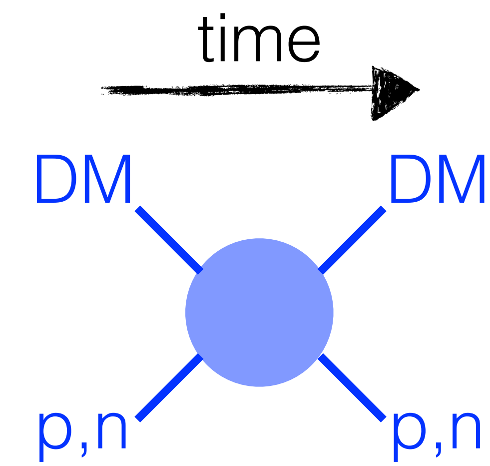
Direct Detection

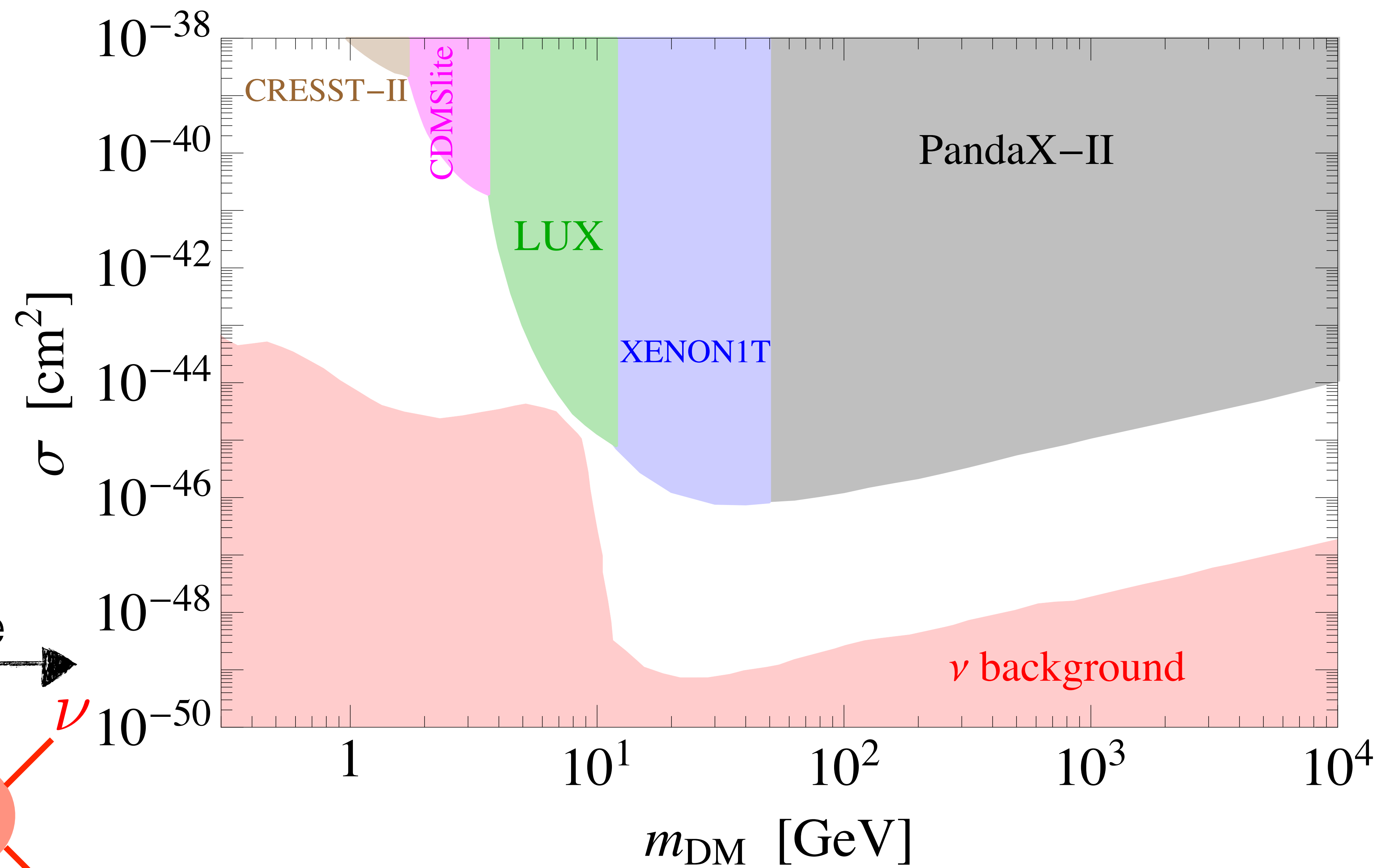


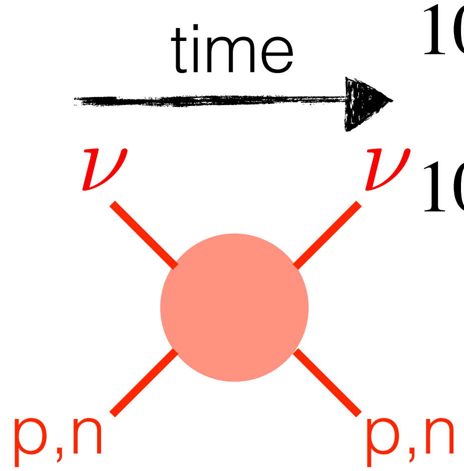


- CRESST collaboration, Eur. Phys. J. C **26,** 25 (2016).
- SuperCDMS collaboration, Phys. Rev. Lett. **116**, 071301 (2016).
- LUX collaboration, Phys. Rev. Lett. **116**, 161301 (2016).
- XENON collaboration, Phys. Rev. Lett. **119**, 181301 (2017).
- PandaX-II collaboration, Phys. Rev. Lett. **119**, 181302 (2017).

Direct Detection

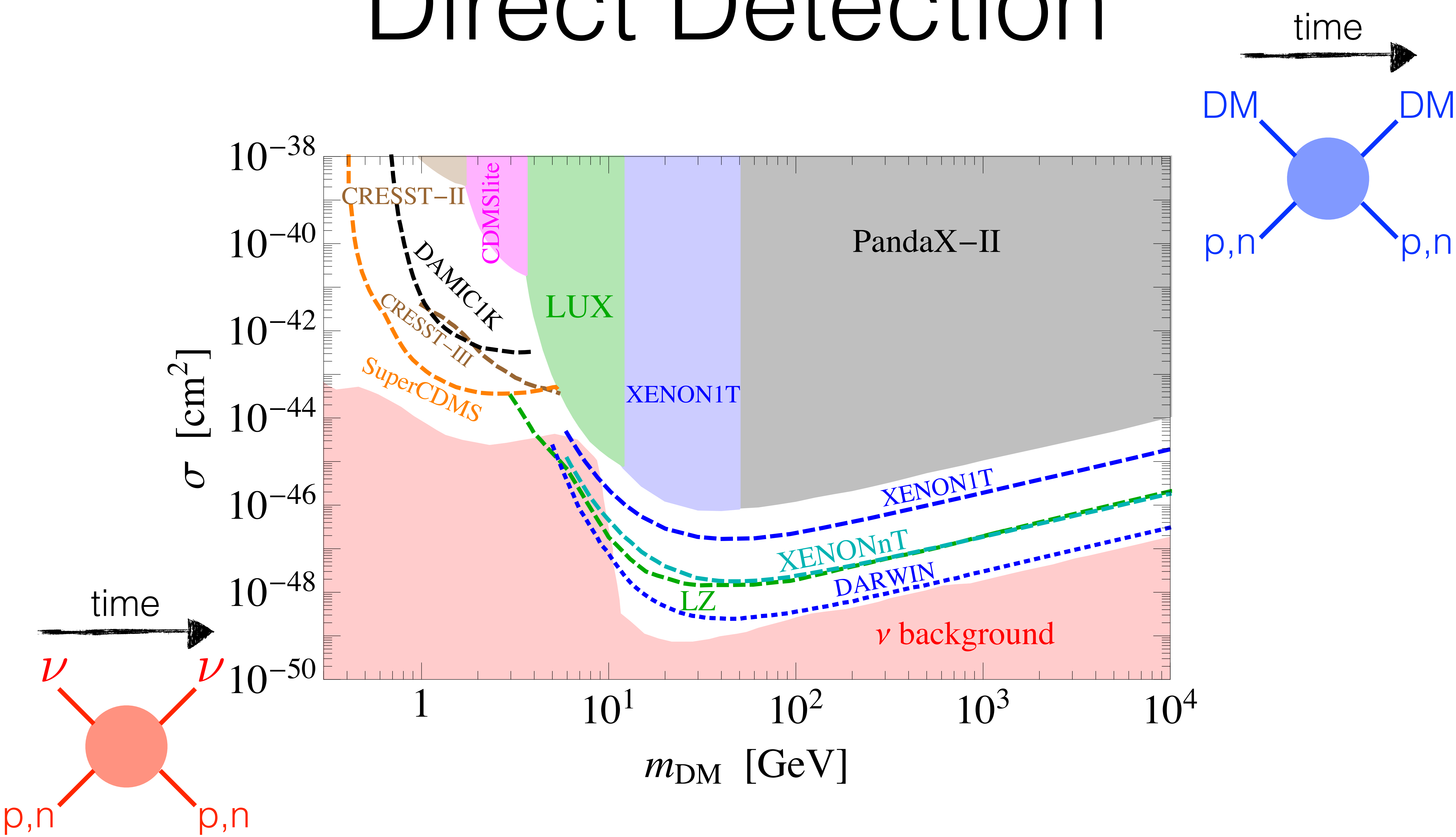






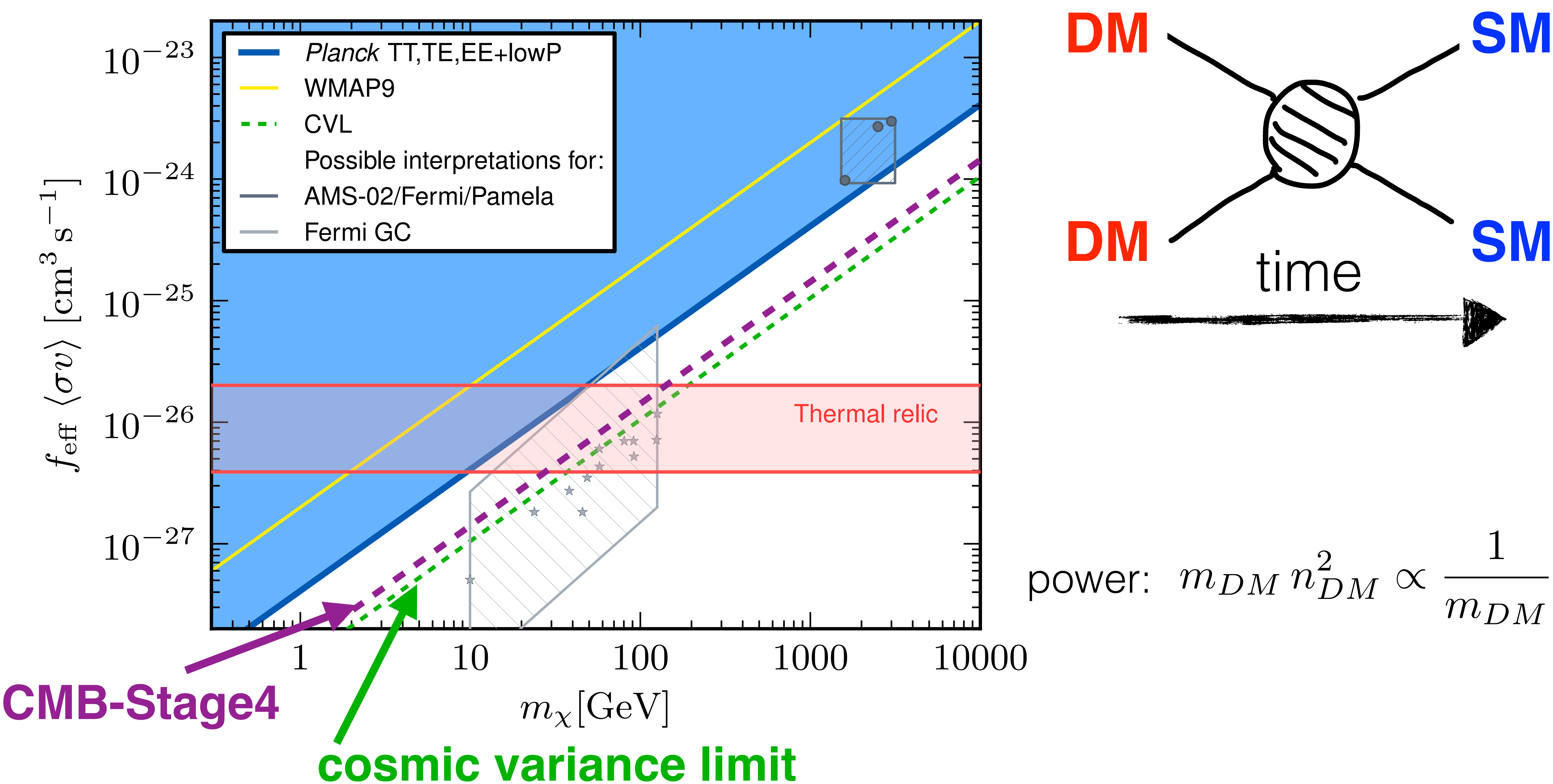
- Billard, Figueroa-Feliciano, Strigari, Phys. Rev. D **89**, 023524 (2014).

Direct Detection



- SuperCDMS Collaboration, Phys. Rev. D **95**, 082002 (2017).
- DAMIC1K, US Cosmic Visions, arXiv:**1707.04591** (2017).
- CRESST Collaboration, arXiv:**1503.08065** (2015).
- XENON Collaboration, JCAP **1604**, 027 (2016).
- DARWIN Collaboration, JCAP **1611**, 017 (2017).
- LUX-ZEPLIN Collaboration, TDR, arXiv:**1703.09144** (2017).

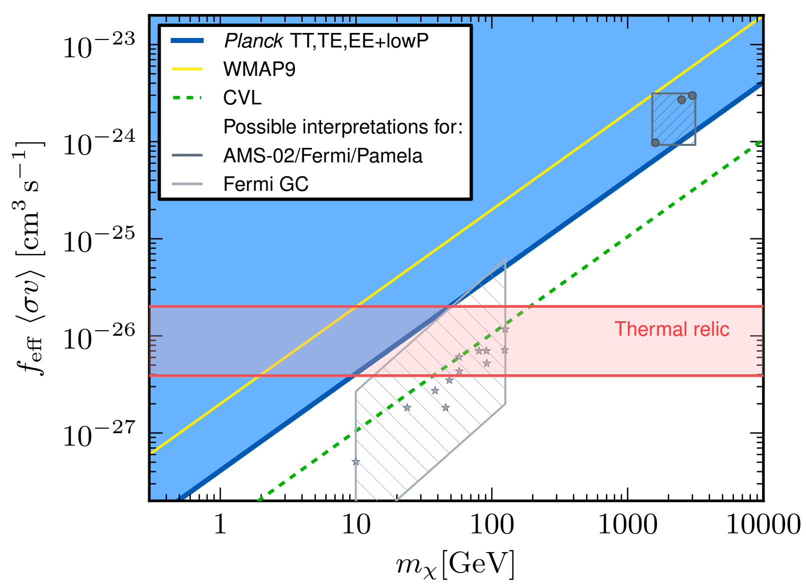
Cosmic Microwave Background vs. Dark Matter

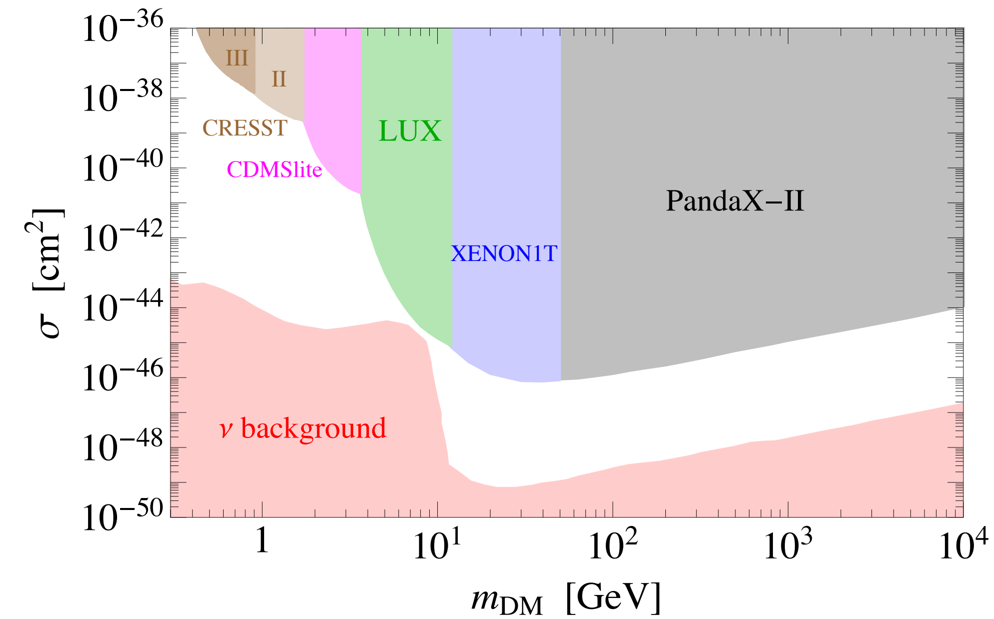


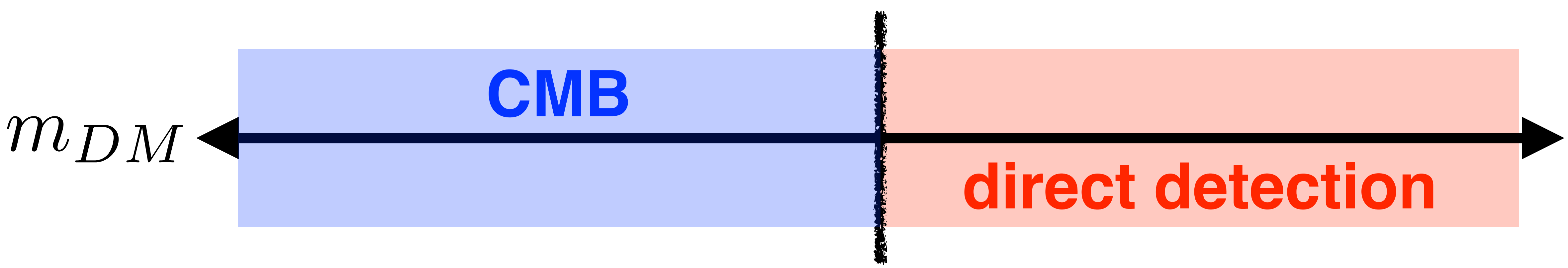
power: $m_{DM}\, n_{DM}^2 \propto \dfrac{1}{m_{DM}}$

- Planck Collaboration, Astronomy & Astrophysics **594**, A13 (2016).
- CMB-S4, arXiv:**1610.02743** (2016).

Indirect/Direct Detection Complementarity

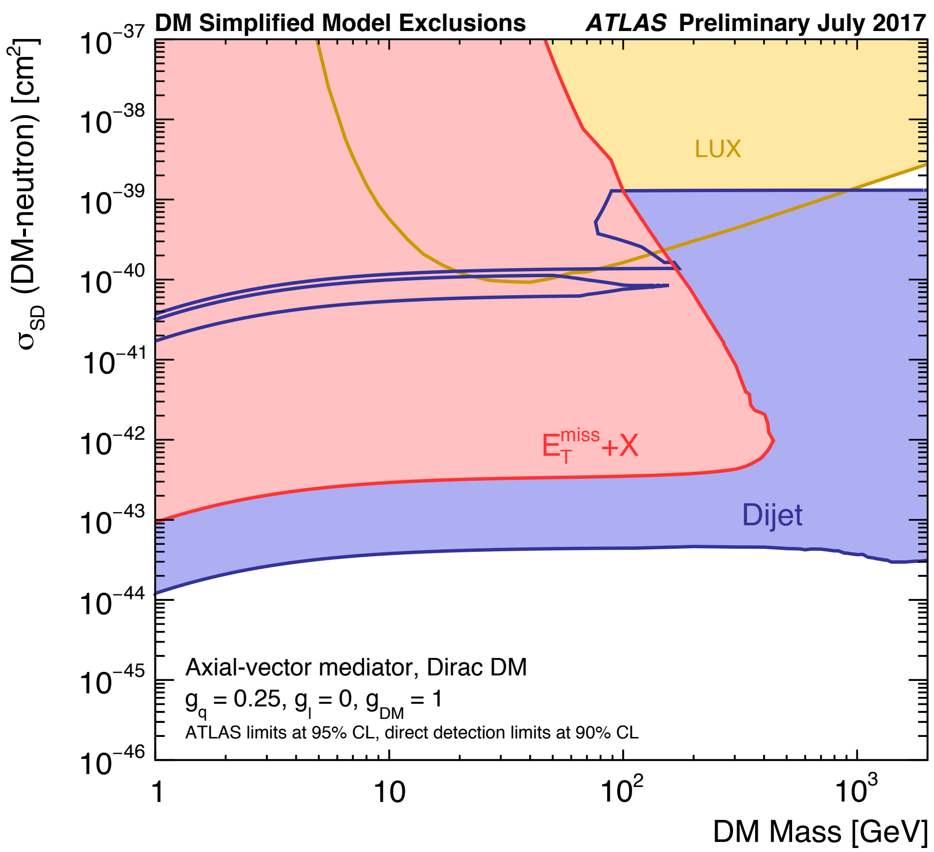


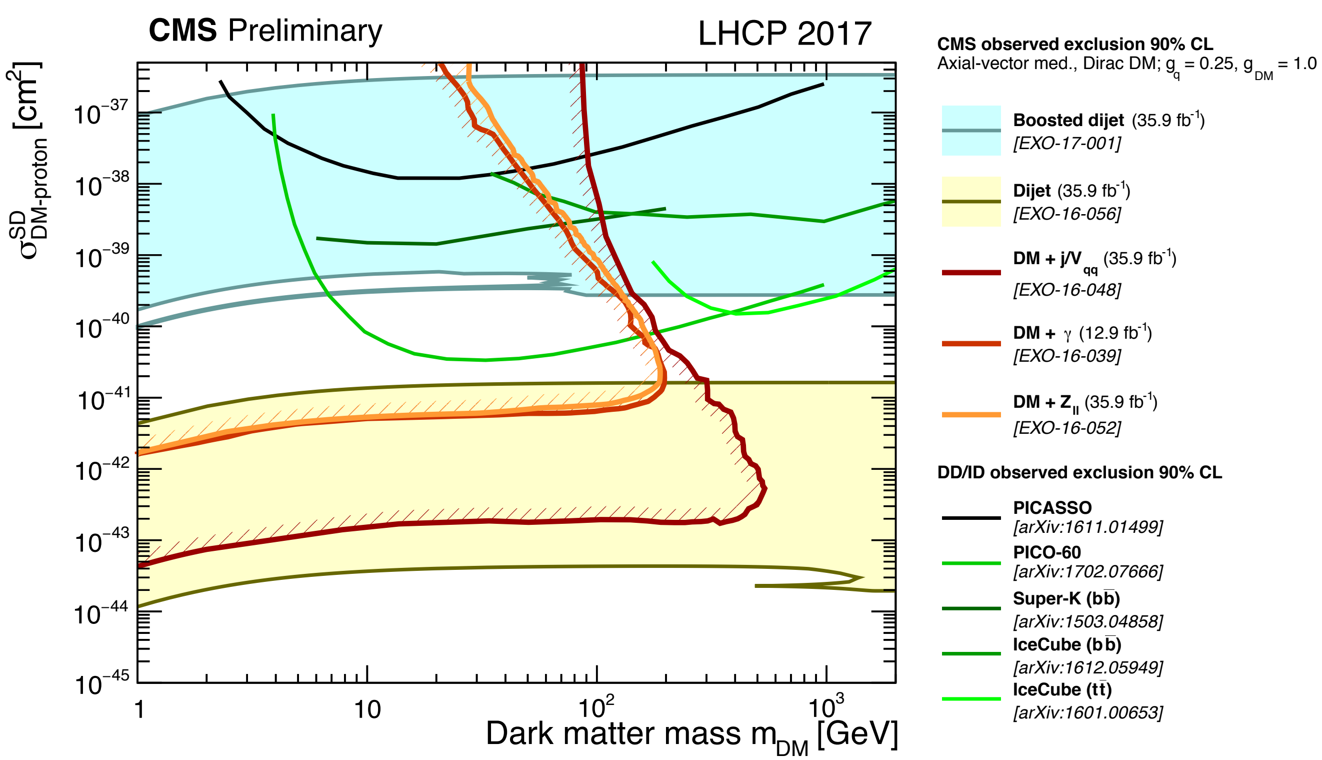


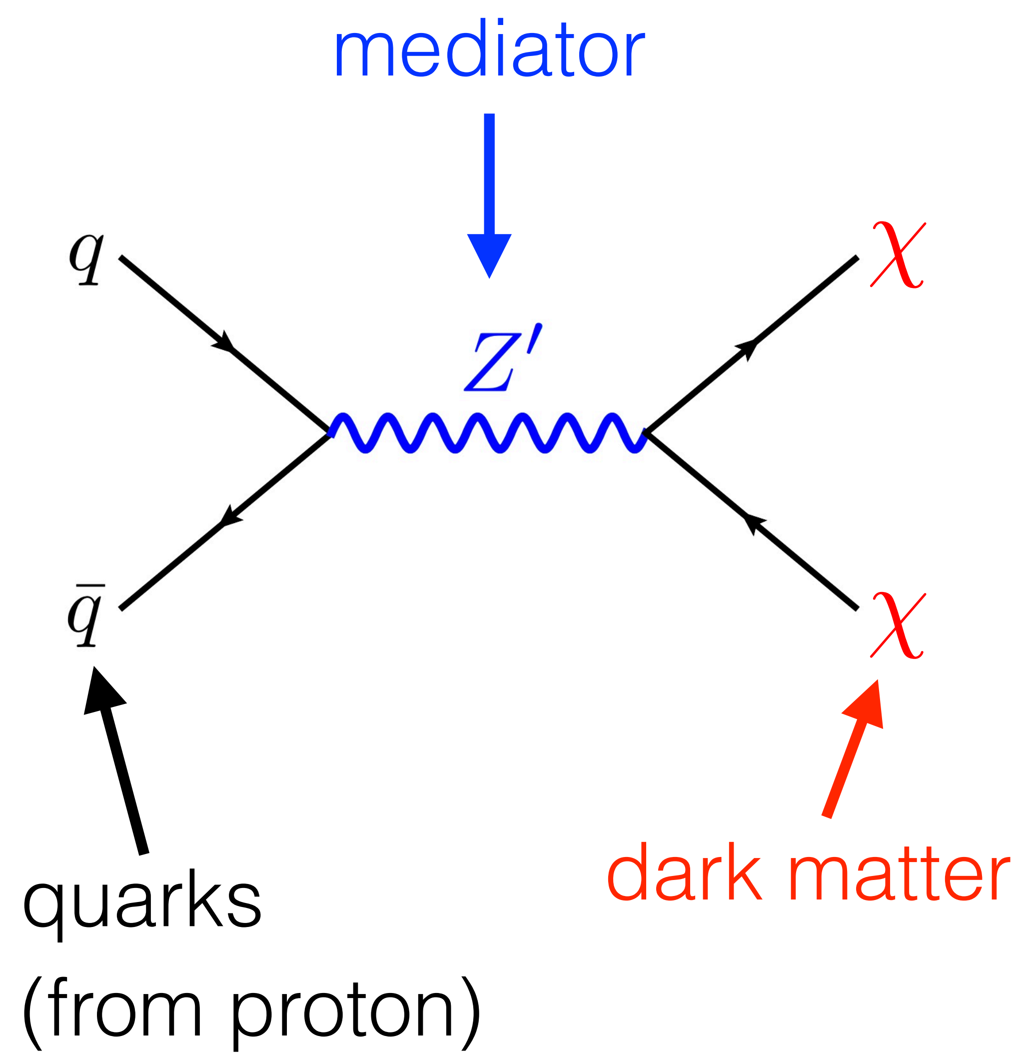


~10 GeV

LHC vs. Direct Detection (with a dark Mediator)



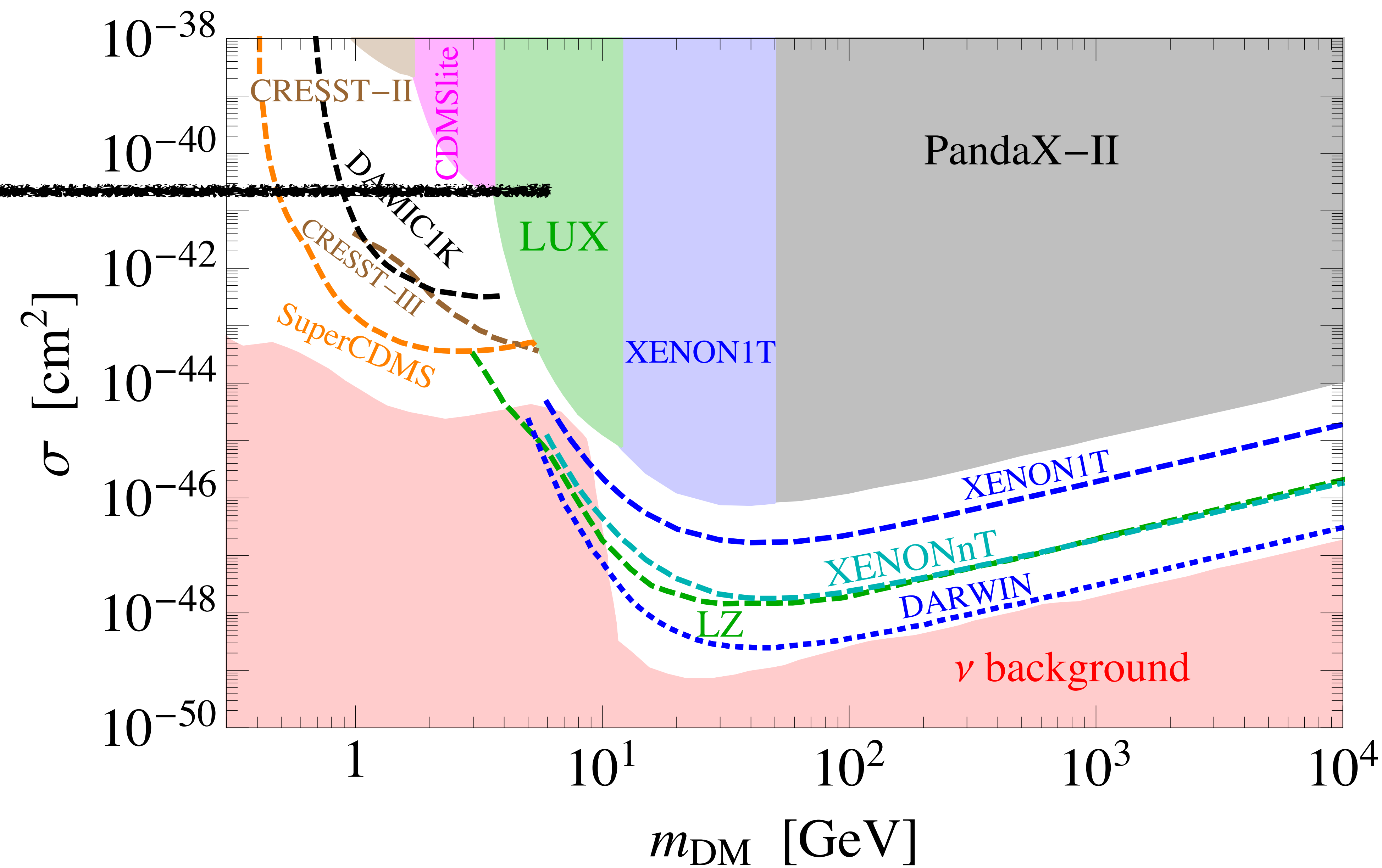




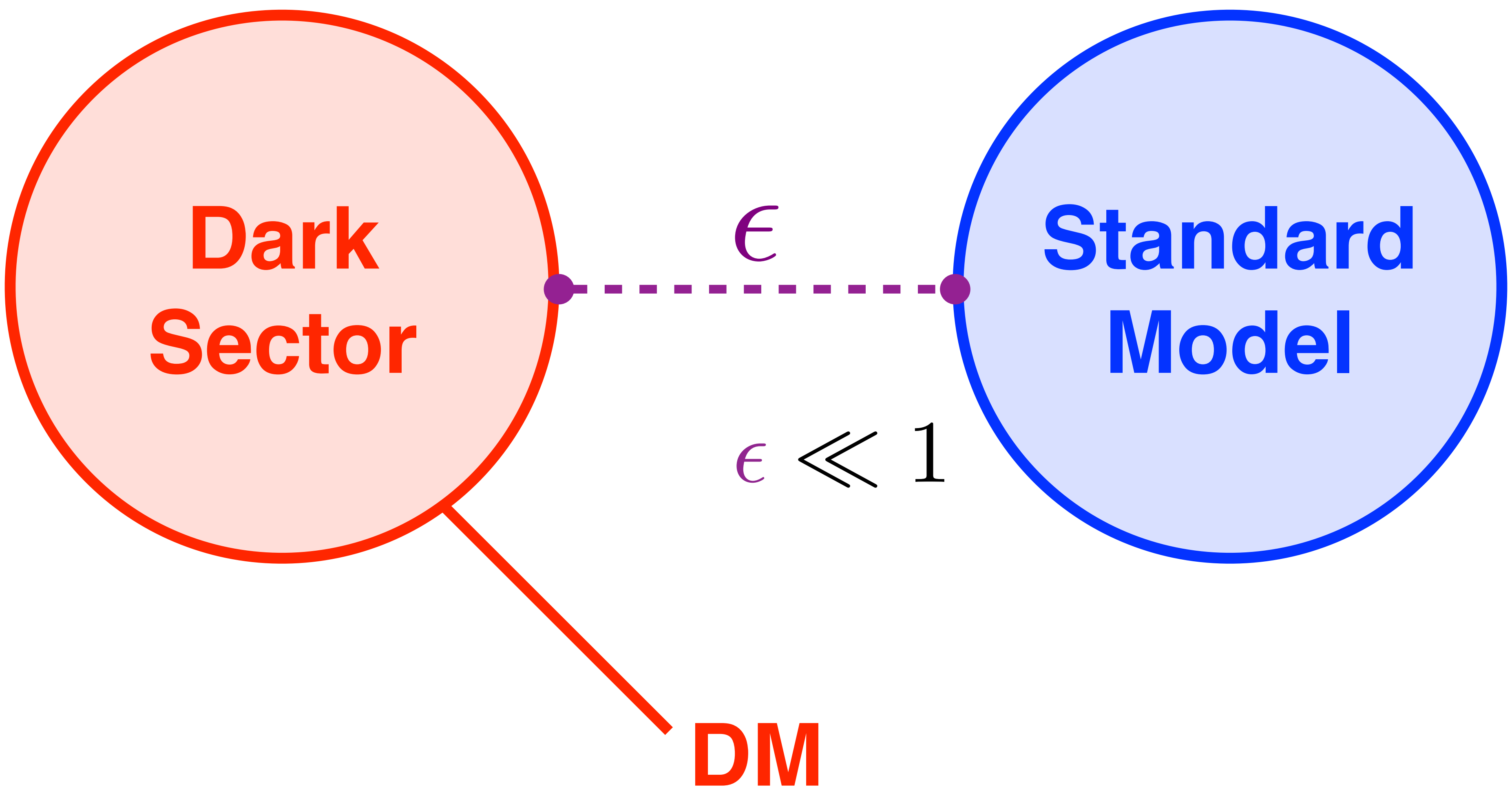
Experimental Summary

3. Dark Matter Below the Higgs Scale

light dark matter



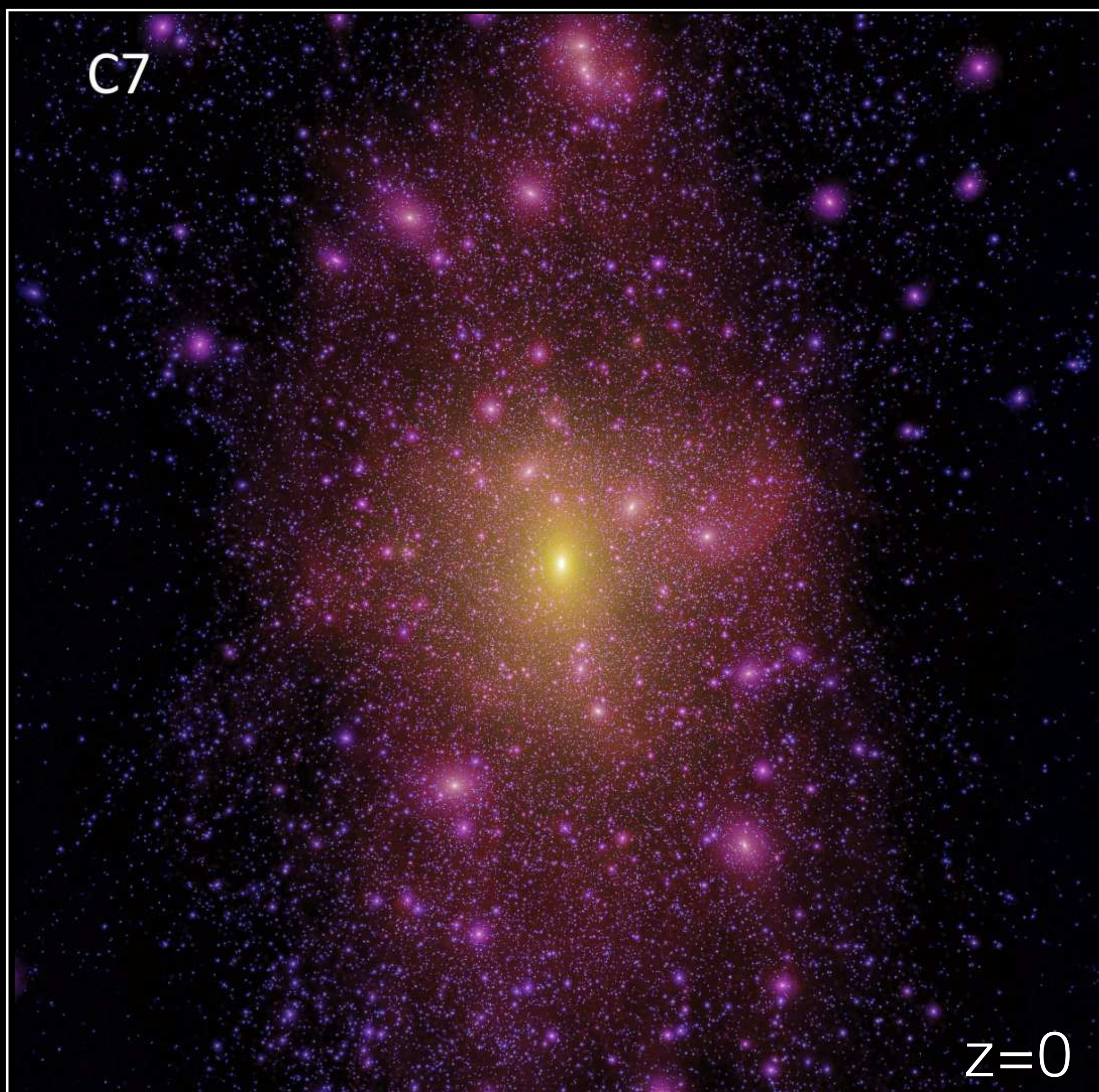
Hidden Sector Dark Matter



- Goldberg, Hall, Phys. Lett. B **174**, 151 (1986).
- Finkbeiner, Weiner, Phys. Rev. D **76**, 083519 (2007).
- Arkani-Hamed, Finkbeiner, Slatyer, Weiner, Phys. Rev. D **79**, 015014 (2009).

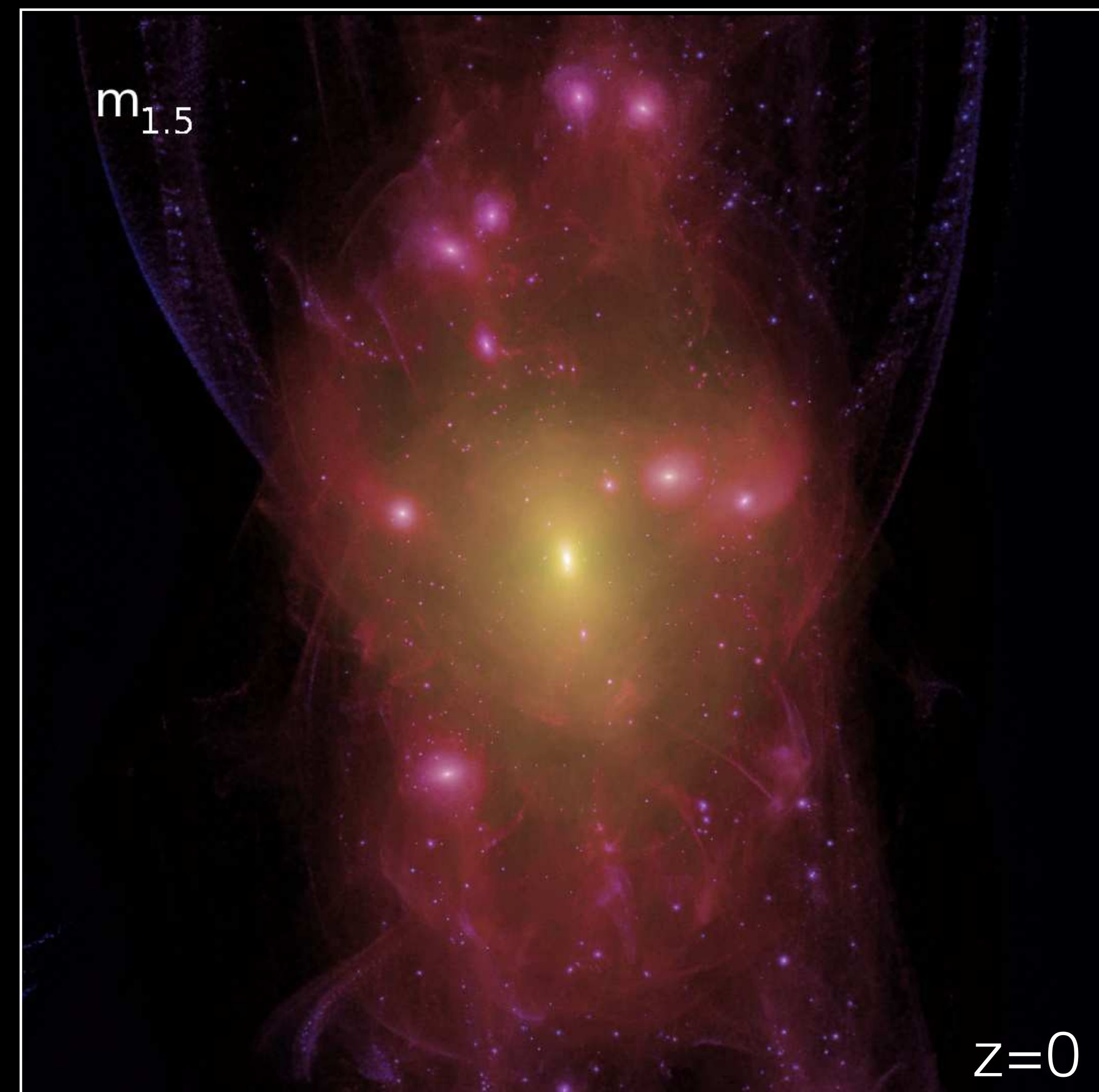
Cold vs. Warm Dark Matter

Cold: $m_{DM} \gg 1 \text{ keV}$



1.5 Mpc

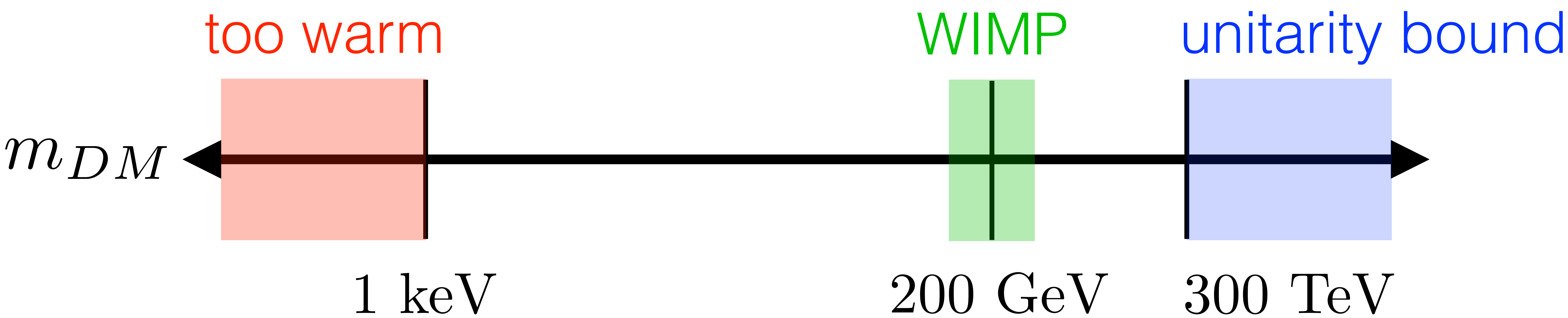
Warm: $m_{DM} = 1.5 \text{ keV}$



1.5 Mpc

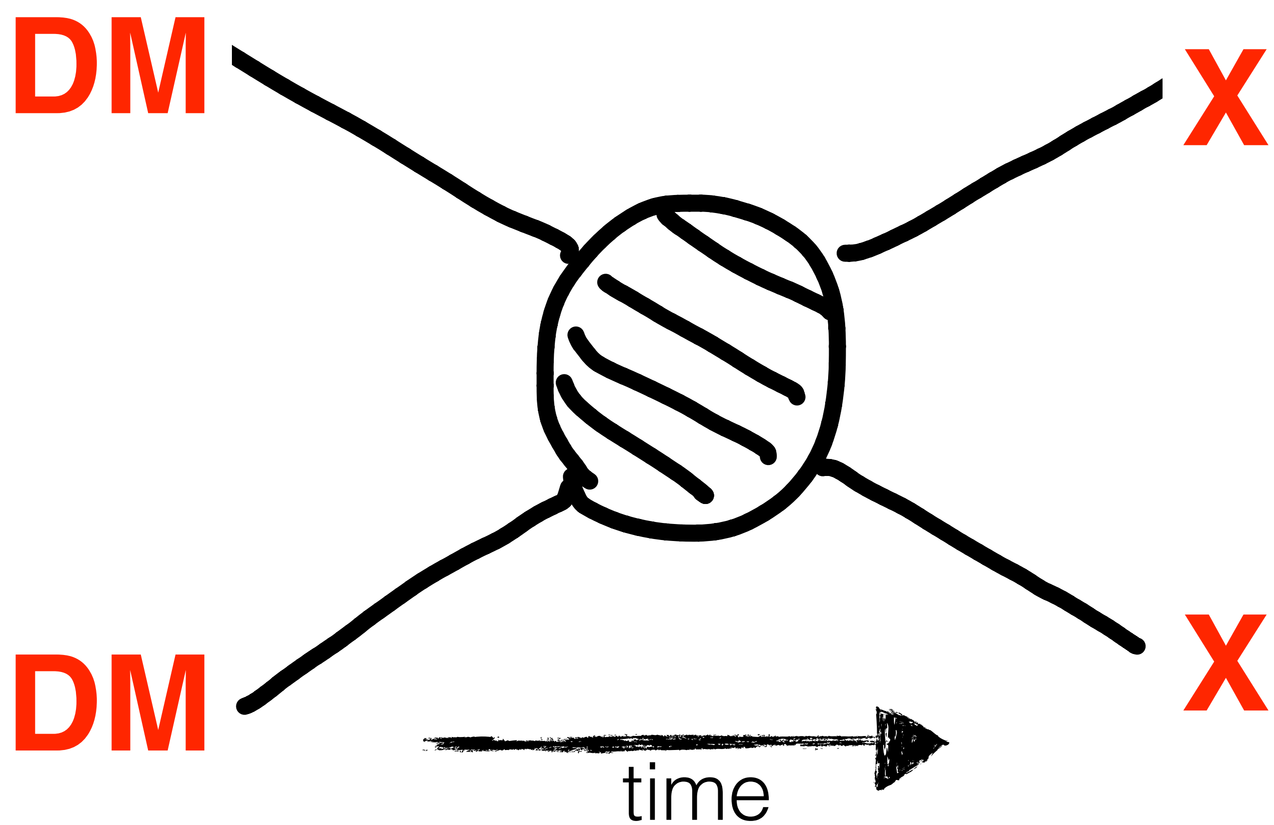
- Lovell *et. al.*, MNRAS **439**, 300 (2014).

Thermal Relic Spectrum



- Viel *et al.*, Phys. Rev. D **71**, 063534 (2005).
- Lovell *et al.*, MNRAS **439**, 300 (2014).
- Griest, Kamionkowski, Phys. Rev. Lett. **64**, 615 (1990).

Ultraweakly Coupled Dark Matter

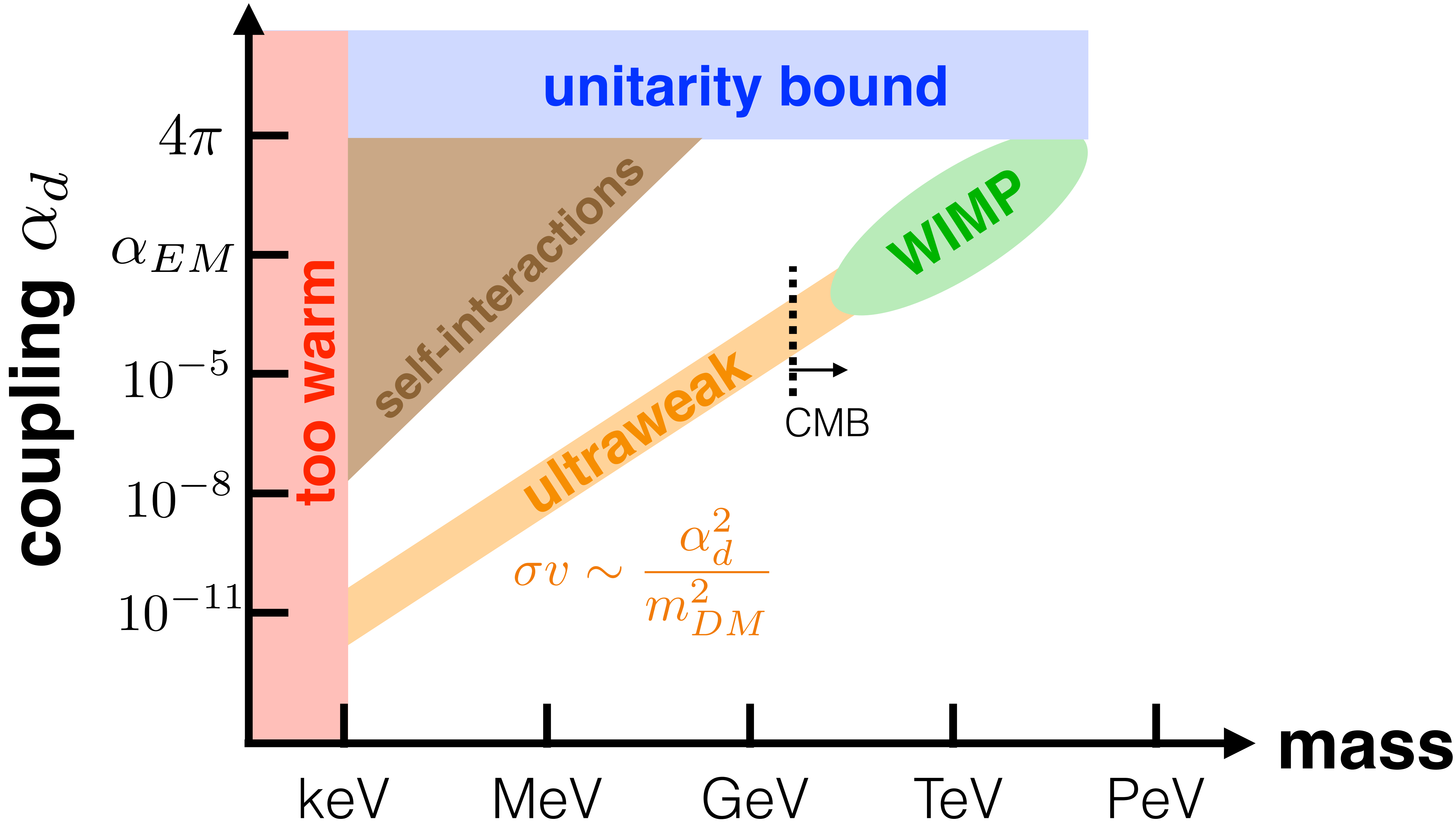


$$\sigma v \sim \frac{\alpha_d^2}{m_{DM}^2}$$

$$\alpha_d \ll \alpha_{EM} \approx \frac{1}{137}$$

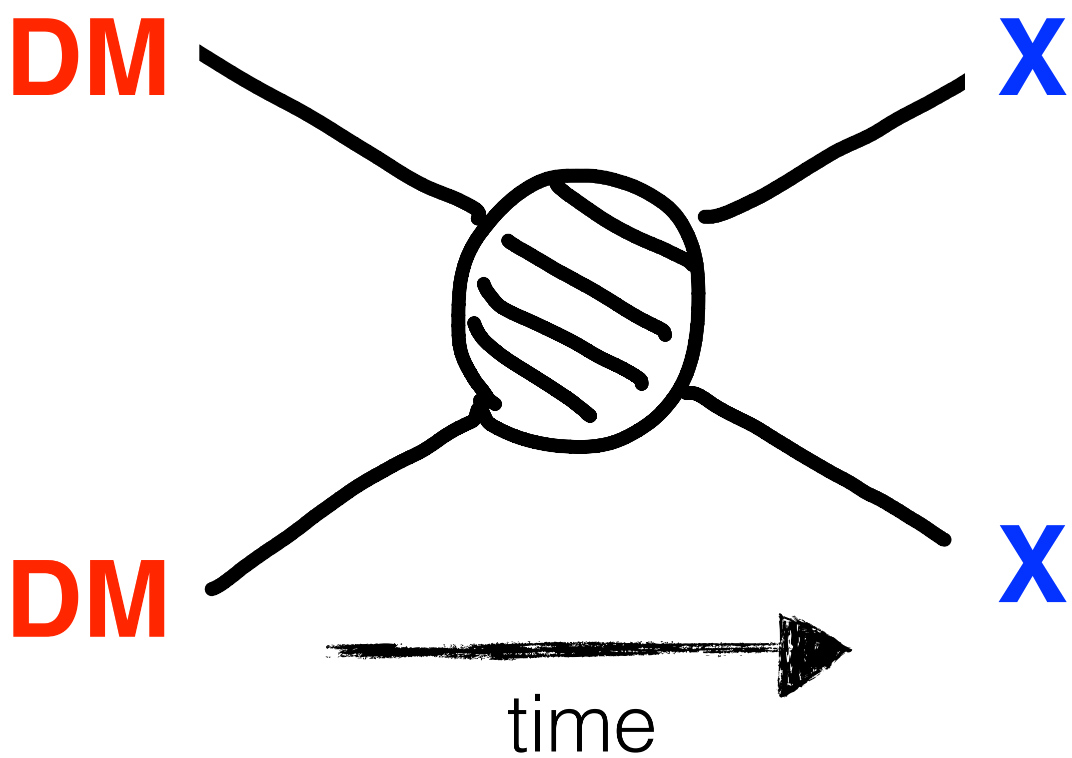
- Boehm, Fayet, Nucl. Phys. B **683**, 219 (2004).
- Finkbeiner, Weiner, Phys. Rev. D **76**, 083519 (2007).
- Pospelov, Ritz, Voloshin, Phys. Lett. B **662**, 52 (2008).
- Feng, Kumar, Phys. Rev. Lett. **101**, 231301 (2008).

dark matter freezeout



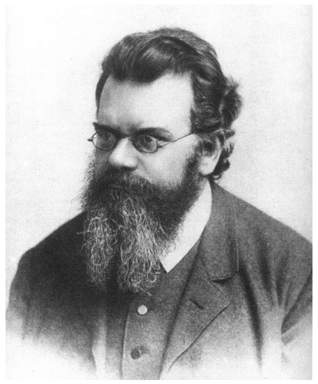
Forbidden Dark Matter

$$m_{DM} < m_X$$



$$\delta m = m_X - m_{DM}$$

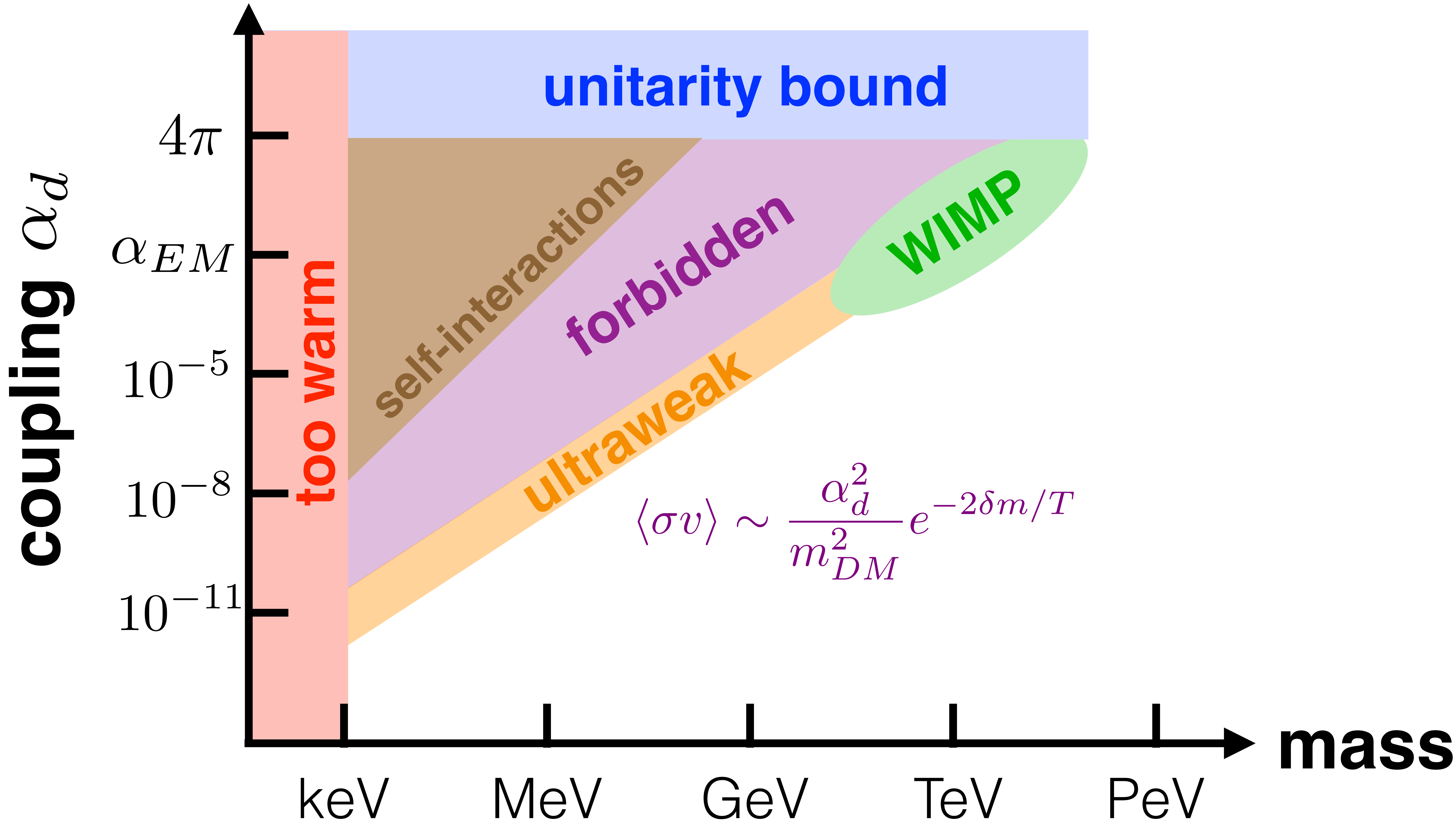
- thermal average: $\langle \sigma v \rangle \sim \frac{\alpha_d^2}{m_{DM}^2} e^{-2\delta m/T}$



$$e^{-2\delta m/T_{FO}} \ll 1$$

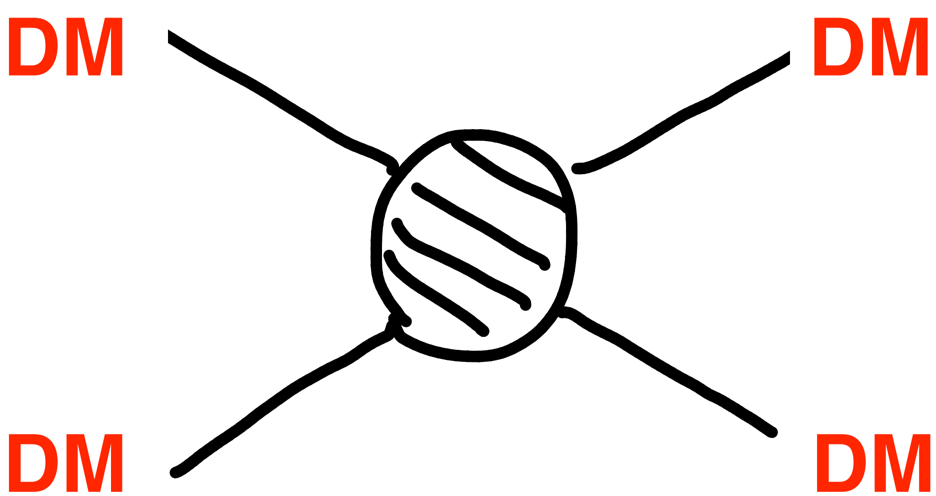
- Griest, Seckel, Phys. Rev. D **43**, 3191 (1991).
- D'Agnolo, Ruderman, Phys. Rev. Lett. **115** 061301 (2015).

dark matter freezeout

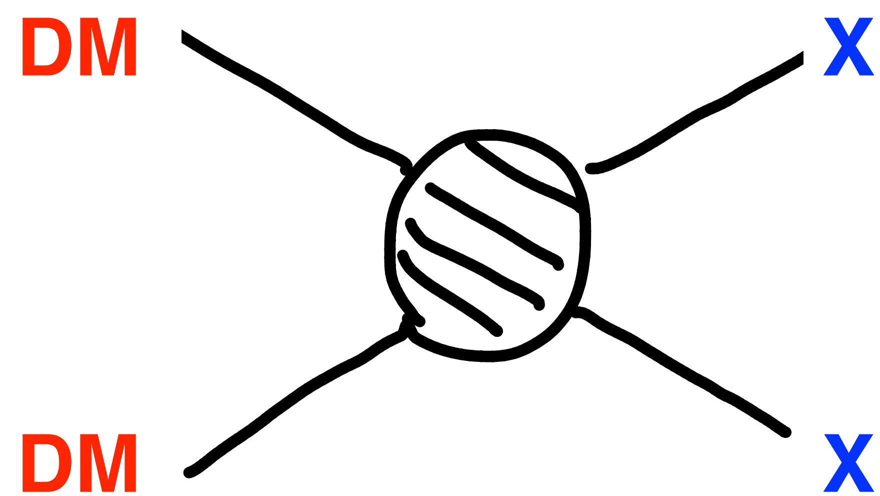


Forbidden DM Phenomenology

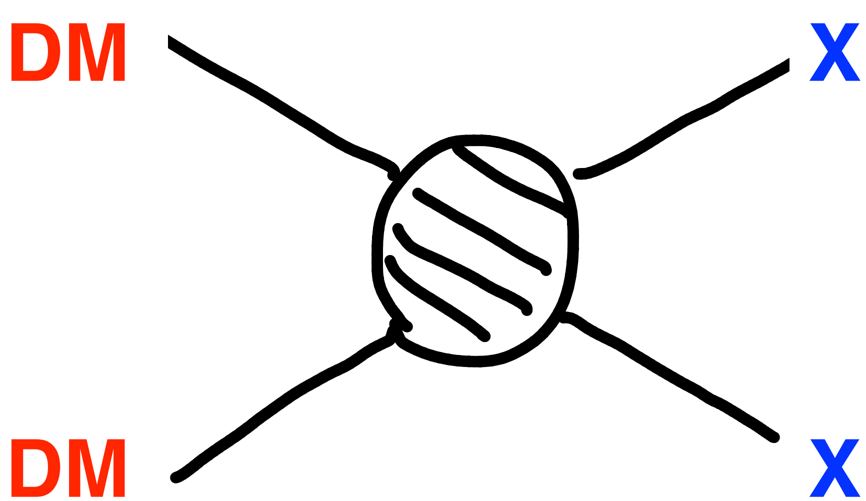
- sizable self-interactions:



$\gg$



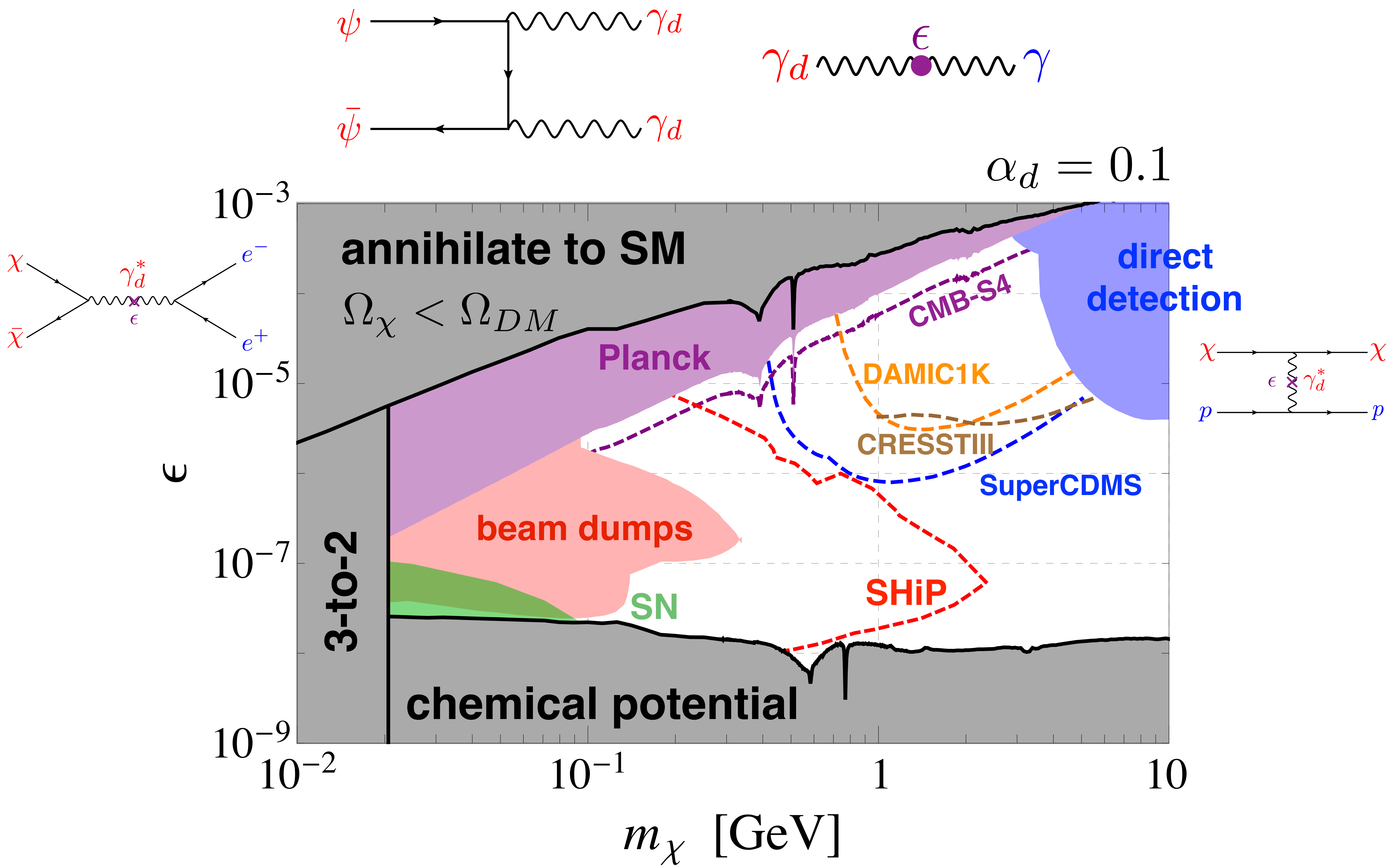
- evades cosmic microwave background:



$$\propto e^{-2\delta m/T_{CMB}}$$

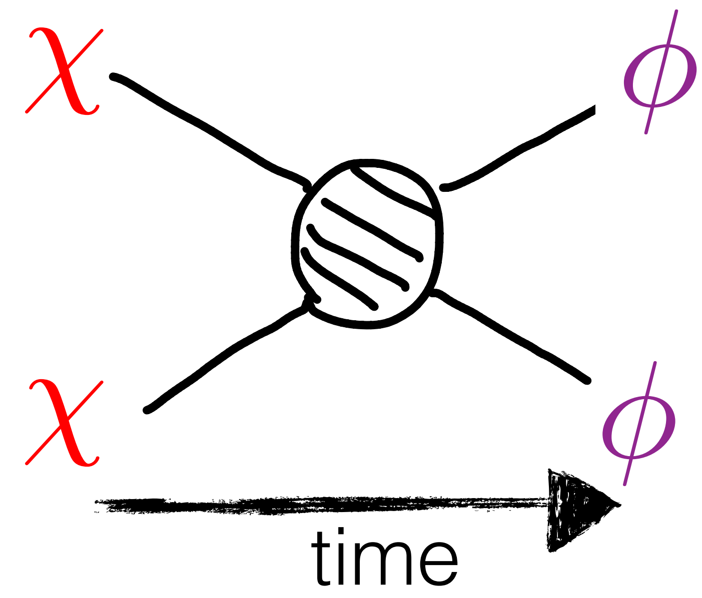
$$\delta m \gg T_{CMB} \sim 1 \text{ eV}$$

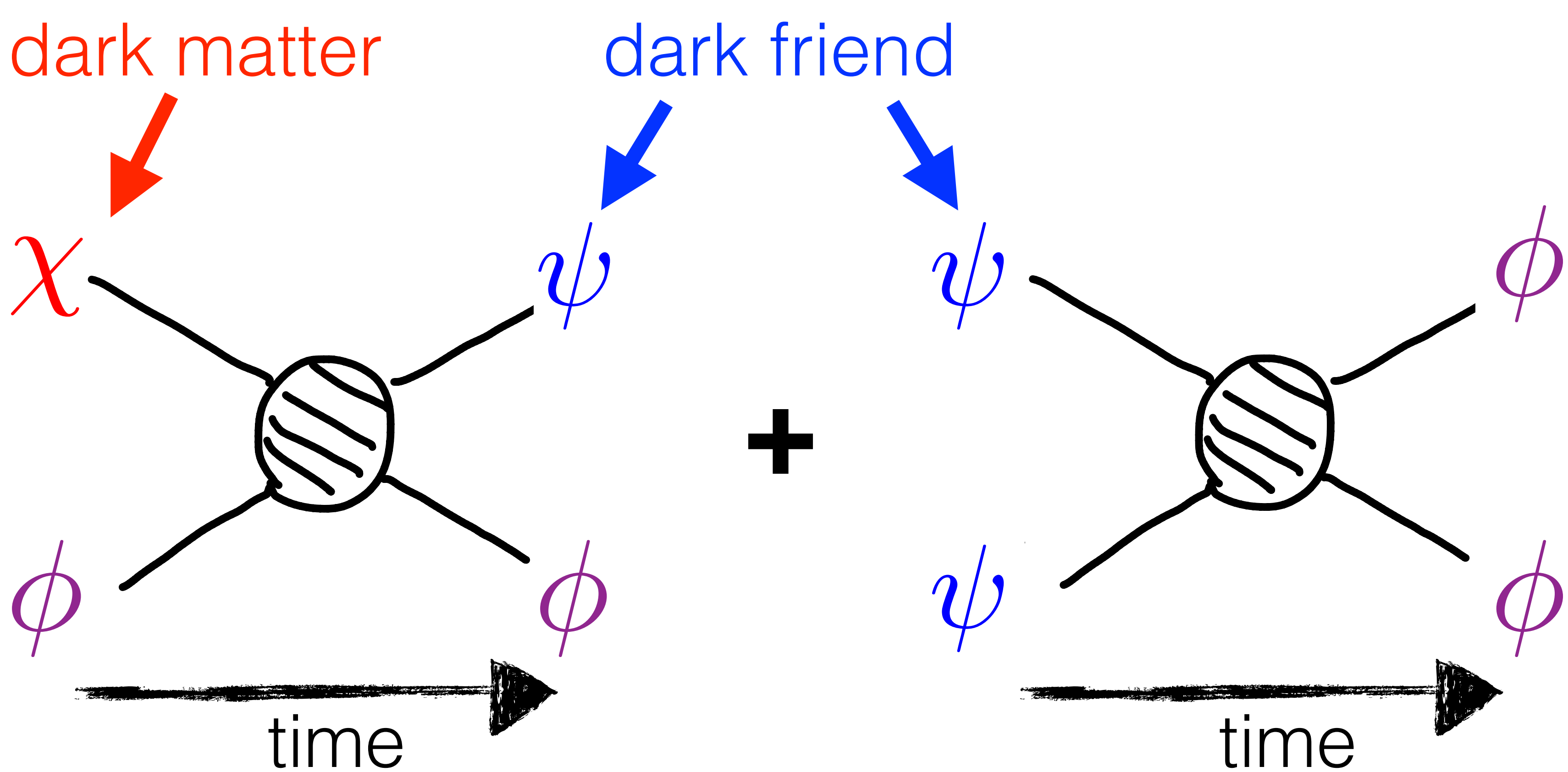
Forbidden DM with Kinetic Mixing Portal

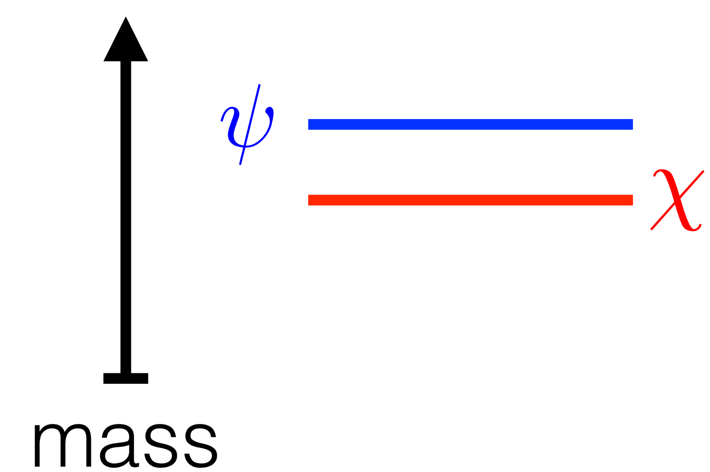


Coscattering

- what if the annihilation rate is too small?

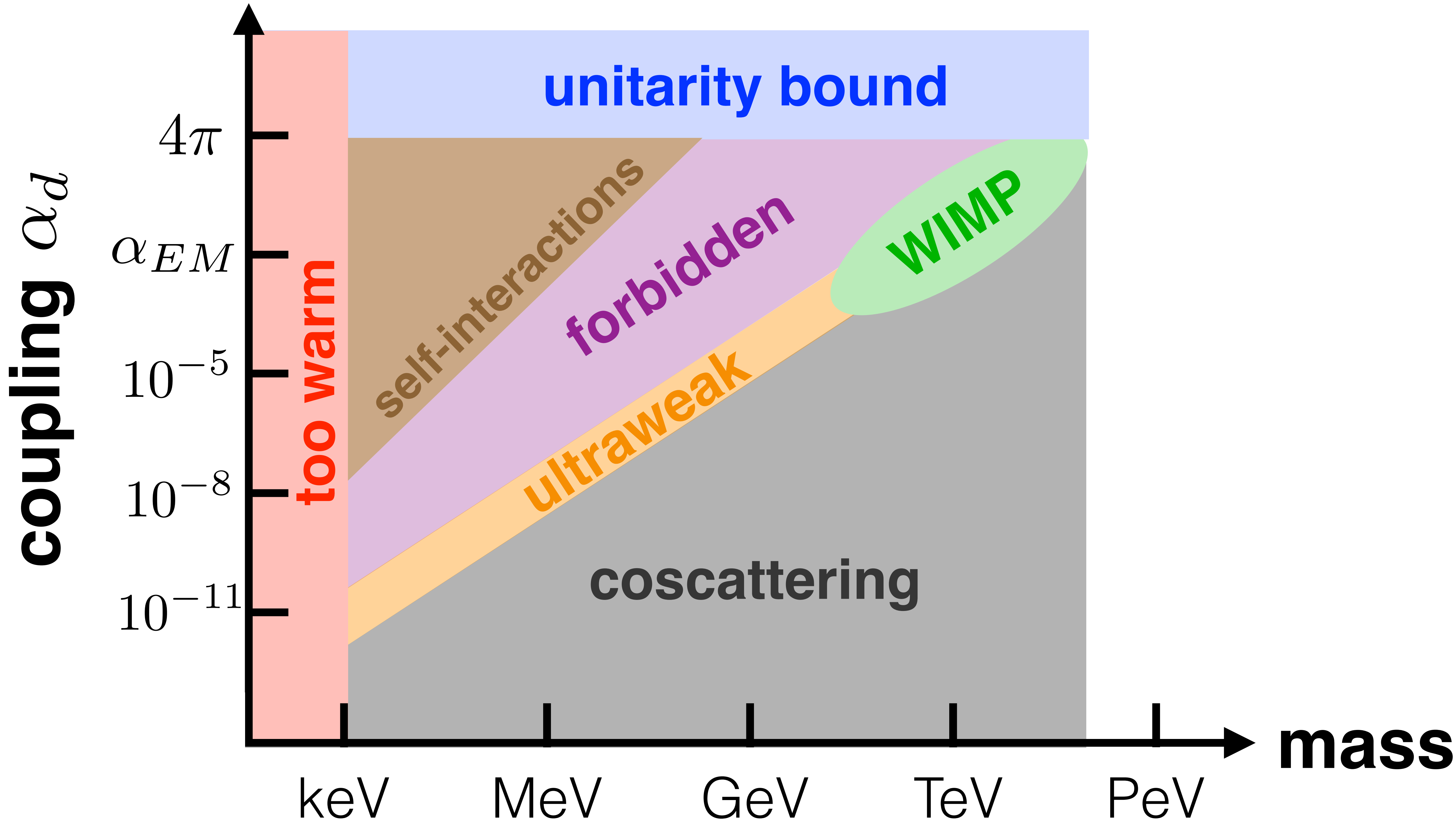






- D'Agnolo, Pappadopulo, Ruderman, Phys. Rev. Lett. **119**, 061102 (2017).

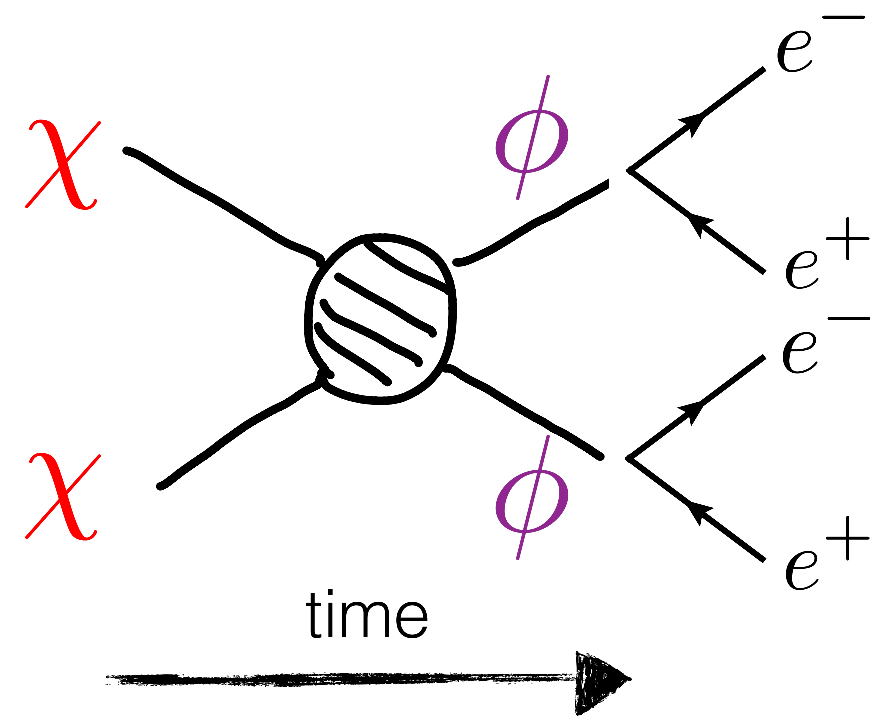
dark matter freezeout



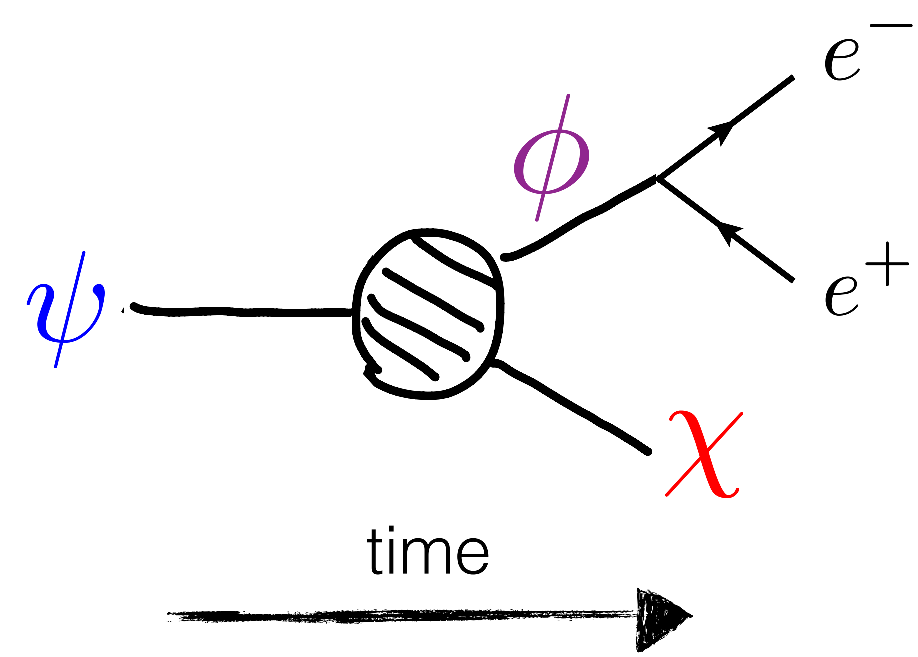
Coscattering Phenomenology

- suppressed annihilations

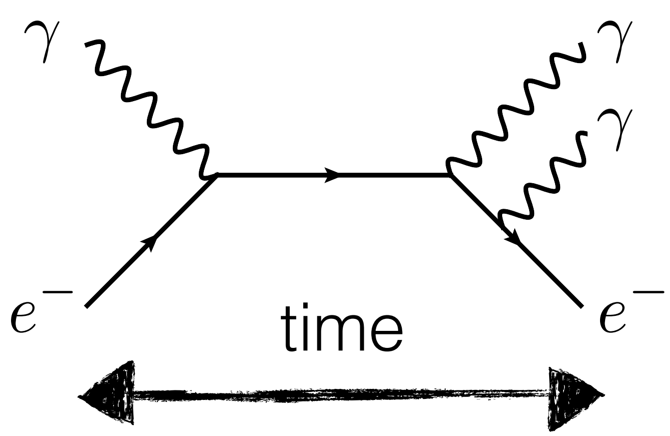
$$\sigma v \ll 3 \times 10^{26} \mathrm{cm}^3/\mathrm{s}$$

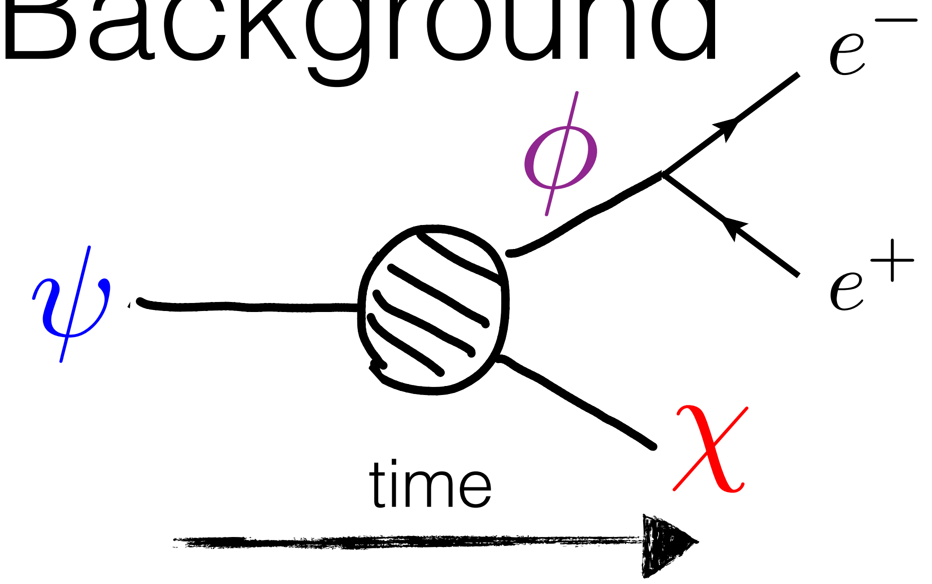


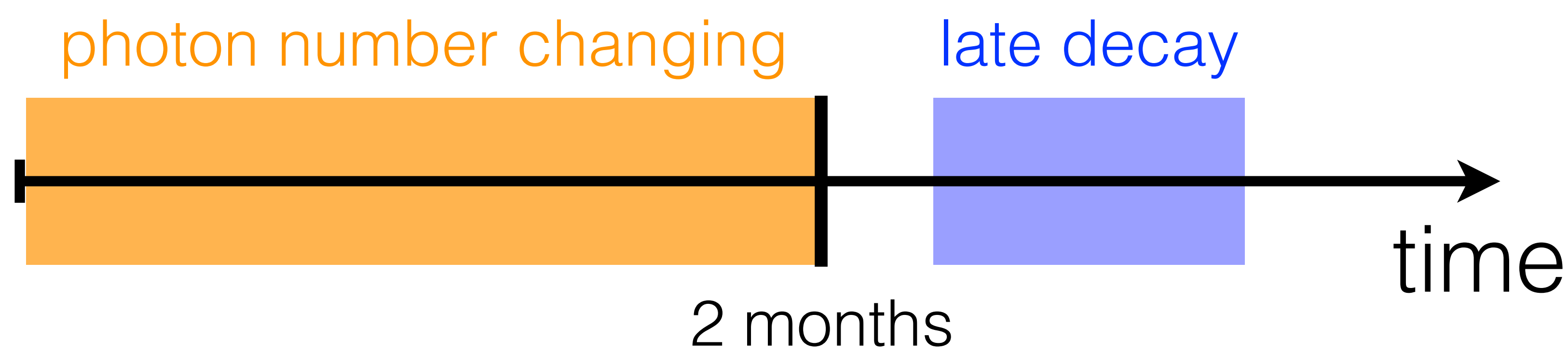
- late decays of dark friend

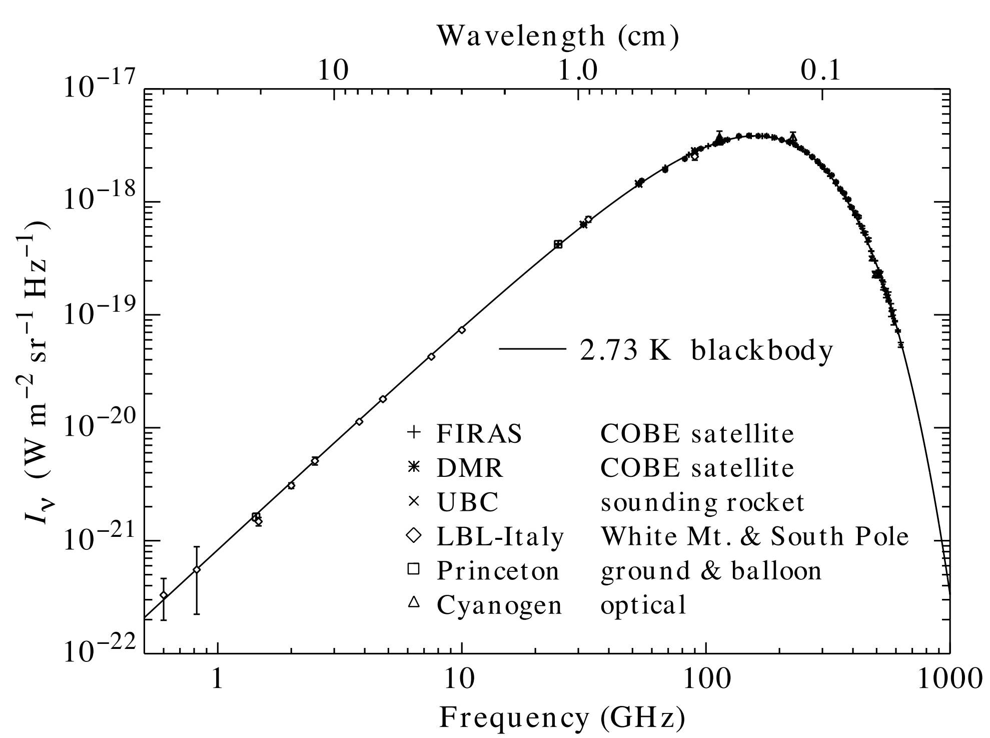


Spectral Distortions of Cosmic Microwave Background





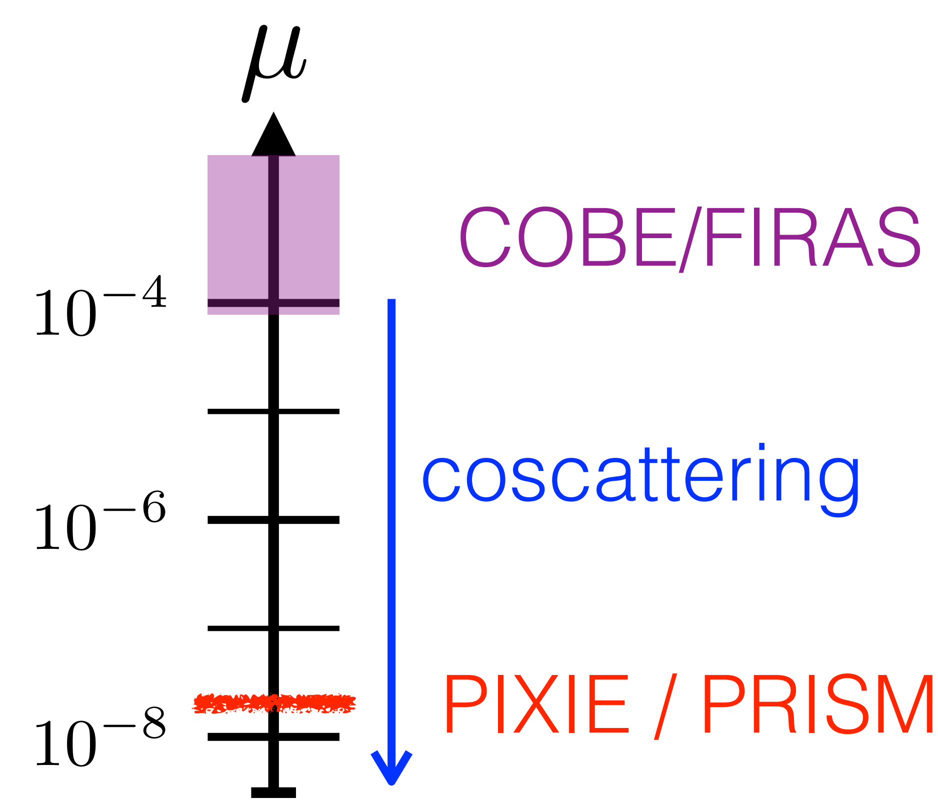




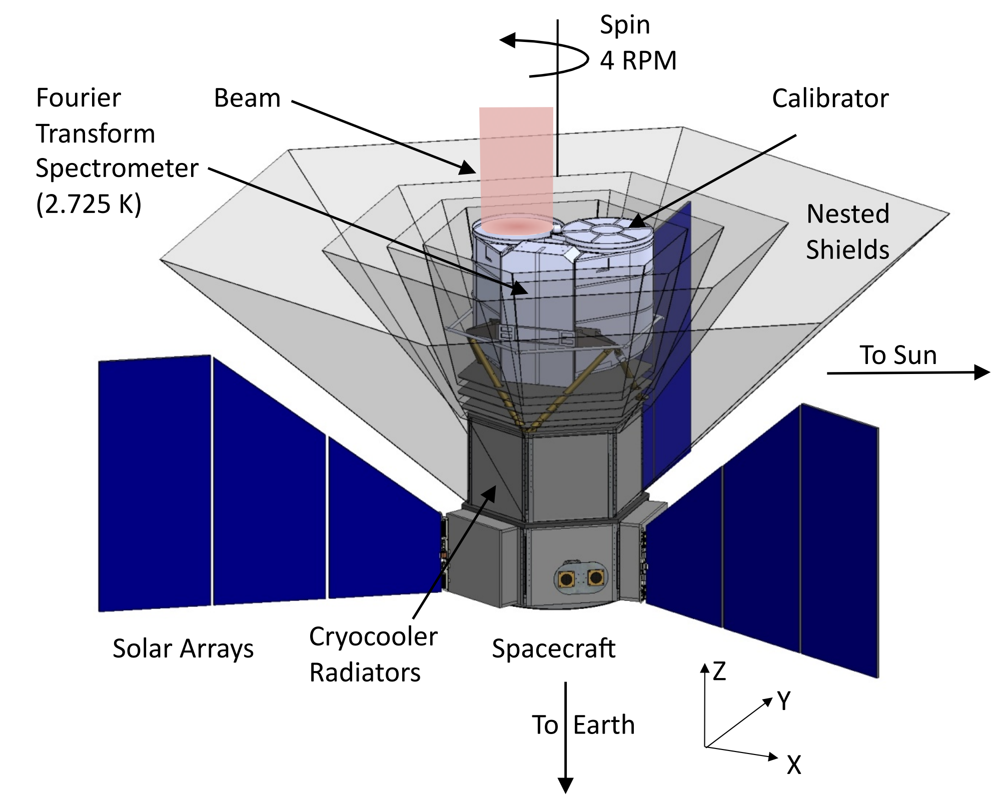
Spectral Distortions of Cosmic Microwave Background

$$\mu - \text{distortion}$$

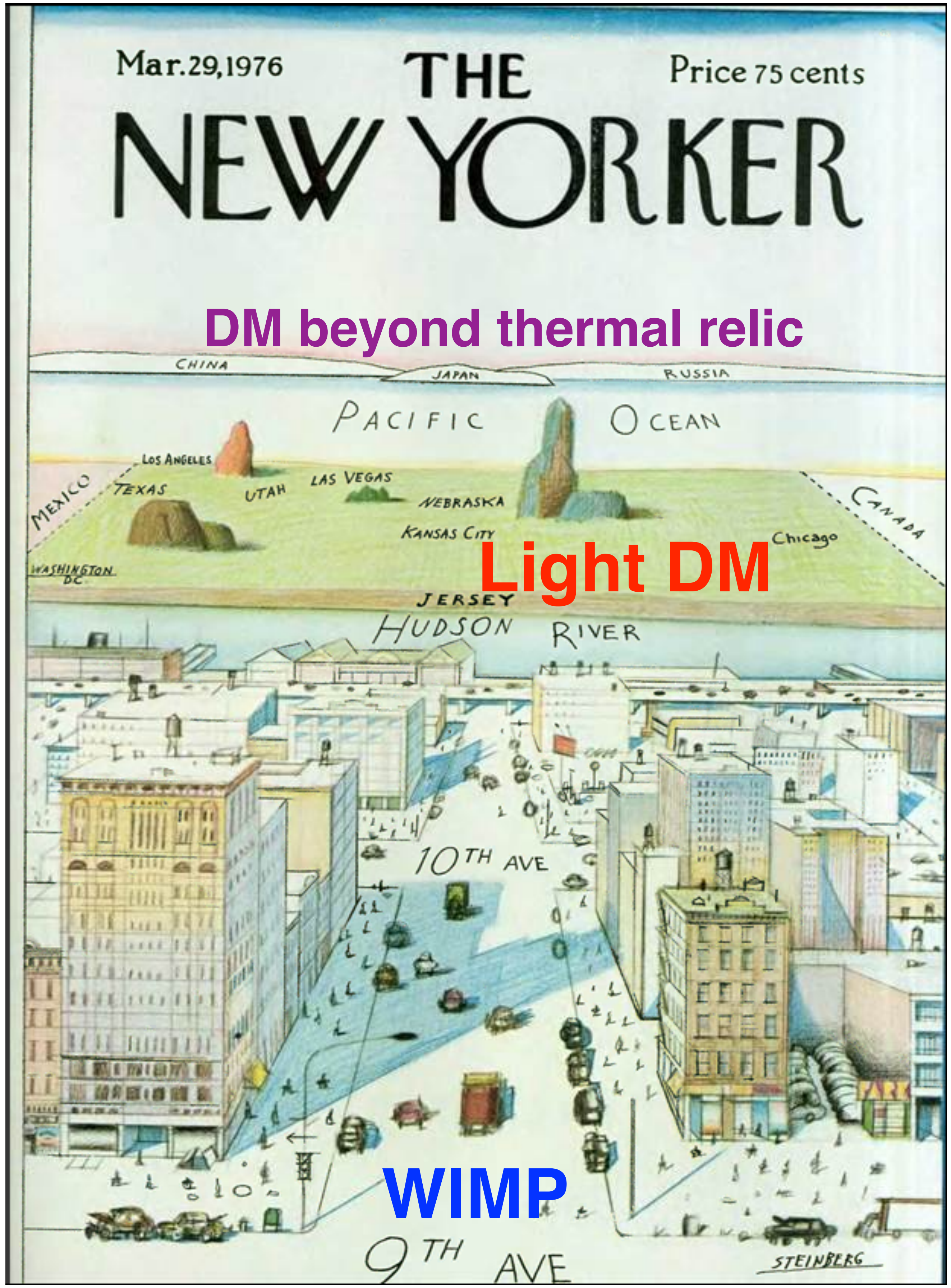
$$f_\gamma(E) = \frac{1}{e^{E/(kT)+\mu} - 1}$$



PIXIE / PRISM can improve sensitivity to *spectral distortions* by factor of ~1000



- Chuss et. al., JCAP **1107**, 025 (2011).
- PRISM Collaboration, JCAP **1402**, 006 (2014).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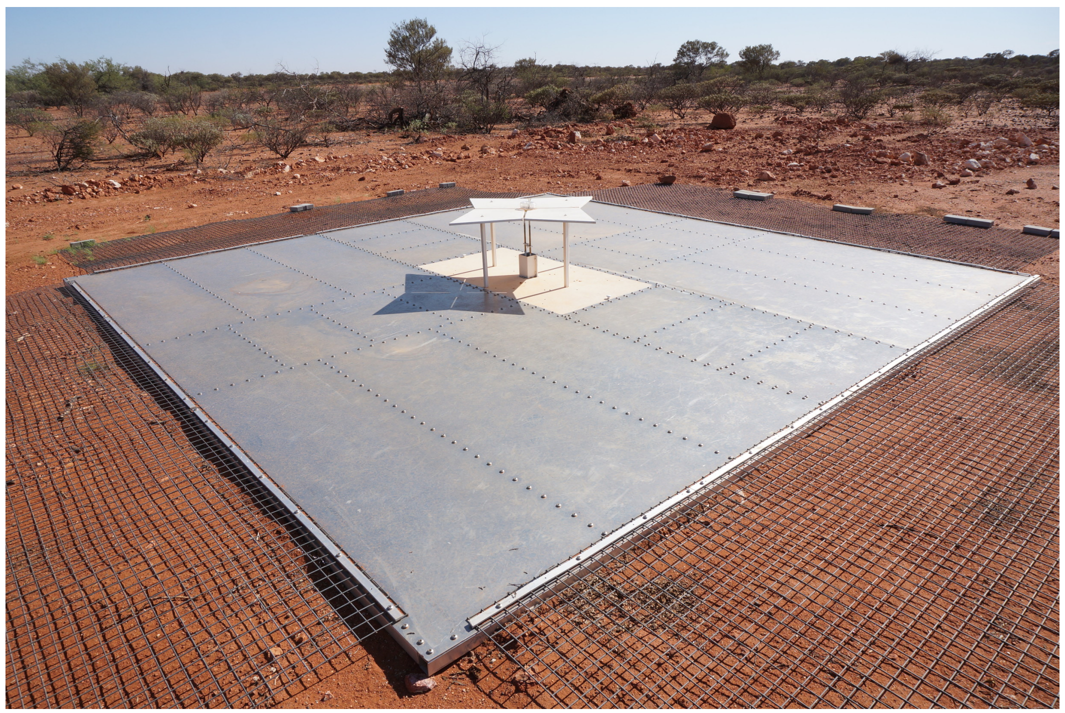
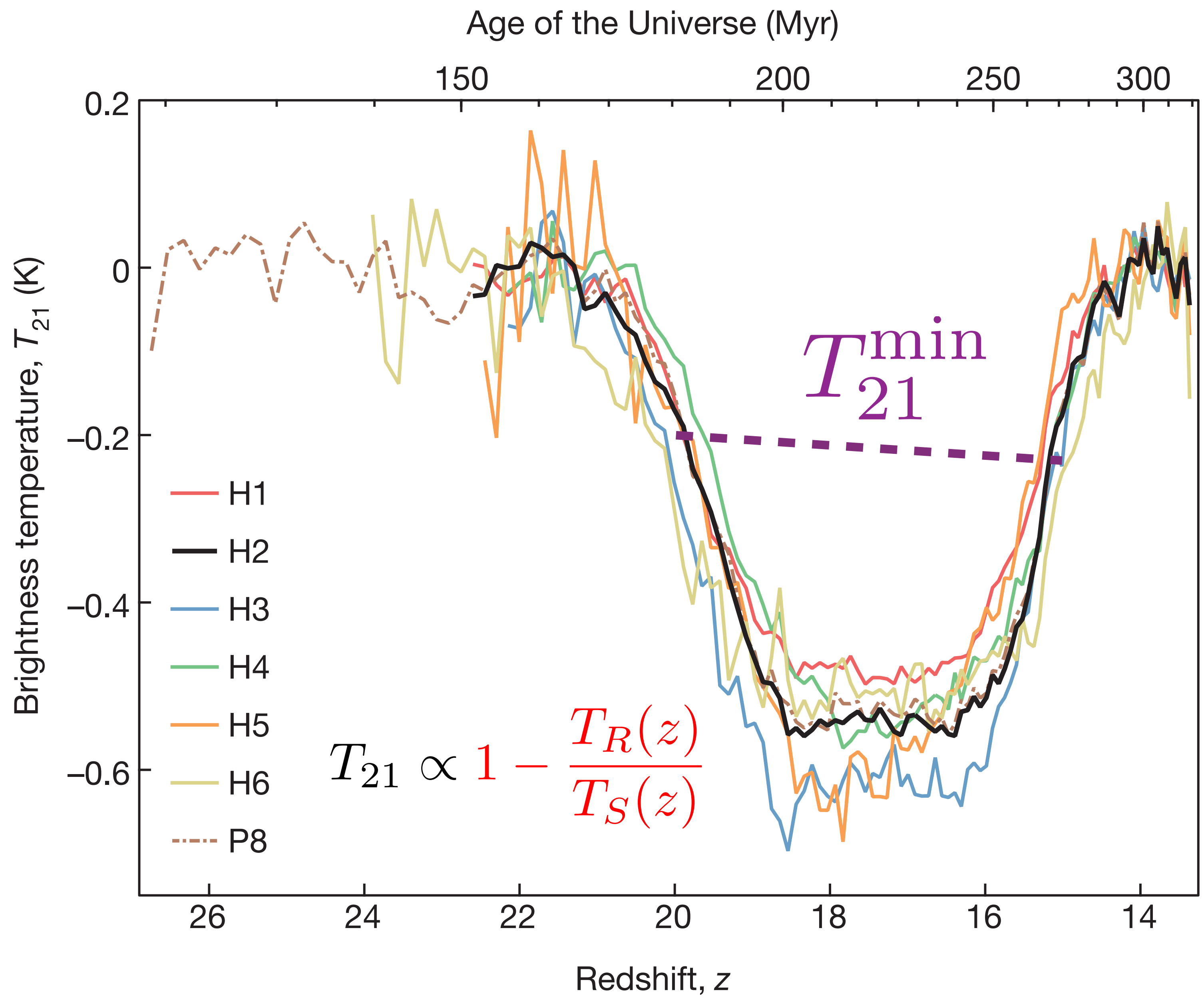
WIMP
9TH AVE
STEINBERG

21cm: Data are Coming!

EDGES



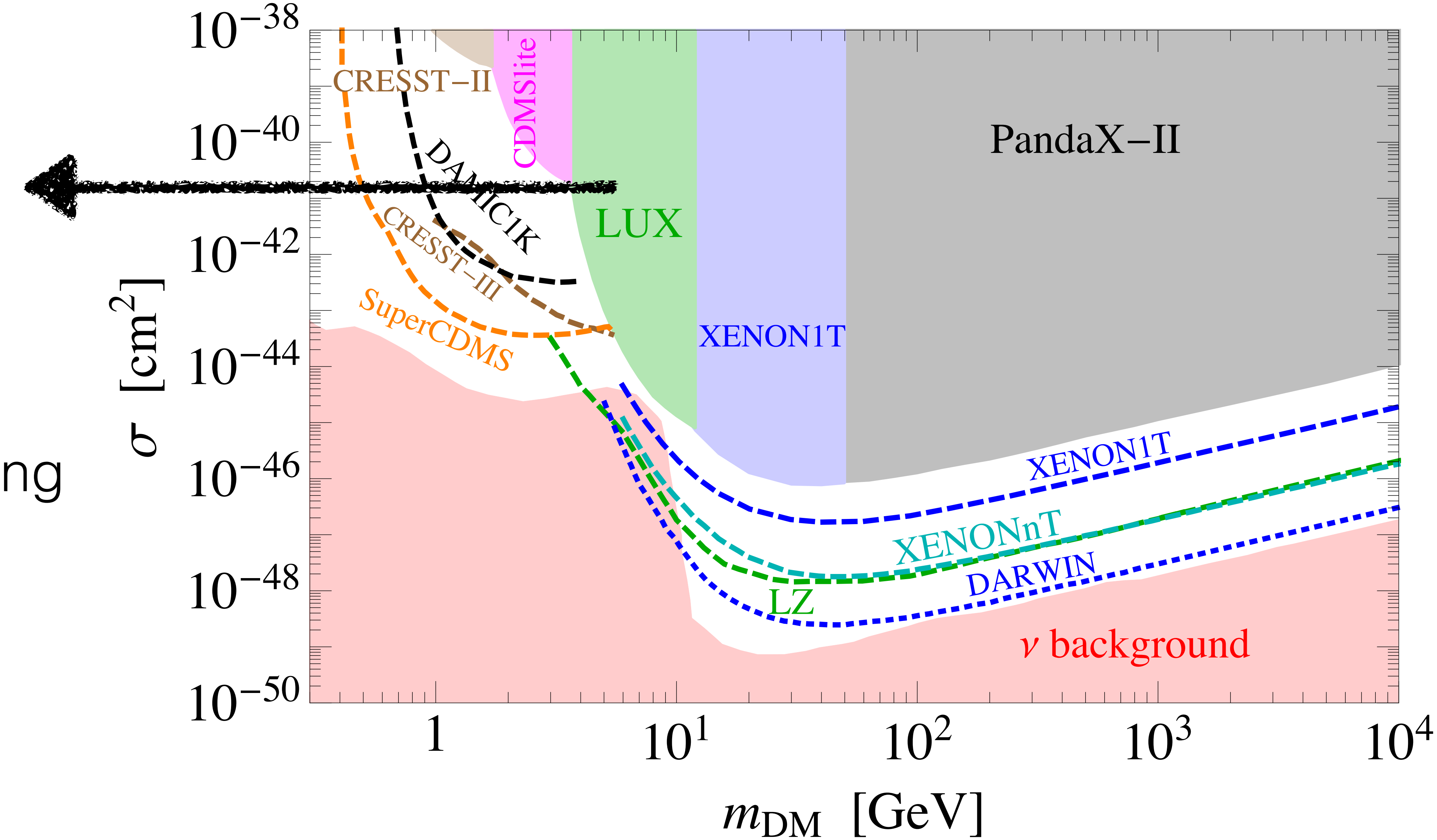


$$T_{21}(17) = -0.5^{+0.2}_{-0.5}\,\mathrm{K} \quad (99\%)$$

- Bowman *et. al.* Nature **555**, 67 (2018)

take away

light DM



1. ultraweak
2. forbidden
3. coscattering

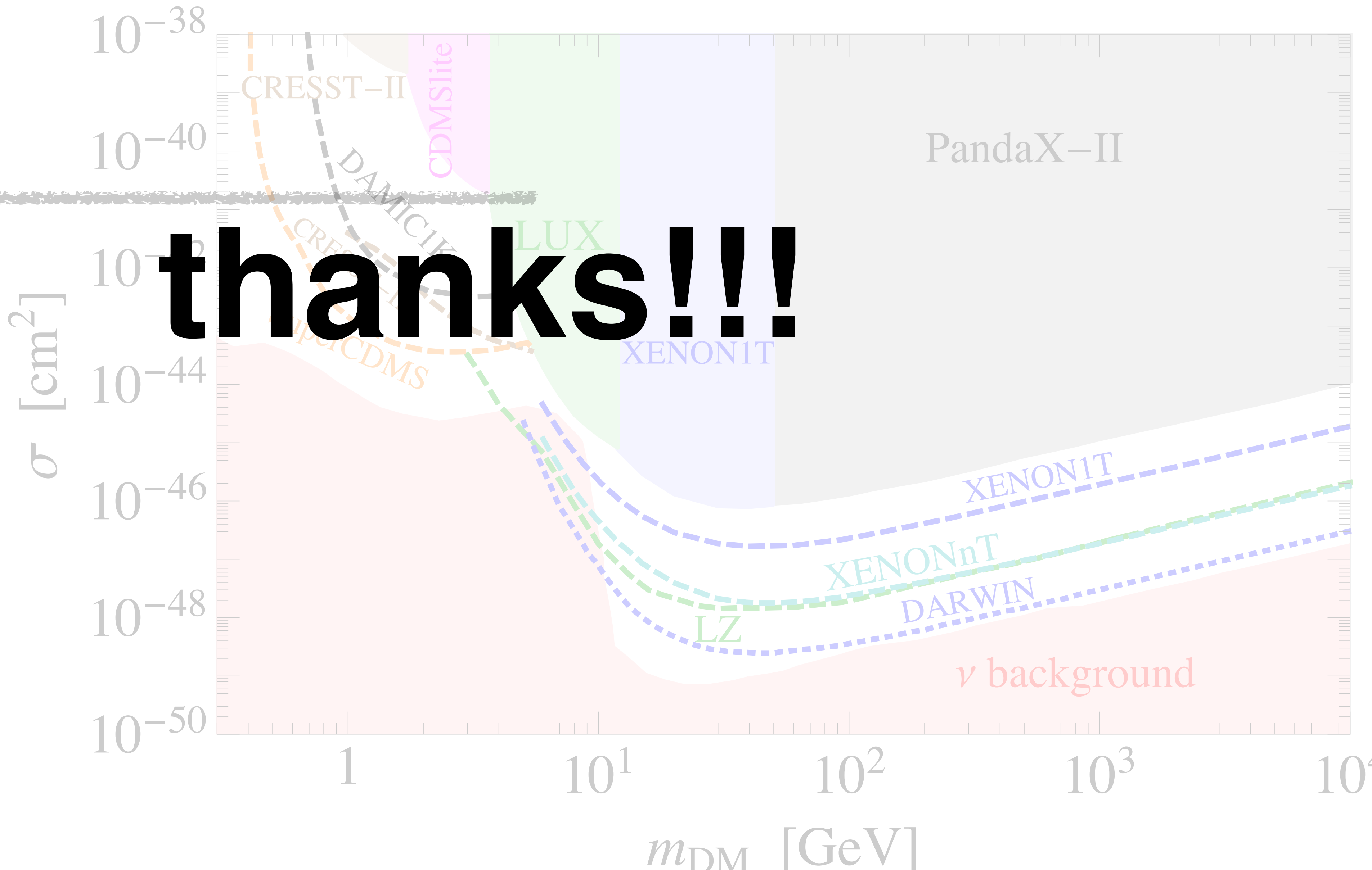
...

take away

light DM

1. ultraweak
2. forbidden
3. coscattering

...



thanks!!!