

New Frontiers in Dark Matter Detection

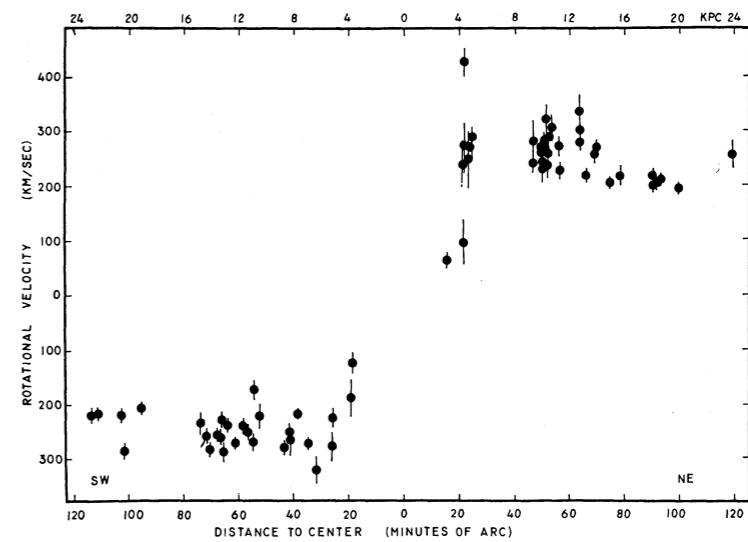
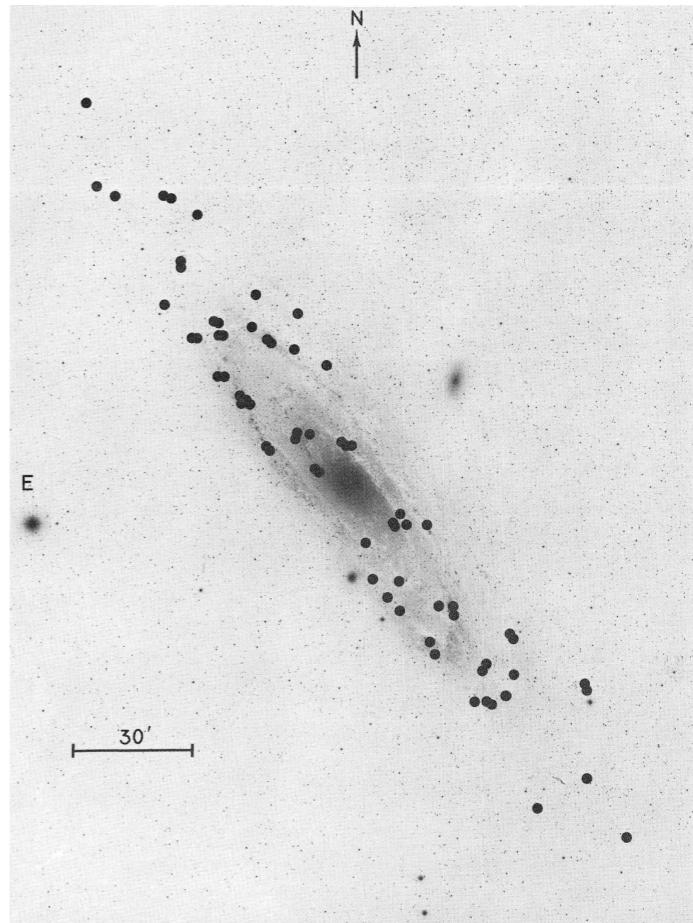
Jesse Thaler



APS “April” Meeting, Washington, DC — January 29, 2017

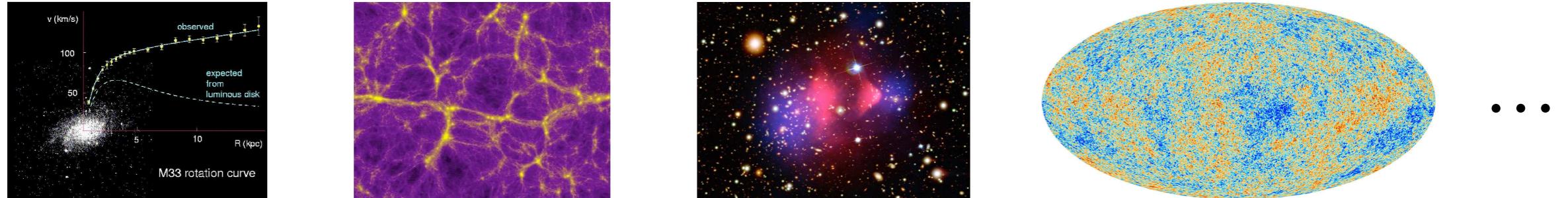


Vera Rubin, 1928–2016

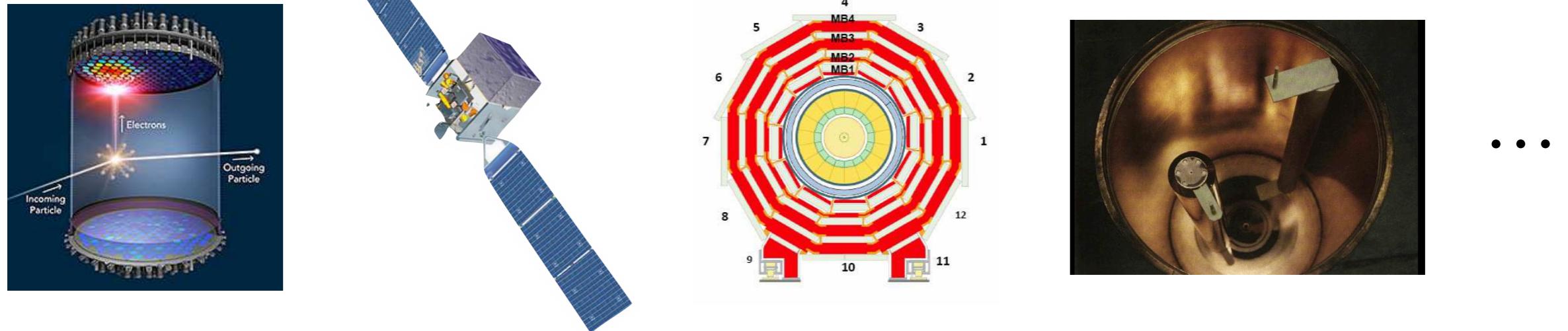


[Rubin, Ford, 1970]

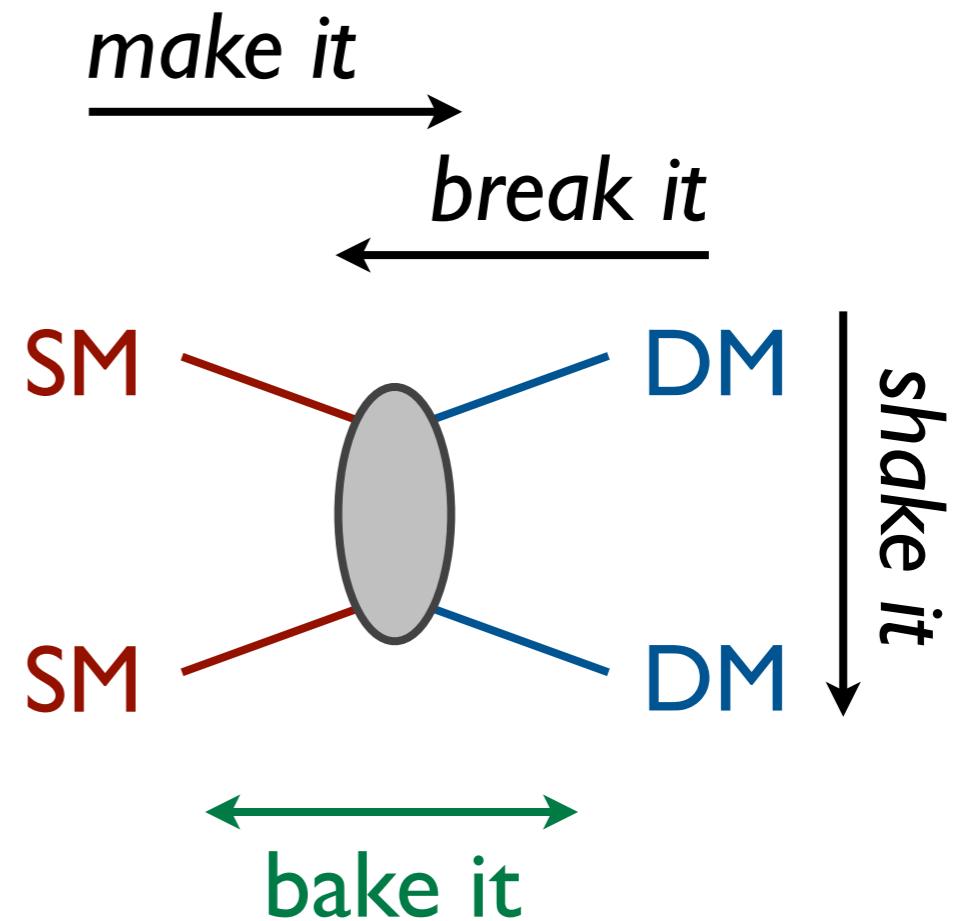
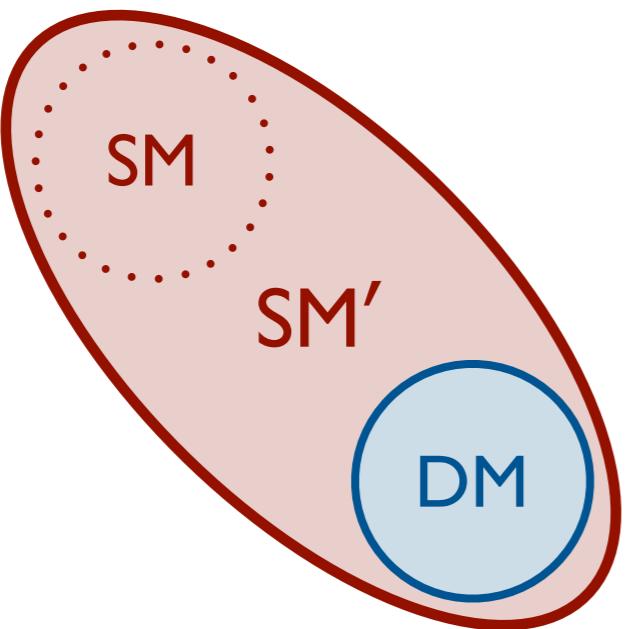
Robust evidence from gravity...



...inspires broad dark matter search program



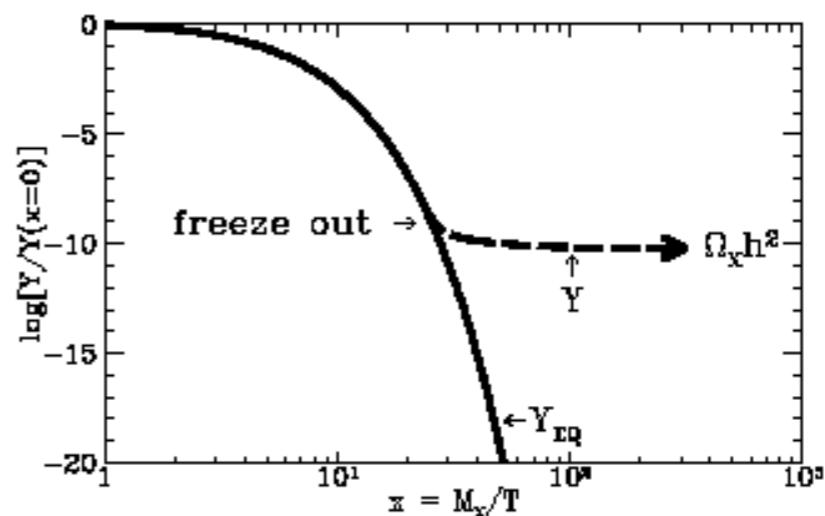
WIMP Dark Matter



Motivations:

Hierarchy Problem
Thermal Freezeout

*Mature experimental search
program for GeV–TeV masses*



Non-WIMP Dark Matter

↑
my least favorite retronym

Huge space of possibilities!

Q: How is DM produced in early universe?

freeze-out, freeze-in, freeze-out and decay, non-thermal, asymmetric, late time dilution, cannibalism, misalignment (e.g. axions), primordial density fluctuations (e.g. black holes), ...

Q: How is DM detected today?

quarks, gluons, charged leptons, neutrinos, photons, weak bosons, only gravity, via weak-scale mediator, via hypercharge/Higgs/neutrino/axion portal, via fifth force, ...

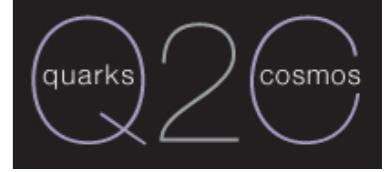
Q: What are properties of dark sector?

mass, spin, effective temperature, self interactions, light states, multiple stable states, approximate global symmetries, (spontaneously broken) gauge symmetries, ...

[adapted from 2017 talk by Tomer Volansky]

Dark Matter in “April” 2017

Apologies if I
missed a session!



Group on Precision Measurements and Fundamental Constants

Friday Ultralight Dark Matter Workshop

Saturday B8: Ultralight Dark Matter

Division of Particles and Fields

Saturday B9: Dark Matter: DarkLight, Sequest, Other Ongoing Efforts

C9: Dark Matter: R&D and New Directions

E9: Dark Matter with Solid State Detectors

Sunday H9: Dark Matter with Lux/LZ, DarkSide and Axions and ADMX

J9: Dark Matter with Xenon

Division of Astrophysics

Saturday C10: Indirect Detection of Dark Matter

H15: Cosmology with Ultra Low Mass Fields

Sunday J5: Dwarf Galaxies, Dark Matter and Magnetic Fields

M5: Simulating Dark Matter and Galaxies

Monday R5: The Galactic Center Excess

U5: Gravitational Waves and Dark Matter

Division of Physics of Beams

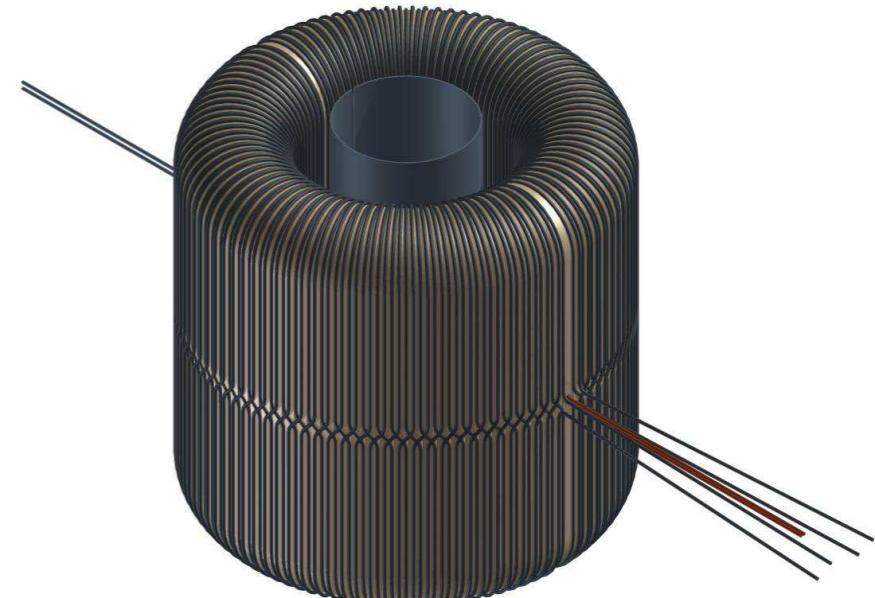
Sunday K7: Future Accelerator-based Dark Sector Searches

Division of Nuclear Physics

Saturday B13: Detecting Neutral Particles with Low-energy Thresholds

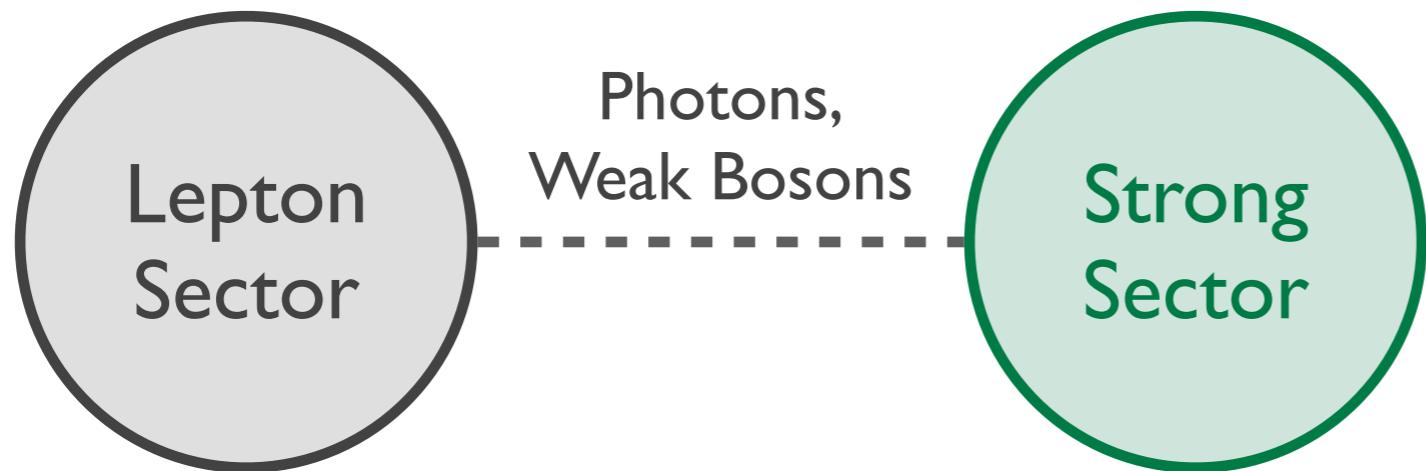
Sunday J13: New Approaches to Search for non-WIMP Dark Matter

ABRACADABRA
sub- μ eV axion-like DM

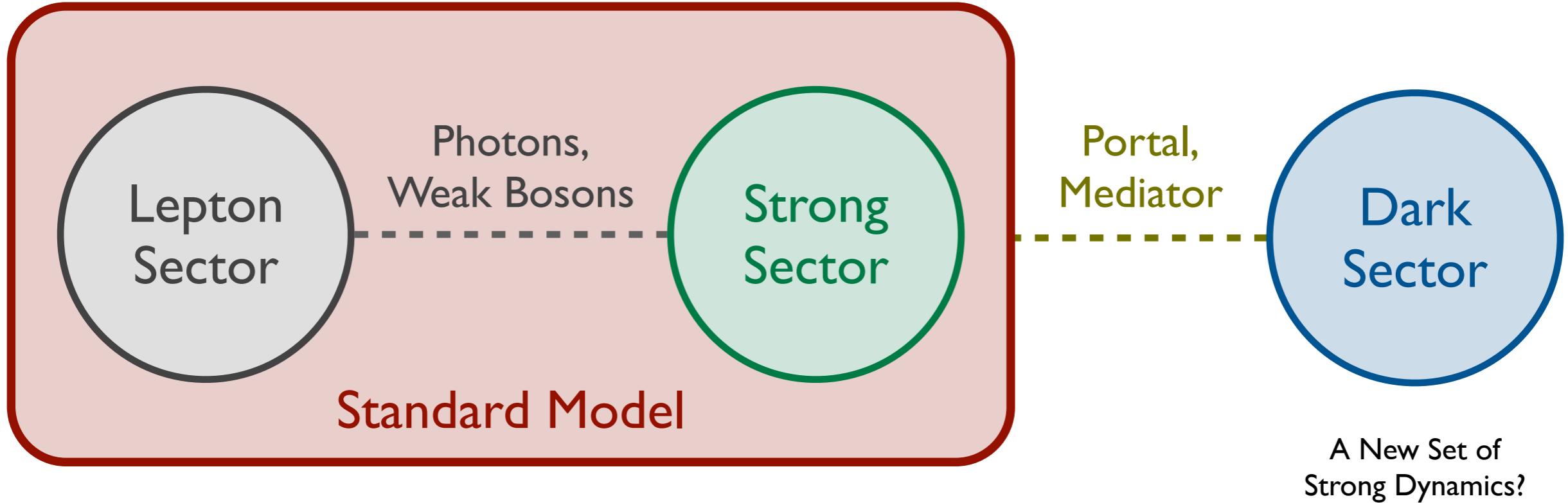


[Kahn, Safdi, JDT, 1602.01086;
development under NSF EAGER with PI Winslow]

Dark Sector as Rich as QCD?



Dark Sector as Rich as QCD?



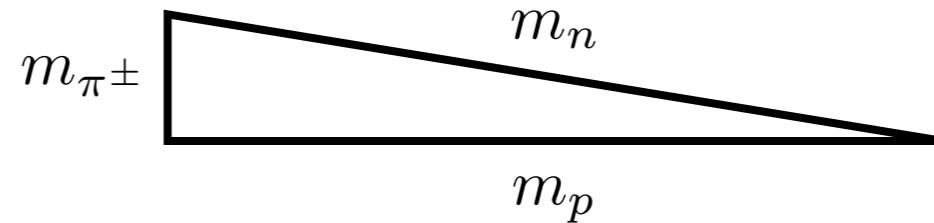
Relatively weak DM self-scattering bounds:
 $\sigma/m \lesssim \text{barn}/\text{GeV}$

[see, e.g., Spergel, Steinhardt, 2000]

Dark Sector as Copy of QCD?

Scaled-up QCD without weak decays, with dark photons

Mutually stability from triangle inequality:

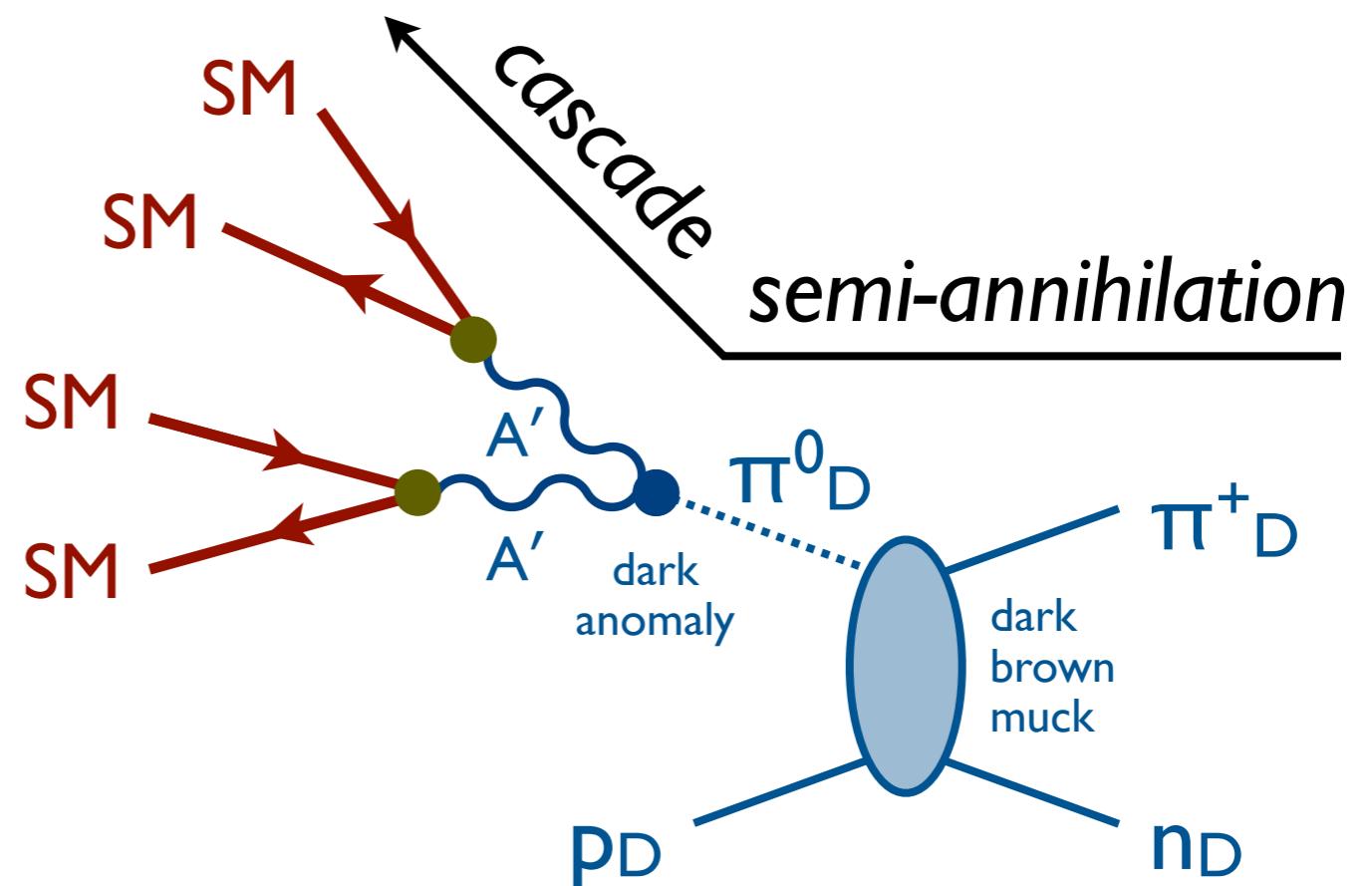
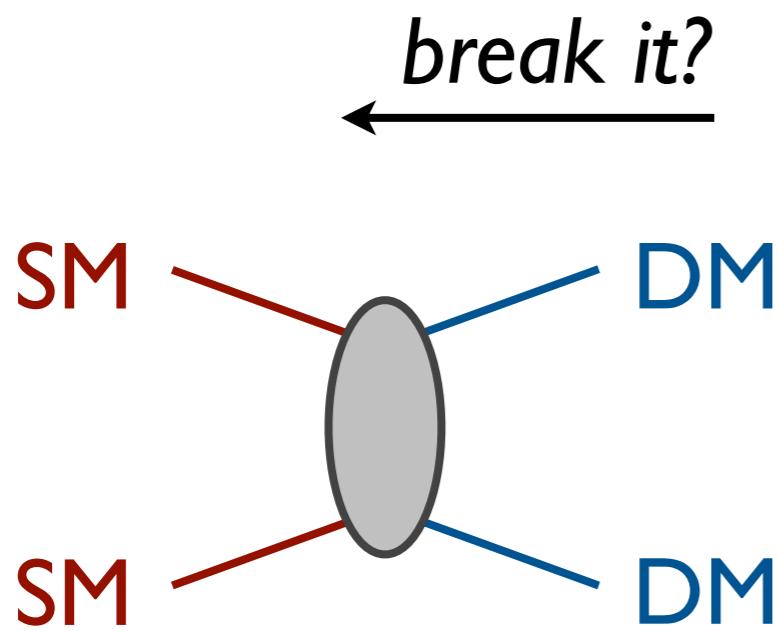
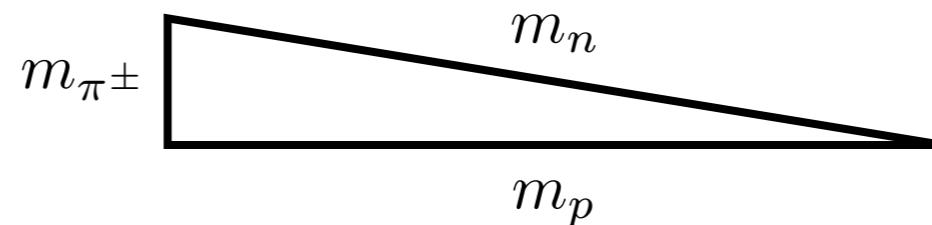


[D'Eramo, JDT, 2010; see also Hambye, 2008; Hambye, Tytgat, 2009; Detmold, McCullough, Pochinsky, 2014]

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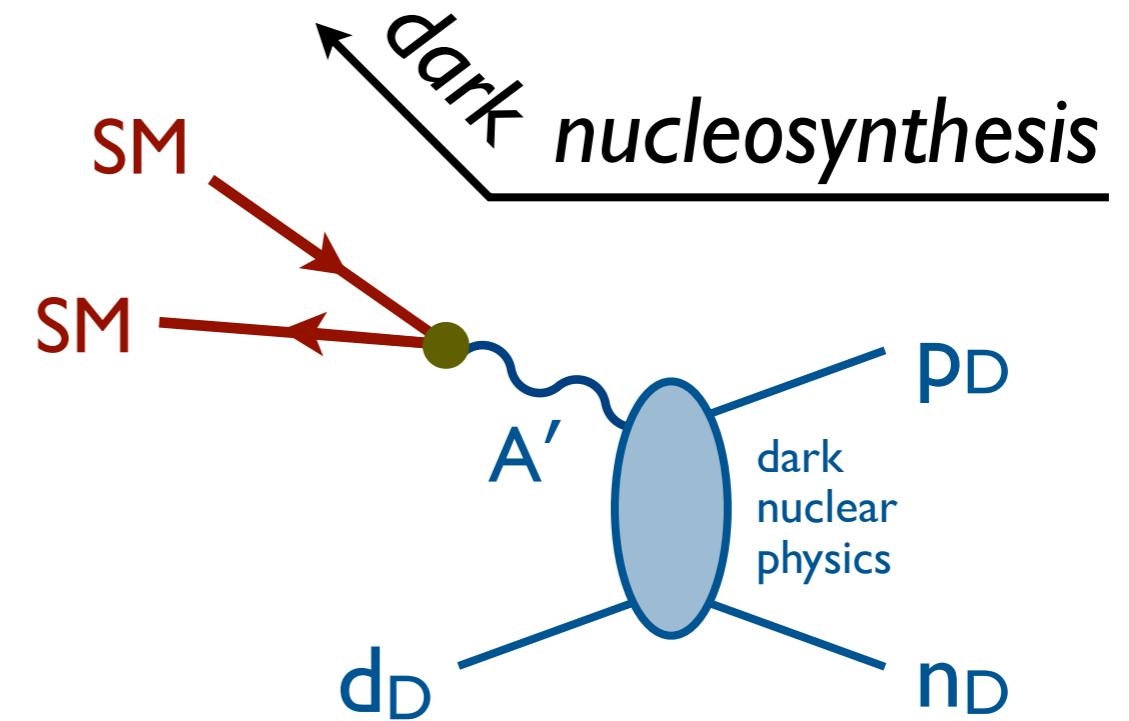
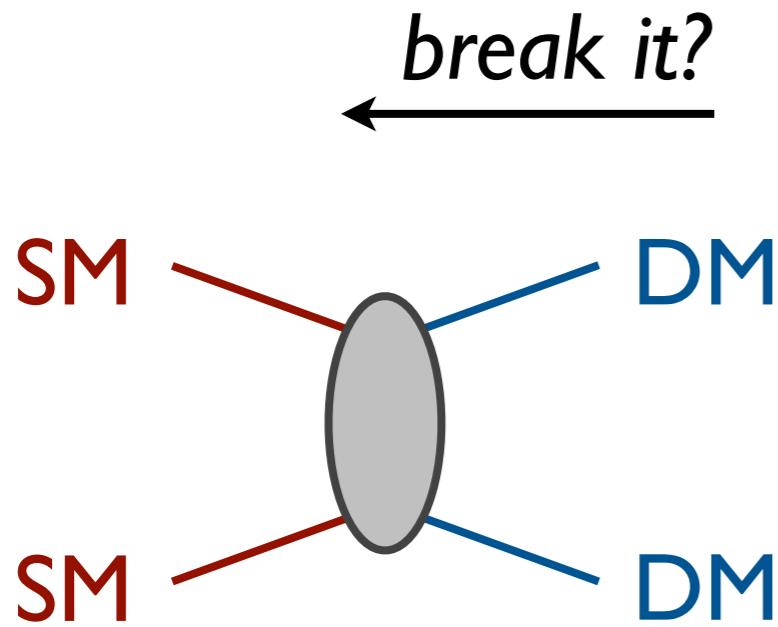
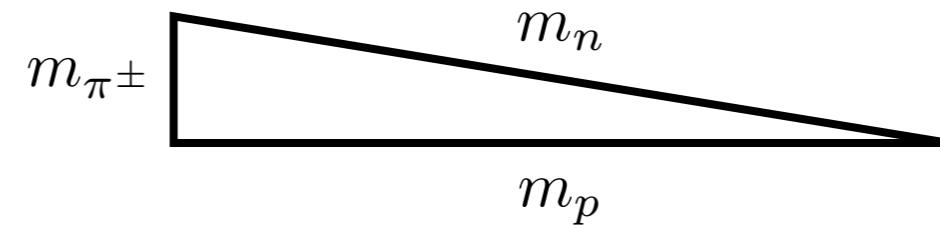


[D'Eramo, JDT, 2010; see also Hambye, 2008; Hambye, Tytgat, 2009; Detmold, McCullough, Pochinsky, 2014]

Dark Sector as Copy of QCD?

Scaled-up QCD without weak decays, with dark photons

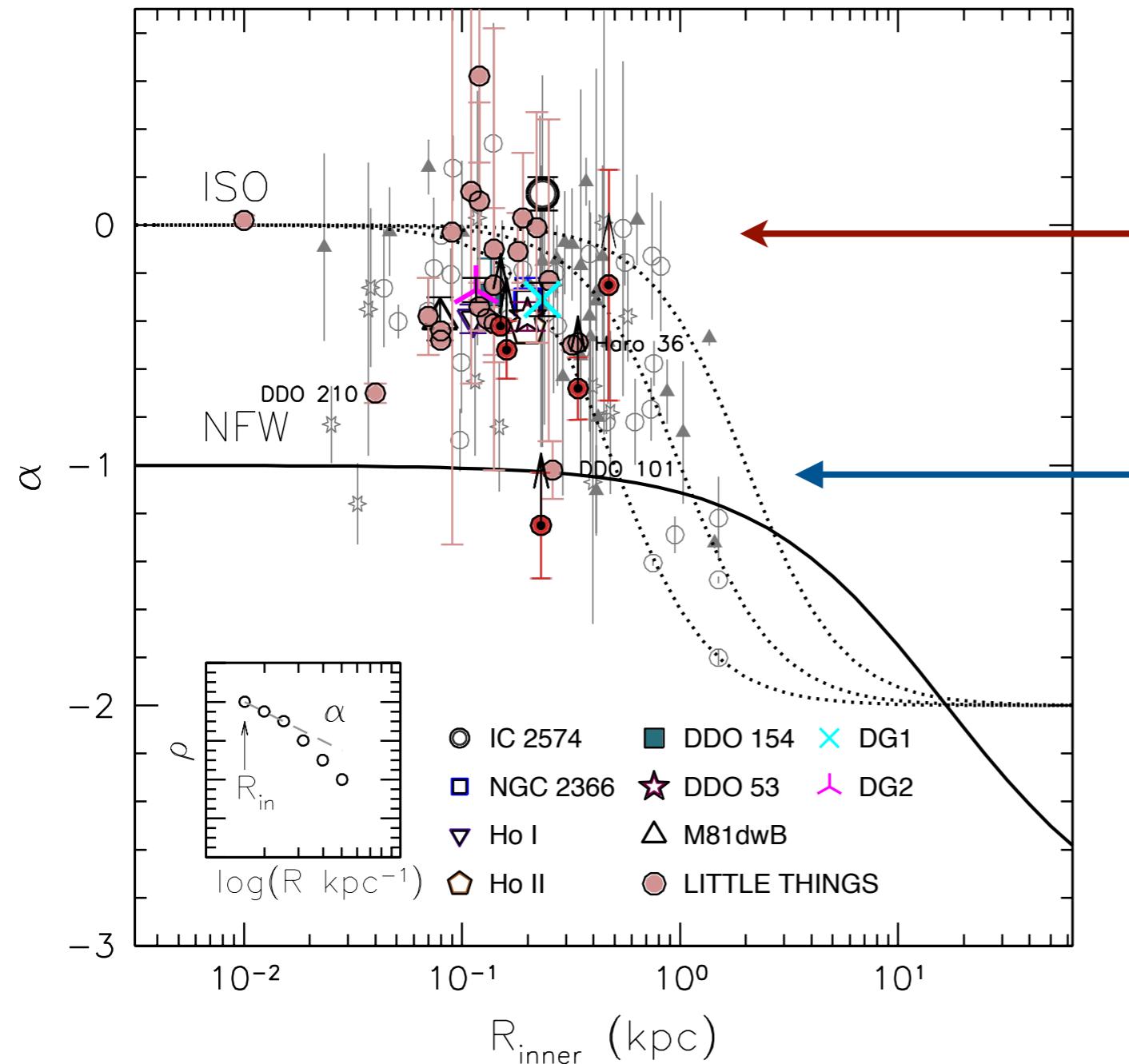
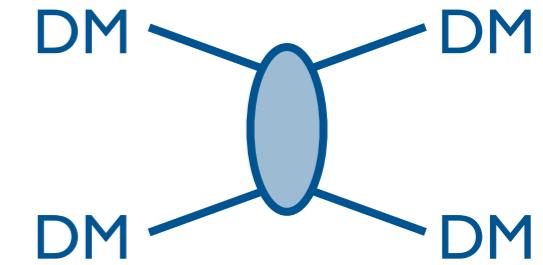
Mutually stability from triangle inequality:



[D'Eramo, JDT, 2010; see also Hambye, 2008; Hambye, Tytgat, 2009; Detmold, McCullough, Pochinsky, 2014]

E.g. Core vs. Cusp Problem

Dark matter self-interaction without dissipation?



“Thermalized” Core:
Baryon feedback?
DM self-interaction?

“Cold” Cusp:
Standard DM Expectation

Motivates further DM
studies with QCD-sized
self-interactions

[Moore, 1994; Flores, Primack, 1994; ...; plot from Oh, et al., 1502.01281]

Today's Mini-Symposium

Creative ideas to probe novel dark sector interactions

Absorption of keV-scale DM

Massarczyk: The low-energy program of the Majorana Demonstrator

Dark-Sector-Mediated Nuclear Transitions?

Zhang, Miller: Can nuclear physics explain the anomaly observed in the internal pair creation in Beryllium-8 nucleus?

Ward, Koltick, Wang: ${}^8\text{Be}$ Anomalous Internal Pair Production: Possible E2 Transitions

Creating/Detecting Beams of Dark Matter

Cooper, Tayloe: Sub-GeV Dark Matter Search with MiniBooNE

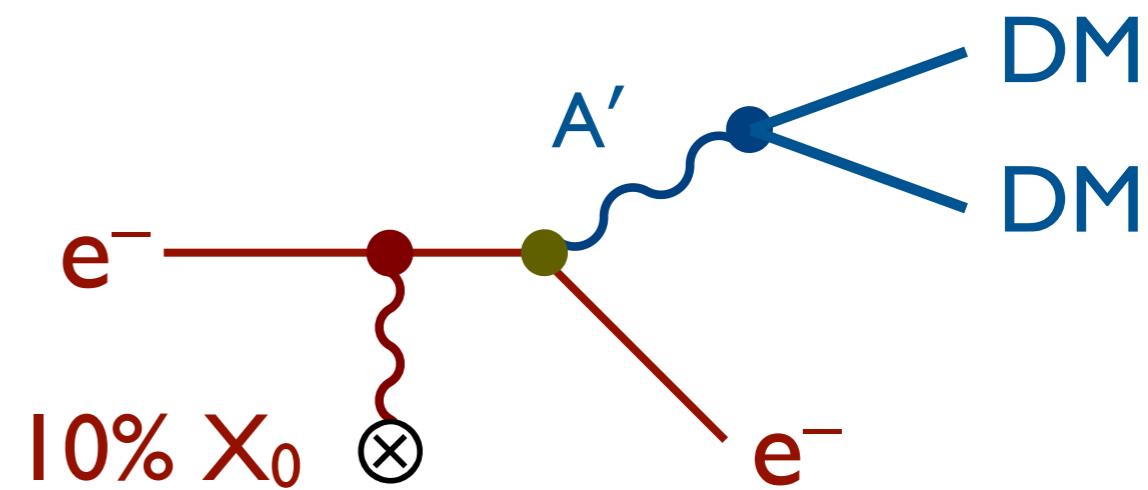
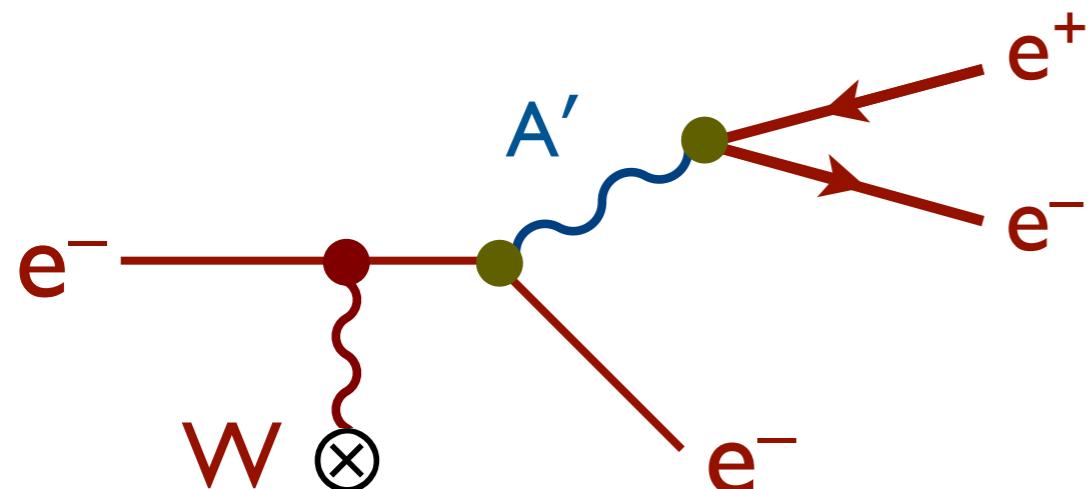
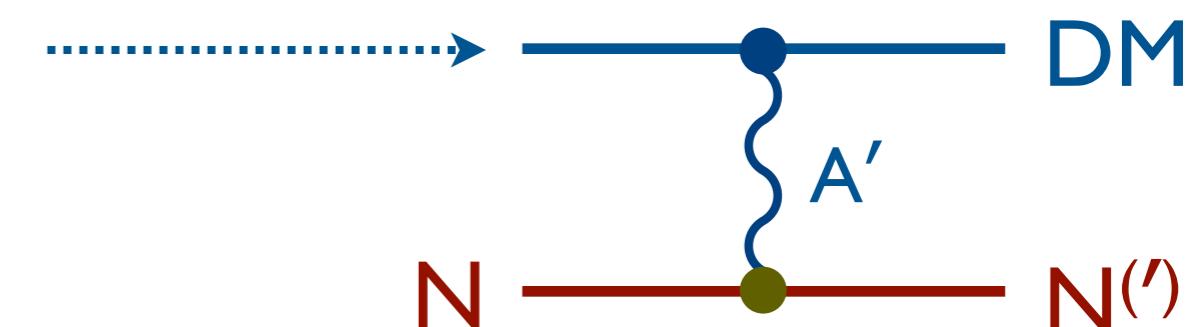
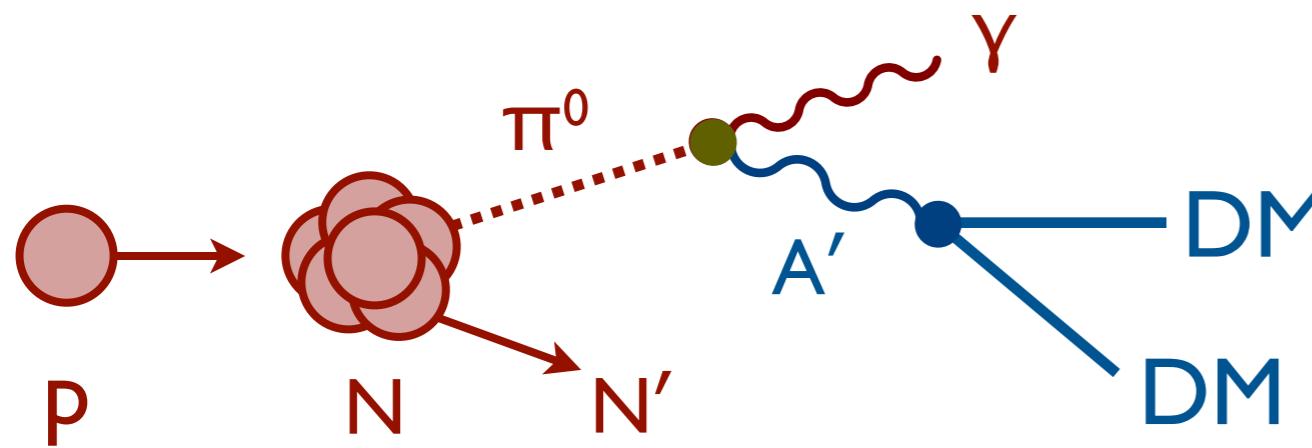
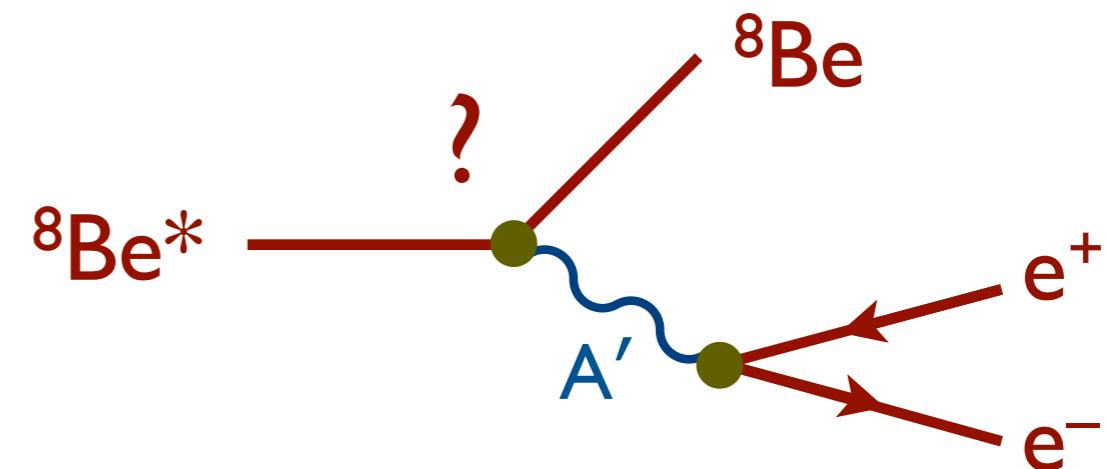
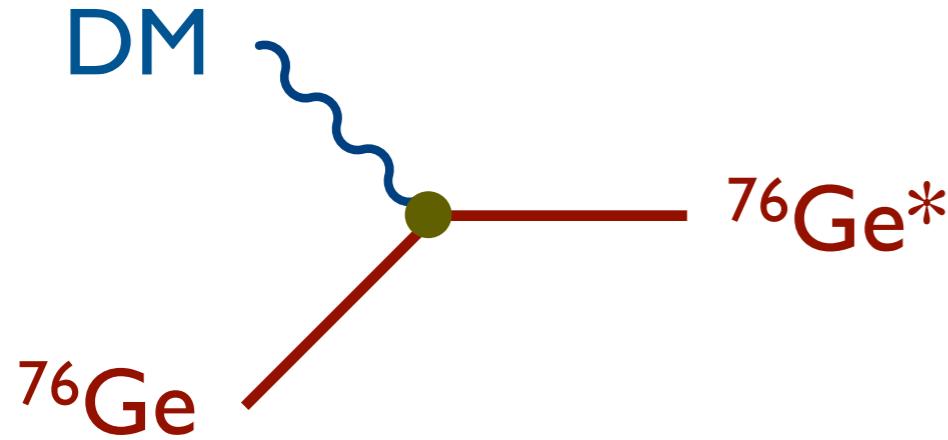
Fixed-Target Dark Photon Searches

Moreno: Resonance Search for a Heavy Photon in the 2015 Engineering Run Data of the Heavy Photon Search Experiment

Weinstein, Szumila-Vance: Searching for heavy photons at Jefferson Lab using detached vertices

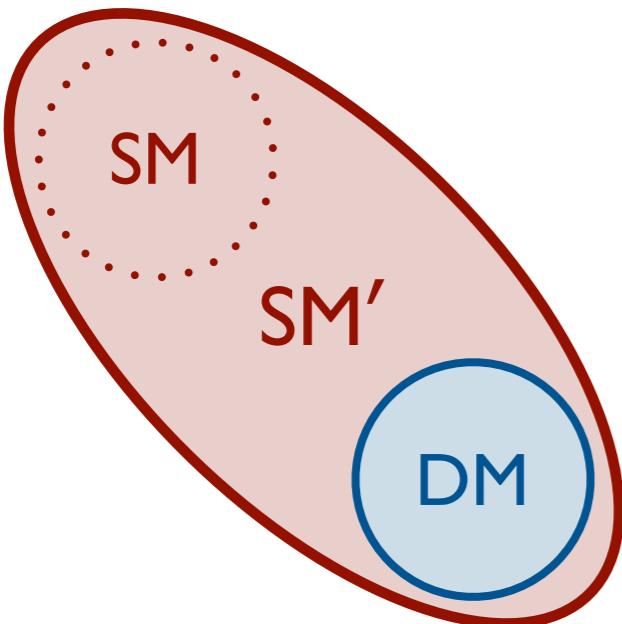
Missing Momentum through Dark Bremsstrahlung

Colegrove: The Light Dark Matter eXperiment



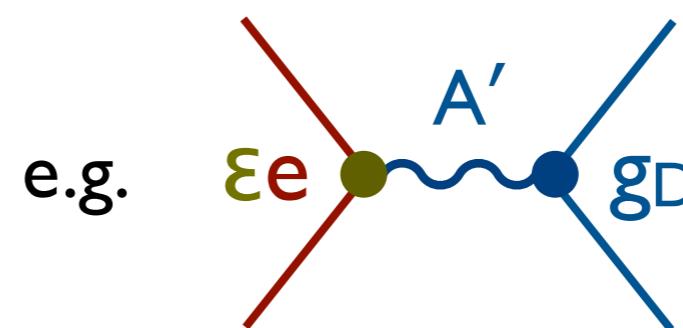
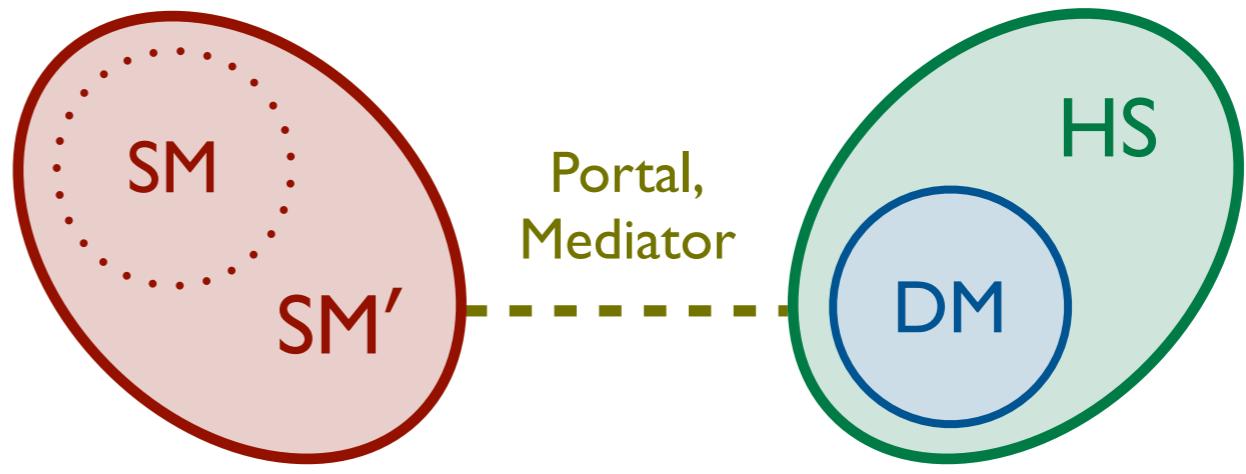
DM

WIMP Paradigm



VS.

Hidden Sector Paradigm



Required Reading: Dark Sectors 2016 Report (1608.08632)

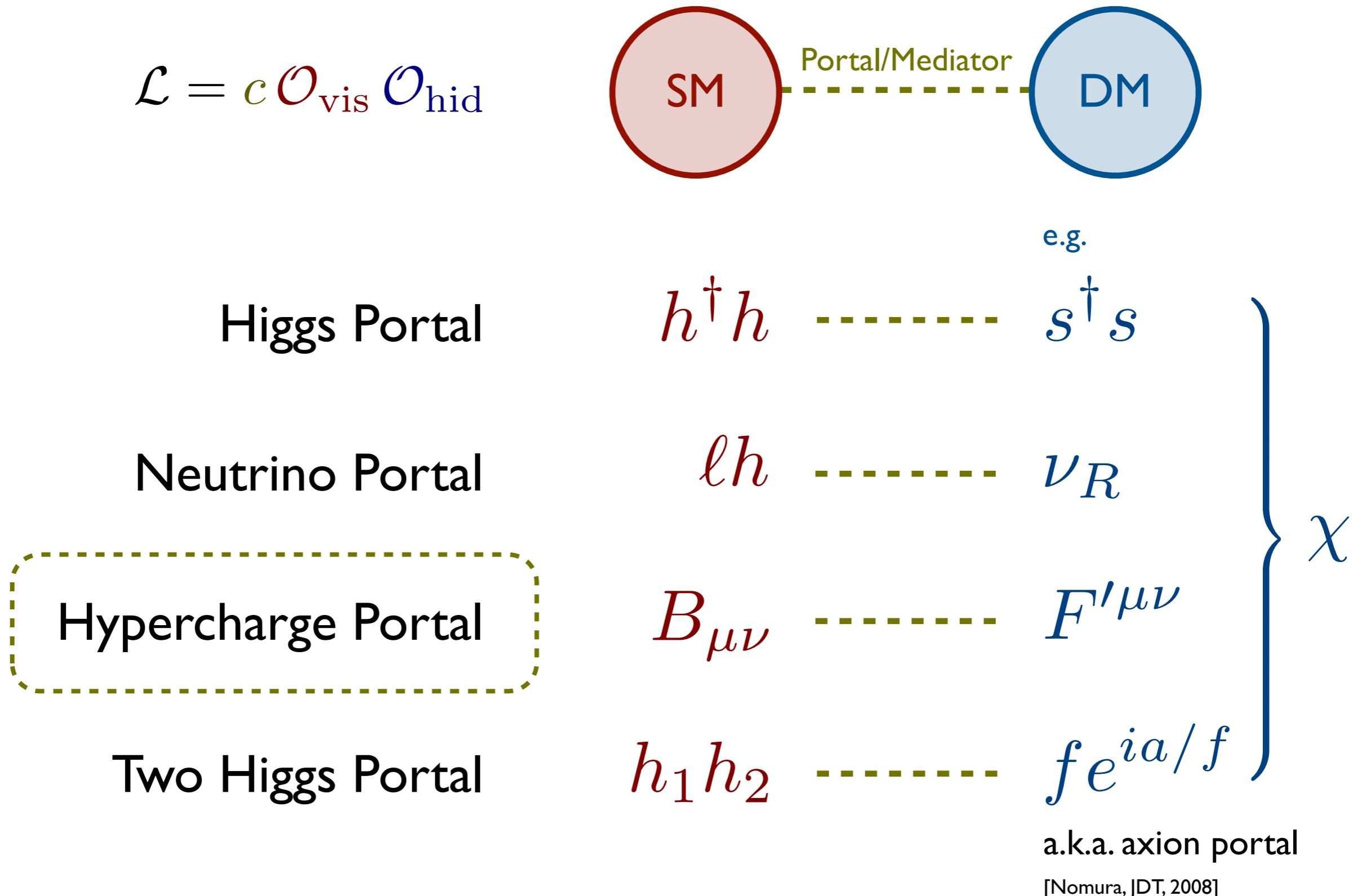
$W \otimes$

e^-

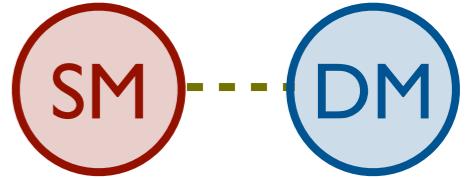
$10\% X_0 \otimes$

e^-

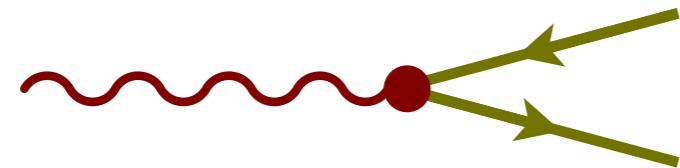
Minimal Hidden Sector Paradigm



Fun with $U(1)'$



Hypercharge

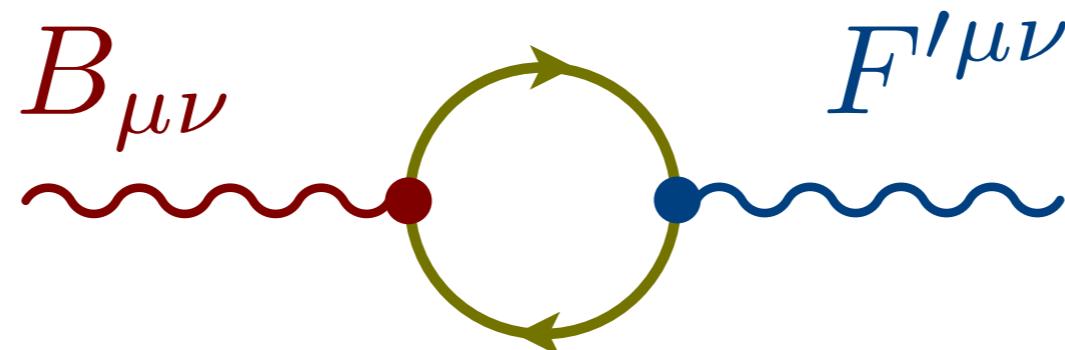


Dark Charge



Anomaly
Cancellation: $\sum q = \sum q^3 = \sum qq'^2 = \sum q^2q' = \sum q' = \sum q'^3 = 0$

Kinetic Mixing?

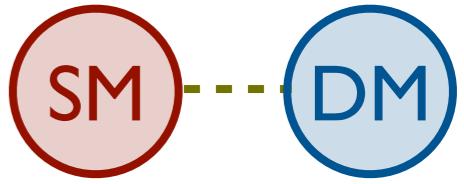


$$\sum qq' \neq 0$$

unless C symmetry or
accident (then two loop)

Generically loop-level ($\epsilon \lesssim 10^{-3}$)

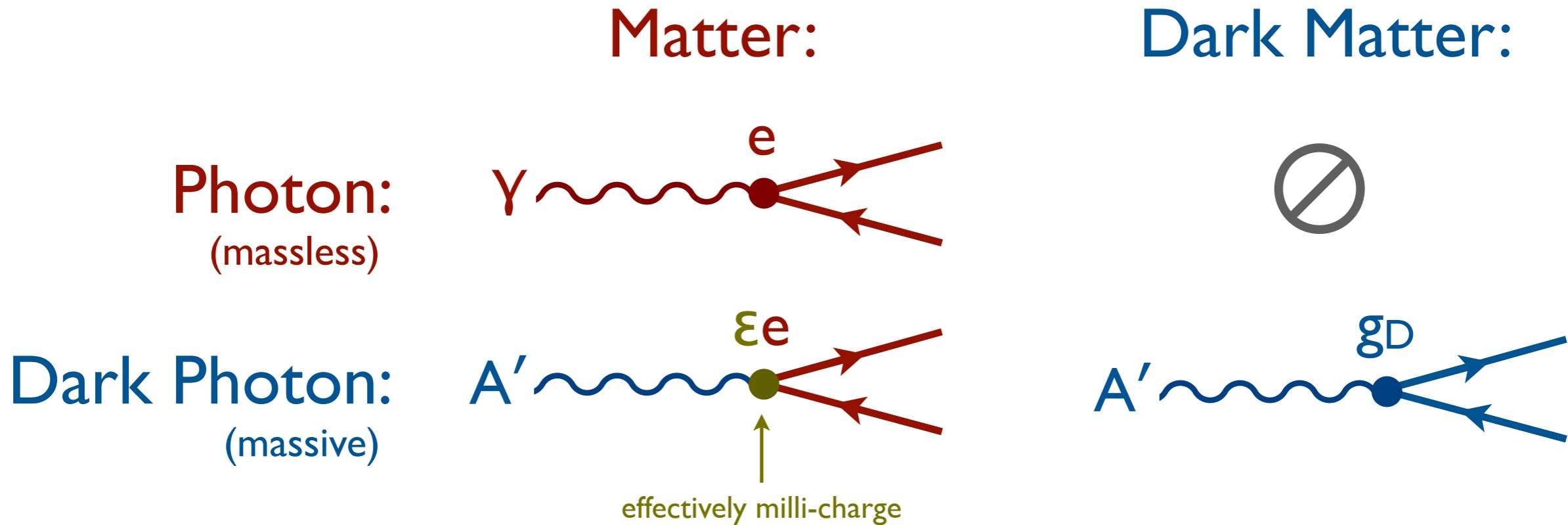
Dark Photon with Light-like Couplings



$$\mathcal{L} \supset g_Y B_\mu J^{Y\mu} + \frac{1}{2} \epsilon_Y B_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu$$

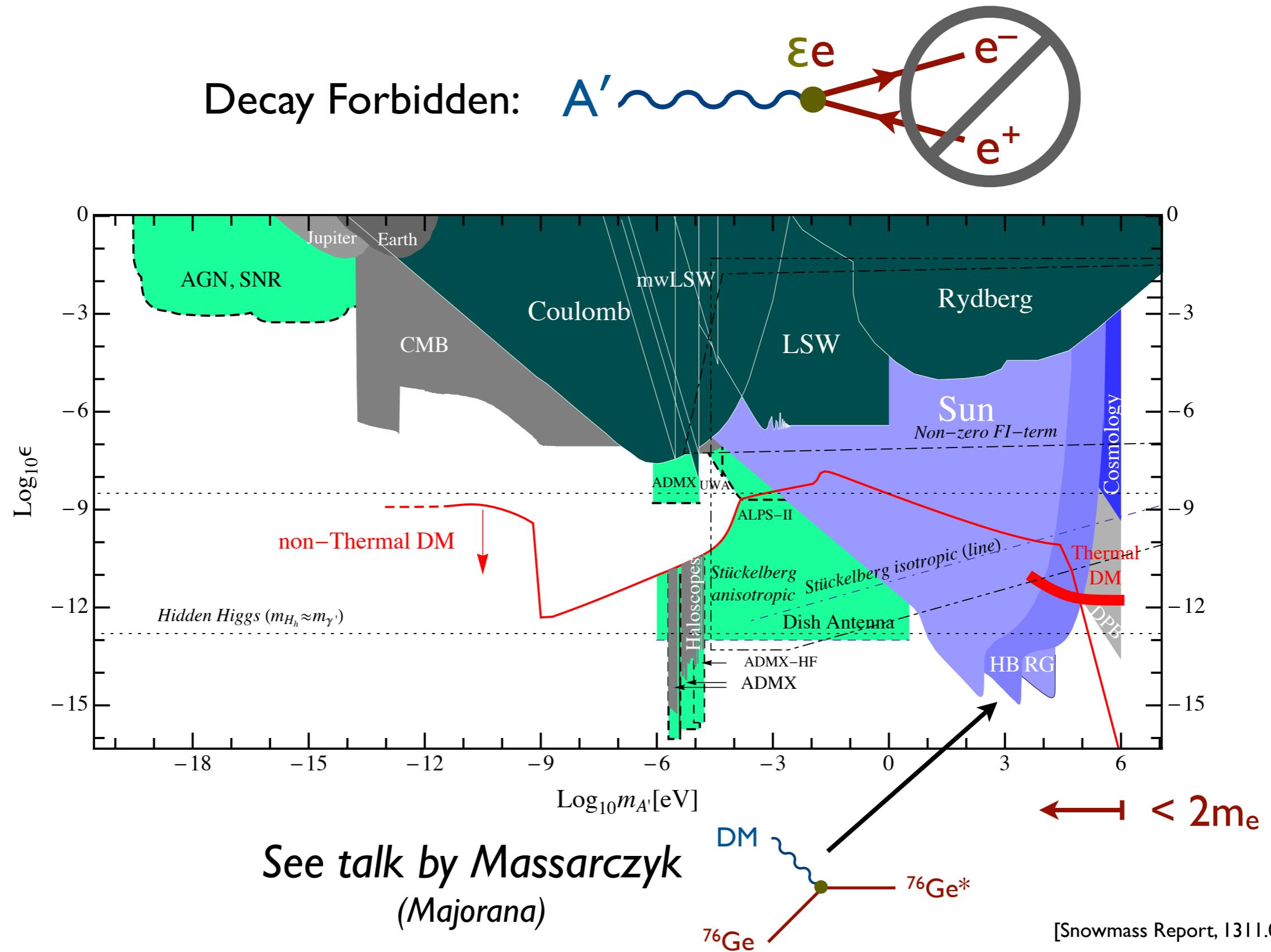
SM hypercharge kinetic mixing dark photon mass

Diagonalize: $B_\mu \rightarrow B_\mu + \epsilon_Y A'_\mu$ EWSB: $\epsilon = \epsilon_Y \cos \theta_W$

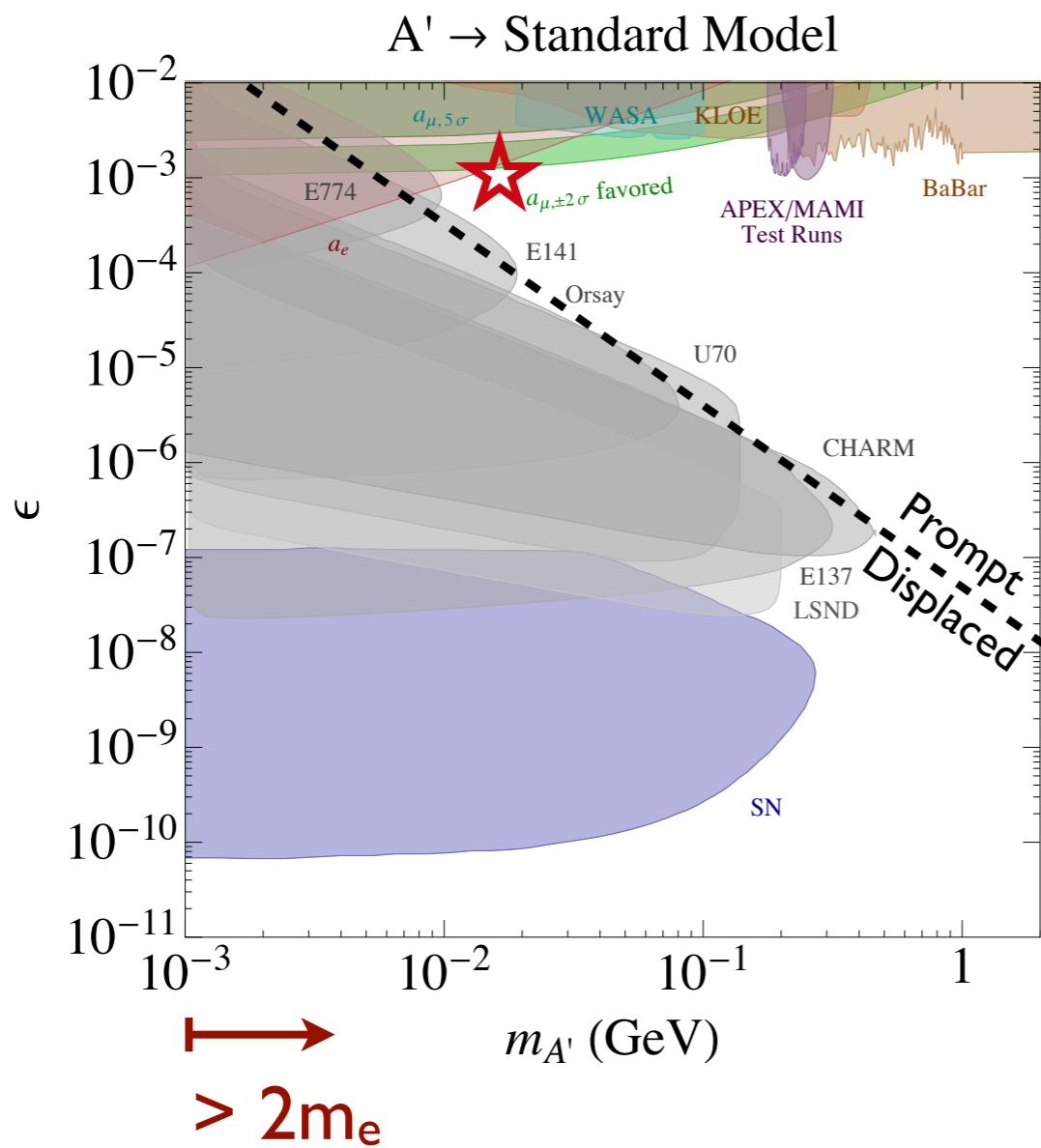


[see Okun, 1982; Galison, Manohar, 1984; Holdom, 1986; ...; Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008; Pospelov, Ritz, 2008; ...]

Dark Force Bounds: $m_{A'}$ vs. ϵ

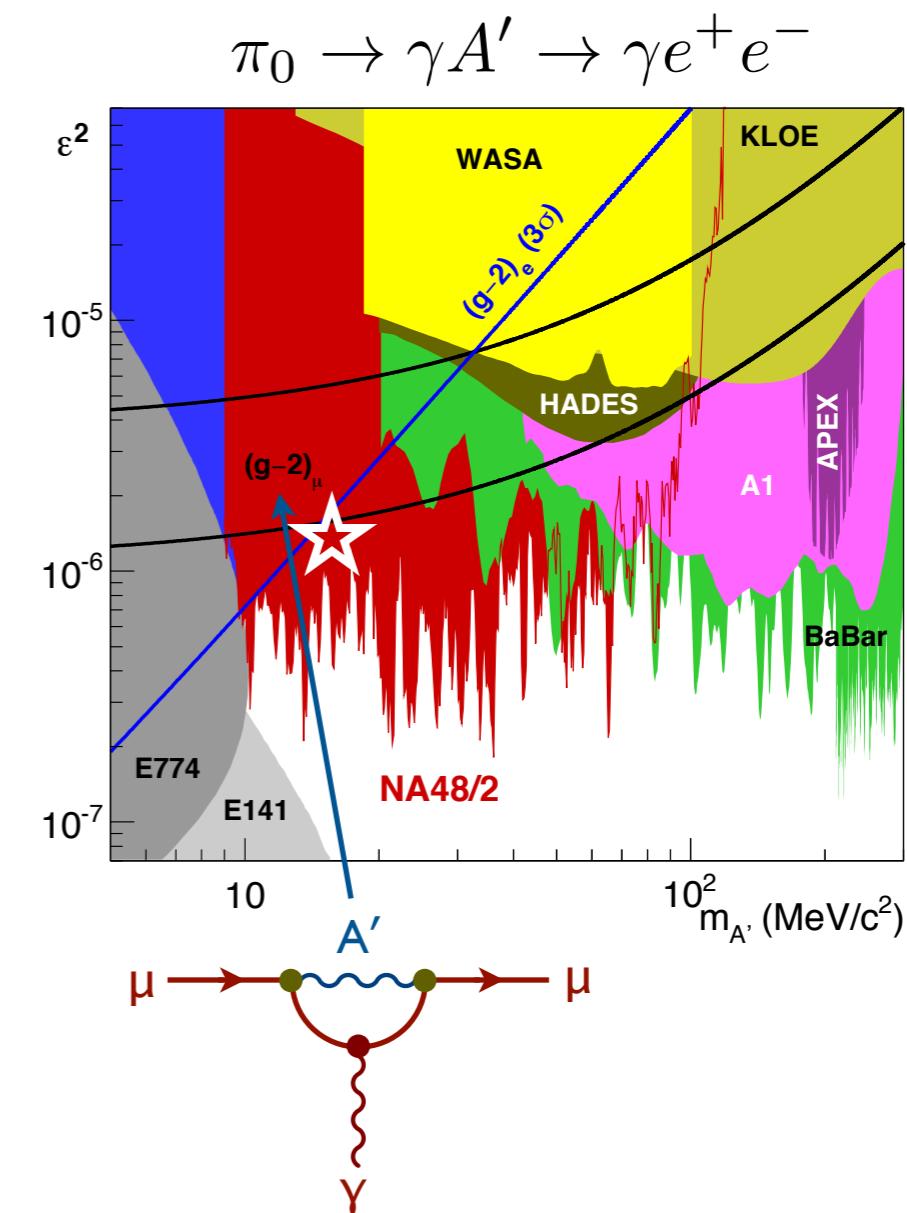
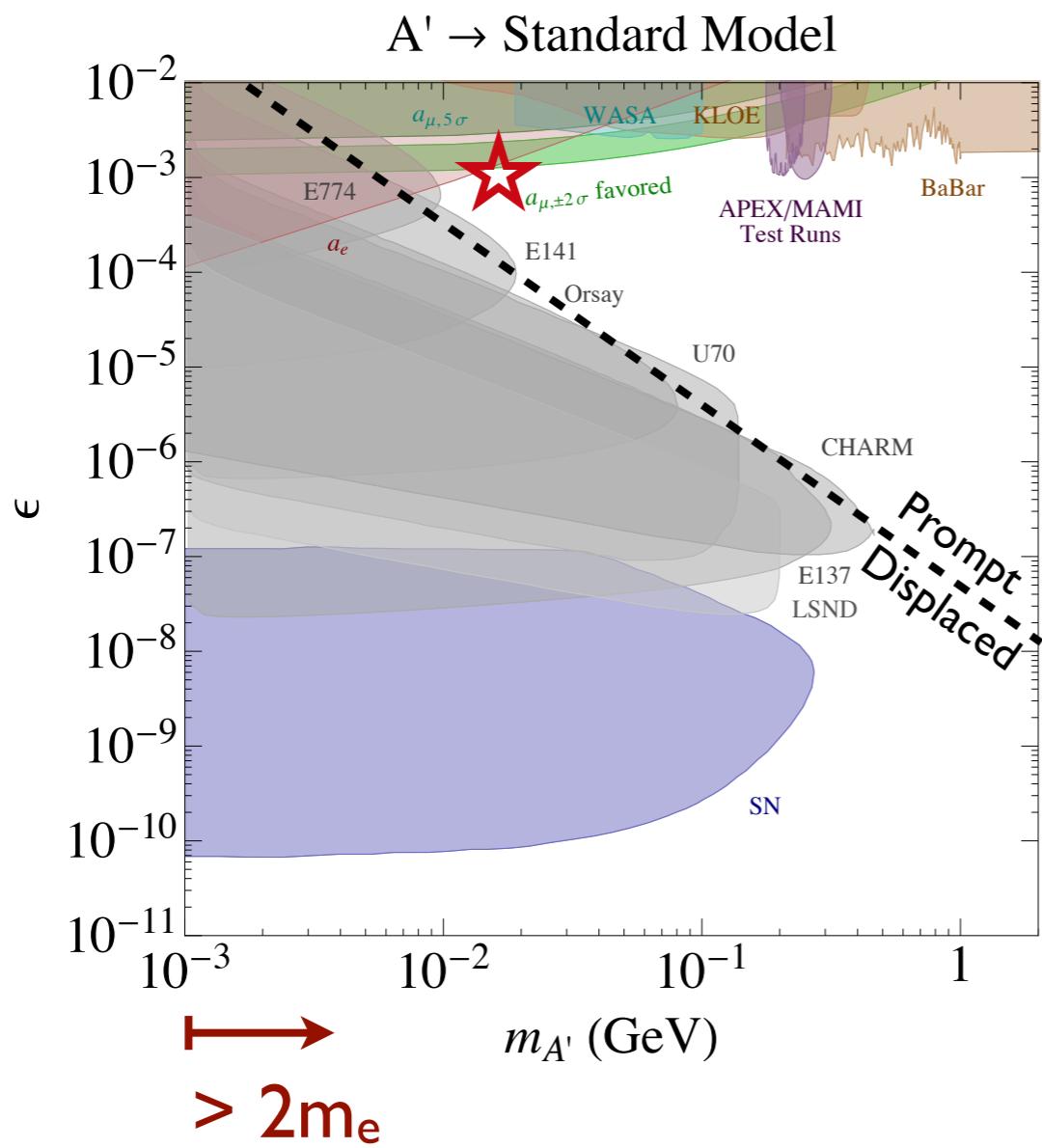


Dark Force Bounds: $m_{A'}$ vs. ϵ



[Snowmass Report, 2013; NA48/2, 2015; see Pospelov, 2008]

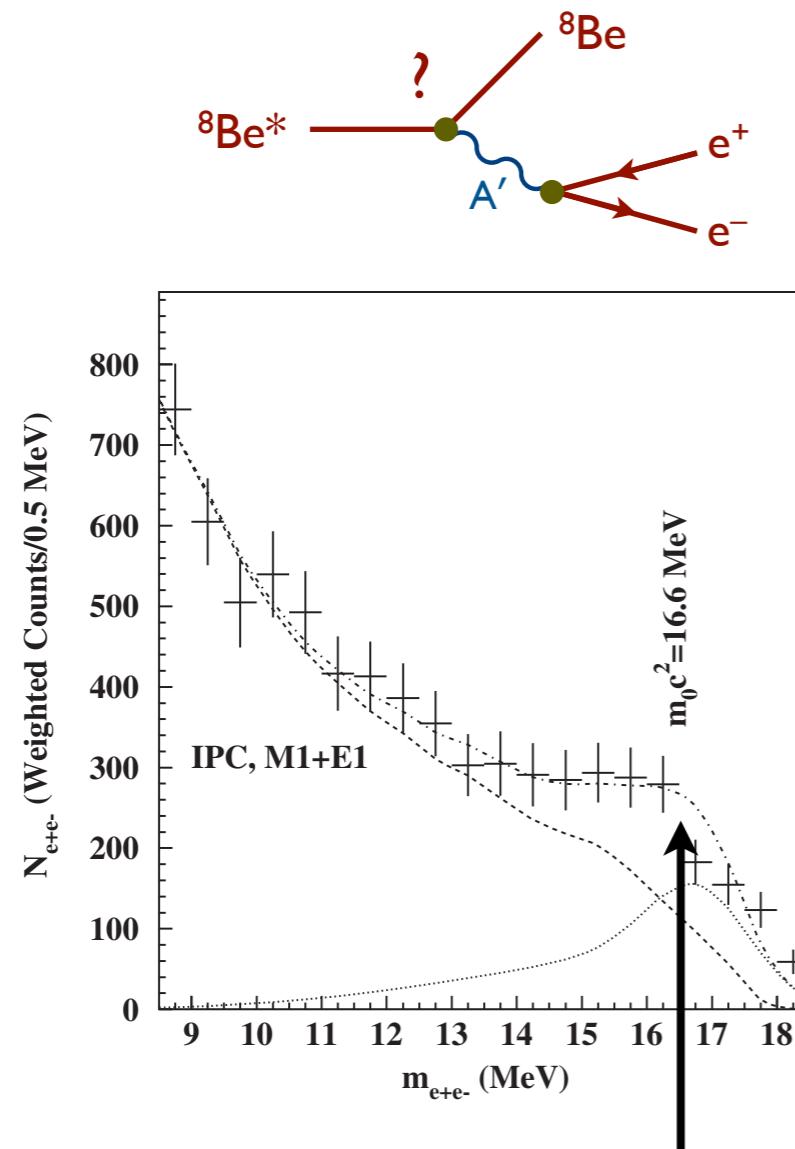
Dark Force Bounds: $m_{A'}$ vs. ϵ



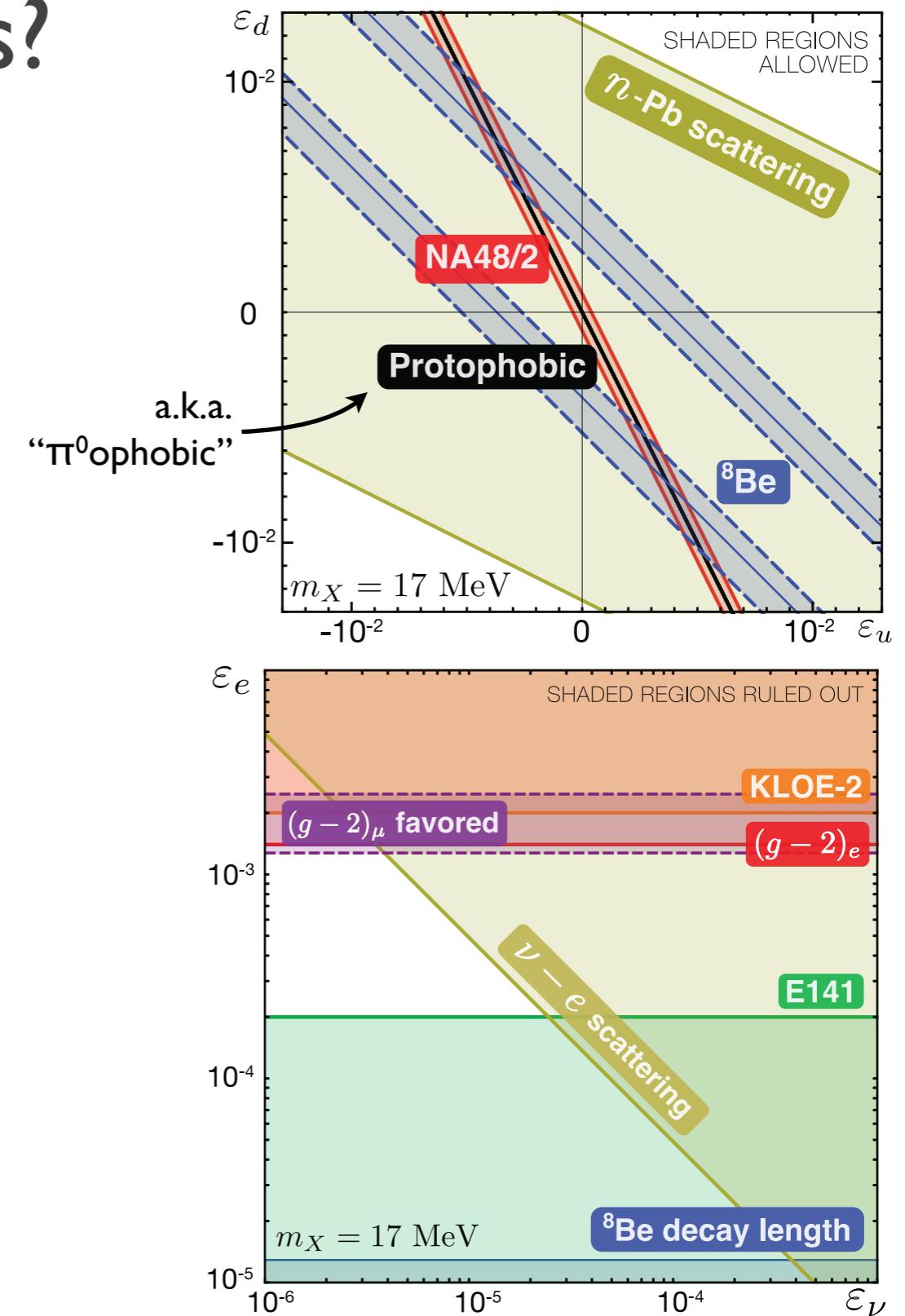
[Snowmass Report, 2013; NA48/2, 2015; see Pospelov, 2008]

More General Couplings?

The Atomki Anomaly



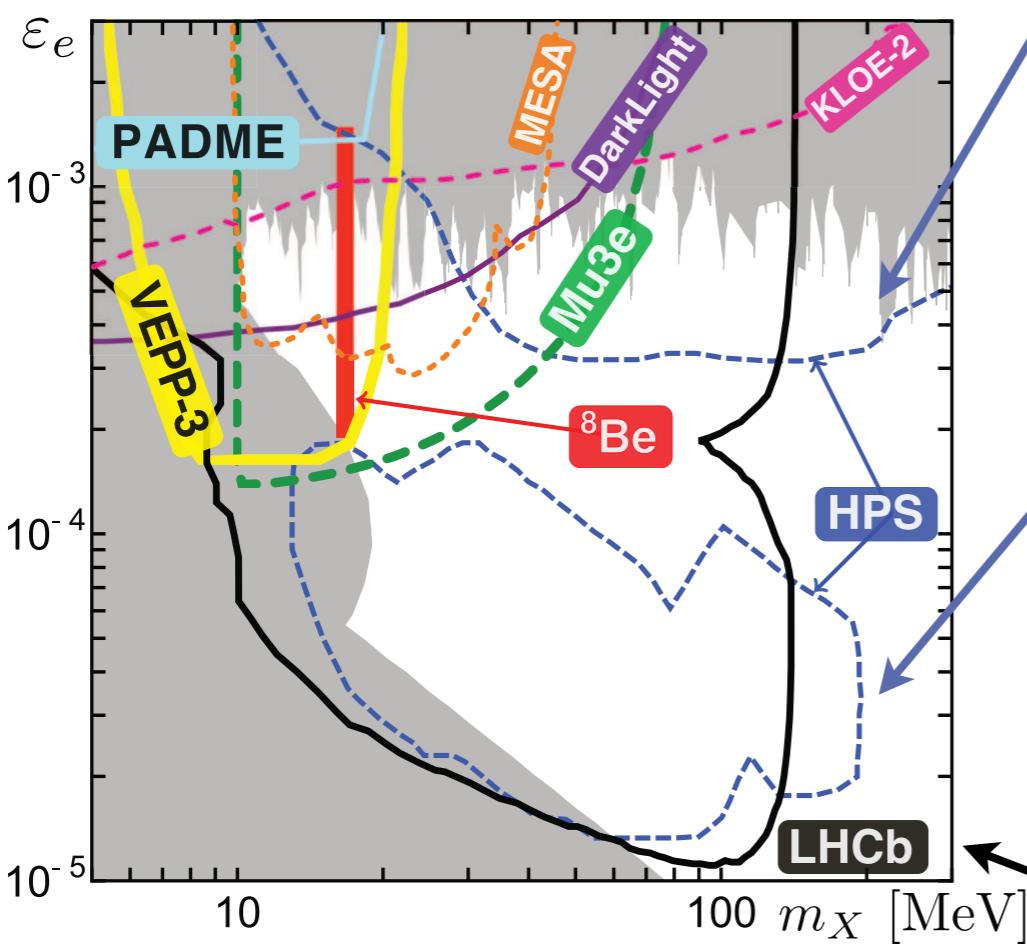
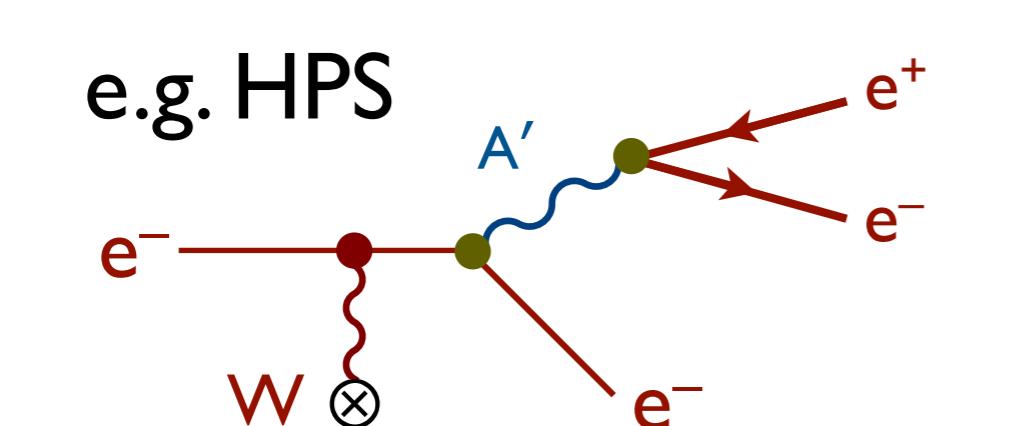
See talks by Zhang, Miller;
Ward, Koltick, Wang



[Krasznahorkay et al., 1504.01527]

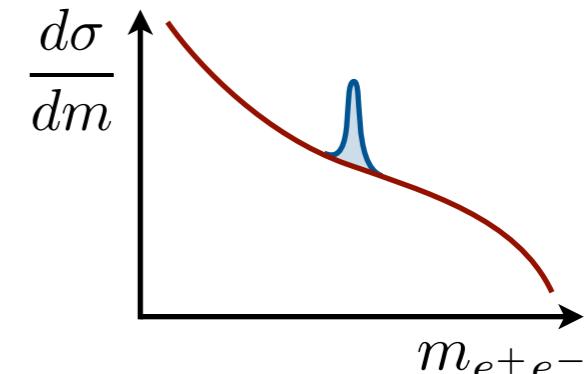
[Feng, Fornal, Galon, Gardner, Smolinsky, Tait, Tanedo, 1604.07411]

Anticipating Future Bounds/Discoveries



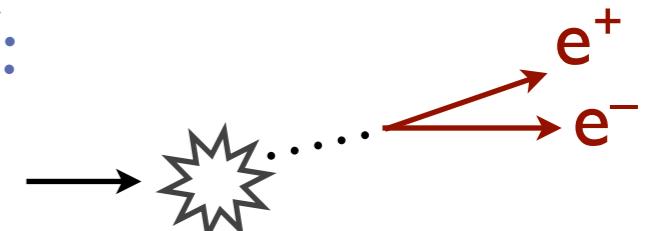
[Feng, Fornal, Galon, Gardner, Smolinsky, Tait, Tanedo, 1608.03591]

Prompt A' :



See talk by Moreno

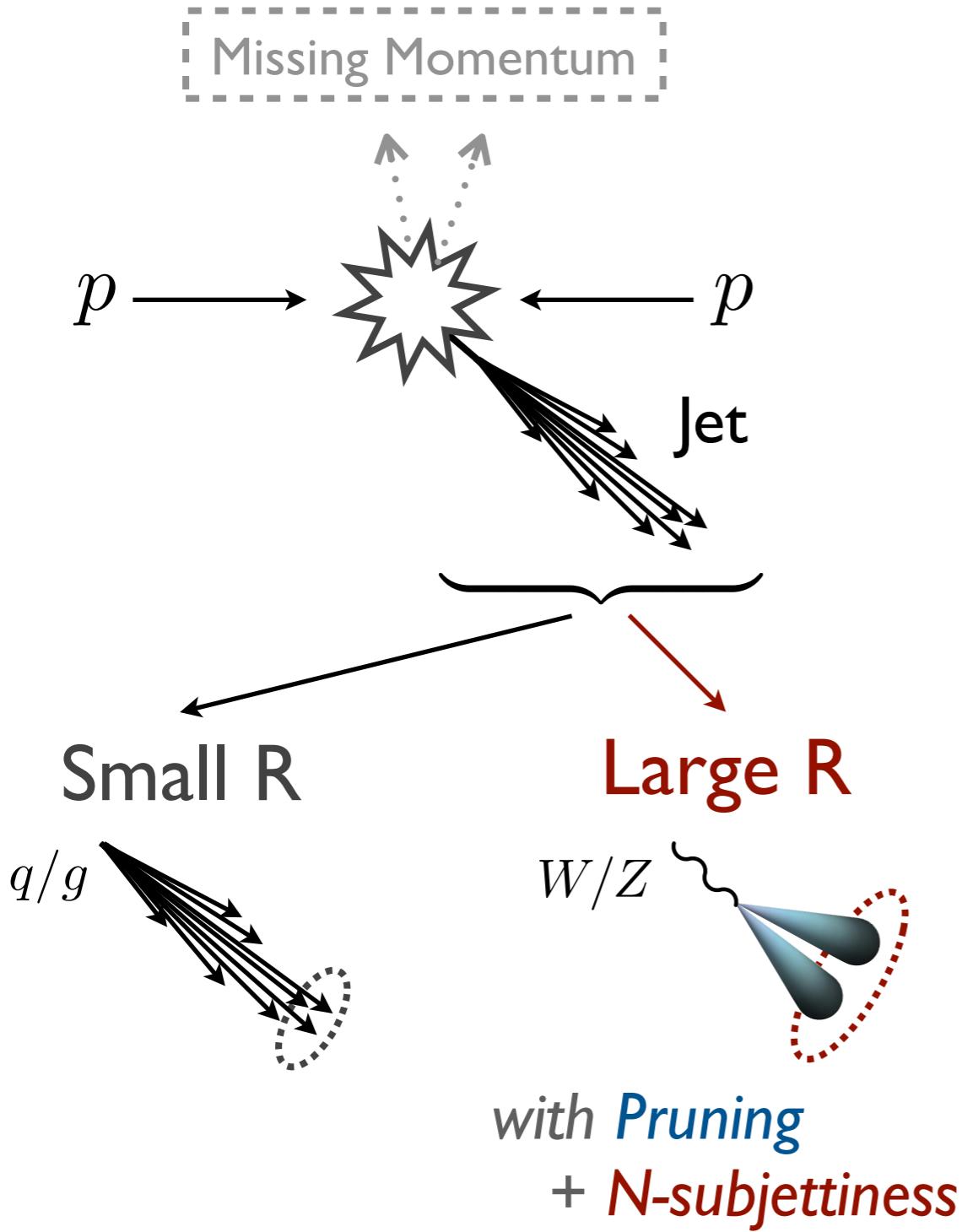
Displaced A' :



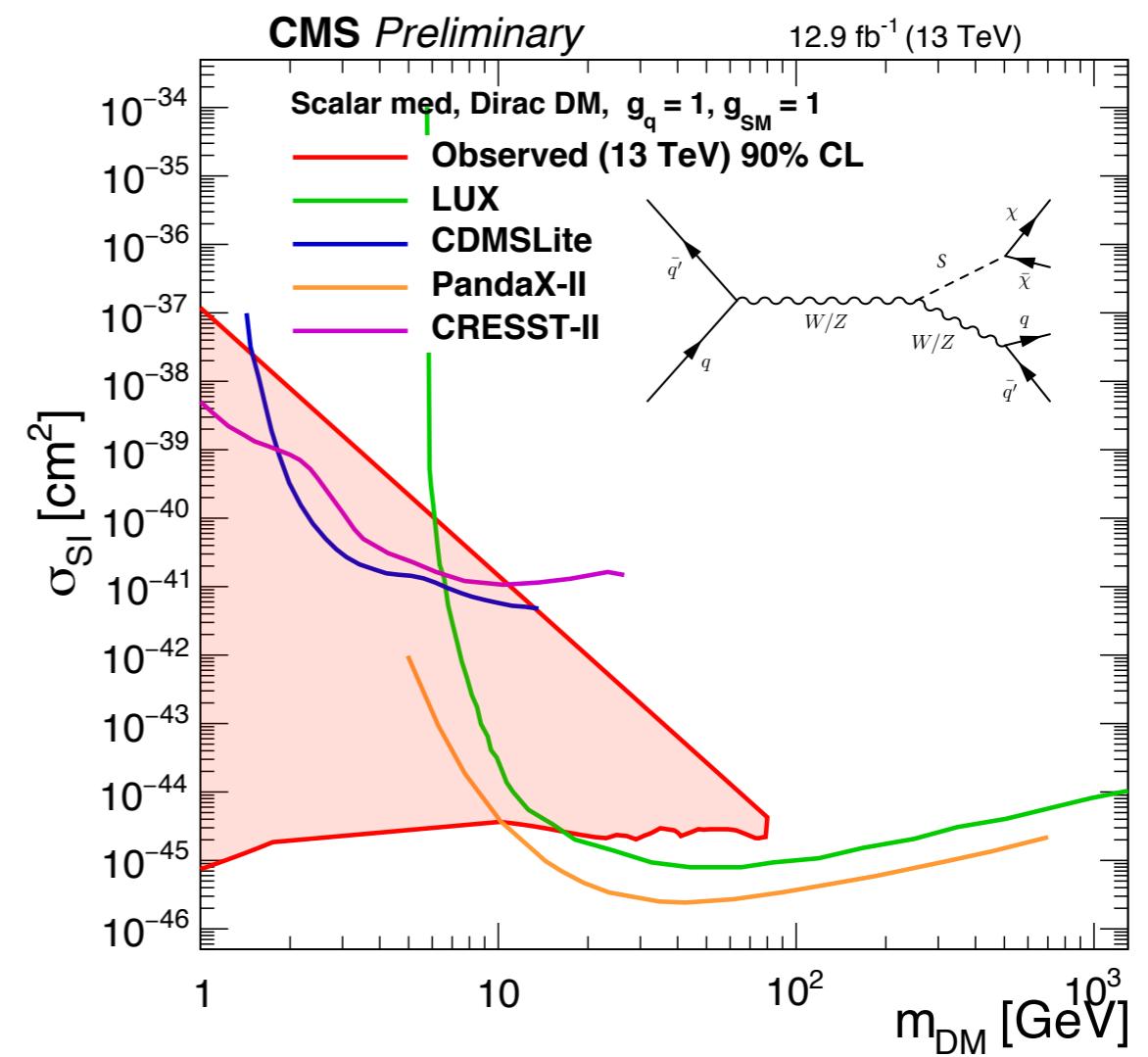
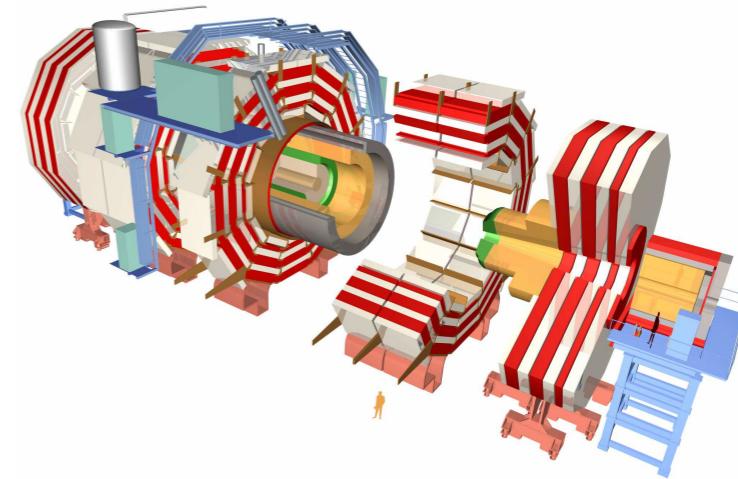
See talk by
Weinstein, Szumila-Vance

LHCb (?)

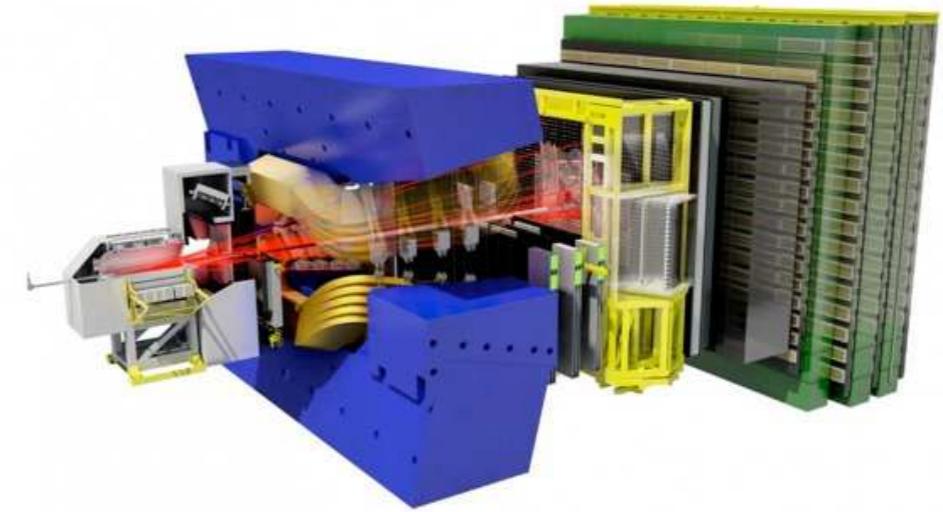
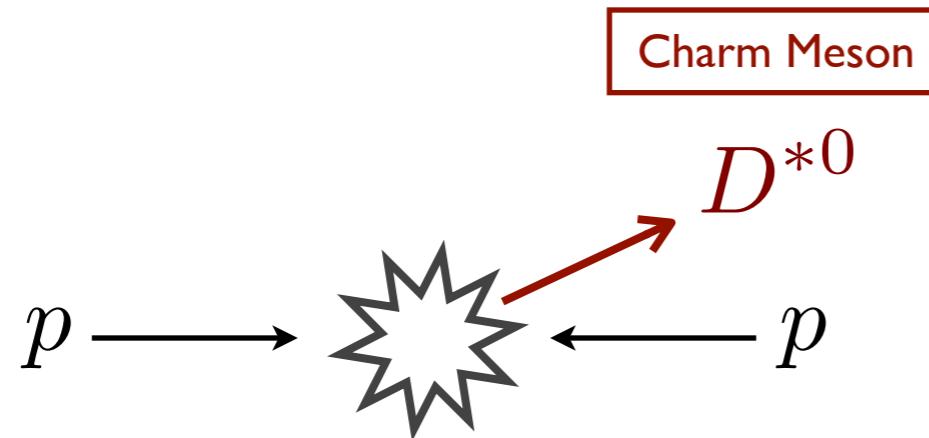
Dark Matter at Colliders: e.g. CMS



[CMS, 2016; using [Ellis, Vermilion, Walsh, 2009](#); [JDT, Van Tilburg, 2010, 2011](#)]



Dark Forces at Colliders: LHCb



For LHC Run 3 (2021–2023):

Triggerless detector readout, real-time data calibration, upgraded vertex locator (VELO), excellent mass resolution

$$\text{PP} \rightarrow D^{*0} \rightarrow D^0 \gamma$$

$\approx 14 \text{ trillion} \quad \times 38\%$

kinetic mixing

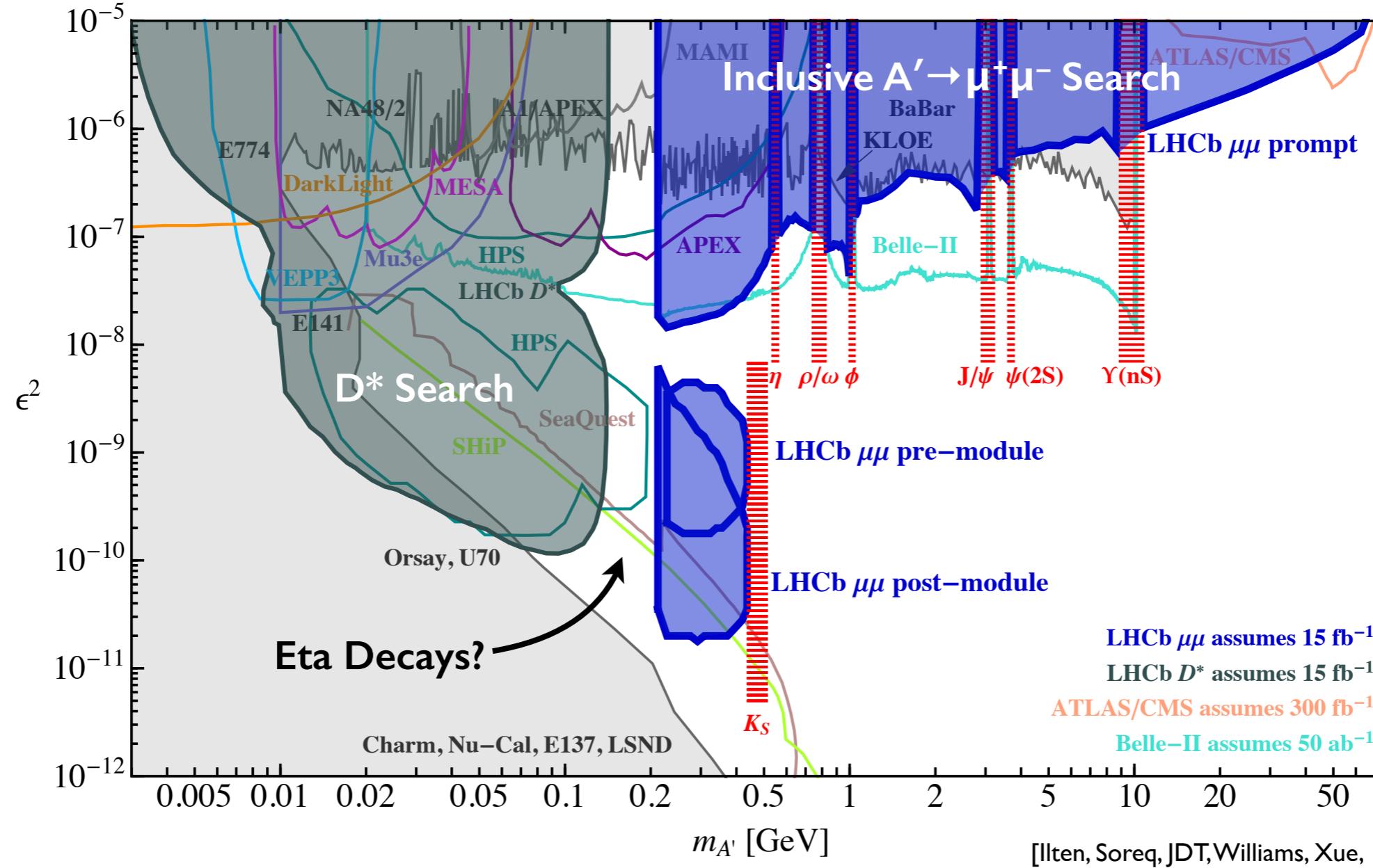
$m(D^{*0}) = 2007 \text{ MeV}$
 $m(D^0) = 1865 \text{ MeV}$
 $\Delta m = 142 \text{ MeV}$

$$A' \rightarrow e^+ e^-$$

[Ilten, JDT, Williams, Xue, 1509.06765]

Dark Forces at Colliders: LHCb

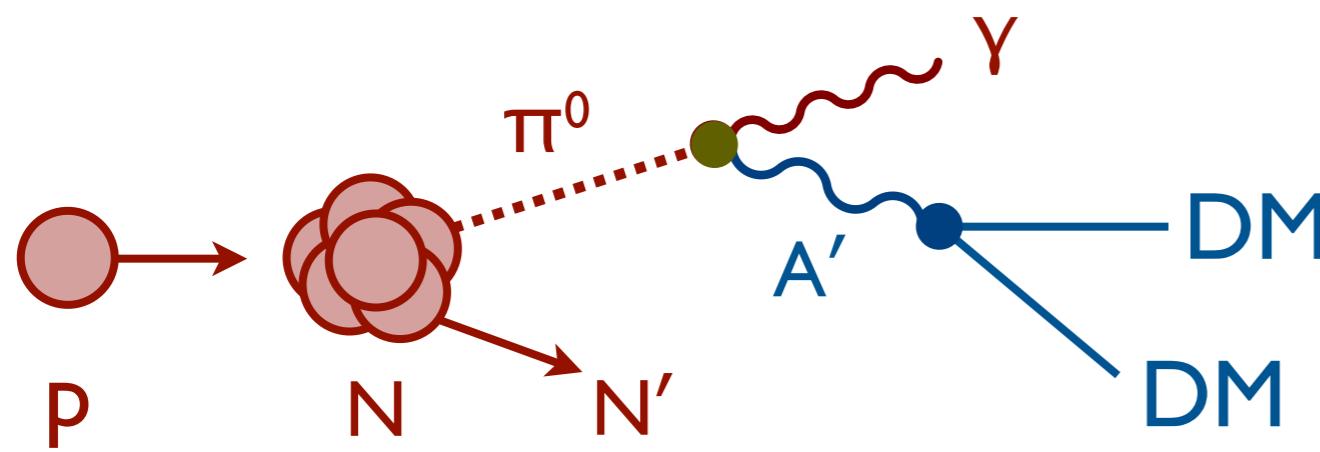
Anticipated Reach by 2023



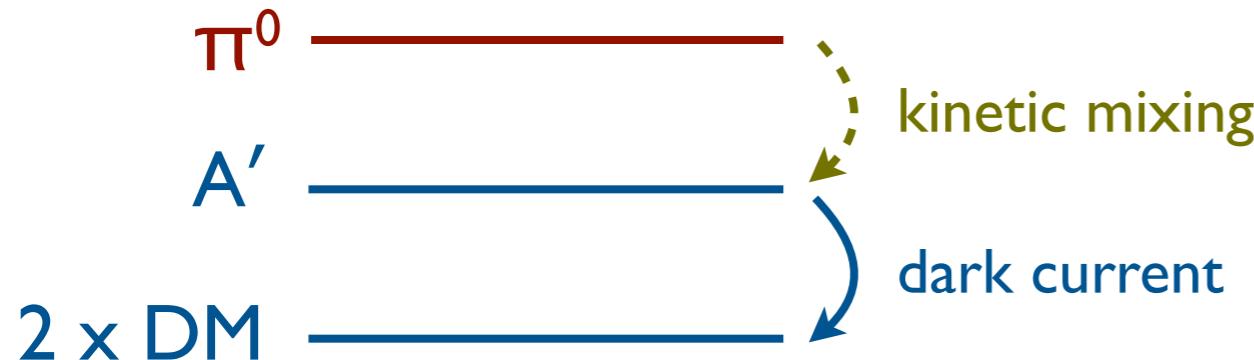
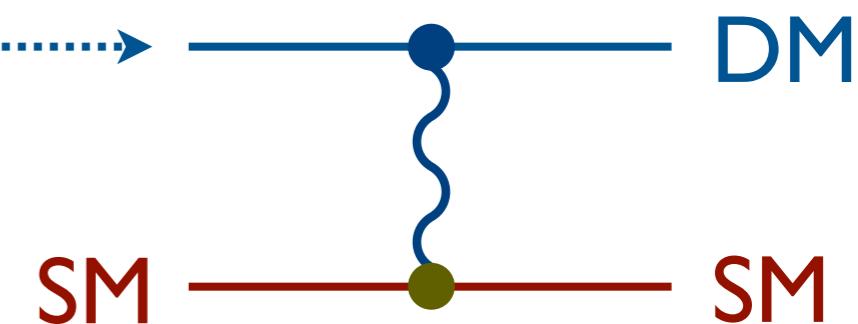
[Ilten, JDT, Williams, Xue, 1509.06765]

Making Dark Matter Beams

Production in beam dump...



...detection downstream

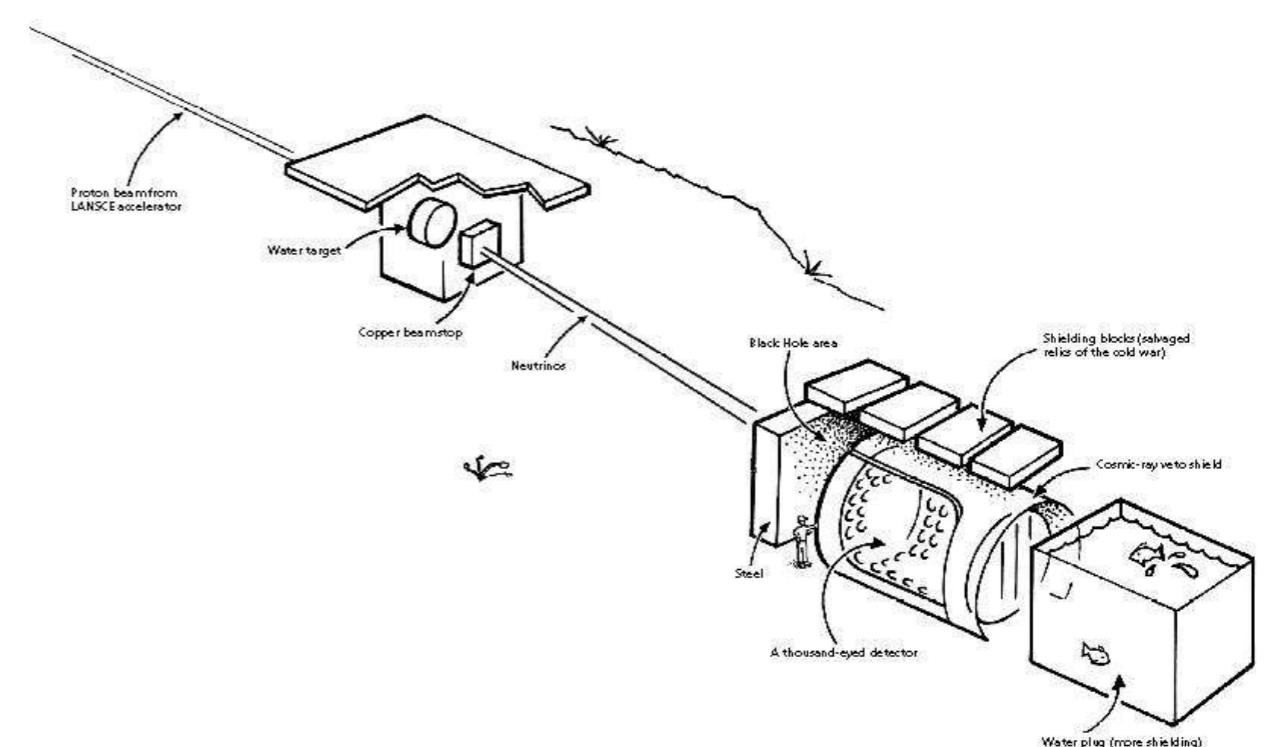
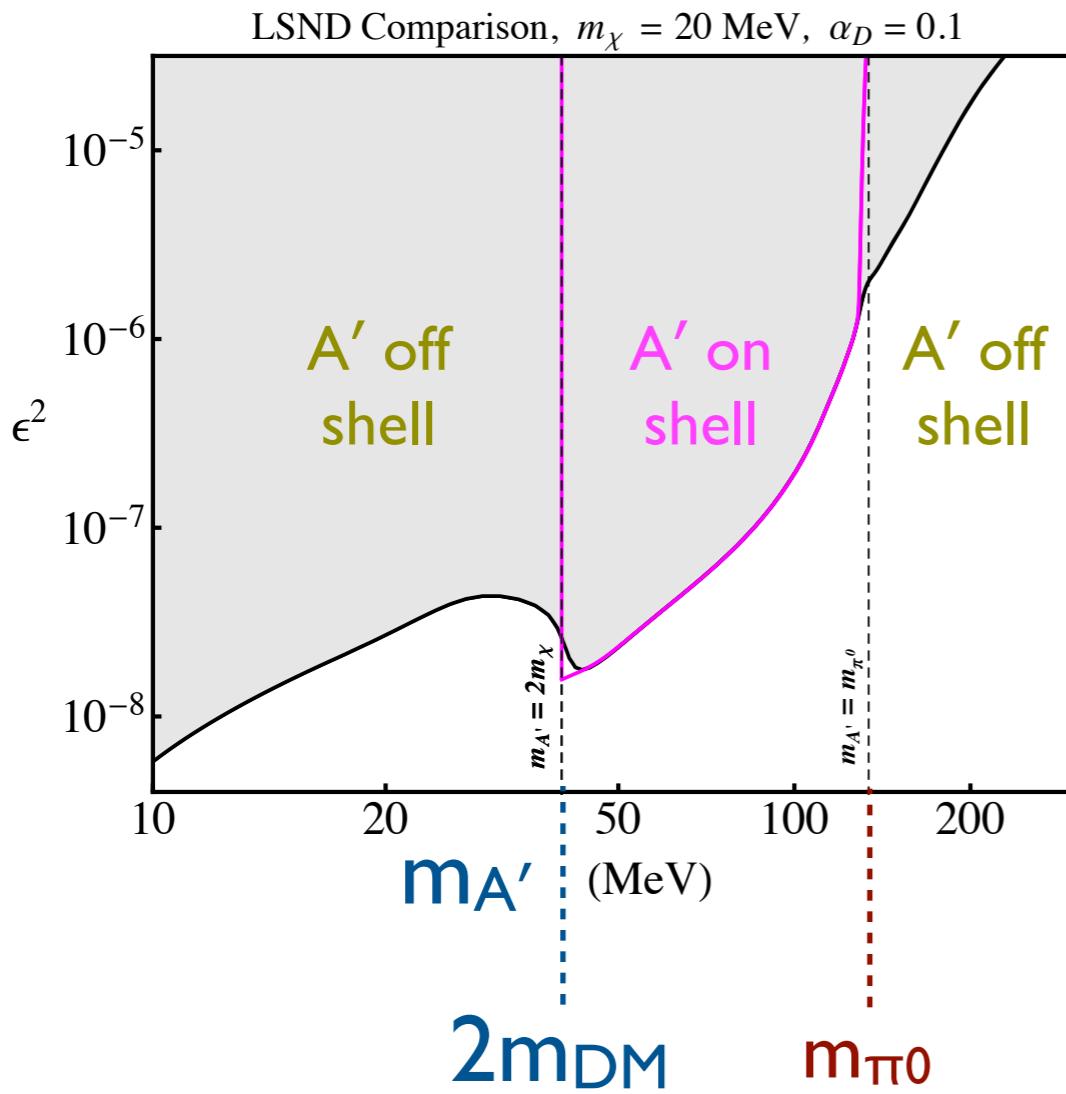


See talk by Cooper, Tayloe
(*MiniBooNE*)

[Batell, Pospelov, Ritz, 2009; + deNiverville, 2011; + McKeen, 2012; Izaguirre, Krnjaic, Schuster, Toro, 2013]

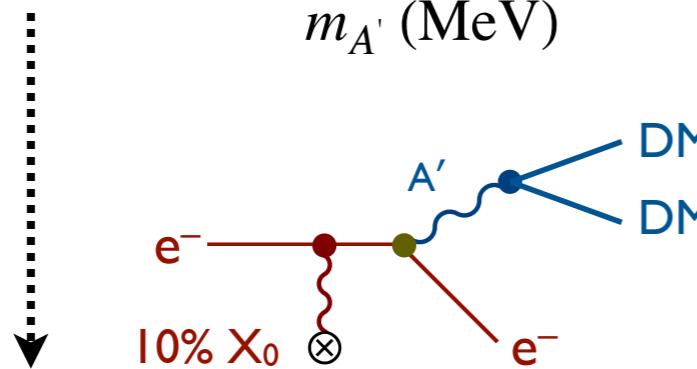
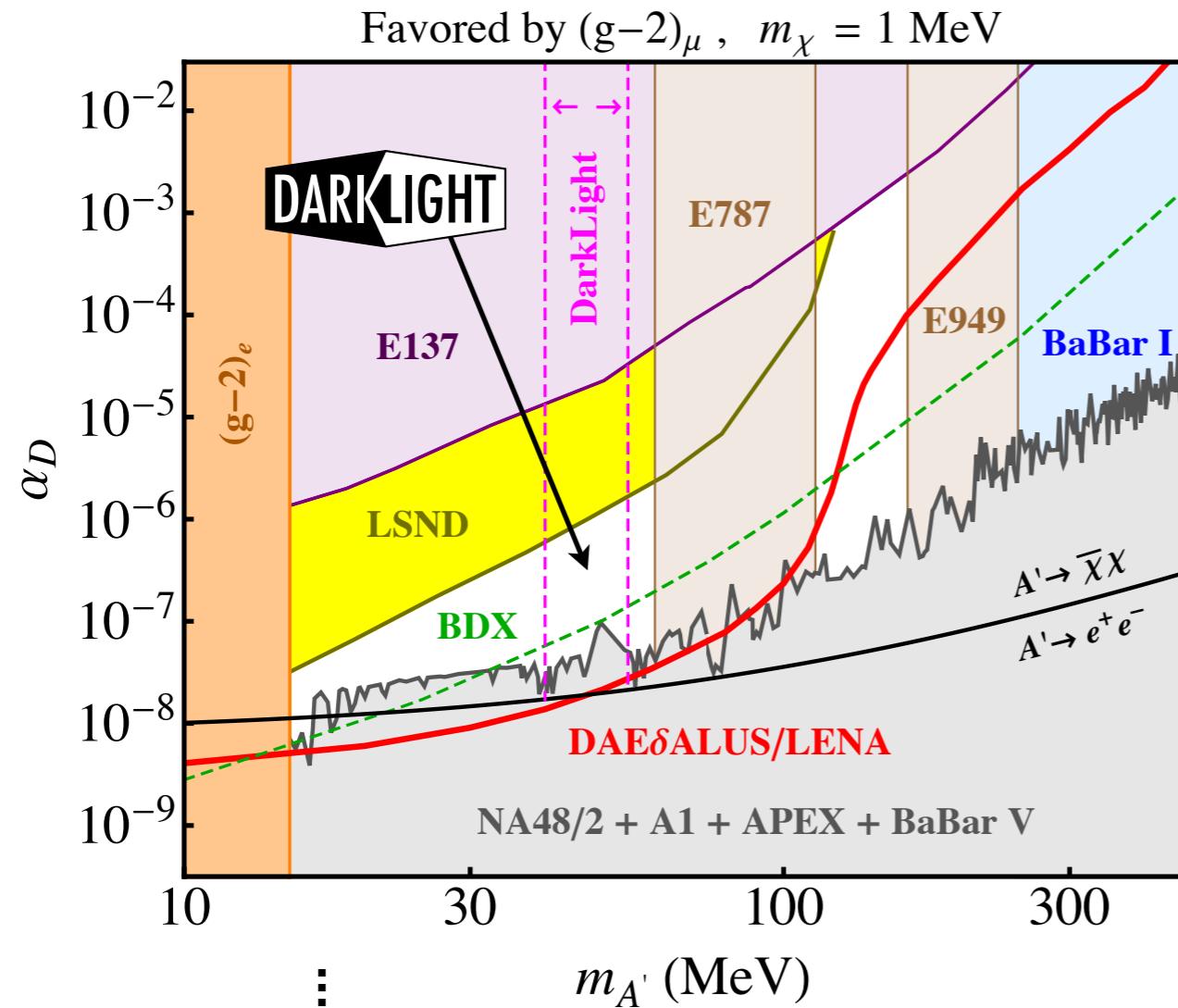
LSND Reinterpretations

$$\begin{aligned}
 p &\rightarrow \pi \rightarrow \mu \rightarrow \nu_e \dots \dots \nu_e e^- \rightarrow \nu_e e^- \\
 p &\rightarrow \pi^0 \xrightarrow{A'(*)} \gamma \text{DM DM} \dots \dots \text{DM } e^- \rightarrow \text{DM } e^-
 \end{aligned}$$

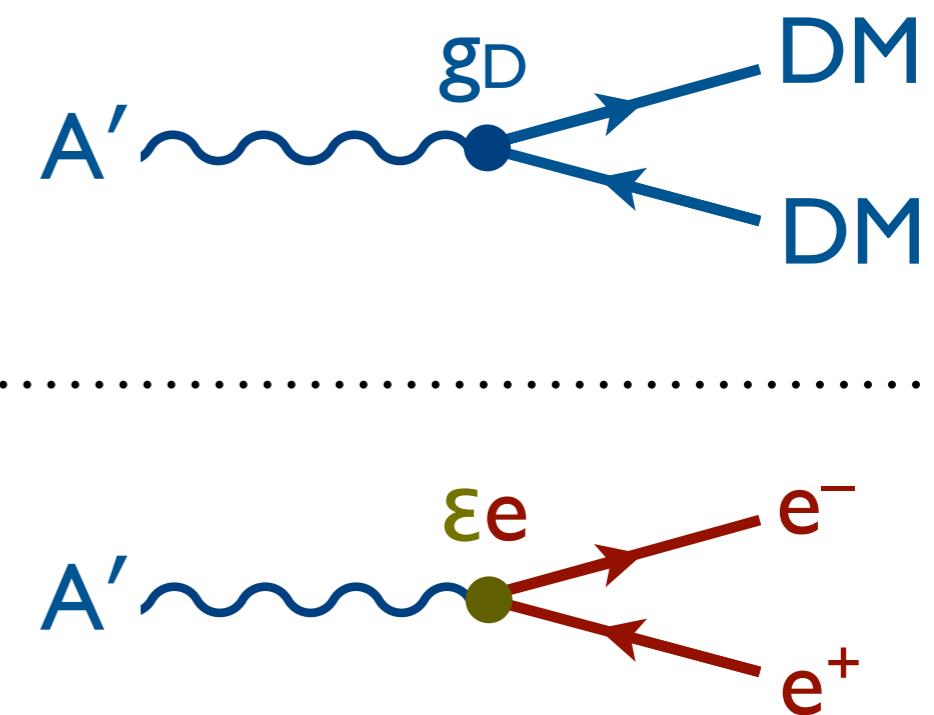
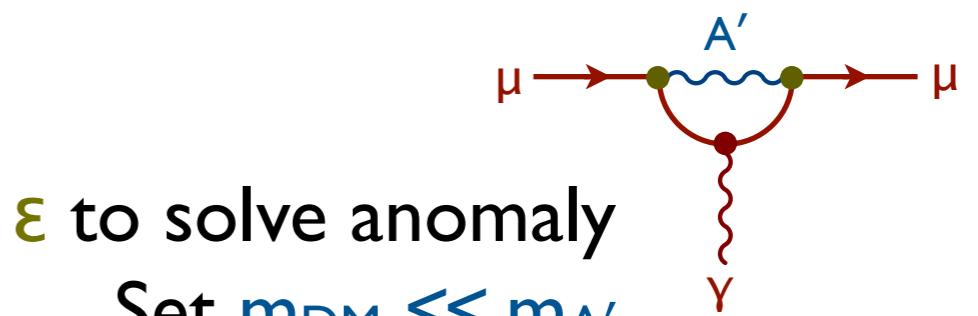


[using LSND, 2001; Kahn, Krnjaic, JDT, Toups, 2014]

Dark Forces for $(g-2)_\mu$?



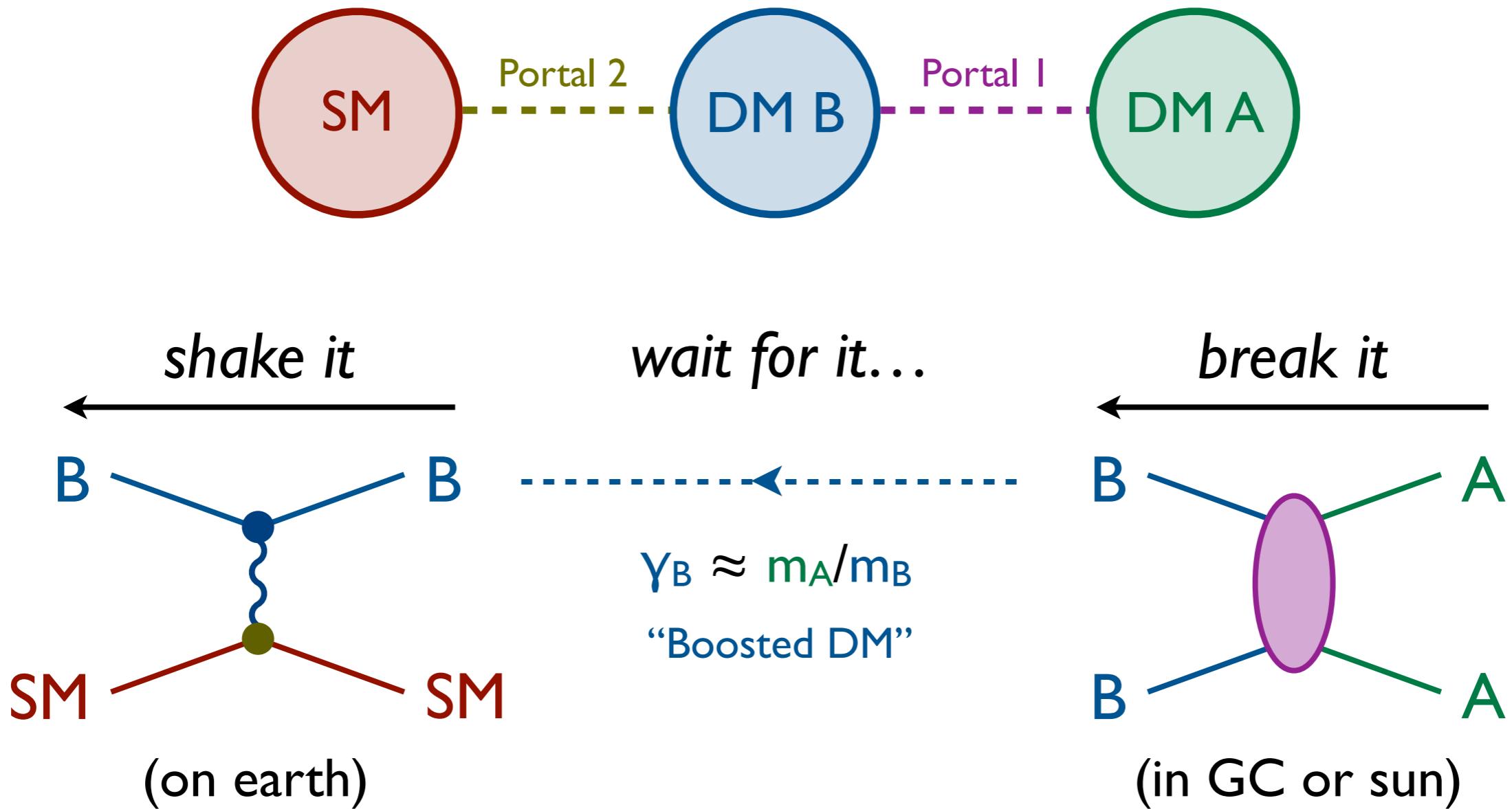
Set ϵ to solve anomaly
Set $m_{\text{DM}} \ll m_{A'}$



See talk by Colegrove
(LDMX)

[plot from Kahn, Krnjaic, JDT, Toups, 2014; see Pospelov, 2008]

Dark Matter Gives Itself a Boost

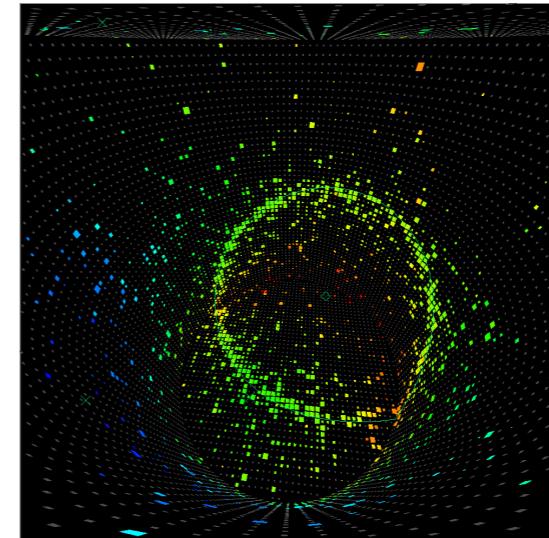
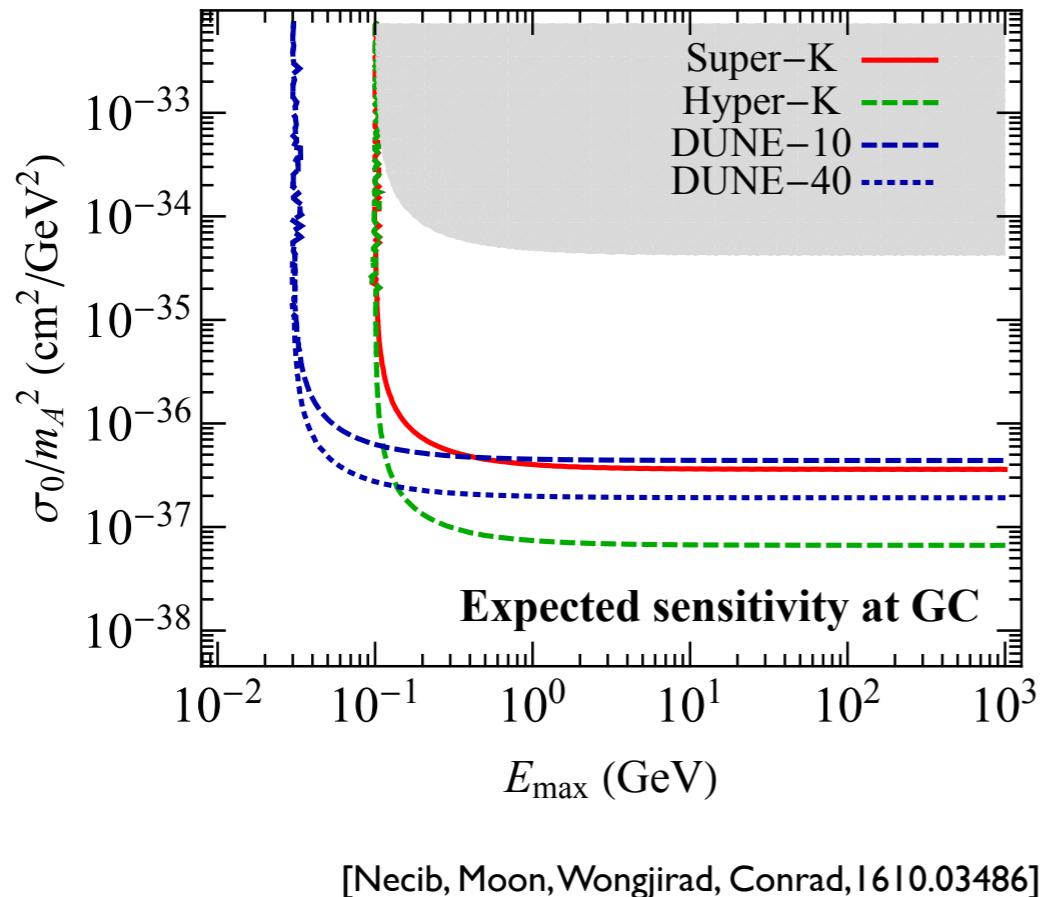


DM as quasi-relativistic cosmic ray / not-so-sterile “neutrino”

[Agashe, Cui, Necib, JDT, 2014; see also Huang, Zhao, 2013; Berger, Cui, Zhao, 2014]

Dark Matter Gives Itself a Boost

Promising signals for neutrino telescopes “pointing” at GC



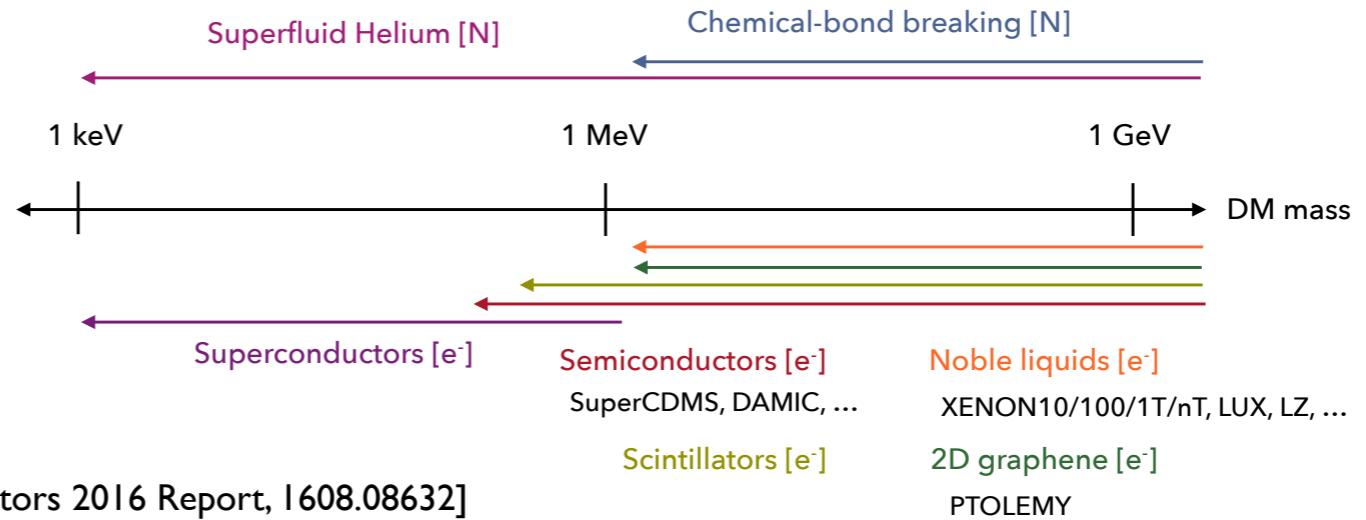
VS.



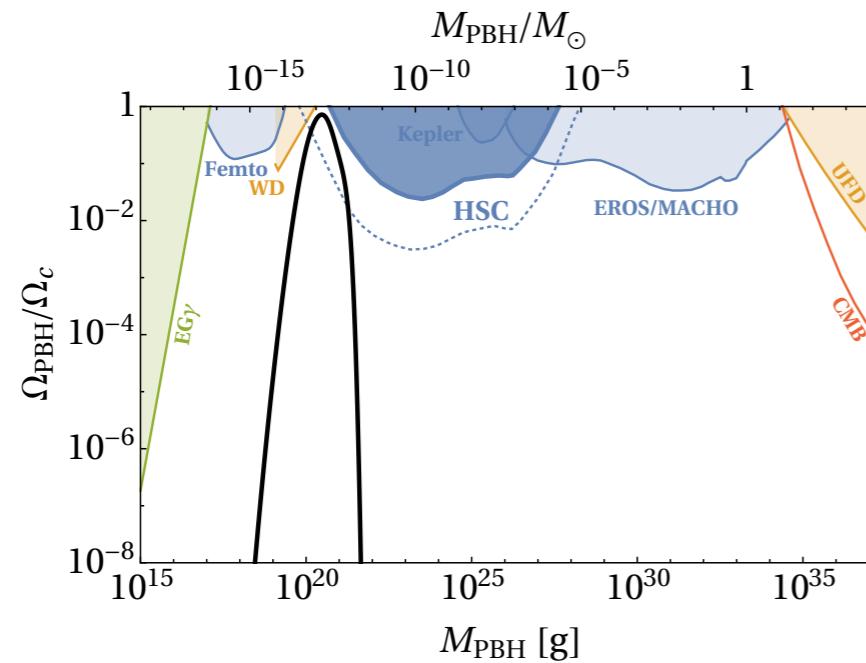
[Agashe, Cui, Necib, JDT, 2014; see also Huang, Zhao, 2013; Berger, Cui, Zhao, 2014]

Other Non-WIMP Investigations (not exhaustive...)

New Sub-GeV Detection Strategies

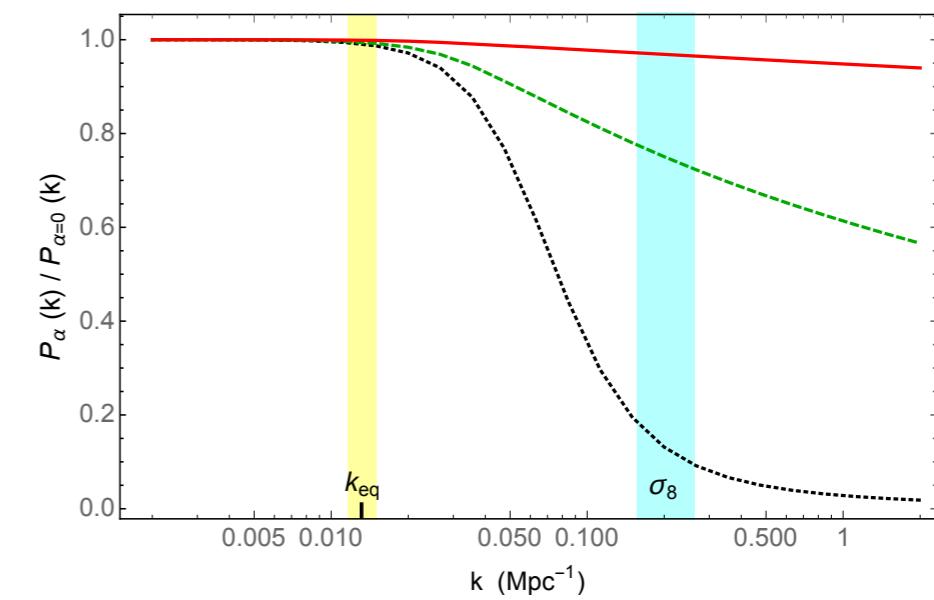


Revisiting Primordial Black Holes



[plot from Inomata, Kawasaki, Mukaida, Tada, Yanagida, 1701.02544]

Dark Radiation and Large Scale Structure



[plot from Buen-Abad, Marques-Tavares, Schmaltz, 1505.03542]

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

March 23–25, 2017, University of Maryland, College Park



“The DOE HEP office has requested that a community-organized workshop be held in early 2017 to examine the next experimental step(s) in the search for dark matter. The focus will be on opportunities for dark matter searches in line with the P5-recommended portfolio of small-scale projects, targeting well-motivated areas of parameter space that are not expected to be covered by existing projects. The workshop will be the first step toward a white-paper report that lays out the science case and possible project concept.

*This workshop represents an important opportunity to consider new **small-scale experimental thrusts** for the U.S. Dark Matter program and we encourage all those interested in Dark Matter experiments to attend.”*

<https://indico.fnal.gov/conferenceDisplay.py?confId=13702>

Looking forward to a great mini-symposium!

