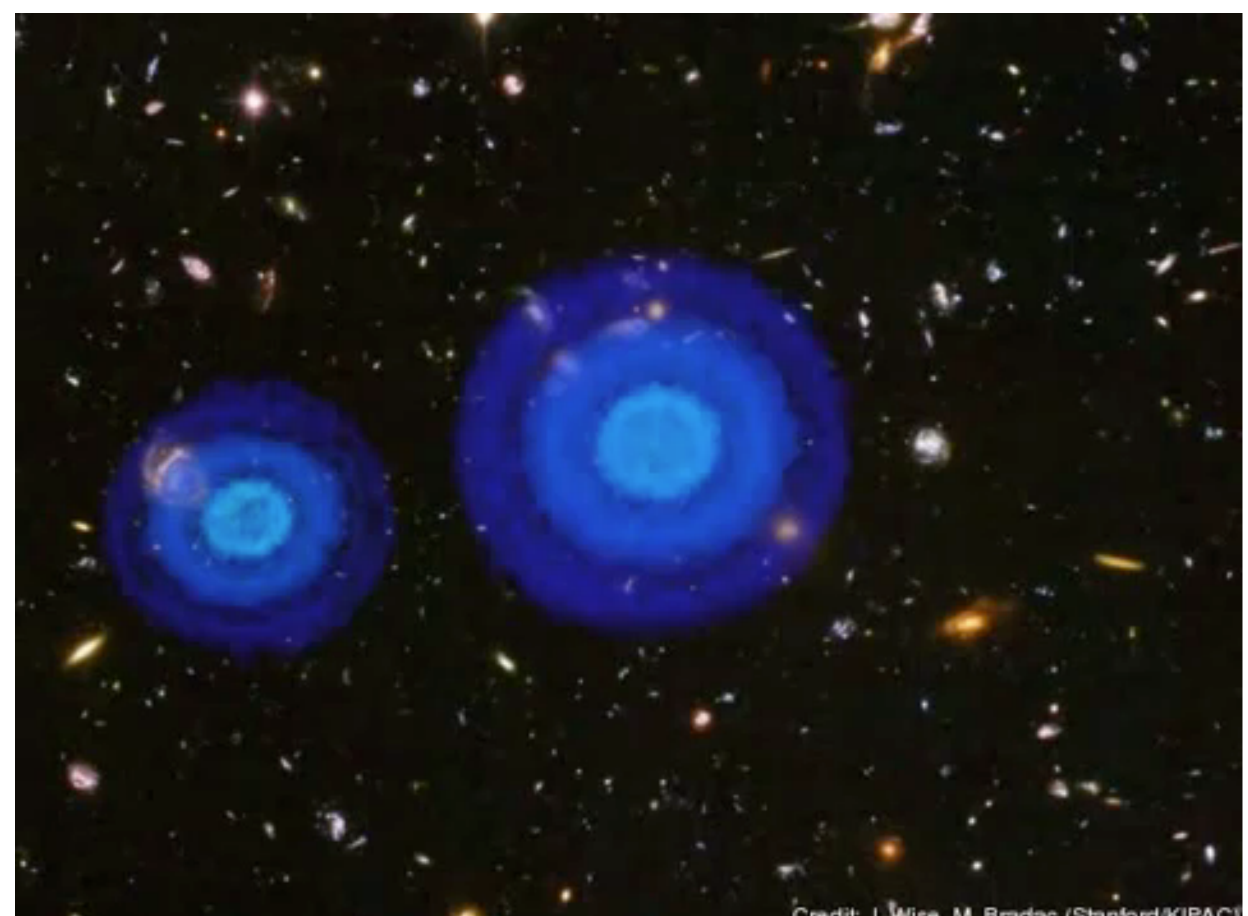
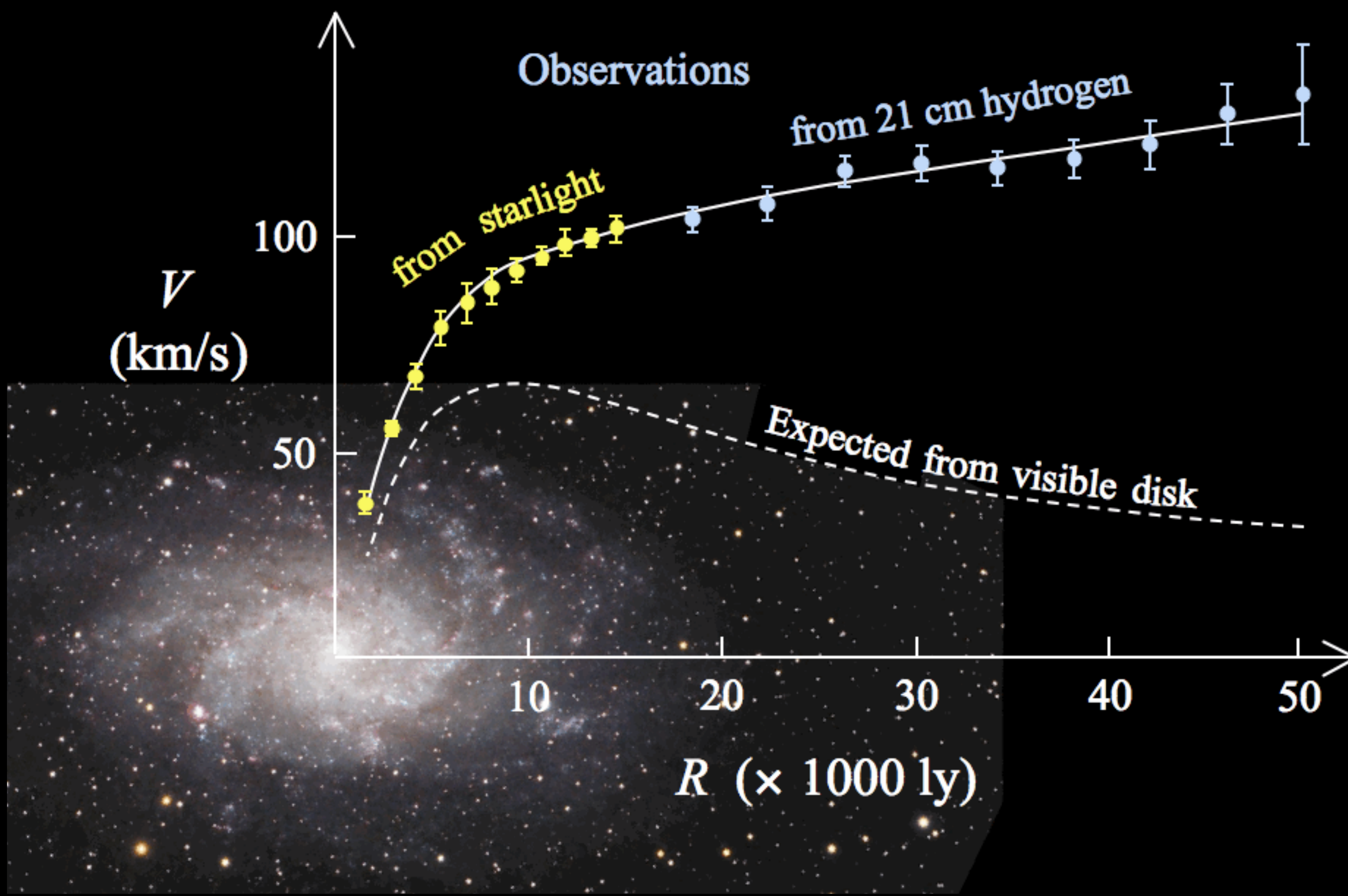
Dark Matter Below the Higgs Scale



Josh Ruderman
(NYU, CERN)
@DESY, 4/3/2018

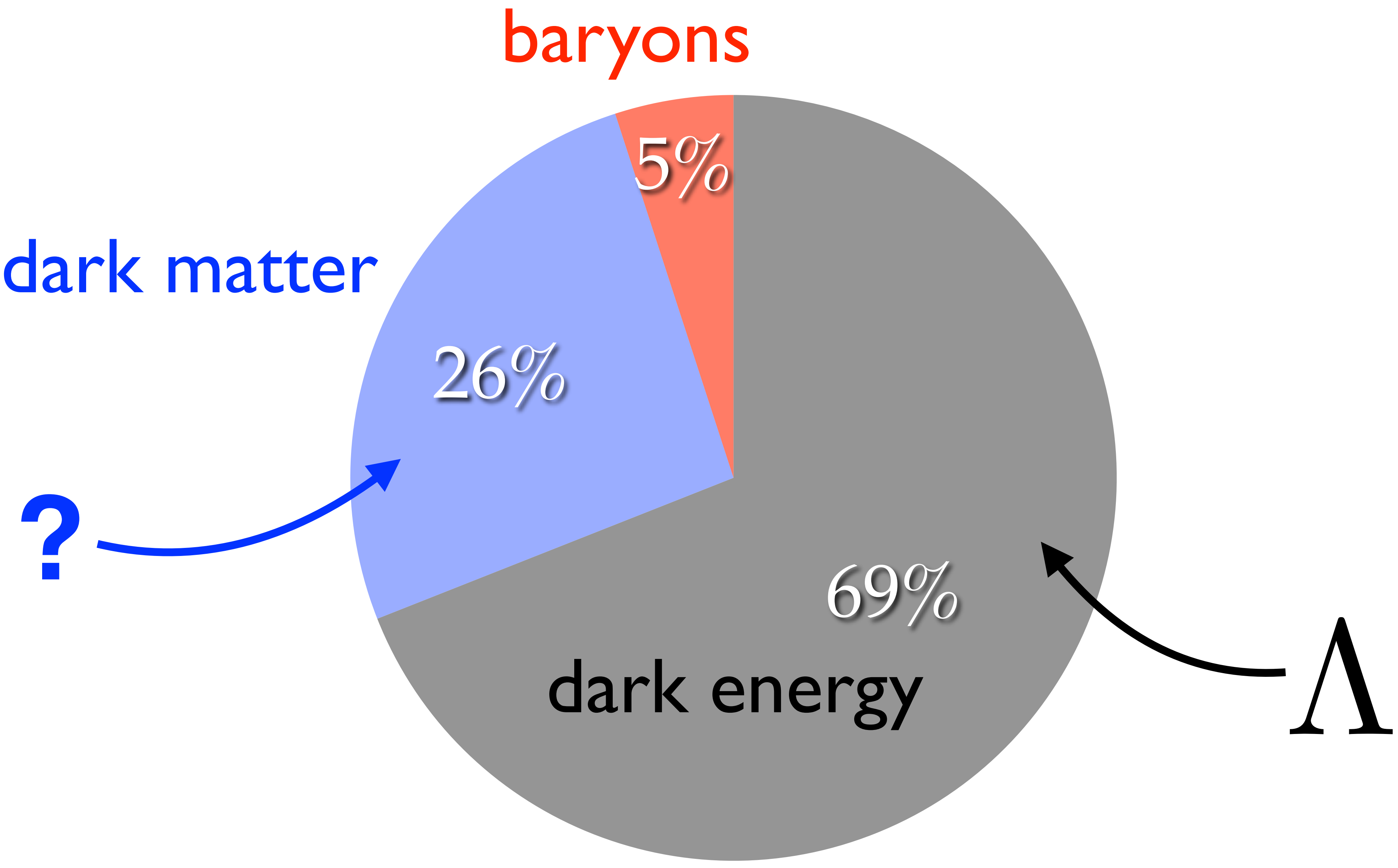
Galactic Rotation Curves

M33

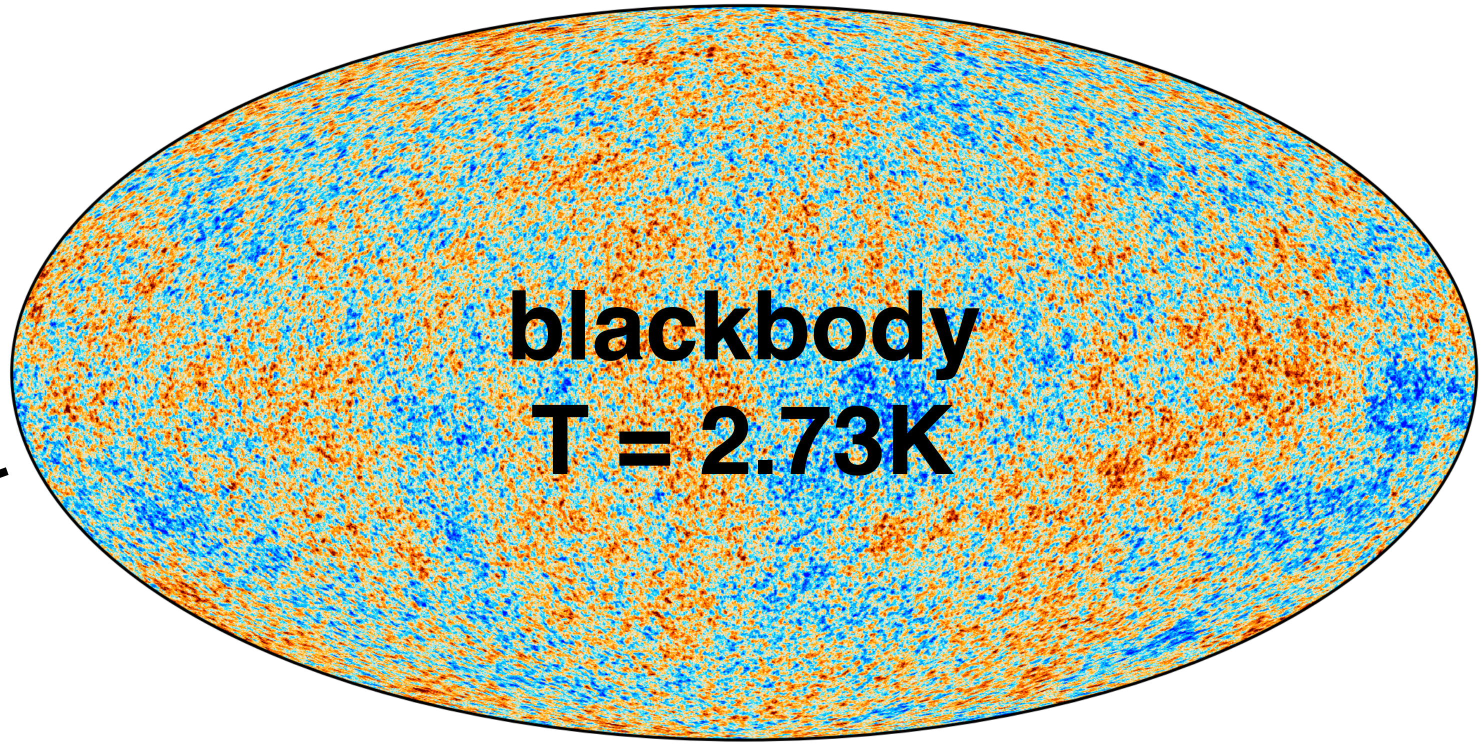


- Corbelli, Salucci, MNRAS **311**, 411 (2000).

Energy Budget of our Universe

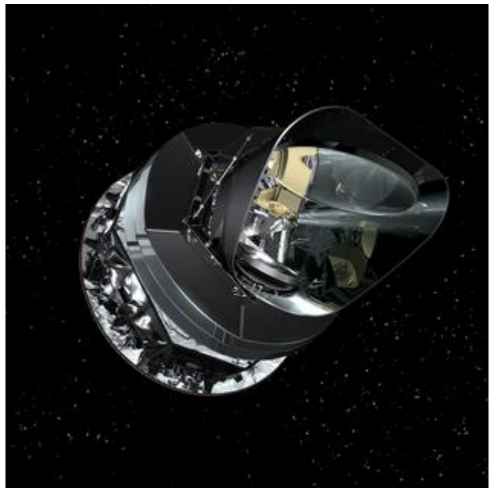


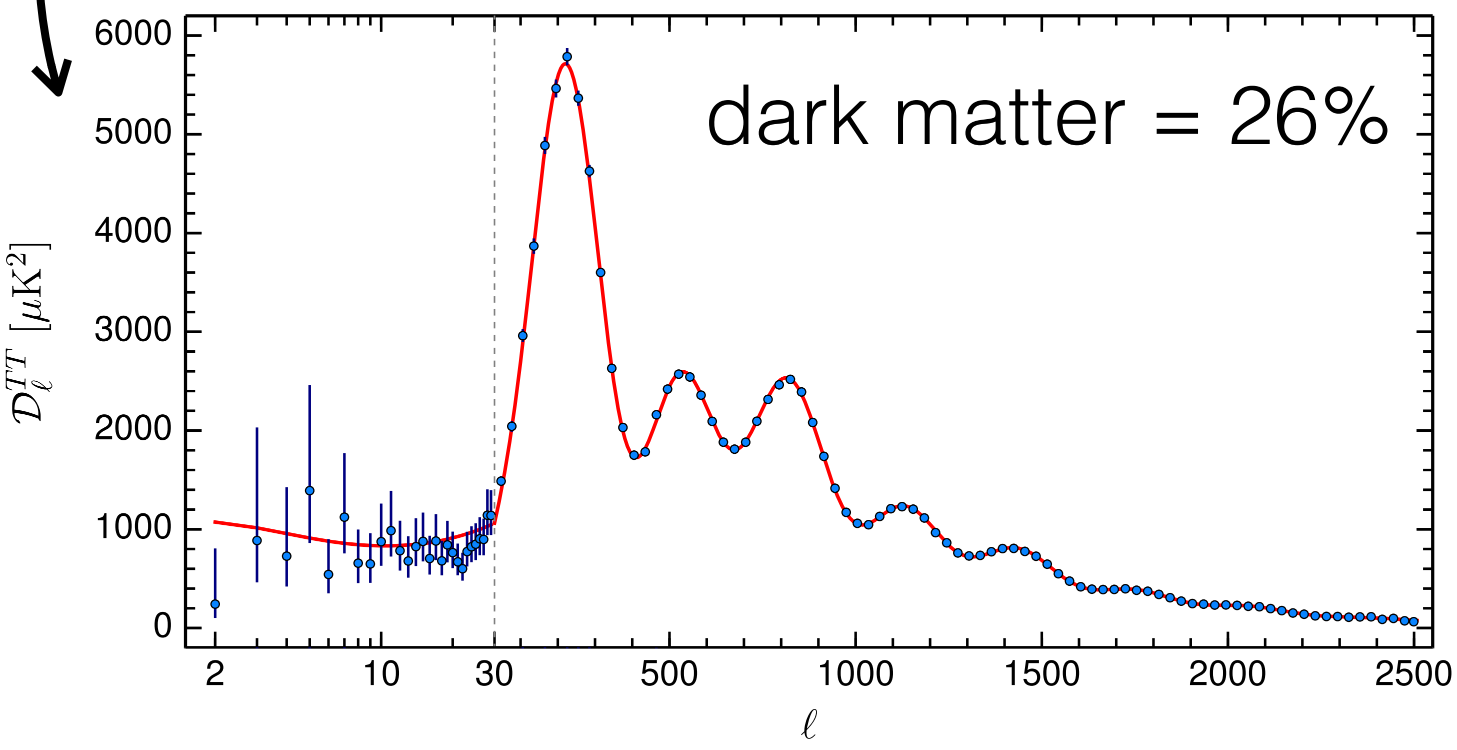
Cosmic Microwave Background

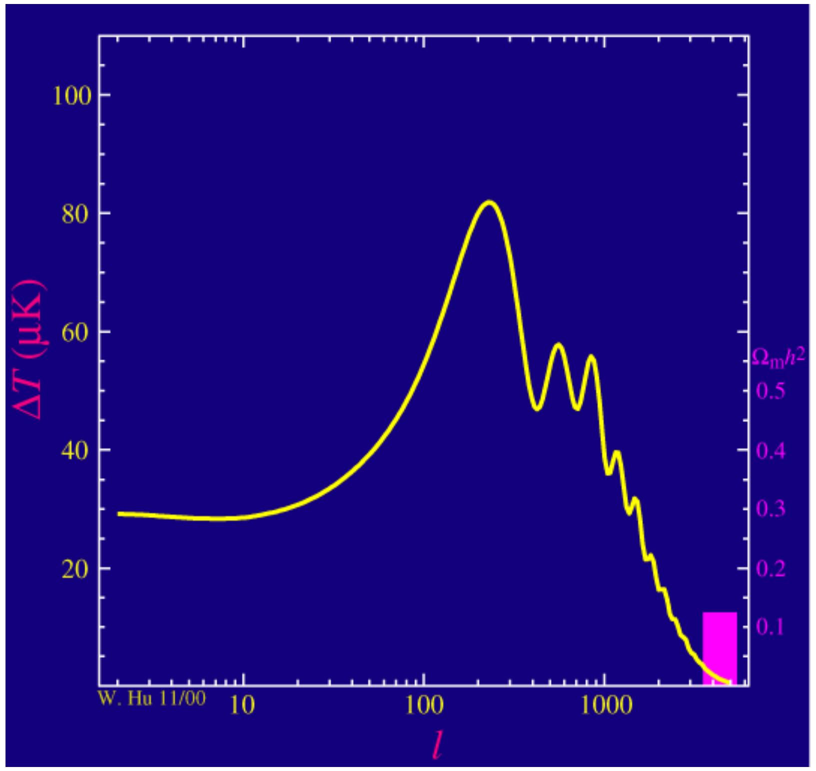


power spectrum

Planck Satellite

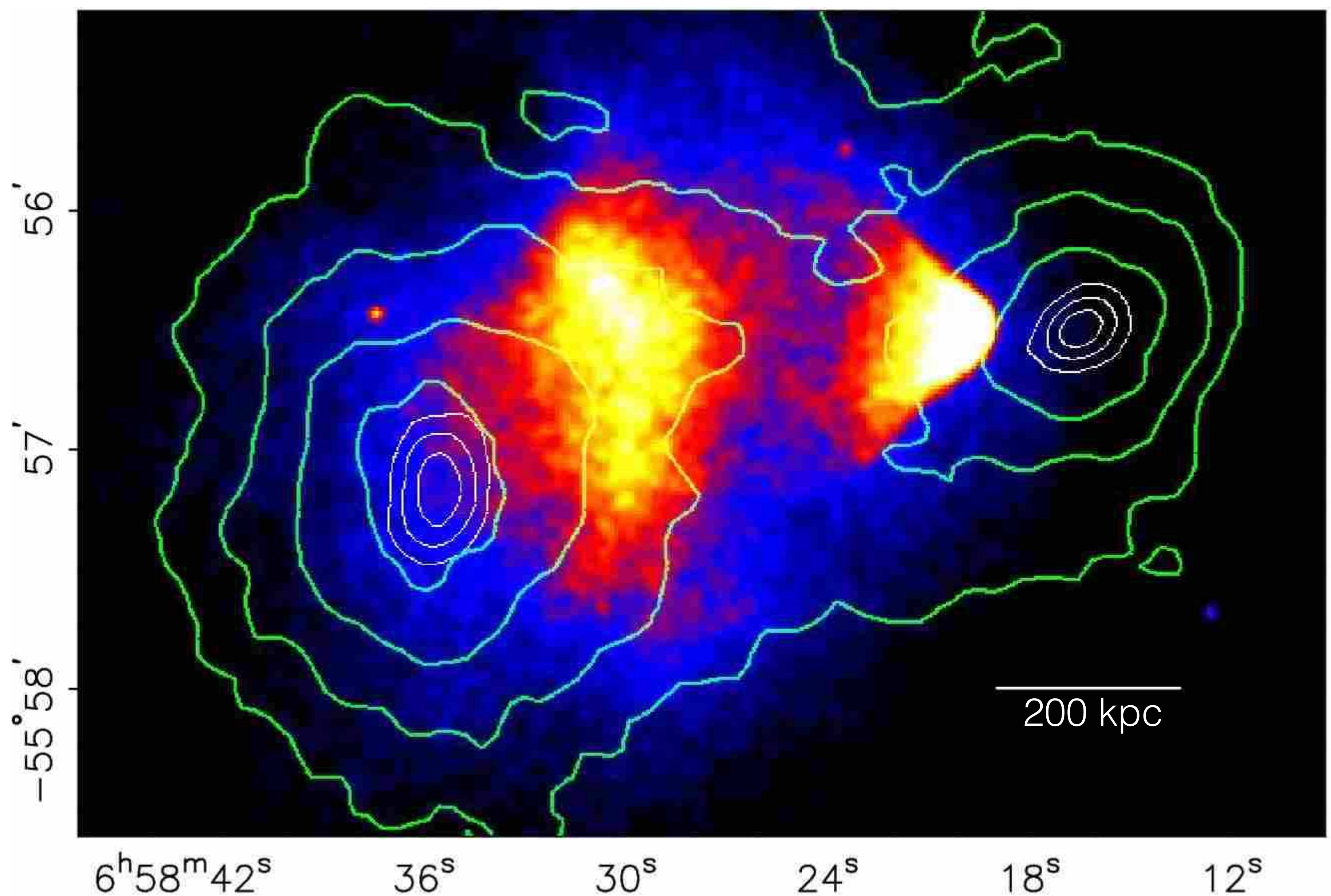






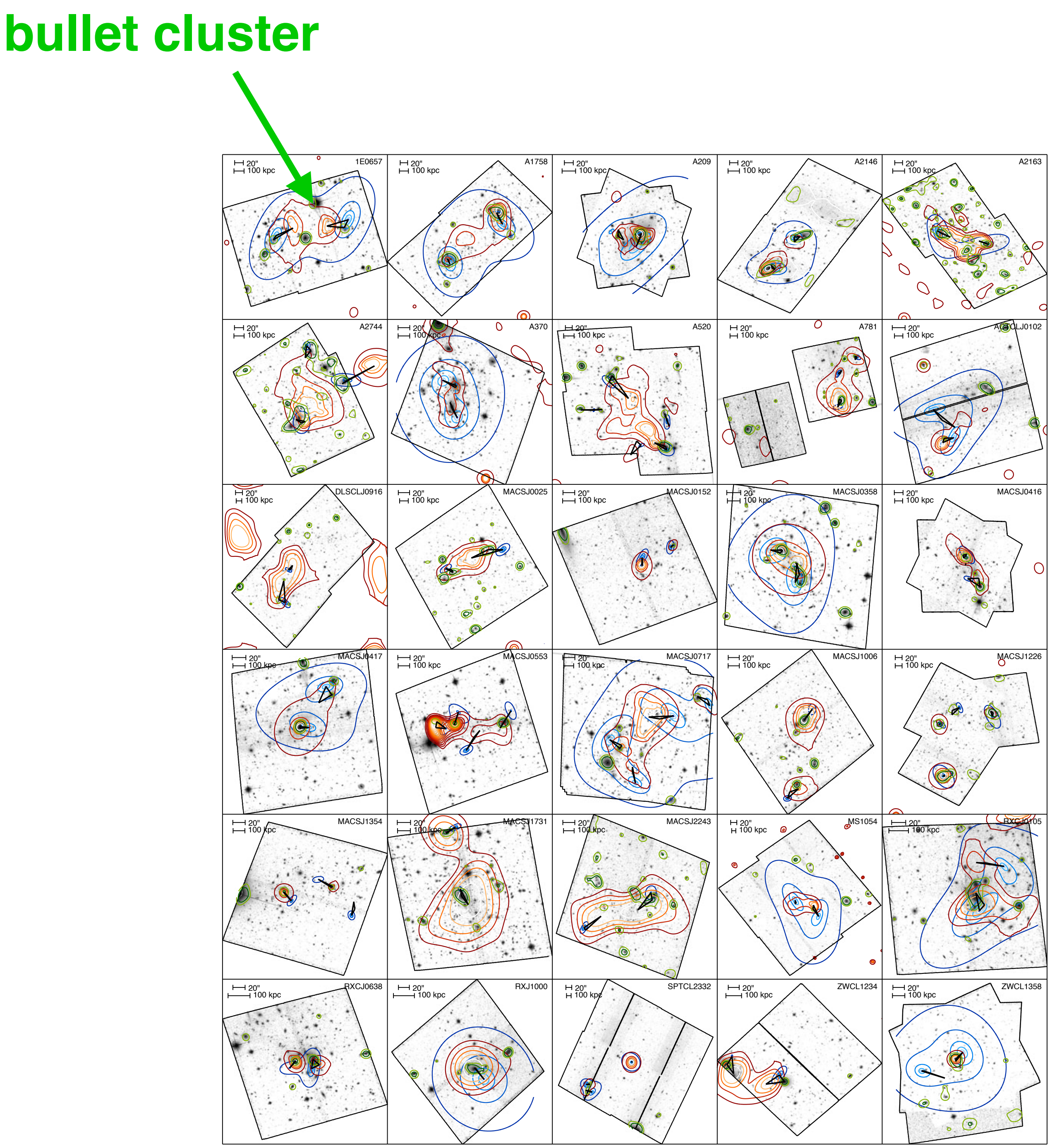
Wayne Hu

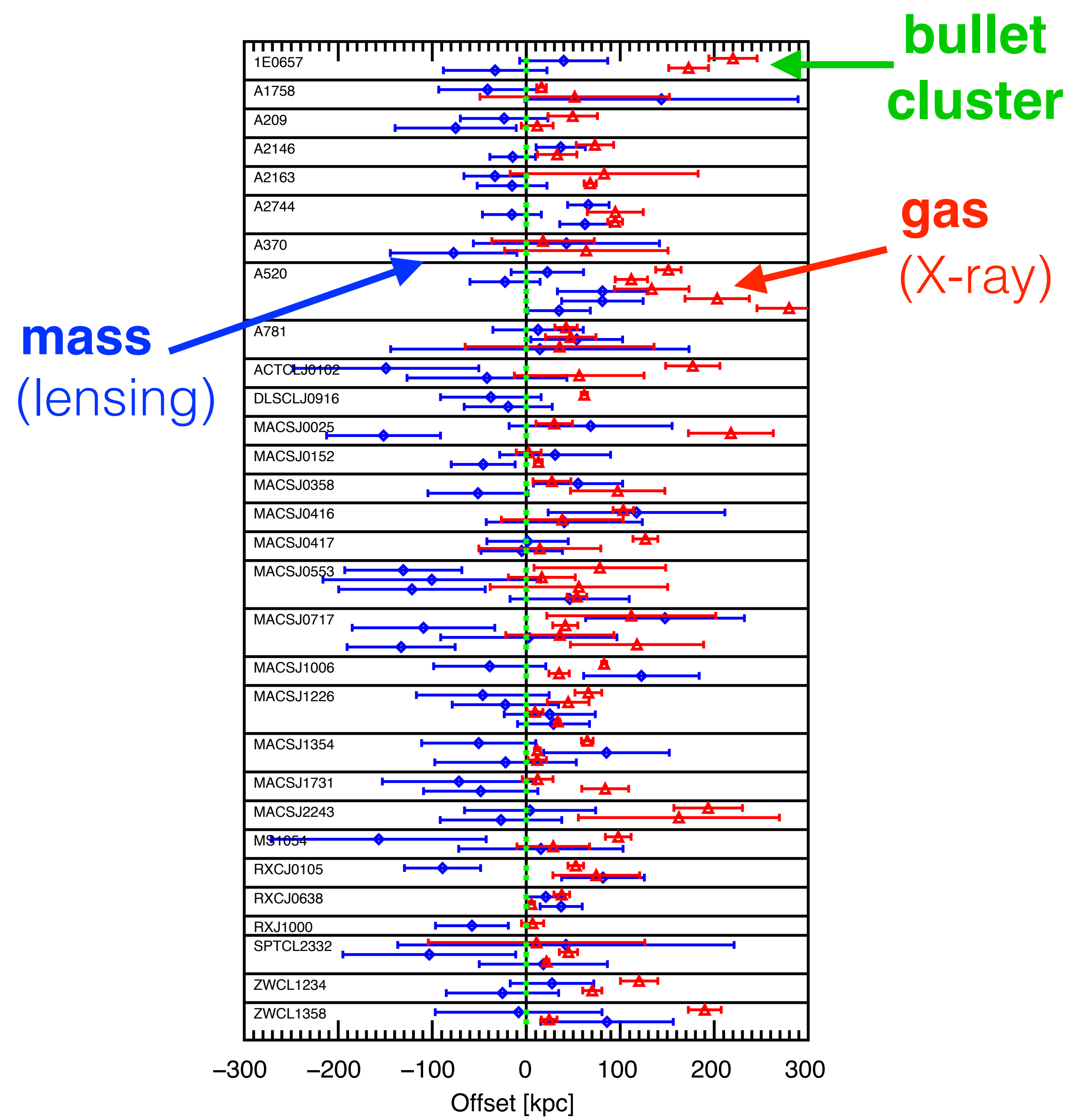
Bullet Cluster



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

Cluster Merger Zoo

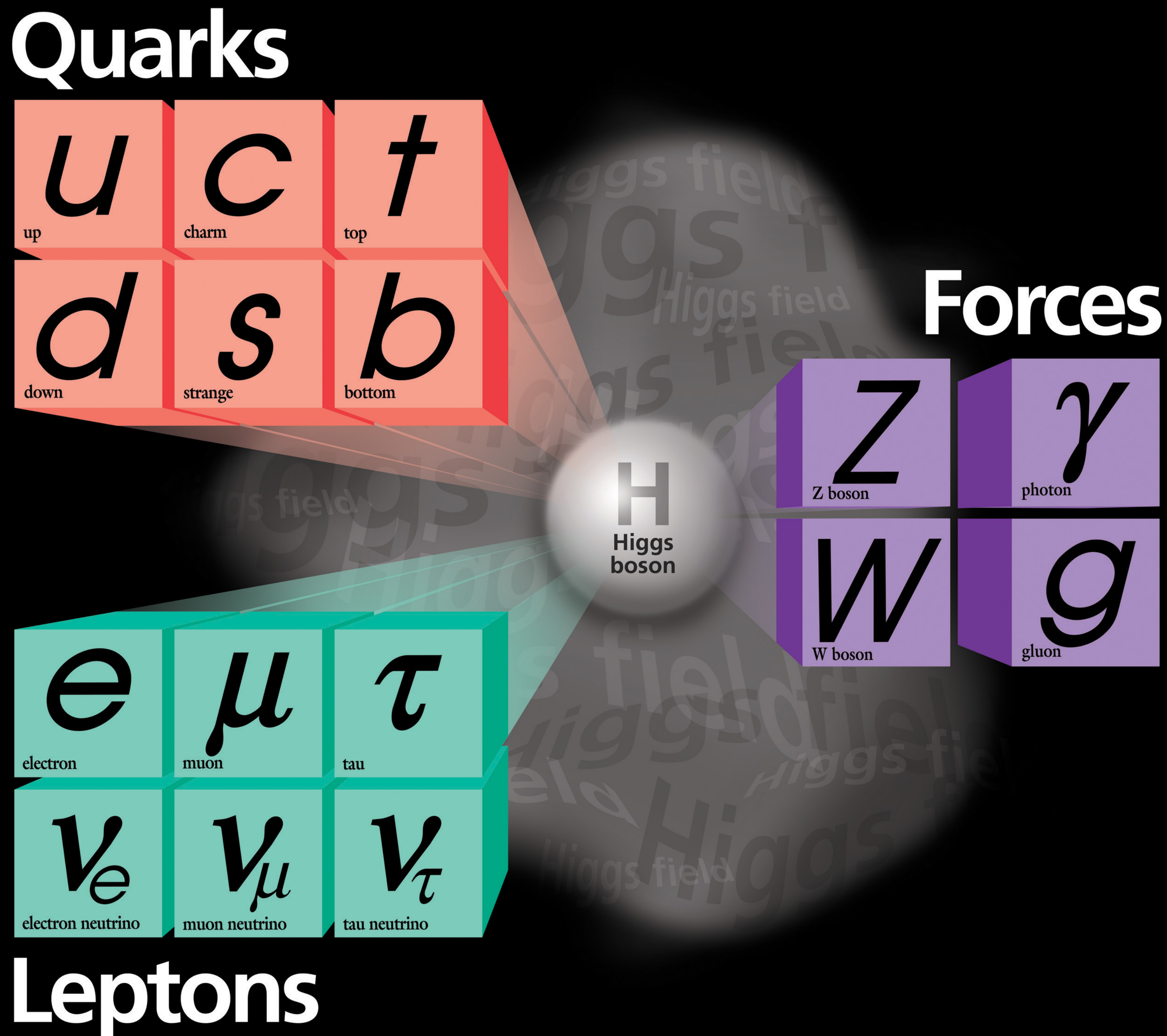




dark matter: 7.6σ

- 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} ⟷

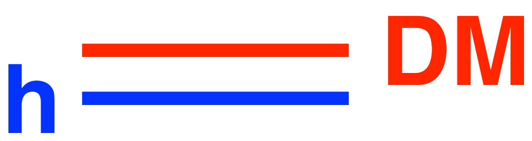
de Broglie wavelength = 1 kpc

black holes

50 decades!

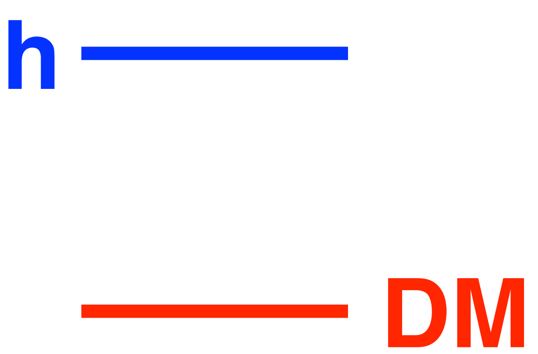
plan

1. Dark Matter at the Higgs Scale

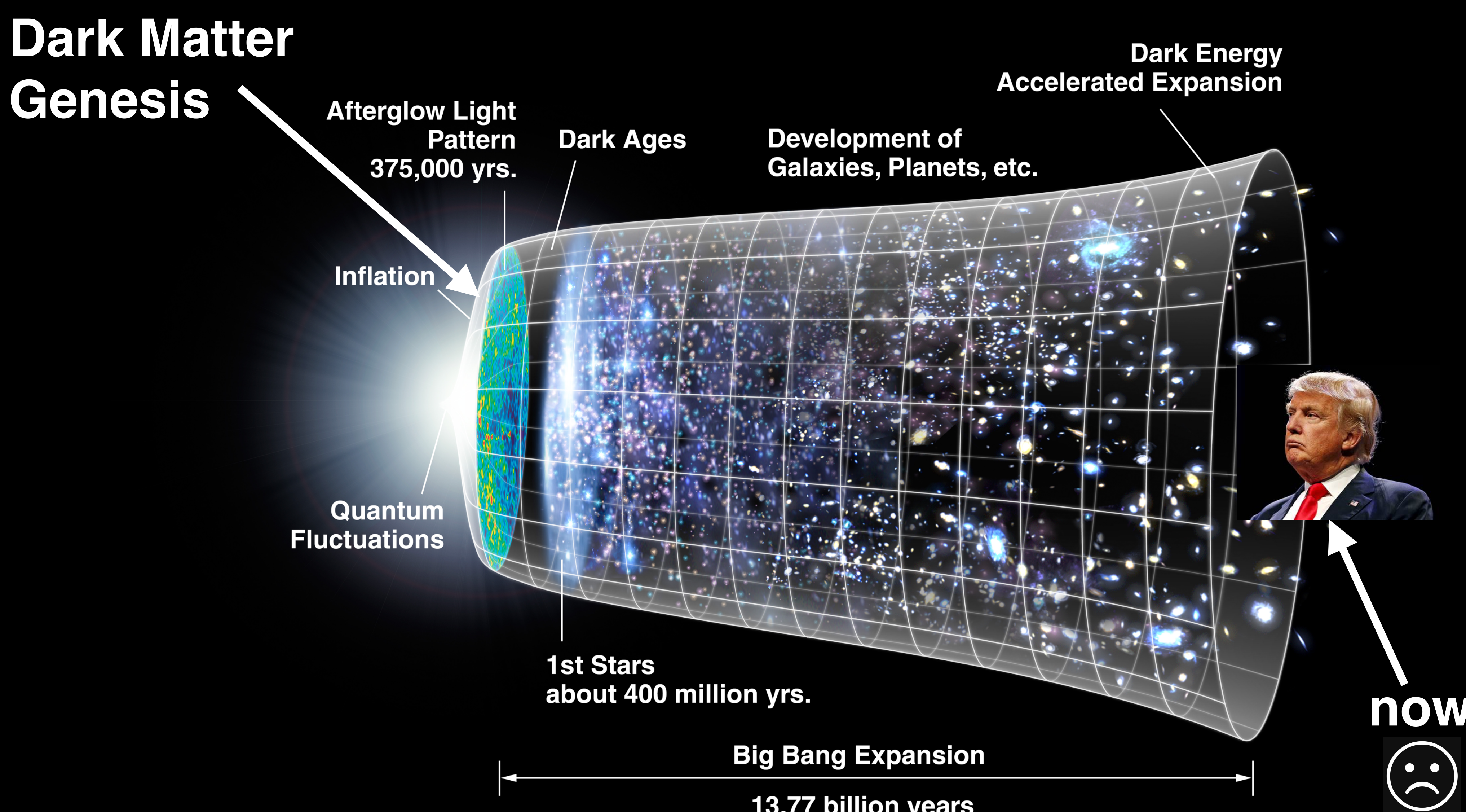


2. Experiment vs. Dark Matter

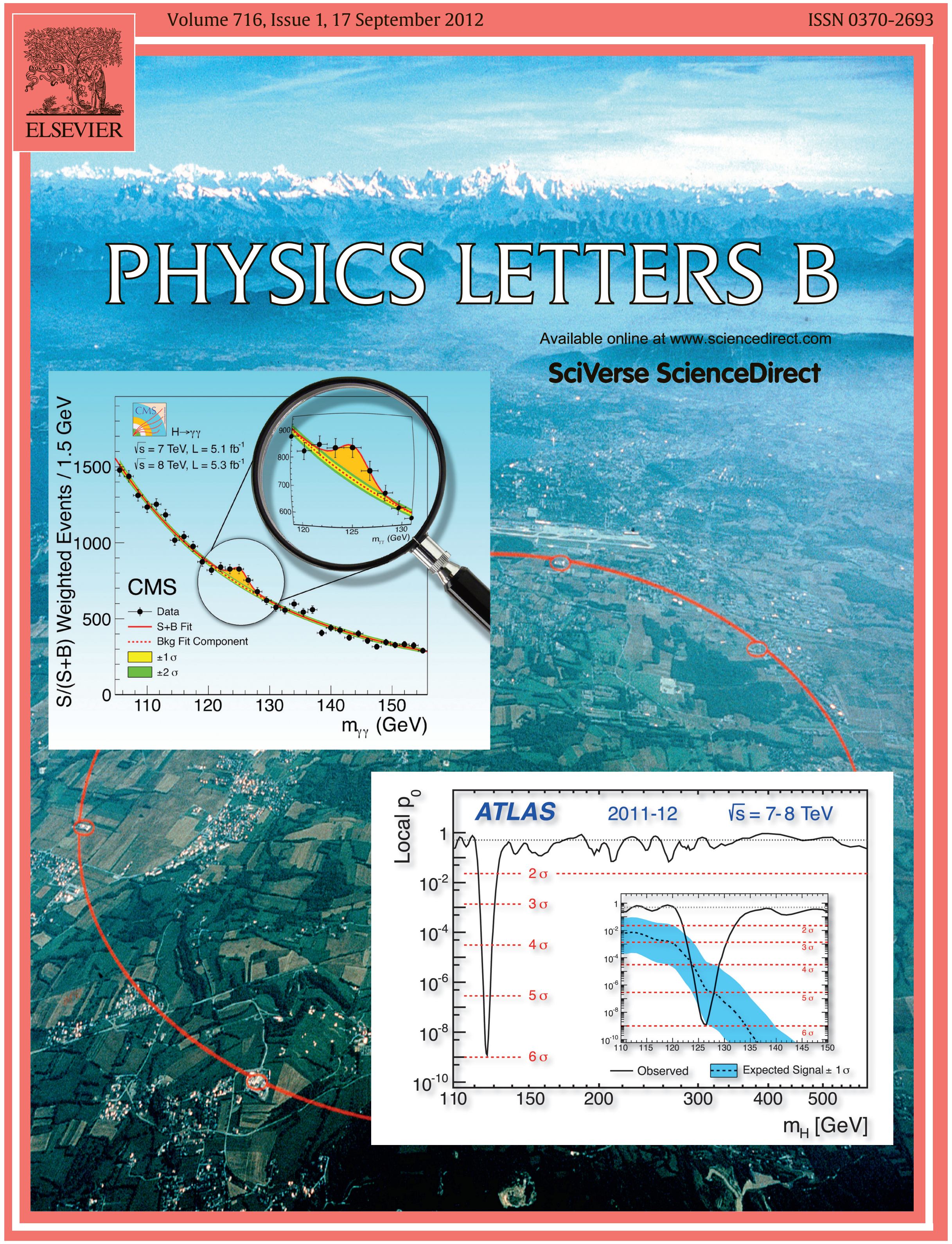
3. Dark Matter Below the Higgs Scale



1. Dark Matter at the Higgs Scale

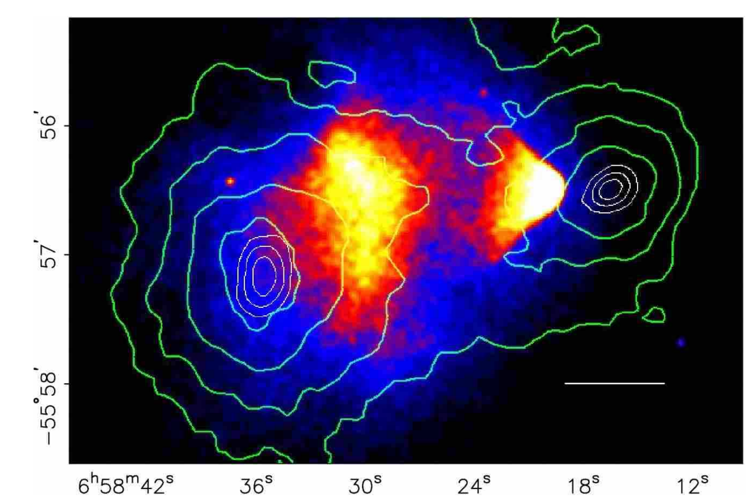


The Higgs Boson



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

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

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

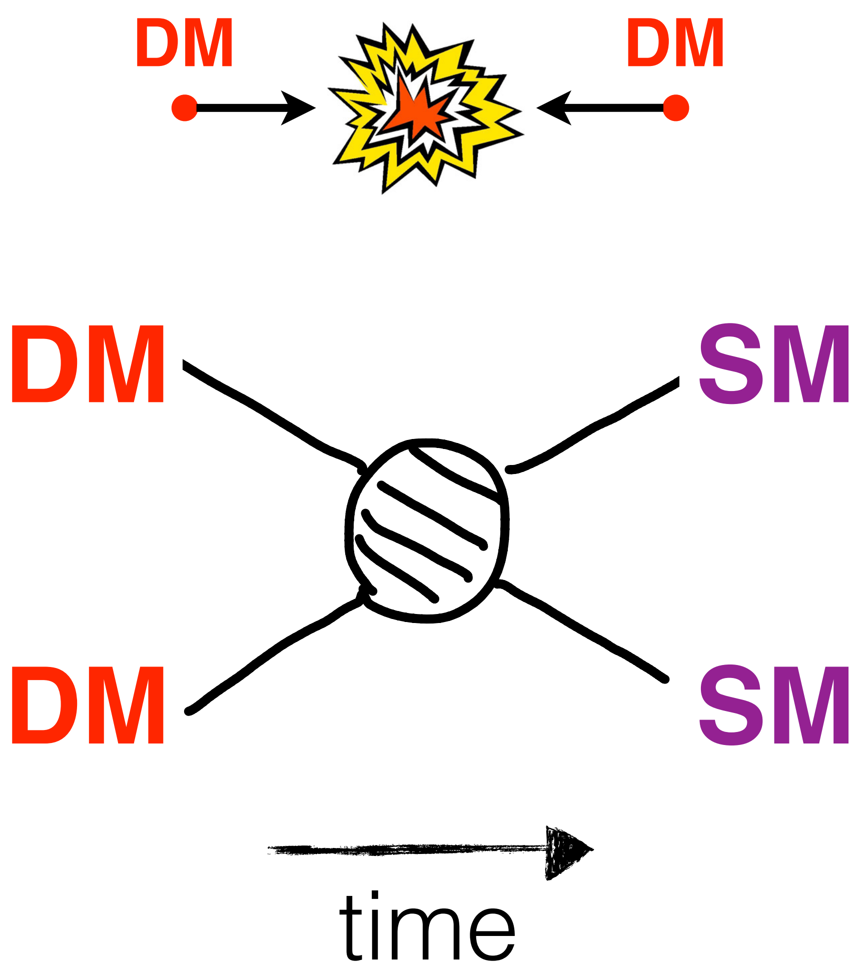
- maybe dark matter also had a high temperature*

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

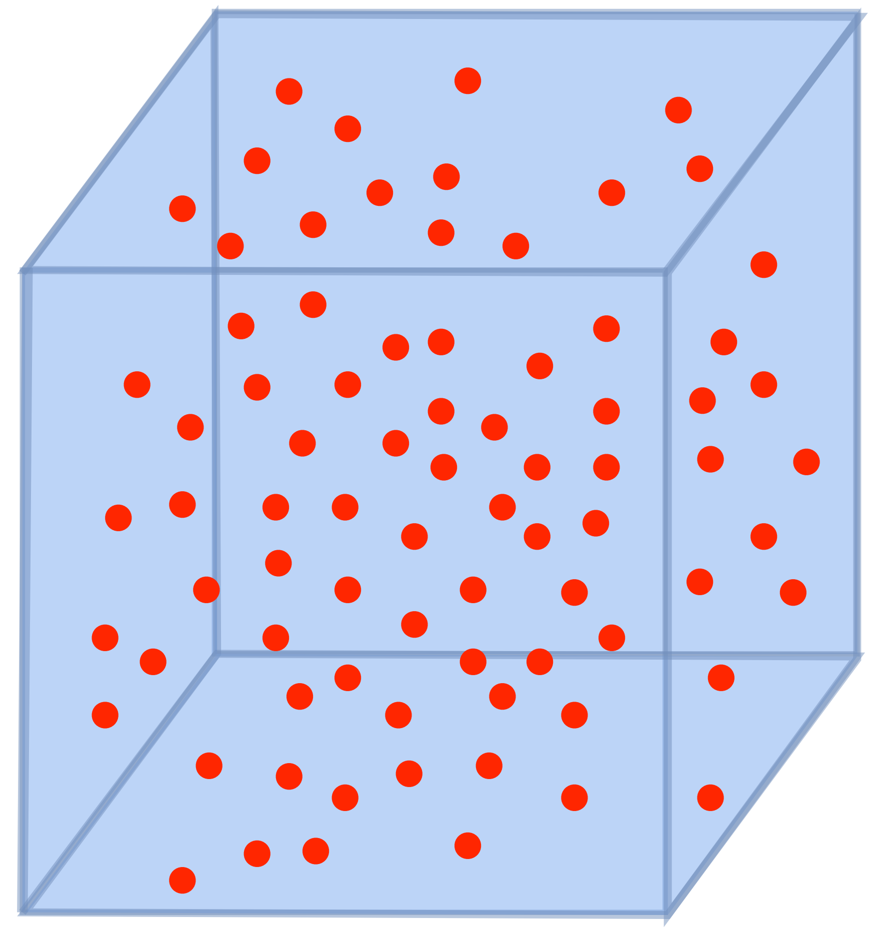
"thermal relic"

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

Dark Matter Freezeout



$T = m_{DM}$

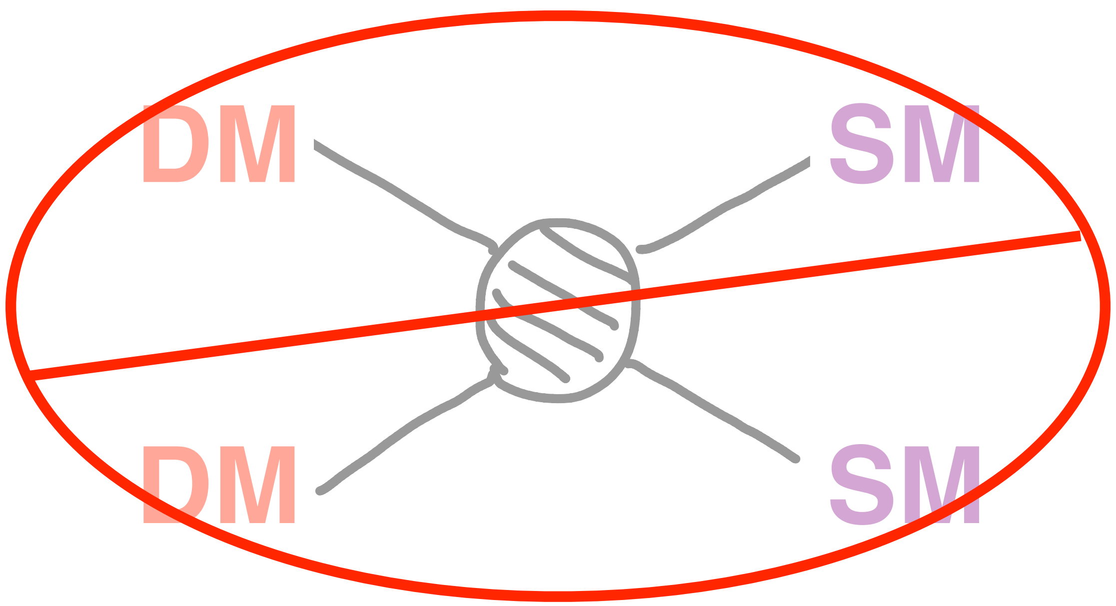


comoving volume: $V \propto T^{-3}$

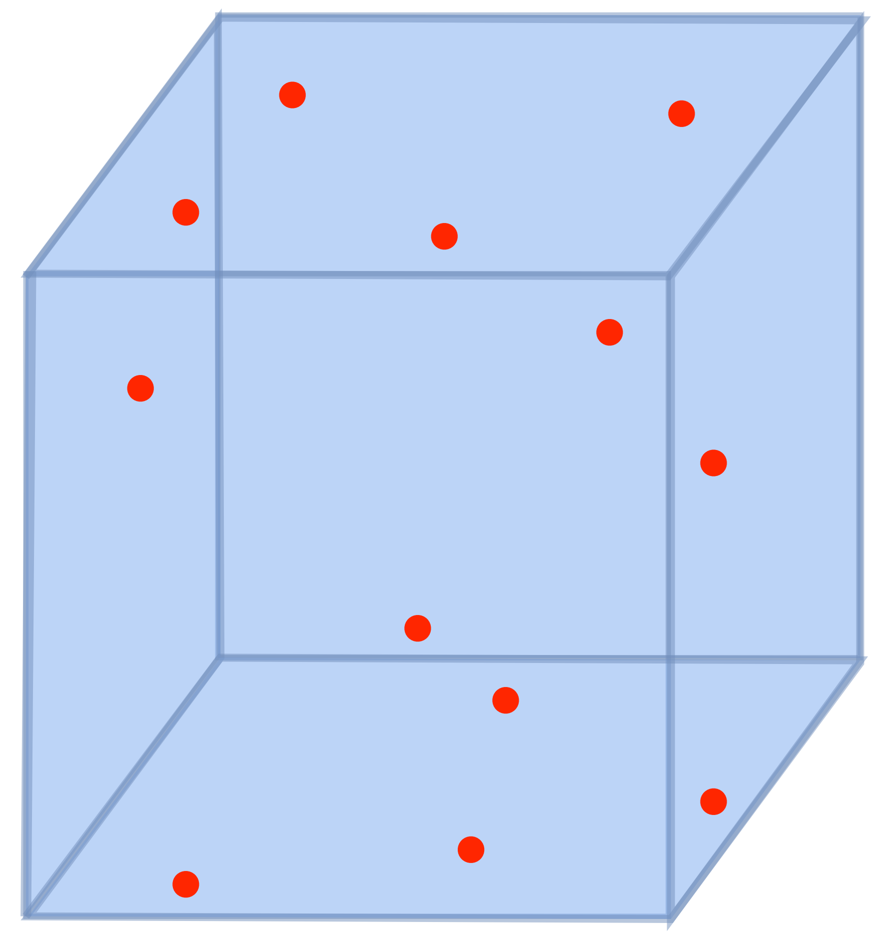
- Lee, Weinberg, Phys. Rev. Lett. **39**, 165 (1977).

Dark Matter Freezeout

annihilations “freezeout”



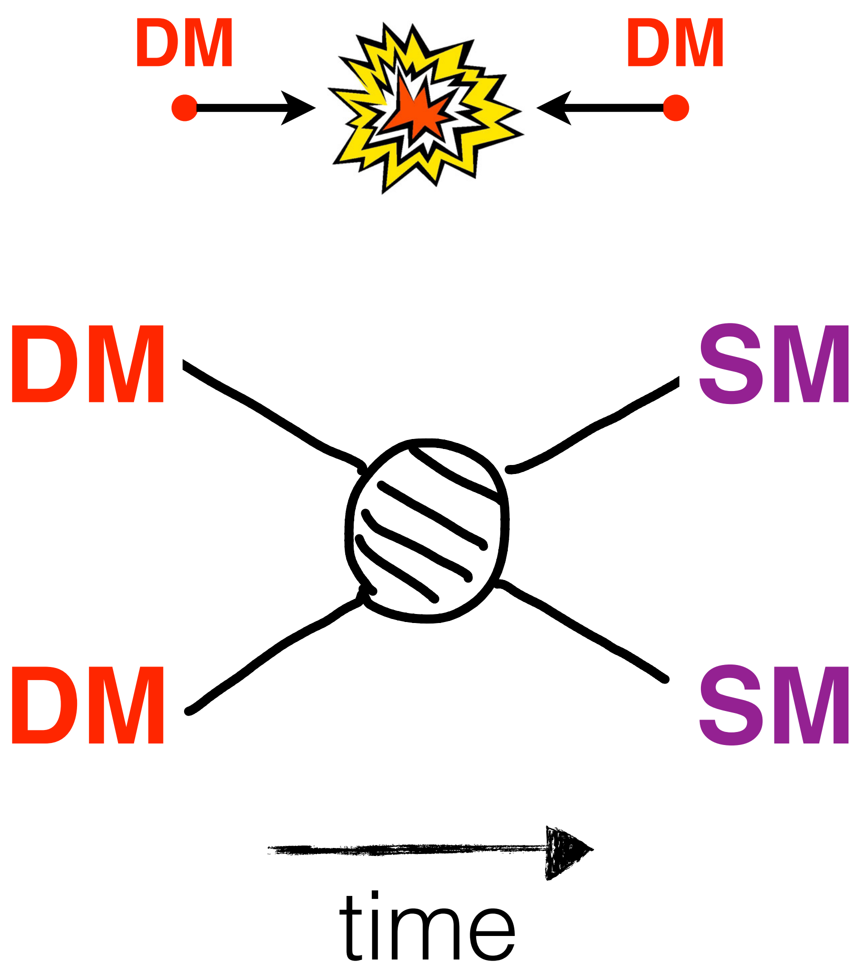
$T = T_{FO}$

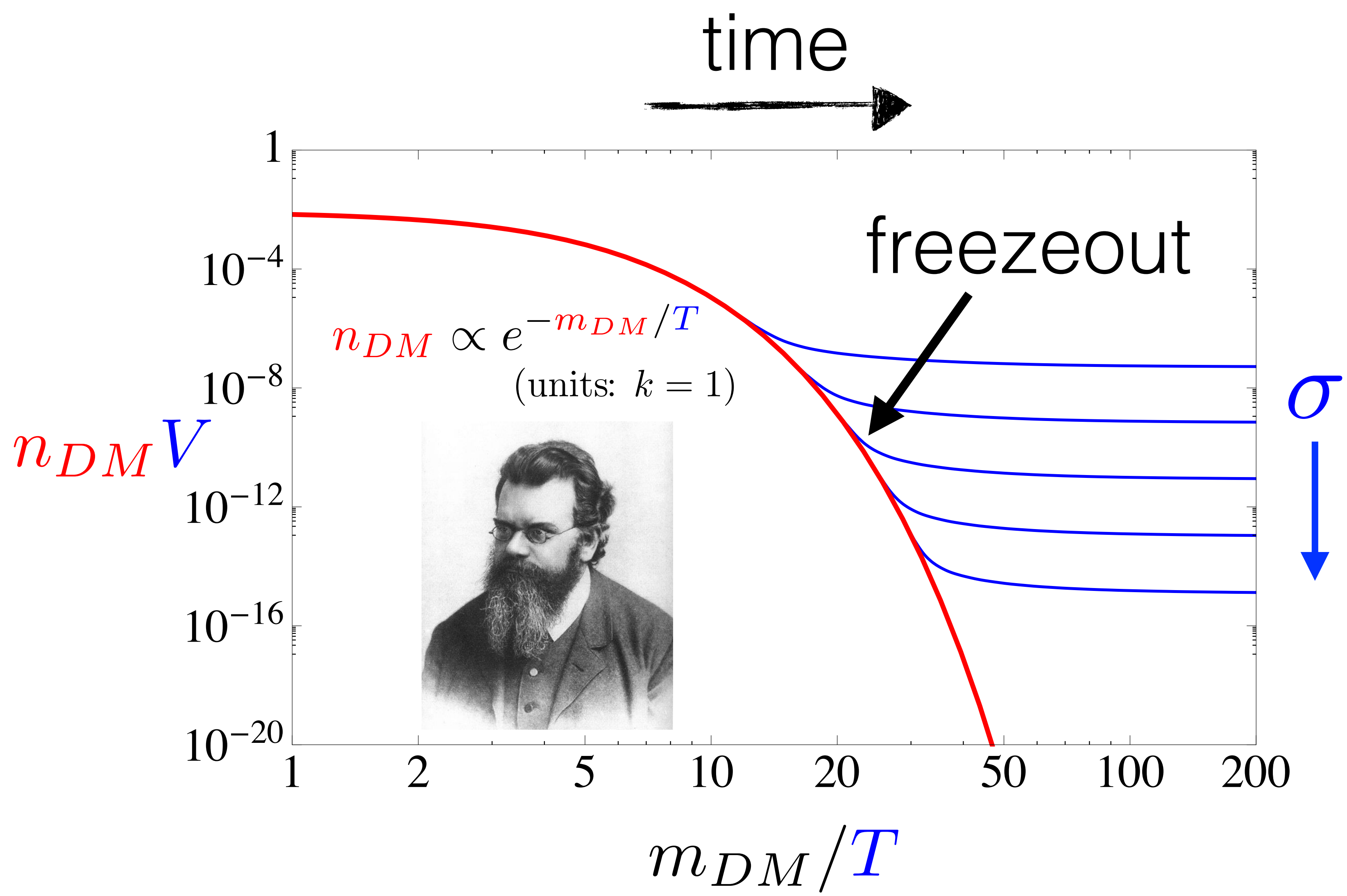


comoving volume: $V \propto T^{-3}$

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

Dark Matter Freezeout

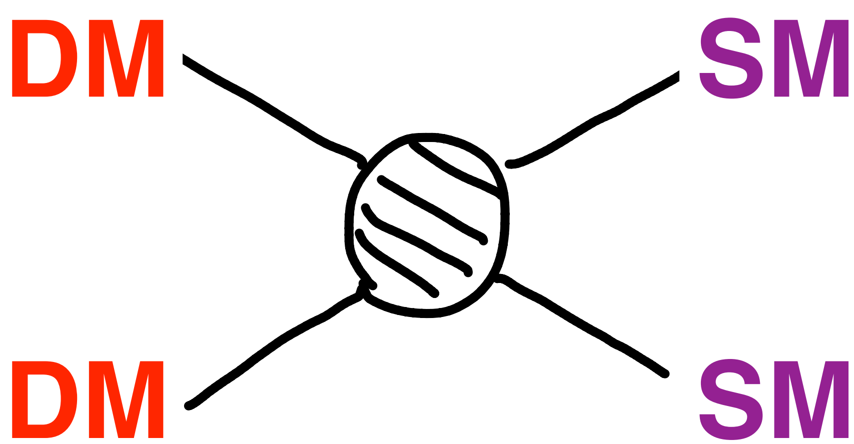




- Lee, Weinberg, Phys. Rev. Lett. **39**, 165 (1977).

WIMP "Miracle"

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



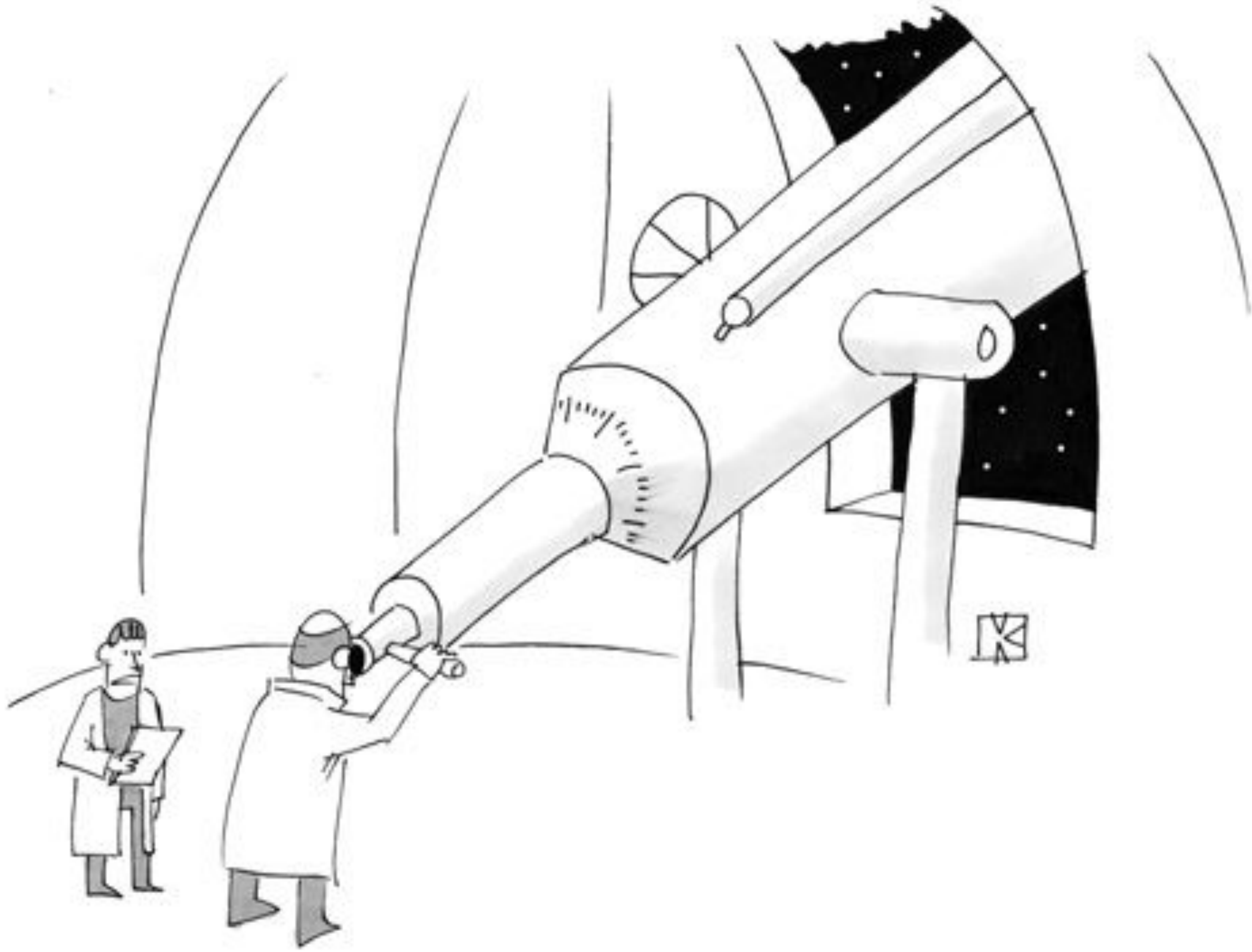
$$\sigma v = 3 \times 10^{26}\ \mathrm{cm}^3/\mathrm{s}$$

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

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

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

2. Experiment vs. Dark Matter

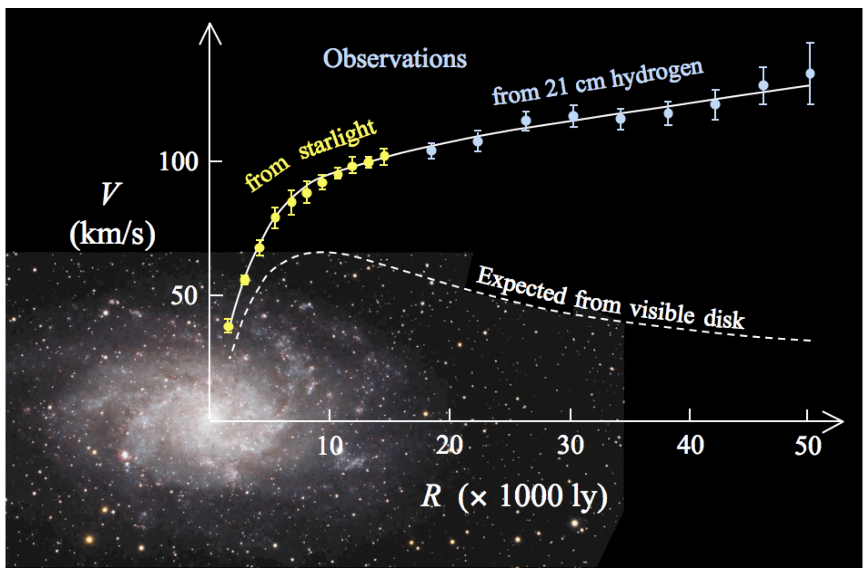


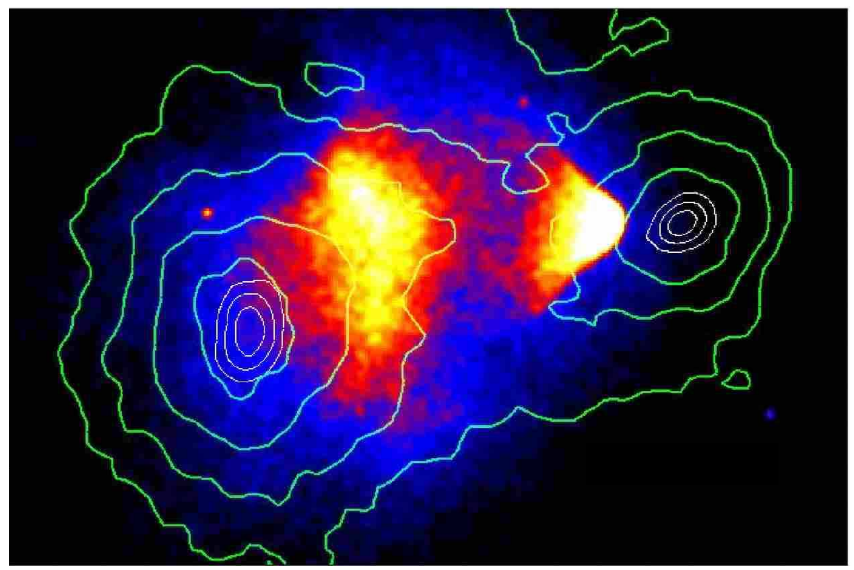
“That isn’t dark matter, sir—you just forgot to take off the lens cap.”

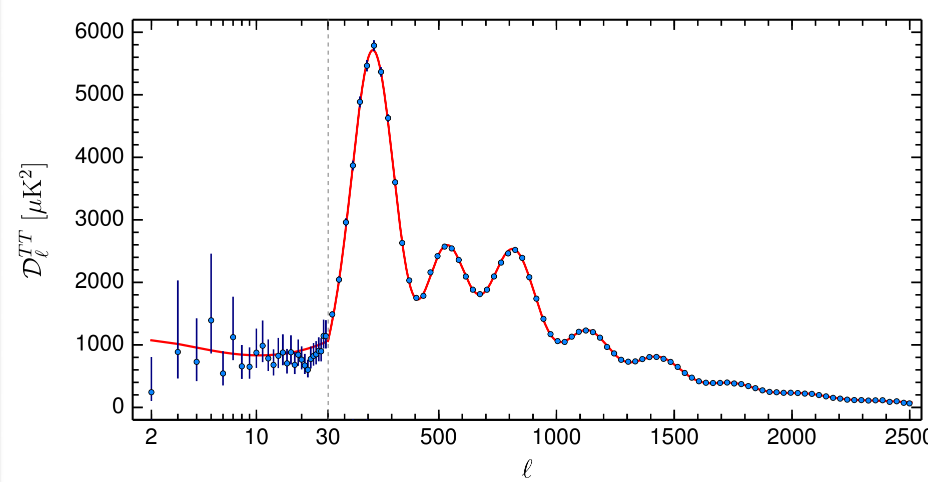
Gregory Kogan.

2. Experiment vs. Dark Matter

- evidence for Dark Matter relies on gravity

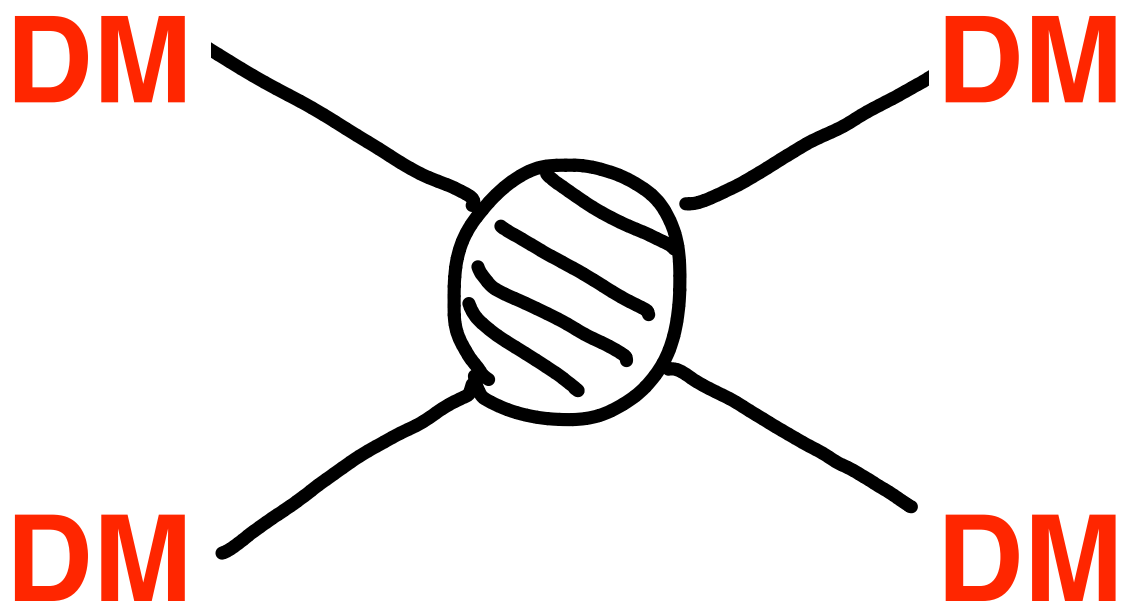


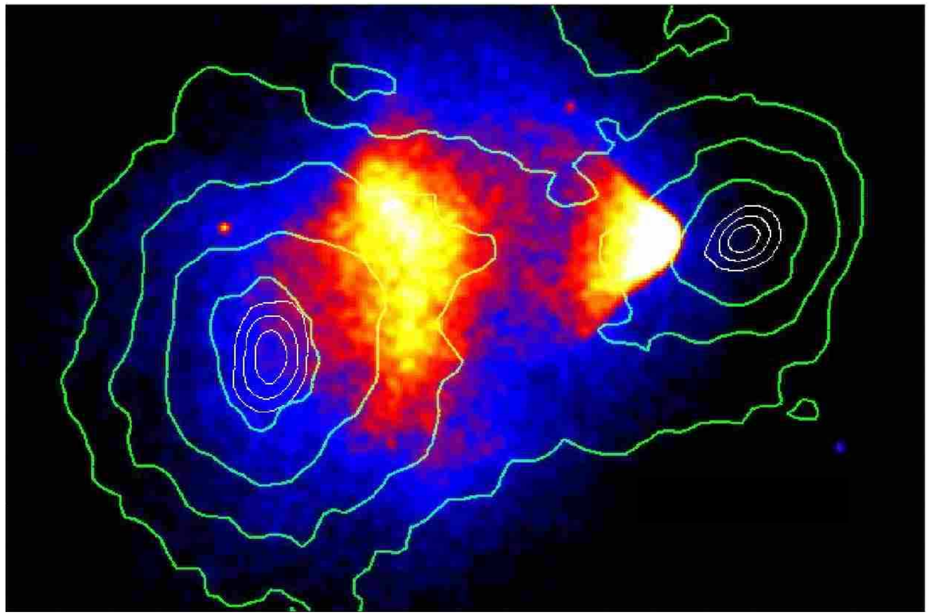




- Dark Matter Holy Grail: non-gravitational interactions

Dark Matter Self-Interactions

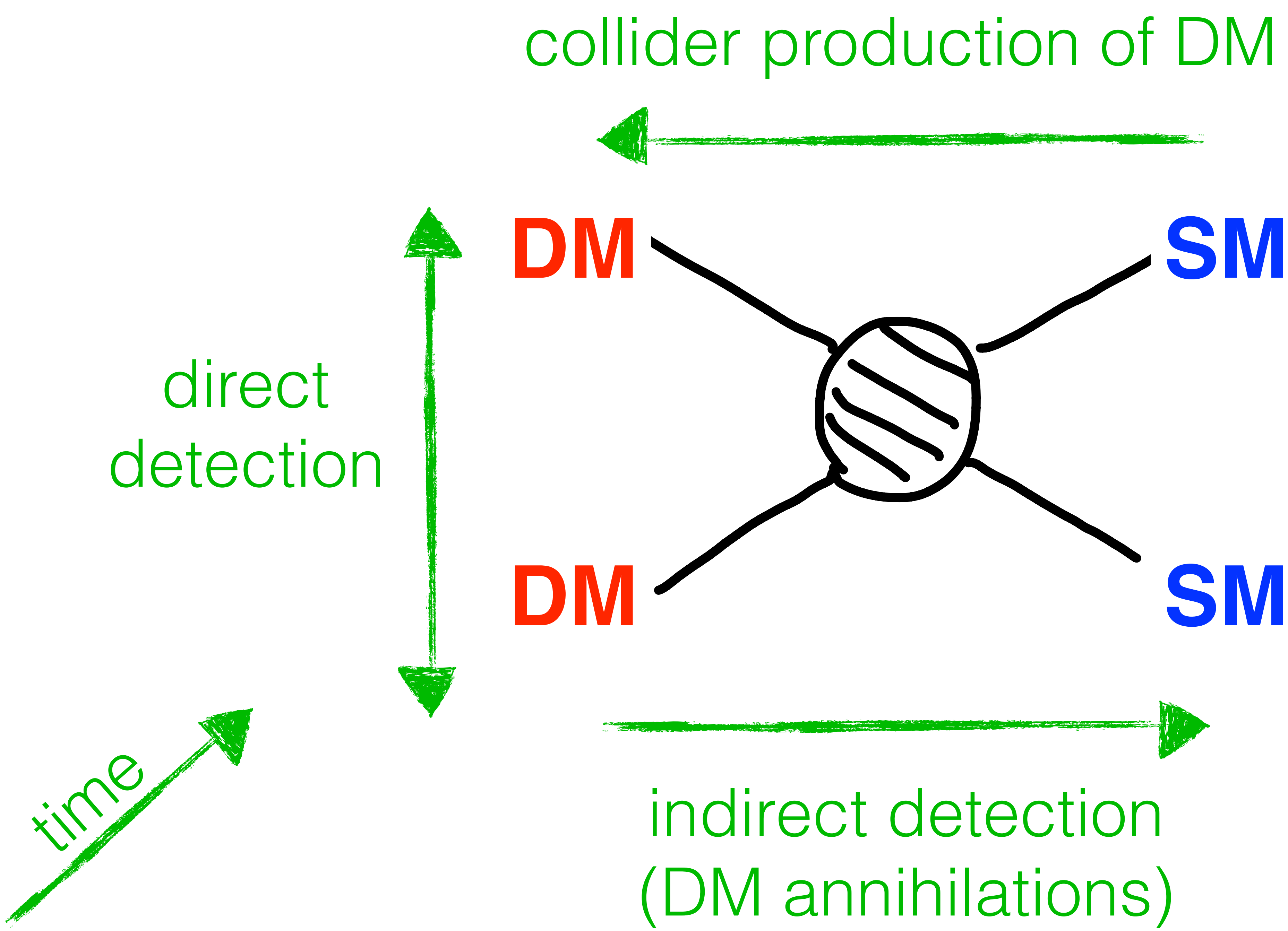




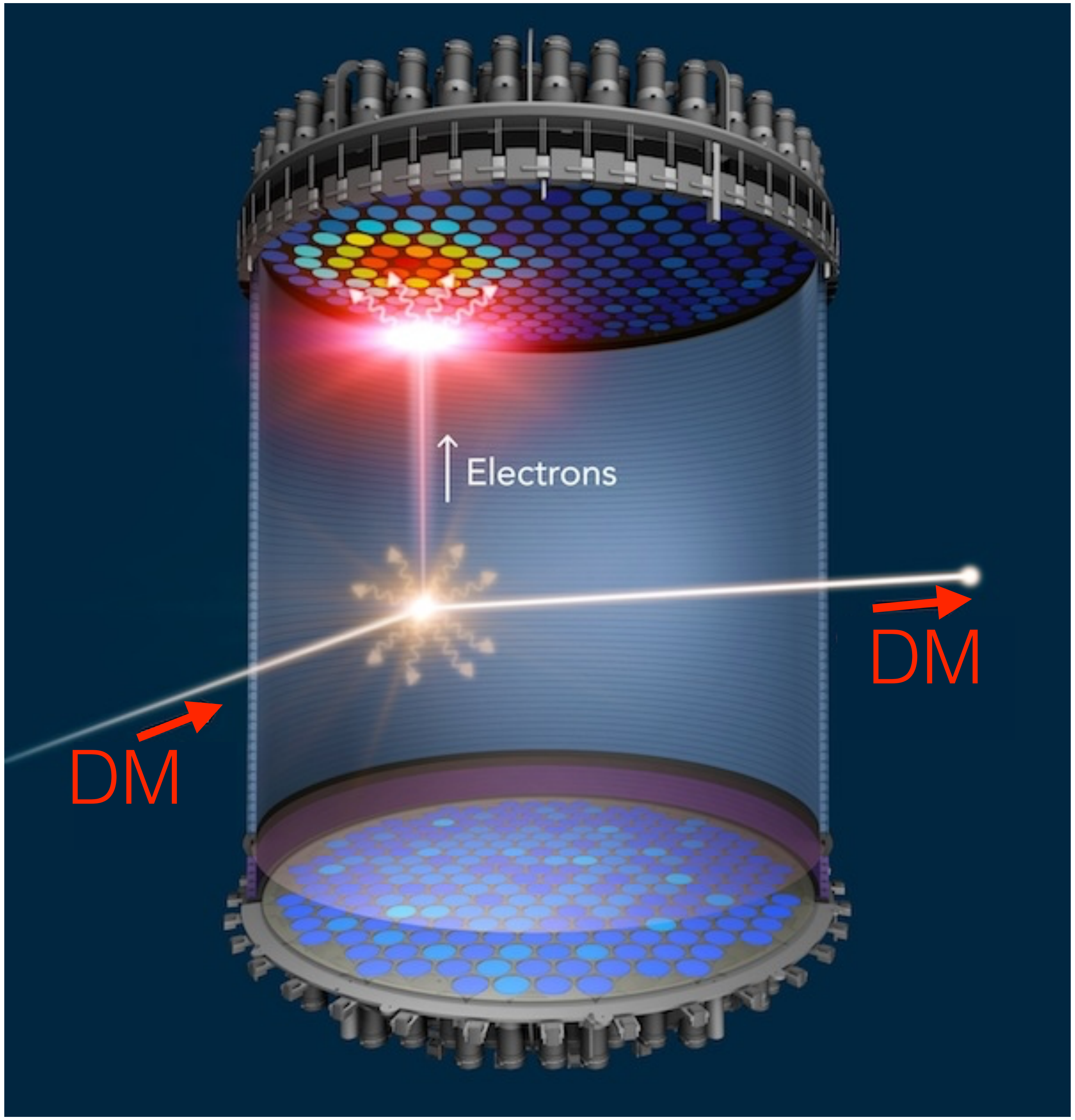
$$\frac{\sigma_{SI}}{m_{DM}} \lesssim 1\ \mathrm{cm}^2/\mathrm{g}$$

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

How to test if Dark Matter couples to the Standard Model

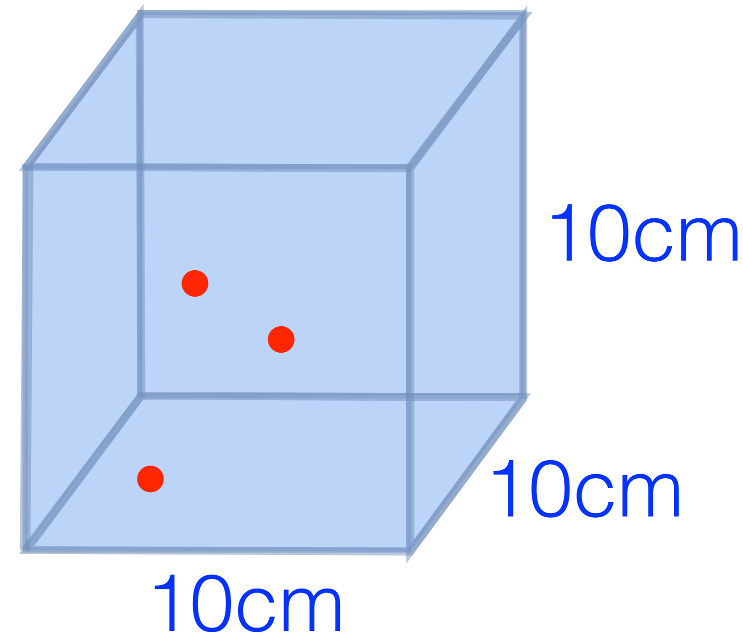


Direct Detection



Some Dark Numbers

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



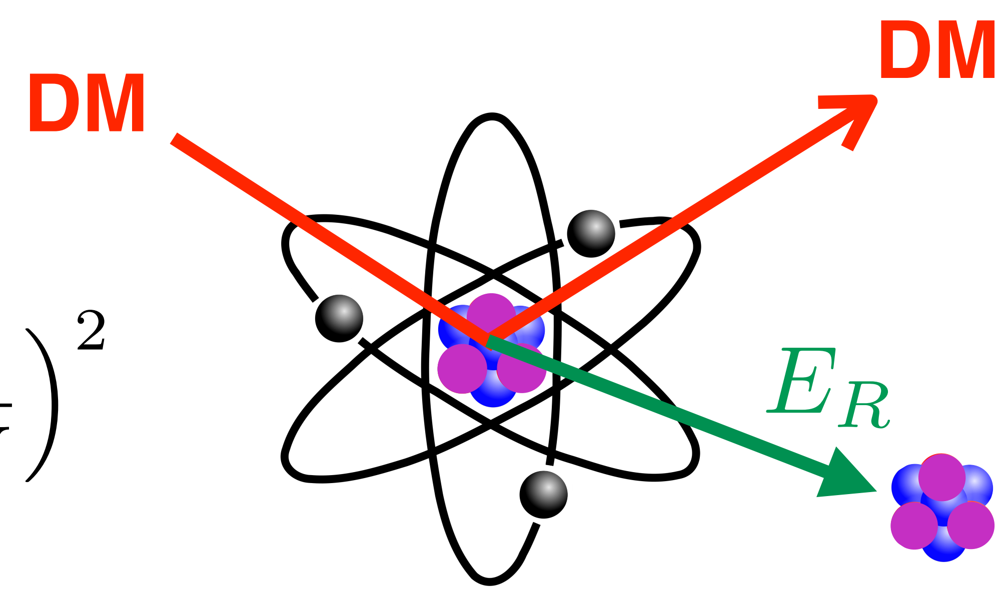
- local DM density:

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

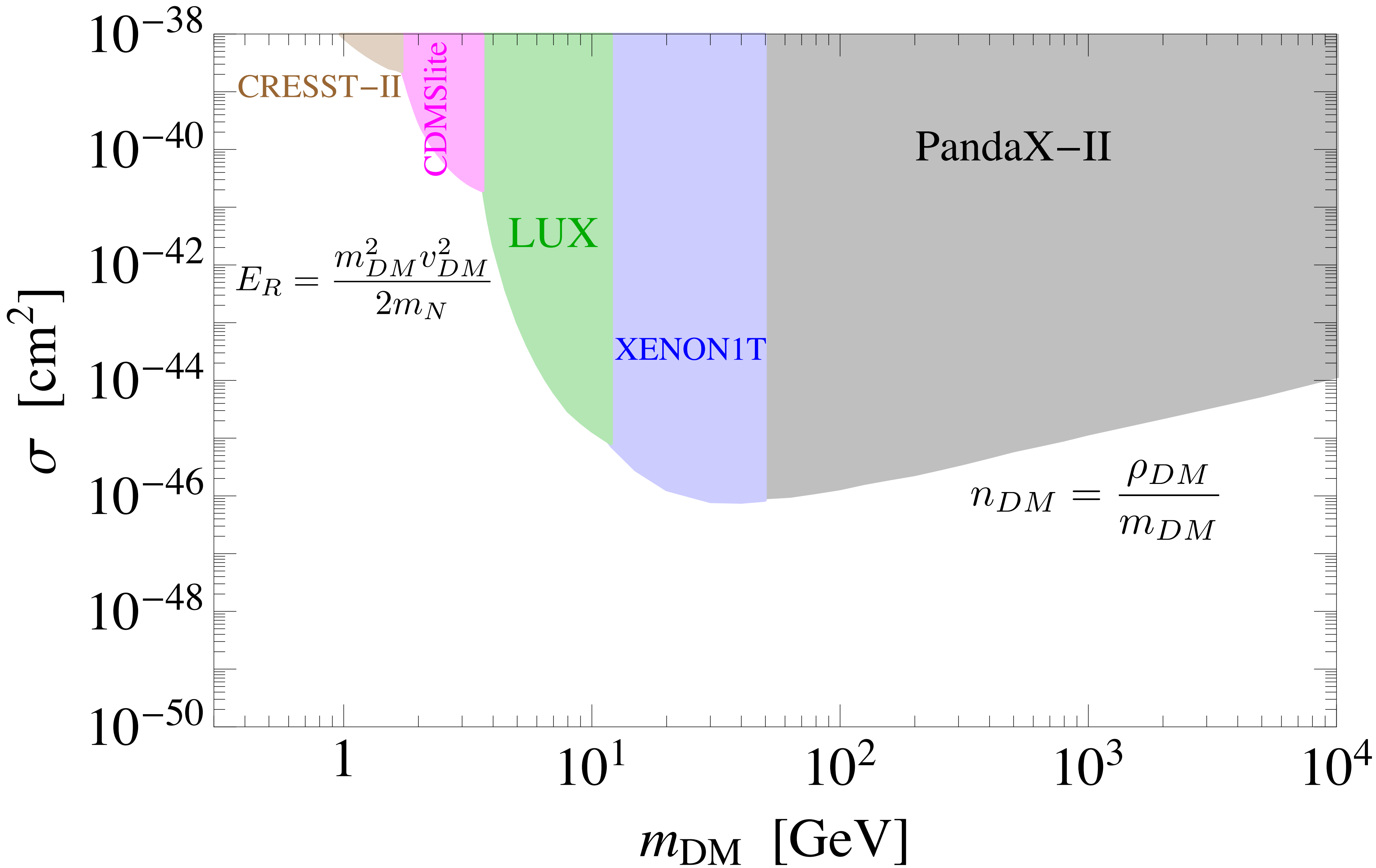
- dark matter velocity: $v_{DM} \sim 200 \text{ km/s} \sim 10^{-3} c$

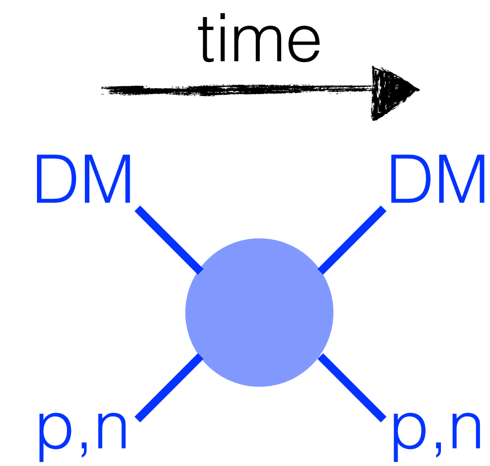
- nuclear recoil energy:

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



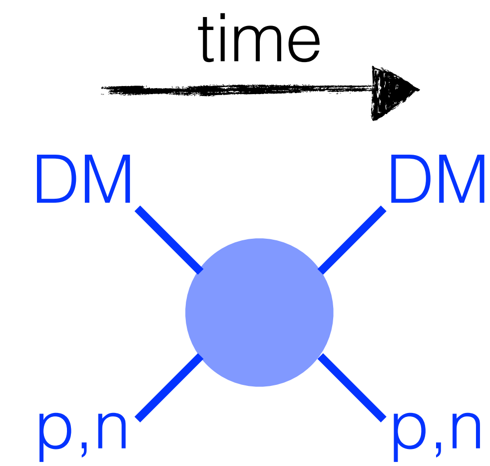
Direct Detection

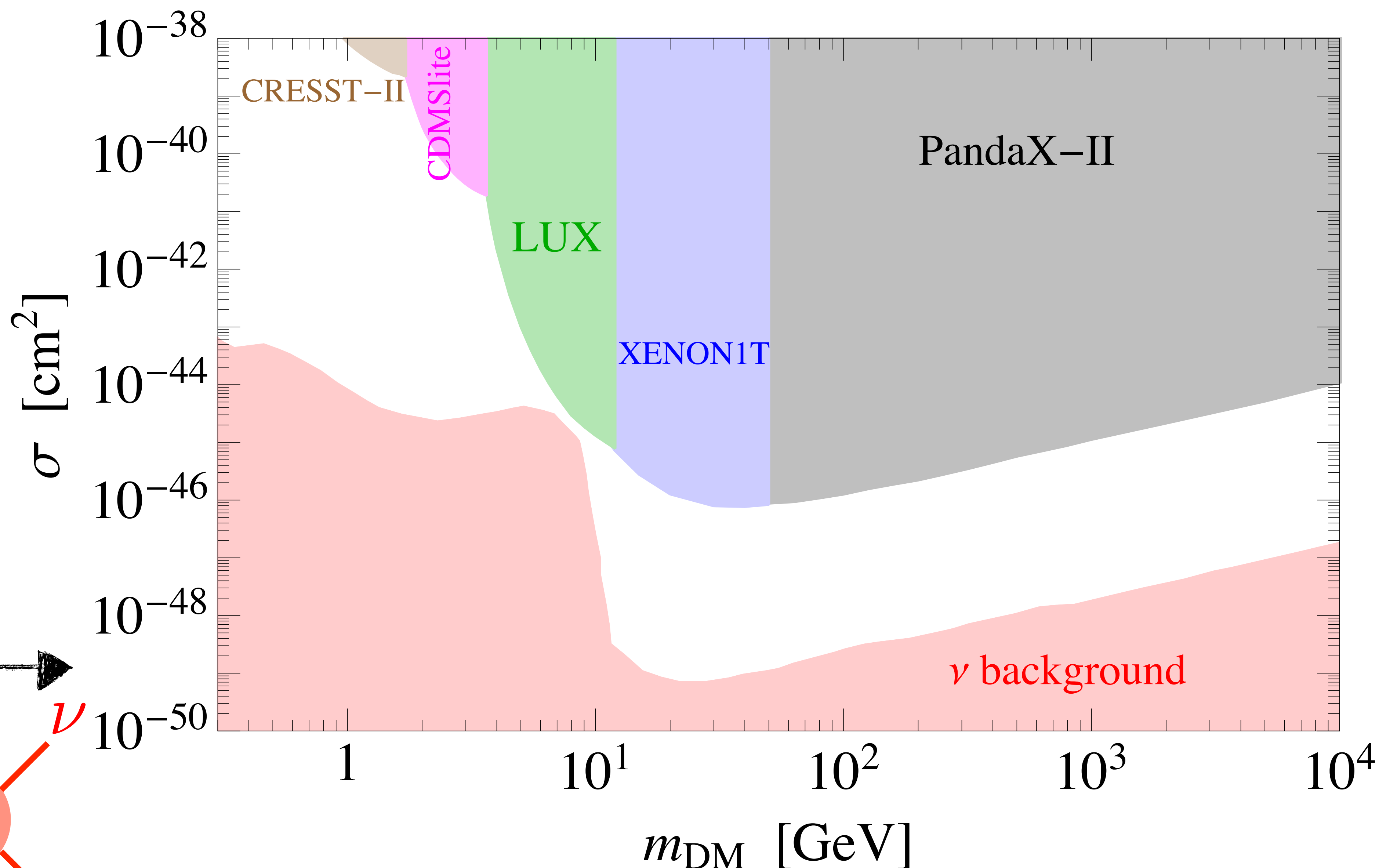


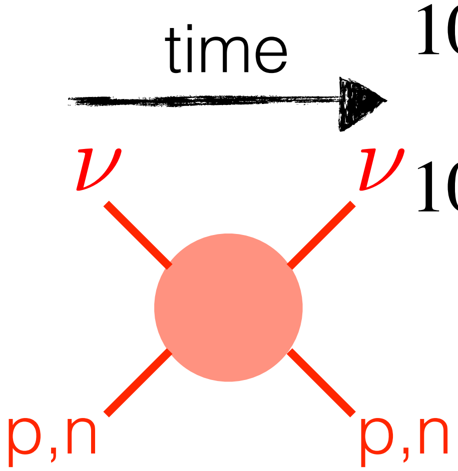


- CRESST collaboration, Eur. Phys. J. C **26,** 25 (2016).
- SuperCDMS collaboration, Phys. Rev. Lett. **116**, 071301 (2016).
- LUX collaboration, Phys. Rev. Lett. **116**, 161301 (2016).
- XENON collaboration, Phys. Rev. Lett. **119**, 181301 (2017).
- PandaX-II collaboration, Phys. Rev. Lett. **119**,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

Direct Detection

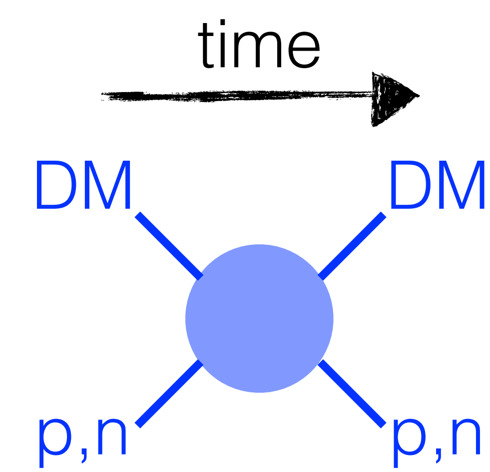


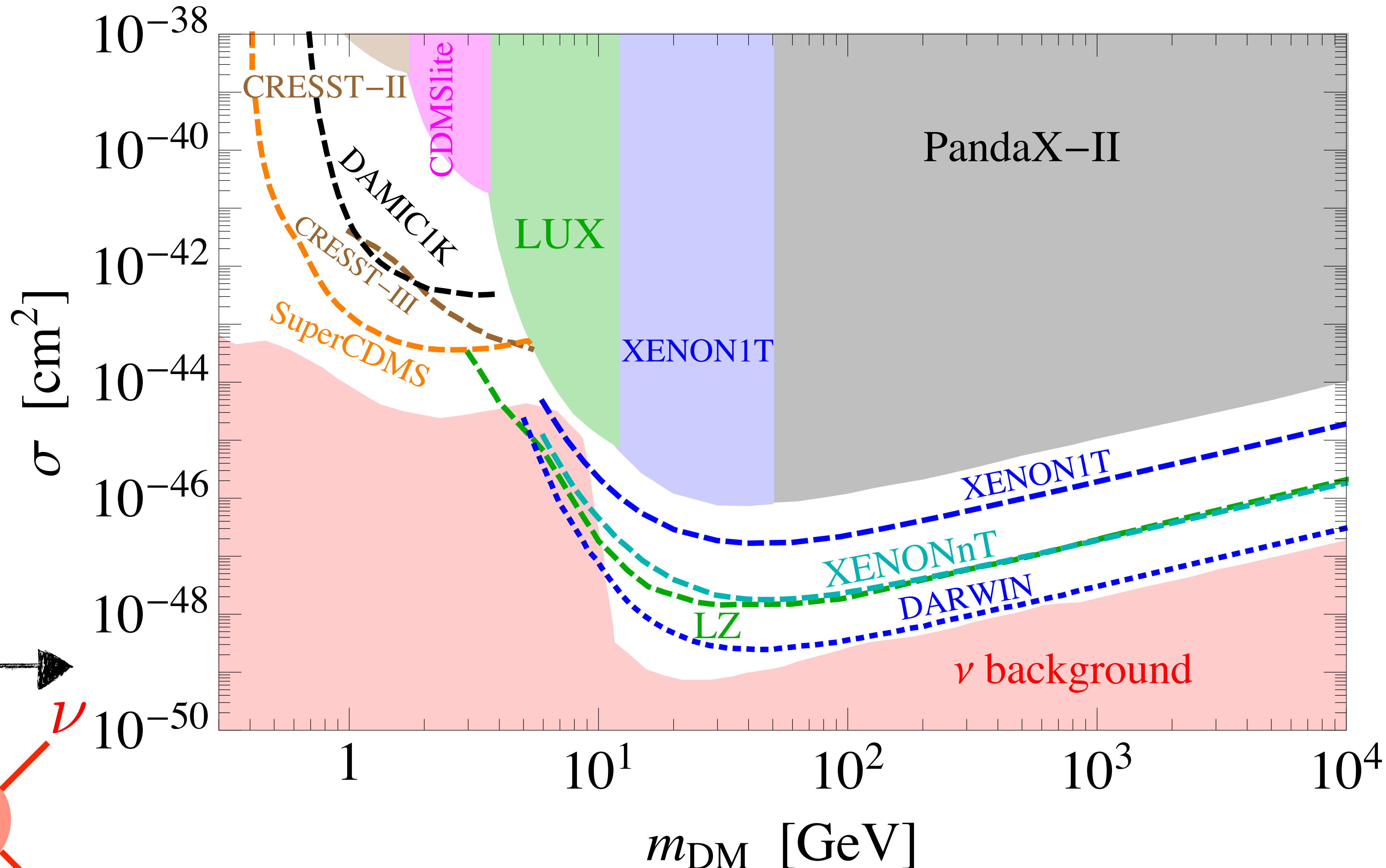


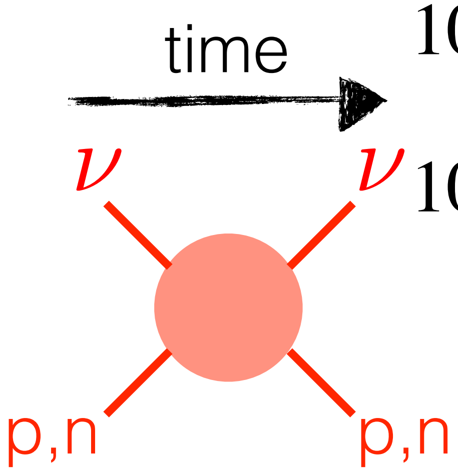


- Billard, Figueroa-Feliciano, Strigari, Phys. Rev. D **89**, 023524 (2014).

Direct Detection

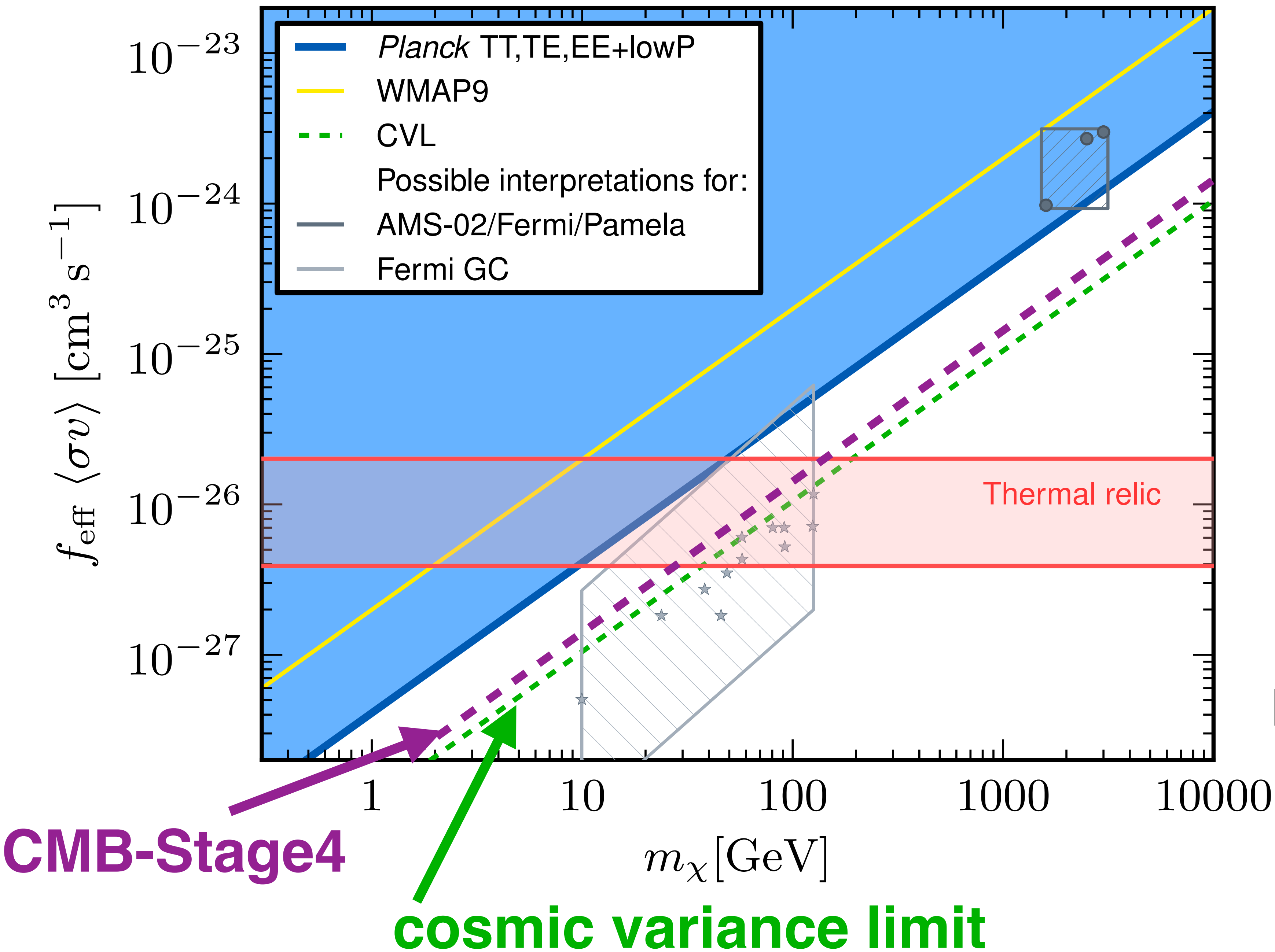


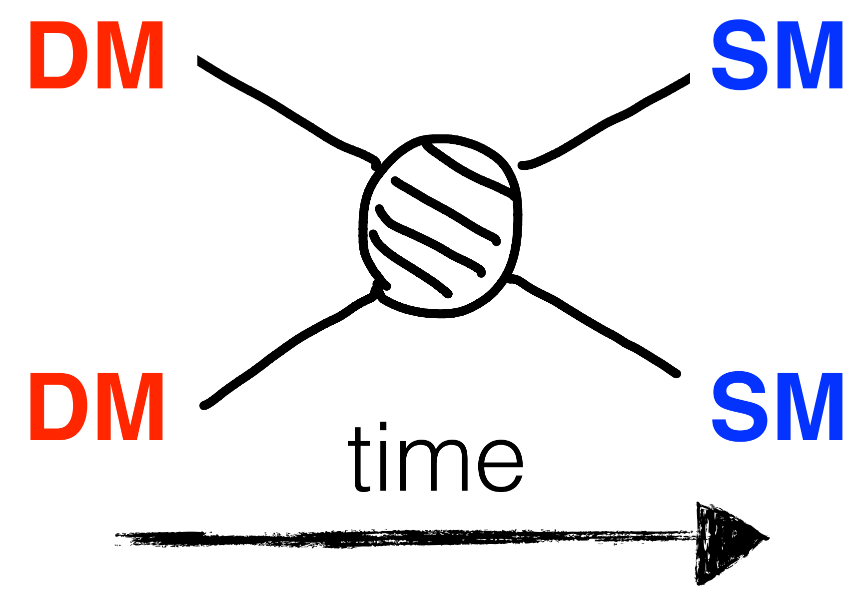




- SuperCDMS Collaboration, Phys. Rev. D **95**, 082002 (2017).
- DAMIC1K, US Cosmic Visions, arXiv:**1707.04591** (2017).
- CRESST Collaboration, arXiv:**1503.08065** (2015).
- XENON Collaboration, JCAP **1604**, 027 (2016).
- DARWIN Collaboration, JCAP **1611**, 017 (2017).
- LUX-ZEPLIN Collaboration,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

Cosmic Microwave Background vs. Dark Matter

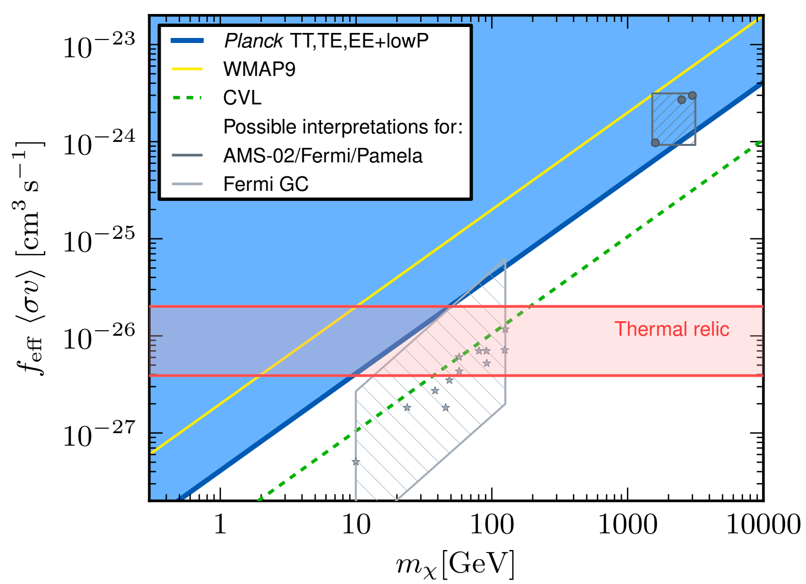


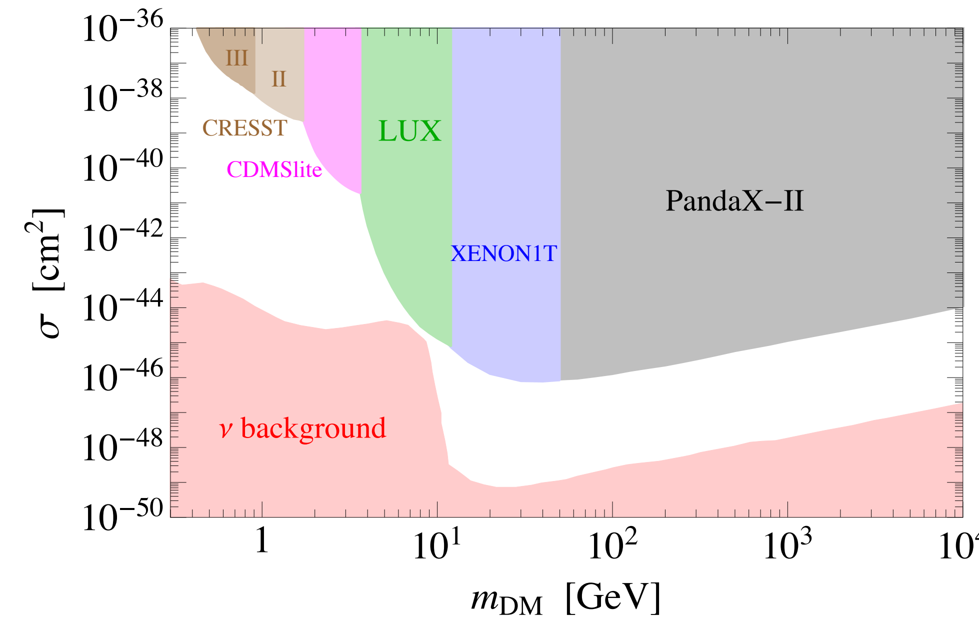


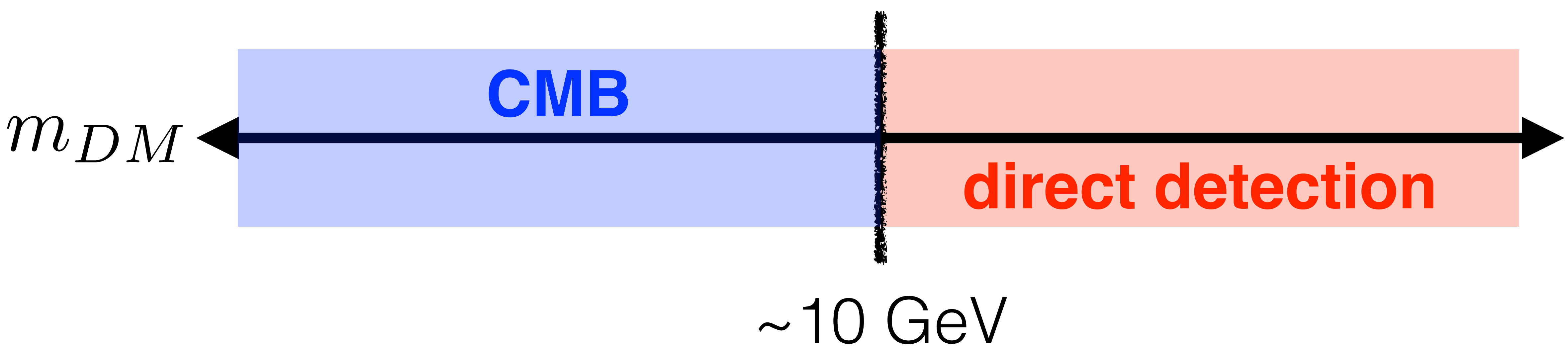
power: $m_{DM}\, n_{DM}^2 \propto \dfrac{1}{m_{DM}}$

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

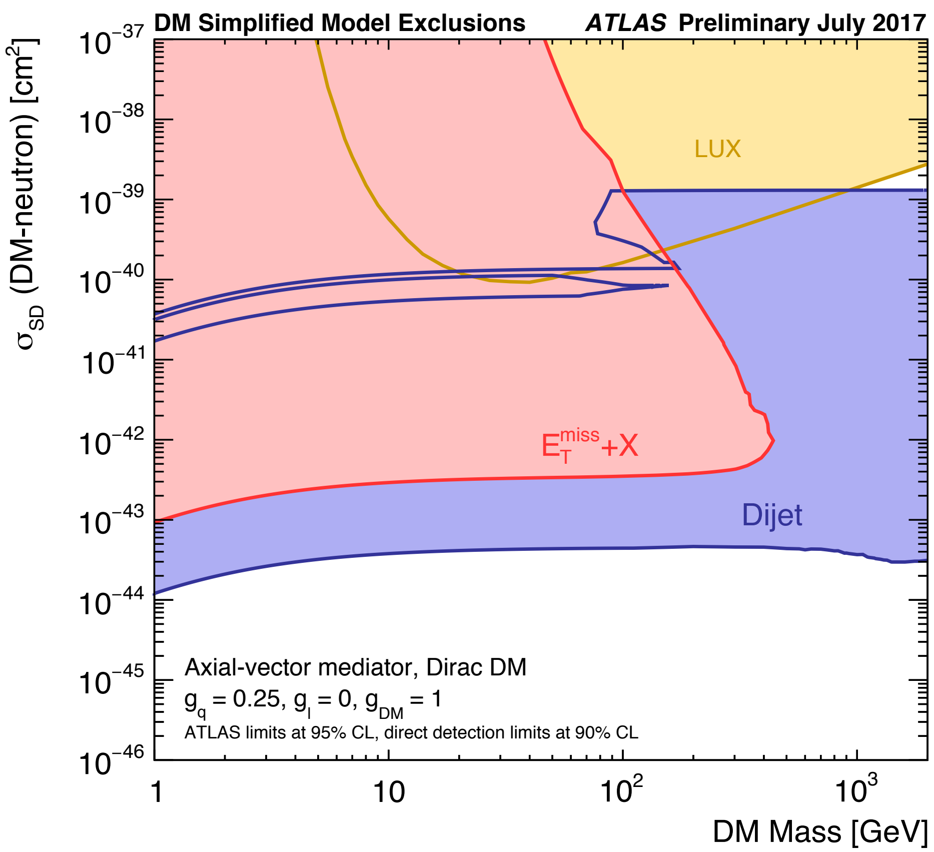
Indirect/Direct Detection Complementarity

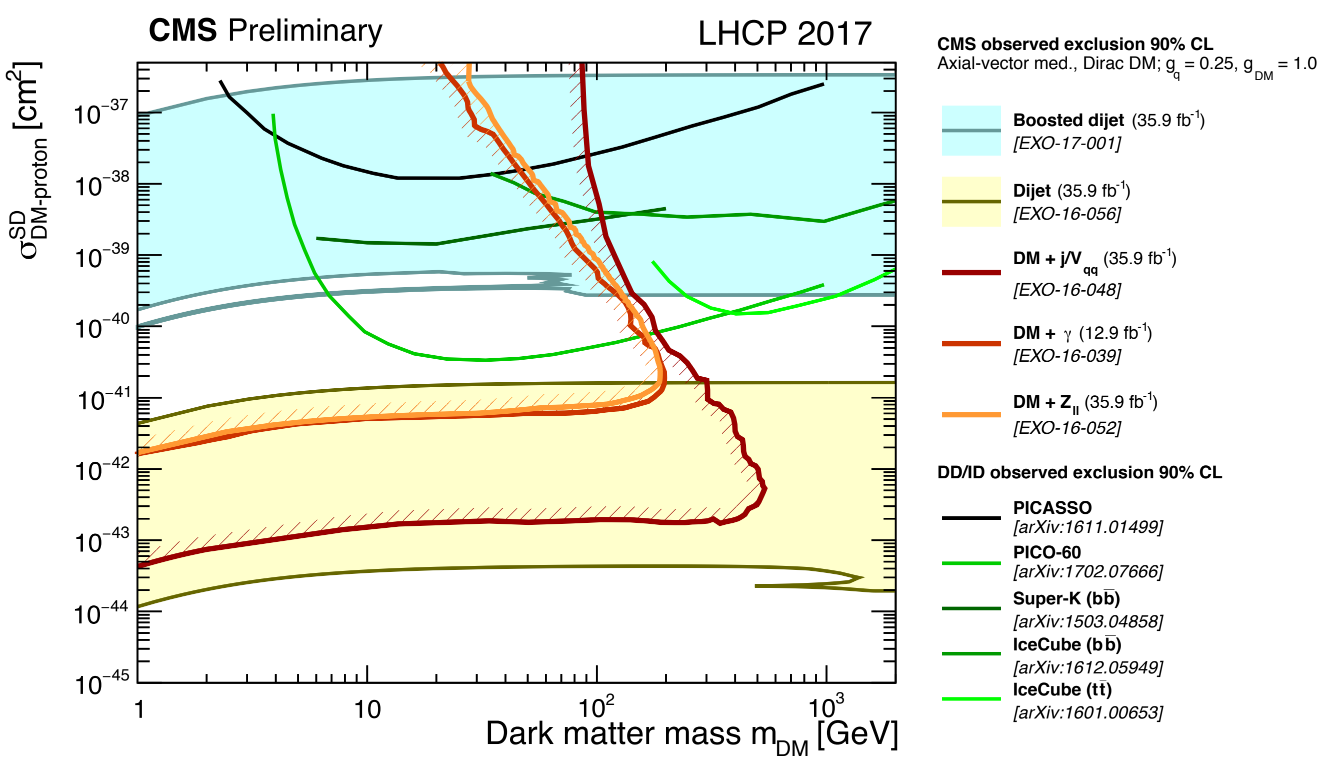


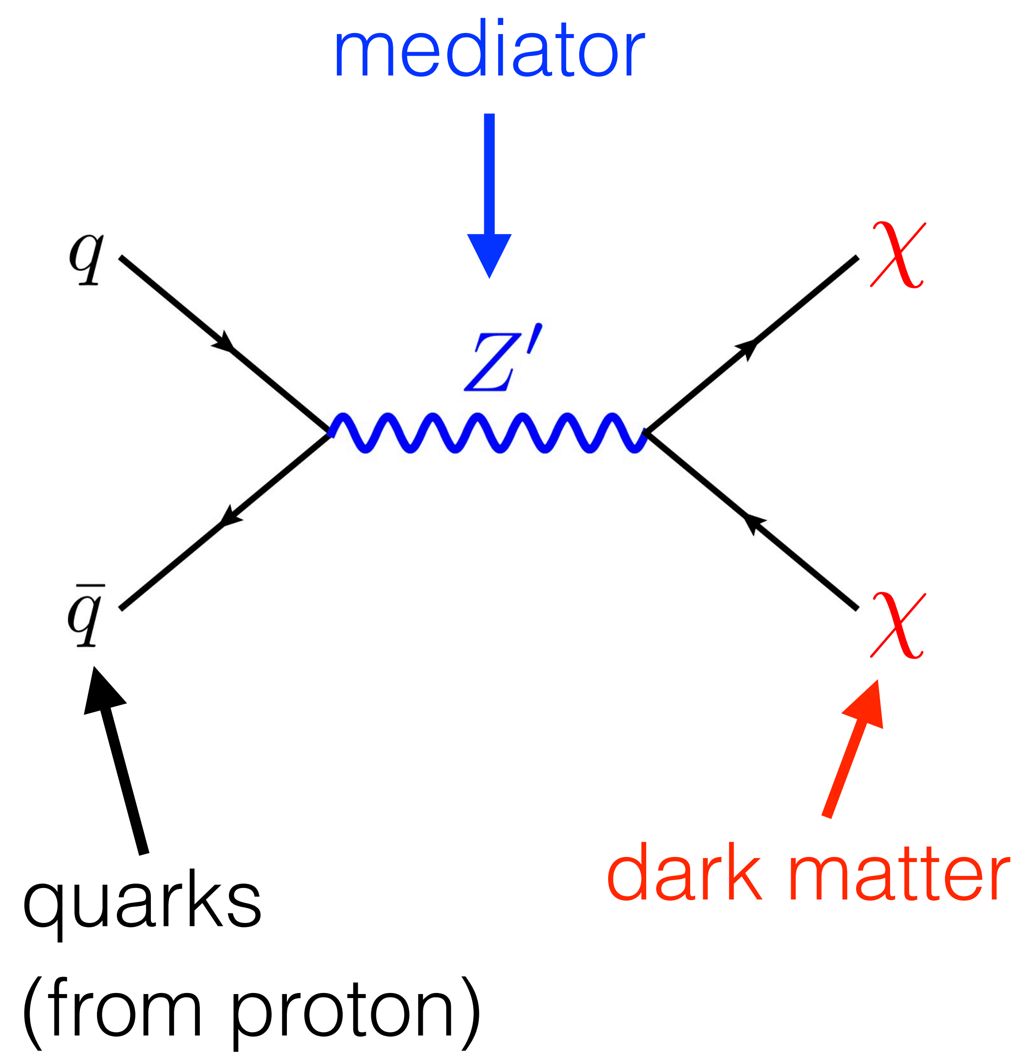




LHC vs. Direct Detection (with a dark Mediator)



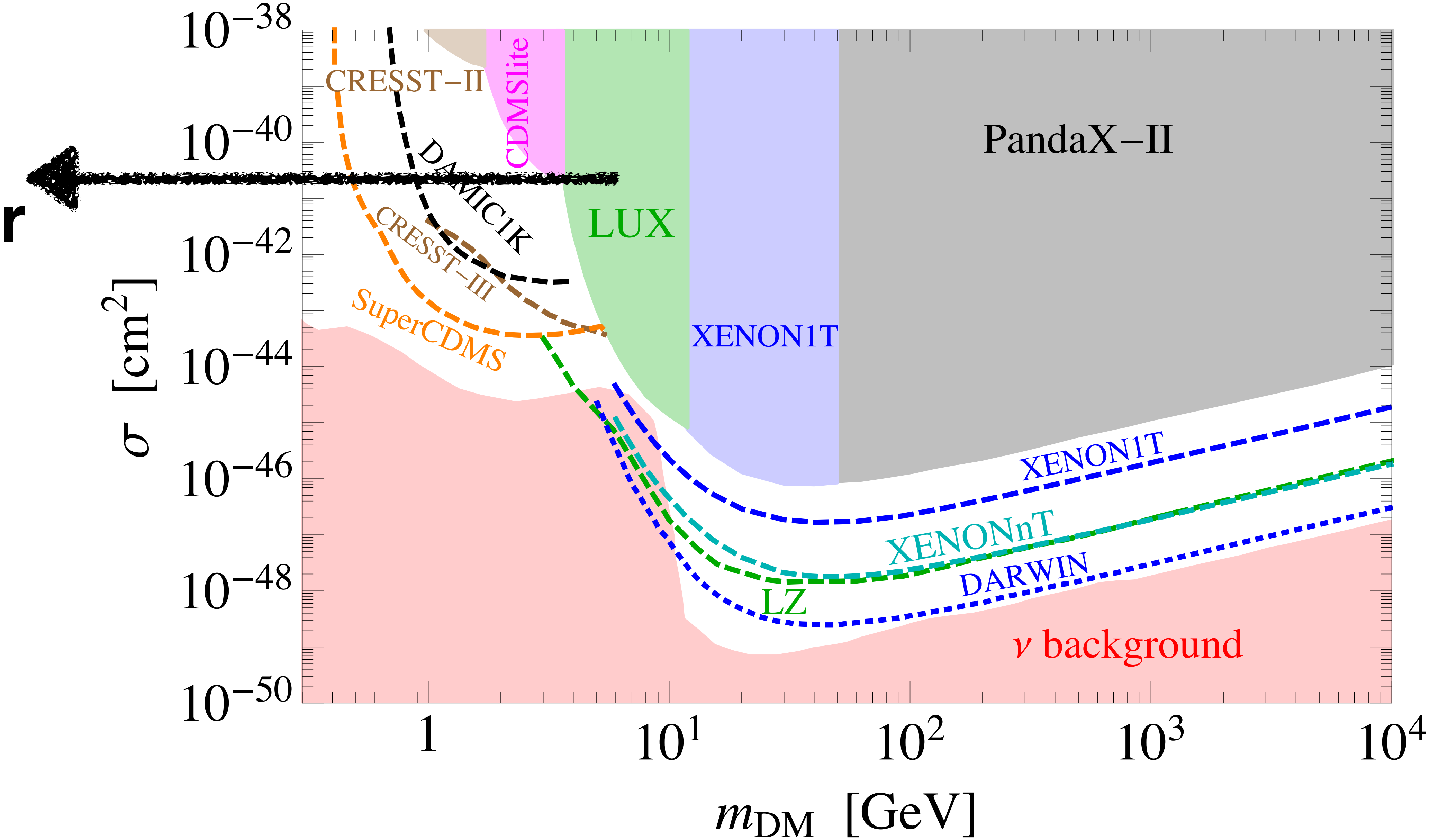




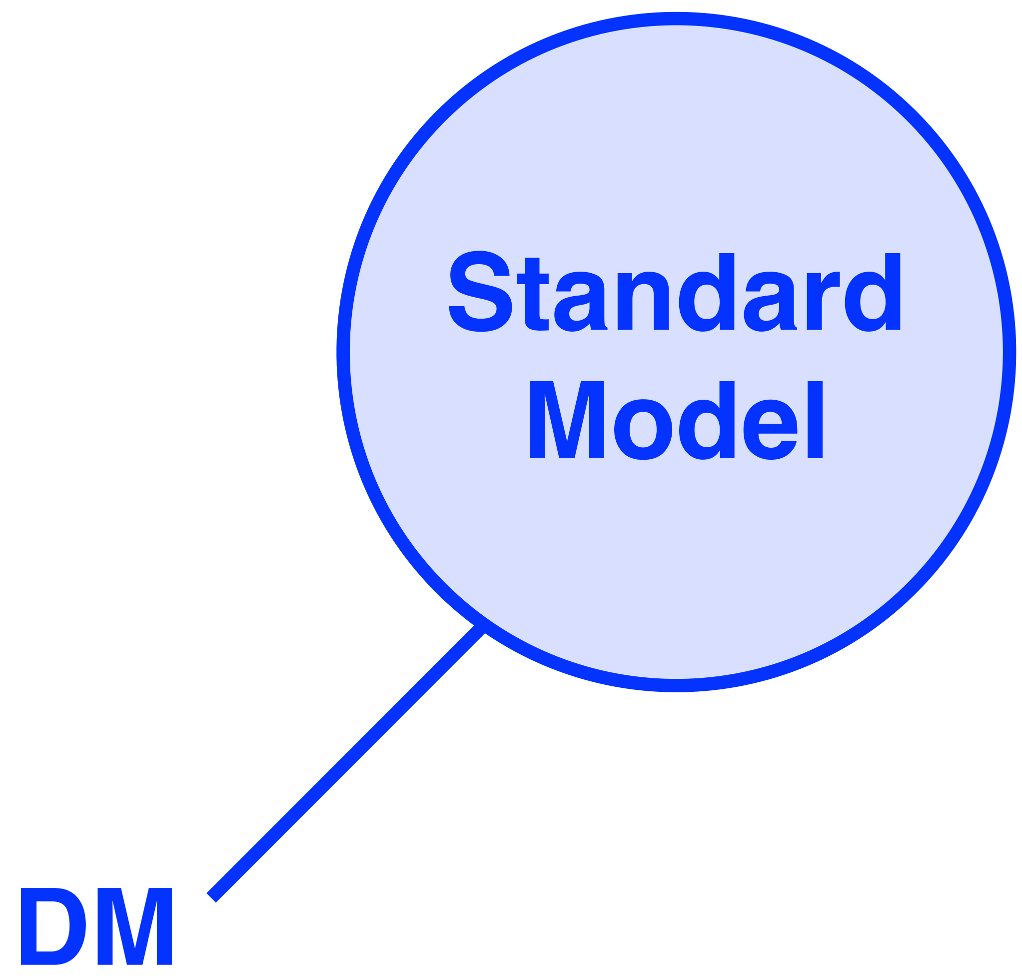
Experimental Summary

3. Dark Matter Below the Higgs Scale

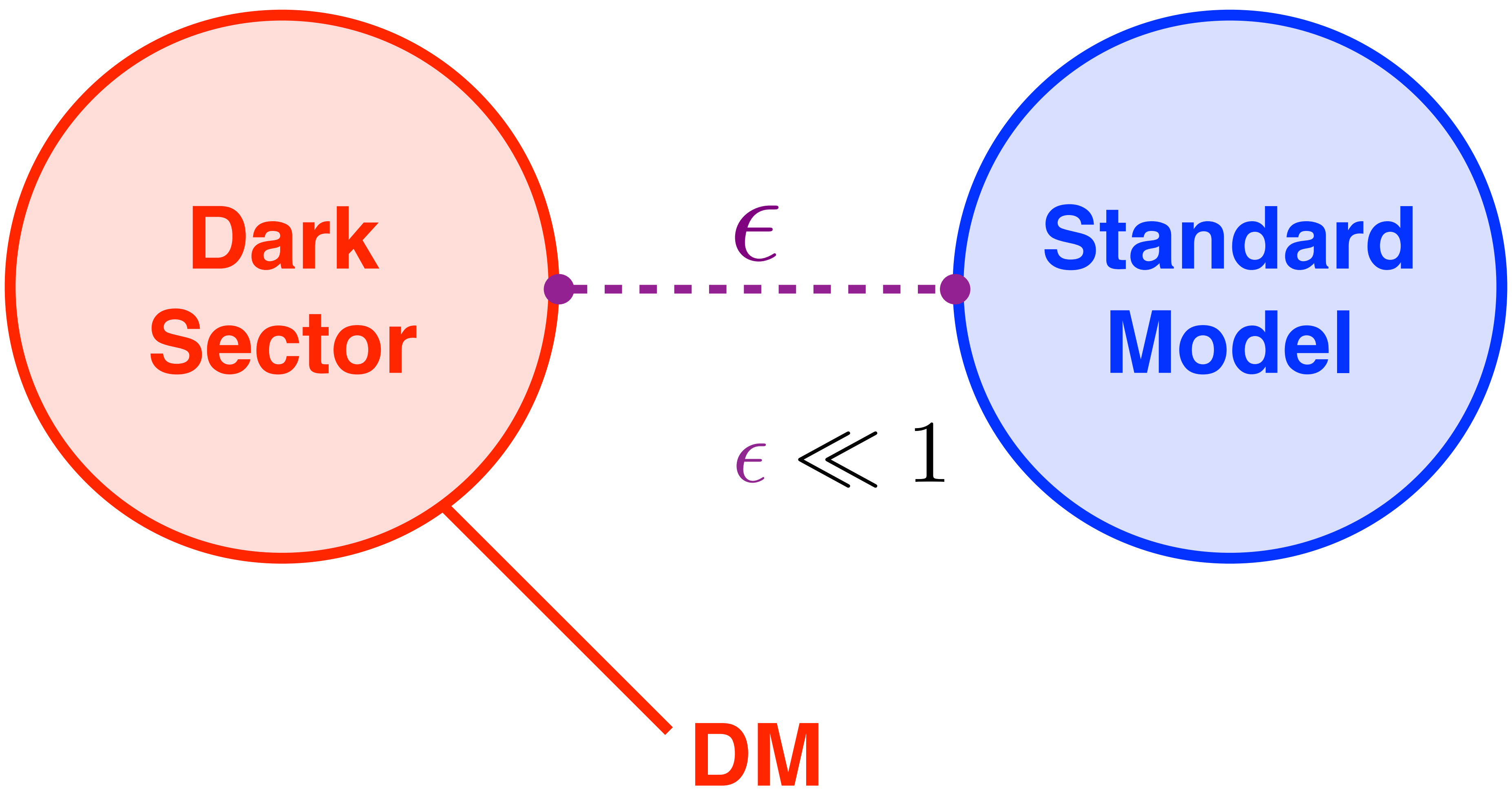
light dark matter



Weakly Interacting Massive Particle



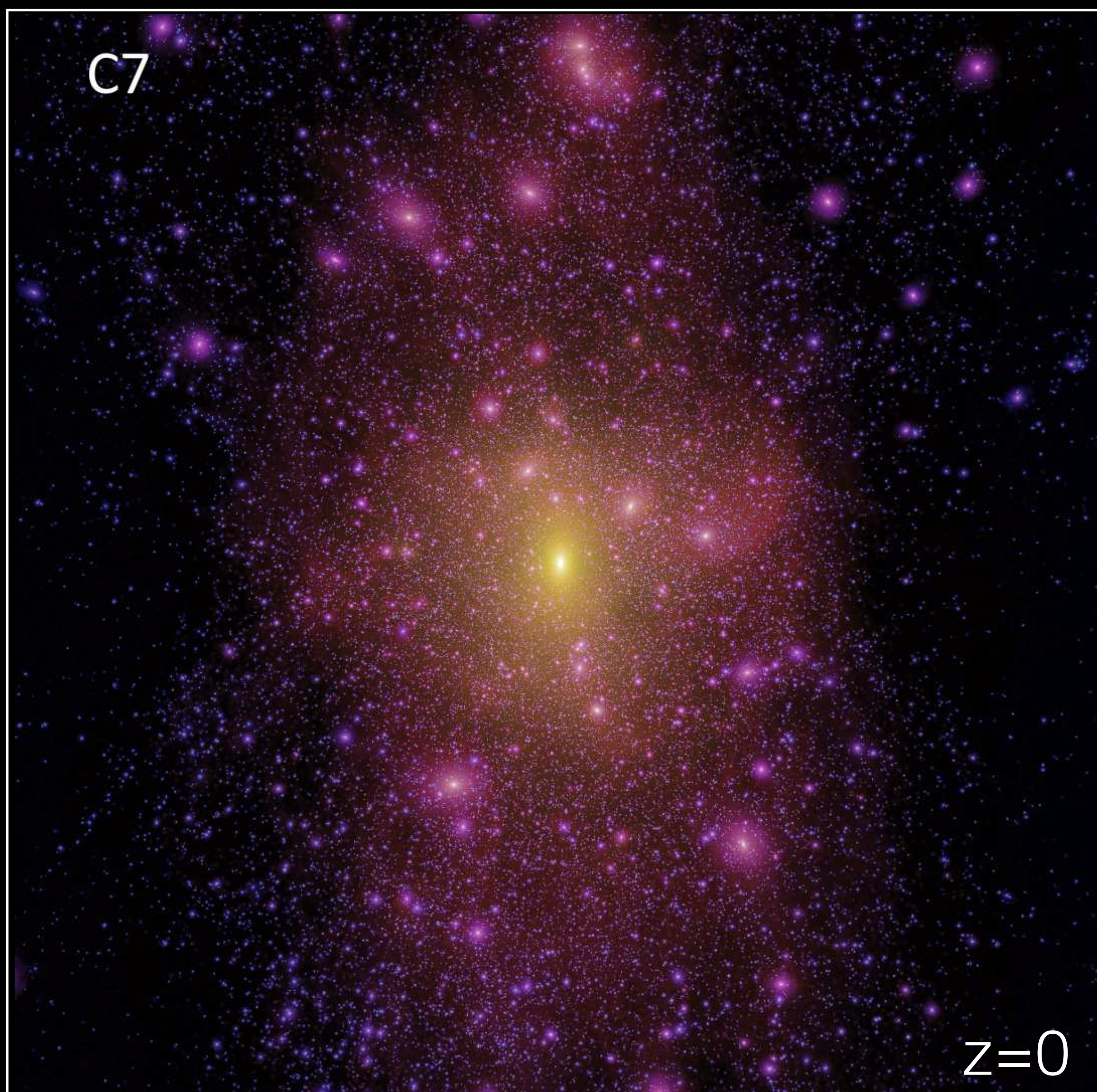
Hidden Sector Dark Matter



- 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).

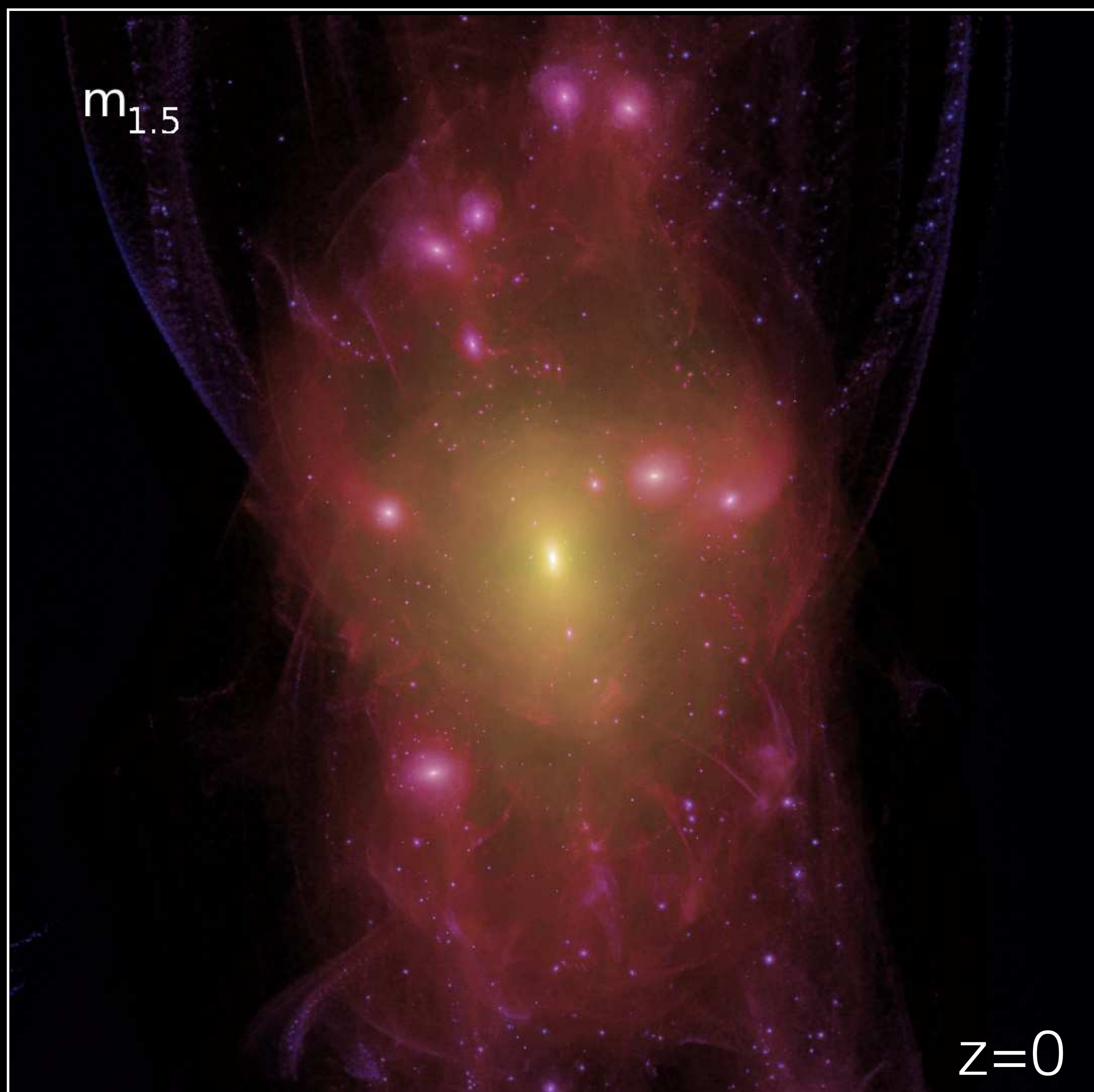
Cold vs. Warm Dark Matter

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



1.5 Mpc

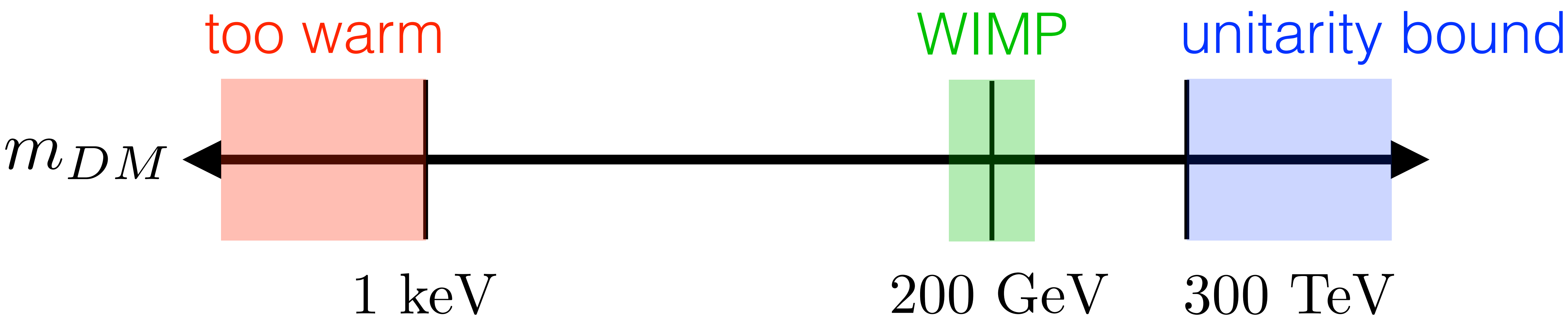
Warm: $m_{DM} = 1.5 \text{ keV}$



1.5 Mpc

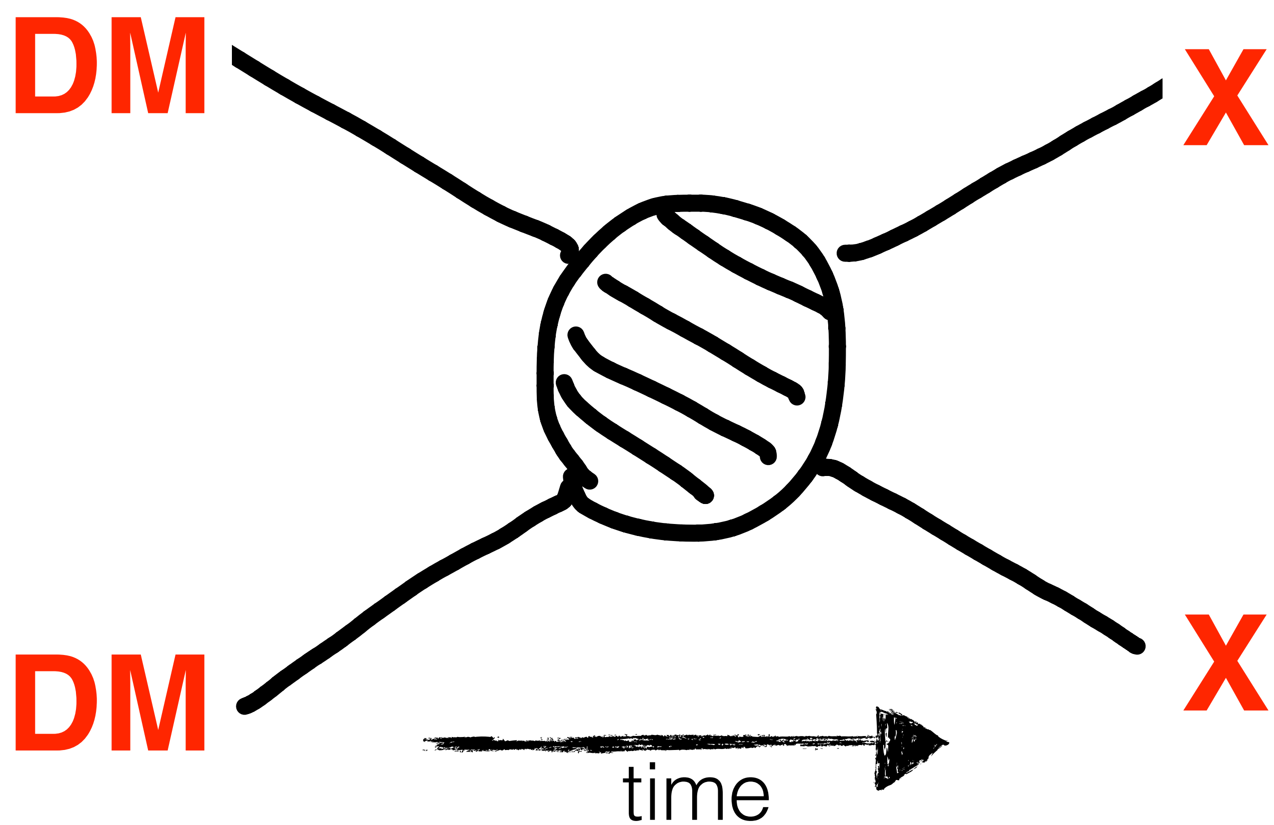
- Lovell *et. al.*, MNRAS **439**, 300 (2014).

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

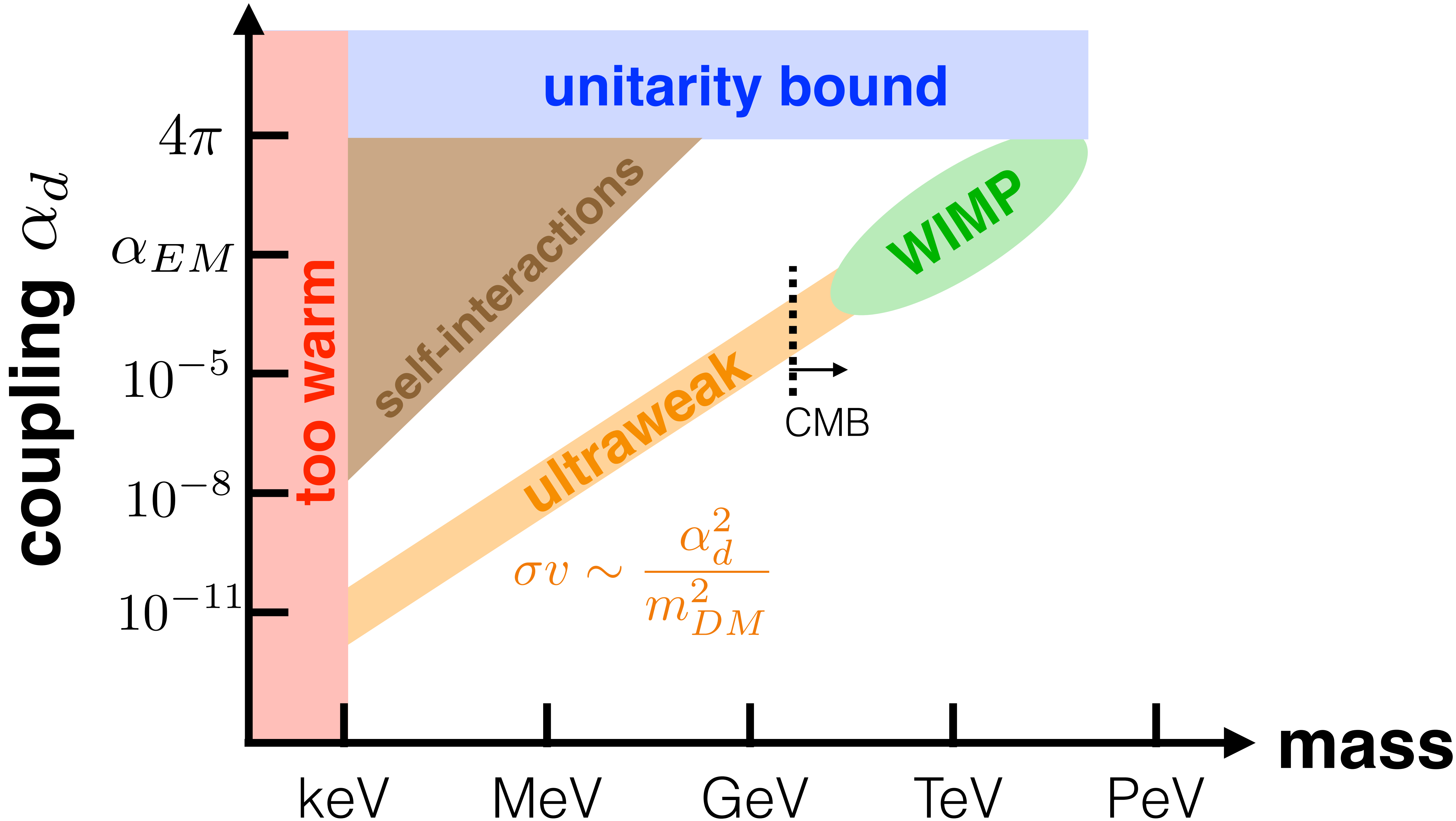


$$\sigma v \sim \frac{\alpha_d^2}{m_{DM}^2}$$

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

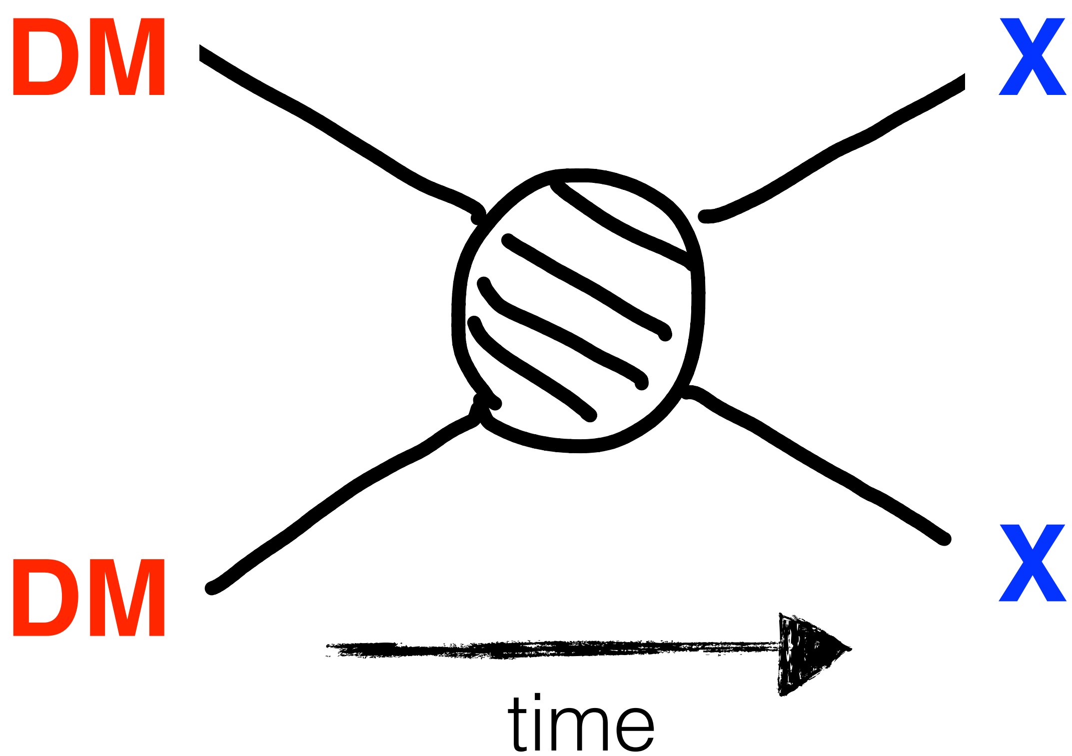
- Boehm, Fayet, Nucl. Phys. B **683**, 219 (2004).
- Finkbeiner, Weiner, Phys. Rev. D **76**, 083519 (2007).
- Pospelov, Ritz, Voloshin, Phys. Lett. B **662**, 52 (2008).
- Feng, Kumar, Phys. Rev. Lett. **101**, 231301 (2008).

dark matter freezeout



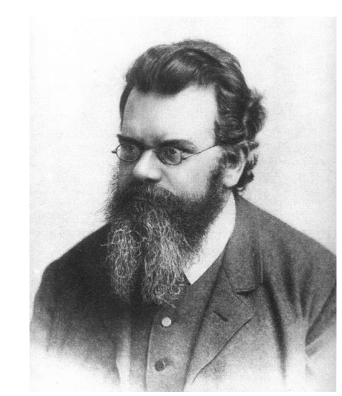
Forbidden Dark Matter

$$m_{DM} < m_X$$



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

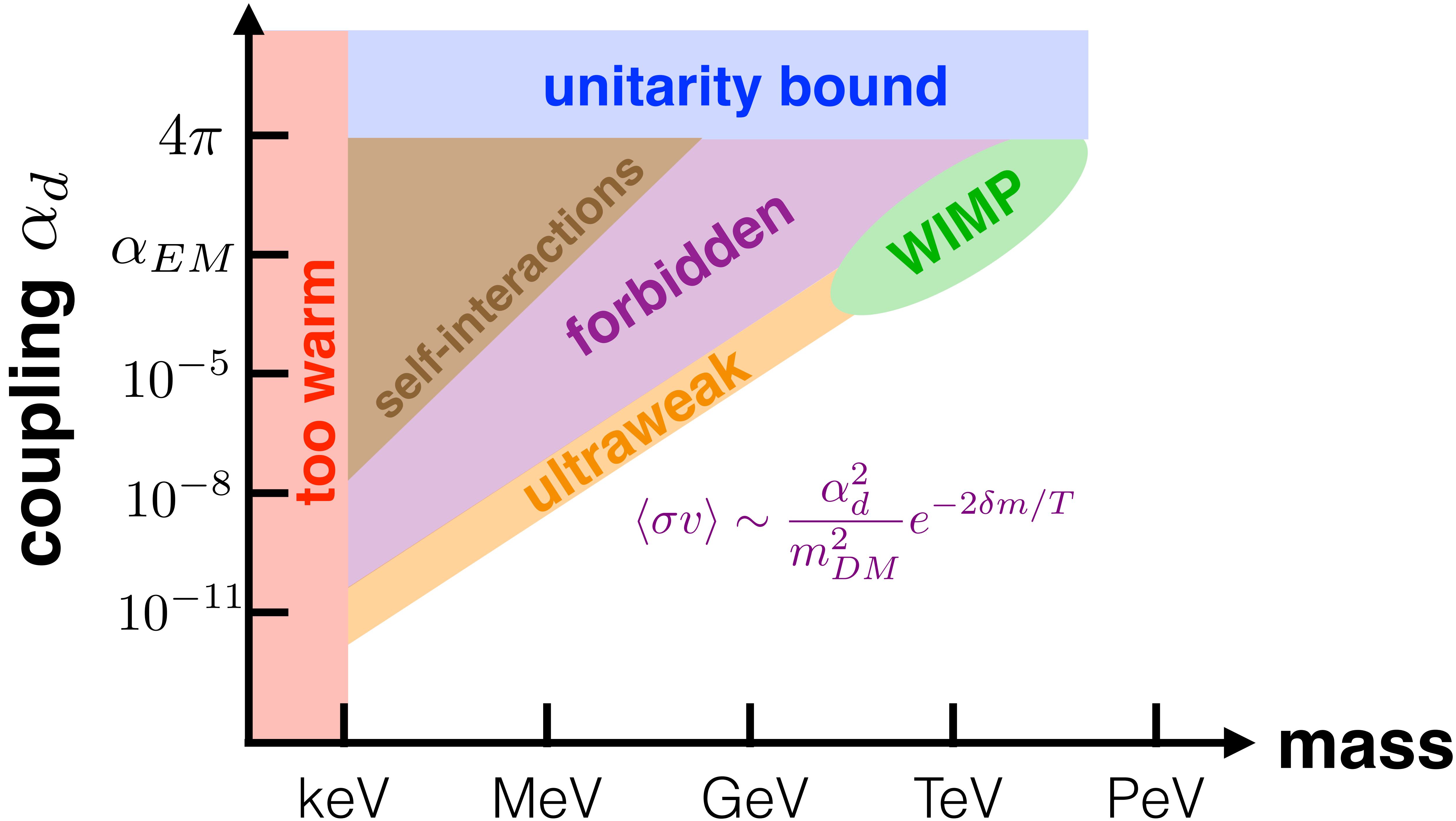
- thermal average: $\langle \sigma v \rangle \sim \frac{\alpha_d^2}{m_{DM}^2} e^{-2\delta m/T}$



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

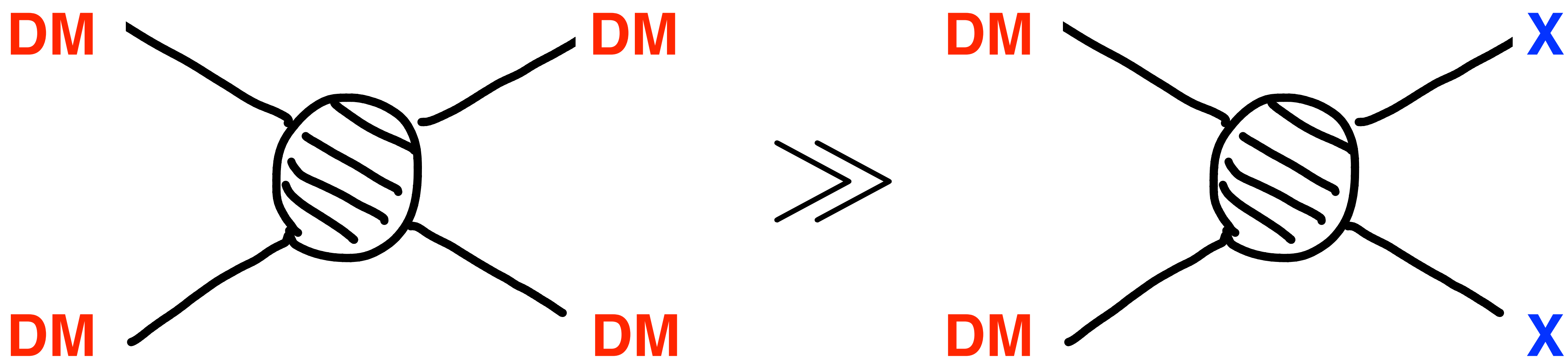
- Griest, Seckel, Phys. Rev. D **43**, 3191 (1991).
- D'Agnolo, Ruderman, Phys. Rev. Lett. **115** 061301 (2015).

dark matter freezeout

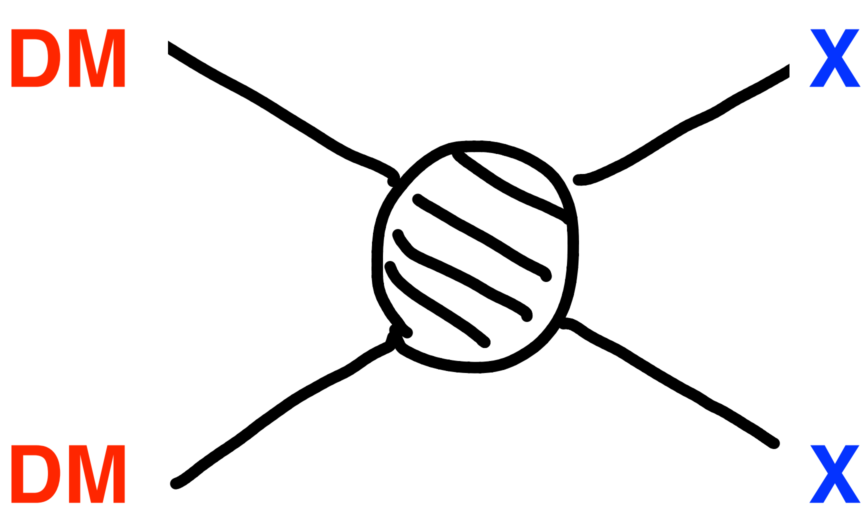


Forbidden DM Phenomenology

- sizable self-interactions:



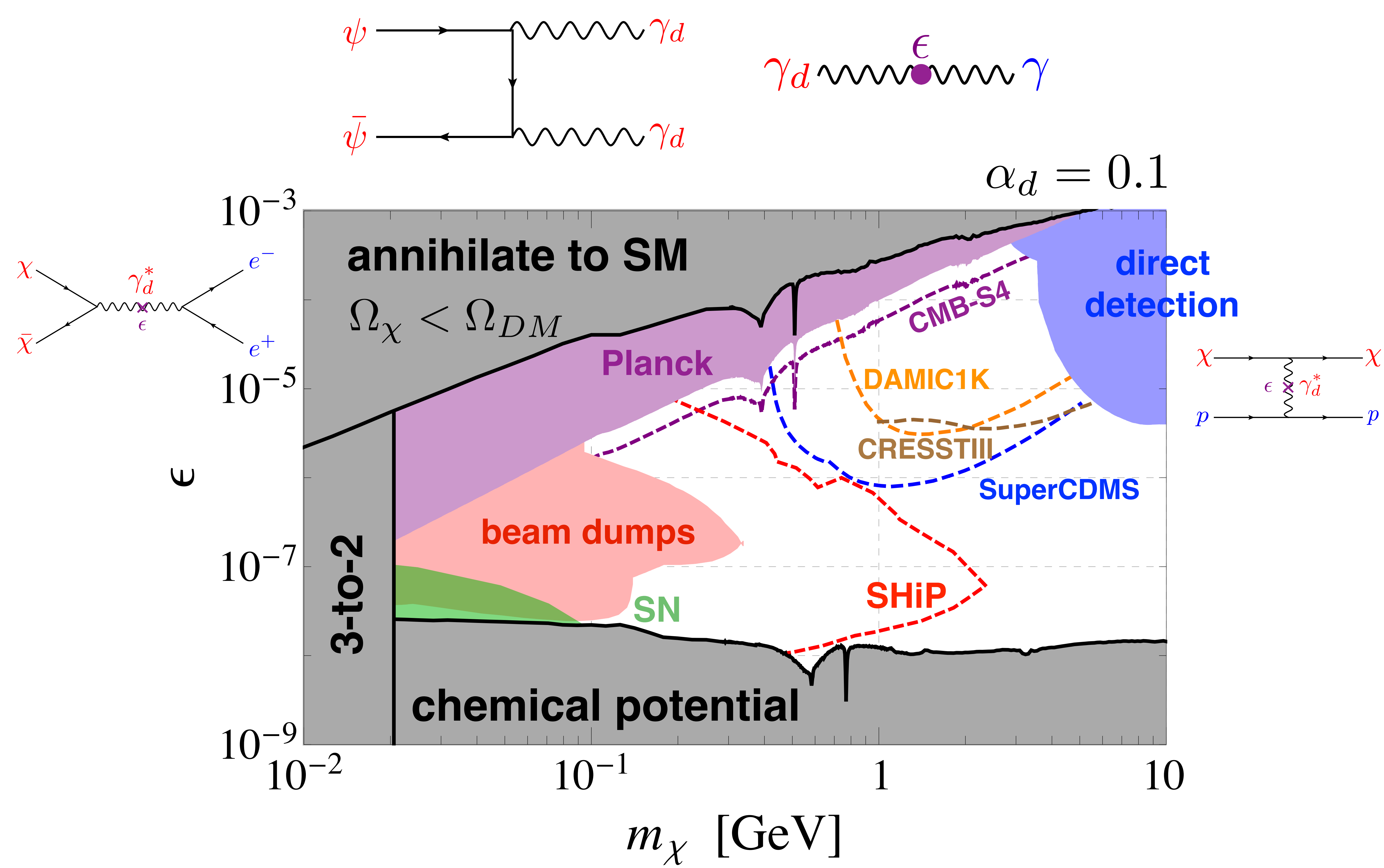
- evades cosmic microwave background:



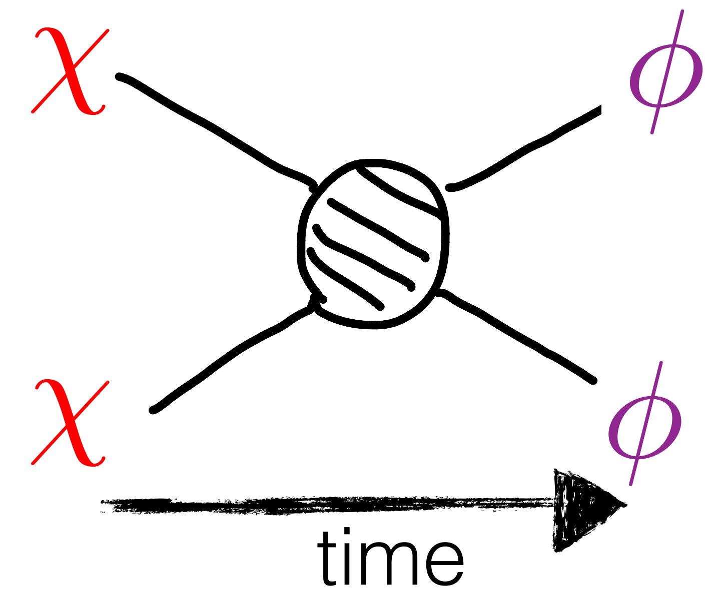
$$\propto e^{-2\delta m / T_{CMB}}$$

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

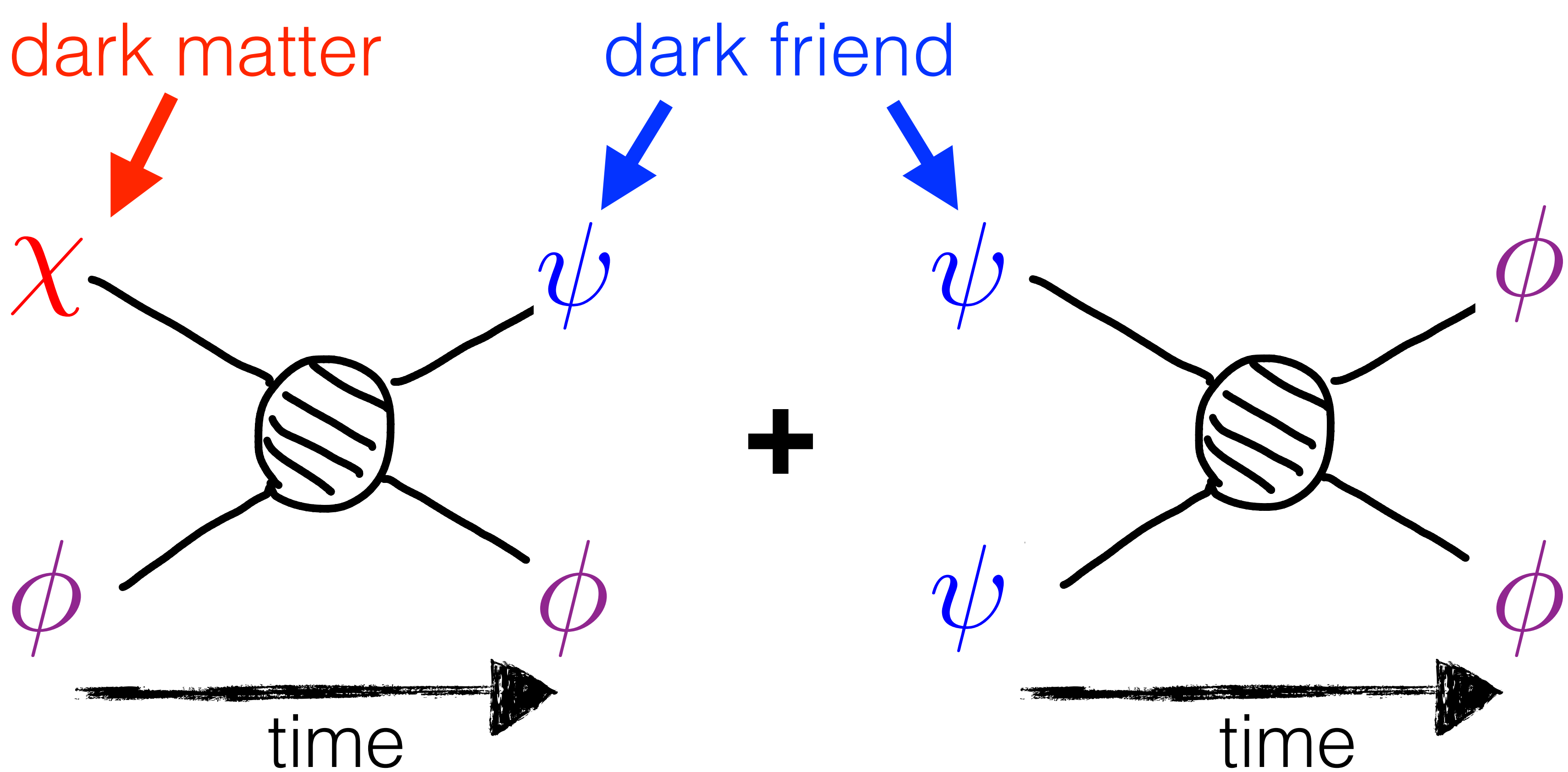
Forbidden DM with Kinetic Mixing Portal

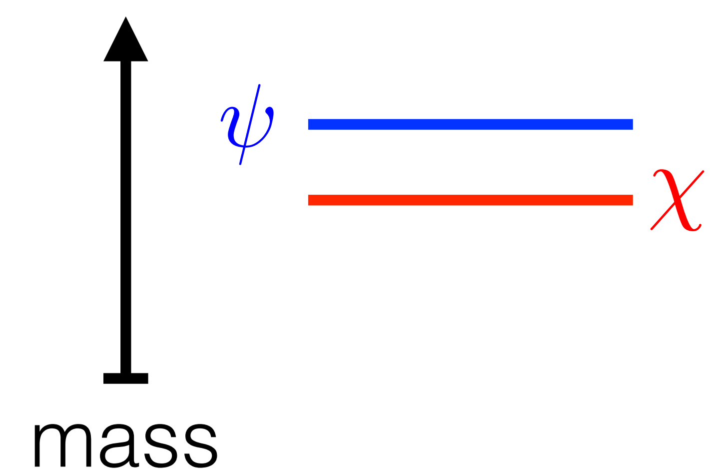


Coscattering



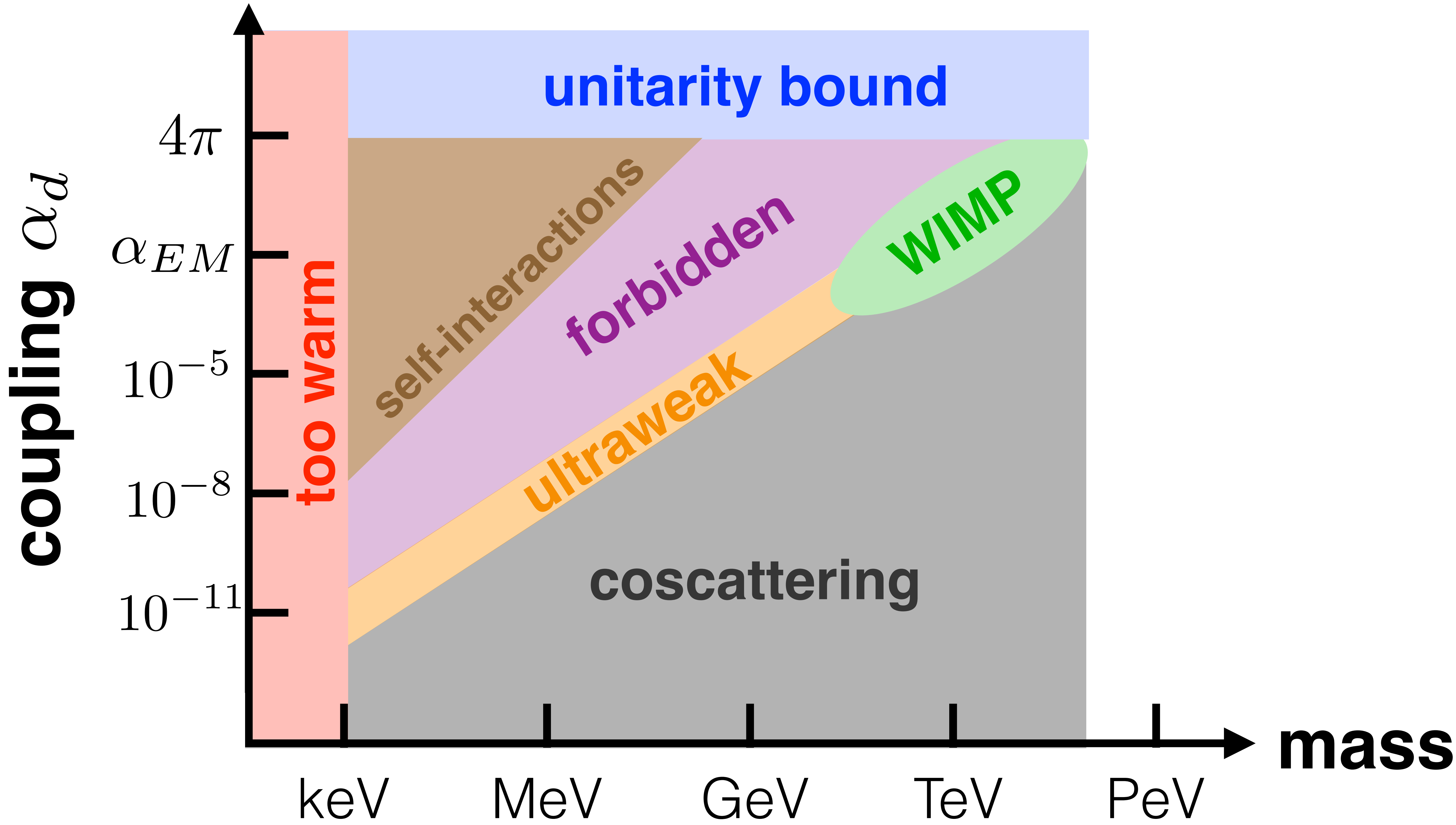
- what if the annihilation rate is too small?





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

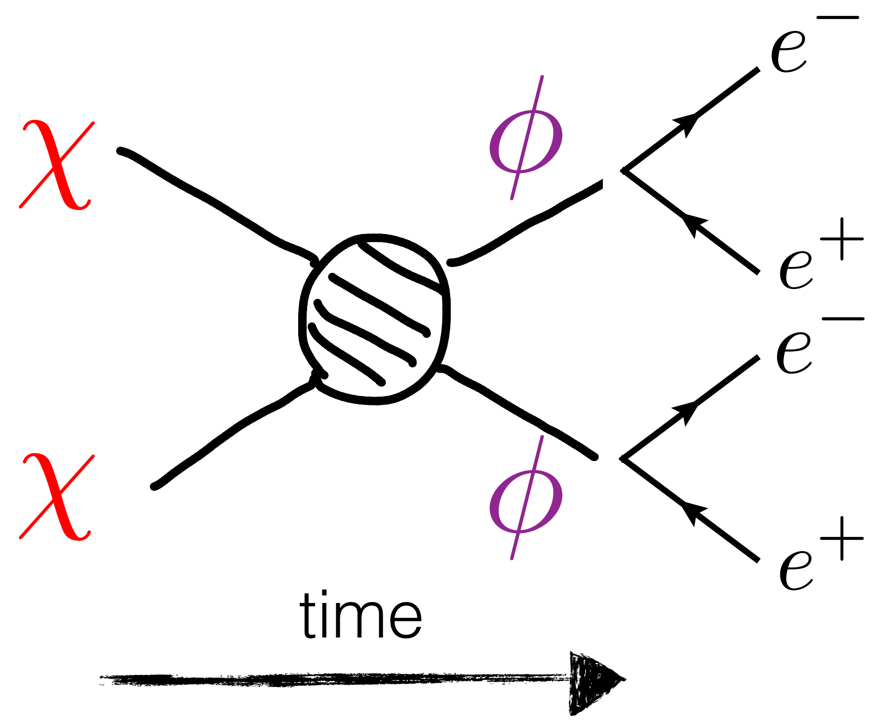
dark matter freezeout



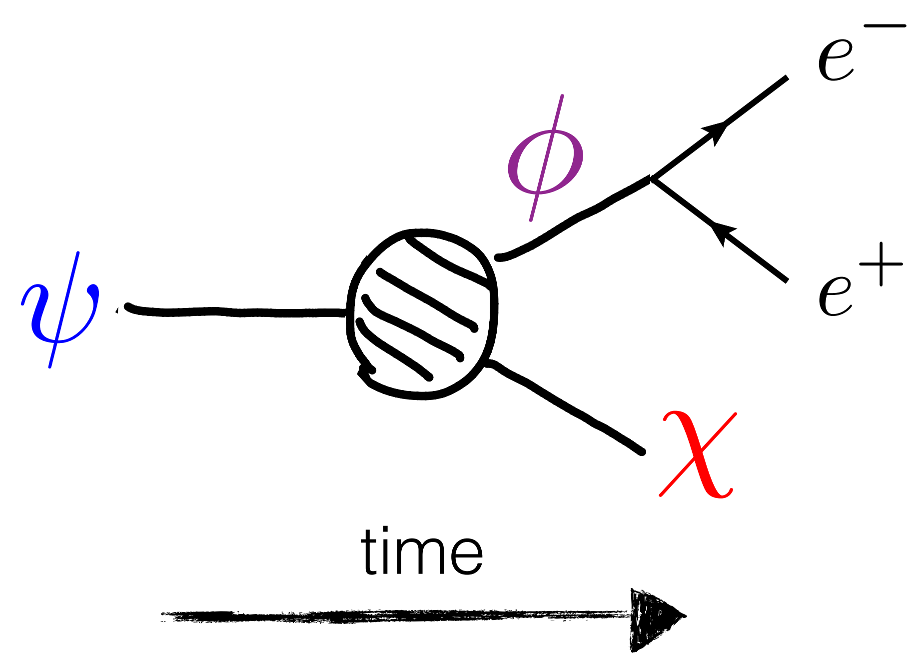
Coscattering Phenomenology

- suppressed annihilations

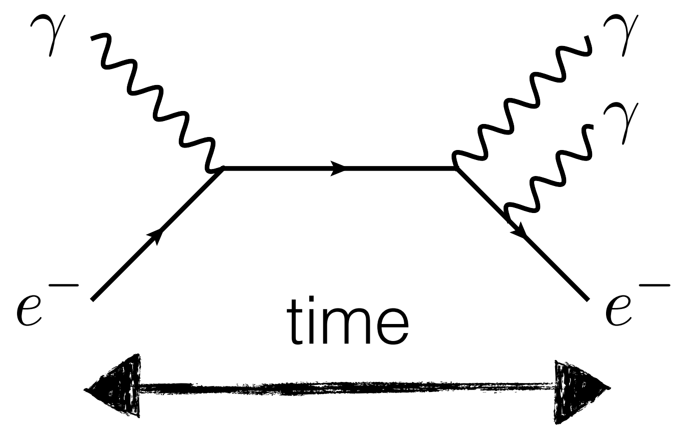
$$\sigma v \ll 3 \times 10^{26} \mathrm{cm}^3/\mathrm{s}$$

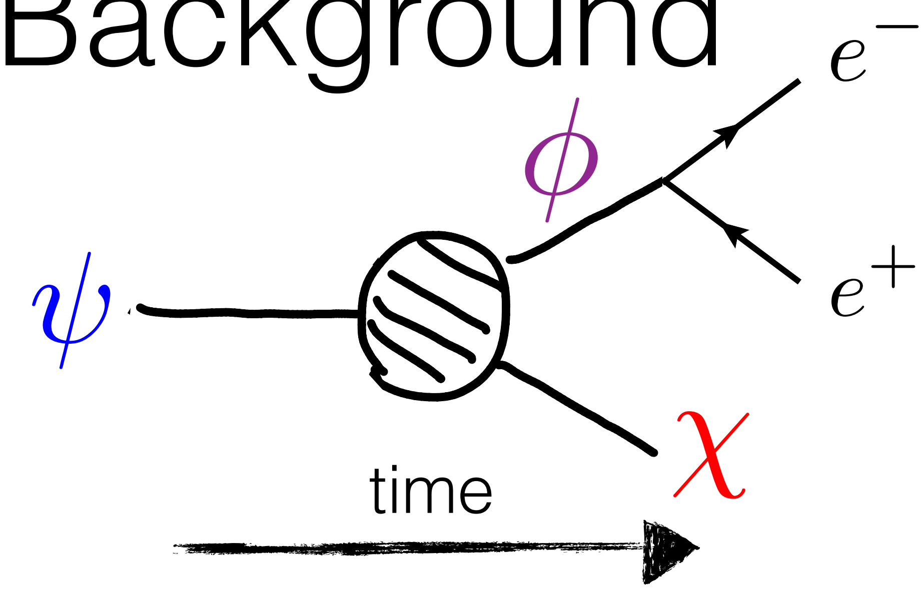


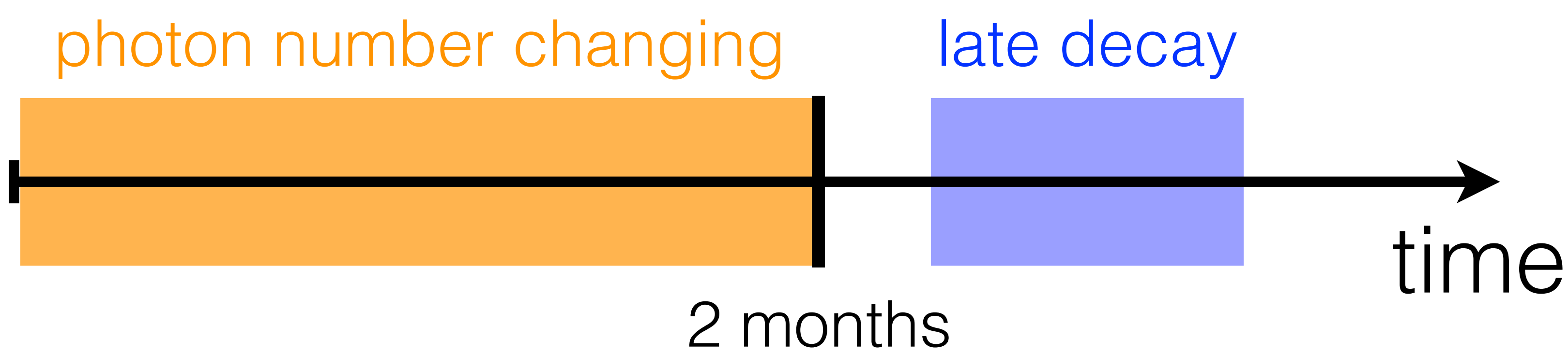
- late decays of dark friend

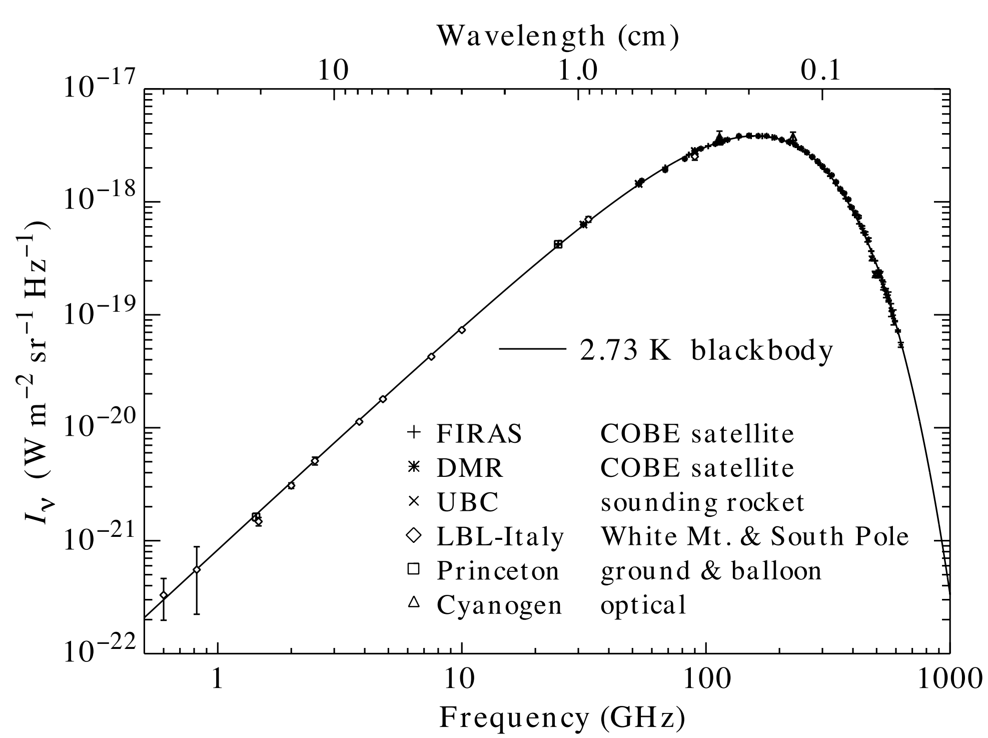


Spectral Distortions of Cosmic Microwave Background

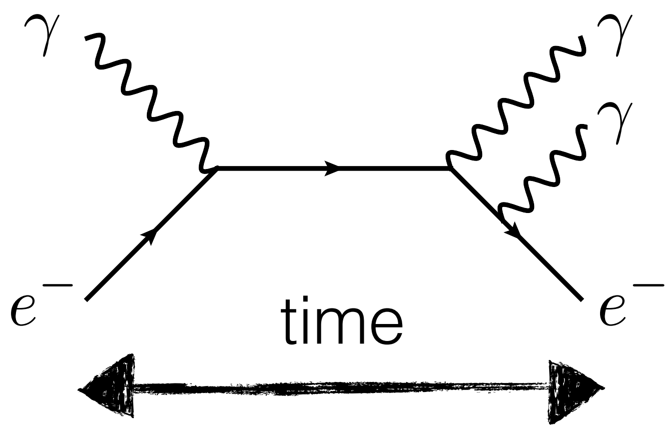


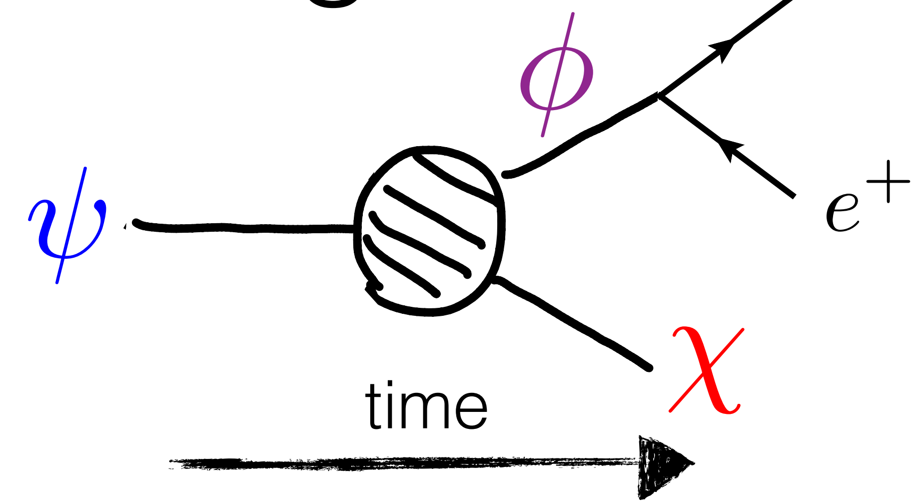


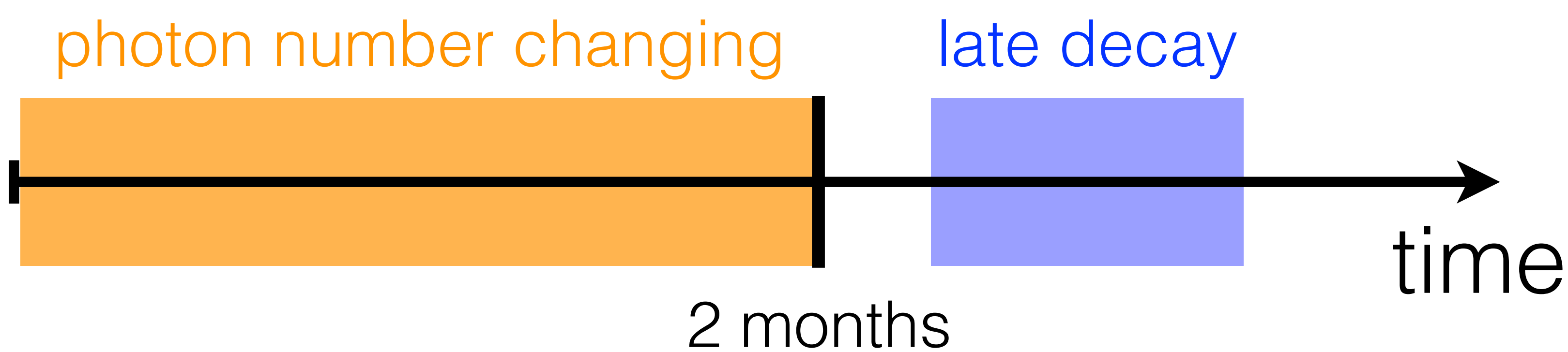




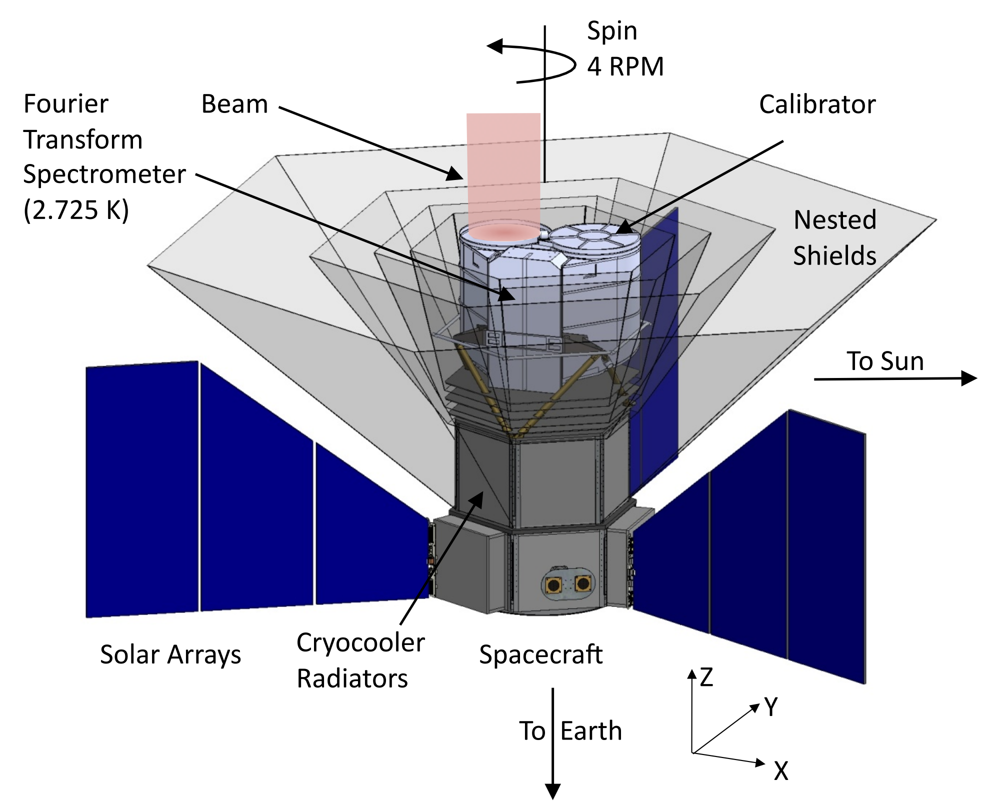
Spectral Distortions of Cosmic Microwave Background







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

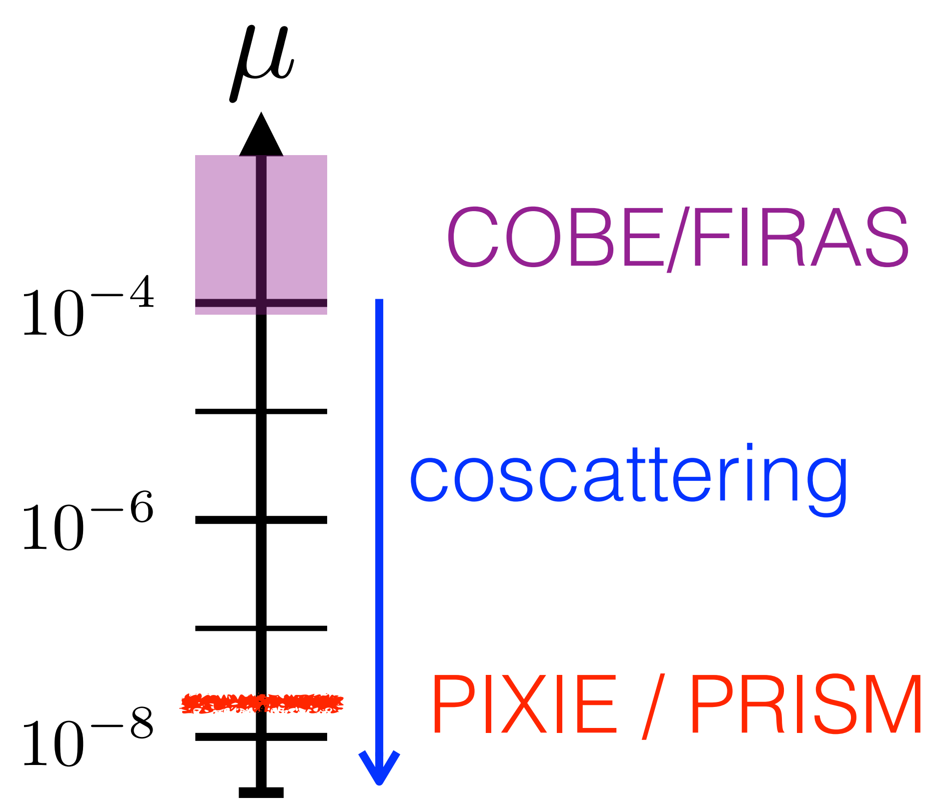


- Chuss et. al., JCAP **1107**, 025 (2011).
- PRISM Collaboration, JCAP **1402**, 006 (2014).

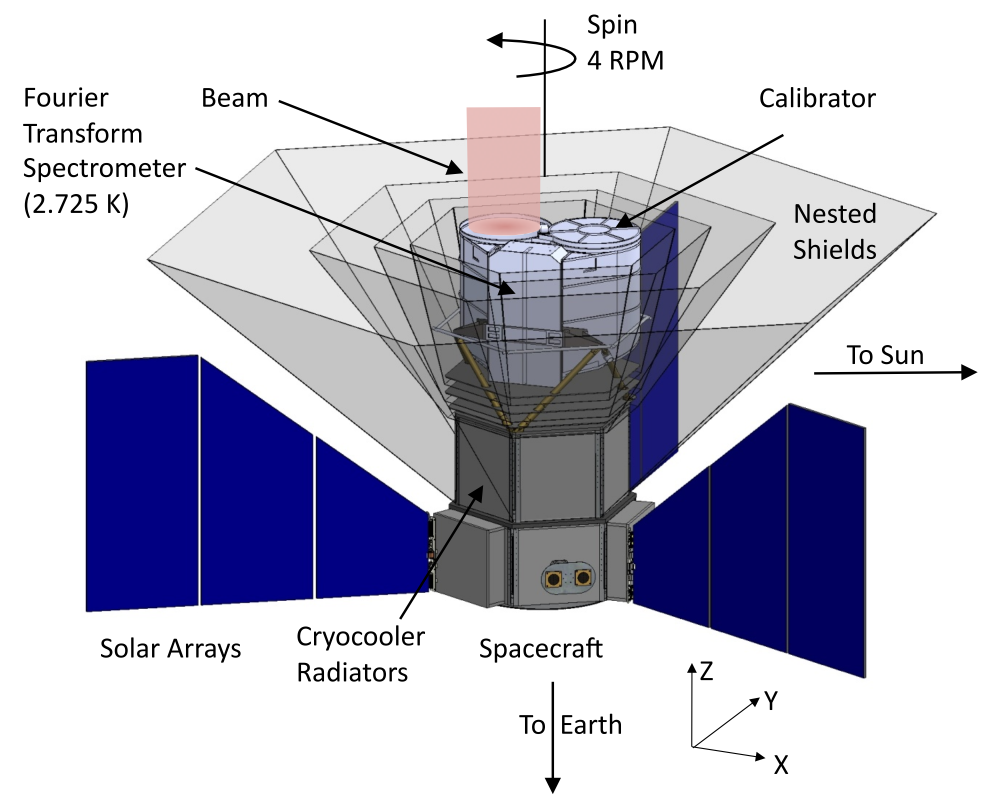
Spectral Distortions of Cosmic Microwave Background

μ – distortion

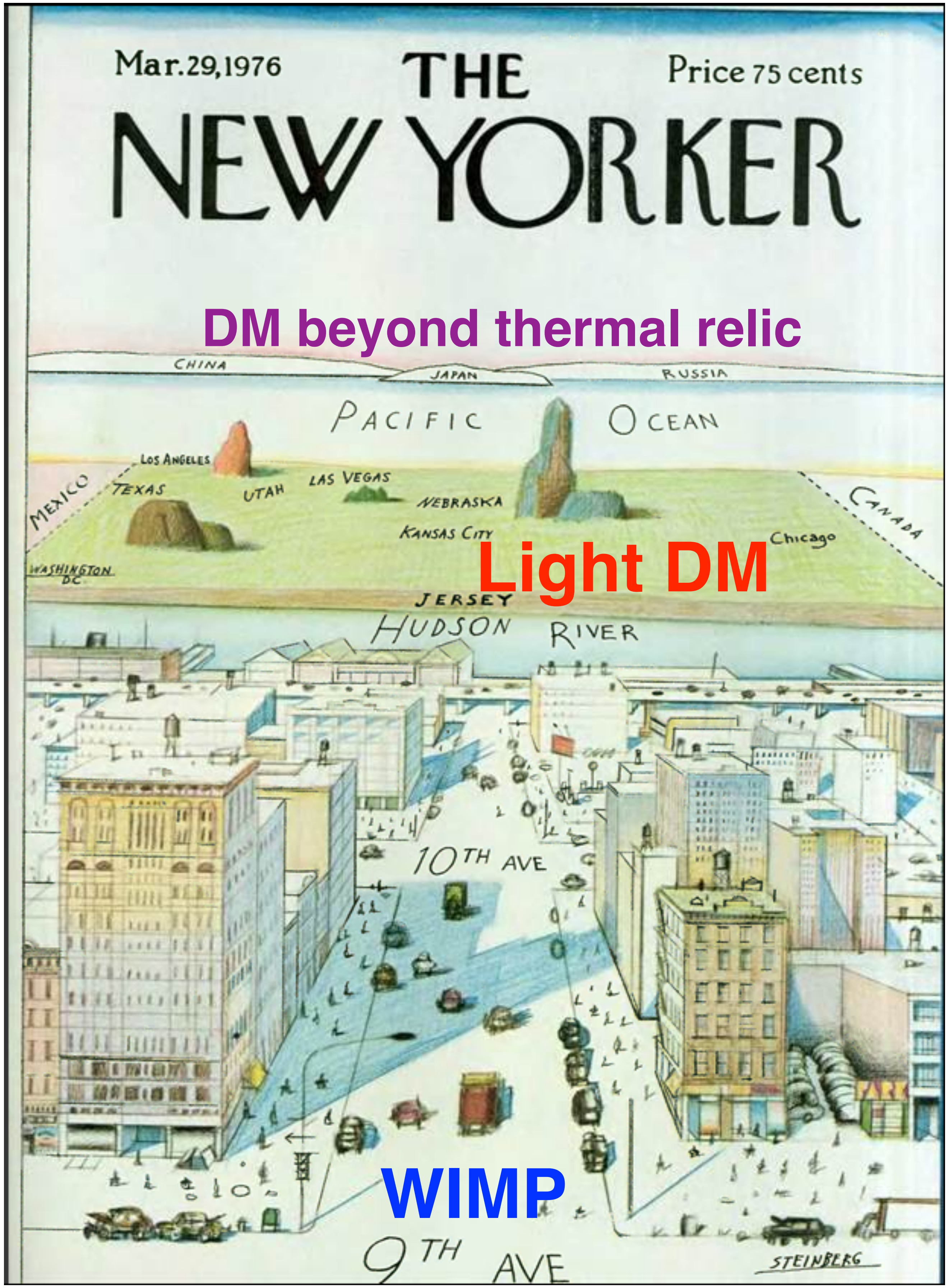
$$f_\gamma(E) = \frac{1}{e^{E/(kT)+\mu} - 1}$$



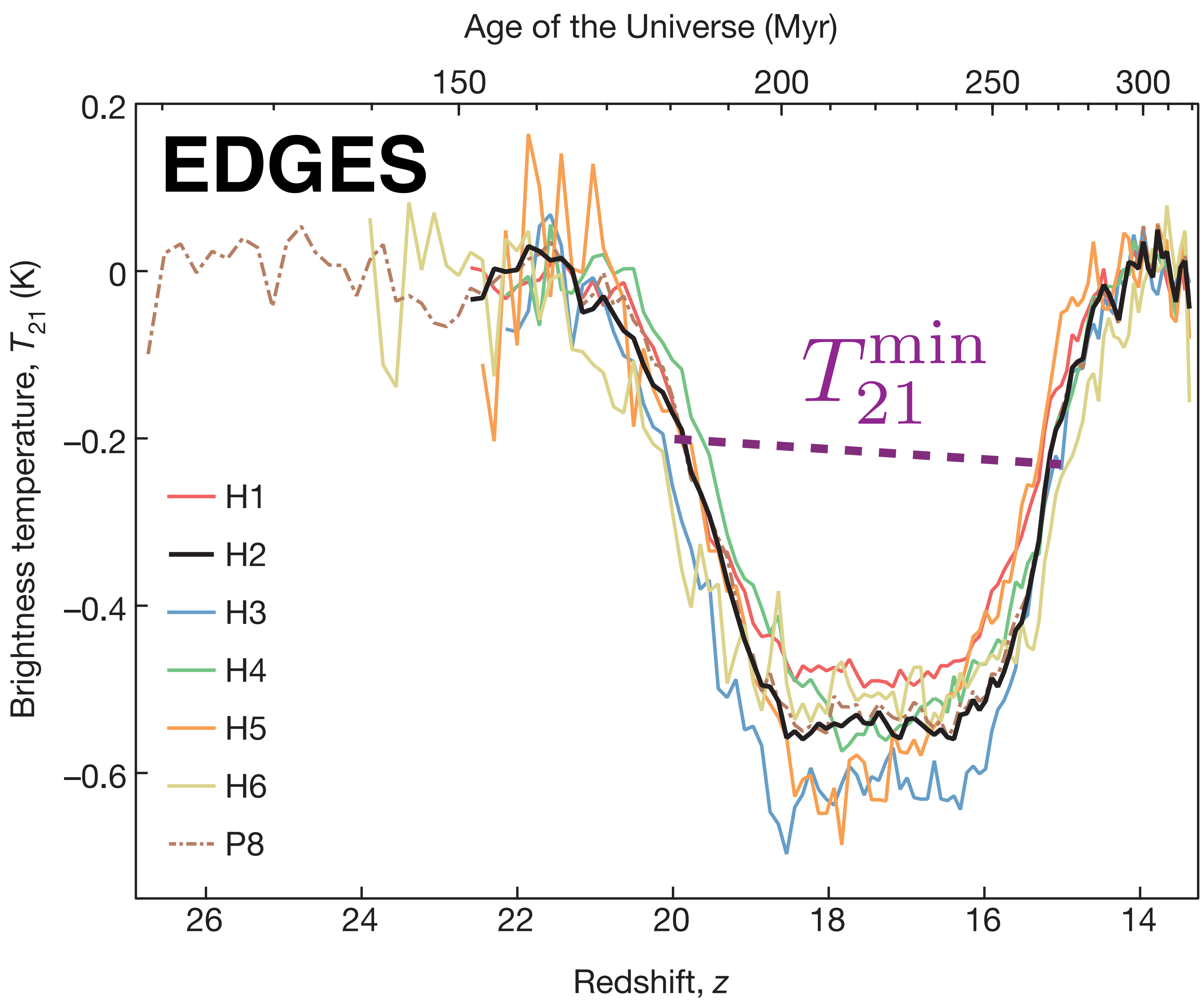
PIXIE / PRISM can improve sensitivity to *spectral distortions* by factor of ~1000



- Chuss et. al., JCAP **1107**, 025 (2011).
- PRISM Collaboration, JCAP **1402**, 006 (2014).


Mar.29,1976
THE
NEW YORKER
Price 75 cents
DM beyond thermal relic
CHINA
JAPAN
RUSSIA
PACIFIC OCEAN
LOS ANGELES
MEXICO
TEXAS
UTAH
LAS VEGAS
NEBRASKA
KANSAS CITY
CANADA
Chicago
WASHINGTON DC
Light DM
JERSEY
HUDSON RIVER
10TH AVE
WIMP
9TH AVE
STEINBERG

21cm: Data are Coming!



$$T_{21}^{\rm min}$$

$$T_{21} \propto 1 - \frac{T_R(z)}{T_S(z)}$$

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

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

take away

light DM

1. ultraweak
2. forbidden
3. coscattering

...