# In Search of Dark Matter:

## Theoretical Models and Their Experimental Signatures

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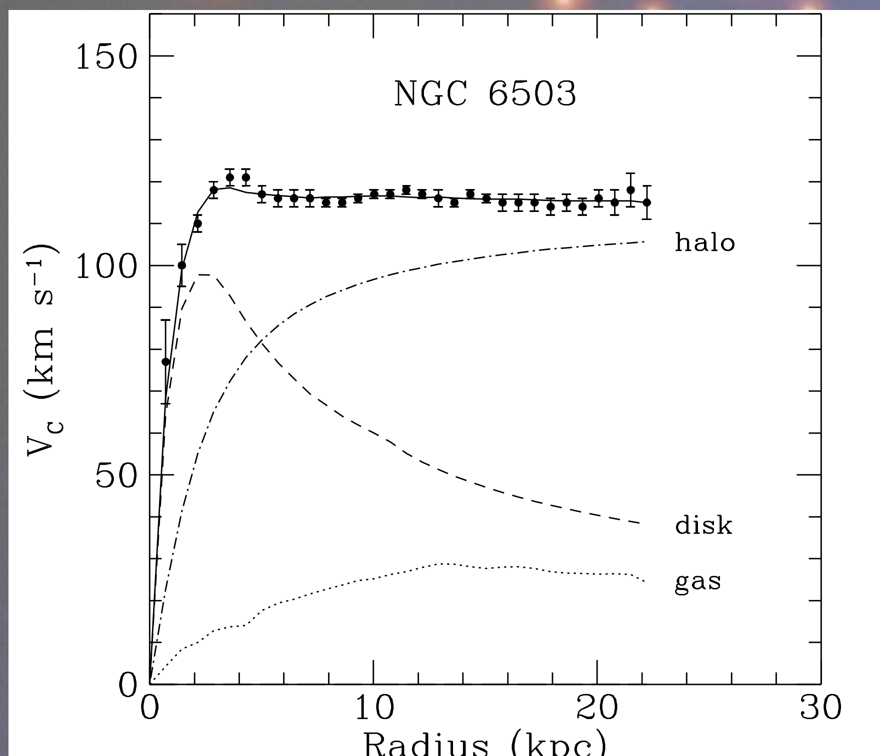
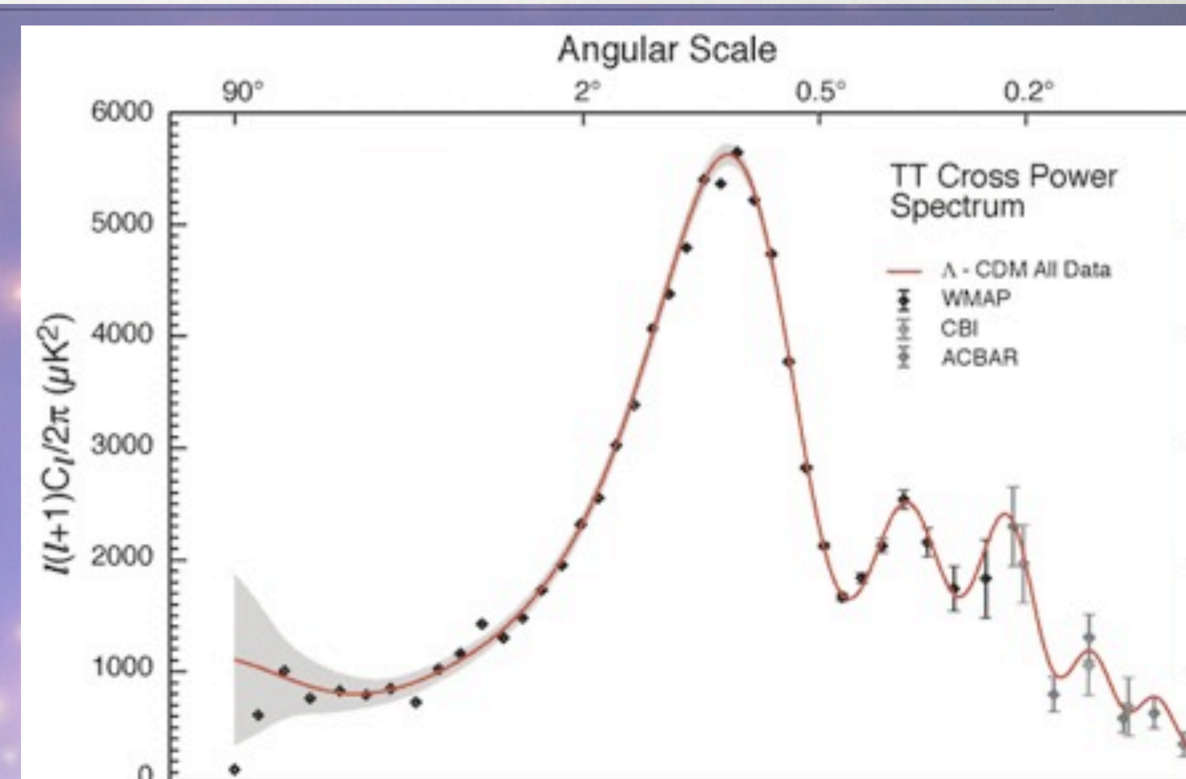
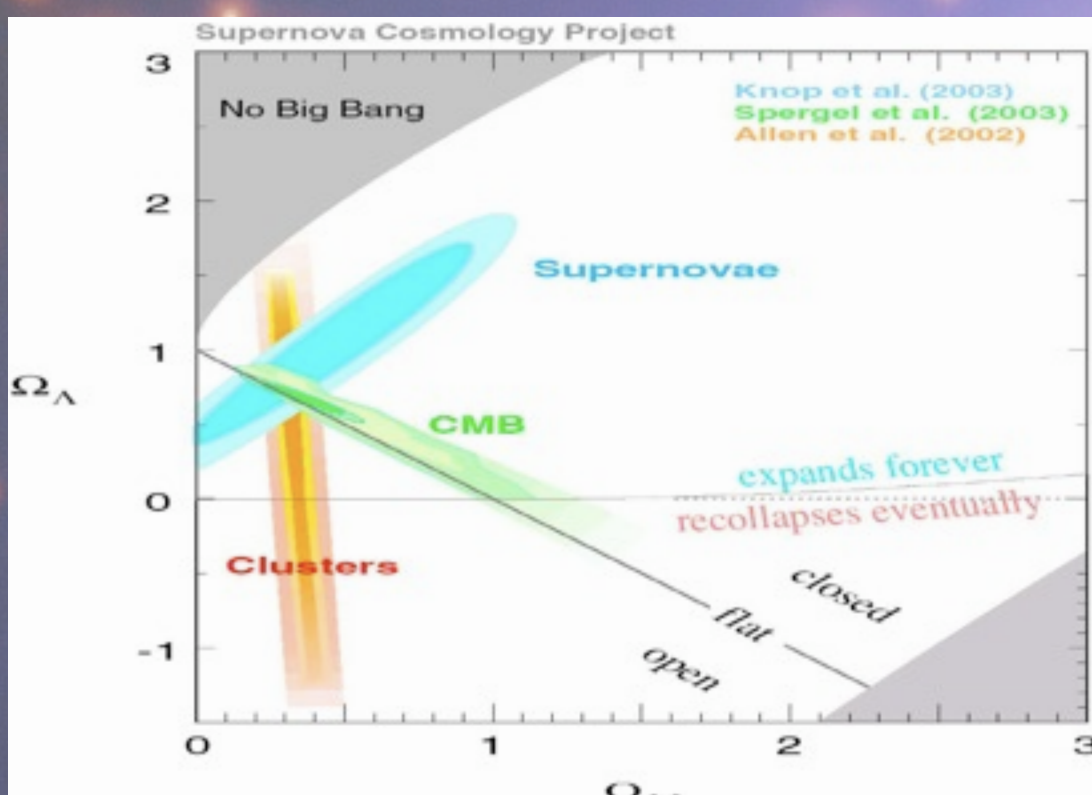
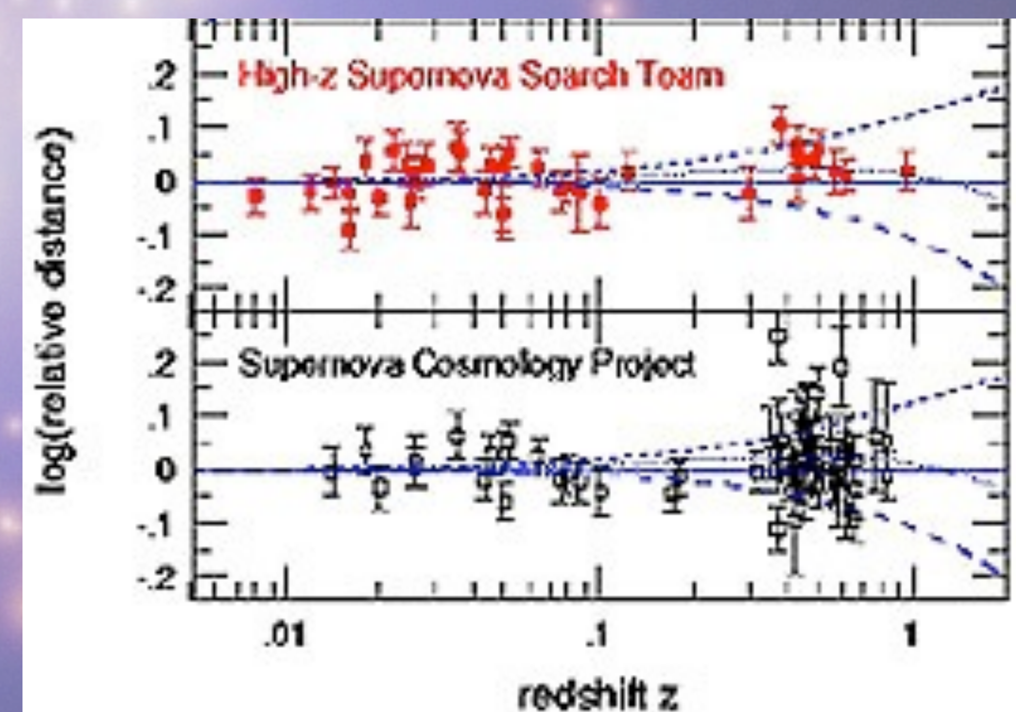
University of Michigan

# Overwhelming Evidence for Dark Matter



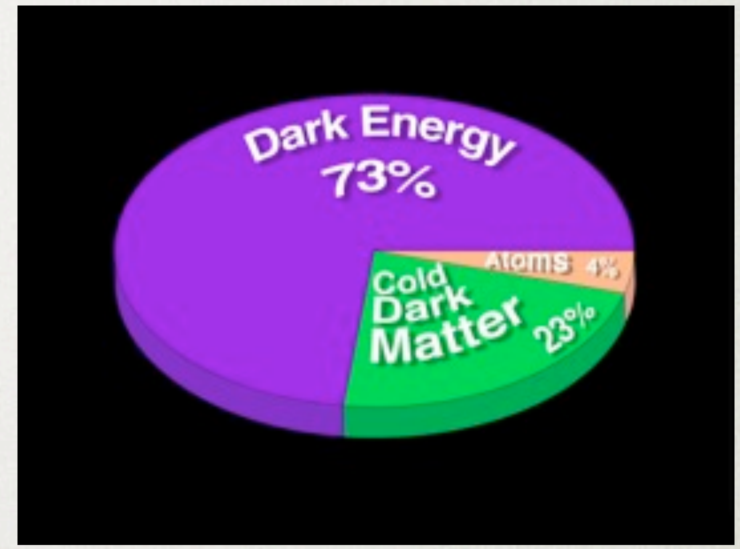



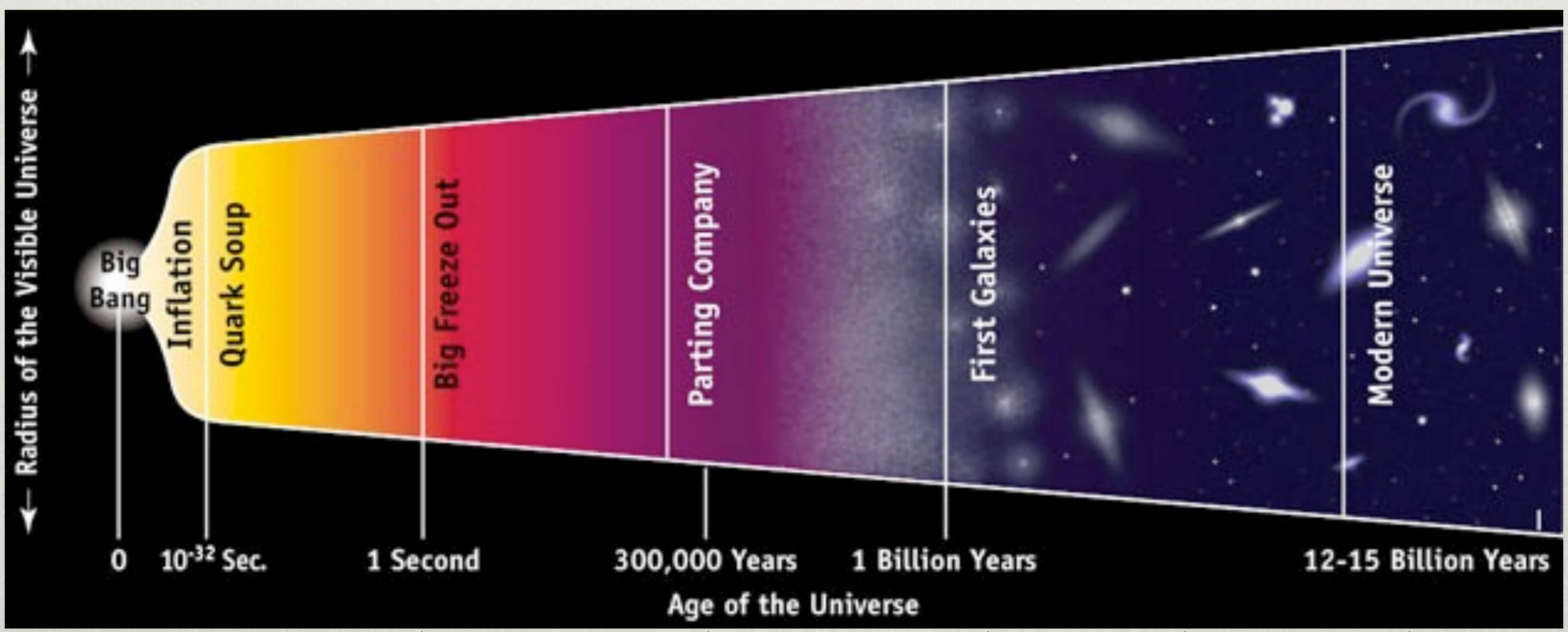



# Evidence for DM Overwhelming

All evidence points toward




↑ BBN (baryons)

↑ CMB (curvature)

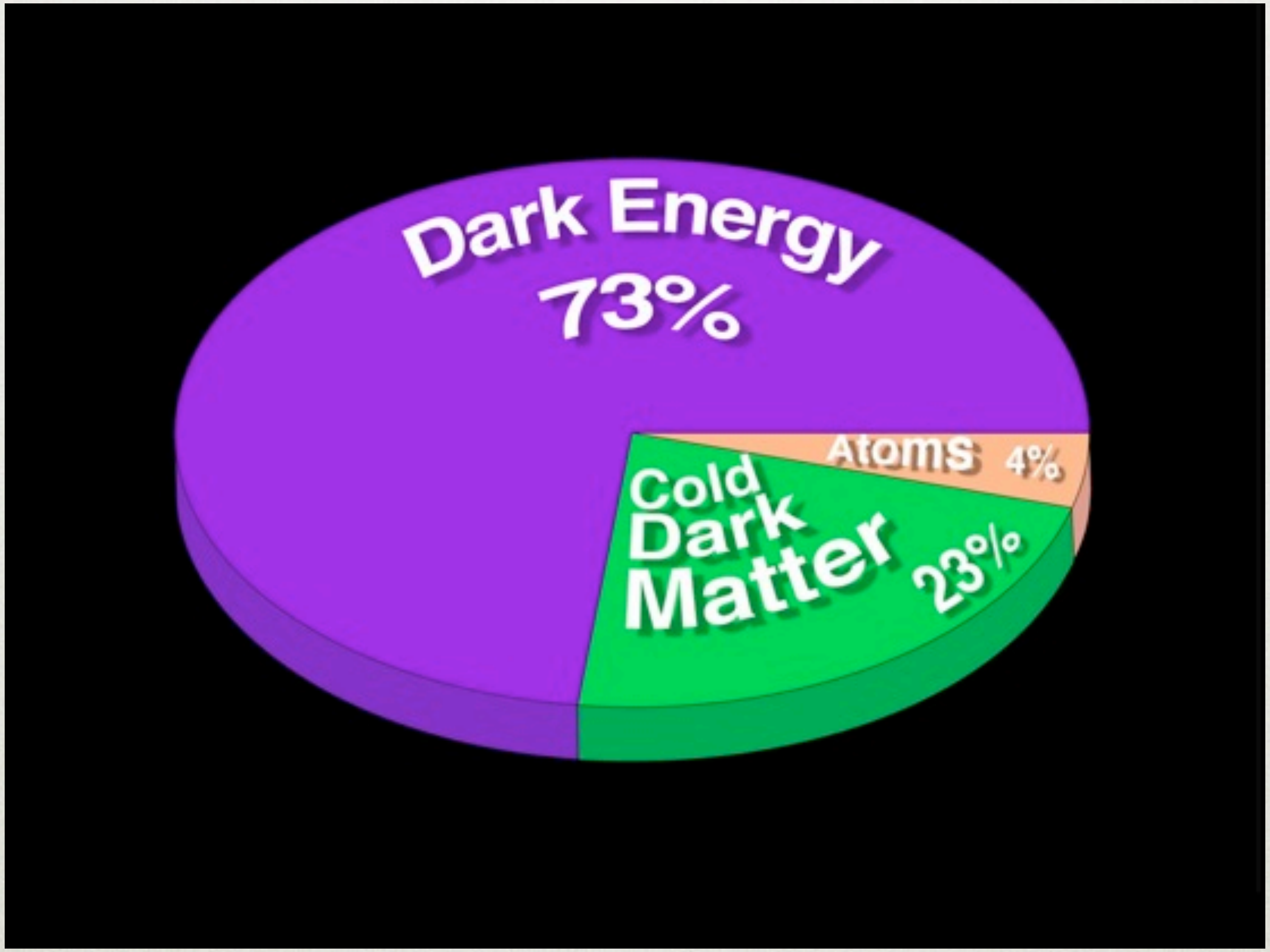
↑ LSS (matter)

↑ Supernovae (DE)

↑ Galaxy curves (matter)

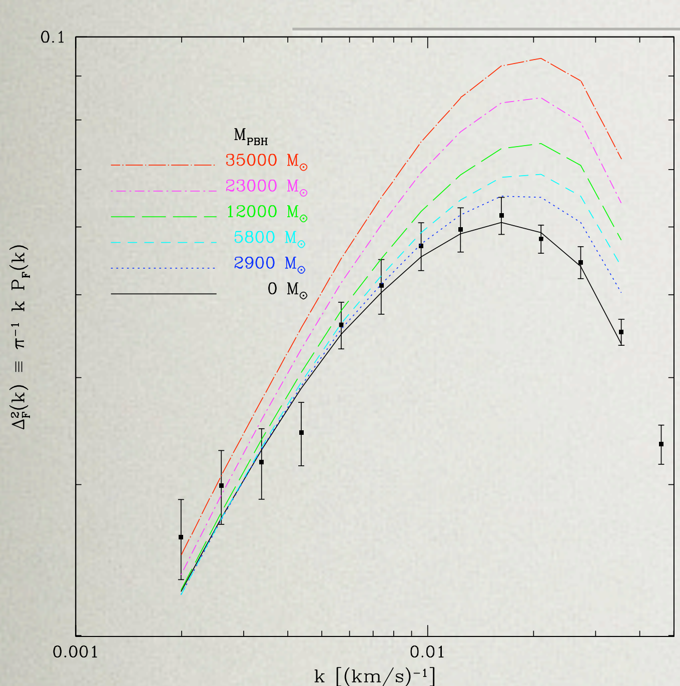
# New Physics

Dynamical Selection?




New Dynamics in Particles, Definitely BSM

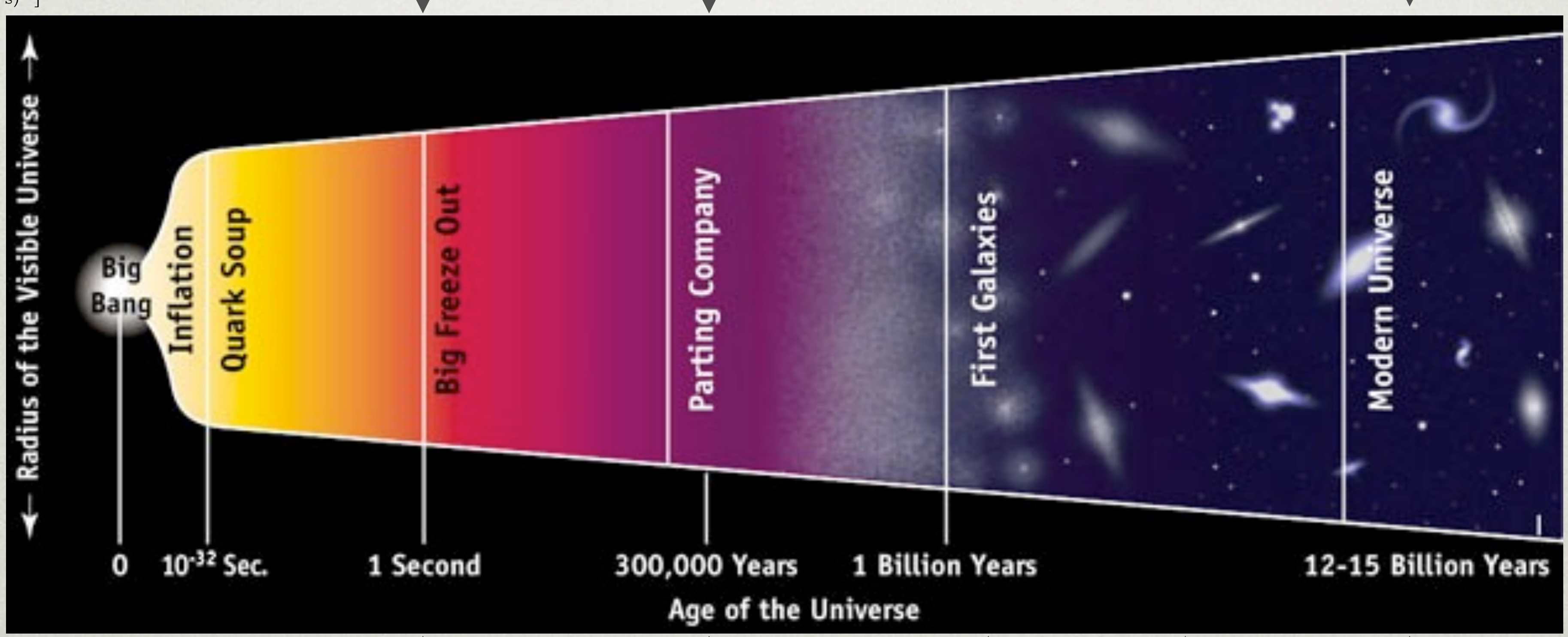
# What Do We Know About the Dark Matter?




Afshordi, McDonald, Spergel

BBN                CMB
Not Free Baryons

MACHO searches + Lya
Not Bound Baryons




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

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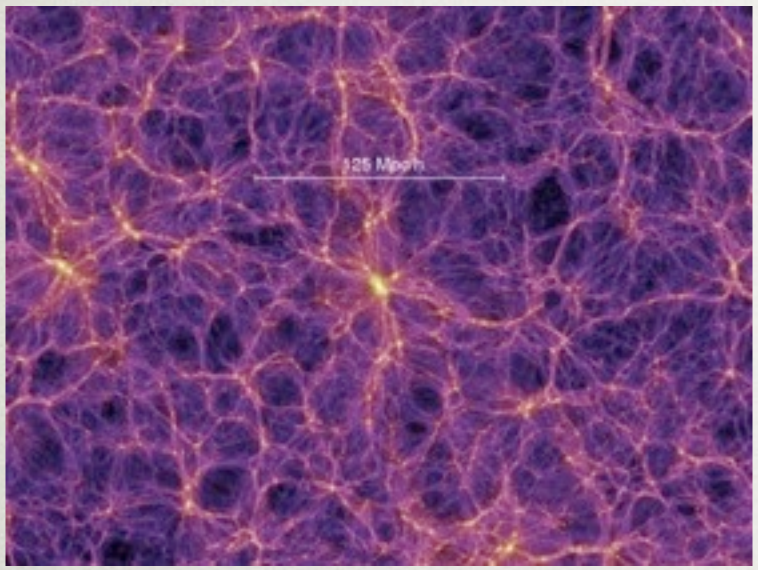
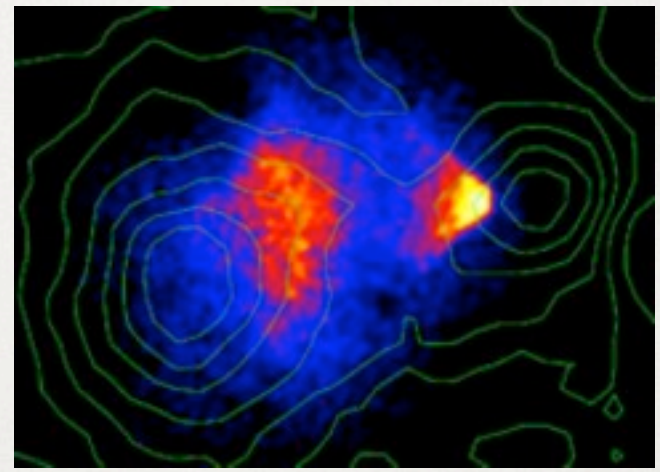
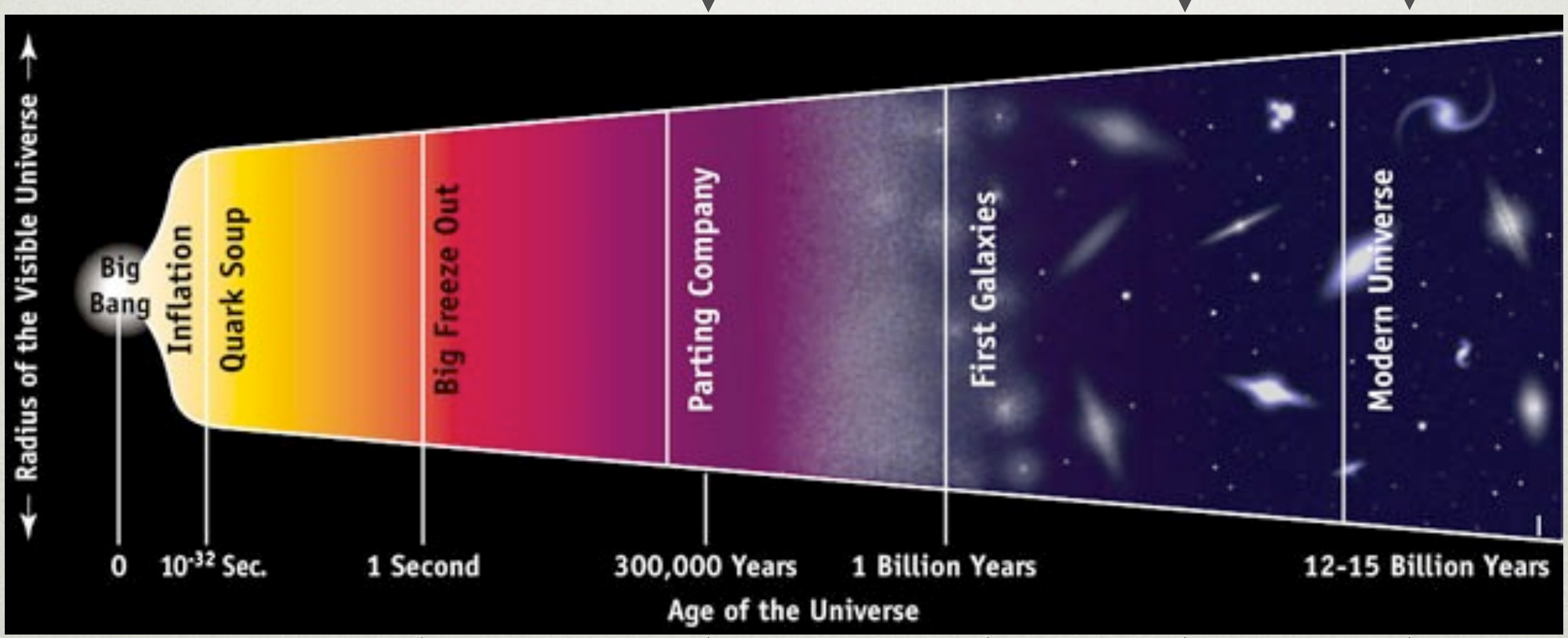




CMB

LSS

LSS+Bullet Cluster
Not Modified Gravity

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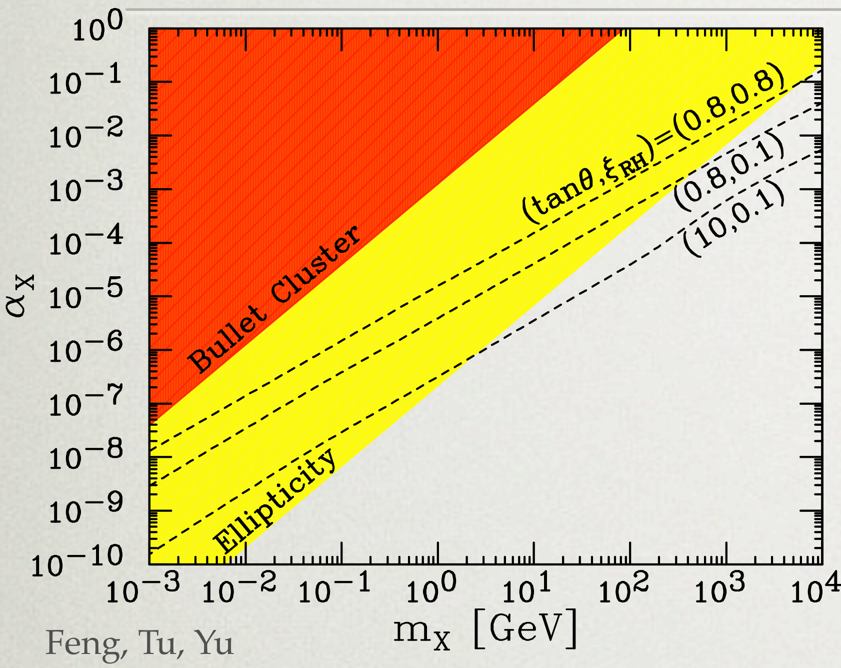
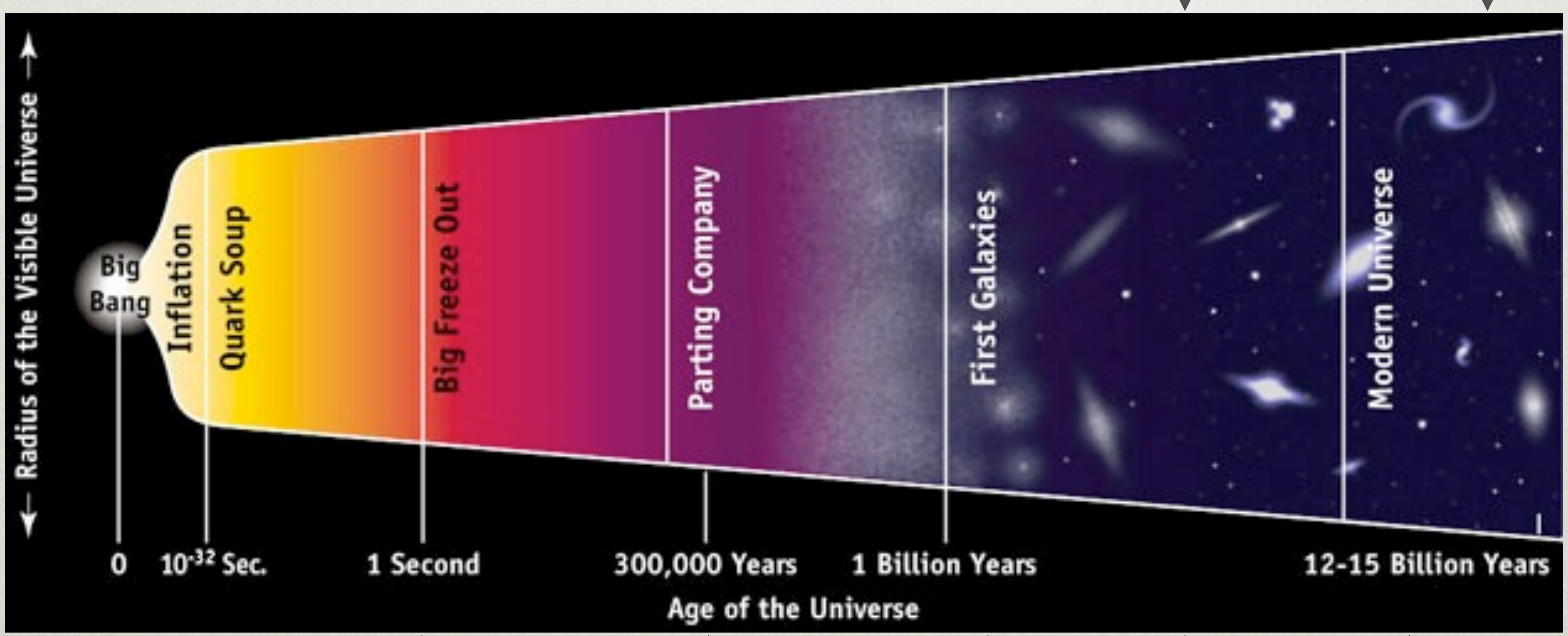



Feng, Tu, Yu

Halo Shapes
Weakly Self-interacting ↓

Direct Probes
Weakly Interacting with Us ↓

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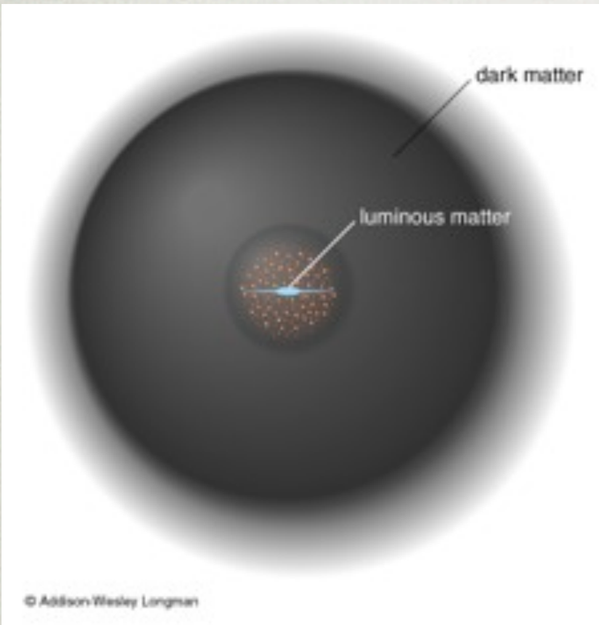
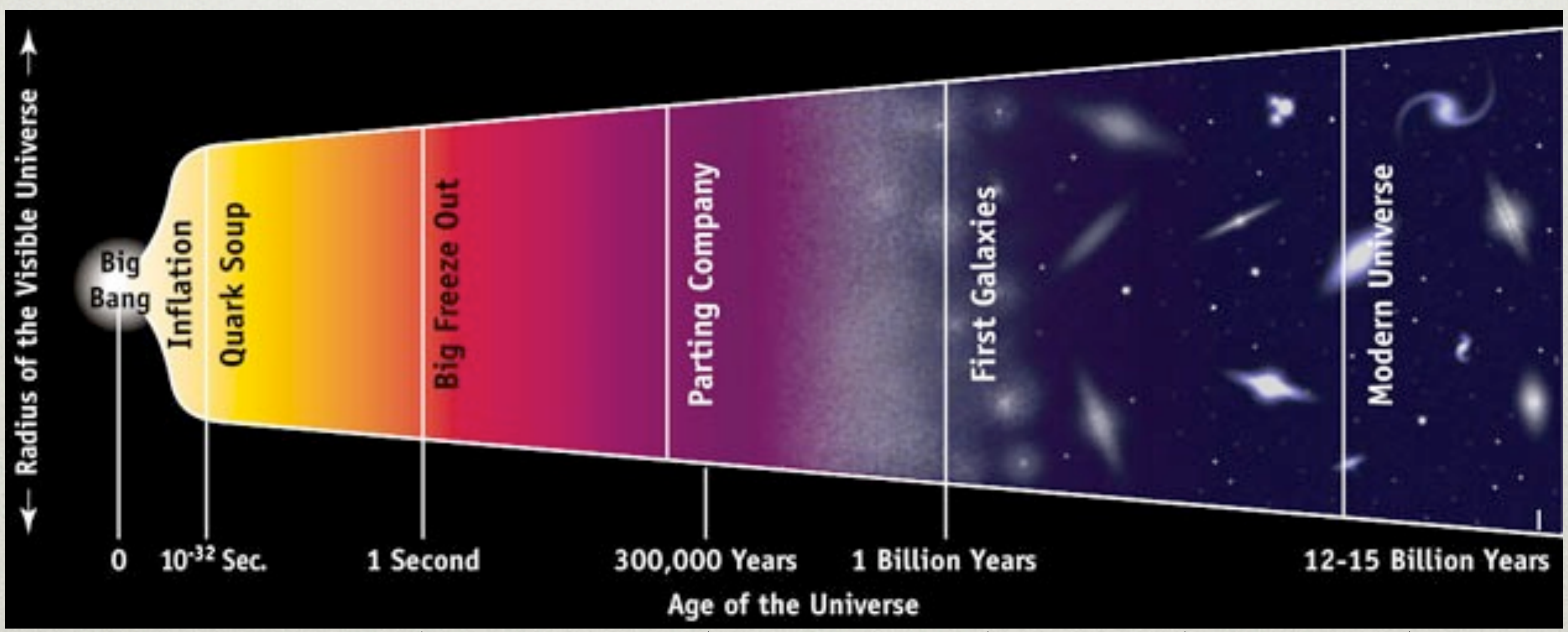
# How Dark is Dark Matter?




McDermott, Yu, KZ '10

Consider All Epochs!

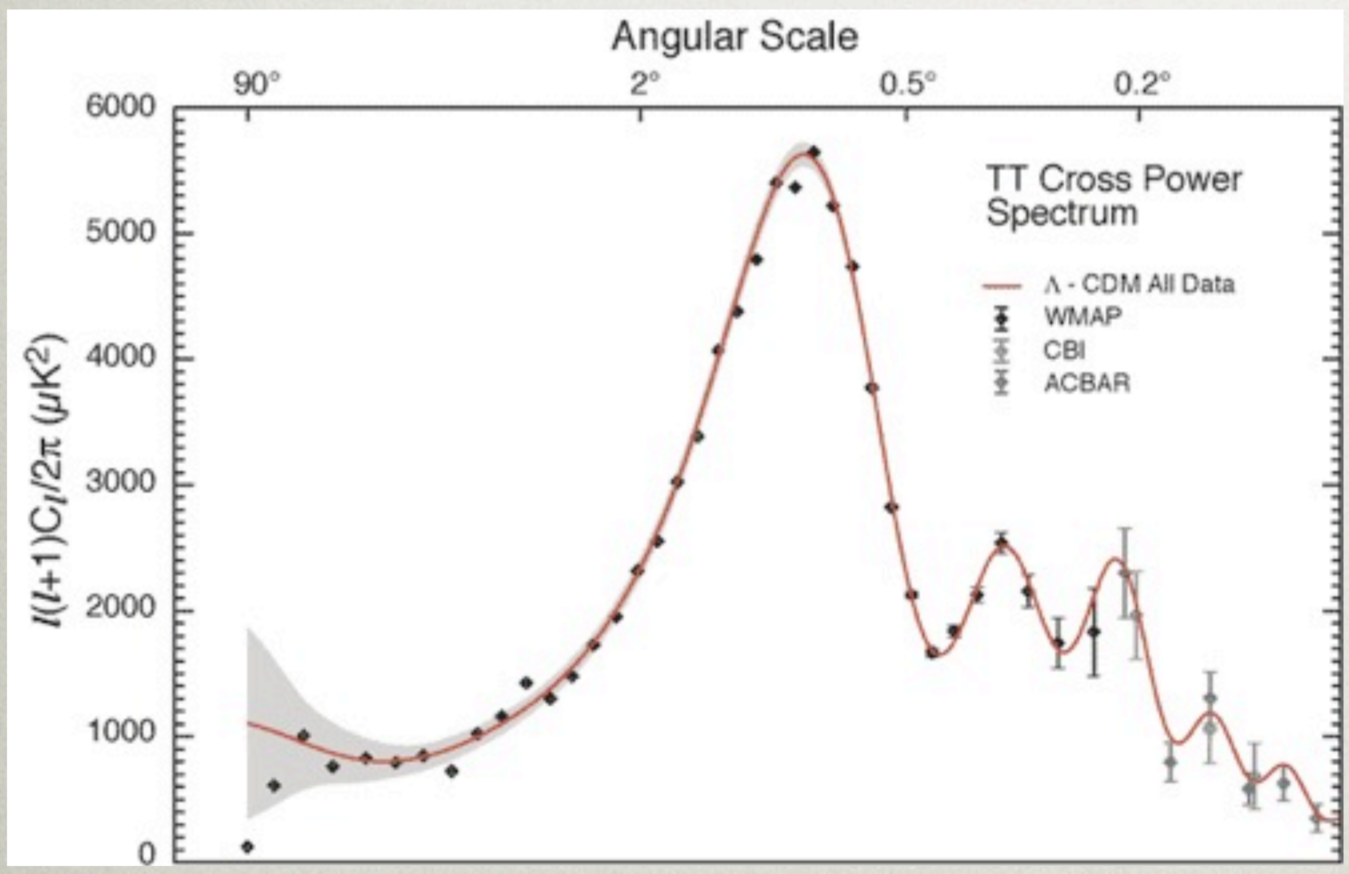


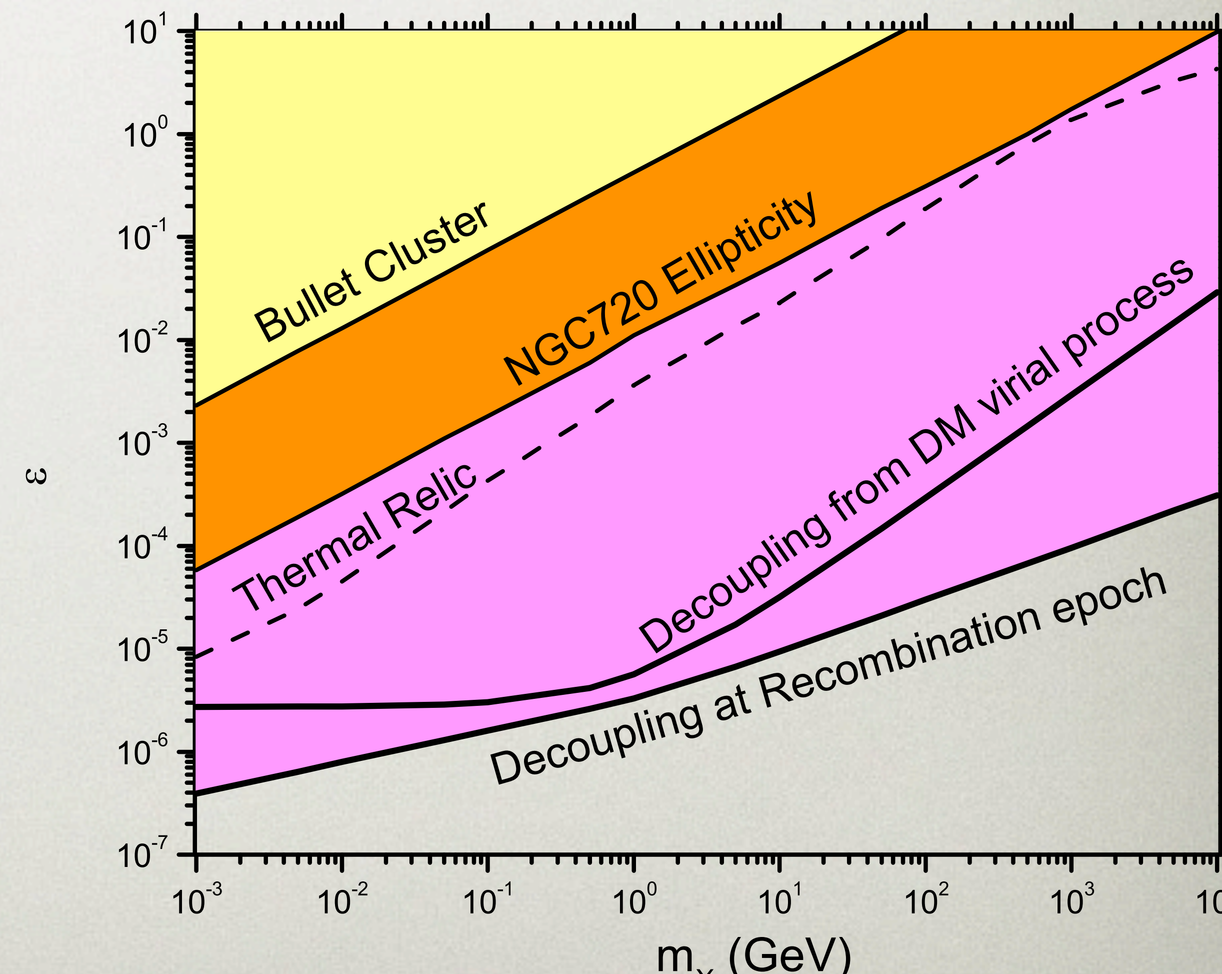

BBN (baryons) | CMB (curvature) | Supernovae (DE) | LSS (matter) | Galaxy curves (matter)

Tuesday, October 2, 12

# How Dark is Dark Matter?

- Which probe is the most constraining?

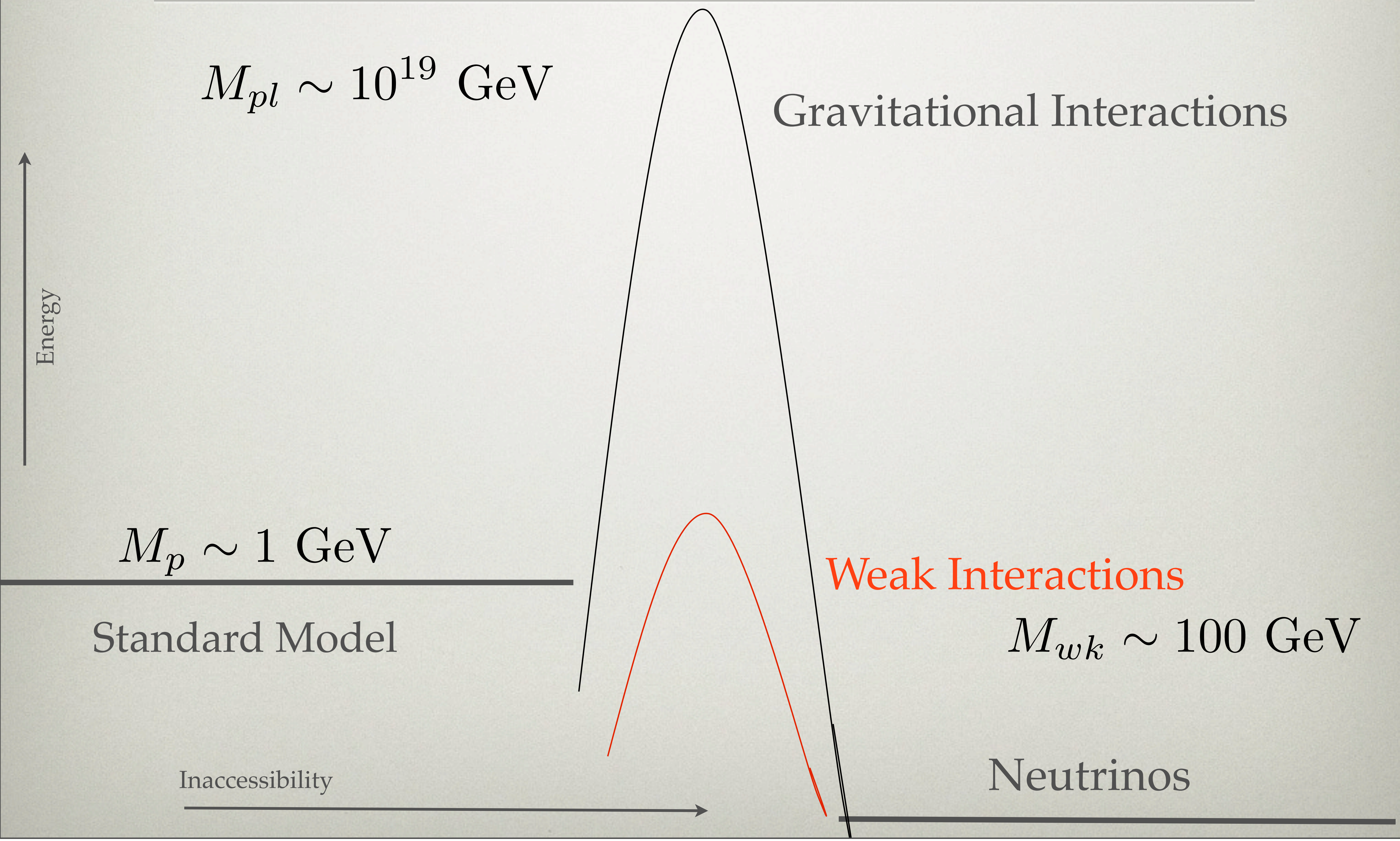



McDermott, Yu, KZ '10

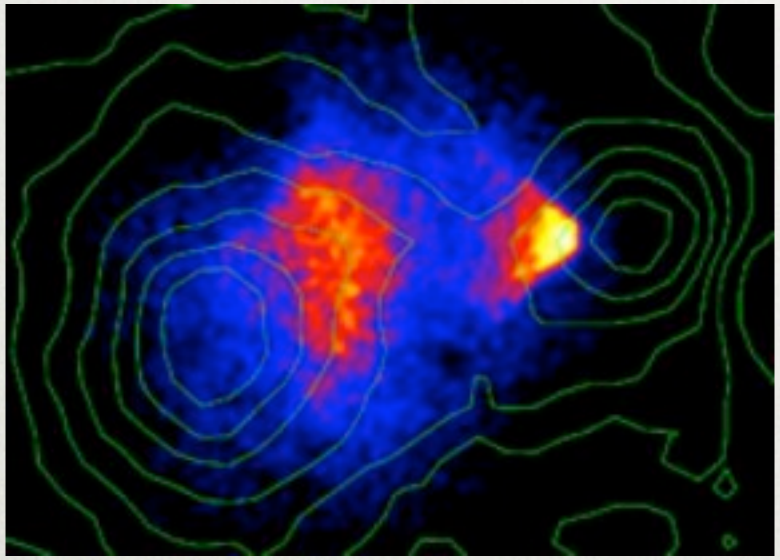
$$\frac{d\sigma}{d\Omega} \propto \frac{1}{v^4}!$$

# Neutrinos and the Weak Interactions



# Super-Weakly Interacting

- Gravitational Coherence

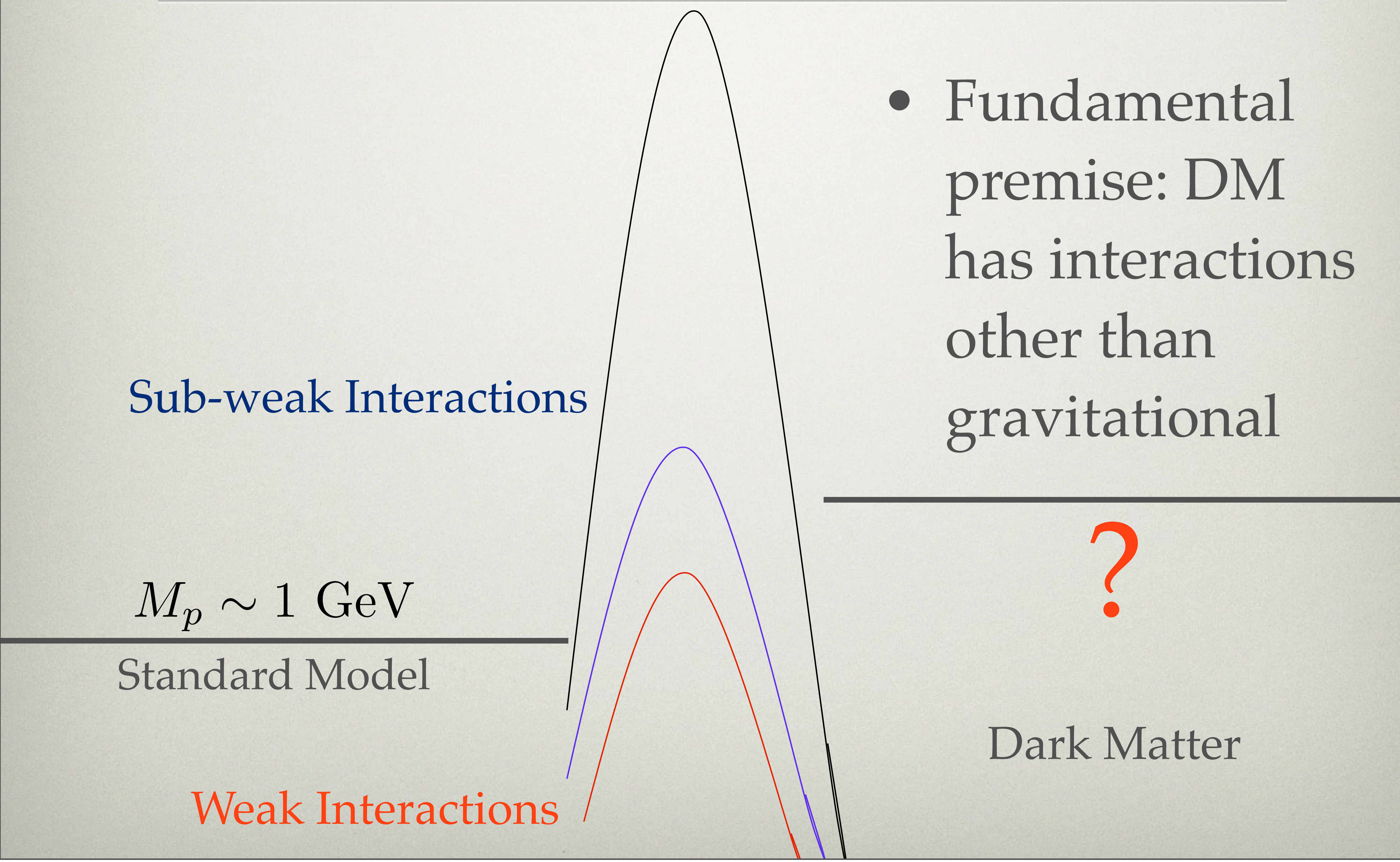


Cosmological Scales!

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

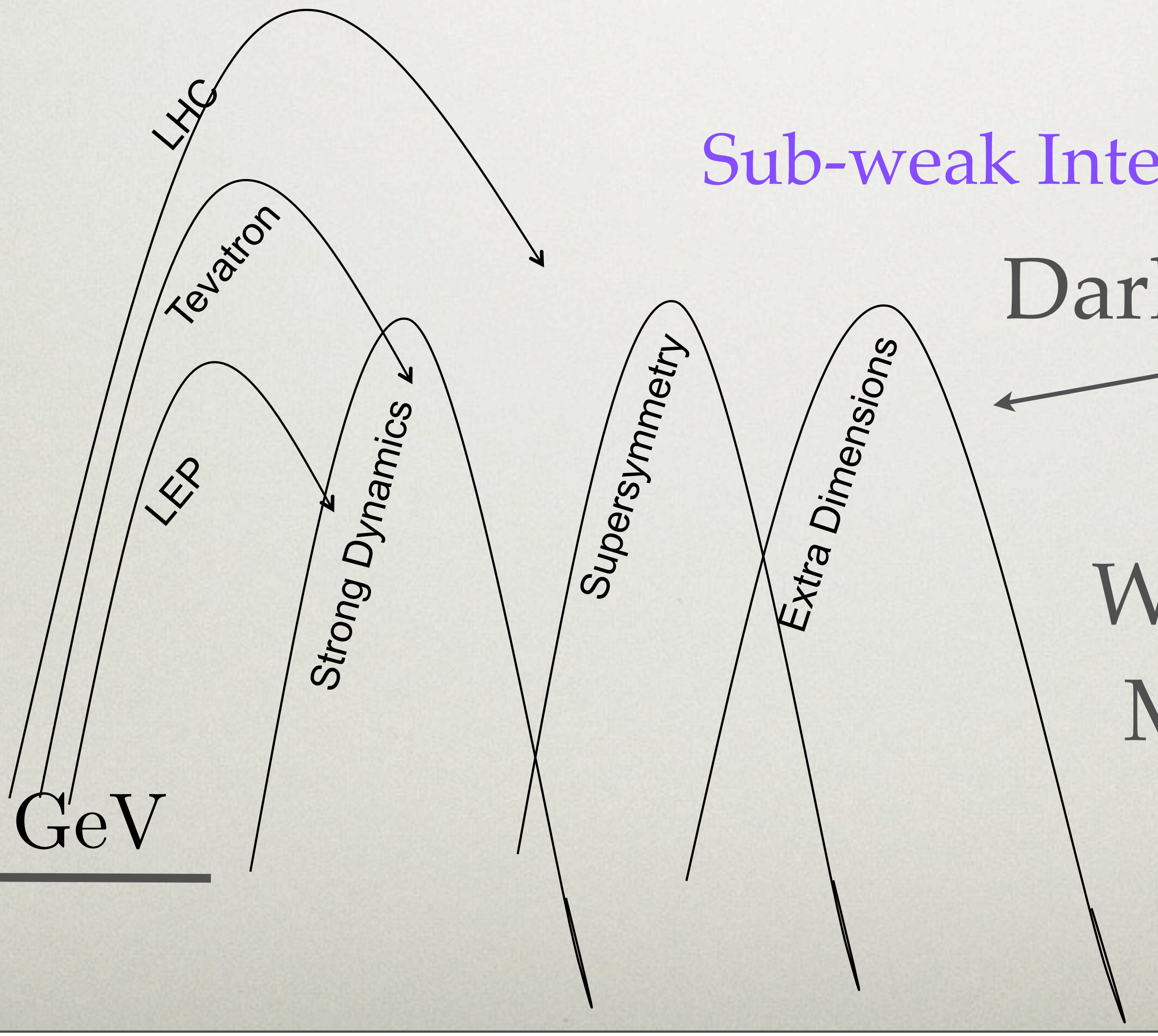
# Particle Physics Provides Some Ideas

- Fundamental premise: DM has interactions other than gravitational



# Particle Physics Provides Some Ideas

- Particle Physics Zoo!

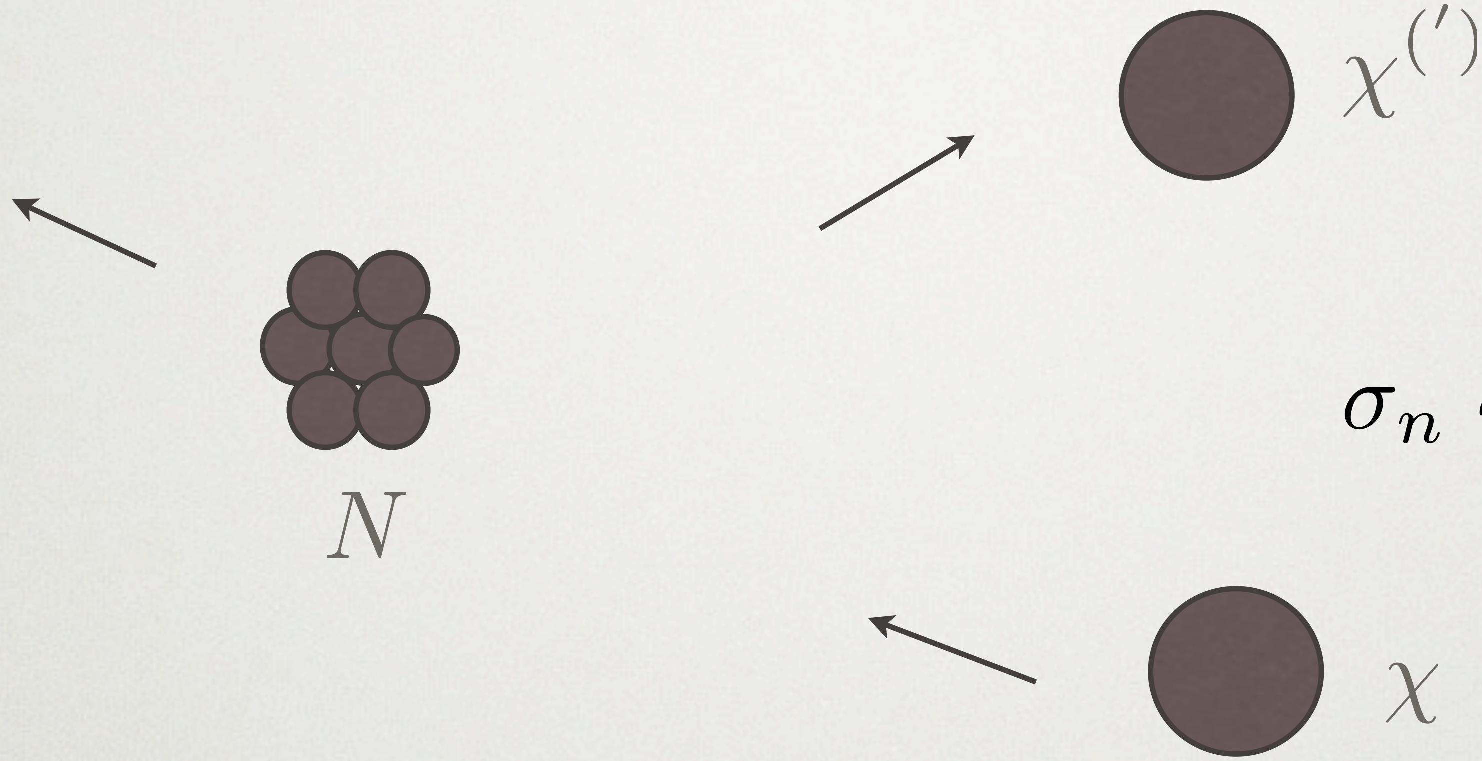



Dark Matter Resides Here!

$M_p \sim 1 \text{ GeV}$

Weakly Interacting Massive Particles (WIMPs)

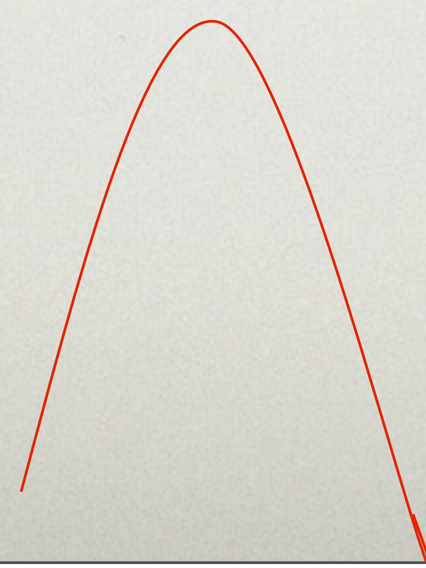
# Sub-Weakly Interacting Massive Particles




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

Weak interactions
Z boson

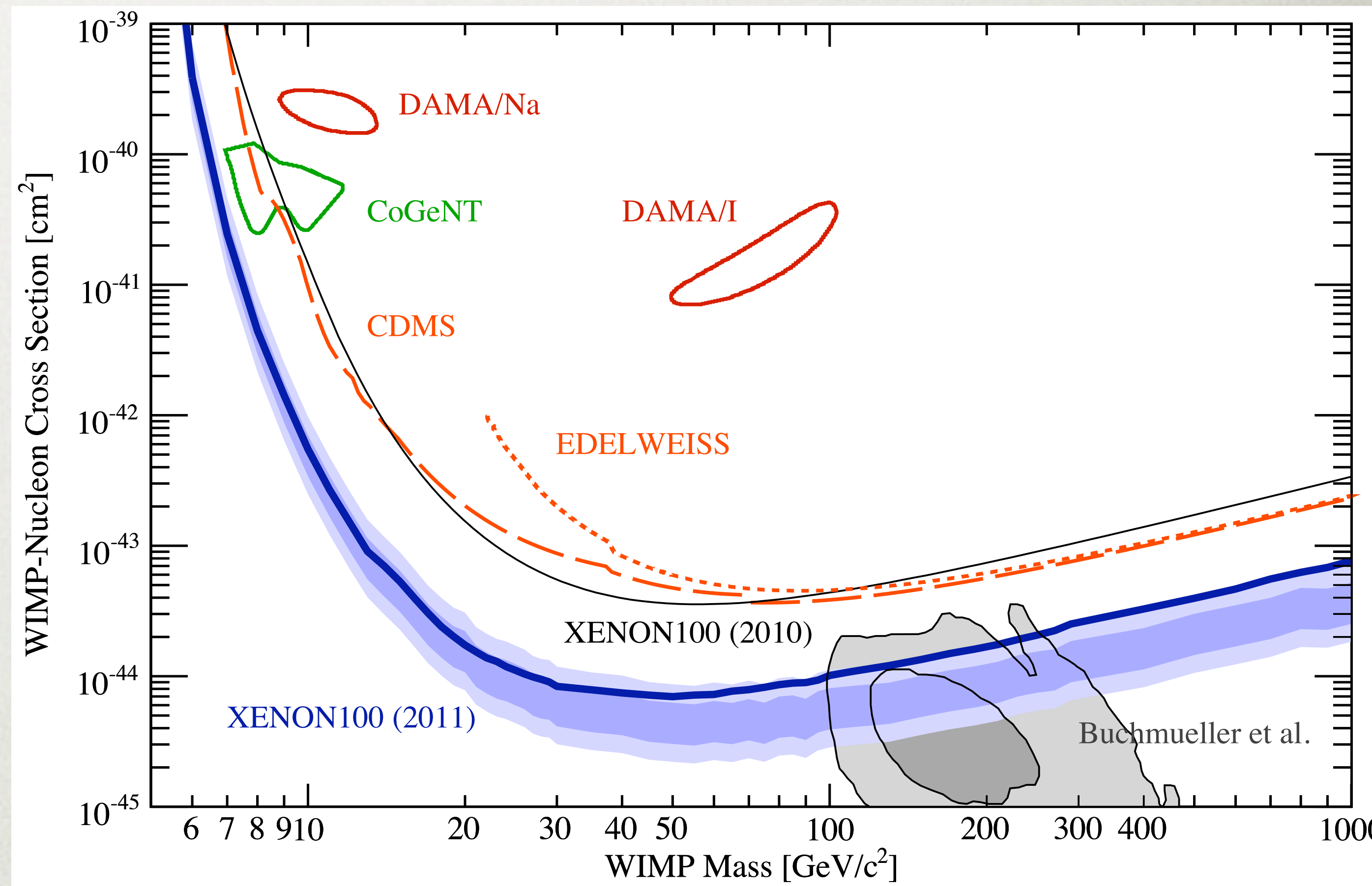
?



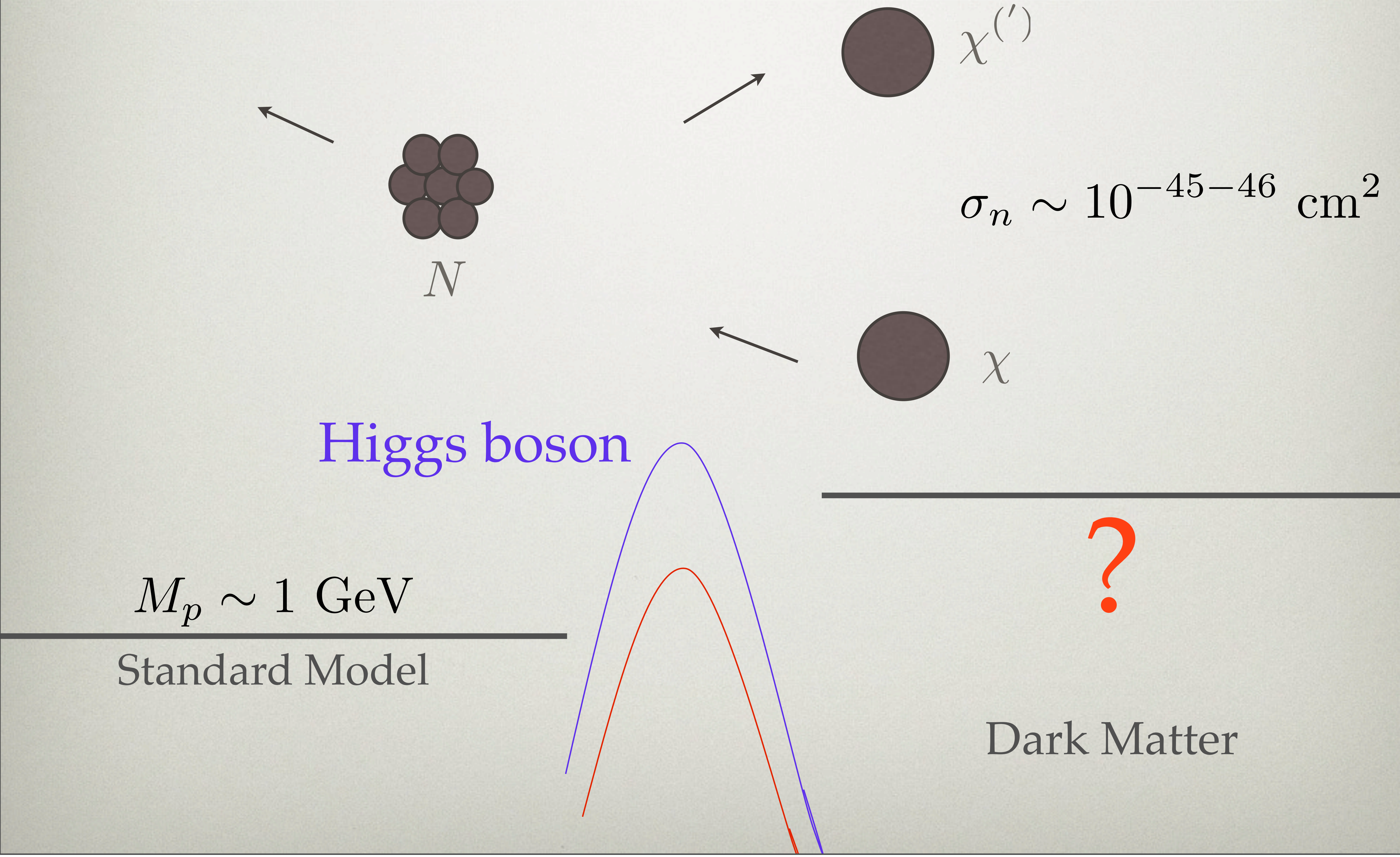
Standard Model

Dark Matter

# Sub-Weakly Interacting Massive Particles

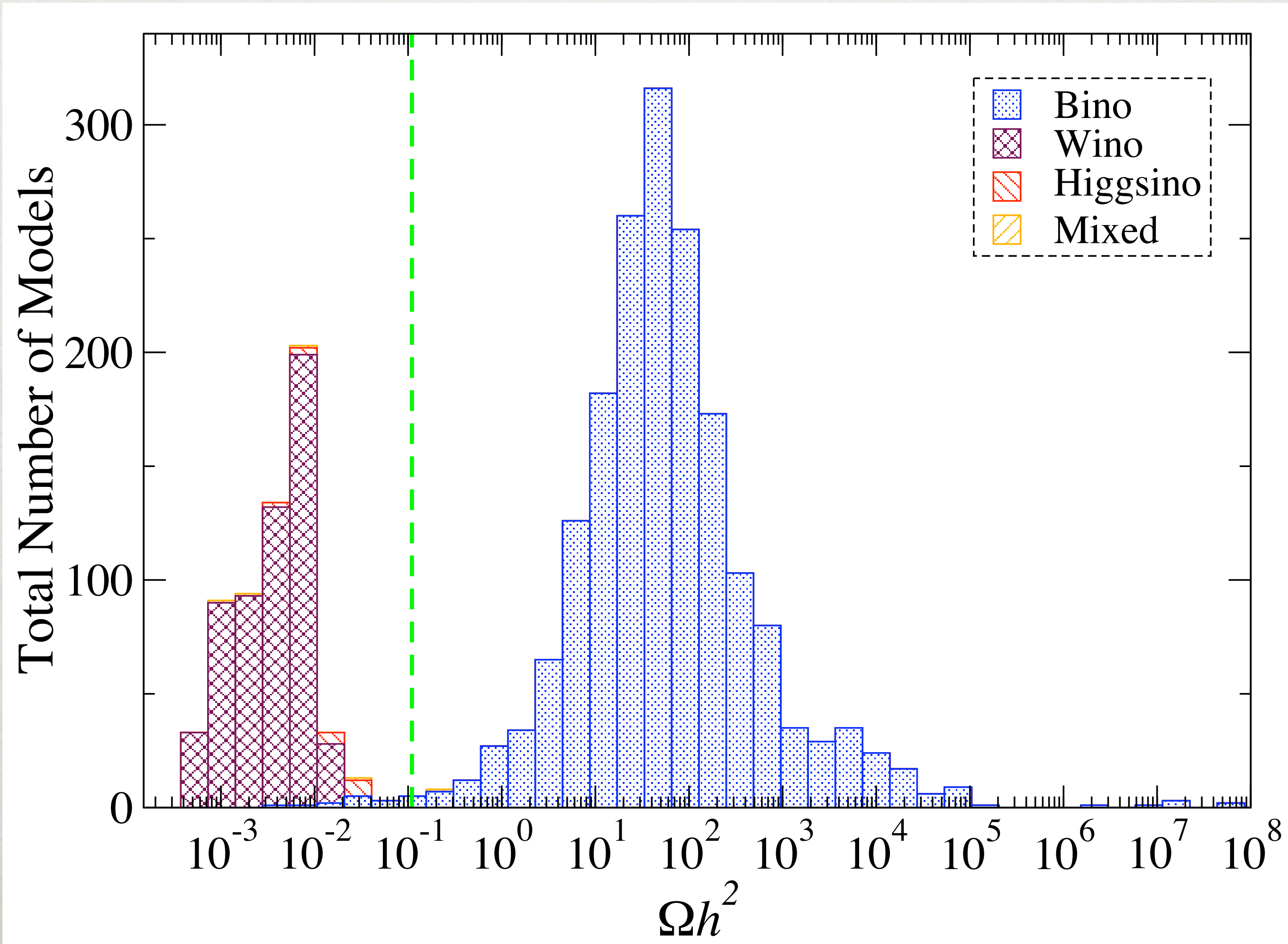


# Sub-Weakly Interacting Massive Particles



# Progress in Dark Matter

- "Generic" WIMP also doesn't give correct relic density

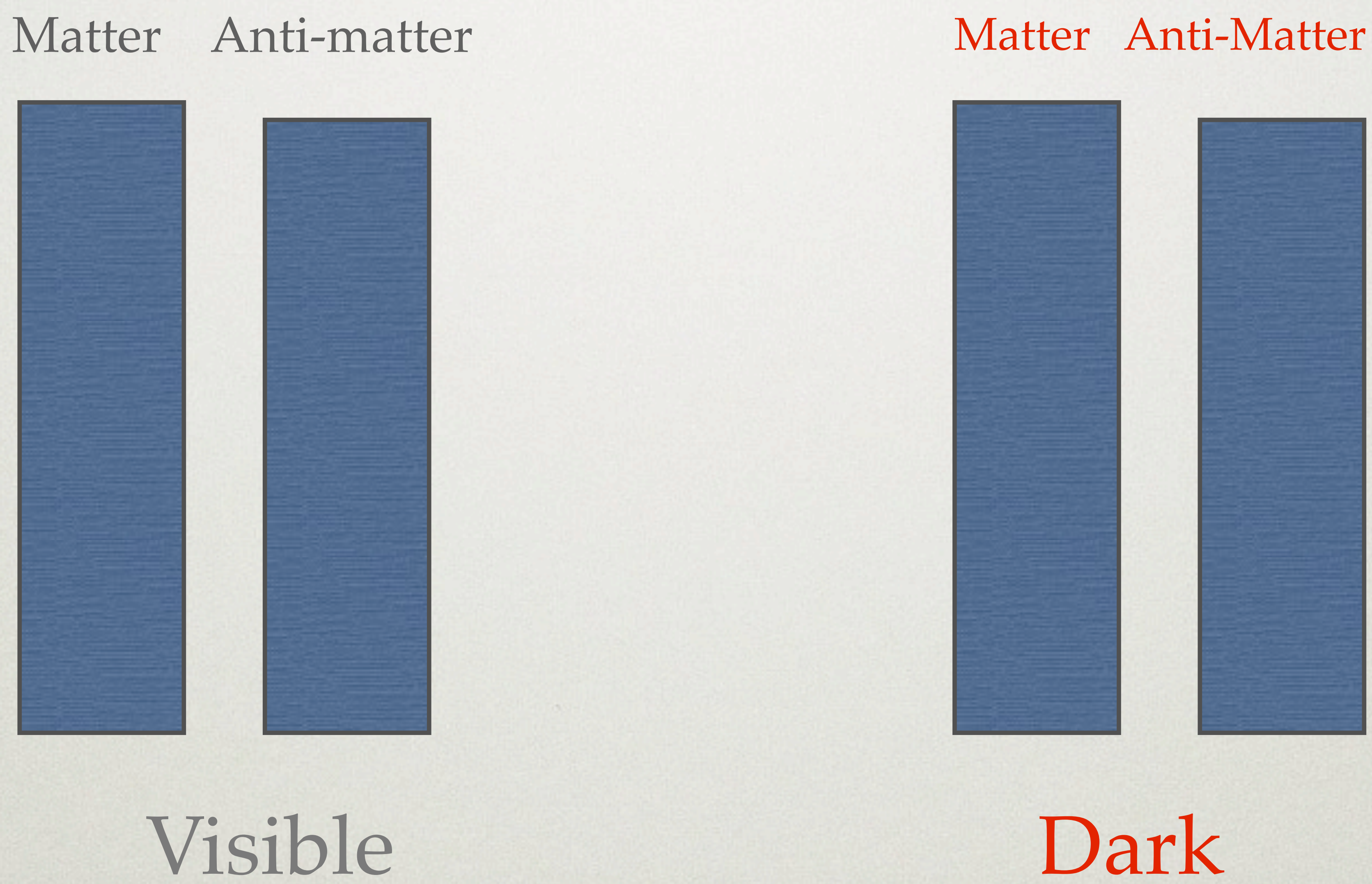



from a talk by H. Baer

# Theories of Dark Matter

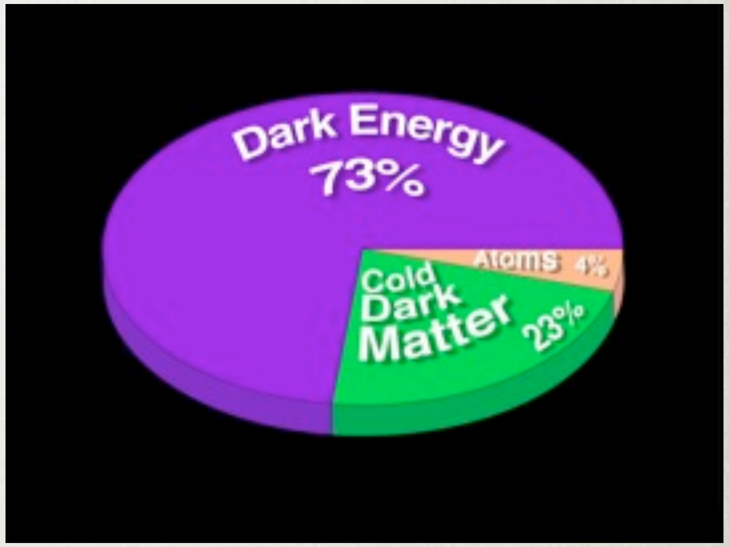
- Axions
  - Solve Strong CP
  - Correct density of high scale axions via selection
- WIMPs
  - Naturally obtain correct density via freeze-out
  - Connected to weak scale
- Chemical Potential Dark Matter
  - Naturally obtain correct density via chemical potential
  - Connected to weak scale

# 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 $n_{DM} \approx n_b$

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

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

# DM Mass Scales

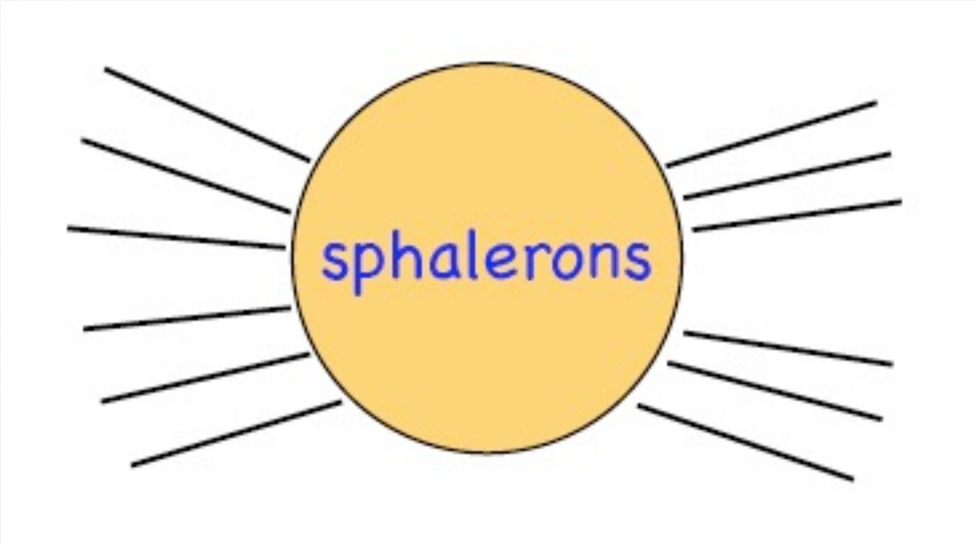
- DM can be heavier if DM number violating operators decouple late

$$n_X - n_{\bar{X}} \sim (n_b - n_{\bar{b}})e^{-m_{DM}/T_d}$$

- Extra Boltzmann suppression

# Technibaryon and Quirky dark matter

- Use sphalerons to transfer asymmetry

B, L  X

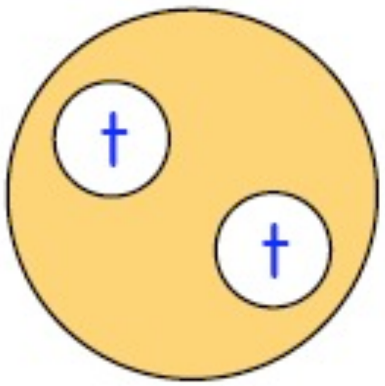


SU(2) carrying dark fields!

- First used in the context of technicolor, by Barr, Chivukula, Farhi; D. B. Kaplan
- Sphalerons mix SM fields carrying B,L with technifermions

# Technicolor and technibaryons

Barr, Chivukula, Farhi
Sannino et al
D.B. Kaplan




Technifermions transform under SM

Technibaryon is gauge singlet
(scalar or fermion)

TB number is accidental global symmetry,
completely analogous to baryon number.

- LEP, precision EW and Technicolor
- Self-interacting Dark Matter constraints
- Struggle to obtain correct relic density

# A simple prescription: Asymmetric DM

Luty, Kaplan, KZ '09

- Avoids the pitfalls of models which have their asymmetry related to the baryon asymmetry via standard model quantum numbers
- Essential idea is to use higher dimension operators to transfer the asymmetry between sectors

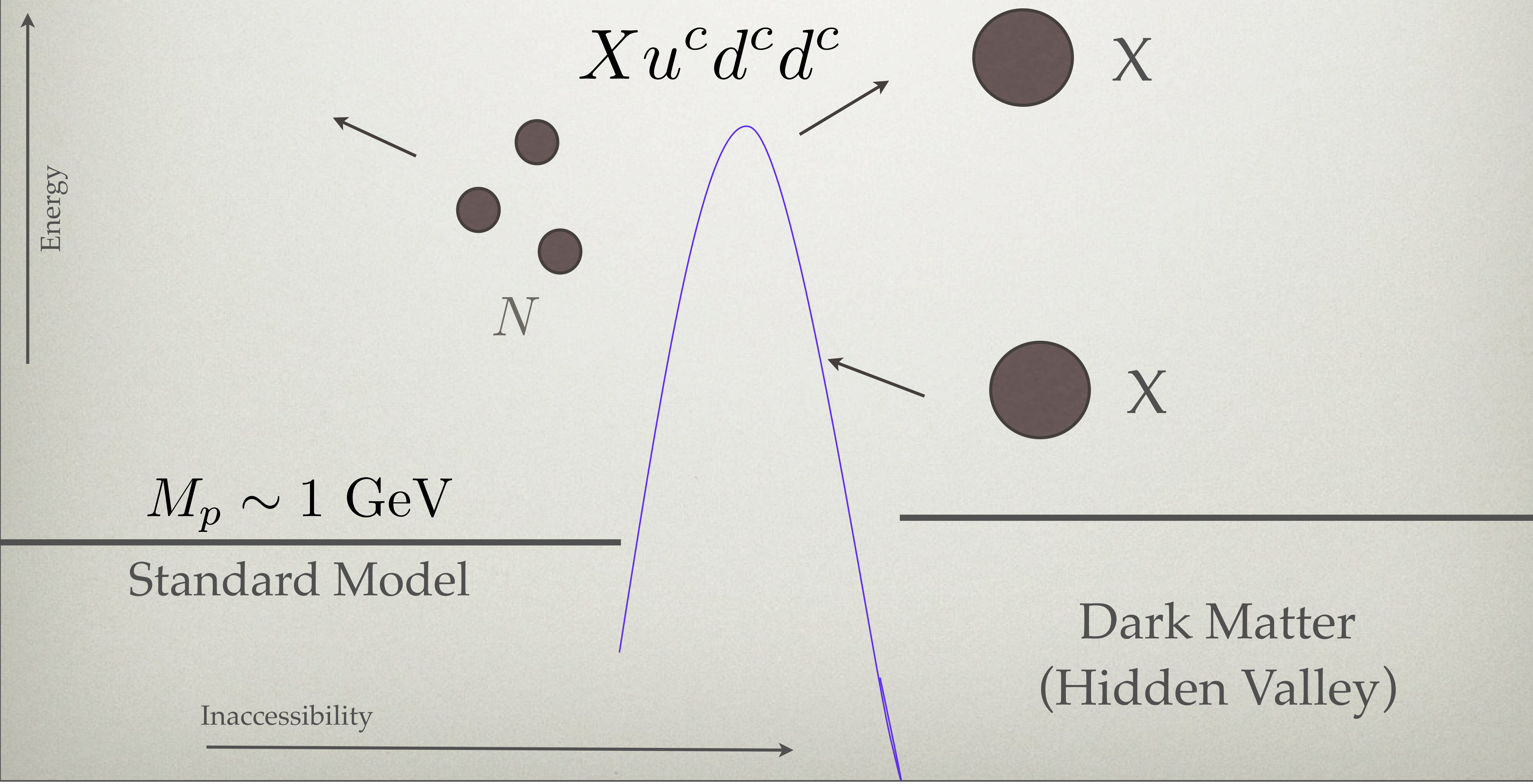
# Asymmetric DM

Integrate out heavy state

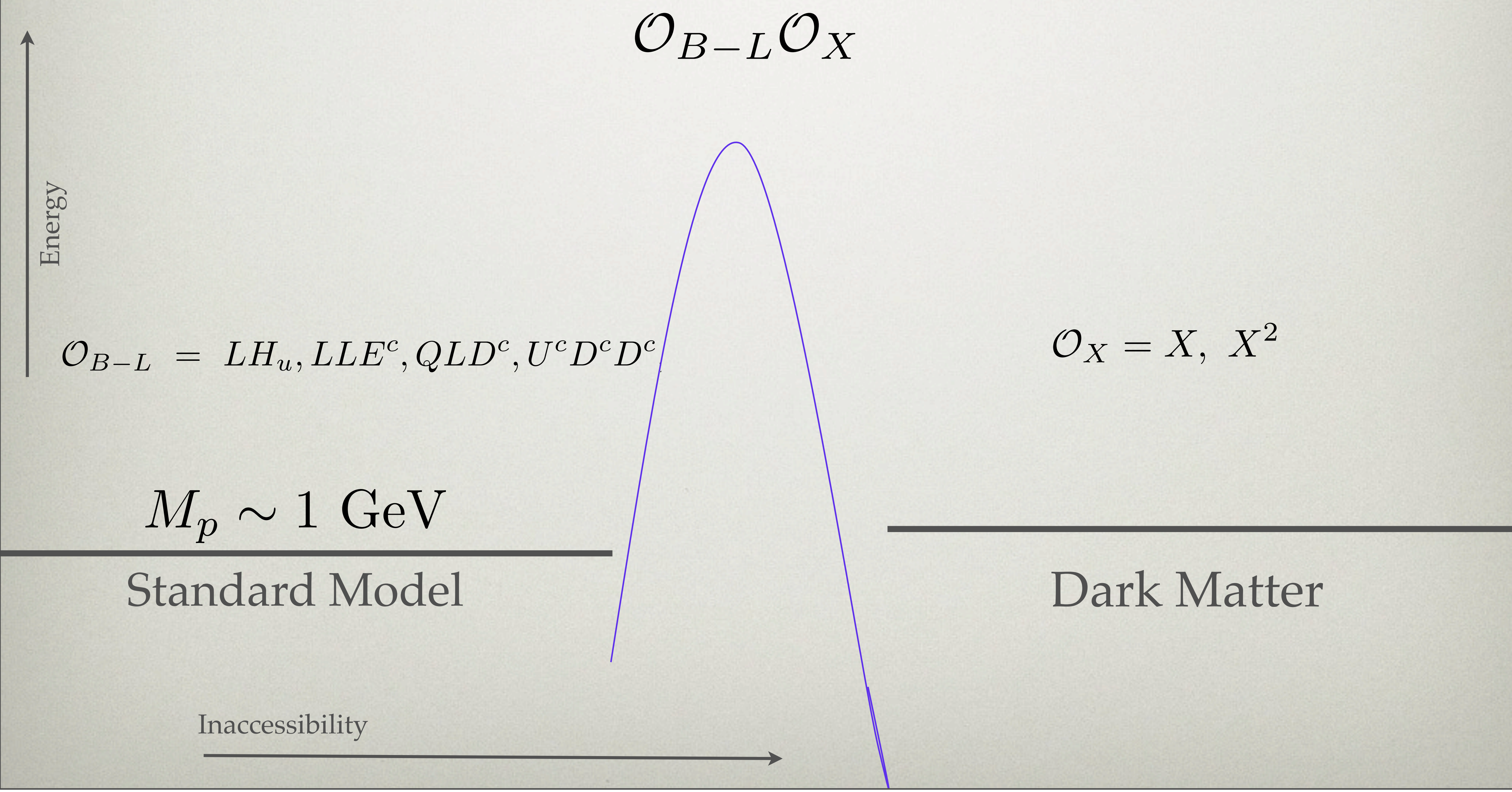
Effective operators:

Luty, Kaplan, KZ ’09

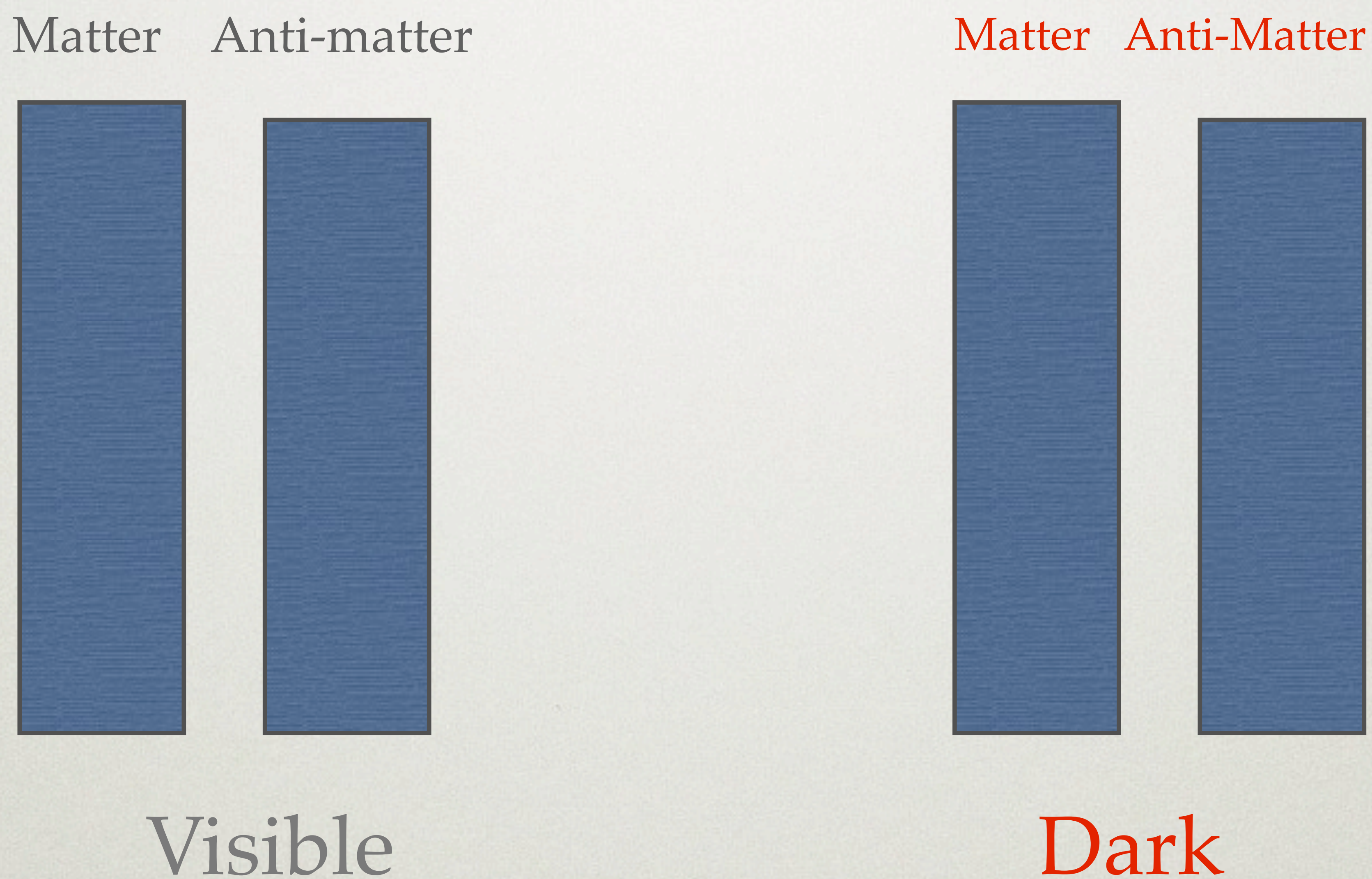
$$X u^c d^c d^c$$



# Asymmetric DM

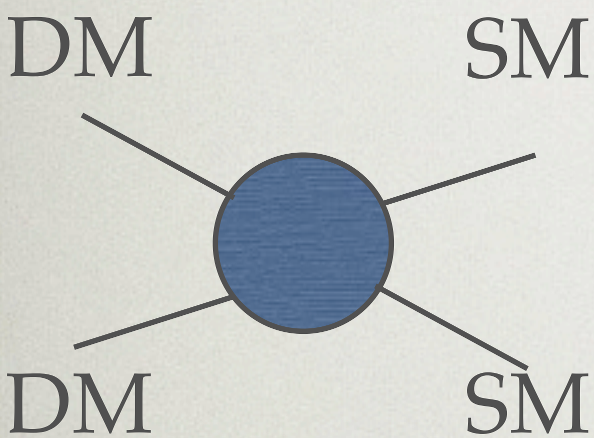


# Asymmetric Dark Matter

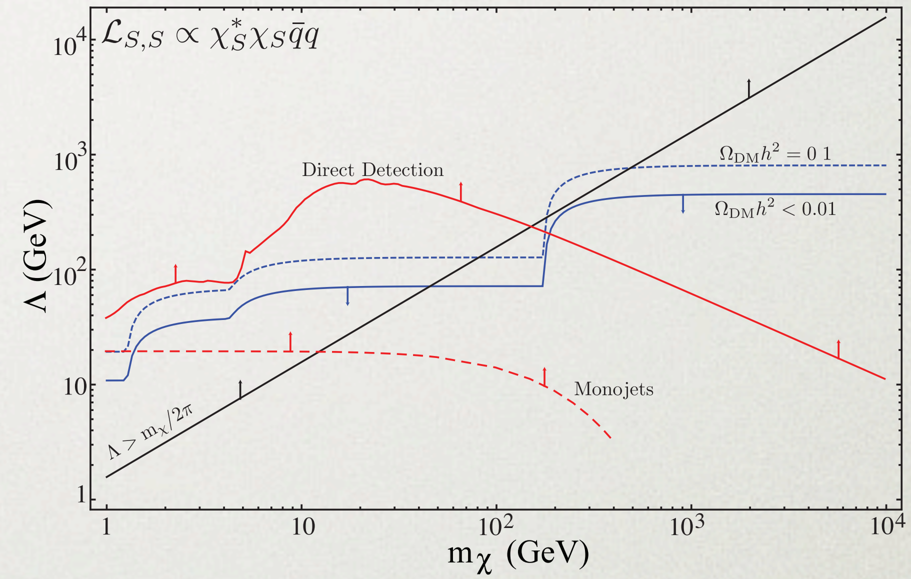


# Annihilating thermal abundance

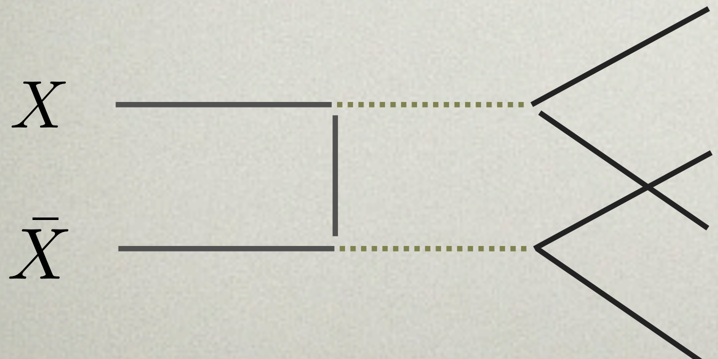
$$n_{DM} \sim T^3 \rightarrow 10^{-10} T^3$$




Buckley



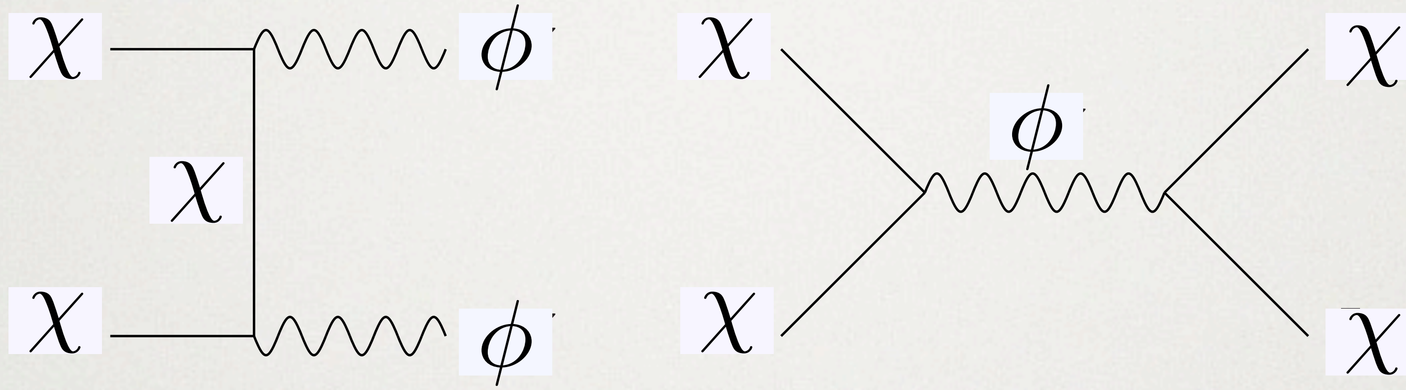

Robust alternative: annihilate to light states!




$$\Delta W = \lambda_X S X \bar{X} + \lambda_H S H_u H_d + \frac{\kappa}{3} S^3.$$

$$\Delta \mathcal{L}_{\rm eff} = m_X \bar{X} X e^{ia/s} + {\rm h.c.},$$

# Dark Forces and DM Self-Interactions




- Dark Forces Natural for ADM
- Structure problems and dark forces
- Very big scattering cross-sections!

$$\sigma/m_X \sim 0.1\ \mathrm{cm}^2/\mathrm{g} \simeq 0.2 \times 10^{-24}\ \mathrm{cm}^2/\ \mathrm{GeV}$$

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

# Is CDM and Halo Structure a Problem?

- Halo substructure: satellite galaxies and sub-halos -- more satellites found
- Halo cores and central densities
- Feedback? Governato et al '10
- In dwarves hard to understand how so little stellar feedback could blow out so much material: $M_* \sim 10^6 M_\odot$ blows out $5 \times 10^7 M_\odot$

Bolyan-Kolchin et al '11 "Too Big to Fail"

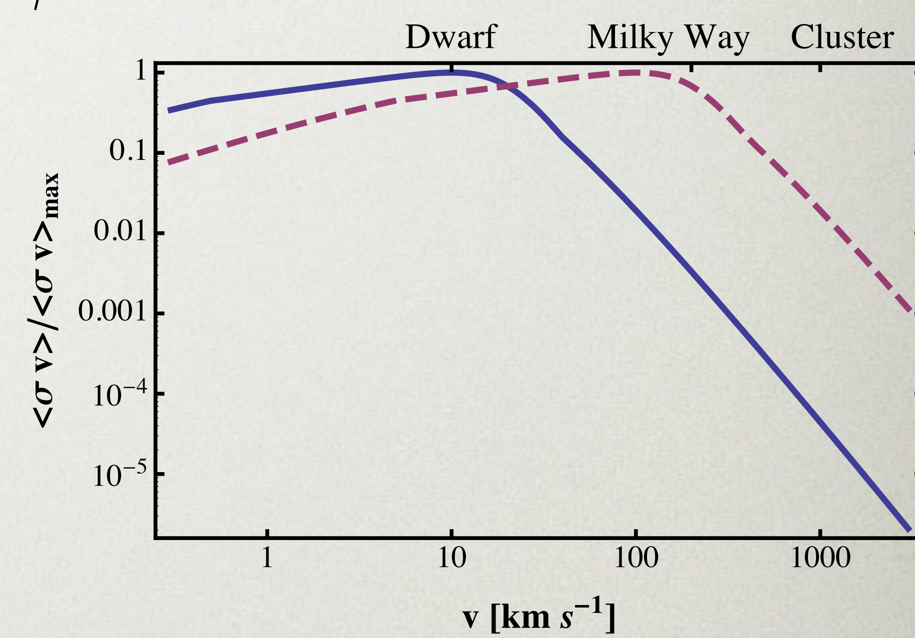
# Scattering Not Generically Constant

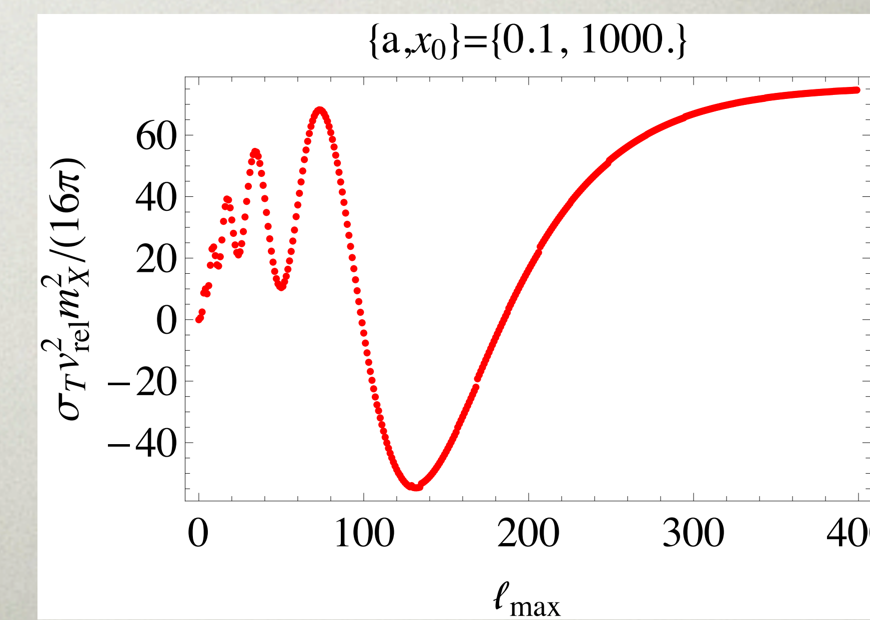
- Quantum $\sigma \sim \dfrac{m_X^2}{(m_X^2 v^2 + m_\phi^2)^2}$
- Classical $\sigma \sim \dfrac{\pi \ln \beta}{m_\phi^2}$
- Resonant -- Born approx breaks down

$$\beta = 2\alpha_X m_\phi / m_X v^2$$

- Many modes contribute -- fairly intensive

Loeb, Weiner '10

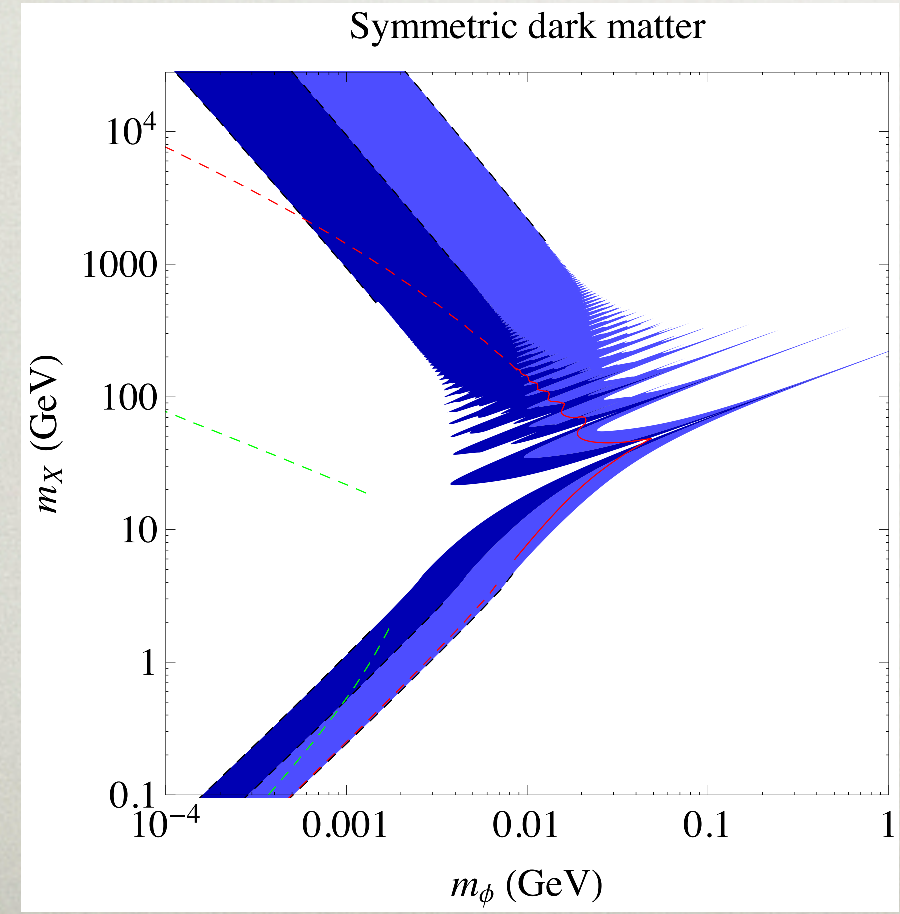


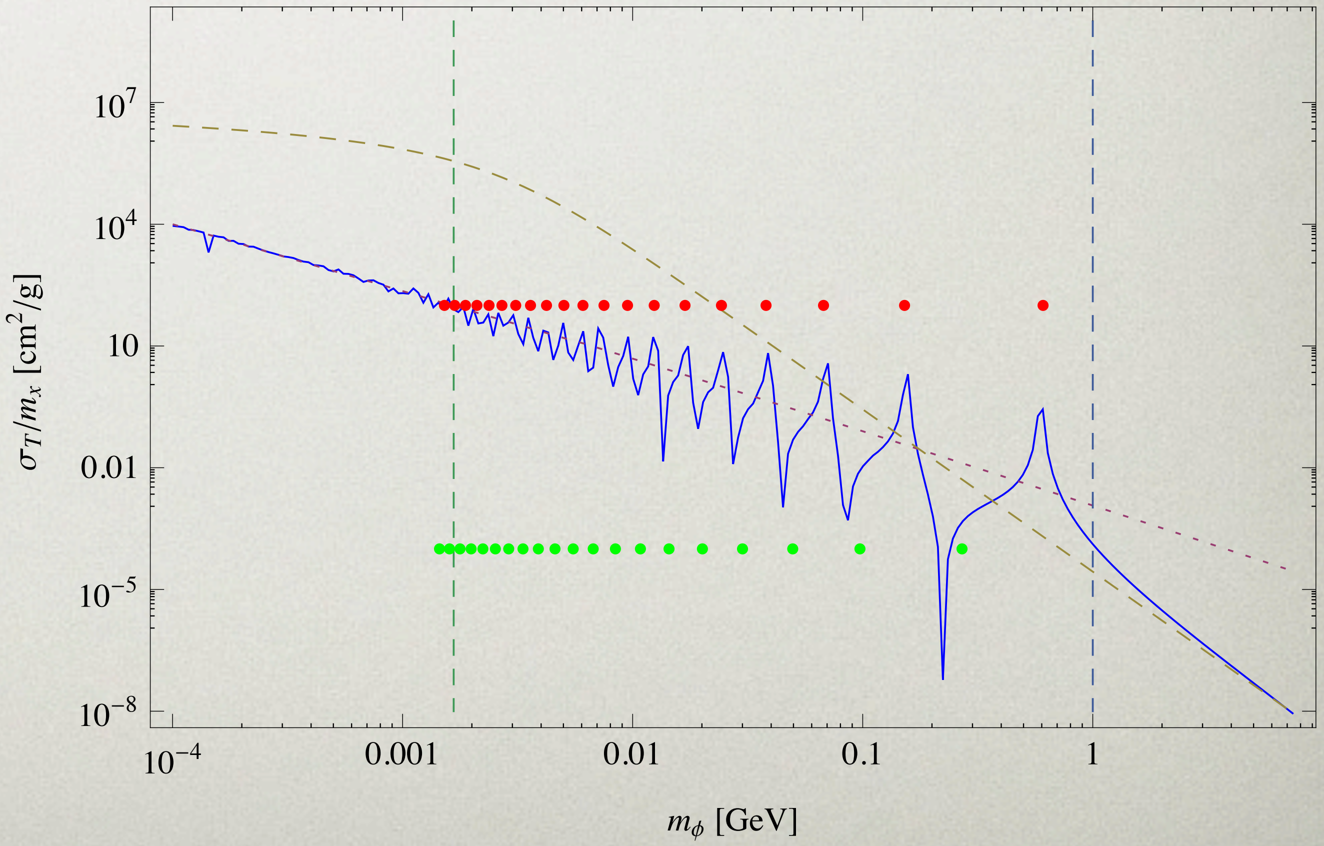



# Resonant Dark Forces and Structure

Tulin, Yu, KZ, in progress

- Verify classical result numerically and presence of Sommerfeld-like effect for scattering



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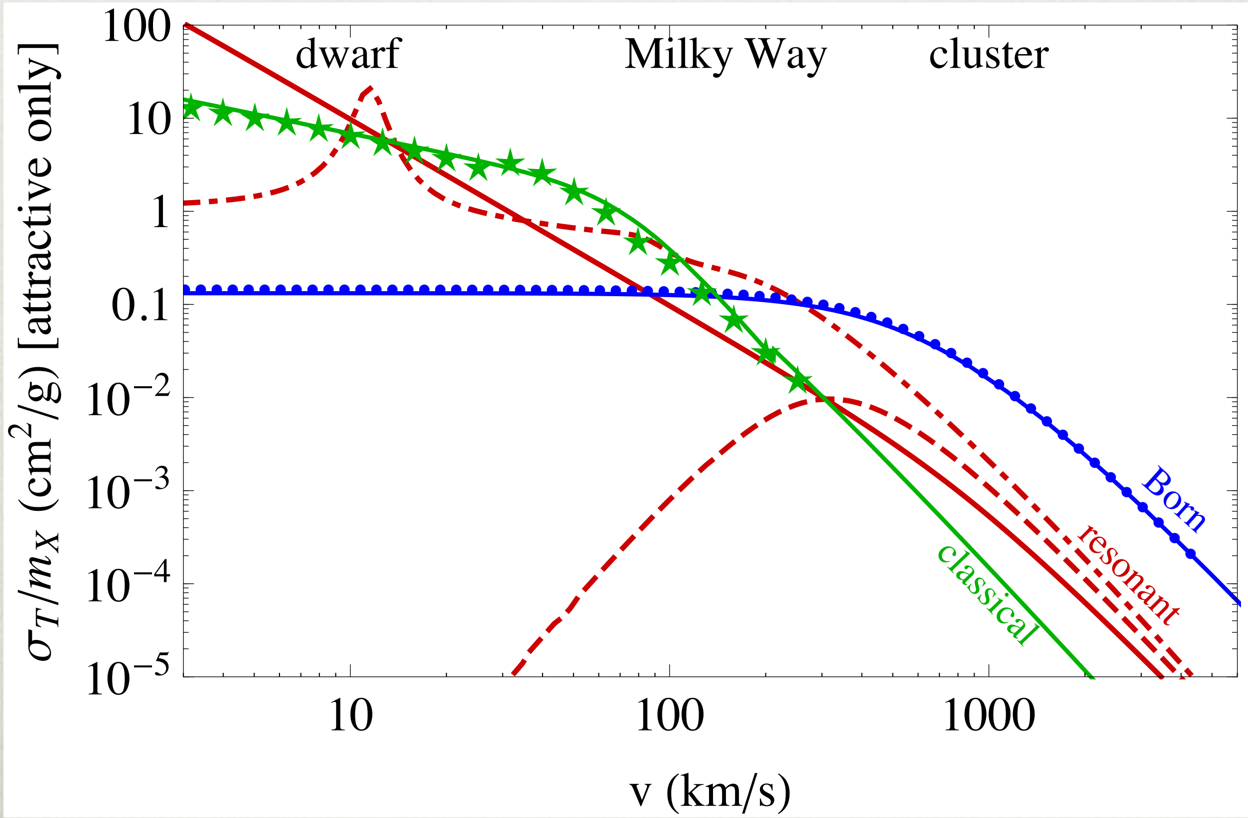
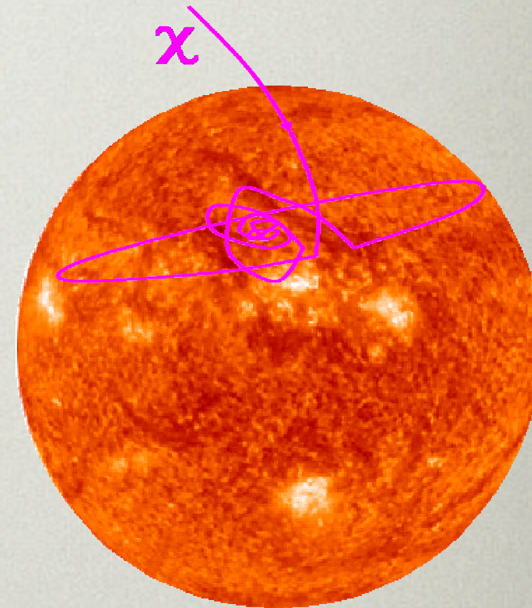


# Astrophysical Implications

McDermott, Yu, KZ '11

- 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!



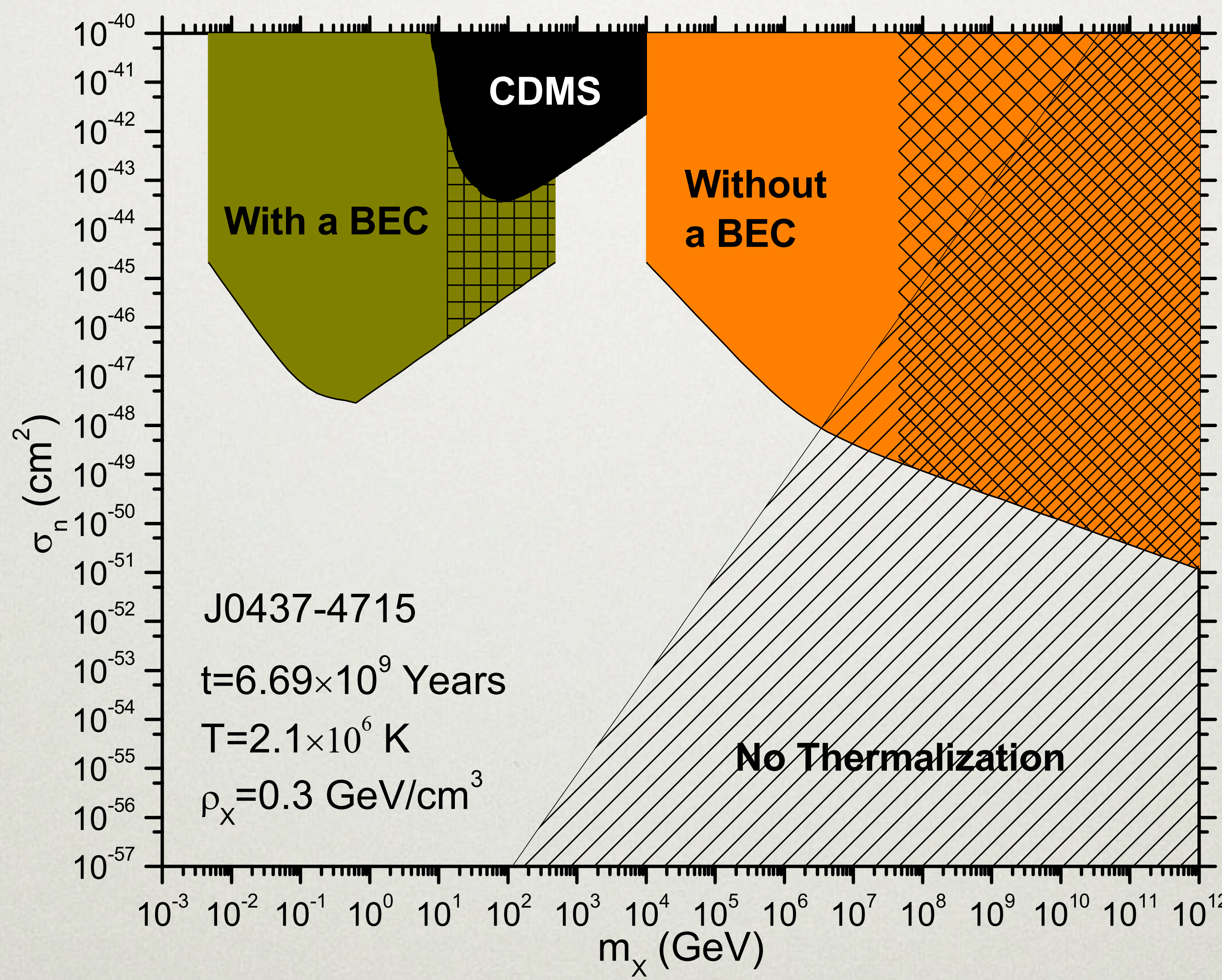
# ADM, Black Hole and Neutron Stars

McDermott, Yu, KZ '11

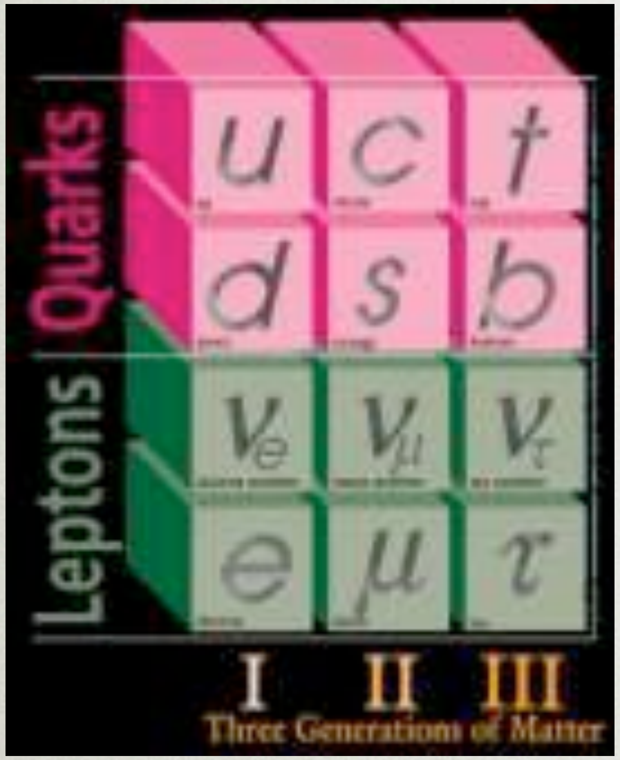
- Scalar case can lead to BH formation
- DM continues to accumulate until there are enough that they self-gravitate
- OR, they first form Bose-Einstein condensate and then self-gravitate
- Once they self-gravitate, they can collapse to form a BH!

# ADM, Black Hole and Neutron Stars

McDermott, Yu, KZ, '11



# New Avenues for Baryogenesis





Need Baryon violation and CP violation beyond what is currently observed in experiments

# Generating an Asymmetry

- Original ADM scenario assumed an asymmetry was generated and then transferred
- Higher dimension operators make a natural playing field for Affleck-Dine Cogenesis = *simultaneous generation of asymmetries* Cheung, KZ '11

Bell, Petraki, Shoemaker, Volkas '11

# Cogenesis -- Natural for ADM!

$\mathcal{O}_{B-L} = LH_u, LLE^c, QLD^c, U^cD^cD^c$  $\mathcal{O}_X = X,\ X^2$

$$\mathcal{O}_{B-L}\mathcal{O}_X$$

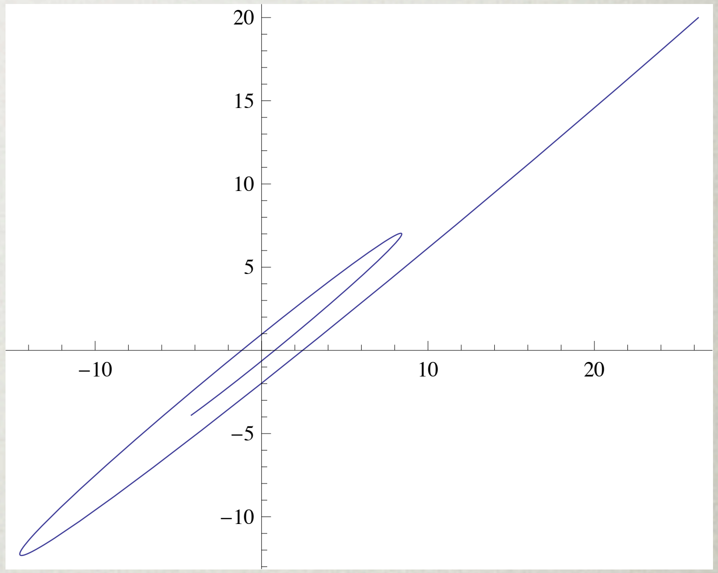
- Affleck-Dine works by utilizing flat directions with non-zero <B-L>
- Note there is a symmetry $U(1)_{B-L+X}$ which generates $-n_{B-L} = n_X \neq 0$.
- At low temperature, symmetry breaks when $\mathcal{O}_{B-L}\mathcal{O}_X$ decouples, separately freezing in the asymmetries

Cheung, KZ '11

$$U(1)_{B-L+X} \rightarrow U(1)_{B-L} \times U(1)_X$$

# Cogenesis in the Early Universe

- To see how it works, map to simple mechanical analog: pseudo-particle in 2-dimensions



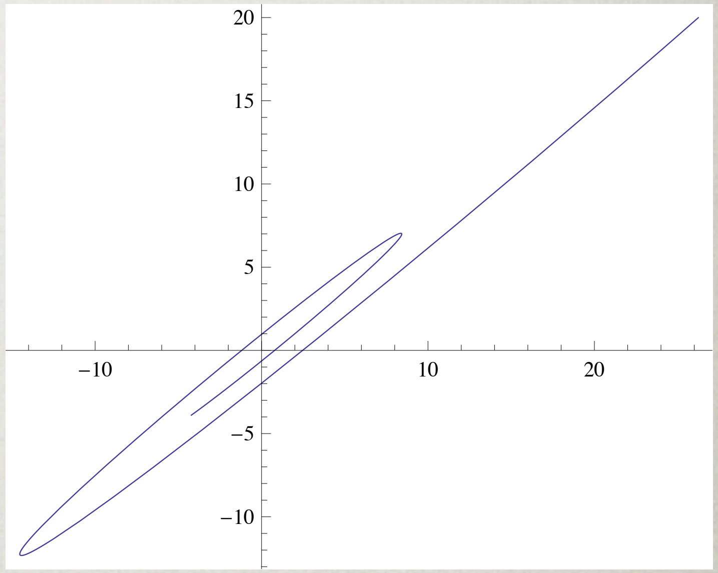

$$\phi = \frac{1}{\sqrt{2}} r_\phi e^{i\theta_\phi}$$

$$n_\phi = j^0 = i(\phi\dot{\phi}^\dagger - \phi^\dagger\dot{\phi}) = r_\phi^2\dot{\theta}_\phi$$

- B-L and X asymmetry: torque on mechanical analog

# Cogenesis in the Early Universe

- Two ingredients for successful Affleck-Dine Cogenesis
  - Stabilization: non-zero B-L and X vevs
  - Torque: non-zero angular momentum



# 2. Torque

- The torque is exerted when fm = gH

$$V_{\rm soft} \supset (fm + gH)\frac{\mathcal{O}_{B-L}\mathcal{O}_X}{M^{d-4}}$$

- Claim is that $-n_{B-L} = n_X \neq 0.$
- Easily seen from Lagrangian

$$\mathcal{L} = \frac{1}{2}(r_{B-L}^2\dot{\theta}_{B-L}^2 + r_X^2\dot{\theta}_X^2) - V(\theta_{B-L} - \theta_X)$$

Note $\theta_+$ conserved!

$$\theta_{\pm} = \theta_{B-L} \pm \theta_X$$

# 2. Torque

- Calculable asymmetry, using impulse approximation

$$\frac{d}{dt}\frac{\partial\mathcal{L}}{\partial\dot{\theta}_-} = \frac{d}{dt}\left(n_{B-L} - n_X\right) = -\frac{\partial V}{\partial\theta_-}$$

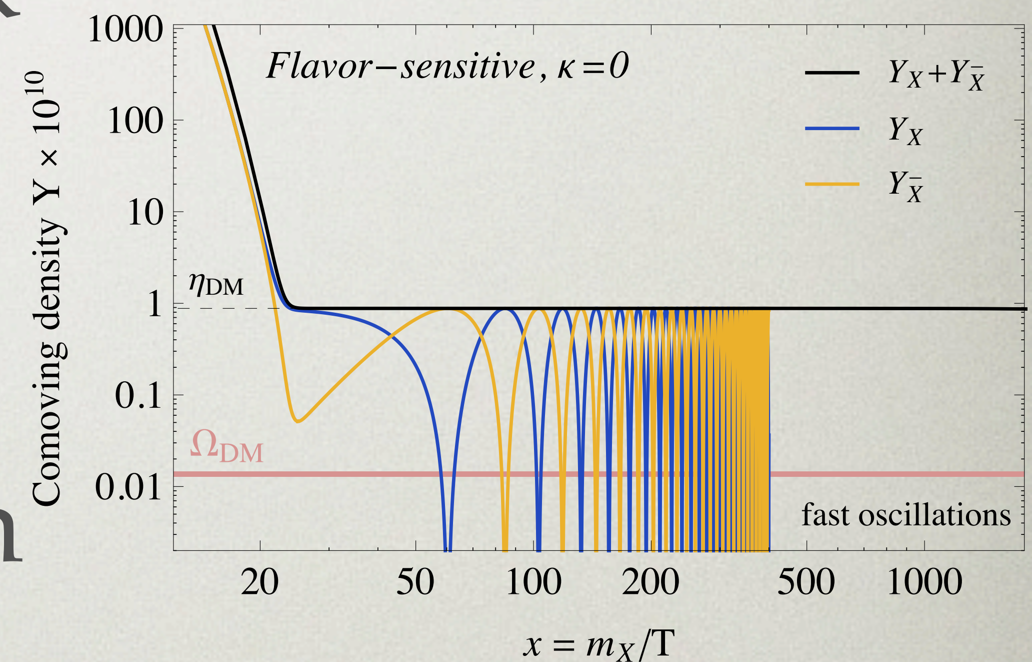
Impulse approximation; evaluate at:

$$V_{\text{soft}} \supset (fm + gH)\frac{\mathcal{O}_{B-L}\mathcal{O}_X}{M^{d-4}} \qquad H \sim fm/g.$$

$$-\,n_{B-L} = n_X \sim \frac{\arg(f/g)\,g\,|\mathcal{O}_{B-L}|\,|\mathcal{O}_X|}{M^{d-4}}$$

# Oscillating ADM

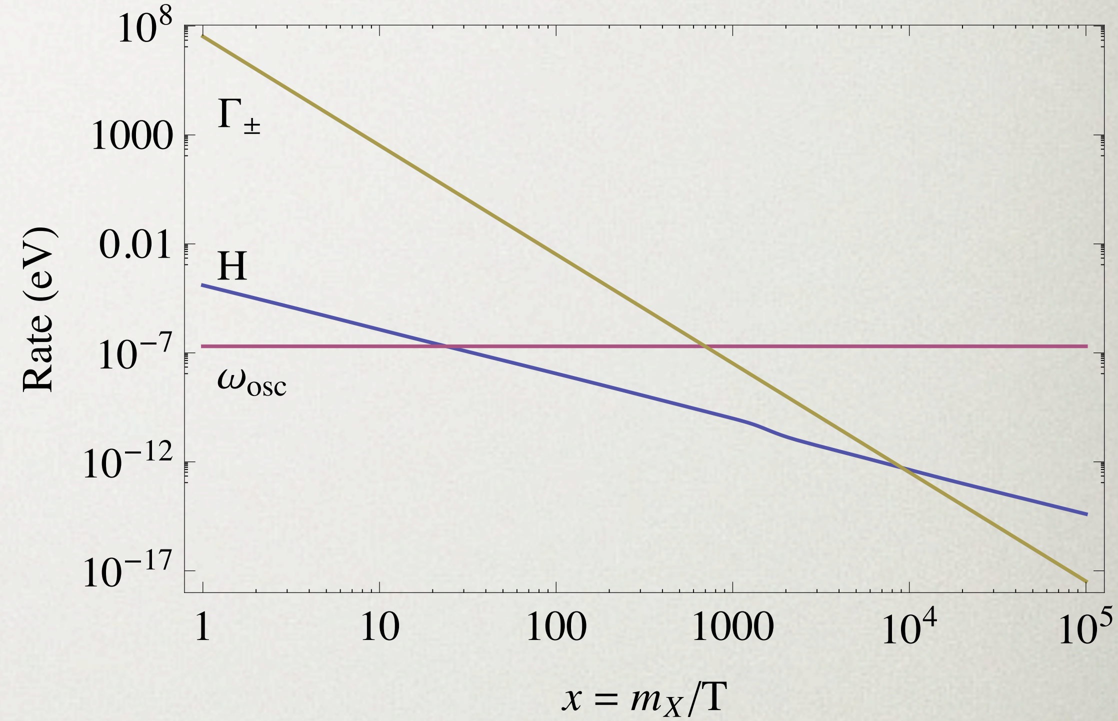
- Asymmetry may be erased
- Any violation of DM number can lead to dark-anti-dark oscillations
- Like $\nu$ oscillations
- Become important when mass exceeds Hubble expansion

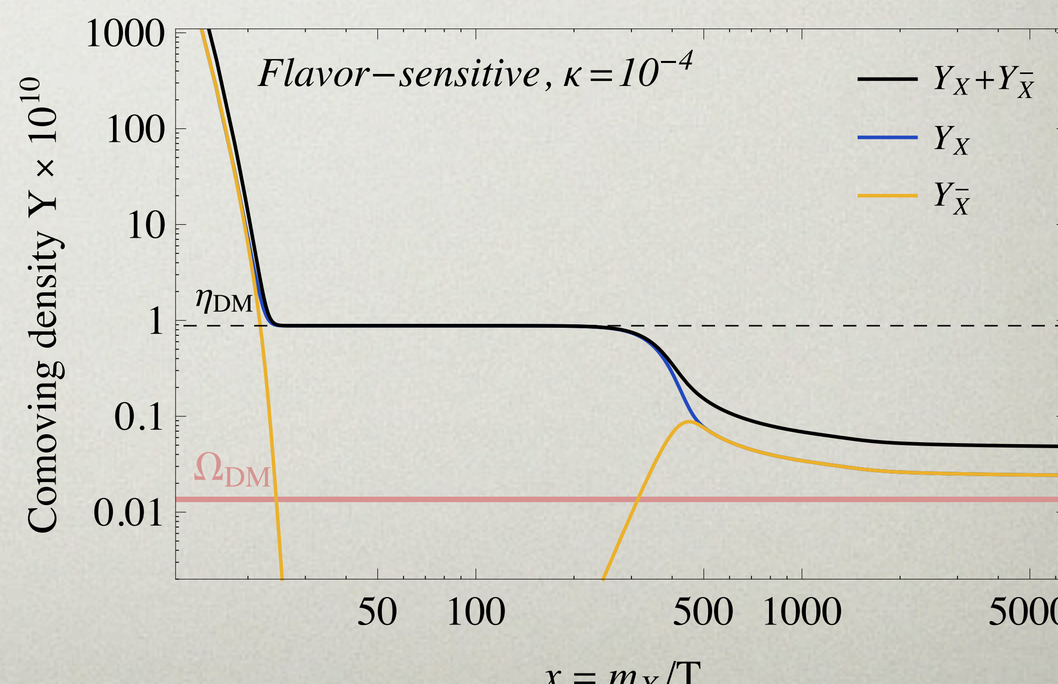



Cohen, KZ ’09
Falkowski, Rudermann, Volansky ’10
Buckley, Profumo ’11
Cirelli, Panci, Servant, Zaharijas ’11
Tulin, Yu, KZ, ’12

# Numerical Results

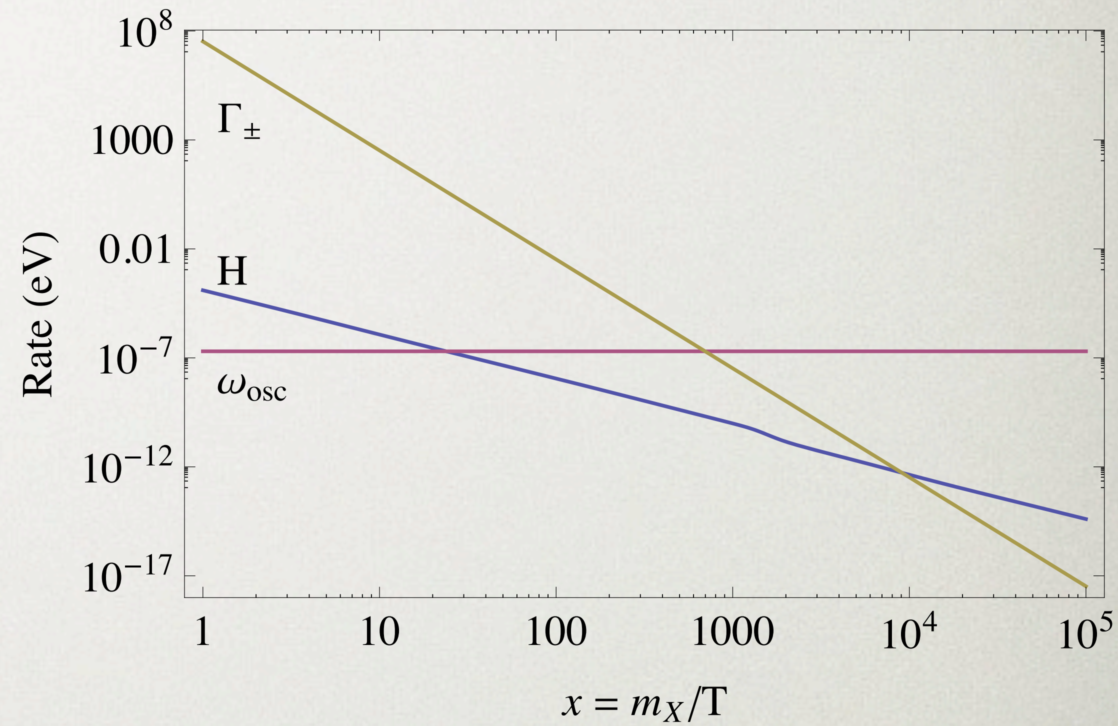
- Vector interactions
- Quantum Zeno prevents oscillation
- Scattering causes de-coherence and washout
- Washout when oscillations commence

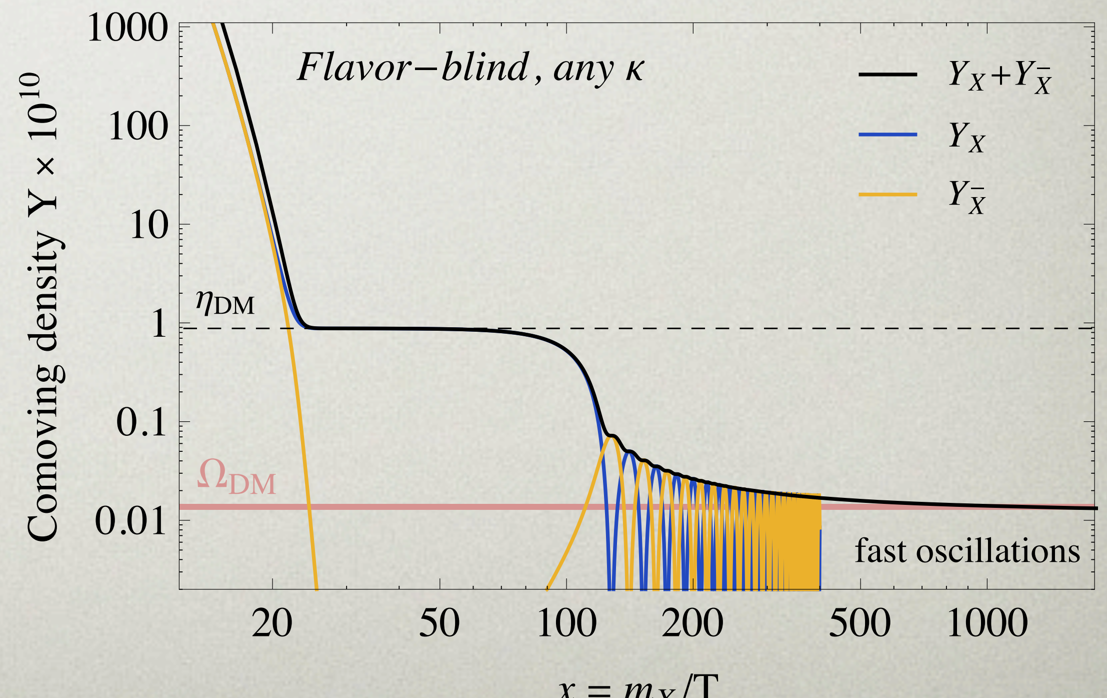


# Numerical Results

- Scalar interactions
- Oscillations turn on
- Depletion continues as soon as oscillations commence



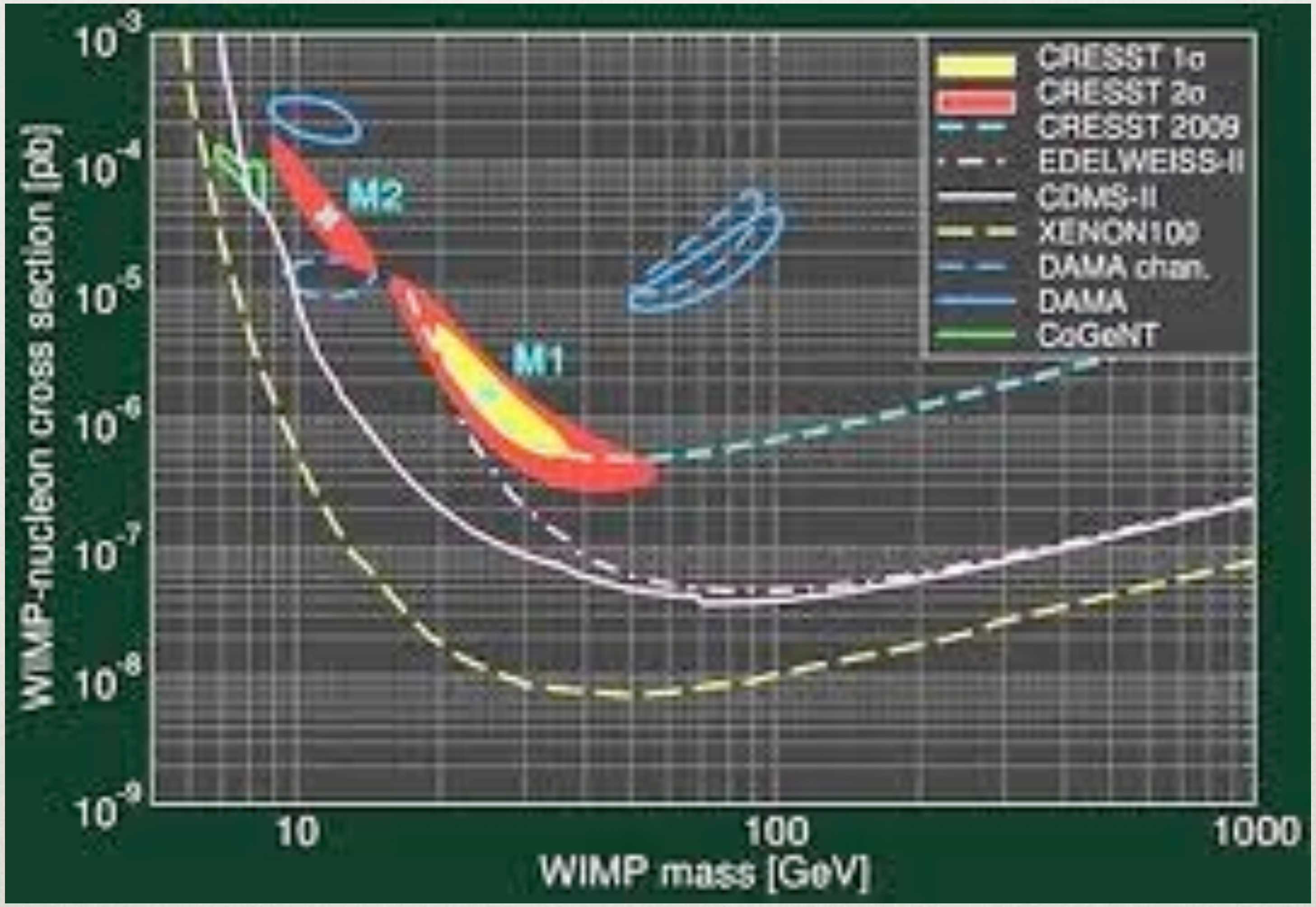



# Why is it Important to Think About New Models?

Lamp post problem:
Experimental results have forced us to look outside the lamp post

# 1. Direct Detection

CRESST 2011

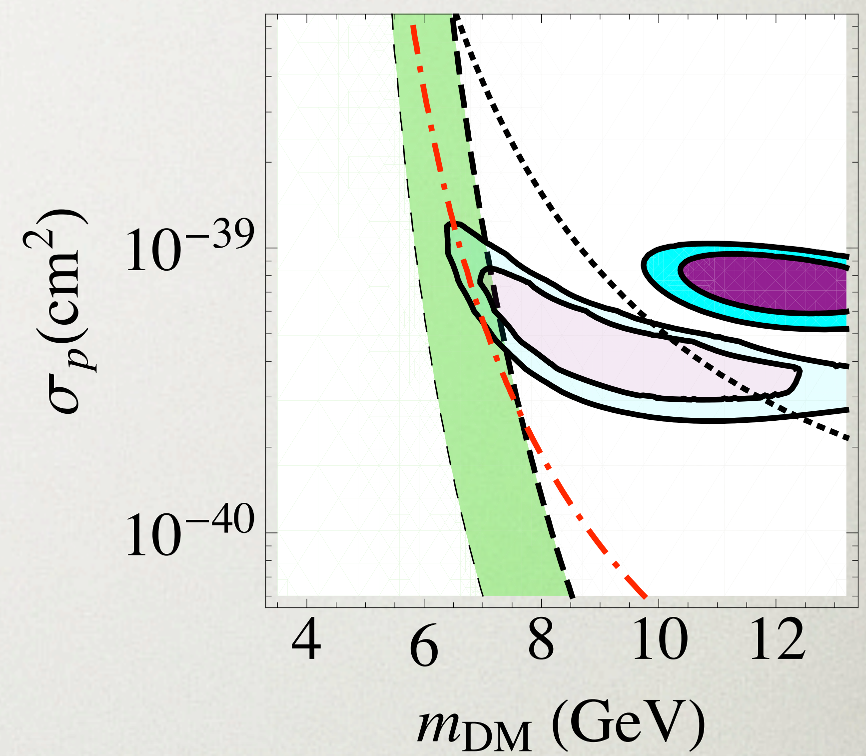



DAMA
CoGeNT
CRESST

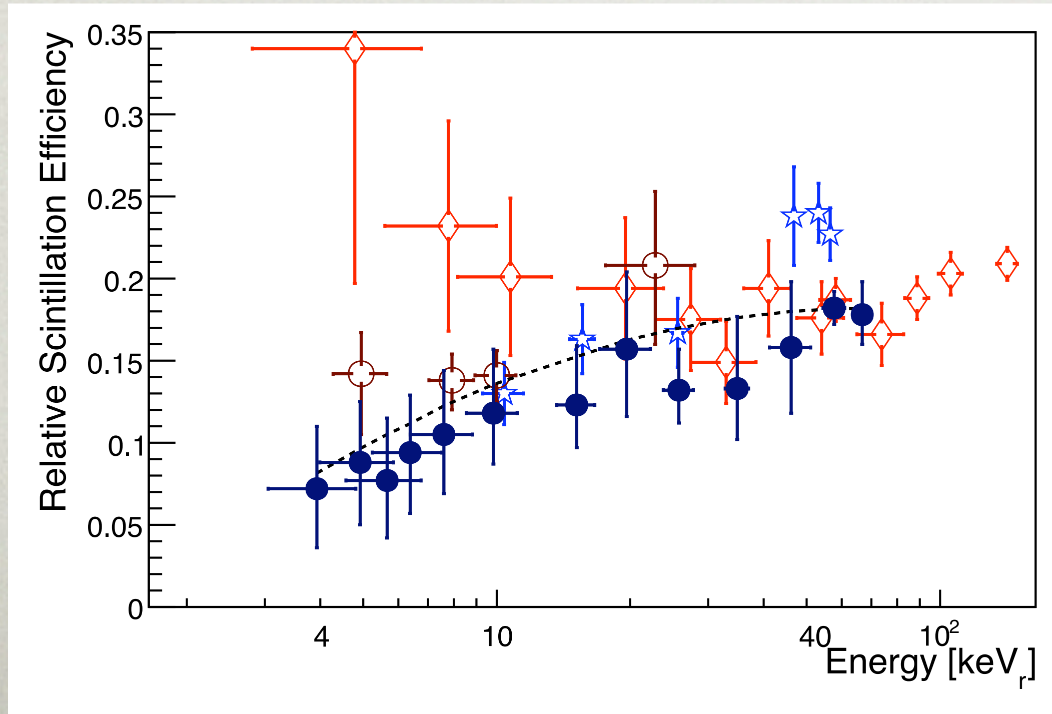
# All complicated by uncertainties ...

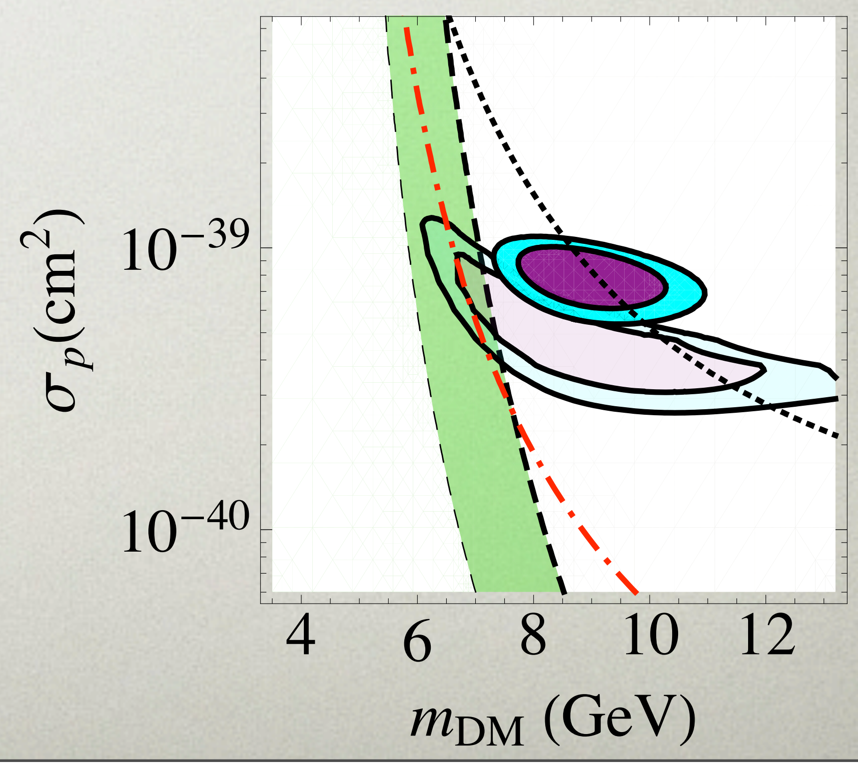
- ... of the experimental kind
- How do you calibrate energy?

Fitzpatrick, KZ '10




Manzur et al

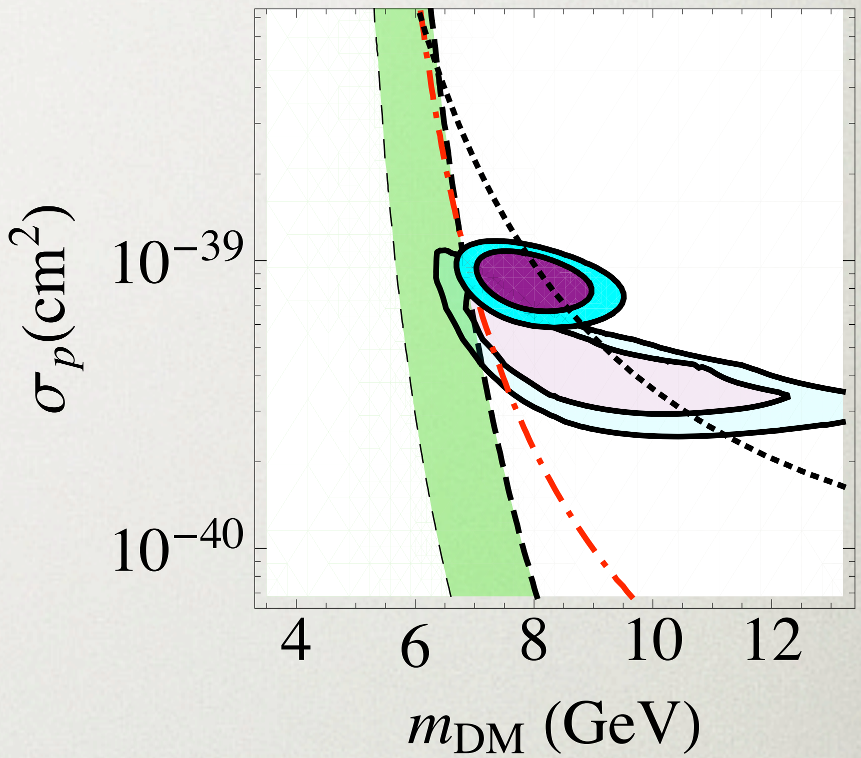


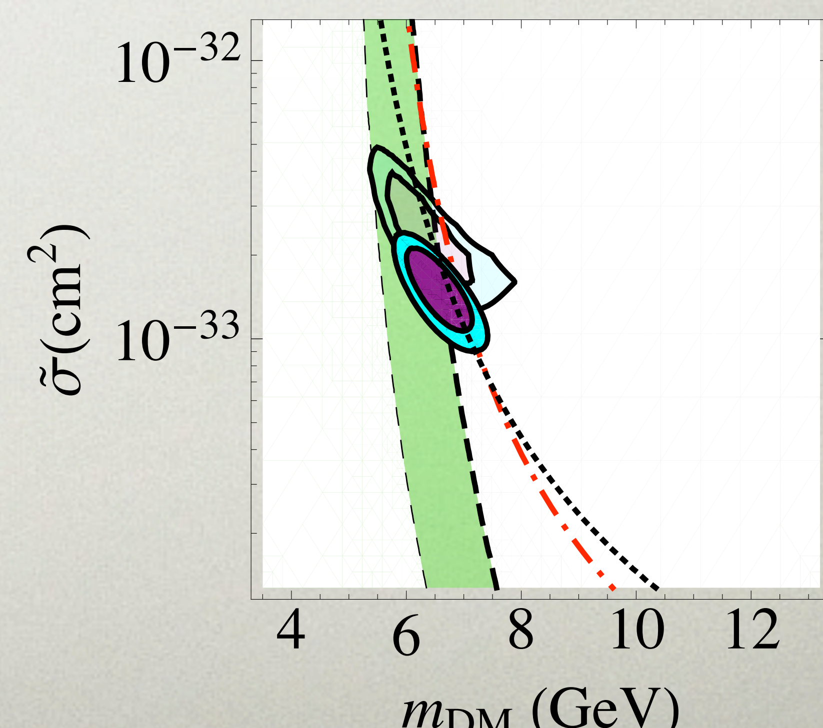



# All complicated by uncertainties ...

Fitzpatrick, KZ '10

- ... of the theoretical kind
- How certain are we of the underlying theory?



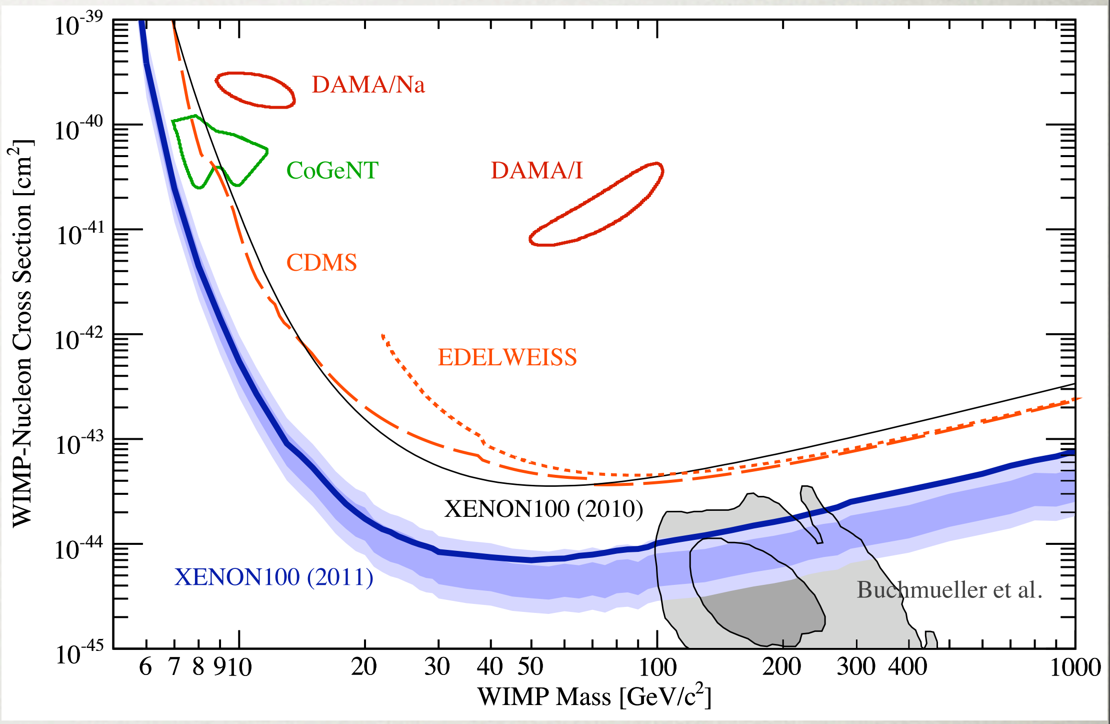

$$\mathcal{O}_N = A^\mu \bar{N}(p)\left(F_1(q)(p+p')_\mu + (F_1(q)+F_2(q))2i\Sigma_{\mu\nu}q^\nu\right)N(p').$$

$$\begin{aligned}\mathcal{O}_a &= \bar{\chi}\gamma^\mu\gamma_5\chi A_\mu \\ \mathcal{O}_d &= \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}/\Lambda\end{aligned}$$

$$\begin{aligned}\sigma_a &= \frac{\mu_N^2}{4\pi(q^2+M^2)^2}\left(\left(4v^2 - q^2\frac{(m_N+m_\chi)^2}{m_N^2 m_\chi^2}\right)F_1^2 + (F_1+F_2)^2 q^2\frac{2}{m_N^2}\right), \\ \sigma_d &= \frac{4\mu_N^2 q^2}{\pi\Lambda^2(q^2+M^2)^2}\left(\left(4v^2 - q^2\left(\frac{1}{m_N^2}+\frac{2}{m_N m_\chi}\right)\right)F_1^2 + (F_1+F_2)^2 q^2\frac{2}{m_N^2}\right)\end{aligned}$$

# DM in a Data Rich Discovery Era

- Meaning of experimental results still unclear -- as not uncommonly the case in a discovery era!



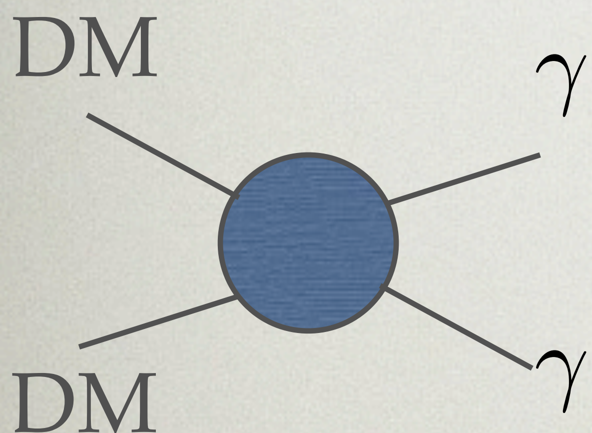

- Neutralino from MSSM not viable   Kuflik, Pierce, KZ '10

- Consider range of theoretically motivated theories

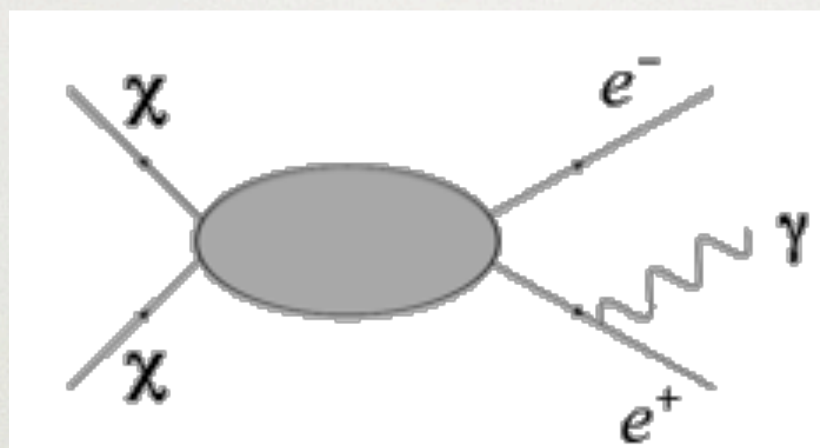
- Is 7-10 GeV mass window suggestive of something else?

# 2. Search Via Annihilations

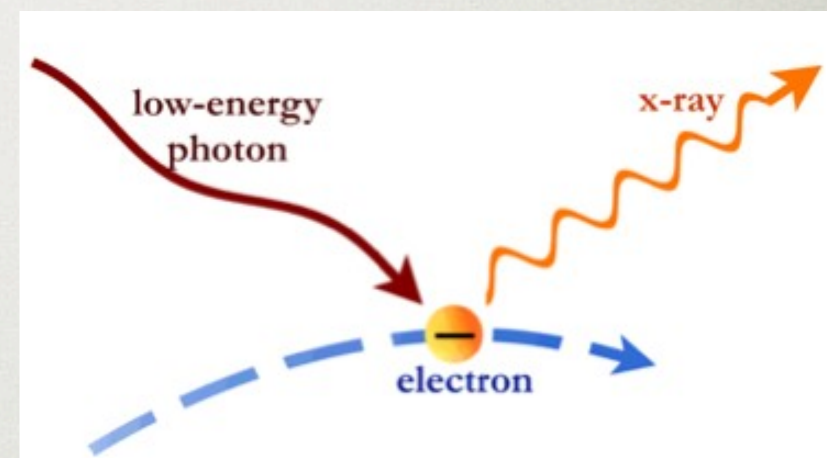
- How do we get photons from DM annihilation?




1. Direct



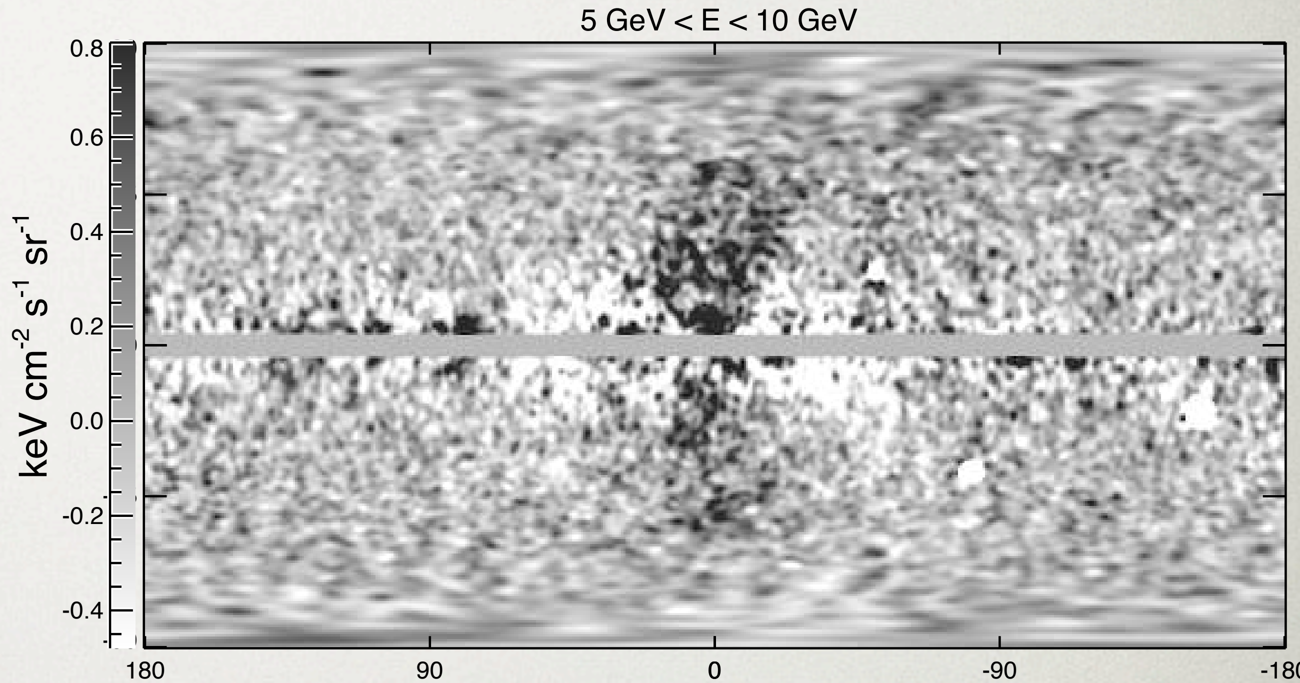

2. Final State Radiation



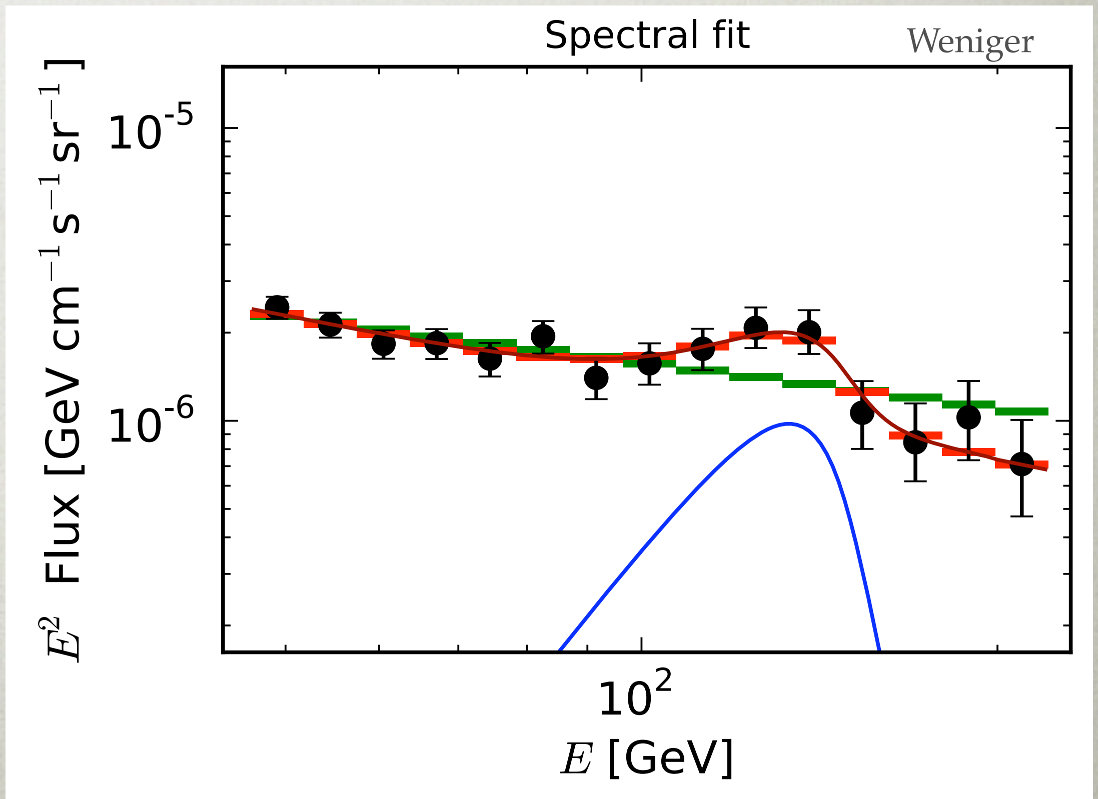

3. Inverse Compton

# 2. Search Via Annihilations

- Missions in space
- 1. Fermi - photons
  - Many anomalies!
  - DM or astrophysical source?

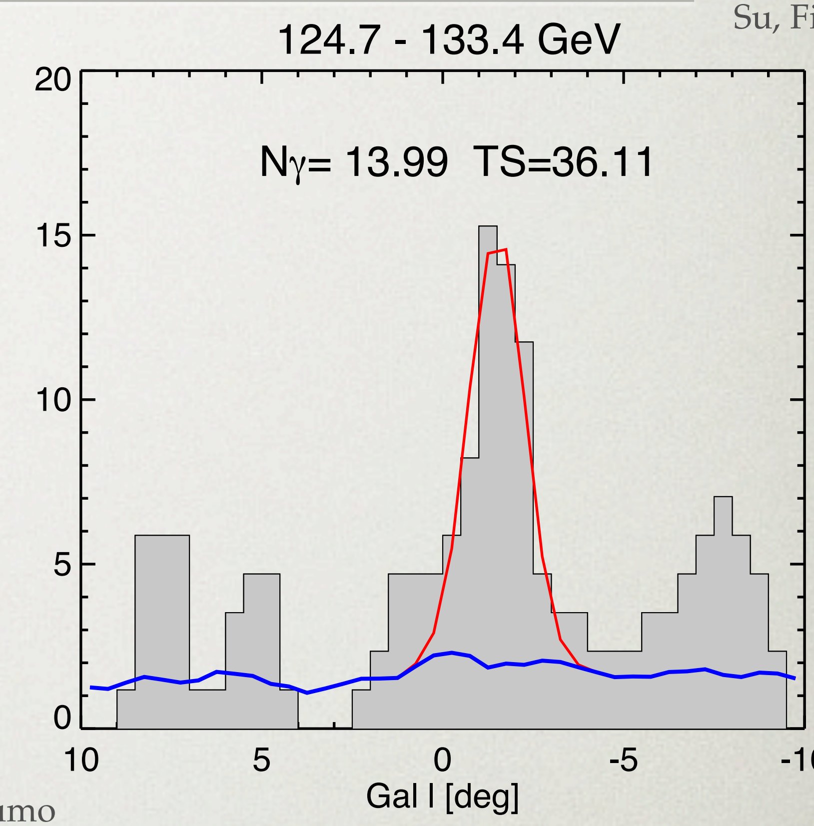



Cholis, Dobler, Finkbeiner, Slatyer, Weiner



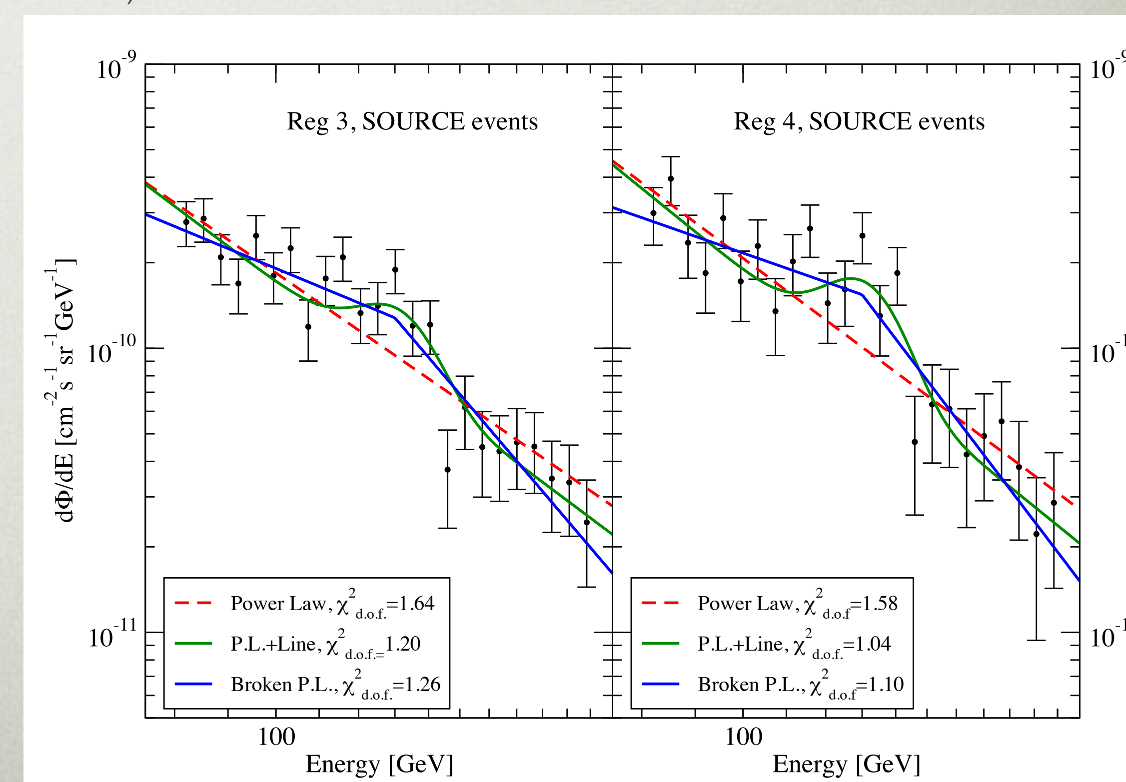
# A Line was Supposed to be a Smoking Gun ...

Su, Finkbeiner

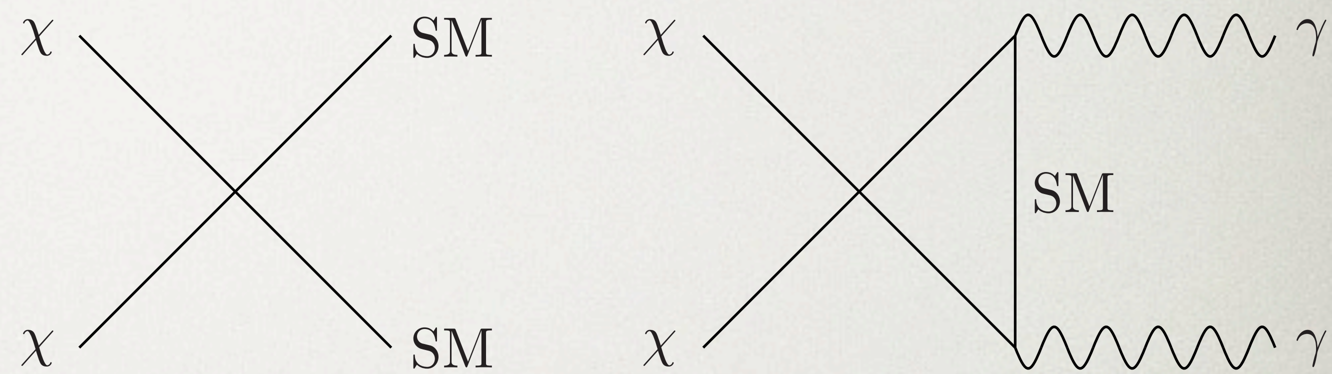



- Slightly off galactic center
- A broken power law?
- Detector systematic?

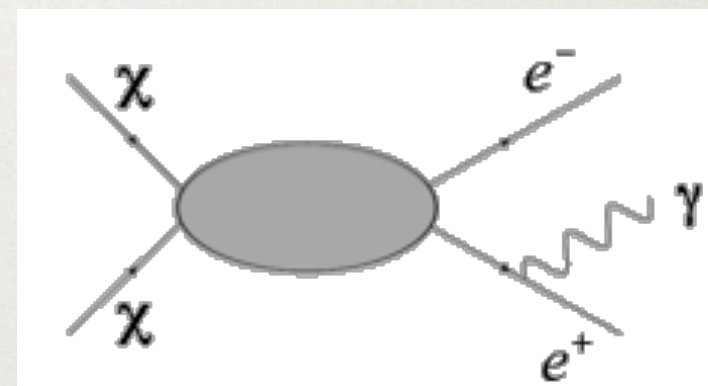
Linden, Profumo



# A Line was Supposed to be a Smoking Gun ...

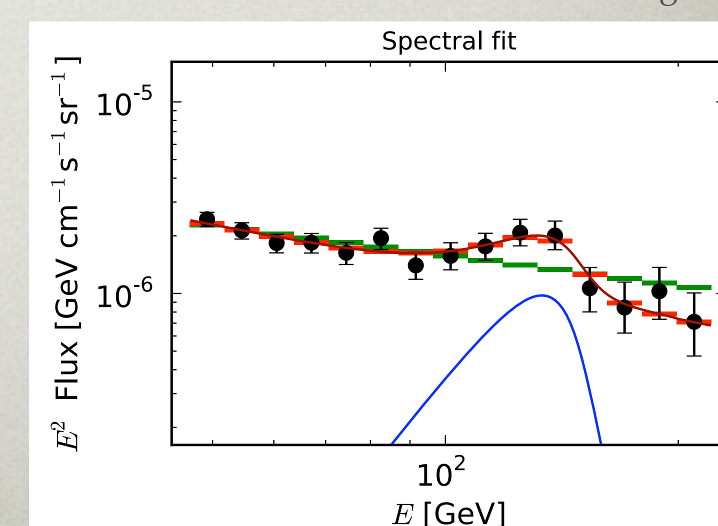



- *Large* rate

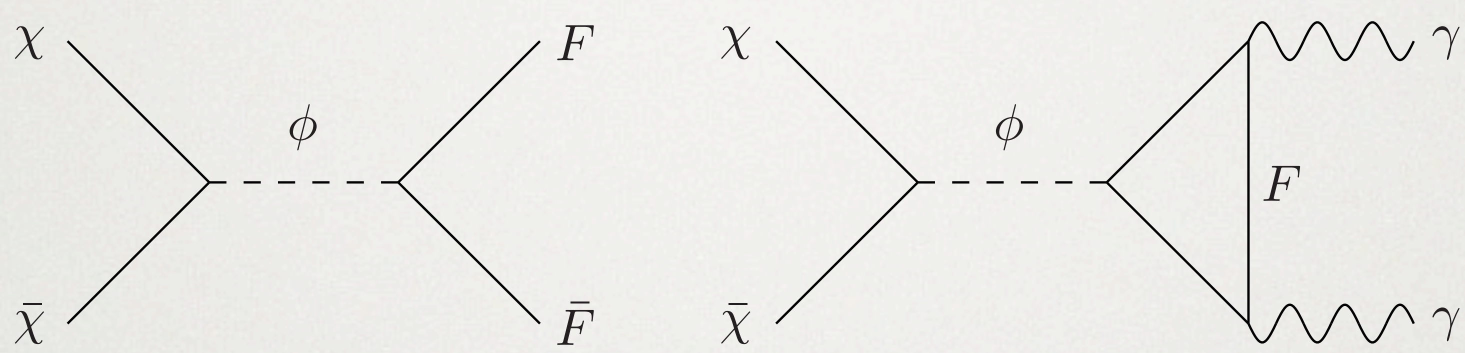



- Why no continuum photons?
- Continuum should dominate by $\frac{R_{SM}}{R_{\gamma\gamma}} \sim (\pi/\alpha)^2 \approx 10^5$
- Need special models

Weniger



# What do you require from a Model?

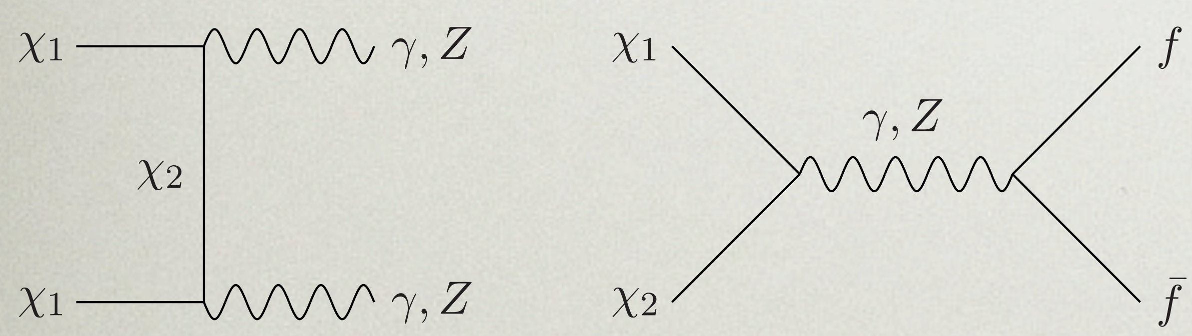



- Some way to:
  - suppress continuum photons
  - obtain the observed abundance of DM

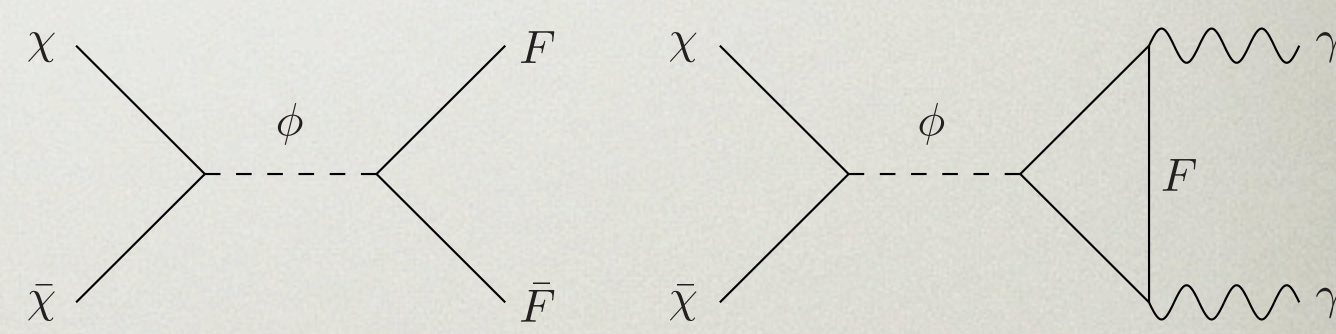
# Three Exceptions

Tulin, Yu, KZ '12

- Can suppress continuum today with p-wave cross-section $\langle \sigma v \rangle \sim v^2$
- Annihilation still too large for relic; need additional mechanism $v \sim 0.3$




1. Coannihilation

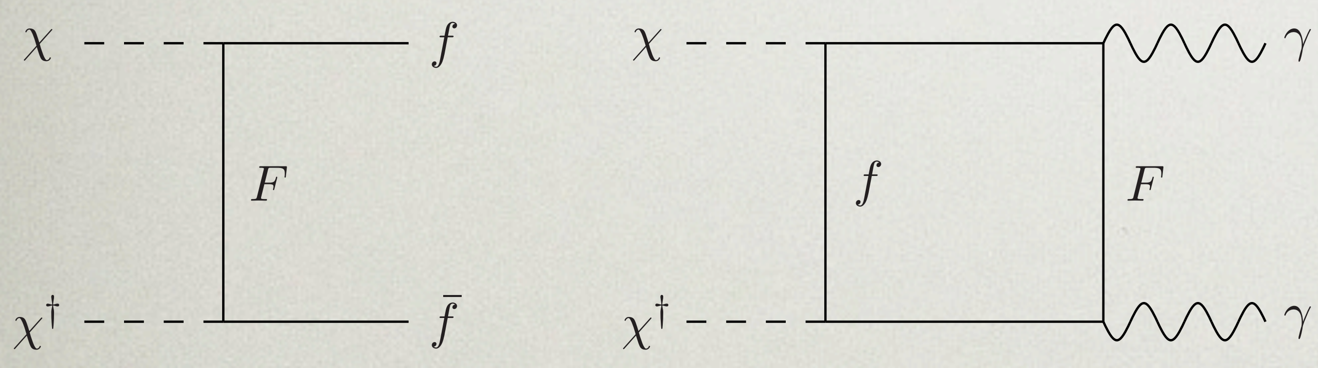



2. Forbidden Channels

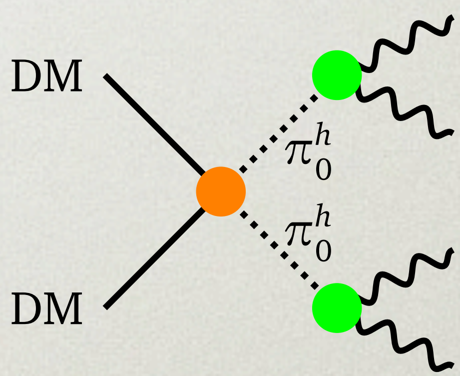
# Three Exceptions

Tulin, Yu, KZ '12

- Can suppress continuum today with p-wave cross-section $\langle \sigma v \rangle \sim v^2$
- Annihilation still too large for relic; need additional mechanism $v \sim 0.3$




3. Asymmetric Dark Matter

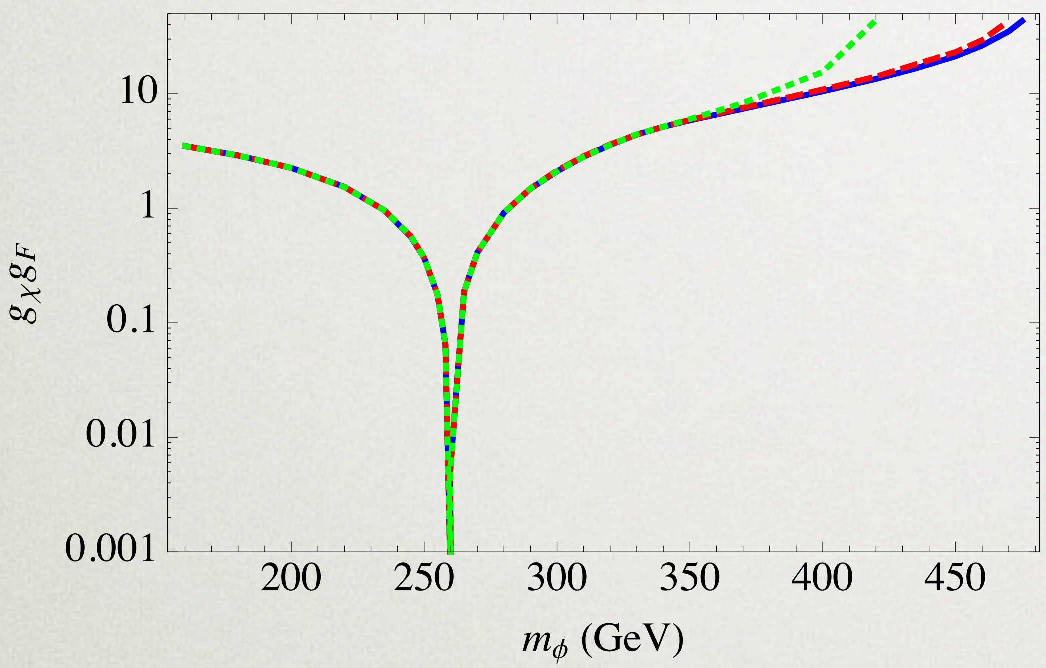


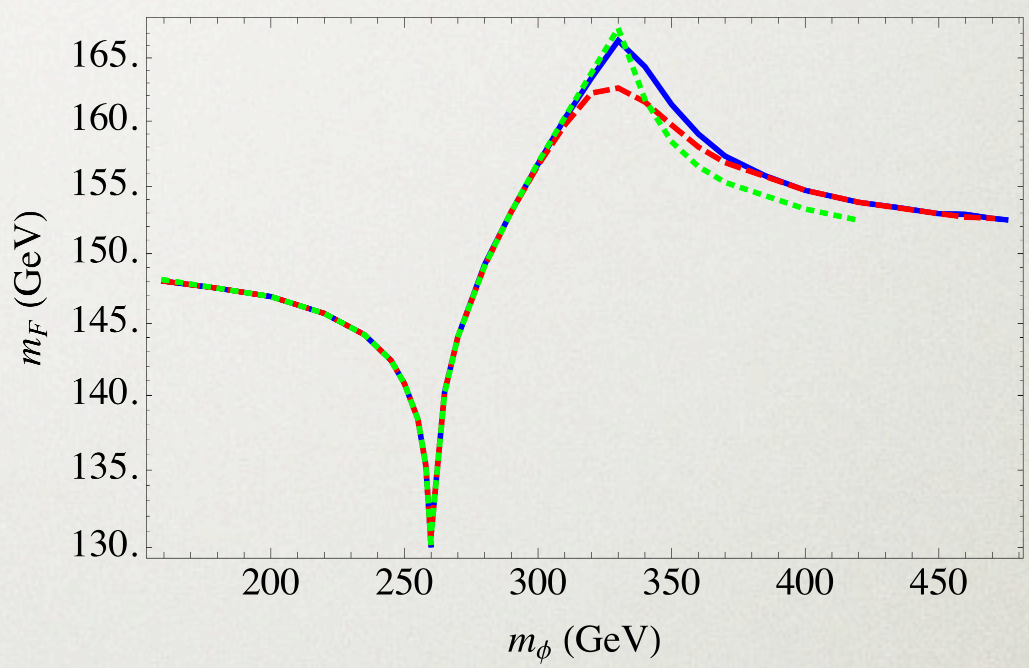

Buckley, Hooper
Bai, Shelton
Fan, Reece

(4.) Degenerate States

# What do you require from a Model?

Tulin, Yu, KZ '12



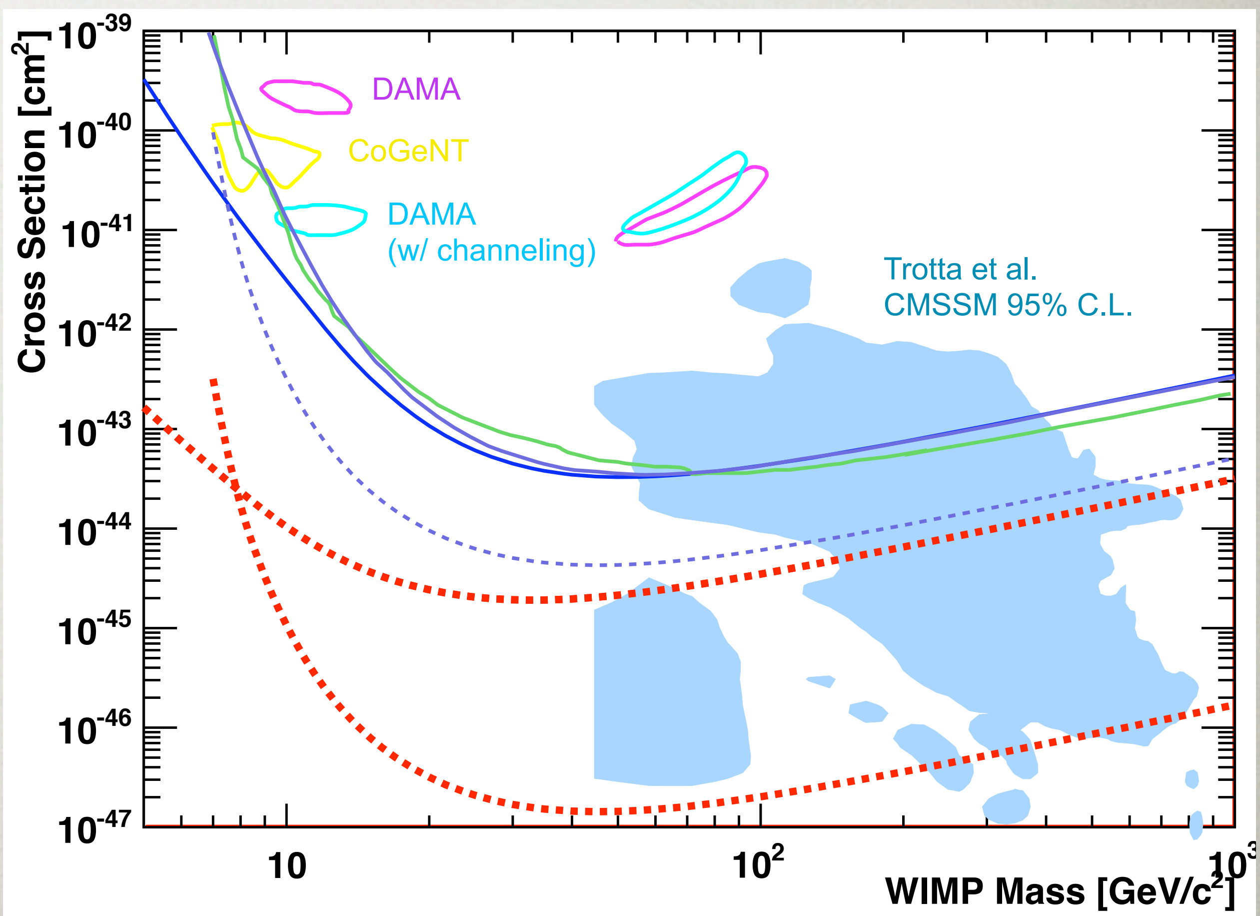

2. Forbidden Channels

# The Road Ahead

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

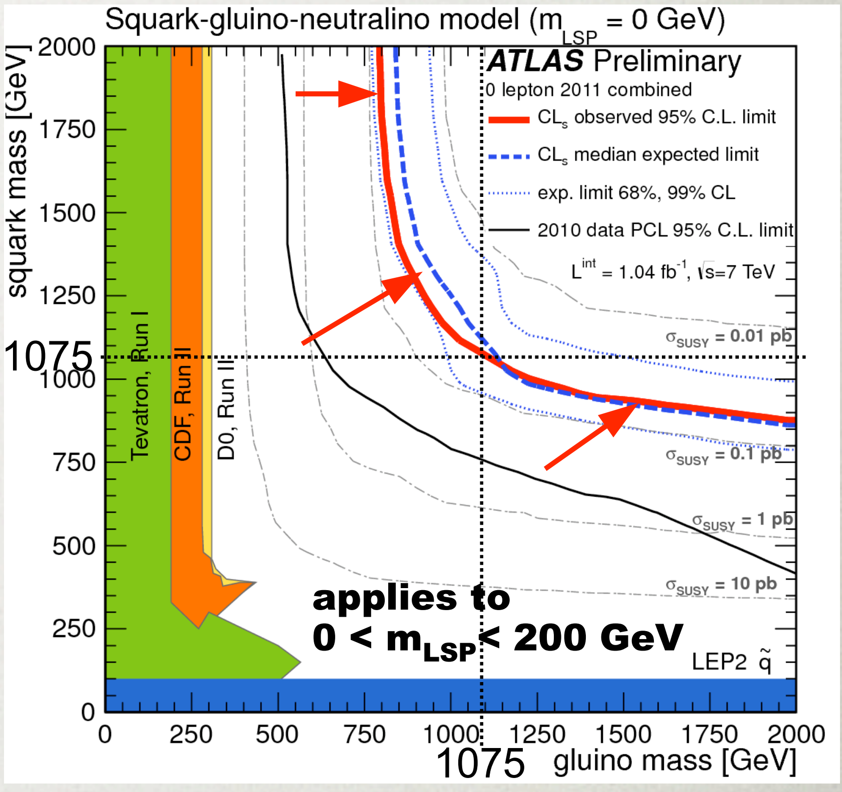
$$\sigma_n \sim 10^{-45-46}\ \mathrm{cm}^2$$

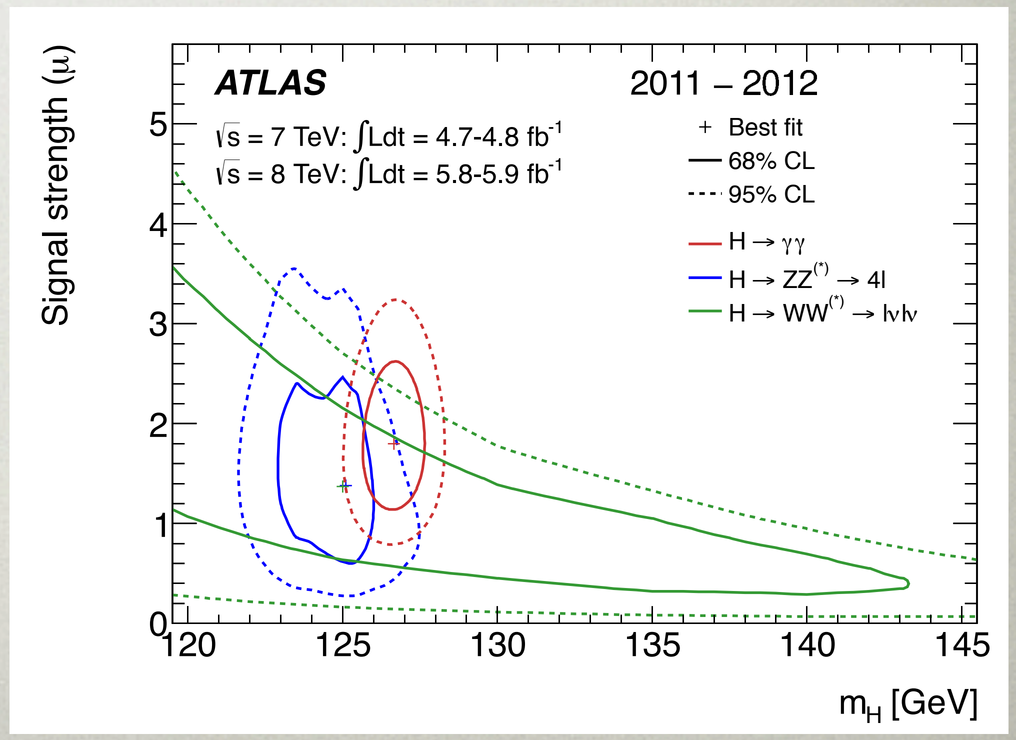
PandaX proposal



# The Road Ahead

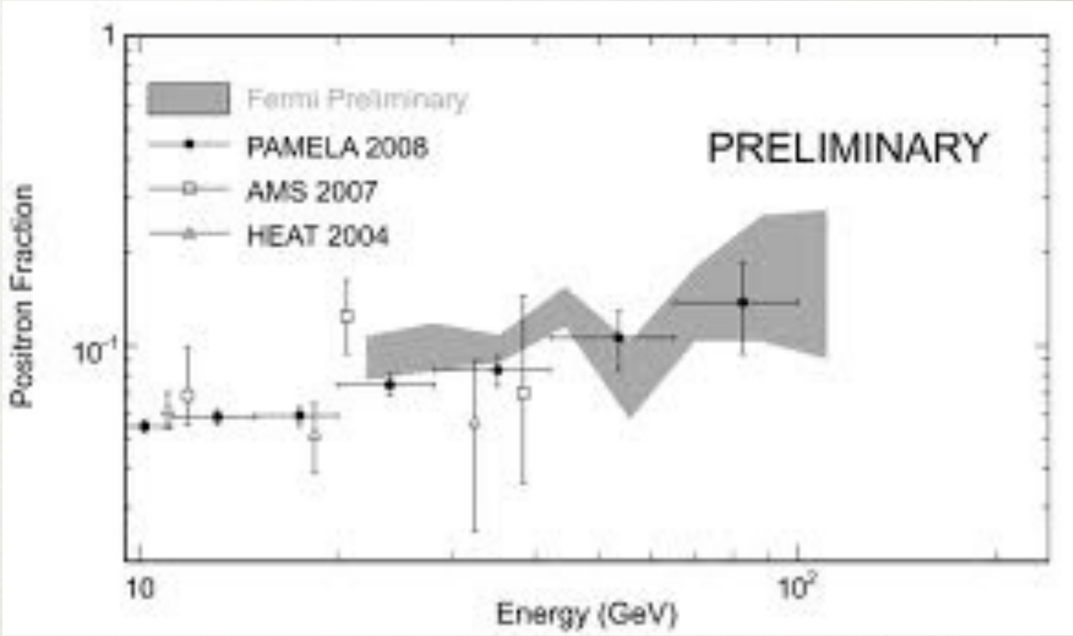
- LHC will continue looking for physics Beyond the Standard Model at the weak scale
- Evidence for Higgs; further accumulate this year
- Be patient! Current energy 8 TeV; Ramp-up to 14 TeV after 1-2 year shutdown

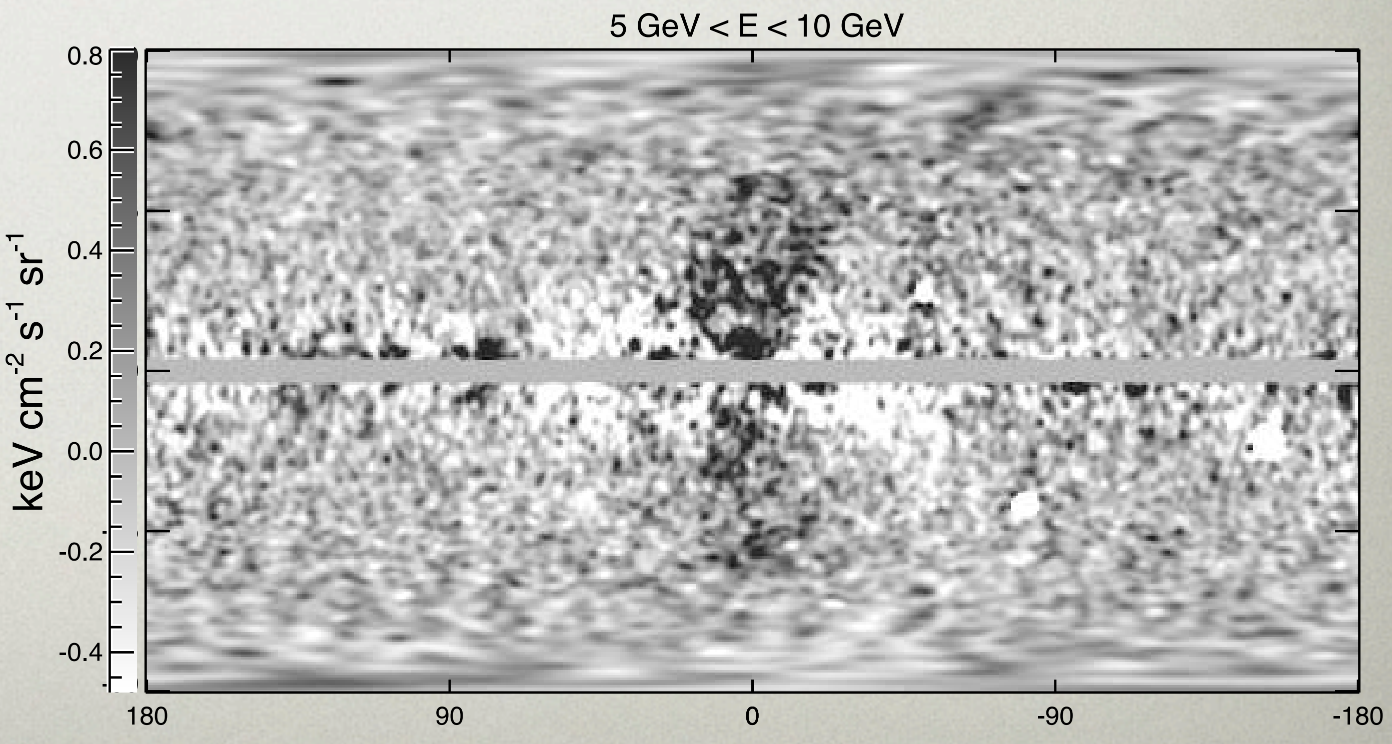


# The Road Ahead

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



# Summary

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

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