Very Biased Dark Matter Theory

Gordan Krnjaic

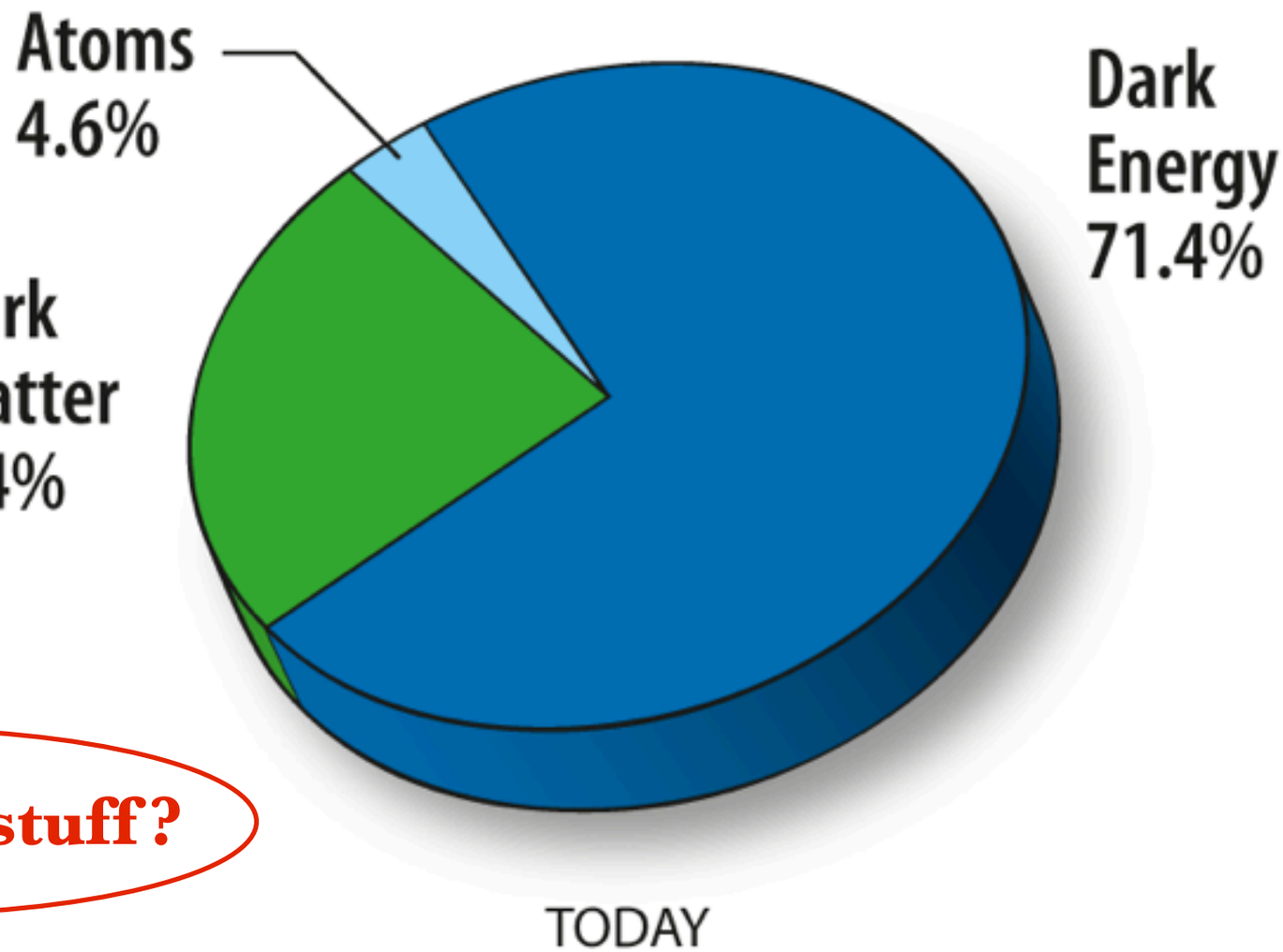
Fermilab

49th Annual Fermilab Users Meeting
Ramsey Auditorium, June 15, 2016

Zeroth Order Outstanding Problems

Matter Asymmetry
Inflation

Accelerated Cosmic Expansion



What is this stuff?

Also Quantum Gravity

Overview

- What's the evidence for dark matter?
- How should we think about it?
- Where else should we look ... and how?

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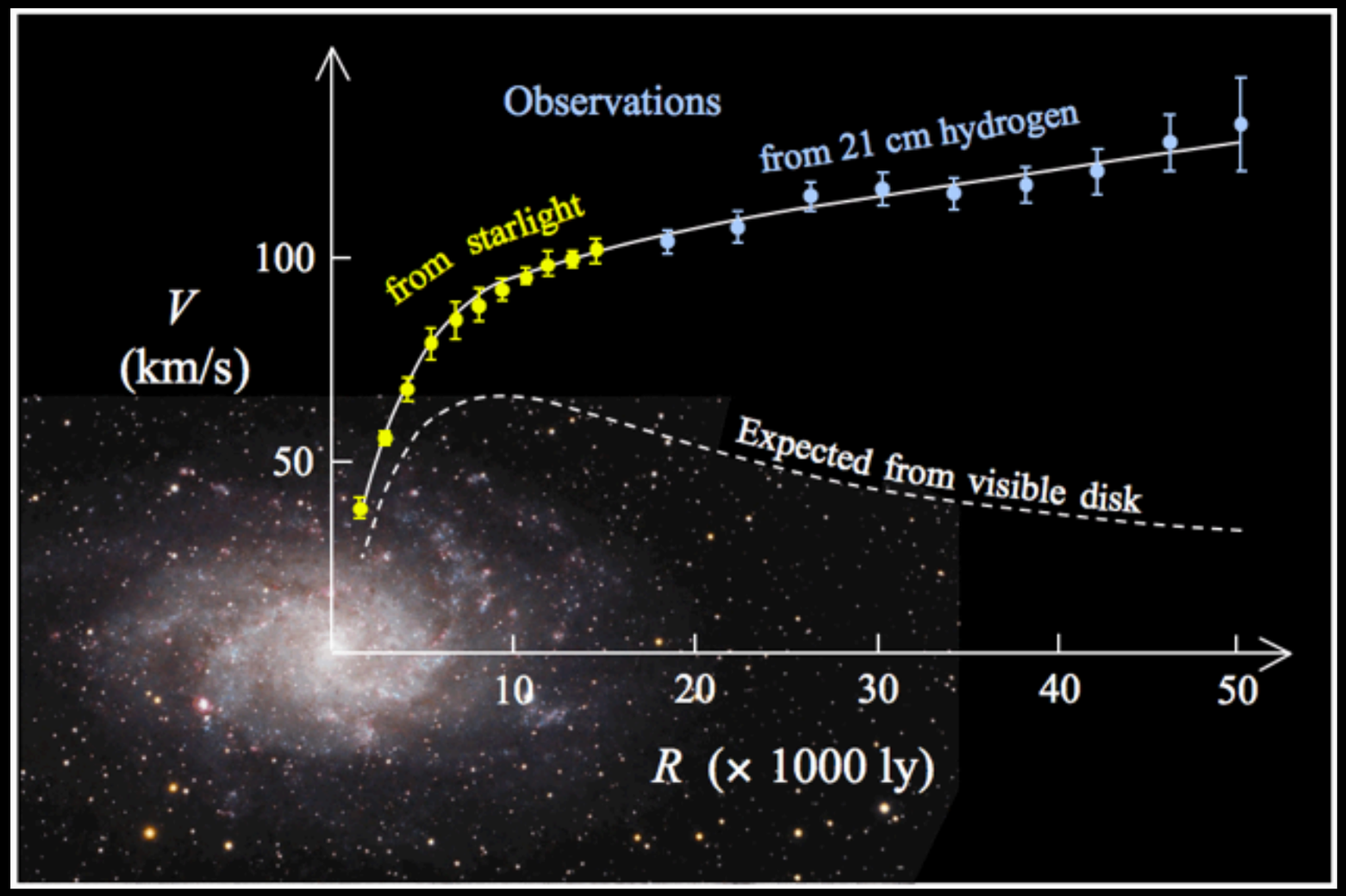
Evidence for Dark Matter

Galactic Rotation Curves

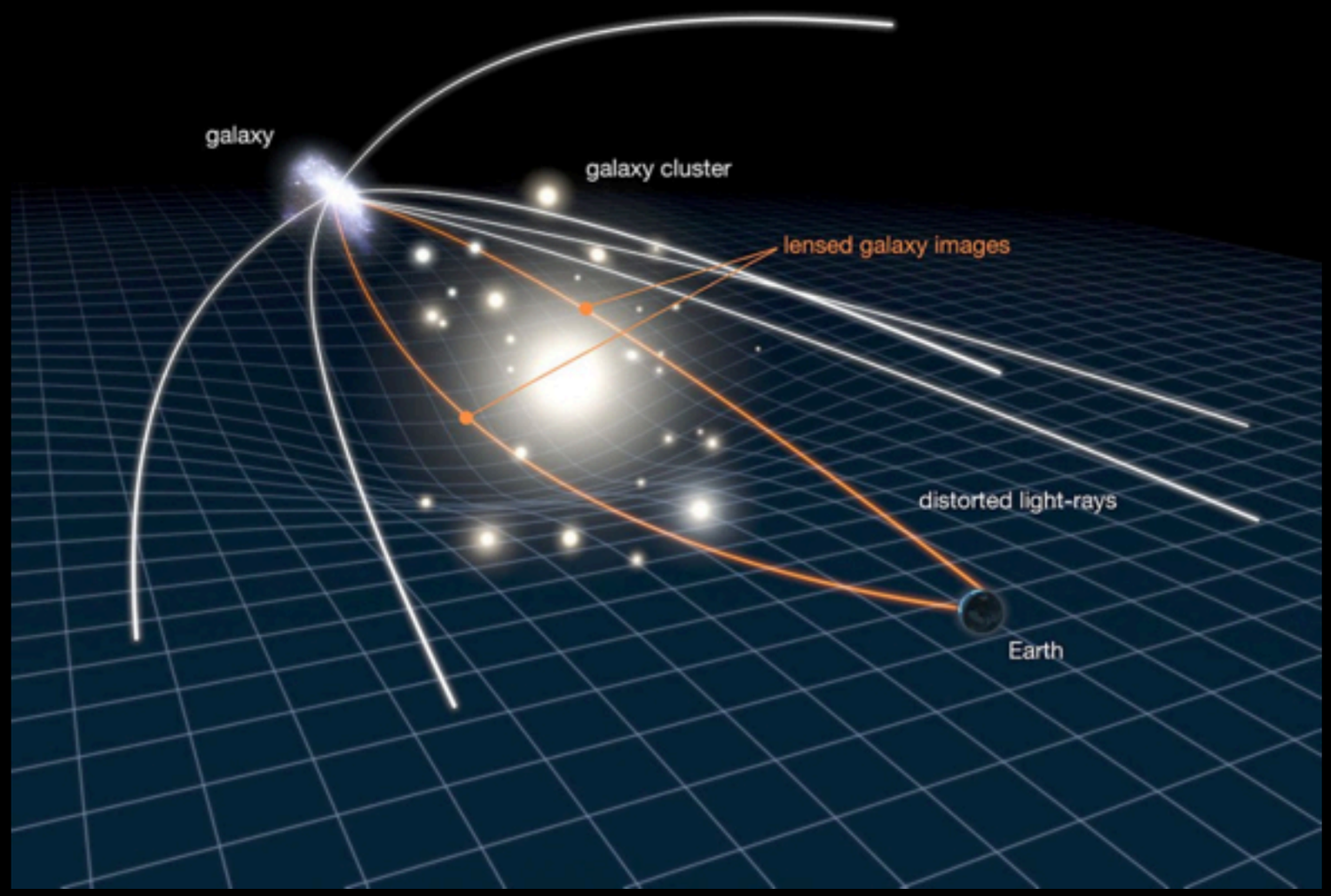


Dramatic effect: requires ~85% of matter to be "dark"

M33 Galaxy, E. Corbelli, P. Salucci (2000)

Evidence for Dark Matter

Gravitational Lensing

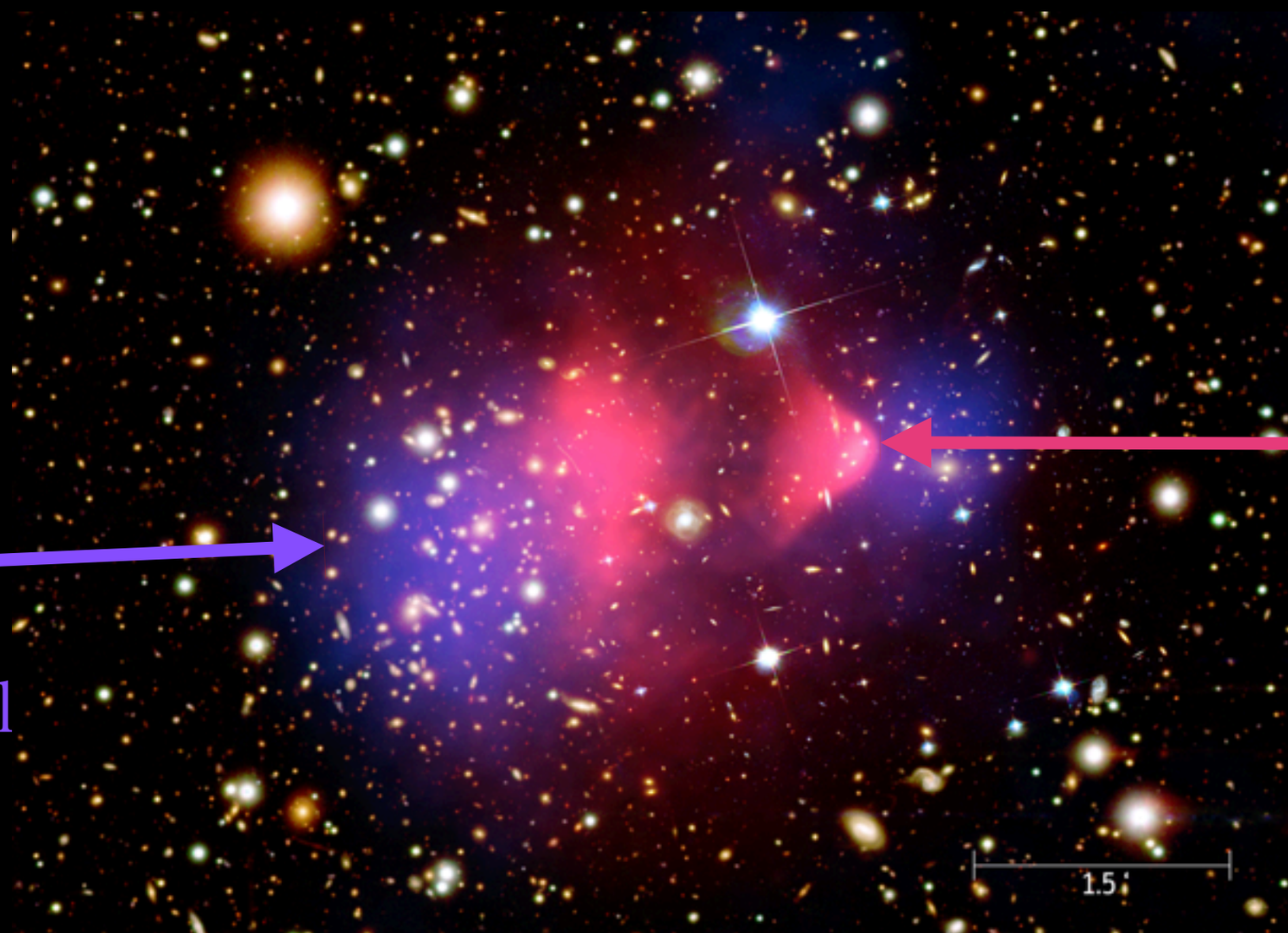


Images NASA/ESA

"Weighs" total matter: requires ~85% of matter to be "dark"

Evidence for Dark Matter

Galaxy Cluster Collisions



Visible Matter

Total Matter

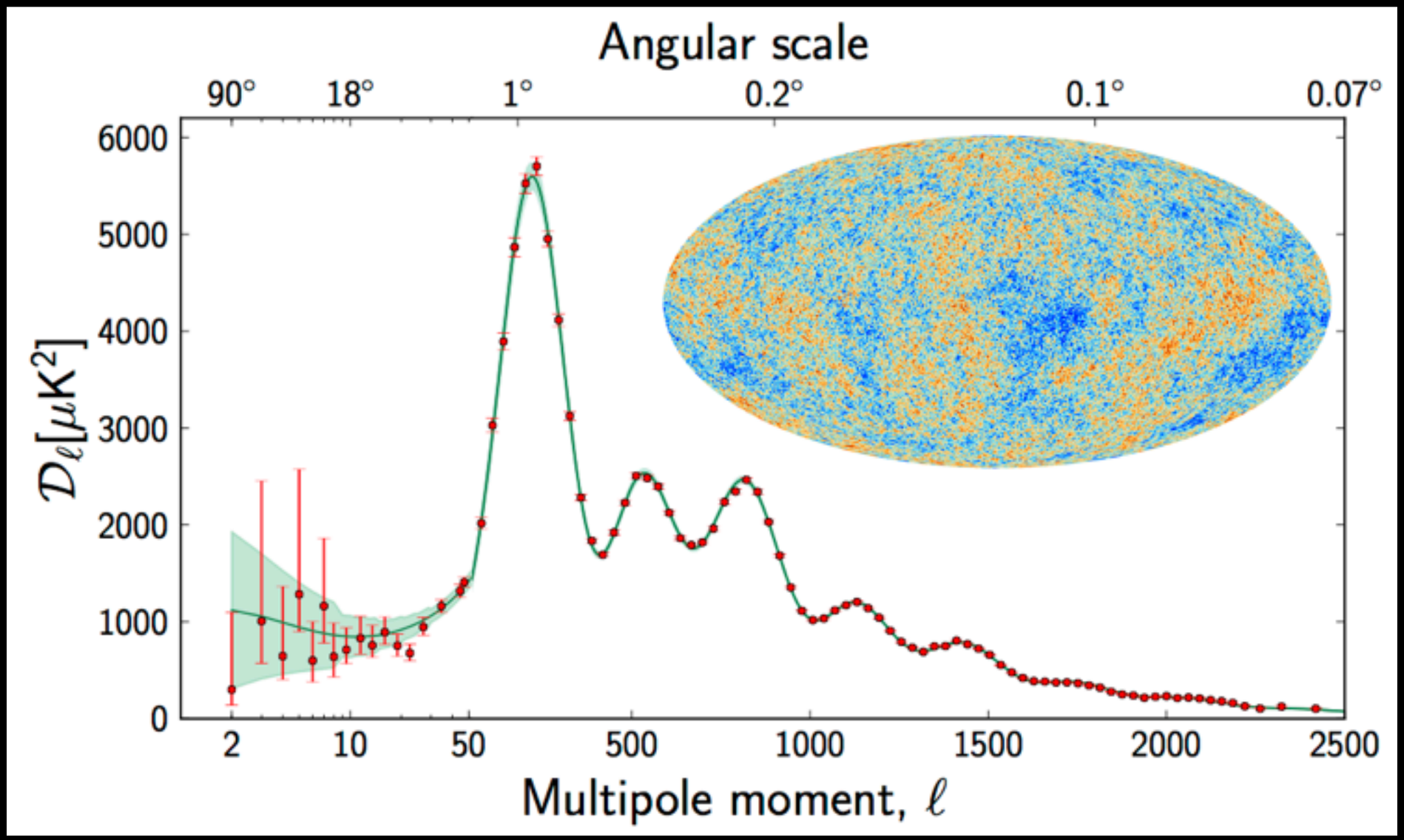
gravitational lensing

~ 85% of total mass passed through without scattering

Image overlay
Hubble & Chandra

Evidence for Dark Matter

CMB Power Spectrum

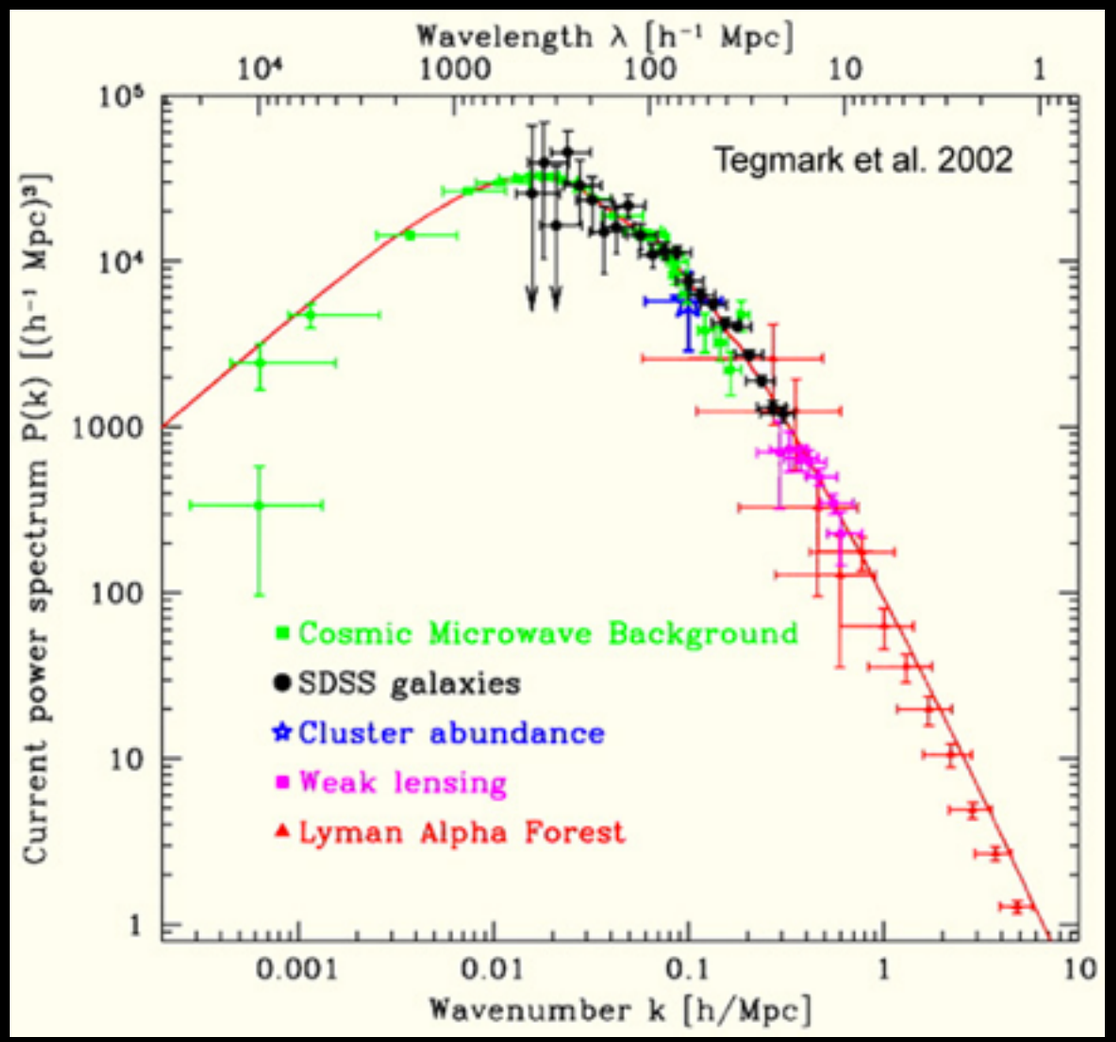


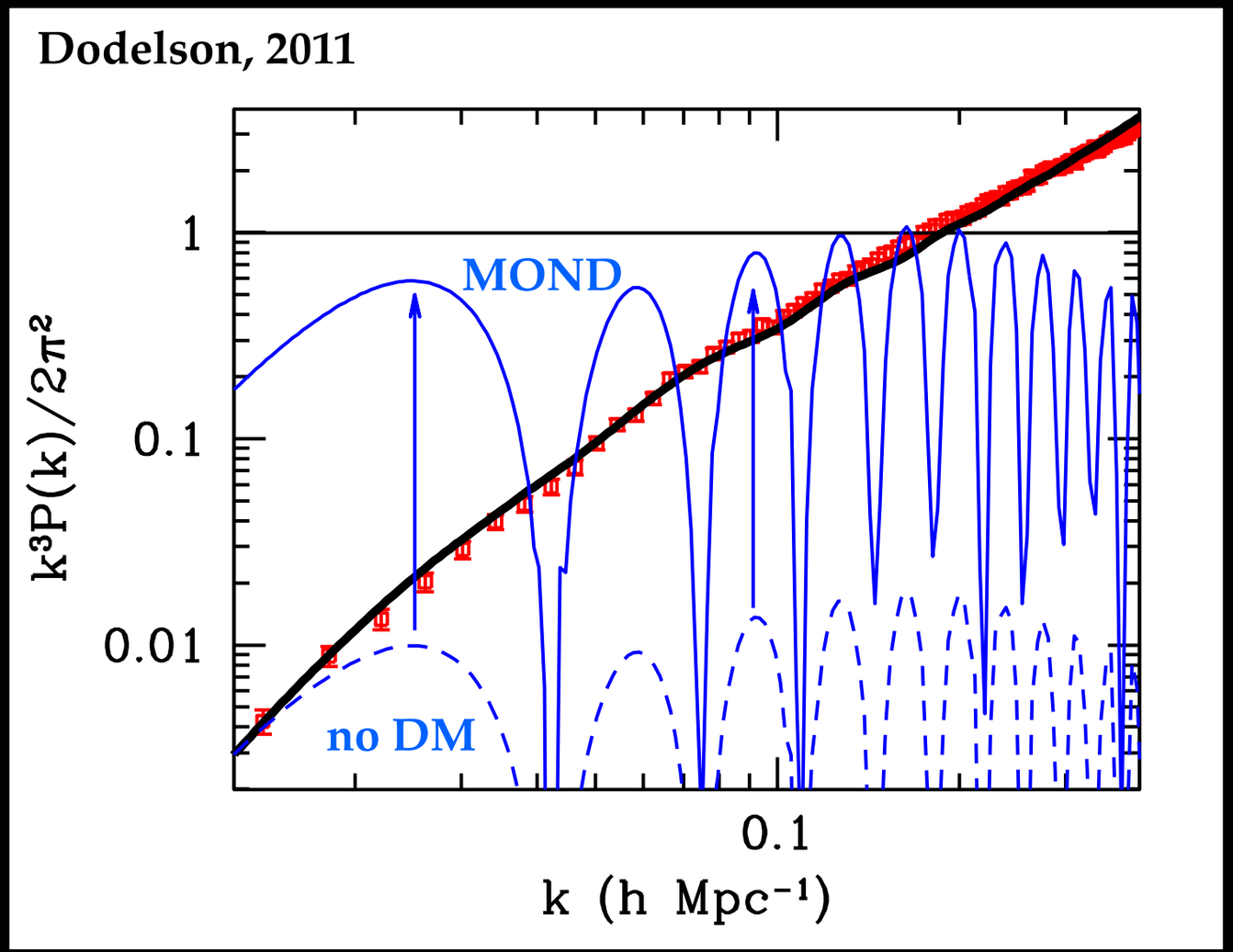
~85% of matter is gravitating, but not exerting pressure

Image:
Planck 2013

Evidence for Dark Matter

Matter Power Spectrum

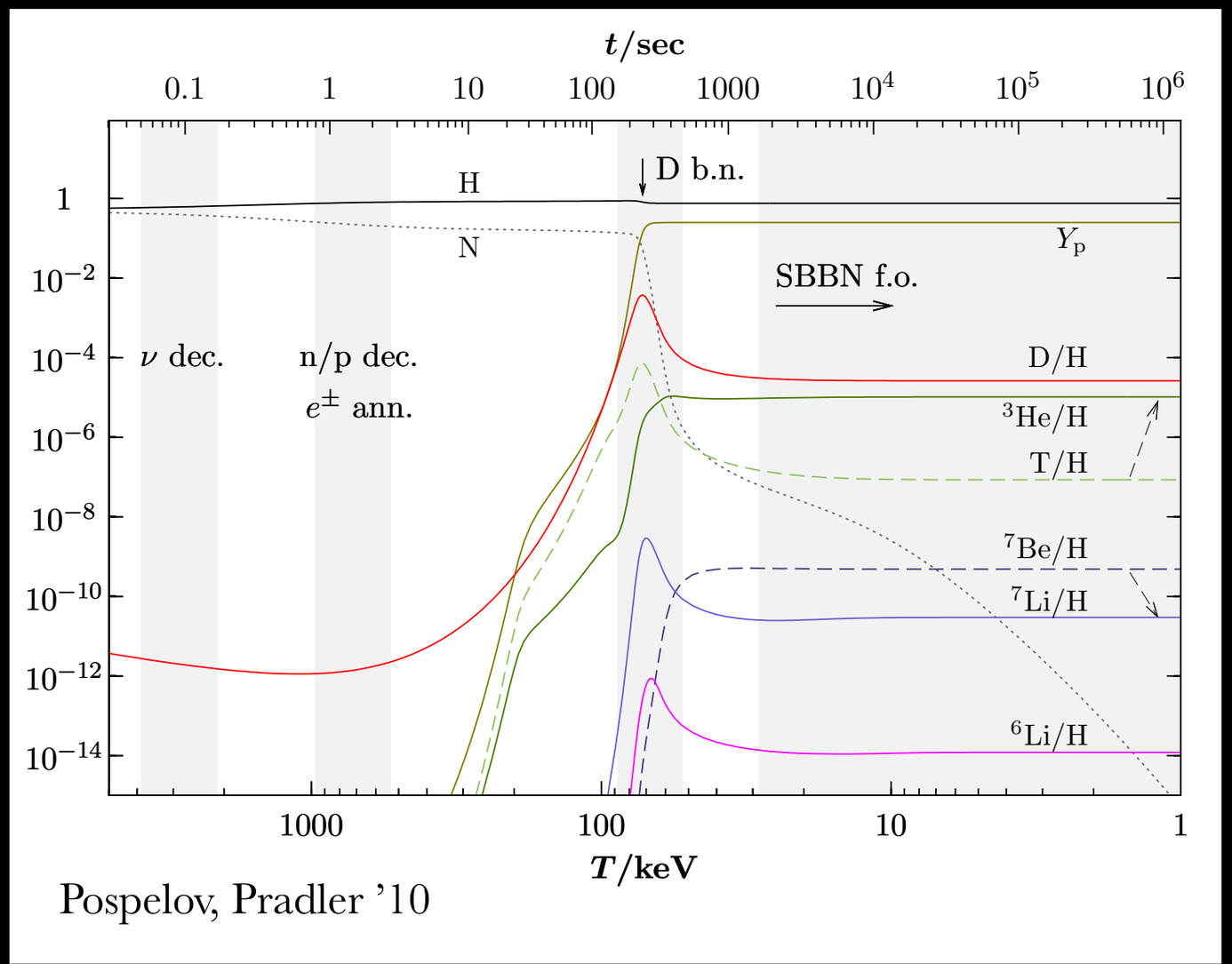




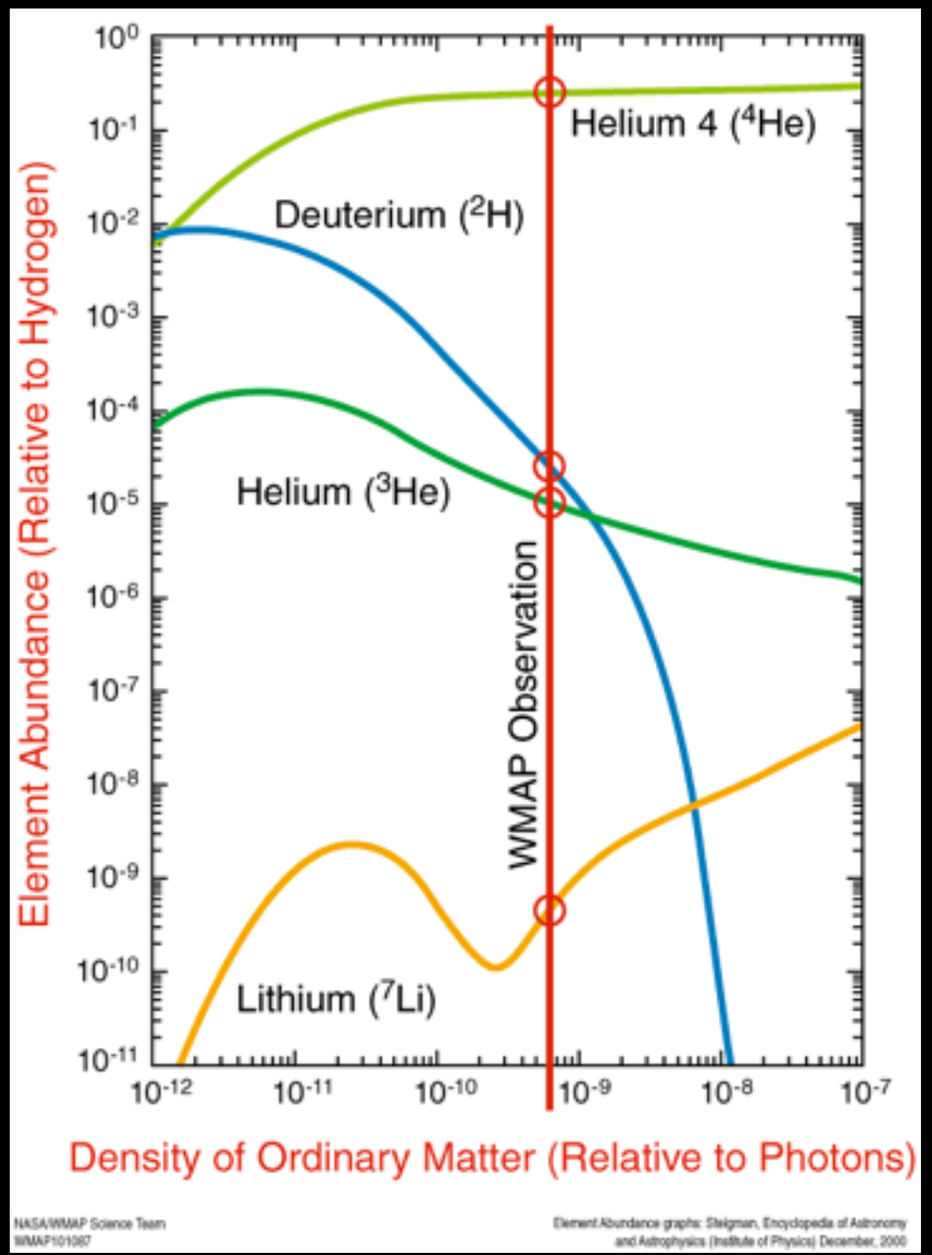
Observation & theory agree with
~85% pressure-less matter, 15% conventional "baryonic"

Evidence for Dark Matter

Light Element Yields @ BBN



Pospelov, Pradler '10



Requires baryon density to be ~ 15% of total

Single parameter theory

$$\Omega_b \equiv \rho_b / \rho_{\rm tot}.$$

Key point: DM can't be SM particles
This counts everything

Impressive Evidence for Dark Matter

Galactic Rotation Curves

Gravitational Lensing

CMB Power Spectrum

Matter Power Spectrum

BBN Element Yields

All consistent with ~ 85 % DM, inconsistent & discrepant without

Independent observations over kpc-Gpc scales spanning ~ 10 Gyr

Overview

- What's the evidence for dark matter?
- How should we think about it?
- Where should we look ... and how?

Historical Comparison

Understanding the Electroweak Sector

Discovery of radioactivity		(1890s)
Fermi Scale identified	$G_F \sim \frac{1}{(100\ \mathrm{GeV})^2}$	(1930s)
Non-Abelian Gauge Theory		(1950s)
Higgs Mechanism Introduced		(1960s)
W / Z bosons discovered		(1970s)
Higgs discovered		(2010s)

Each step required revolutionary theoretical/experimental leaps

$$t \sim 100 \text{ years}$$

How long will we wait for DM?

Discovery of missing mass	(1930s)
Rotation curves	(1970s)
CMB power spectrum	(1990s)
Relevant scale?	**> 2016**

Non-gravitational interactions not guaranteed

No clear target of opportunity

Discovery time frame? $t > 80 \text{ yrs}$

See also:
Hooper & Bertone
1605.04909

DM Prognosis?

Bad news: DM-SM interactions are not obligatory

If nature is unkind, we may never know the right scale

Good news: most *discoverable* DM candidates are in thermal equilibrium with us in the early universe

Why is this good news?

Thermal Equilibrium
Advantage #1: Minimum DM-SM Coupling

Equilibrium (achieved with even a tiny DM/SM coupling)

$$n_{\rm DM}(T) = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \sim T^3$$

Generically overproduces DM

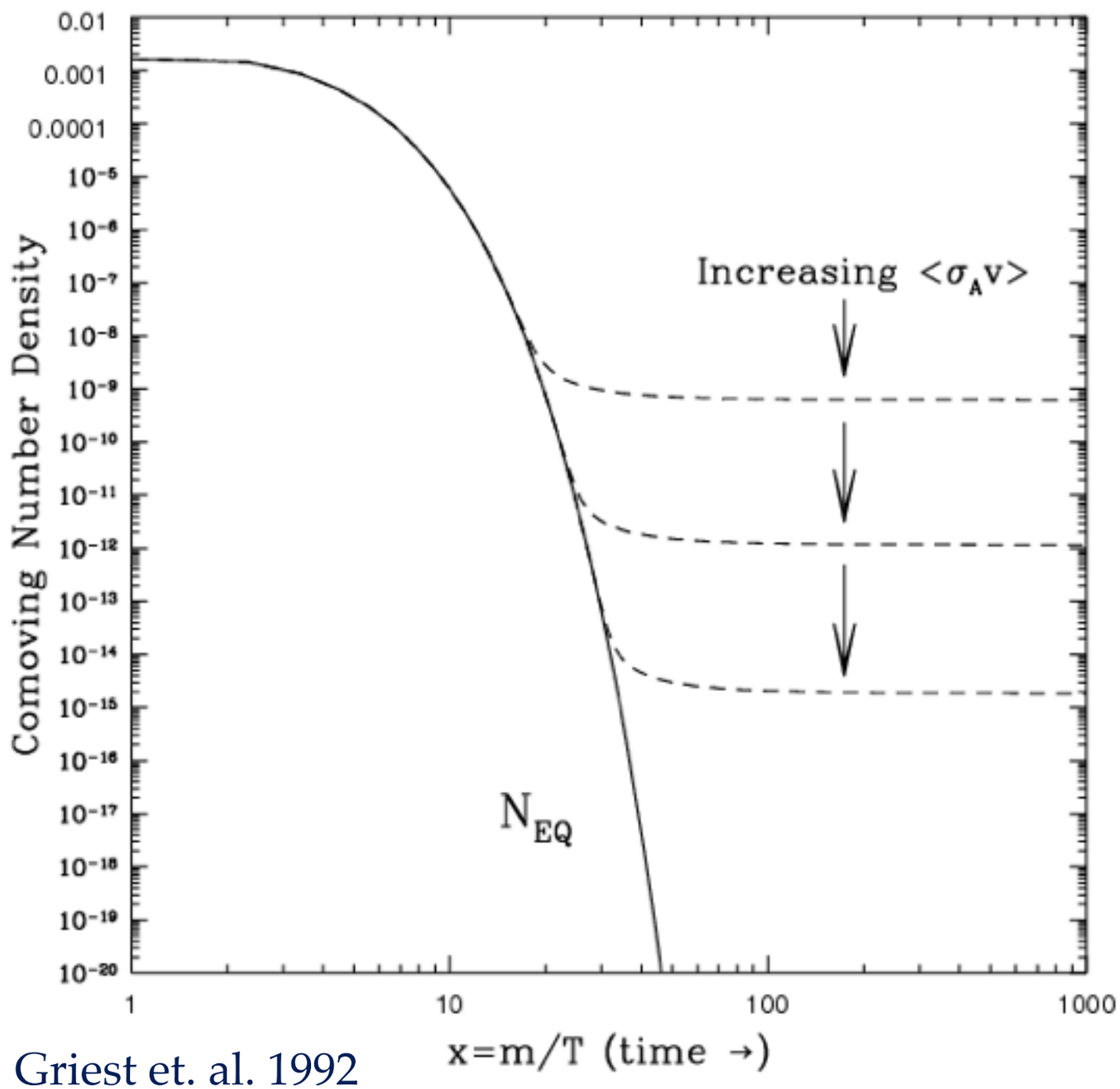
requires *much larger* annihilation cross section to deplete

$$\sigma v \geq \sigma v_{\rm relic} \sim 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

Clear target for discovery/falsification

Thermal Equilibrium
Advantage #1: Minimum DM-SM Coupling

Expansion vs. Annihilation



Griest et. al. 1992

Symmetric DM

total abundance is correct for

$$\sigma v_{\rm relic} \approx 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

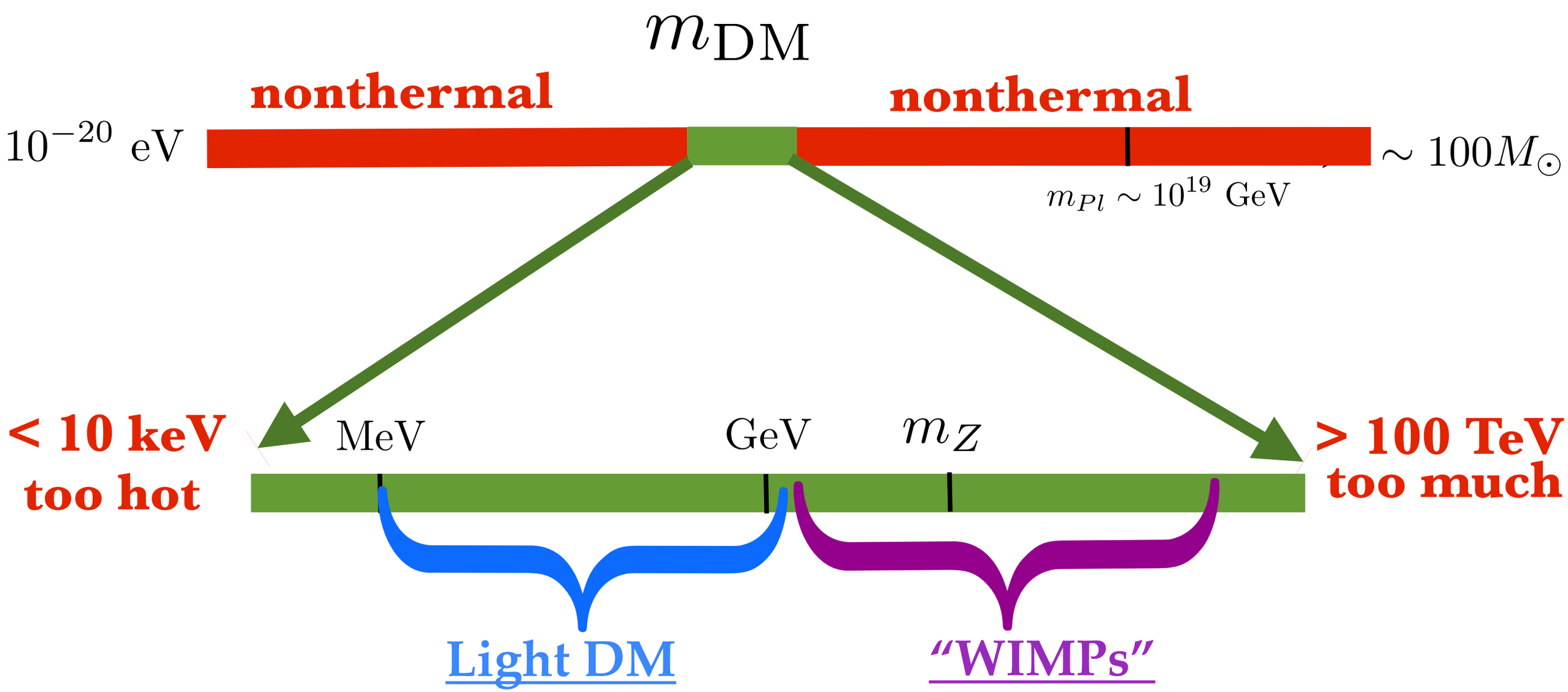
Asymmetric DM:

Just needs to deplete antiparticles

$$\sigma v > 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

can be bigger, but not smaller

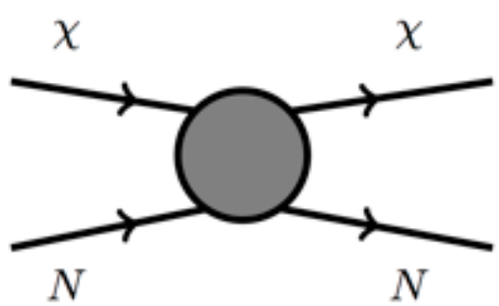
Thermal Equilibrium
Advantage # 2: Narrows Mass Range

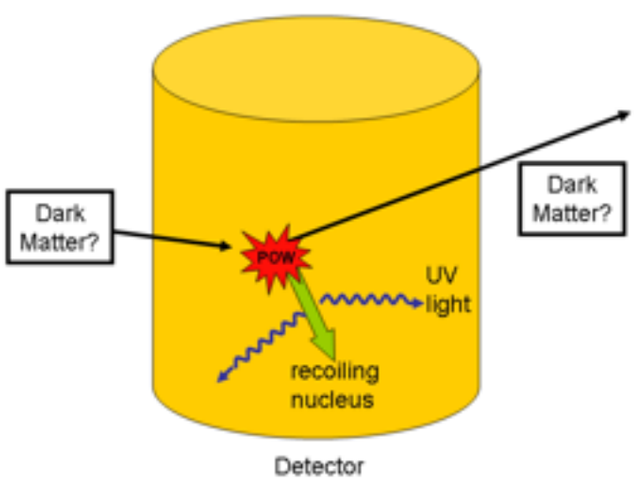


Direct Detection (Alan Robinson)
Indirect Detection (Alex Drlica-Wagner)
Colliders (Yang Bai)

How to look for "WIMPs"

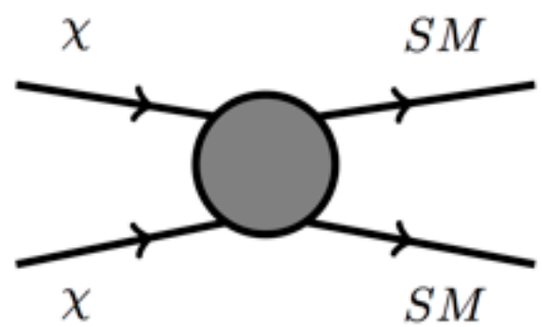
Direct Detection





Goodman, Witten 1984

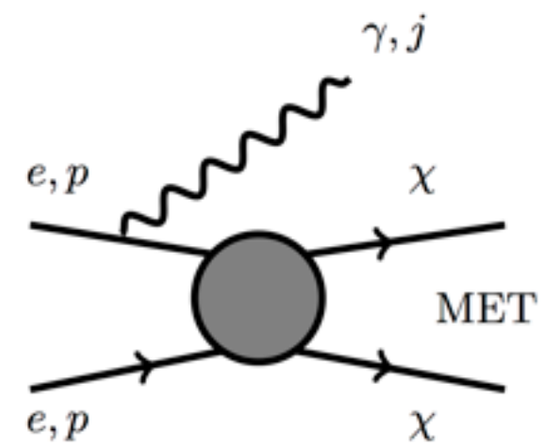
Indirect Detection

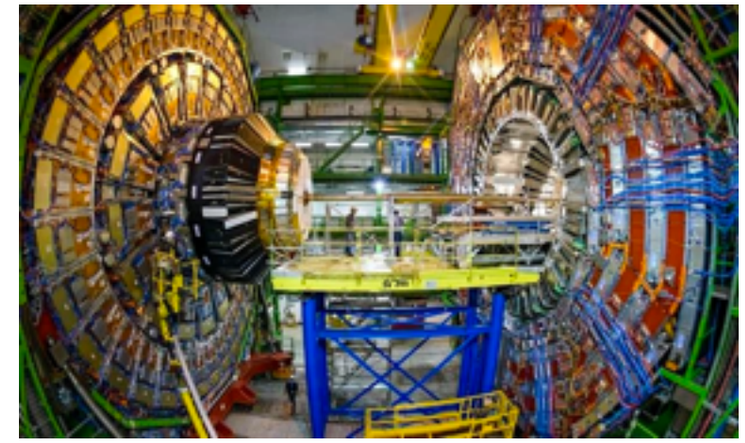


Fermi Telescope

Gunn, **Lee**, Lerche, **Schramm**, Steigman, Stecker 1978

Colliders

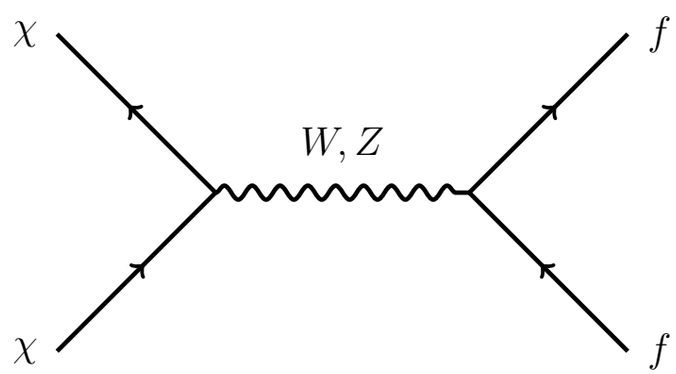




Bai, Fox, Harnik
Goodman, Ibe, Rajaraman, Shepherd, **Tait**, Yu 2010

WIMPs vs. LDM
Light needs new forces

WIMP DM can yield right abundance w/ SM gauge bosons



$$\sigma v \sim \frac{\alpha_W^2 m_\chi^2}{m_Z^4} \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

for $m_\chi \sim$ TeV

For LDM, annihilation via SM forces is too weak

$$m_\chi \sim \mathrm{GeV} \implies \sigma v \ll 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

LDM overproduced unless there are also light, new "mediators"

What kinds of new forces?

Must be SM singlet, options limited by SM gauge invariance

Higgs Portal
Scalar mediator ϕ
(mixes w/ SM Higgs)

$$(H^\dagger H)|\phi^\dagger \phi|$$

couplings scale with mass

Vector Portal
"dark photon" A'
(mixes w/ SM photon)

$$\epsilon\, F_{\mu\nu} F'_{\mu\nu}$$

couplings scale with charge

What kinds of new forces?

Must be SM singlet, options limited by SM gauge invariance

Higgs Portal
Scalar mediator ϕ
(mixes w/ SM Higgs)

$$\lambda\,(H^\dagger H)|\phi^\dagger\phi|$$

much more constrained
GK, arXiv:1512.04119

Vector Portal
"dark photon" A'
(mixes w/ SM photon)

$$\epsilon\, F_{\mu\nu}F'_{\mu\nu}$$

***A'* coupling to SM**

$$\epsilon e$$

***A'* coupling to DM**

$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$

Q: Are there any others?
A: Yes, but very similar

Also mediators that gauge anomaly free subset of SM quantum numbers

$U(1)_{B-L}$

$U(1)_{e-\mu}$

$U(1)_{e-\tau}$

Similar to dark photon but also couple to neutrinos

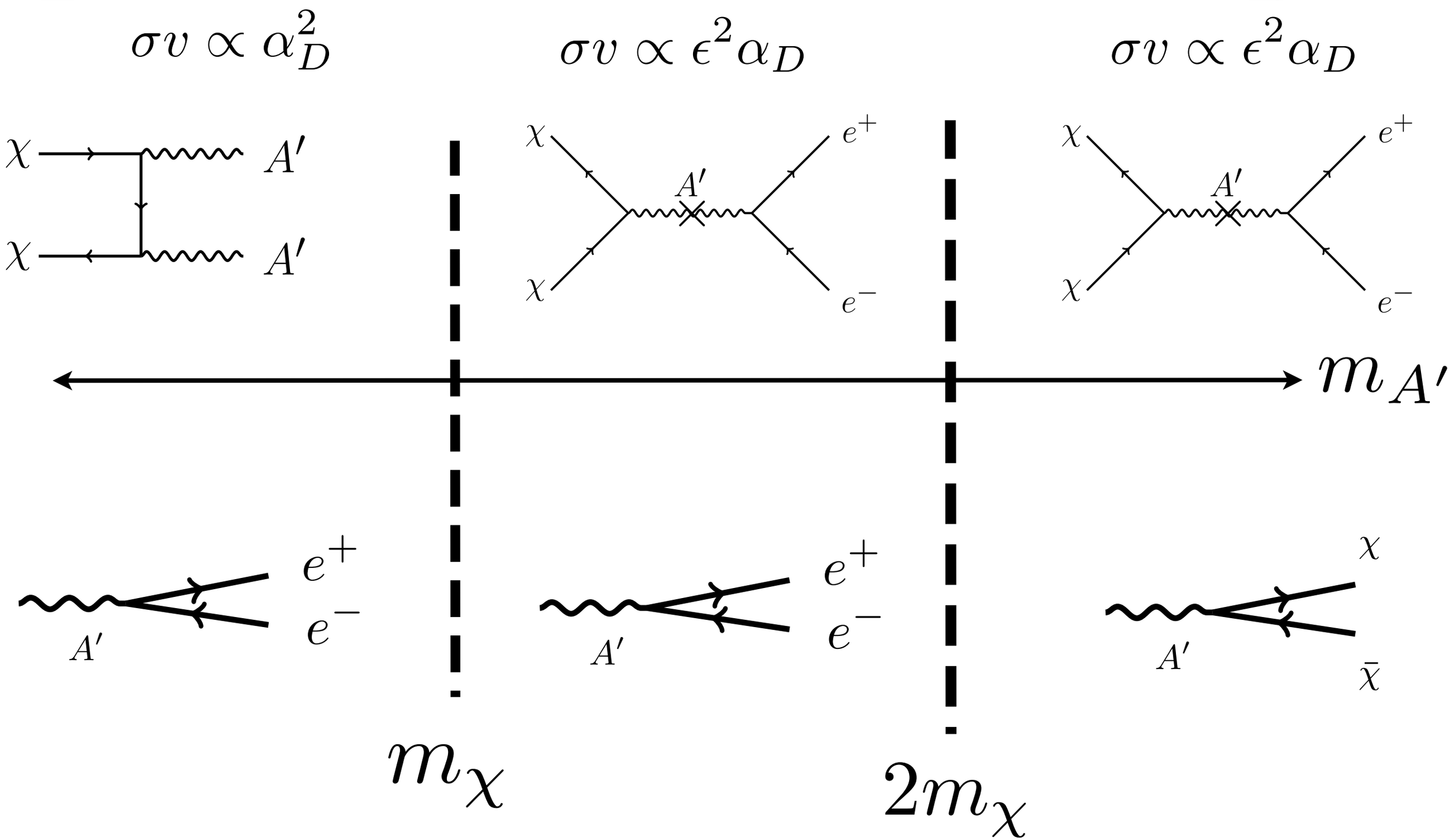
$U(1)_{\mu-\tau}$

electron coupling @ loop level
Harder to test

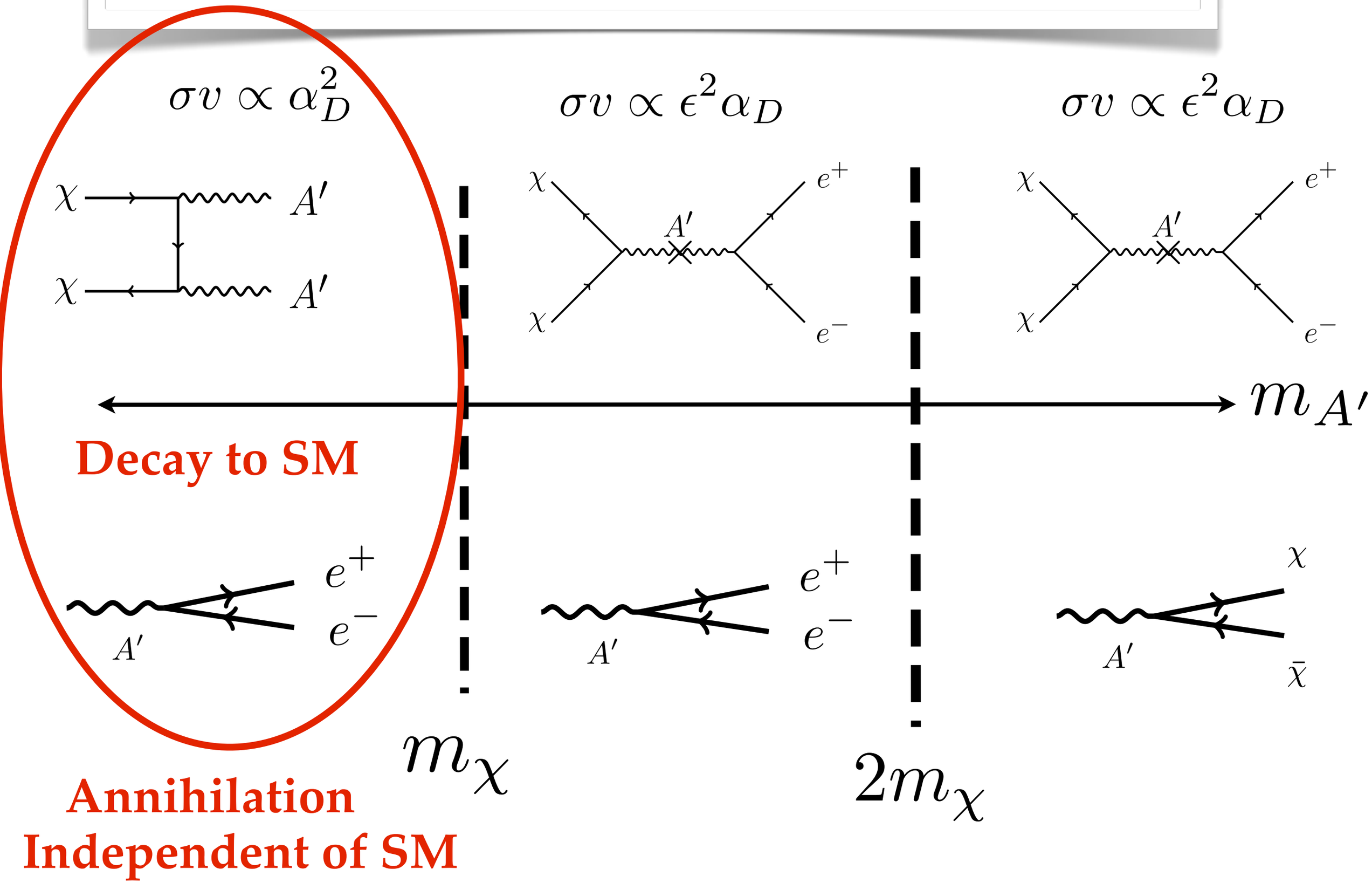
These are the only choices !

(unless we add more SM charged stuff, i.e. 2HDM, anomalons...)

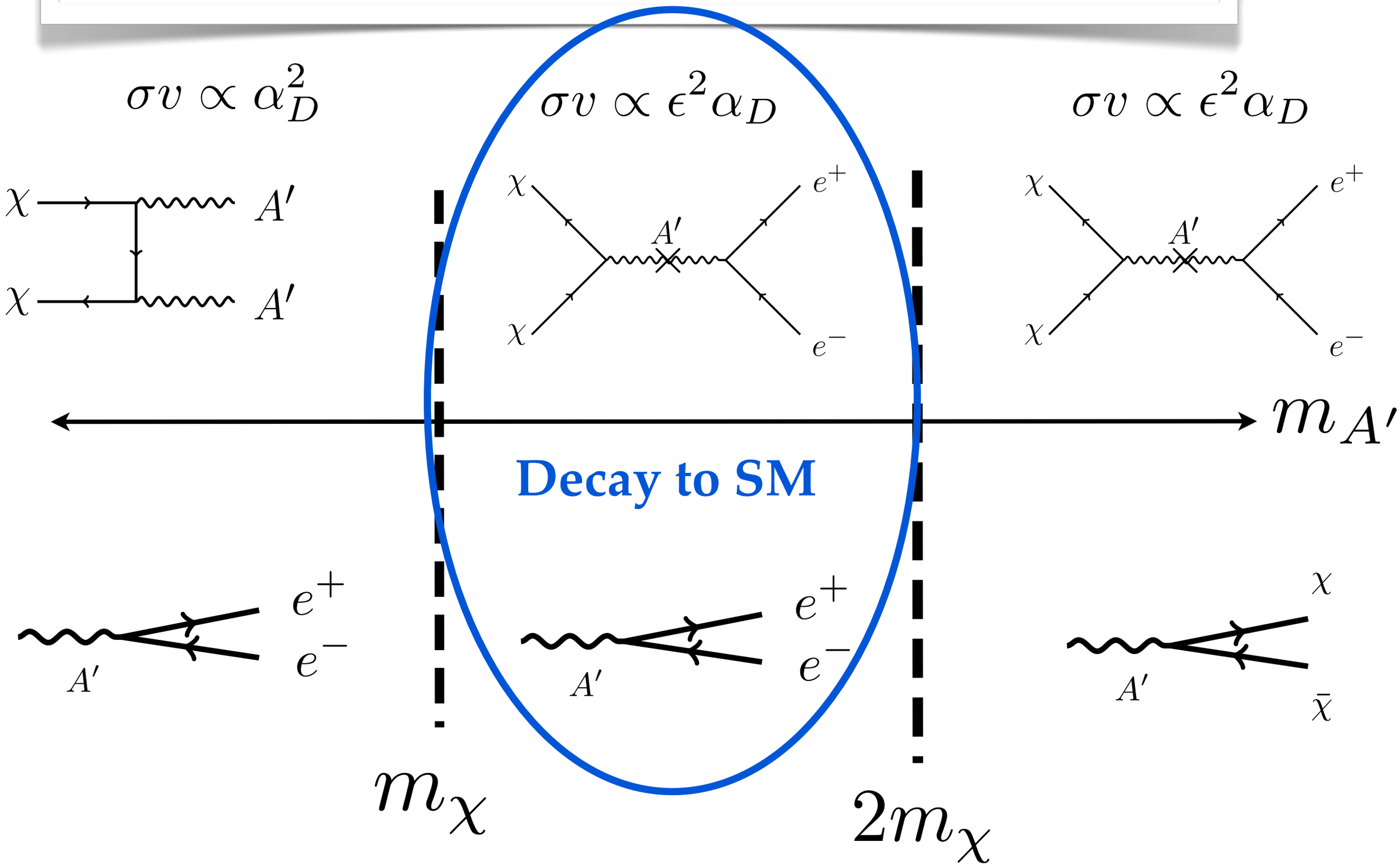
Mediator vs. DM Masses



Mediator vs. DM Masses

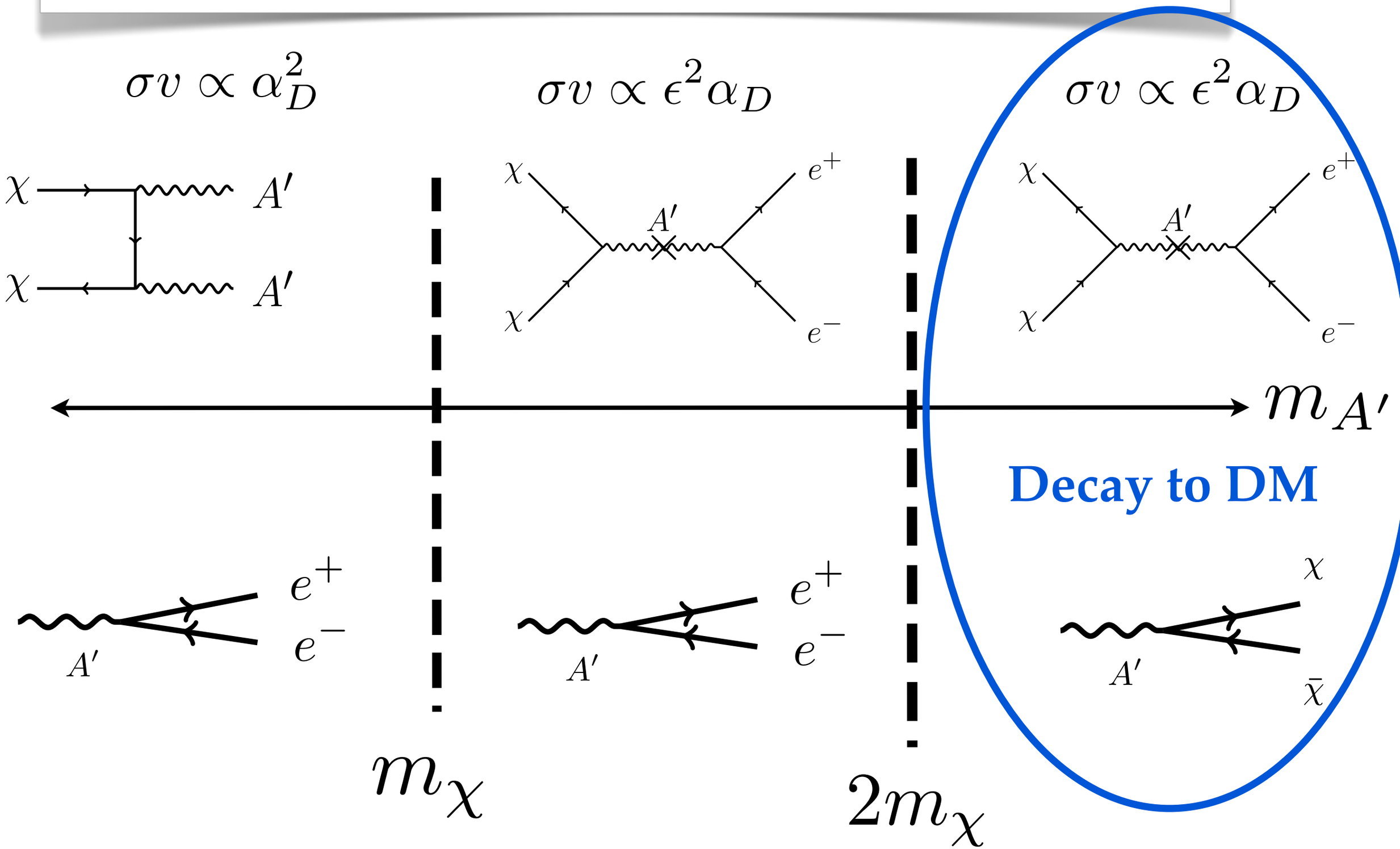


Mediator vs. DM Masses



Annihilation requires SM-*A′* coupling: *decisively testable*

Mediator vs. DM Masses



Annihilation requires SM-*A′* coupling: ***decisively testable***

Overview

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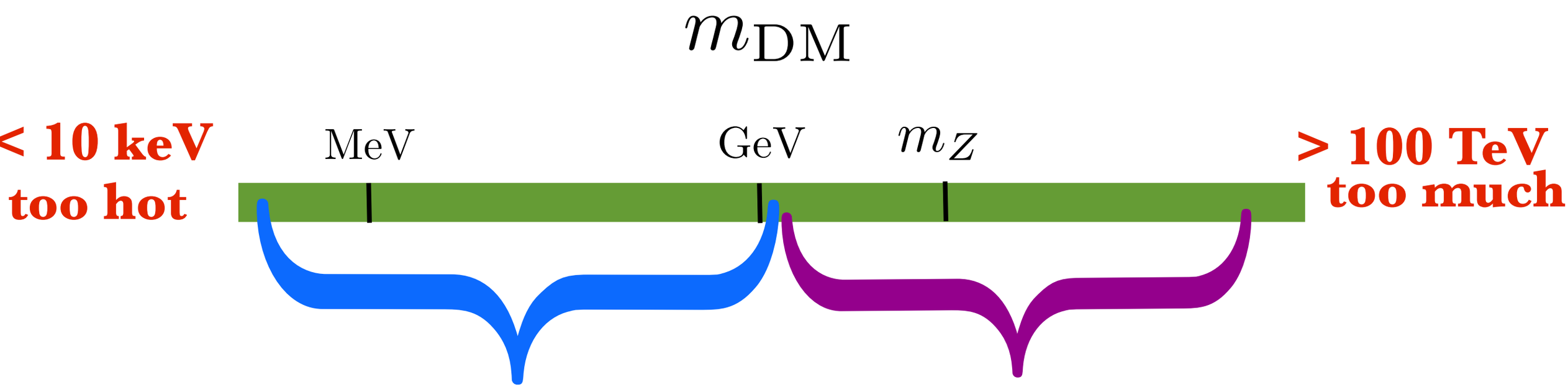
- How should we think about it?
- Where else should we look ... and how?

Emerging Search Program for Testing Light Thermal DM



Light DM ("LDM")

Electron Direct Detection

Electron Fixed Targets

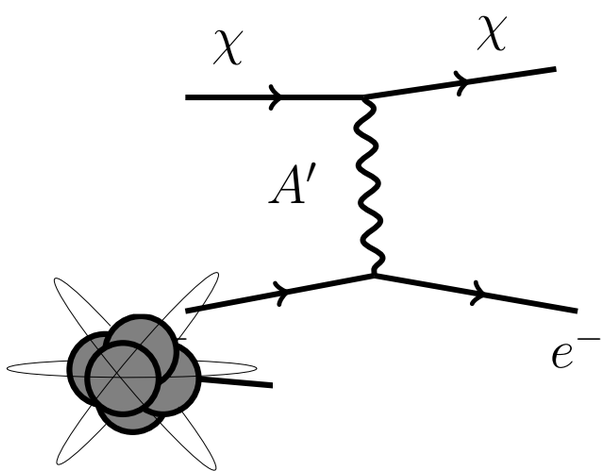
Neutrino Factories

B-Factories

"WIMPs"

Electron Direct Detection: Ionization

Scatter off atomic electrons



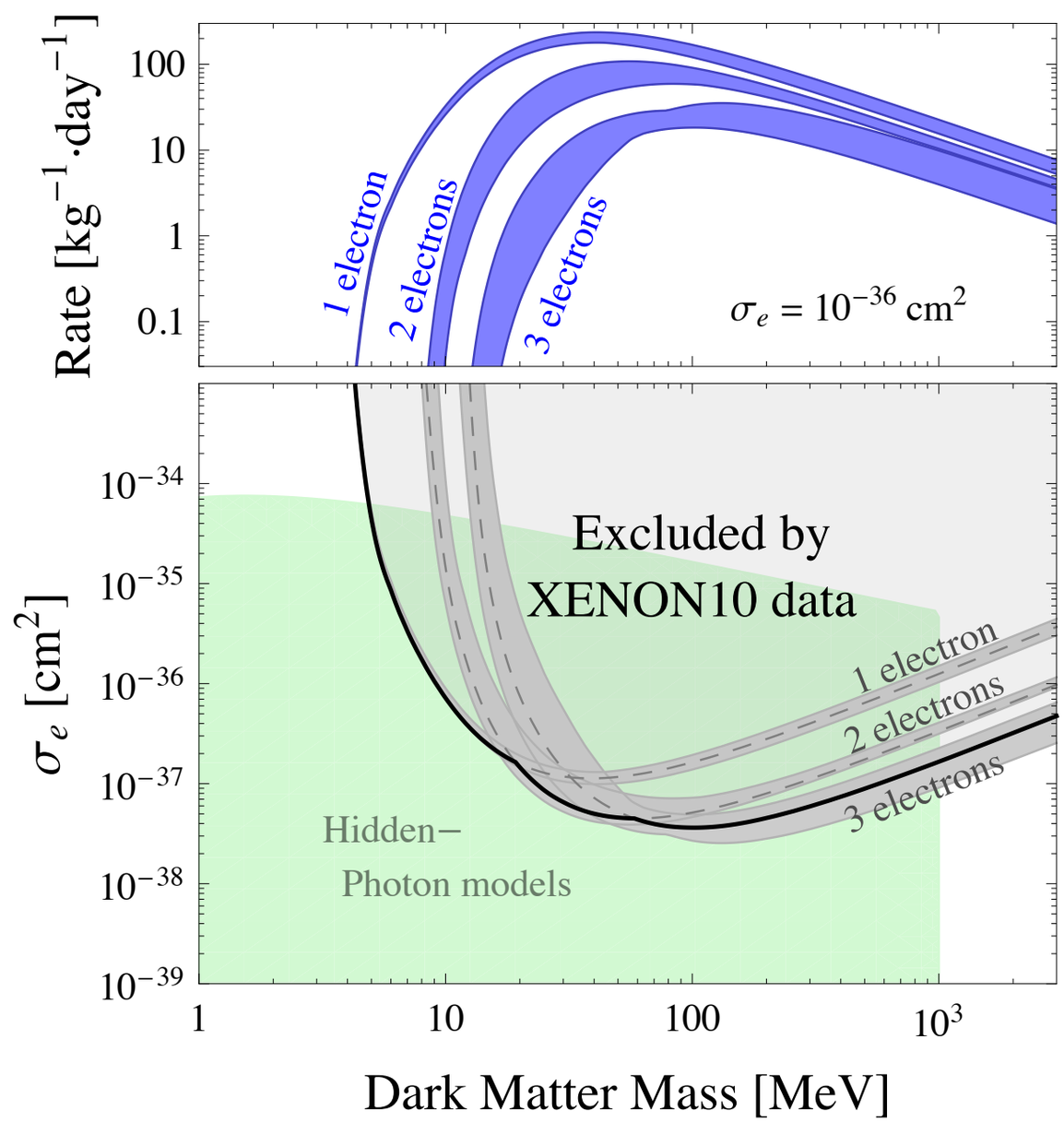
Needs atomic form factor

$$\frac{d\langle\sigma_{ion}^{nl} v\rangle}{d\ln E_{\rm er}} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\left|f_{ion}^{nl}(k',q)\right|^2\left|F_{\rm DM}(q)\right|^2\eta(v_{\rm min})\,dq$$

Best for visibly decaying dark photons

$$m_{A'} \ll m_\chi \to \sigma_e \propto q^{-2} \sim \frac{1}{m_e^2 v^2}$$

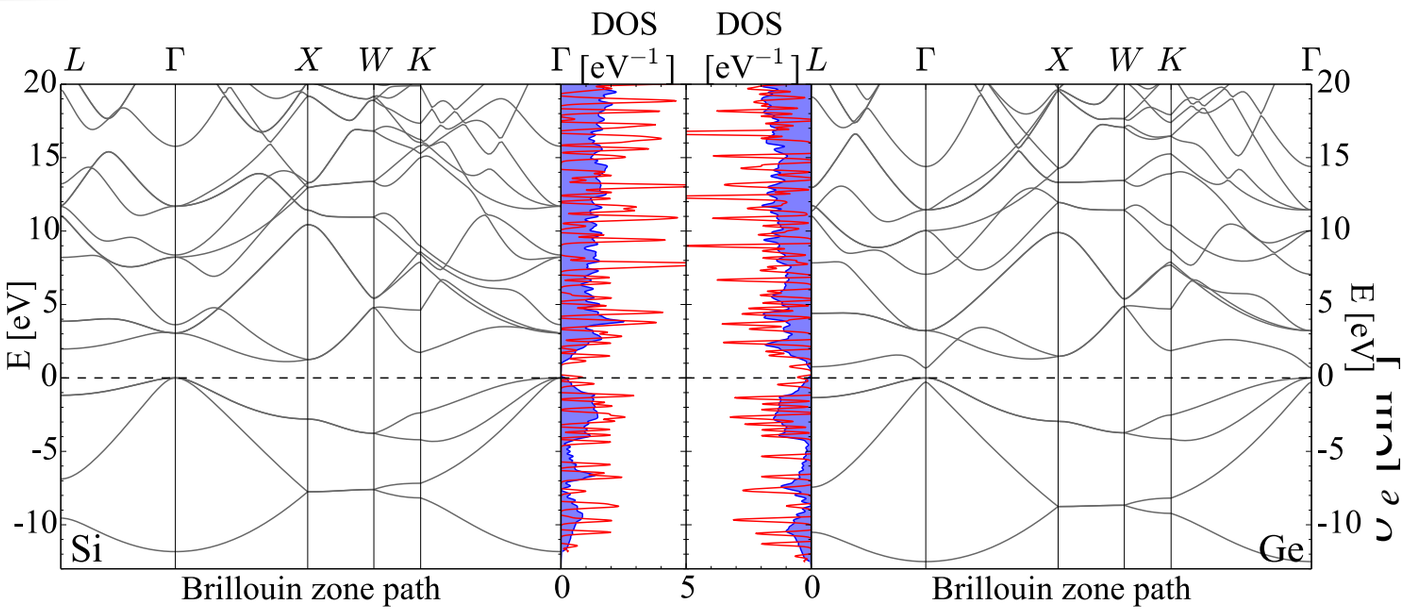
(Stay tuned for Xenon 100)

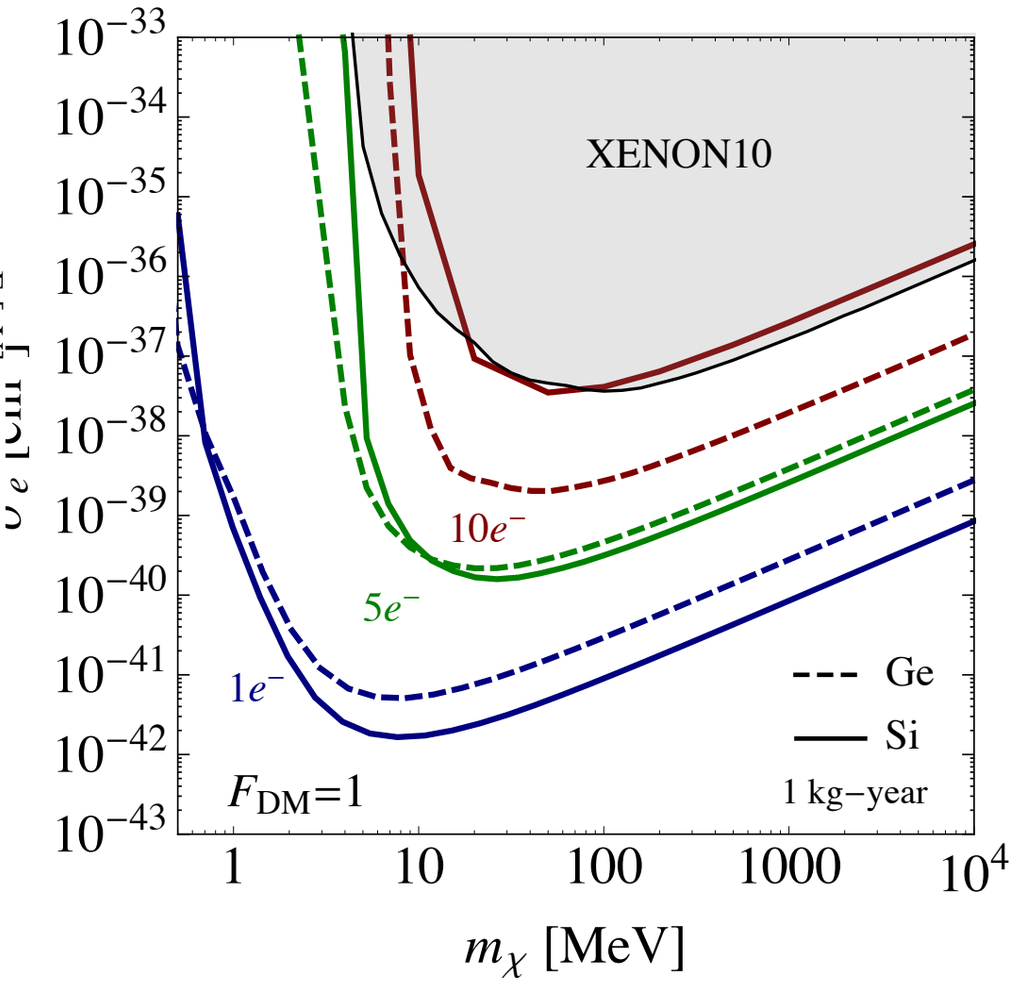


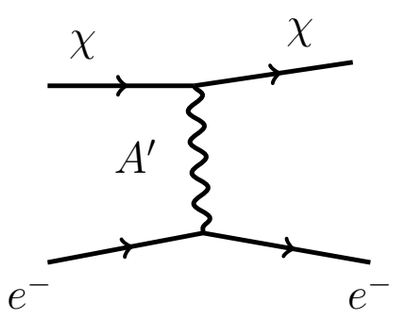
Essig, Mardon, Volansky

arXiv: 1108.5383 1206.2664

Electron Direct Detection: Semiconductors







$$\Delta E_{\text{band gap}} \sim \mathcal{O}(\text{eV})$$

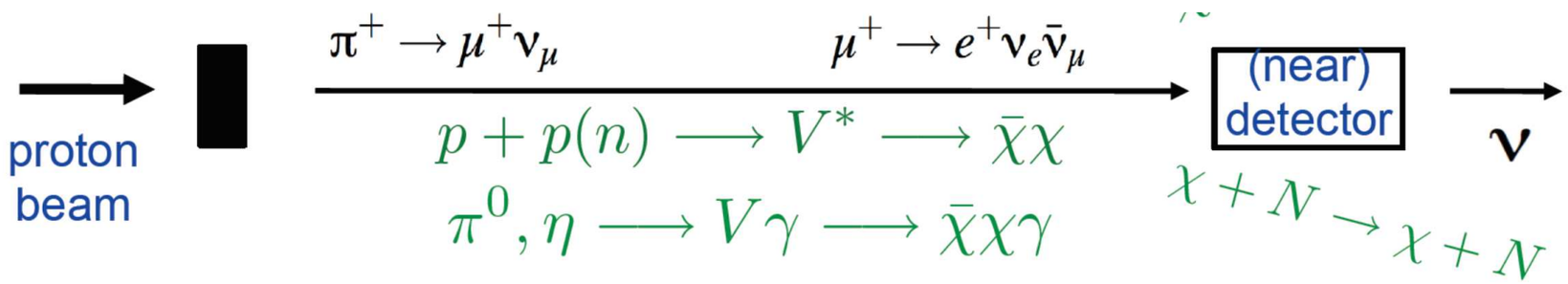
Essig, Fernandez-Serra, Mardon, Soto.Volansky,Yu 1509.01598

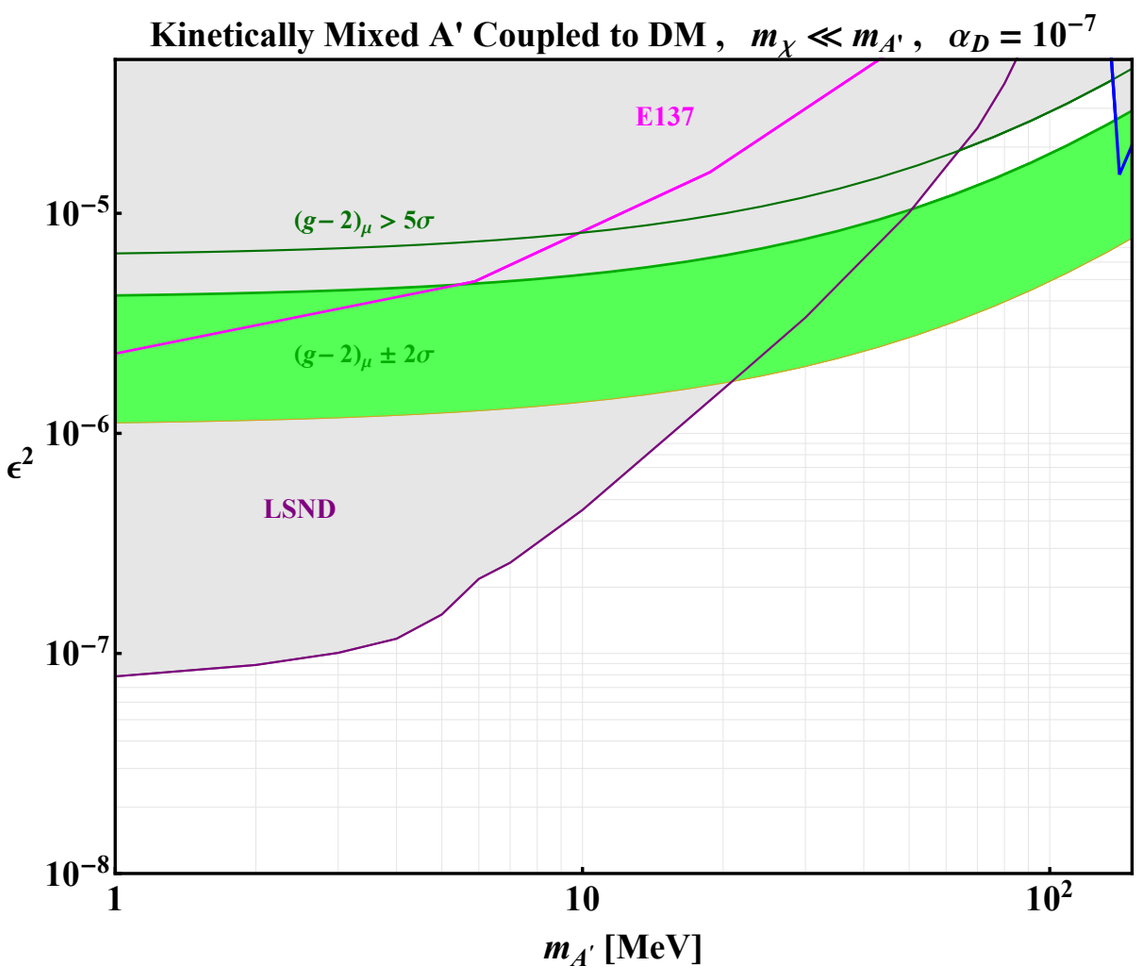
Best for visibly decaying dark photons

$$m_{A'} \ll m_\chi \to \sigma_e \propto q^{-2} \sim \frac{1}{m_e^2 v^2}$$

Awesome potential, but BG poorly understood (R&D in progress)

Neutrino Factories: Proton Fixed Targets





de Niverville, Pospelov, Ritz

arXiv:1107.4580

LDM produced in p-beam dump

Scatters in near detector

Contributes to NC searches

(see Ranjan Dhramapalan's Talk)

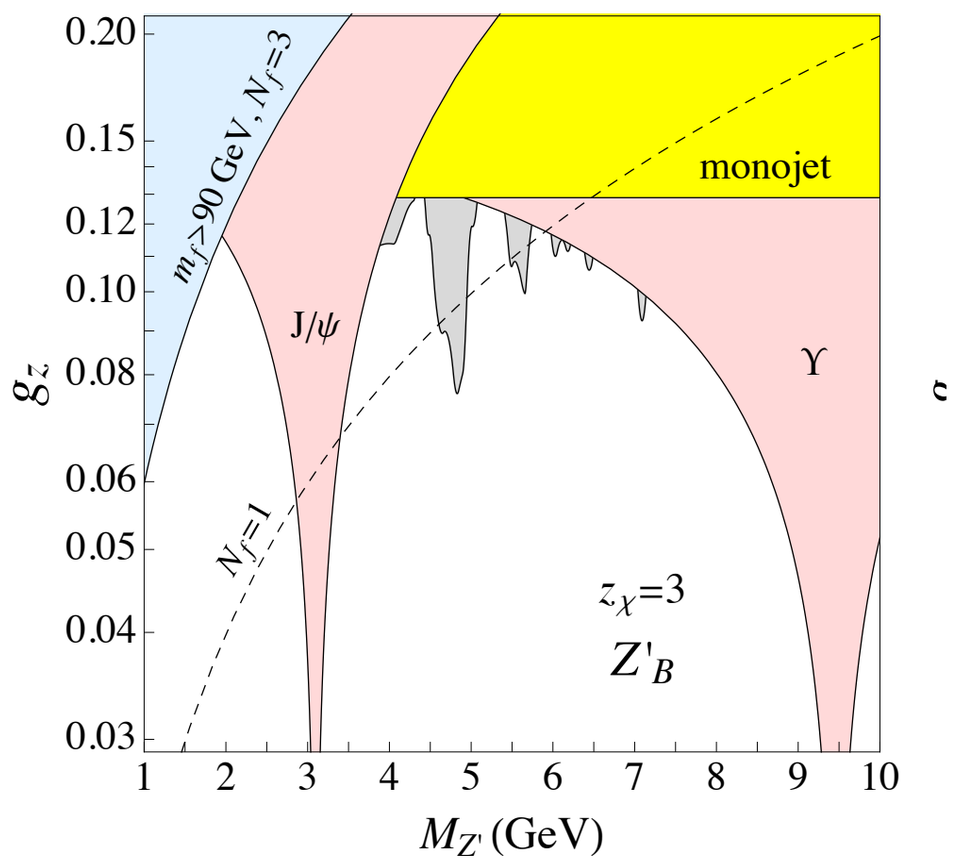
Neutrino Factories: Proton Fixed Targets

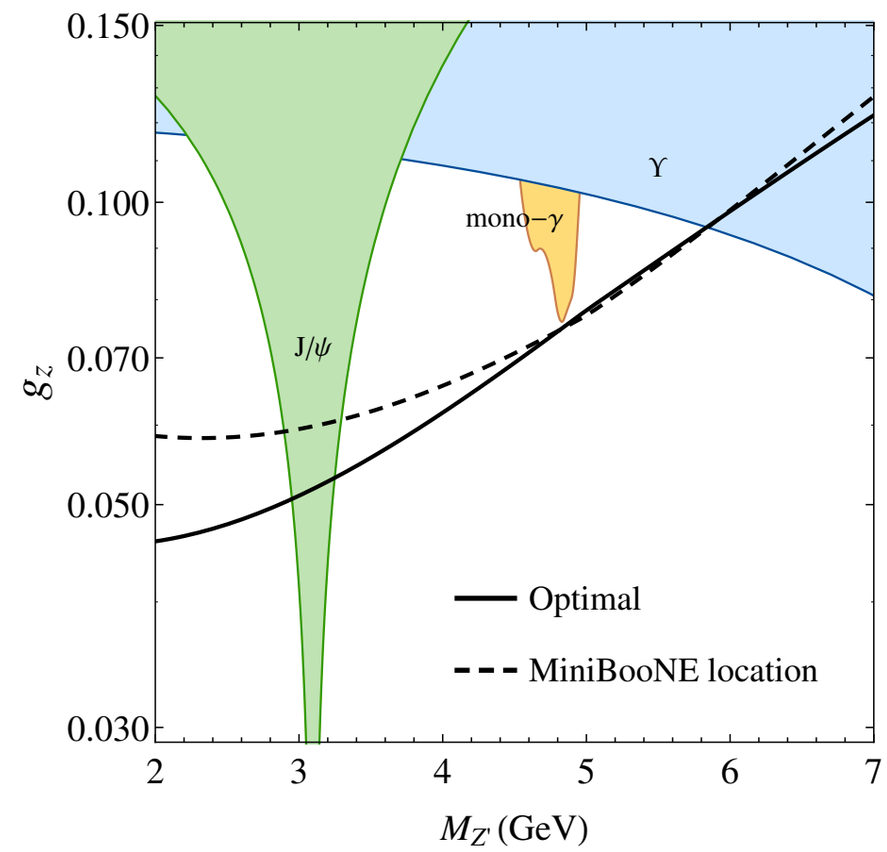
Light DM: production in Main Injector, scattering at NOνA

Dobrescu, Frugiuele arXiv: 1401.1566

Light DM beam @ LBNF

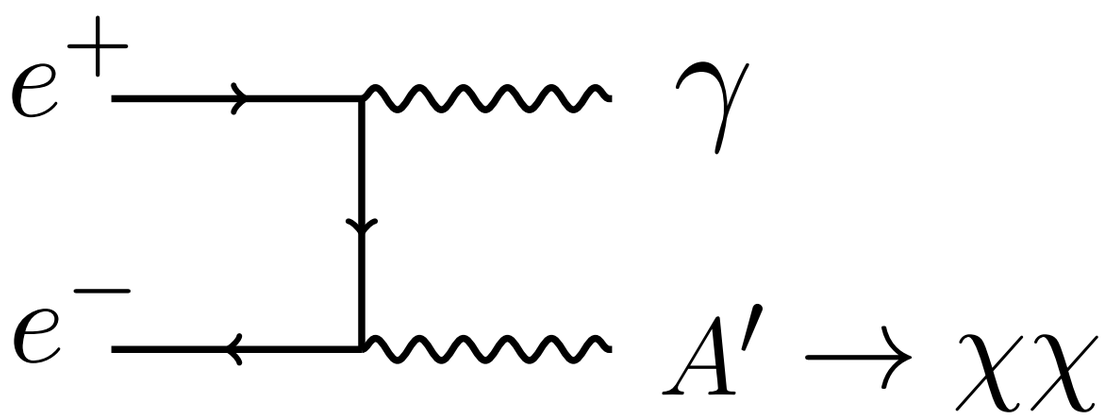
Coloma, Dobrescu, Frugiuele, Harnik arXiv: 1512.03852

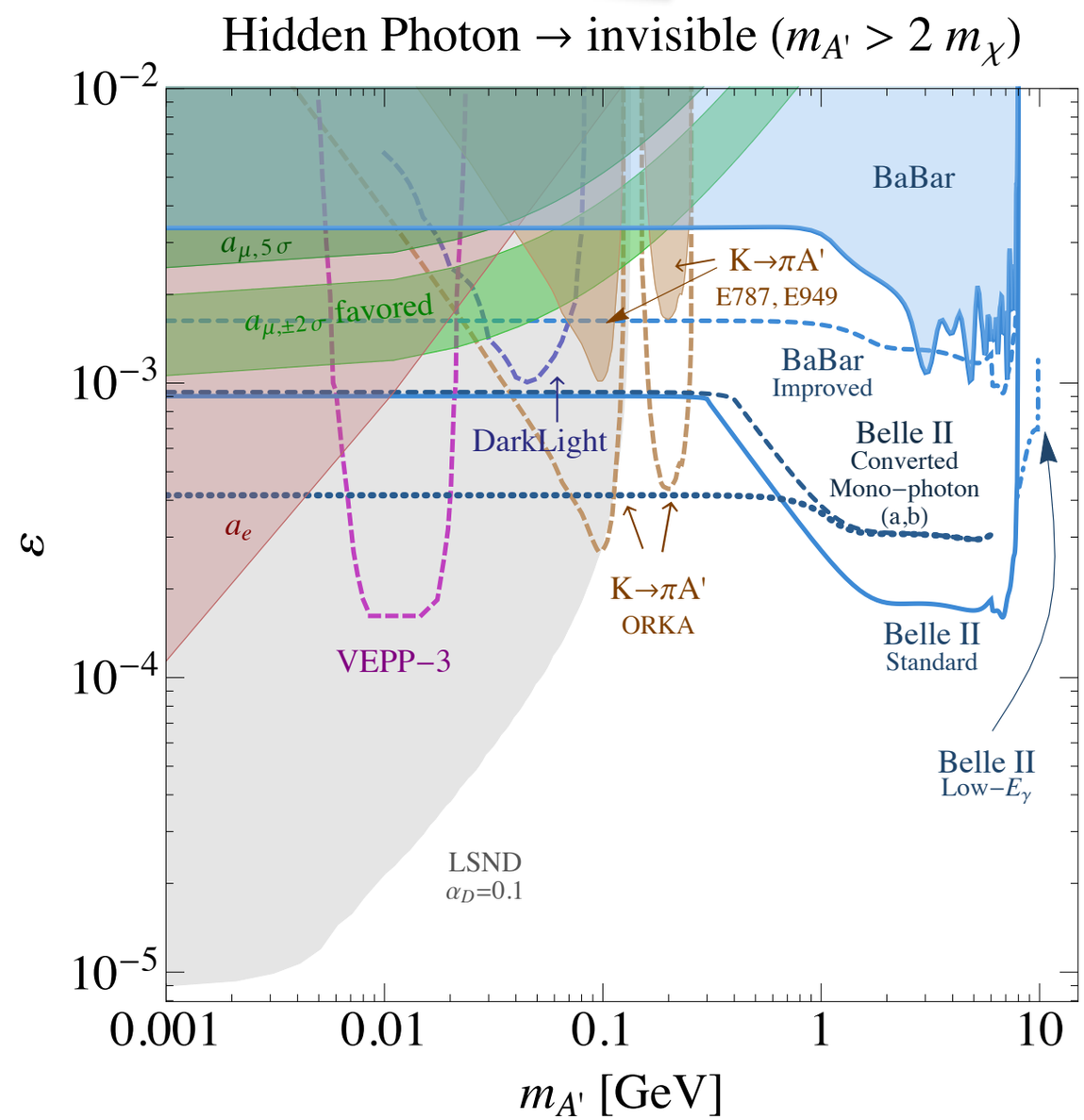




Leptophobic DM coupled to light *Z'*

B Factories: BaBar/Belle II





"Traditional" collider missing energy search

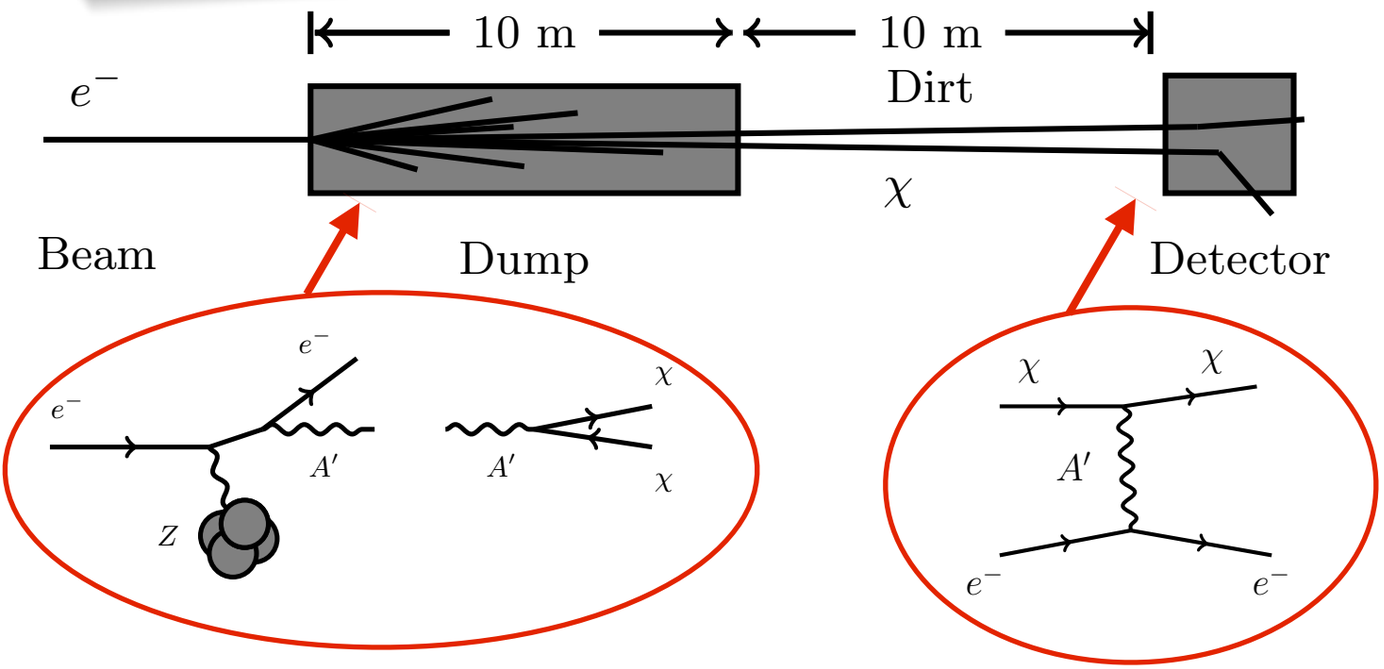
High luminosity ~ 50/ab

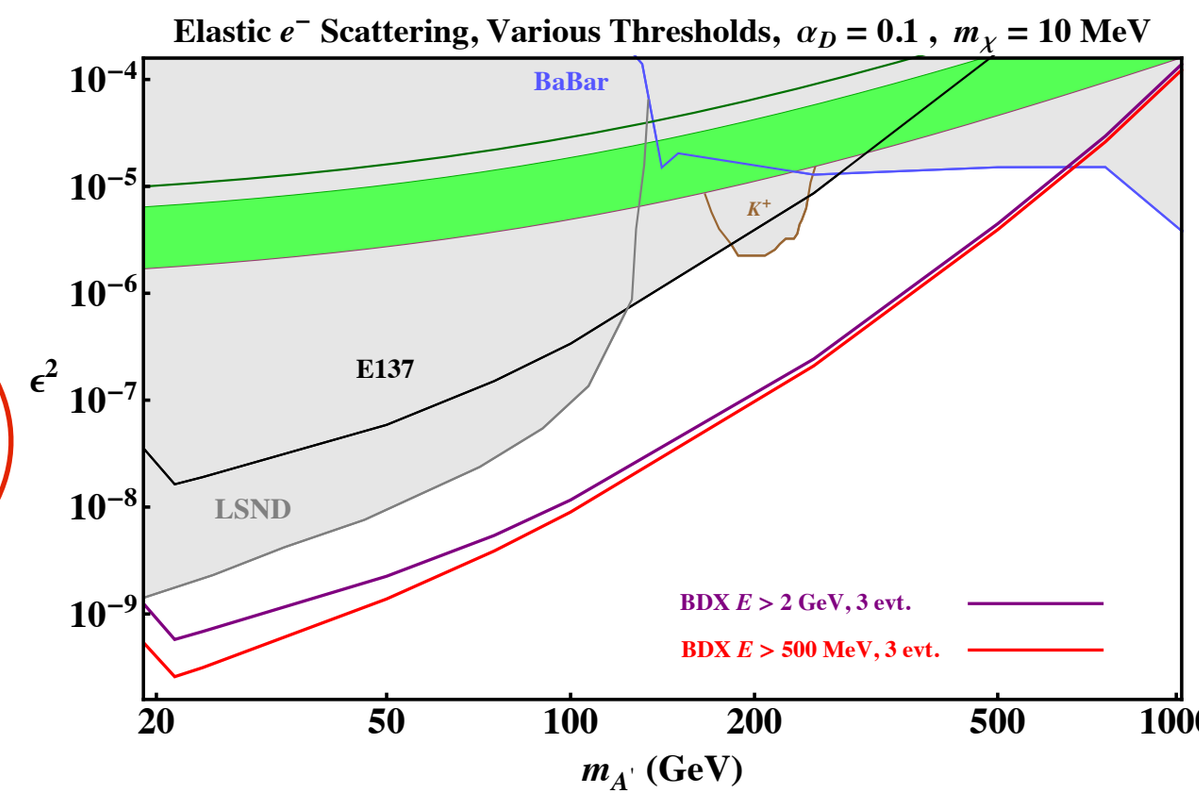
Belle-II reach requires monphoton trigger

Essig, Mardon, Papucci, Volansky, Zhong

arXiv:1309.5084

Electron Fixed Target: Beam Dump





Relativistic DM production & scattering
Best for "dark photons" decaying to DM

$$m_{A'} > 2m_\chi$$

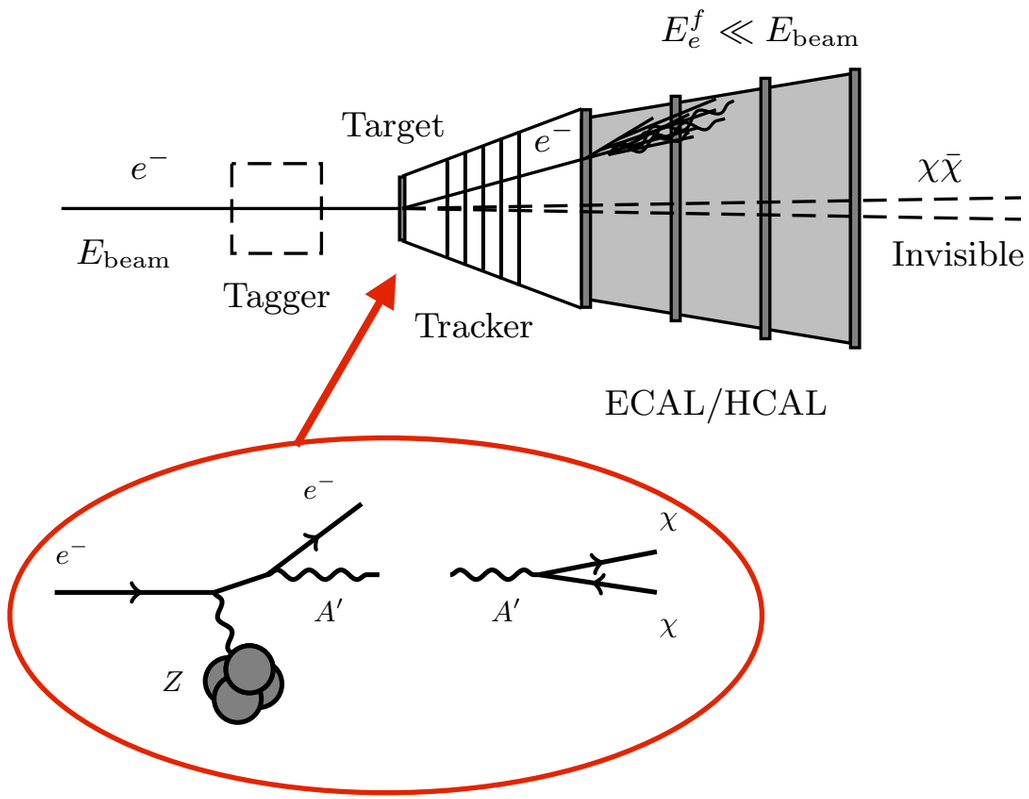
E ~ 10 GeV @ Jefferson Lab (or SLAC)
High intensity 100 mA ~ 1E22 e/yr
Possible cosmic BG*
Tiny beam BG
Real discovery potential

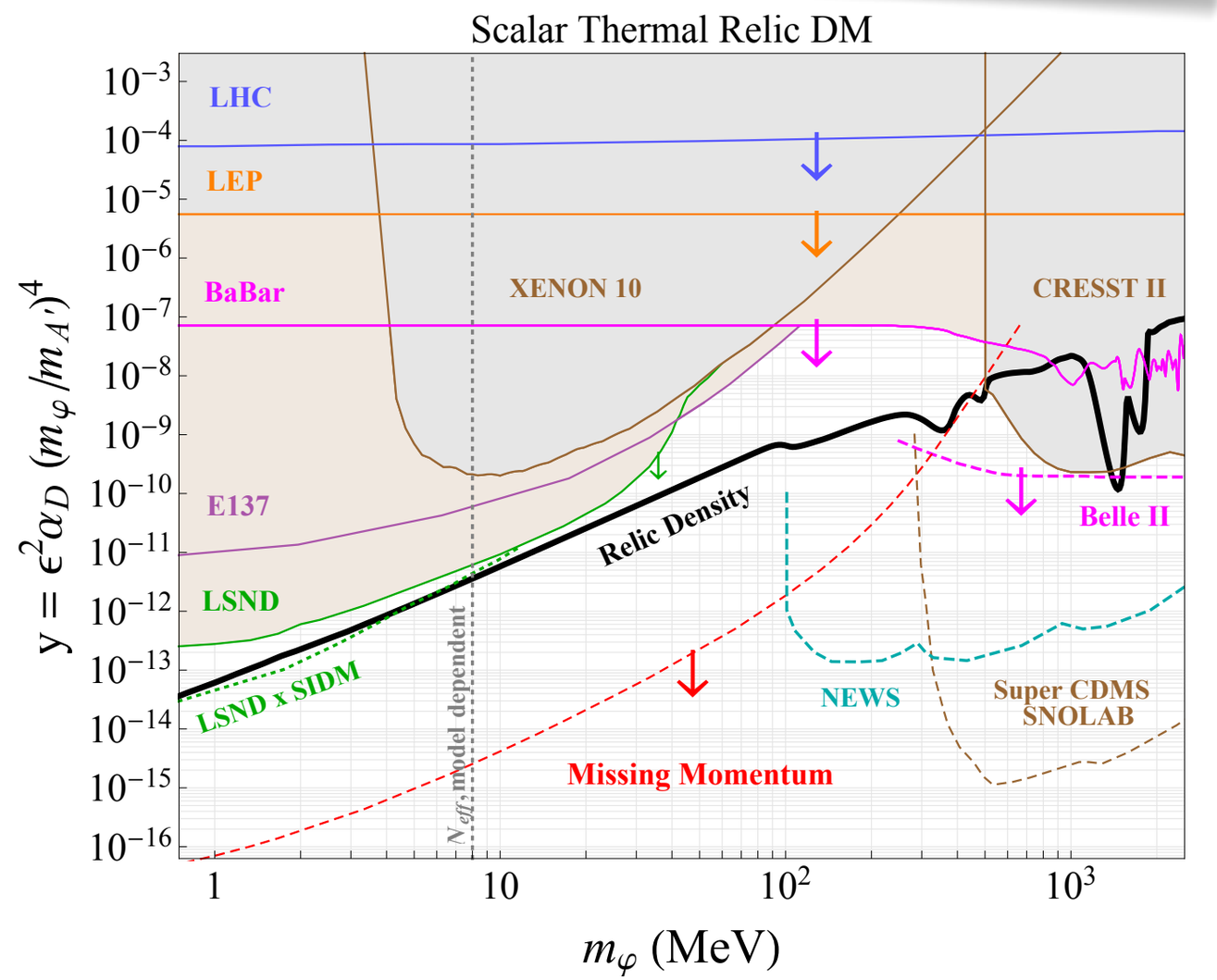
Izaguirre, GK, Schuster, Toro
1304.6554 , 1403.6826

BDX Collaboration
(90+members, 6 countries)
1406.3028

New Proposal: JLab PAC 44
June 2016

Electron Fixed Target: Missing Momentum





Low current ~pA e-beam

Produce DM in thin target

DM receives most of Ebeam

Measure recoil electron energy (< 0.1 Ebeam)

Very hard part: veto everything else!

Need dedicated ECAL/HCAL/tracker

Izaguirre, GK, Schuster, Toro
1411.1404, 1505.00011

LDMX Collaboration
Including @ FNAL
Nhan Tran, Andrew Whitbeck, GK

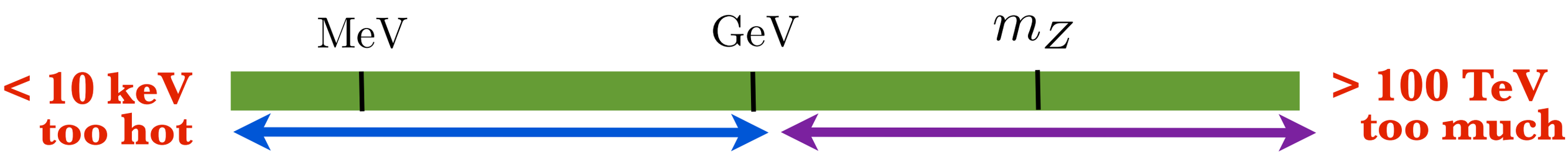
Concluding Remarks

There is abundant, diverse evidence for DM

Guaranteed BSM, does not require* very high scales

Thermal equilibrium between DM & SM

0. Compelling organizing principle
1. Focuses DM mass range
2. Requires minimum annihilation rate



Light DM ("LDM")

Electron Direct Detection
Electron Fixed Targets
Neutrino Factories
B-Factories

"WIMPs"

Direct Detection
Indirect Detection
Colliders (X+MET)

Emerging program of LDM searches & techniques