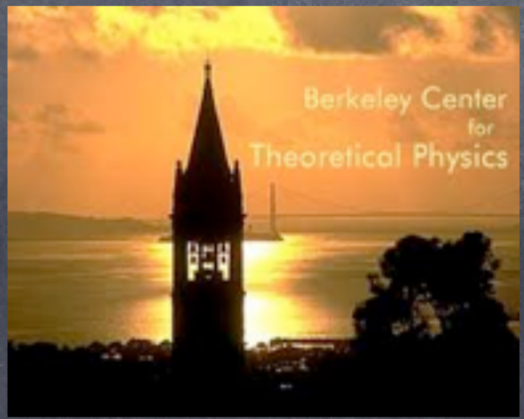
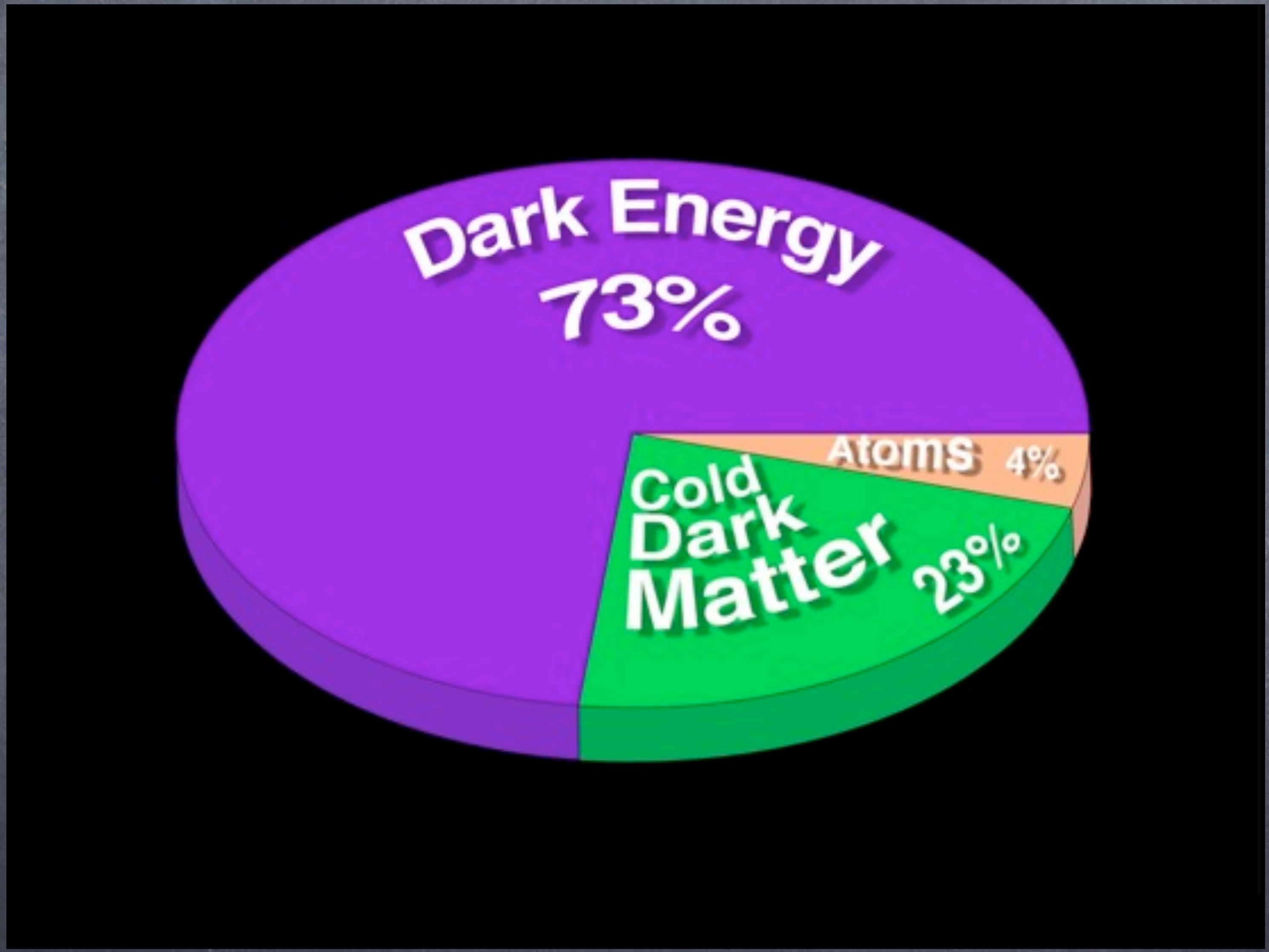
Dark Matter Theory: Status and Updates

Kathryn M Zurek



Universe's Energy Budget

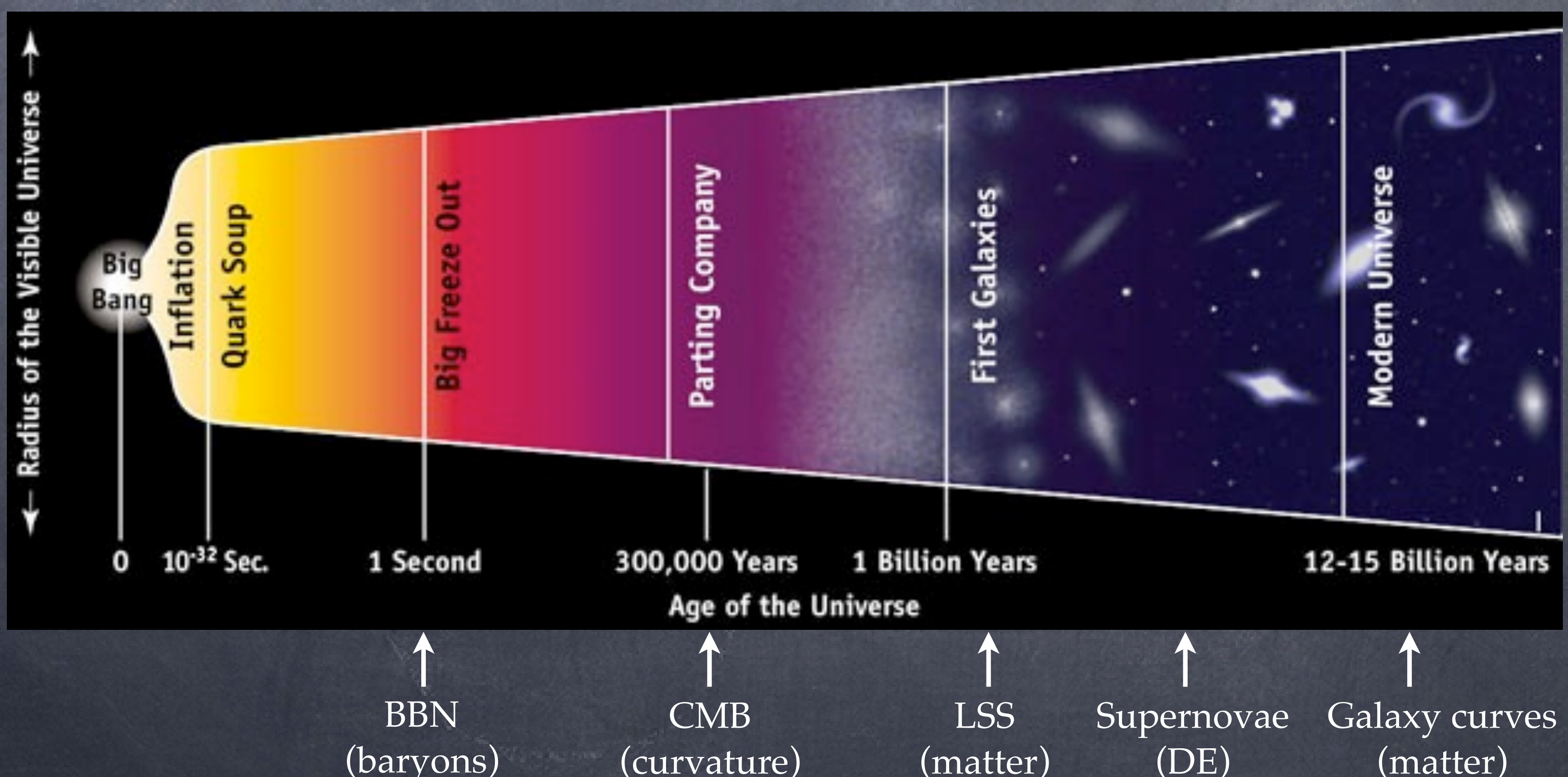
Dynamical selection?



New Dynamics, Definitely BSM

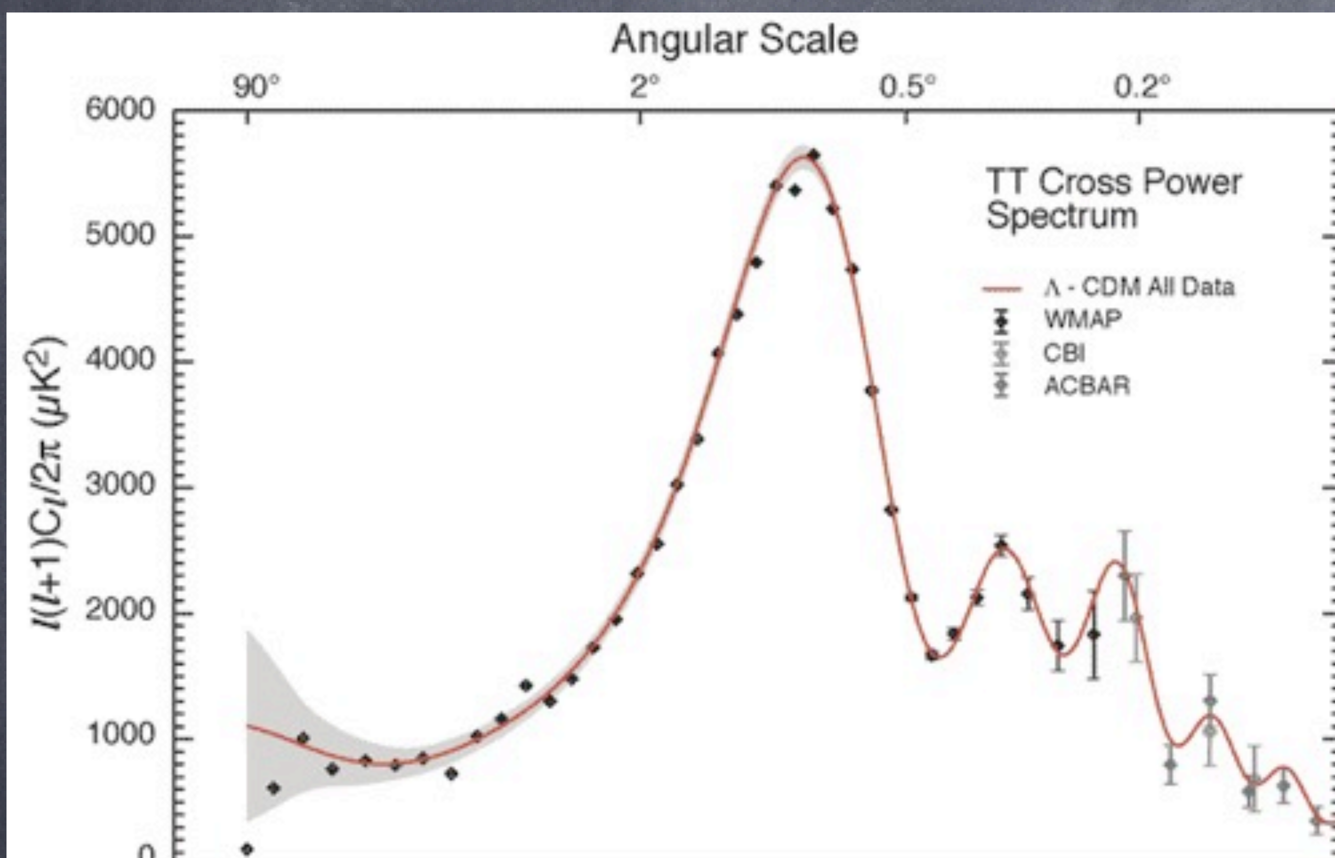
Why particle dark matter?

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



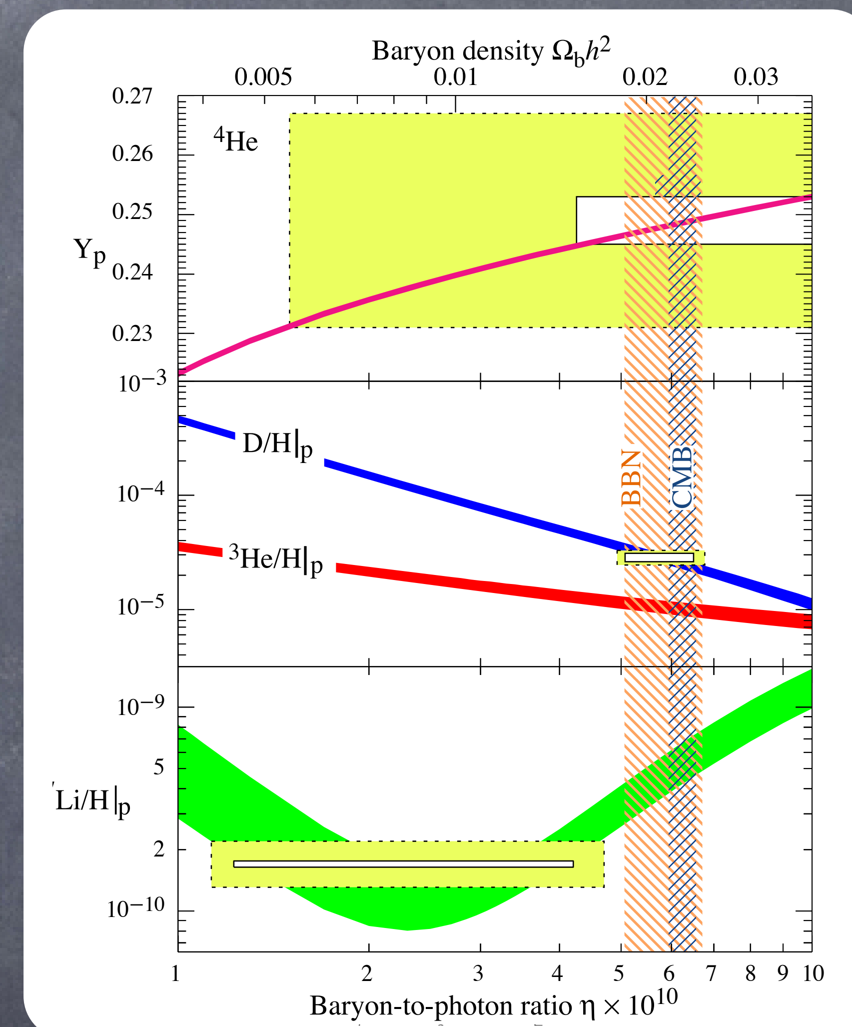
Why particle dark matter?

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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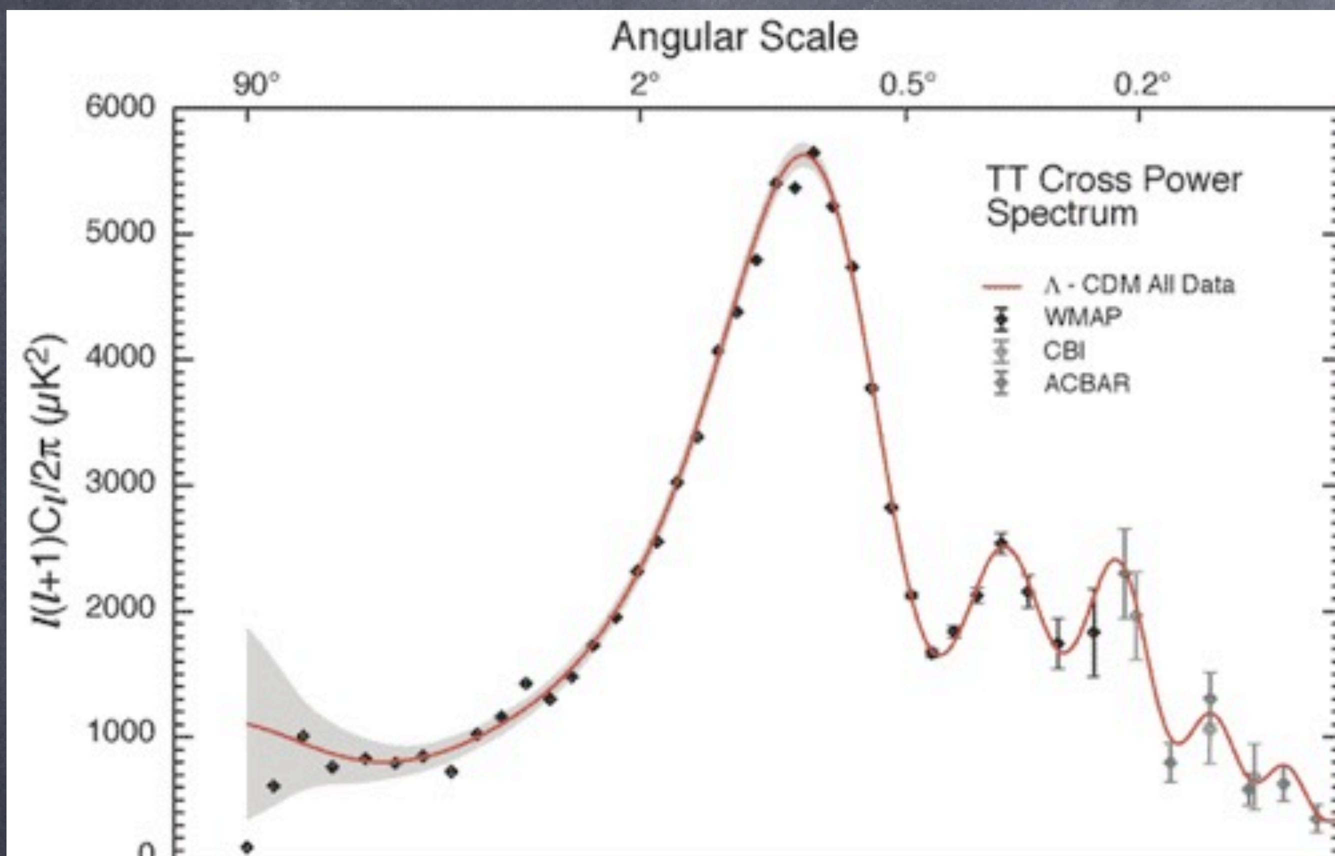
curvature, z_eq



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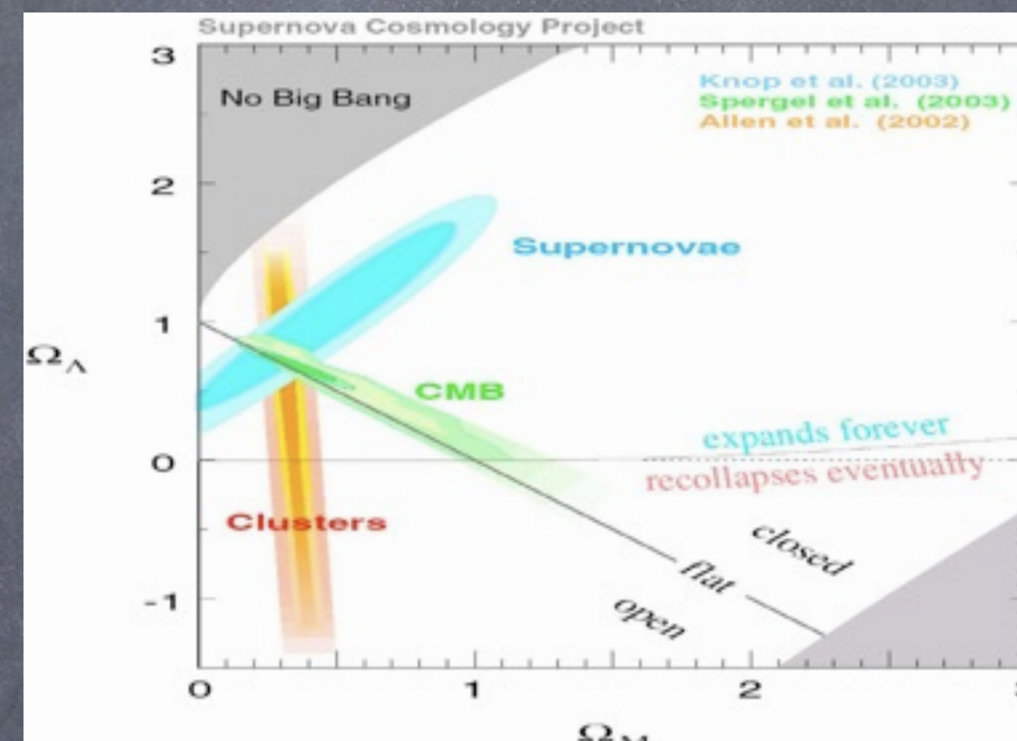

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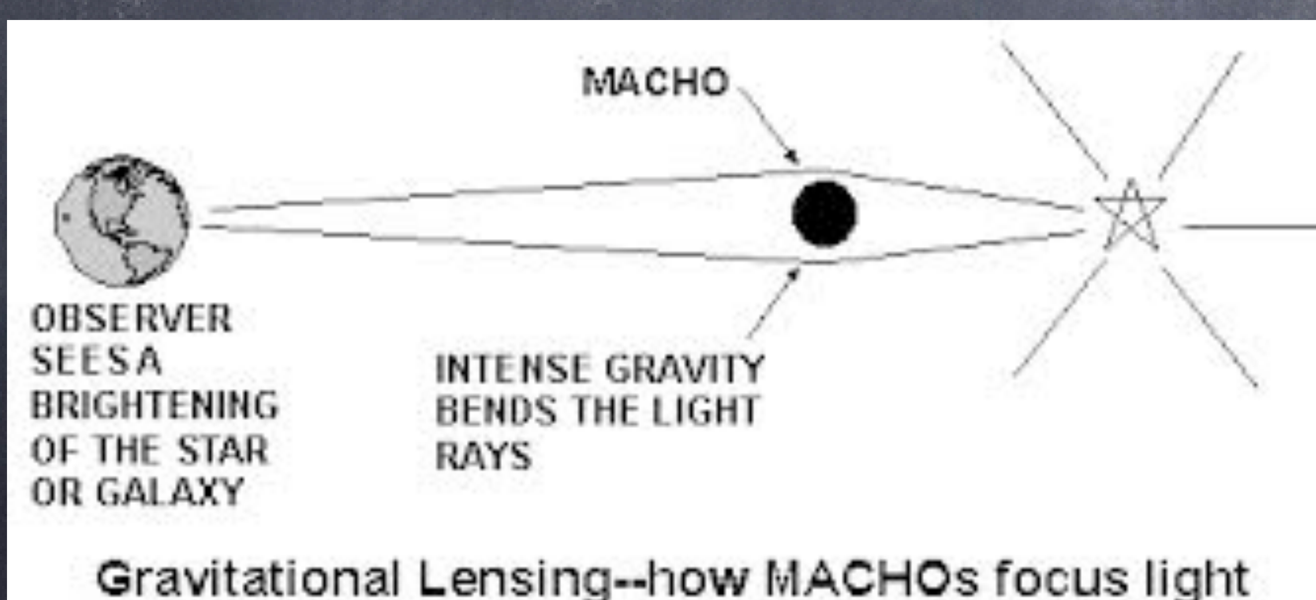
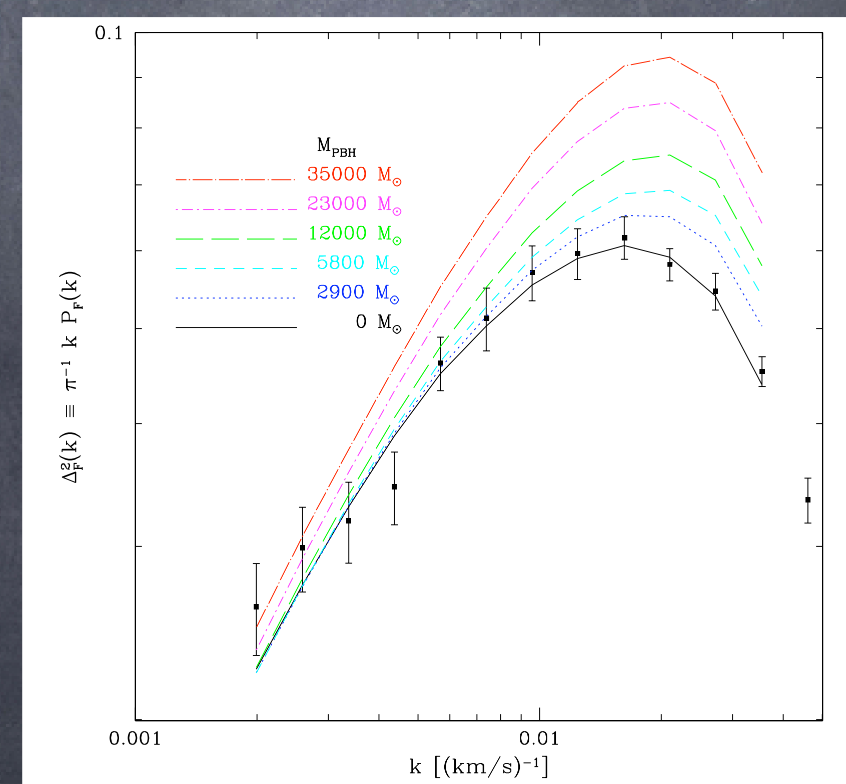
Why particle dark matter?

- 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





Why particle dark matter?

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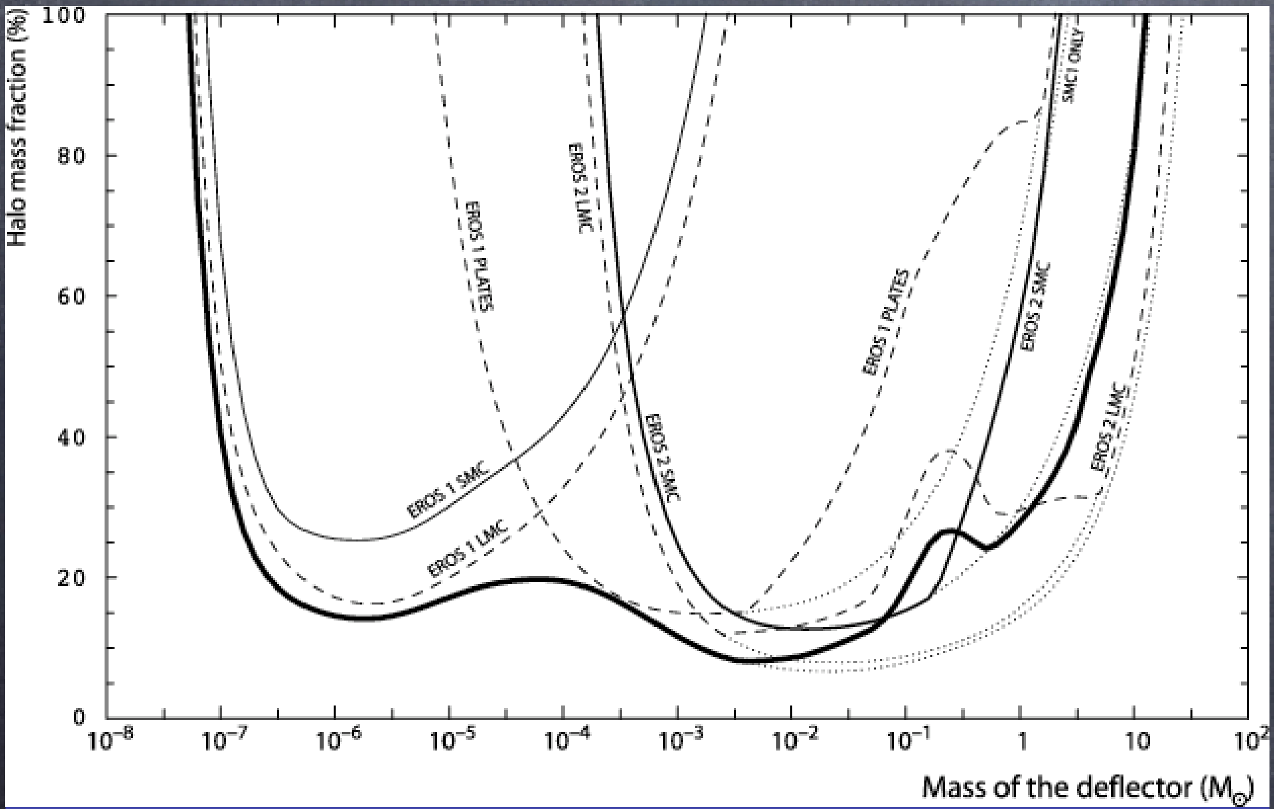
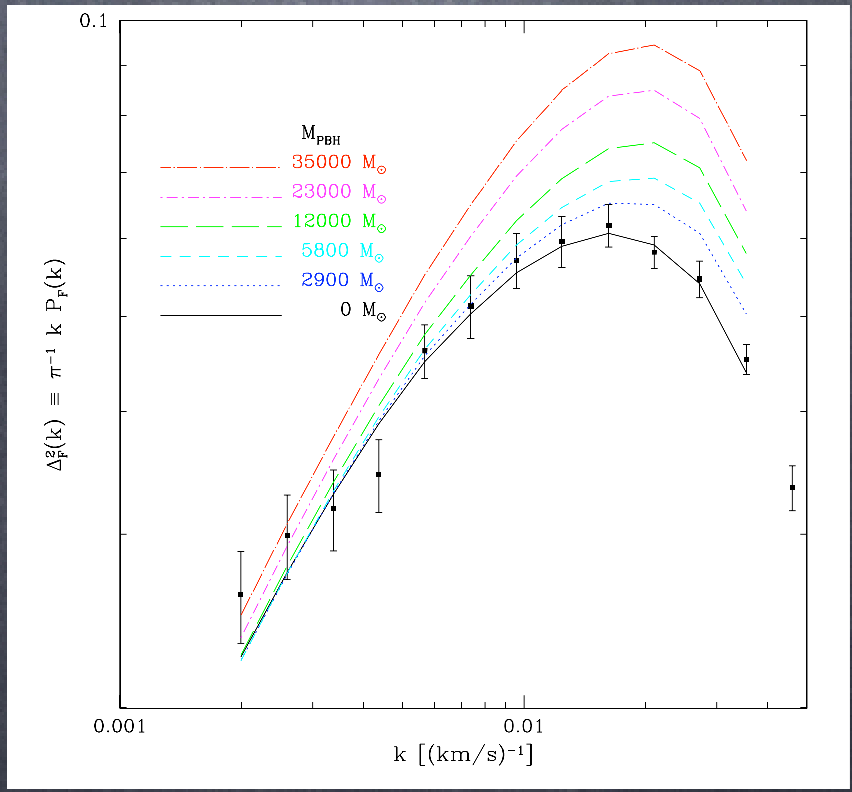
from 2005 talk by K. Griest

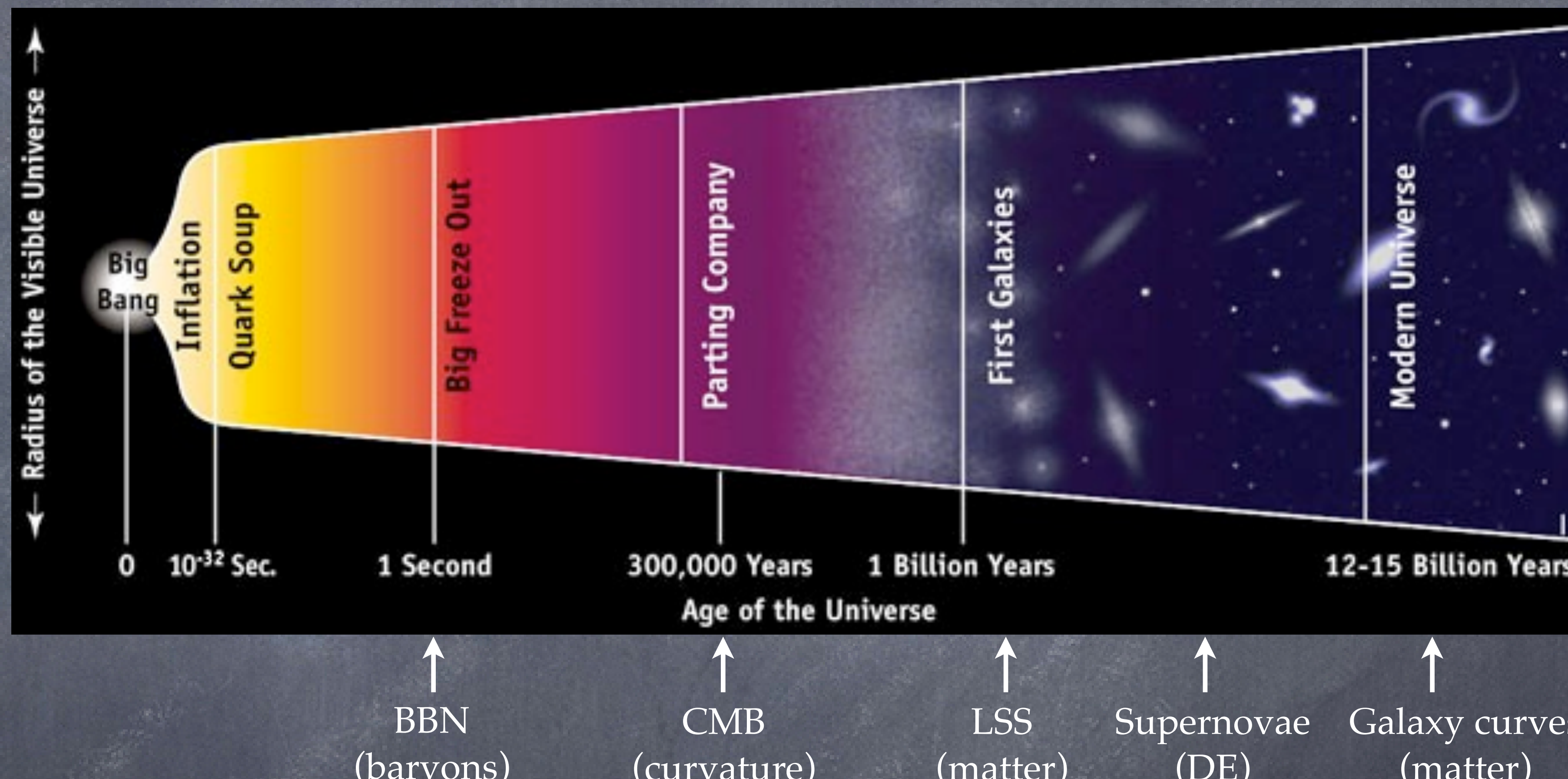


Afshordi, McDonald, Spergel



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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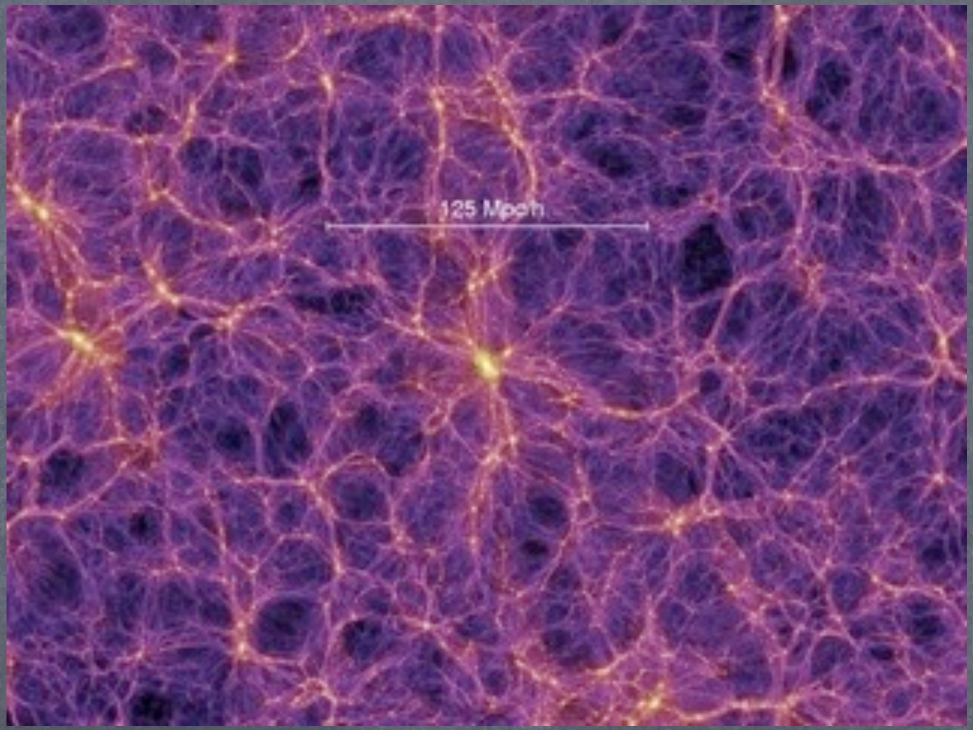
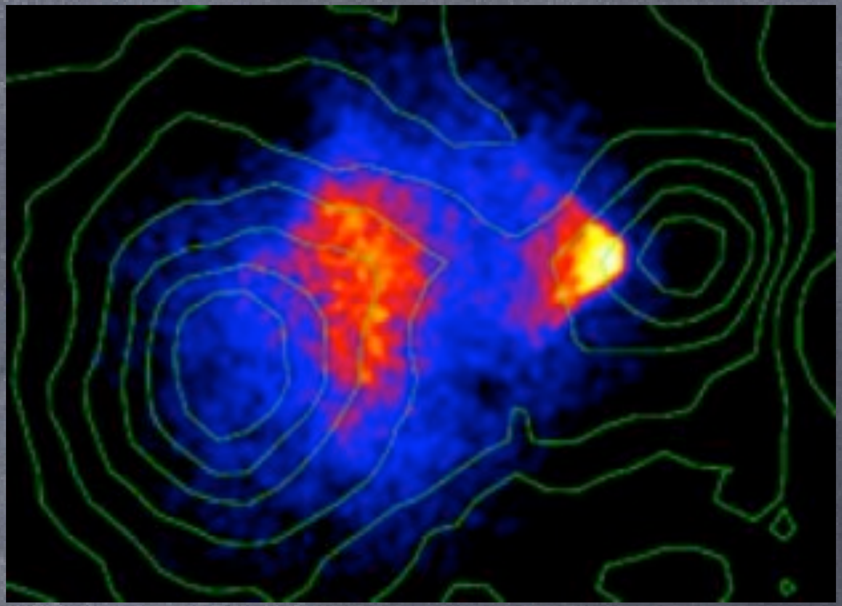




X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al

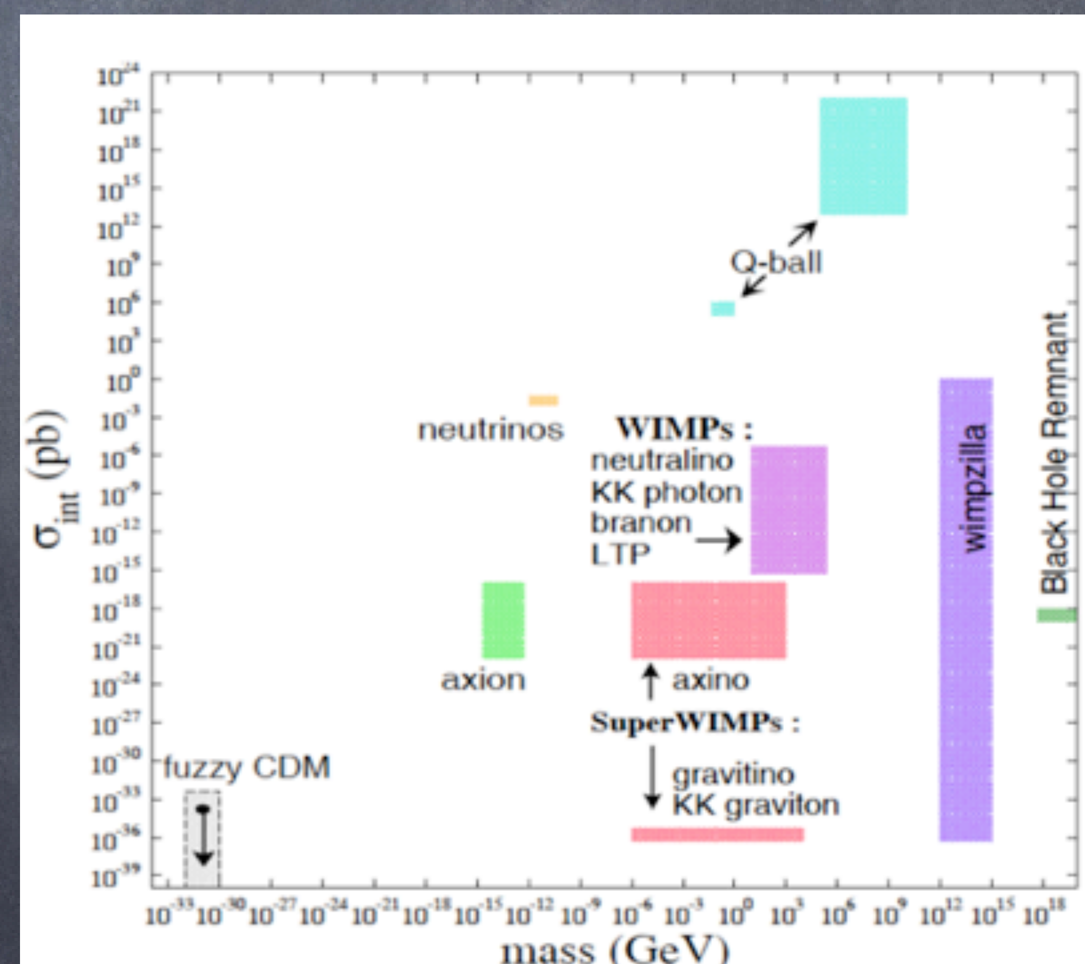
- A: Must get the entire range of observations right, not just galactic rotation curves

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 saying goes:

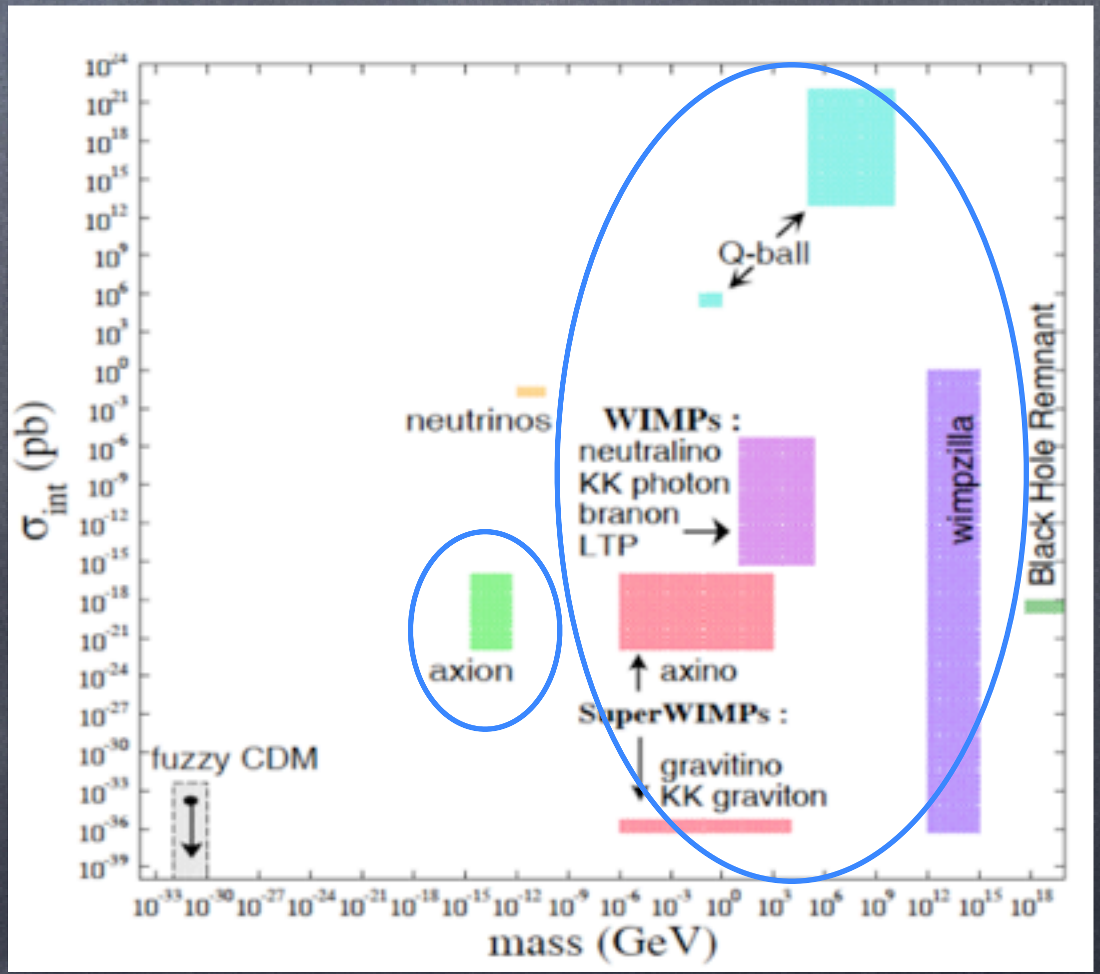
Particle dark matter

- No shortage of theories
- Supersymmetry
- Extra dimensions
- Massive neutrino
- MeV dark matter
- Scalar dark matter
- axion



Particle dark matter

- No shortage of theories
- Note however: most based on a couple of very popular theories
- Axions and WIMPs (usually, supersymmetric)

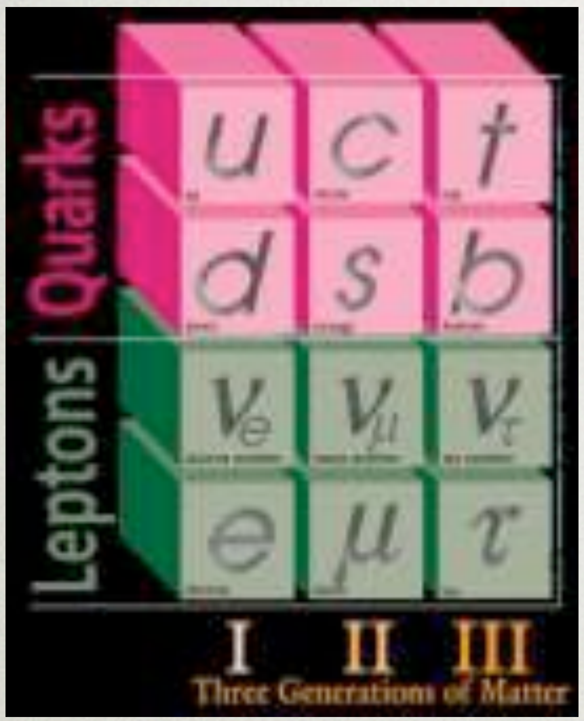


Dark Matter: Standard Paradigm

- Usual picture of dark matter is that it is:
  - single
  - stable
  - (sub-?) weakly interacting
  - neutral

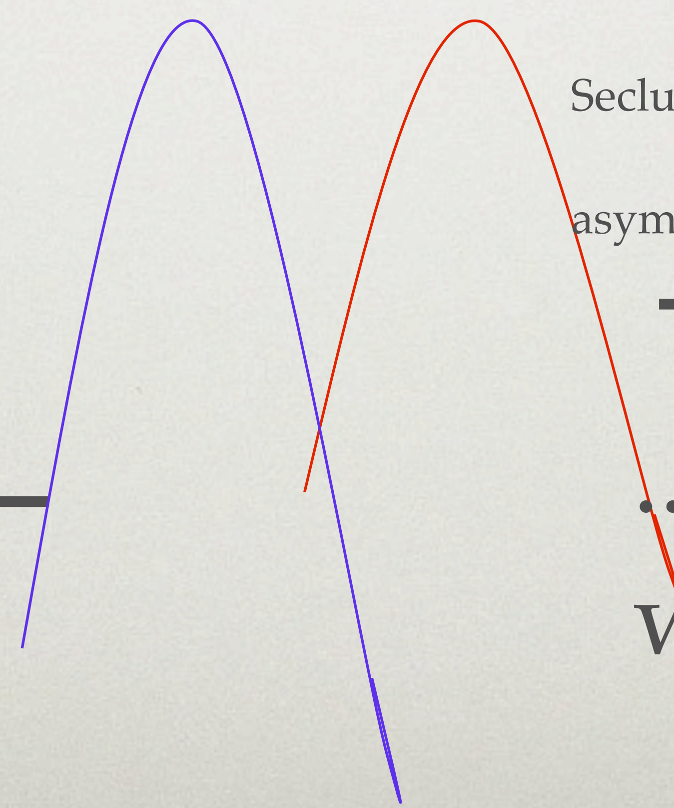
Hidden Dark Worlds

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 Valley with multiple states, new interactions

Models of Dark Matter

- The classic
- SUSY
  - has all the ingredients
  - and they are present for other reasons
  - DM (sort of) free

Idea Focus: Supersymmetry

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

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

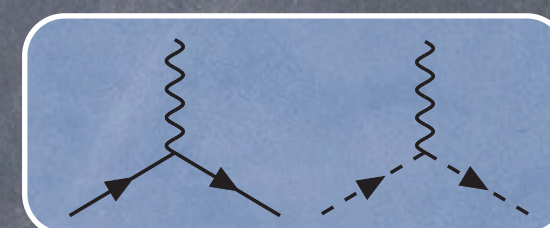
- Sneutrino scatters through Z

Weakly-interacting

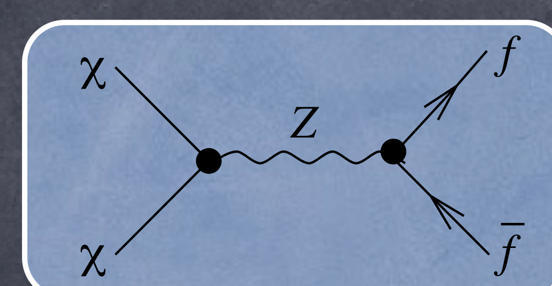
- Sneutrino, also being neutral, is a good DM candidate.... except for direct detection(!)

$$Q|\text{neutrino}\rangle = |\text{sneutrino}\rangle$$

Gauge interaction:



- Its couplings are fixed by gauge interactions
- Scatters off nucleons through Z boson
- Let's compute the rate

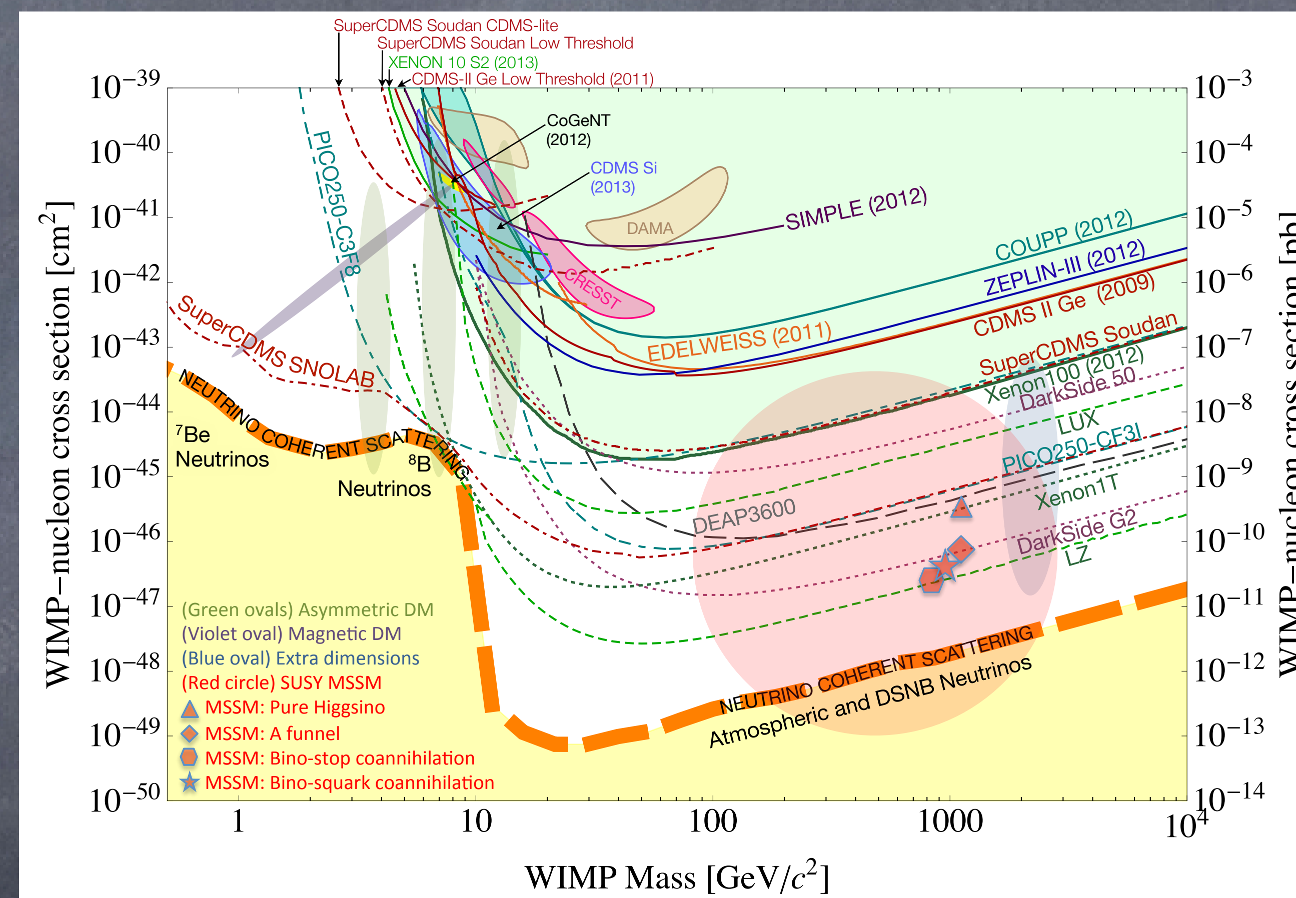


Apply to scattering through Z boson

- plug in and compare

$$\sigma \approx \frac{g^4 \mu_n^2}{4\pi m_Z^4} \approx 10^{-39}\ \mathrm{cm}^2$$

- Active $\tilde{\nu}$ DM excluded by direct detection



Can evade constraint by mixing in sterile $\tilde{\nu}$, $\tilde{N}$. This state does not couple to Z. But is not present in minimal model

What about neutralino?

- 2 component fermion χ Majorana fermion
- Possible operators, four Fermi, V-A structure:

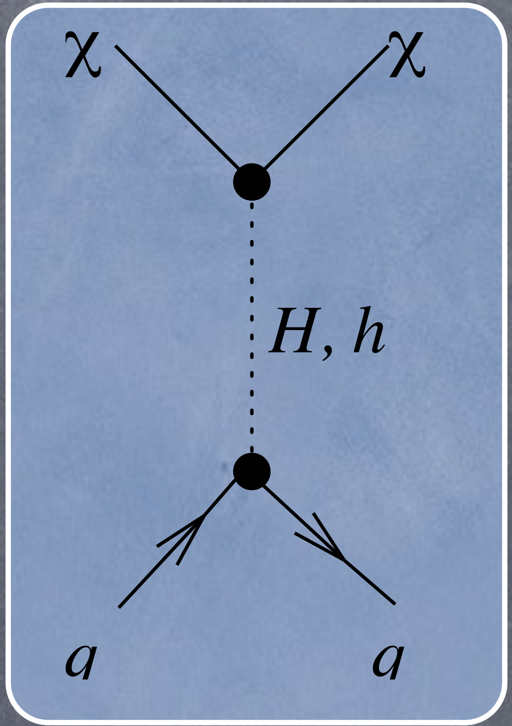
$$\mathcal{O}_{SI} = (\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q) = 0$$

$$\mathcal{O}_{SD} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$$

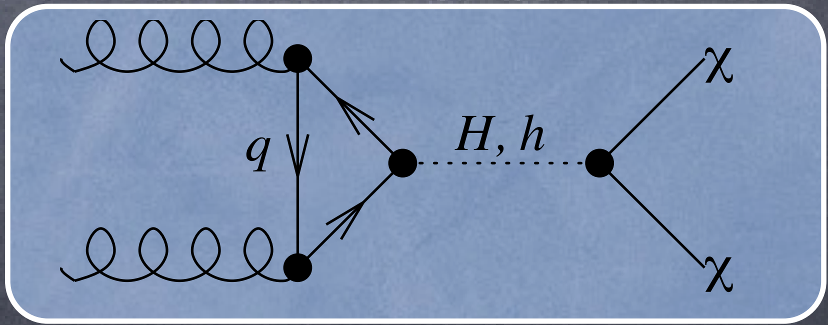
$$\mathcal{O}_{\text{vel dep.}} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu q)$$

- SI vanishes identically; others are SD or velocity suppressed

Higgs Scattering



- So neutralino is safe from Z-pole scattering
- It scatters predominantly through Higgs boson
- Higgs boson coupling to nucleon comes predominantly through a loop

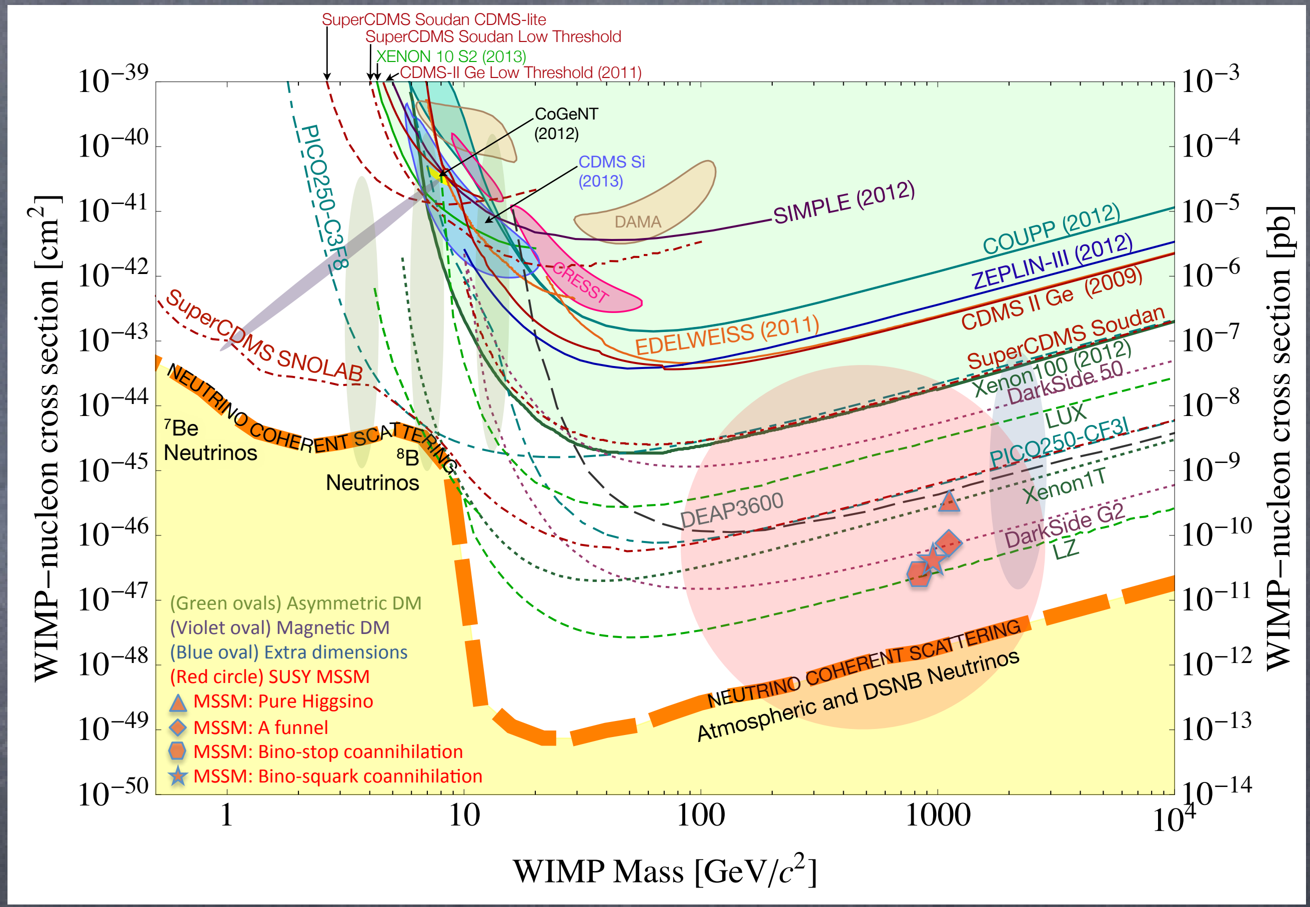


$$\frac{f_{p,n}}{m_{p,n}} = \sum_{q=u,d,s} f_{Tq}^{p,n} \frac{y_q}{m_q} + \frac{2}{27} f_{TG}^{p,n} \sum_{q=c,b,t} \frac{y_q}{m_q}$$

Shifman, Vainshtein, Zakharov,
Phys.Lett. B78 (1978) 443

Higgs scattering cross-section

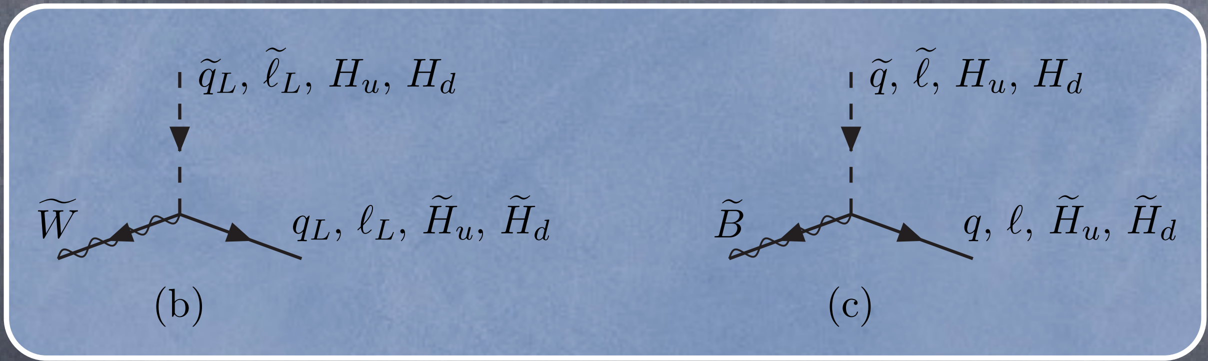
$$\sigma_n \approx 8.3 \times 10^{-42}\ \mathrm{cm}^2 \left(\frac{Z_d}{0.4}\right)^2 \left(\frac{\tan\beta}{30}\right)^2 \left(\frac{100\ \mathrm{GeV}}{m_H}\right)^4$$



Are there ways around?

A bit about neutralino couplings

- Supersymmetry fixes what interactions can and cannot occur
- Higgs does not interact with a "pure" state



- Must have bino-Higgsino or Higgsino-wino mix

Neutral

- Mass matrix:

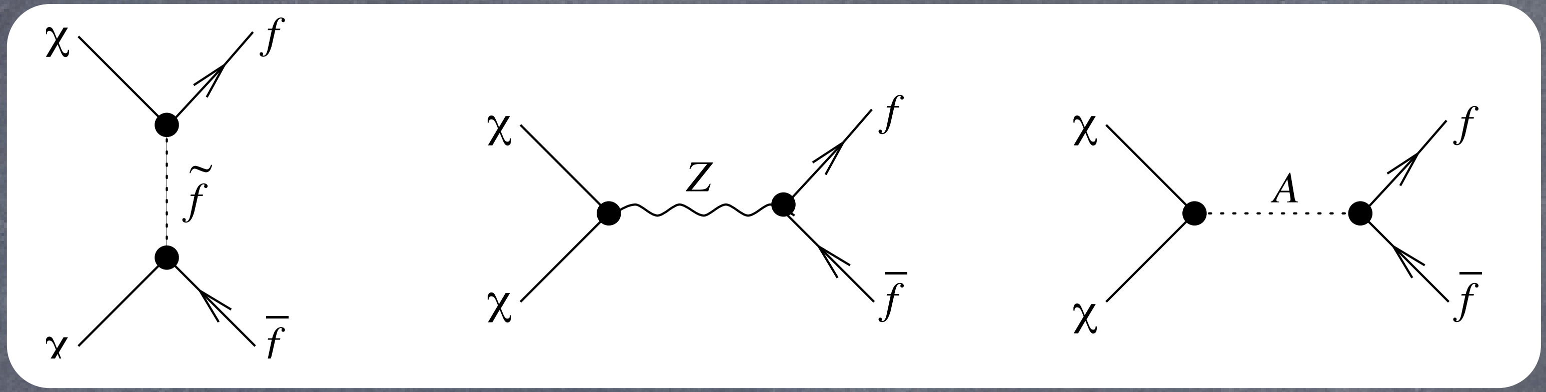
$$\begin{array}{cccc} \tilde{B} & \tilde{W} & \tilde{H}_u & \tilde{H}_d \end{array}$$

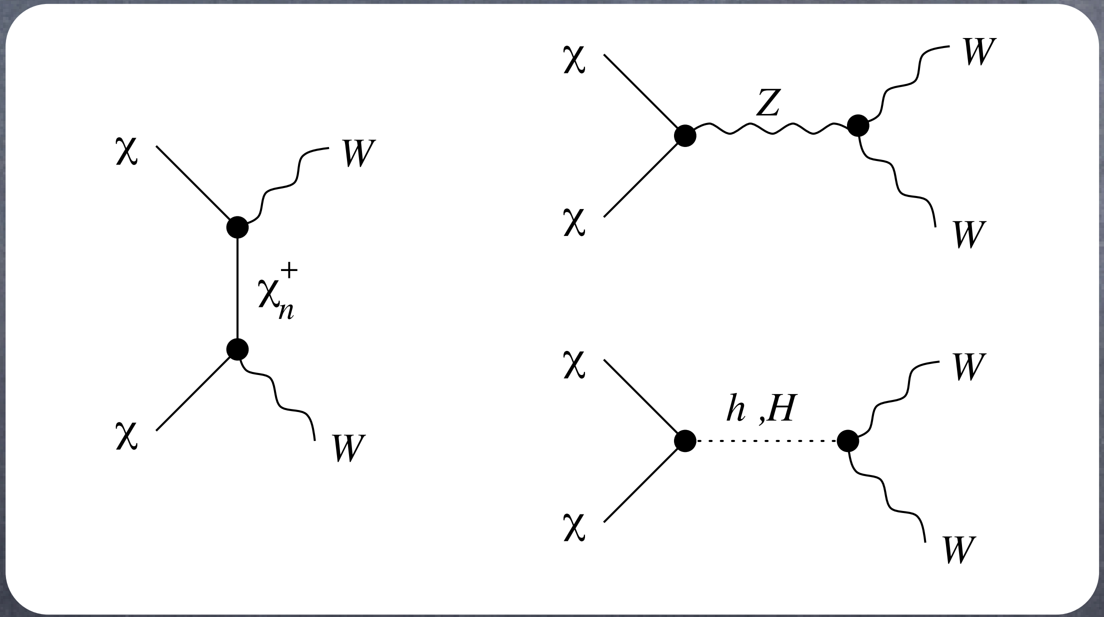
$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -\mu \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix}$$

- Soft parameters, M_1 and M_2. Free in SUSY.
- In SM, one Higgs works b/c can write field and conjugate $\mathcal{L}_{SM} = \bar{u}y_u Q\phi - \bar{d}y_d Q\phi^* - \bar{e}y_e L\phi^*$
- Not so in SUSY: $W_{MSSM} = \bar{u}y_u QH_u - \bar{d}y_d QH_d - \bar{e}y_e LH_d$

$$\tan\beta = \frac{v_u}{v_d} \qquad v_u^2 + v_d^2 = v^2 = (246\ \text{GeV})^2$$

WIMP annihilation processes

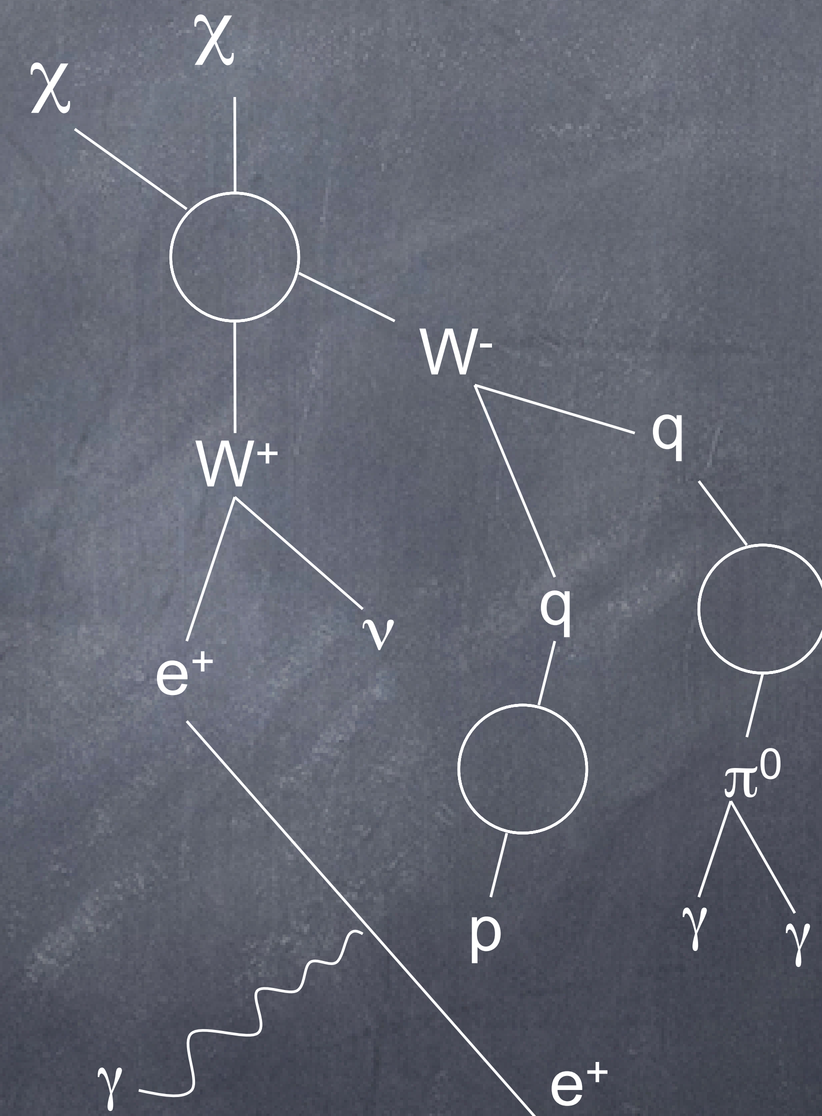




- Bottom diagrams often dominate if DM is largely wino or largely Higgsino

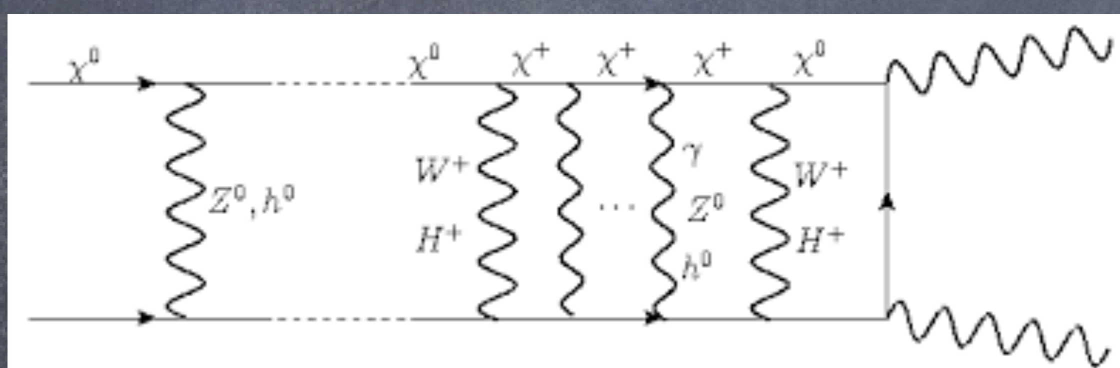
Escaping direct detection constraints

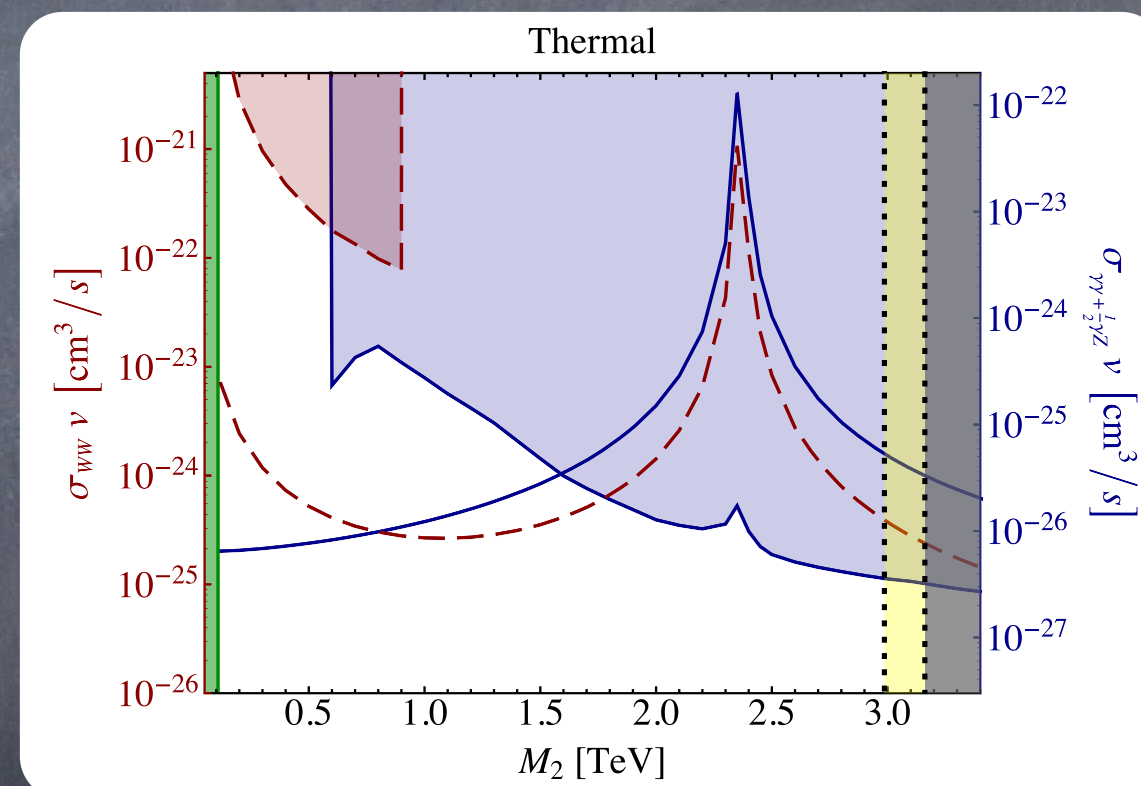
- So even if direct detection constraints are escaped by making neutralino pure ....
- there may be strong indirect detection constraints
- Photons from annihilation in galaxy today constrain pure wino or Higgsino DM



Escaping direct detection constraints

- Big cross-section!





Cohen, Lisanti, Pierce, Slatyer

Pure bino DM escapes

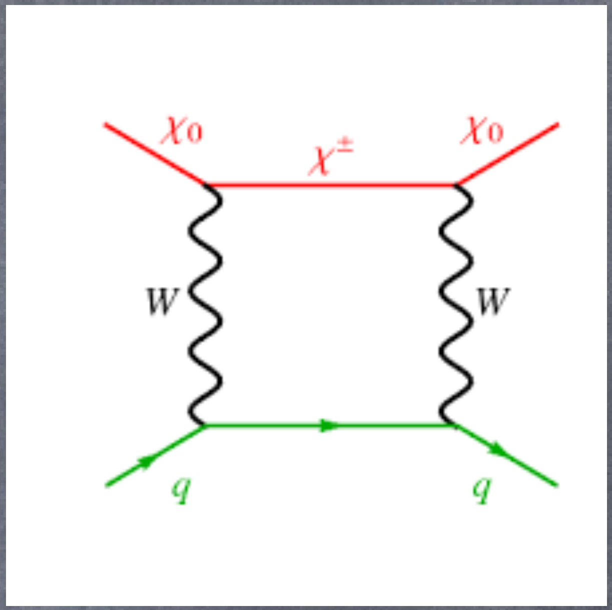
- While wino and Higgsino may be constrained by indirect detection, bino escapes
- But, even bino has Higgsino component set by μ
- Require $\mu \gg M_1 \sim m_{wk}$ to get rid of Higgsino component
- Same parameter enters into Z boson mass

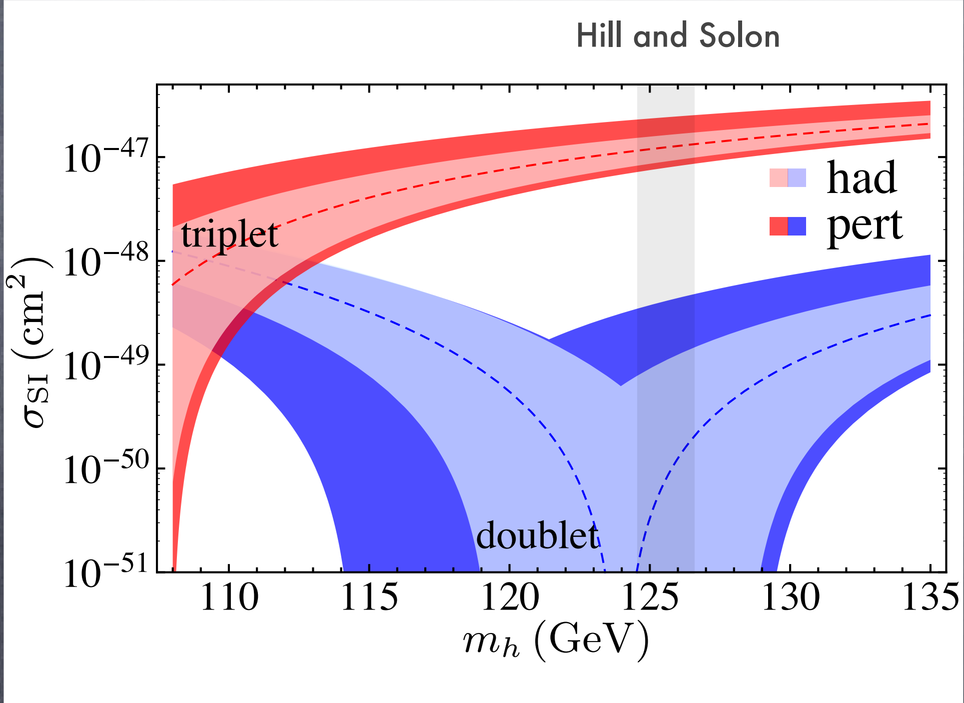
$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

⇒ Must tune parameters

Loops Matter

- Even if Tree scattering process vanishes, Future WIMP DM probes can reach 1-loop suppressed processes!
- 1-loop suppressed wino can be ruled out
- 1-loop Higgsino harder

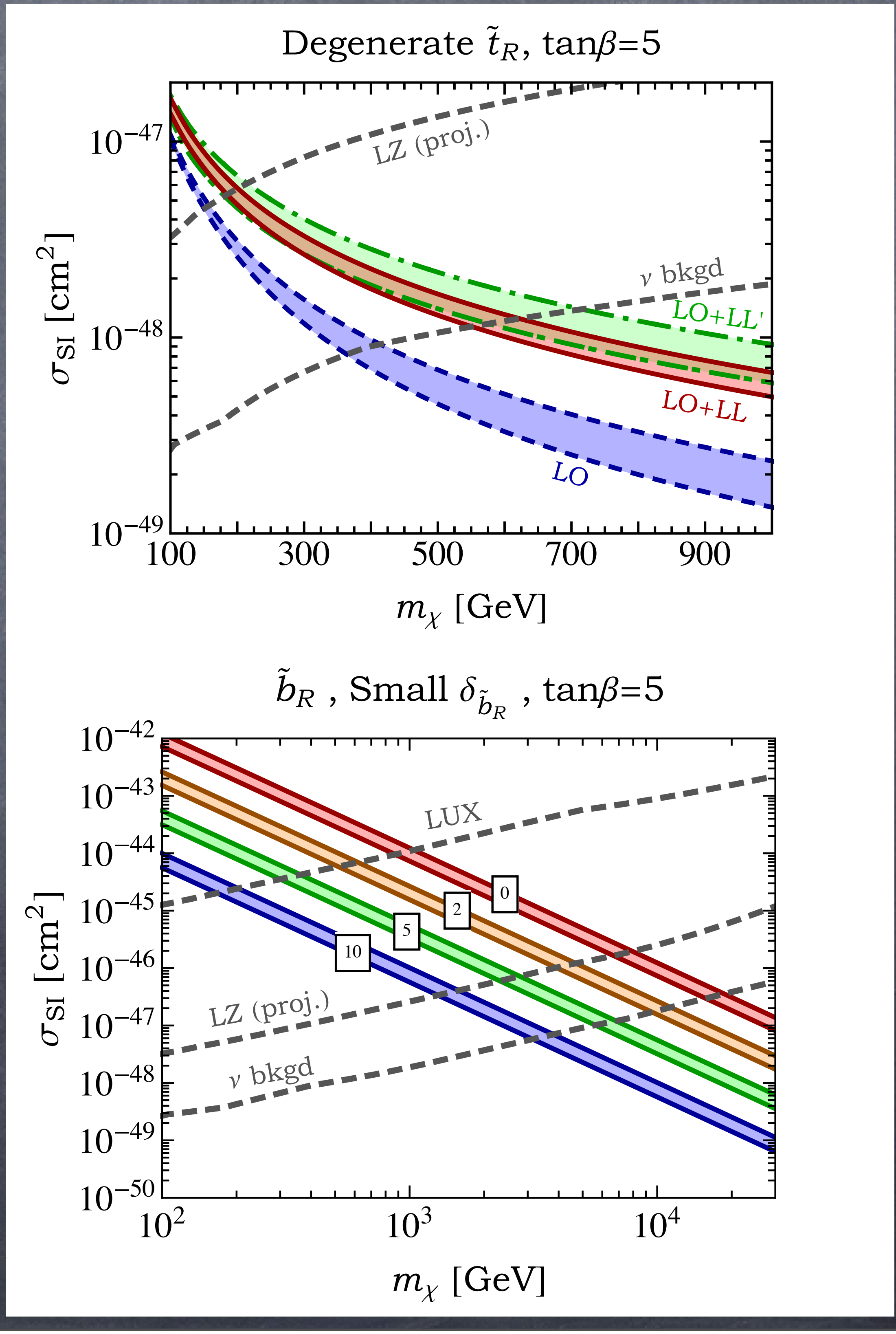


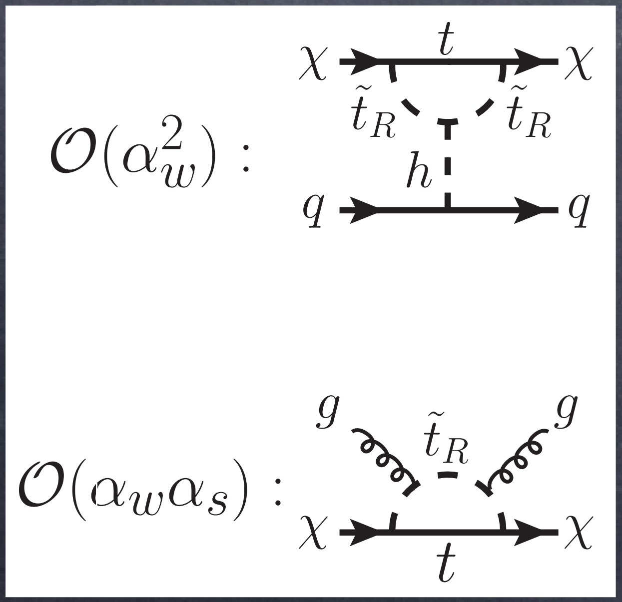


Loops Matter

- Even 1-loop bino can be probed in some cases

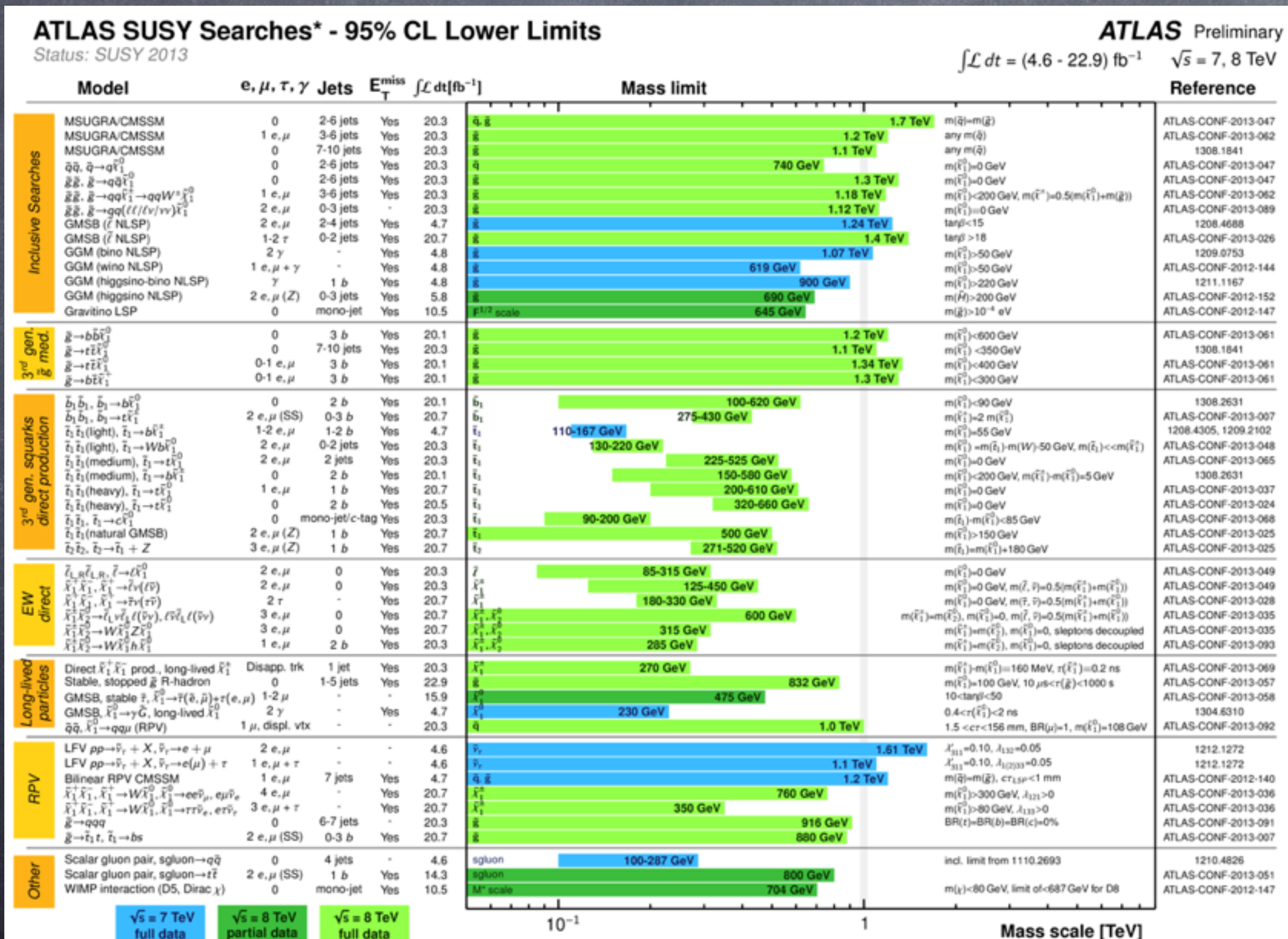
- DM experiments searching for WIMP enter into precision era





Berlin, Robertson, Solon, KZ, 1511.05964

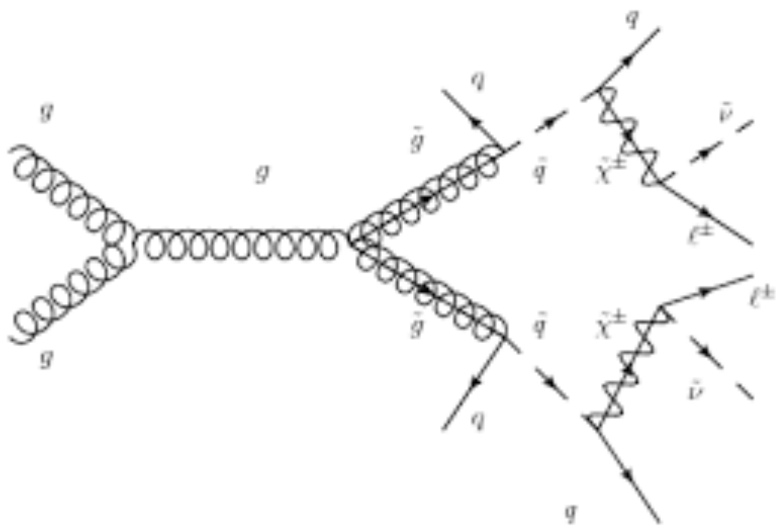
Waiting for SUSY



Tuesday, February 16, 16

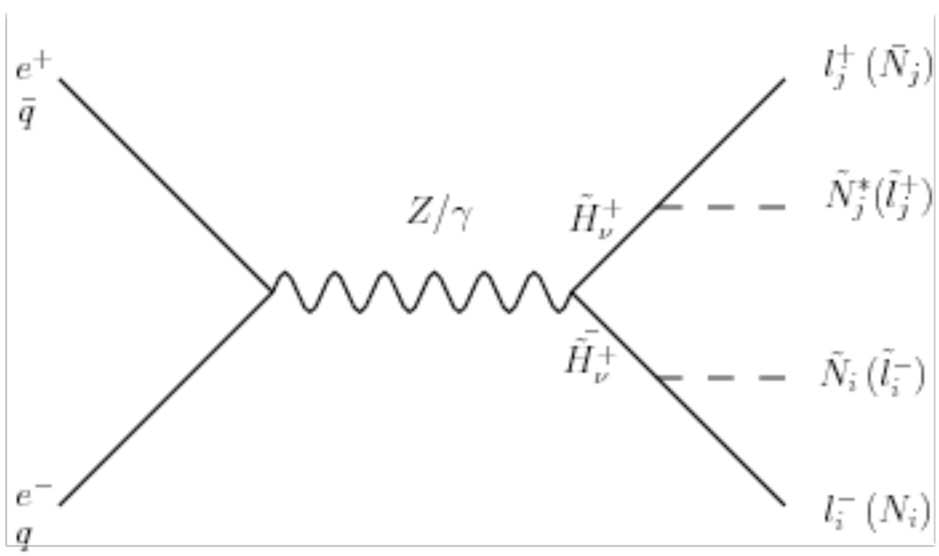
LHC is not a DM Machine

- Strong constraints on strong particles



> 1 TeV

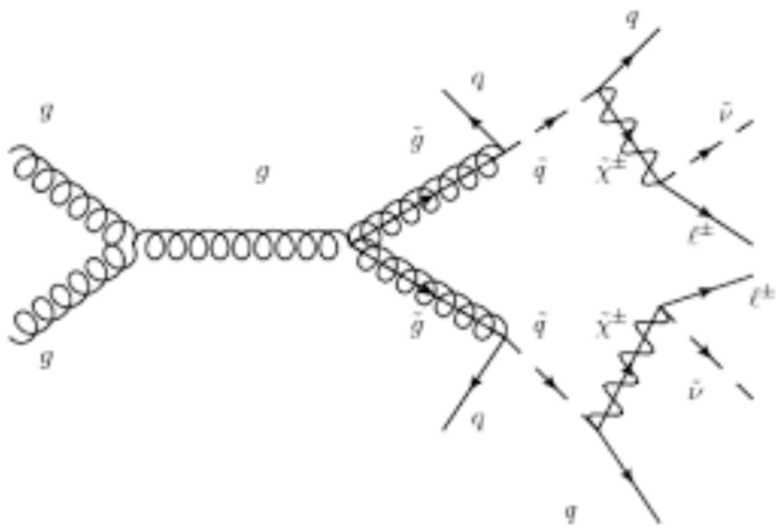
- Weak constraints on weak particles



> 200-300 GeV

LHC is a Mediator Machine

- Strong constraints on strong particles



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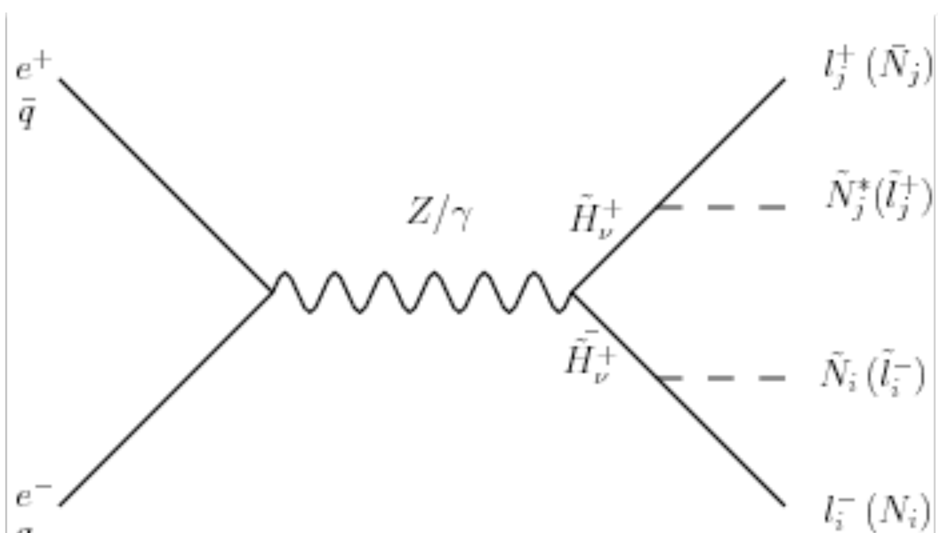
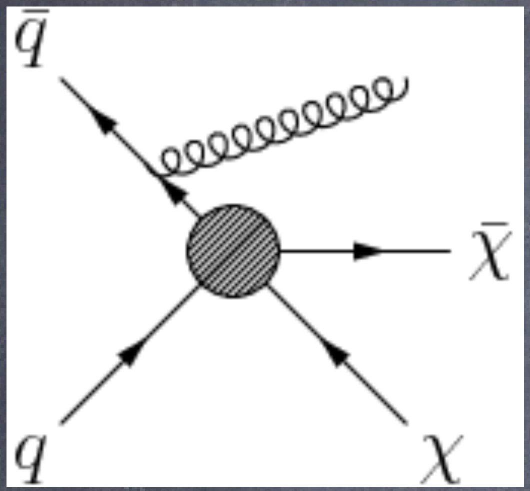
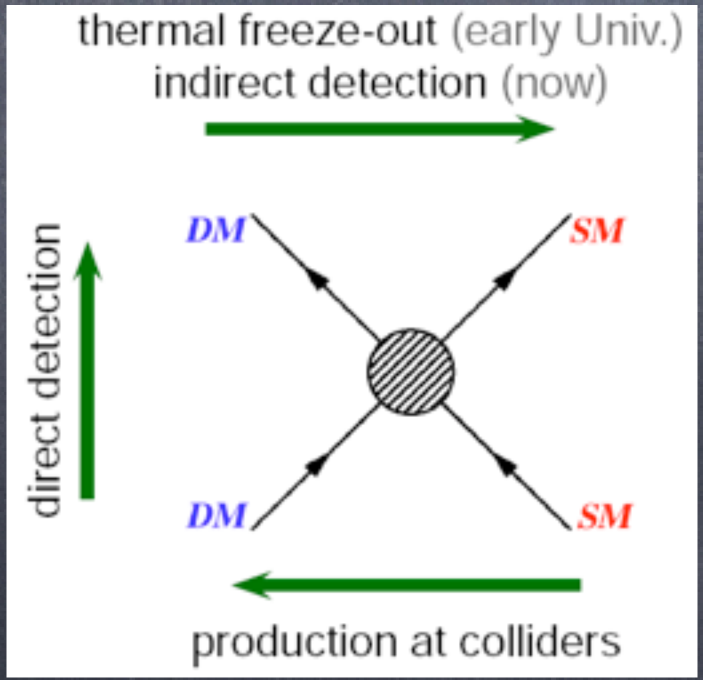
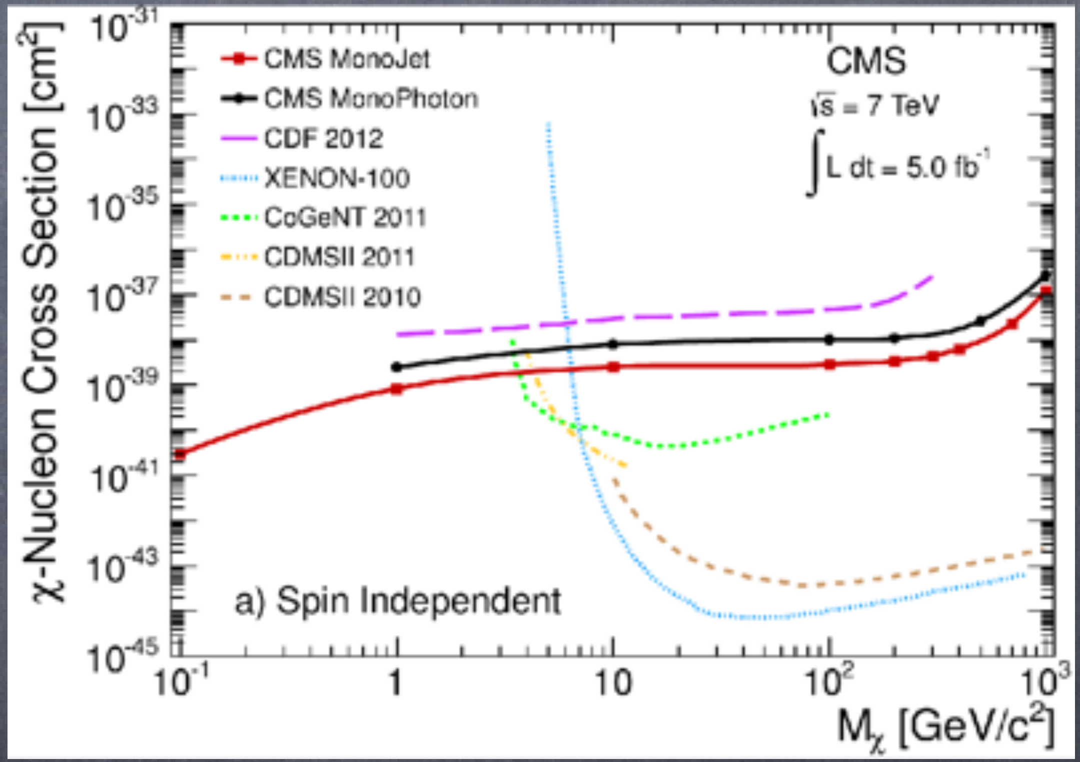


> 200-300 GeV

"Model Independent" Collider Searches for DM

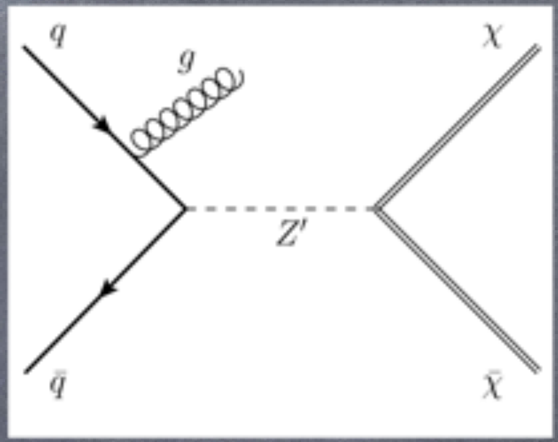


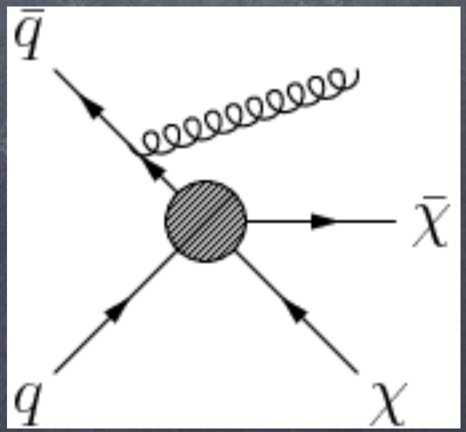




Mono-X is not a discovery mode

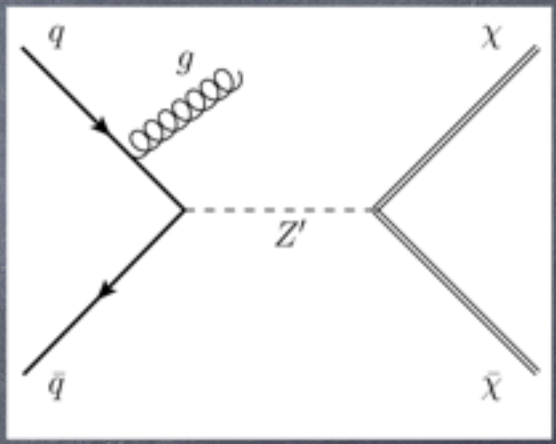
- Important theory dependence in these plots!
- Inappropriate use of higher dimension operators
- Failure to take into account direct searches for mediator

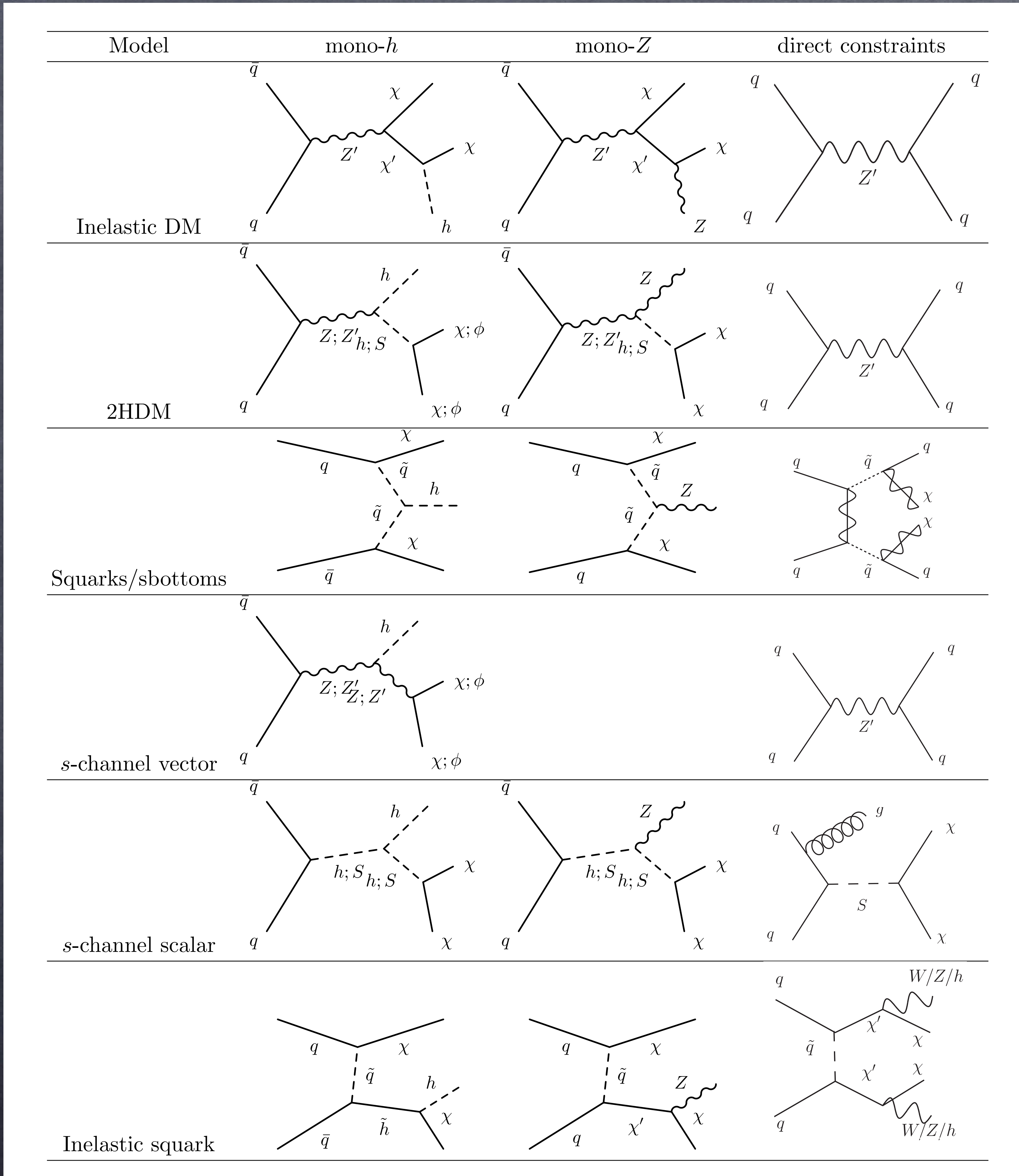




Domain of Importance

- LHC is effective on heavy, relatively strongly coupled mediators
- Direct detection is unparalleled when mediator is light, small couplings to protons
- Direct searches for mediator almost always more constraining than mono-X



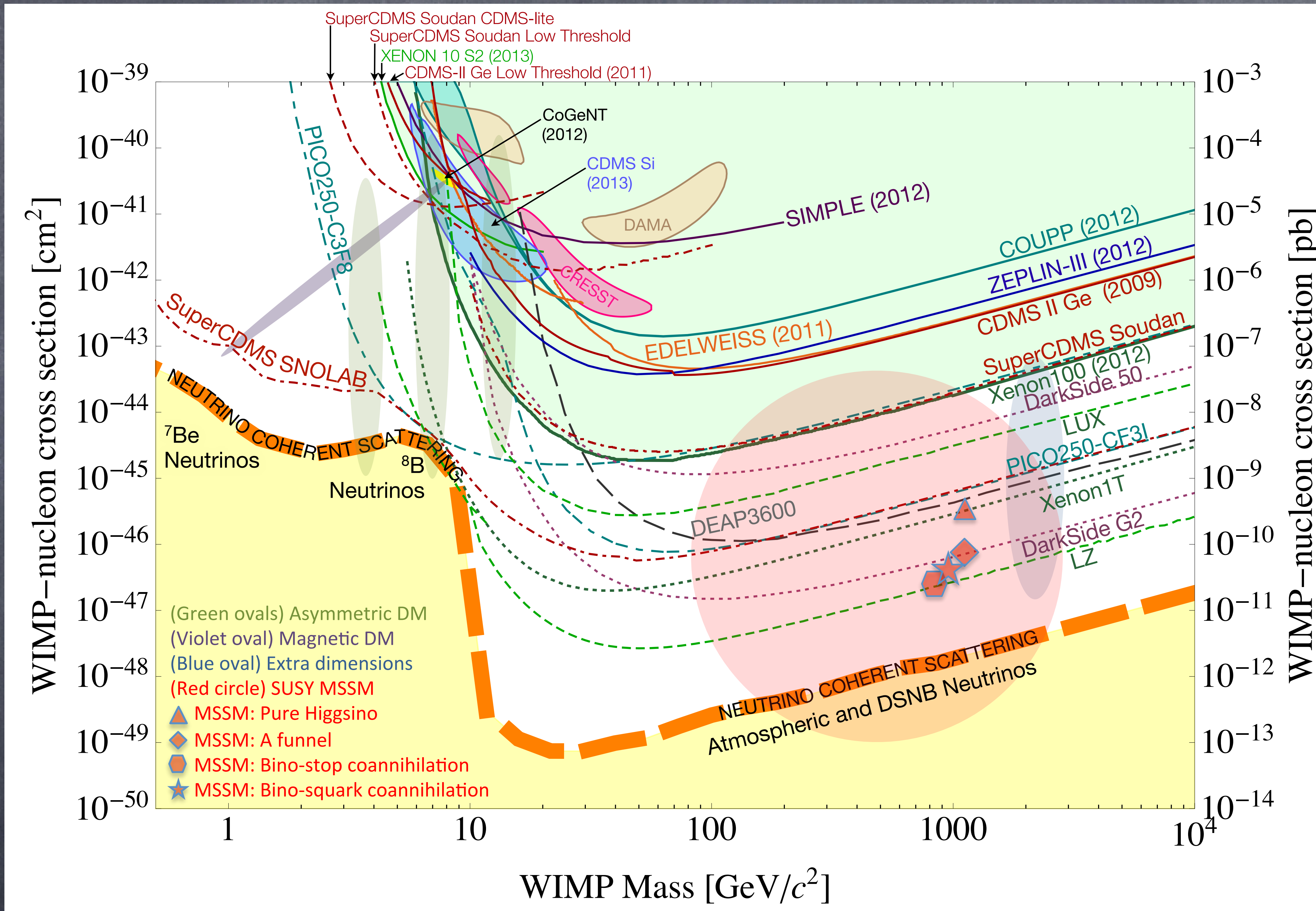


Search	Model where it matters
mono-h	Inelastic DM, 2HDM
mono-z	Inelastic DM, 2HDM
mono-jet	squark mediated production, compressed spectrum
mono-b	sbottom mediated production, compressed spectrum
mono-t	stop mediated production, RPV-like

Liew, Papucci, Vichi, KZ, to appear

When Should We Start Looking Elsewhere?

- Cannot kill neutralino DM via direct detection, but paradigm does become increasingly tuned
- Likewise, LHC will only continue to push constraints on mediating SUSY colored particles up, though relatively weak constraints on DM itself



SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
PICO250-C3F8
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c2]

Dark Matter Model Dynamics

(Looking beyond the vanilla WIMP paradigm)

DM Paradigm: recap

- Usual picture of dark matter is that it is:
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  - stable
  - (sub-?) weakly interacting
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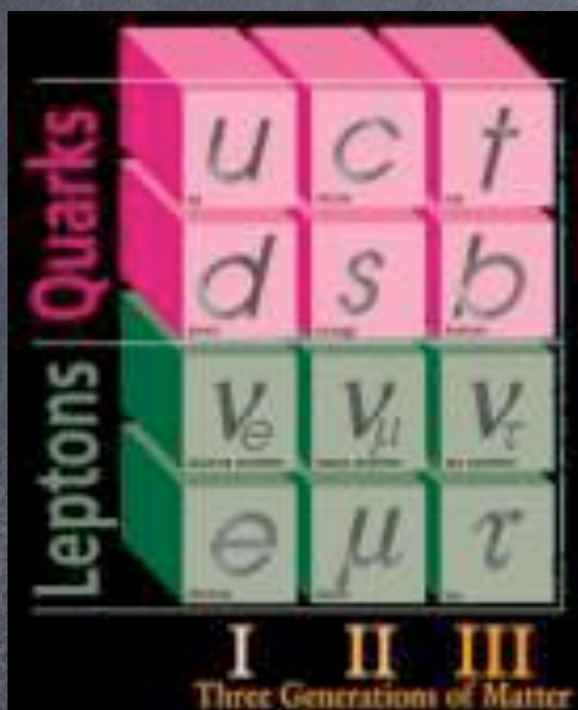
Supersymmetry and axions fit the bill.

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 mechanisms .....

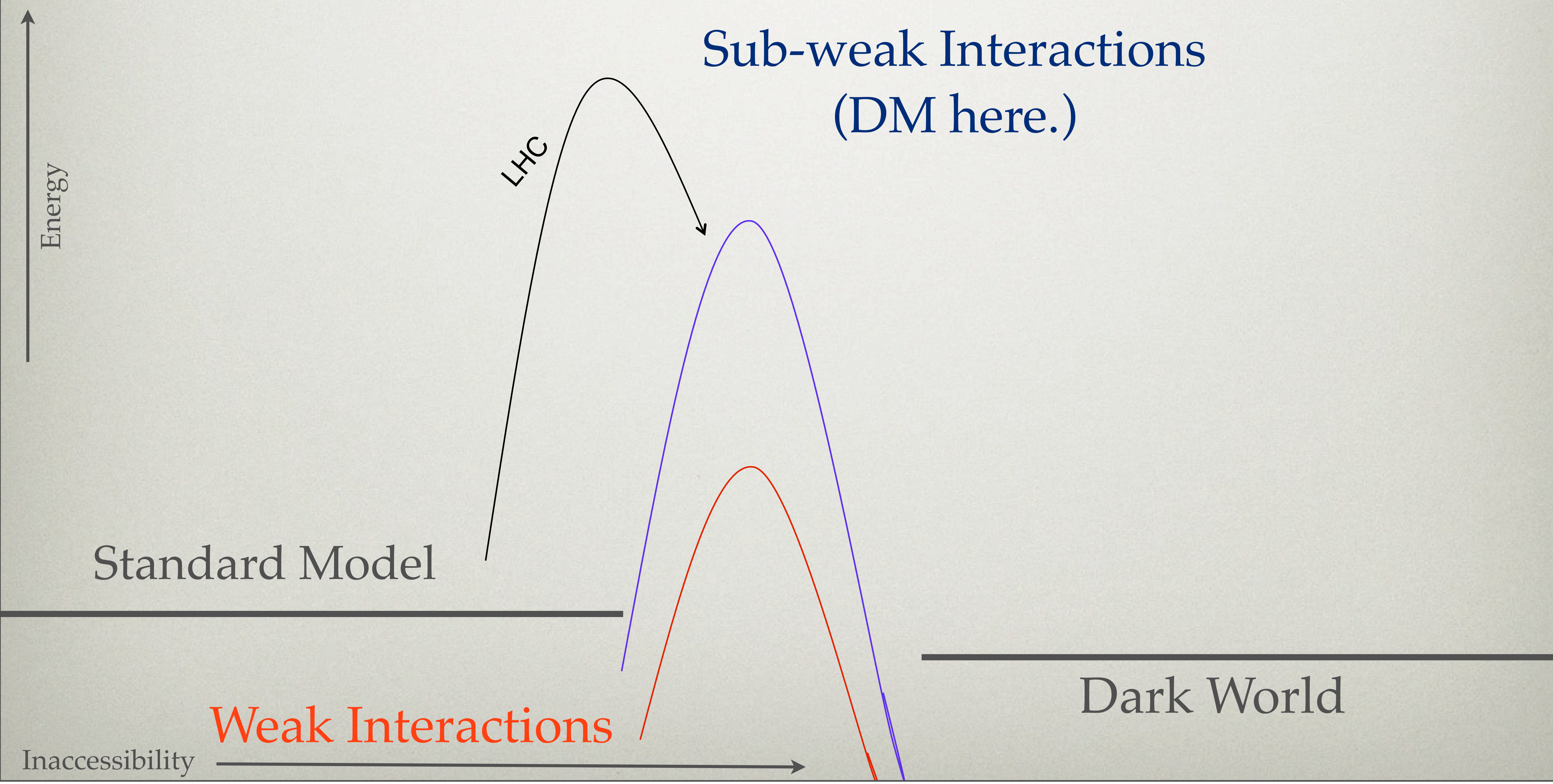
$M_p \sim 1 \text{ GeV}$

Standard Model

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

Hidden Valleys

Strassler, KZ 2006



Hidden Valleys

Strassler, KZ 2006

Sub-weak Interactions

(DM here.)

LHC

Energy

Torres del Paine

Standard Model

Dark World

Weak Interactions

Inaccessibility

Our Thinking Has Shifted: Why?

- Simple, attractive, phenomenologically viable models exist
- Example: ADM. Start with a single DM particle X, and one discovers you need more particles

$n_X \sim 10^{-10} T^3$

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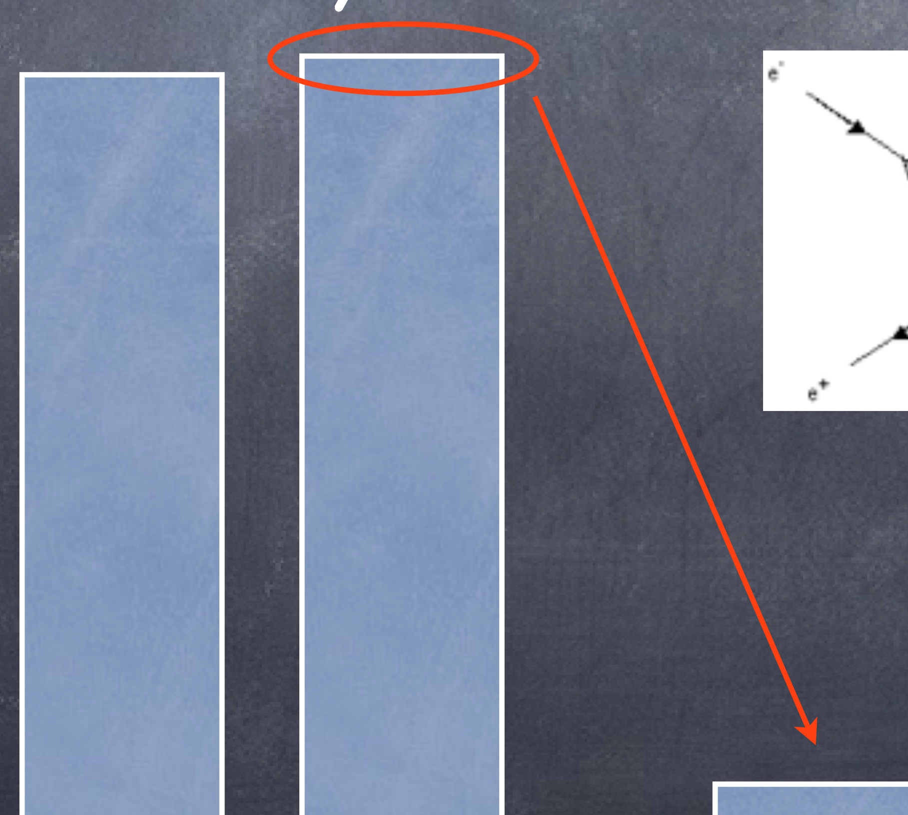
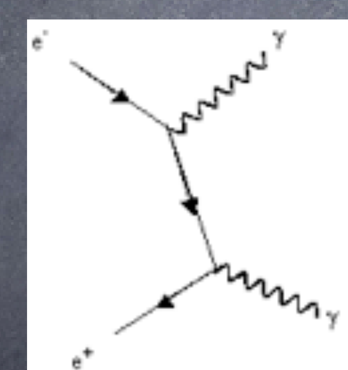
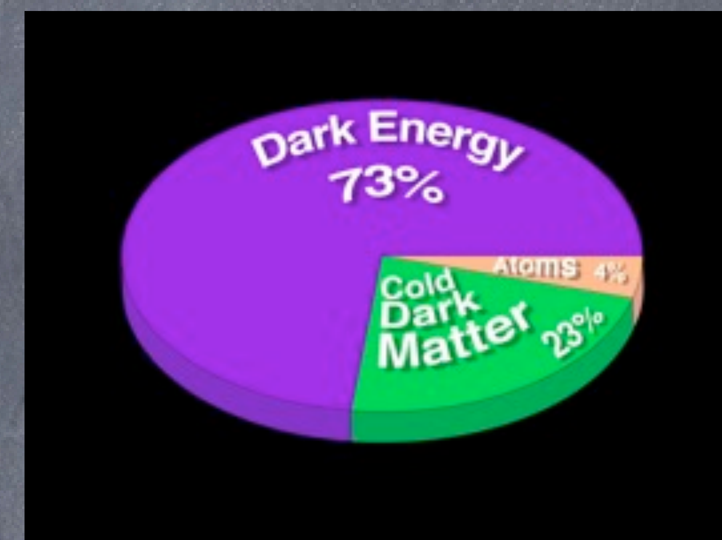




$n_X \sim 10^{-10} T^3$

Baryon and DM Number Related?

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



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

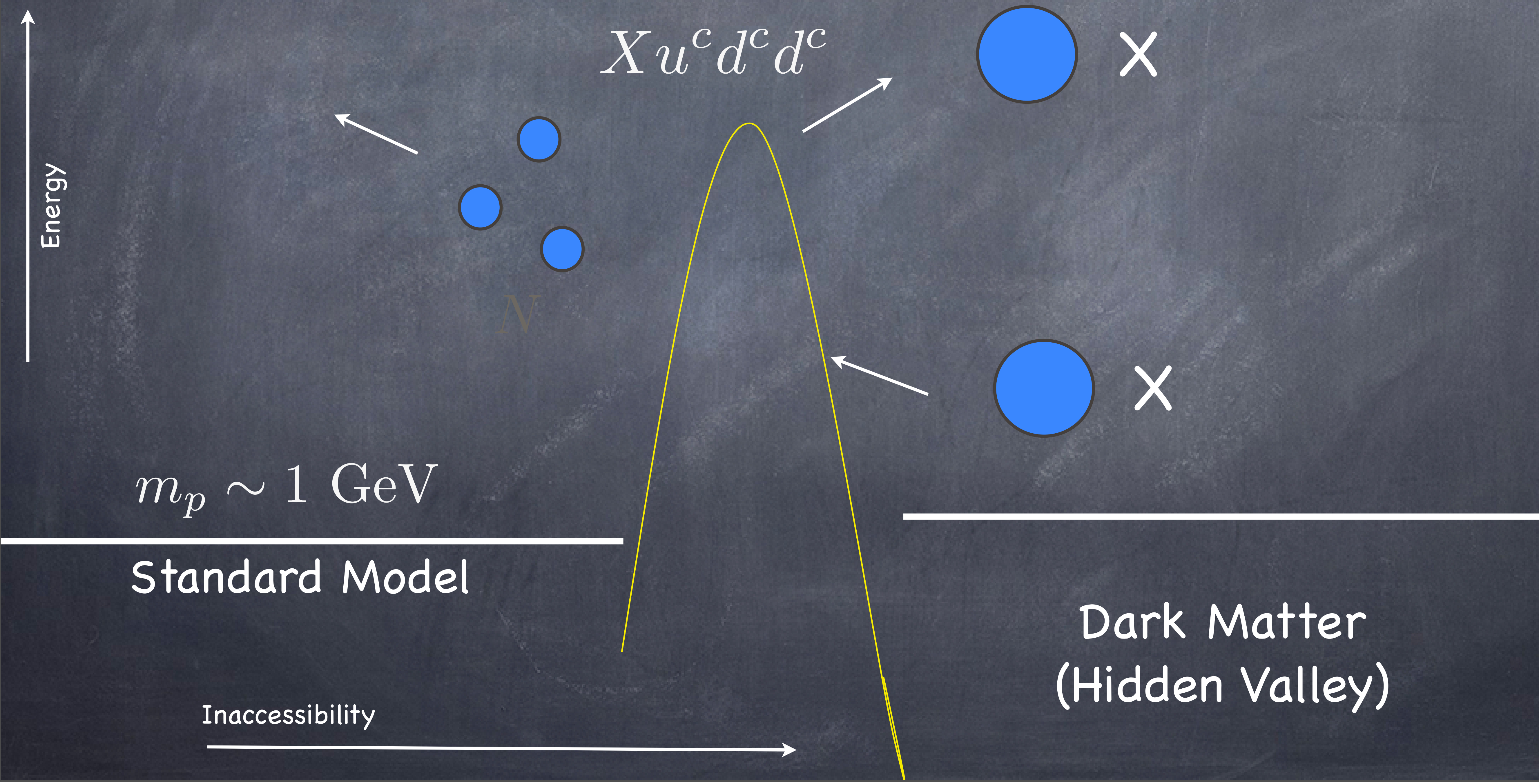
Mechanism $n_{DM} \approx n_b$

$\Rightarrow$ $m_{DM} \sim 5\ \text{GeV}$

Asymmetric DM

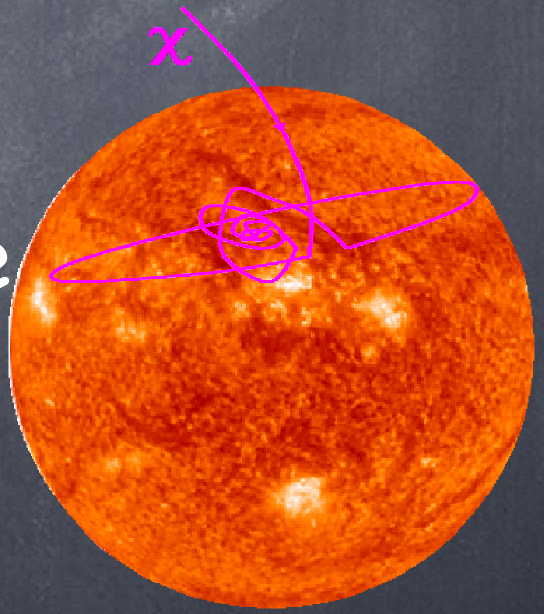
"Integrate out" heavy state
Higher dimension operators:

Luty, Kaplan, KZ
0901.4117



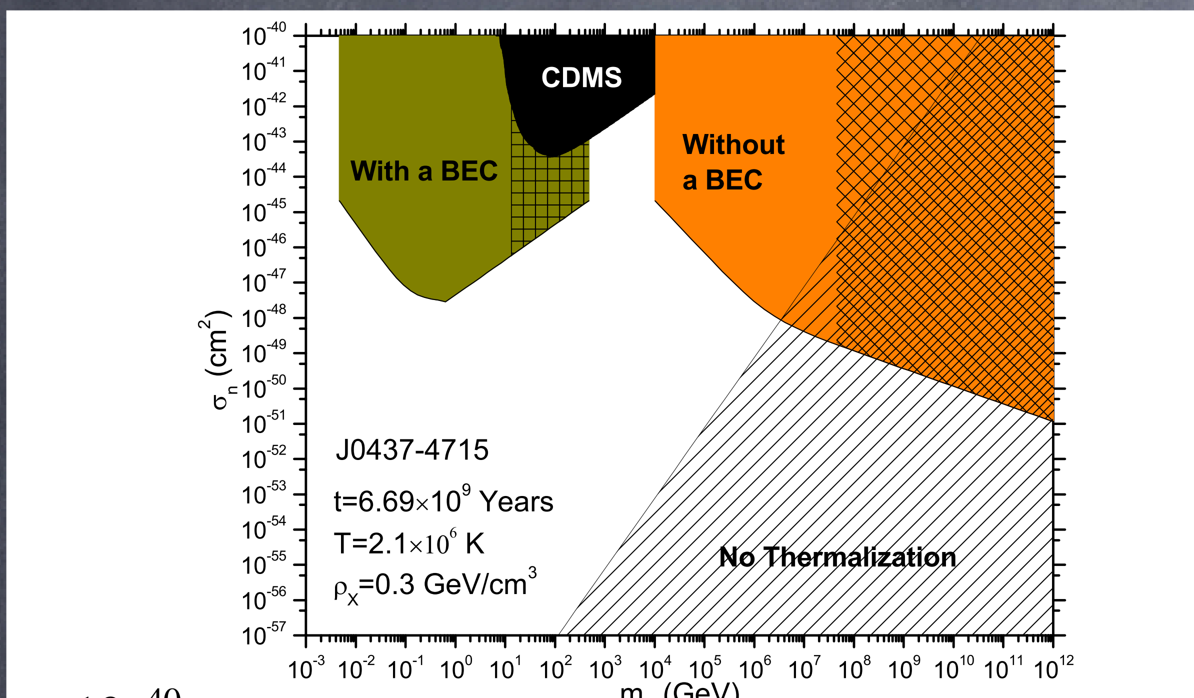
Astrophysical Implications

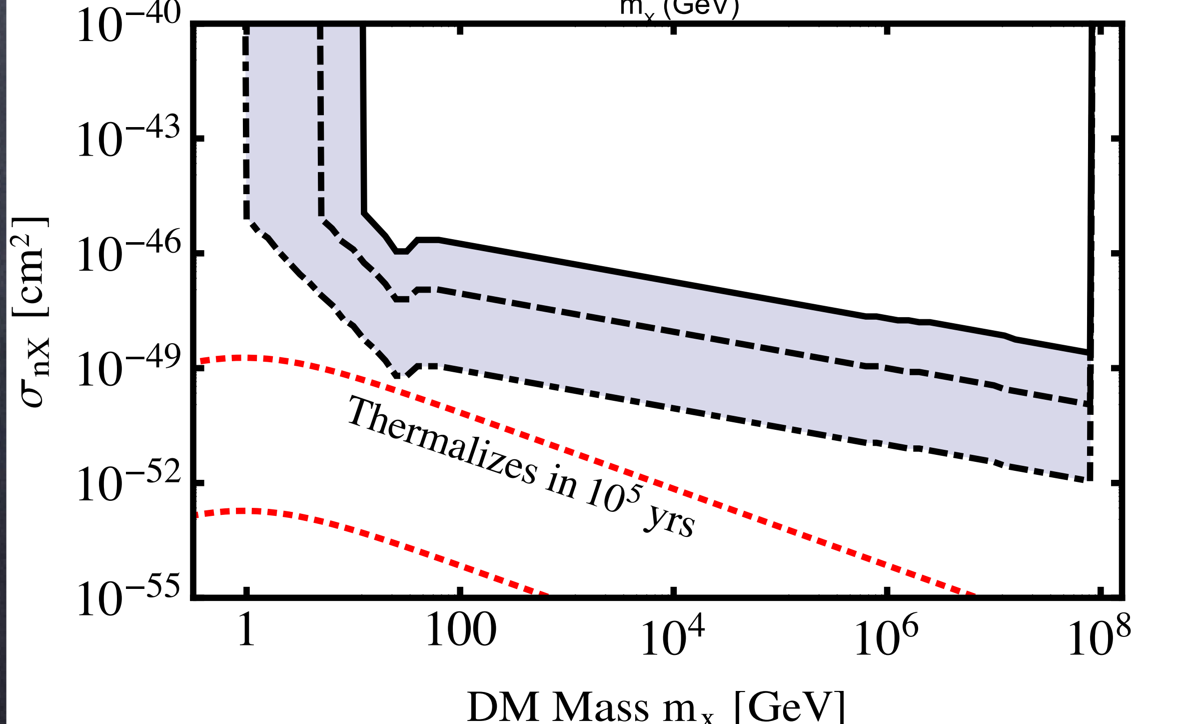
- DM does not annihilate
- It can accumulate in the center of stars
- Notable case: neutron stars
- Elastically scatter, come to rest in core
- High density!

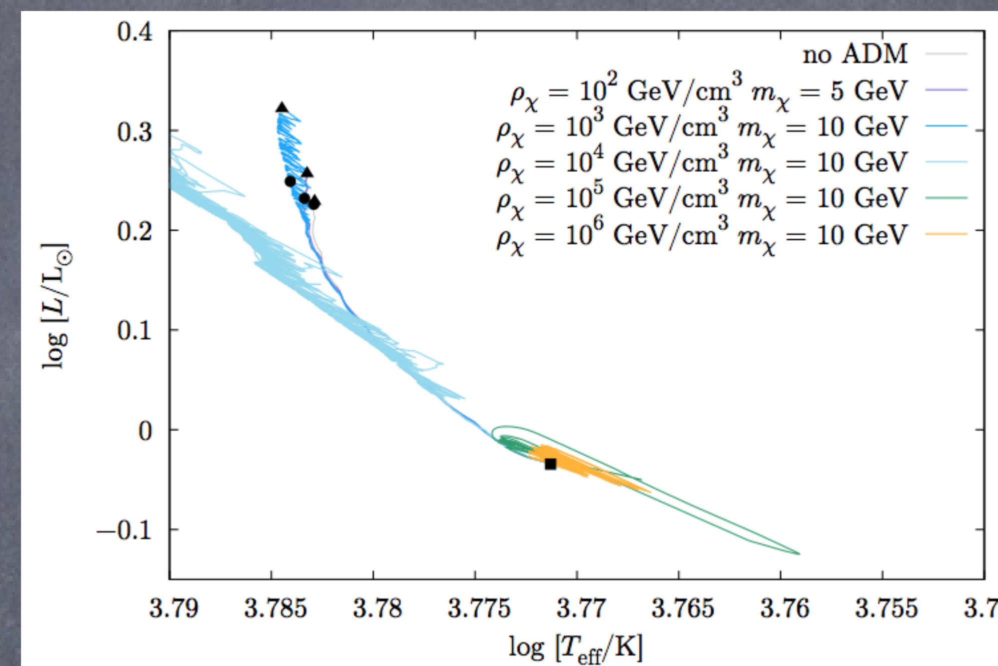


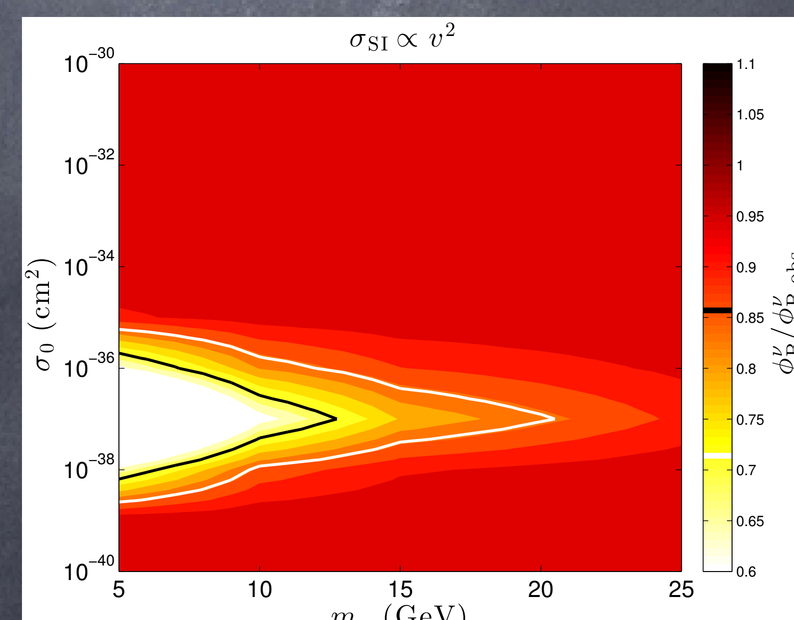
Altering Stellar Interiors

McDermott, Yu, KZ 1103.5472 Bramante, Linden 1405.1031 Taoso et al, 1005.5711 Vincente et al, 1504.04378







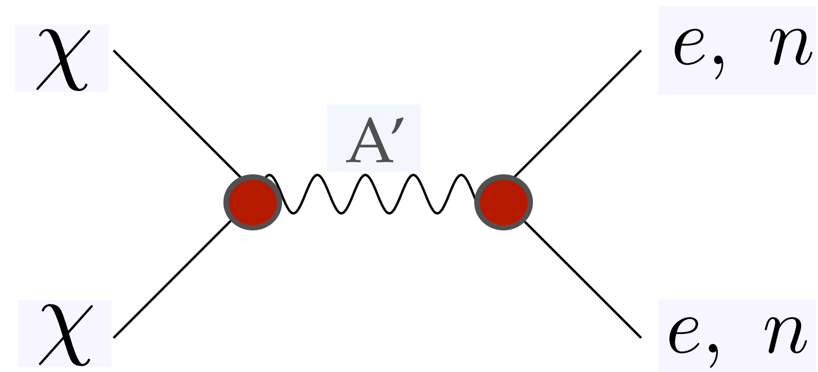


Exp. Implications of Dark Sectors ....

- .... with dark forces
  - Direct Detection
  - Intensity experiments
  - DM self-scattering and halo shapes

Direct Detection

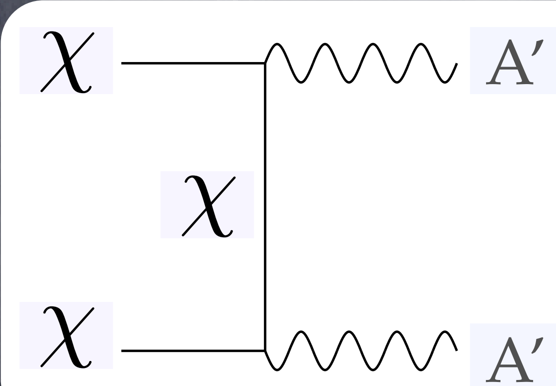
- Mediates _large_ scattering cross-sections



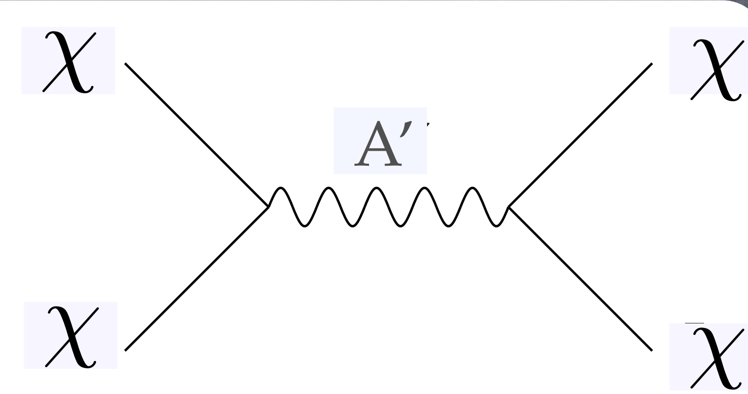
$$\sigma_{SI} \simeq \frac{g_n^2 g_\chi^2 m_r^2}{\pi m_{A'}^4}$$

$$\sim 10^{-40}\ \text{cm}^2 \left(\frac{g_n g_\chi}{10^{-4}}\right)^2 \left(\frac{8\ \text{GeV}}{m_{A'}}\right)^4$$

- Simplified model gives rise to many effects



DM relic abundance

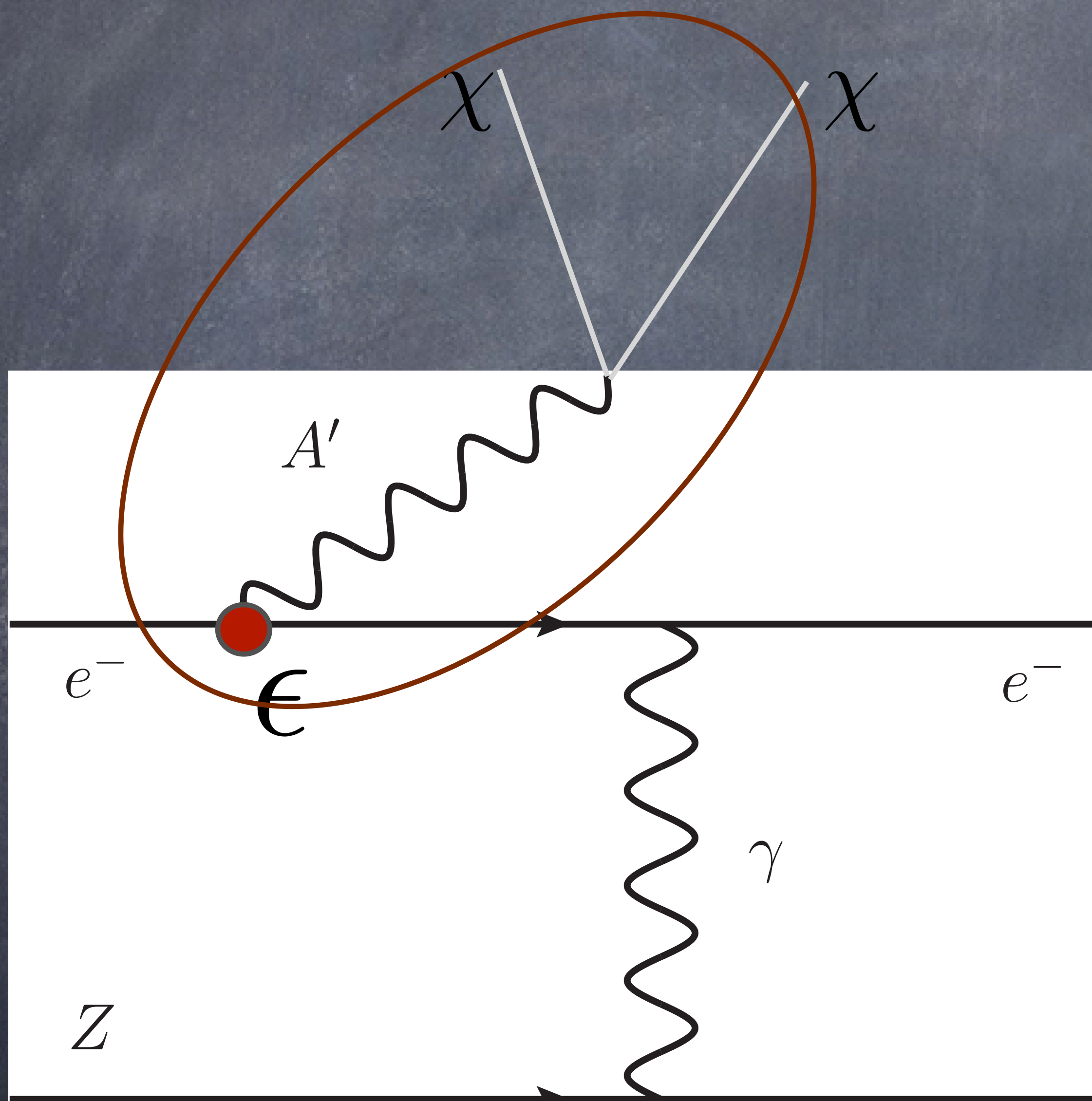


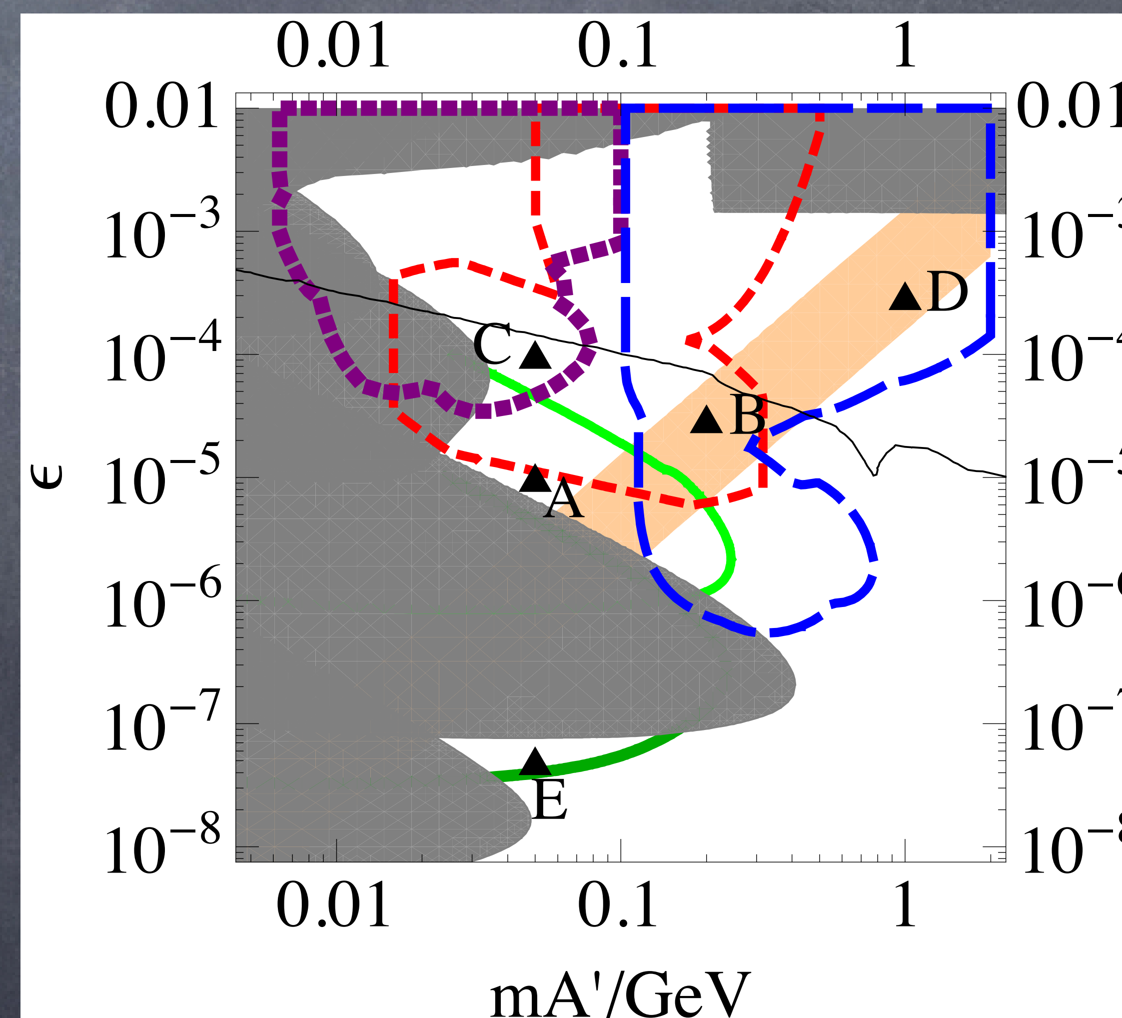
DM self-scattering

Connection to Intensity Experiments

- Dark sectors may be more efficiently produced in low energy intensity experiments
- Once above mass scale of mediator, production x-sect scales as $\sigma \sim \frac{g^4}{E^2}$
- Low energy, very intense beams generated increased sensitivity
- Prefer beam energy sitting on mass of mediator $E \sim m_M$

Connection to Intensity Experiments

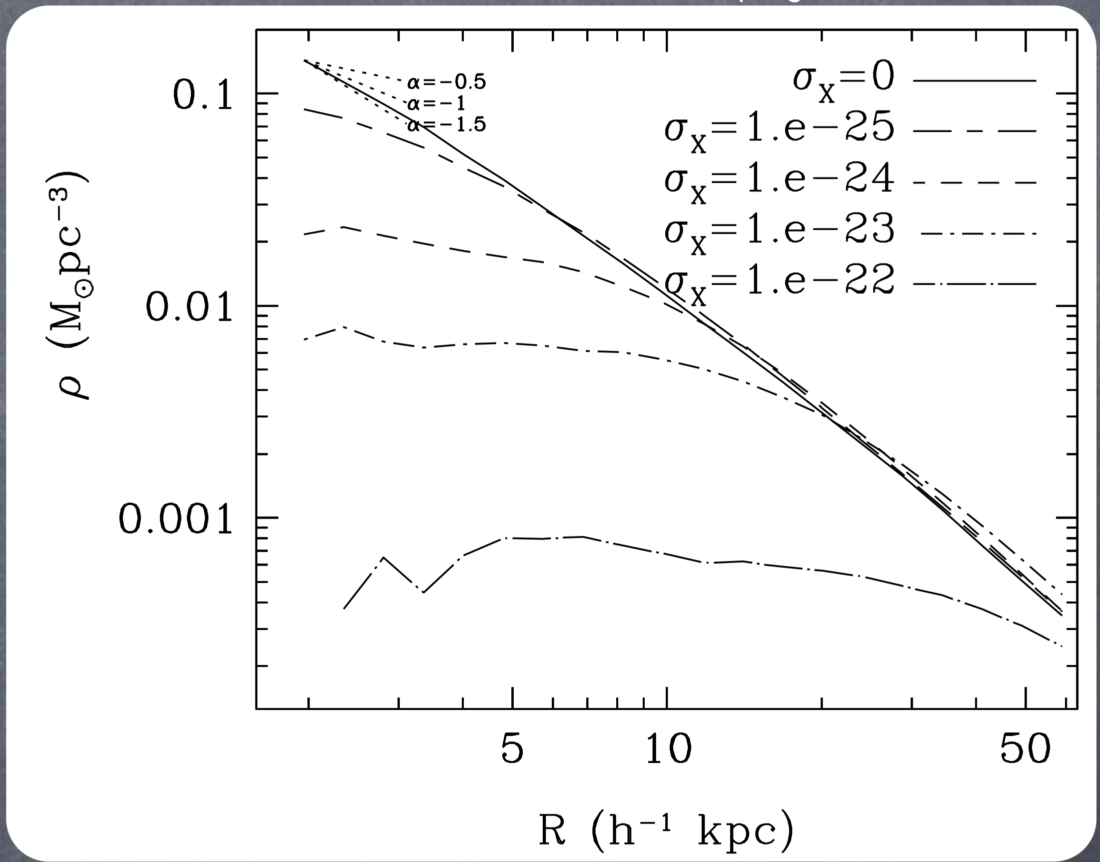




DM Interactions and DM Halos

- 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



Implies Dark Forces!

- Very **big** scattering cross-sections

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

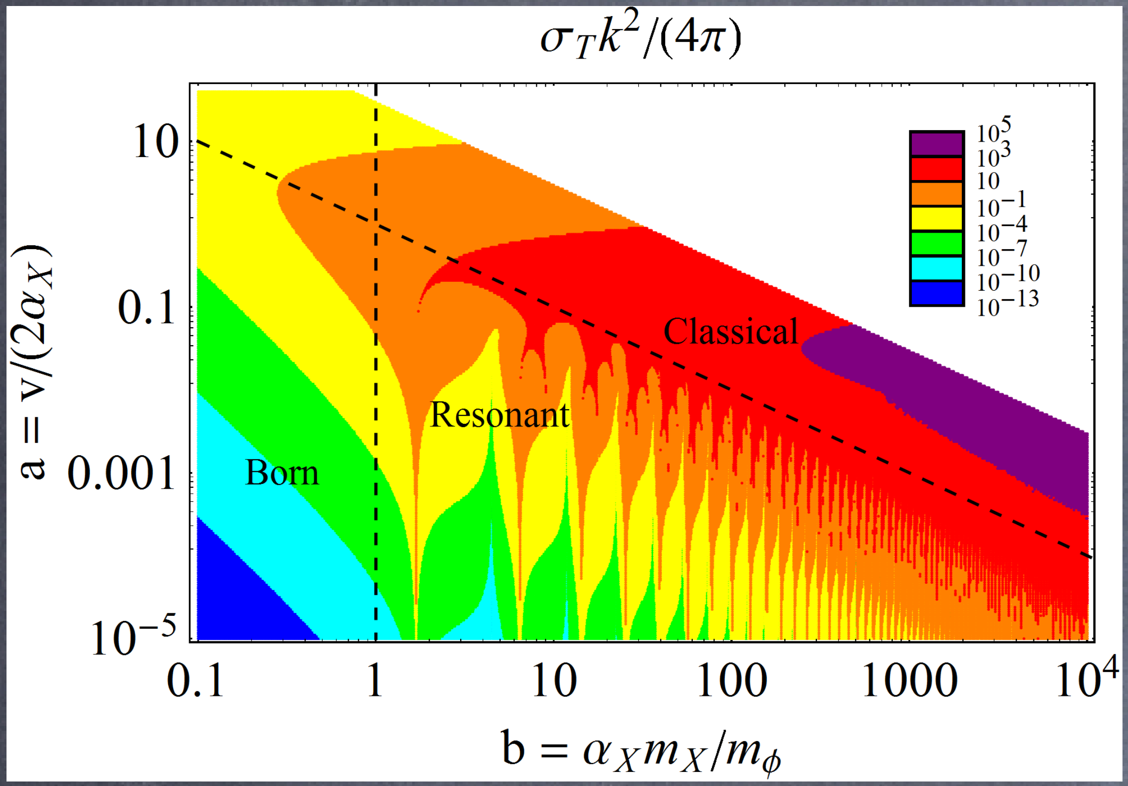
- Fits well with new models of DM!

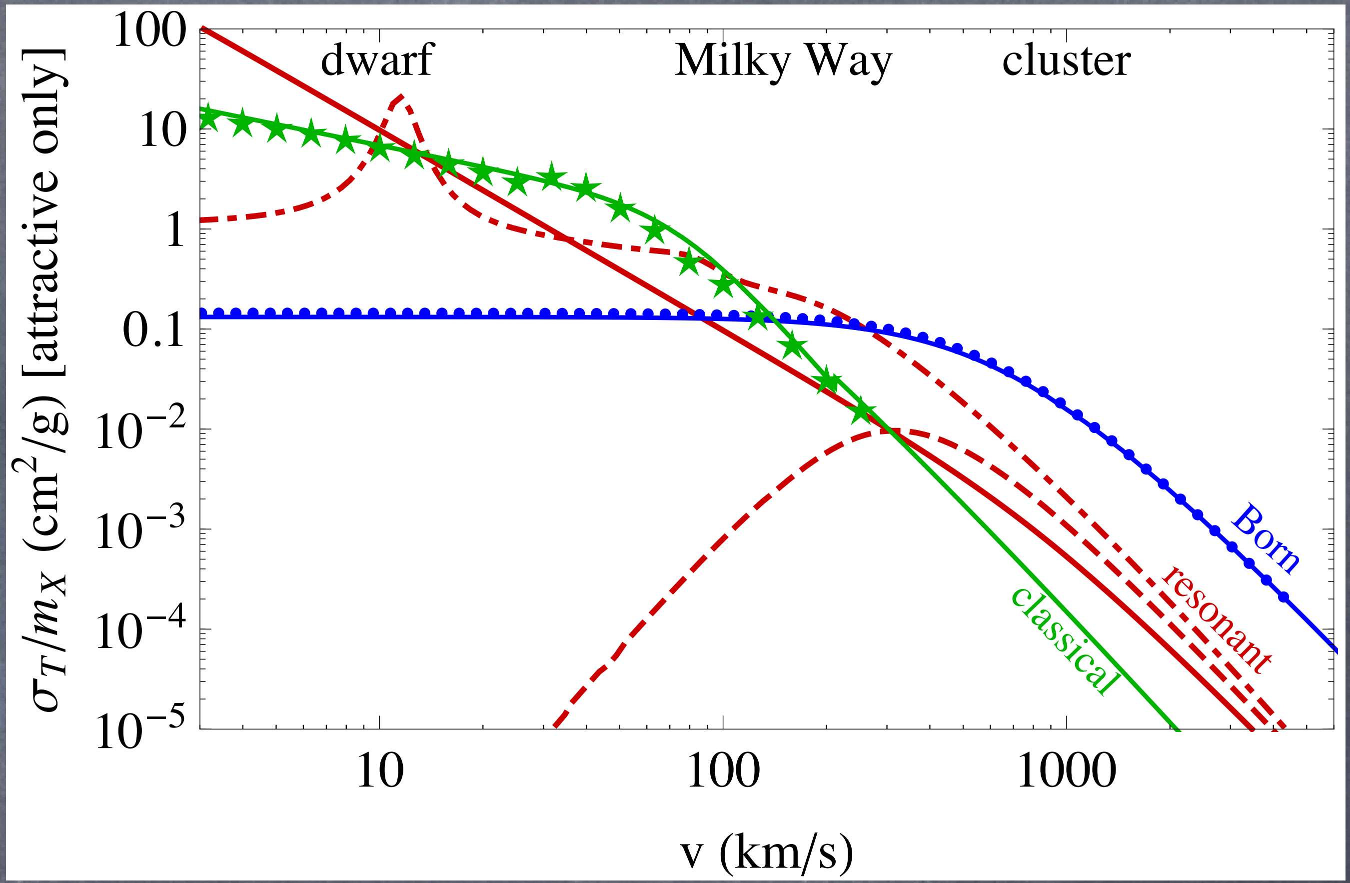
$$\sigma_T \approx 5 \times 10^{-23}\ \mathrm{cm}^2 \left(\frac{\alpha_X}{0.01}\right)^2 \left(\frac{m_X}{10\ \mathrm{GeV}}\right)^2 \left(\frac{10\ \mathrm{MeV}}{m_\phi}\right)^4$$

- Range of dynamics much bigger than previously thought

- Particle imprints on DM halos

Bound State Scattering



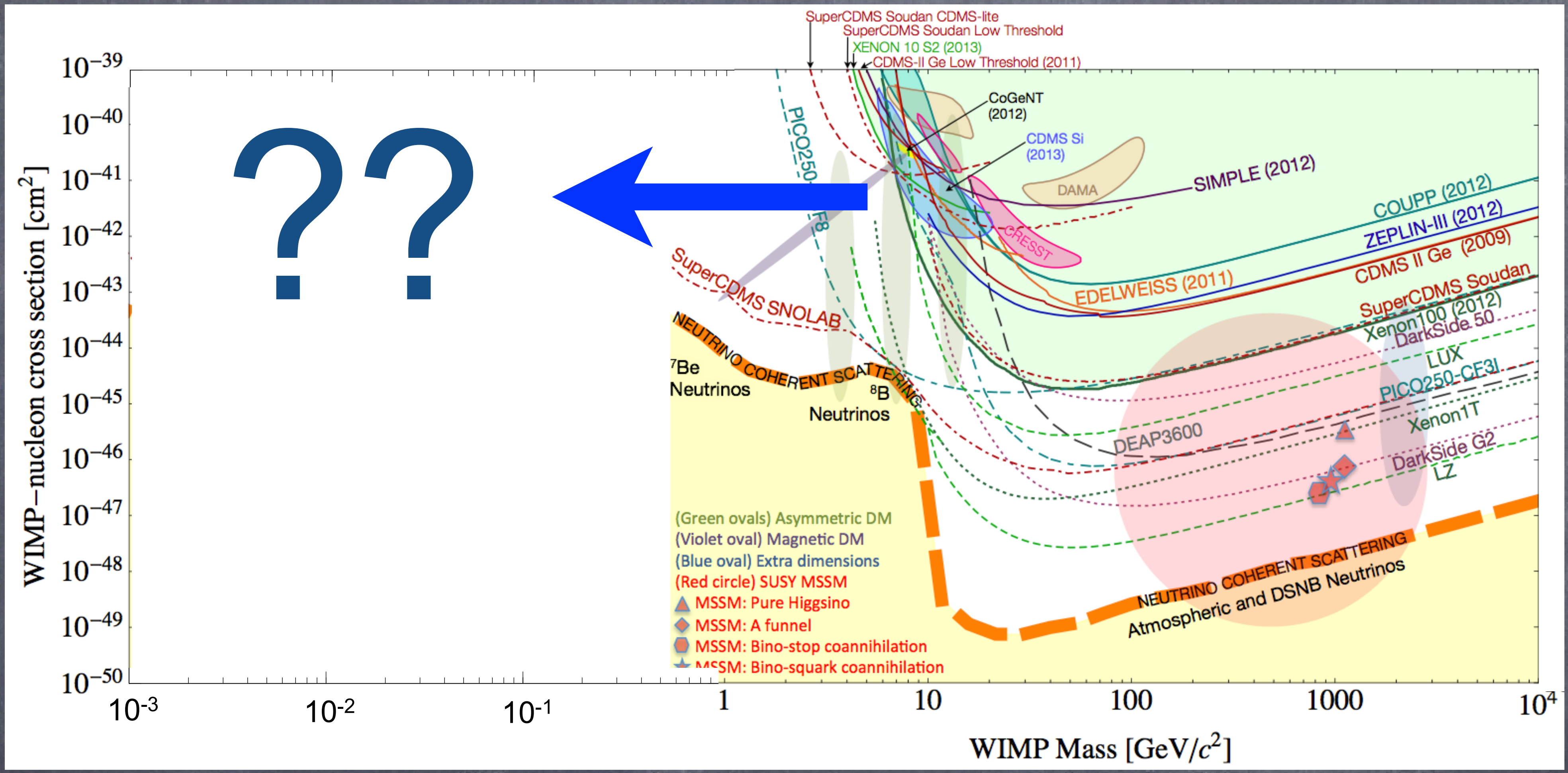


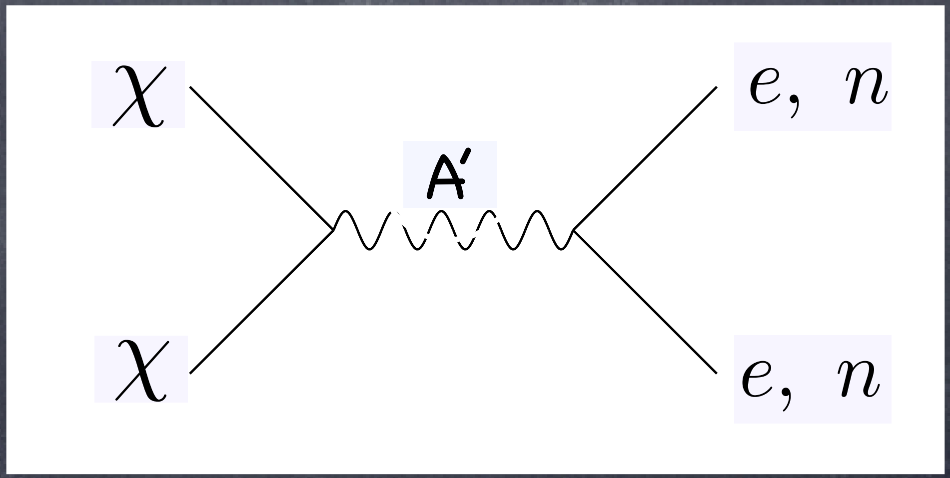
Quantum Resonances and Strongly Coupled Dynamics in DM Halos

Tulin, Yu, KZ, 1210.0900

Tulin, Yu, KZ, 1302.3898

Terra Incognita





New Phases of Matter

- Nuclear Recoils are fundamentally kinematically limited

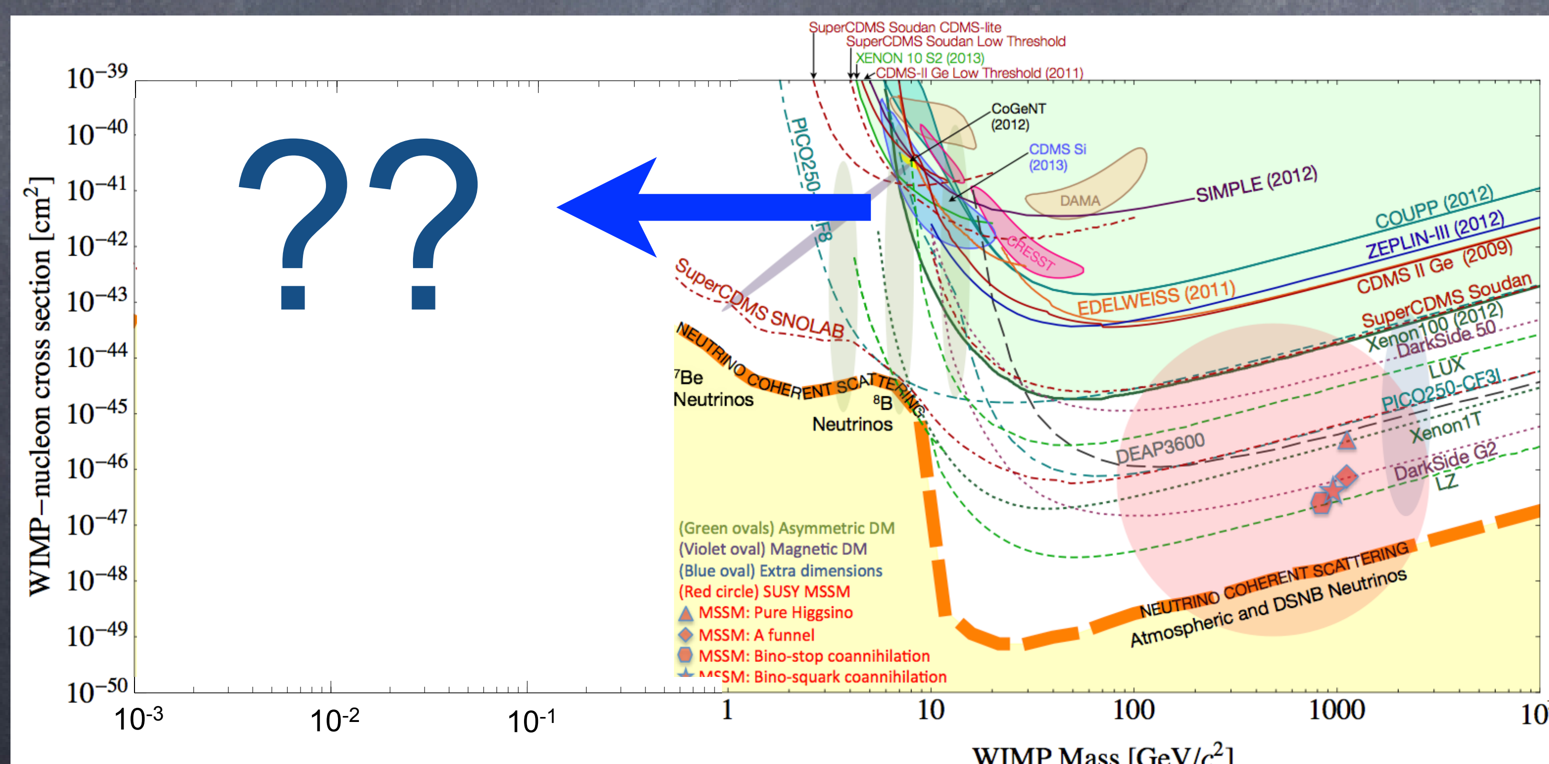
$$E_D \simeq q^2/(2m_{e,N}) \qquad q \sim m_X v$$

- 30 MeV DM corresponds to 1 eV of energy deposit on nucleons

- Electron targets extract more energy

Material Gap

- But target electrons have a gap
- Semi-conductors -- silicon, germanium [CDMS] -- 1 eV gap; Nuclei -- at least 10's of eV
- **Does not allow to detect DM lighter than 1 MeV**



Need new kinematics...

- .... Dark matter has much more kinetic energy than is extracted in nuclear recoils

$$E_D \simeq q^2/(2m_{e,N}) \qquad q \sim m_X v$$

vs

$$E = \frac{1}{2} m_X v^2$$

- How do we extract all the kinetic energy?

Superconductors have the needed features

- Need a nearly gapless material
- Metals are gapless (conduction electrons)
- But also very susceptible to thermal vibrations
- Superconductors are perfect: meV gap decouples phonon vibrations from electrons

Y. Hochberg, Y. Zhao, KZ, 1504.07237
Y. Hochberg, M. Pyle, Y. Zhao, KZ
1512.07630

Target Fermi Velocity

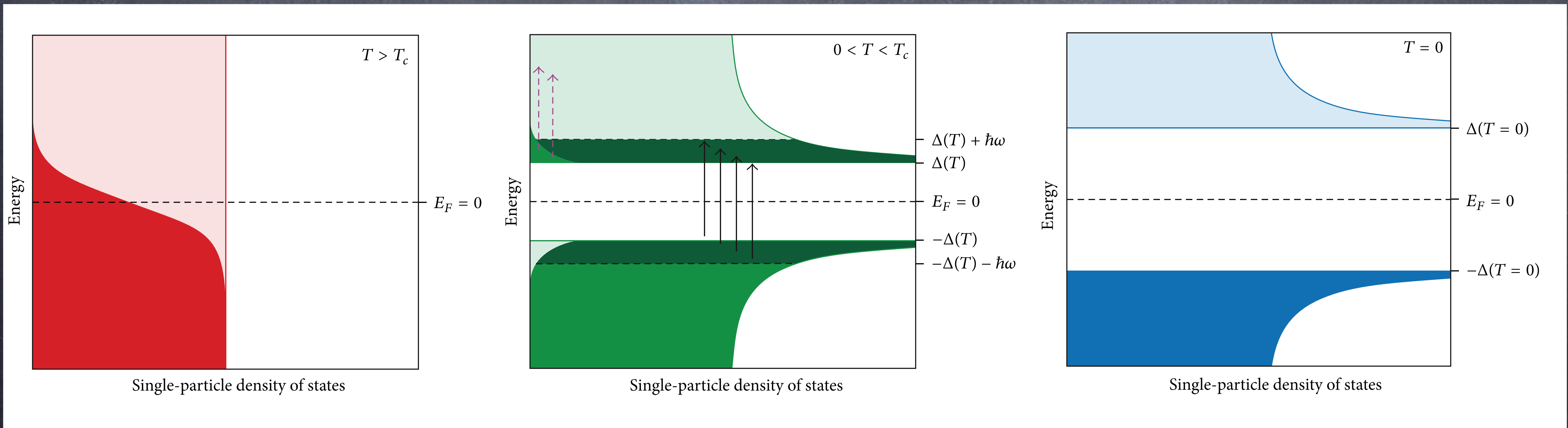
- Allows to extract entire DM kinetic energy $m_X = 1 \text{ keV} \leftrightarrow E_{\text{kin}} = 1 \text{ meV}$
- Non-rel (nuclear or electron) target: deposited energy reduced by target mass

$$E_D \simeq \frac{1}{2}\left(\frac{q^2}{m_T} + 2\vec{q}\cdot\vec{v}_{i,T}\right)$$

- In metal: $v_F \sim 10^{-2}$

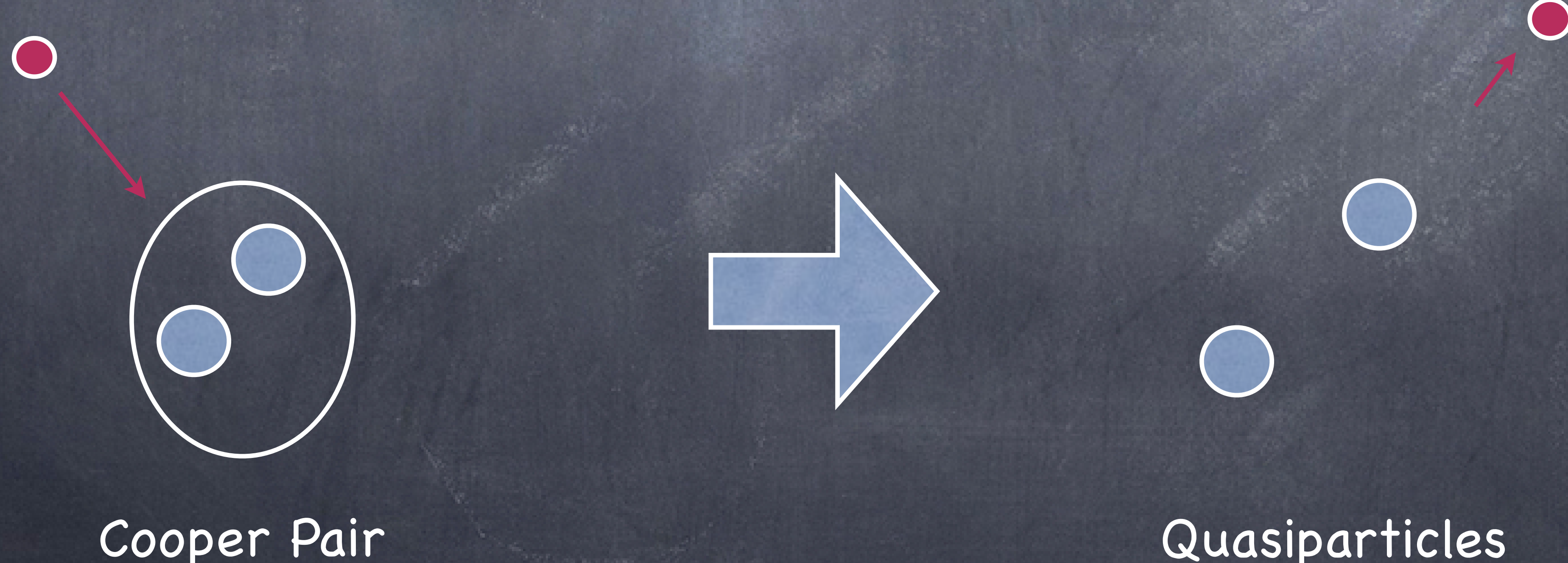
Superconductors and Dark Matter

- Ordinary metal undergoes phase transition as temp is cooled
- Energetically favorable for electrons in pair up; gap appears



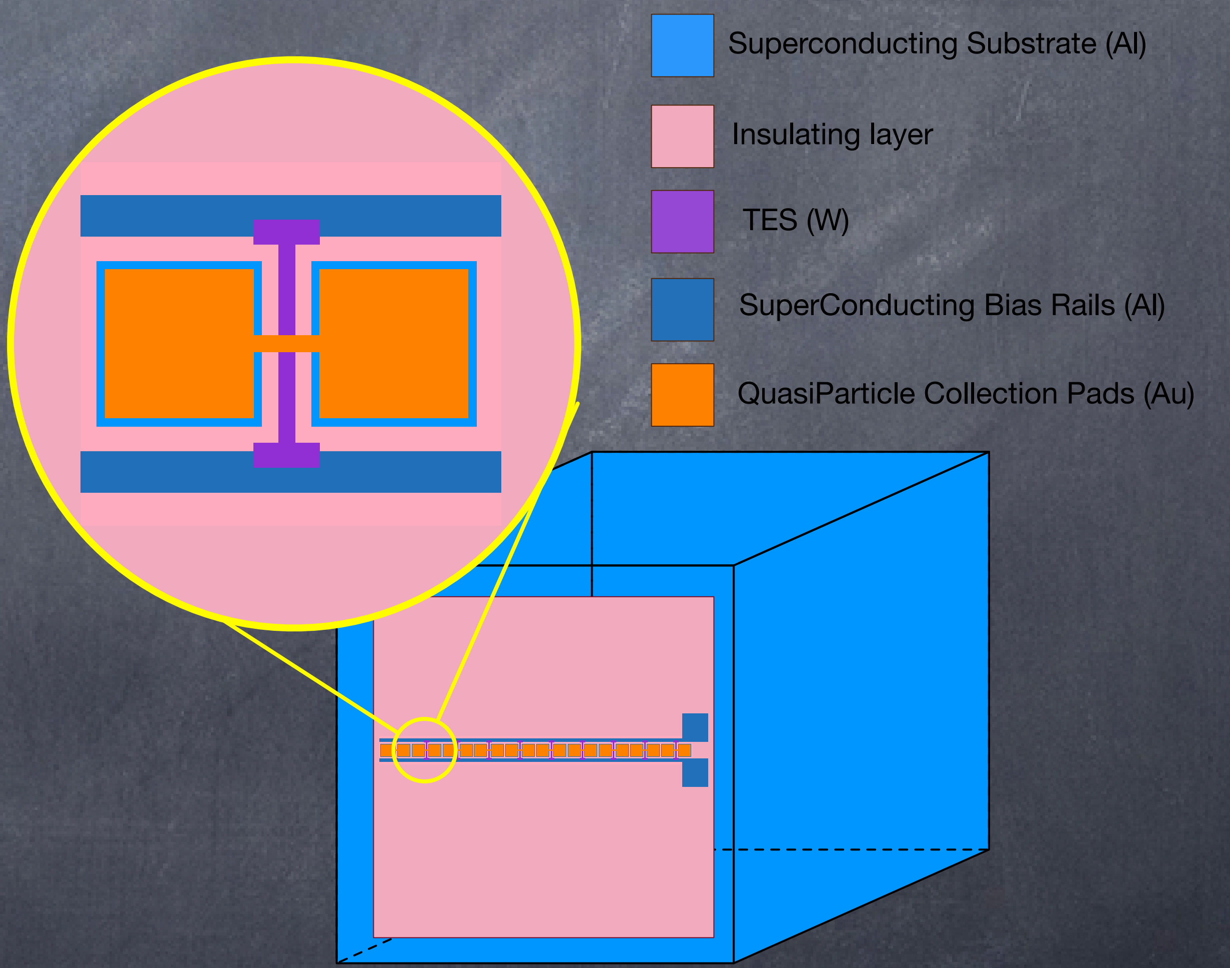
The Idea

- DM scatters with electrons in Cooper pair. If energy deposited is greater than meV, break Cooper pair and create quasi-particles. Detect quasi-particle.



Down to the Warm Dark Matter Limit?

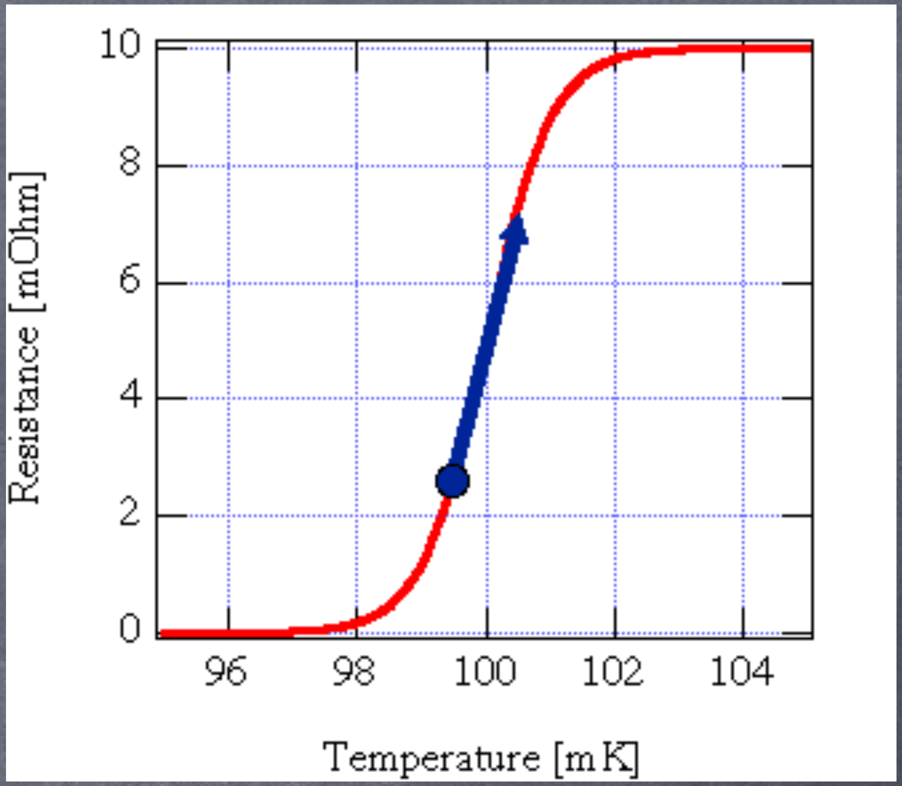
- Energy in resulting quasiparticles must be collected
- Concentrate quasiparticles onto heat sensor
- Heat sensor = TES



Matt Pyle

Transition Edge Sensor

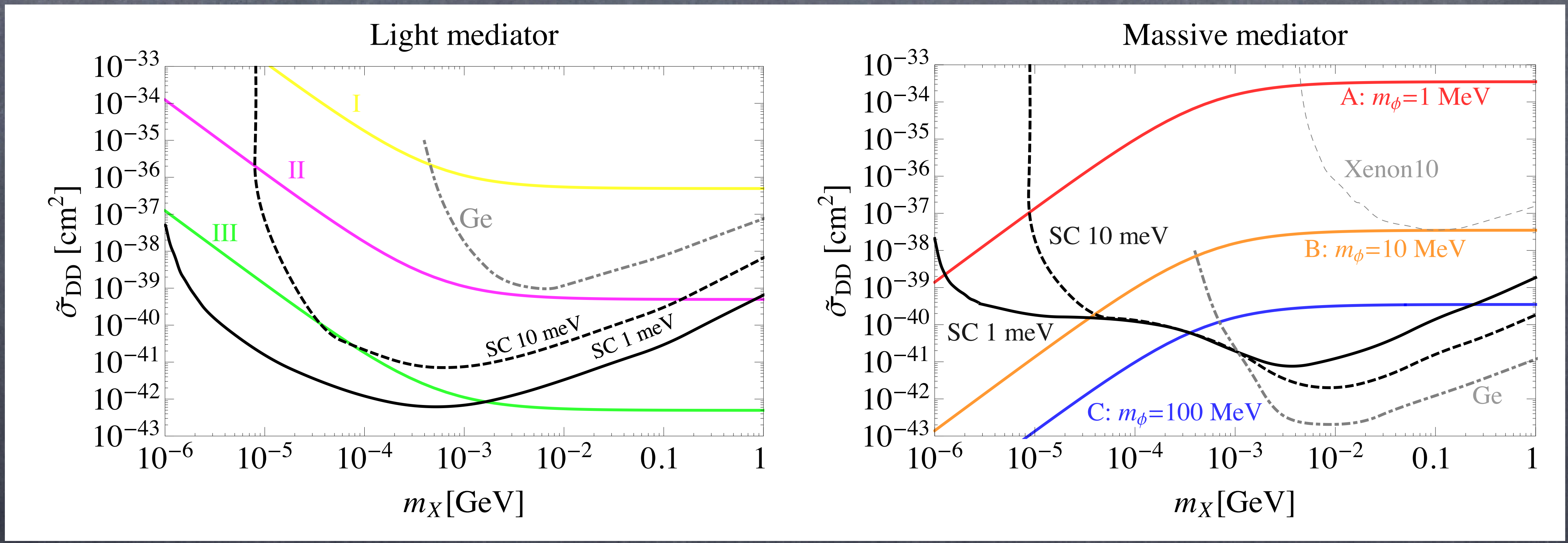
- Superconducting heat sensor doped at superconducting transition
- Already in use in microwave, x-ray and DM applications (SPT, ACT, SuperCDMS)
- Need energy resolution sufficient to detect meV deposits -- not there yet



TES	T_c [mK]	Volume [μm $\times$ μm $\times$ nm]	Power Noise [W/$\sqrt{\text{Hz}}$]	σ_E^{now} [meV]	σ_E^{scale} [meV]
W [18]	125	$25 \times 25 \times 35$	2.72×10^{-18}	120	1.1
Ti [19]	50	$6 \times 0.4 \times 56$	2.97×10^{-20}	47	22
MoCu [20]	110.6	$100 \times 100 \times 200$	4.2×10^{-19}	295.4	0.3

Y. Hochberg, M. Pyle, Y. Zhao, KZ
1512.07630

Astrophysically Feasible?



Y. Hochberg, Y. Zhao, KZ,
1504.07237
Y. Hochberg, M. Pyle, Y. Zhao, KZ
1512.07630

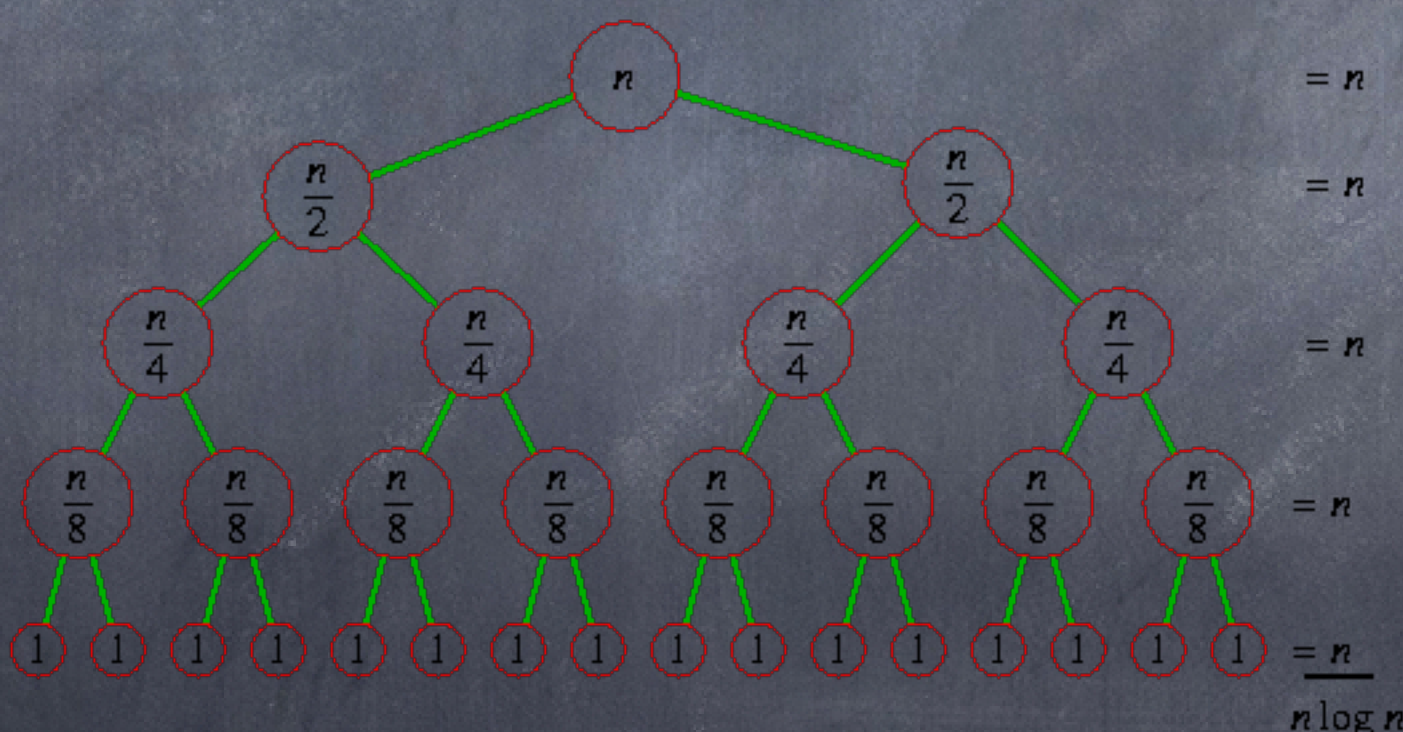
Summary

- We have some good ideas about the DM sector. A couple of directions have become very well developed: SUSY and axions
- New ideas and corresponding search strategies are developing.
- Important to keep searches and ideas as broad and inclusive as possible

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
....