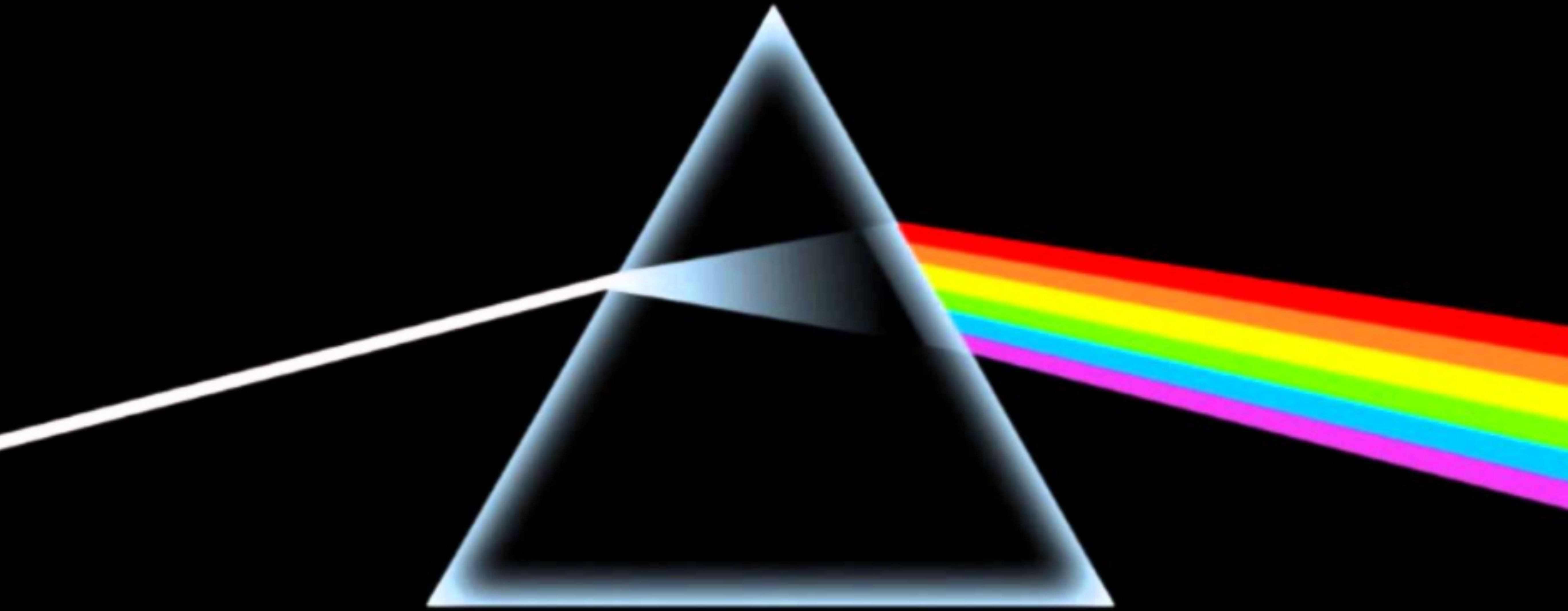
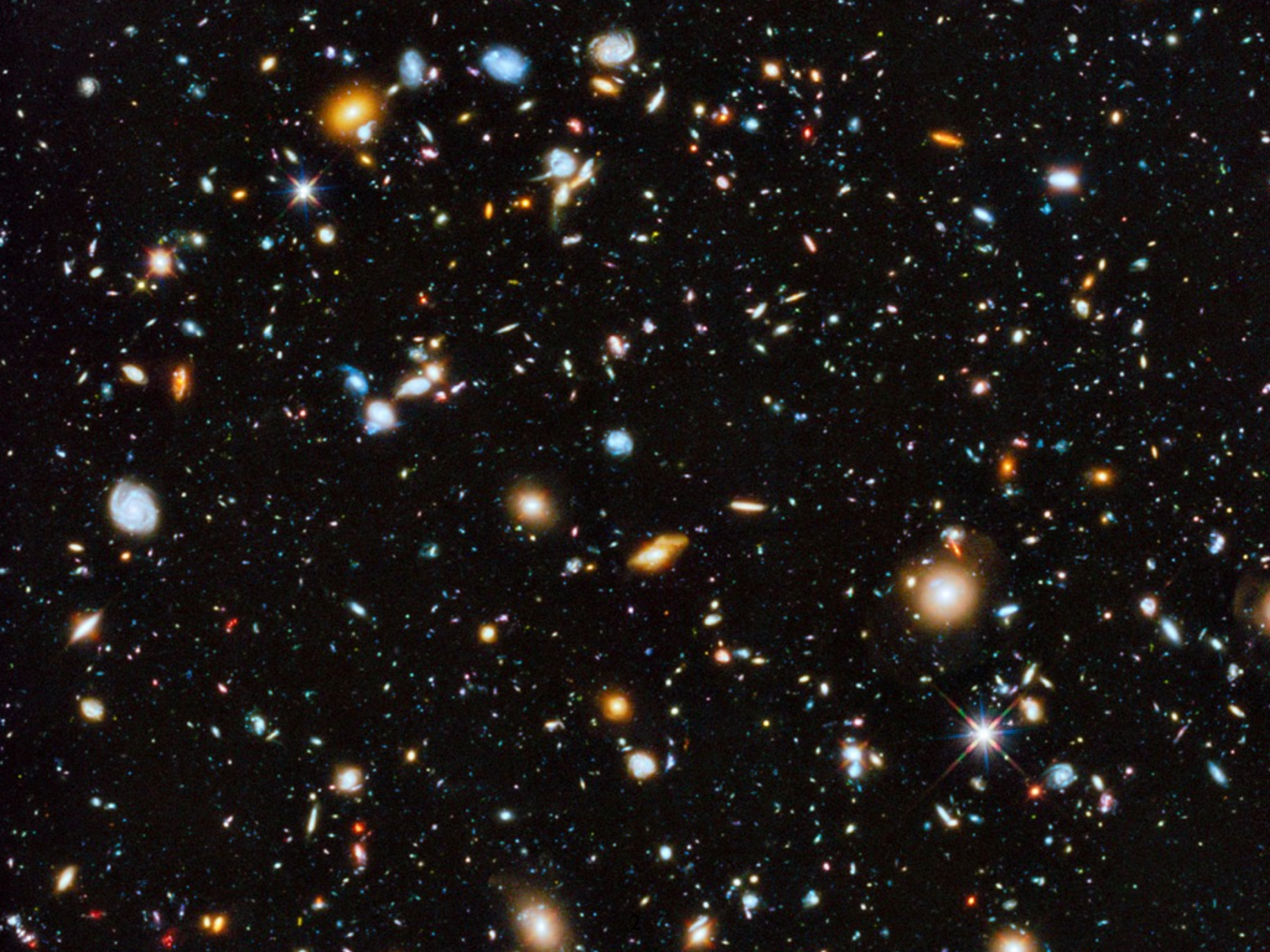
Dark Matter

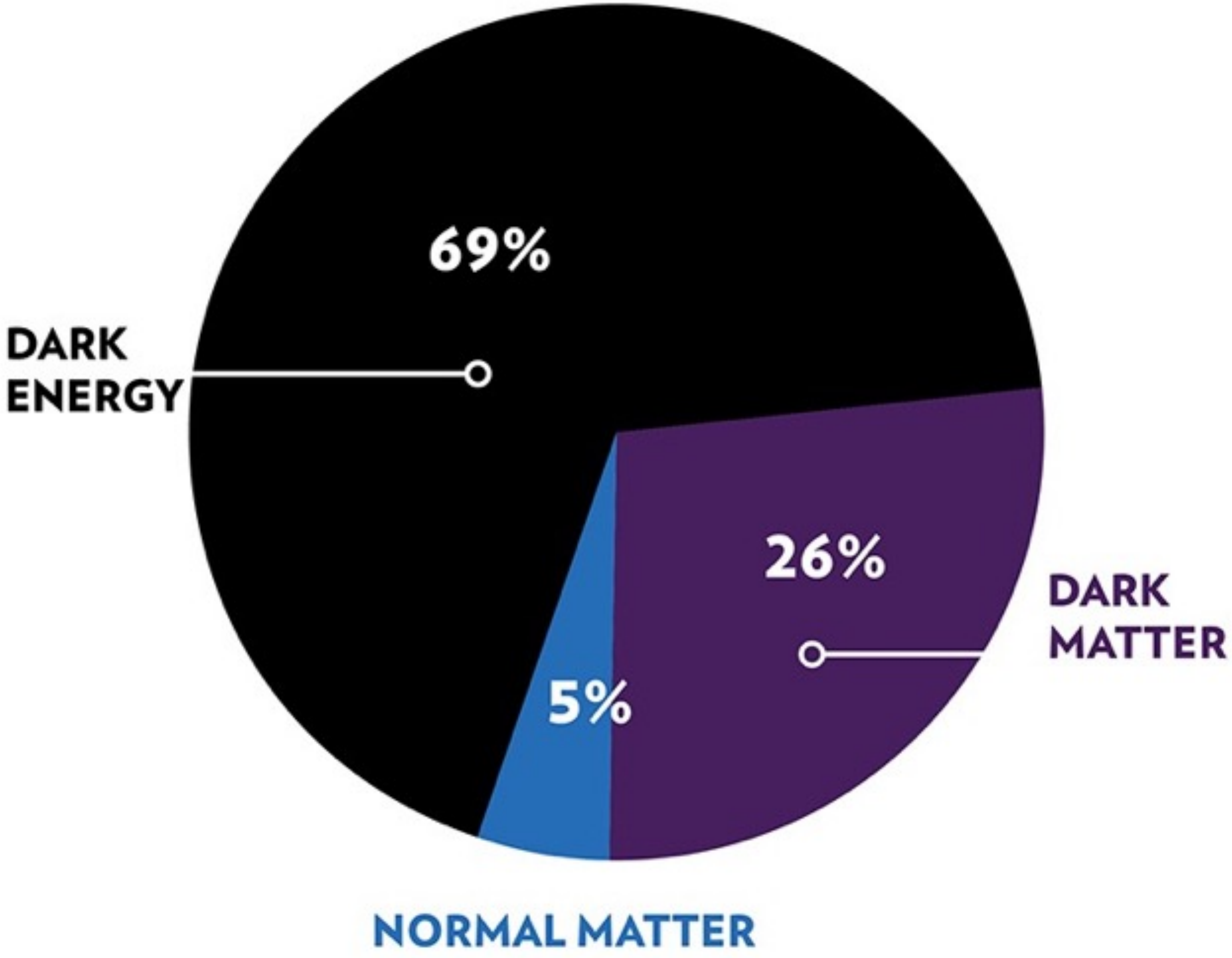


Brian Batell
University of Pittsburgh

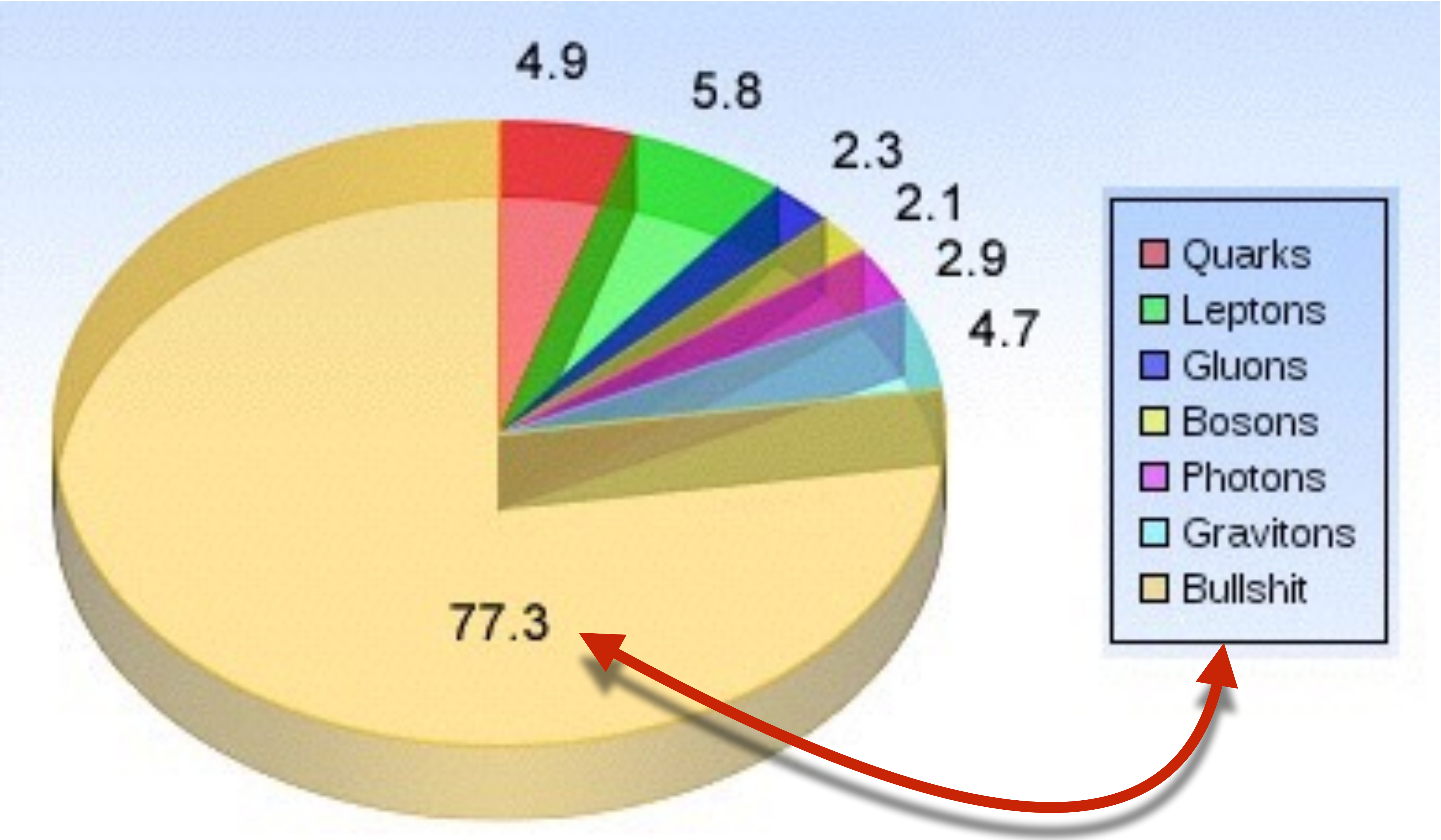
2019 CTEQ School



The Energy Budget of the Universe

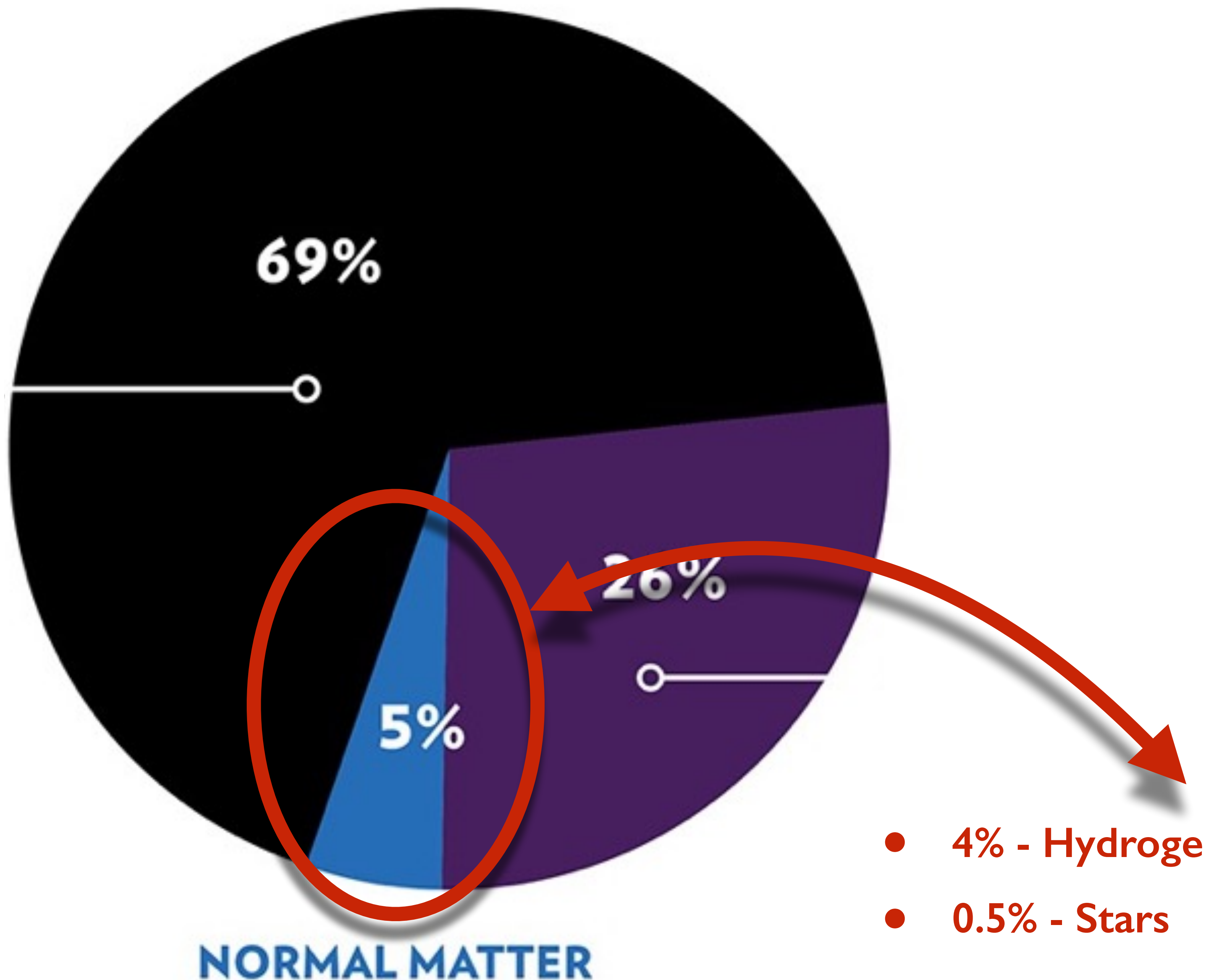


We’ve made progress in our understanding…



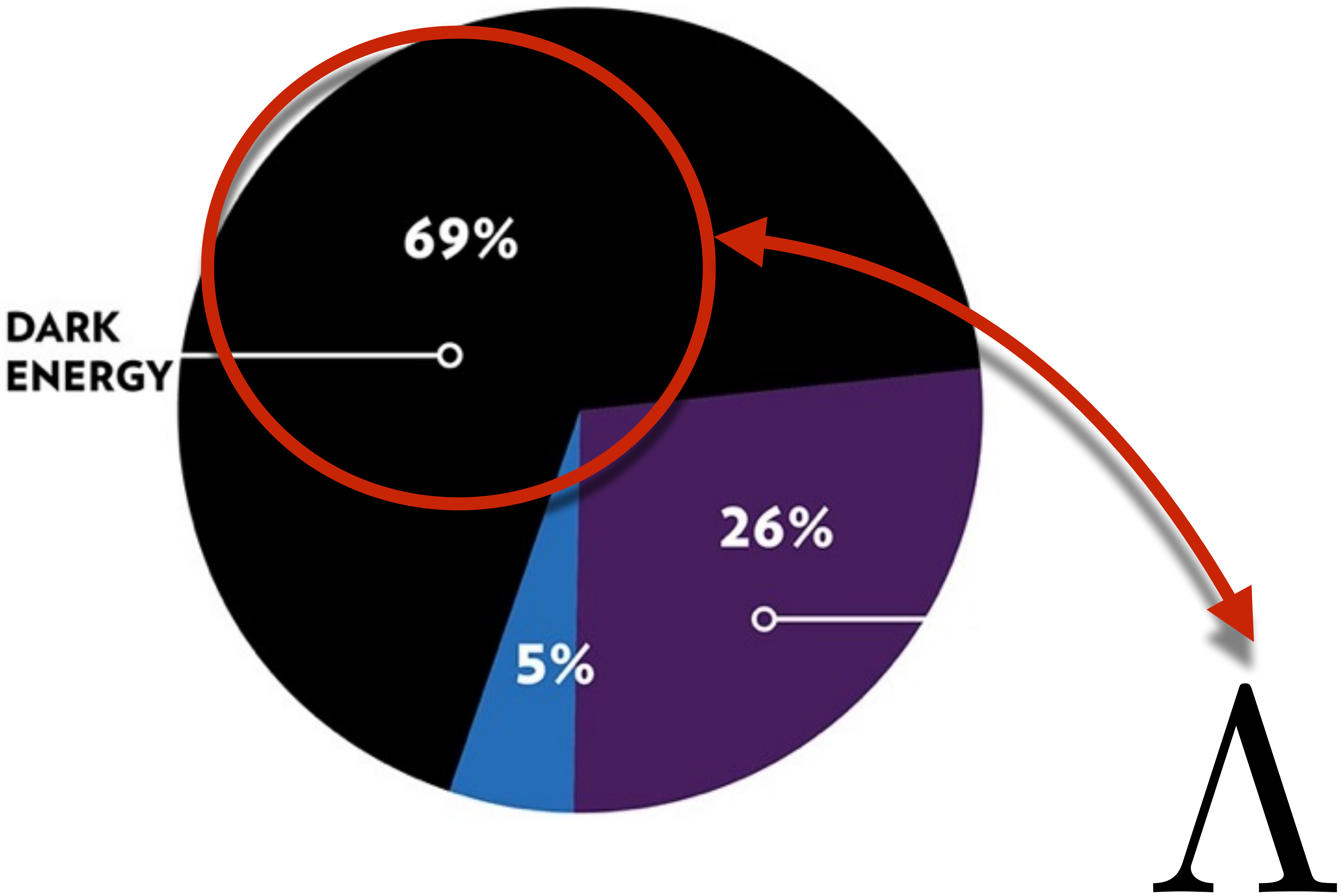
www.sardonika.com

Normal Matter



- 4% - Hydrogen & Helium
- 0.5% - Stars
- 0.3% - Neutrinos
- 0.03% - Heavy Elements

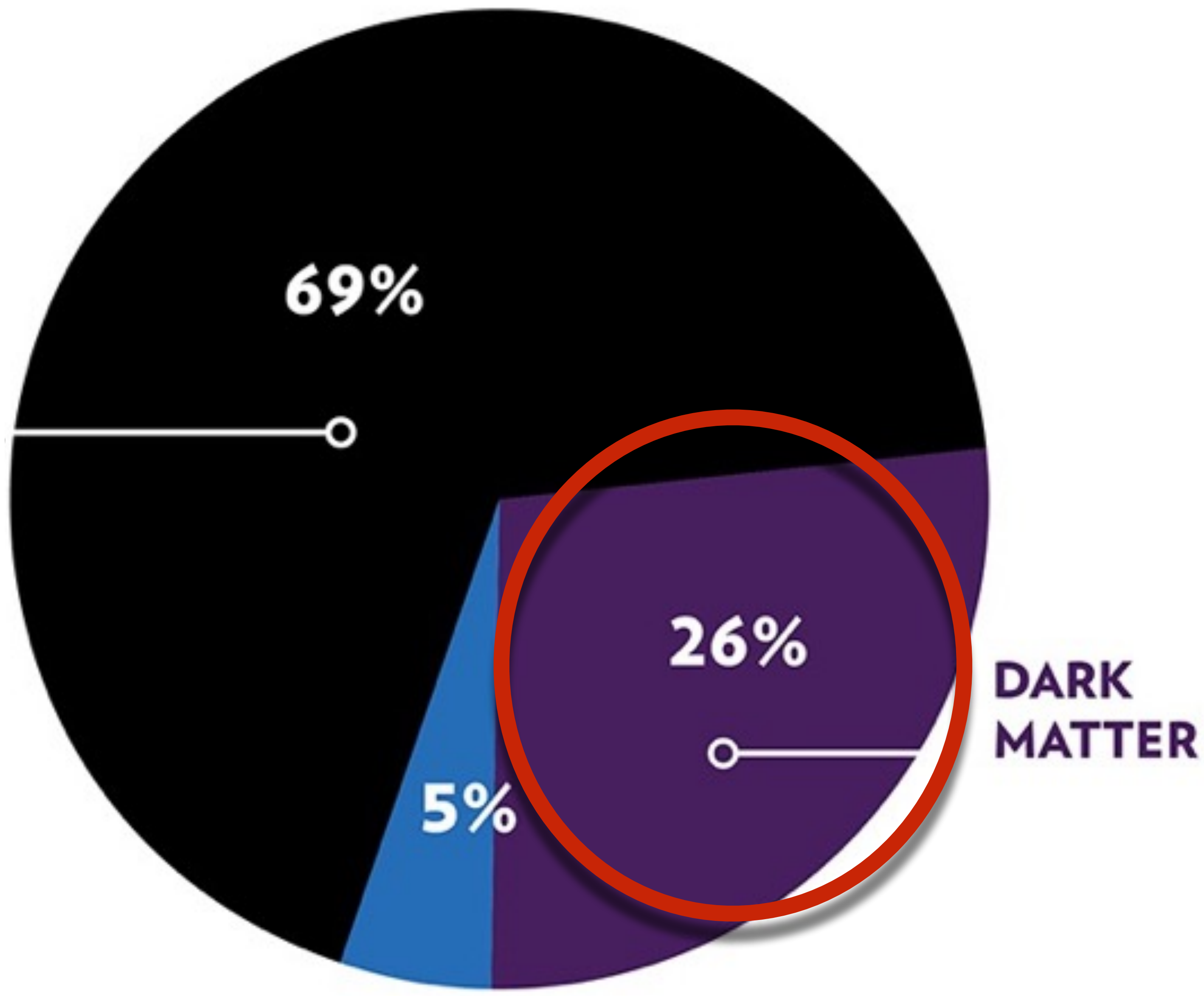
Dark Energy



Cosmological
Constant???

Not covered in this talk
(i.e., too hard for me to solve!)

Dark Matter



Coma Cluster

- Zwicky (~1930s) studied the Coma galaxy cluster

- From measured velocity dispersion of galaxies, applied virial theorem to determine total mass of Coma

- This estimate was larger by a factor of ~500 than the observed luminous mass

Galaxy Rotation Curves

- Rubin et al. and other studied the velocity rotation curves in 70s

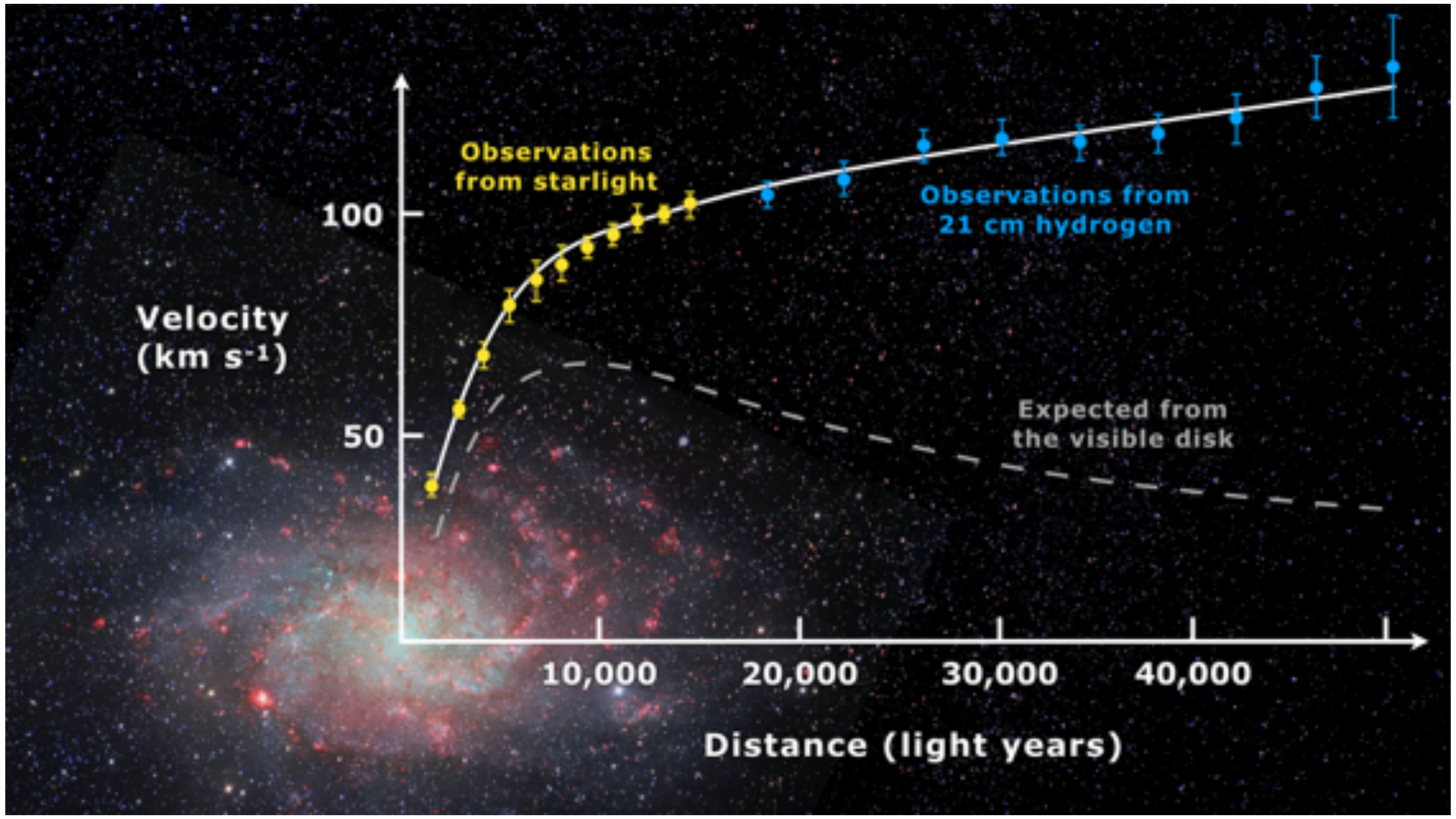
- Newtonian dynamics expectation

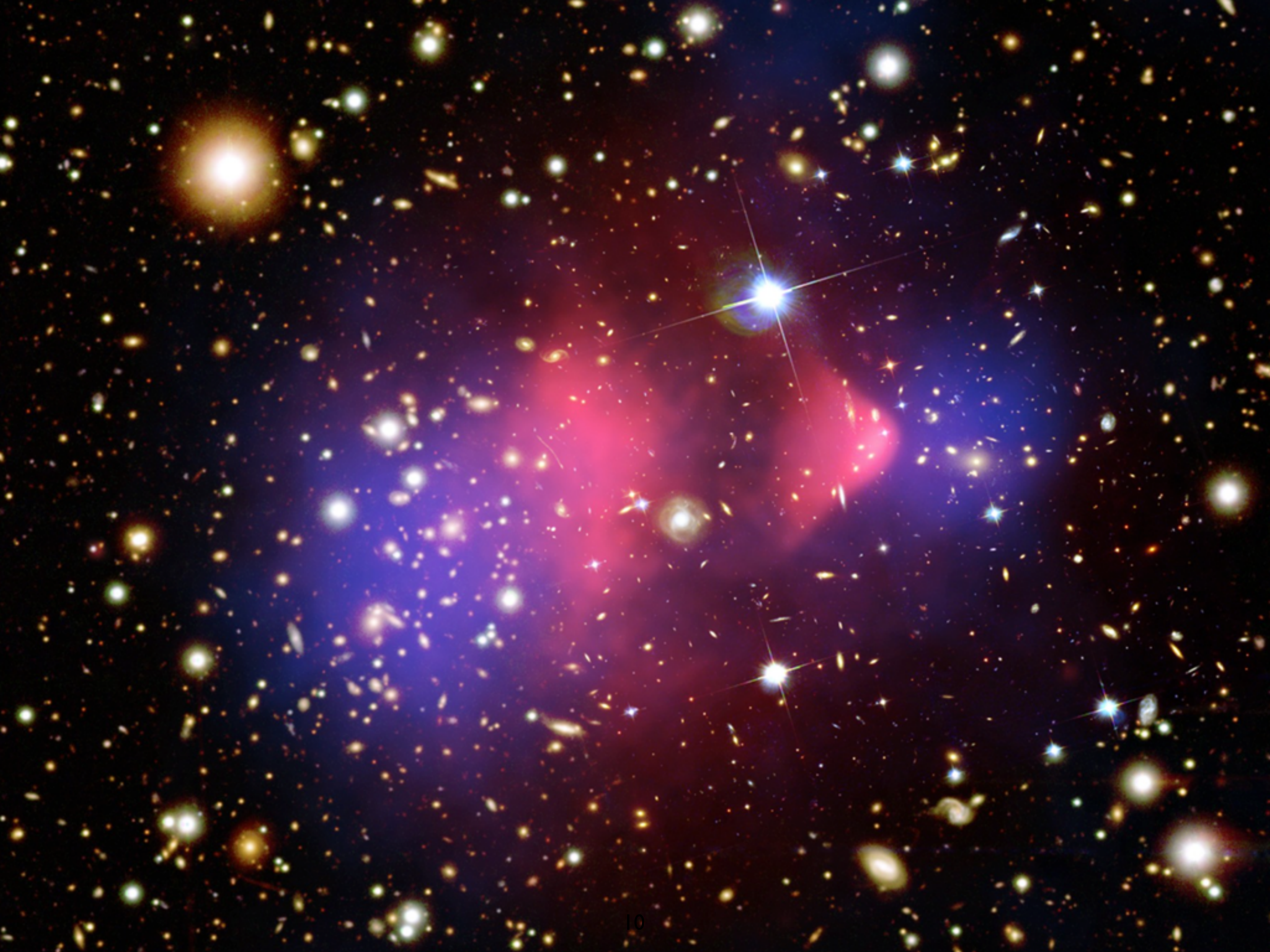
$$\frac{mv^2}{r} = G\frac{mM}{r^2}$$

$$\Rightarrow \quad v(r) \propto r^{-1/2}$$

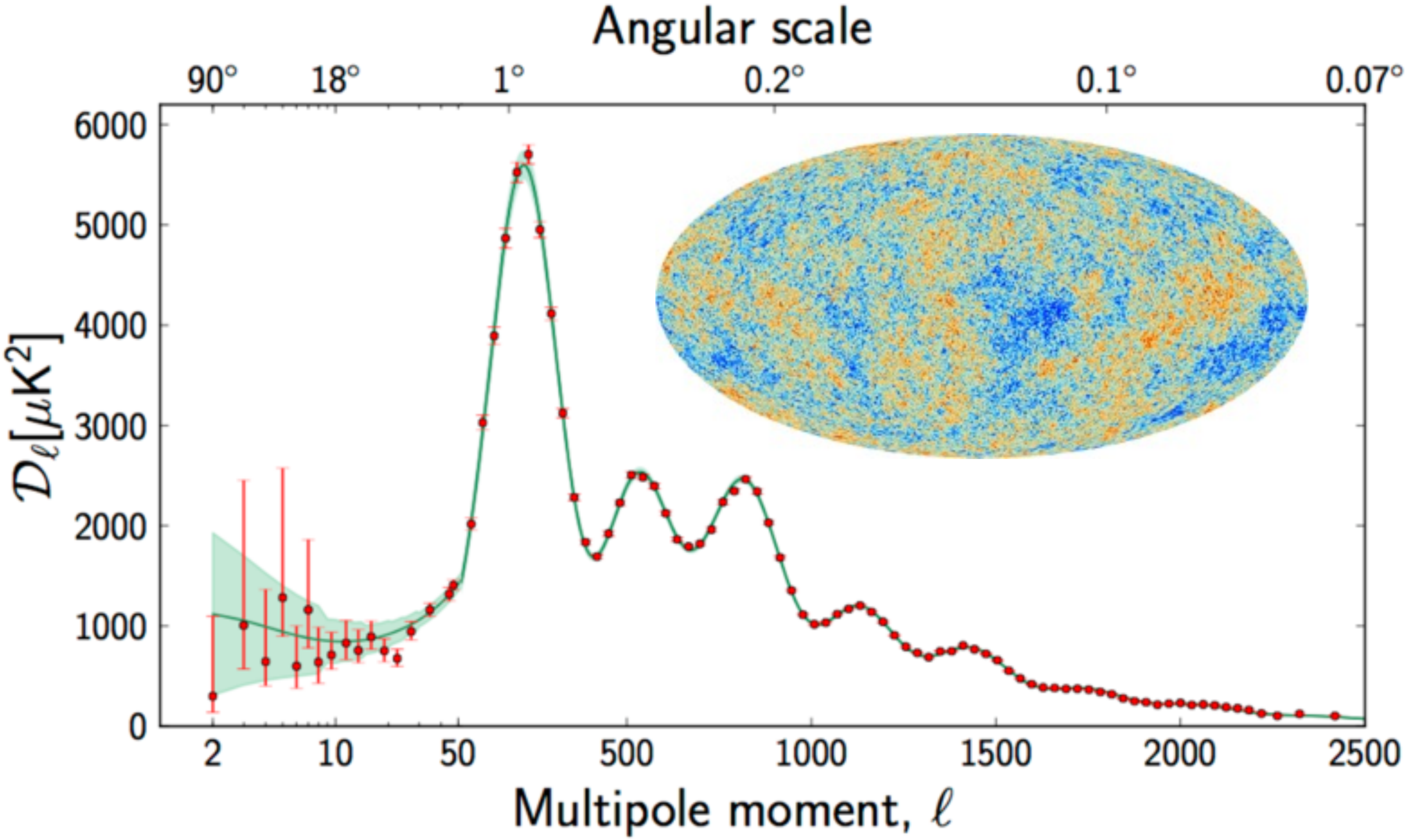
- However, the rotation curves are observed to be constant (flat) at large radii

[Credit: M. De Leo, Wikipedia]



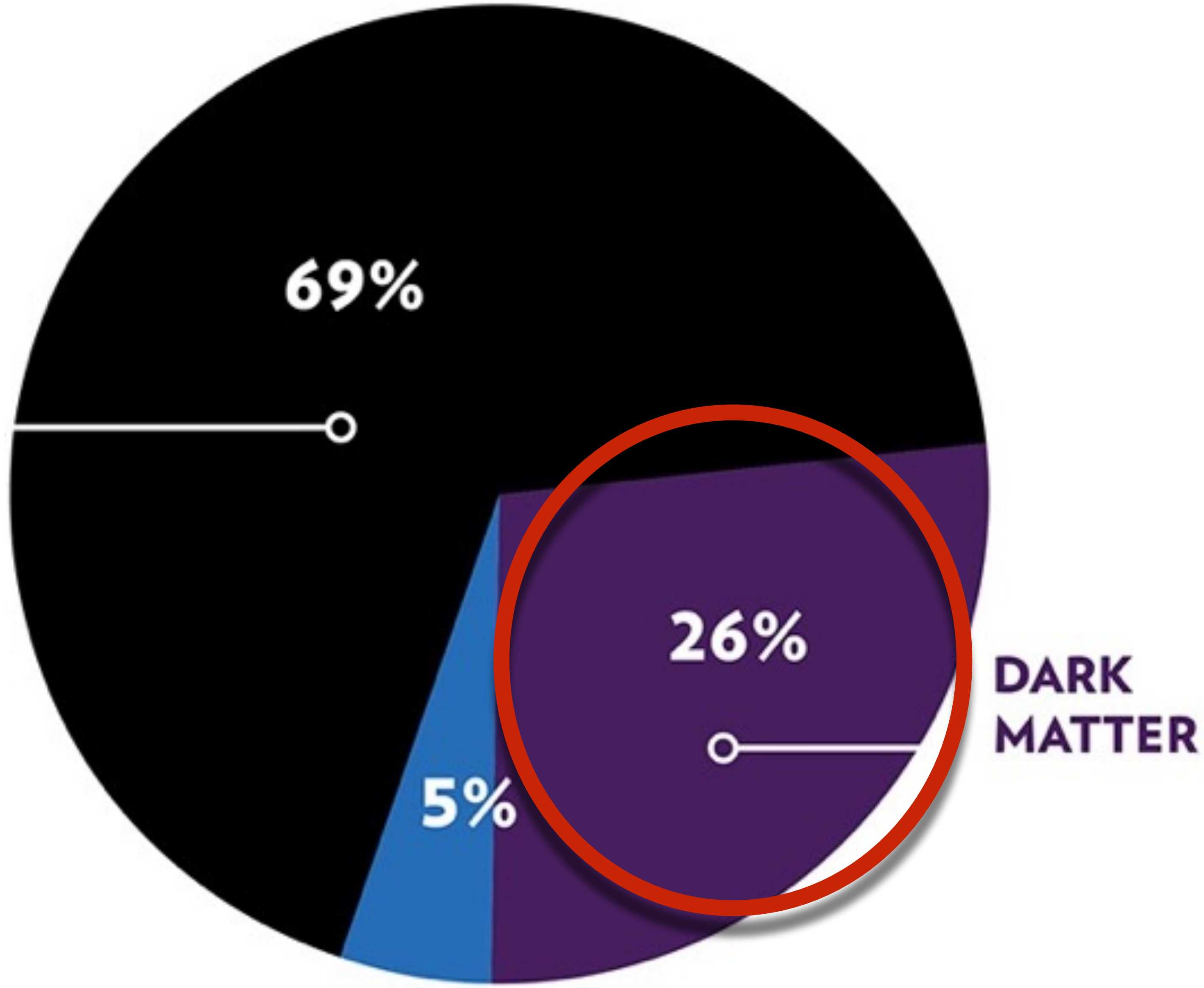


Cosmic Microwave Background



~26% of the energy in the universe is dark matter and only ~5 % in normal matter

Dark Matter



What is dark matter?

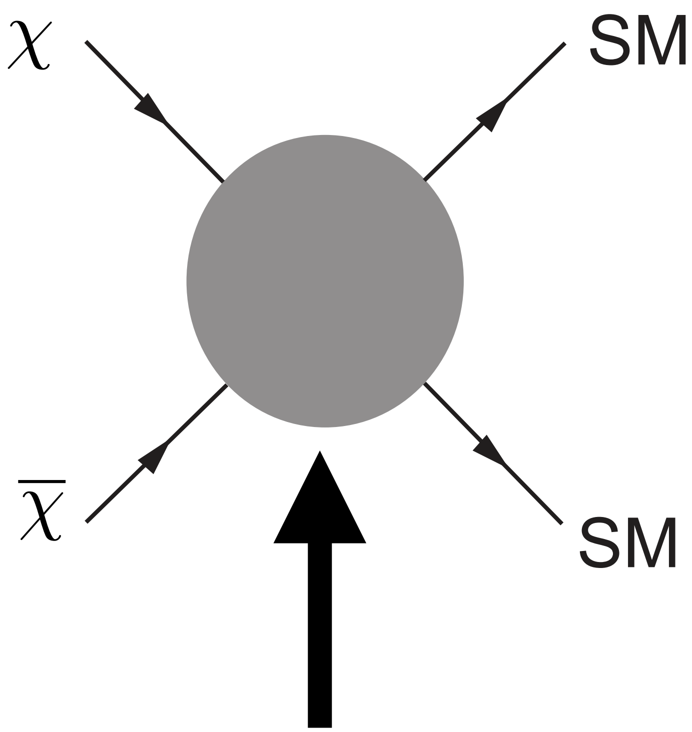
Basic questions about dark matter

- Is it a particle?
- Is it stable?
- What is its mass (or dynamical scale)?
- One dark matter particle or multiple species?
- Additional dark forces - a dark sector?
- Does dark matter have non-gravitational interactions with normal matter?

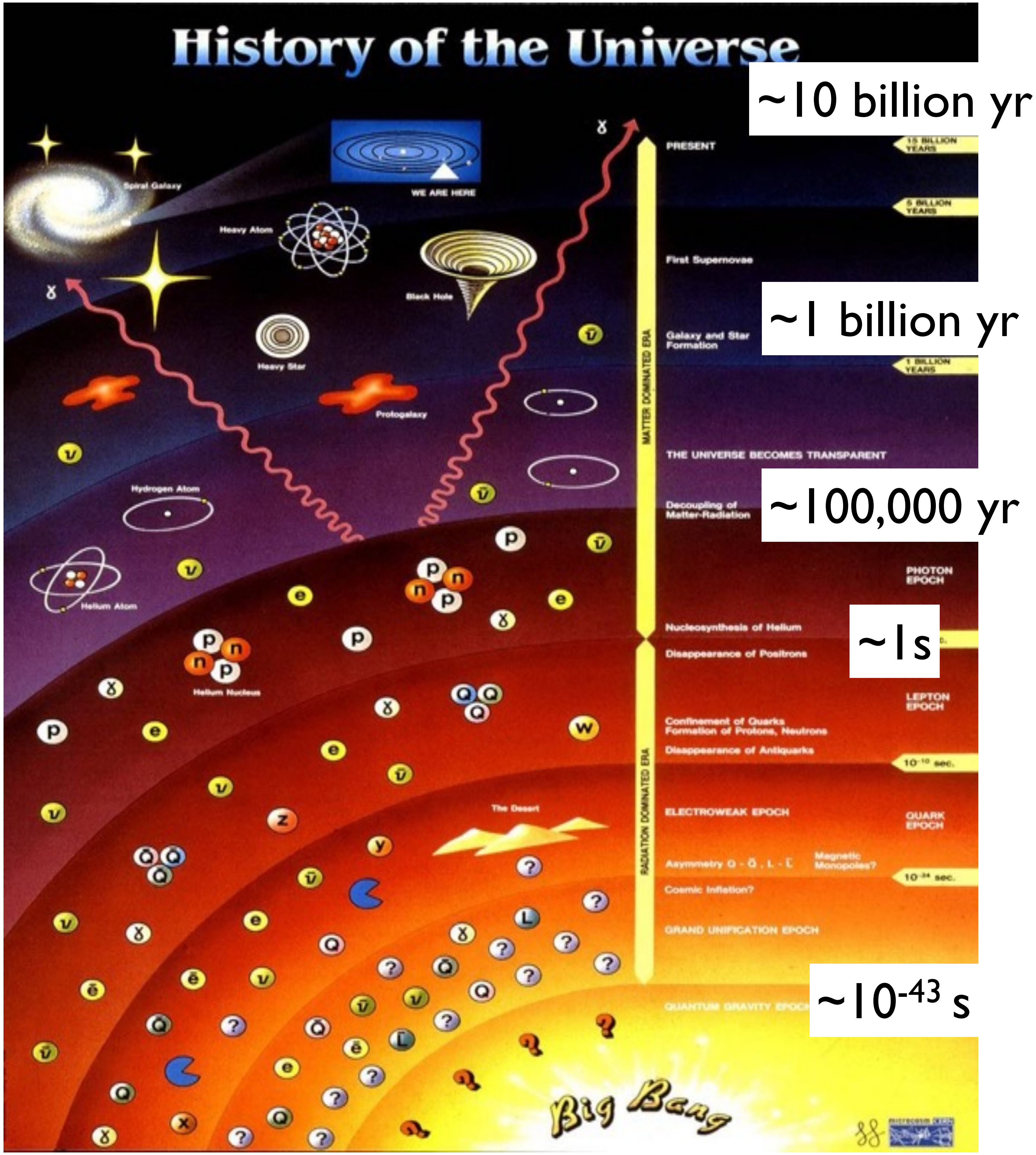
Is there any good reason to expect dark matter to have non-gravitational interactions?

Cosmological Genesis of Dark Matter

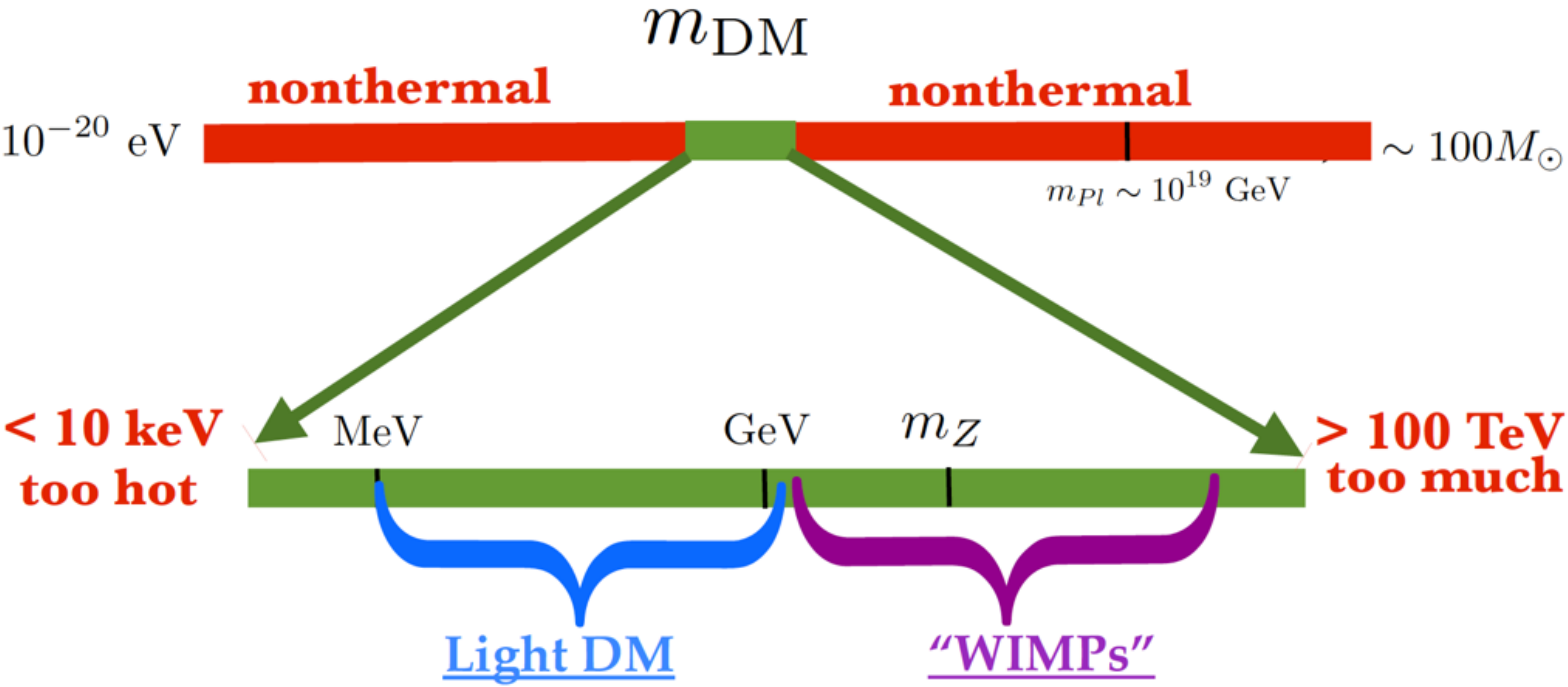
Dark Matter may have been produced from the hot plasma during the Big Bang



Requires non-gravitational interactions with normal matter



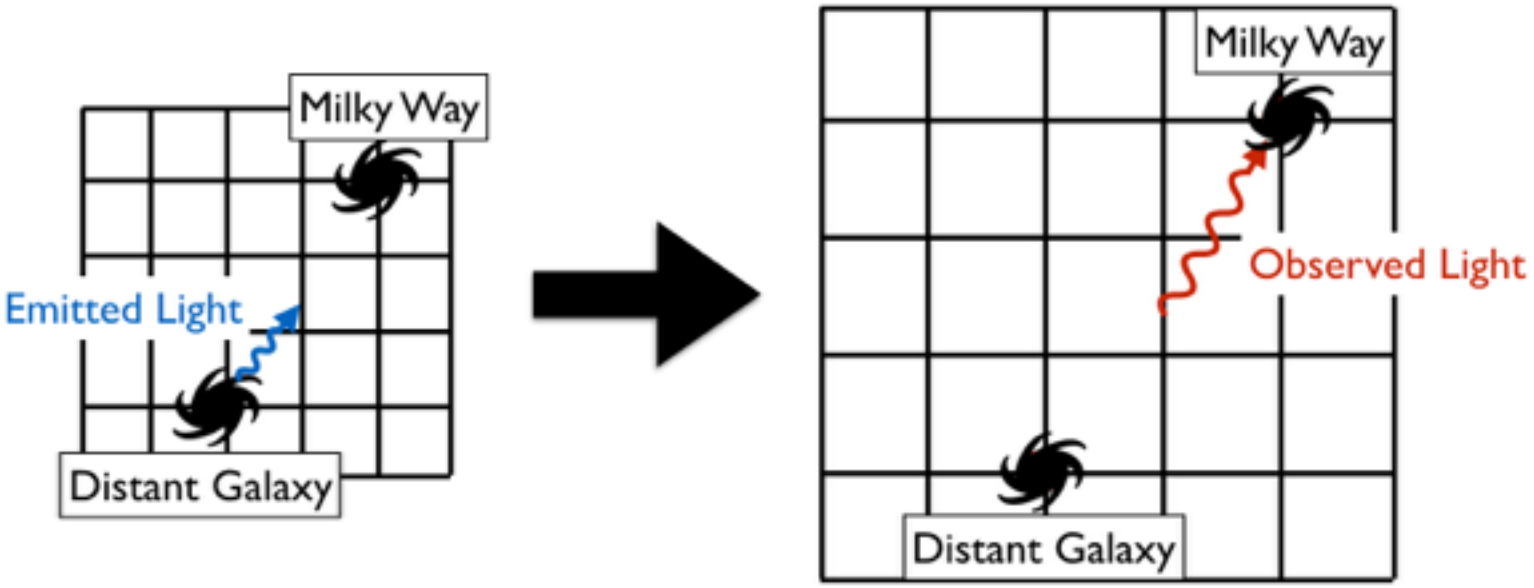
Thermal Dark Matter Window



Credit: G. Krnjaic

FRW Cosmology

- Our universe is expanding



- Expansion is encoded in the scale factor a(t)

$$ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu = -dt^2 + a(t)^2 d\mathbf{x}^2$$

- Dynamics governed by Einstein's equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

➡ Freidmann Equation:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

- Three types of fluids influence the expansion: radiation, matter, and vacuum energy

Dark matter production via thermal freeze-out

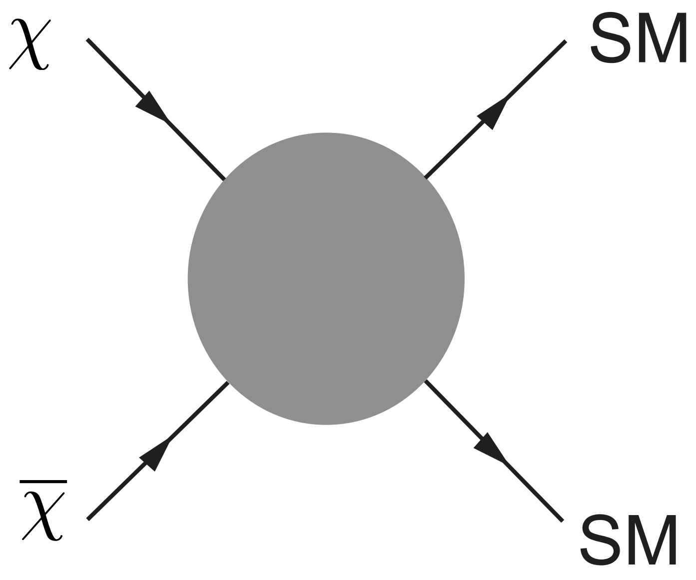
- At early times, $T \gg m_\chi$, both DM annihilation and production (inverse annihilation) are efficient

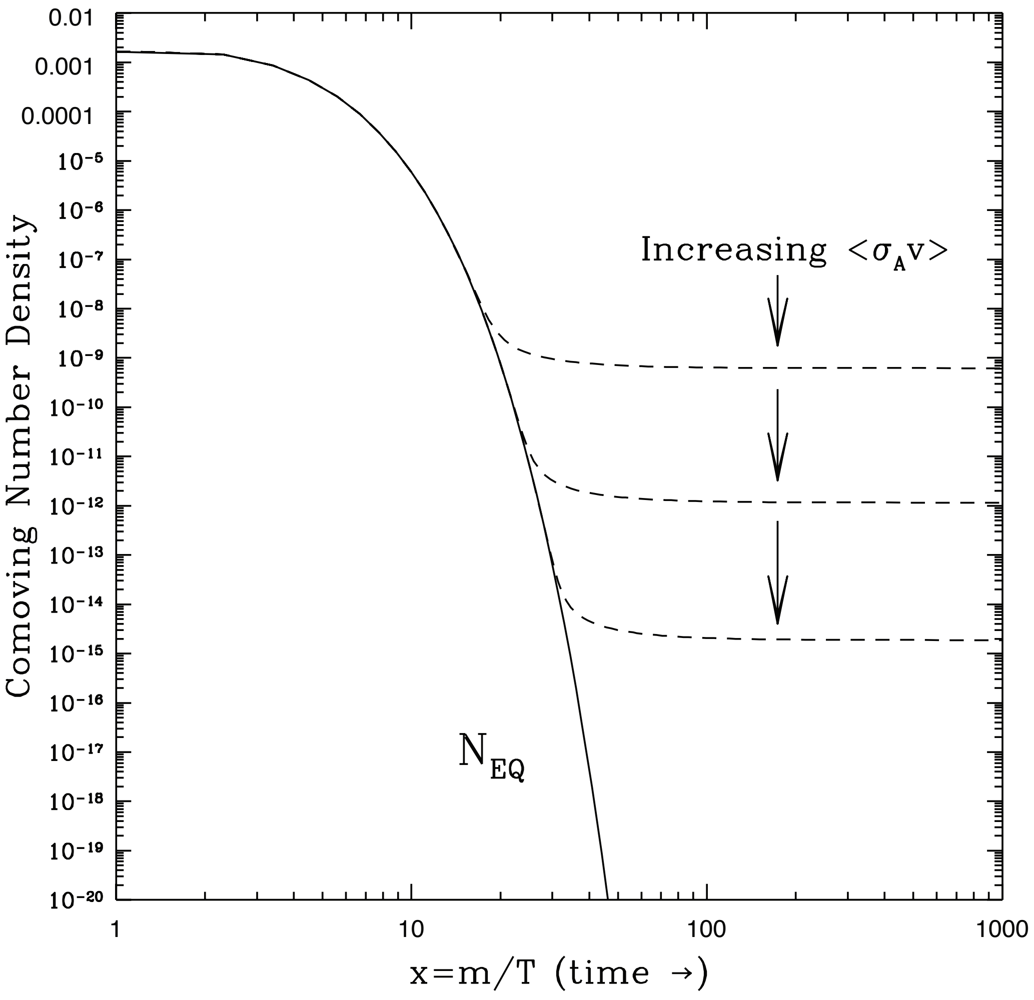
- As temperature drops, $T \lesssim m_\chi$, DM production is kinematically disfavored, and DM begins to annihilate away

- As DM depletes and universe expands, DM annihilation is more and more rare

- Eventually, DM will freeze-out, once annihilation rate becomes smaller than the Hubble rate

- Relic abundance of DM controlled by the annihilation cross section $\langle \sigma v \rangle$





Estimation of relic density

- Dark matter freeze-out occurs when the annihilation rate falls below the expansion rate

$$H(T_f) = \langle \sigma v \rangle n_\chi$$

Estimation of relic density

- Dark matter freeze-out occurs when the annihilation rate falls below the expansion rate

$$H(T_f) = \langle \sigma v \rangle n_\chi$$

- At early times, universe is radiation dominated

(Friedmann Eq)

$$H^2 = \frac{8\pi\rho}{3M_P^2}$$

(Radiation Energy density)

$$\rho = \frac{\pi^2}{30} g_* T^4$$

$$\Rightarrow \quad H \sim g_*^{1/2} \frac{T^2}{M_P}$$

$$\Rightarrow \quad n_\chi \sim g_*^{1/2} \frac{T_f^2}{M_P \langle \sigma v \rangle}$$

Estimation of relic density

- DM freeze-out occurs when the annihilation rate falls below the expansion rate

$$H(T_f) = \langle \sigma v \rangle n_\chi$$

- At early times, universe is radiation dominated

$$n_\chi \sim g_*^{1/2} \frac{T_f^2}{M_P \langle \sigma v \rangle}$$

- Once DM freezes out, the comoving density is constant.

(Comoving density or "yield")

$$Y_\chi = \frac{n_\chi}{s}$$

(Entropy density)

$$s = \frac{2\pi^2}{45} g_{*S} T^3$$

$$\Longrightarrow \quad Y_\chi \sim g_*^{-1/2} \frac{1}{M_P \langle \sigma v \rangle T_f}$$

Estimation of relic density

- DM freeze-out occurs when the annihilation rate falls below the expansion rate

$$H(T_f) = \langle \sigma v \rangle n_\chi$$

- At early times, universe is radiation dominated

$$n_\chi \sim g_*^{1/2} \frac{T_f^2}{M_P \langle \sigma v \rangle}$$

- Once DM freezes out, the comoving density is constant.

$$Y_\chi \sim g_*^{-1/2} \frac{1}{M_P \langle \sigma v \rangle T_f}$$

- DM energy density today

(DM energy density)

$$\rho_\chi = m_\chi n_\chi = m_\chi Y_\chi s$$

(Critical energy density)

$$\rho_c = \frac{3 M_P^2 H^2}{8\pi}$$

freeze-out temp fraction

$$x_f = \frac{m_\chi}{T_f}$$

$$\Rightarrow \quad \Omega_\chi = \left. \frac{\rho_\chi}{\rho_c} \right|_{T_0} = \frac{8\pi m_\chi Y_\chi s_0}{3 M_P^2 H_0^2} \sim g_*^{-1/2} \frac{x_f}{M_P^3 \langle \sigma v \rangle} \frac{s_0}{H_0^2}$$

Estimation of relic density

- DM freeze-out occurs when the annihilation rate falls below the expansion rate

$$H(T_f) = \langle \sigma v \rangle n_\chi$$

- At early times, universe is radiation dominated

$$n_\chi \sim g_*^{1/2} \frac{T_f^2}{M_P \langle \sigma v \rangle}$$

- Once DM freezes out, the comoving density is constant.

$$Y_\chi \sim g_*^{-1/2} \frac{1}{M_P \langle \sigma v \rangle T_f}$$

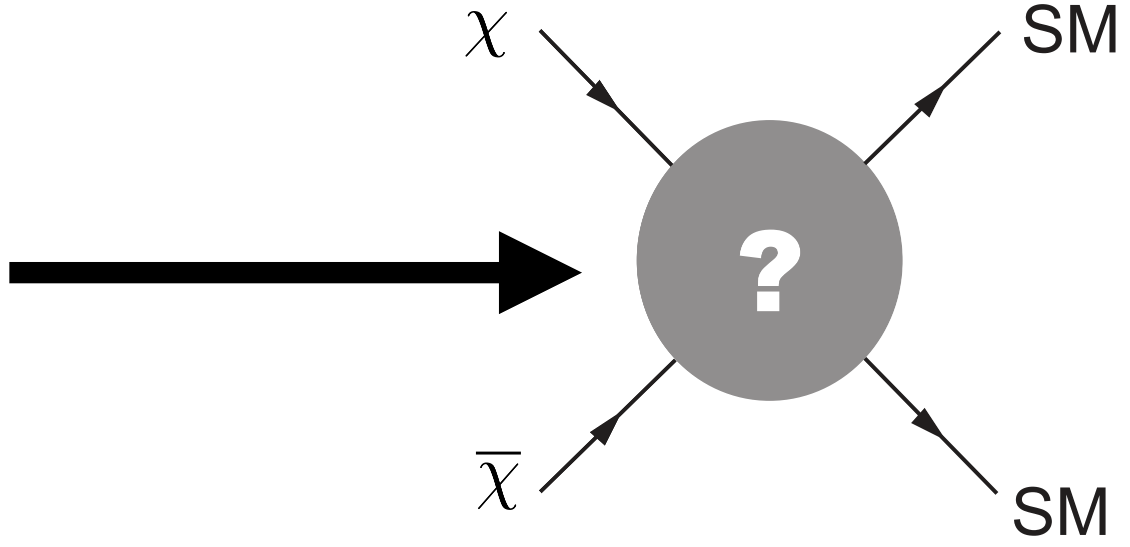
- DM energy density today

$$\begin{aligned} \Omega_\chi &\sim 30 \frac{x_f}{g_*^{1/2} M_P^3 \langle \sigma v \rangle} \frac{s_0}{H_0^2} \\ &\approx 0.1 \left(\frac{100}{g_*} \right)^{1/2} \left(\frac{x_f}{20} \right) \left(\frac{\mathrm{pb}}{\langle \sigma v \rangle} \right) \end{aligned}$$

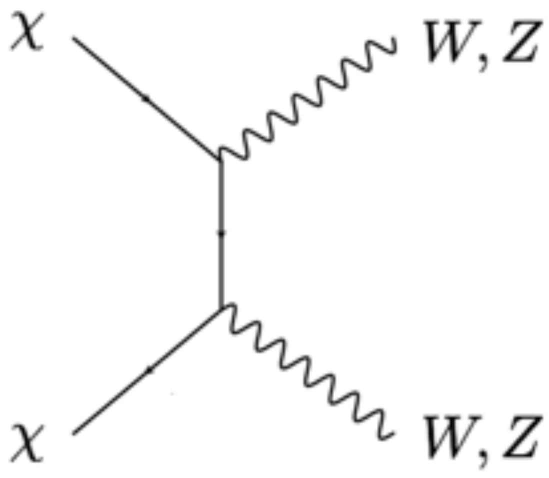
- Compare to measured value from CMB, $\Omega_\chi \simeq 0.27$; correct abundance obtained if

$$\langle \sigma v \rangle \sim 1\,\mathrm{pb} \sim 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

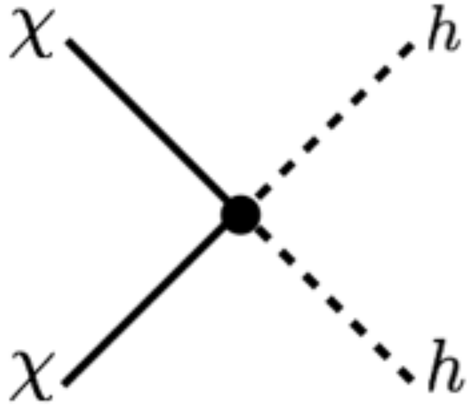
What's here?



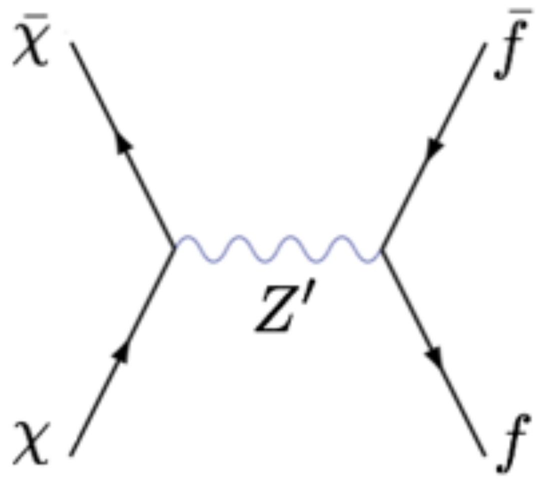
Some model realizations:



Electroweak DM

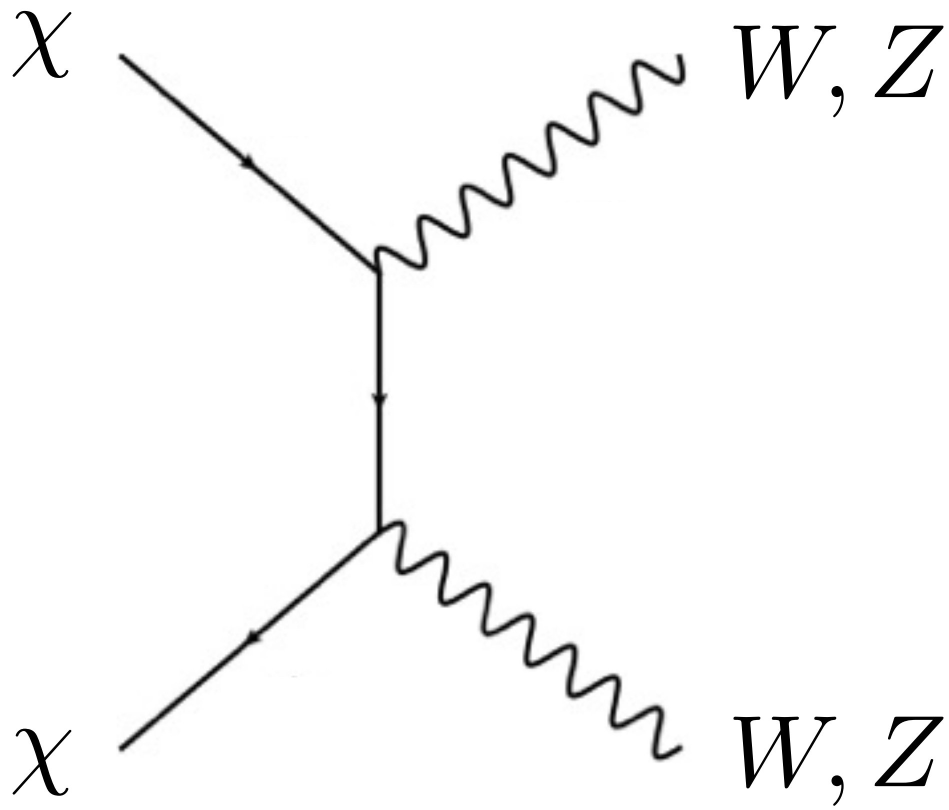


Higgs portal



BSM mediator
(Z', sfermion, etc.)

Weakly Interacting Massive Particle (WIMP)

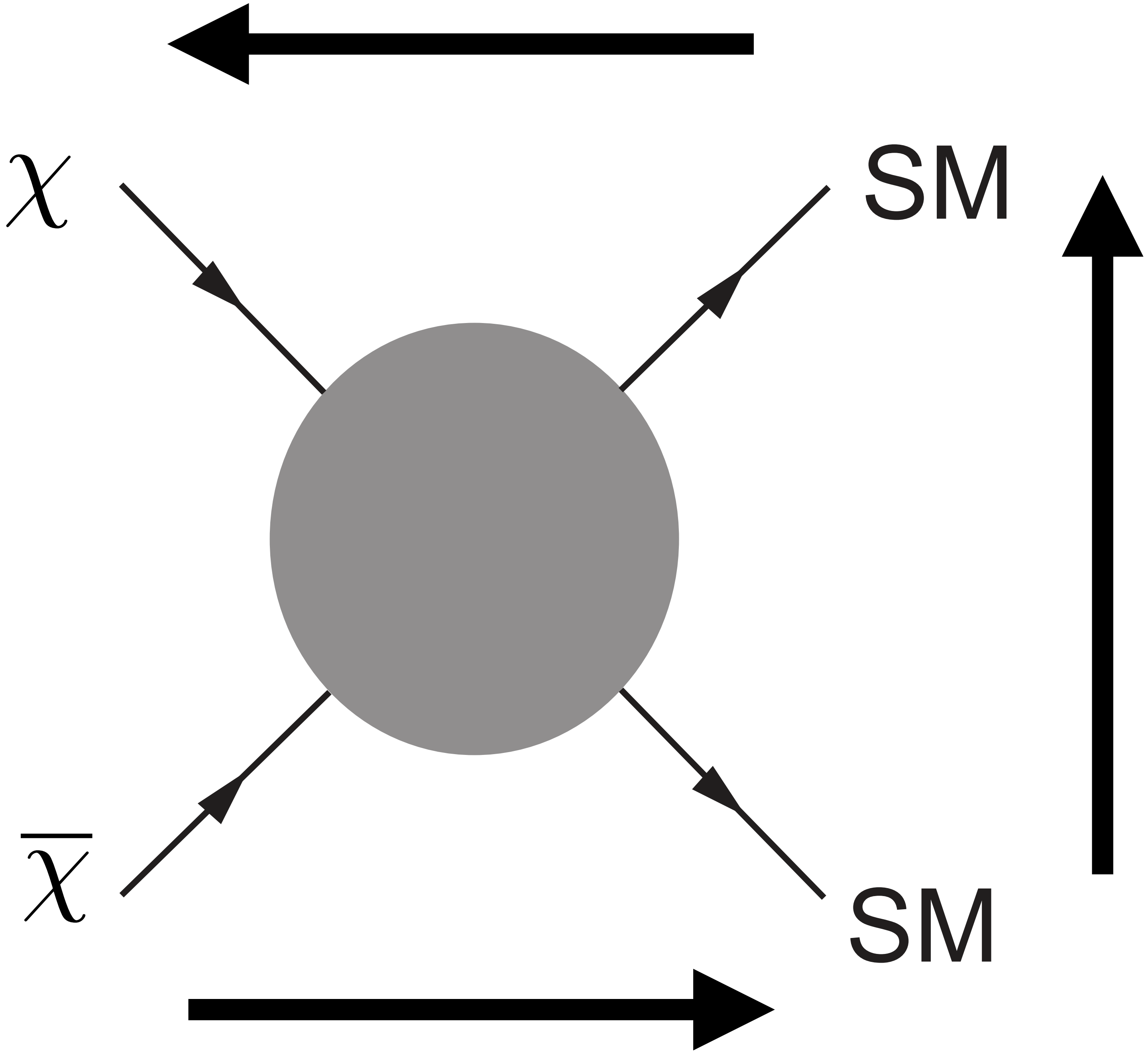


$$\langle \sigma v \rangle \sim \frac{\pi \alpha_W^2}{m_\chi^2} \sim 1\,\mathrm{pb} \times \left(\frac{\alpha_W}{(1/30)} \right)^2 \left(\frac{\mathrm{TeV}}{m_\chi} \right)^2$$

Dark Matter with weak interaction and weak scale mass is automatically produced with the observed relic abundance

The “WIMP Miracle”

WIMP Phenomenology



Production at Colliders

Direct Detection

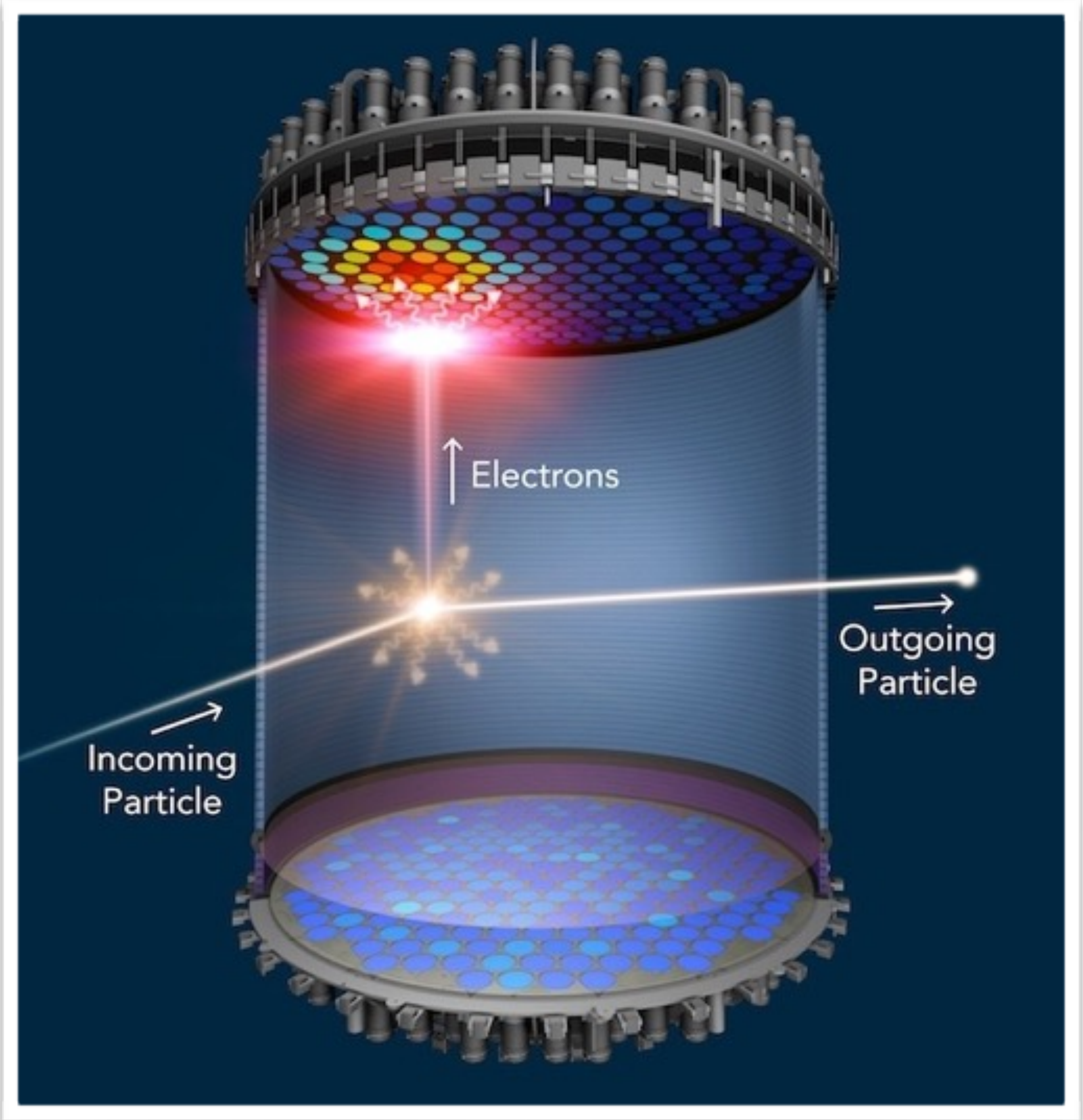
Indirect Detection

Direct detection of dark matter

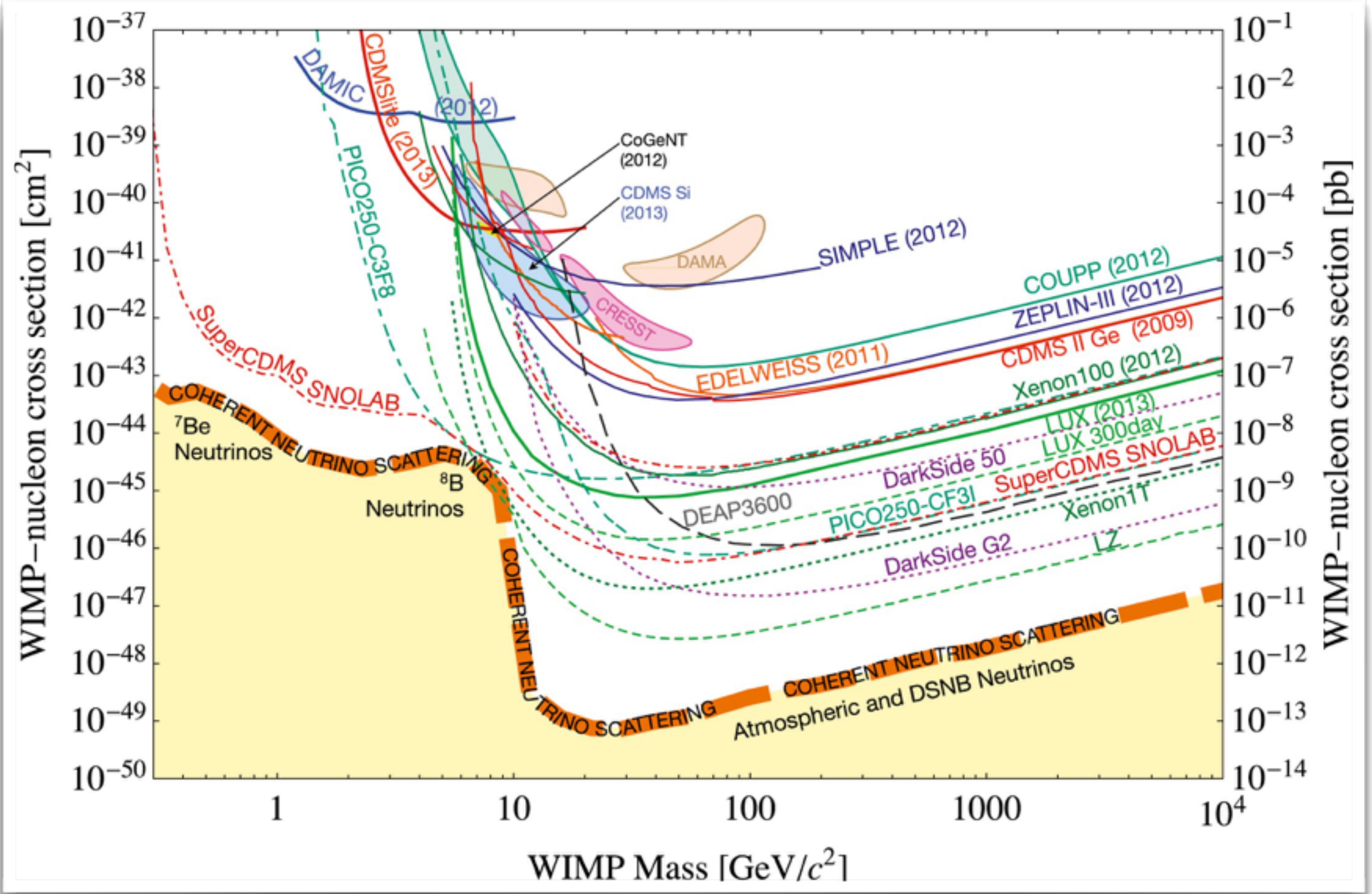
Dark Matter particles are passing through you as you read this

Occasionally, dark matter may collide with a nucleus

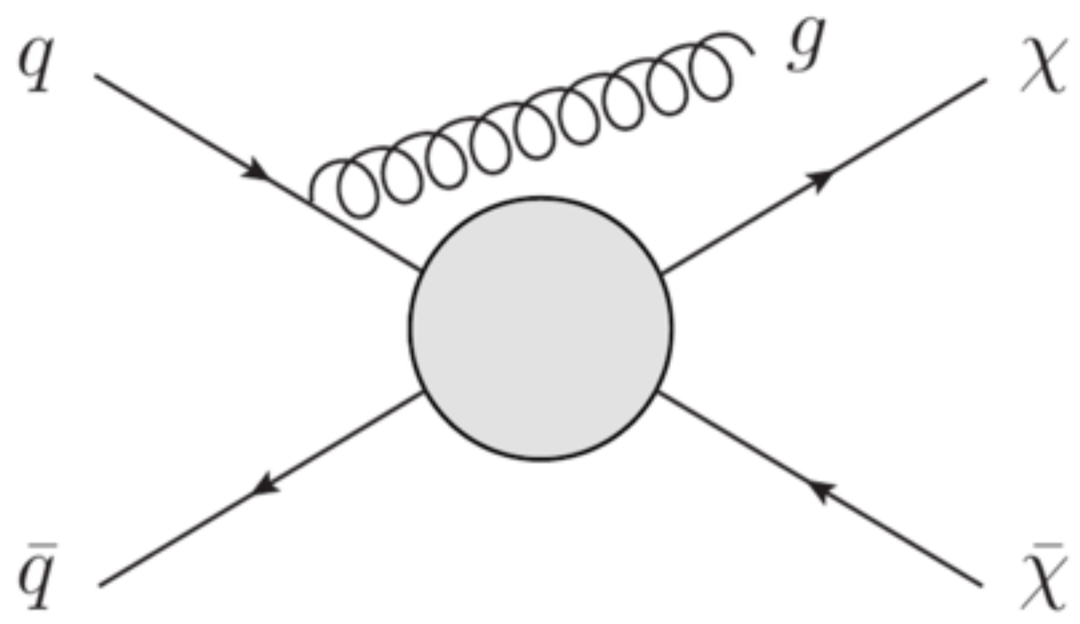
We can look for anomalous nuclear recoils in a detector

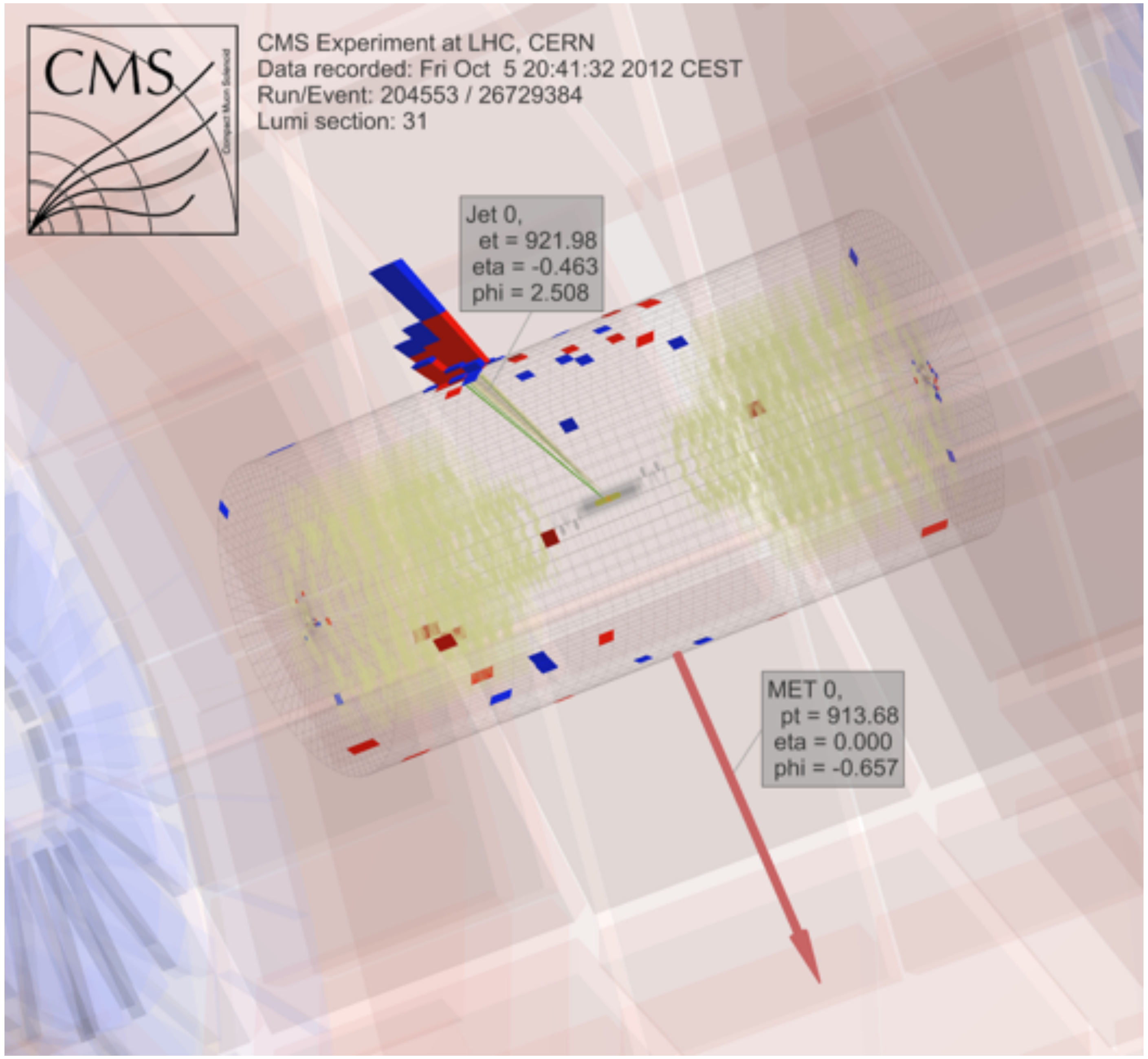


[LZ detector]


10^−37
10^−38
10^−39
10^−40
10^−41
10^−42
10^−43
10^−44
10^−45
10^−46
10^−47
10^−48
10^−49
10^−50
WIMP–nucleon cross section [cm²]
10^−1
10^−2
10^−3
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
10^−12
10^−13
10^−14
WIMP–nucleon cross section [pb]
1
10
100
1000
10^4
WIMP Mass [GeV/c²]
DAMIC
CDMSlite (2013)
(2012)
PICO250-C3F8
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
LUX 300day
DarkSide 50
SuperCDMS SNOLAB
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
COHERENT NEUTRINO SCATTERING
⁷Be Neutrinos
⁸B Neutrinos
COHERENT NEUTRINO SCATTERING
COHERENT NEUTRINO SCATTERING
Atmospheric and DSNB Neutrinos

Production of dark matter at colliders





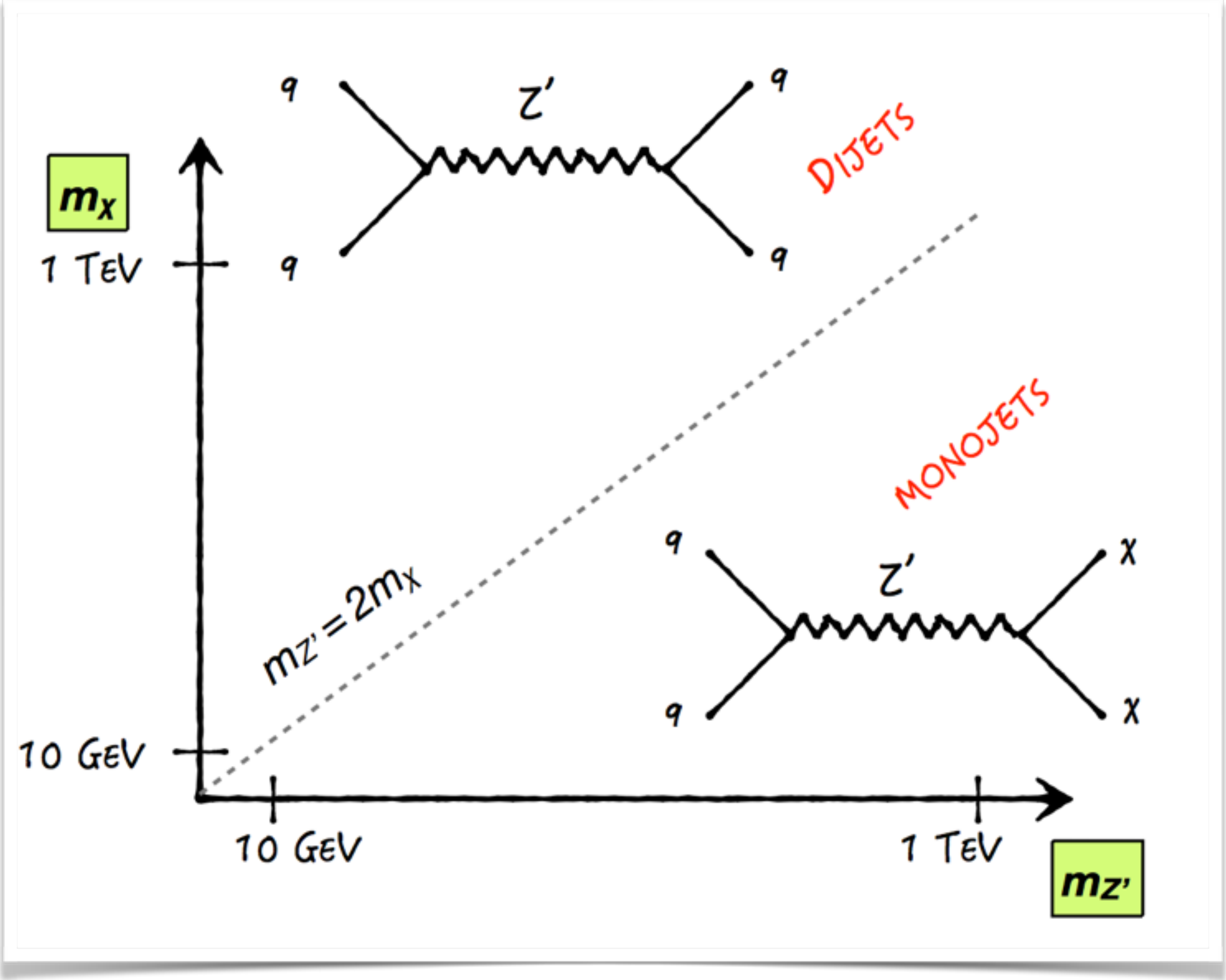
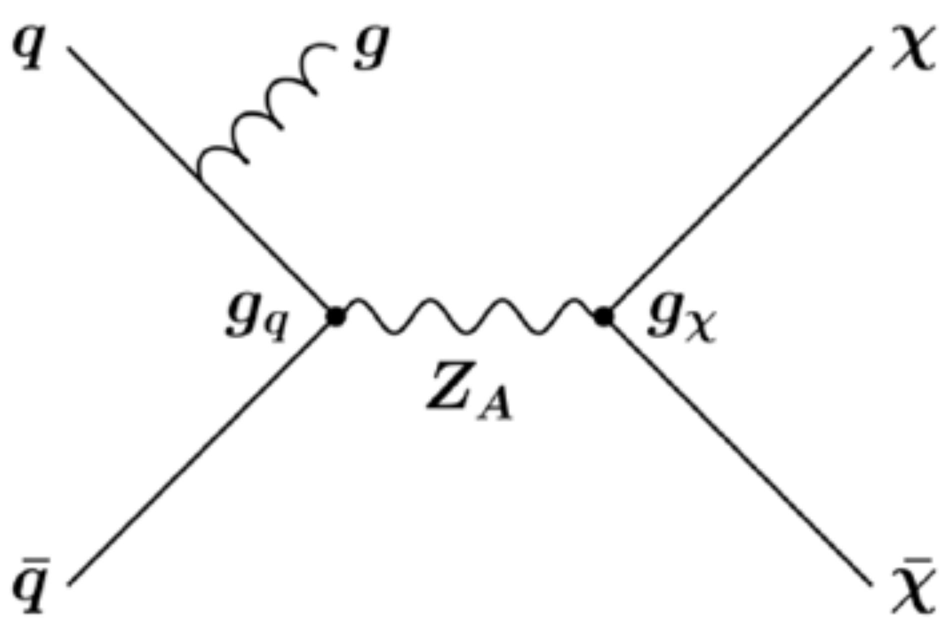
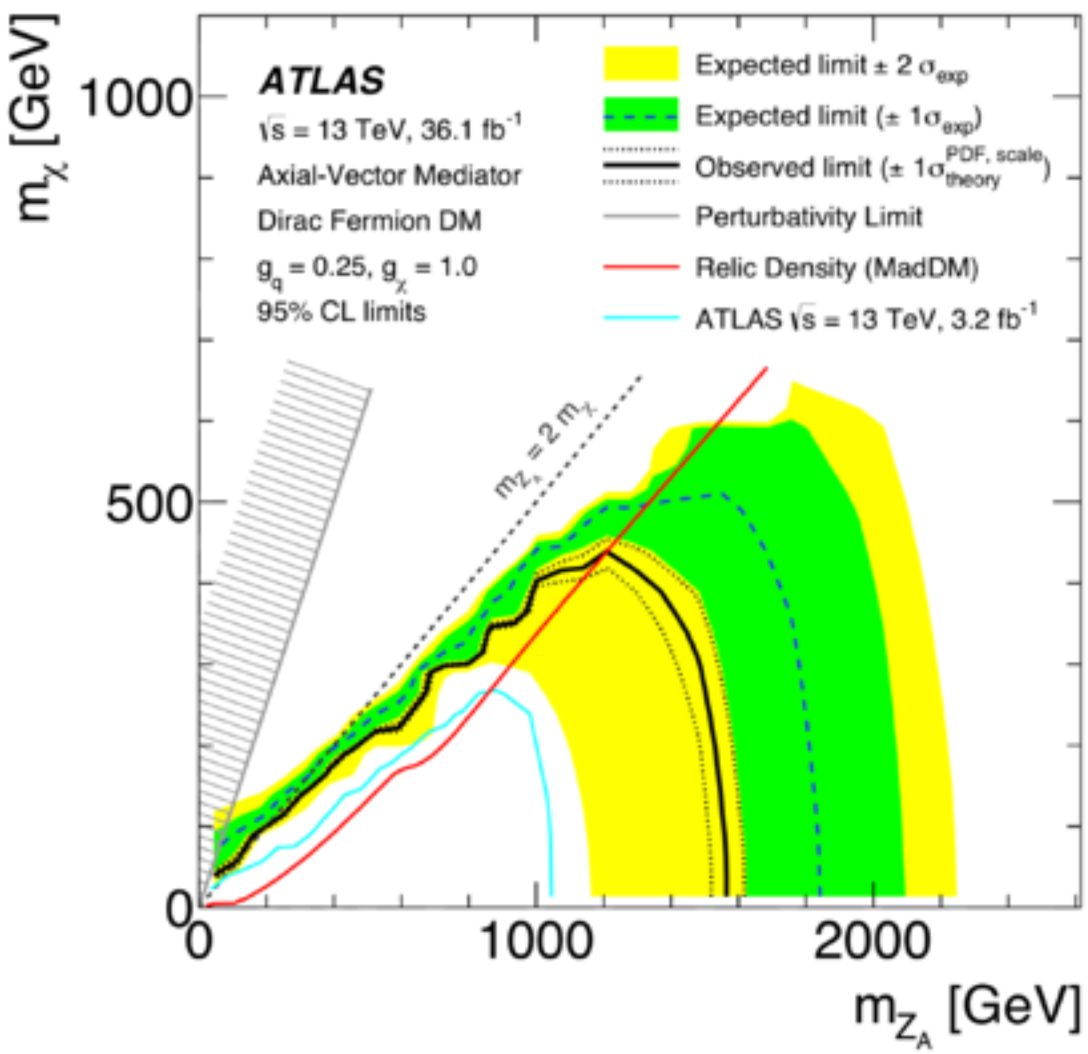
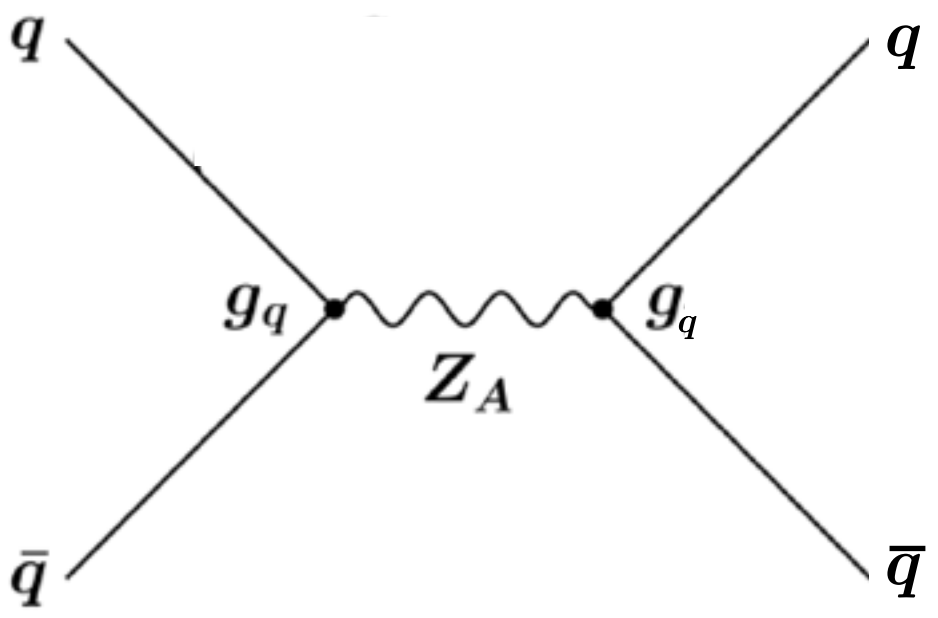


Fig. from N. Saoulidou

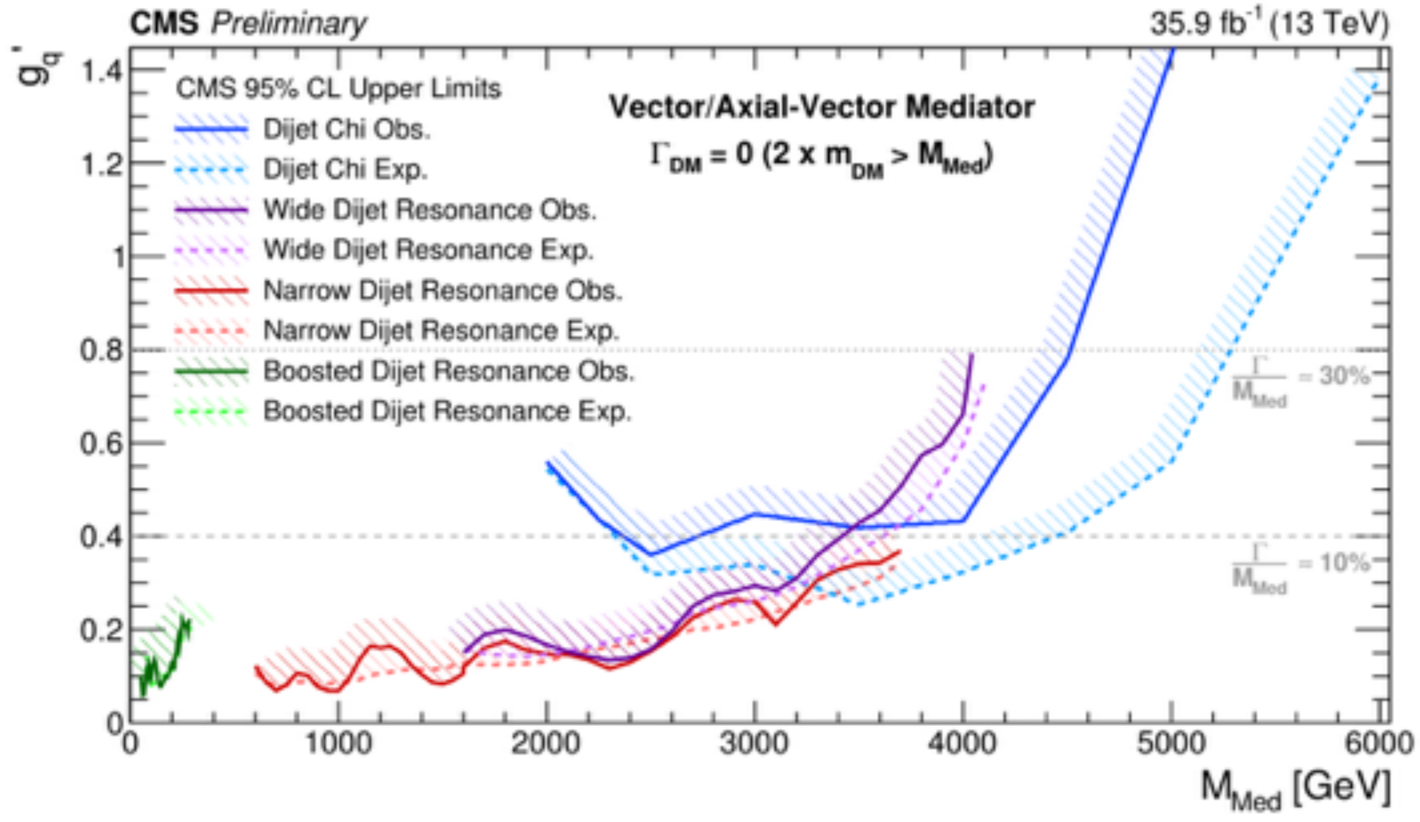


Mono-jet

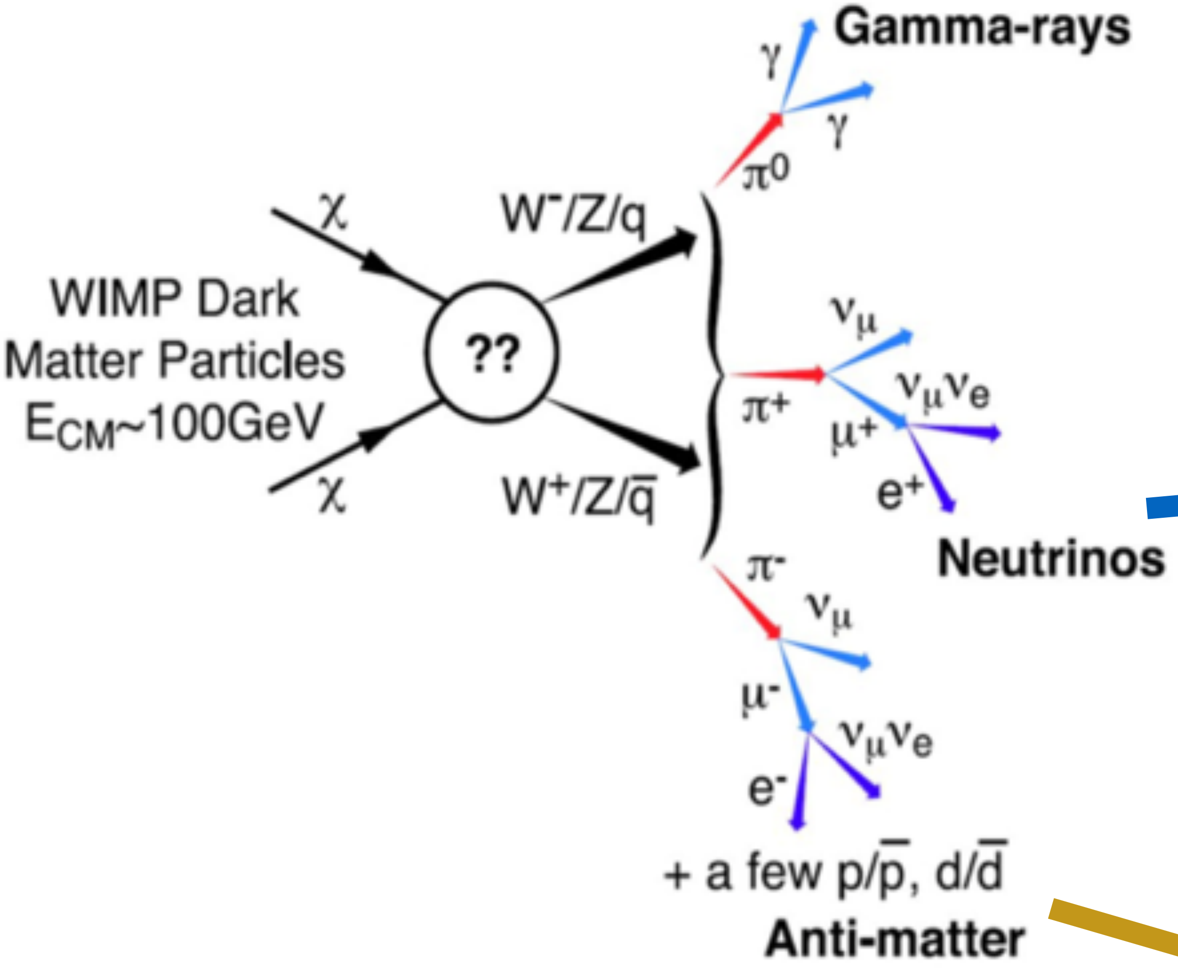


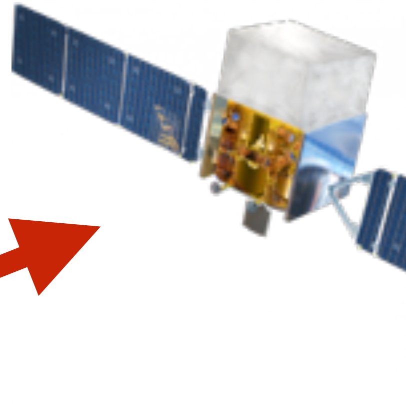


Di-jet



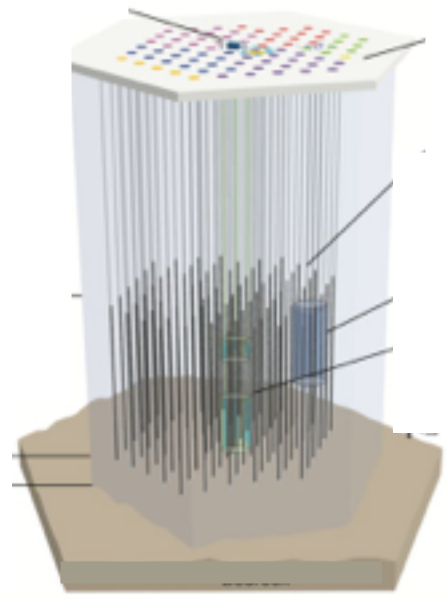
Indirect detection of dark matter

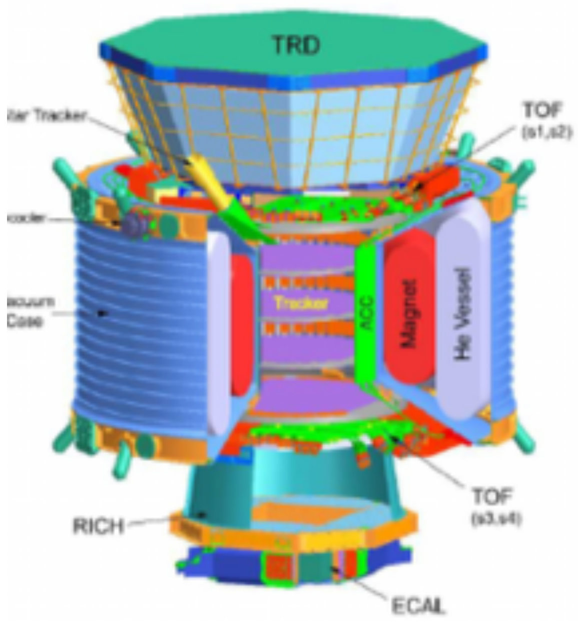




Fermi

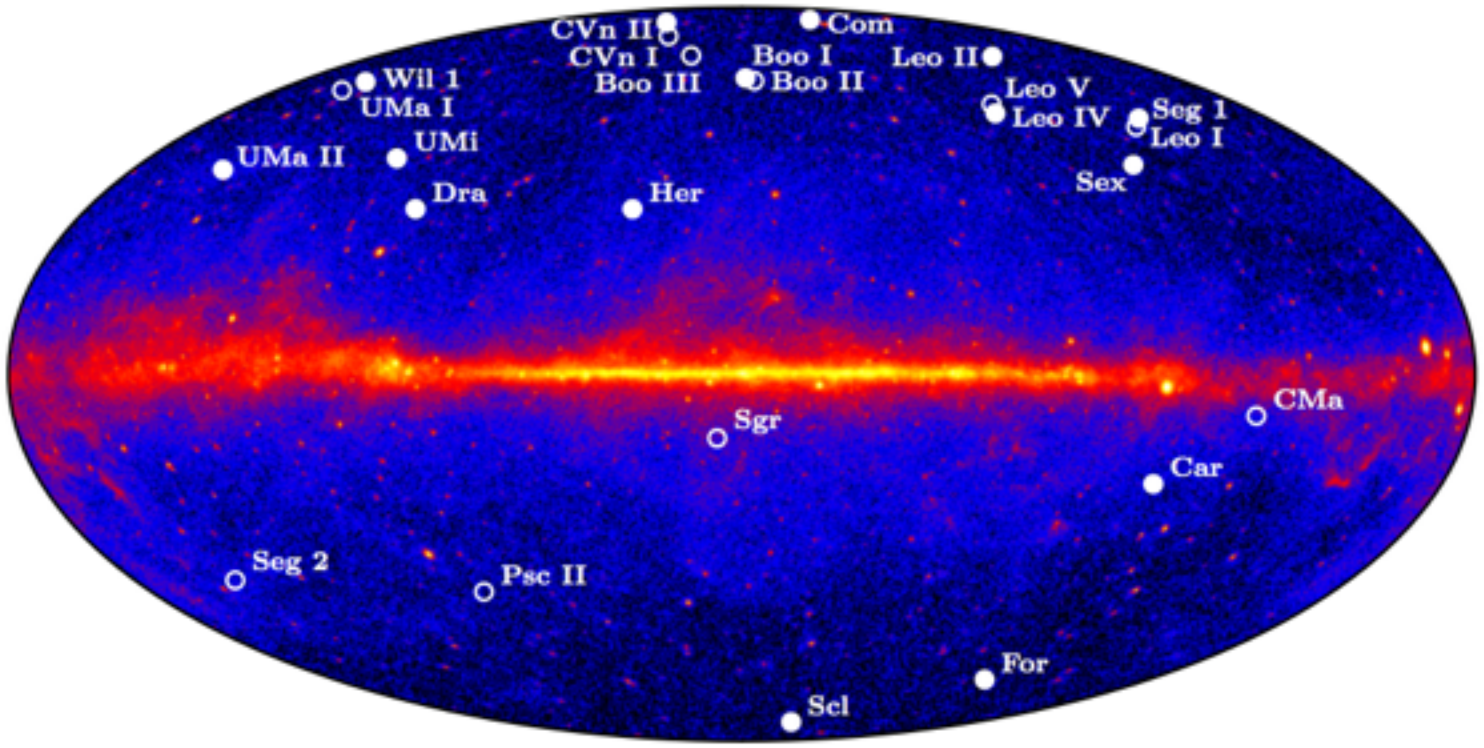
IceCube



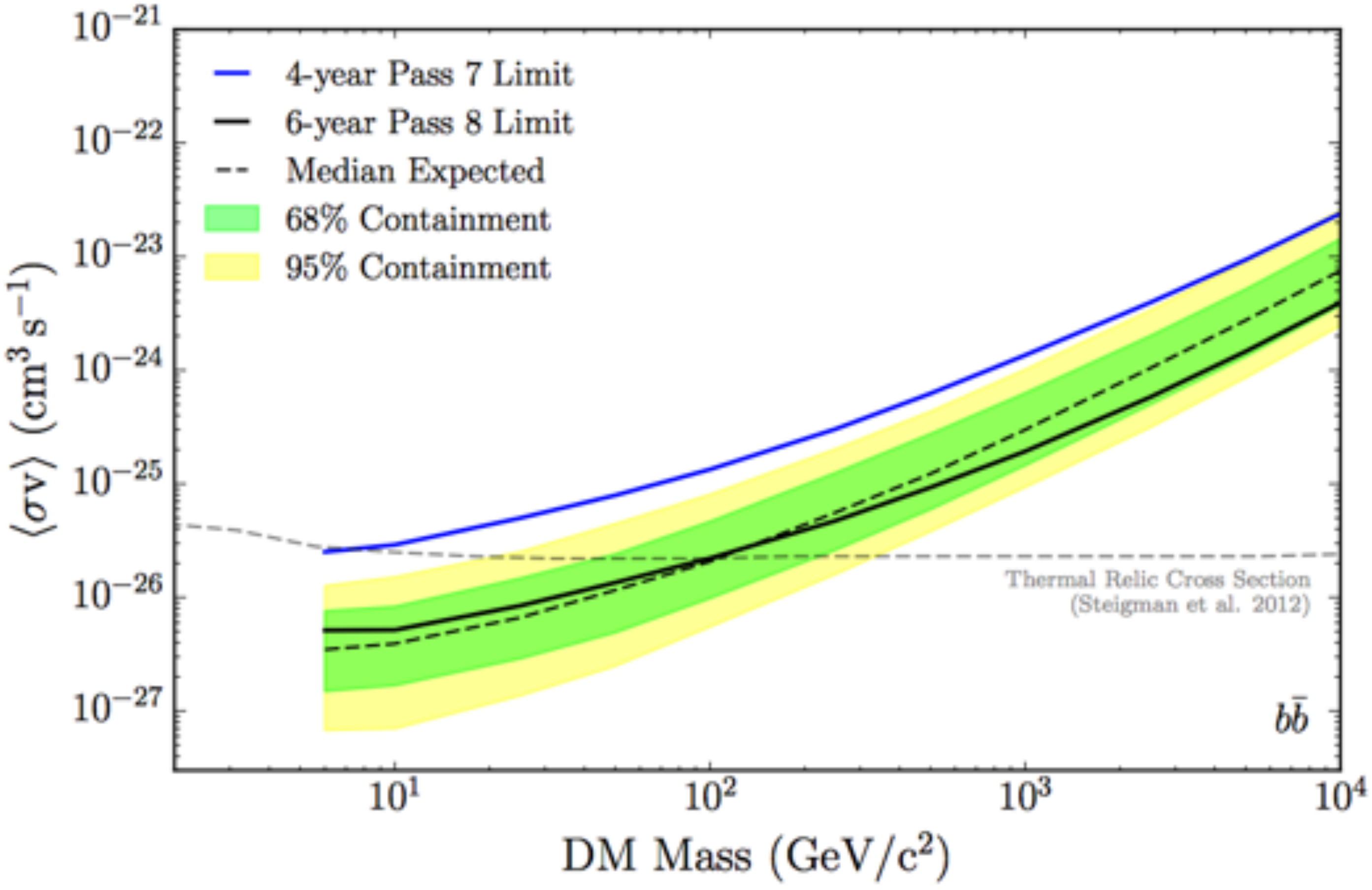


AMS-02

e.g., Milky Way dwarf spheroidal satellites



- Promising target for DM annihilation to gamma-rays
  - DM-dominated objects
  - Close in proximity
  - Lack of astrophysical background



Fermi constrains thermal annihilation cross sections

Electroweak WIMPs

- DM is electrically neutral component of SU(2)xU(1) multiplet

$$\chi \sim (1, \mathbf{2}, \tfrac{1}{2}) = \begin{pmatrix} \chi^+ \\ \chi^0 \end{pmatrix}$$

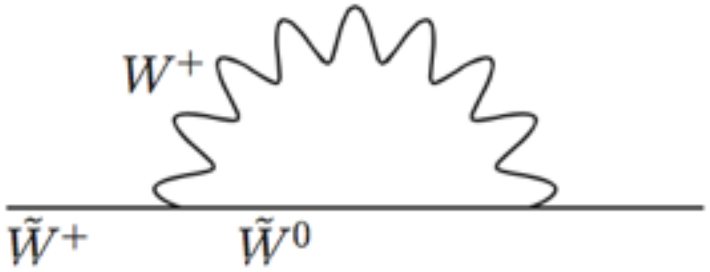
SU(2) doublet - “Higgsino"

$$\chi \sim (1, \mathbf{3}, 0) = \begin{pmatrix} \frac{1}{\sqrt{2}}(\chi^+ + \chi^-) \\ \frac{i}{\sqrt{2}}(\chi^+ - \chi^-) \\ \chi^0 \end{pmatrix}$$

SU(2) triplet - “Wino"

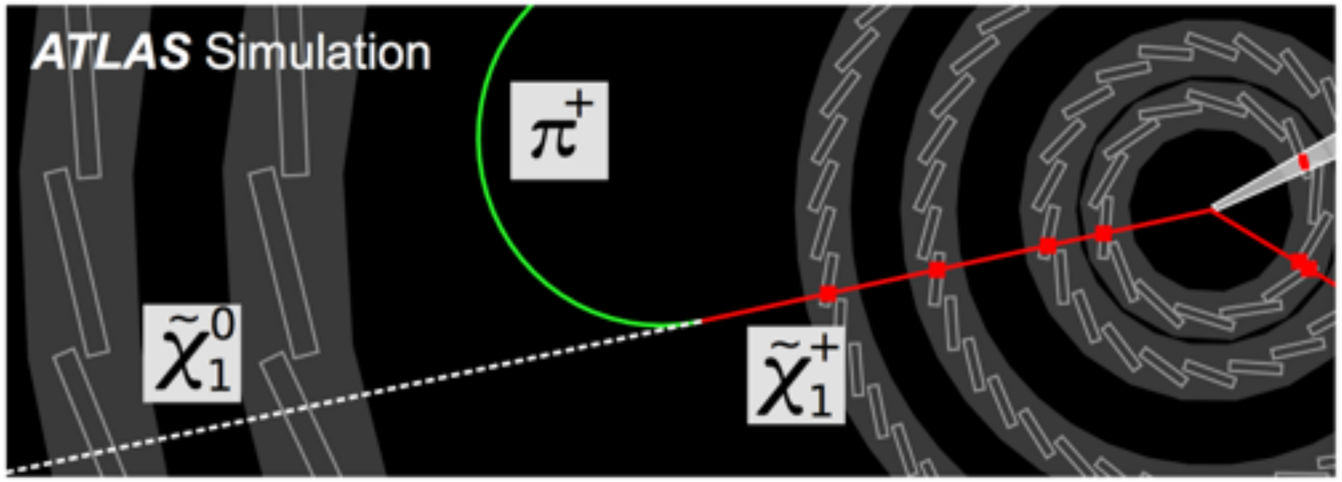
- Radiative Mass splitting:

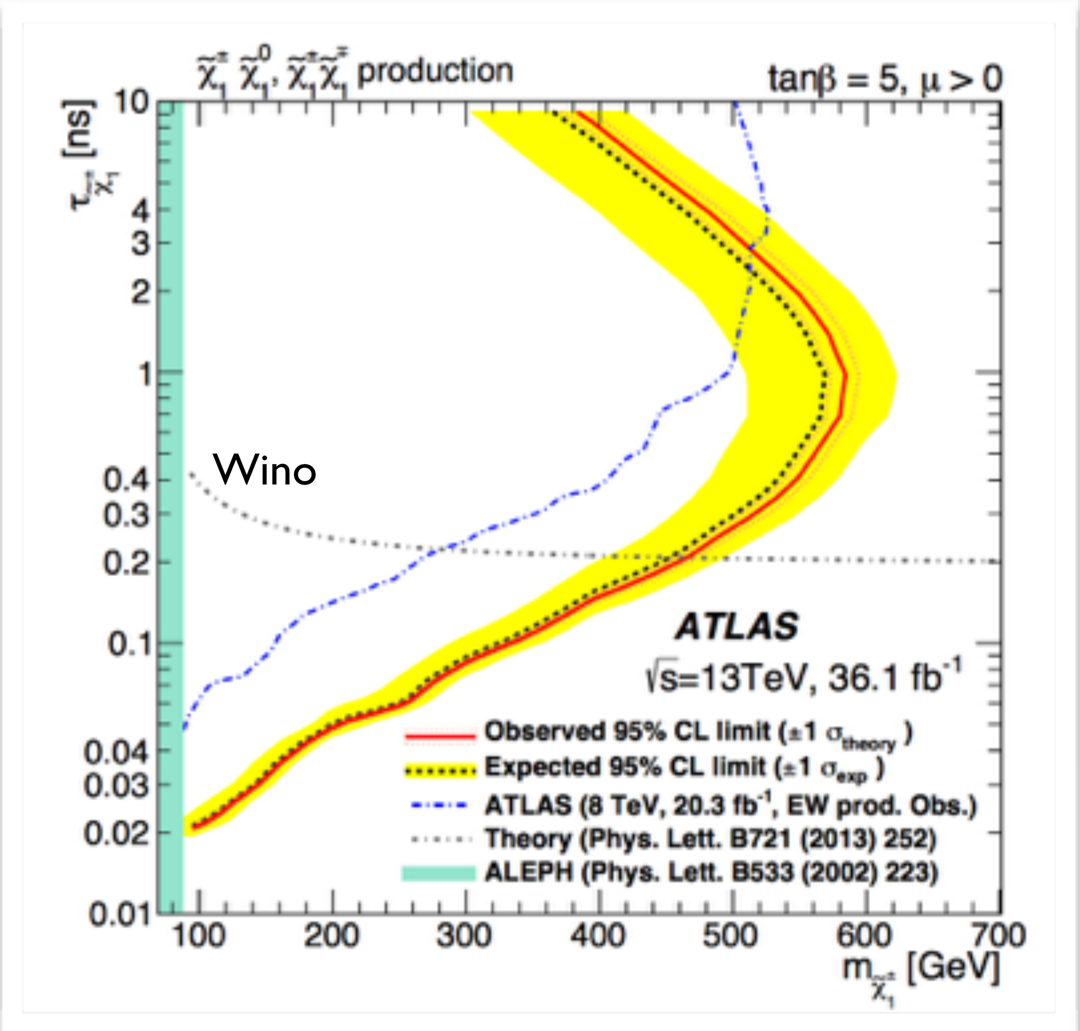
$$M_\pm - M_0 \approx \begin{cases} 300\,\mathrm{MeV} & \text{(Higgsino)} \\ 160\,\mathrm{MeV} & \text{(Wino)} \end{cases}$$

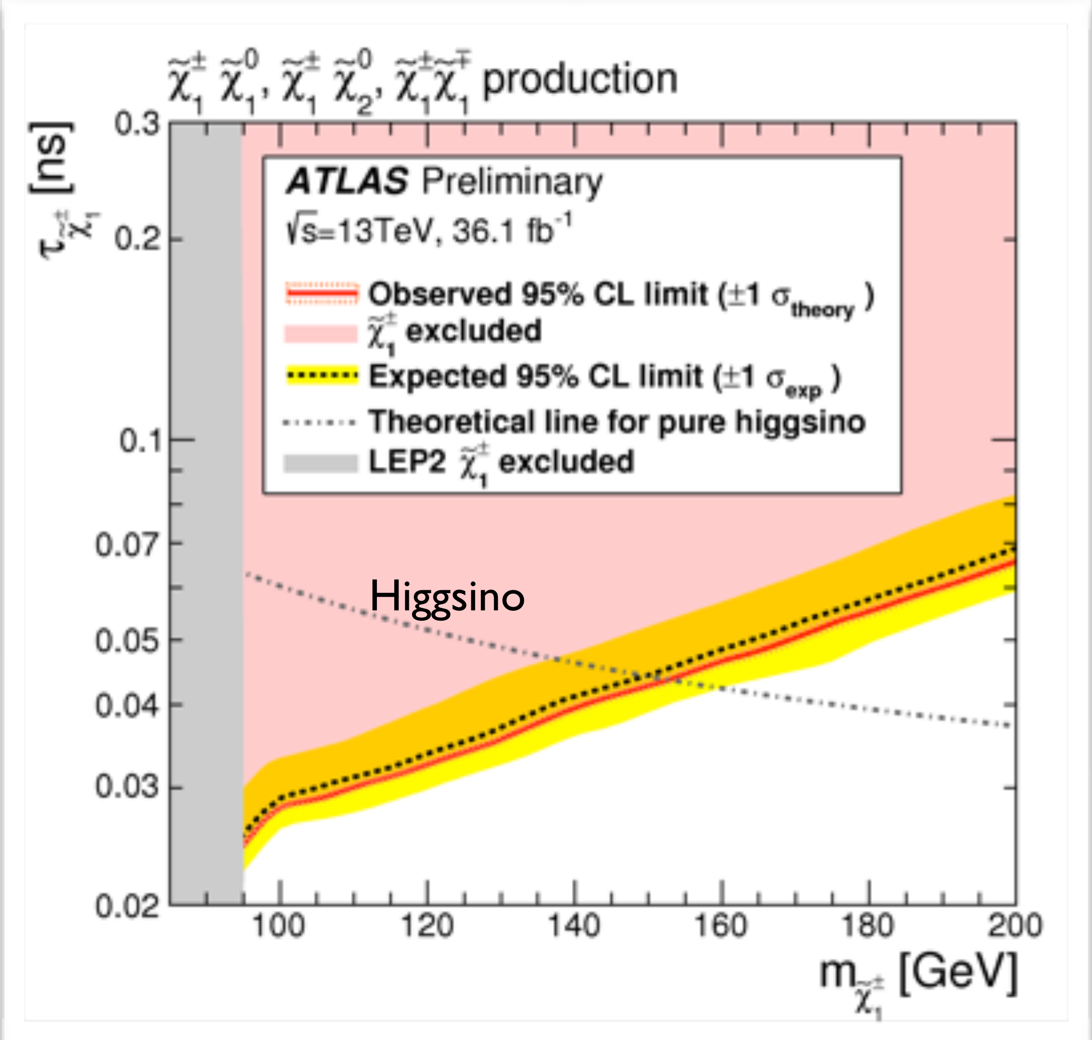


- Observed relic density achieved for DM masses of 1 TeV for doublet and 3 TeV for triplet

Disappearing track searches for electroweak DM





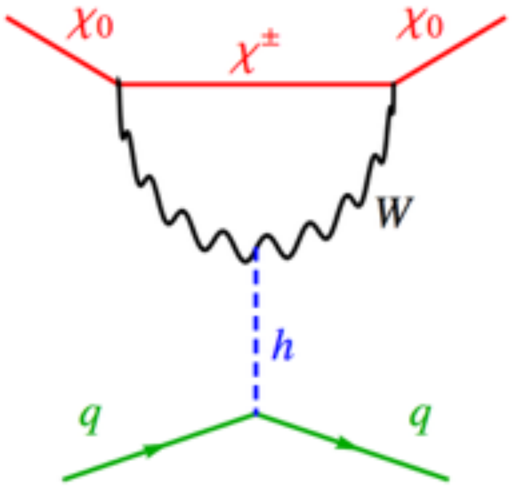


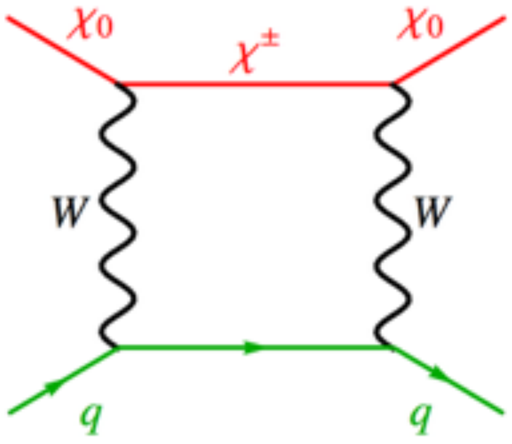
Direct detection of electroweak DM

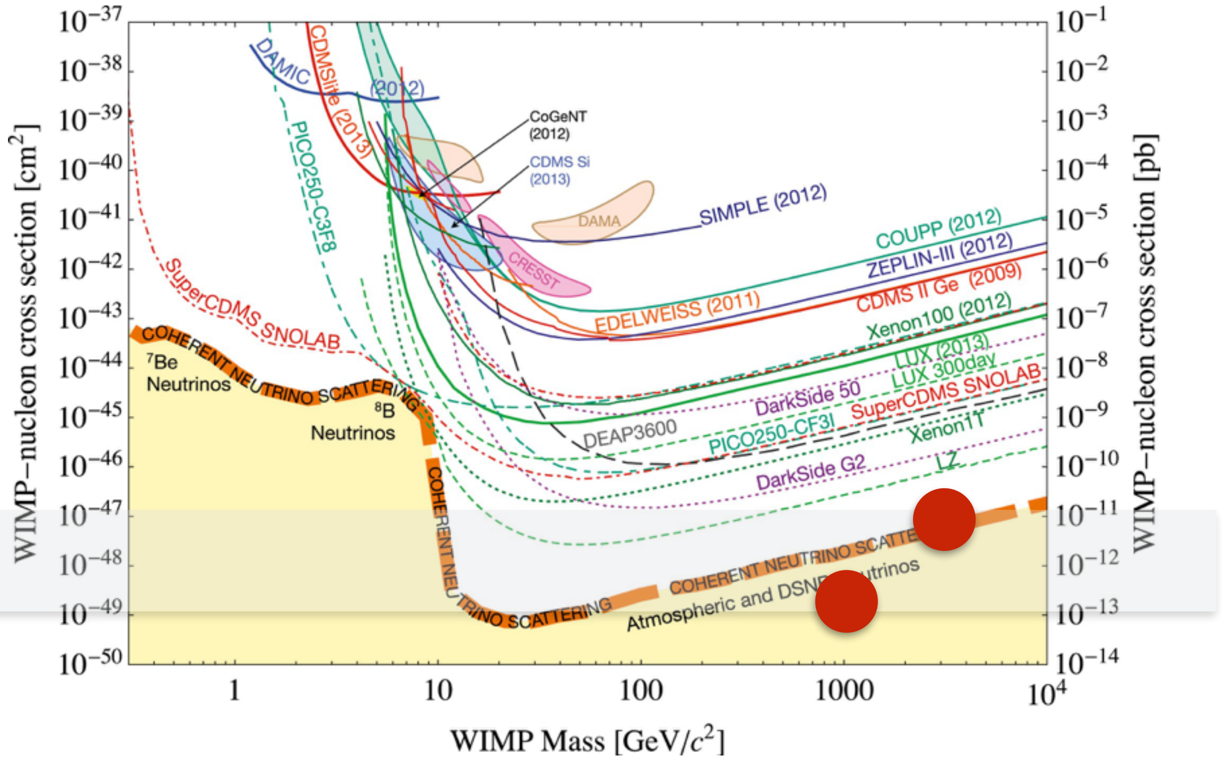
- Spin-independent nuclear scattering is suppressed (loop level + accidental cancellation)

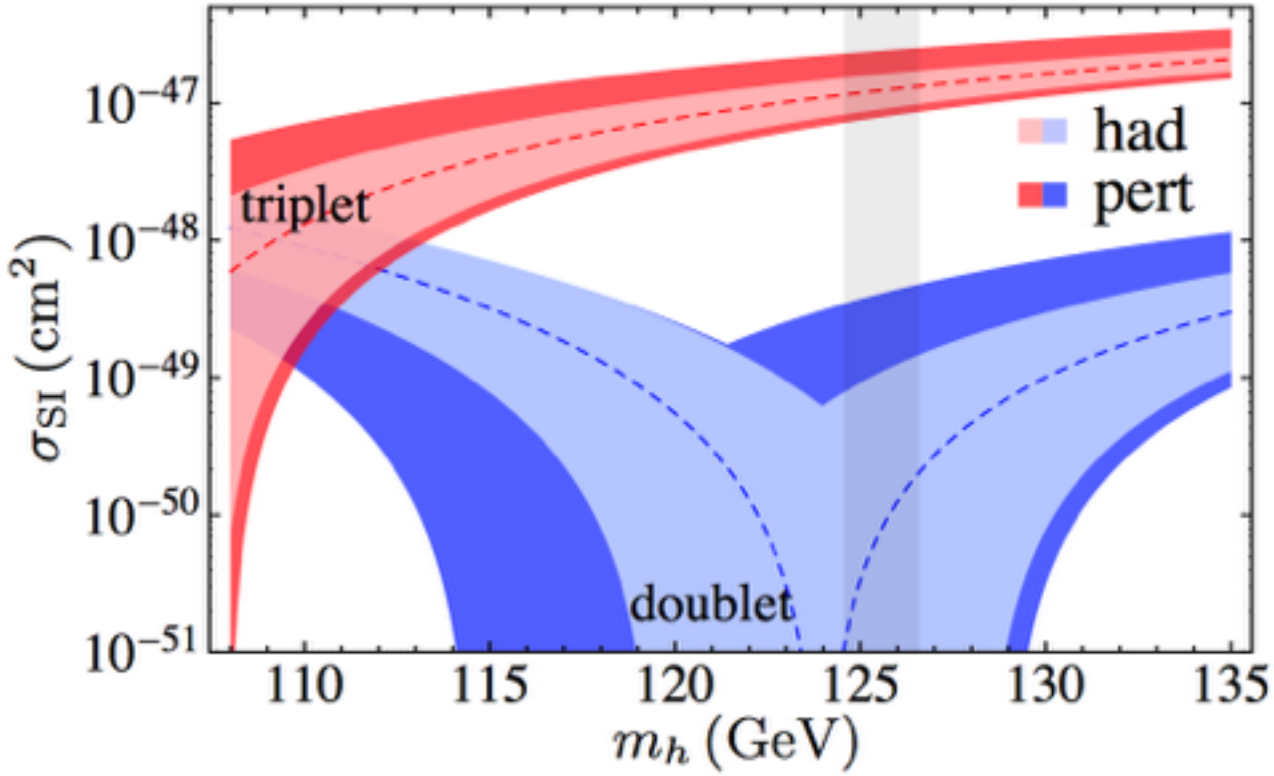
$$\sigma_n \sim 10^{-47} - 10^{-49}\ \mathrm{cm}^2$$

[1111.0016,1210.5985,1309.4092]

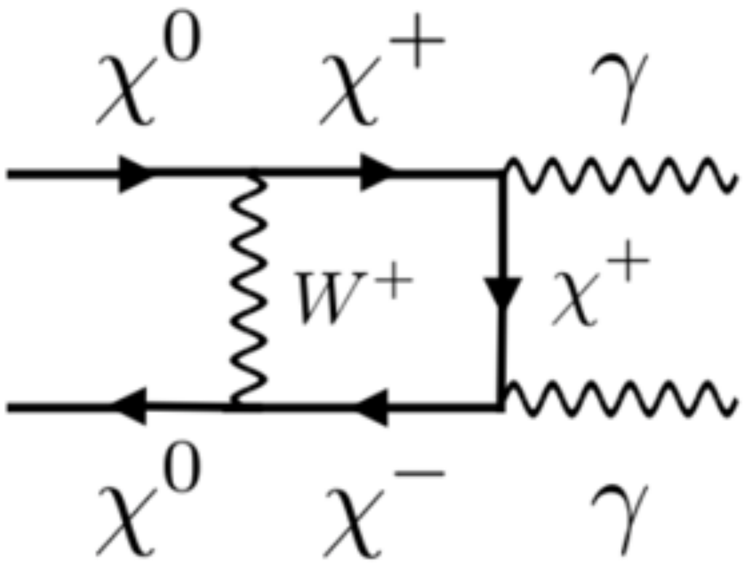




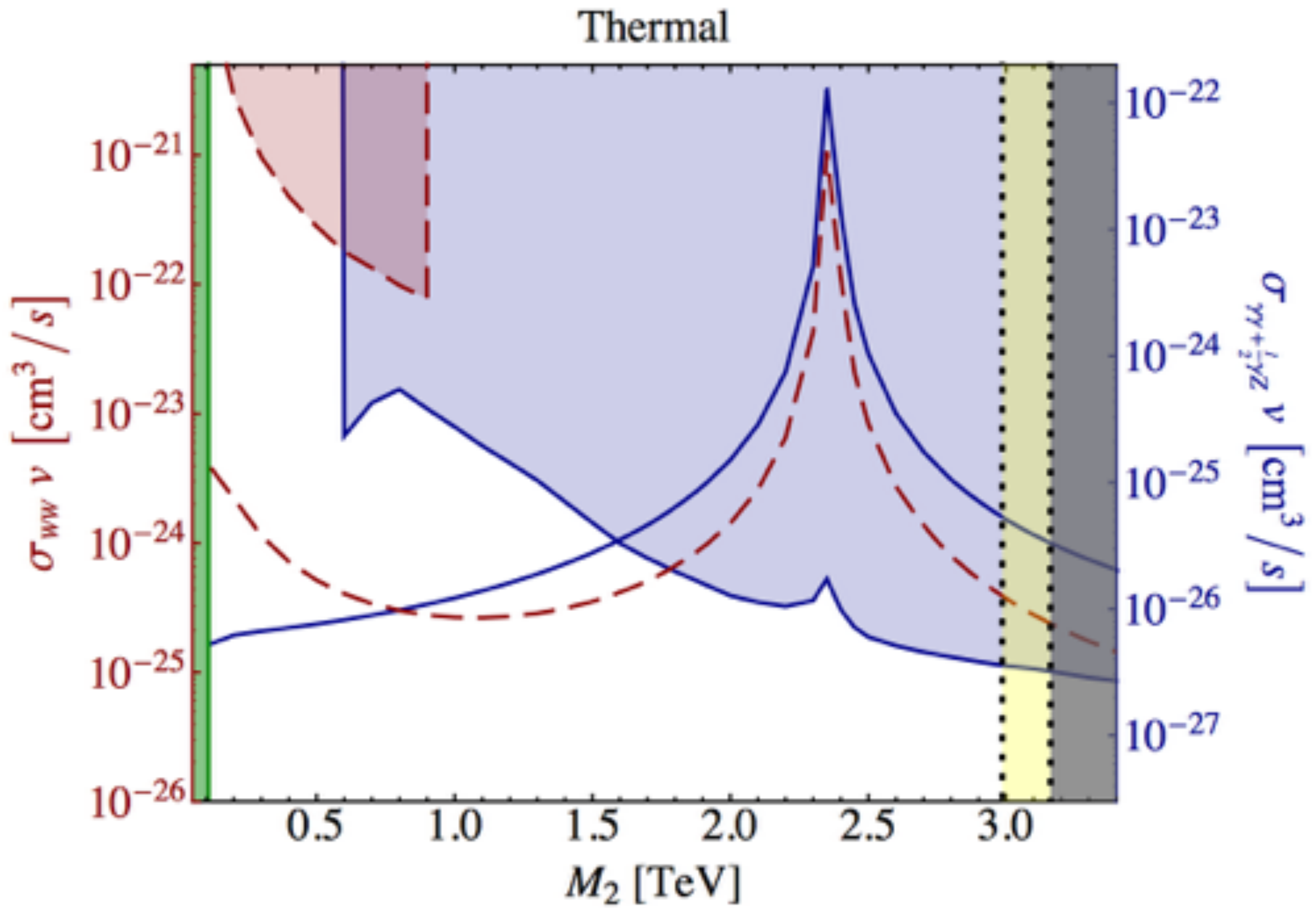




Gamma-ray lines from electroweak DM



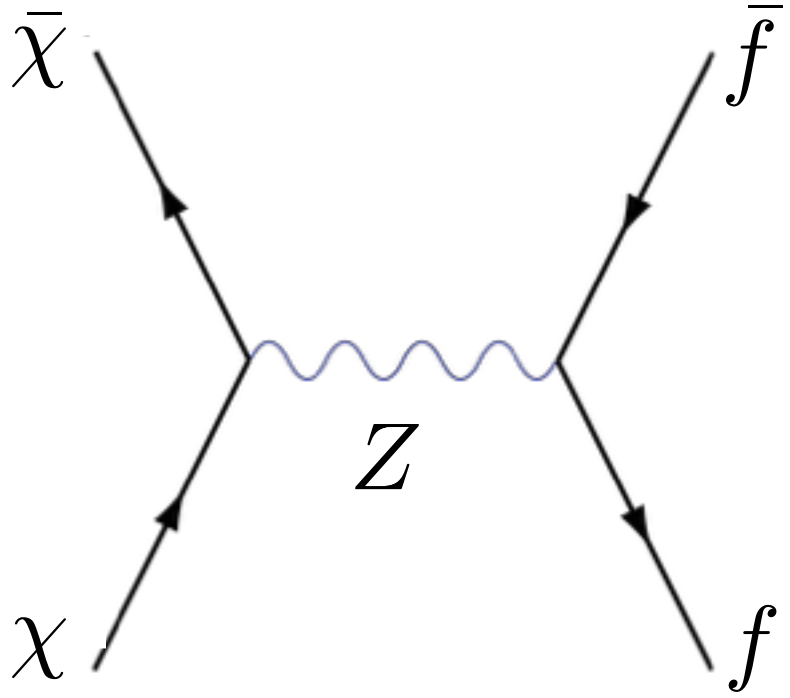
- Monochromatic gamma-ray lines provide a striking signal of DM annihilation
- H.E.S.S., HAWC, VERITAS, MAGIC, CTA can search for gamma-ray lines
- Important constraints already exist for thermal Wino
- These are sensitive to the distribution of dark matter in the Milky Way, which has significant uncertainties



[1307.4082,1307.4400]

Lee-Weinberg bound

- Consider DM lighter than W, Z, boson; then it can only annihilate to SM fermions through s-channel Z exchange



$$\mathcal{L} \sim G_F [\bar{\chi}\, \Gamma\, \chi][\bar{f}\, \Gamma\, f]$$

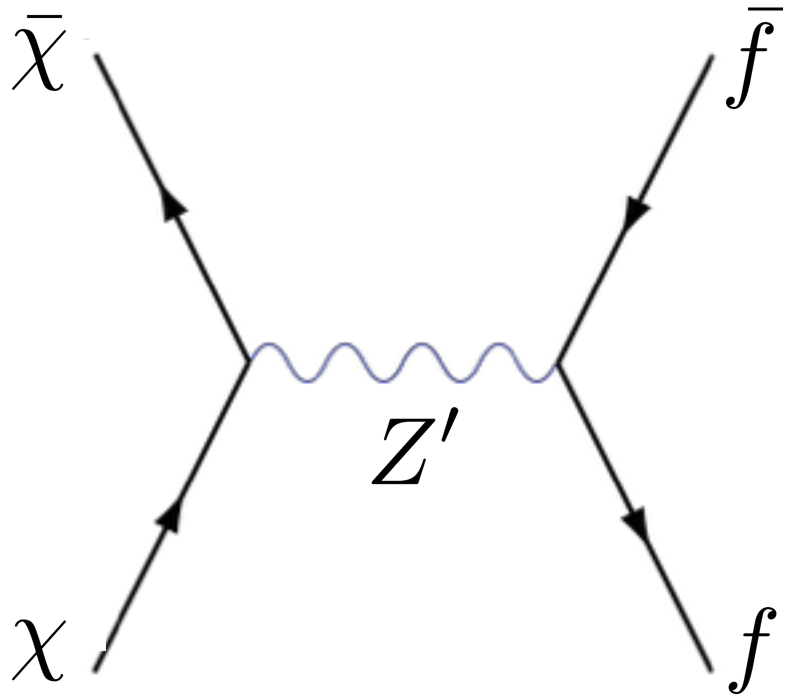
$$\langle \sigma v \rangle \sim \frac{G_F^2 m_\chi^2}{\pi} \approx 1\,\mathrm{pb} \times \left(\frac{m_\chi}{5\,\mathrm{GeV}}\right)^2$$

$$\Rightarrow \quad m_\chi \gtrsim \mathcal{O}(\mathrm{GeV})$$

- If DM only interacts through weak interactions, we generically require it to be above the GeV scale; otherwise it is overproduced

Evading Lee-Weinberg with light mediators

- It is possible that dark matter interacts with the SM through light mediators, in which case the Lee-Weinberg bound must be revisited



$$\mathcal{L} \supset g_\chi \, Z'_\mu \, \bar{\chi} \, \Gamma^\mu \, \chi + g_f \, Z'_\mu \, \bar{f} \, \Gamma^\mu \, f$$

$$\langle \sigma v \rangle \sim \frac{g_\chi^2 \, g_f^2 \, m_\chi^2}{m_{Z'}^4} \sim 1 \, \mathrm{pb} \times \left(\frac{g_\chi}{0.5}\right)^2 \left(\frac{g_f}{0.001}\right)^2 \left(\frac{m_\chi}{100 \, \mathrm{MeV}}\right)^2 \left(\frac{1 \, \mathrm{GeV}}{m_{Z'}}\right)^4$$

- The lightness of the mediator allows for efficient annihilation even for smallish couplings to the SM fields; i.e., interaction strengths as large or larger than G_F

[hep-ph/0305261]

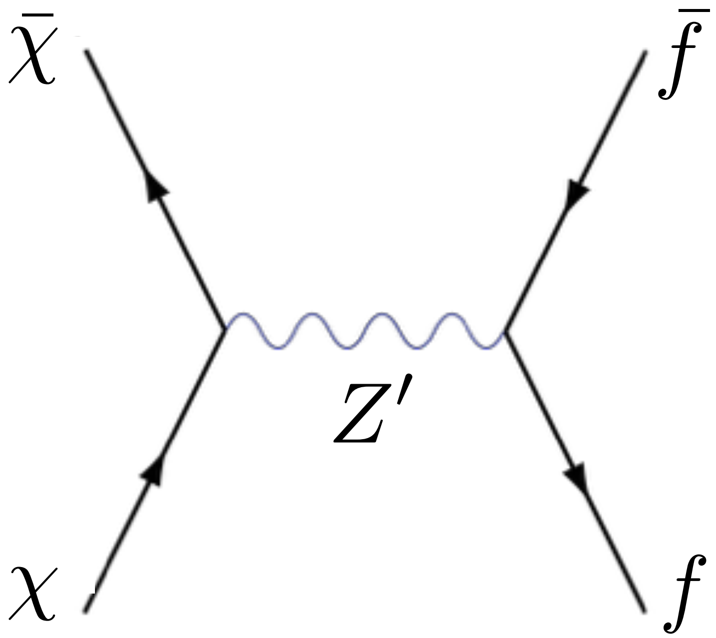
Direct vs. secluded annihilation

[0711.4866]

Two characteristic regimes:

$$\mathcal{L} \supset g_\chi \, Z'_\mu \, \bar{\chi} \, \Gamma^\mu \, \chi + g_f \, Z'_\mu \, \bar{f} \, \Gamma^\mu \, f$$

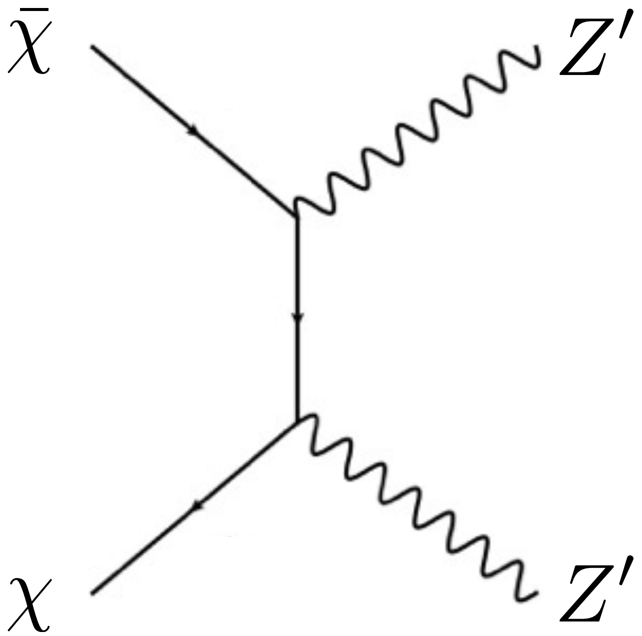
1. Direct annihilation: $m_\chi < m_{Z'}$



$$\langle \sigma v \rangle \sim \frac{g_\chi^2 \, g_f^2 \, m_\chi^2}{m_{Z'}^4}$$

Requires sizable portal coupling to deplete DM abundance

2. "Secluded annihilation: $m_\chi > m_{Z'}$



$$\langle \sigma v \rangle \sim \frac{g_\chi^4}{8\pi m_\chi^2}$$

Requires only minuscule portal coupling to maintain kinetic equilibrium

The Dark Sector Paradigm

Standard Model

Dark Sector

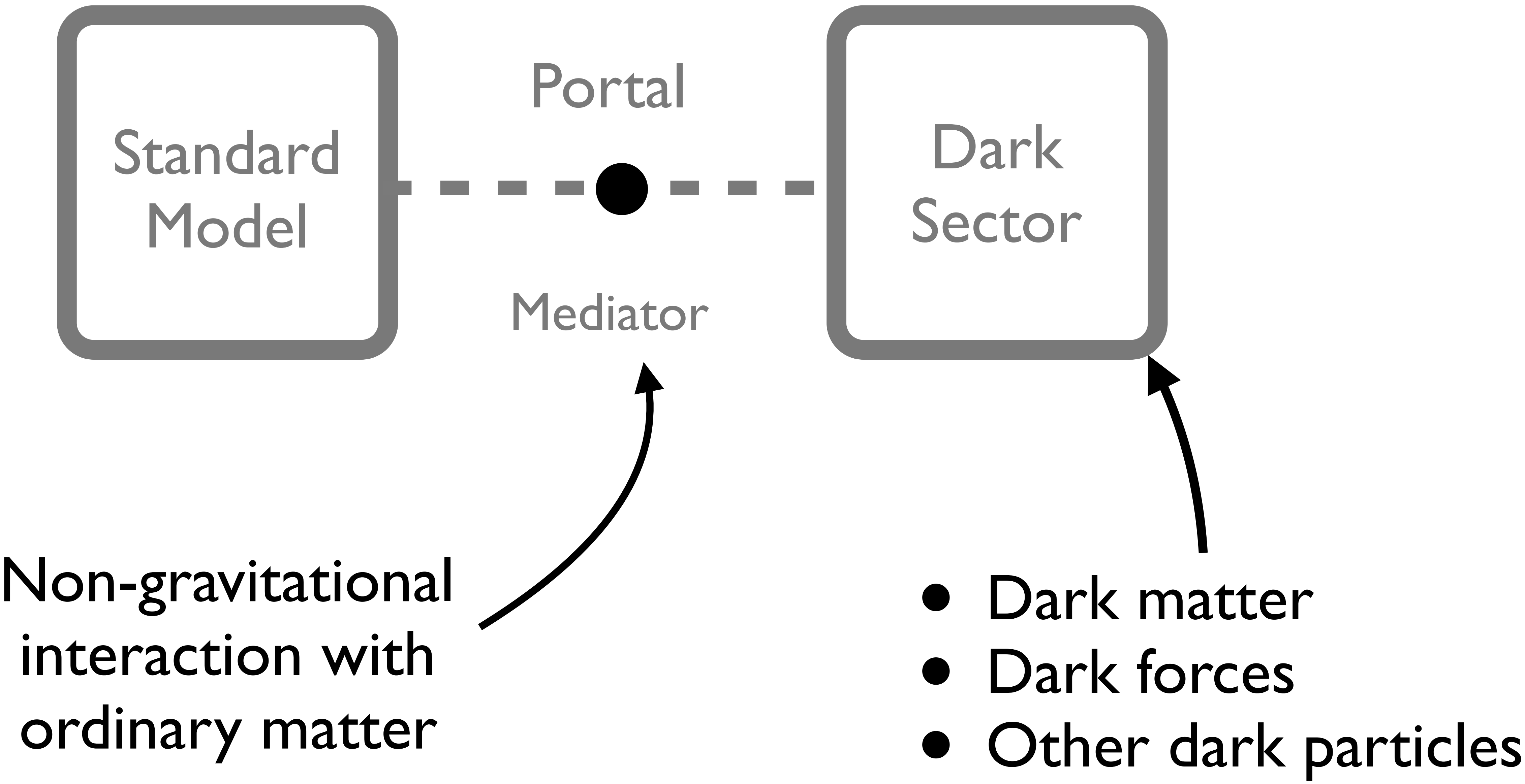
The Dark Sector Paradigm

Standard Model

Dark Sector

- Dark matter
- Dark forces
- Other dark particles

The Dark Sector Paradigm


Standard Model

Portal

Mediator

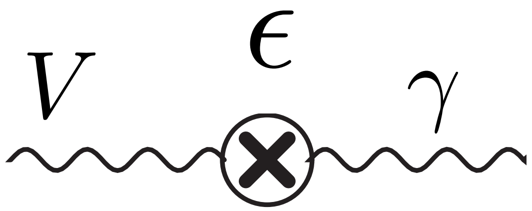
Dark Sector

Non-gravitational interaction with ordinary matter

- Dark matter
- Dark forces
- Other dark particles

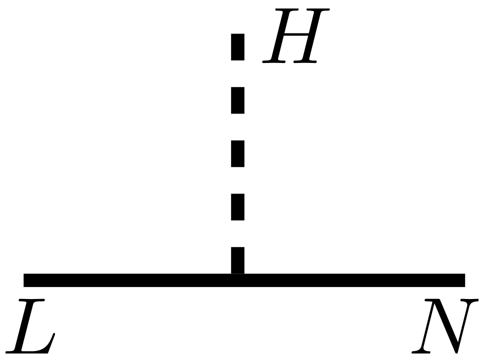
Portals

$$\frac{\epsilon}{2} B_{\mu\nu} V^{\mu\nu}$$



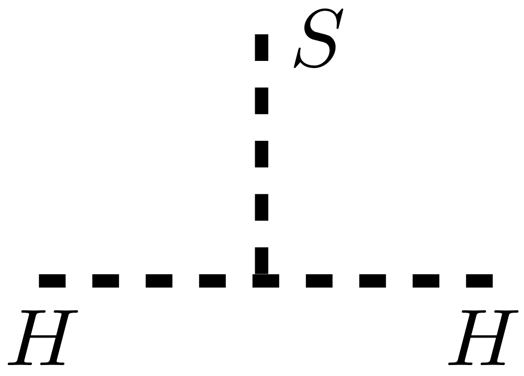
Vector Portal

$$y L H N$$



Neutrino portal

$$(\mu S + \lambda S^2) H^\dagger H$$



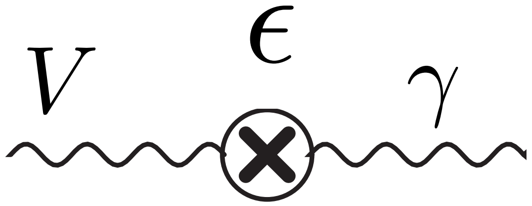
Higgs Portal

Portals may mediate non-gravitational interactions between dark matter and ordinary matter

Portals

- If new light particles with mass below the weak scale exist, they should not interact through the known forces.
  "hidden" states?

$$\frac{\epsilon}{2} B_{\mu\nu} V^{\mu\nu}$$



Vector Portal

$$yLHN$$

Neutrino portal

$$(\mu S + \lambda S^2) H^\dagger H$$

Higgs Portal

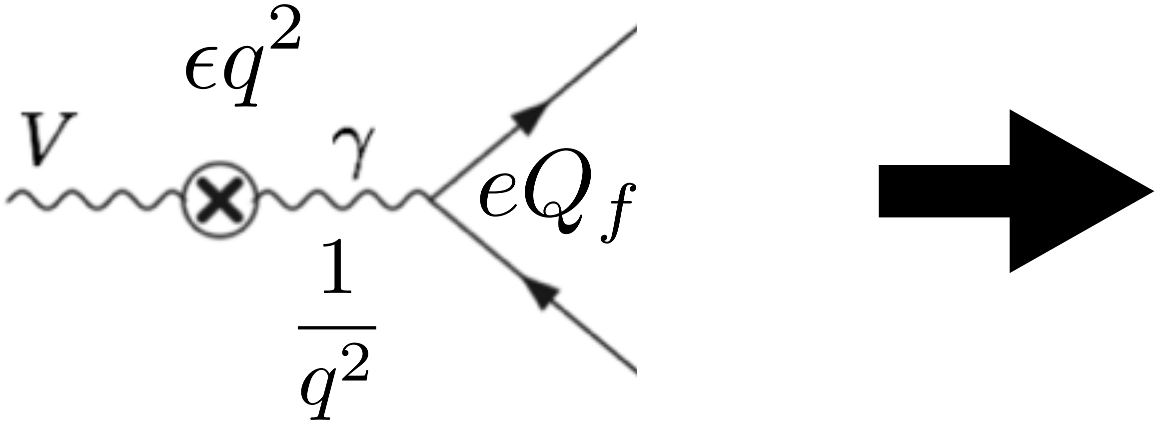
Vector portal dark matter

[0711.4866, 0810.0713]

- The basic Lagrangian for the model is given by

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + \sum_f Q_f e A_\mu \bar{f}\gamma^\mu f + g_D V_\mu \bar{\chi}\gamma^\mu \chi$$

- V_μ is the dark photon; χ is the dark matter; Four parameters $m_V, m_\chi, \epsilon, g_D$
- We can treat the kinetic mixing as an interaction, e.g.,



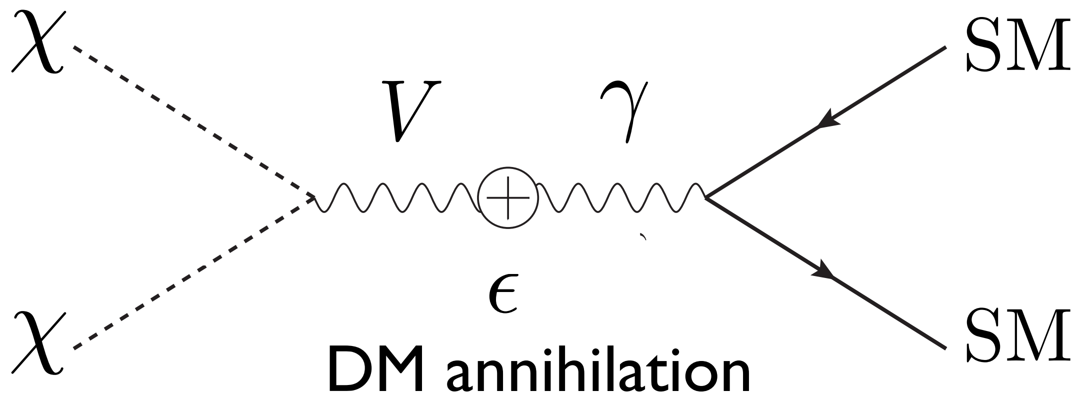
$\epsilon\, e\, Q_f$ “Milli-dark charge”

- Or we can diagonalize the Lagrangian via

$$\begin{aligned} A_\mu &\rightarrow A_\mu - \epsilon V_\mu, \\ V_\mu &\rightarrow V_\mu. \end{aligned}$$

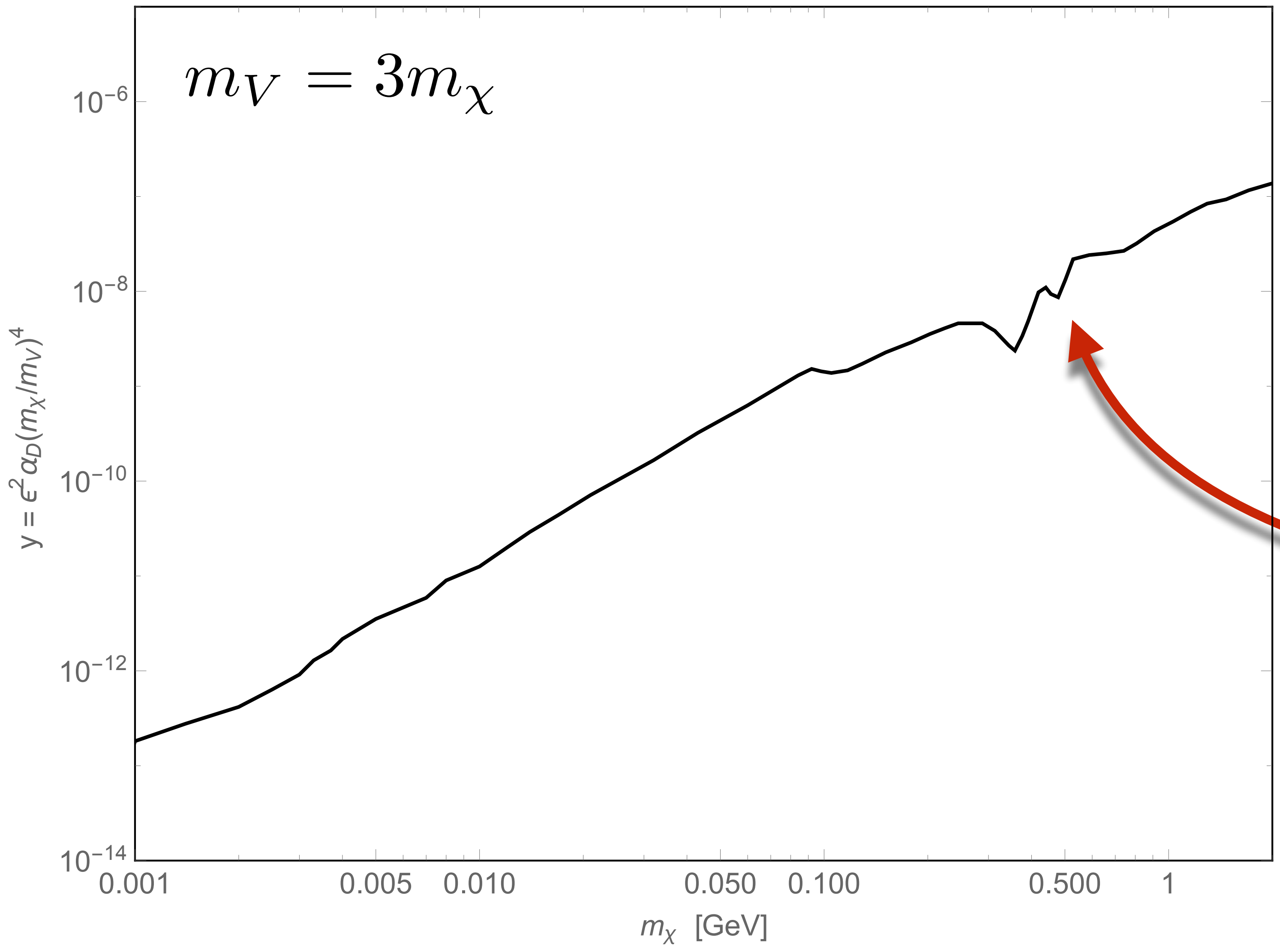
- This gives the interaction: $\mathcal{L} \supset \sum_f Q_f\, \epsilon\, e\, V_\mu\, \bar{f}\gamma^\mu f$

Relic abundance



DM annihilation

$$\langle \sigma v \rangle \sim \frac{\epsilon^2 \alpha_D m_\chi^2}{m_V^4} \equiv \frac{y}{m_\chi^2}$$



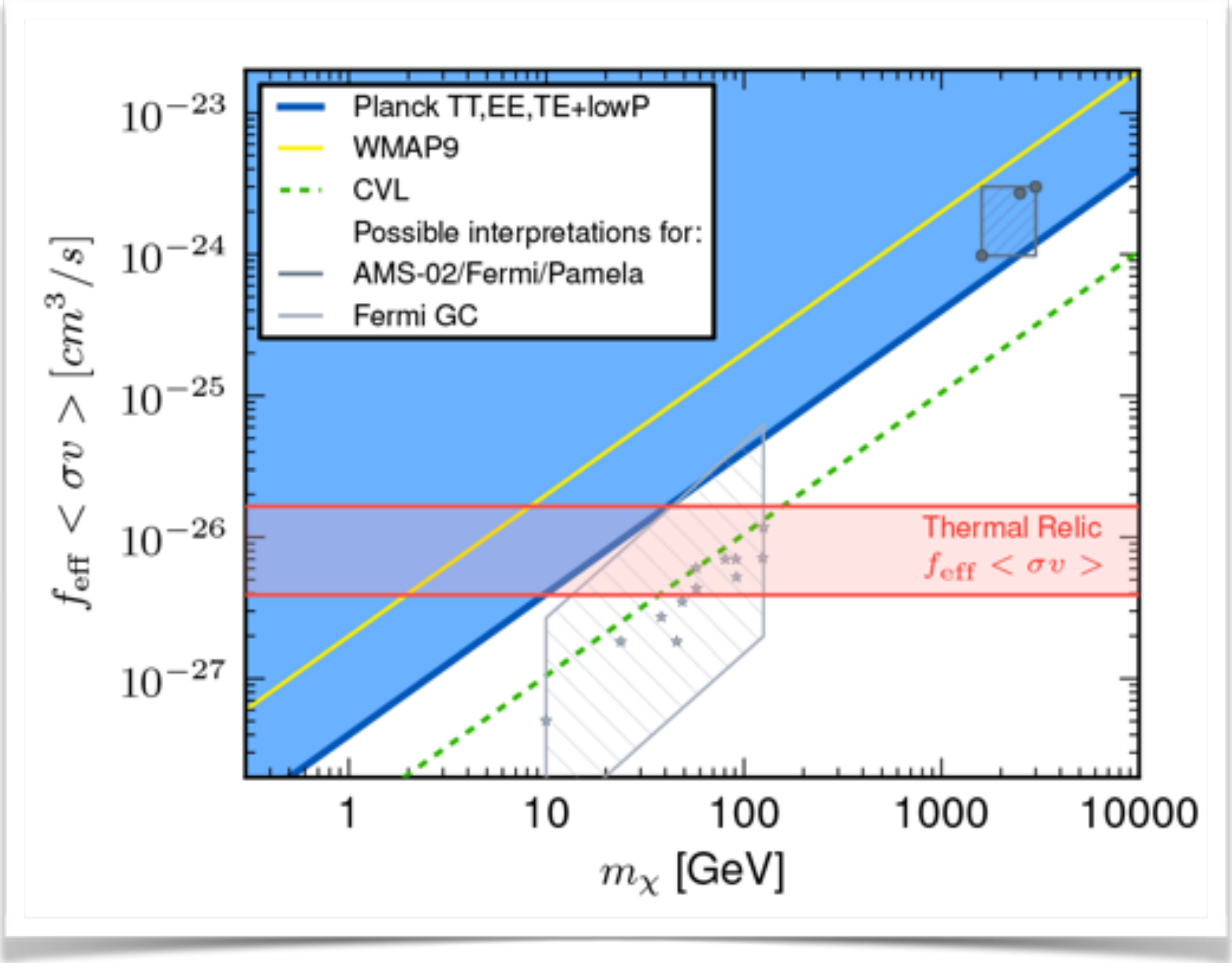
observed DM abundance predicted along this line

[see e.g., 1505.00011]

CMB as a probe of the dark sector

- The cosmic microwave background provides a sensitive test of DM annihilation around the epoch of recombination

- If the annihilation products include energetic photons, electrons, this will modify ionization history, leaving imprints on the temperature and polarization anisotropies



[1502.01589]

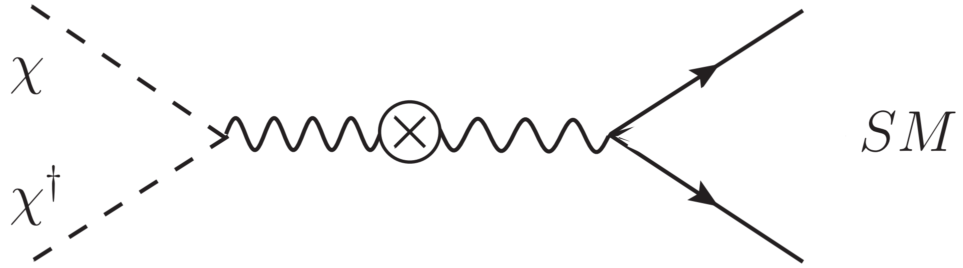
- Current constraints probe thermal dark matter candidates below about 10 GeV

A closer look at the CMB bounds

- The CMB bounds depend on the particle physics model and DM cosmology
- In general, the DM annihilation cross section can be written as

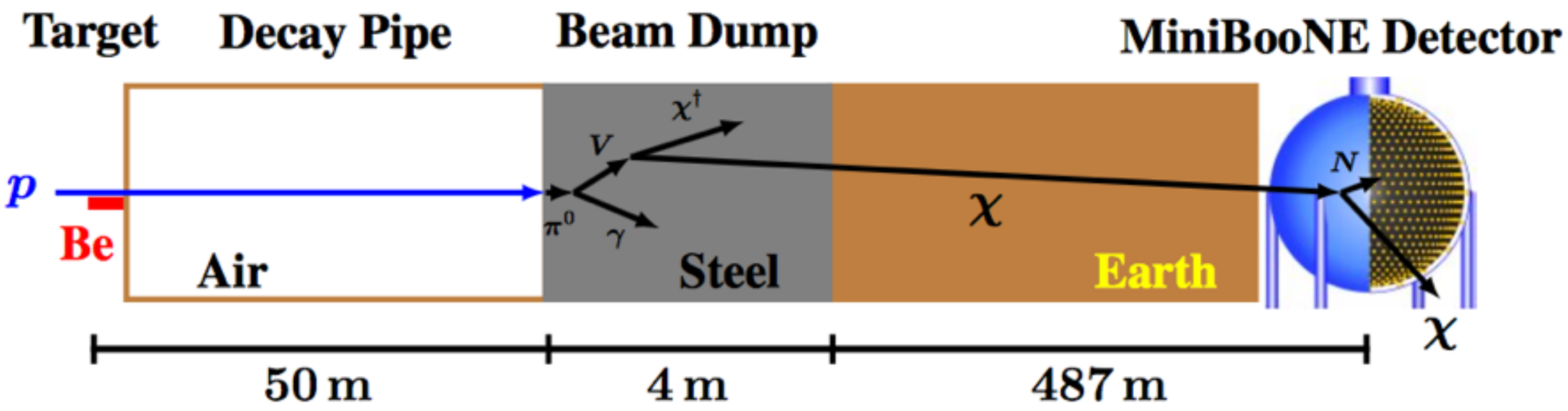
$$\langle \sigma v \rangle = a + b v^2 + \ldots$$

- The first term occurs if annihilation in the s-wave (L=0) is present. In this case, the CMB bounds will apply and strongly constrain the model
- In some models, the s-wave process is not allowed, and the leading term is the p-wave (L=1) process. In this case the cross section is velocity suppressed.
- DM was highly non-relativistic during the recombination epoch, and therefore the bounds can be evaded if annihilation proceeds in the p-wave
- In the dark photon model, p wave annihilation to the SM occurs if DM is a scalar

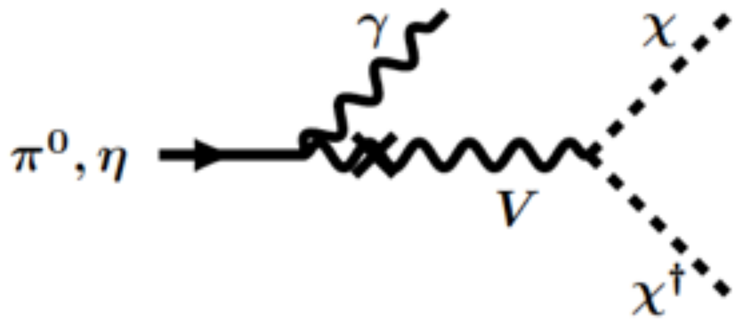


-Vector mediator has J =1
-scalars are spin = 0;
-Conservation of J requires L = 1

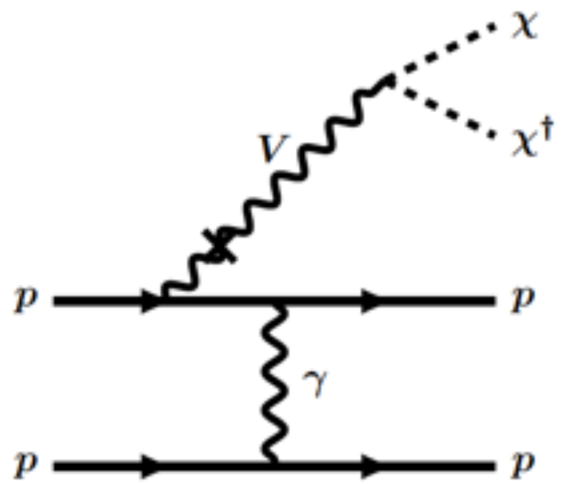
Beam dump search for dark matter



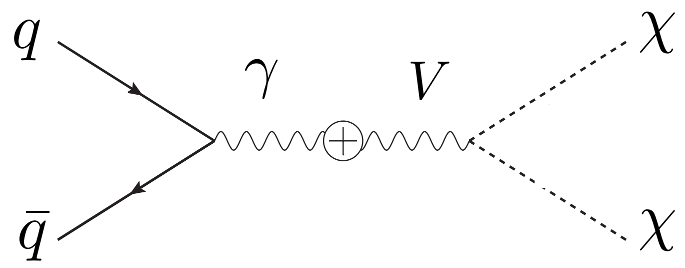
Production of the DM beam



Neutral mesons decays

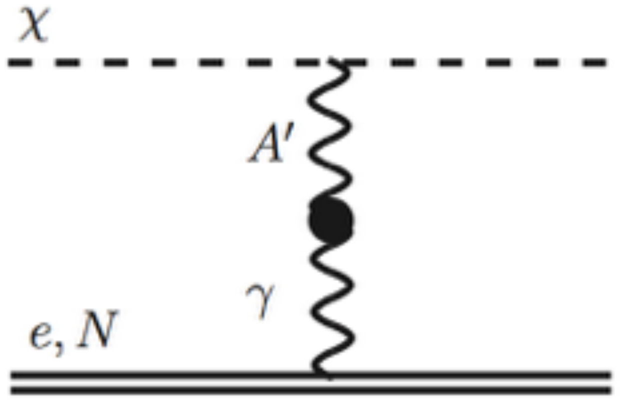


Bremsstrahlung + vector meson mixing

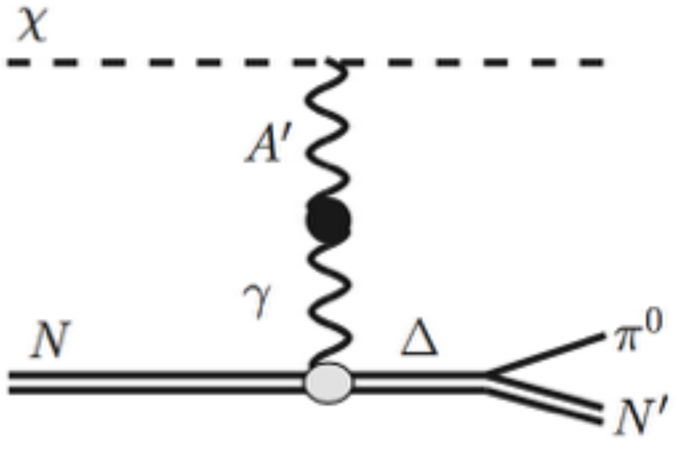


Direct production

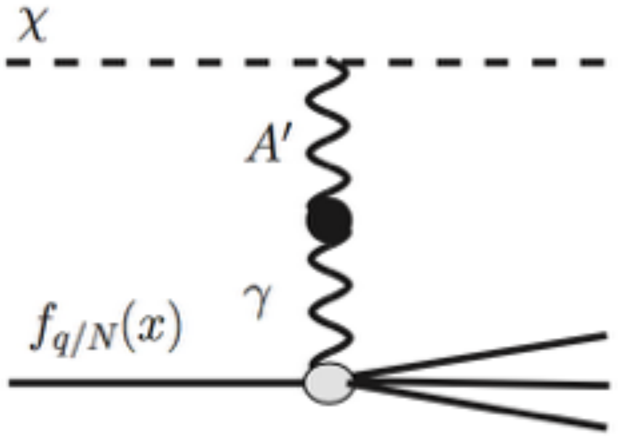
Detection of DM via scattering



Elastic NC nucleon or electron scattering



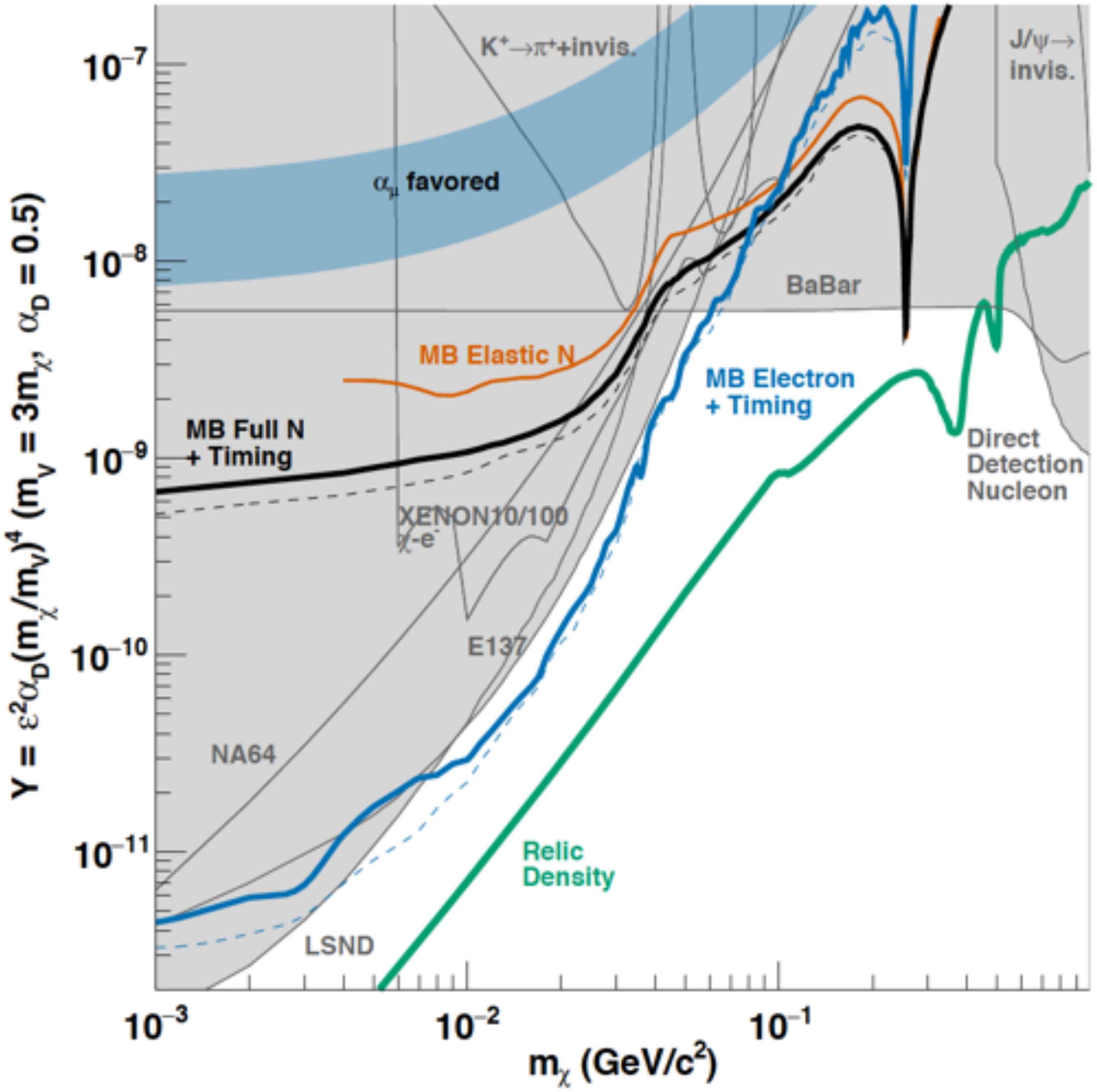
Inelastic NC neutral pion - like scattering



Deep Inelastic scattering

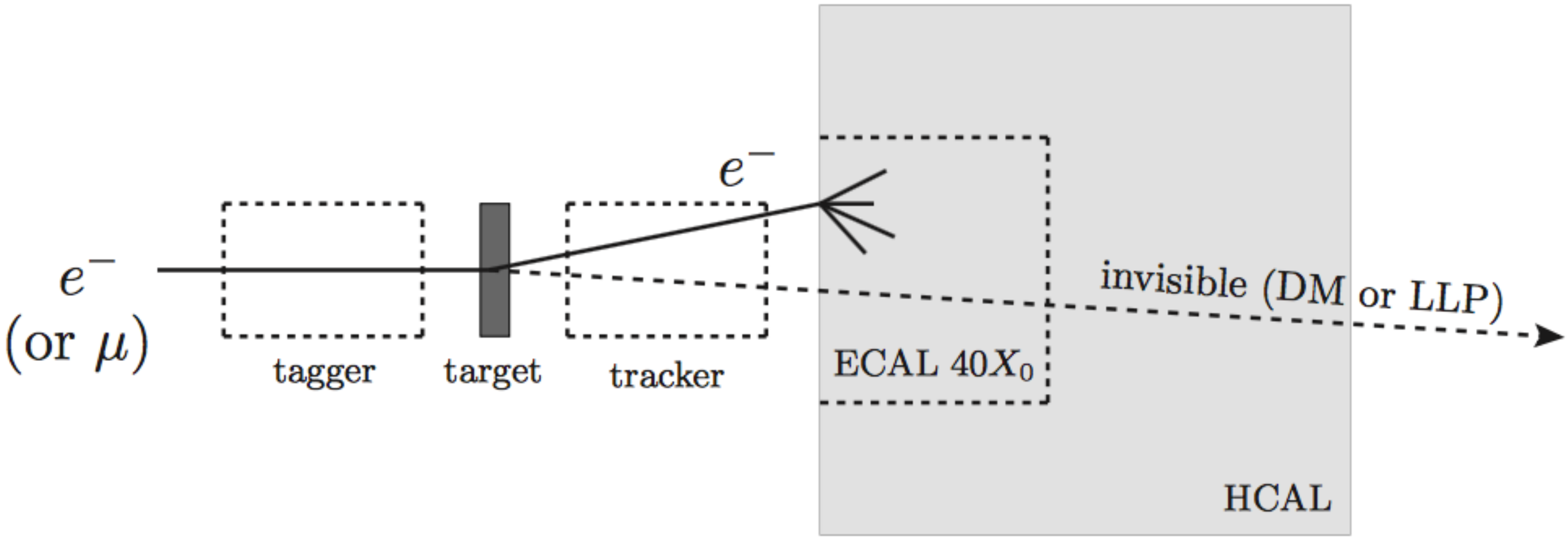
MiniBooNE-DM experiment

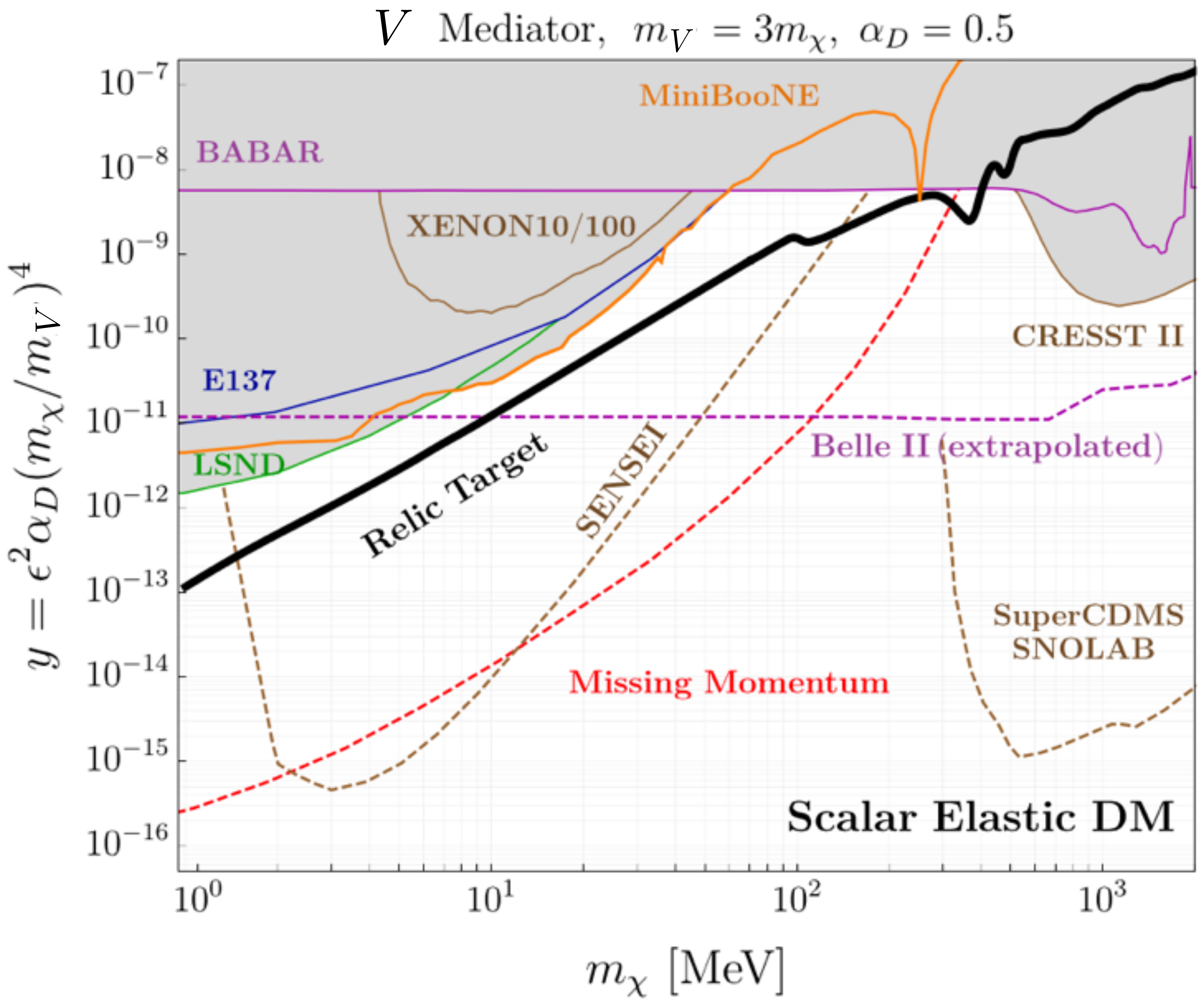
[1807.06137]



LDMX experiment

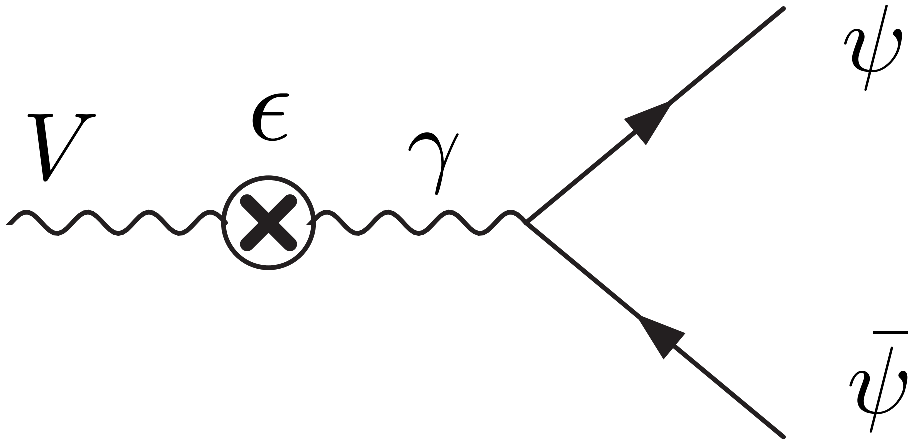
[1807.01730]

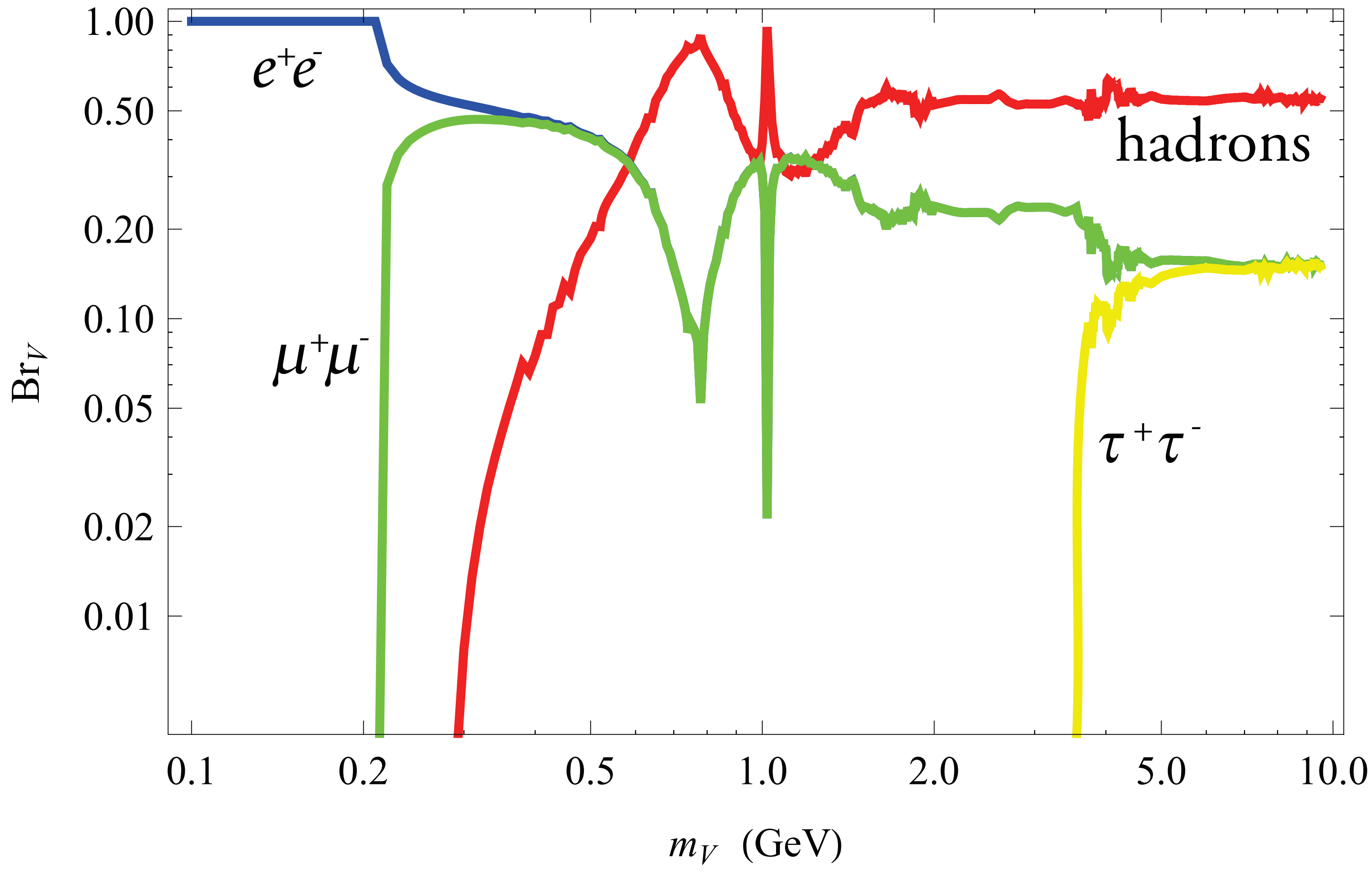



V Mediator, $m_{V} = 3m_\chi$, $\alpha_D = 0.5$
$y = \epsilon^2 \alpha_D (m_\chi/m_{V})^4$
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
MiniBooNE
BABAR
XENON10/100
CRESST II
E137
Belle II (extrapolated)
LSND
Relic Target
SENSEI
SuperCDMS SNOLAB
Missing Momentum
Scalar Elastic DM
10^0
10^1
10^2
10^3
m_χ [MeV]

[1808.05219]

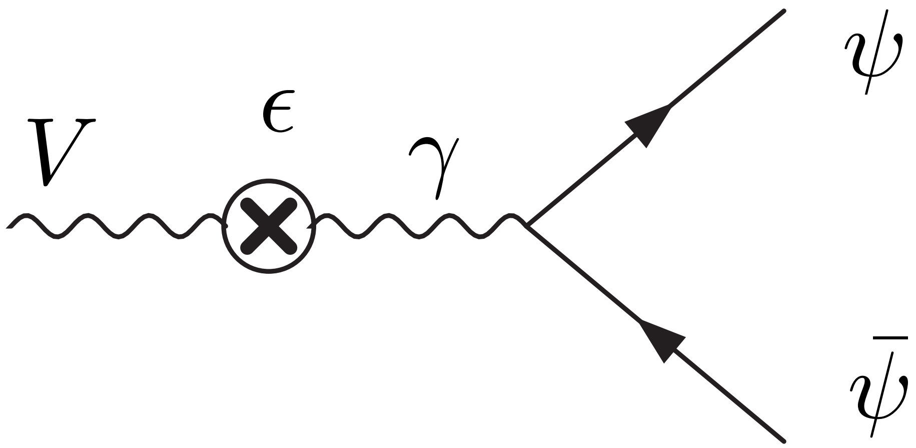
Visible dark photon decays



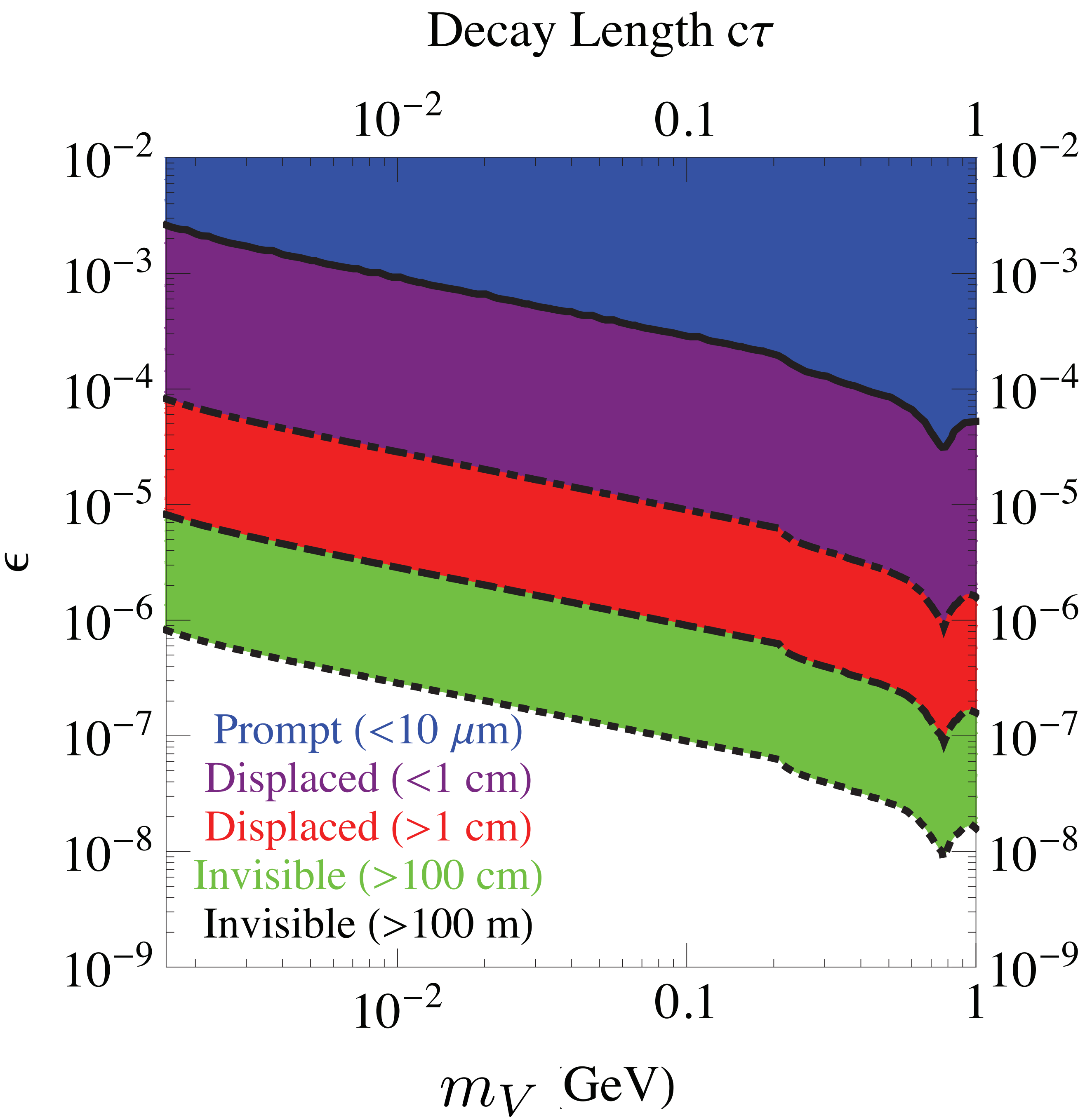


[0903.0363]

Dark photon lifetime



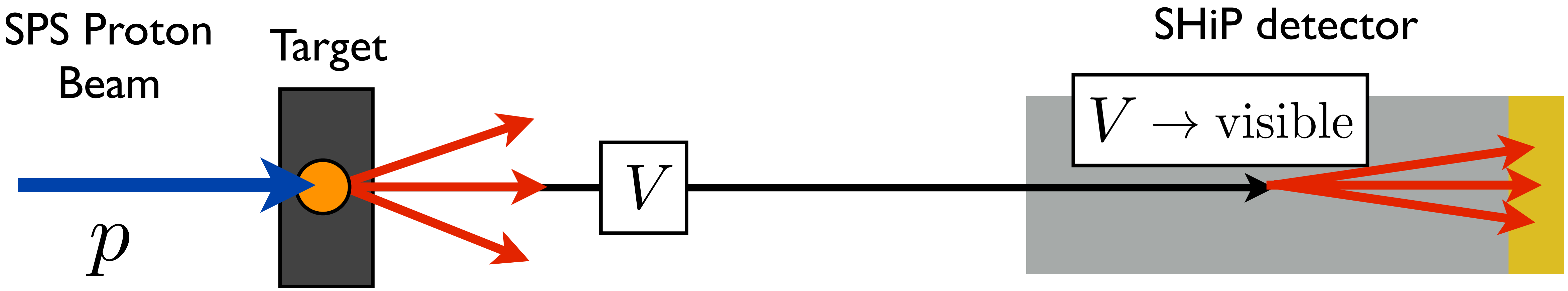
$$\Gamma_V \sim \epsilon^2 \alpha m_V \quad \Rightarrow \quad c\tau_V \sim \frac{1}{\epsilon^2 \alpha m_V}$$



- Depending on lifetime, one can search for a bump in the invariant mass distribution or a displaced vertex/long-lived particle

[1008.0636]

SHiP Experiment



SPS Proton Beam

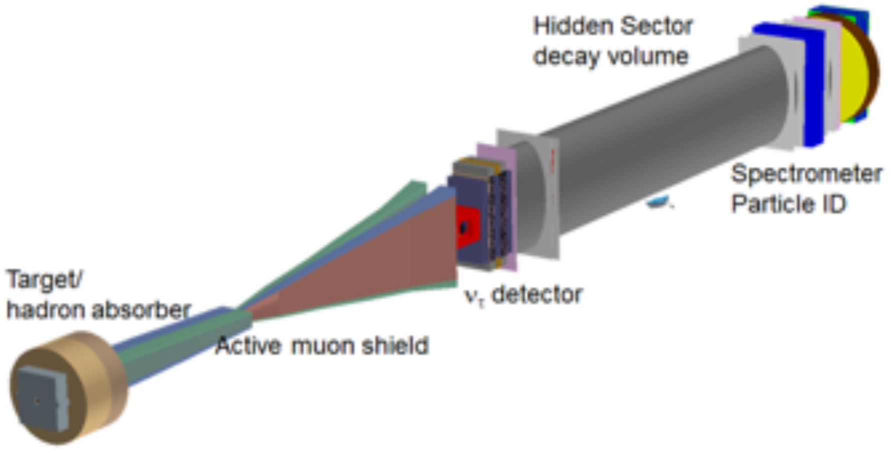
p

Target

V

SHiP detector

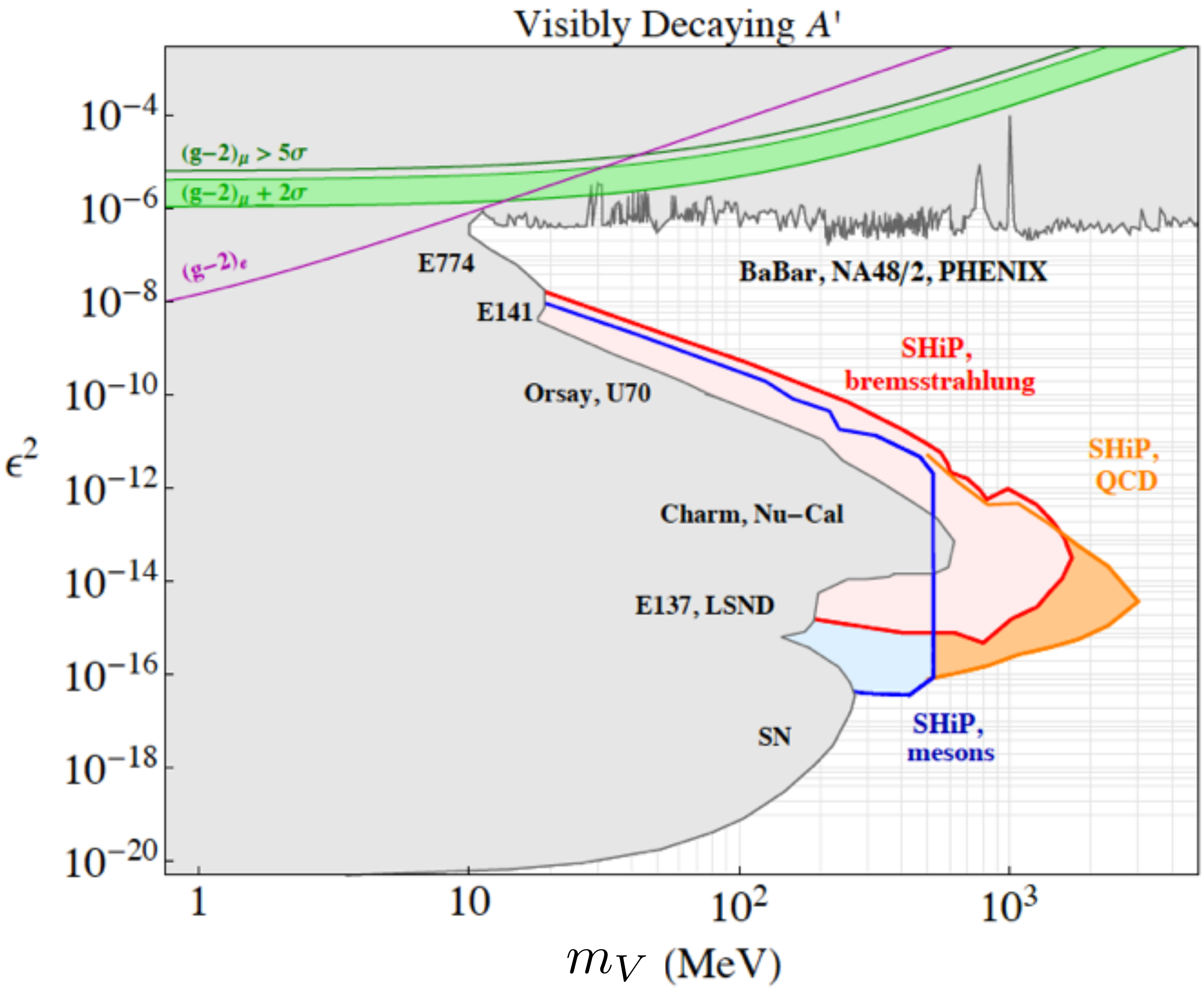
$V \to \text{visible}$



- 400 GeV protons from CERN SPS
- 4 E 20 POT
- Large detector volume, close to the target
- Hadron absorber mitigates background from strongly interacting particles
- Active muon shielding to magnetically deflect muons away from SHiP detector
- Evacuated decay volume to minimize interaction of residual muons and neutrinos
- Goal is to achieve near zero background experiment

http://ship.web.cern.ch/ship/

SHiP sensitivity to dark photons



[1504.04855]

Many other new ideas to search for dark sectors!

U.S. Cosmic Visions: New Ideas in Dark Matter

23-25 March 2017 *Stamp Student Union, University of Maryland, College Park*
US/Eastern timezone

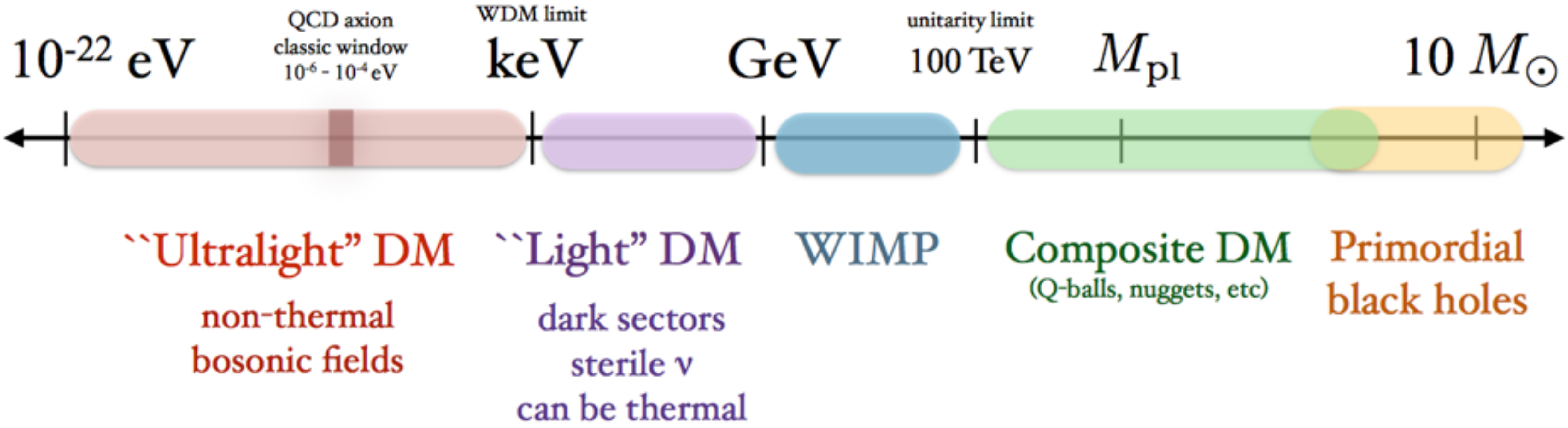
- **Overview**
- Scientific Programme
- Timetable
- Contribution List
- Author index
- Registration
  - Registration Form
- List of registrants

A workshop focusing on potential new small-scale projects in the U.S. Dark Matter search program will be held at the University of Maryland, College Park March 23-25, 2017.

Dates:	from March 23, 2017 08:00 to March 25, 2017 13:04
Timezone:	US/Eastern
Location:	*Stamp Student Union, University of Maryland, College Park* University of Maryland College Park MD 20742 USA
Chairs:	Cushman, Priscilla Flaugher, Brenna Hall, Carter Hewett, JoAnne Roe, Natalie Prof. Incandela, Joseph Belloni, Alberto
Material:	Instructions for remote participation Travel, accommodations, and logistics
Additional info:	*The following is the request by the DoE HEP office:*

Mass scale of dark matter

(not to scale)



10^{-22} eV

QCD axion
classic window
10^{-6} - 10^{-4} eV

WDM limit
keV

GeV

unitarity limit
100 TeV

M_{pl}

10 $M_{\odot}$

``Ultralight” DM
non-thermal
bosonic fields

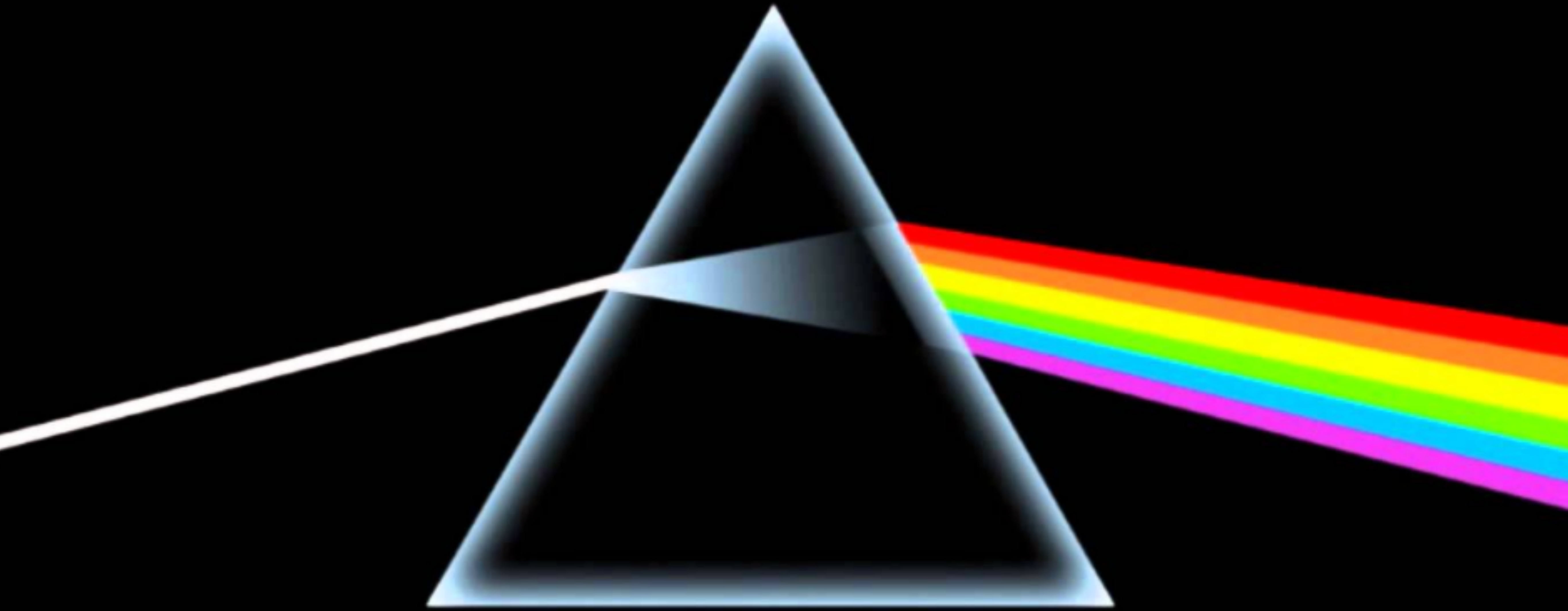
``Light” DM
dark sectors
sterile ν
can be thermal

WIMP

Composite DM
(Q-balls, nuggets, etc)

Primordial
black holes

Credit: T. Lin, 1904.07915



Thanks!