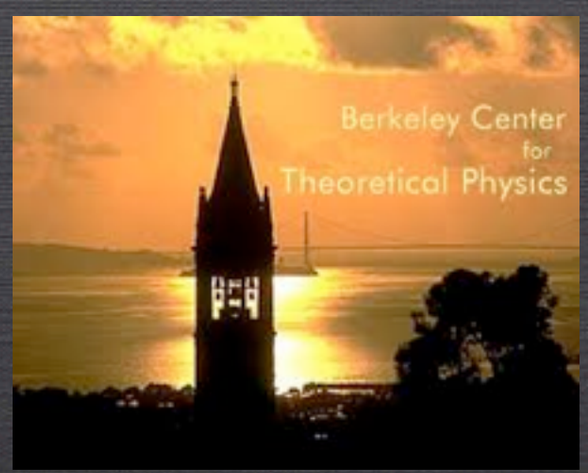
Cosmic Clues for Dark Matter

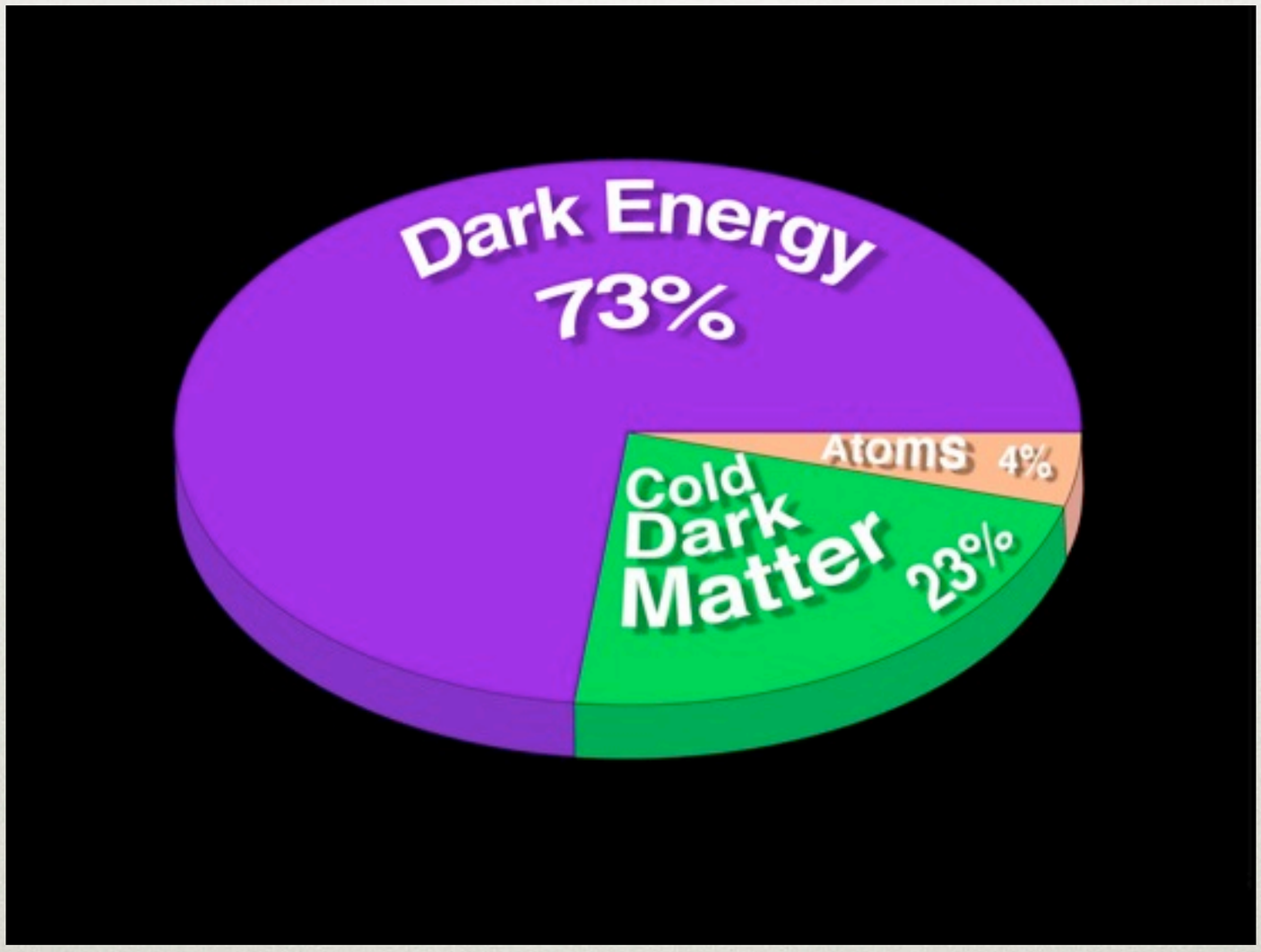
Direct, Indirect and LHC Detection Update

Kathryn M. Zurek



Universe's Energy Budget

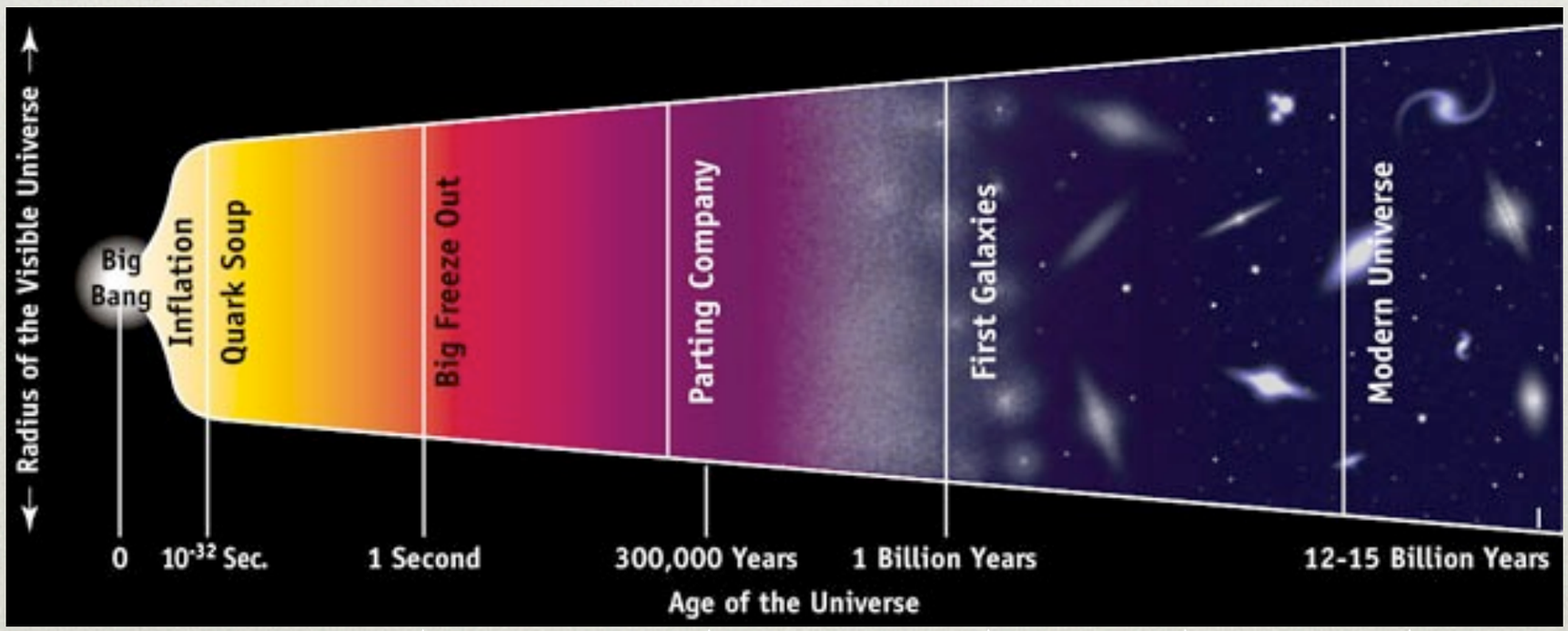
Dynamical selection?



New Dynamics, Definitely BSM

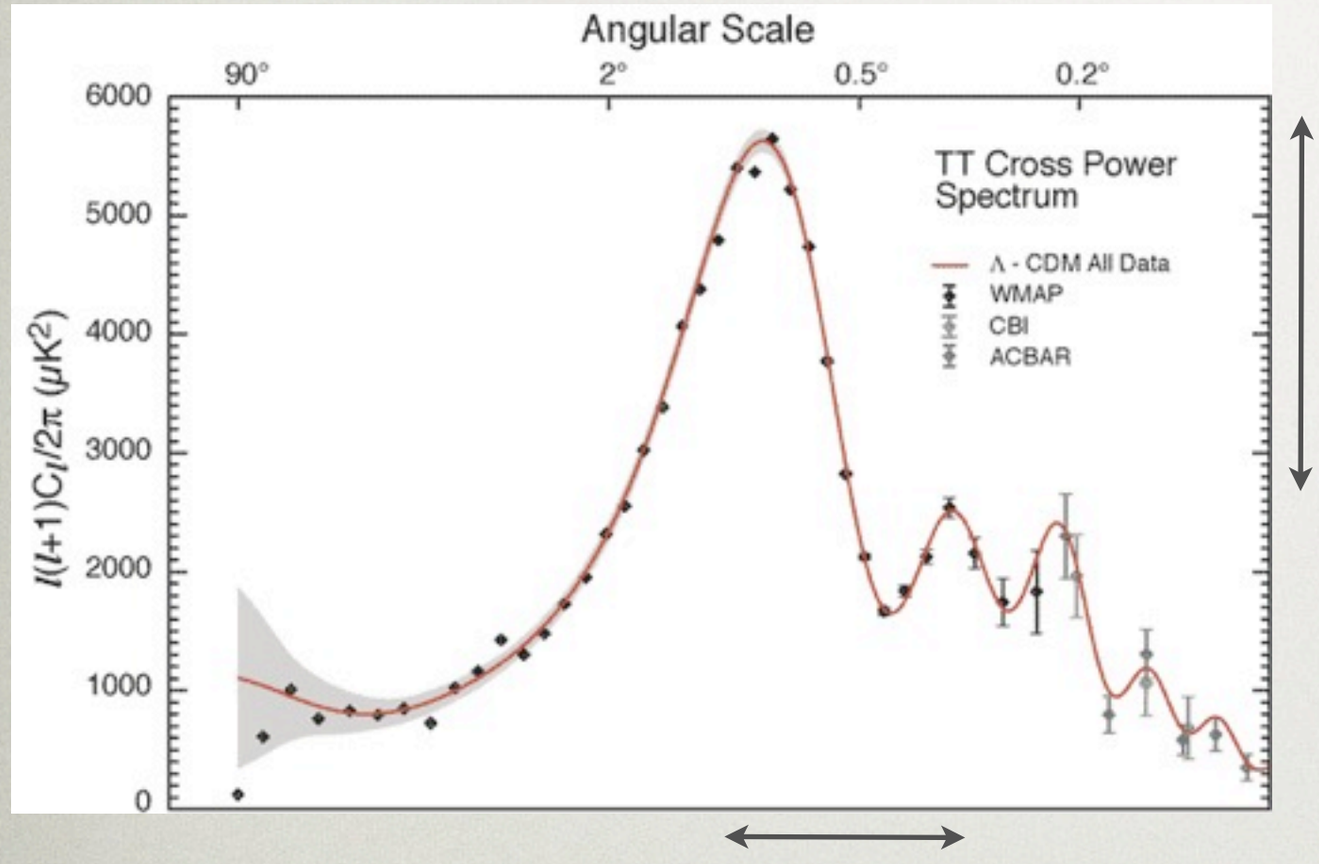
Why particle dark matter?

- We have essentially eliminated a SM explanation; need physics BSM

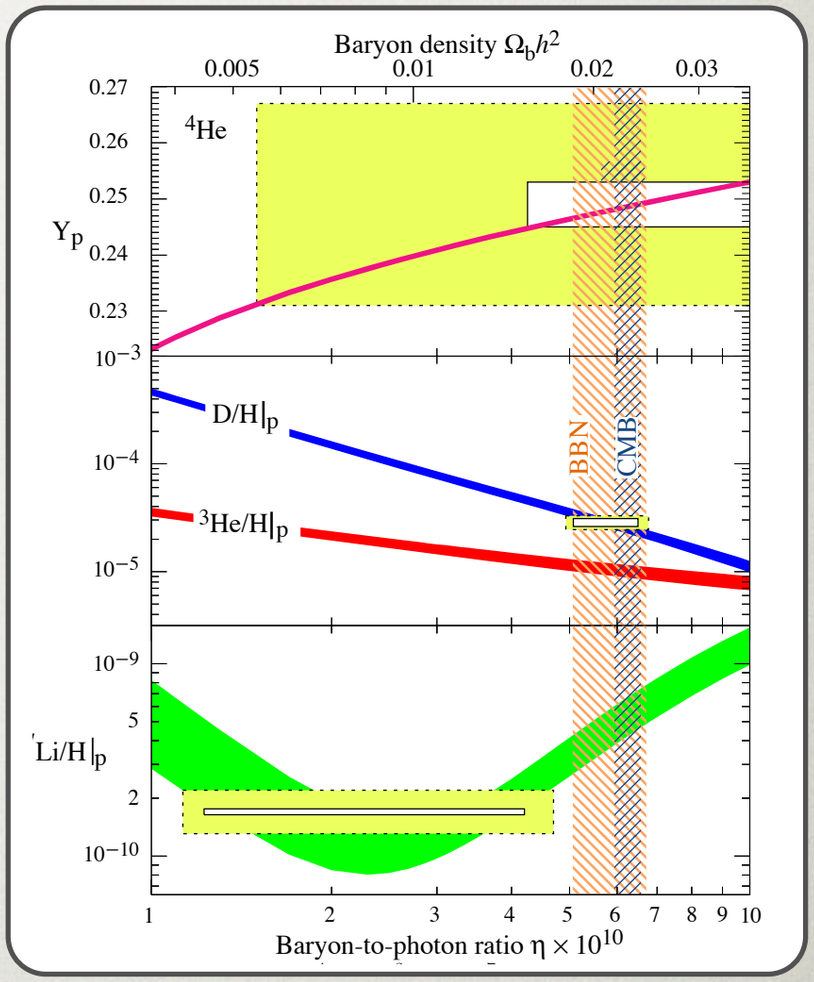


Why particle dark matter?

curvature, z_eq



Baryon density



sound speed = baryon to radiation ratio

- Why not just ordinary (dark) baryons?
- A: BBN and CMB make independent measurements of the baryon fraction. Observations only accounted for with **non-interacting** matter

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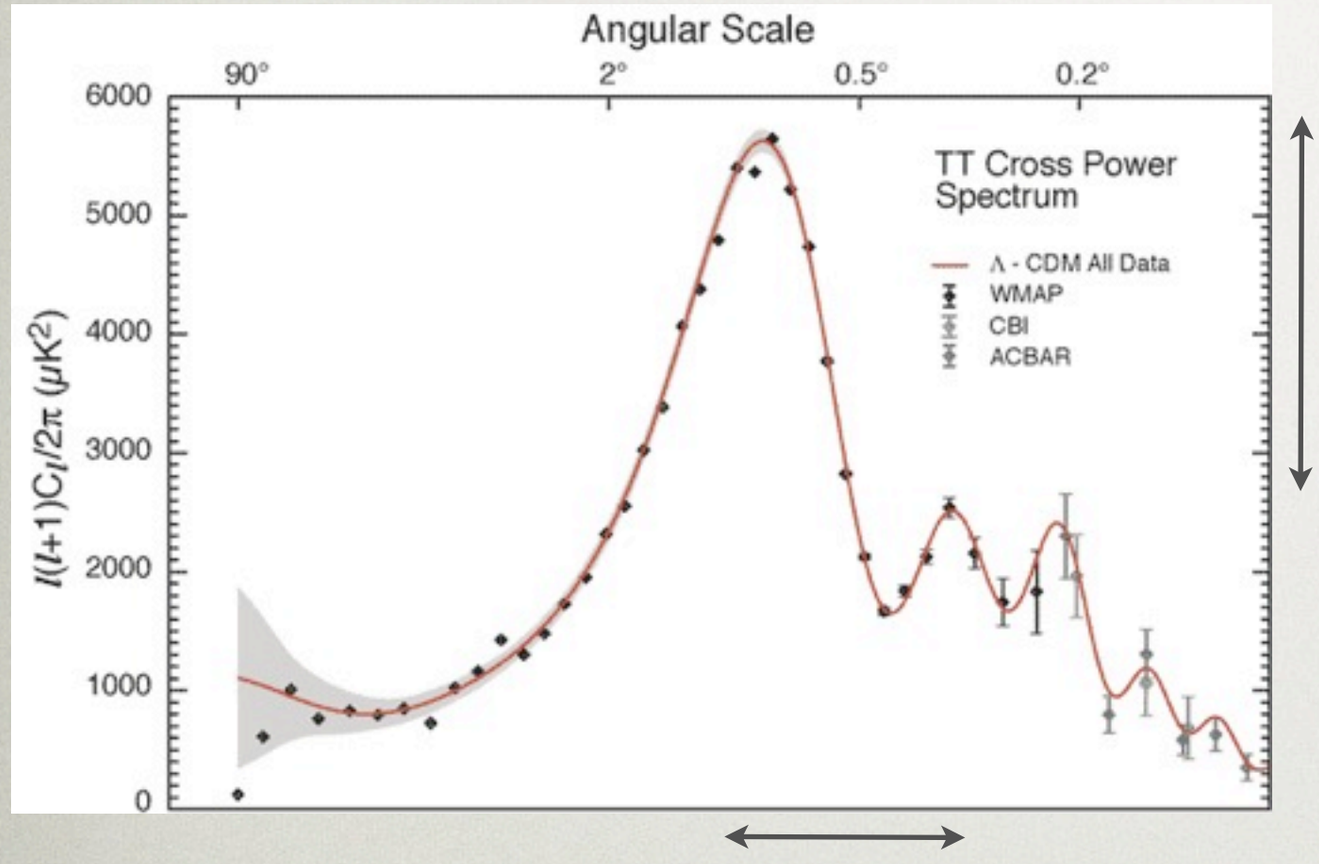

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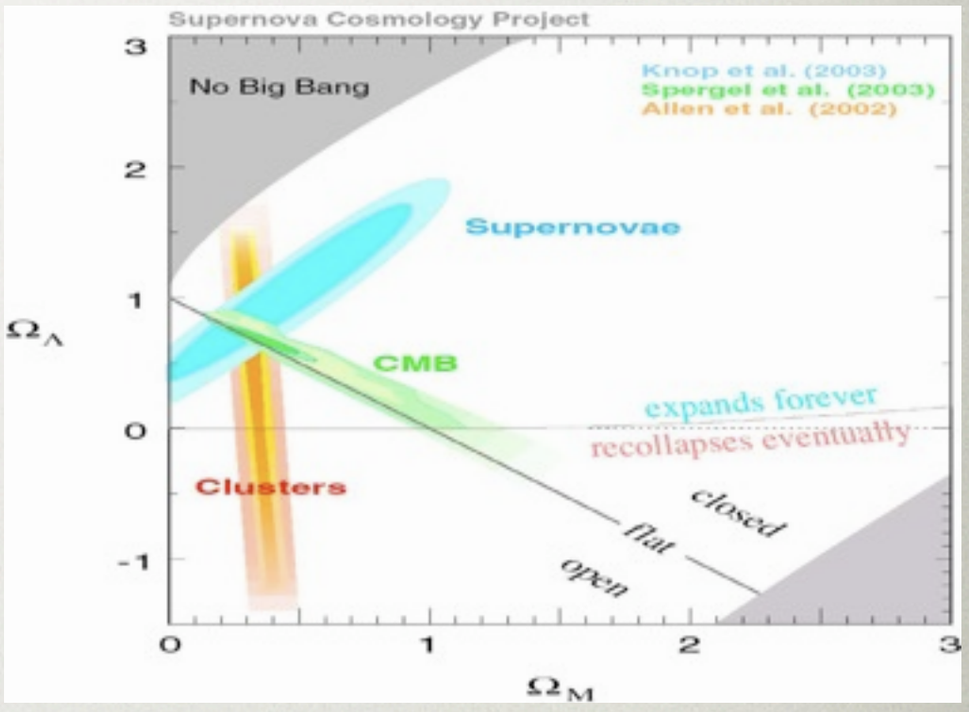

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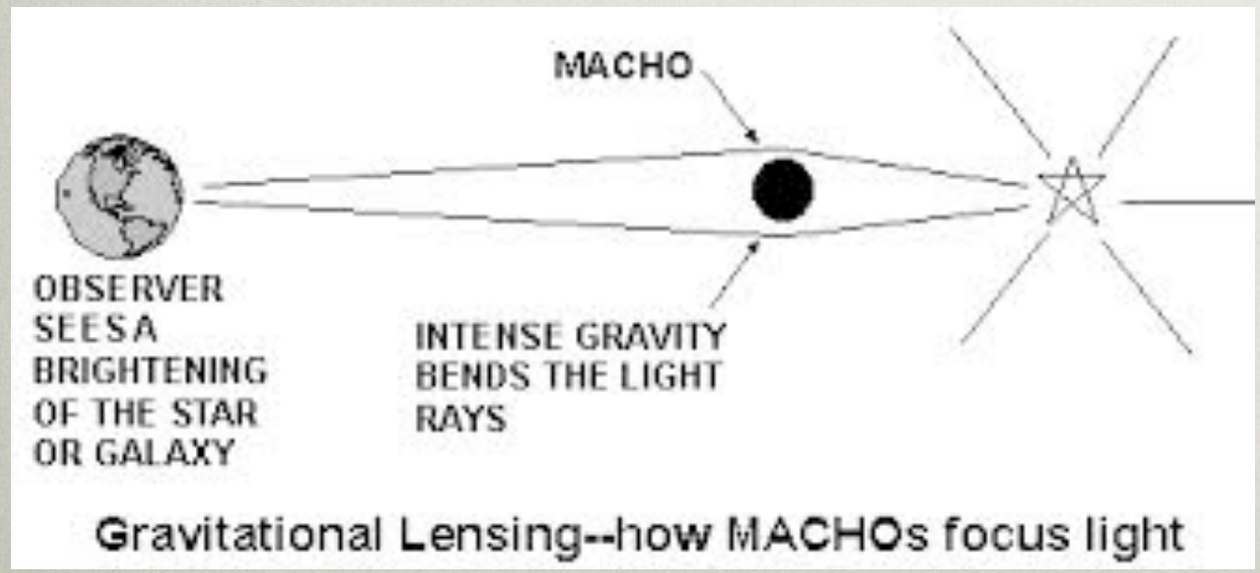
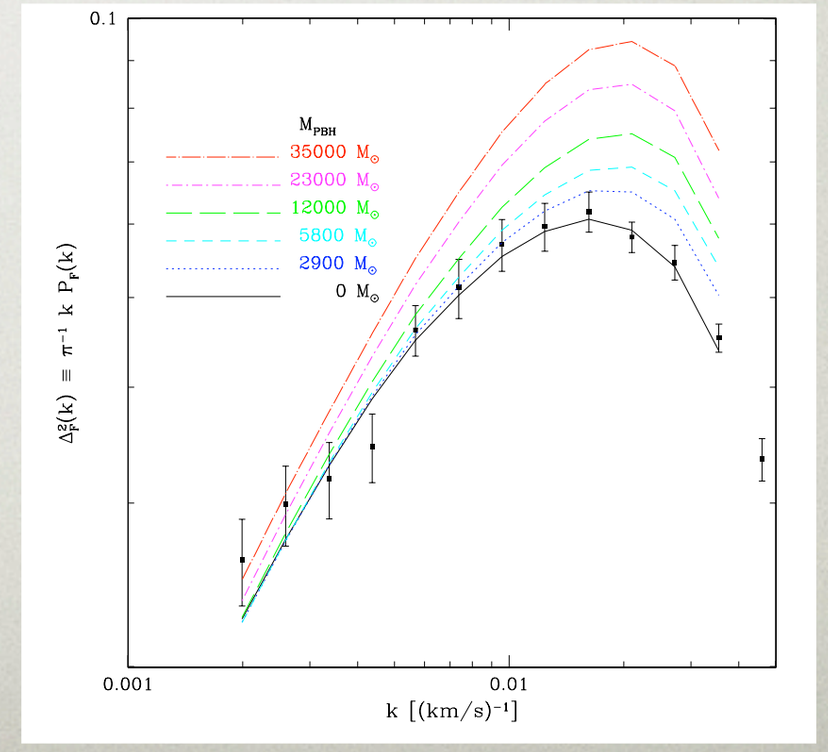
Why particle dark matter?

- Make baryons non-interacting by binding DM into MaCHOs?
- A: looked for those and did not find them; eliminated MACHO range from $\gtrsim 10^{-8} M_\odot$

Afshordi, McDonald, Spergel



Gravitational Lensing--how MACHOs focus light



Why particle dark matter?

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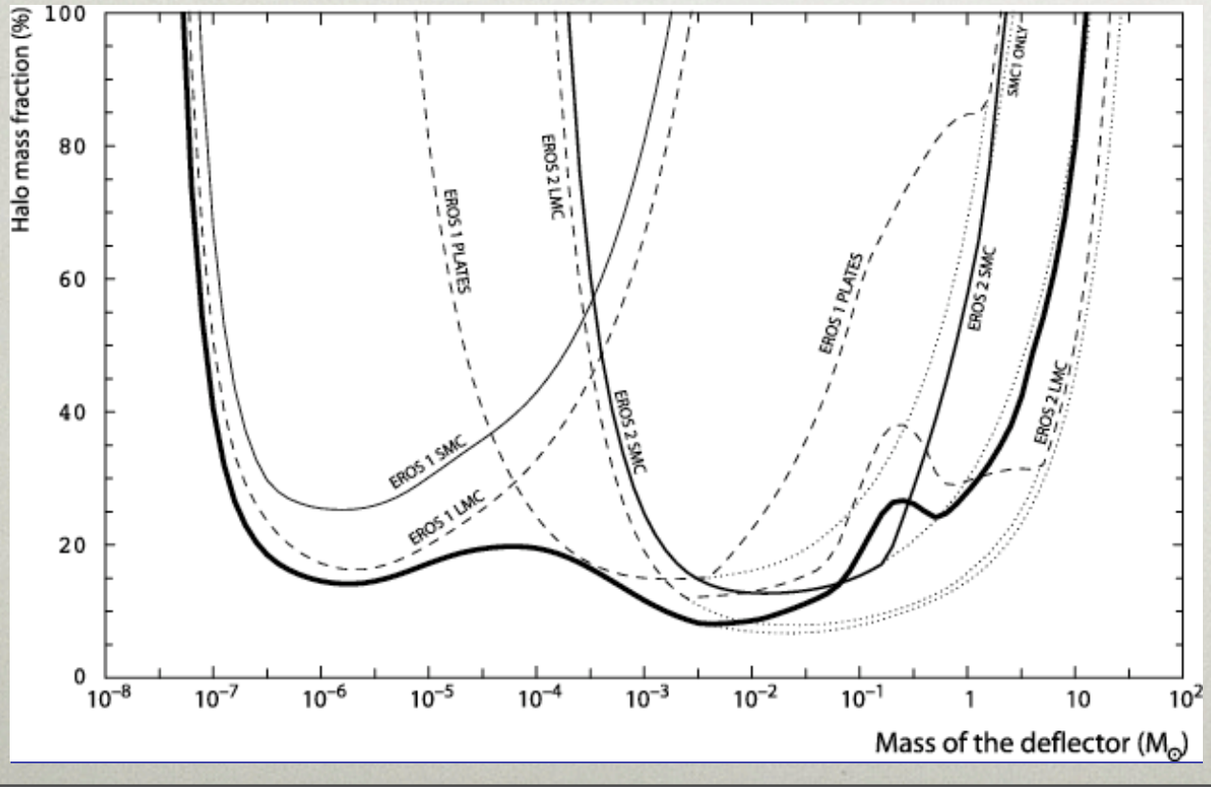
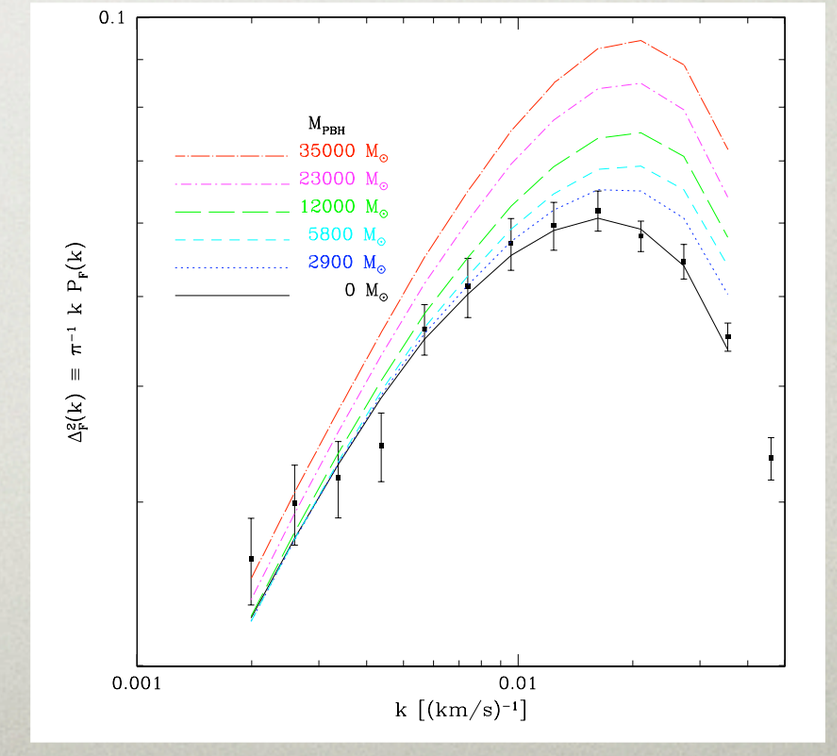
from 2005 talk by K. Griest

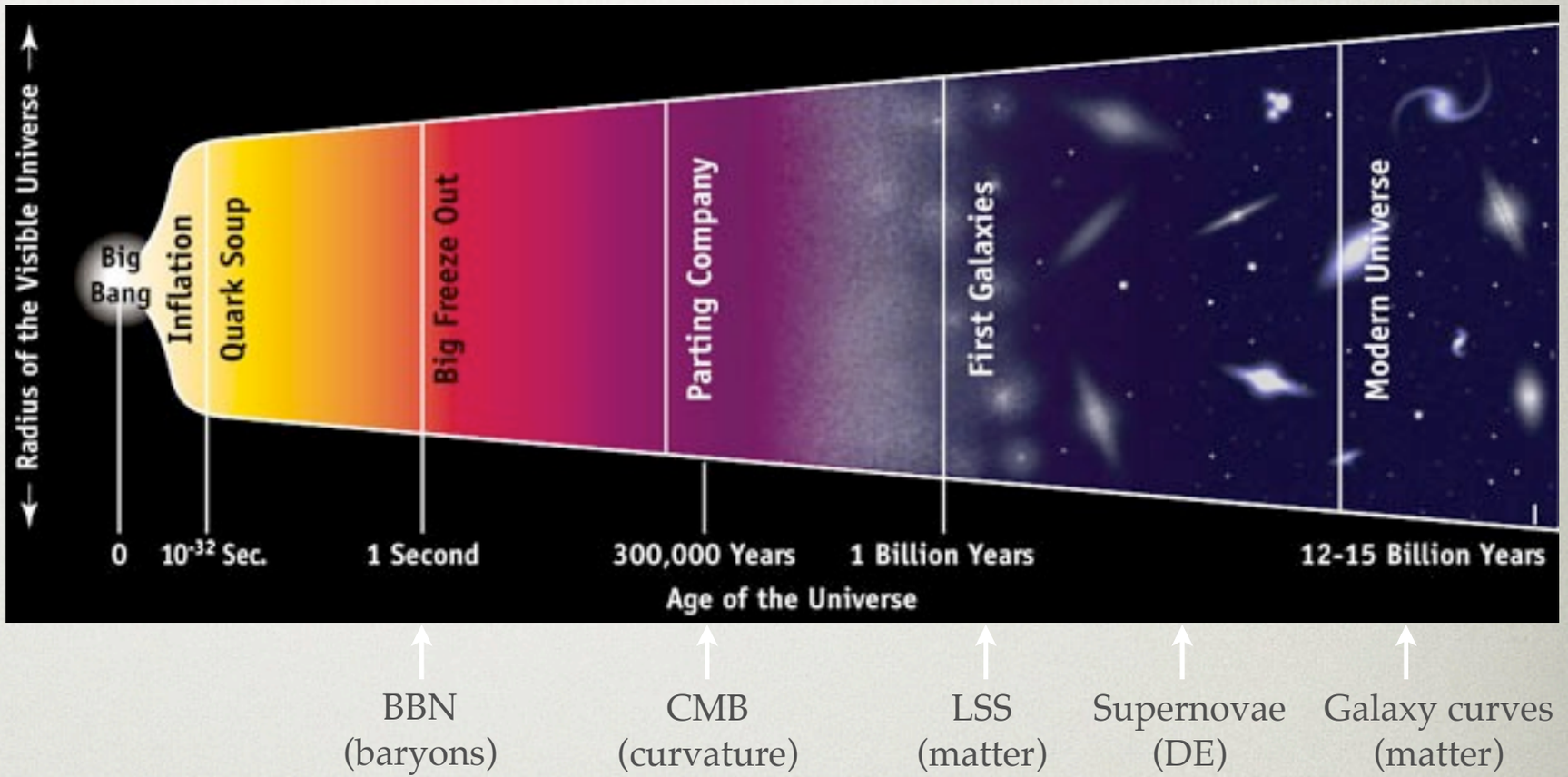


Afshordi, McDonald, Spergel



Why particle dark matter?

- Why not modify gravity?
- A: Modified gravity theories tend to be sick



- A: Must get the entire range of observations right, not just galactic rotation curves

Why particle dark matter?

- Why not modify gravity?
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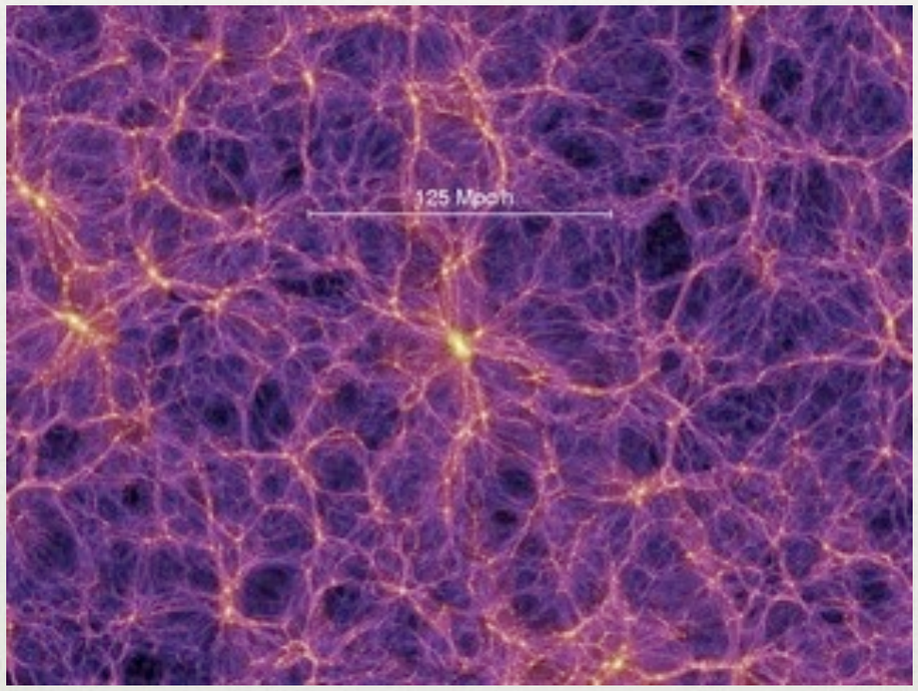
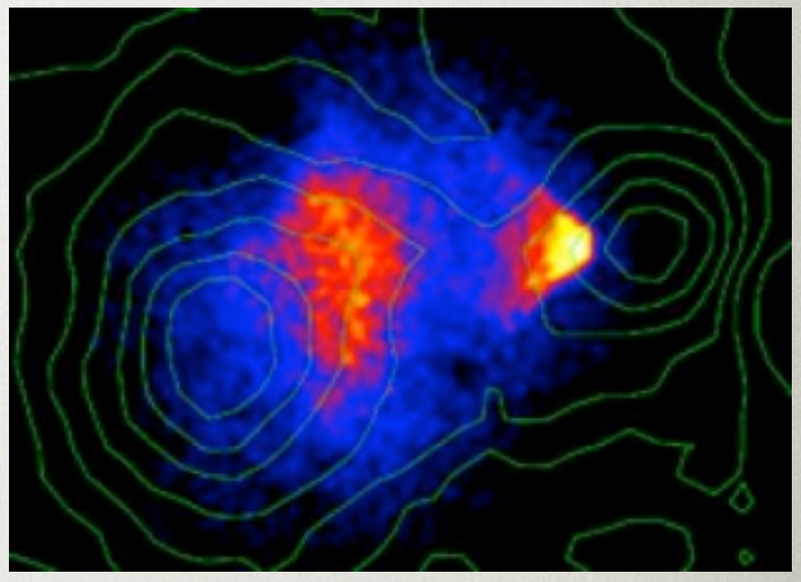




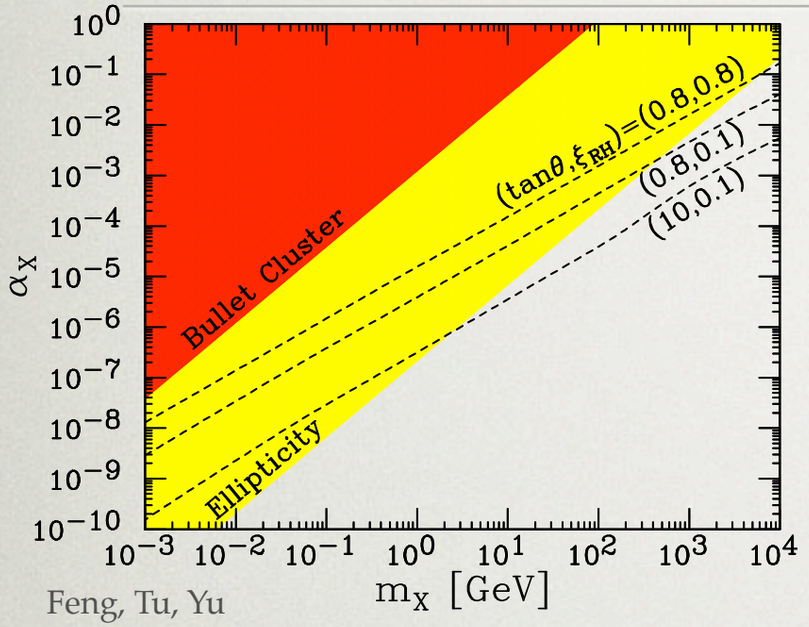
X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al

- A: Must get the entire range of observations right, not just galactic rotation curves

Why particle dark matter?

- By contrast, it is easy to explain everything with particle dark matter
- From theoretical point of view, theories are compelling, testable.
- As the proverb says:

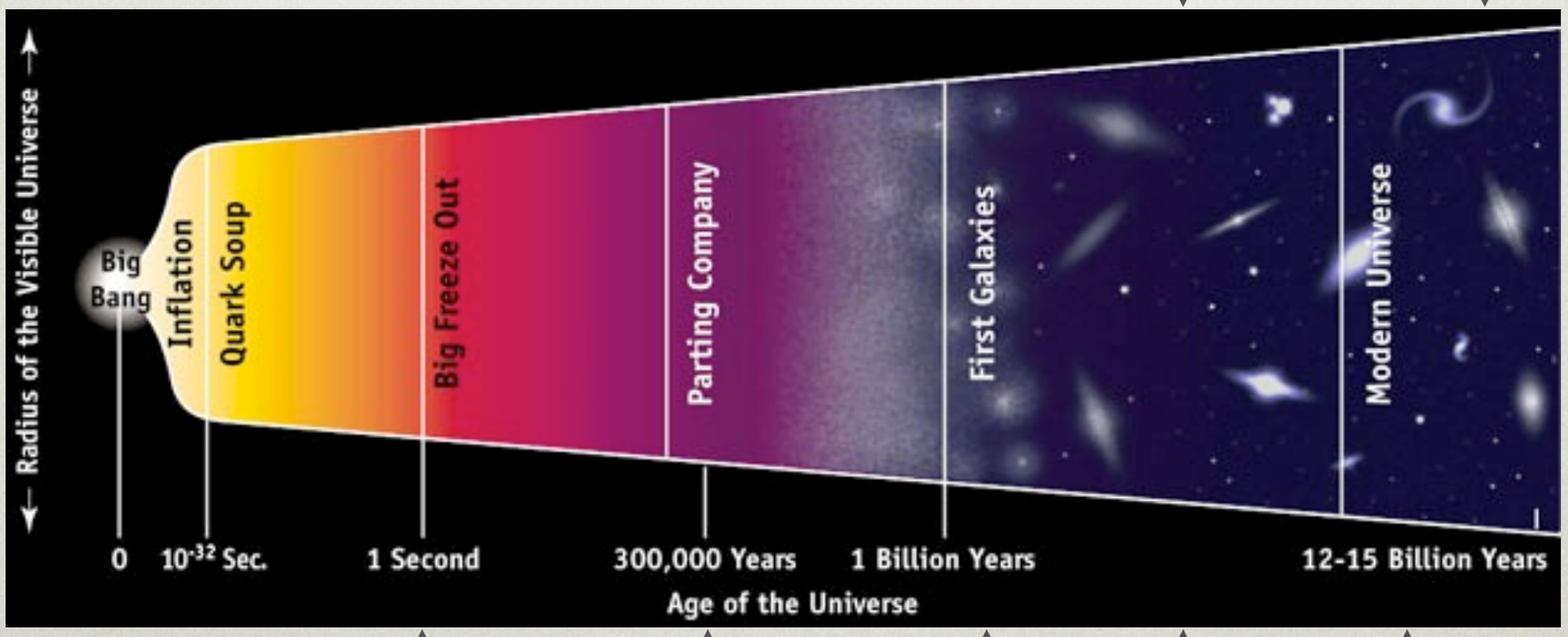
What Do We Know About the Dark Matter?



Feng, Tu, Yu

Halo Shapes
Weakly Self-interacting

Direct Probes
Weakly Interacting with Us



BBN (baryons)

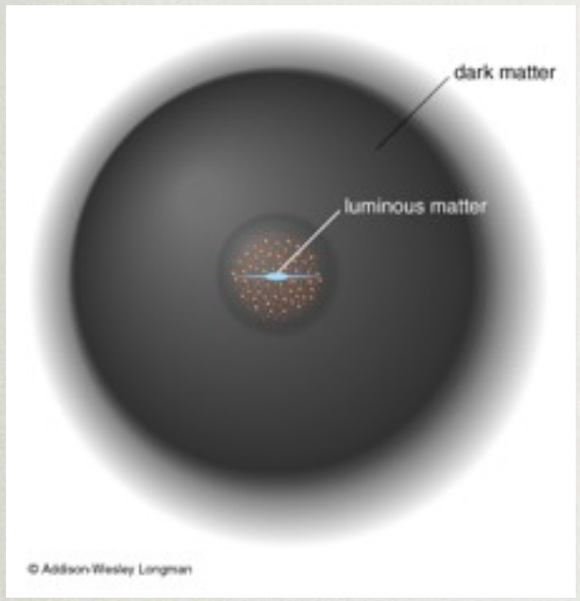
CMB (curvature)

Supernovae (DE)

LSS (matter)

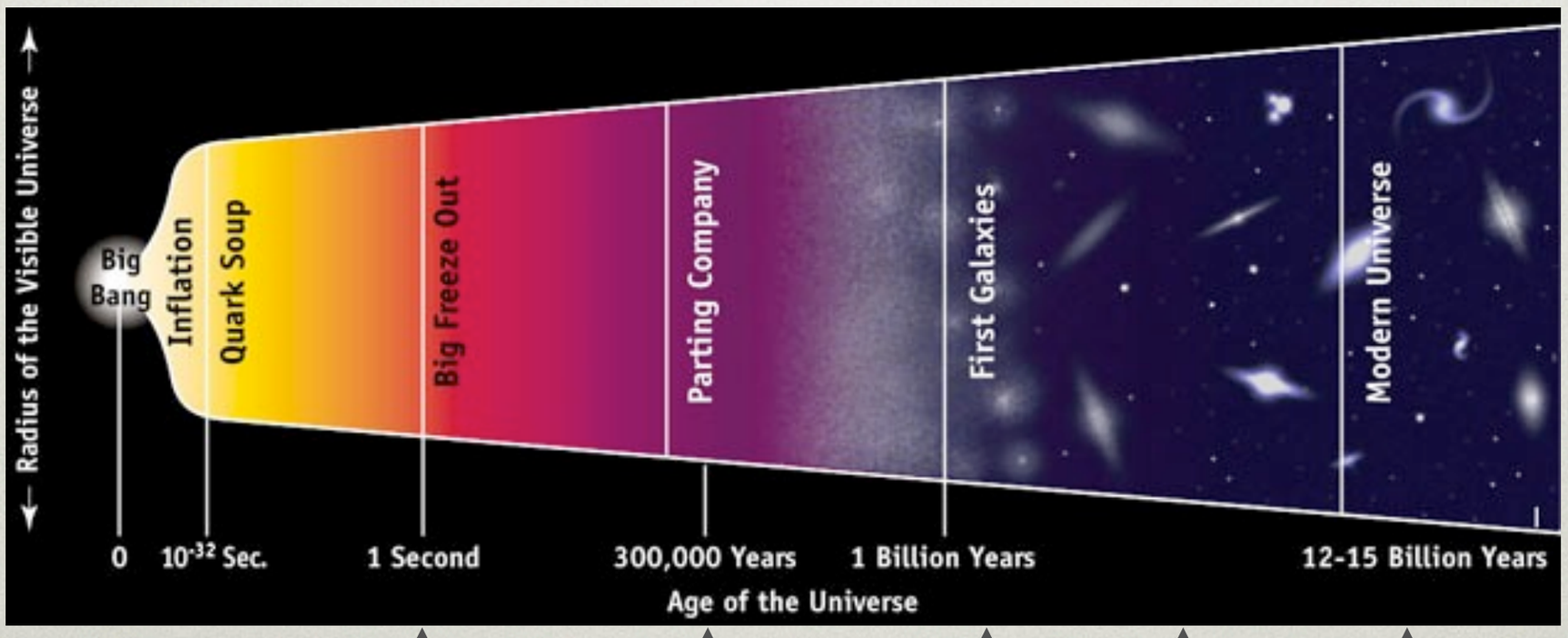
Galaxy curves (matter)

How Dark is Dark Matter?



McDermott, Yu, KZ
1011.2907

Consider All Epochs!



BBN (baryons)

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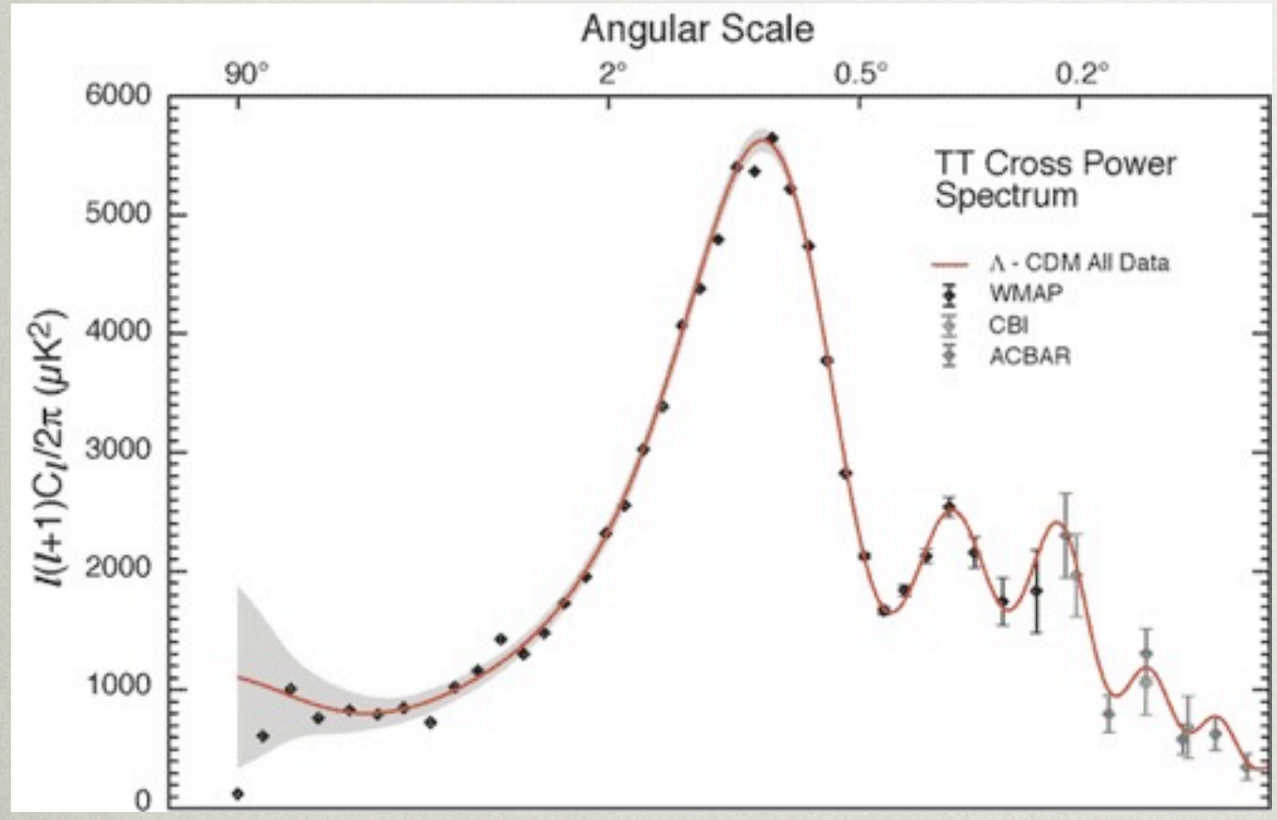
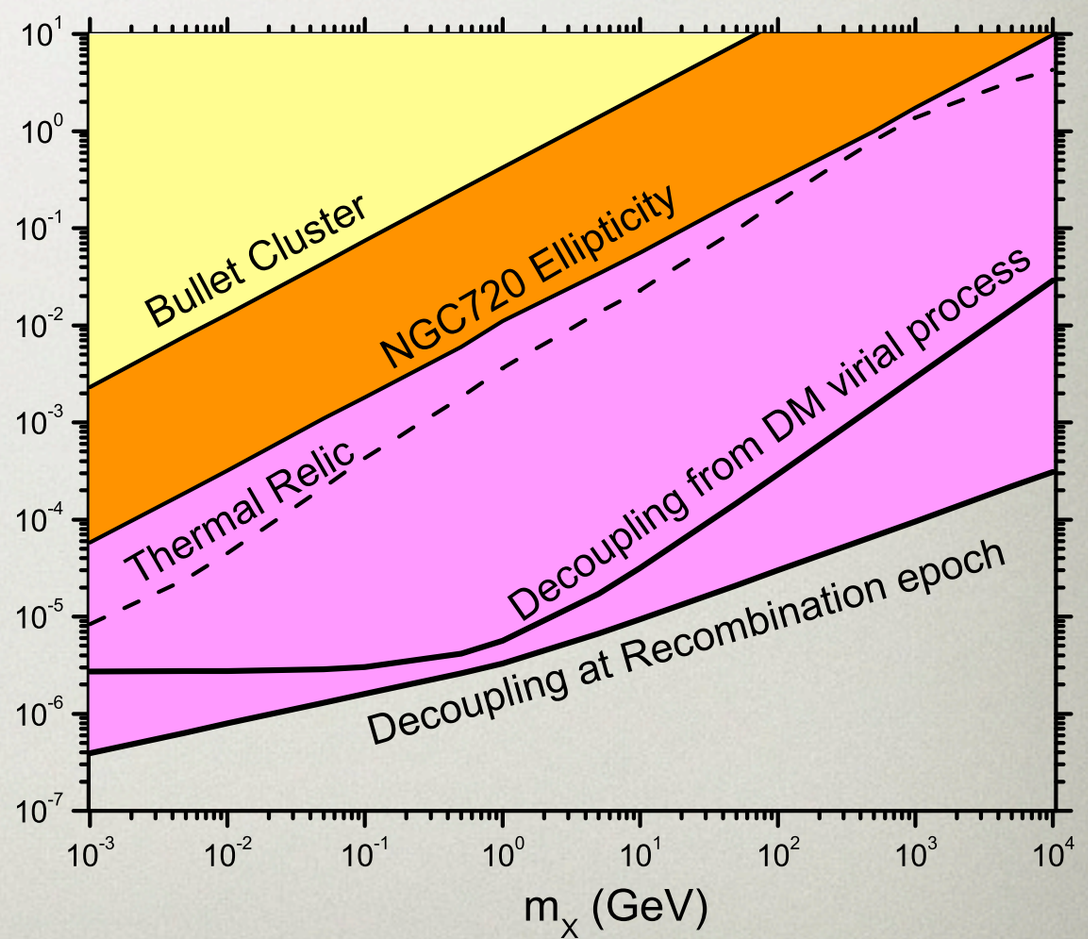
How Dark is Dark Matter?

- Which probe is the most constraining?



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

Constraint on DM charge ε



McDermott, Yu, KZ
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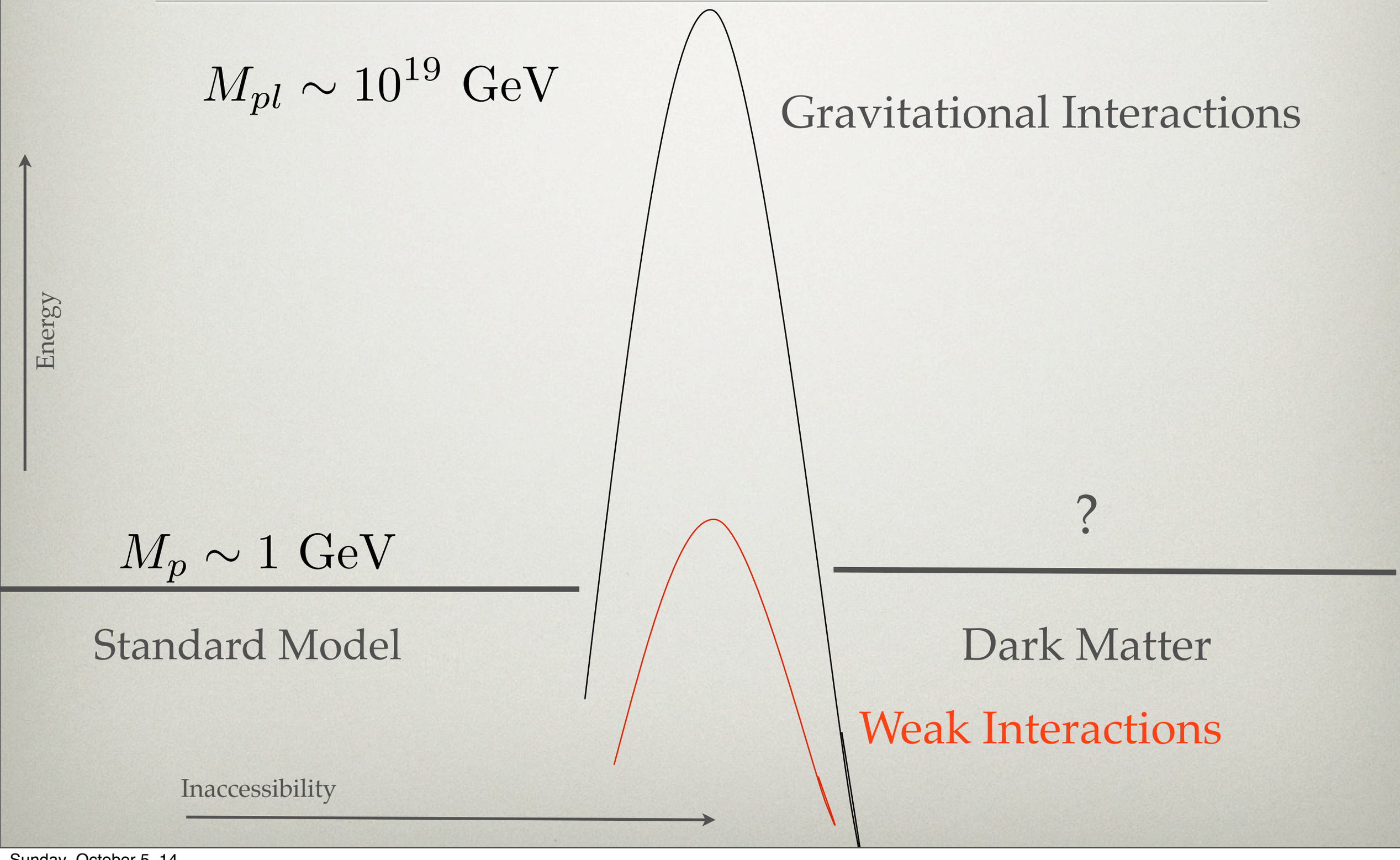
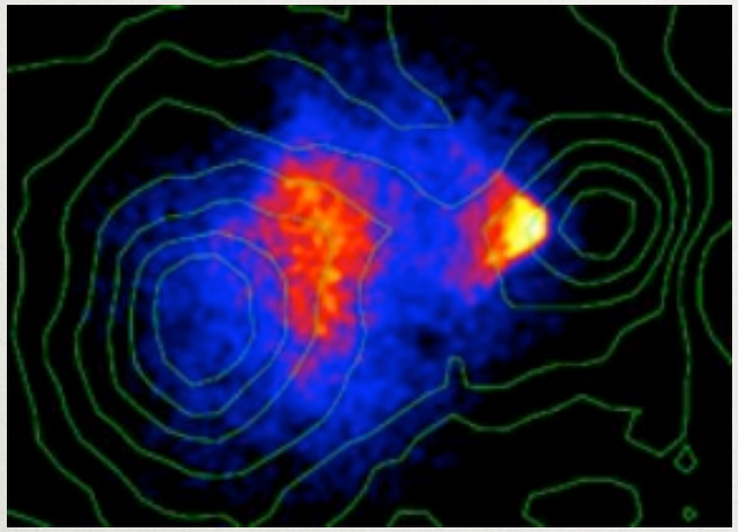
Super-Weakly Interacting



Super-Weakly Interacting

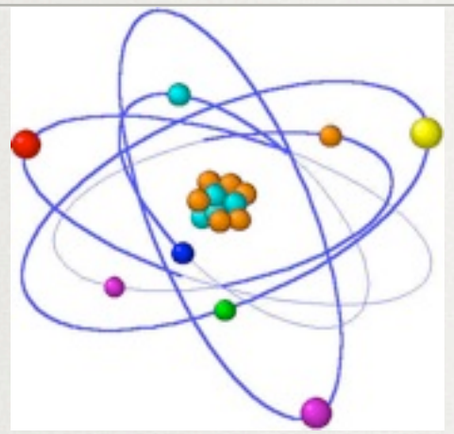
- Gravitational Coherence ....

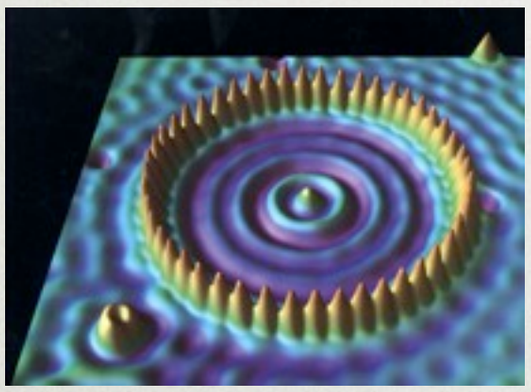


... on cosmological scales!

  - Helps us learn about aggregate properties of dark matter
- Particle properties much harder

Super-Weakly Interacting





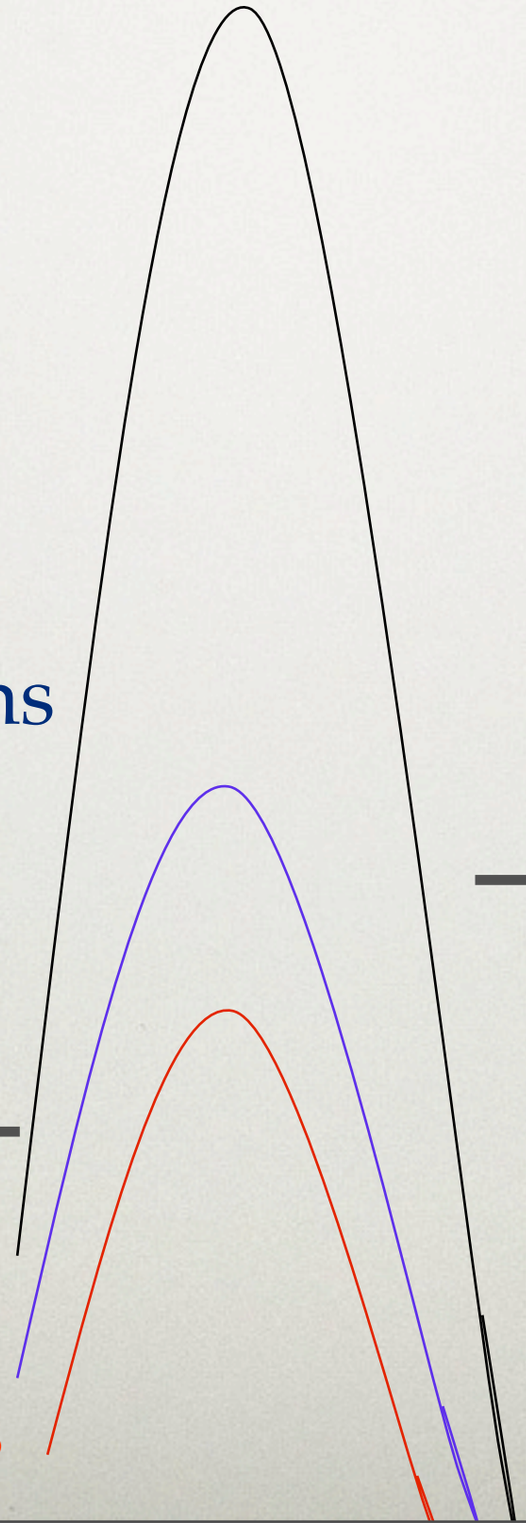
$M_p \sim 1$ GeV

Standard Model

- Astronomy and Cosmology can give aggregate properties, but we need particle physics to go beyond that ?

Dark Matter

Particle Physics Provides Some Ideas



Sub-weak Interactions

$M_p \sim 1$ GeV

Standard Model

Weak Interactions

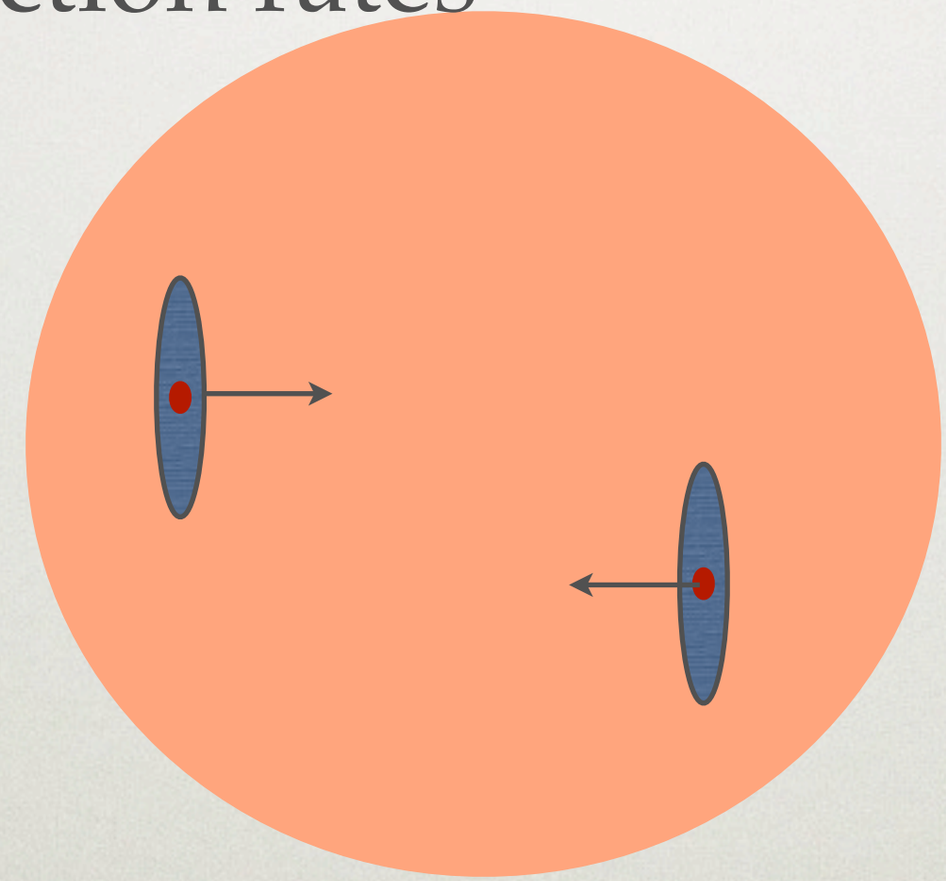
- Fundamental premise: DM has interactions other than gravitational

?

Dark Matter

Why the (sub-)Weak Scale is Compelling

- Abundance of new stable states set by interaction rates



Freeze-out

Measured by CMB + LSS

$$\Gamma = \hat{n}\sigma v = H \qquad \Longrightarrow \sigma \sim \frac{1}{(100\mathrm{GeV})^2}$$

Idea Focus: Supersymmetry

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

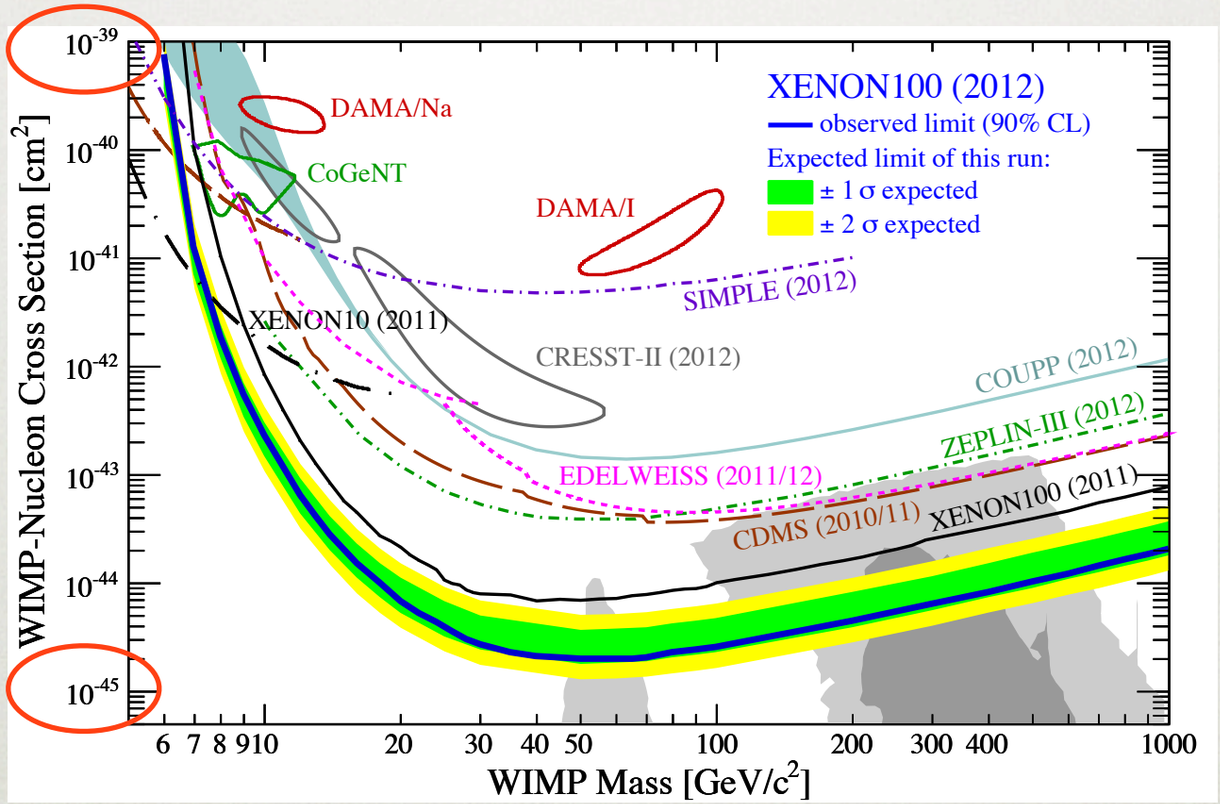
$$\tilde{\nu} \qquad \tilde{B},\ \tilde{W}_3,\ \tilde{H}$$

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

Sub-Weakly Interacting Massive Particles

Scattering through the Z boson: ruled out

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

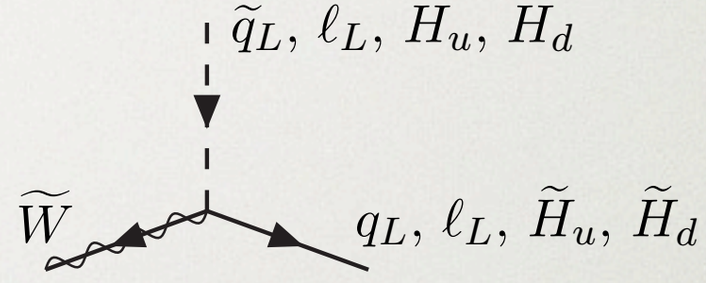


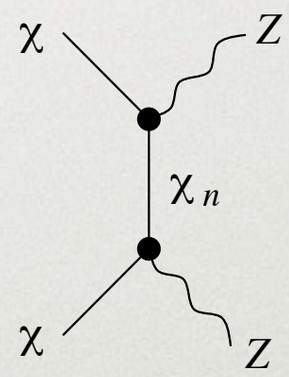
Next important benchmark:
Scattering through the Higgs

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

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!

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

Are there ways around for the Neutralino?

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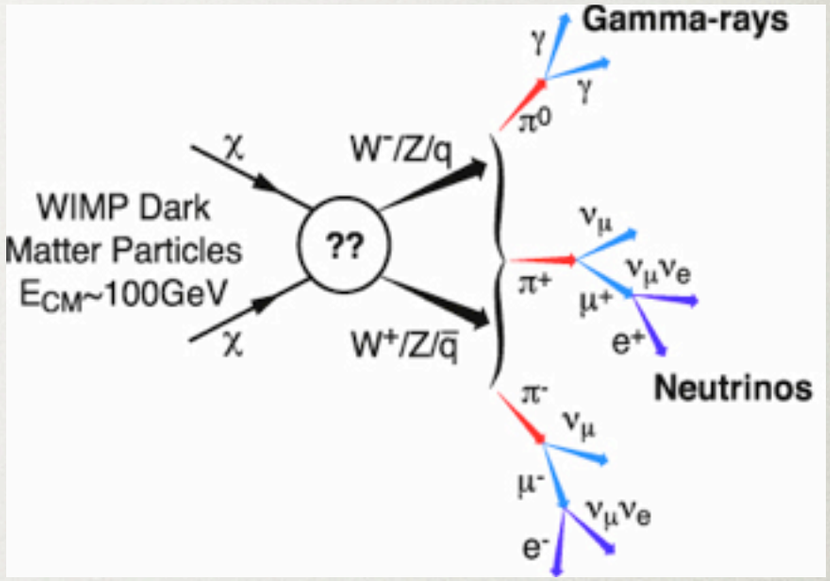
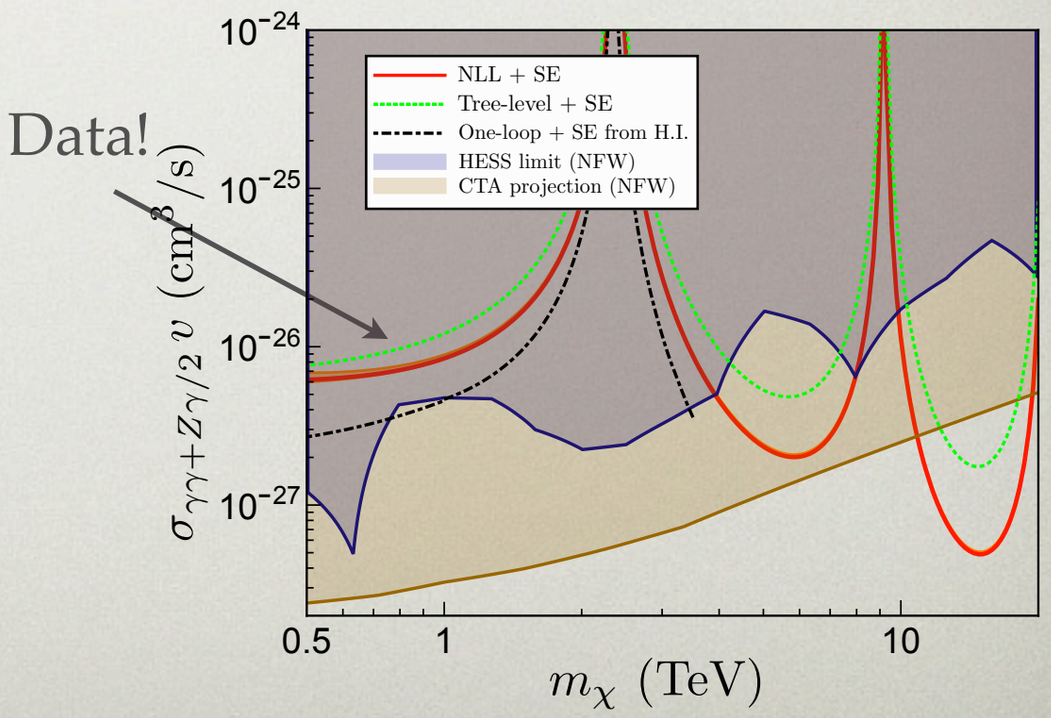




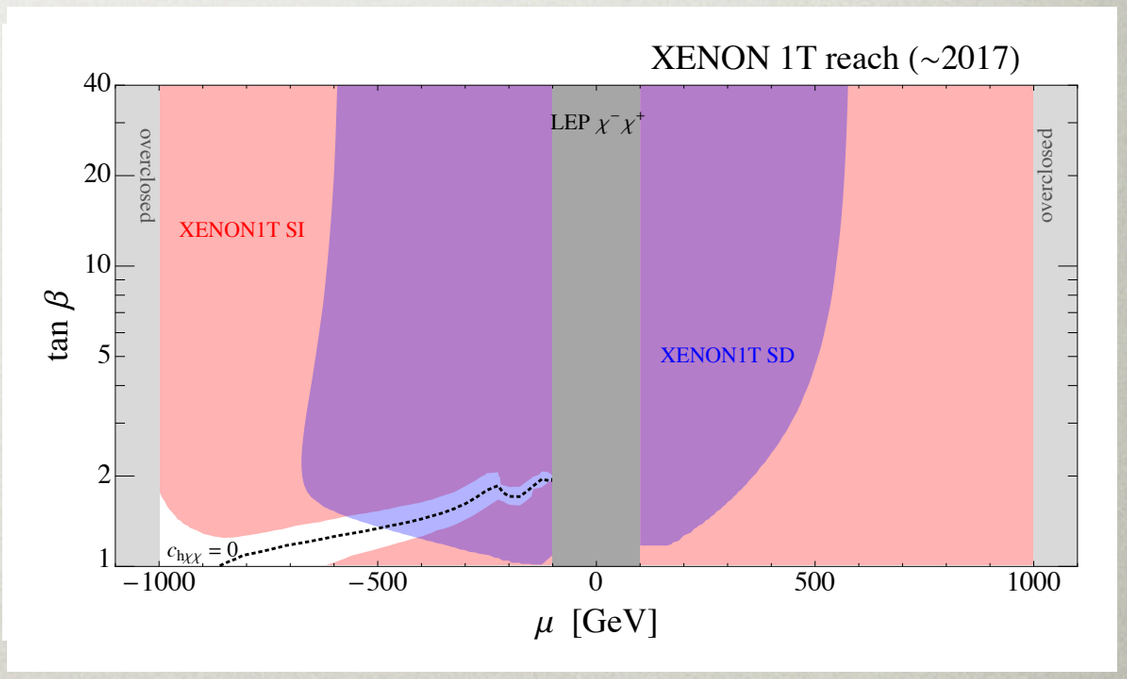
Ovaneysan, Slatyer, Stewart '14

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

$\mathbf{m}_\chi$	**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

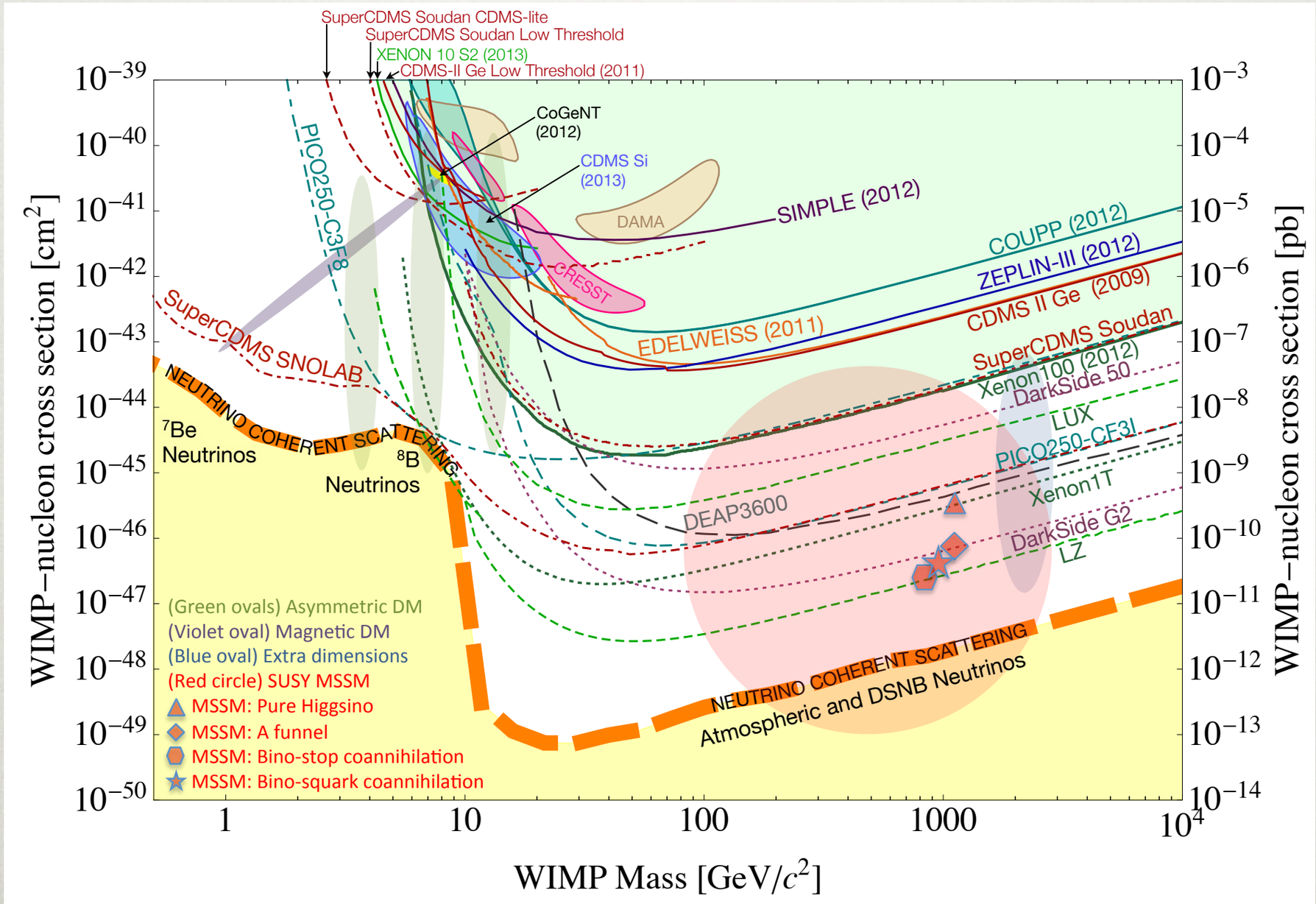


When Should We Start Looking Elsewhere?

- 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

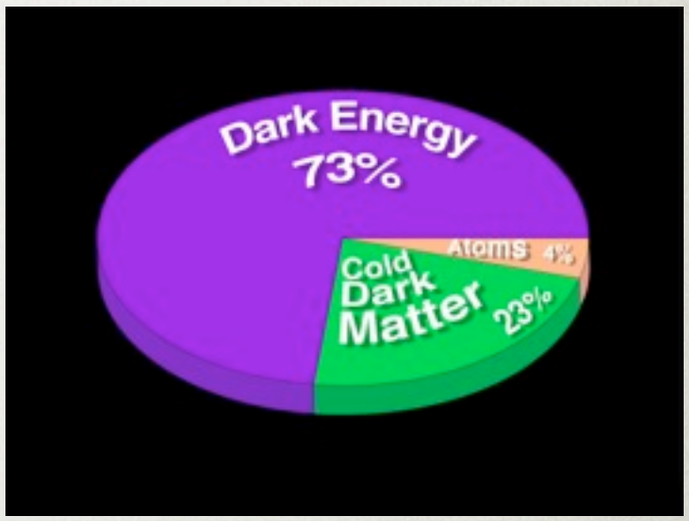
Terra Incognita

CF1 Snowmass report, 1310.8327



Baryon and DM Number Related?

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

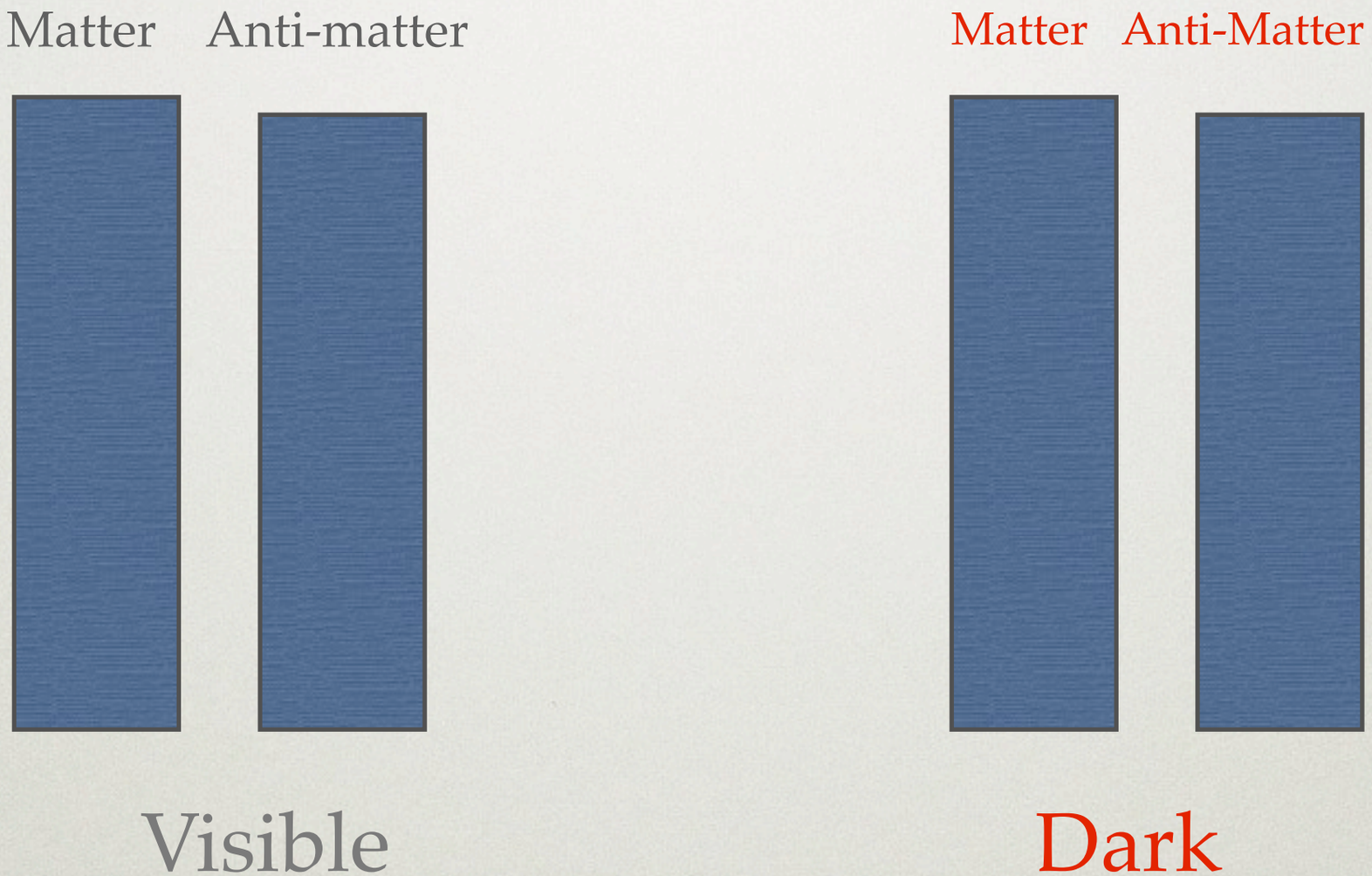


Experimentally, $\Omega_{DM} \approx 5\Omega_b$

Mechanism $n_{DM} \approx n_b$

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

Chemical Potential Dark Matter

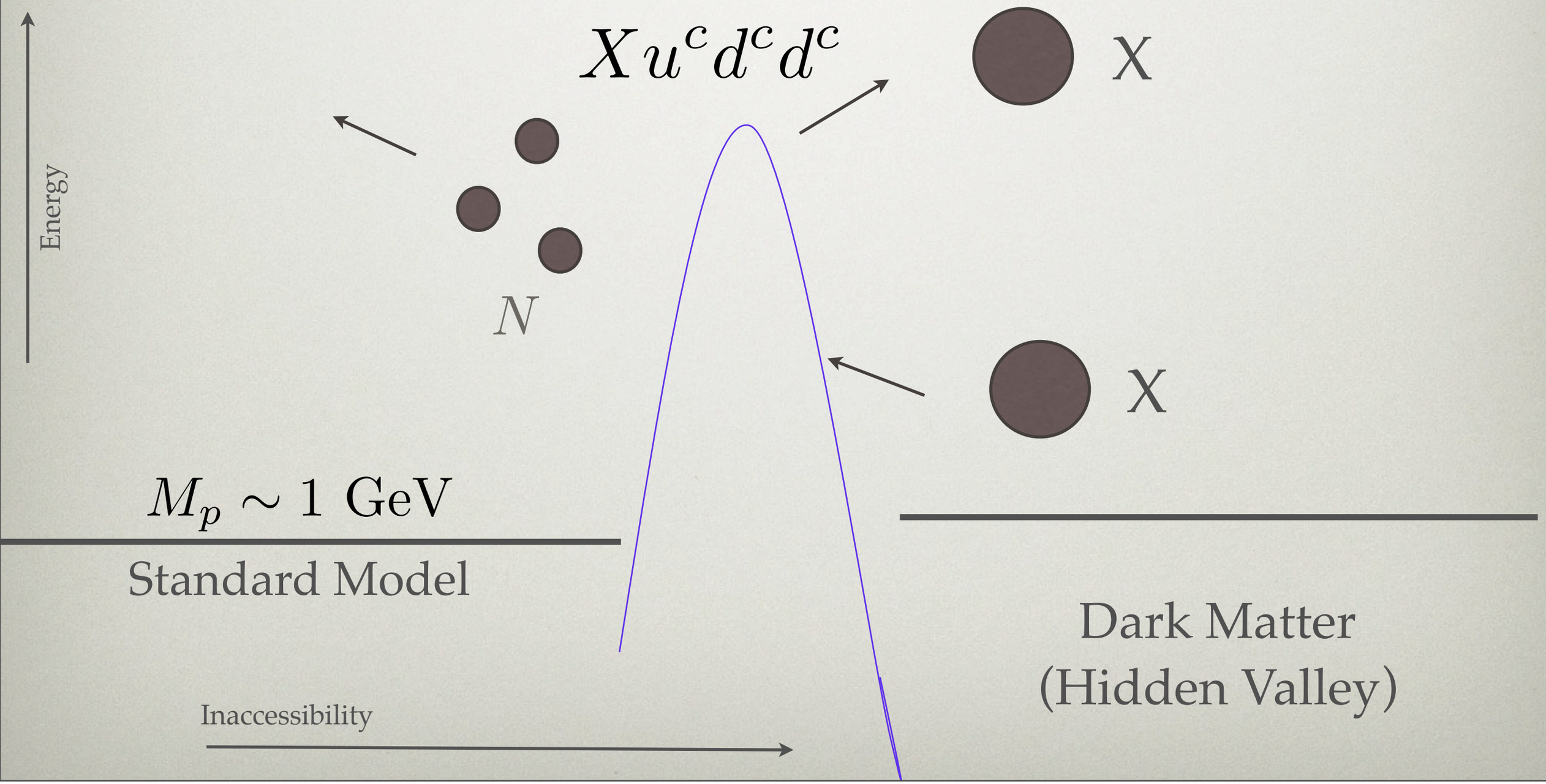


Asymmetric DM

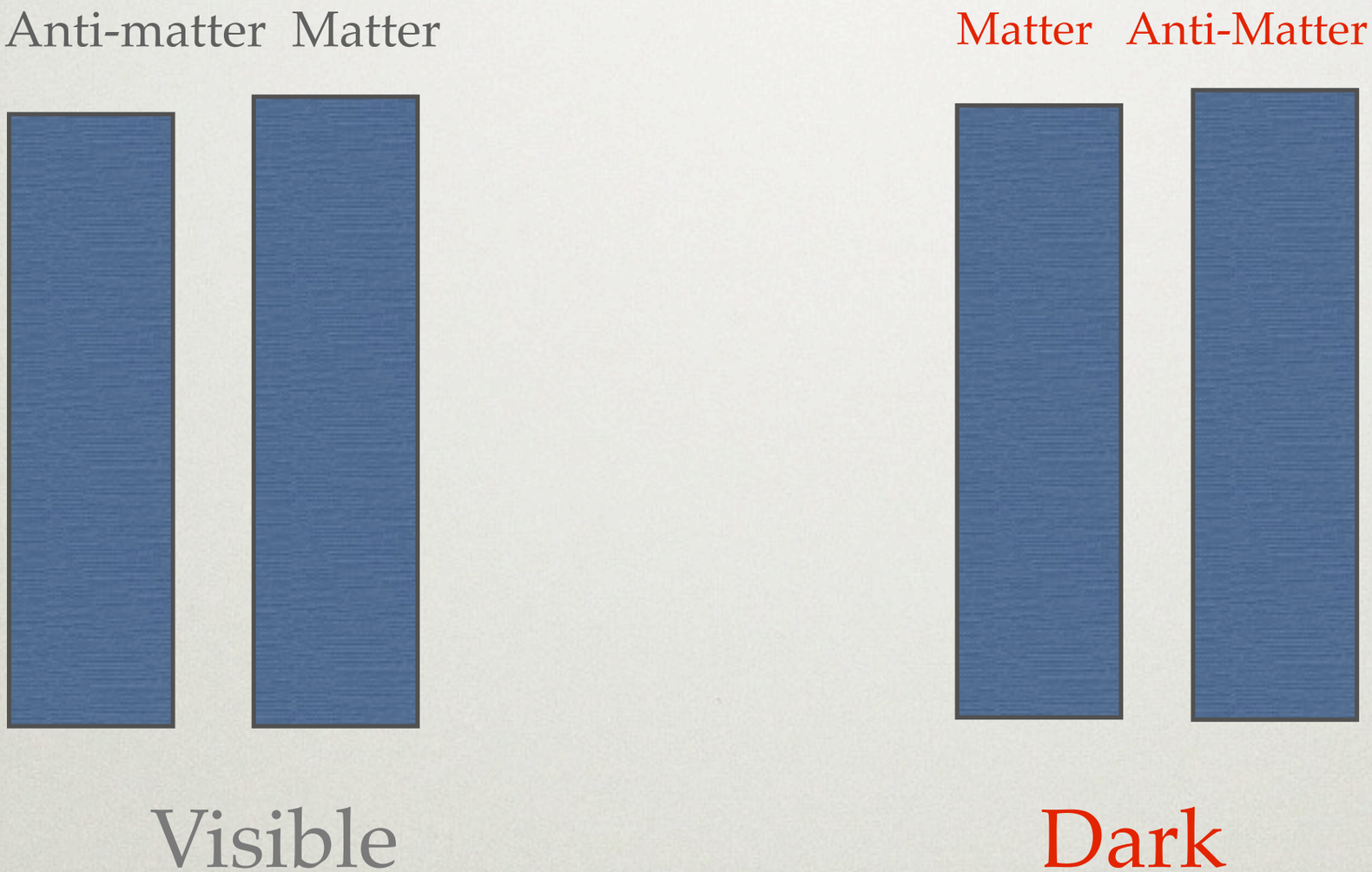
"Integrate out" heavy state
Higher dimension operators:

Luty, Kaplan, KZ
0901.4117

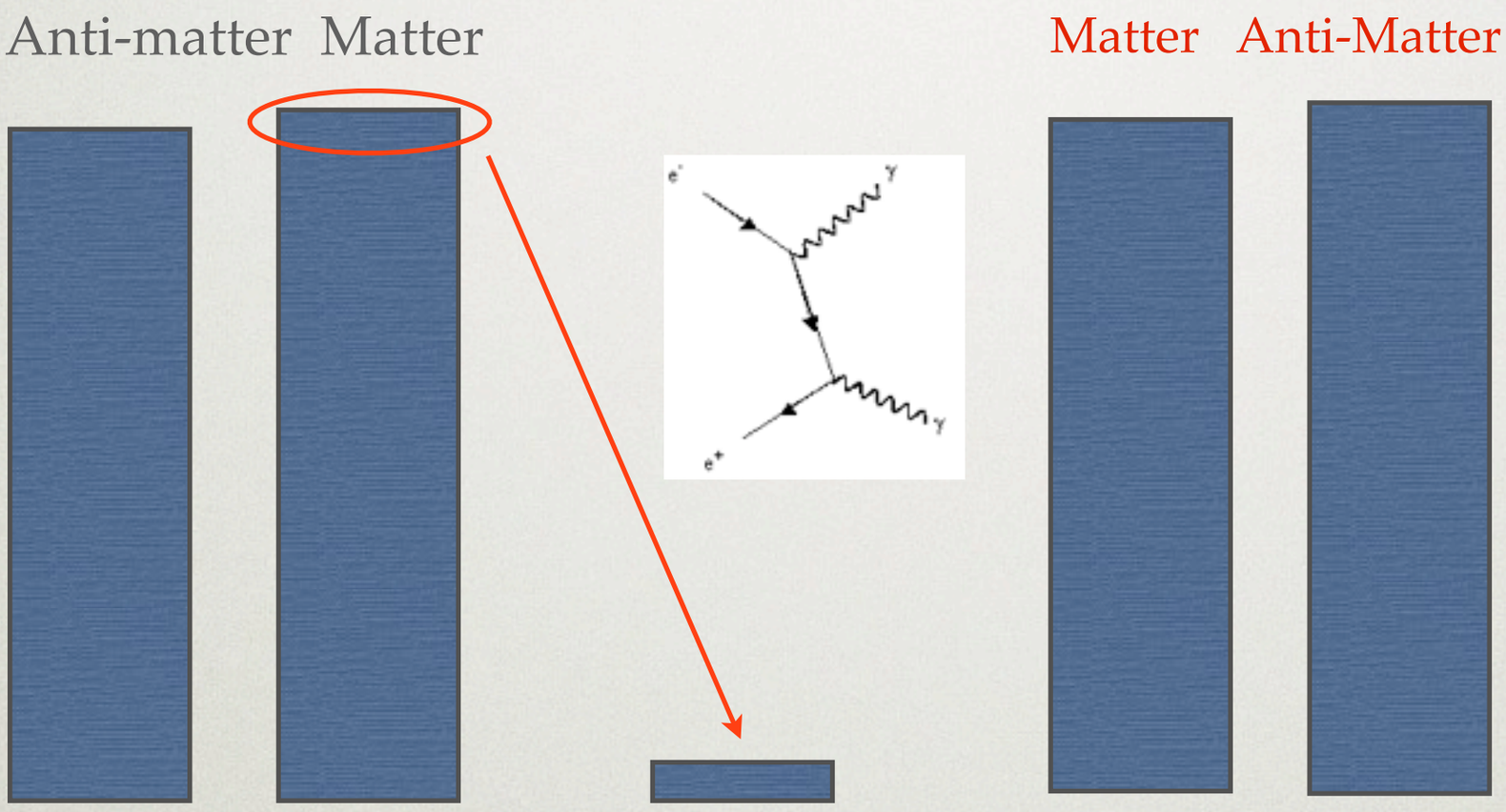
$$X u^c d^c d^c$$



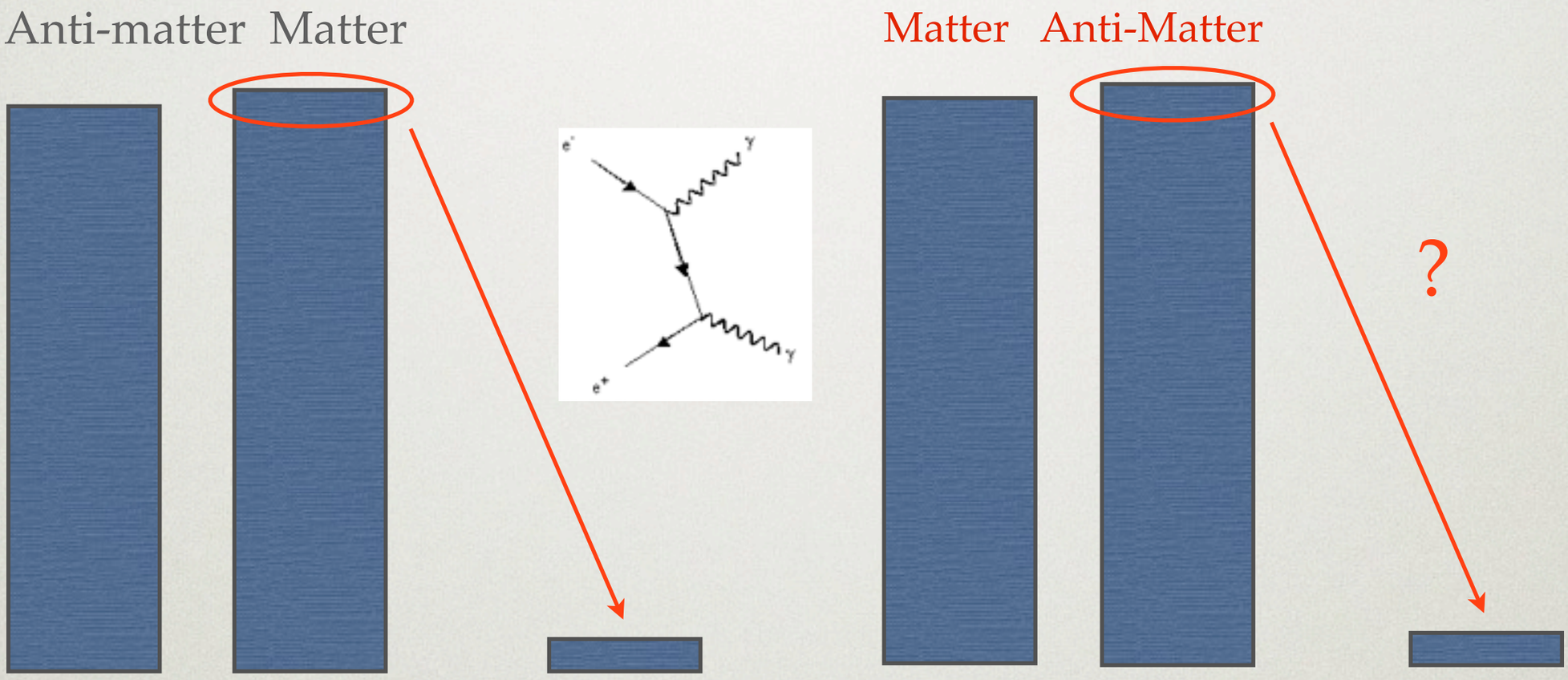
Asymmetric Dark Matter



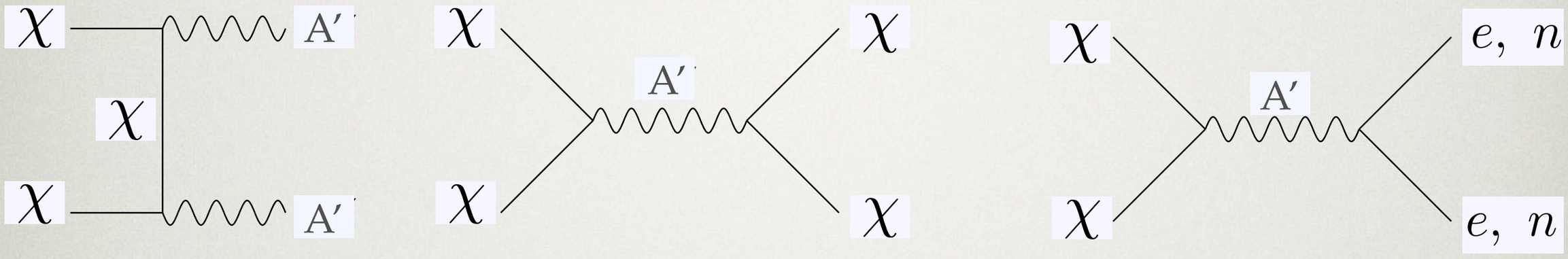
Asymmetric Dark Matter



Asymmetric Dark Matter

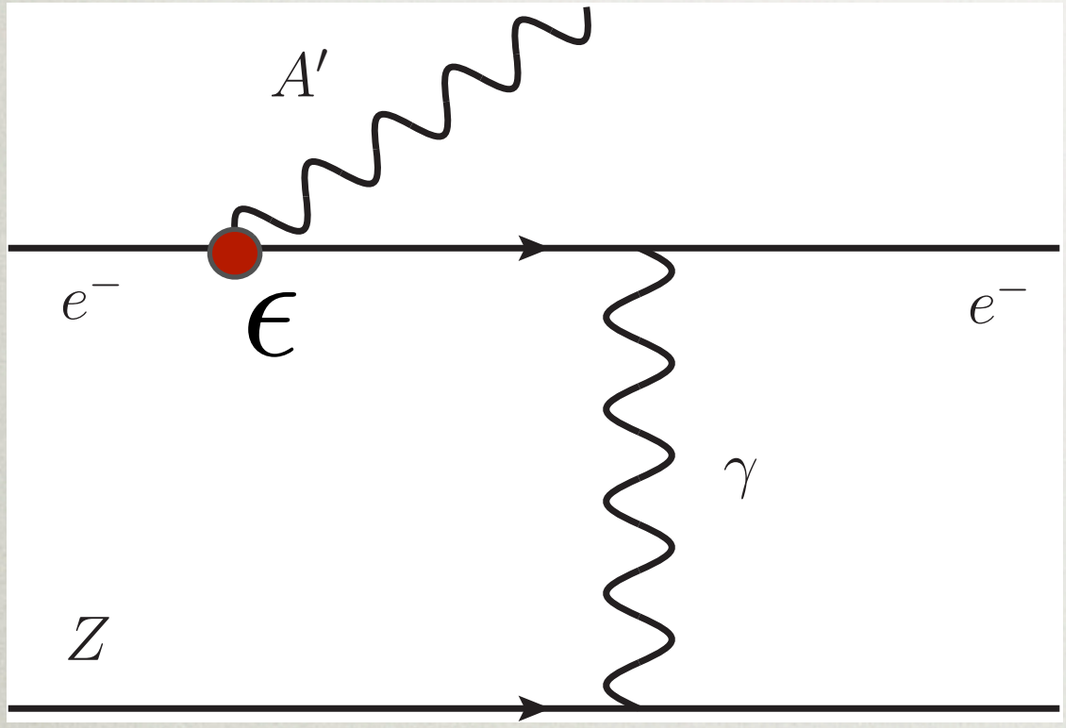


Dark Forces and DM Interactions

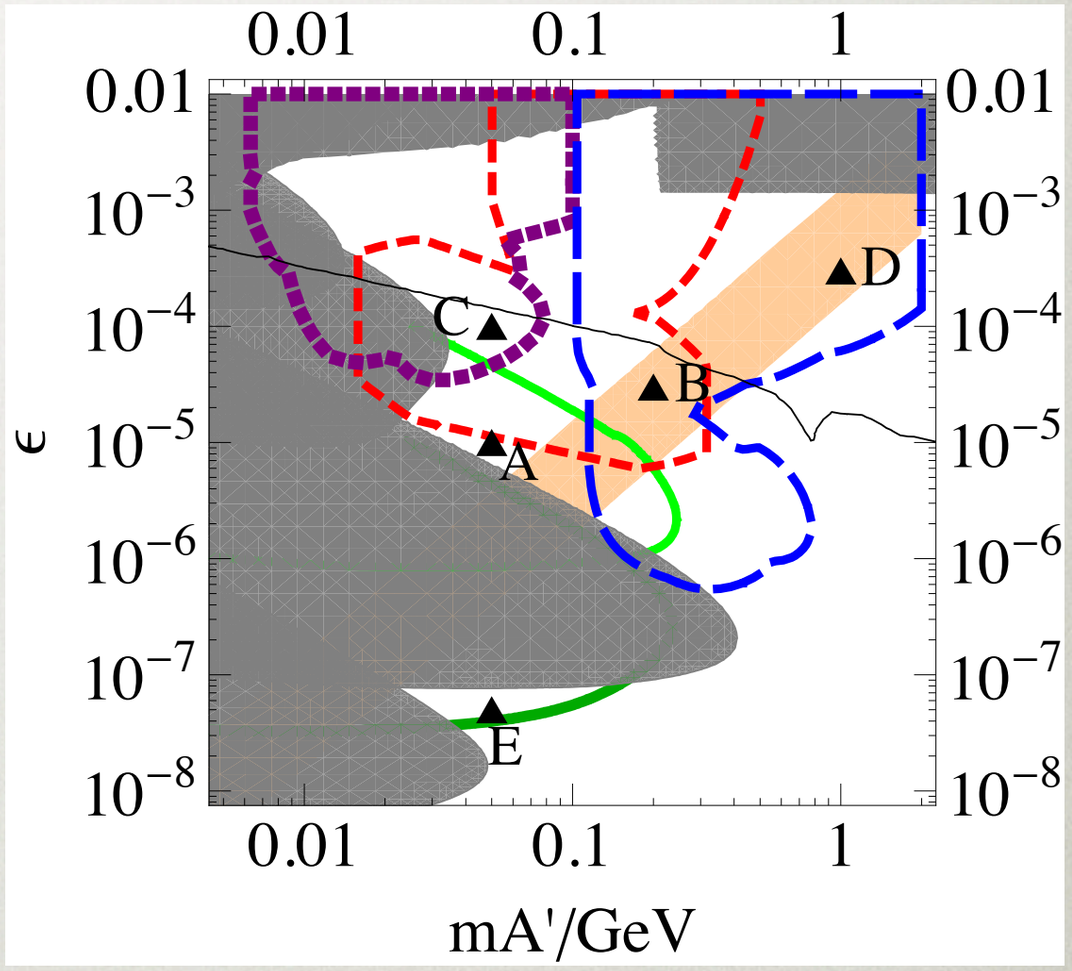


- Dark Forces Very Important for Asymmetric Dark Matter!
- May also be important for structure of DM halos
- May be important for DM direct detection and collider searches

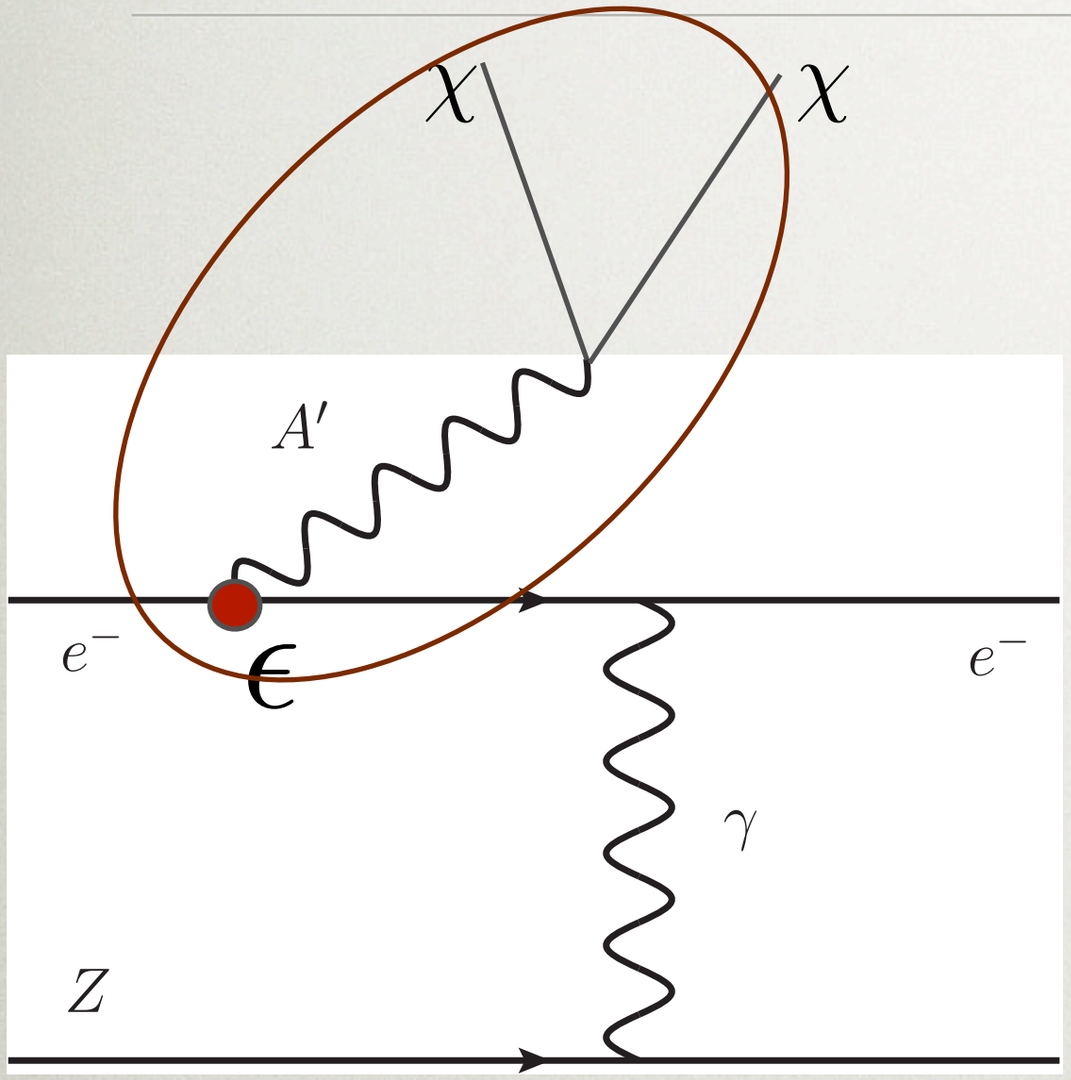
Low Energy Accelerator Constraints



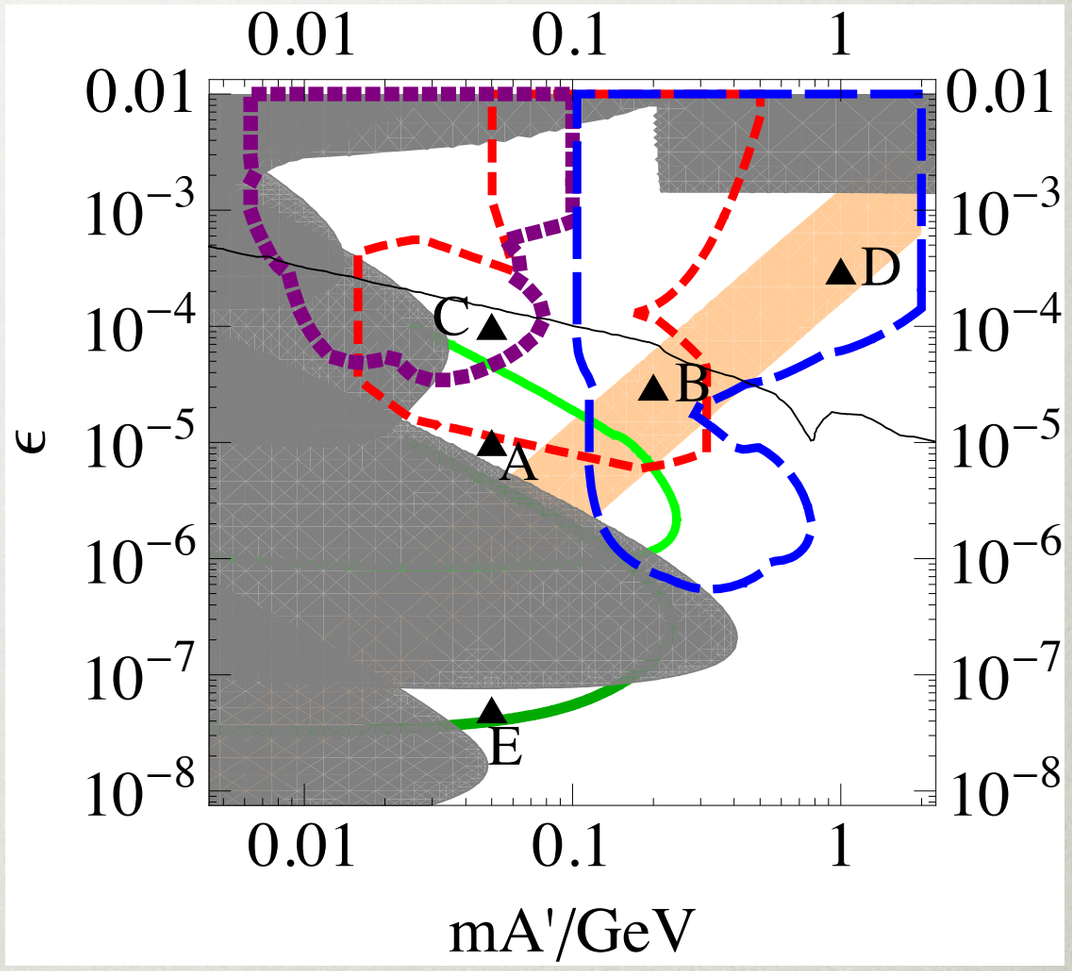
Bjorken, Essig, Schuster, Toro



Translate to Direct Detection



Bjorken, Essig, Schuster, Toro



The Lamppost Problem

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

Galactic Center Excess

PAMELA

CoGeNT

Fermi positron

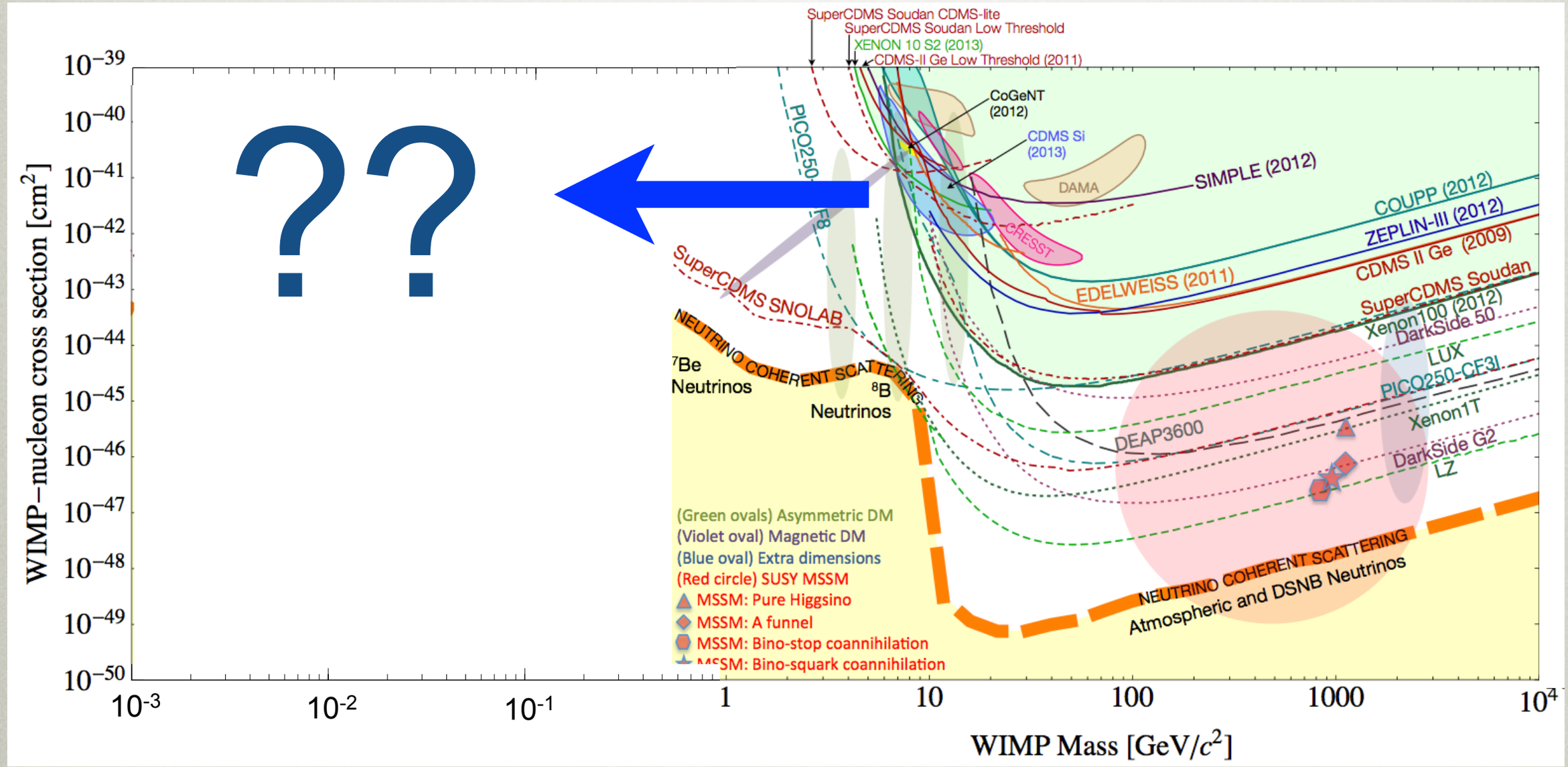
CDMS

DAMA

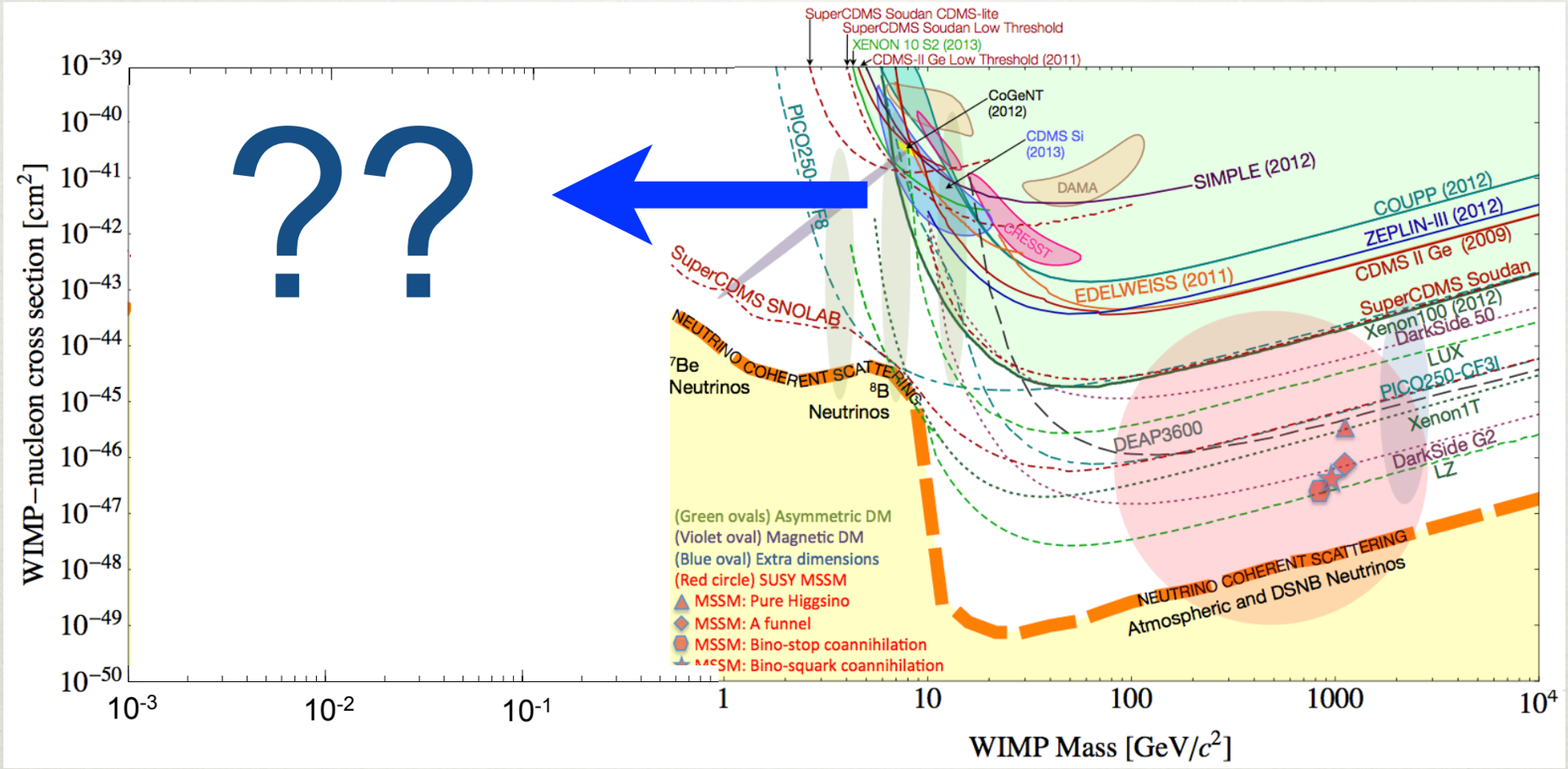
Fermi line

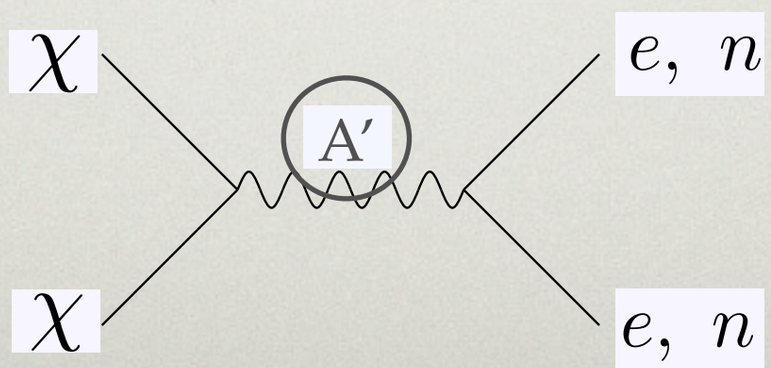
- How can we be ready for anything?

Terra Incognita



Terra Incognita

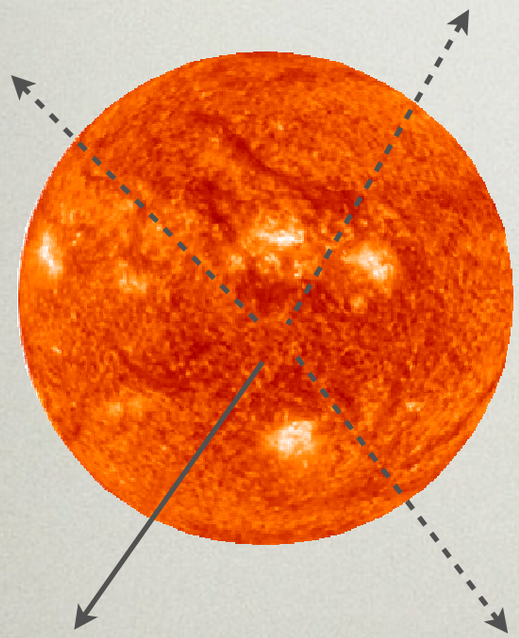




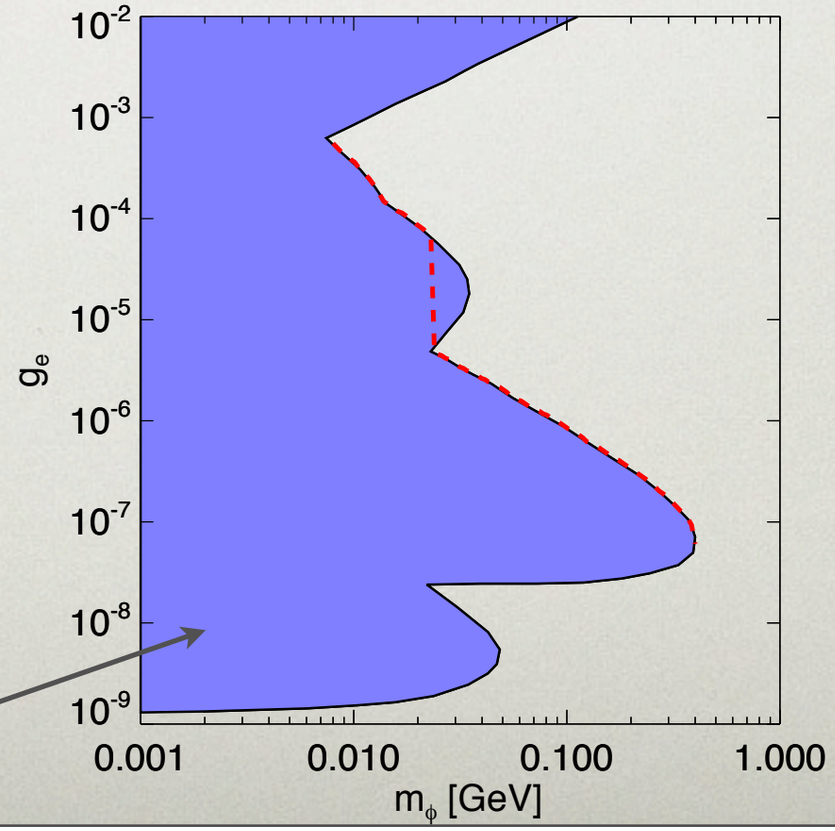
Low Mass DM Constrained by Astro

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

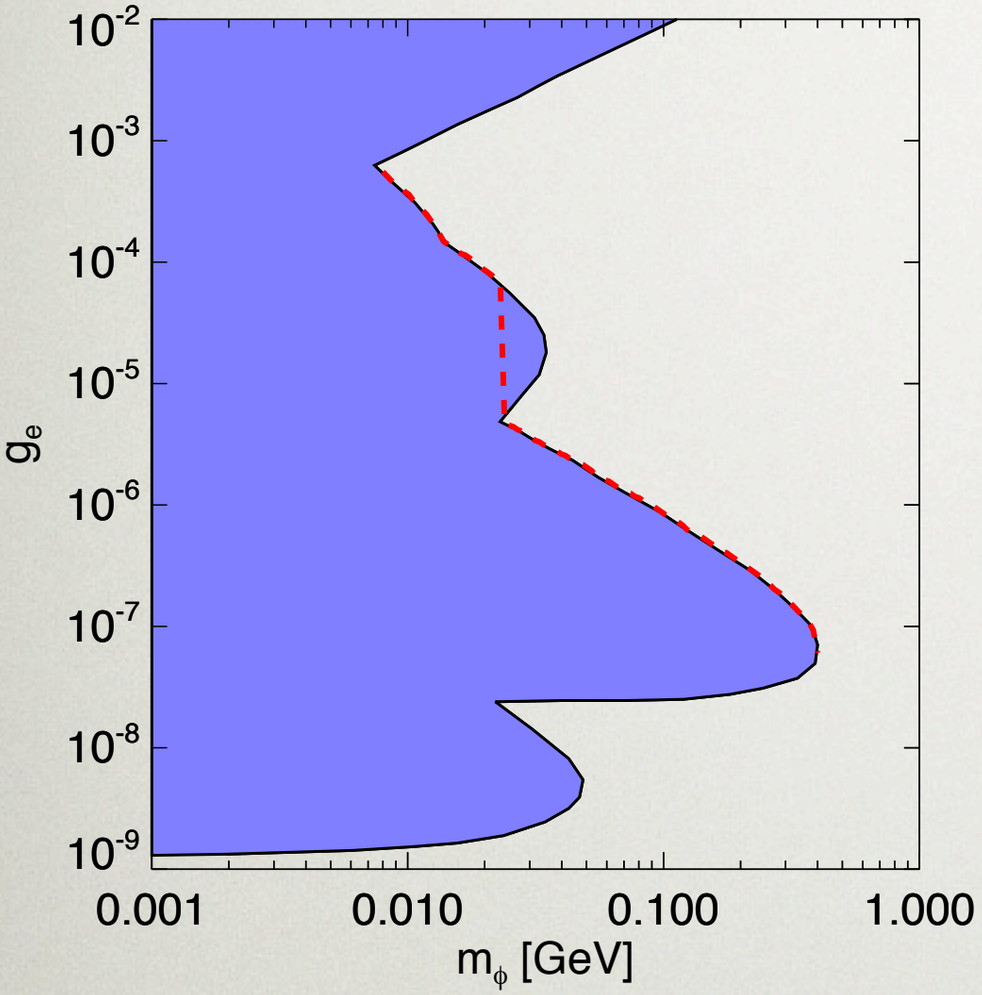
Cooling constraints places tight bounds

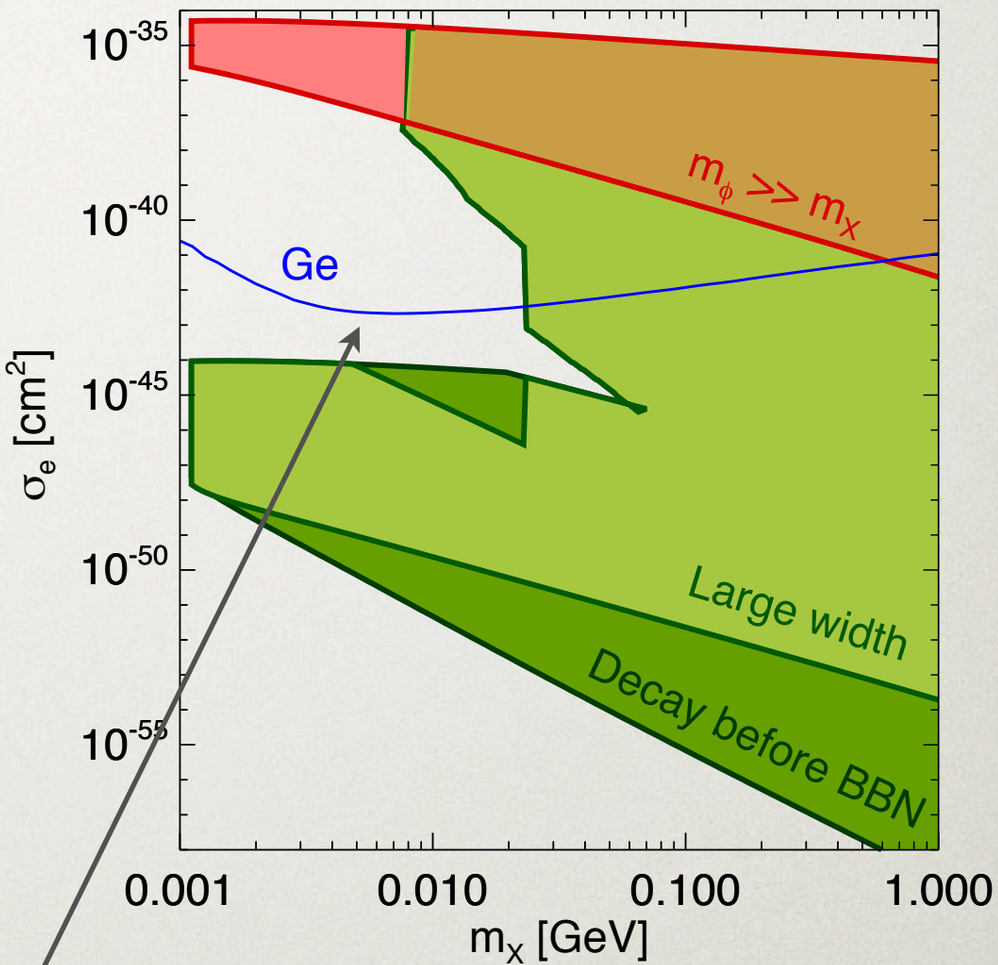


Supernova cooling



Map into Direct Detection Plane





Lin, Yu, KZ 1111.0293

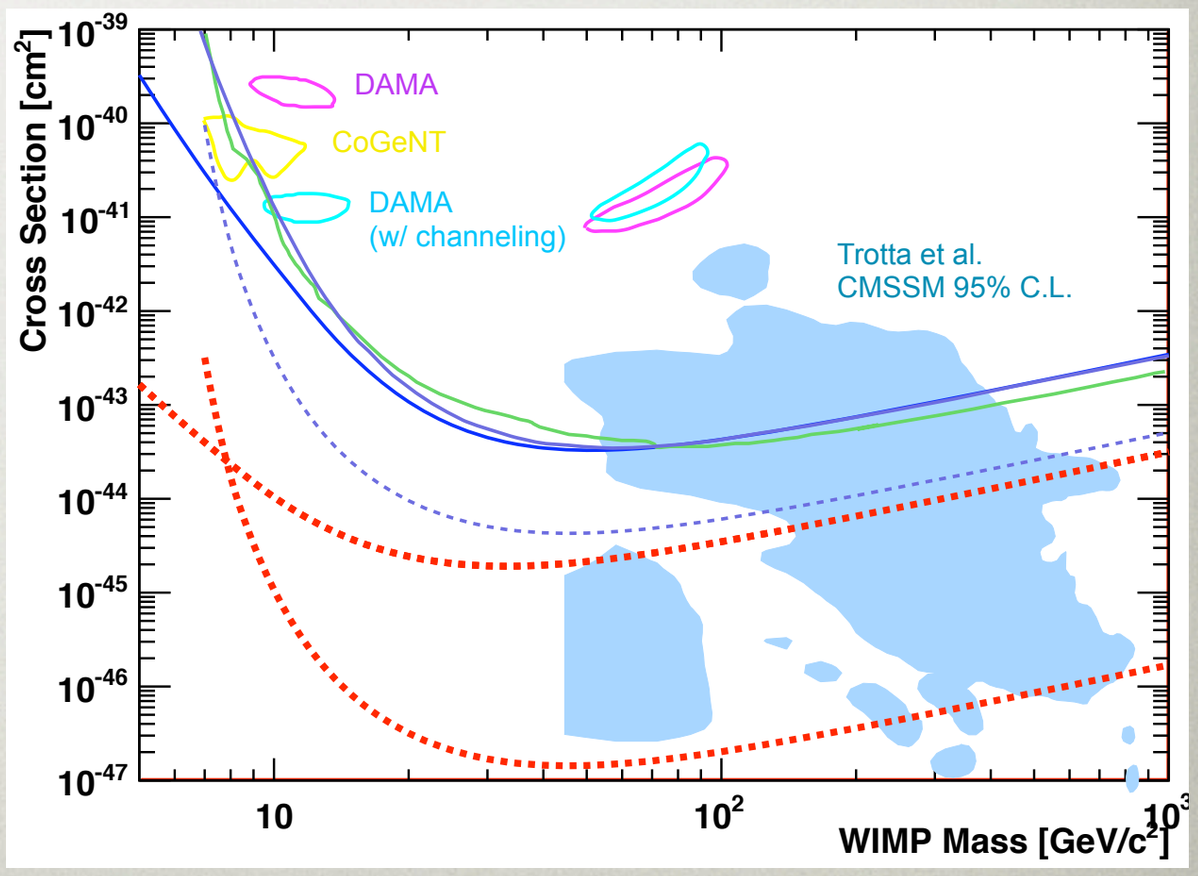
Projected maximum sensitivity of direct detection experiment

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

The Road Ahead

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

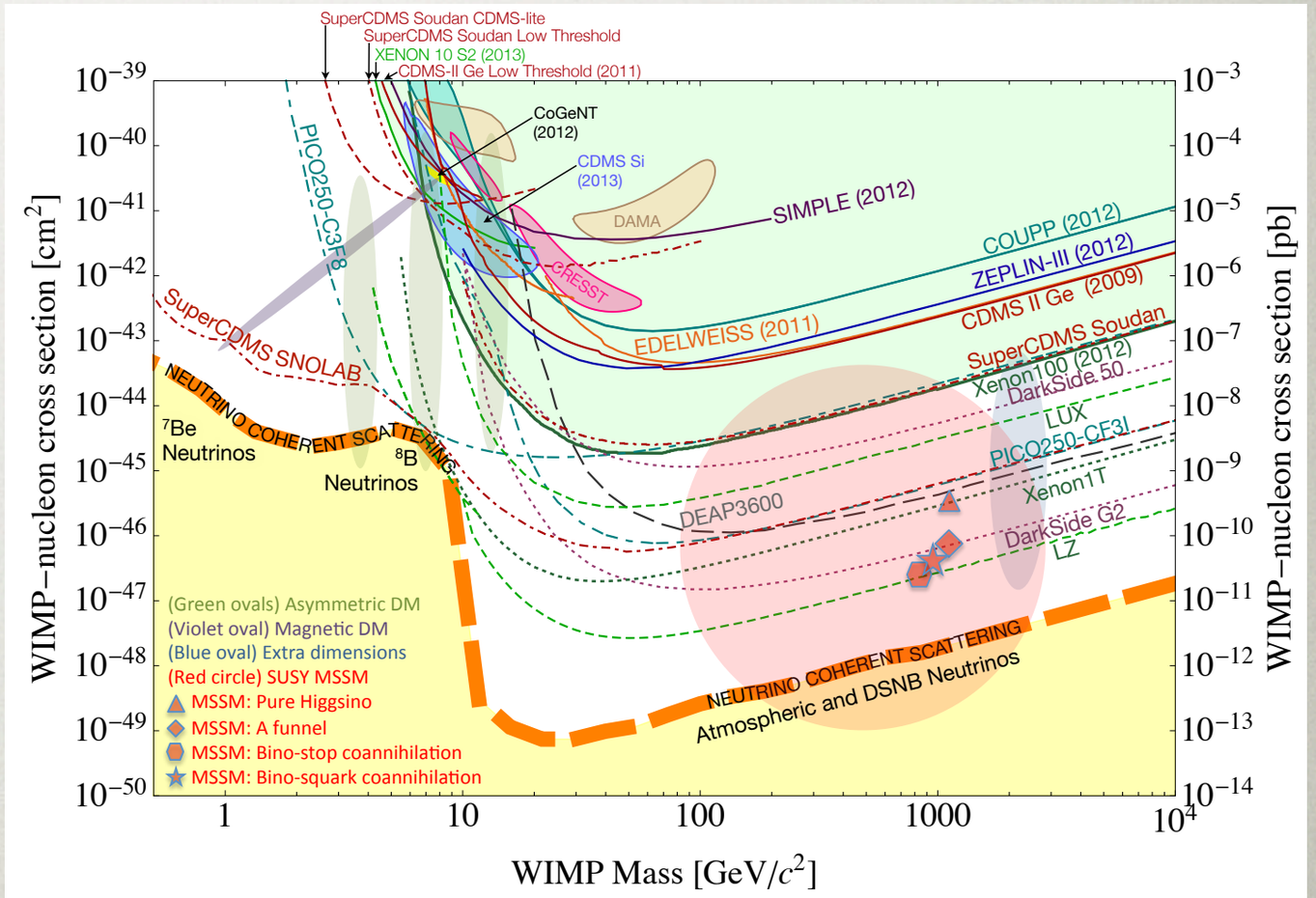
$$\sigma_n \sim 10^{-45-46}\ \mathrm{cm}^2$$



The Road Ahead

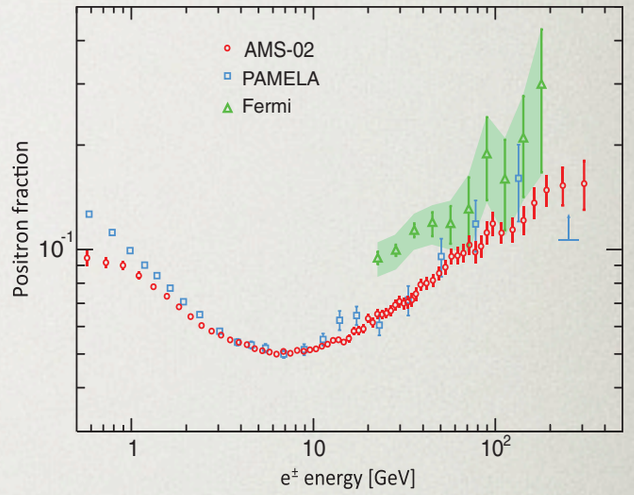
- Direct Detection experiments will continue to probe Higgs mediated scattering
- Higgs pole largely covered within 5 - 10 years

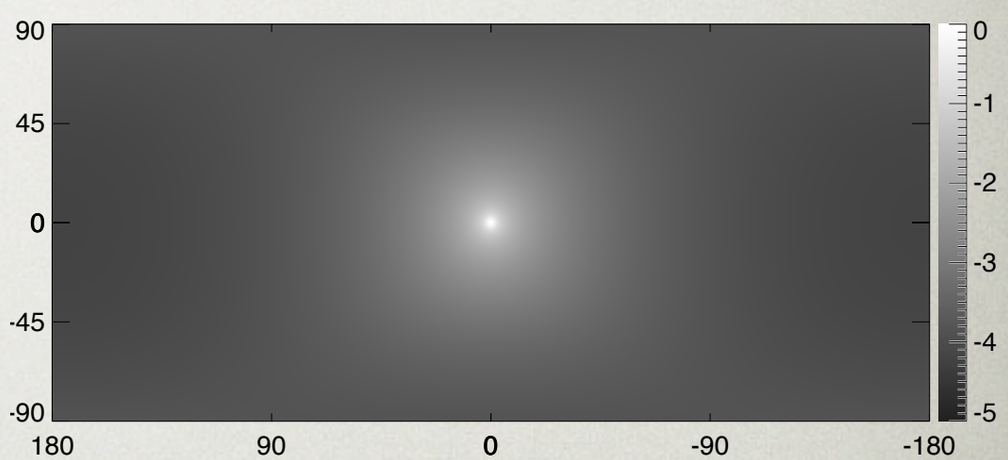
$$\sigma_n \sim 10^{-45-46}\ \mathrm{cm}^2$$

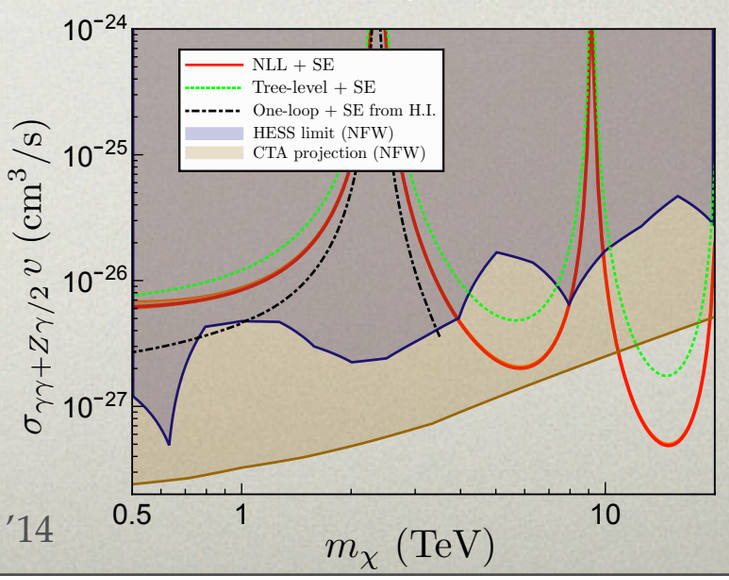


The Road Ahead

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







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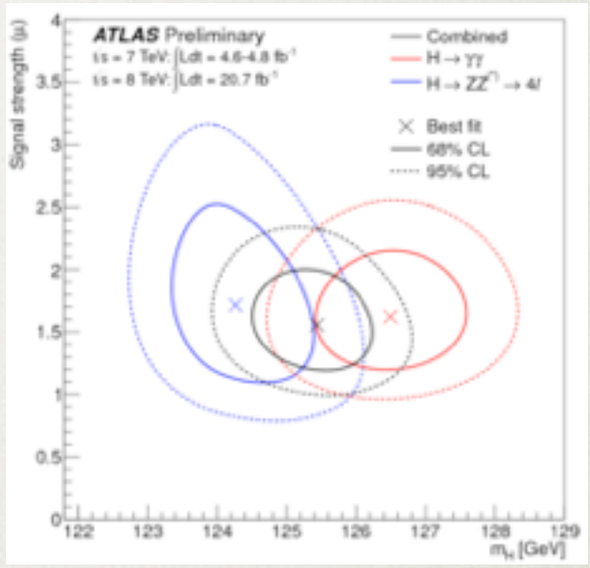
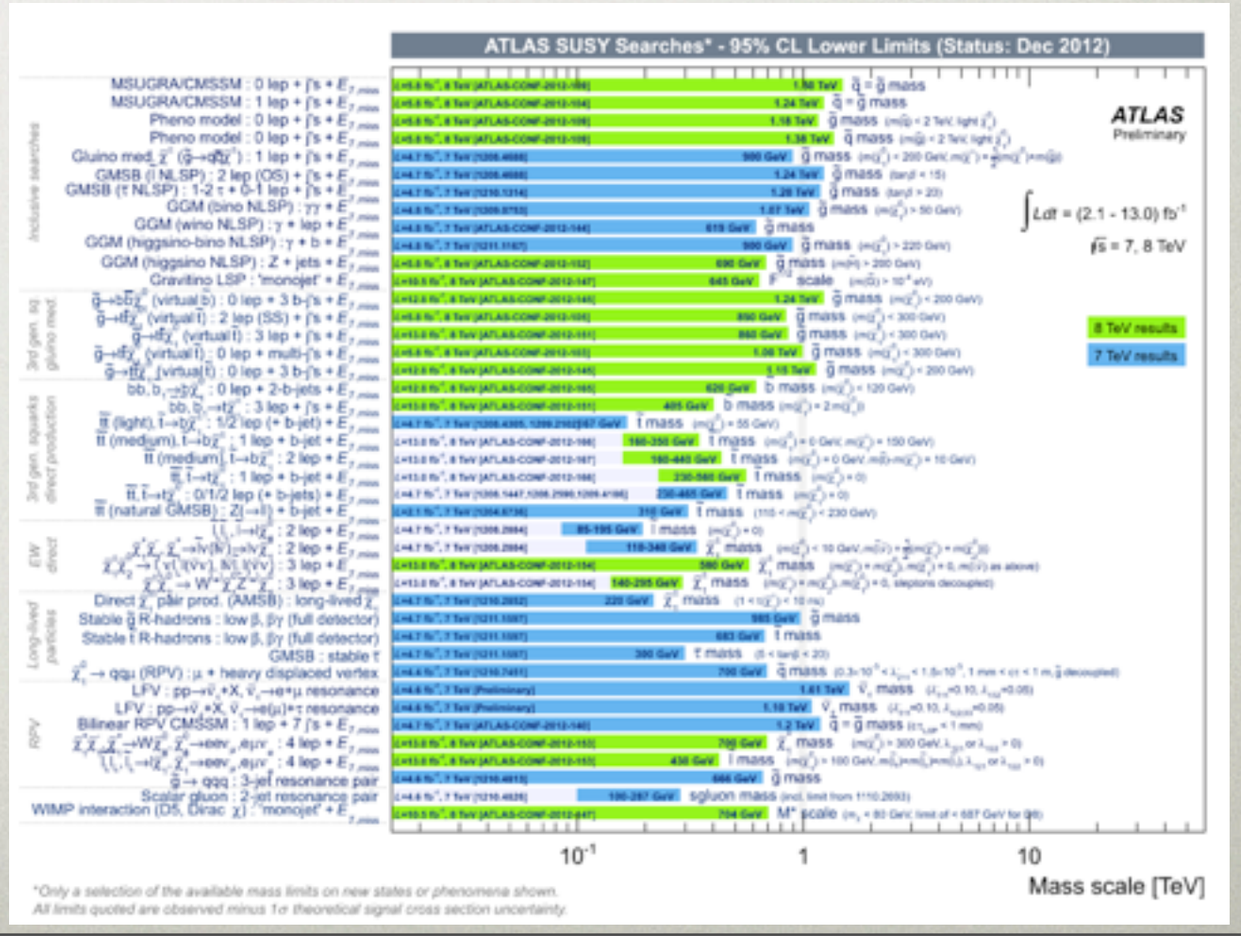
The Road Ahead

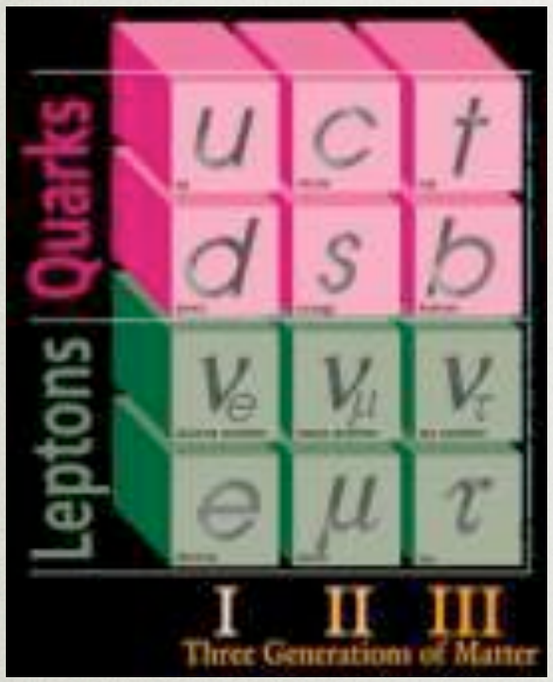
- Higgs discovered
- Many models covered
- Many models still buried → theoretical and model input





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 .....

Standard Model

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