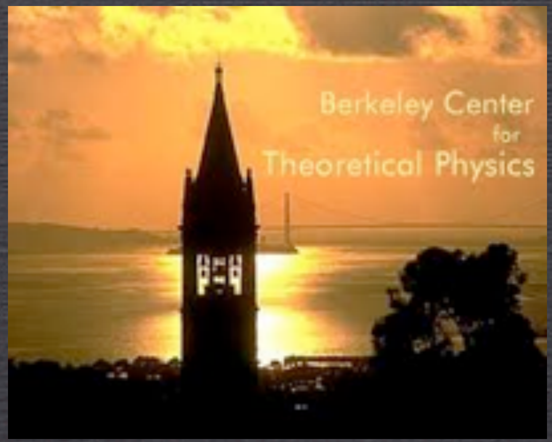
Cosmic Clues for Dark Matter

Direct, Indirect and LHC Detection Update

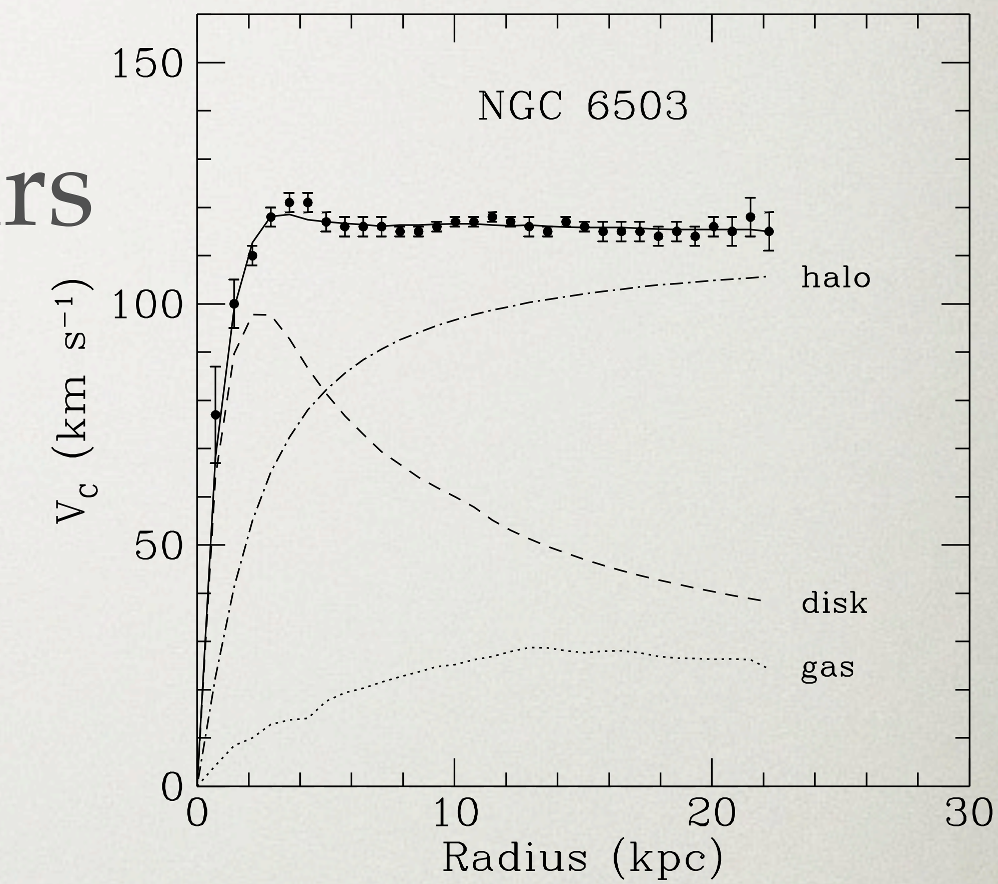
Kathryn M. Zurek

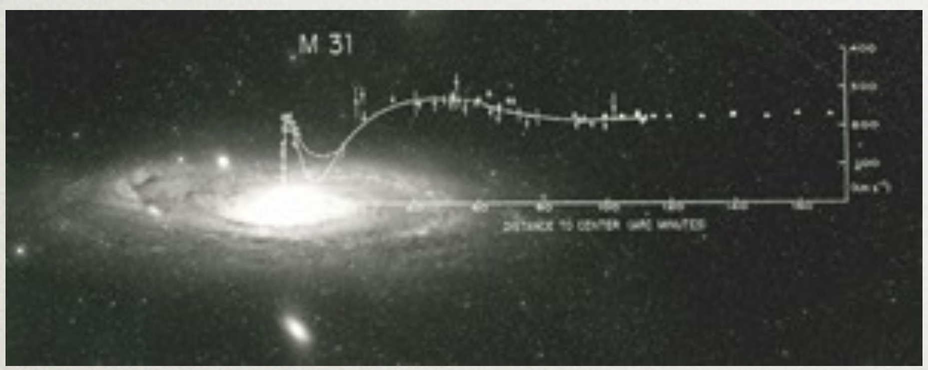


Evidence for DM Overwhelming

Begeman, Broels and Sanders (1991)

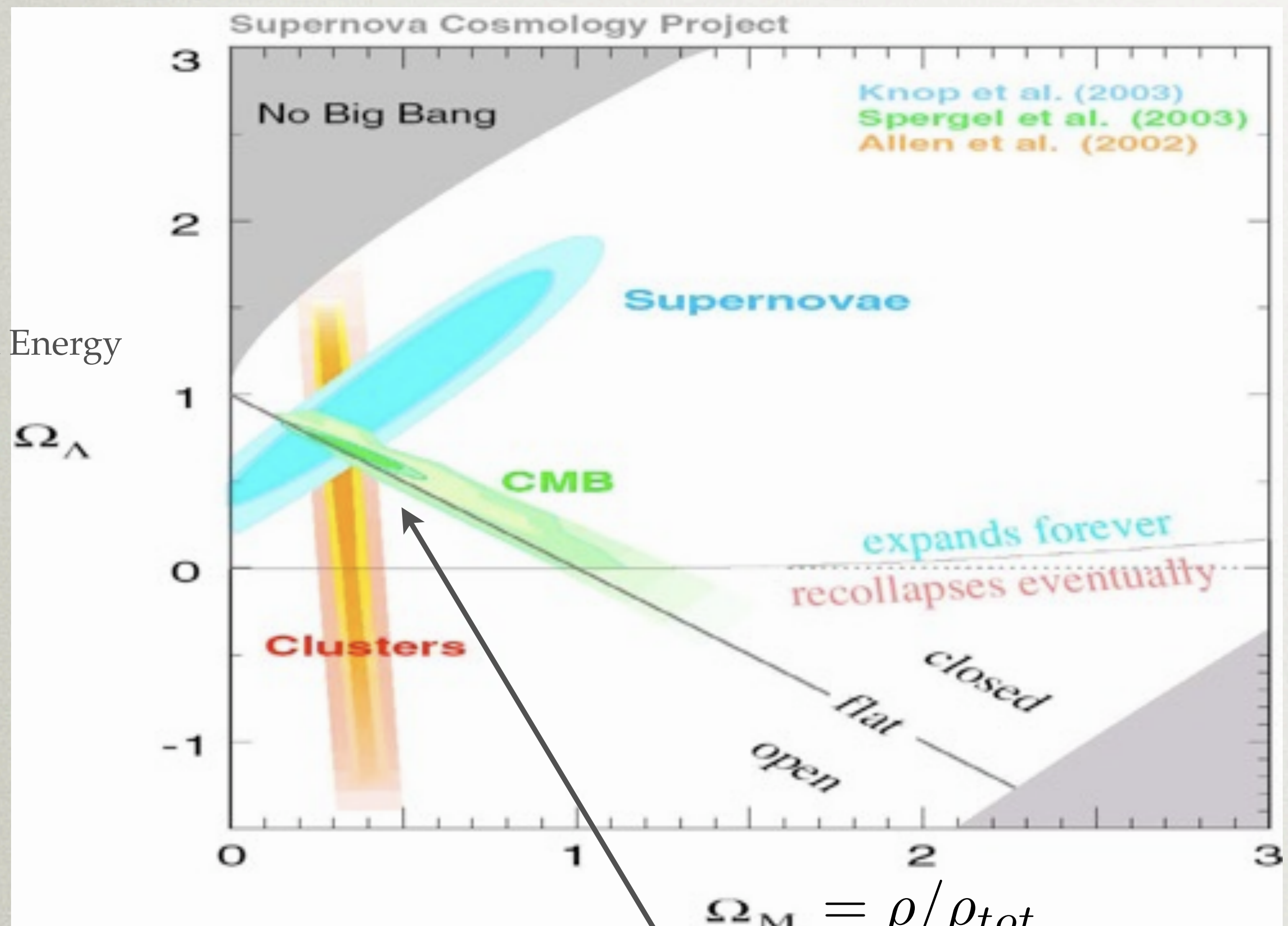
- Hunt dates over 75 years



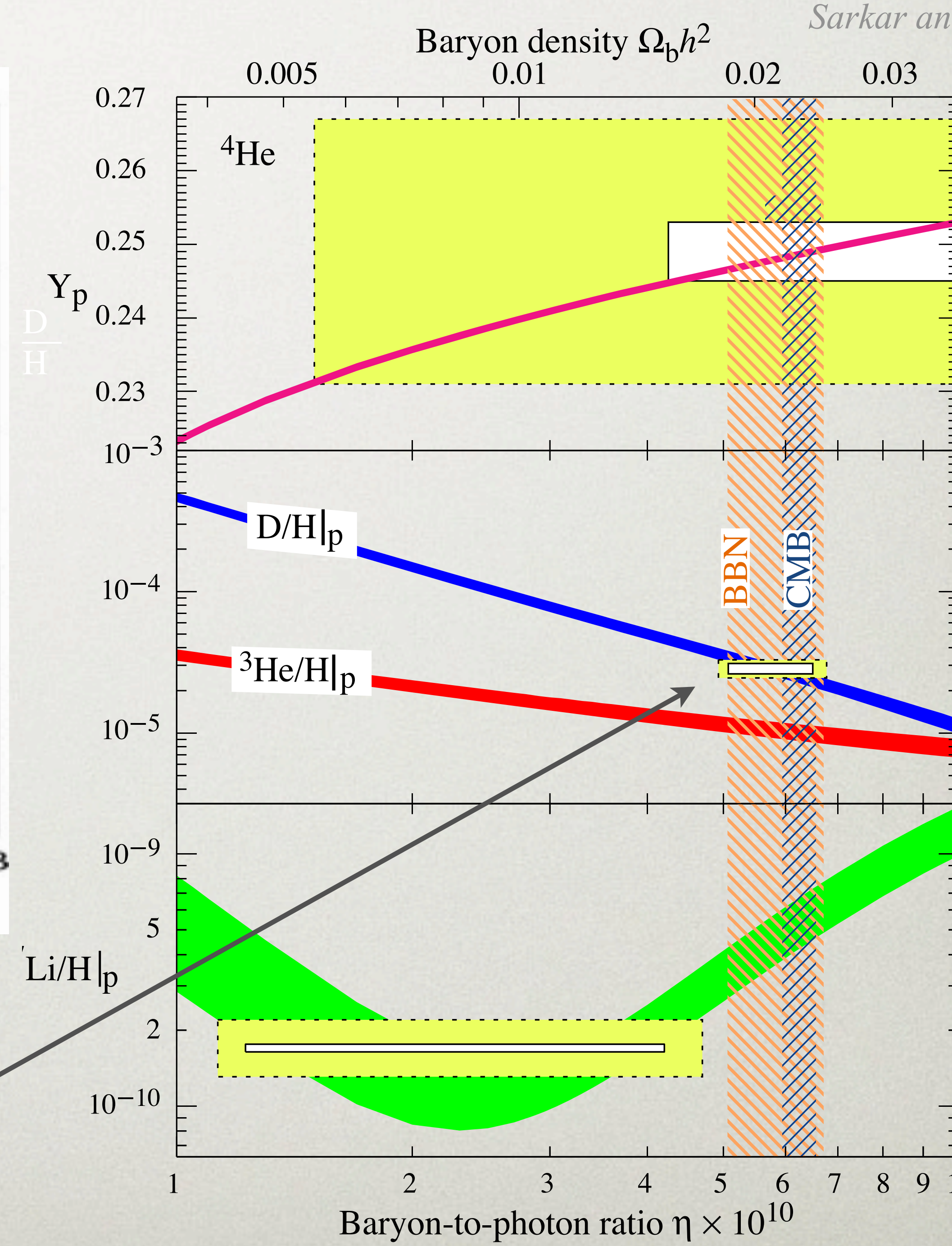


Advent of Precision Cosmology

Dark Energy



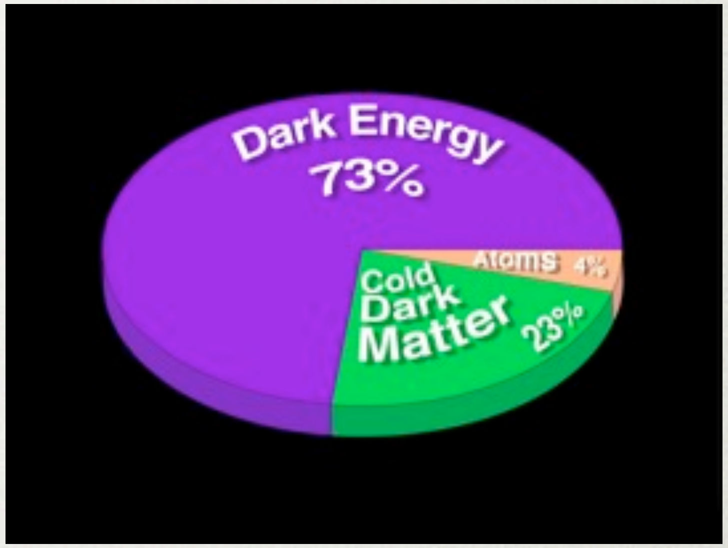
Sarkar and Fields

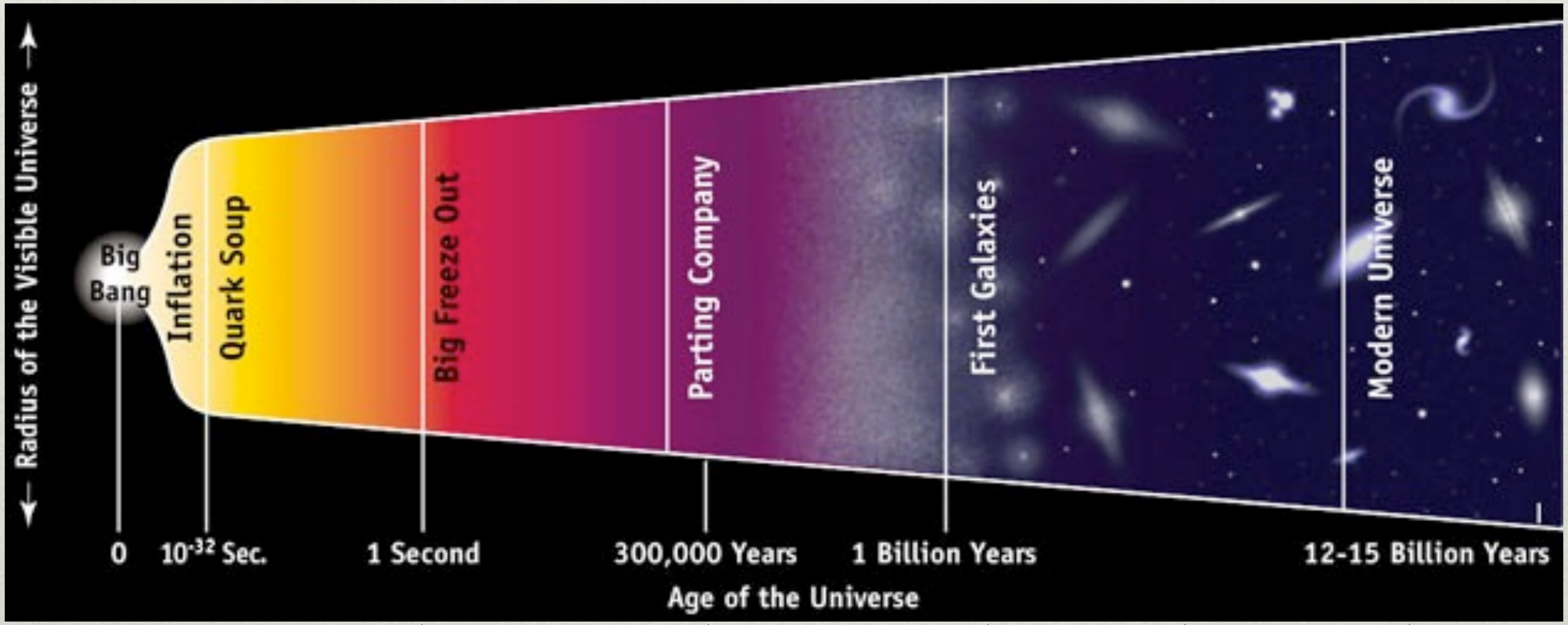


Concordance!

Evidence for DM Overwhelming

All evidence points toward

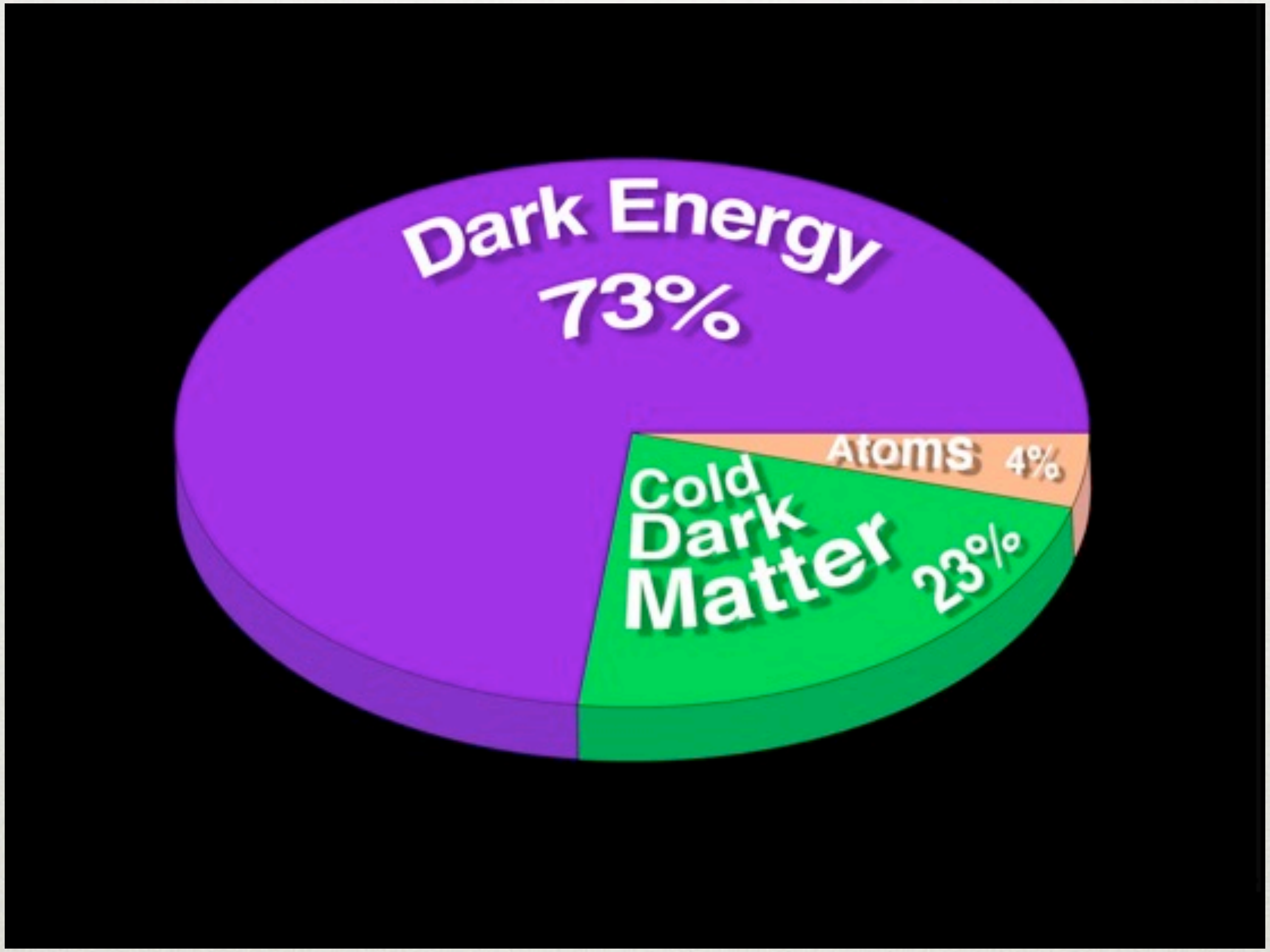




↑ BBN (baryons)
↑ CMB (curvature)
↑ LSS (matter)
↑ Supernovae (DE)
↑ Galaxy curves (matter)

New Physics

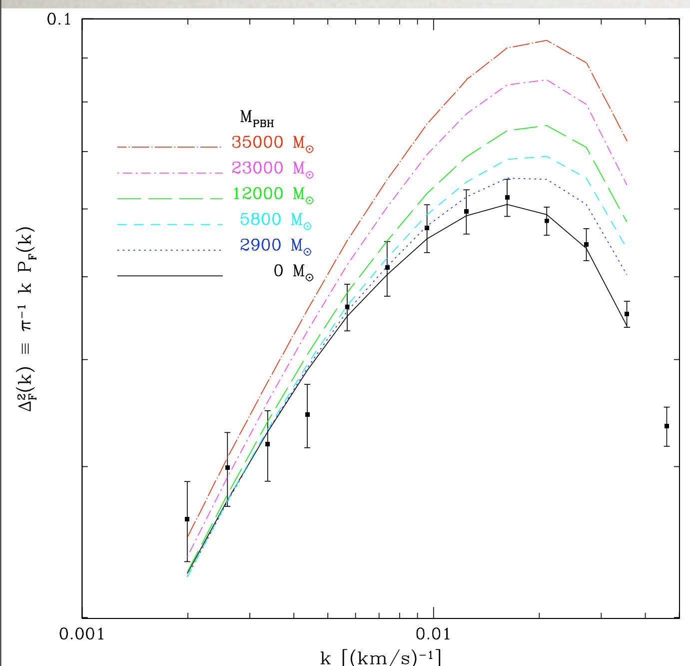
Dynamical Selection?



New Dynamics in Particles, Definitely BSM

What Do We Know About the Dark Matter?

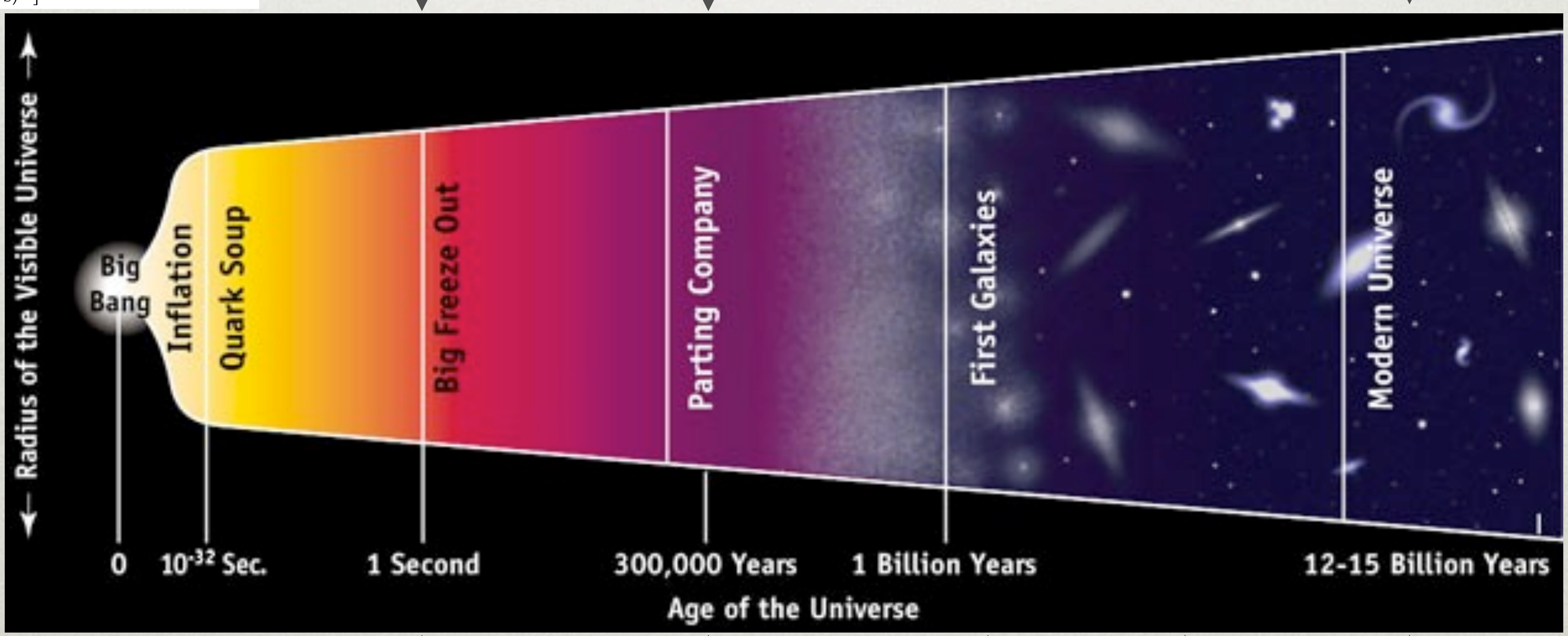
DM clumpiness



Afshordi, McDonald, Spergel

BBN CMB
Not Free Baryons

MACHO searches + Lya
Not Bound Baryons



BBN (baryons)

CMB (curvature)

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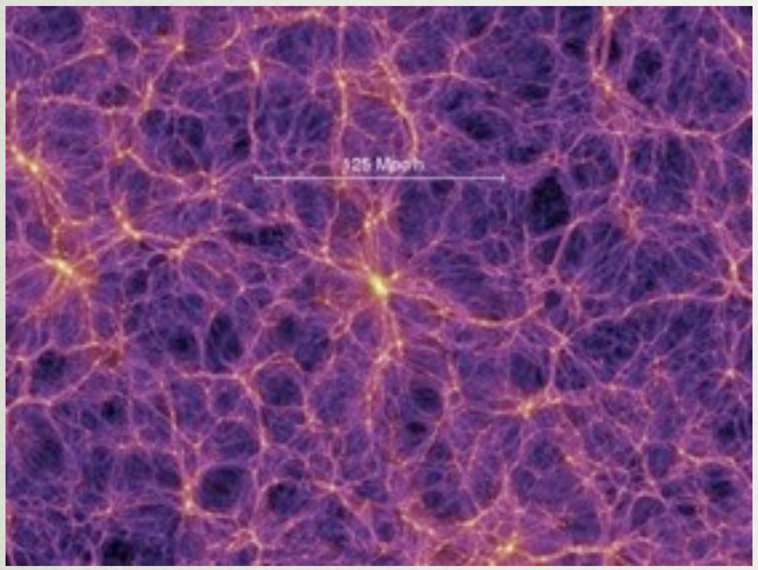
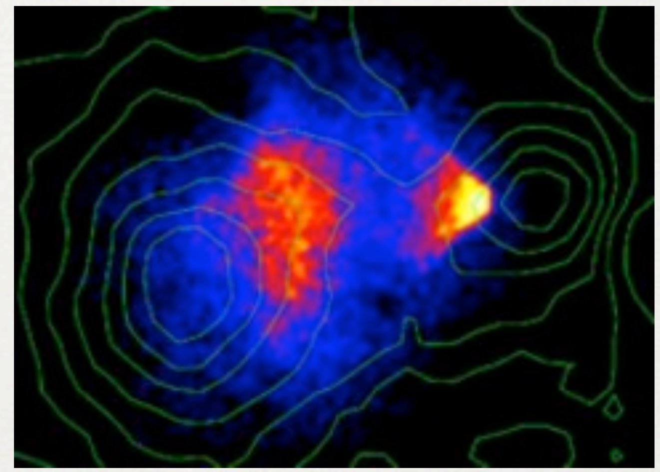
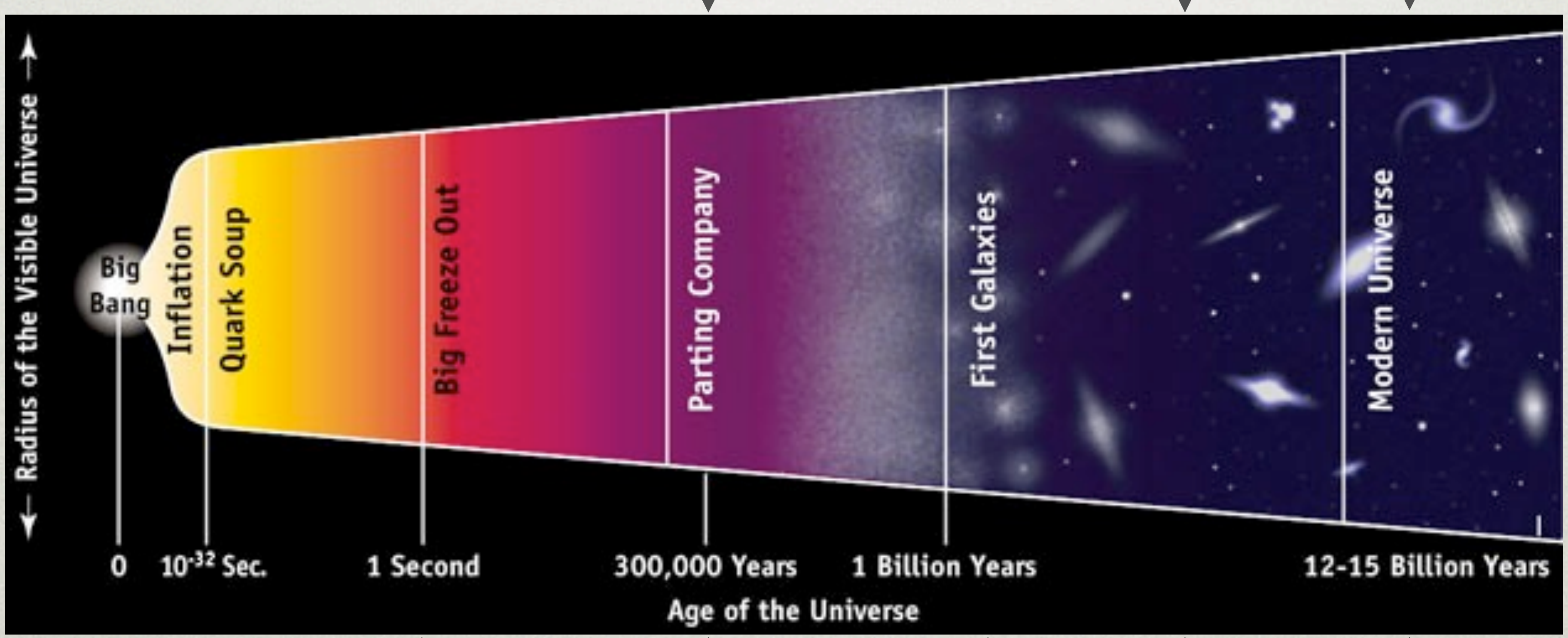
What Do We Know About the Dark Matter?





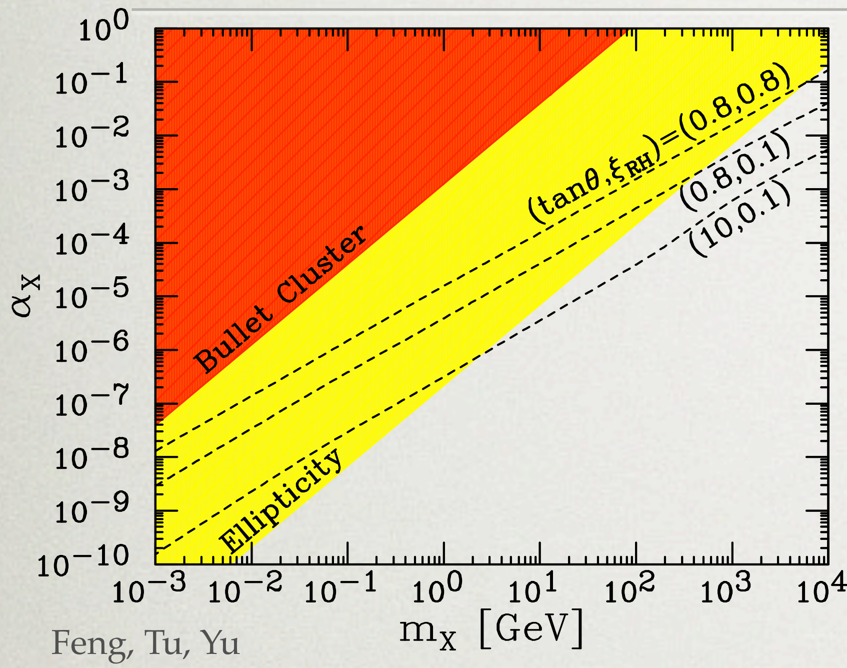
X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al

CMB ↓ LSS ↓ LSS+Bullet Cluster Not Modified Gravity ↓



↑ BBN (baryons) ↑ CMB (curvature) ↑ Supernovae (DE) ↑ LSS (matter) ↑ Galaxy curves (matter)

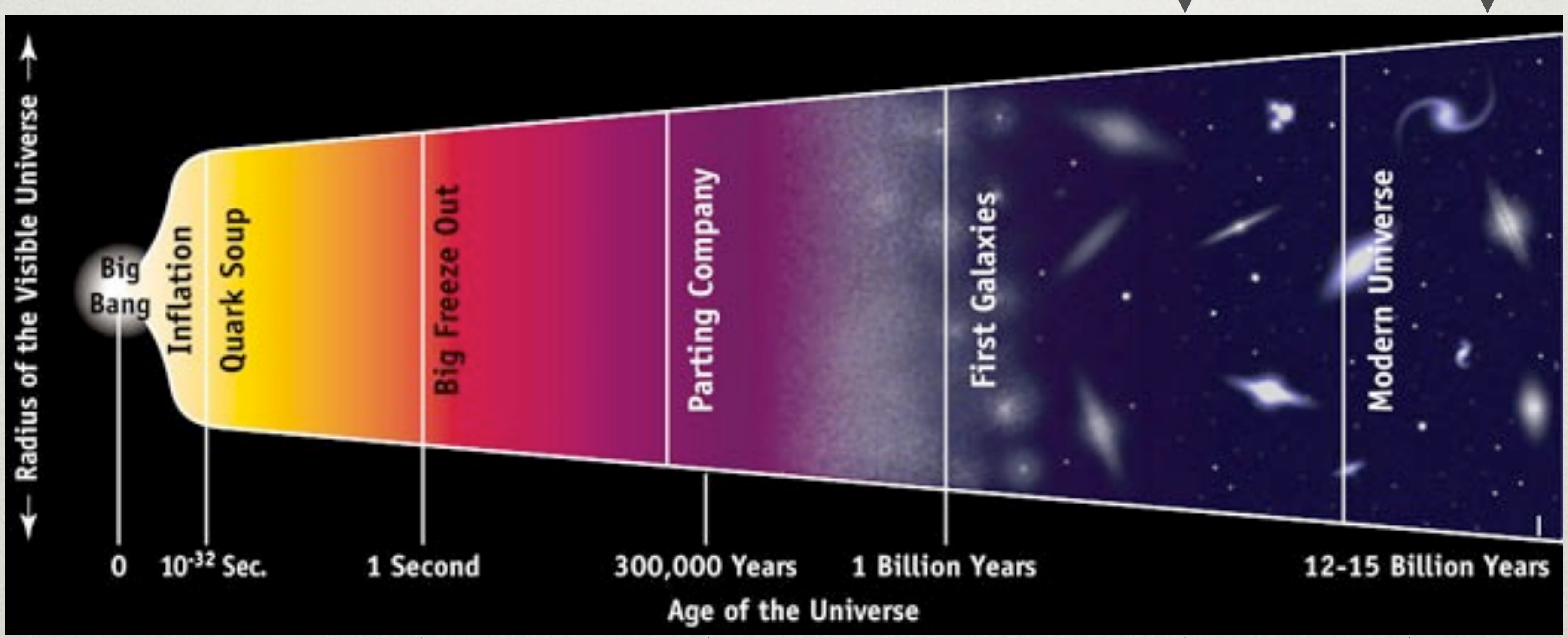
What Do We Know About the Dark Matter?



Feng, Tu, Yu

Halo Shapes
Weakly Self-interacting

Direct Probes
Weakly Interacting with Us



BBN (baryons)

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Supernovae (DE)

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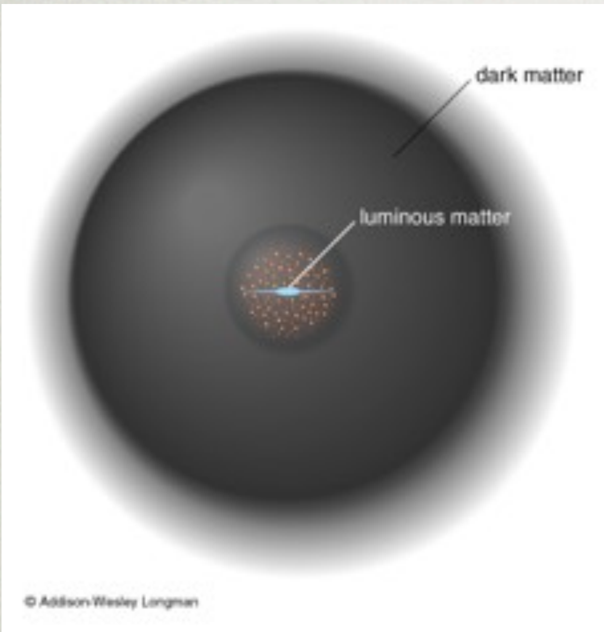
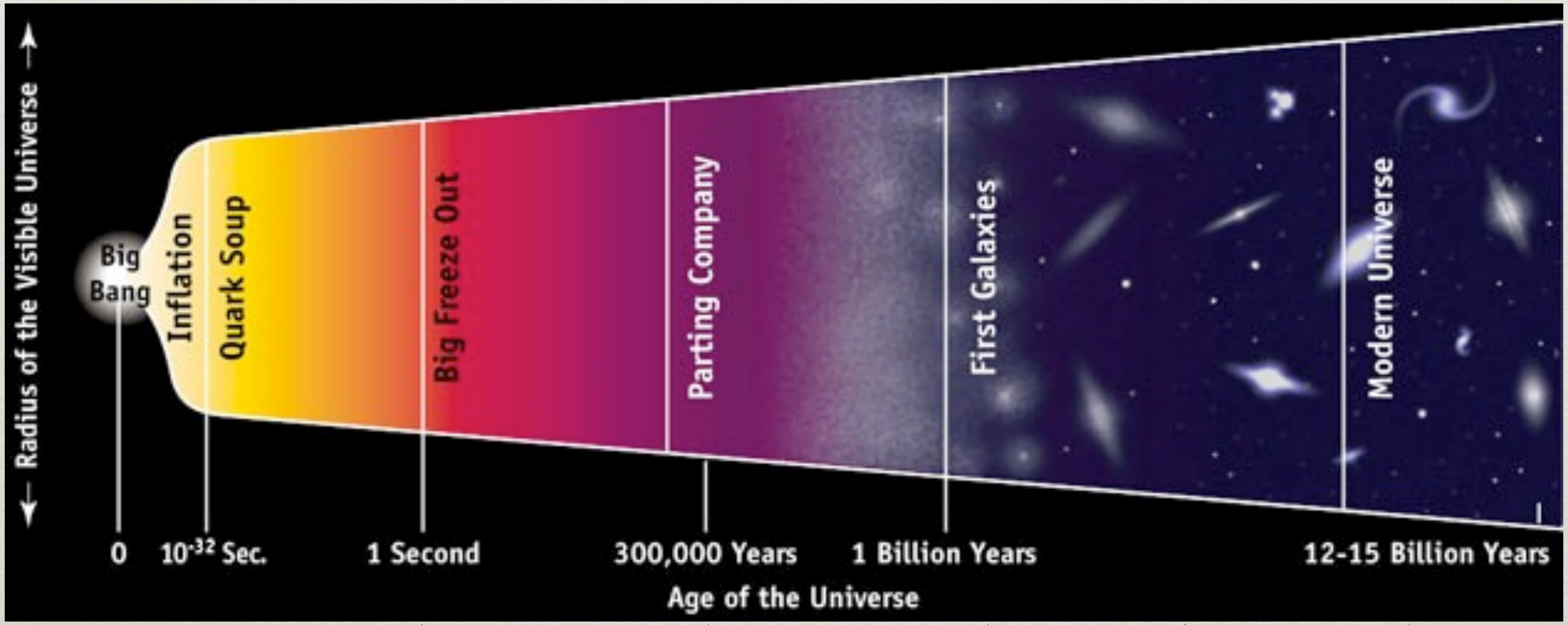
Galaxy curves (matter)

How Dark is Dark Matter?

McDermott, Yu, KZ
1011.2907



Consider All Epochs!

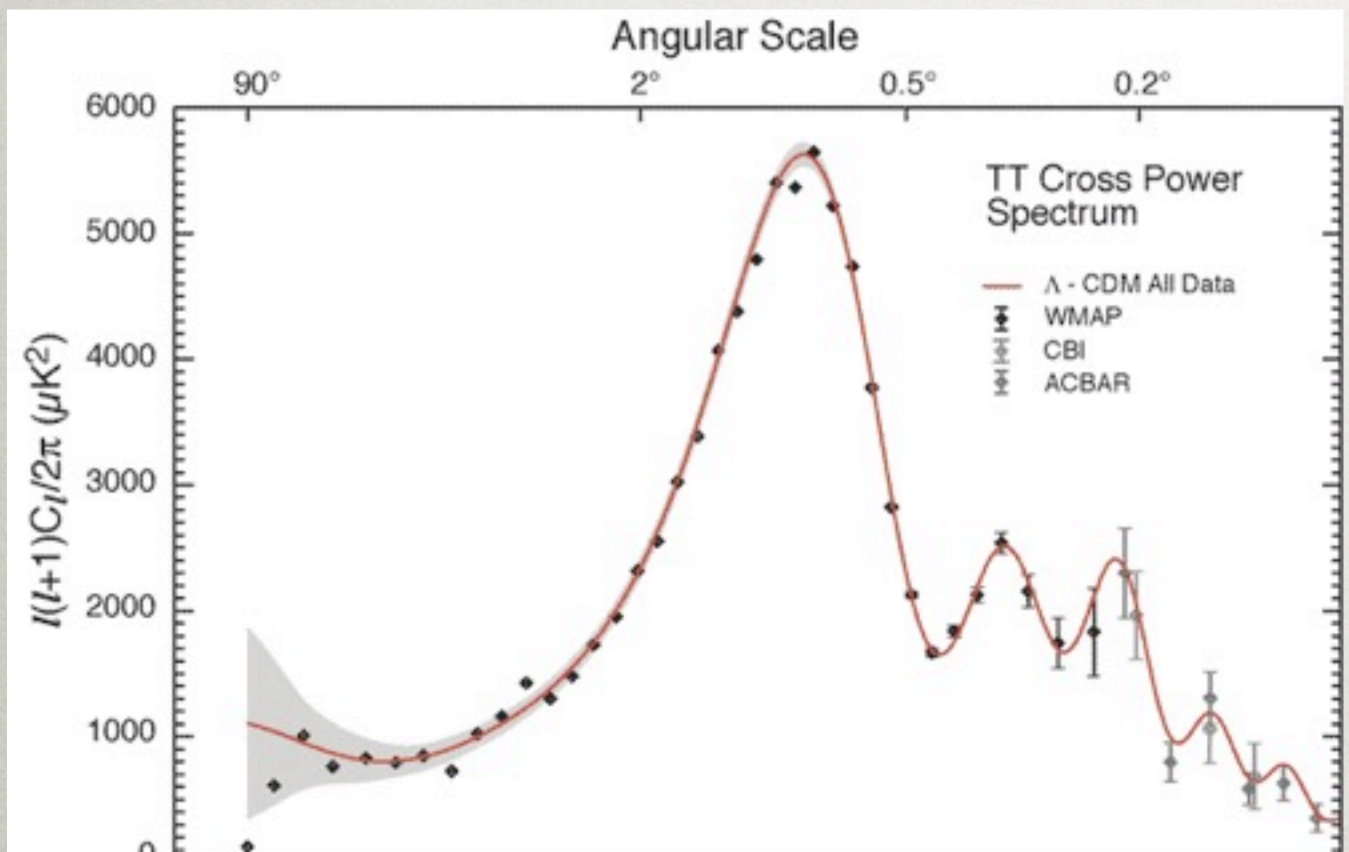


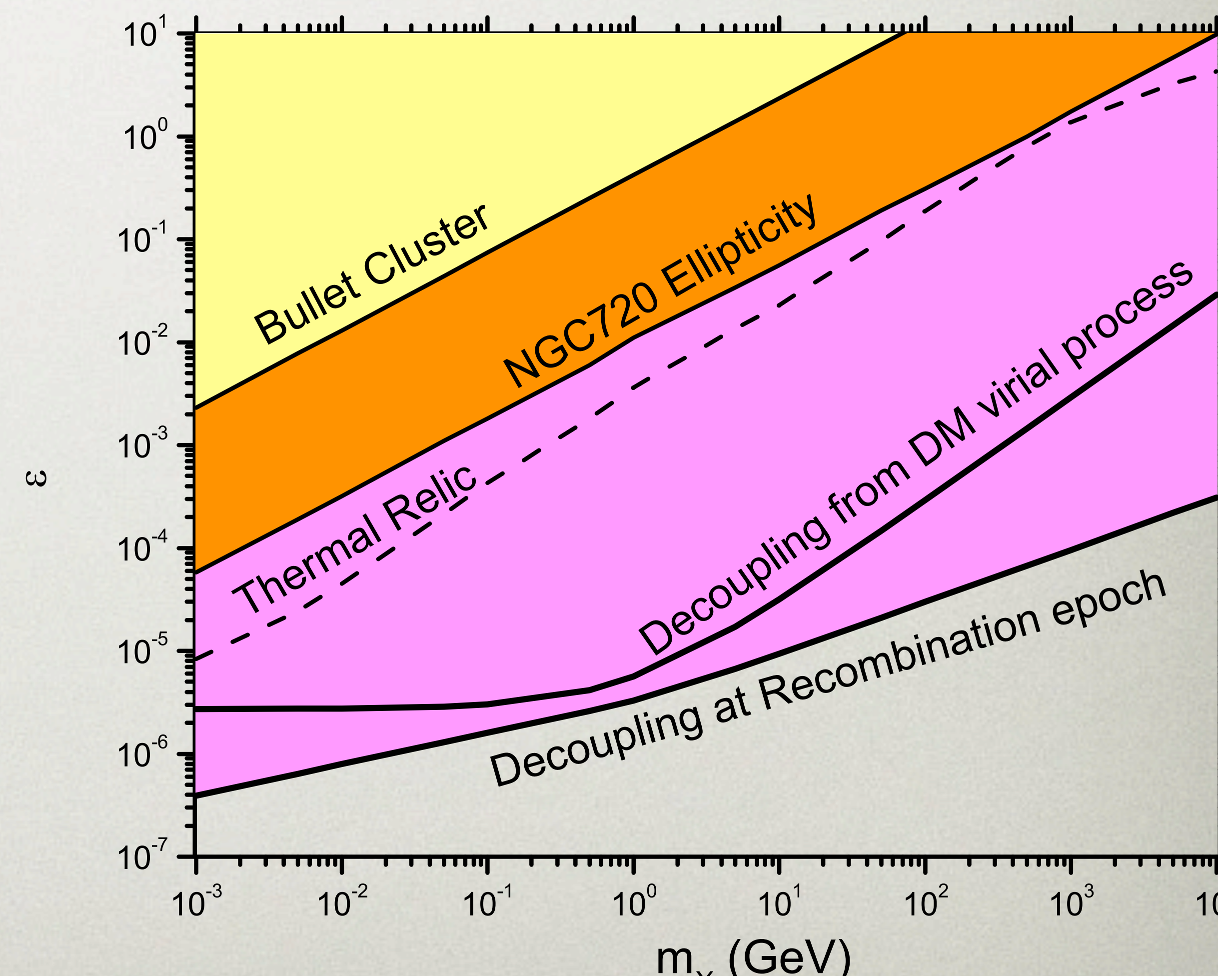
BBN (baryons) | CMB (curvature) | Supernovae (DE) | LSS (matter) | Galaxy curves (matter)

How Dark is Dark Matter?

- Which probe is the most constraining?

Constraint on DM charge ε

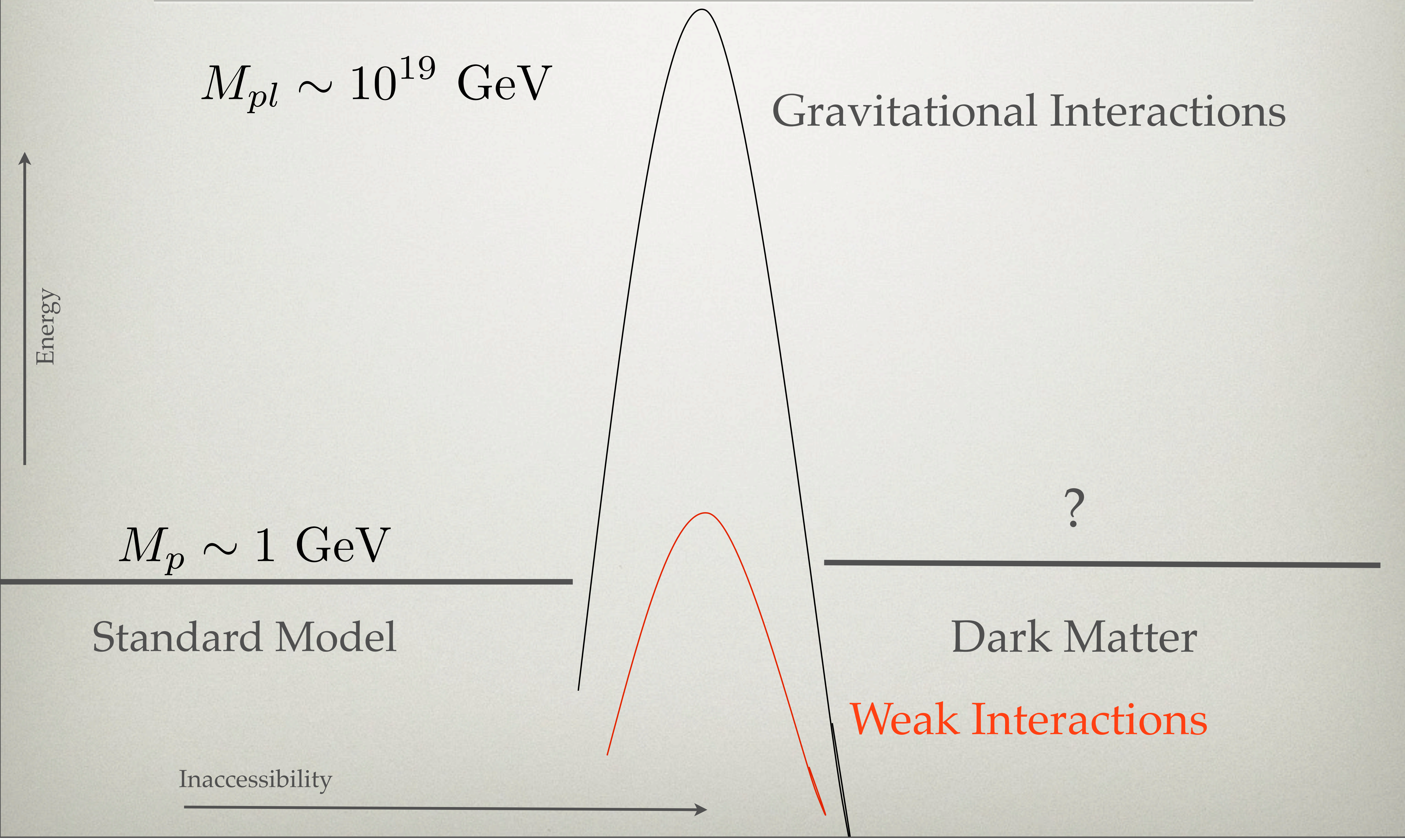




$$\frac{d\sigma}{d\Omega} \propto \frac{1}{v^4}!$$

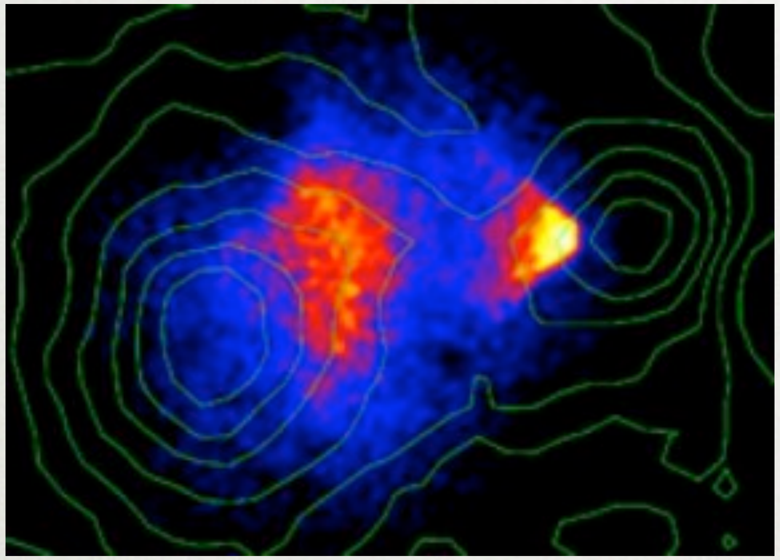
McDermott, Yu, KZ
1011.2907

Super-Weakly Interacting



Super-Weakly Interacting

- Gravitational Coherence ....

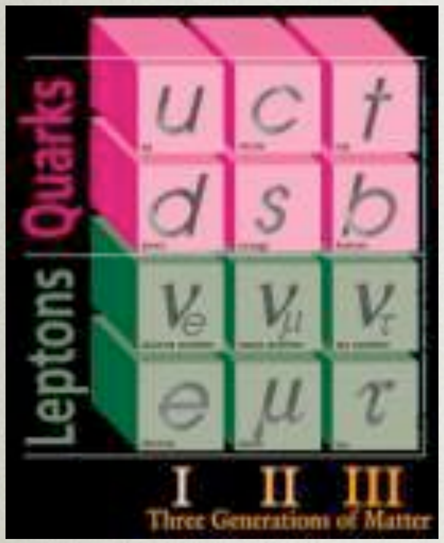


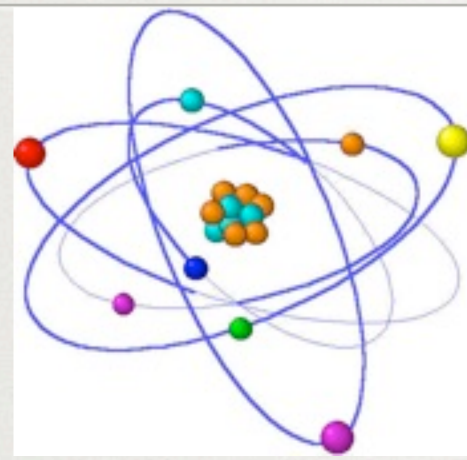
... on cosmological scales!

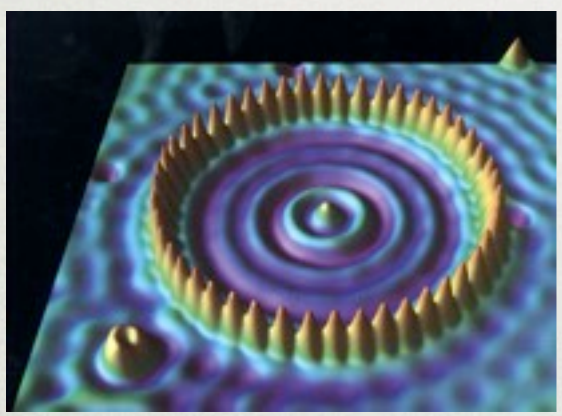
  - Helps us learn about aggregate properties of dark matter

- Particle properties much harder
- Fundamental premise: DM has interactions other than gravitational

Particle Physics Provides Some Ideas







- Fundamental premise: DM has interactions other than gravitational

?

$M_p \sim 1\ \mathrm{GeV}$

Standard Model

Dark Matter

Sub-weak Interactions

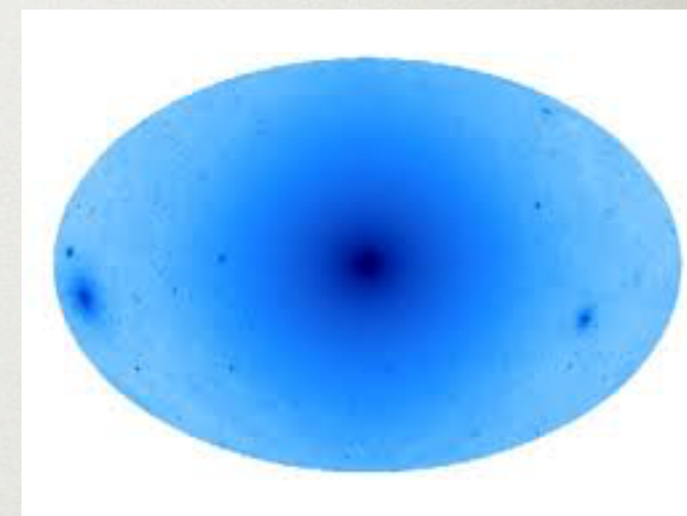
Weak Interactions

Dark Matter Hunter's Tool Kit

Astrophysical and Cosmological

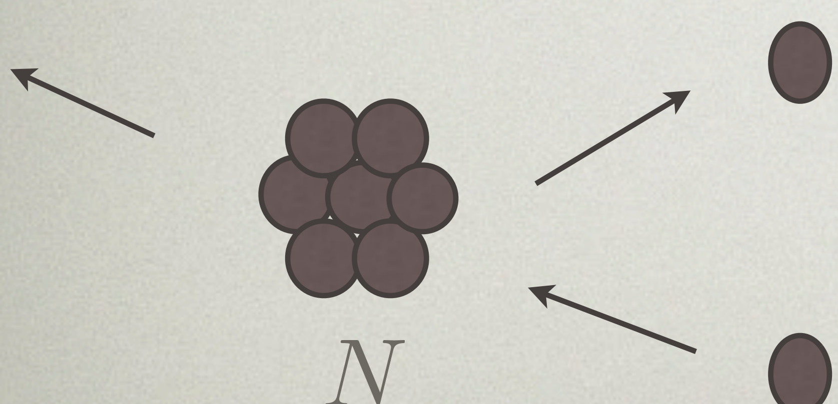
History of Universe
Structure formation
Relic abundance
Stellar Evolution (sun; supernovae; white dwarves; neutron stars)
BBN
CMB Neff; DM interactions

Indirect Detection



PAMELA (charged particles)
COMPTEL, EGRET, Fermi (gammas)
AMS (charged particles)
HESS (gammas)
ACT (future, gammas)
HEAO-1,INTEGRAL .... (x-ray)
IceCube / DeepCore / PINGU (neutrinos)

Direct Detection



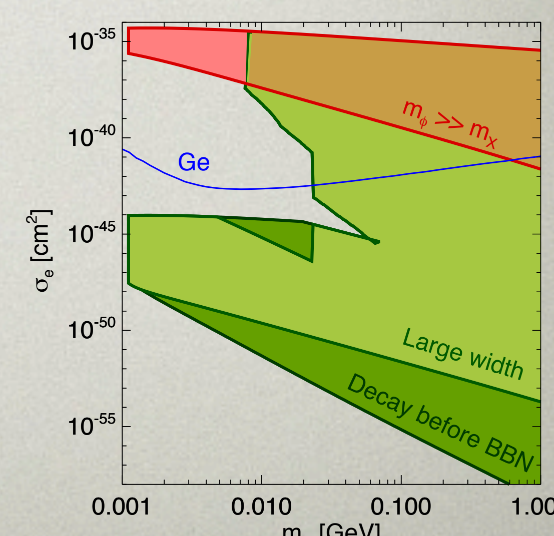
Terrestrial

LHC

Intensity -- low energy, weak couplings -- B-factories (Belle, BaBar), beam dumps (APEX, DarkLight, Heavy Photon Search)

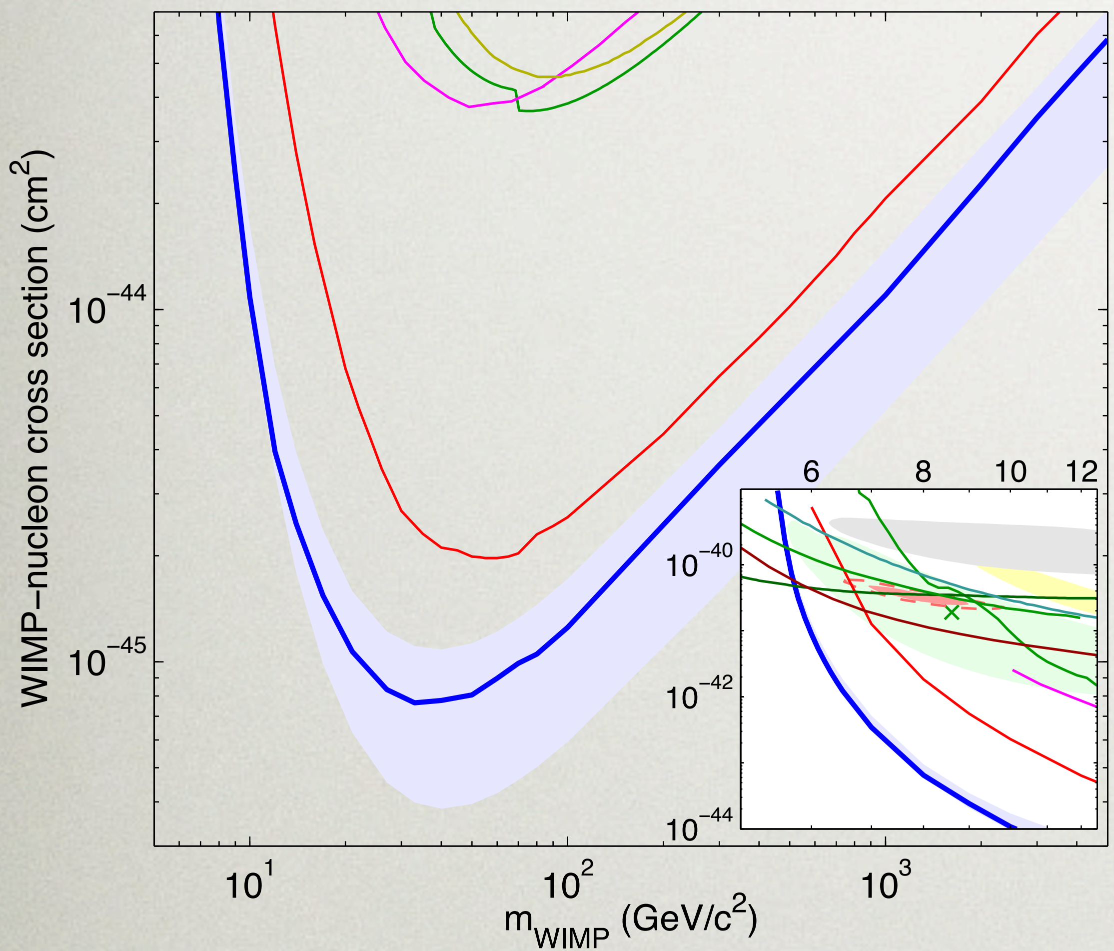
More exotic?

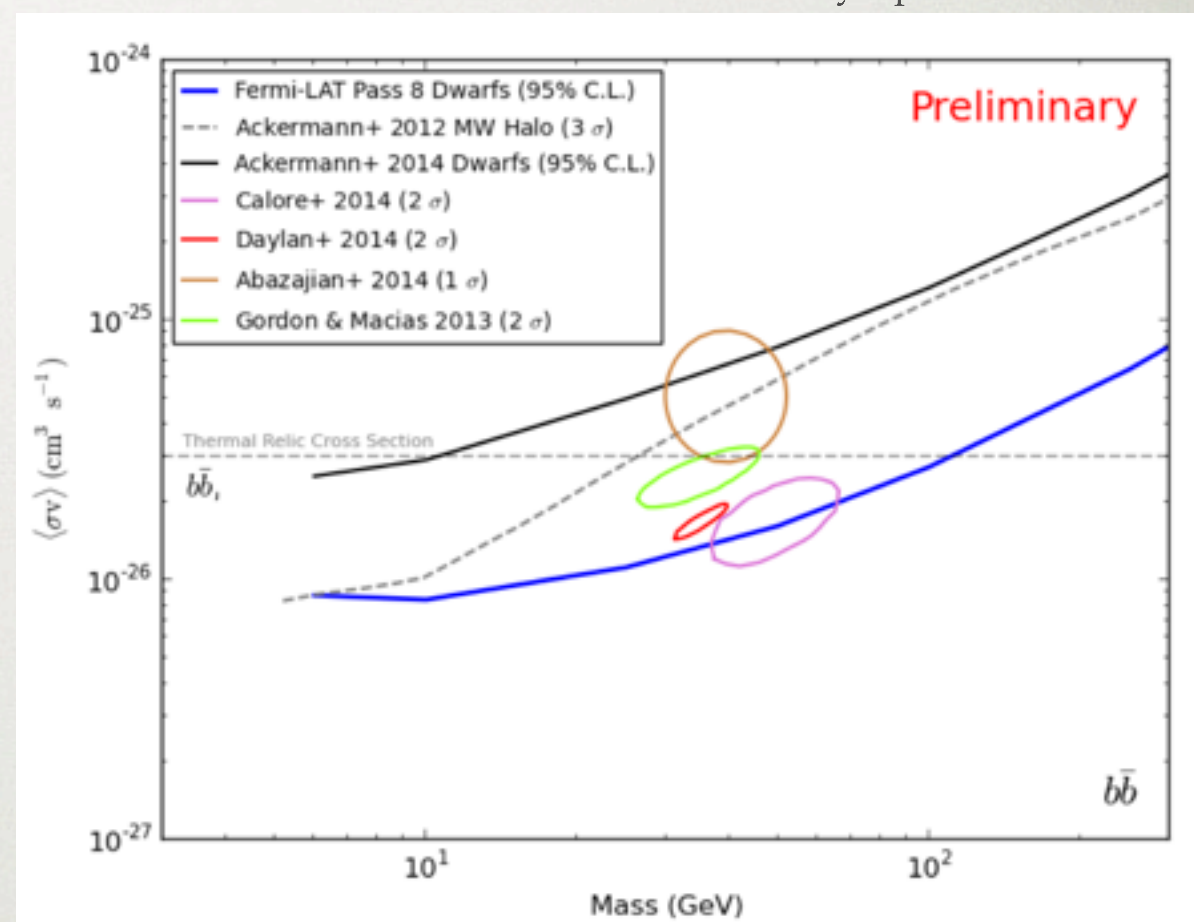
Lin, Yu, KZ



Viability Assumes Rates

Fermi Symposium 2014



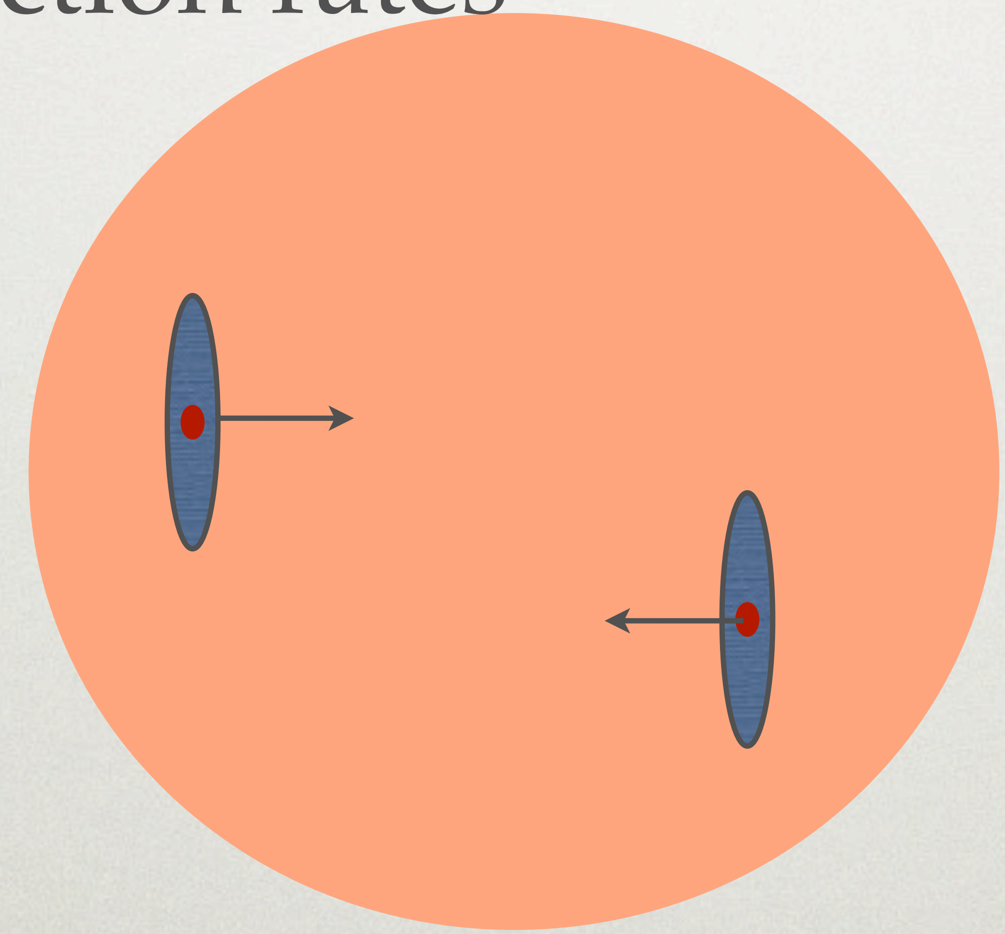


LUX collaboration 2013

$$\sigma v \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \sim \frac{1}{(20\ \mathrm{TeV})^2}$$

Why the (sub-)Weak Scale is Compelling

- Abundance of new stable states set by interaction rates



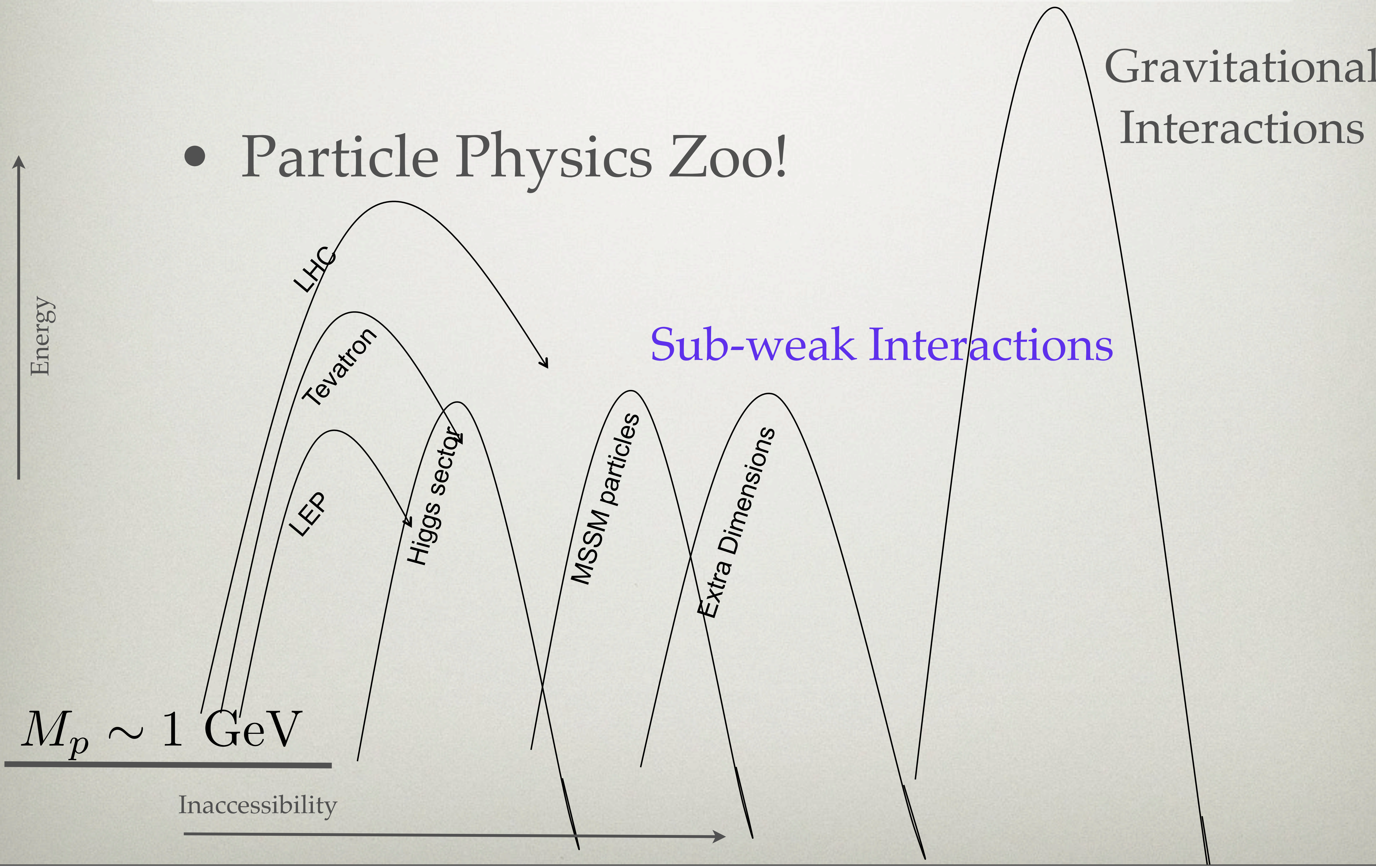
Freeze-out

Measured by CMB + LSS

$$\Gamma = n\sigma v = H \qquad \Longrightarrow \sigma \sim \frac{1}{(20\ \mathrm{TeV})^2}$$

Particle Physics Provides Some Ideas

- Particle Physics Zoo!



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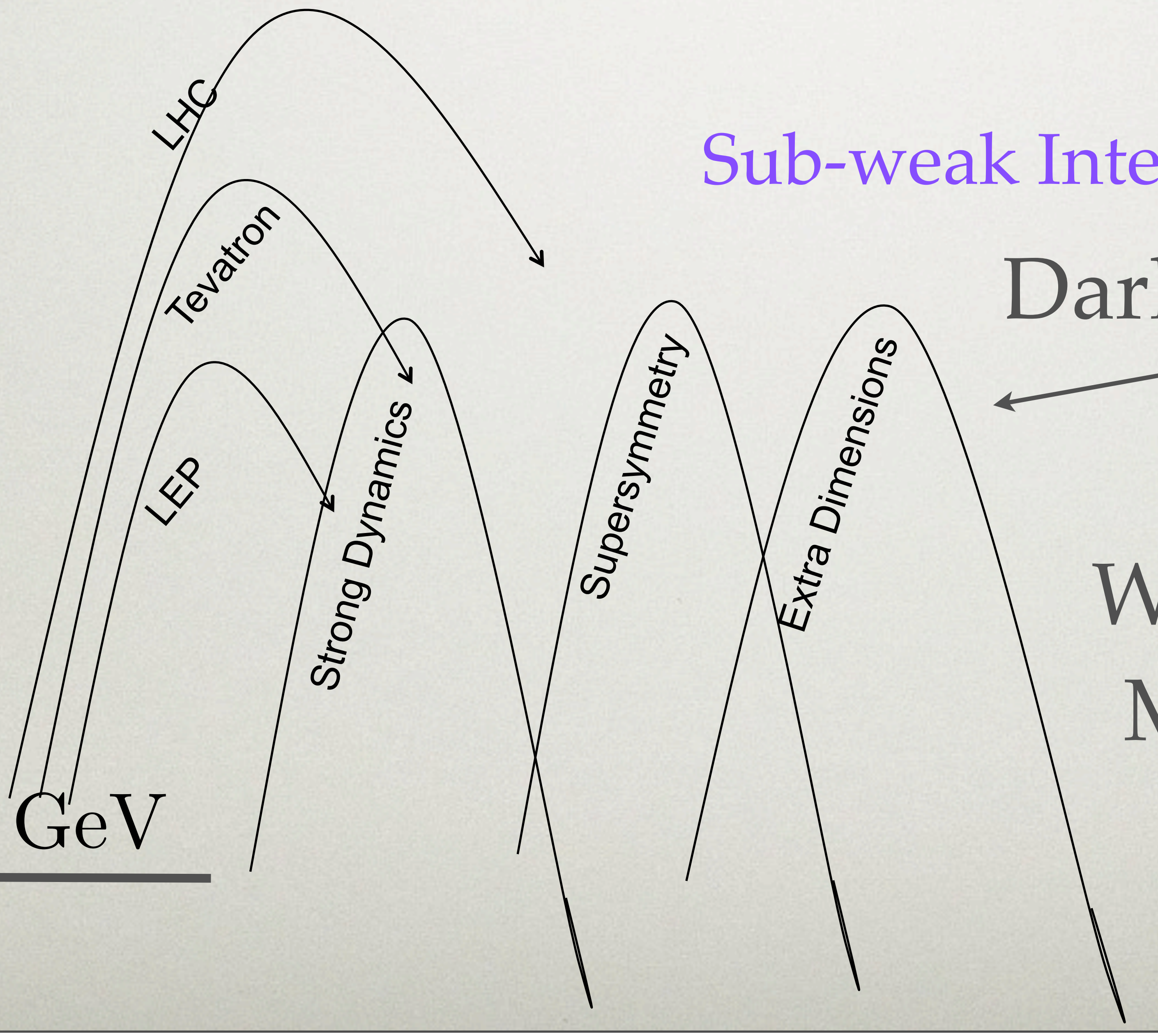


Sub-weak Interactions

Dark Matter Resides Here!

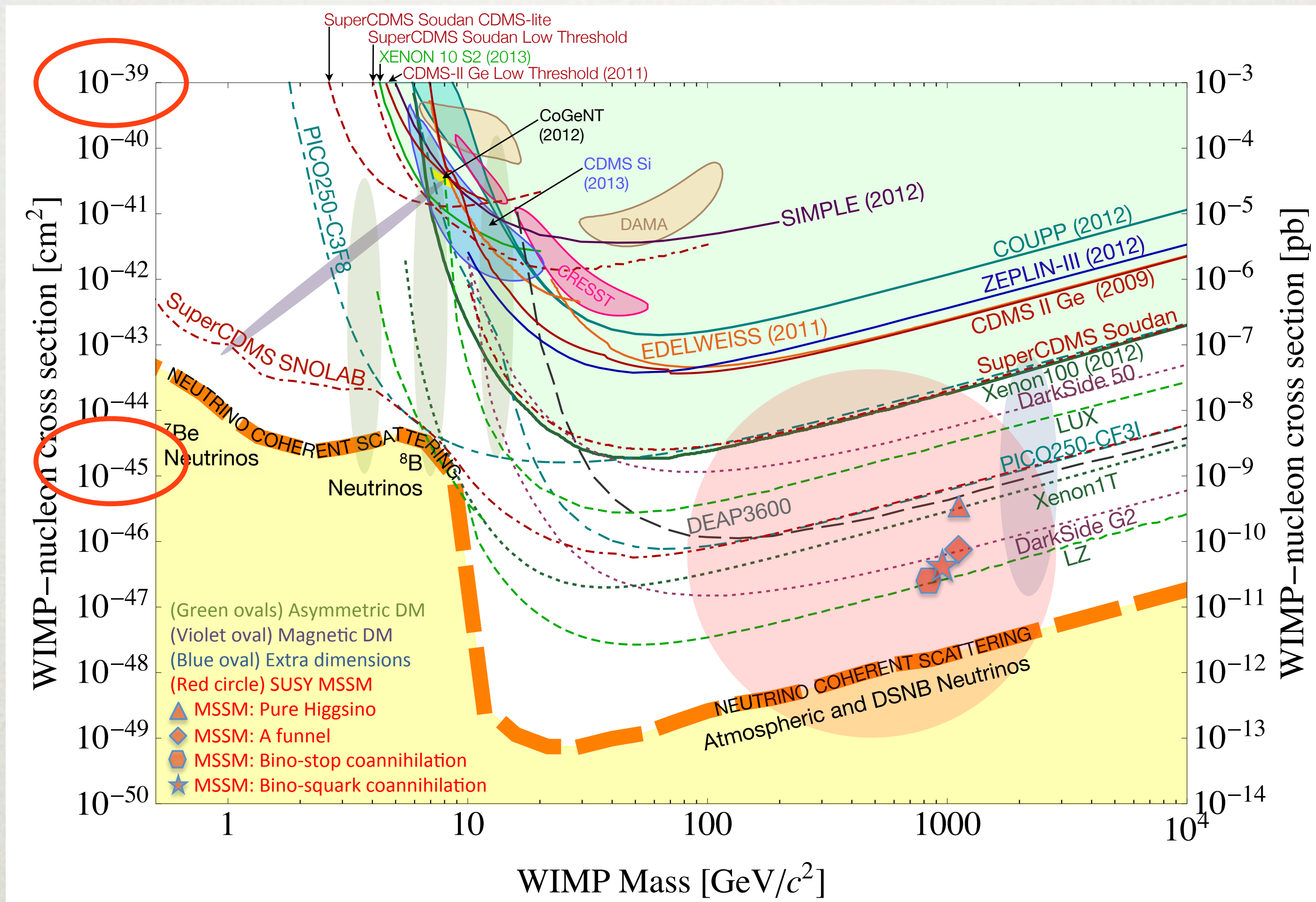
Weakly Interacting Massive Particles (WIMPs)

$M_p \sim 1$ GeV

Sub-Weakly Interacting Massive Particles

Scattering through the Z boson: ruled out

$$\sigma_n \sim 10^{-39}\ \mathrm{cm}^2$$



Next important benchmark:
Scattering through the Higgs

$$\sigma_n \sim 10^{-45-46}\ \mathrm{cm}^2$$

Idea Focus: Supersymmetry

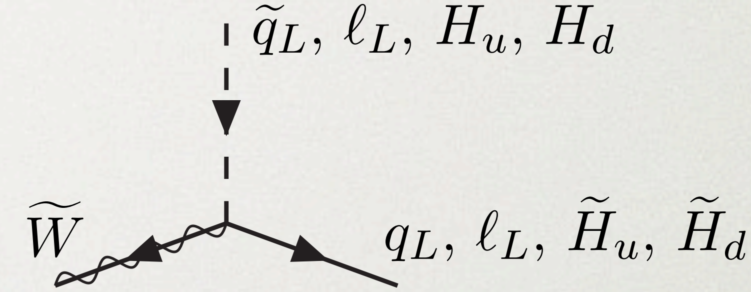
- Provides sharp predictions
- Must be neutral.
- Options sneutrino, bino, wino, higgsino

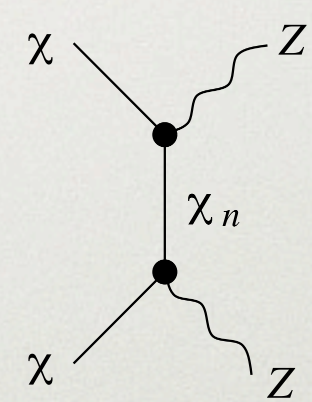
$$\tilde{\nu} \qquad\qquad \tilde{B},\ \tilde{W}_3,\ \tilde{H}$$

- Sneutrino scatters through Z
- Neutralino scattering through Z spin-dependent or velocity suppressed

Are there ways around for the Neutralino?

- Make the Neutralino a pure state -- coupling to Higgs vanishes
- However, Wino and Higgsino pure states can be probed by indirect detection





Large!

$$\langle \sigma v \rangle \sim \left(\frac{2\ \mathrm{TeV}}{m_\chi} \right)^2 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

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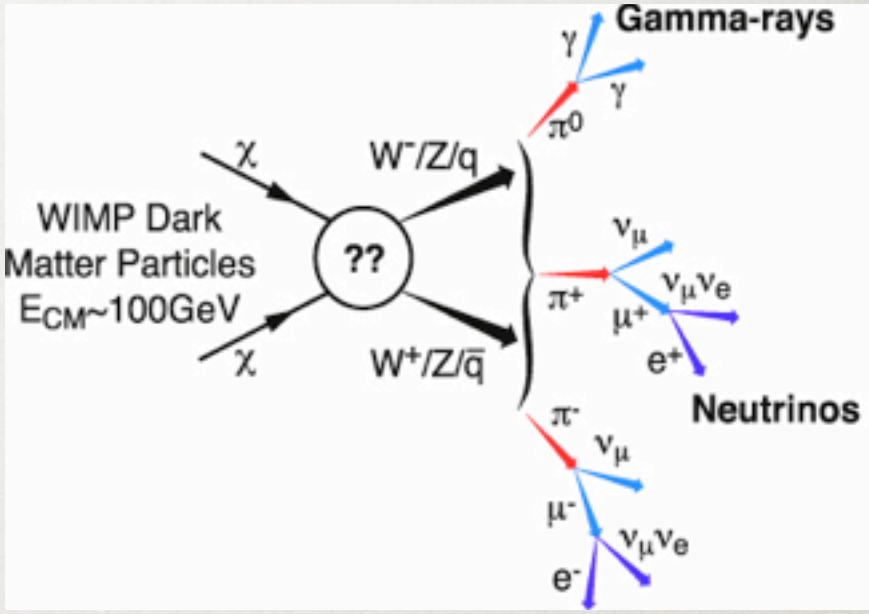
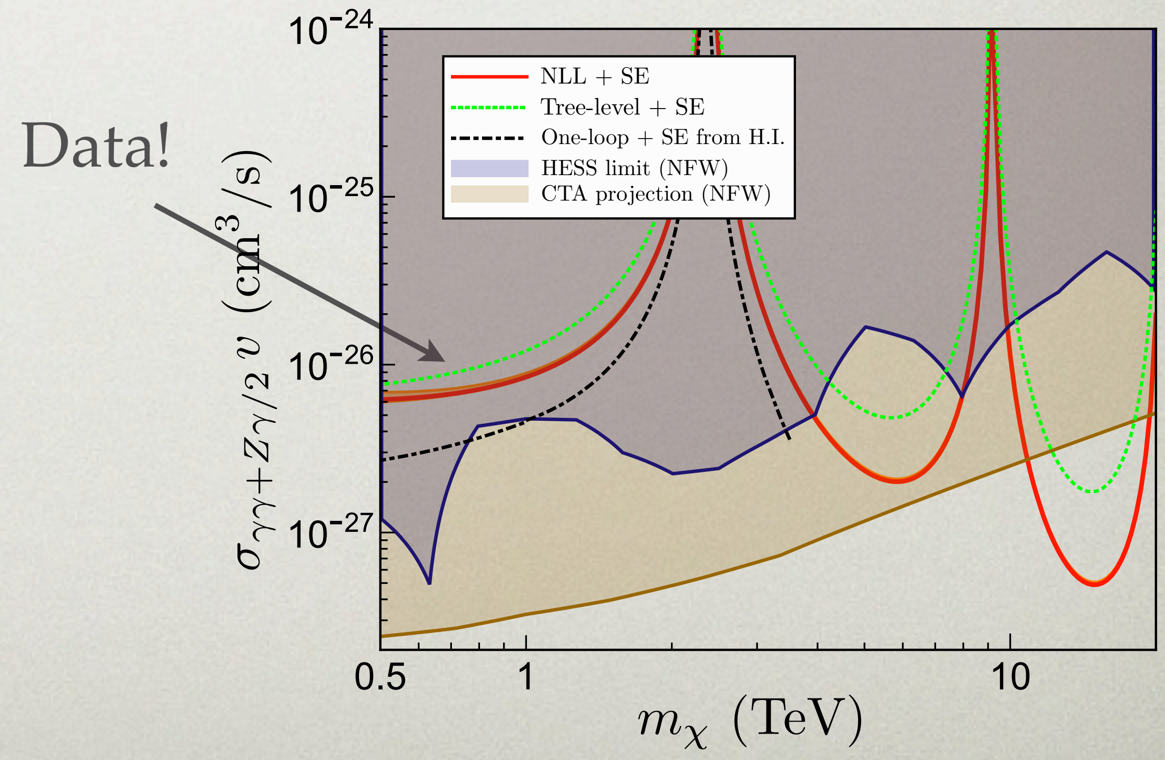




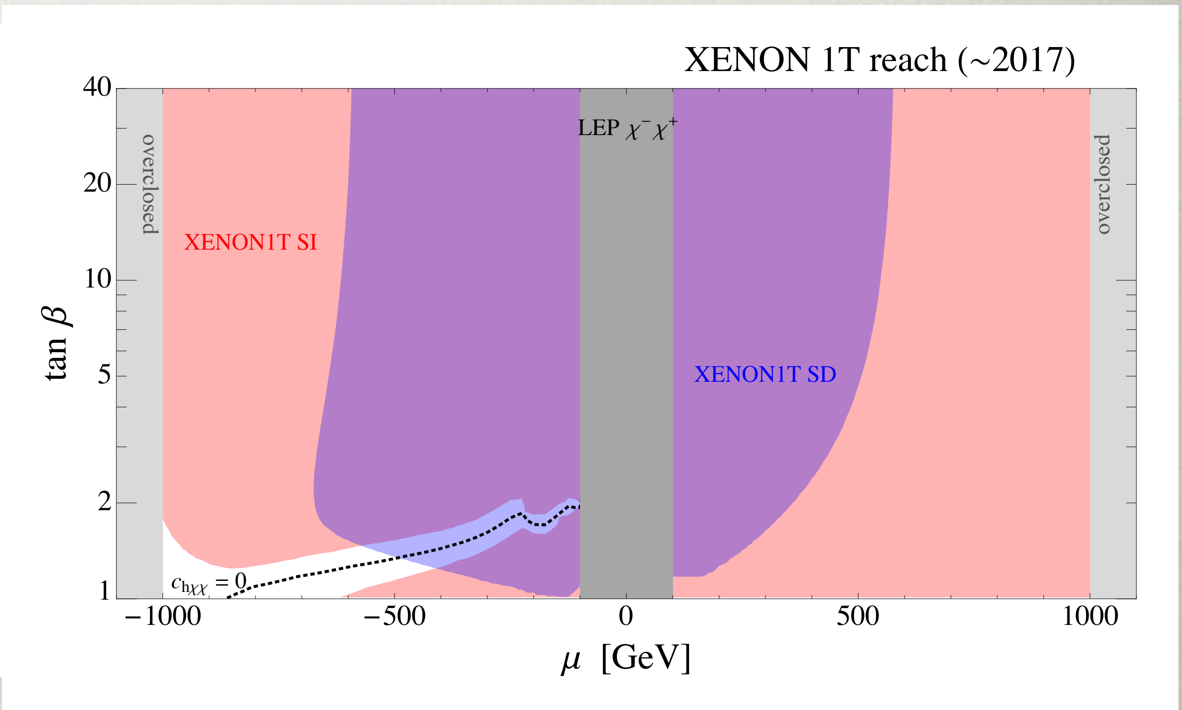
Ovaneysan, Slatyer, Stewart

Are there ways around for the Neutralino?

- Tune away the coupling to the Higgs
- Smaller cross-sections correspond to more tuning in the neutralino components

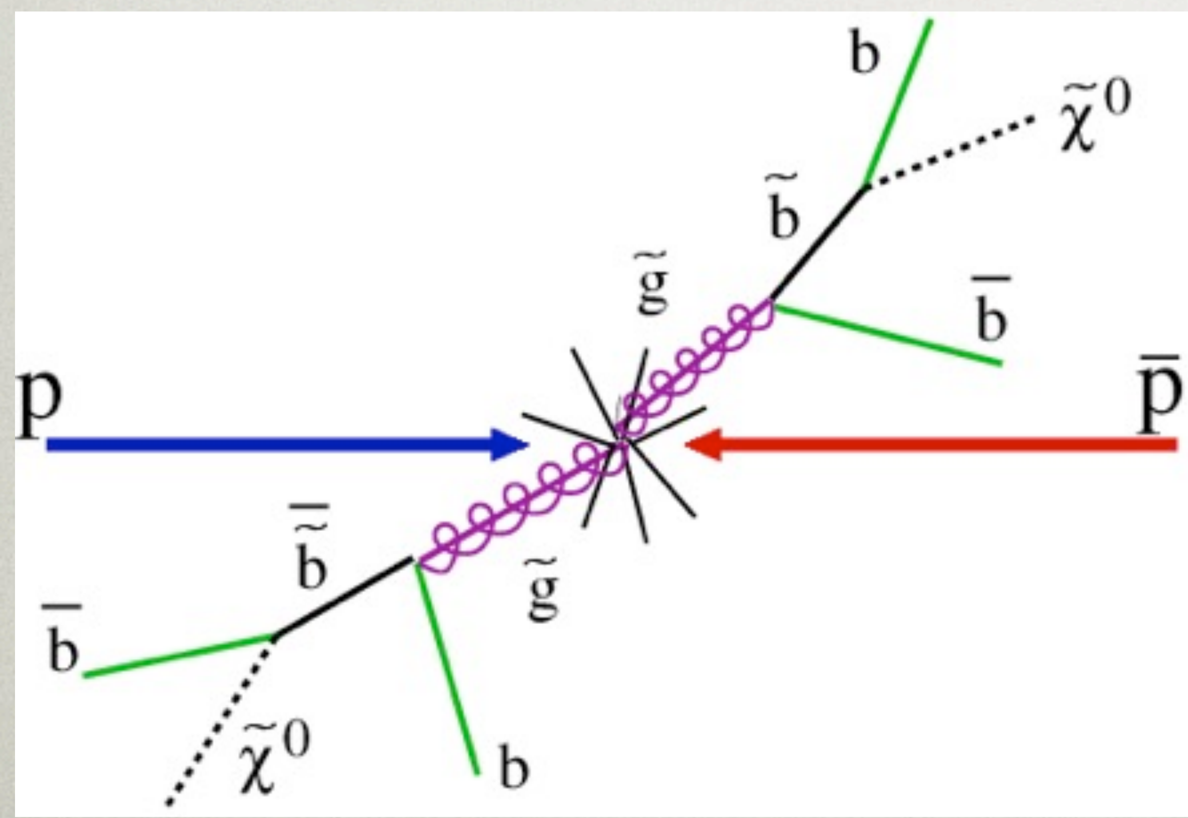
m_χ	condition
M_1	$M_1 + \mu \sin 2\beta = 0$
M_2	$M_2 + \mu \sin 2\beta = 0$
$-\mu$	$\tan\beta = 1$
M_2	$M_1 = M_2$

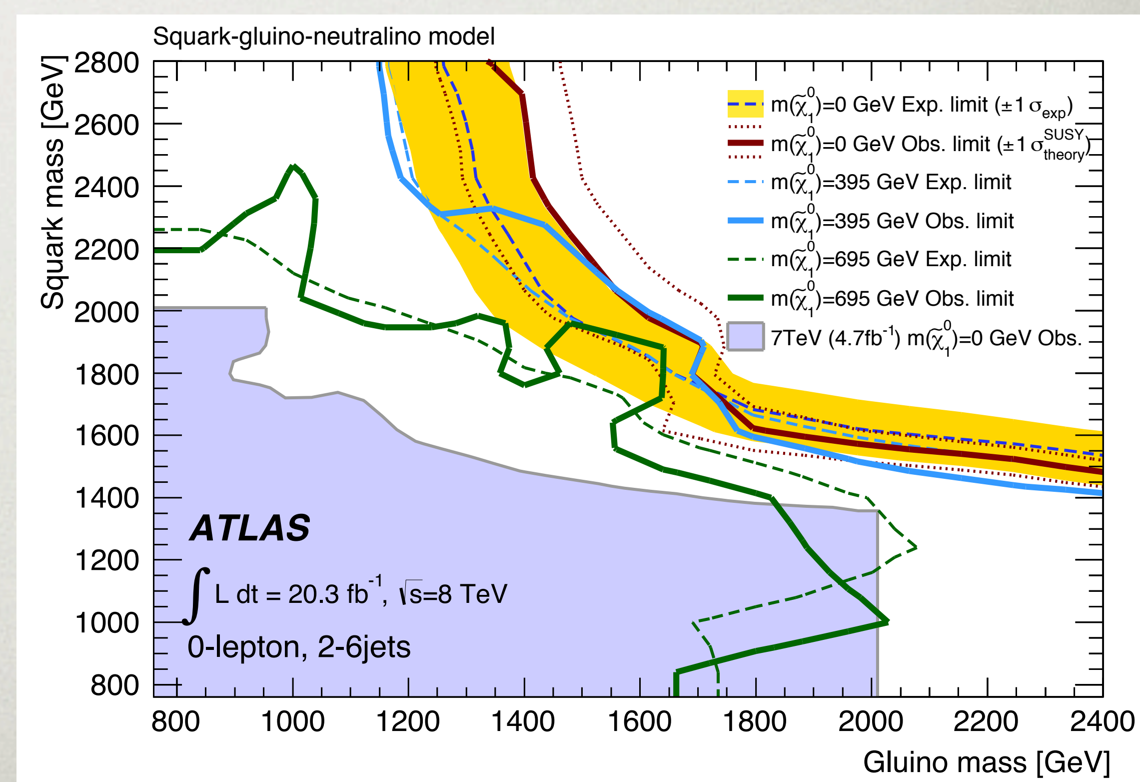
Cheung, Hall, Pinner, Ruderman



Where Does the LHC Come In?

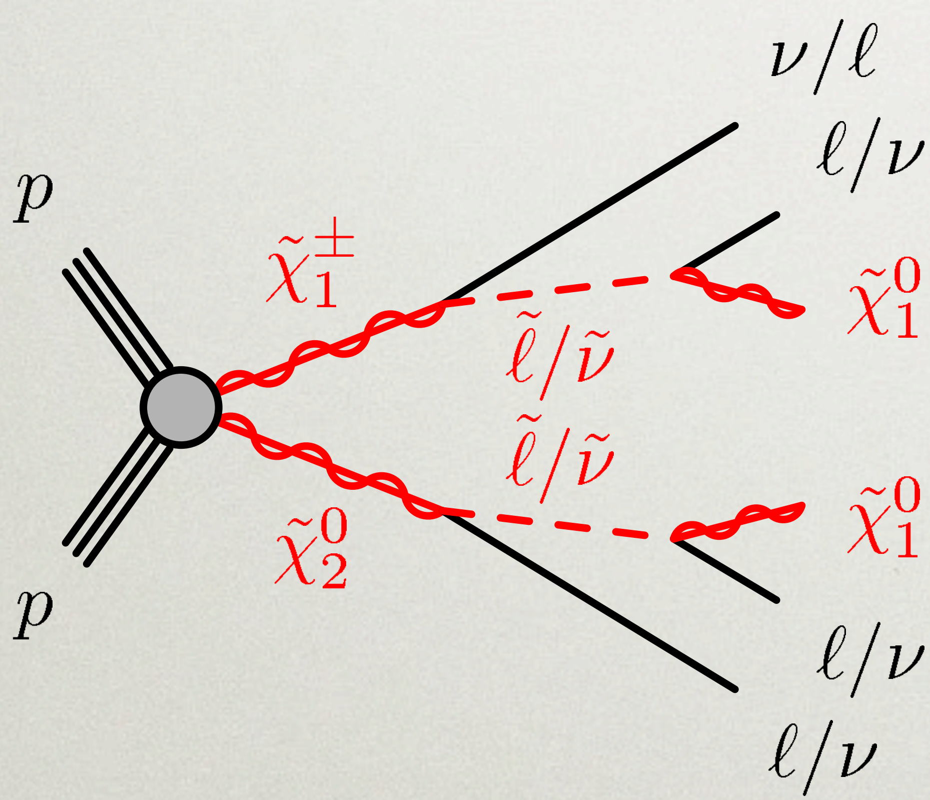
- LHC provides strongest constraints when there are new colored states in addition to the dark matter

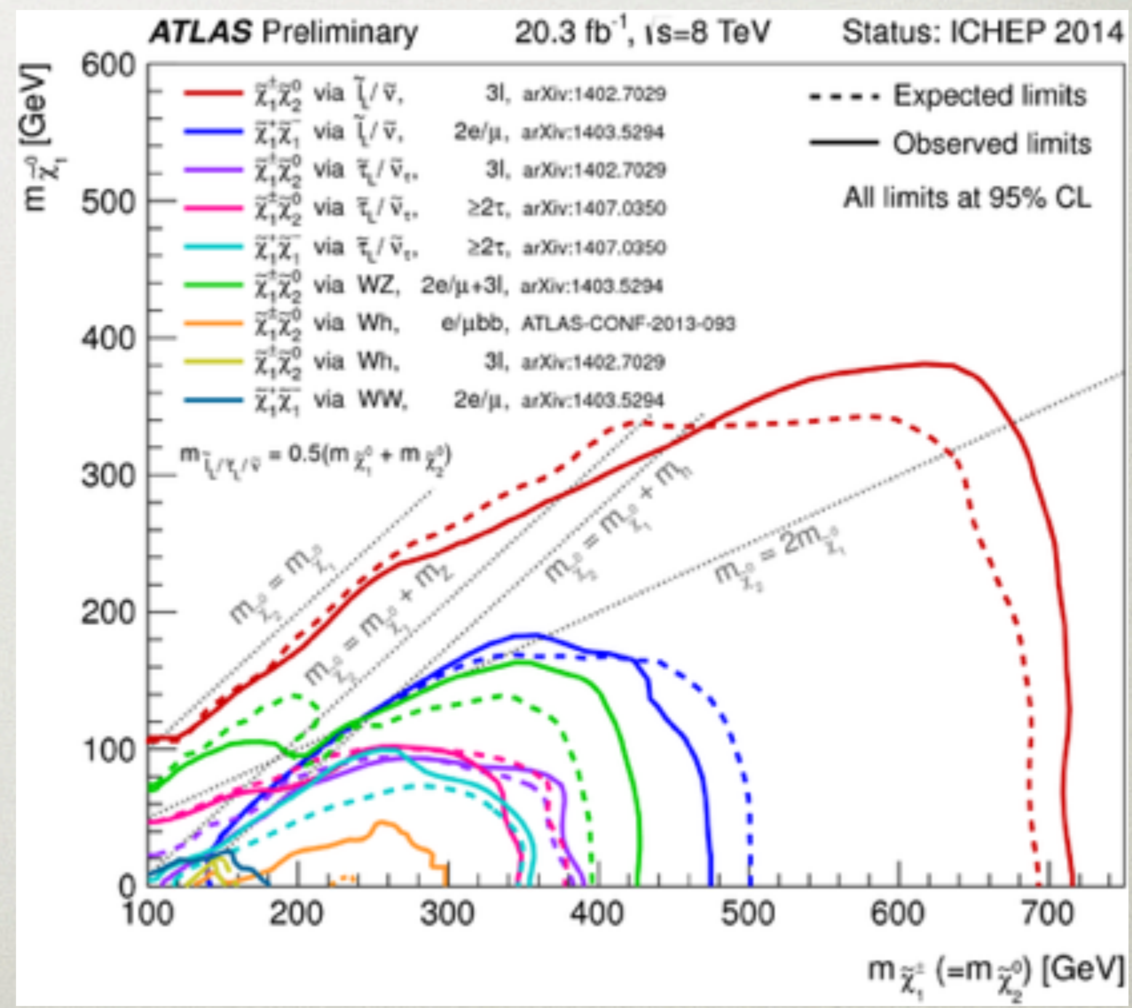




Where Does the LHC Come In?

- Constraints are much weaker when it is dark matter being directly produced



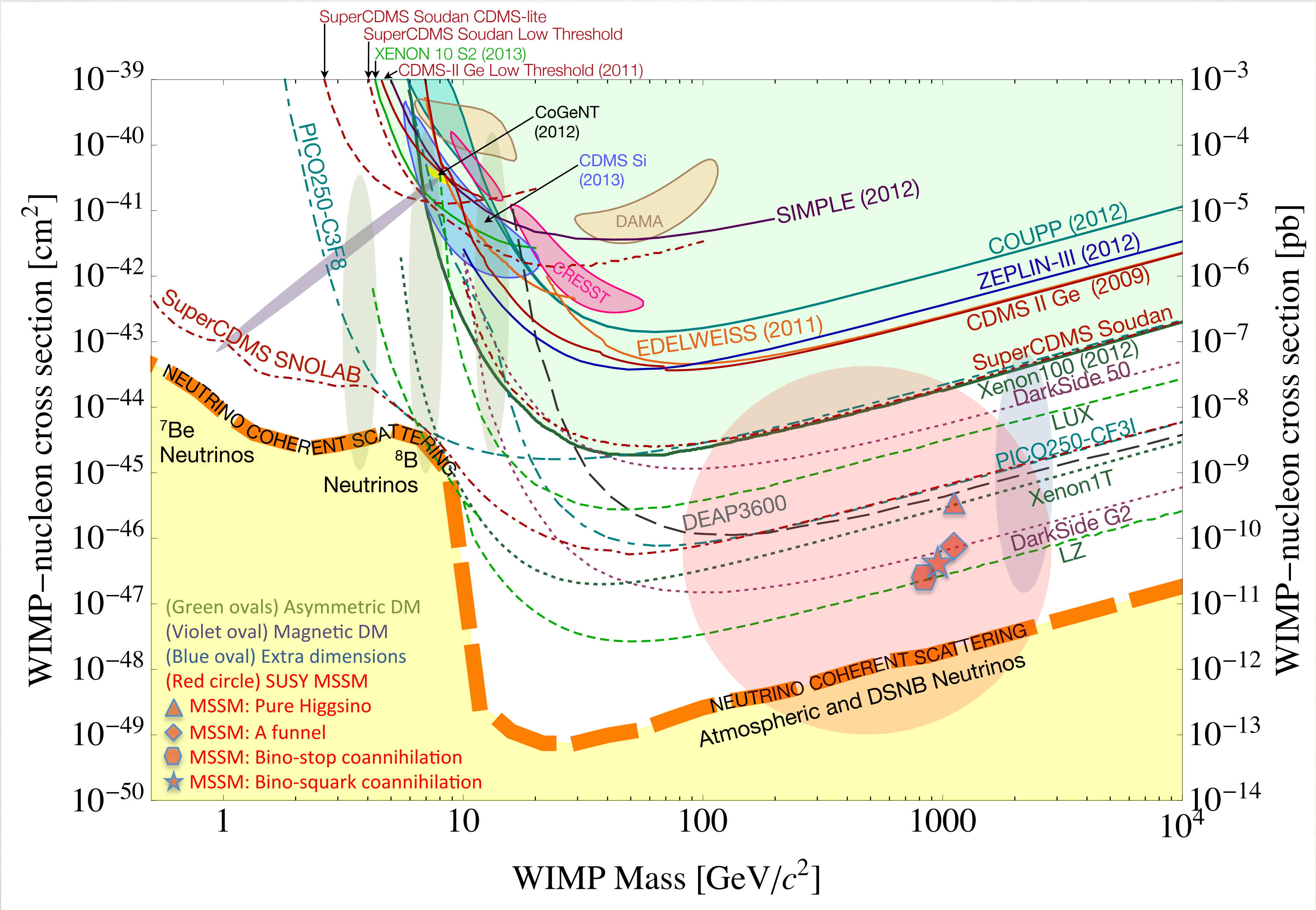


When Should We Start Looking Elsewhere?

- Cannot kill neutralino DM, but paradigm does become increasingly tuned
- Somewhat below Higgs pole -- Neutrino background?
- Well-motivated candidates that are much less costly to probe
- Light WIMPs

Terra Incognita

CF1 Snowmass report, 1310.8327



The Lamppost Problem

- Great ideas! But are we too restricted by them?

CoGeNT

CDMS

DAMA

PAMELA

Fermi positron

Fermi line

- How can we be ready for anything?

Hidden Valleys

Sub-weak Interactions

~~(DM here.)~~

LHC

Torres del Paine

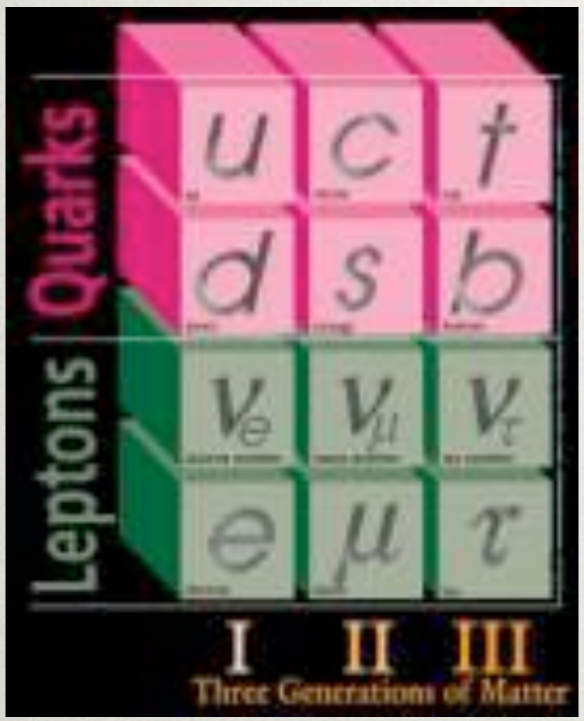
Standard Model

Dark World

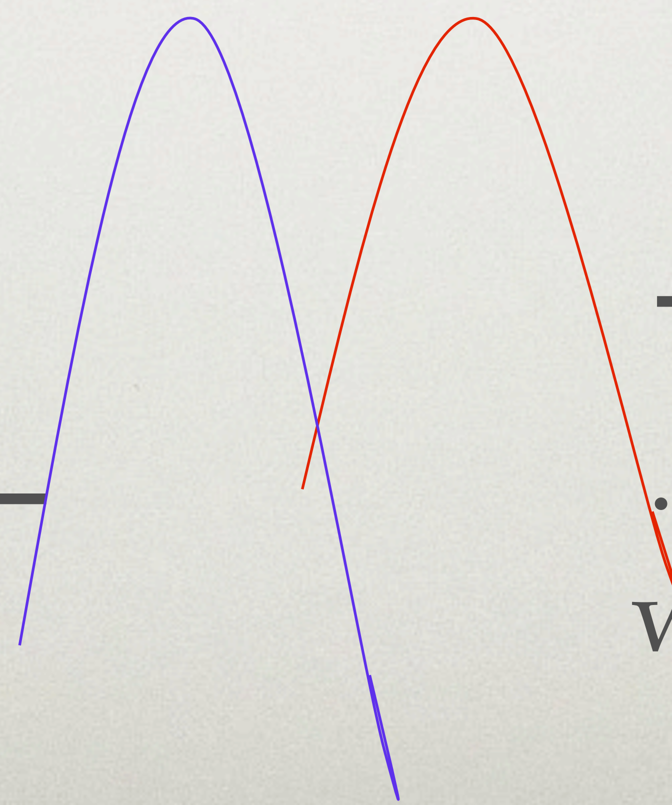
Weak Interactions

Hidden Dark Worlds

Our thinking has shifted



From a single, stable weakly interacting particle .....
(WIMP, axion)



?

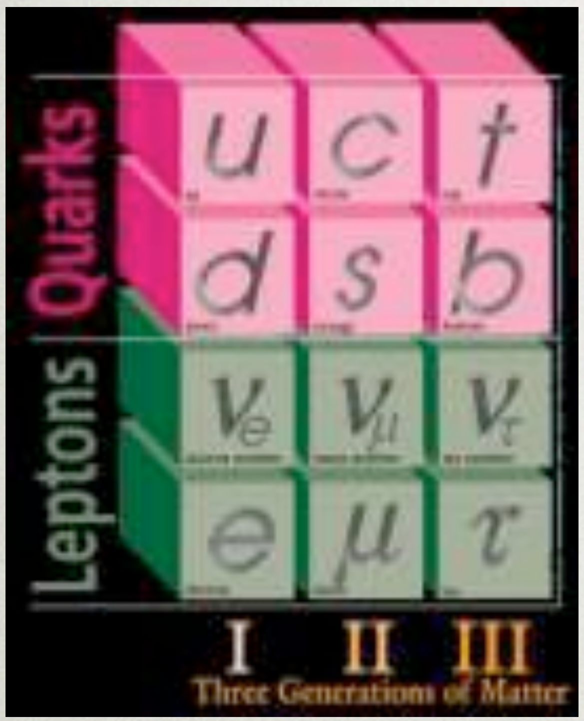
$M_p \sim 1$ GeV

Standard Model

...to a hidden world with multiple states, new interactions

Hidden Dark Worlds

Our thinking has shifted



From a single, stable weakly interacting particle .....
(WIMP, axion)

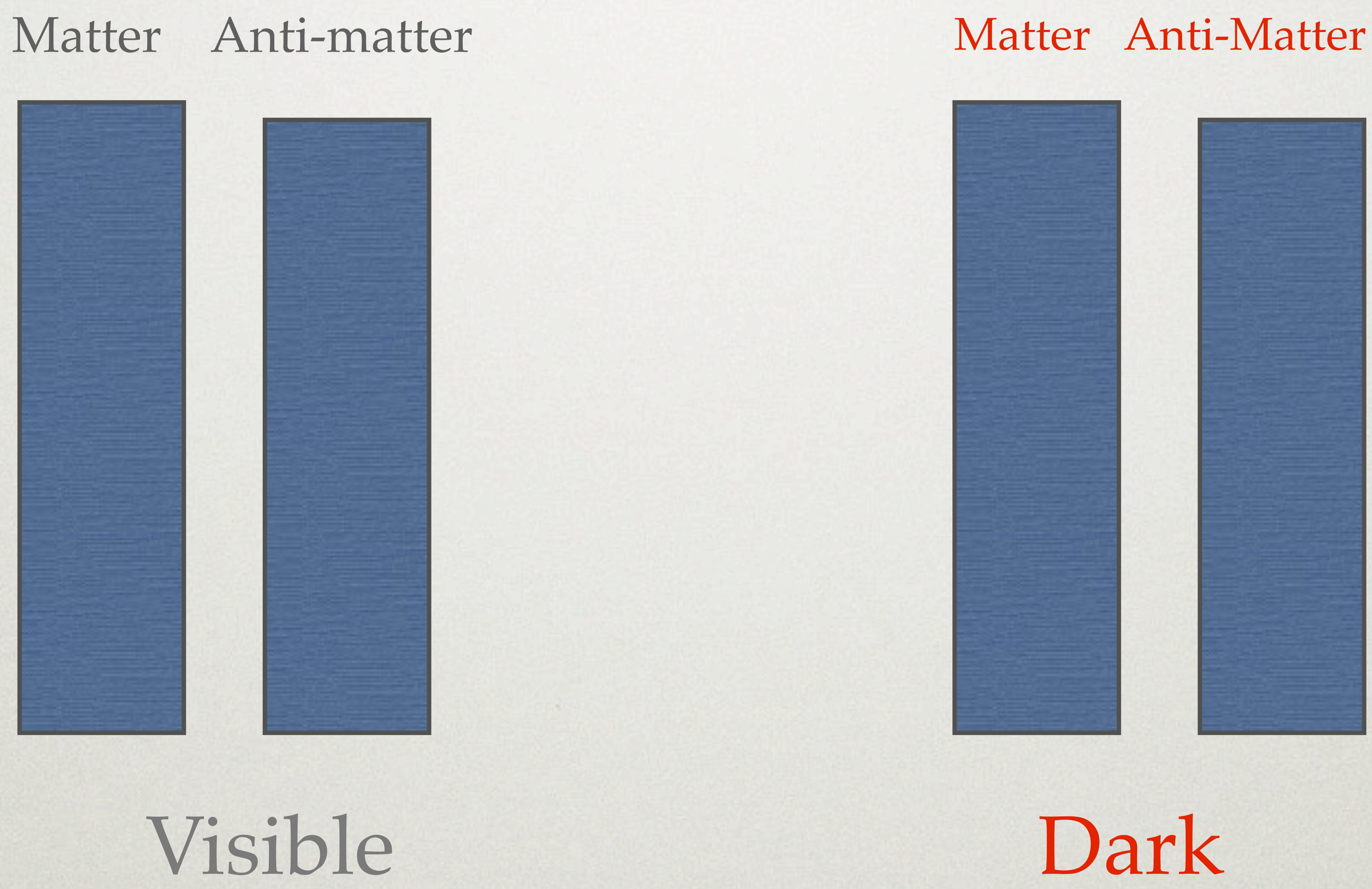
Models: Supersymmetric light DM sectors,
Secluded WIMPs, WIMPless DM, Asymmetric DM .....
Production: freeze-in, freeze-out and decay,
asymmetric abundance, non-thermal mechanicsms .....

$M_p \sim 1$ GeV

Standard Model

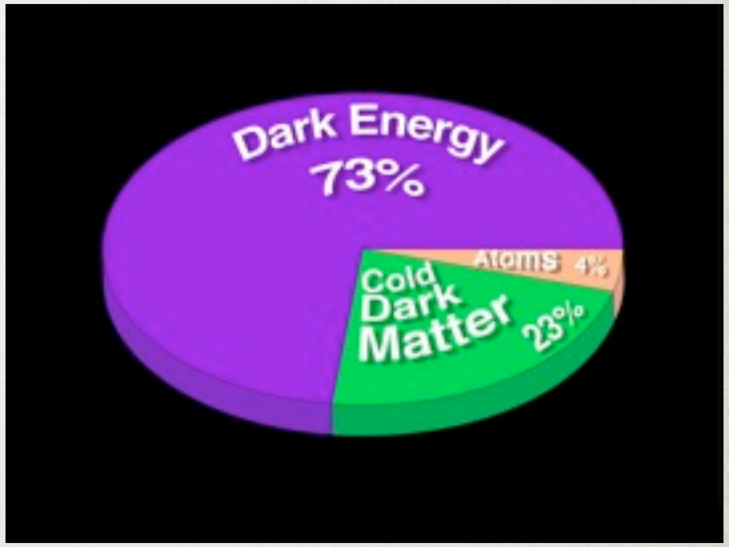
...to a hidden world with multiple states, new interactions

Chemical Potential Dark Matter



Baryon and DM Number Related?

- Standard picture: freeze-out of annihilation; baryon and DM number unrelated
- Accidental, or dynamically related?



Experimentally, $\Omega_{DM} \approx 5\Omega_b$

Mechanism $n_{DM} \approx n_b$

$\Rightarrow$ $m_{DM} \approx 5m_p$

Nussinov,
Hall, Gelmini,
Barr, Chivukula, Farhi,
D.B. Kaplan

What Does an ADM Model Do?

KZ 1308.0338

1. *Share* an asymmetry between the visible and dark sectors
2. *Decouple* transfer mechanism to separately freeze-in the asymmetries in both sectors
3. *Annihilate* the symmetric abundance

$n_X - n_{\bar{X}} \sim n_b - n_{\bar{b}}$ ⇒ $m_X \sim 5 m_p \simeq 5 \text{ GeV}$

1. Sharing

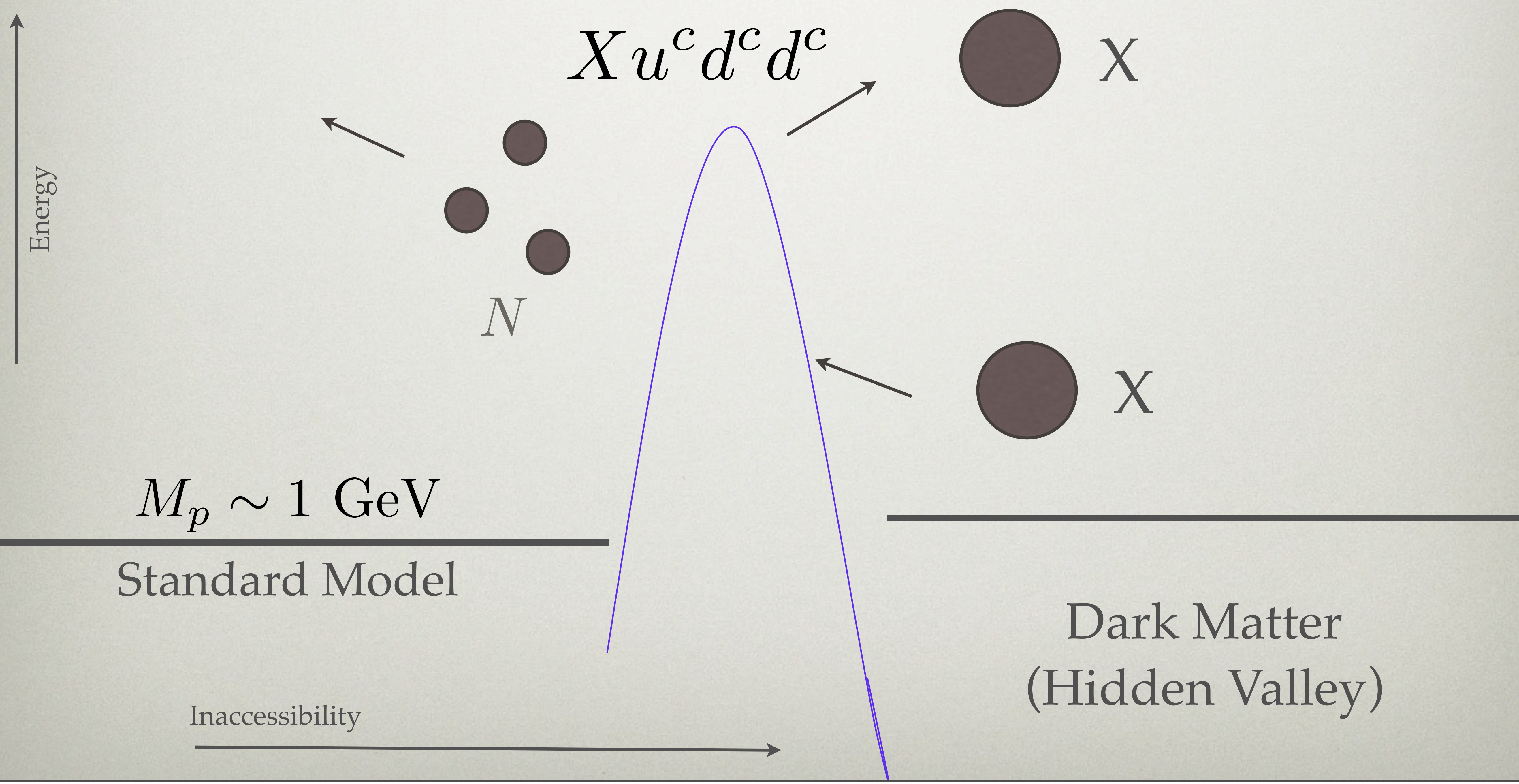
- Really 3 basic mechanisms
  1. Sphalerons (often EW)
  2. Higher dimension operators (HDO)
  3. Decay (different dynamics than HDO but same Lagrangian)

KZ 1308.0338

2. Decoupling

"Integrate out" heavy state
Higher dimension operators:

Luty, Kaplan, KZ
0901.4117



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Luty, Kaplan, KZ
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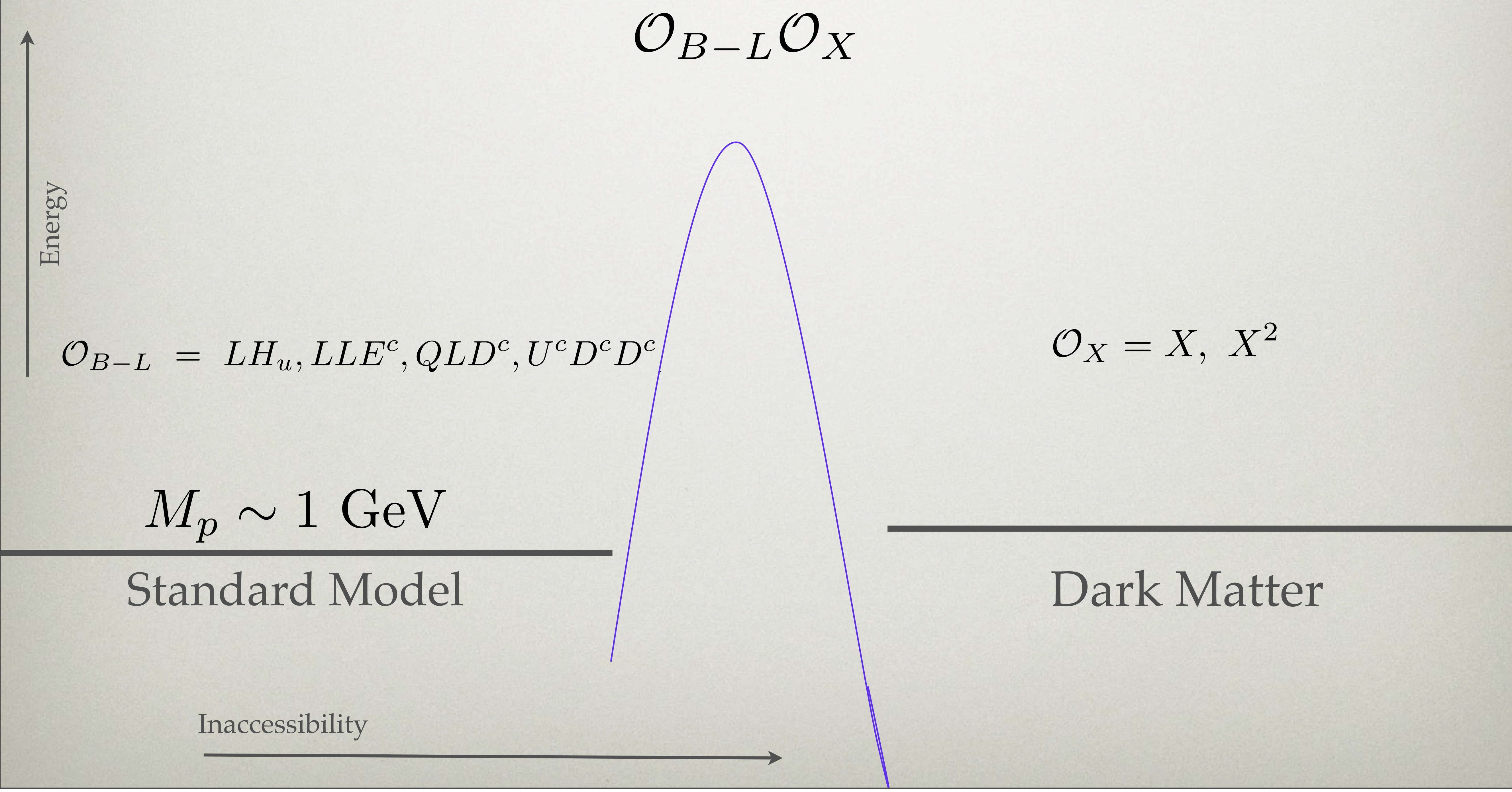
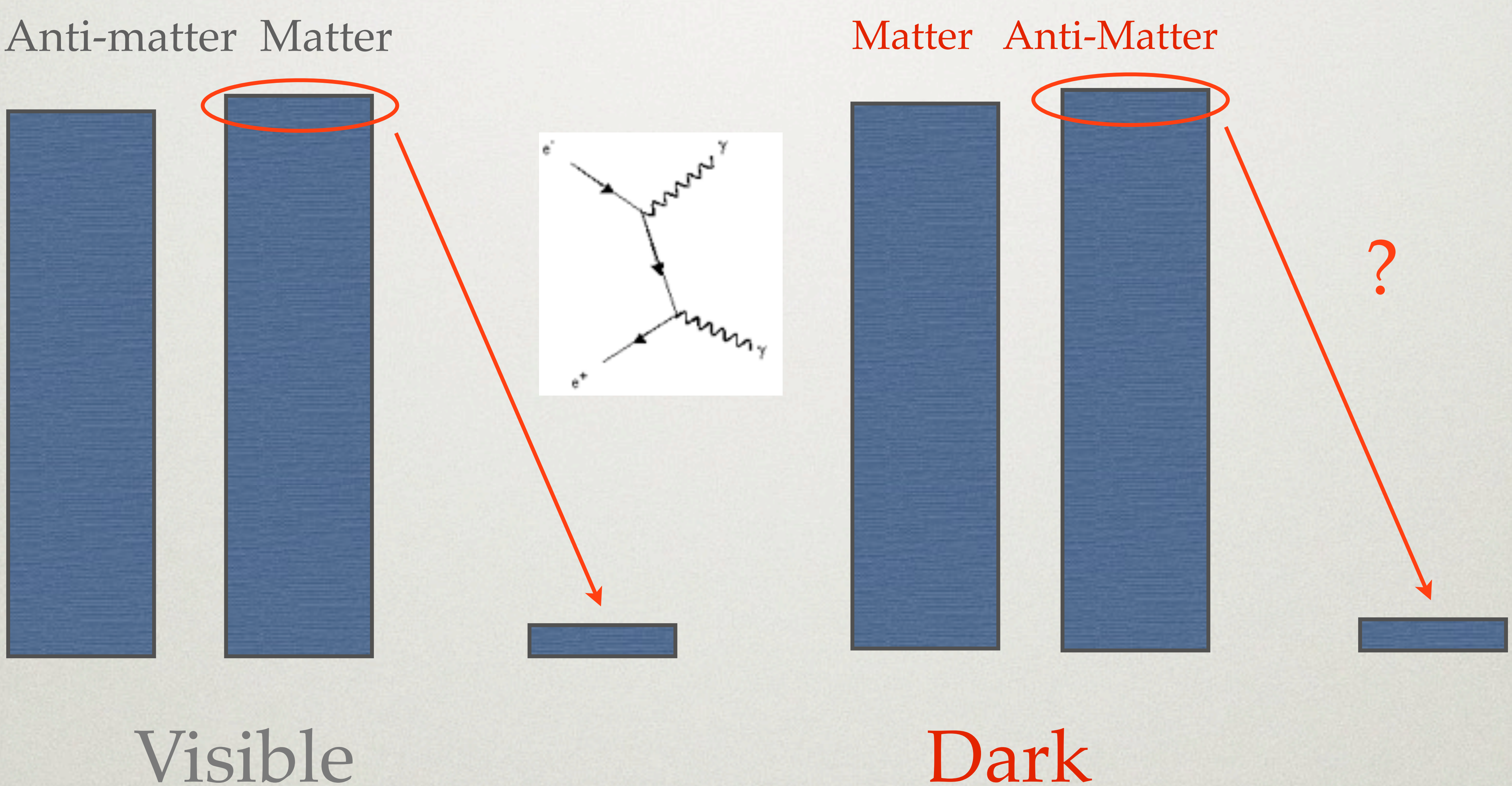
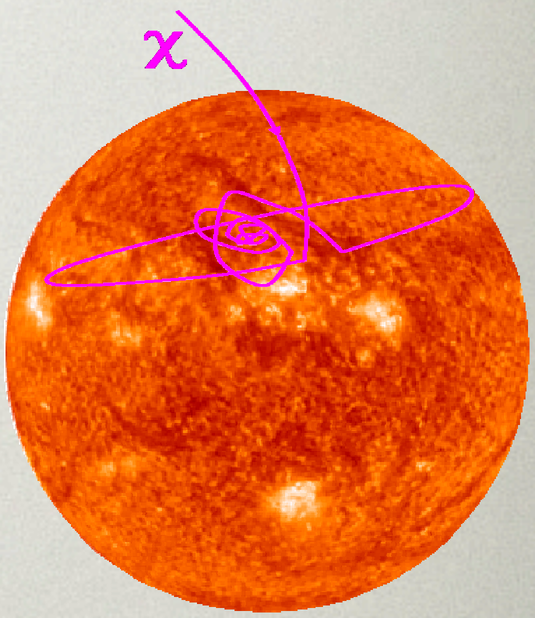


3. Annihilation



Astrophysical Implications

- DM does not annihilate
- It can accumulate in the center of stars
- Notable case: neutron stars
- Elastically scatter, come to rest in core
- High density!



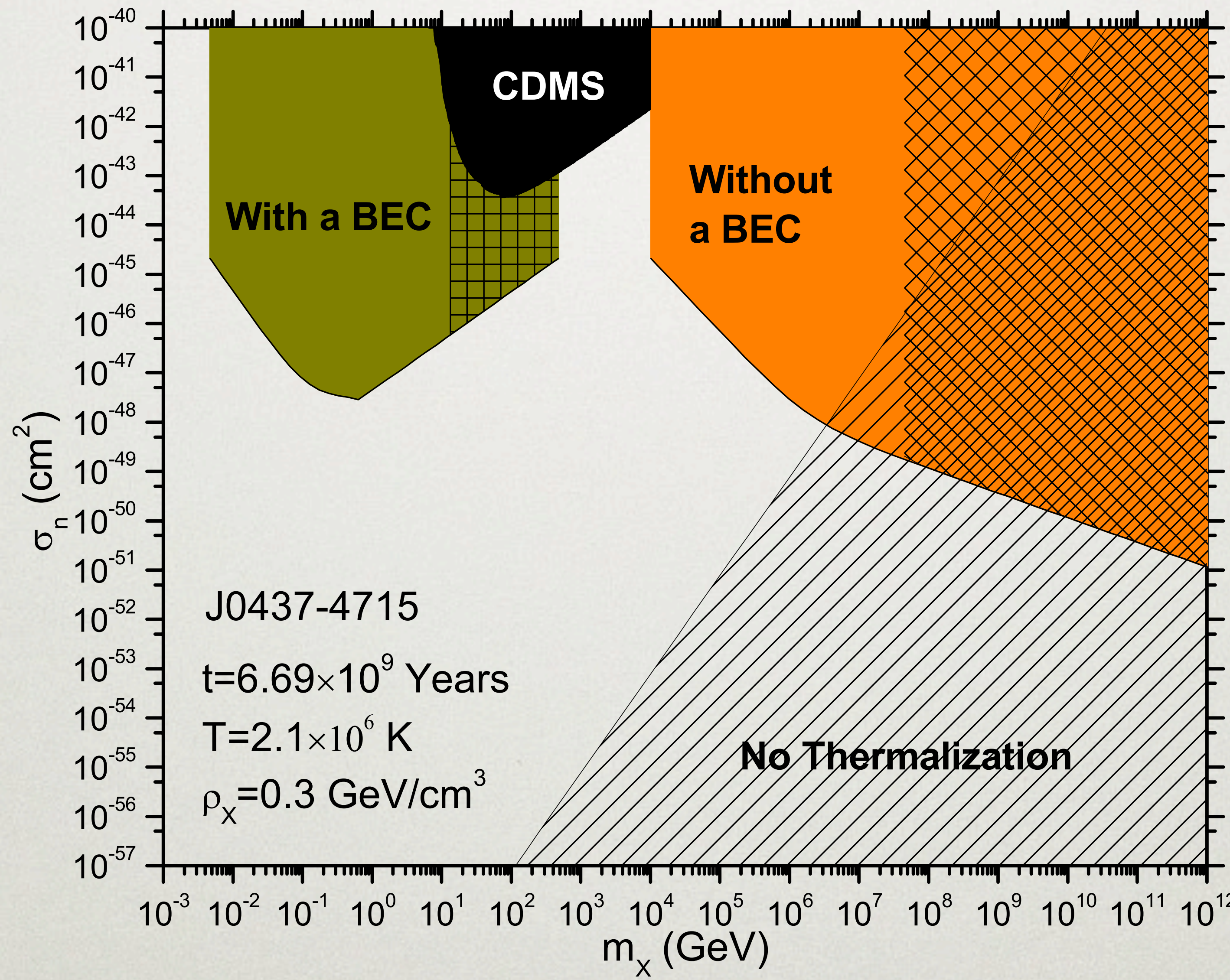
ADM, Black Hole and Neutron Stars

McDermott, Yu, KZ 1103.5472

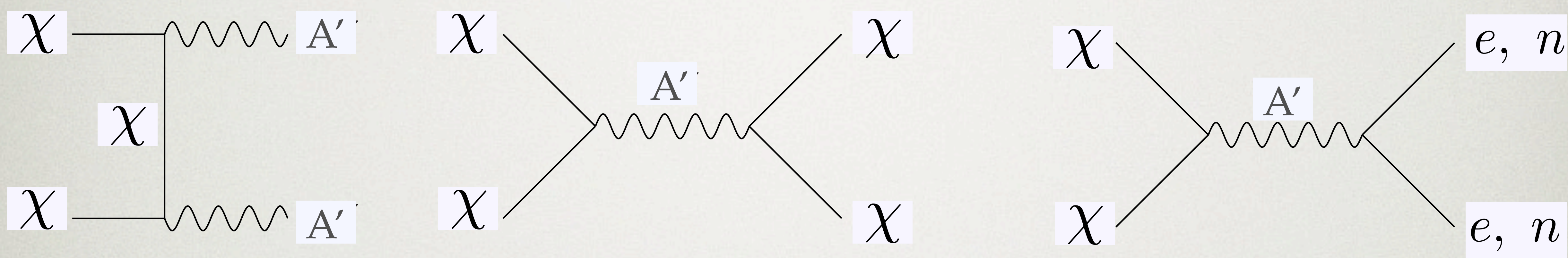
- Spin-0 ADM can lead to BH formation:
  - DM continues to accumulate until there are enough that they self-gravitate
  - OR, they first form Bose-Einstein condensate and then self-gravitate
  - Once they self-gravitate, they can collapse to form a BH!

ADM, Black Hole and Neutron Stars

McDermott, Yu, KZ 1103.5472



Dark Forces and DM Interactions

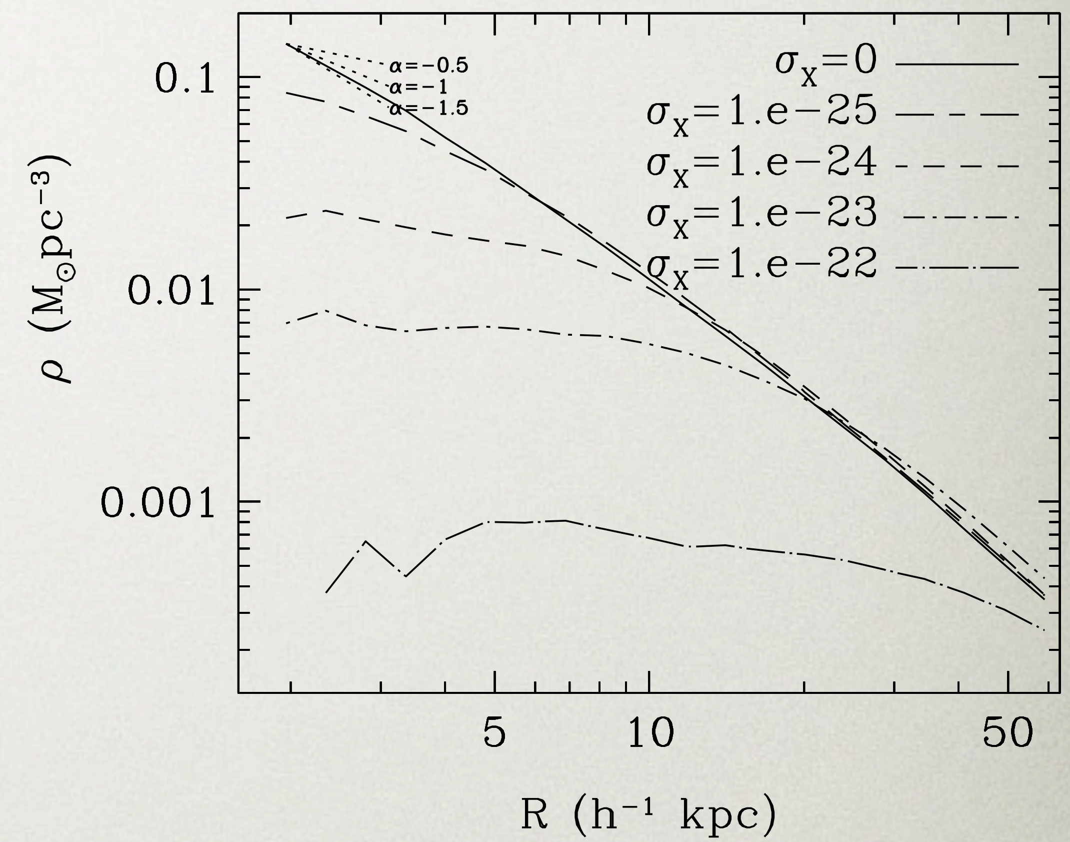


- Dark Forces Very Important for Asymmetric Dark Matter!
- May also be important for structure of DM halos
- May be important for DM direct detection and collider searches

DM Interactions and DM Halos

- Dark matter self-interactions randomize momenta and isotropize halos
- Lead to lower density dark matter halo cores
- Dark matter halos (including baryon poor dwarf galaxies) seem to have cores rather than cusps (still controversy as to cause)

Dave, Spergel, Steinhardt, Wandelt



$$\sigma_T \approx 5\times10^{-23}\,\mathrm{cm}^2\left(\frac{\alpha_X}{0.01}\right)^2\left(\frac{m_X}{10\,\mathrm{GeV}}\right)^2\left(\frac{10\,\mathrm{MeV}}{m_\phi}\right)^4$$

Implies Dark Forces!

- Very **big** scattering cross-sections

$$\sigma/m_X \sim 0.1 \text{ cm}^2/\text{g} \simeq 0.2 \times 10^{-24} \text{ cm}^2/\text{ GeV} \quad (\sigma_{weak} \sim 10^{-39} \text{ cm}^2)$$

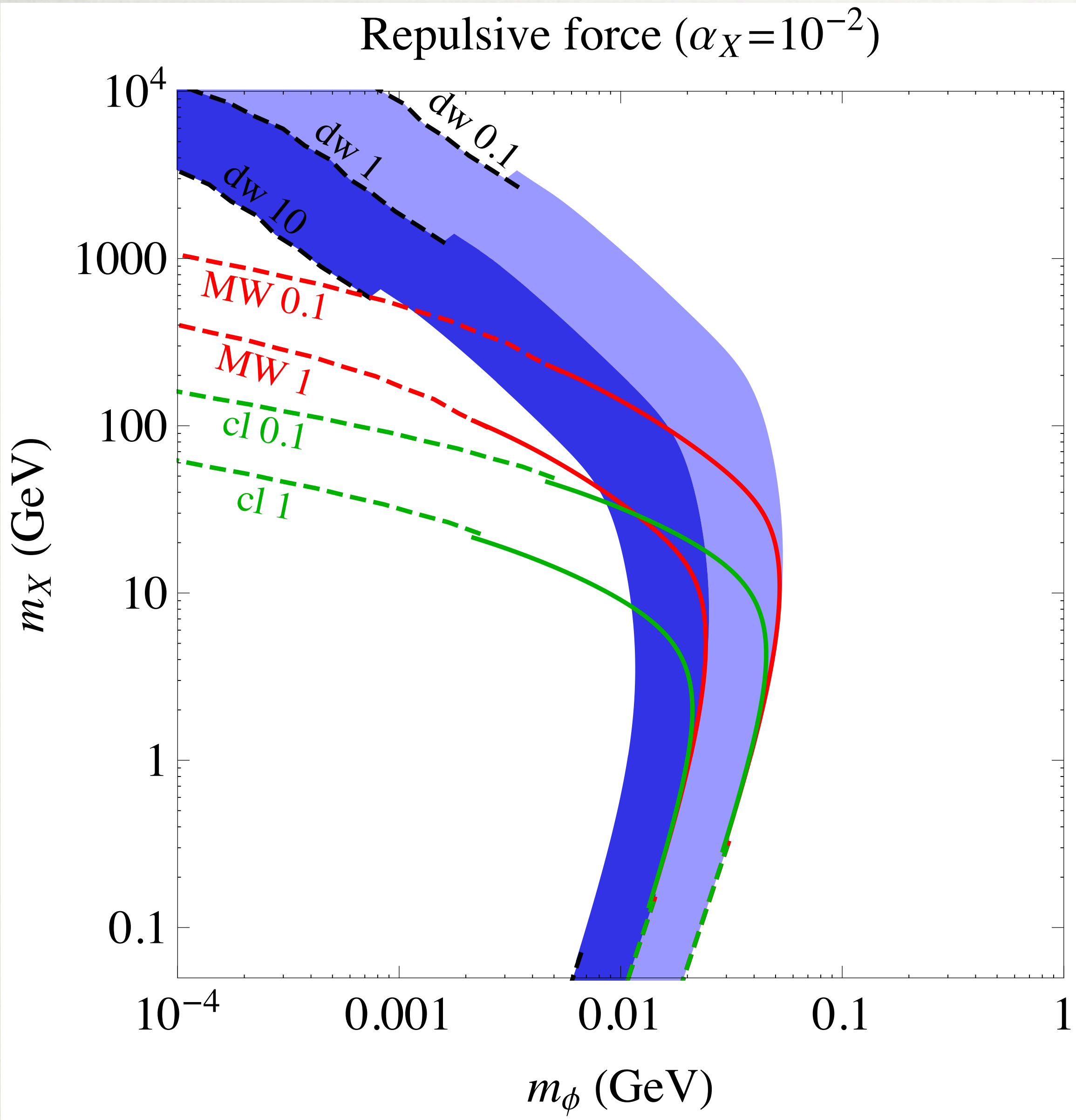
- Fits well with our new models of DM!

$$\sigma_T \approx 5 \times 10^{-23}\,\text{cm}^2 \left(\frac{\alpha_X}{0.01}\right)^2 \left(\frac{m_X}{10\,\text{GeV}}\right)^2 \left(\frac{10\,\text{MeV}}{m_\phi}\right)^4$$

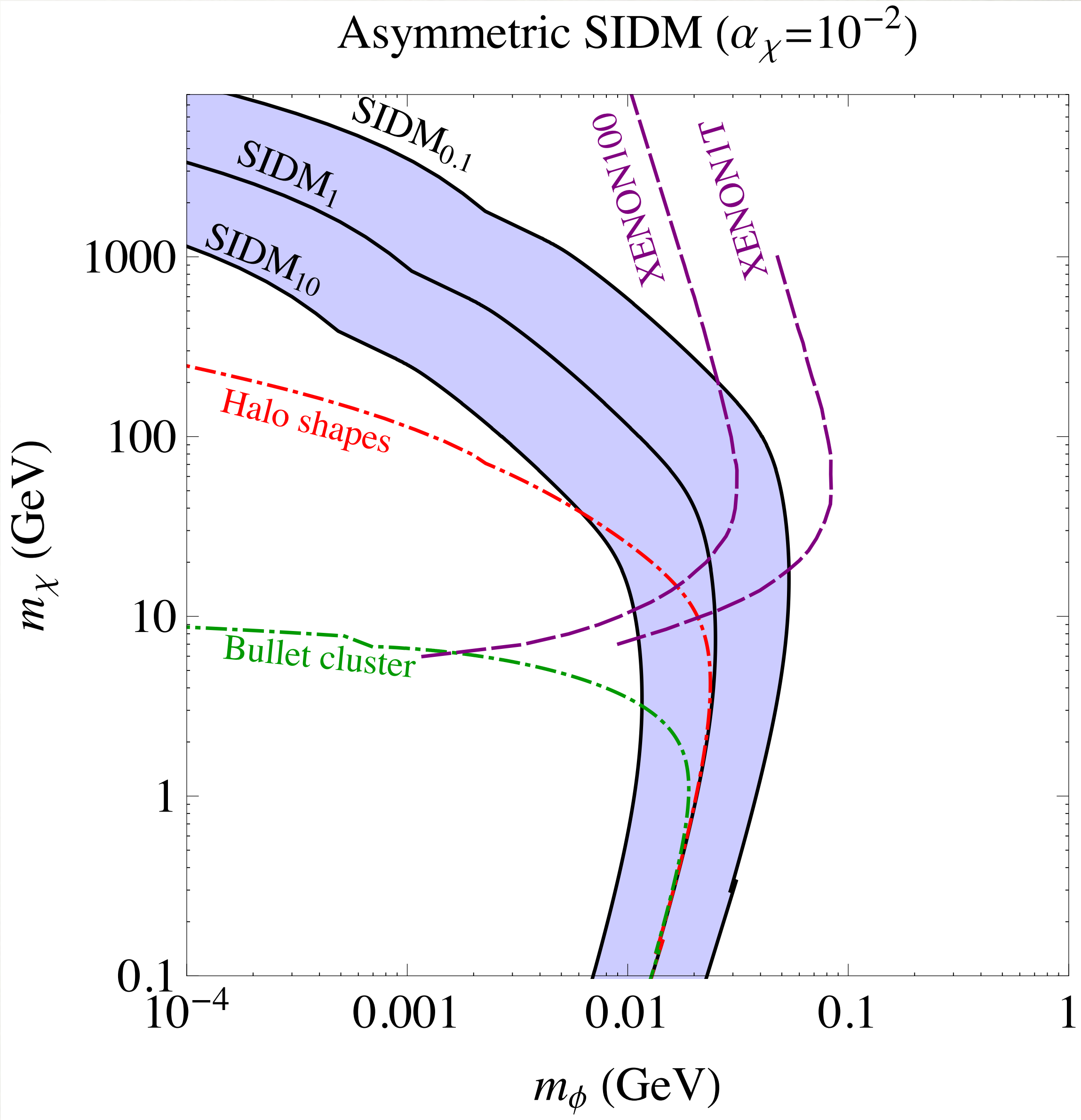
- Range of dynamics much bigger than previously thought

- Particle imprints on DM halos

Implications for Direct Detection



Tulin, Yu, KZ



$\epsilon = 10^{-10}$

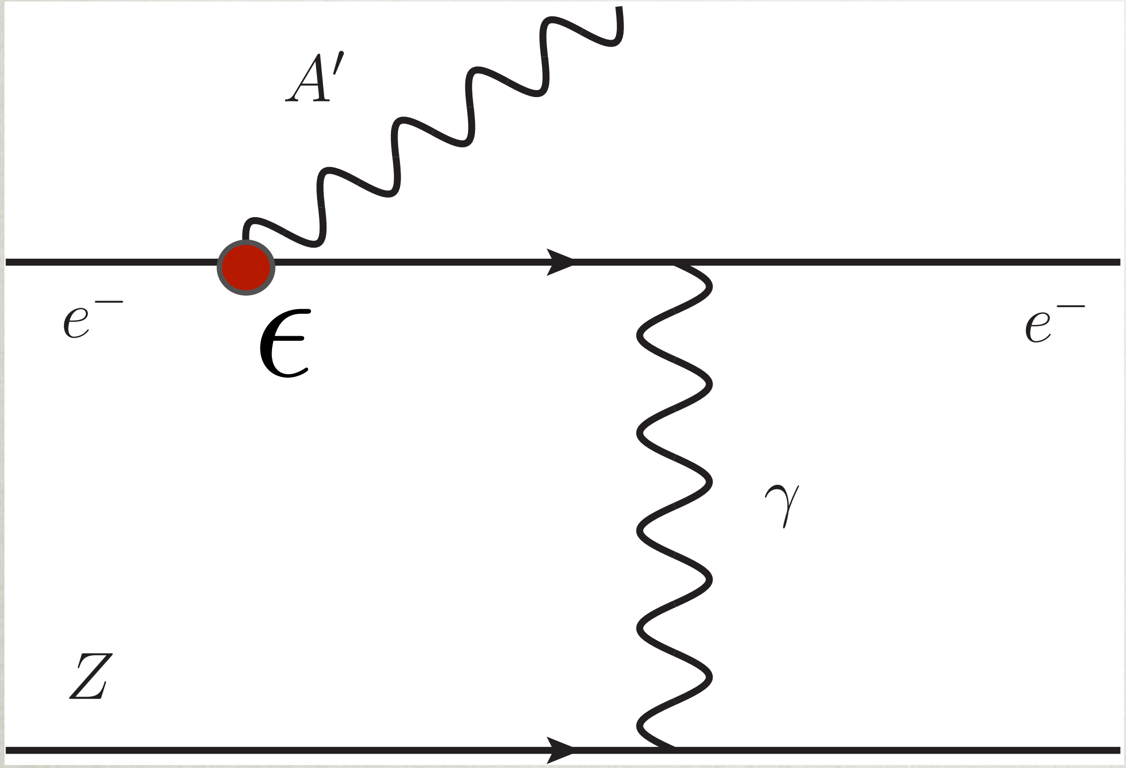
Kaplinghat, Tulin, Yu

$g_q \gtrsim 1.6 \times 10^{-11} \sqrt{1\ \mathrm{GeV}/m_\phi}$ from BBN

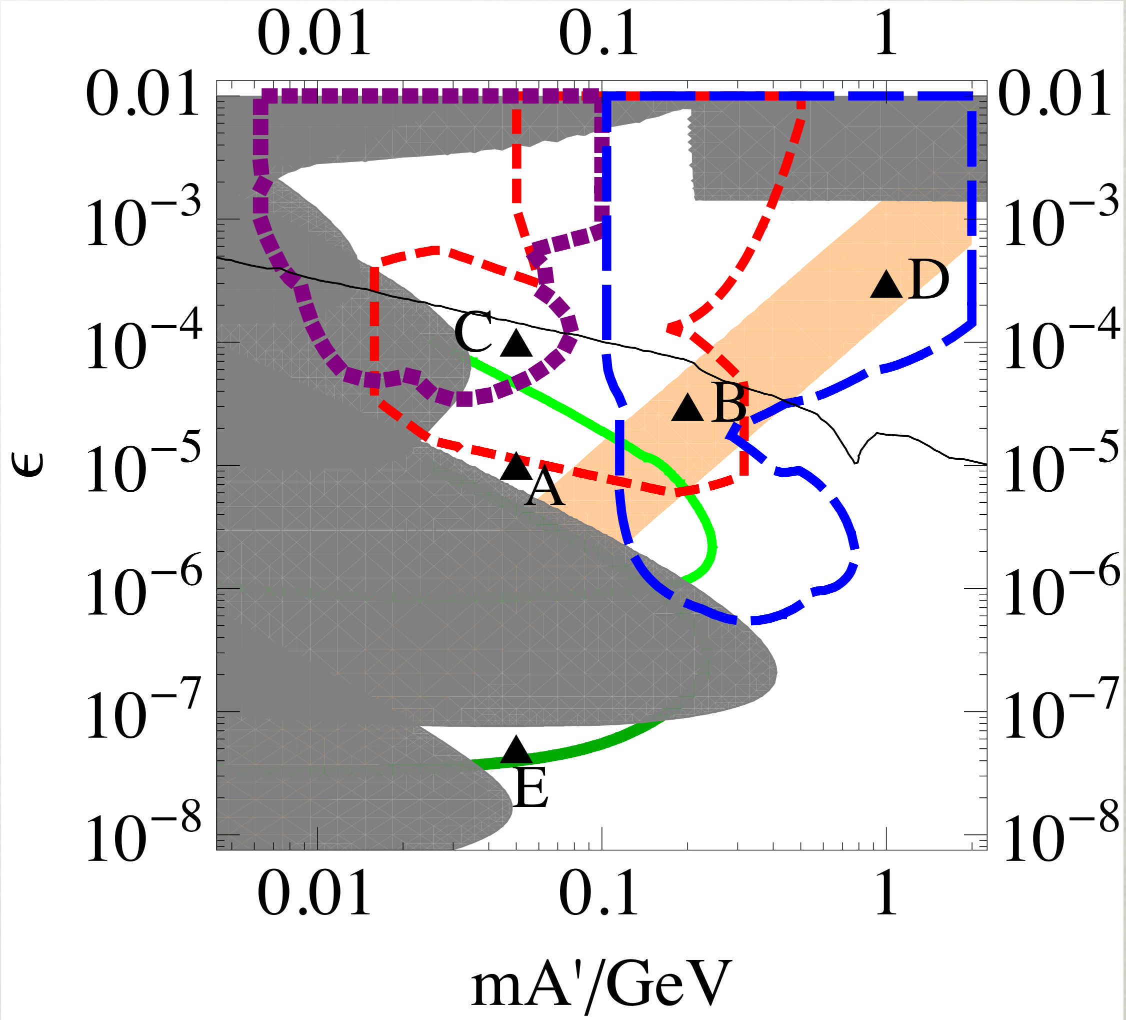
Lin, Yu, KZ

Reachable scattering cross-sections!

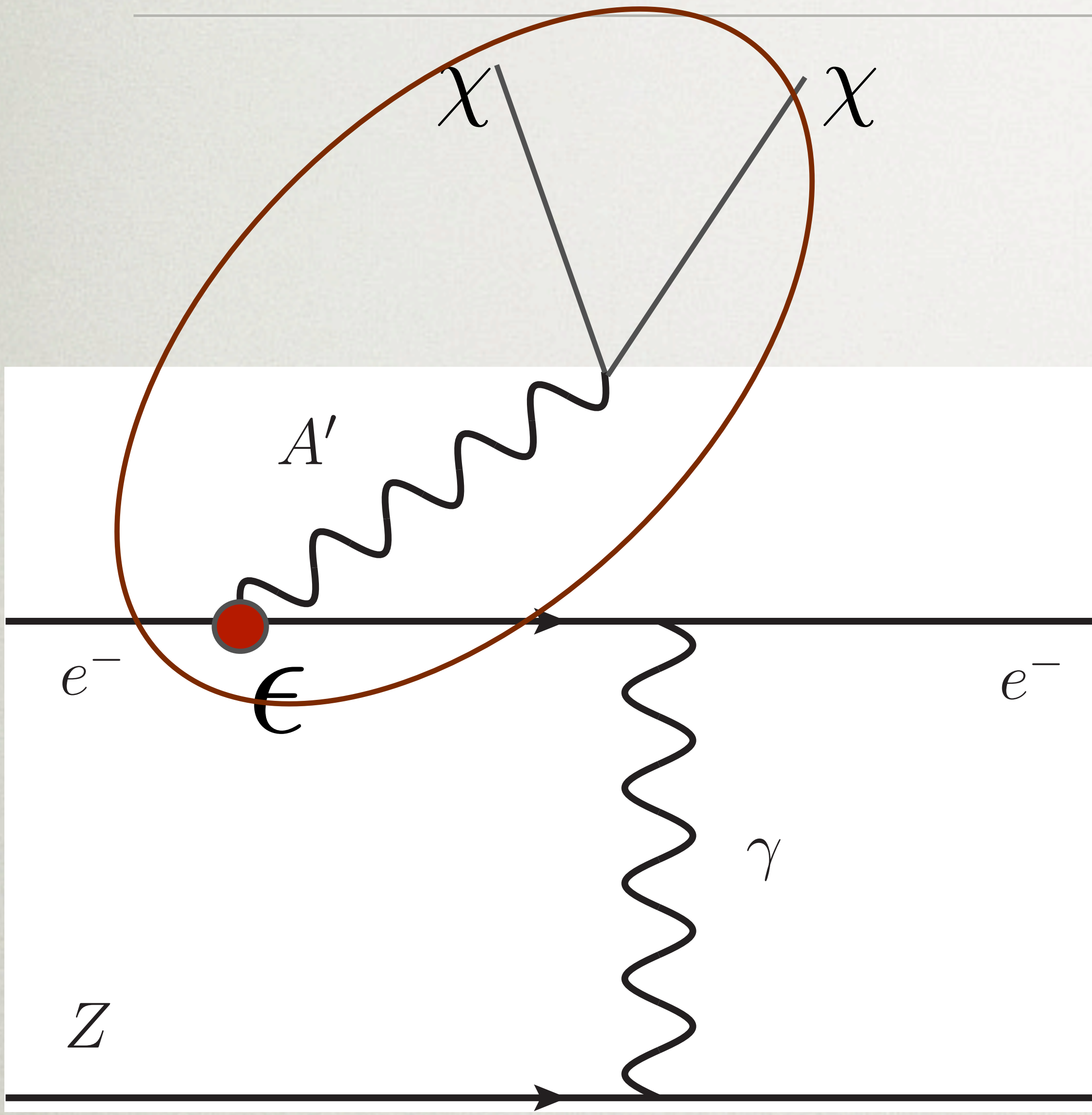
Low Energy Accelerator Constraints



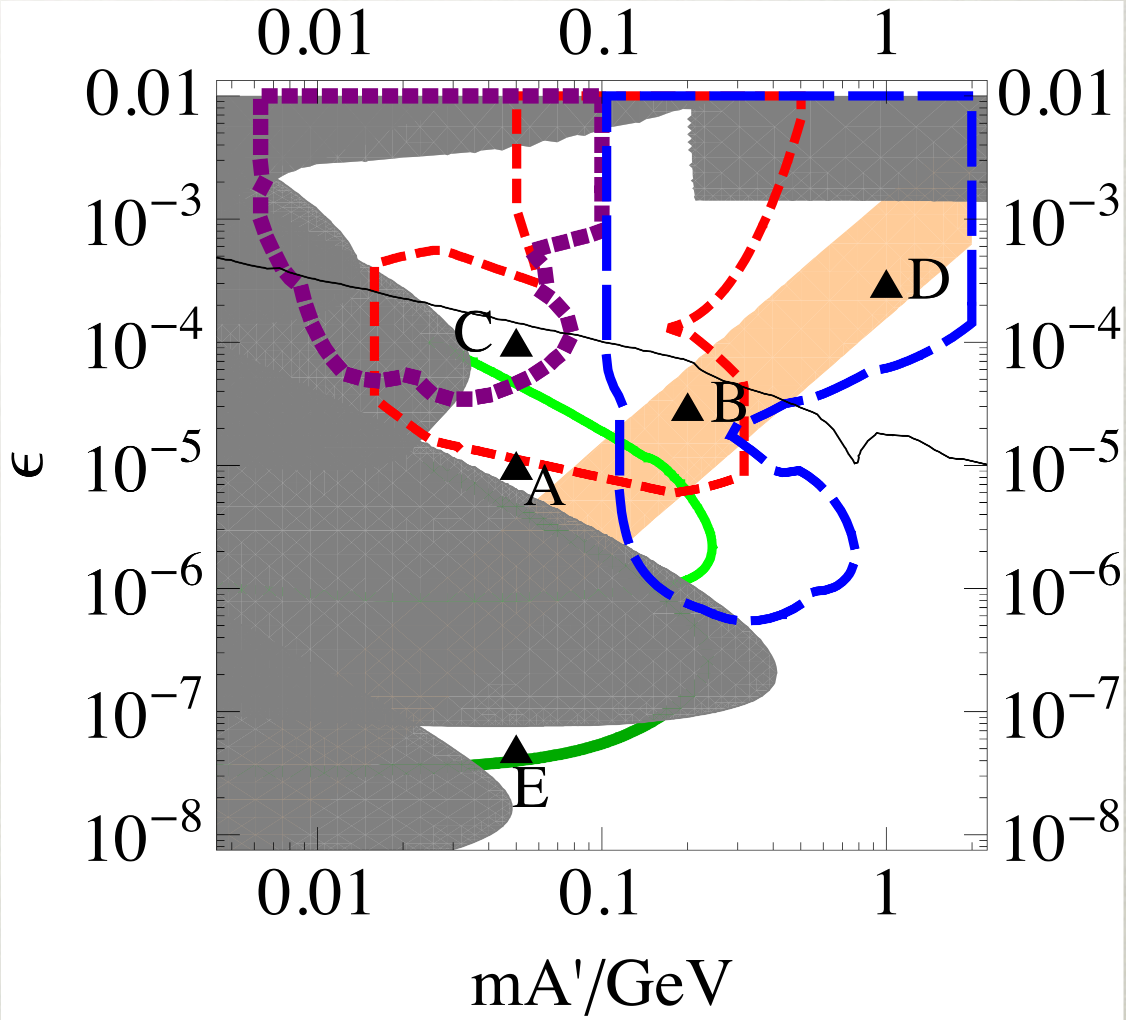
Bjorken, Essig, Schuster, Toro



Translate to Direct Detection



Bjorken, Essig, Schuster, Toro



The Lamppost Problem

- Great ideas! But are we too restricted by them?

CoGeNT

CDMS

DAMA

Galactic Center Excess

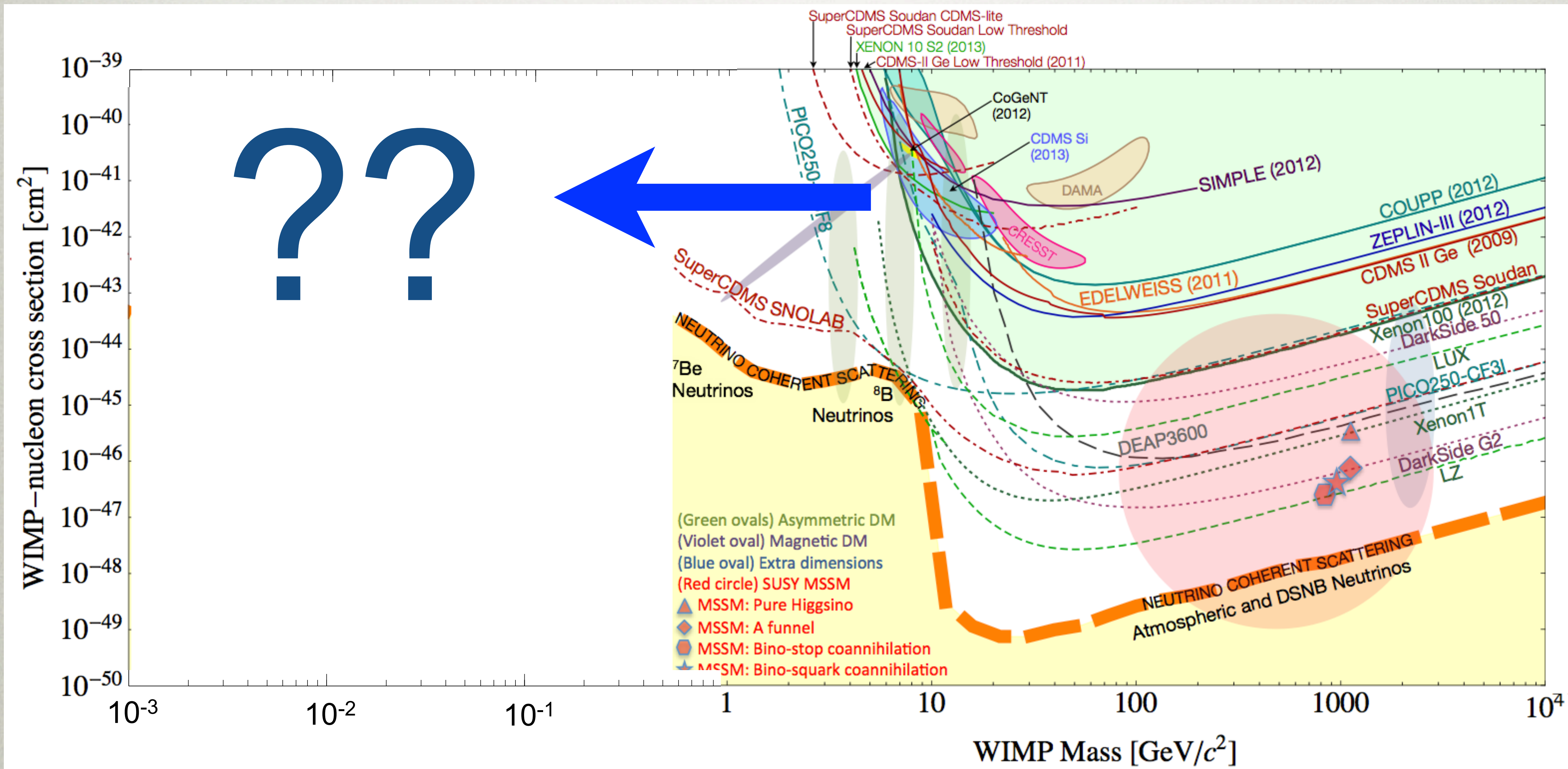
PAMELA

Fermi positron

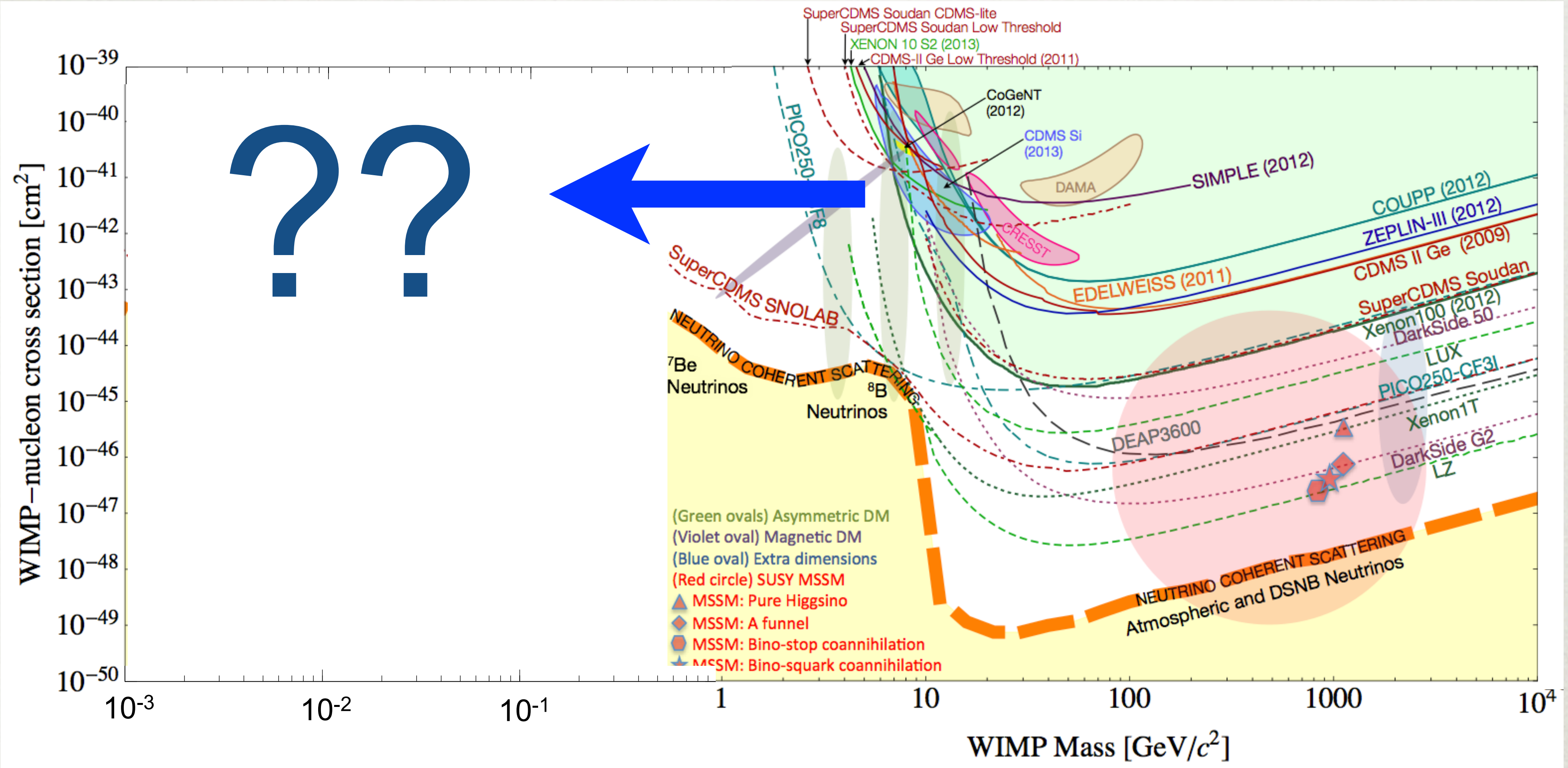
Fermi line

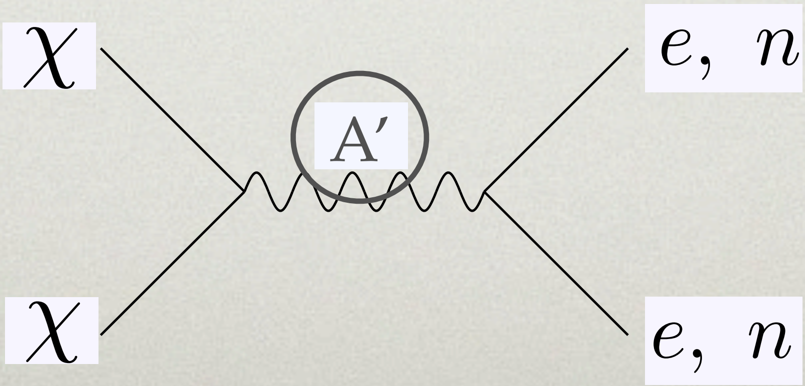
- How can we be ready for anything?

Terra Incognita



Terra Incognita

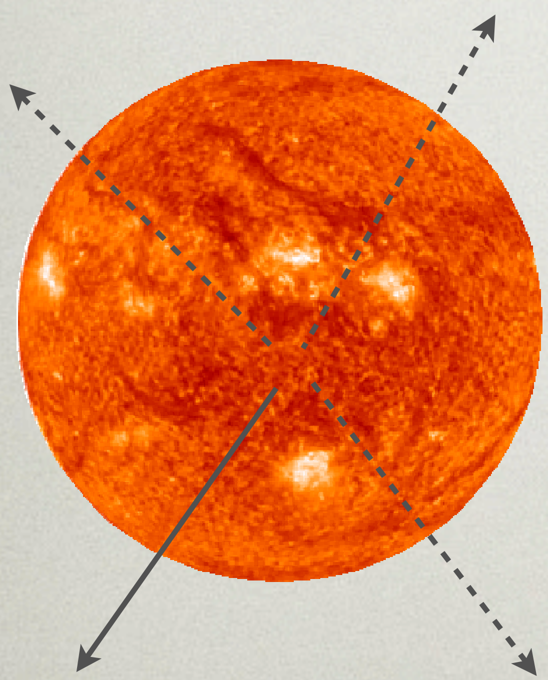


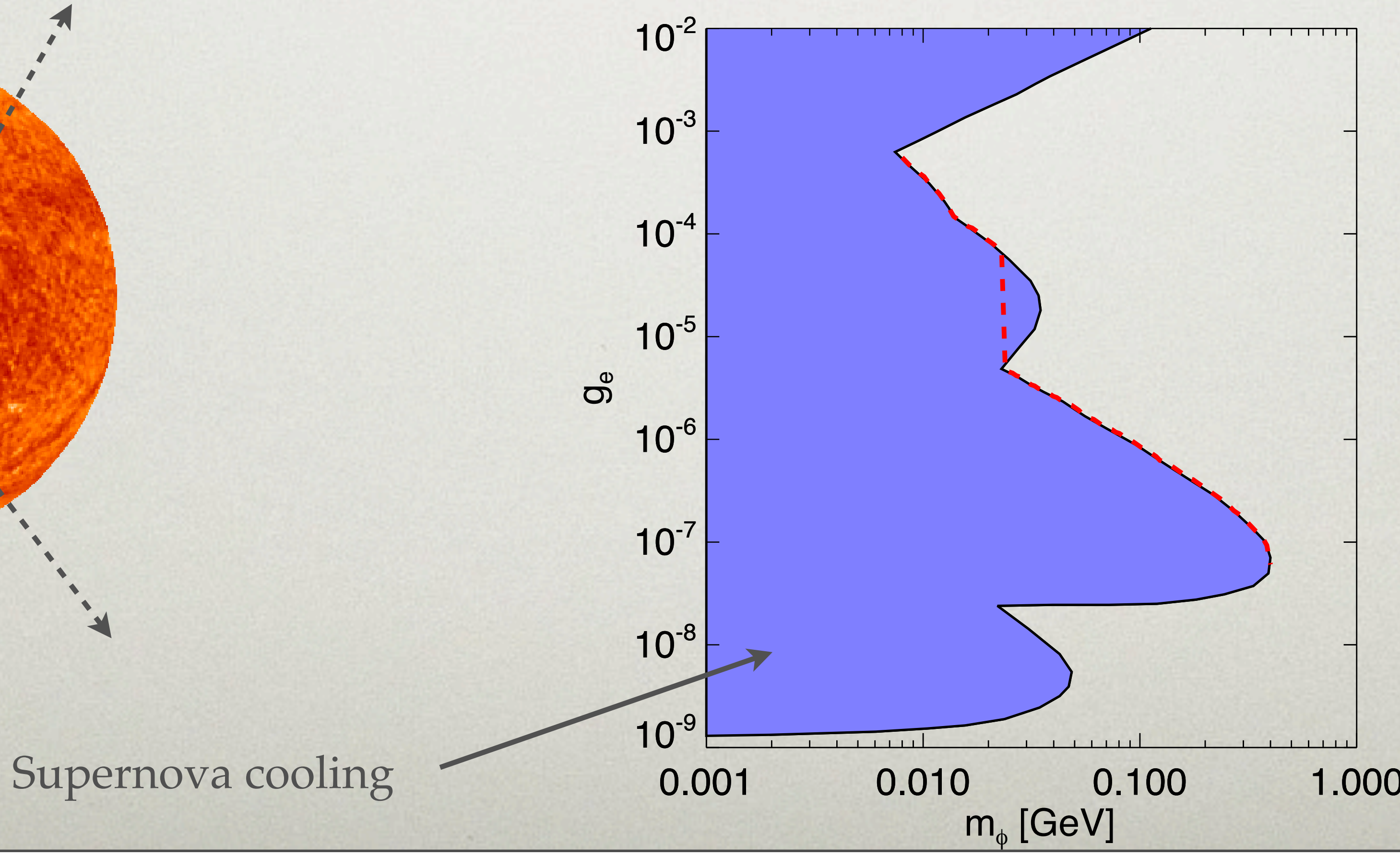


Low Mass DM Constrained by Astro

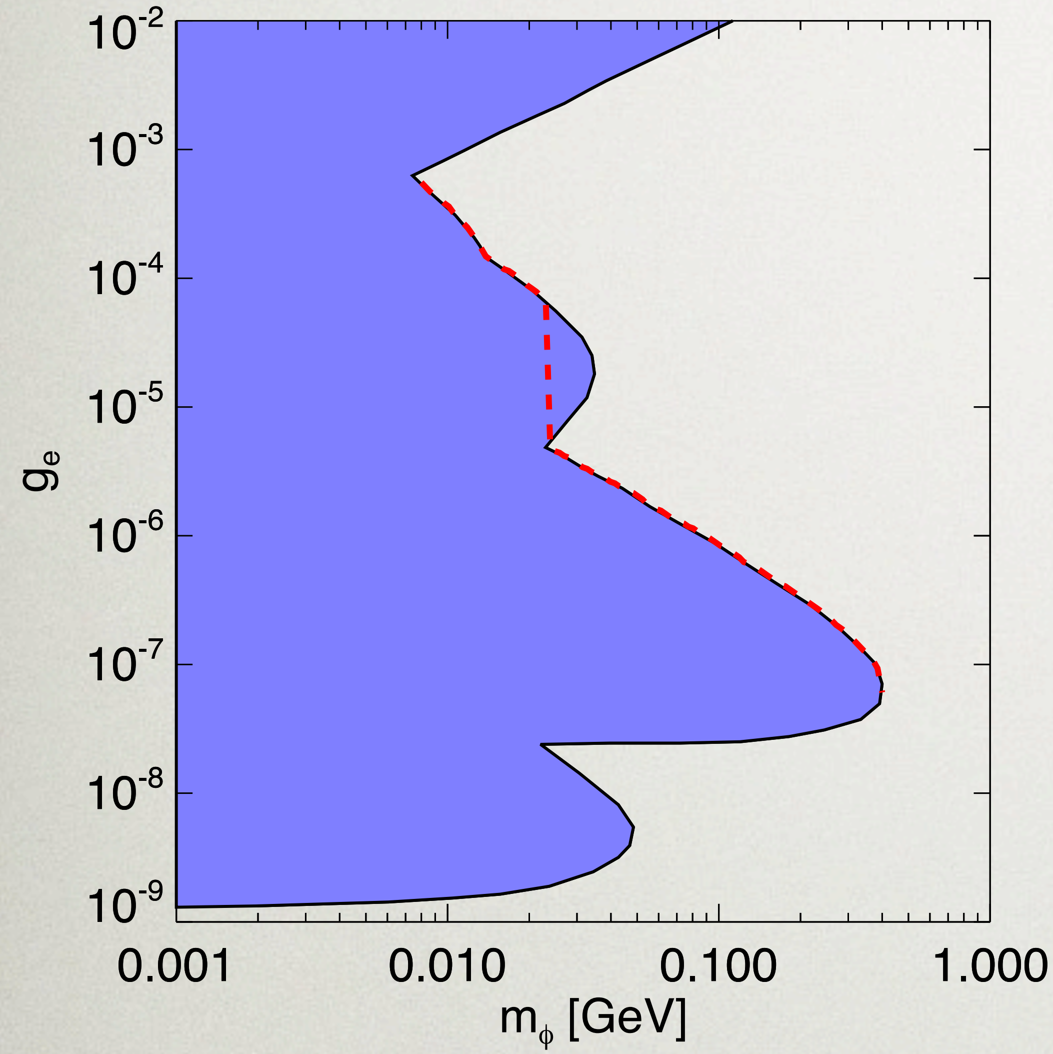
- objects like supernovae .... may be produced inside object.

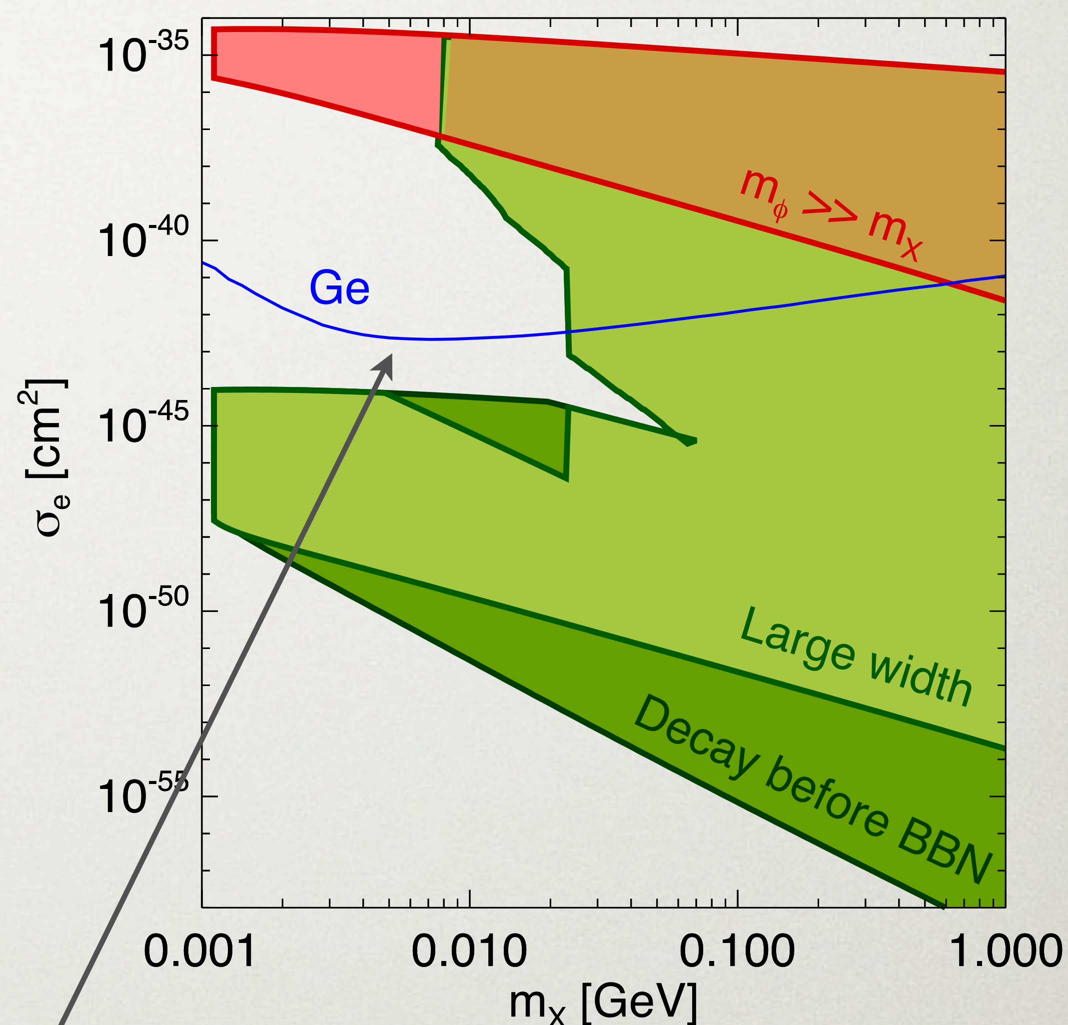
Cooling constraints places tight bounds





Map into Direct Detection Plane



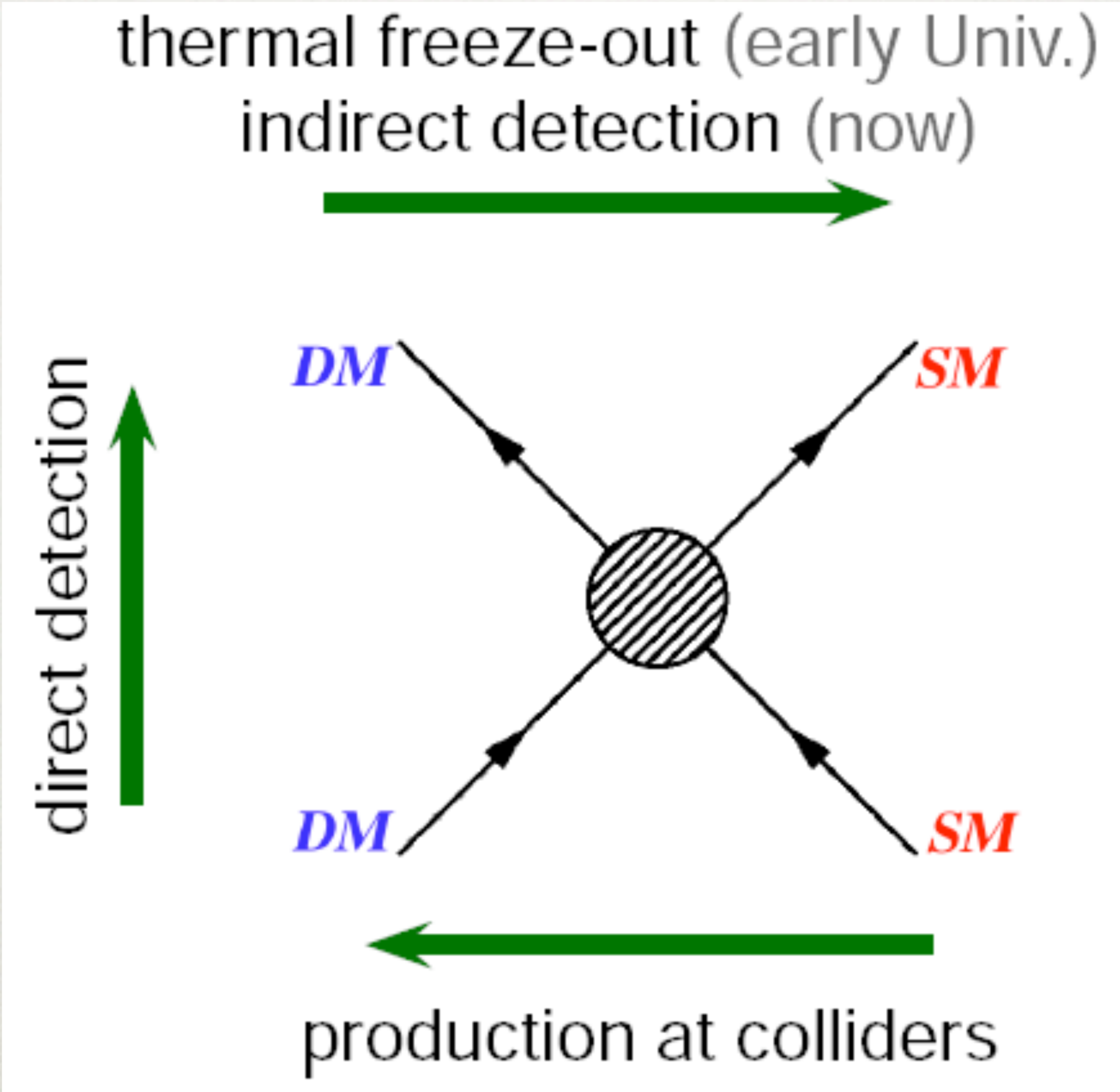


Lin, Yu, KZ 1111.0293

Projected maximum sensitivity of direct detection experiment

Cut-out gives combined constraints of beam dump + supernova + g-2

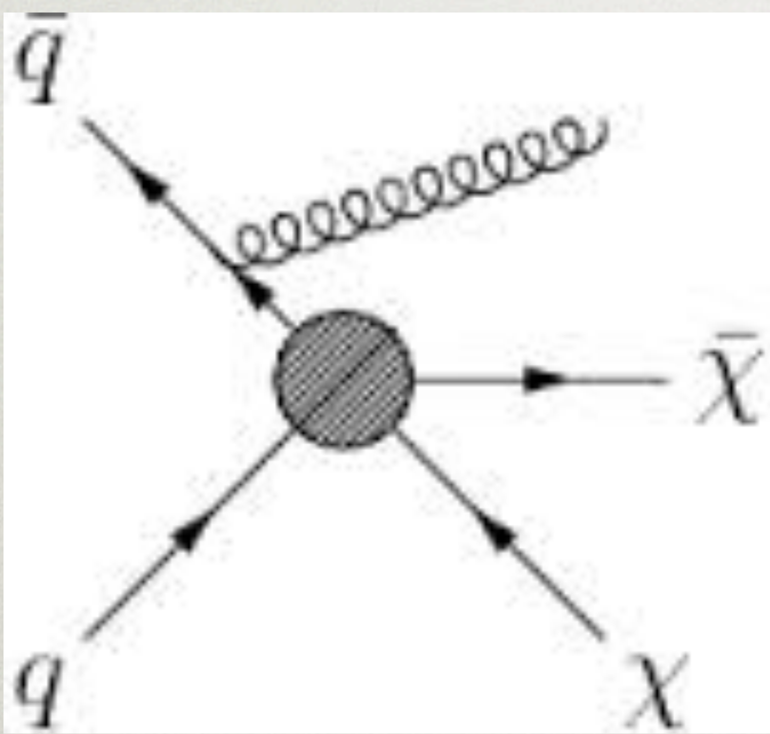
Complementarity with LHC Searches

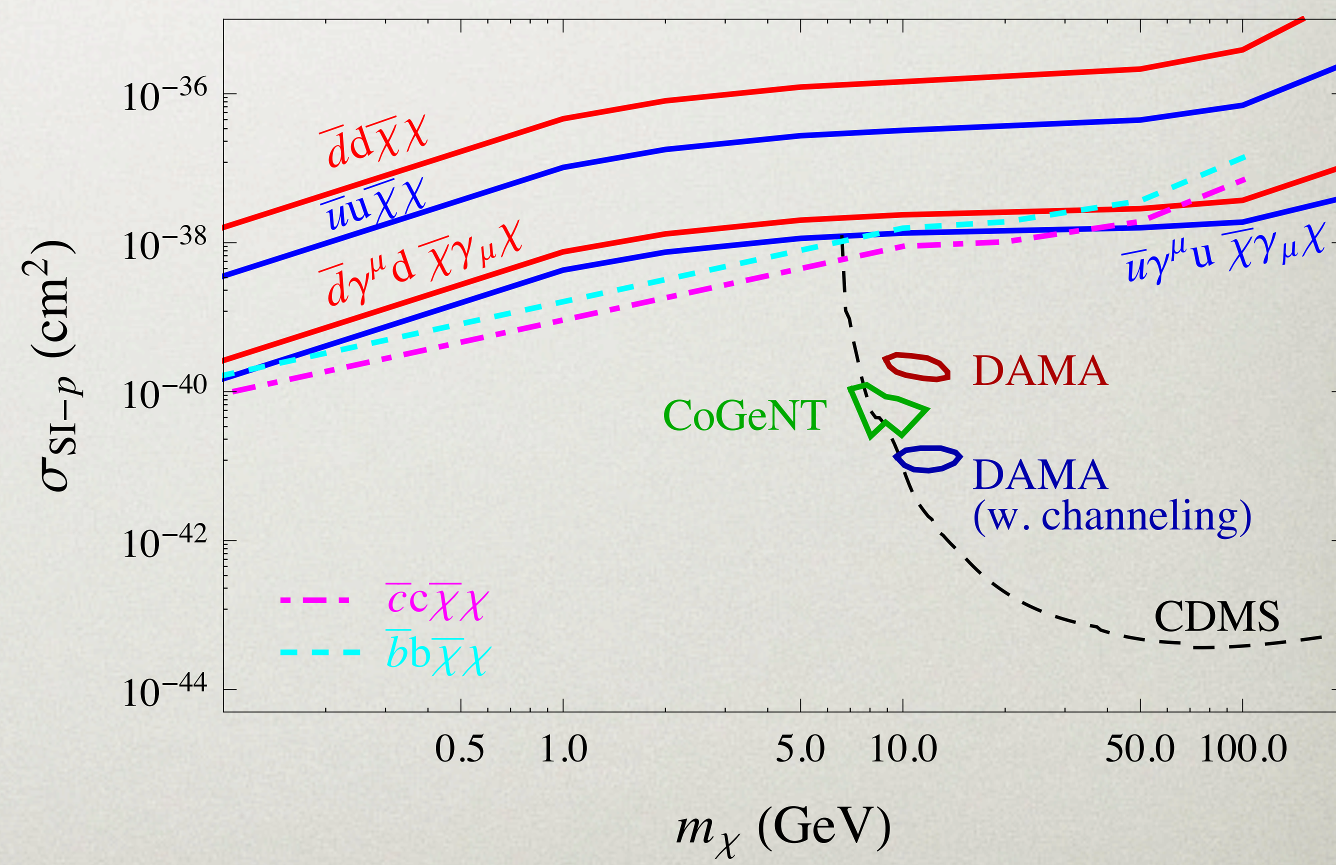


Complementarity with LHC Searches

- Monojet searches appear to rule out low mass dark matter

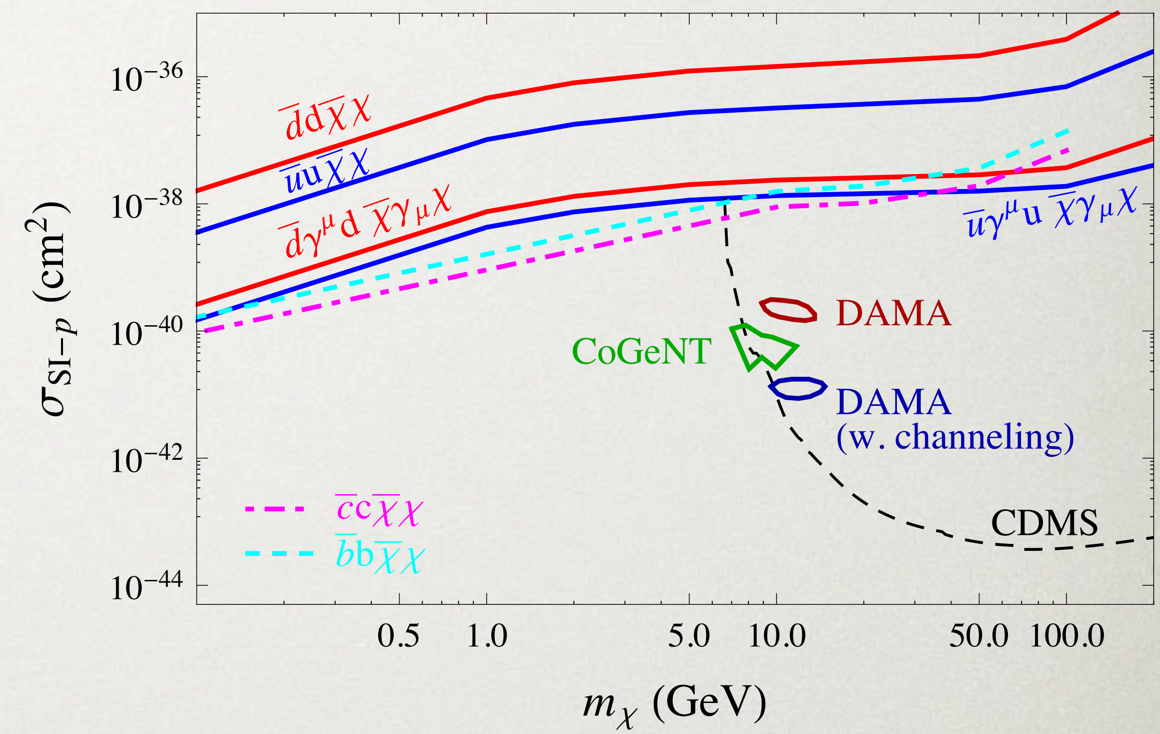
Bai, Fox, Harnik, 1005.3797

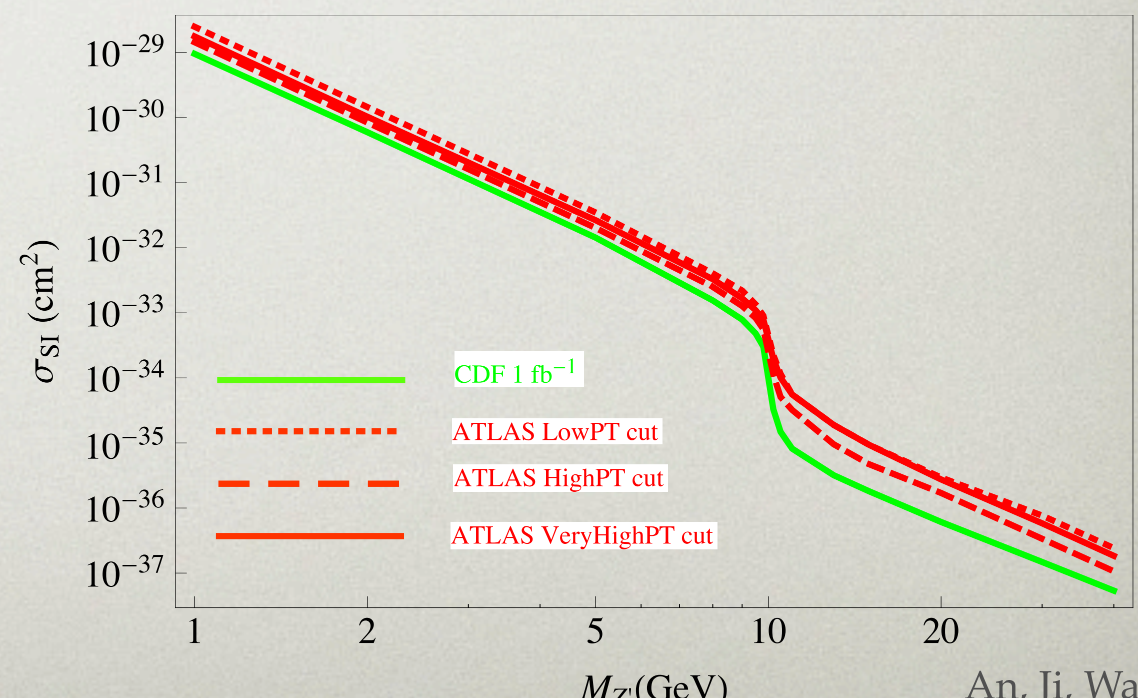




When Direct Detection Beats Colliders...

- Direct detection experiments are like a collider based intensity experiment *at low energies*
- Far more effective than high energy colliders -- e.g. monojets with light A′ mediator





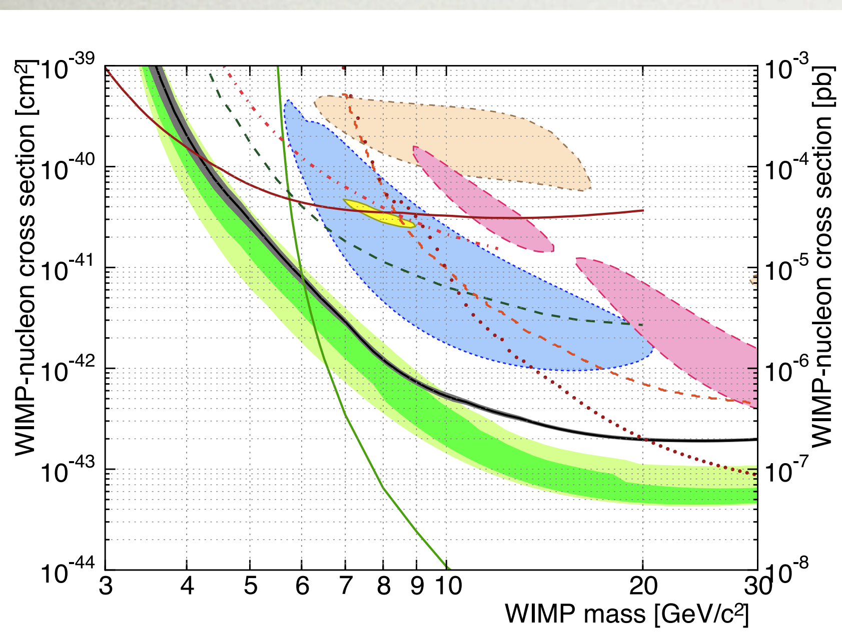
An, Ji, Wang

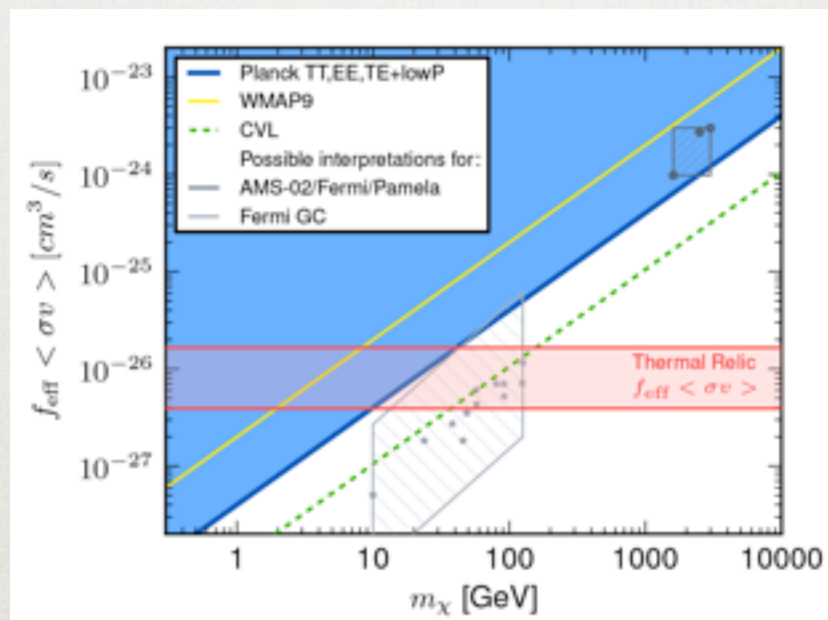
We Should Be Ready for Surprises ....

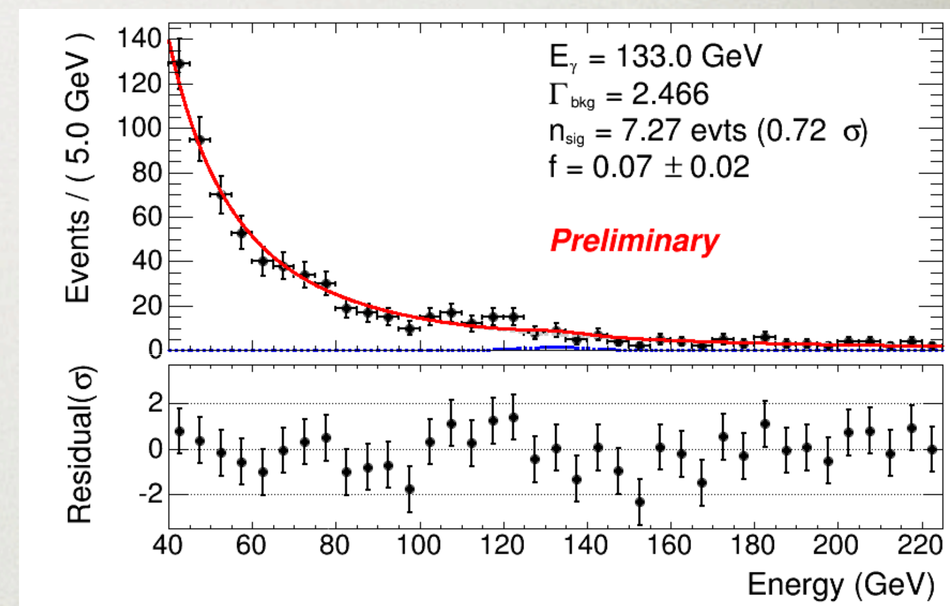
CoGeNT
CDMS
DAMA

PAMELA
Fermi positron
AMS

Fermi 130 GeV line



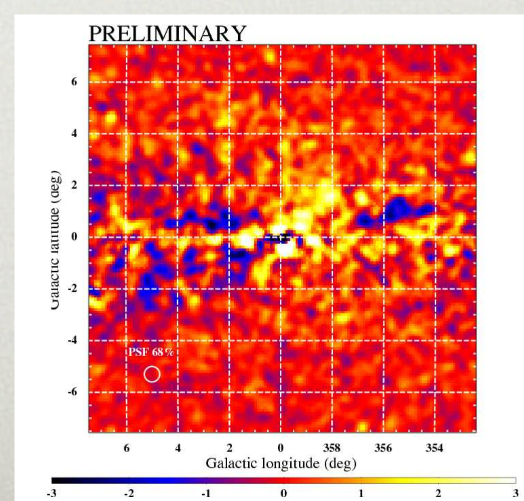


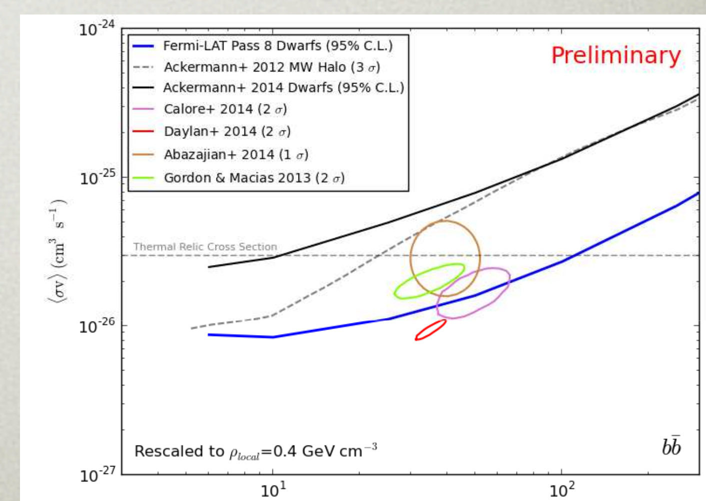


SuperCDMS 1402.7137

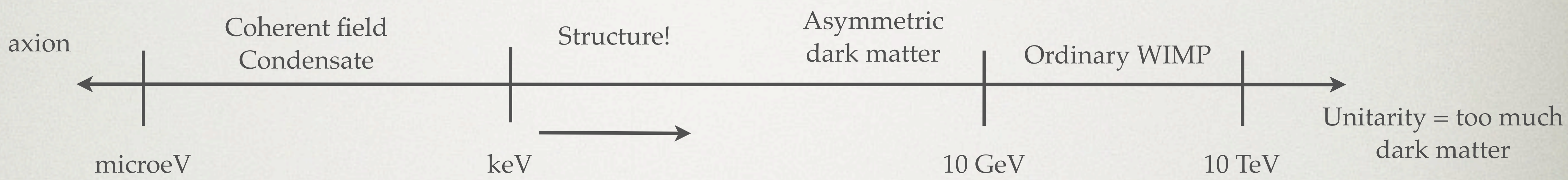
Planck results 2014

Galactic Center Excess ?

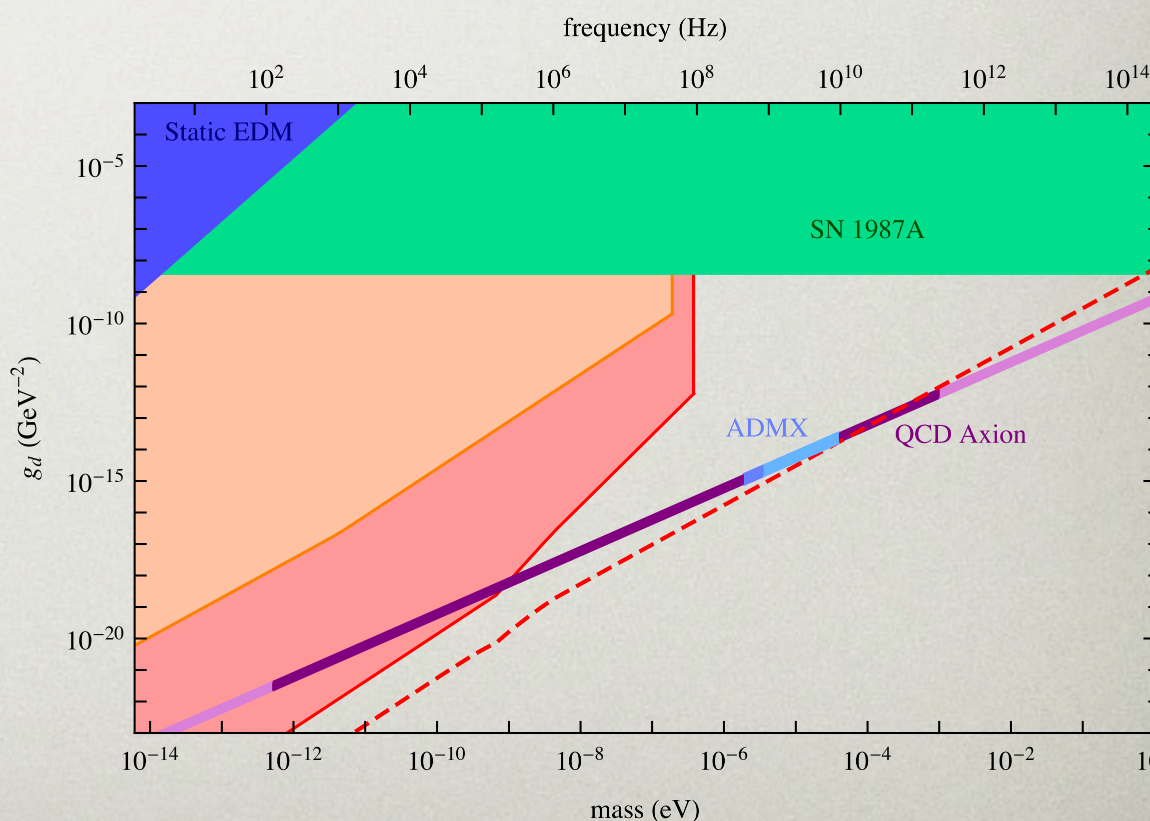




Ultralight Direction



- Axion
- Can make use of coherence effects (bose einstein condensate)
- New experimental directions to probe more of this parameter space



Barbieri et al Phys Lett B226 (1989) 357 Budker et al 1306.6089

New Experimental Results ...

... have forced us to look outside the lamp post. This is very complimentary to the new theoretical landscape.

CoGeNT

CDMS

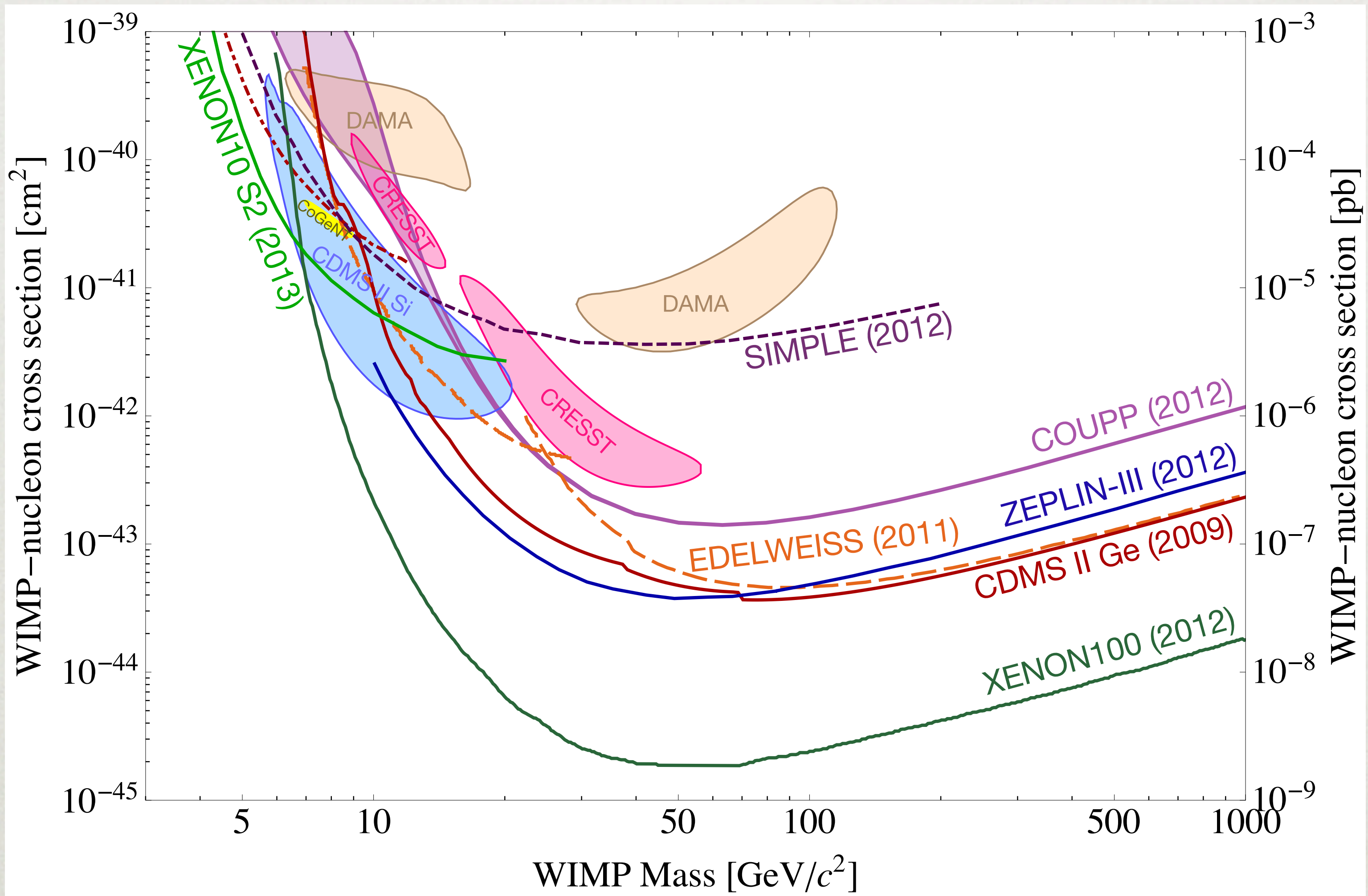
DAMA

PAMELA

Fermi positron

Fermi line

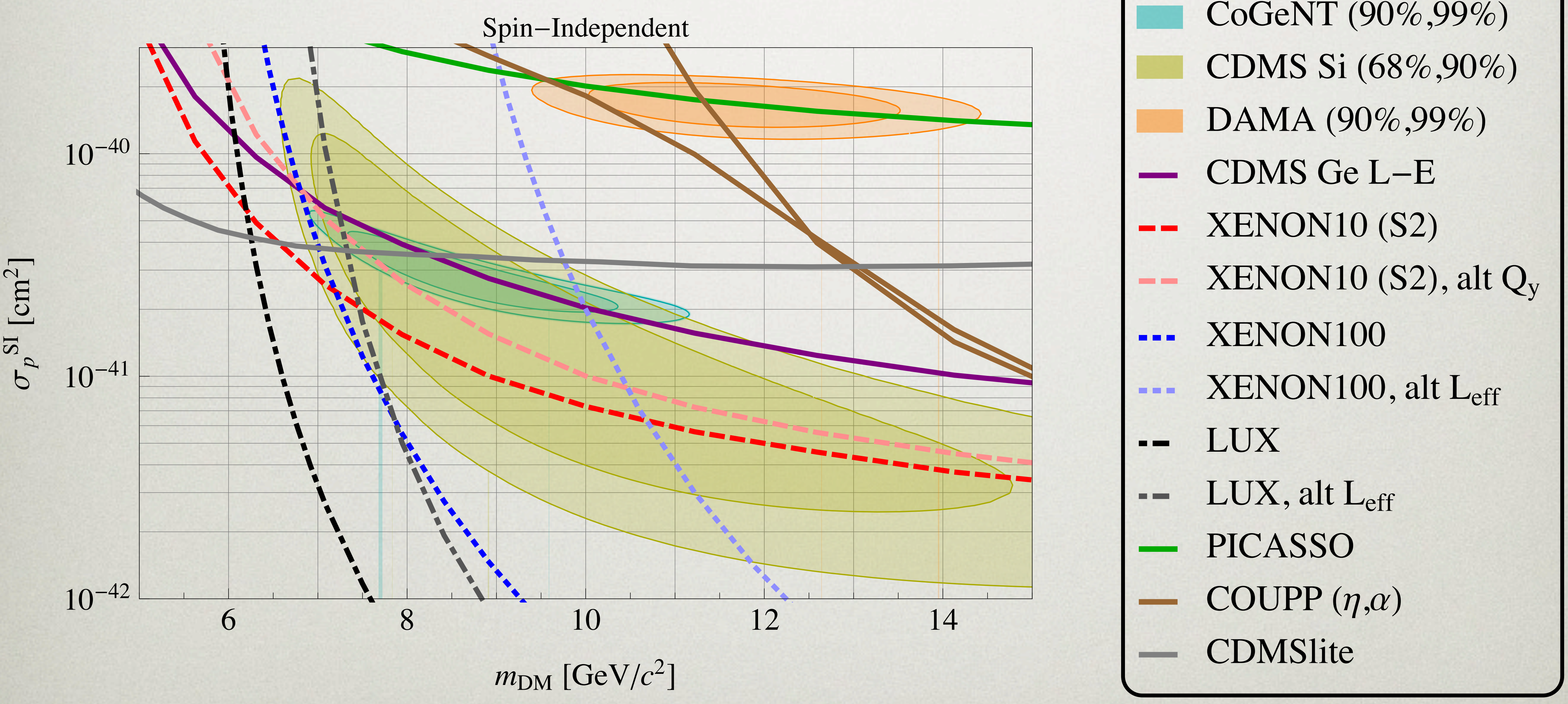
Direct Detection Anomalies



CF1 Snowmass report, 1310.8327

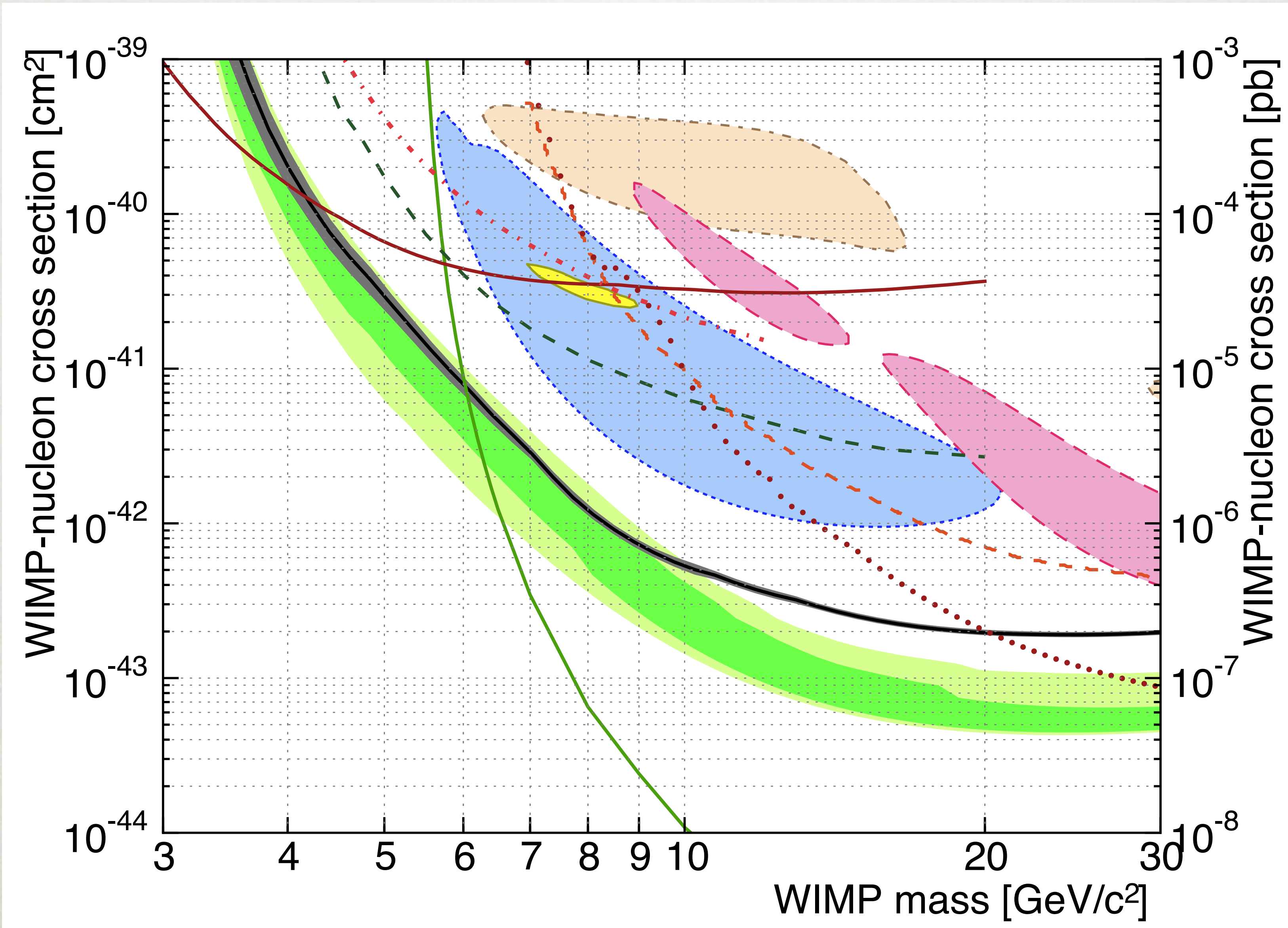
Direct Detection Anomalies

Gresham, KZ 1311.2082



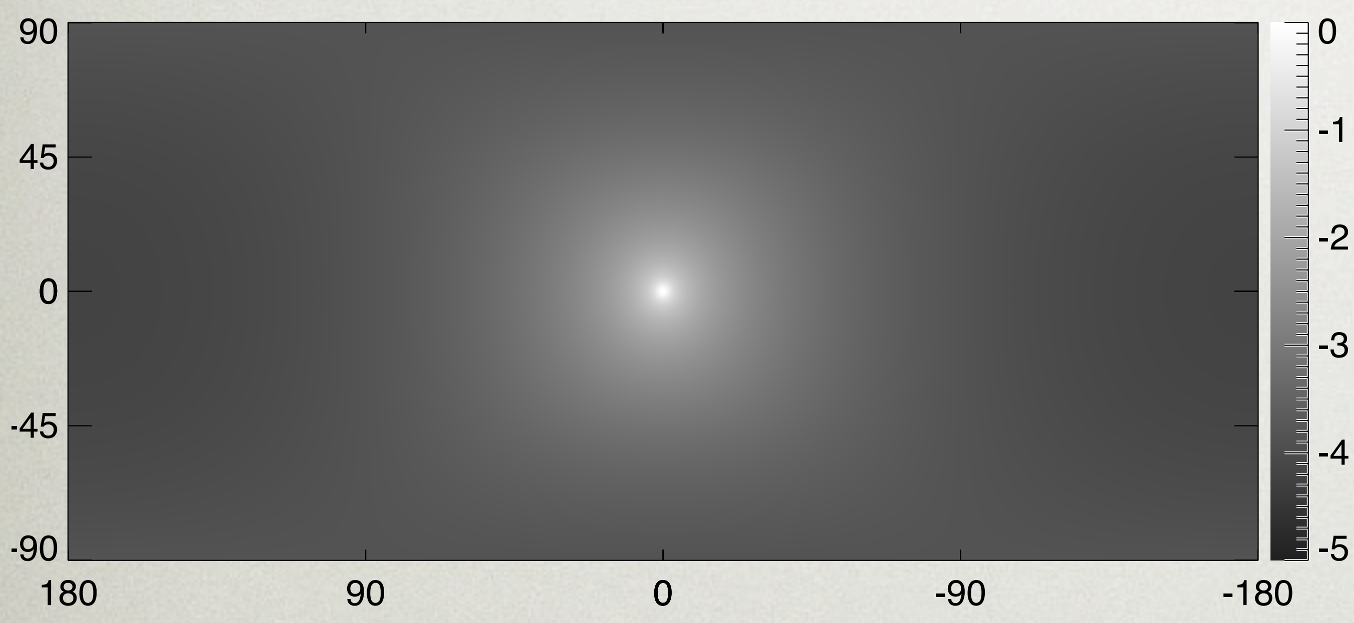
SuperCDMS Weighs In

SuperCDMS, 1402.7137

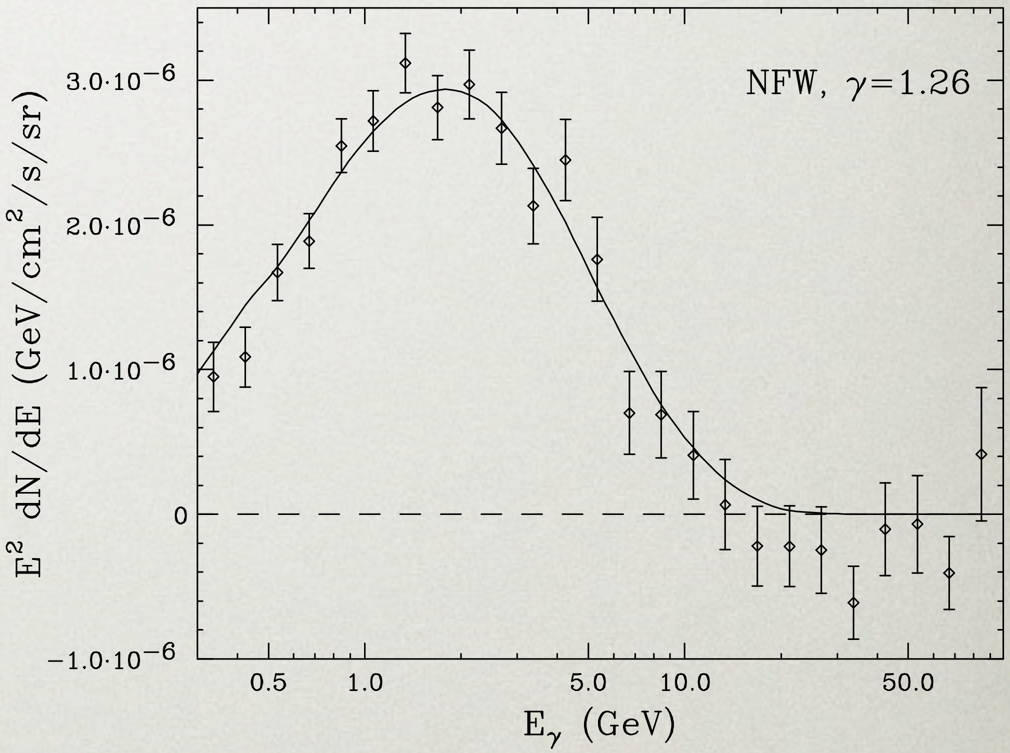


Latest Indirect Detection Anomaly

- From the galactic center

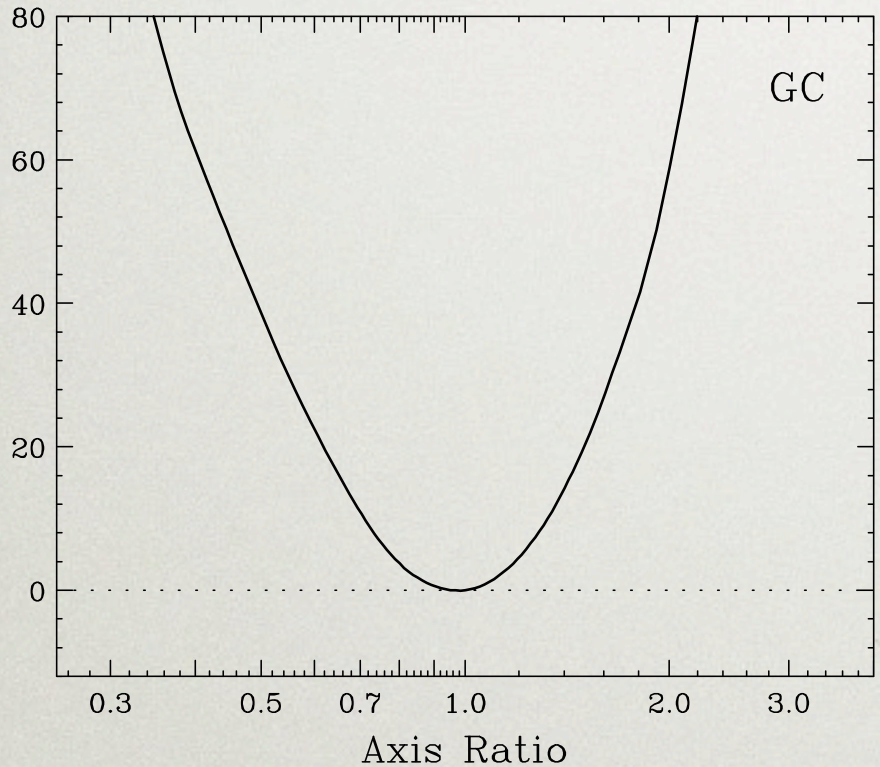


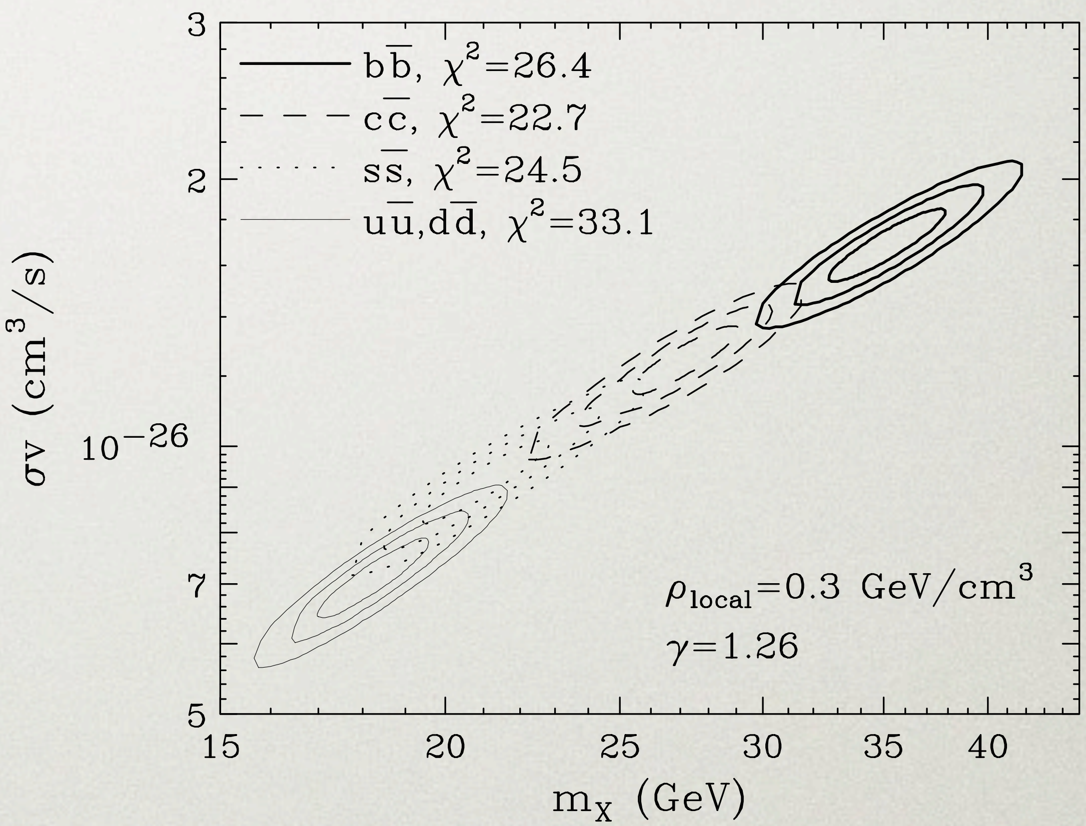
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1406.6703



Fit Well By Annihilation to b

- From the galactic center

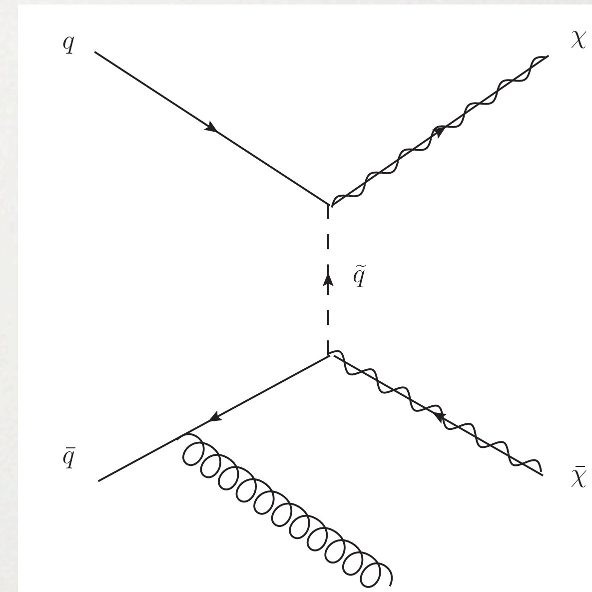




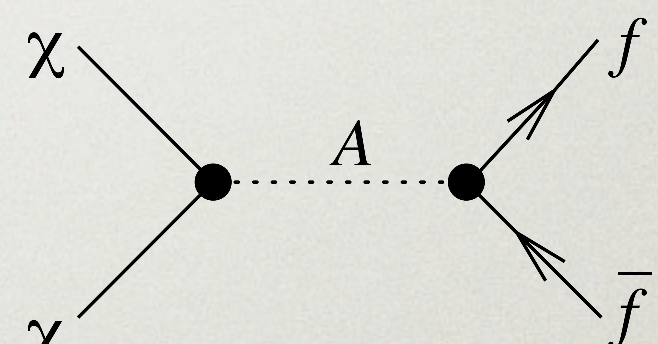
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1406.6703

Models for the GC Excess -- Easy!

- t-channel -- strongly constrained by colliders

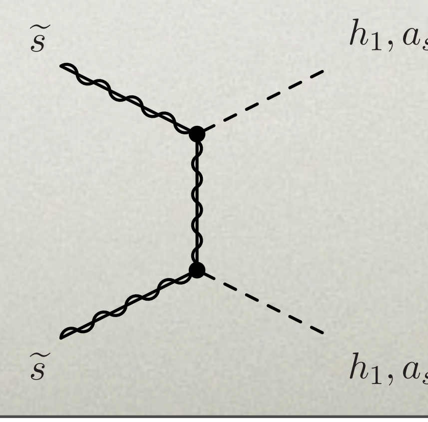


- s-channel -- via pseudo scalar



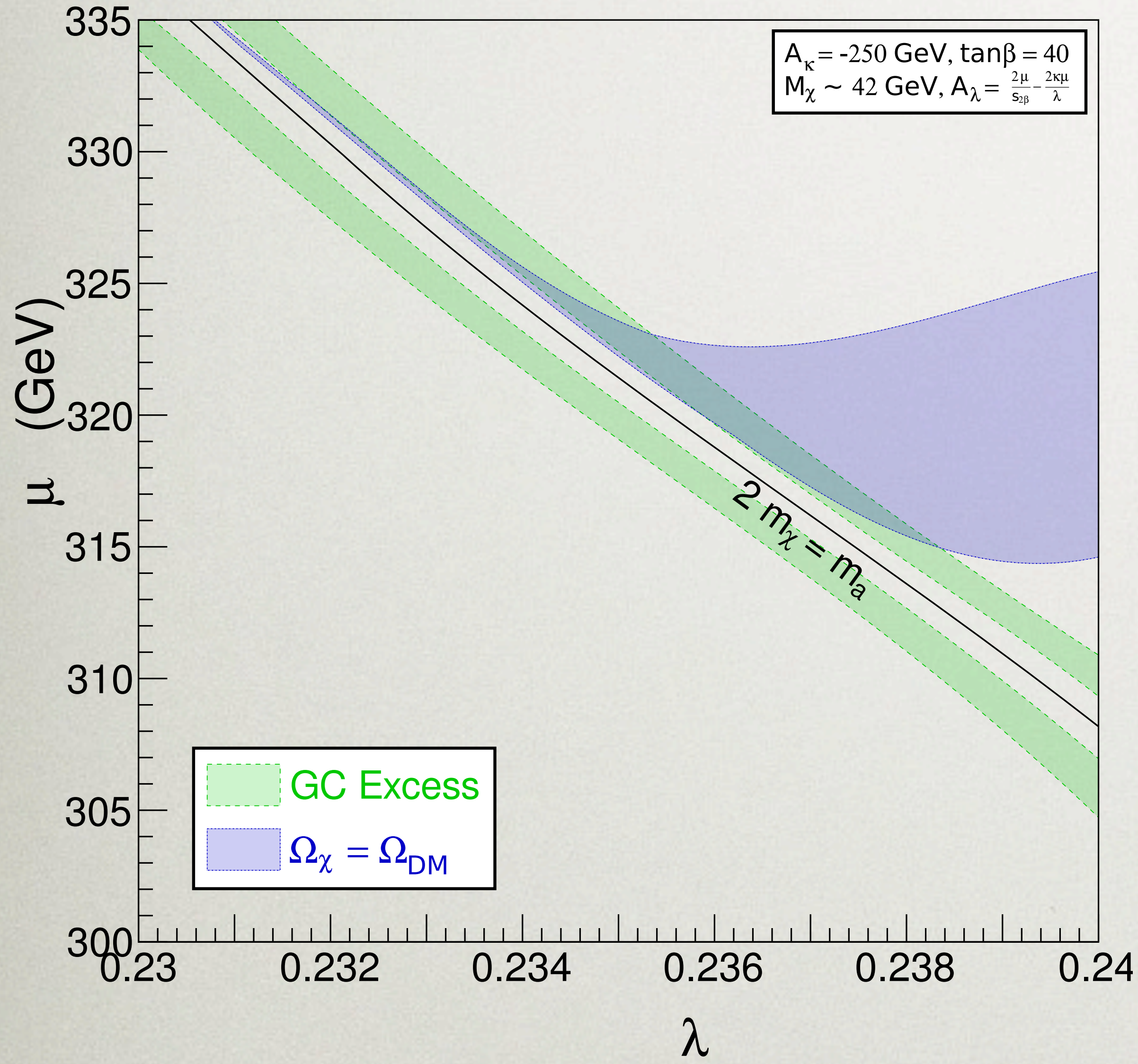
- 2-->4 -- viable, and simplest possibility
- Not MSSM; NMSSM viable

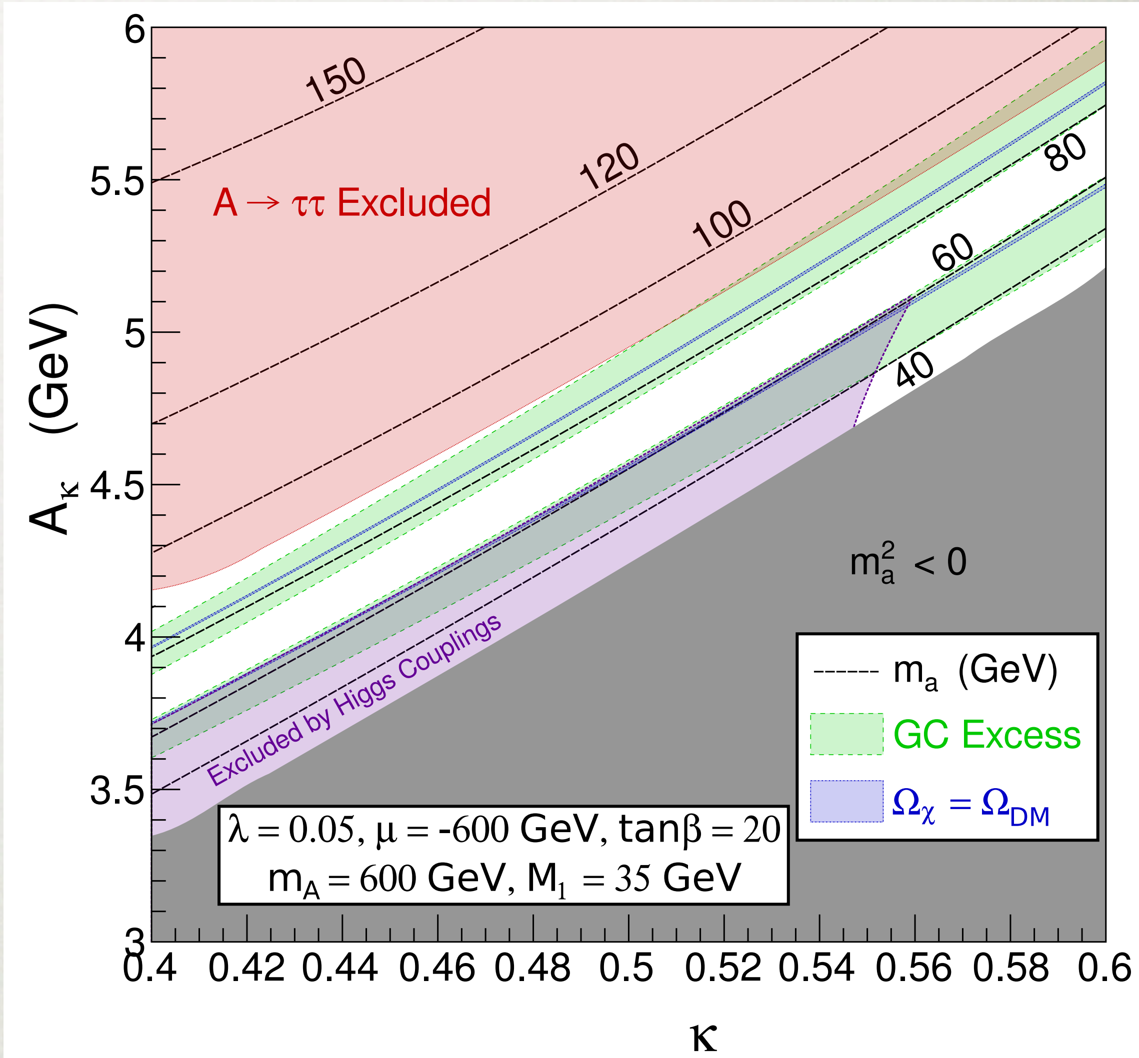
Cheung, Papucci, Sanford, Shah, KZ, 1406.6372



… but Narrow Parameter Region

Cheung, Papucci, Sanford, Shah, KZ, 1406.6372





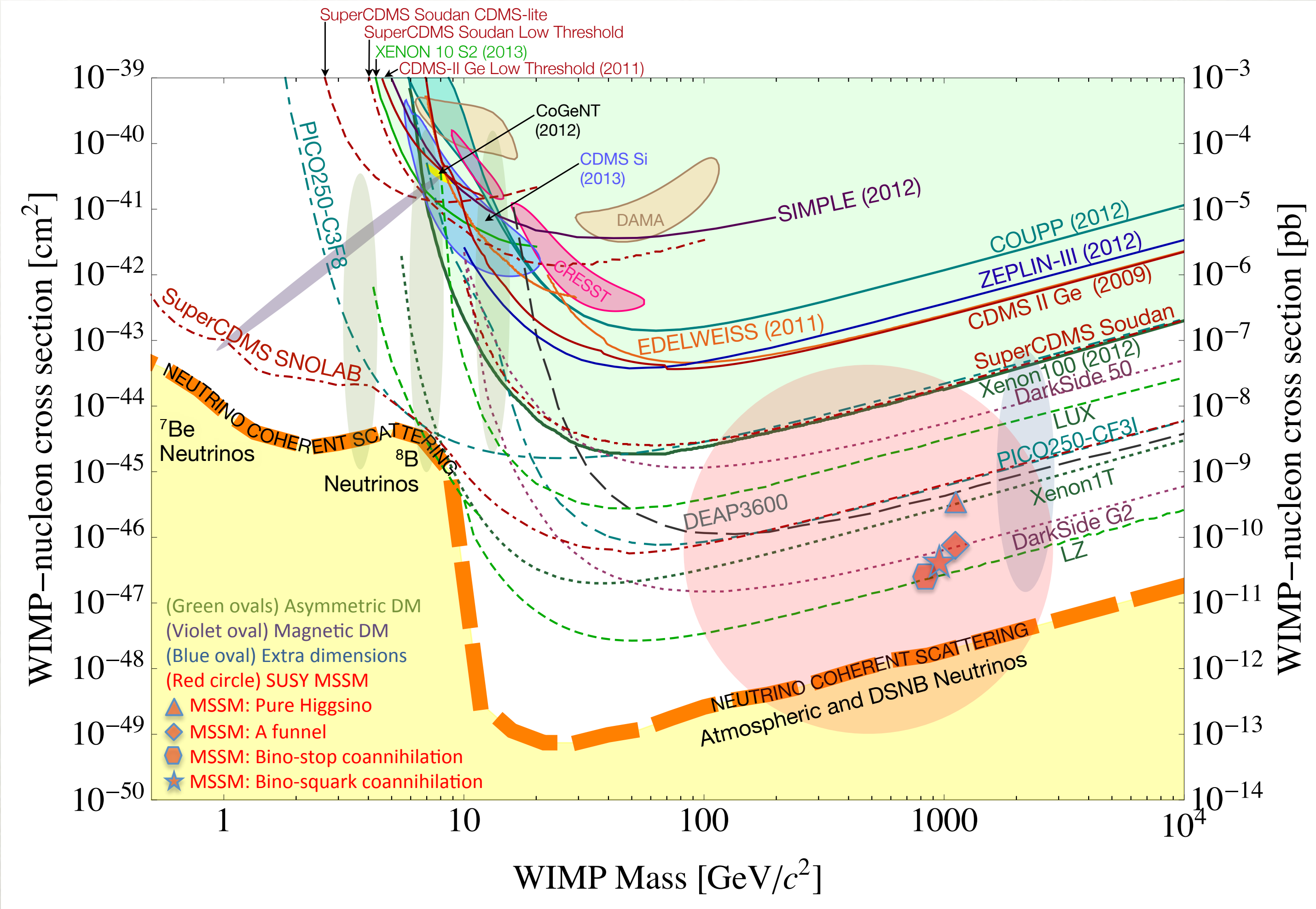
Singlino/Higgsino Dominated on Resonance

Bino/Higgsino Off-Resonance

The Road Ahead

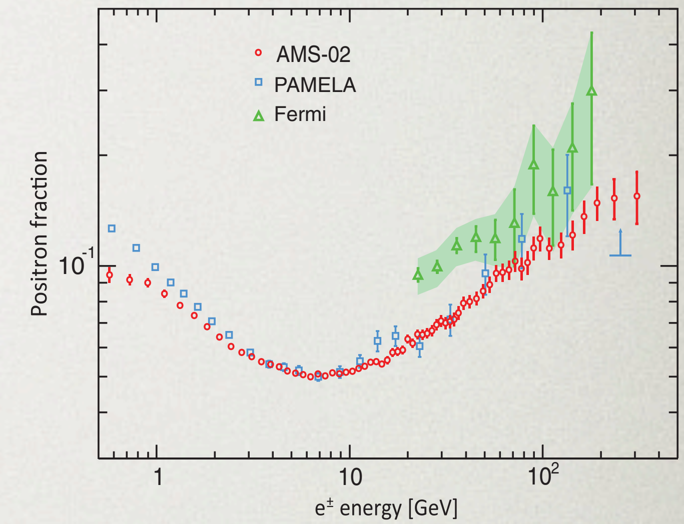
- Direct Detection experiments will continue to probe Higgs mediated scattering
- Higgs pole largely covered within 5 - 10 years

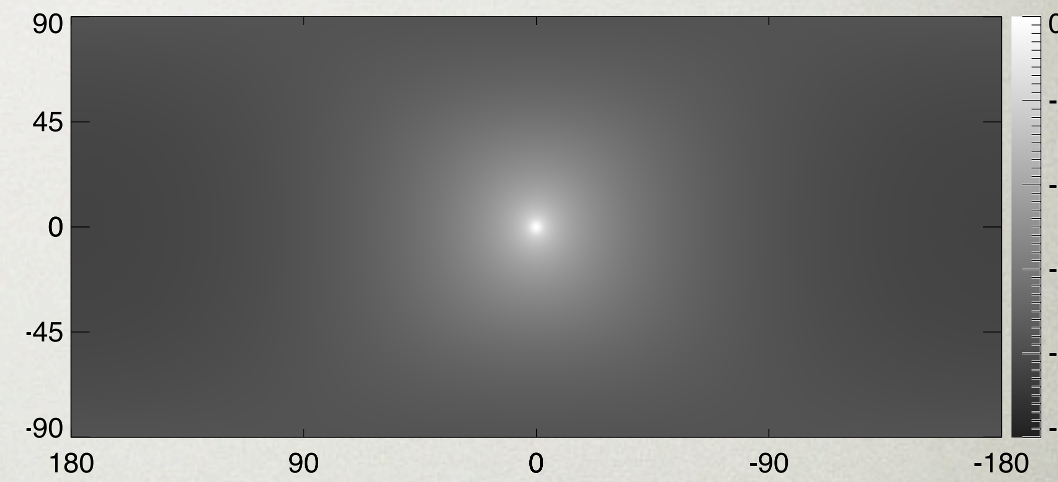
$$\sigma_n \sim 10^{-45-46}\ \mathrm{cm}^2$$

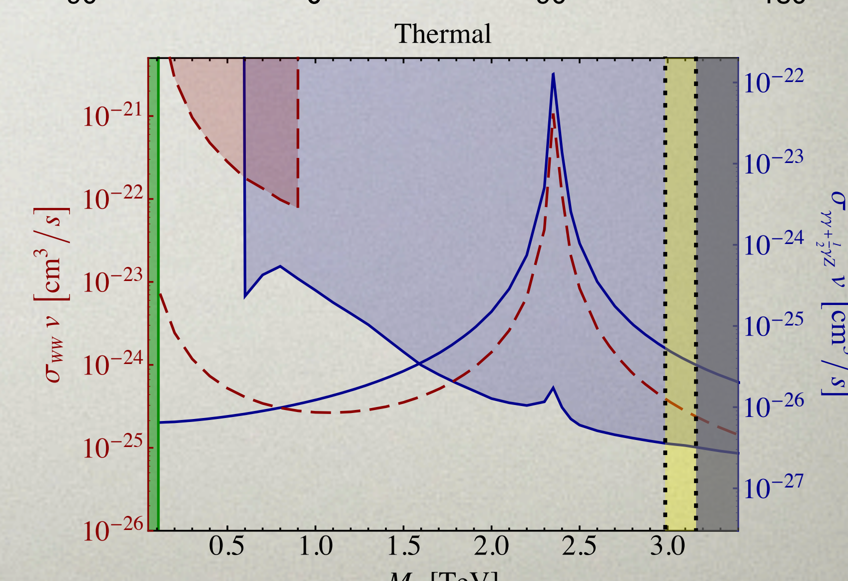


The Road Ahead

- PAMELA / Fermi / AMS and cosmic ray positrons
- Fermi photons
- Data rich! Many experiments collecting data

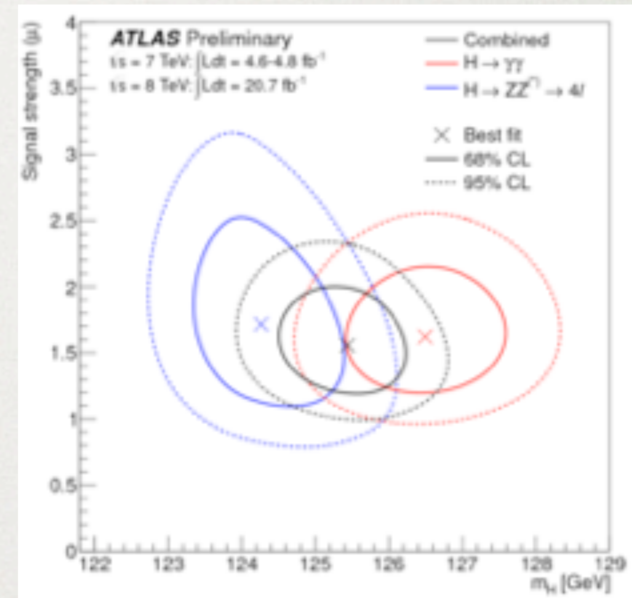






Cohen, Lisanti, Pierce, Slatyer

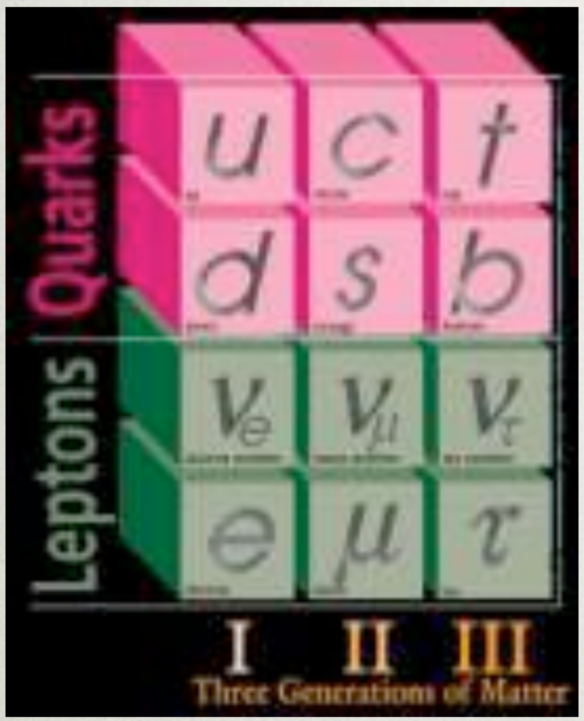
The Road Ahead



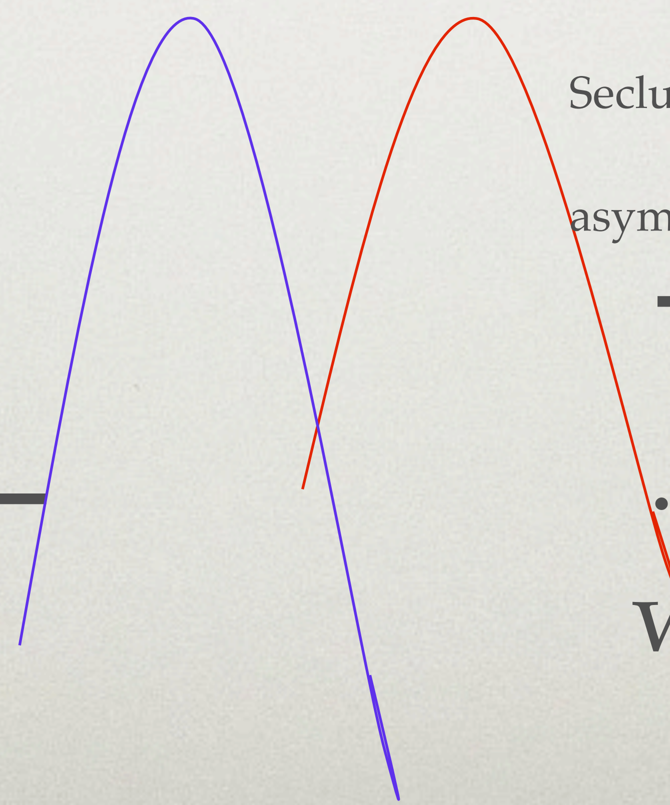
- Higgs discovered
- Many models covered
- Many models still buried → theoretical and model input

New Theoretical Landscape

Our theoretical tools have broadened ....



From a single, stable weakly interacting particle ..... (WIMP, axion)



Models: Supersymmetric light DM sectors, Secluded WIMPs, WIMPless DM, Asymmetric DM .....
Production: freeze-in, freeze-out and decay, asymmetric abundance, non-thermal mechanicsms .....

...to a hidden world with multiple states, new interactions

Standard Model

Summary

- Dark Matter has not shown itself yet, but we continue to probe from all sides!

SUSY light
Hidden
Valley
Secluded
WIMPless
ADM
freeze-in
freeze-out
and decay
non-
thermal

Astro
Objects
AMS
CDMS
COUPP
CoGeNT
Cresst
DM ICE
Fermi
Icecube
KIMS
LHC
LUX
PAMELA
Panda-X
XENON
....