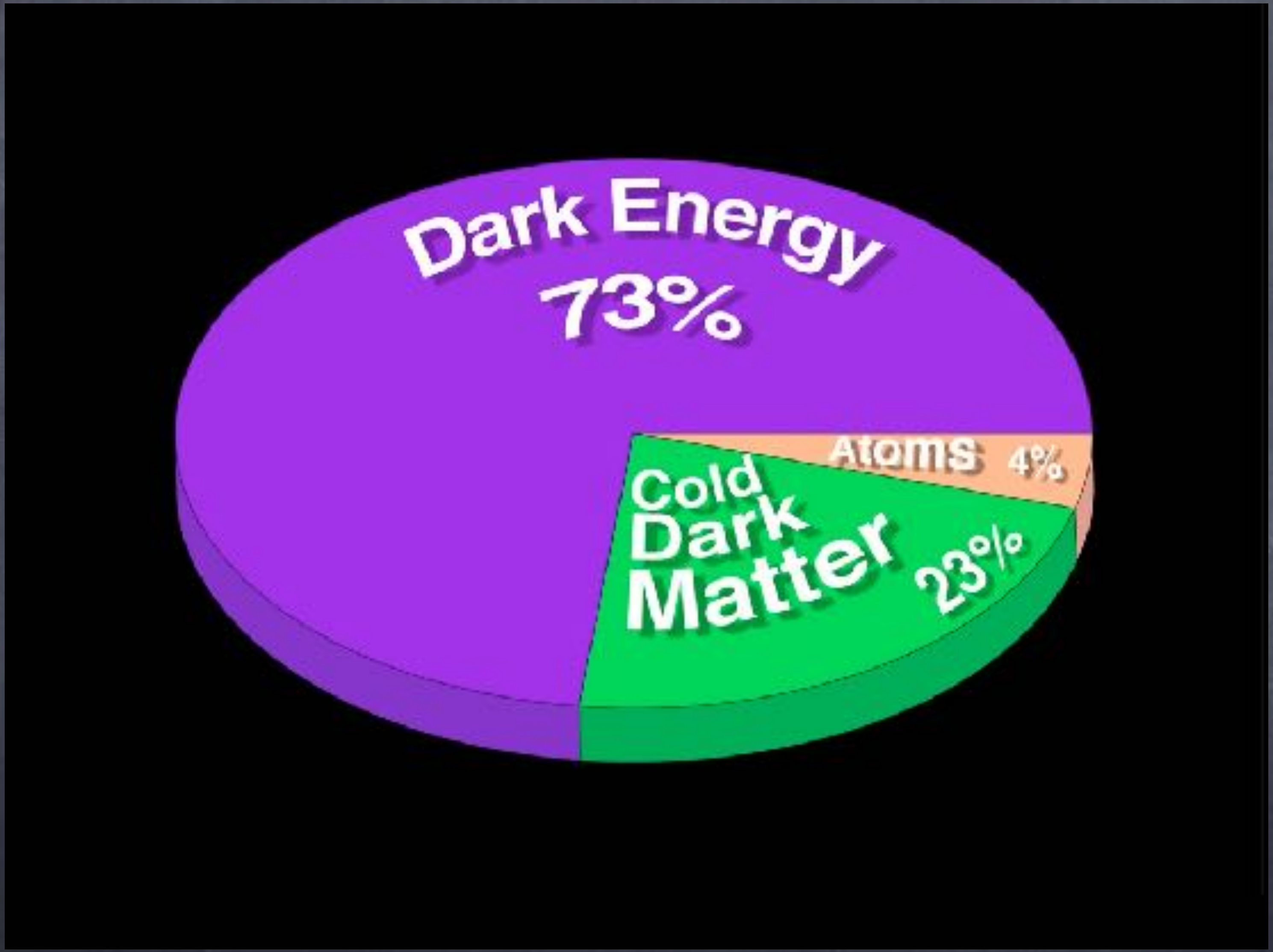
DM Without Prejudice

Kathryn M Zurek
LBL Berkeley, CERN

Universe's Energy Budget

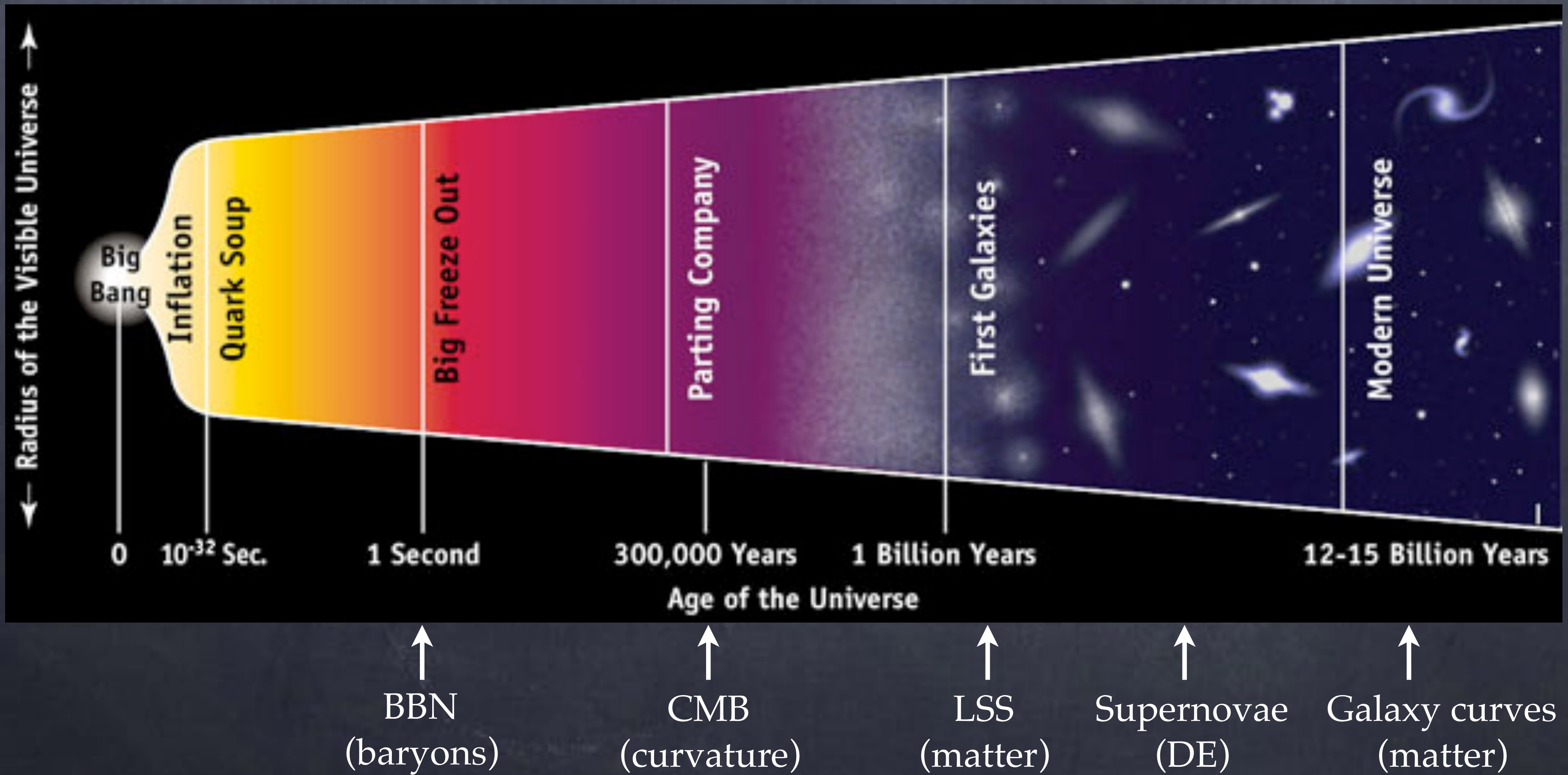
Dynamical selection?



New Dynamics, Definitely BSM

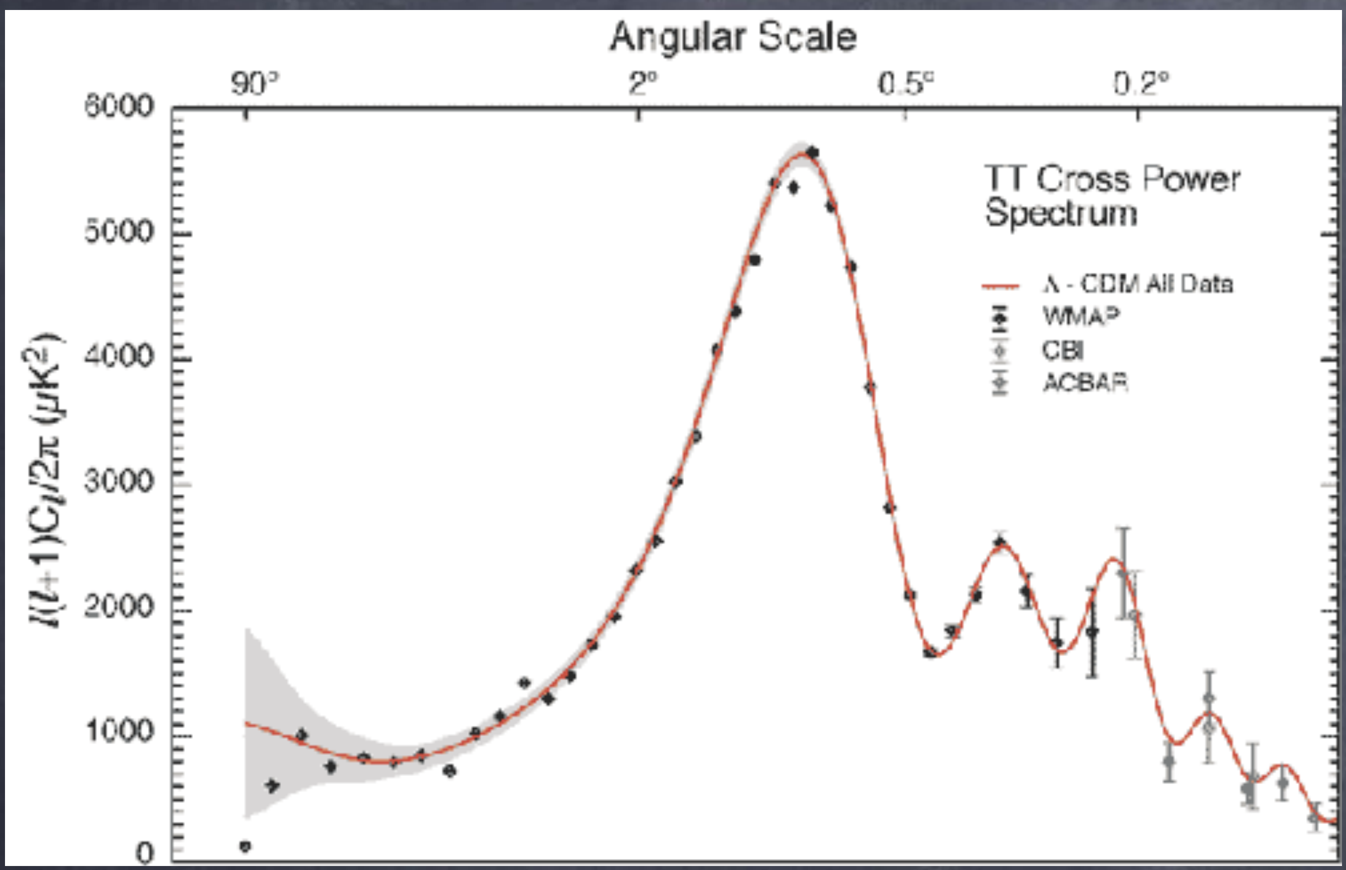
Why particle dark matter?

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



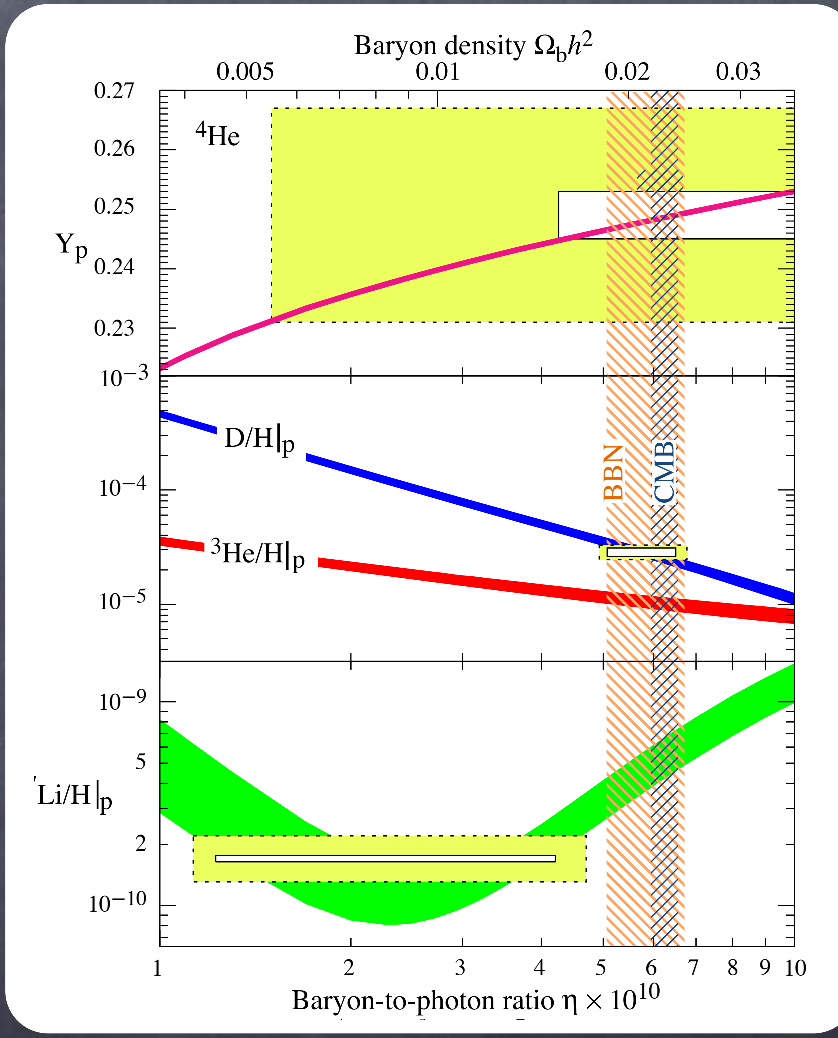
Why particle dark matter?

curvature, z_eq



Baryon density

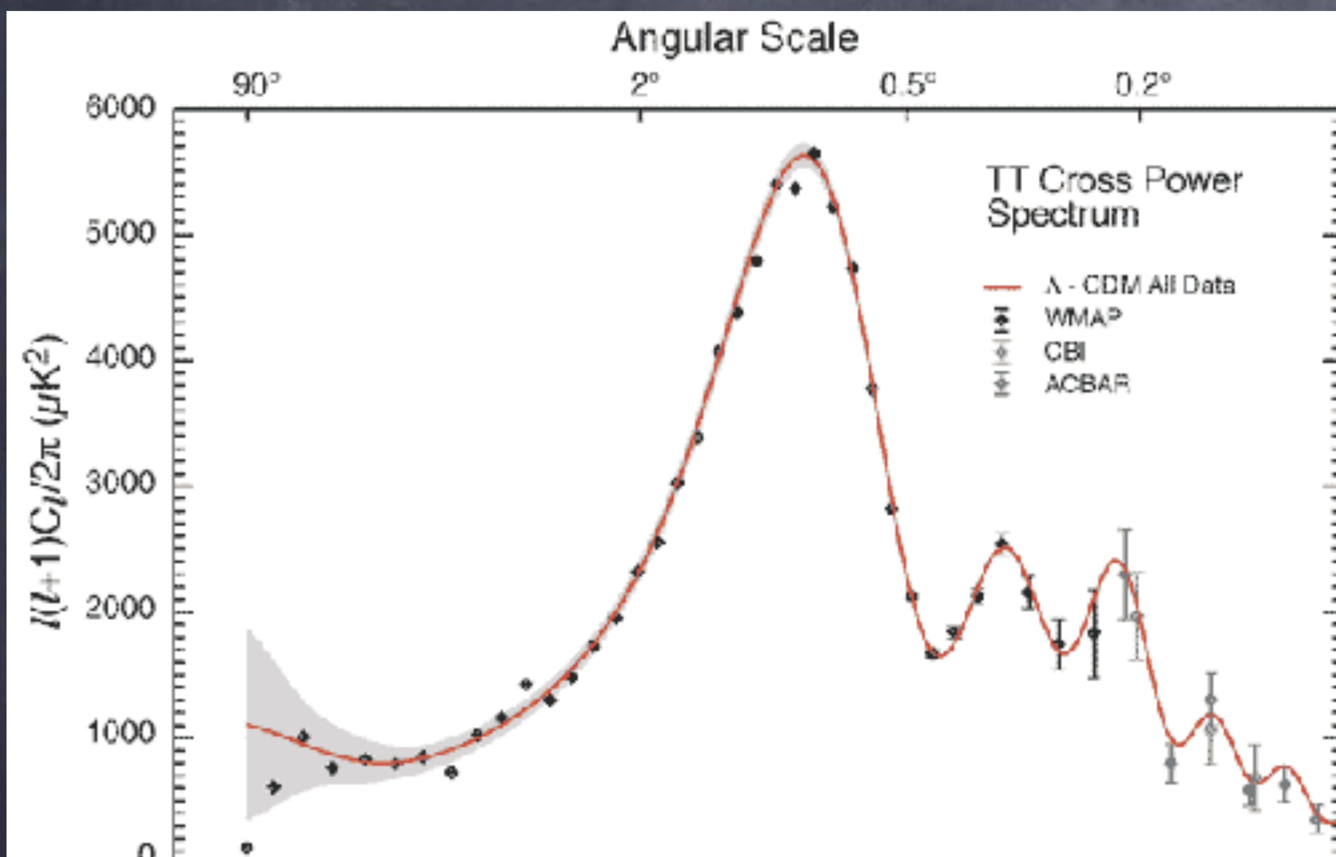
sound speed = baryon to radiation ratio



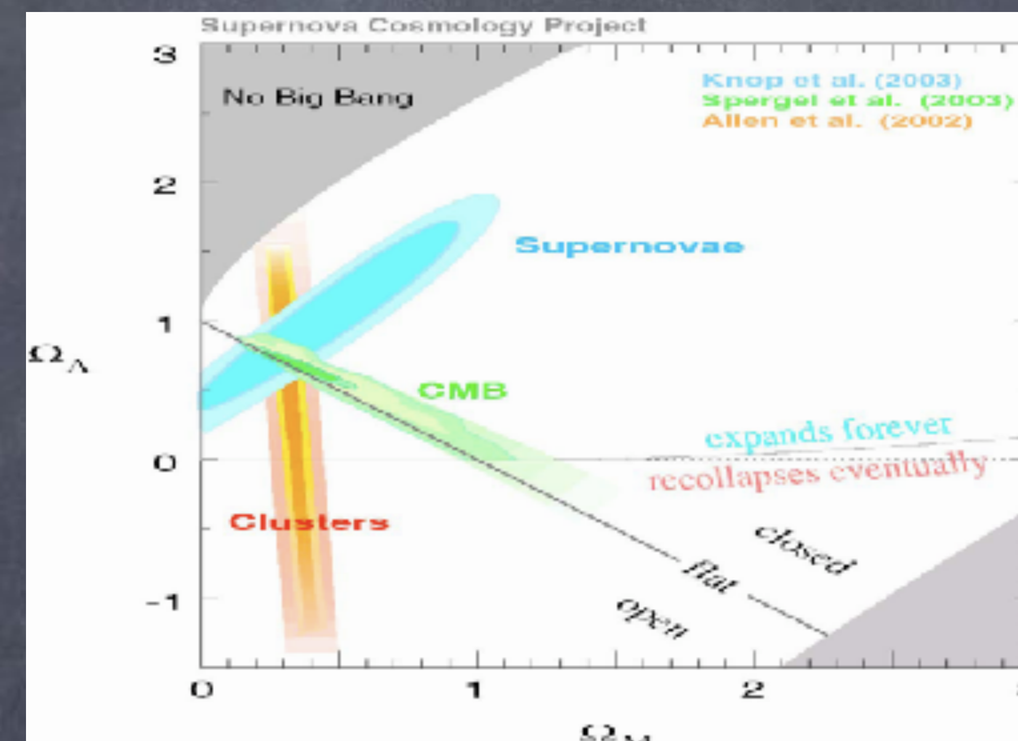
- Why not just ordinary (dark) baryons?
- A: BBN and CMB make independent measurements of the baryon fraction. Observations only accounted for with **non-interacting** matter

Why particle dark matter?

curvature, z_eq



Baryon density



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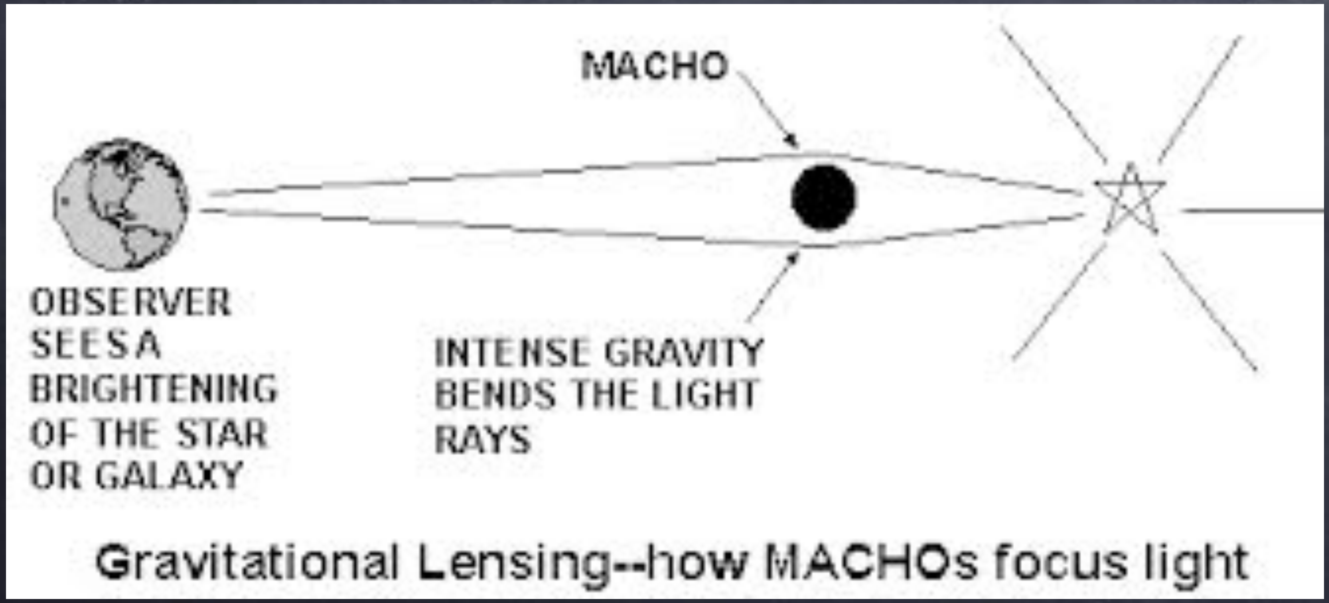
- Why not just ordinary (dark) baryons?
- A: BBN and CMB make independent measurements of the baryon fraction. Observations only accounted for with **non-interacting** matter

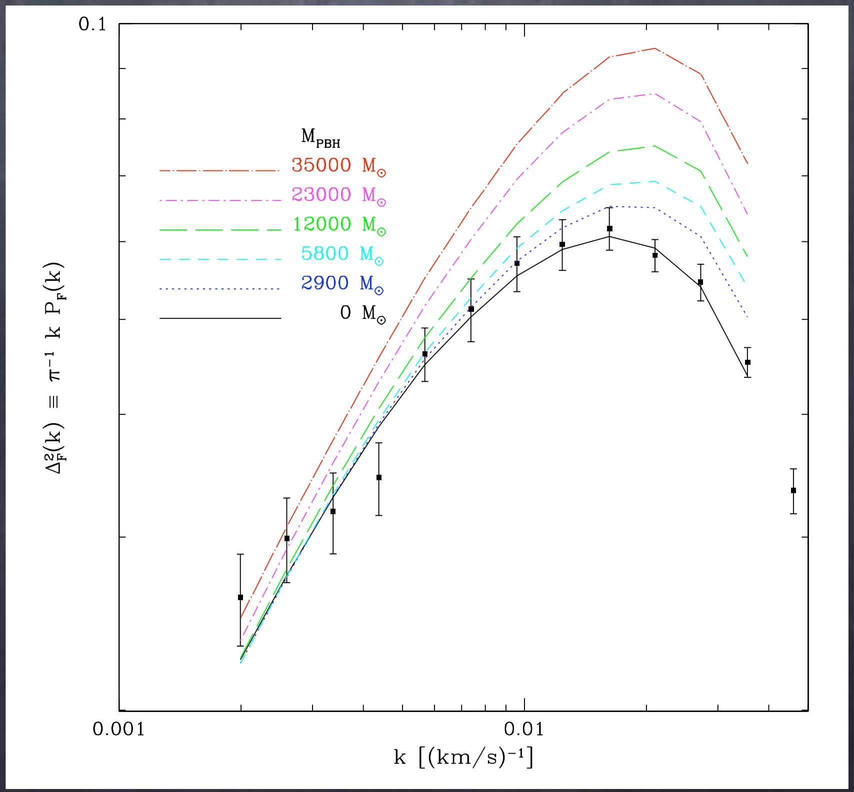
Why particle dark matter?

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



Gravitational Lensing--how MACHOs focus light

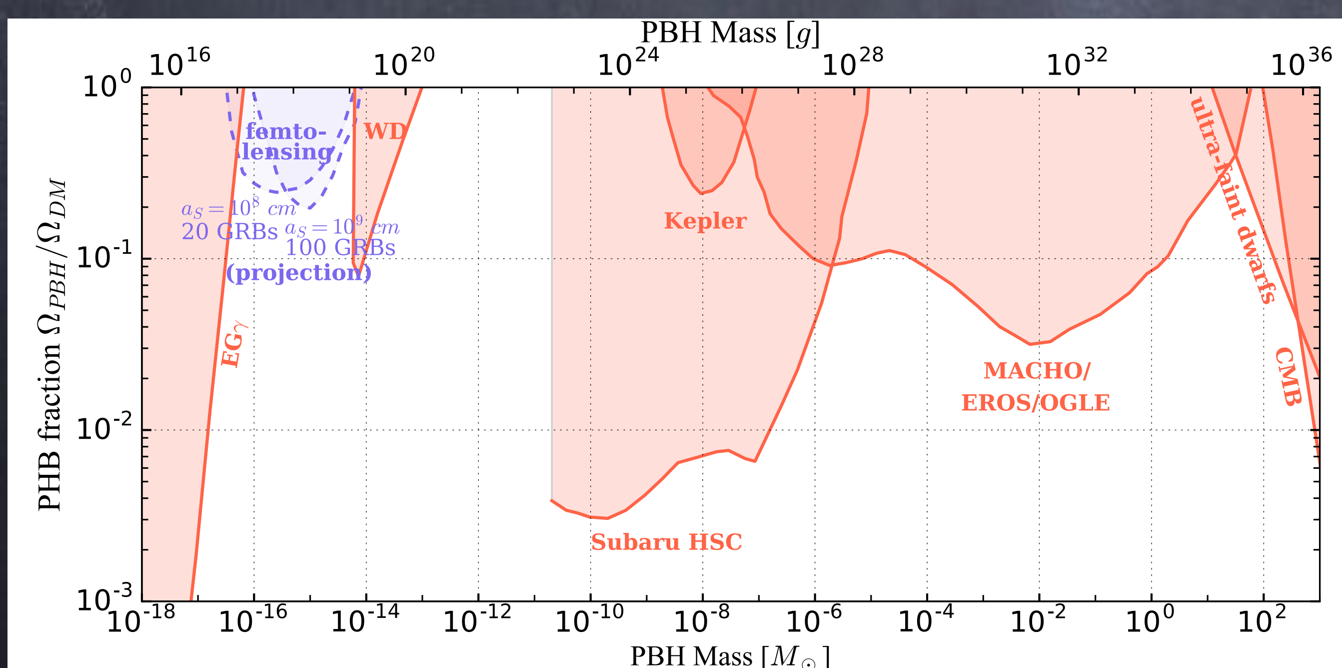
Afshordi, McDonald, Spergel



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 $\gtrsim 10^{-8} M_\odot$

Katz et al, 1807.11495



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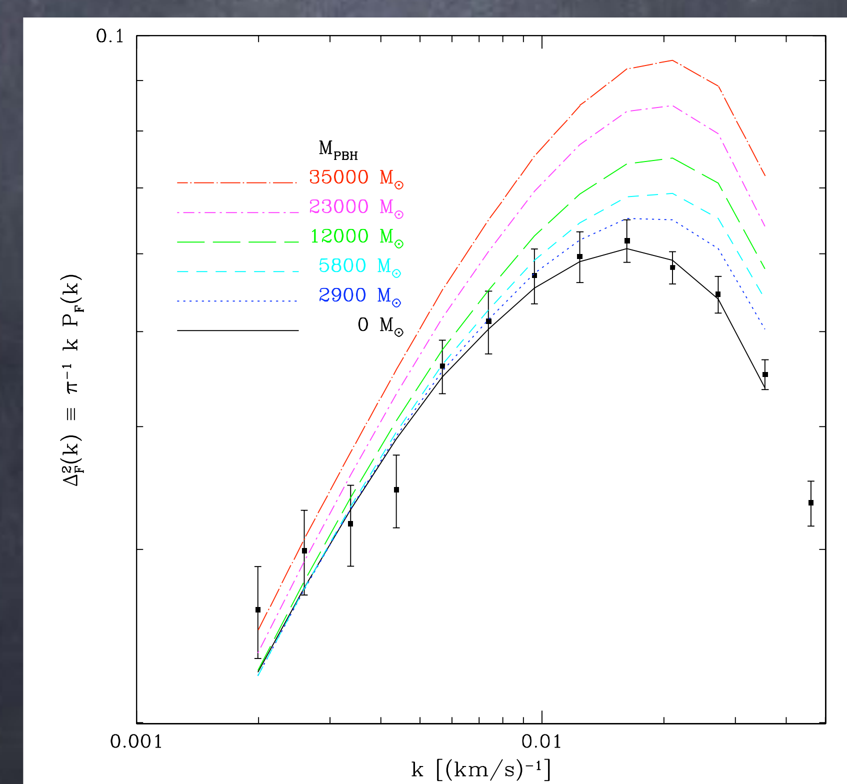
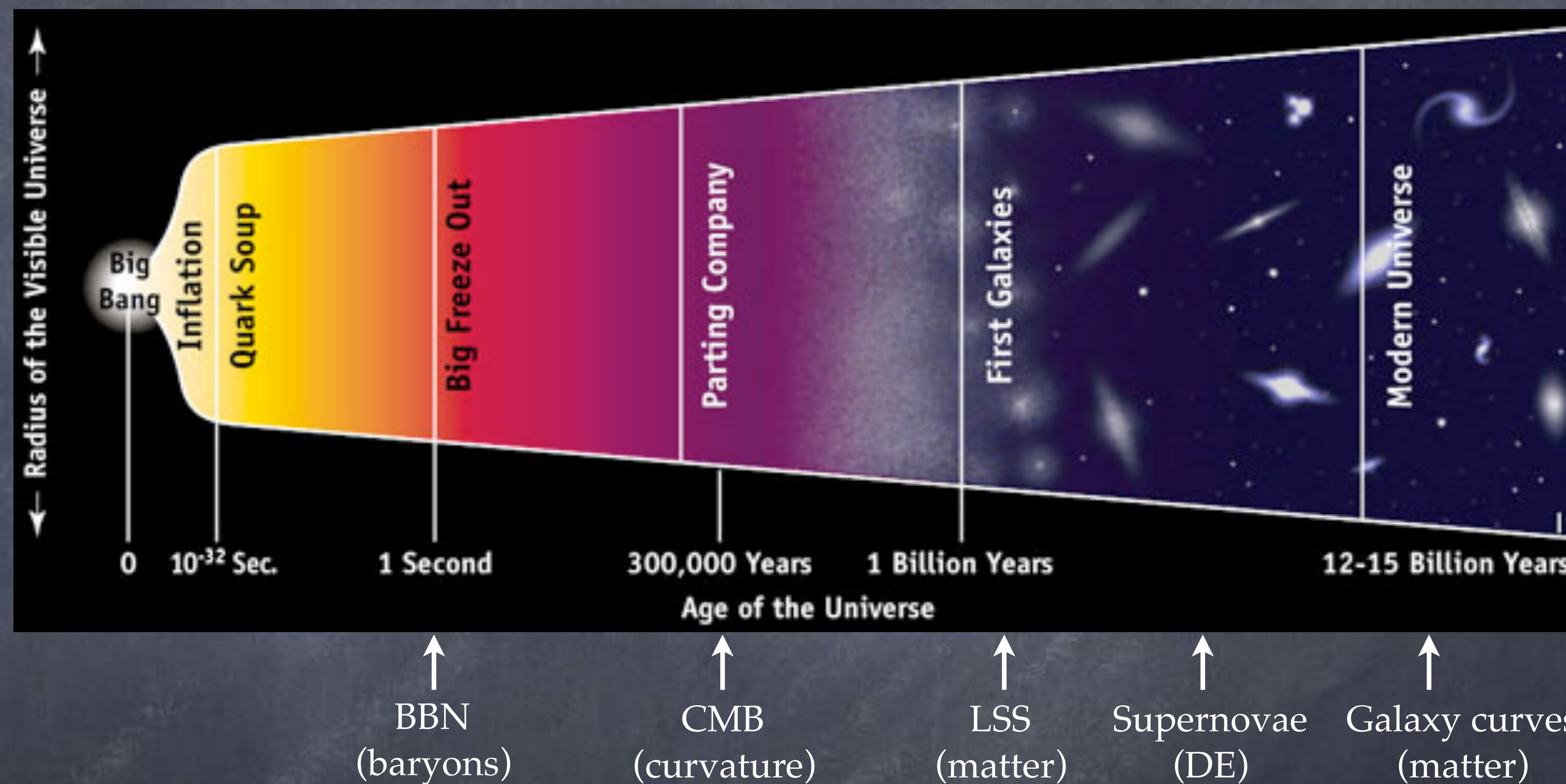


Why particle dark matter?

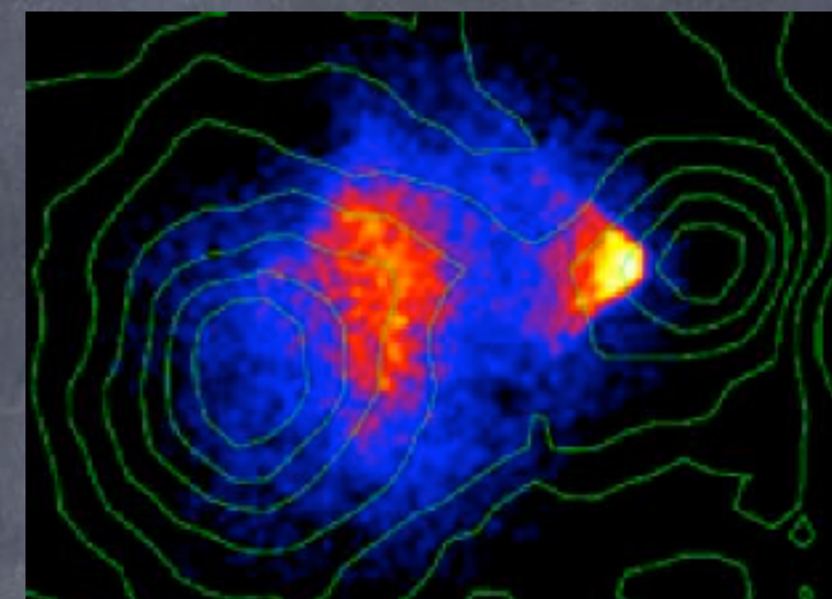
- Why not modify gravity?
- A: Modified gravity theories tend to be sick



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

Why particle dark matter?

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



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

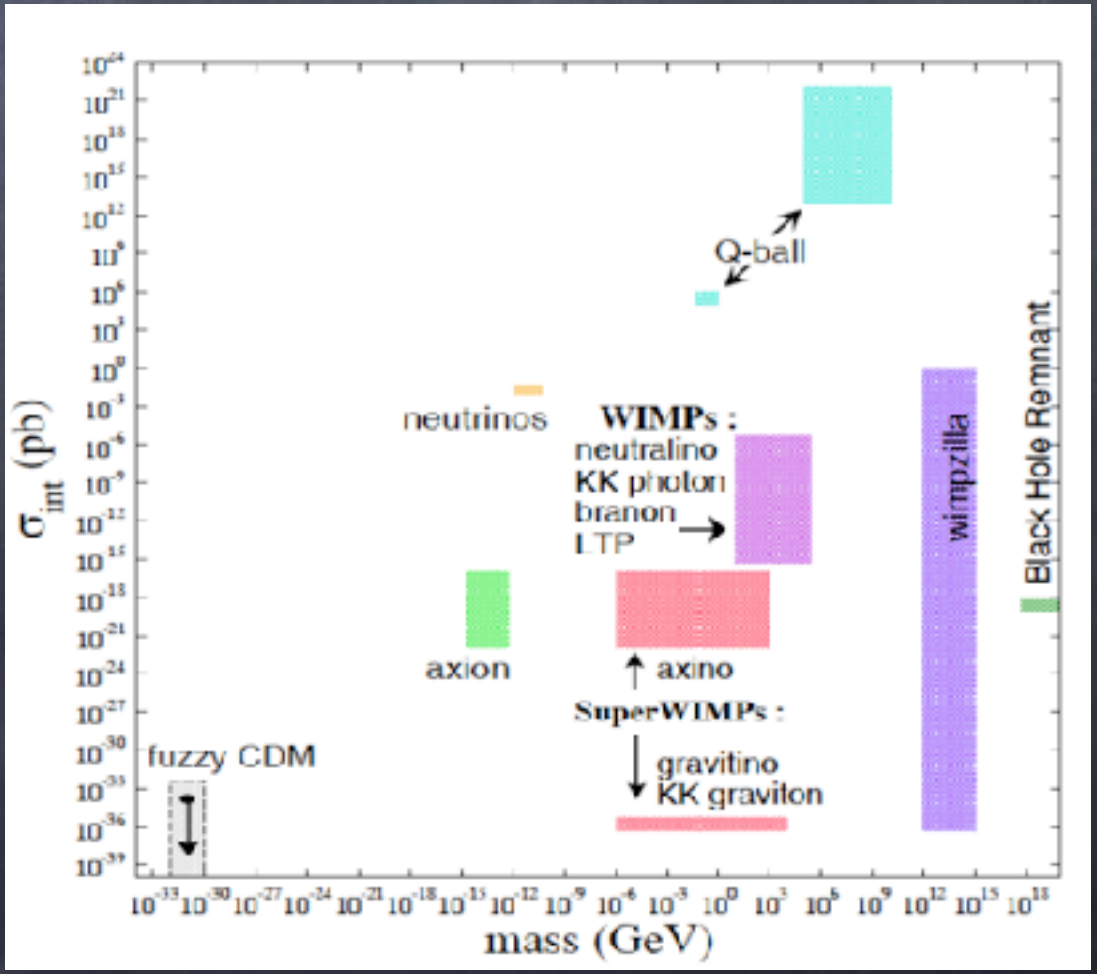
- A: Must get the entire range of observations right, not just galactic rotation curves

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:

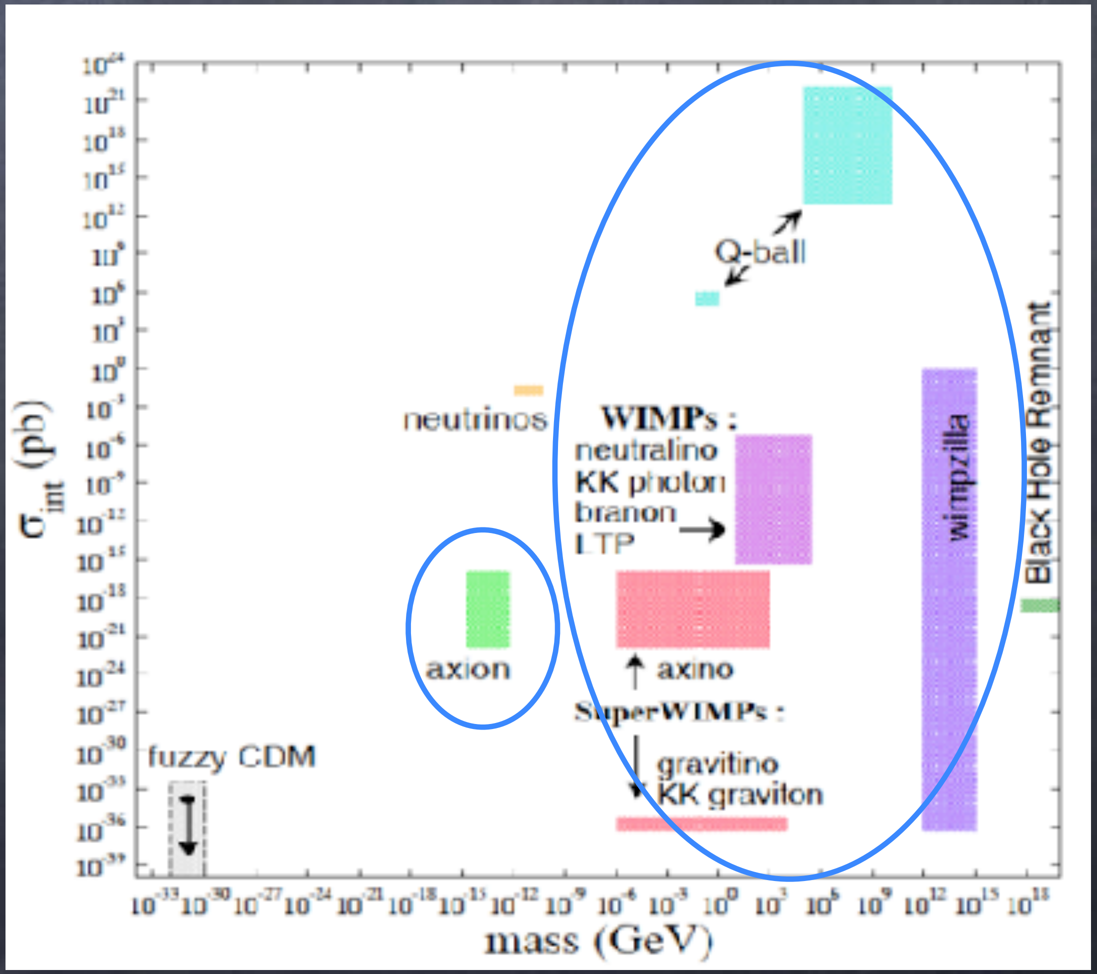
Particle dark matter

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

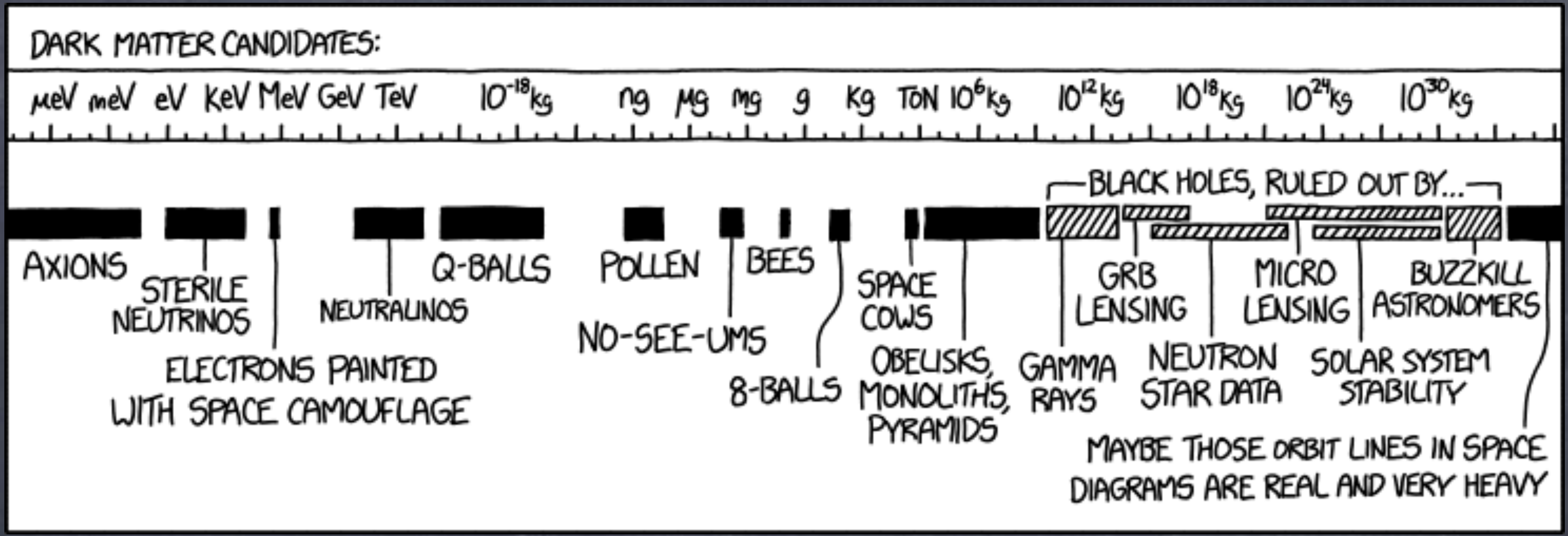


Particle dark matter

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



XKCD Version



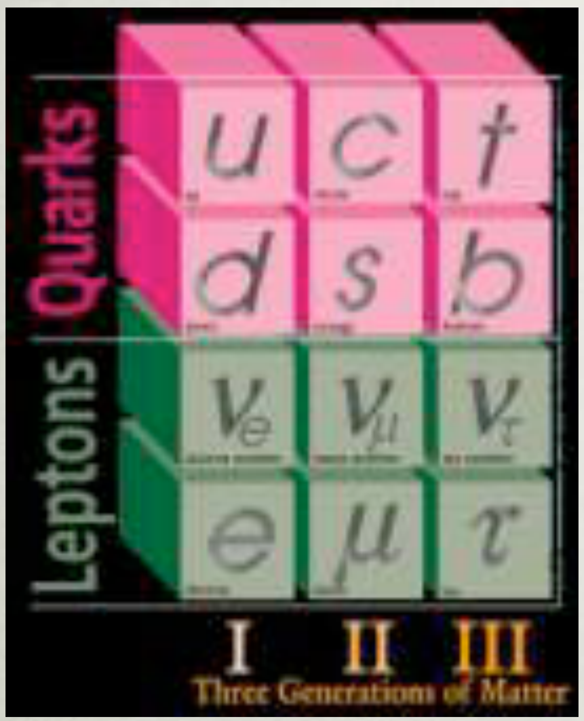
My theory is that dark matter is actually just a thin patina of grime covering the whole universe, and we don't notice it because we haven't thoroughly cleaned the place in eons.

Dark Matter: Standard Paradigm

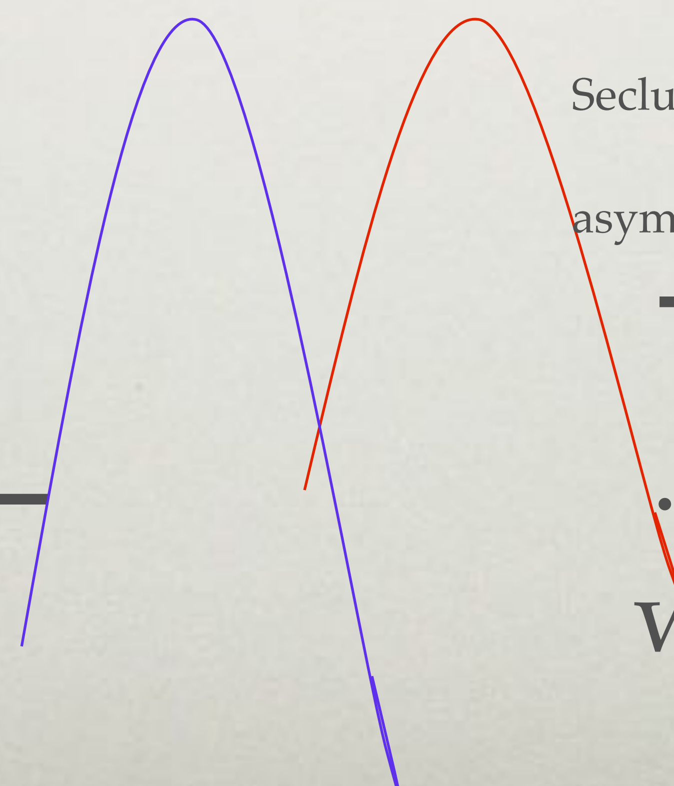
- Usual picture of dark matter is that it is:
  - single
  - stable
  - (sub-?) weakly interacting
  - neutral

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 world
with multiple states,
new interactions

PROGRAM

- Paradigms for DM density
  - freeze-out, freeze-in, asymmetric DM, freeze-out and decay, misalignment, compact object formation
- The classic: Supersymmetric Dark Matter
  - Direct and indirect detection basics

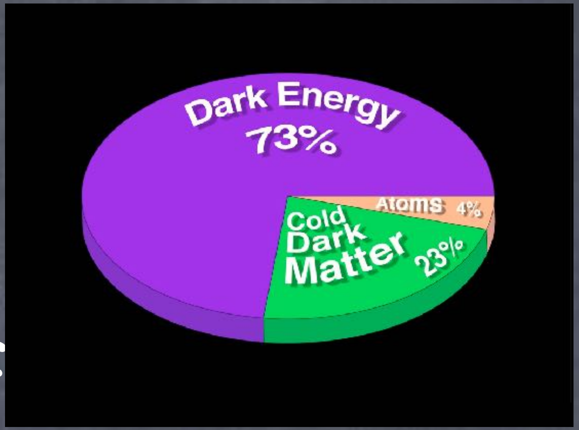
PROGRAM

- Looking beyond the vanilla WIMP
  - motivations, experimental search techniques
- Cosmological constraints on particle DM
  - BBN, CMB, formation of structure, stellar capture, DM self-interactions
- New Ideas in Dark Matter Direct Detection

Paradigms for Dark Matter Density

(Thermal freeze-out is only one mechanism for setting the DM density)

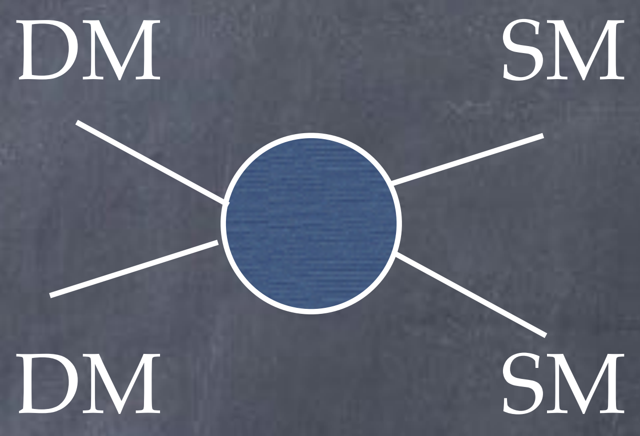
Setting the dark matter density



- Relate the macroscopic observable of density to the microscopic properties of DM
- Mechanisms to review:
  - thermal DM, freeze-out, freeze-in, asymmetric abundance, production through decay
- Microscopic properties: mass and interactions
  - i.e. a Lagrangian!

Thermal Dark Matter

- Assumption: Dark matter has strong enough interactions at early time that it thermalizes with SM



- Then number densities set by Bose-Einstein or Fermi-Dirac distributions

$$\rho = \frac{g}{(2\pi)^3} \int E(\vec{p}) f(\vec{p}) d^3p$$

$$f(\vec{p}) = [\exp((E-\mu)/T) \pm 1]^{-1}$$

- If particles remain in thermal equilibrium, number densities become exponentially suppressed

Thermal Dark Matter

- Assumption: Dark matter has strong enough interactions at early time that it thermalizes with SM
- Then number densities set by Bose-Einstein or Fermi-Dirac distributions
- If particles remain in thermal equilibrium, number densities become exponentially suppressed

Relativistic

$$\rho = (7/8)\frac{\pi^2}{30} g T^4$$

$$n = (3/4)\frac{\zeta(3)}{\pi^2} g T^3$$

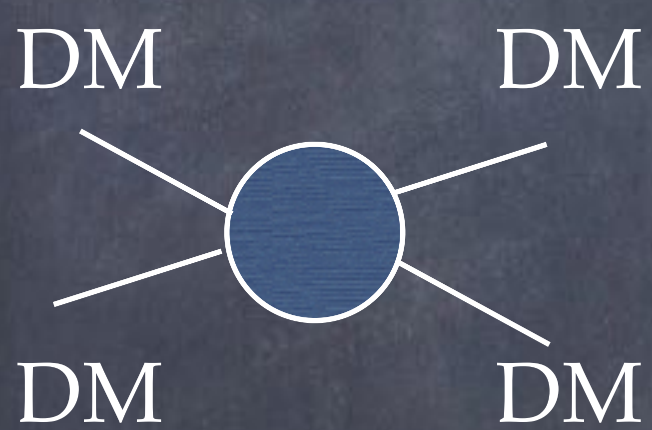
Non-relativistic

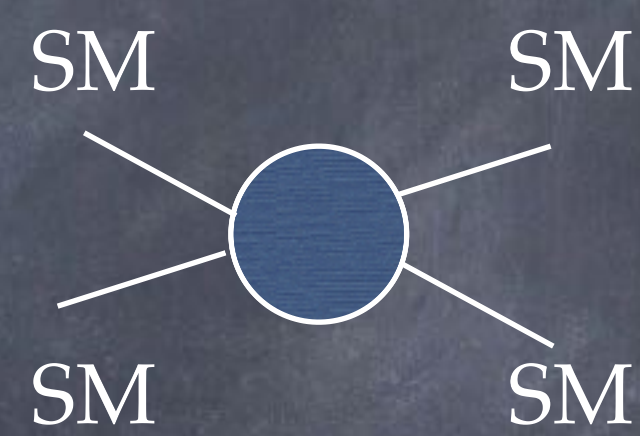
$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

$$\rho = mn$$

Thermal Dark Matter'

- Assumption: Dark matter has strong enough interactions at early time that it thermalizes





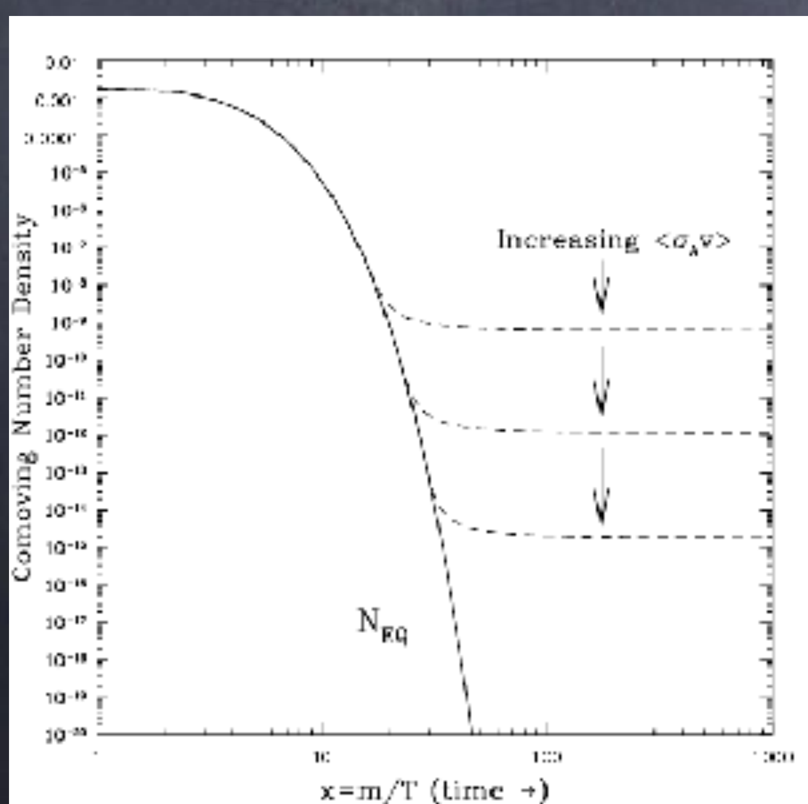
T_1 T_2

$$f(\vec{p}) = [\exp((E-\mu_1)/T_1) \pm 1]^{-1} \qquad f(\vec{p}) = [\exp((E-\mu_1)/T_2) \pm 1]^{-1}$$

Thermal Dark Matter

- --> dark matter must drop out of thermal equilibrium (or have a chemical potential)
- This process is called freeze-out

$$Y \equiv \frac{n}{s}$$



$$n = g \left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

$$s = \frac{2\pi^2}{45} g_{*s} T^3$$

More efficient annihilation = lower DM density

Kolb and Turner, The Early Universe, chapters 3 and 5

Back of the envelope estimates

- Often helpful in cosmology to know how things scale

Friedmann Equation $$H^2 = \frac{8\pi G\rho}{3}$$

$$G \sim \frac{1}{M_{pl}^2} \qquad \rho \sim T^4$$

(Non-relativistic DM is subdominant and scales as $\rho_X \sim \rho_X^0 \frac{T^3}{T_0^3}$)

$$\Rightarrow \quad H \sim \frac{T^2}{M_{pl}}$$

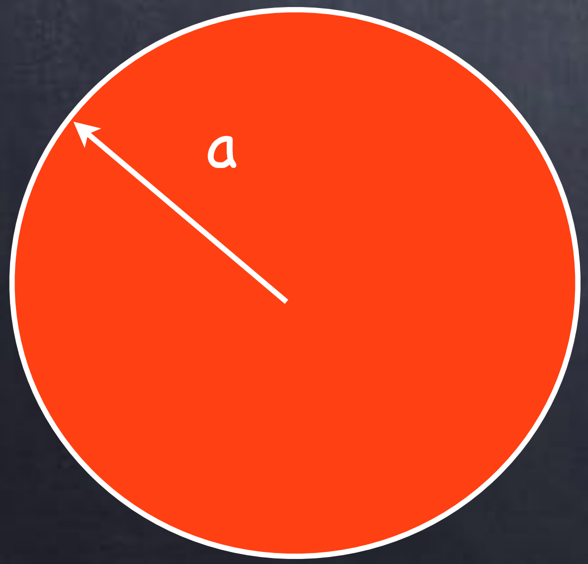
Boltzmann Eq

- Evolution of number density described by Boltzmann Eq. In the absence of interactions, it simply describes the dilution of the number density with the expansion of the universe.

$$\frac{dn_X}{dt} + 3Hn_X = 0$$

$$\frac{\dot{a}}{a} = H \qquad a \sim \frac{T_0}{T}$$

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



Thermal Dark Matter

- In equations, not words. Boltzmann Eqn:

$$\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma_{X\bar{X}\to f\bar{f}} |v| \rangle (n_X^2 - n_X^{EQ\,2})$$

$$Y \equiv \frac{n}{s} \quad x = m/T \qquad \frac{dY}{dx} = -\frac{x\langle \sigma |v| \rangle s}{H(m)} (Y^2 - Y_{EQ}^2)$$

- i.e. Y = const if Y = Y_EQ
- Then Y_EQ drops precipitously, so annihilation begins
- Eventually RHS becomes small and Y = const

Thermal Dark Matter

- In equations, not words. Boltzmann Eqn:

$$\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma_{X\bar{X}\to f\bar{f}} |v| \rangle (n_X^2 - {n_X^{EQ}}^2)$$

$$Y \equiv \frac{n}{s} \quad x = m/T \qquad \frac{dY}{dx} = -\frac{x\langle \sigma |v| \rangle s}{H(m)} (Y^2 - Y_{EQ}^2)$$

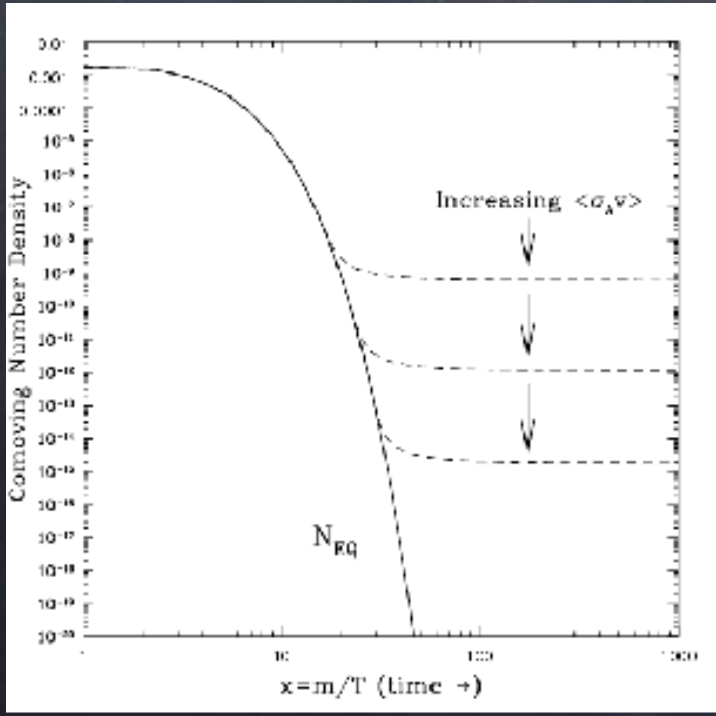
- Relevant threshold is always

$$\Gamma_{ann} = n_X \langle \sigma_{X\bar{X}\to f\bar{f}} |v| \rangle \gtrsim H$$

- Equilibrium distribution maintained when condition met $n_X \simeq {n_X}^{EQ}$

Thermal Dark Matter

- When $m_X \gtrsim T$, equilibrium distribution becomes exponentially suppressed
- Freeze-out occurs when equilibrium condition is no longer met $\Gamma_{ann} = n_X \langle \sigma_{X\bar{X}\to f\bar{f}} |v| \rangle \gtrsim H$

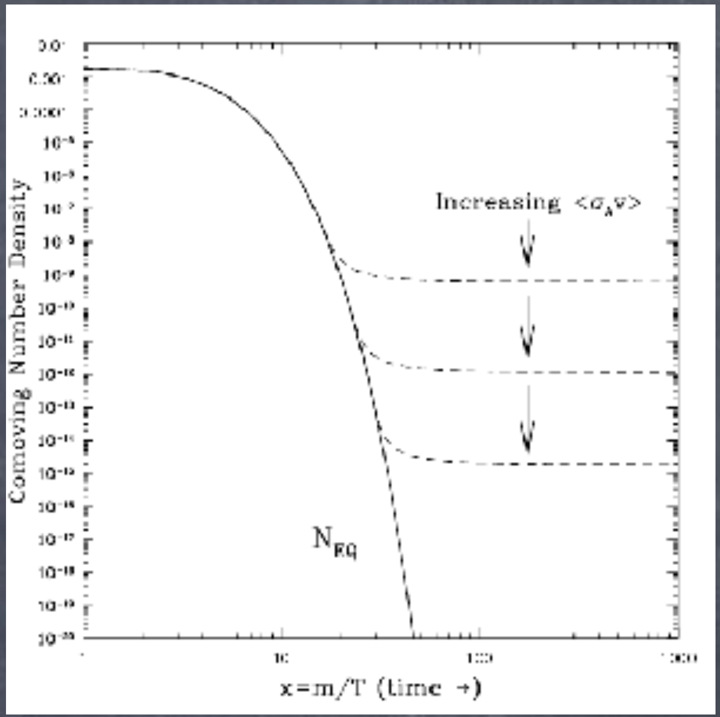


$$n_X \sigma_{ann} v \simeq H(T_{fo}) \sim 1.66 g_*^{1/2} \frac{T_{fo}^2}{M_{pl}}$$

$$n_X \sim (m_X T_{fo})^{3/2} e^{-m_X/T_{fo}}$$

Thermal Dark Matter

$$m_X/T_{fo} \simeq 20$$



$$\sigma_{ann}v \sim \frac{T_{fo}^2}{M_{pl}}\frac{m_X}{\rho_X(T_{fo})}$$

$$= \frac{T_{fo}^2}{M_{pl}}\frac{m_X}{\rho_X^0}\frac{T_0^3}{T_{fo}^3}$$

$$= \frac{m_X}{T_{fo}\rho_X^0}\frac{T_0^3}{M_{pl}}$$

$$\simeq 3\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

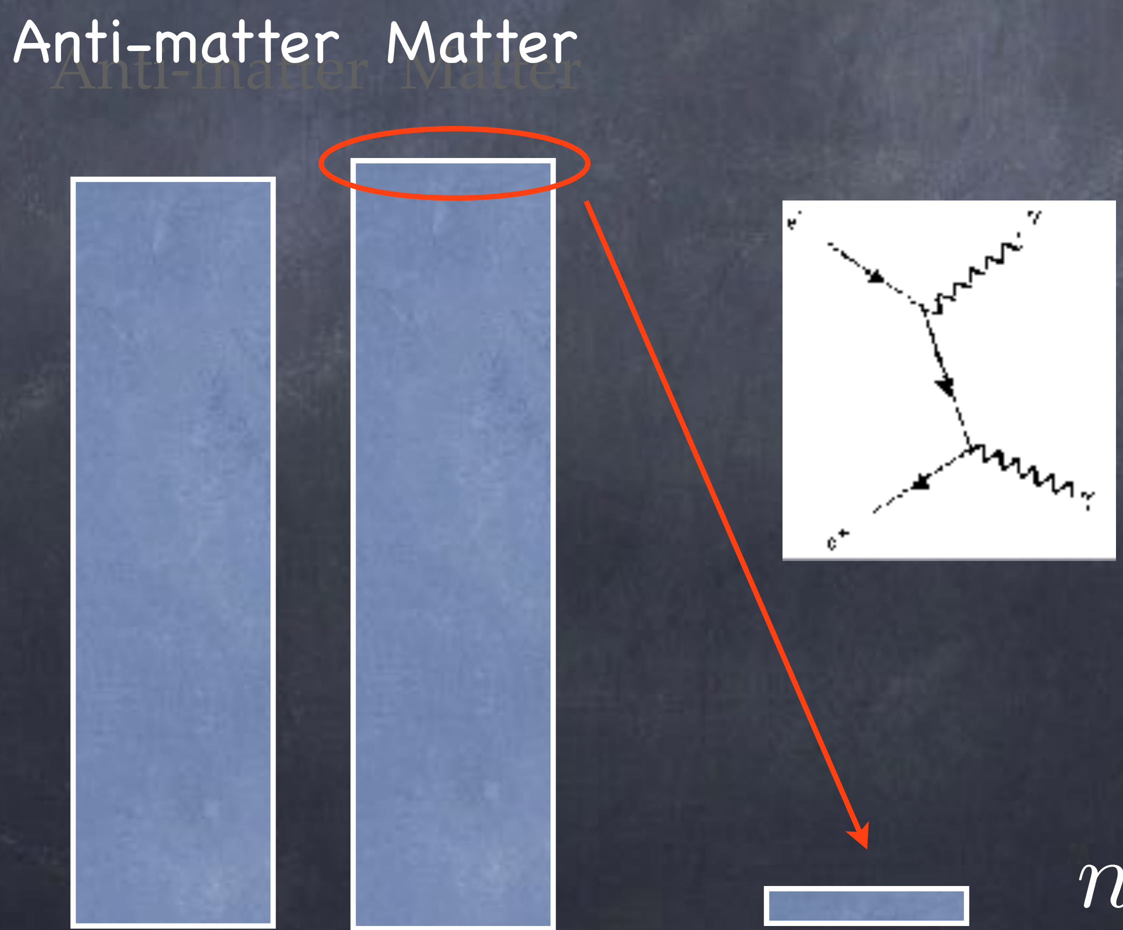
$$3\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \simeq \frac{1}{(20\ \mathrm{TeV})^2}$$

$$\simeq \frac{g_{wk}^4}{(2\ \mathrm{TeV})^2}$$

Chemical Potential Dark Matter

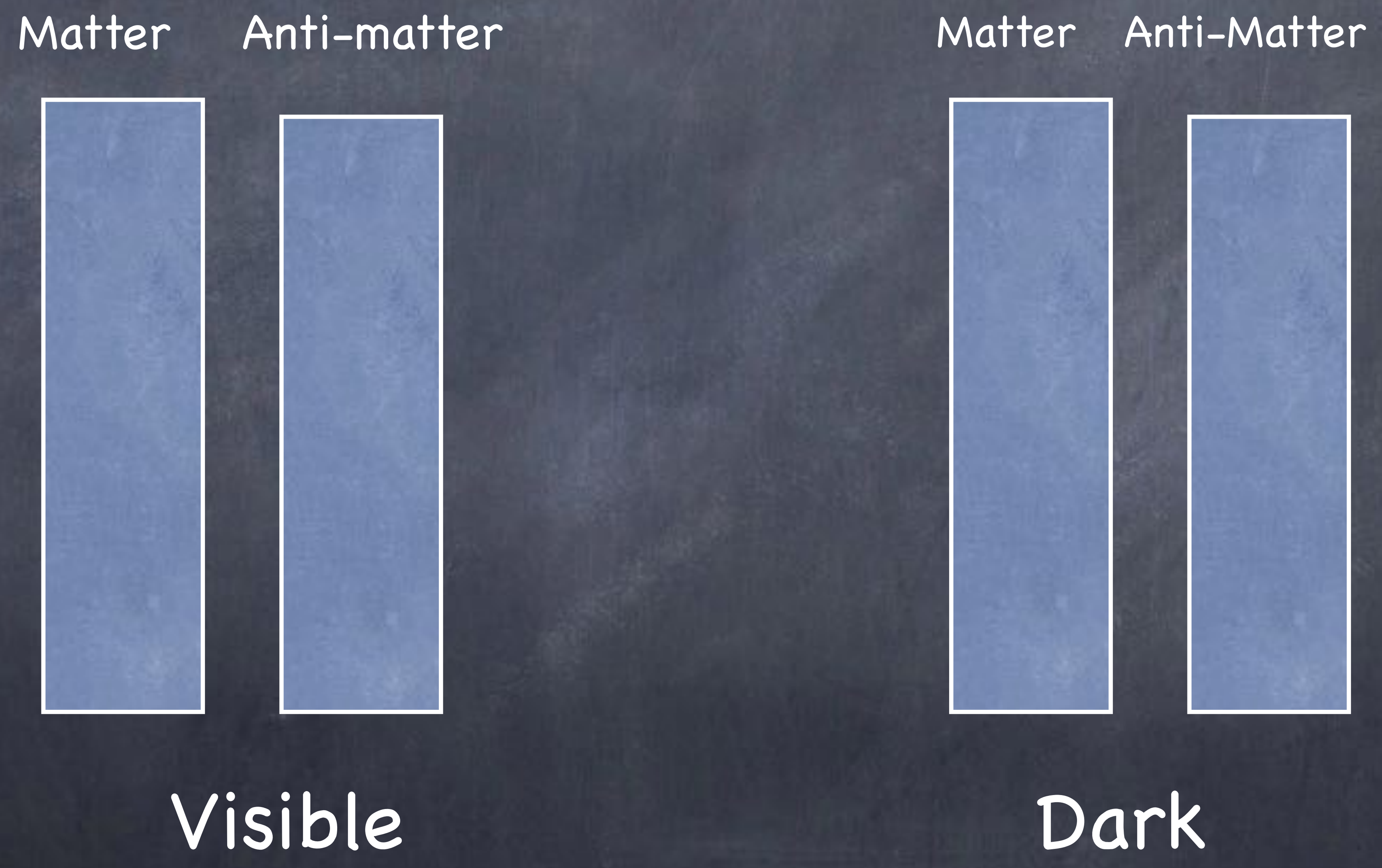
- Another way to stop the annihilation is simply to run out of anti-particles. This is what happens with baryons in the SM.

$n_X \sim T^3$



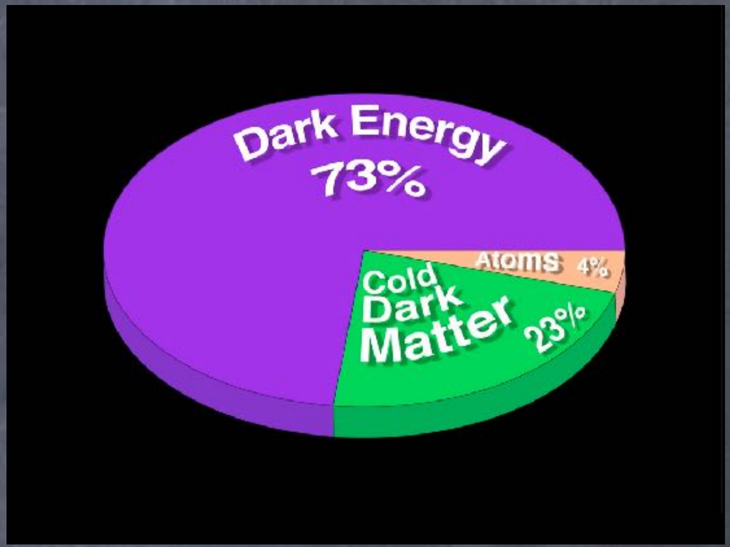
$n_X \sim 10^{-10} T^3$

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 $n_{DM} \approx n_b$

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

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

$$n_X - n_{\bar{X}} \sim n_b - n_{\bar{b}} \quad \Rightarrow \quad m_{DM} \sim 5 \text{ GeV}$$

Sharing

- Really 3 basic mechanisms

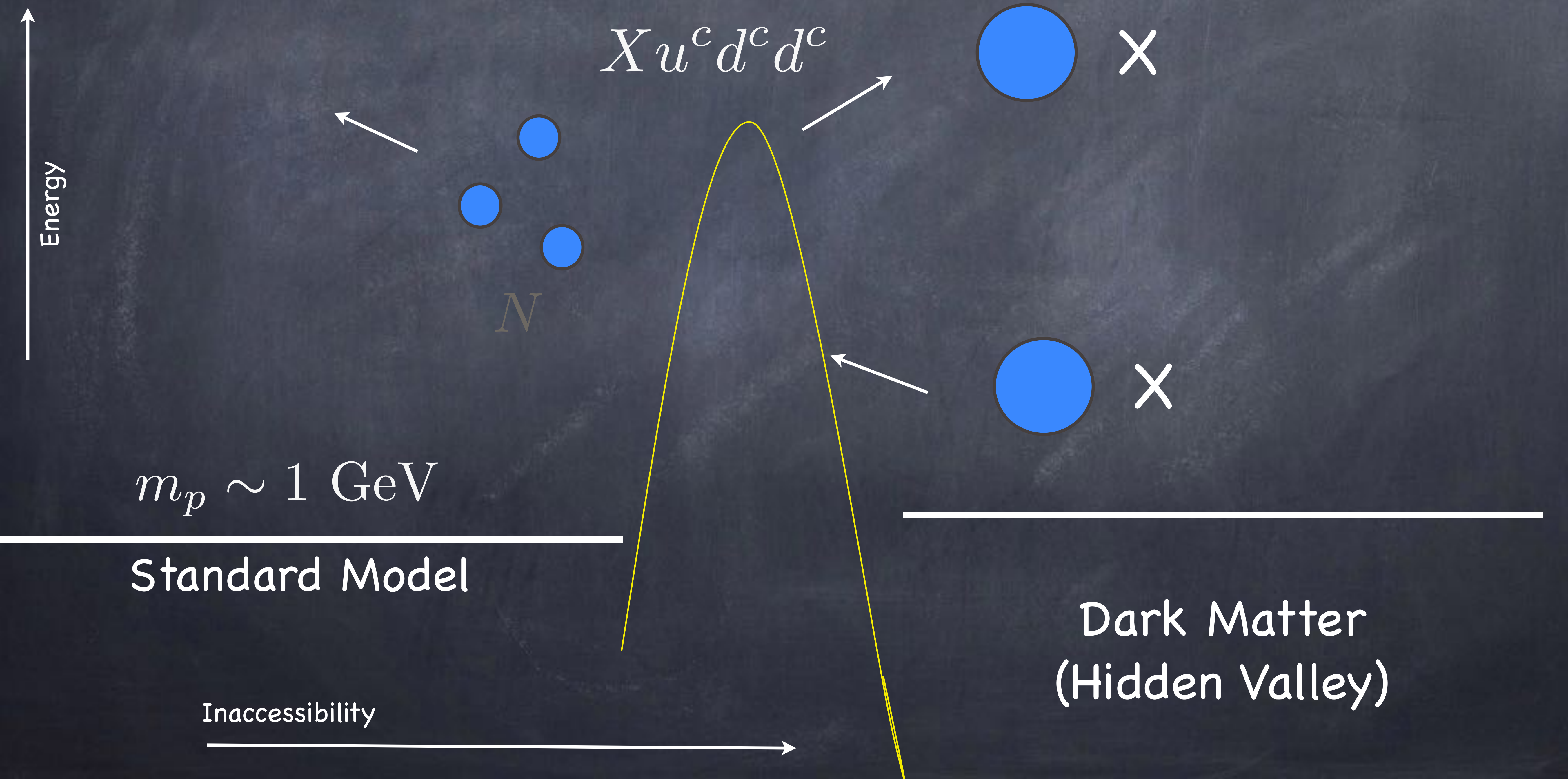
1. Sphalerons (often EW) ← Strongly constrained by colliders
2. Higher dimension operators (HDO)
3. Decay (different dynamics than HDO but same Lagrangian)

KZ 1308.0338

Asymmetric DM

"Integrate out" heavy state
Higher dimension operators:

Luty, Kaplan, KZ
0901.4117



Asymmetric DM

"Integrate out" heavy state
Higher dimension operators:

Luty, Kaplan, KZ
0901.4117

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

Energy

$\mathcal{O}_{B-L} = LH_u,\ LLE^c,\ QLd^c,\ u^c d^c d^c$

$\mathcal{O}_X = X,\ X^2$

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

Standard Model

Dark Matter
(Hidden Valley)

Inaccessibility

What Does an ADM Model Do?

KZ 1308.0338

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3. Annihilate the symmetric abundance

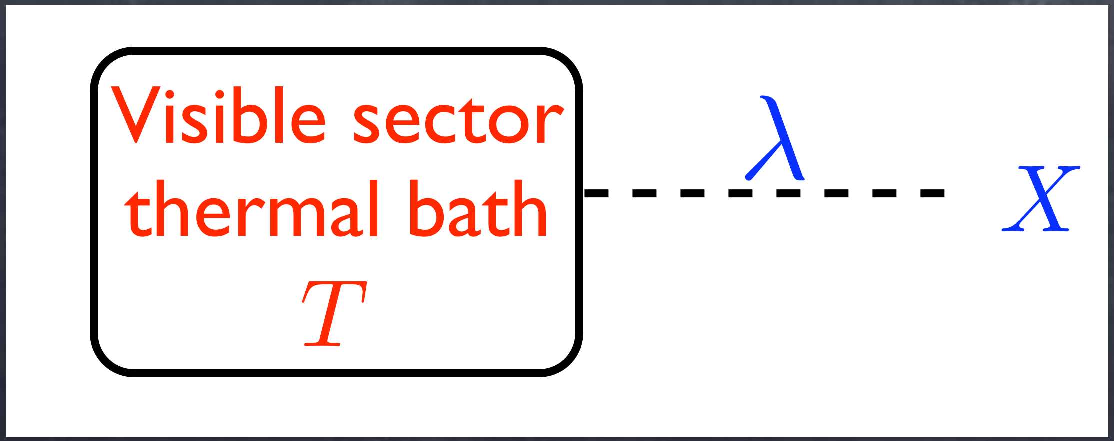
$$n_X - n_{\bar{X}} \sim n_b - n_{\bar{b}} \quad \Rightarrow \quad m_{DM} \sim 5 \text{ GeV}$$

Late time dark matter production

- The dark matter may not have strong enough interactions to thermalize with the SM
- Two other well-known ways for dark matter to be produced:
  - "Freeze-in"
  - Freeze-out and decay

Freeze-in

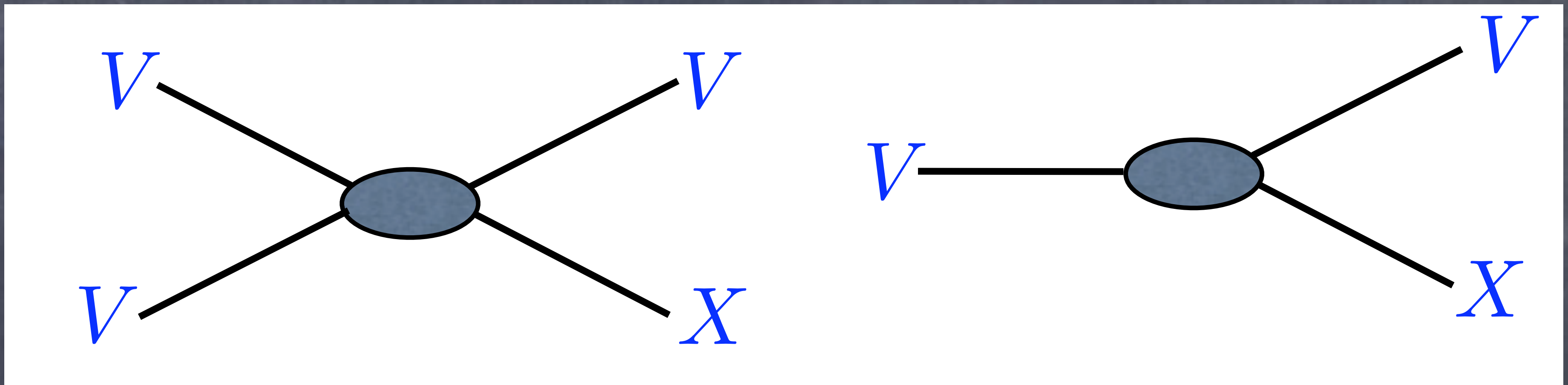
- DM not part of thermal bath to start
- Production is IR (low temp) dominated
  - --> no sensitivity to initial conditions
- SM thermal bath; no DM production



Hall et al, 0911.1120

Freeze-in

- Production through low temp interactions



- Naive dimensional analysis says IR dominated

$$Y_X(T) \sim \lambda^2 \; \frac{M_{Pl}}{T}$$

Freeze-in

- Naive dimensional analysis says IR dominated:

Boltzmann Eq:

$$\frac{dY}{dx} = -\frac{x\langle\sigma|v|\rangle s}{H(m)}(Y^2 - Y_{EQ}^2) \quad \Rightarrow \quad \frac{dY}{dT} = -\frac{\langle\sigma v\rangle}{HTs}n^2$$

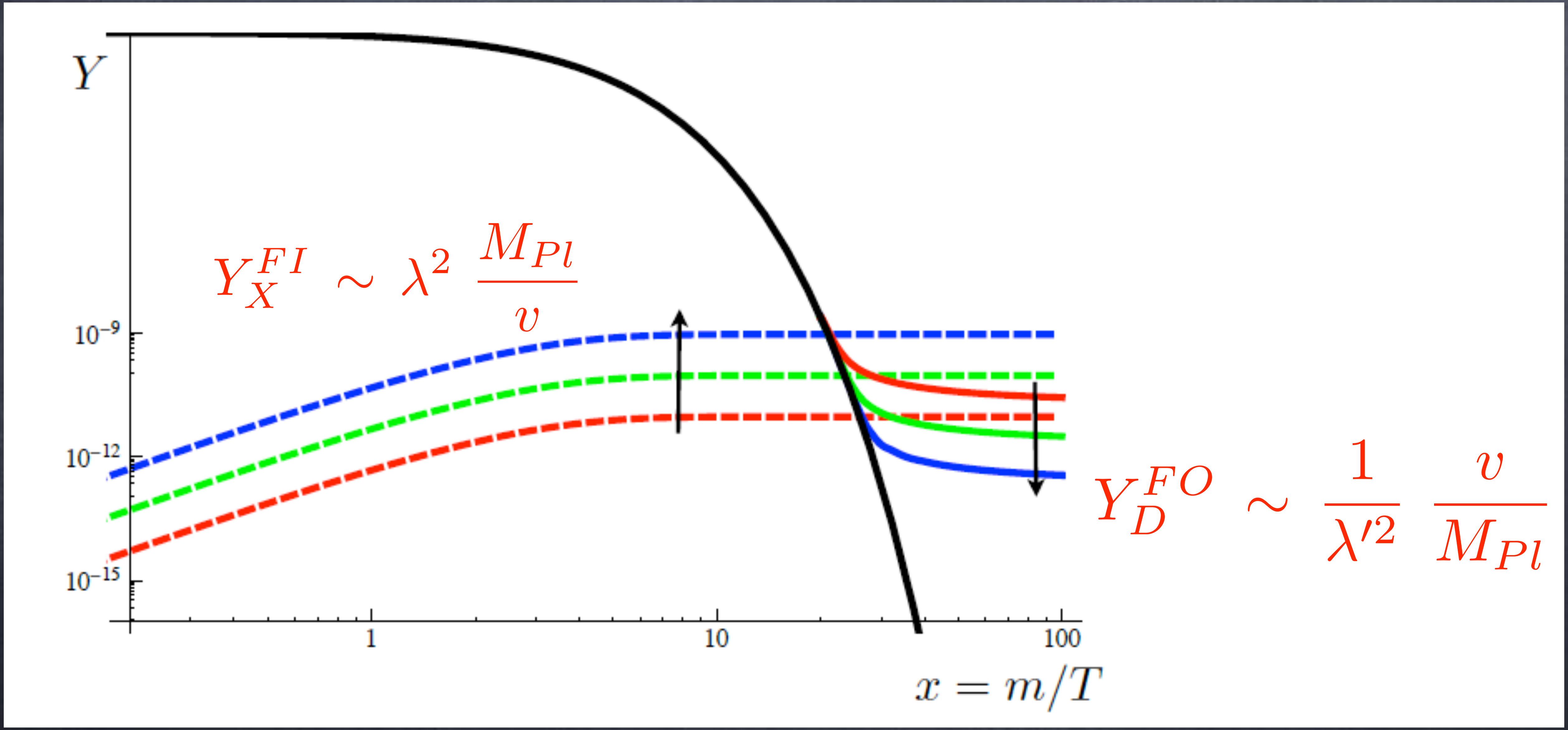
$$\left(Y \equiv \frac{n}{s} \qquad x = m/T\right)$$

$$n \sim s \sim T^3 \qquad \langle\sigma v\rangle \sim \frac{\lambda^2}{s} \sim \frac{\lambda^2}{T^2}$$

NDA!

$$\Longrightarrow \; Y \sim \lambda^2 \frac{M_{pl}}{T}$$

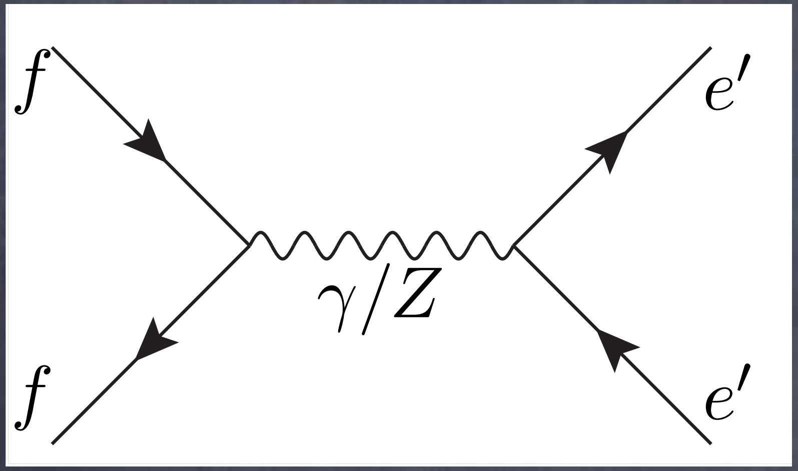
Freeze-in

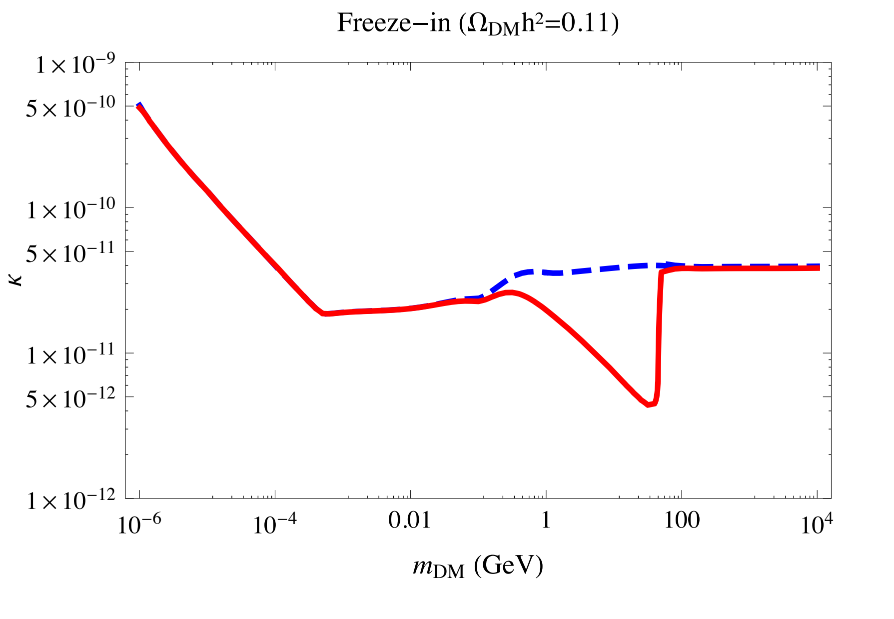


Hall et al, 0911.1120

Freeze-in

- Naive dimensional analysis says IR dominated:





Hambye et al 1112.0493

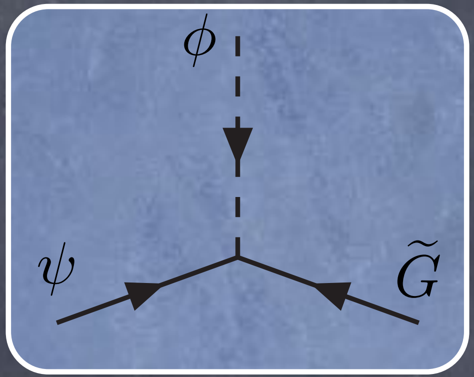
$$n \sim s \sim T^3 \qquad \langle \sigma v \rangle \sim \frac{\lambda^2}{s} \sim \frac{\lambda^2}{T^2}$$

NDA!

$$\implies Y \sim \lambda^2 \frac{M_{pl}}{T}$$

Freeze-out and decay

- Most common example: gravitino DM

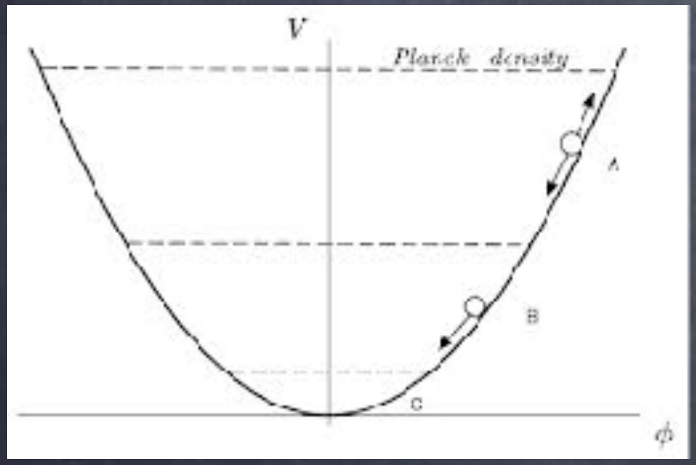


- Freeze-out of parent, which then decays
- Simple relationship between parent relic density

$$\Omega_{\mathrm{SWIMP}} = \frac{m_{\mathrm{SWIMP}}}{m_{\mathrm{WIMP}}} \Omega_{\mathrm{WIMP}}$$

Mis-alignment mechanism

- Oscillating field in a quadratic potential behaves like cold DM



$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2 \qquad p = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m^2\phi^2$$

$$\phi = A\cos(mt)$$

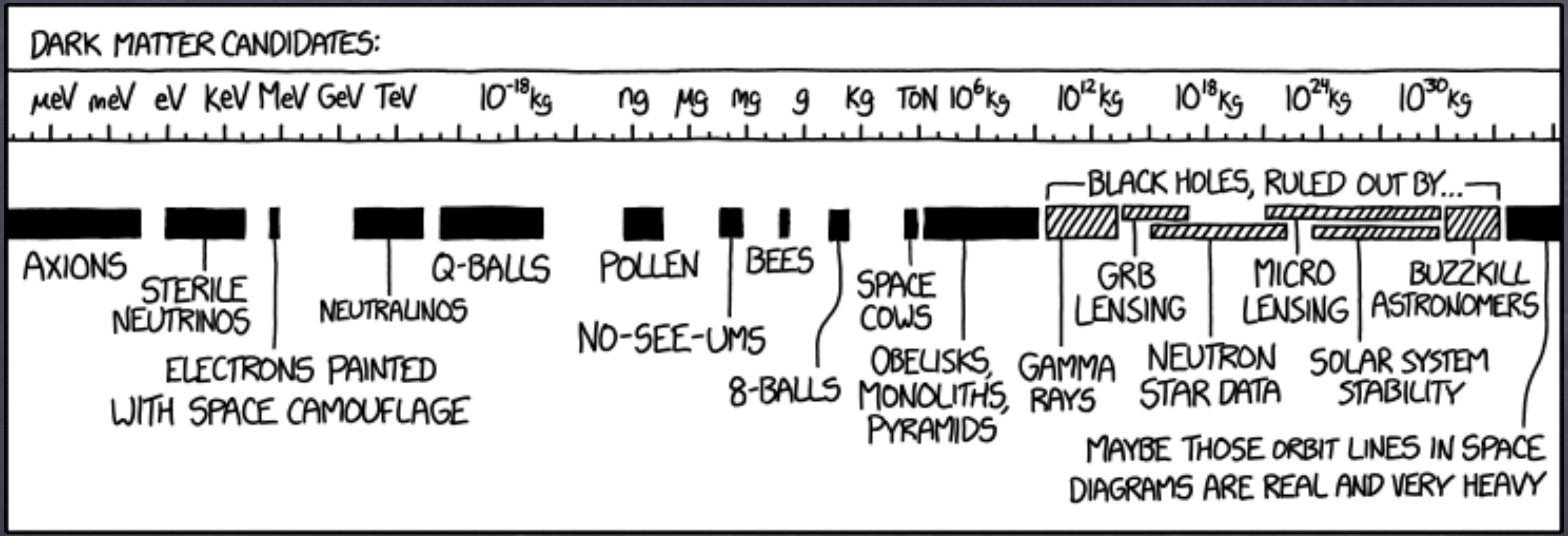
$$\Rightarrow \quad \langle\rho\rangle = \frac{1}{2}m^2A^2 \qquad \langle p\rangle = 0$$

Bose Einstein condensate = CDM! (Ex: axion)

Summary: paradigms for DM relic density

- thermal freeze-out is the most commonly considered paradigm for setting the DM density, but it is not the only way, e.g.
  - chemical potential (ADM)
  - freeze-out and decay
  - freeze-in
  - mis-alignment mechanism (oscillating scalar field)

XKCD Version



My theory is that dark matter is actually just a thin patina of grime covering the whole universe, and we don't notice it because we haven't thoroughly cleaned the place in eons.

Remove EM from SM

- What size nuclei do I synthesize?
- Reactions increasingly exothermic (set aside small-N bottlenecks)
- Simple synthesis freeze-out exercise for a nucleus of size N

$$\frac{dN}{dt} = N\sigma_N n_N v_N = N\sigma_0 N^{2/3} e^{-\alpha N^2/v_N} \frac{n_X}{N} v_N$$

Geometric Cross Section

(Constant) saturation density

Coulomb Barrier

Remove EM from SM

- Take BBN temp at 0.1 MeV (due to deuterium bottleneck)
- Solve equation
  - With Coulomb barrier $N \approx 2.56$
  - Without Coulomb barrier $N \sim 10^4$

$$\frac{dN}{dt} = N\sigma_N n_N v_N = N\sigma_0 N^{2/3} e^{-\alpha N^2/v_N} \frac{n_X}{N} v_N$$

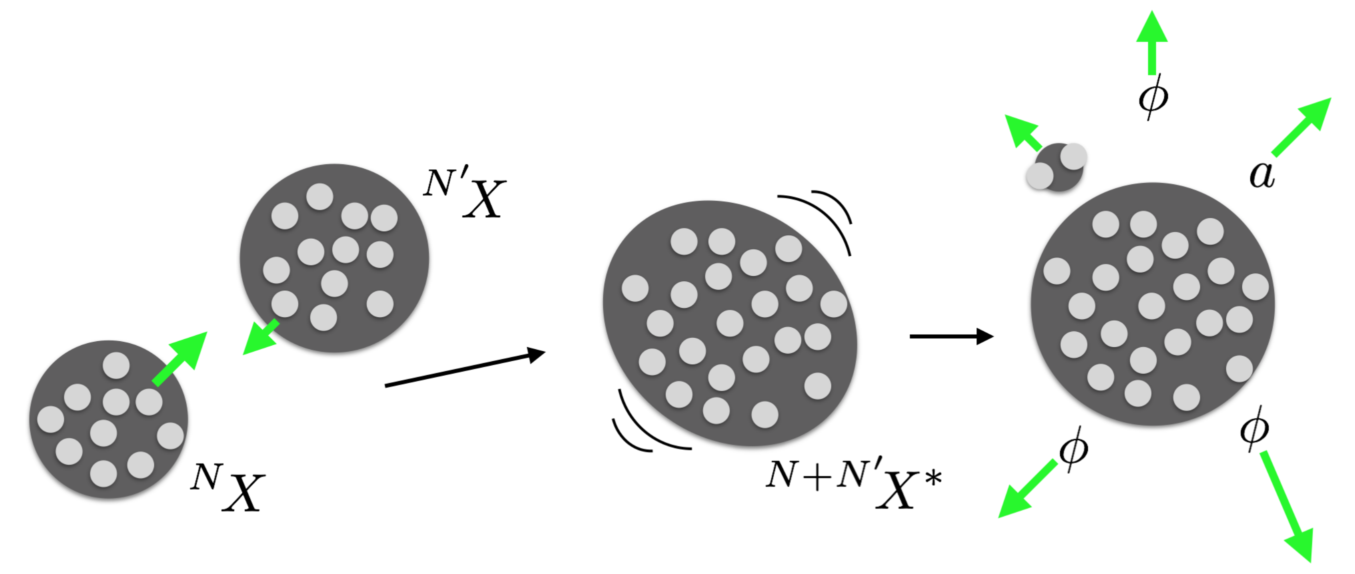
Geometric Cross Section

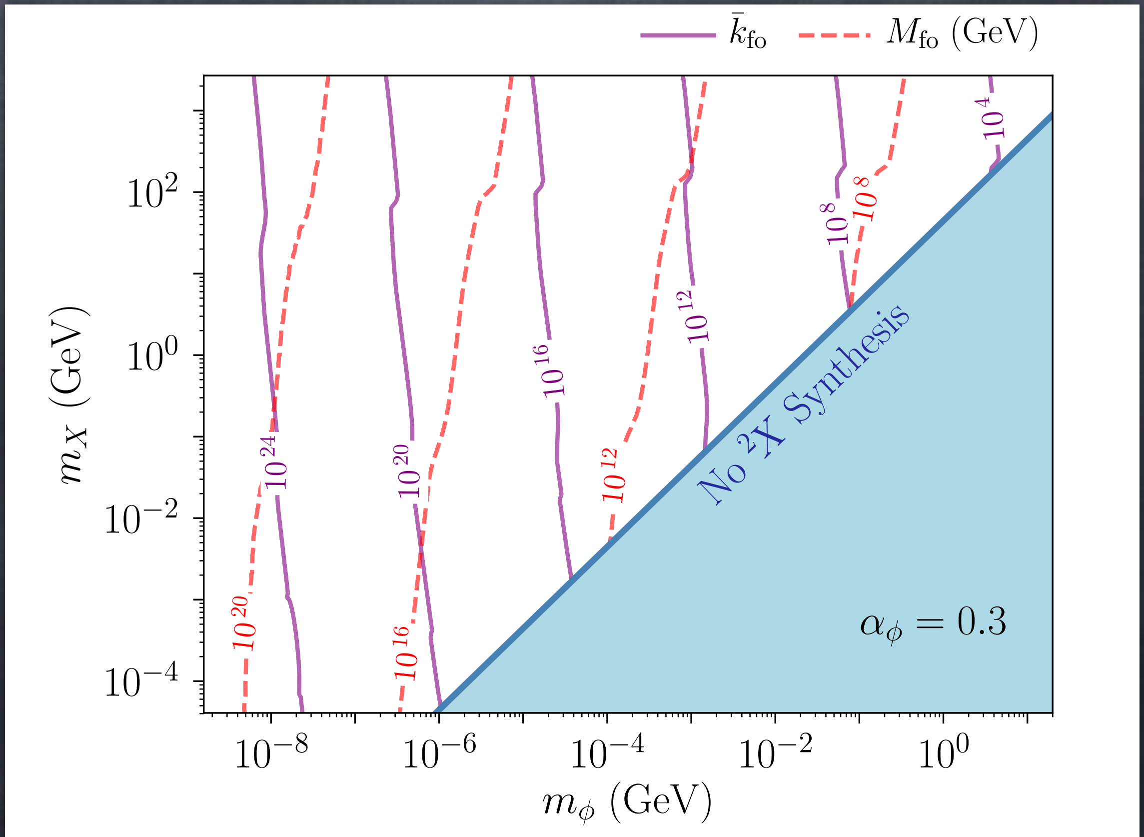
(Constant) saturation density

Coulomb Barrier

Compound Nucleus Model

- Like Clay Putty: two nuclei fuse together
  - Excited state settles to ground state by emitting fragments or force mediators





Gresham, Lou, KZ 1707.02316

PROGRAM

- Paradigms for DM density
  - freeze-out, freeze-in, asymmetric DM, freeze-out and decay, misalignment, compact object formation
- The classic: Supersymmetric Dark Matter
  - Direct and indirect detection basics

PROGRAM

- Looking beyond the vanilla WIMP
  - motivations, experimental search techniques
- Cosmological constraints on particle DM
  - BBN, CMB, formation of structure, stellar capture, DM self-interactions
- New Ideas in Dark Matter Direct Detection

Standard SUSY Dark Matter

(let's back up and talk about the most studied case)

Further reading:
Martin, a Supersymmetry primer, hep-ph/9709356
Supersymmetric Dark Matter, Jungman, Kamionkowski, Griest

Models of Dark Matter

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

DM Paradigm: recap

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

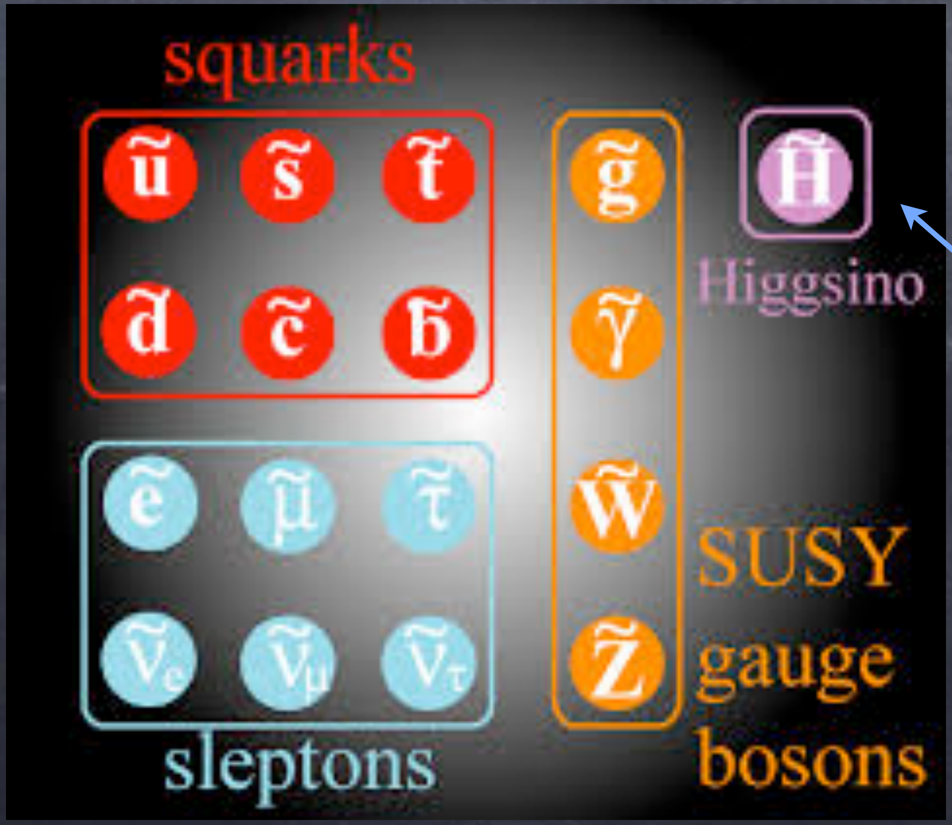
Stability

- To make candidate absolutely stable, need a symmetry in the theory
- In SM:
  - p: stable by baryon number (global symm)
  - e-: electric charge (gauge symm)
  - nu's: lepton number (global symm)

Stability

- SUSY has built in symmetry to stabilize one of the SUSY particles
- Each SM particle has a superpartner that differs in spin by 1/2 from SM particle

scalar superpartners to SM fermions



fermionic superpartners to SM scalar and gauge bosons

(actually, require two Higgses in SUSY)

gauginos

Stability

- Why is one of these states stable? R-parity
- Symmetry which appears in UV completions
- For proton stability; DM stability by-product
- Because, scalars in SUSY allow to write down additional interactions

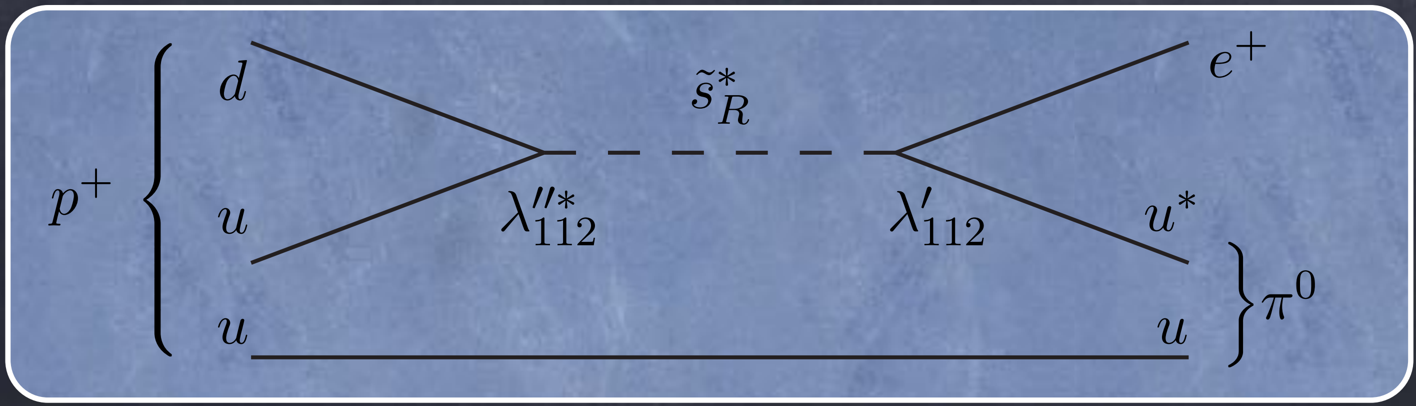
$$W_{\Delta\mathrm{L}=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \overline{e}_k + \lambda'^{ijk} L_i Q_j \overline{d}_k + \mu'^{i} L_i H_u$$

$$W_{\Delta\mathrm{B}=1} = \frac{1}{2}\lambda''^{ijk} \overline{u}_i \overline{d}_j \overline{d}_k$$

Stability

$$
\begin{aligned}
W_{\Delta \mathrm{L}=1} &= \frac{1}{2}\lambda^{ijk} L_i L_j \overline{e}_k + \lambda'^{ijk} L_i Q_j \overline{d}_k + \mu'^i L_i H_u \\
W_{\Delta \mathrm{B}=1} &= \frac{1}{2}\lambda''^{ijk} \overline{u}_i \overline{d}_j \overline{d}_k
\end{aligned}
$$

- Preserve gauge symmetries of Standard Model
- Violate baryon and lepton number; induce proton decay



Stability

- Introduce new symmetry (= R-parity) to forbid those interactions

$$P_R = (-1)^{3(\mathrm{B-L})+2s}$$

- All SM particles carry R-parity +1

lepton: s=1/2, L=1
quark: s=1/2, B=1/3
gauge boson, s=1, B=L=0

- All super-partners carry R-parity -1

slepton: s=0, L=1
squark: s=0, B=1/3
gaugino, s=1,/2 B=L=0

→ Lightest super-partner is stable

Neutral

- Gauge bosons mix

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B \\ W^0 \end{pmatrix}$$

- Their superpartners the gauginos also mix
  - neutral and charged states -- neutralinos and charginos
  - diagonalize mass matrix to obtain mass eigenstates

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: $W_{MSSM} = \bar{u}y_u QH_u - \bar{d}y_d QH_d - \bar{e}y_e LH_d$

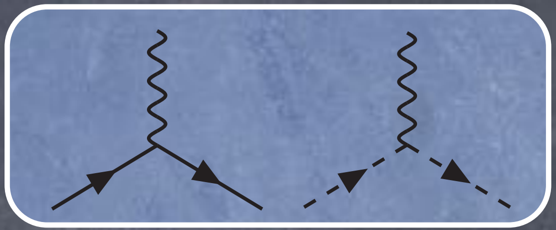
$$\tan\beta = \frac{v_u}{v_d} \qquad v_u^2 + v_d^2 = v^2 = (246\ \mathrm{GeV})^2$$

Weakly-interacting

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

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

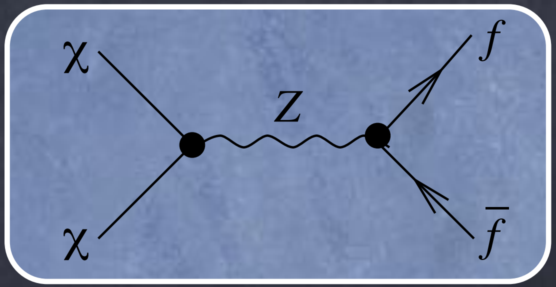
Gauge interaction:



- Its couplings are fixed by gauge interactions

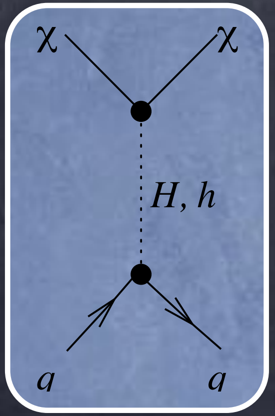
- Scatters off nucleons through Z boson

- Let's compute the rate



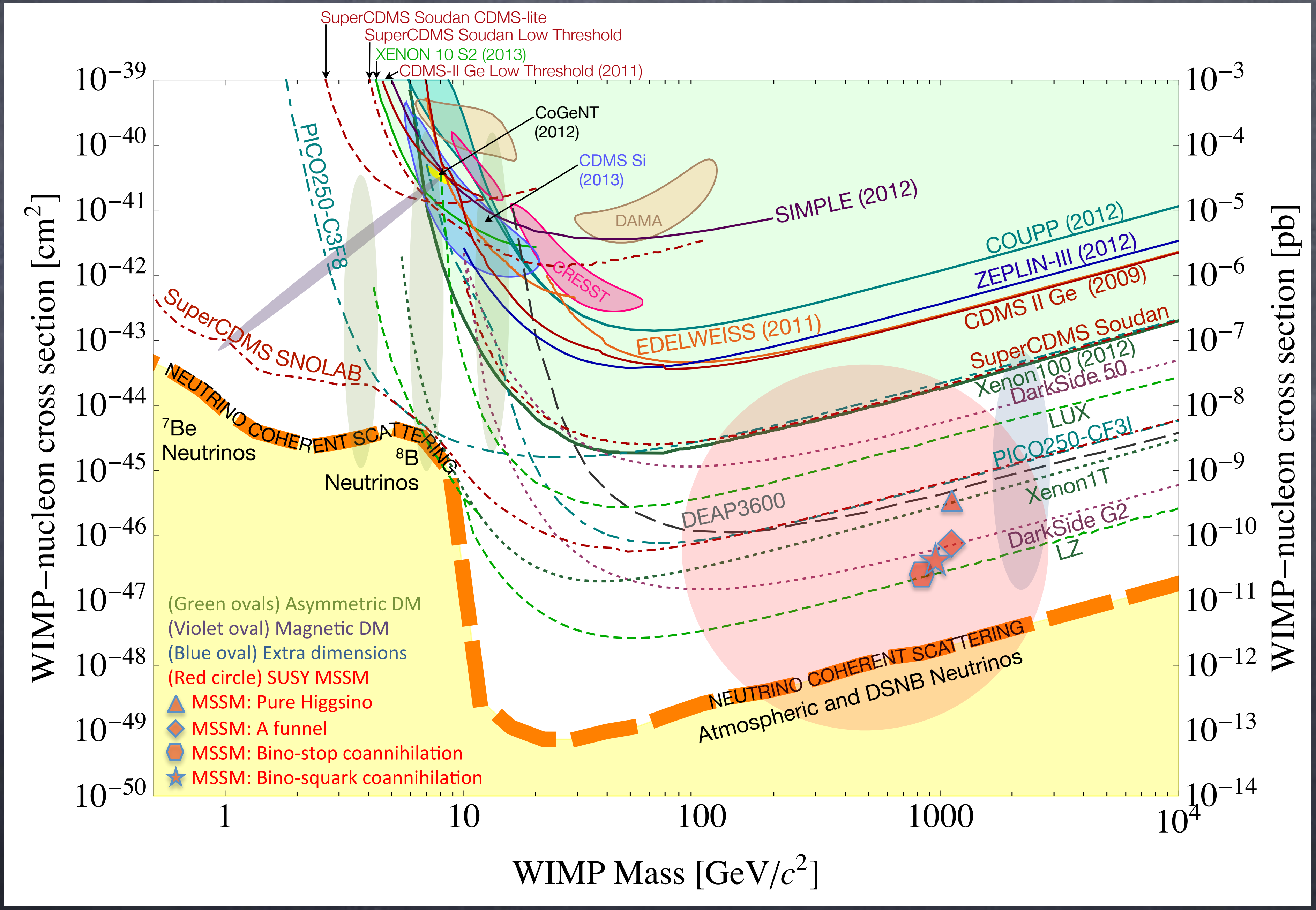
Direct detection basics

- Two types of interactions: spin-dependent, spin-independent
- Spin-independent couples to charge of nucleus --> coherent interactions
- Examples of spin-independent interaction: Higgs



Direct Detection Reach

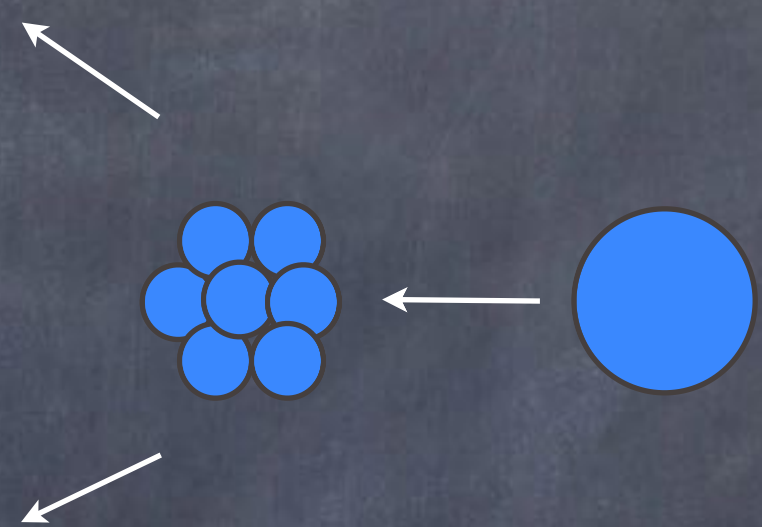
CF1 Snowmass report, 1310.8327



Kinematics of scattering

$$p_X^i = \begin{pmatrix} m_N \\ 0 \end{pmatrix}$$

$$p_X^f = \begin{pmatrix} \frac{{p_f^N}^2}{2m_N} + m_N \\ \vec{p}_f^N \end{pmatrix}$$



$$p_X^i = \begin{pmatrix} \frac{1}{2} m_X v^2 + m_X \\ m_X \vec{v} \end{pmatrix}$$

$$p_X^f = \begin{pmatrix} \frac{{p_f^X}^2}{2m_X} + m_X \\ \vec{p}_f^X \end{pmatrix}$$

$$E_i = E_f \qquad \vec{p}_i = \vec{p}_f$$

$$\Longrightarrow \; 2\mu_N v = |\vec{p}_F^N| = \sqrt{2 m_N E_R} \qquad \mu_N \equiv \frac{m_N m_X}{m_X + m_N}$$

$v \sim 300\ \mathrm{km/s} \sim 10^{-3} c \Longrightarrow E_R \sim 100\ \mathrm{keV}$ for 50 GeV target

Apply to scattering through Z boson

$$\sigma_N = \frac{m_{DM}^2 m_N^2}{4\pi(m_{DM}+m_N)^2}\frac{(Zf_p+(A-Z)f_n)^2}{m_Z^4}$$

$$\sigma_N = \sigma_p \frac{\mu_N^2}{\mu_n^2}\frac{(Zf_p+(A-Z)f_n)^2}{f_p^2}F^2(E_R)$$

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi}\int_{|\vec{v}|>v_{min}} d^3v\, v f(\vec{v},\vec{v}_e)\frac{d\sigma}{dE_R}$$

Maxwell-Boltzmann distribution:

$$f \sim \frac{1}{(\pi v_0)^{3/2}} e^{-v^2/v_0^2}$$

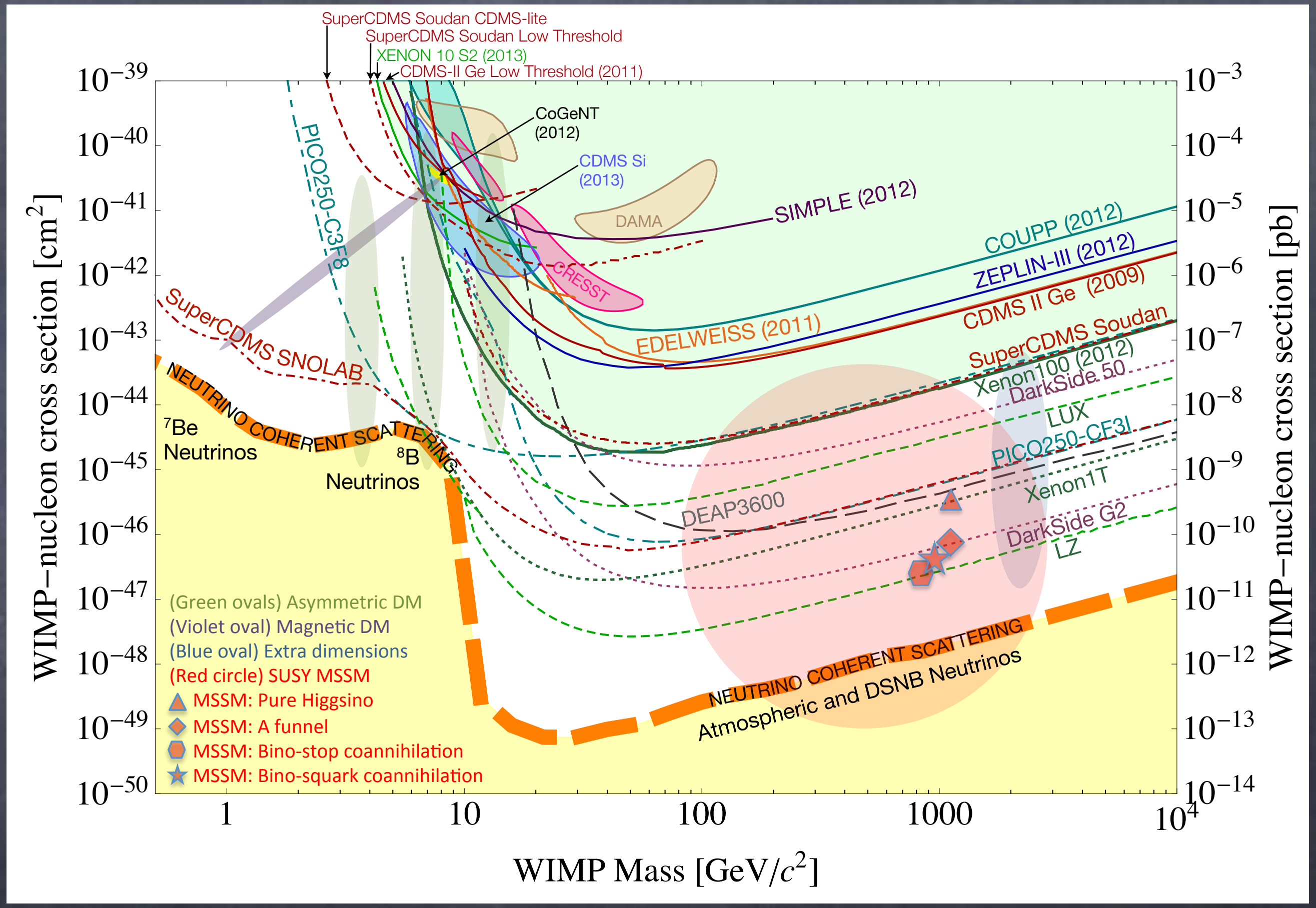
$$\frac{d\sigma}{dE_R} = \frac{m_N \sigma_N}{2\mu_N^2 v^2}$$

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

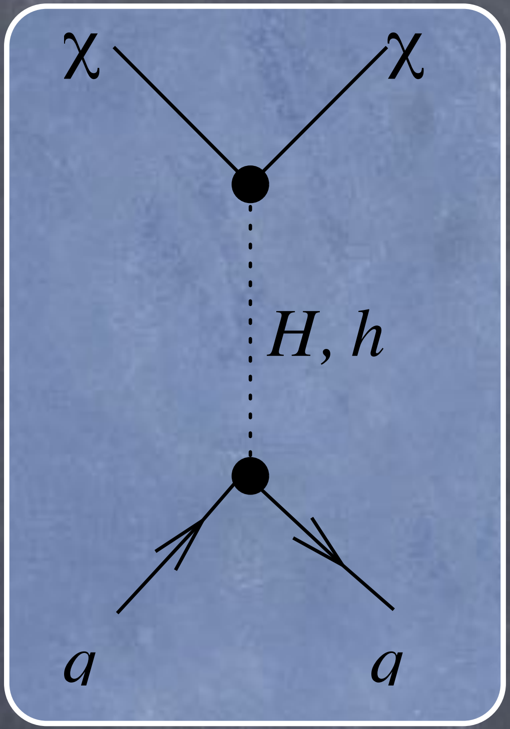
What about neutralino?

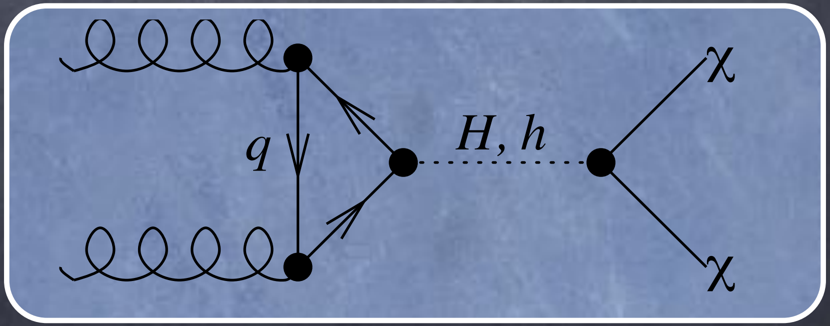
- Actually, a little worse.
- Bino and Wino do not couple to Z
- Higgsino does, but in the limit that bino and Wino decouple, SD coupling via the Z vanishes

$$\sigma_{\rm SD}^{\rm MSSM}(\chi\, p \to \chi\, p) \approx 4\times 10^{-4}\,{\rm pb}\,\left(\frac{|Z_{H_d}|^2 - |Z_{H_u}|^2}{0.1}\right)^2$$

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

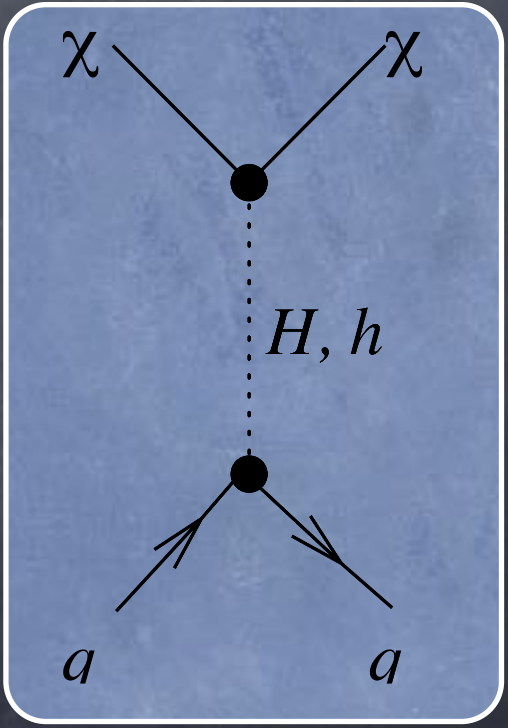
- Scattering cross-section depends on DM coupling to Higgs; structure of Higgs boson sector.
- MSSM has two Higgses, H_u and H_d
- Ratio of vevs $\tan\beta = \frac{v_u}{v_d}$

$$m_{u,c,t} = y_{u,c,t} v_u \qquad m_{d,s,b} = y_{d,s,b} v_d$$

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

- Cross-section:

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



Higgs scattering cross-section

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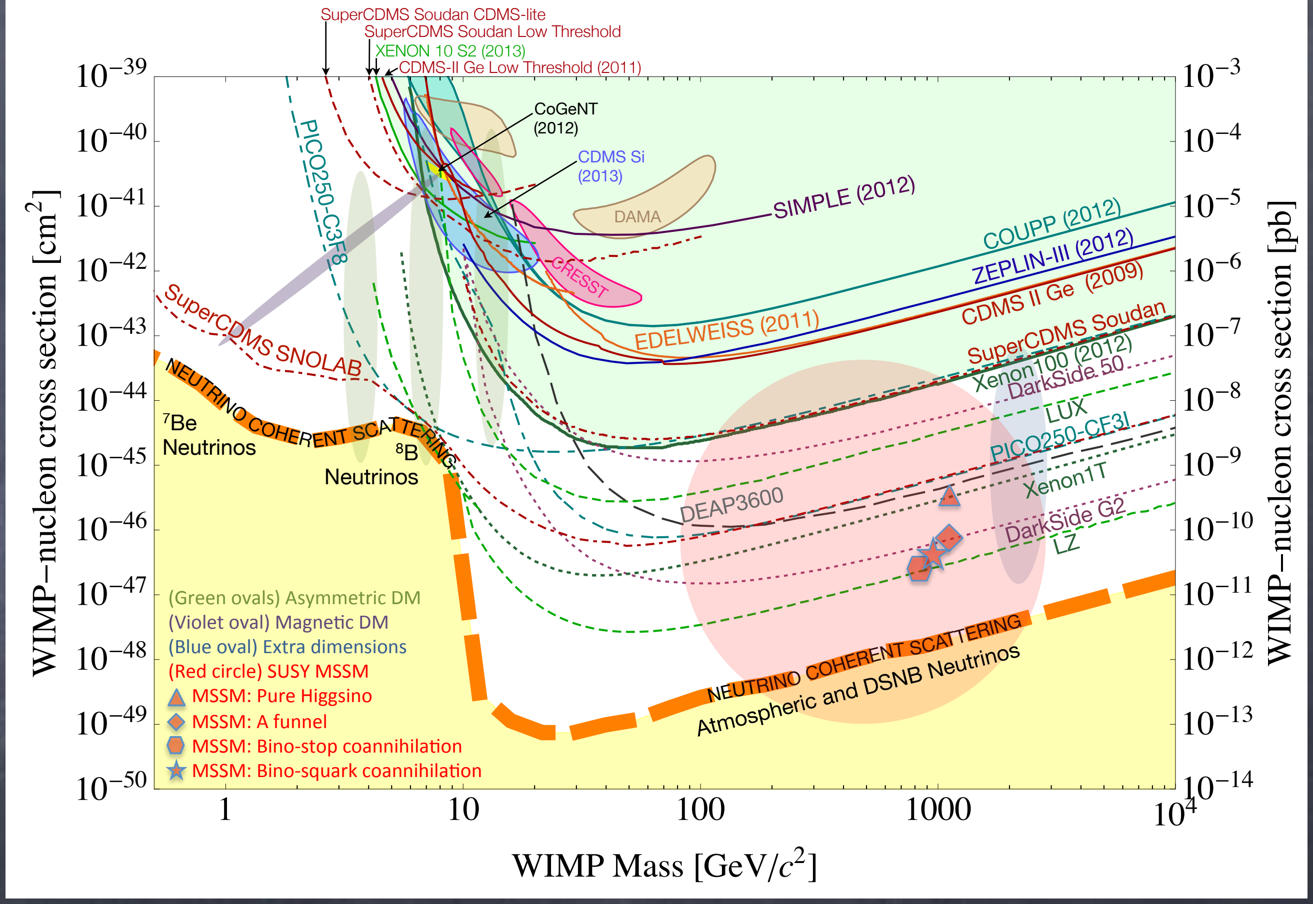
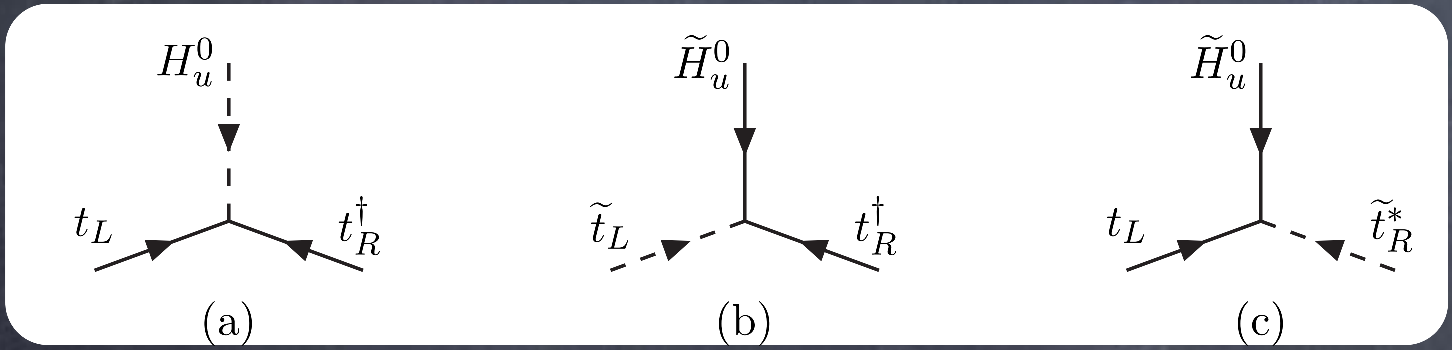


Are there ways around?

A bit more about neutralino couplings

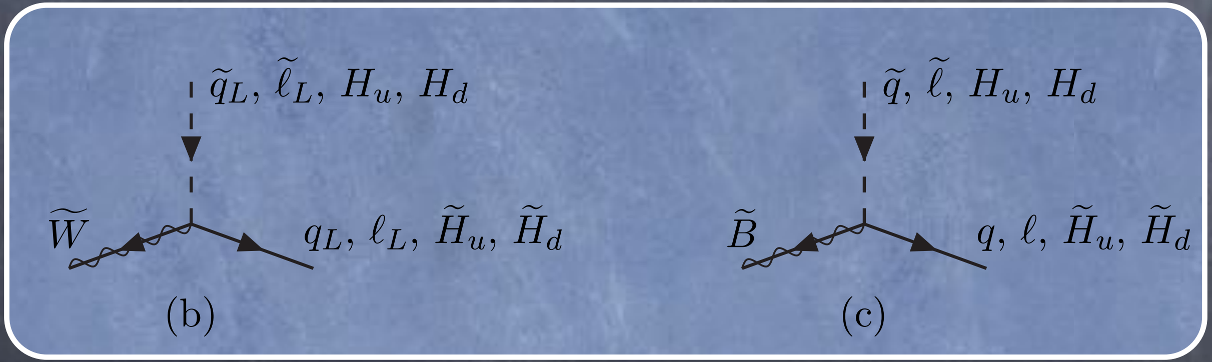
- Supersymmetry relates SM couplings to SUSY particle couplings



- This fixes the interactions that can occur ....

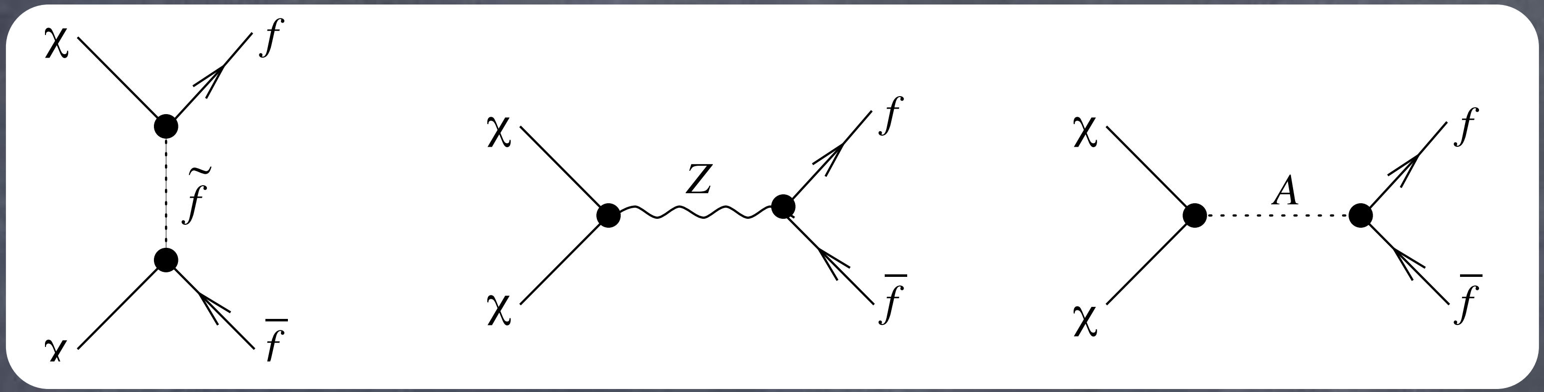
A bit about neutralino couplings

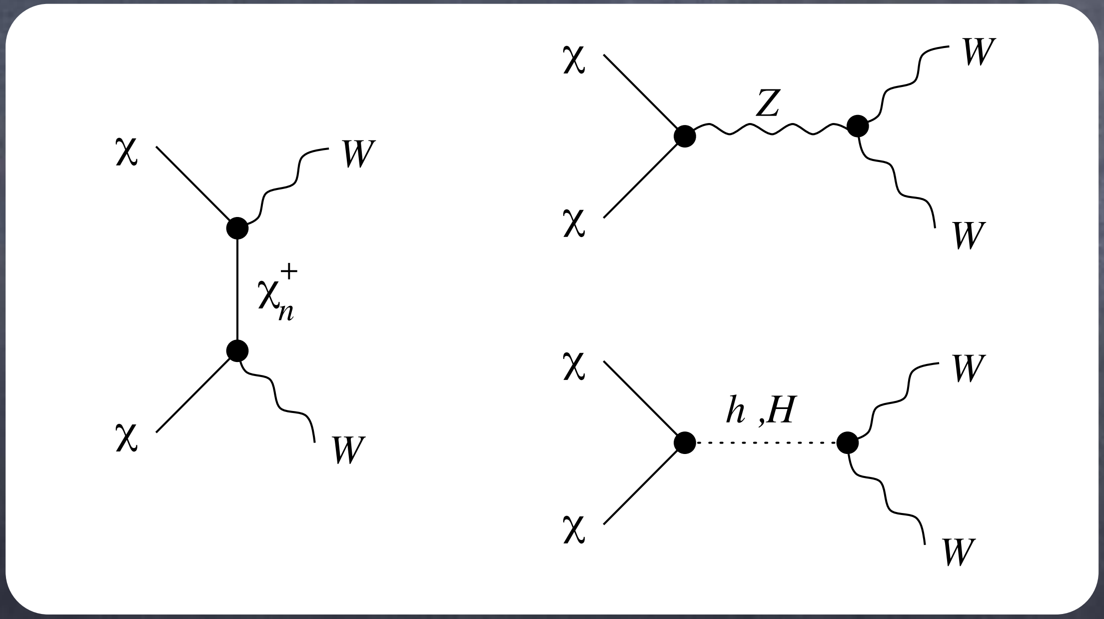
- .... and what interactions cannot occur
- Higgs does not interact with a "pure" state



- Must have bino-Higgsino or Higgsino-wino mix

WIMP annihilation processes

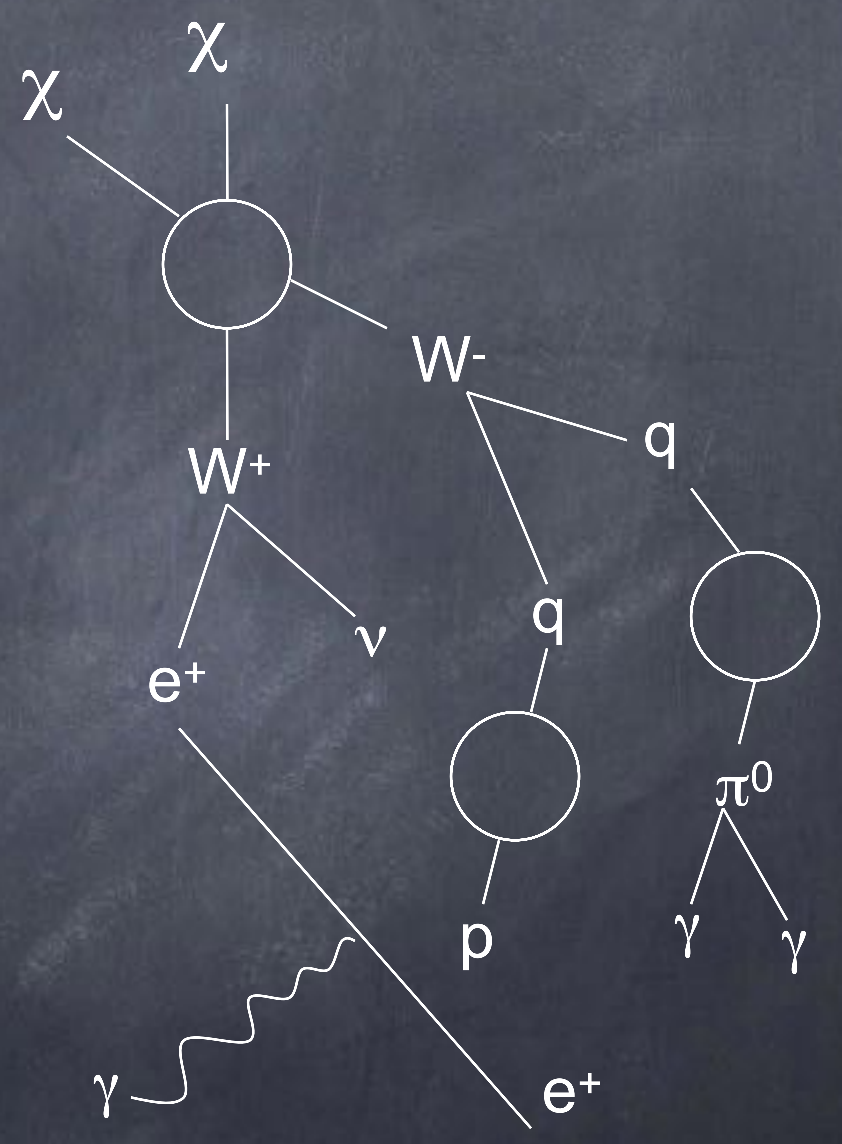




- Bottom diagrams often dominate if DM is largely wino or largely Higgsino

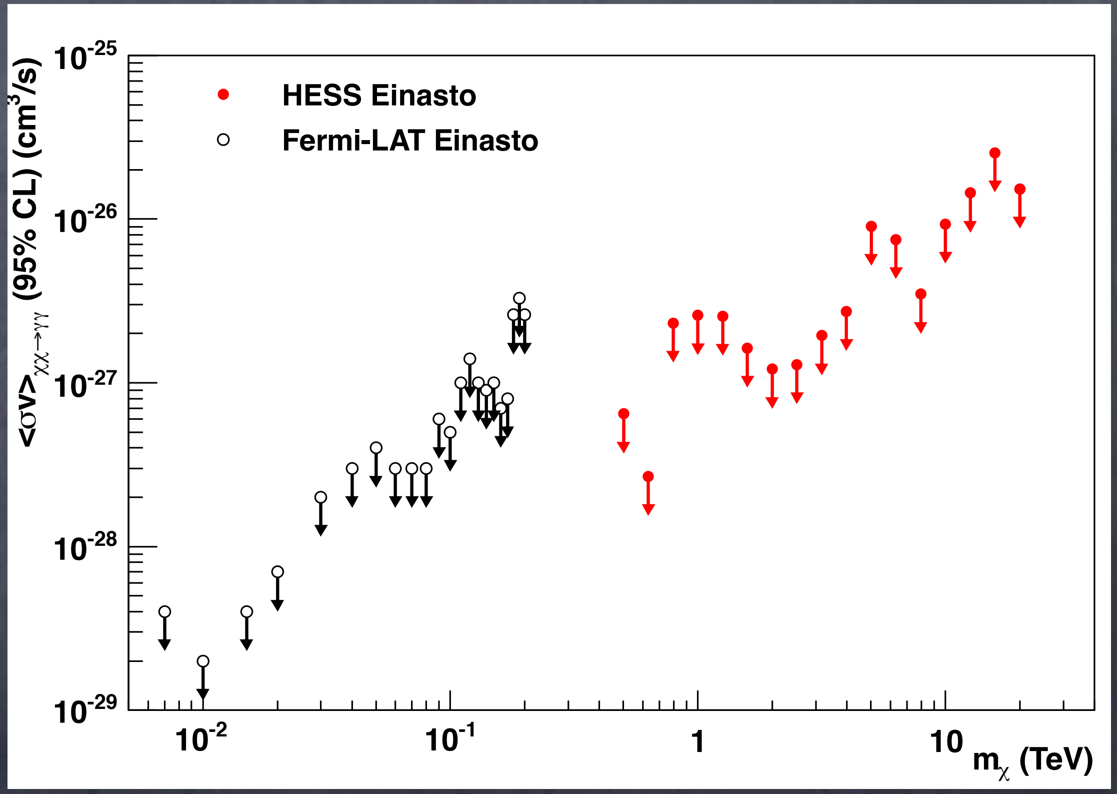
Escaping direct detection constraints

- 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

- Make neutralino a pure state -- wino, Higgsino, or bino
- Wino and Higgsino: strong indirect detection constraints
- Photons from annihilation in galaxy today constrain pure wino or Higgsino DM



Escaping direct detection constraints

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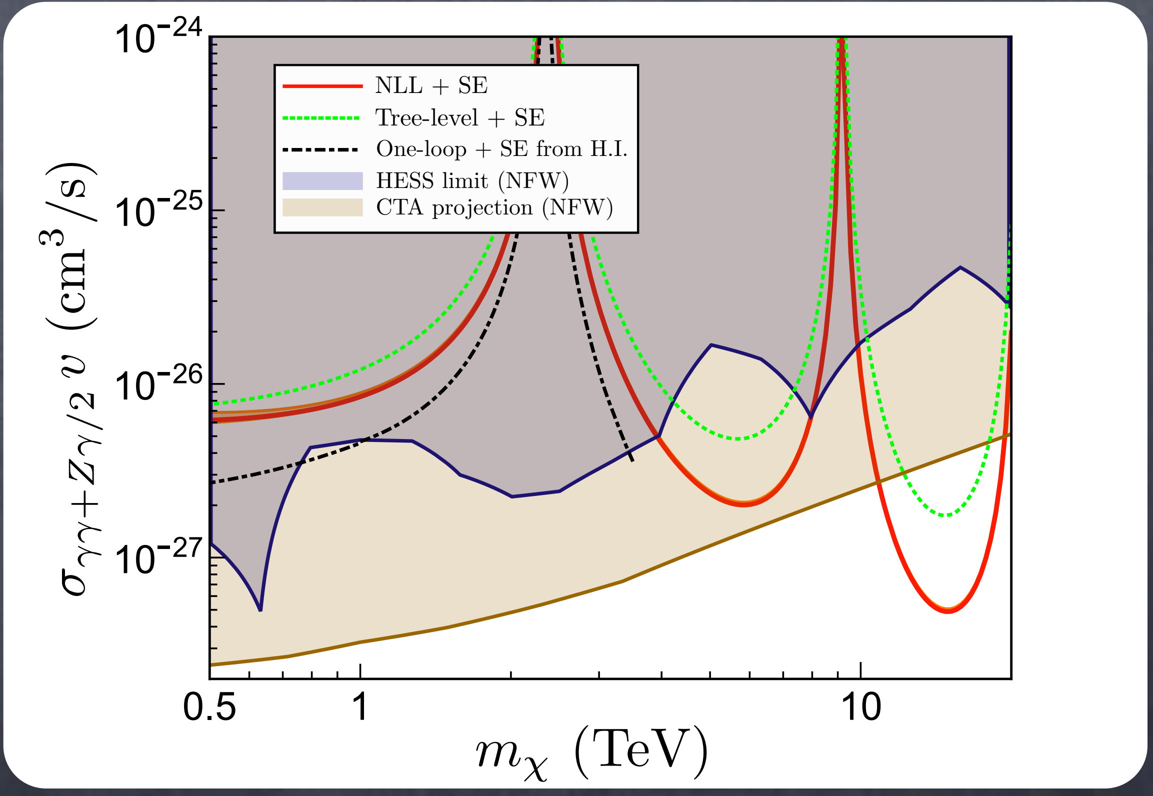
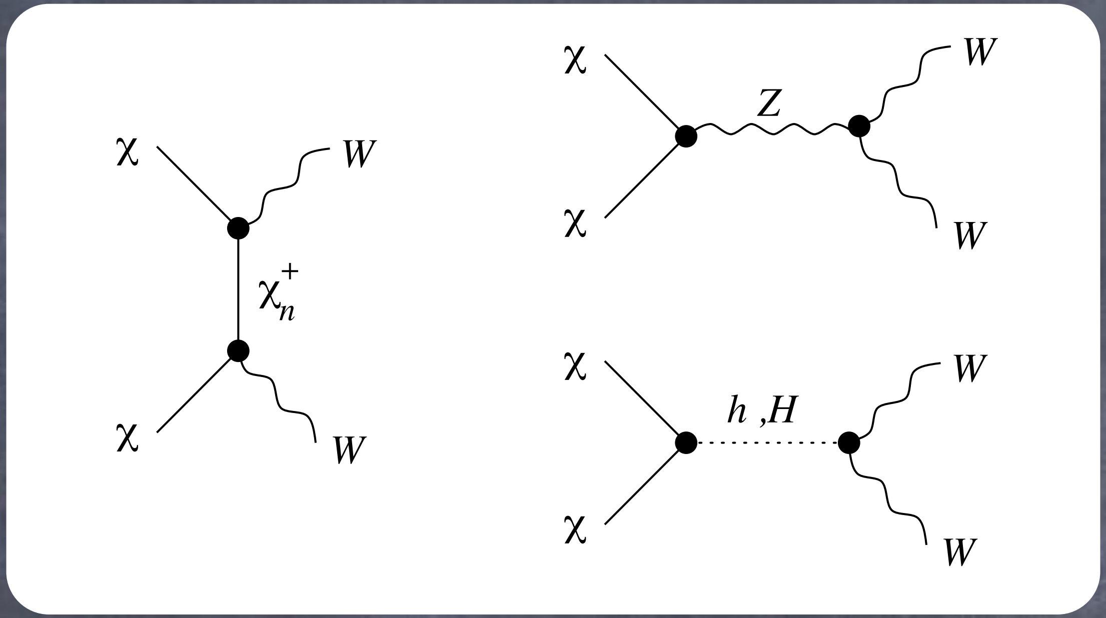


Ovanesyan, Stewart, Slatyer

Relic density of wino or Higgsino



$$3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \simeq \frac{g_{wk}^4}{(2\ \mathrm{TeV})^2} \sim \frac{g_{wk}^4}{\pi m_X^2}$$

Thermal wino or Higgsino DM is heavy!

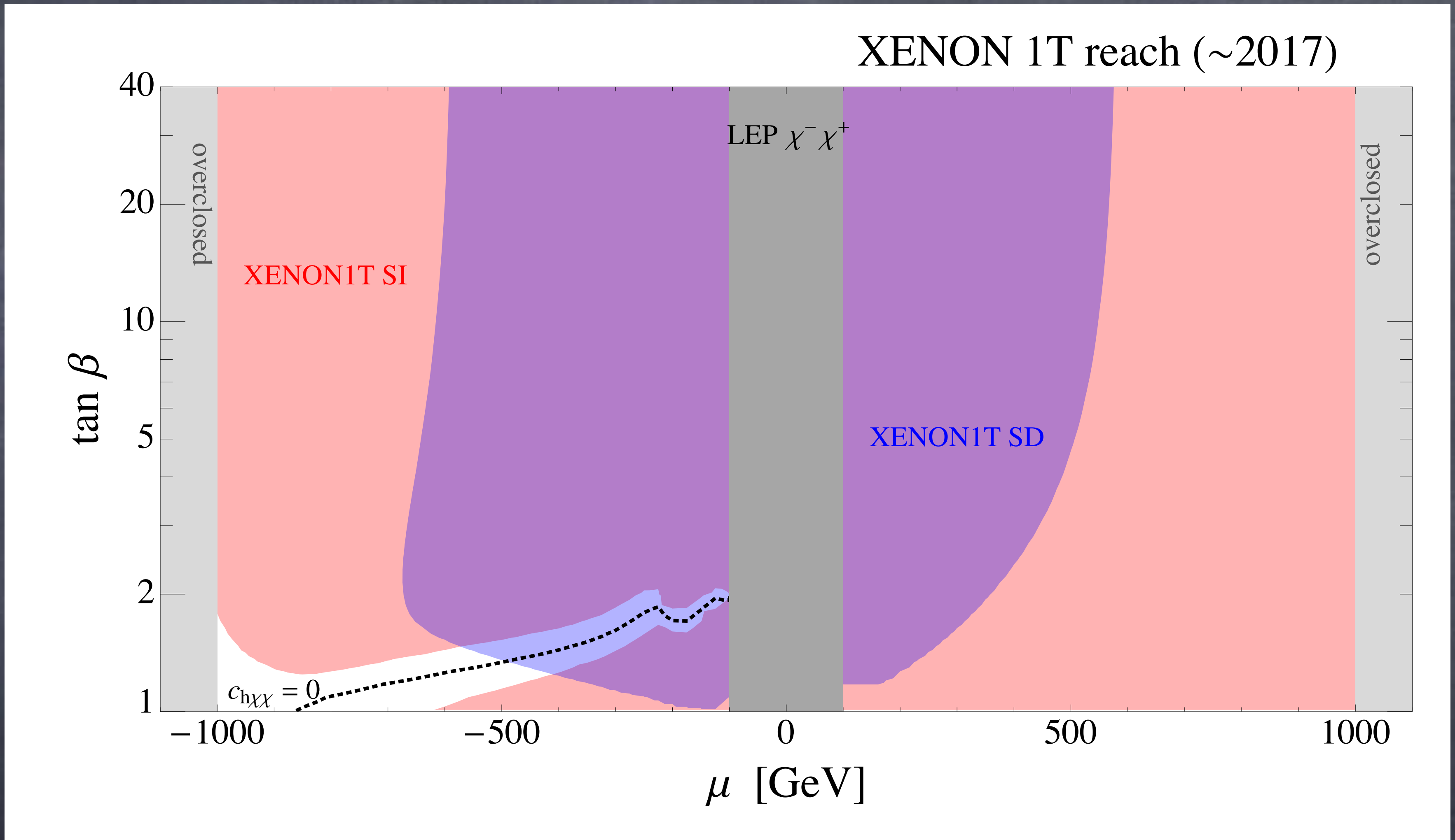
Pure bino DM escapes

- 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

How much param space escapes?



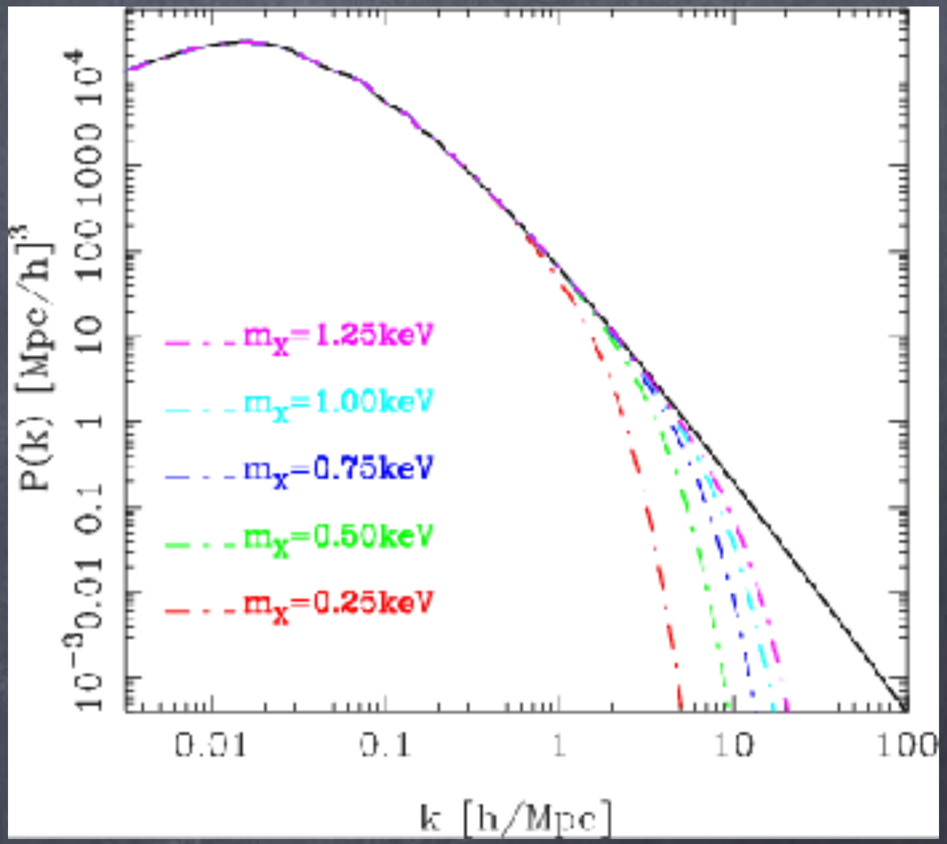
Cheung, Hall, Pinner, Ruderman

When Should We Start Looking Elsewhere?

- Cannot kill neutralino DM via direct detection, but paradigm does become increasingly tuned
- Somewhat below Higgs pole -- Neutrino background?
- Well-motivated candidates that are much less costly to probe
- We will talk about **alternative** models later

"Massive" Dark Matter

- Typically means heavier than a keV
- Relativistic and non-relativistic matter form structure differently
- Relativistic matter free-streams out of gravitational wells (hard to trap) -- allows us to constrain neutrinos
- Dark matter needs to clump



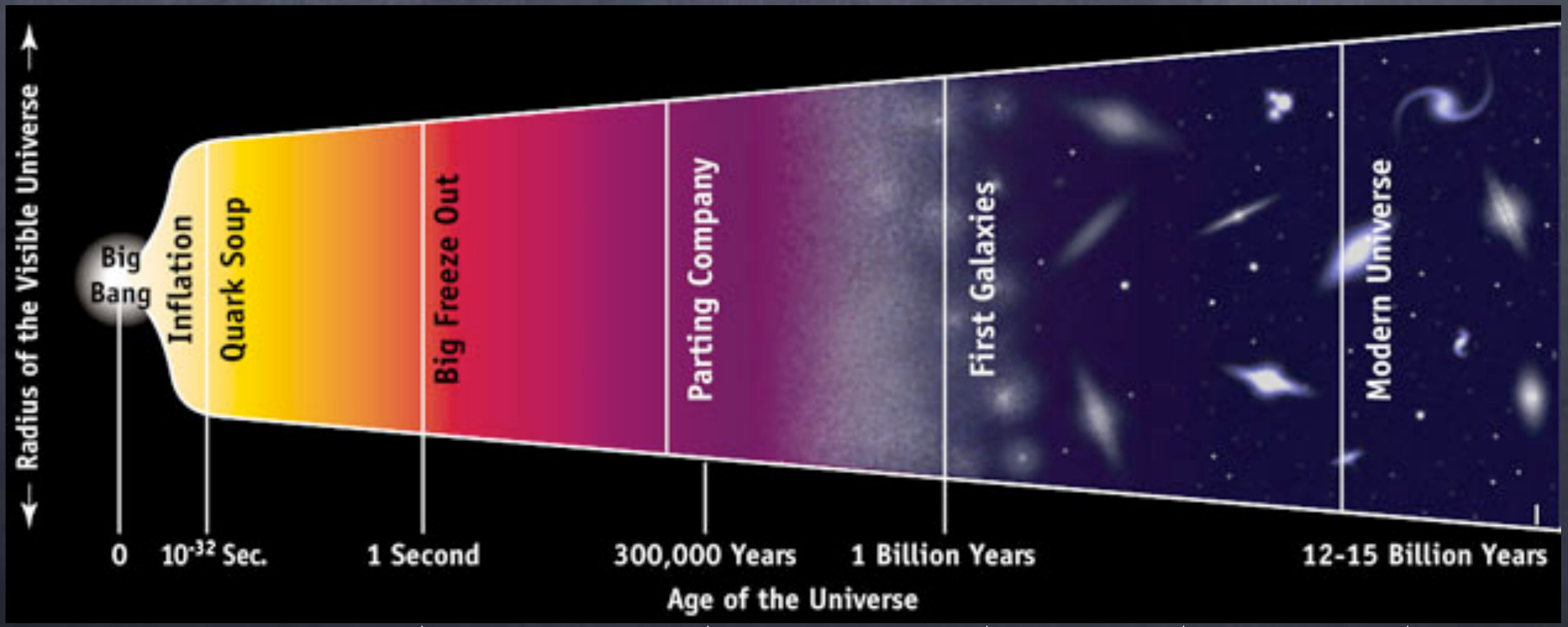
Smith and Markovic 1103.2134

Astrophysical and Cosmological Constraints on the Dark Matter

(The DM sector is not as unconstrained as you thought)

Check Cosmology

- What are good things to look for?
- We have a lot of information about the DM sector from the time of BBN (t = 1 sec)



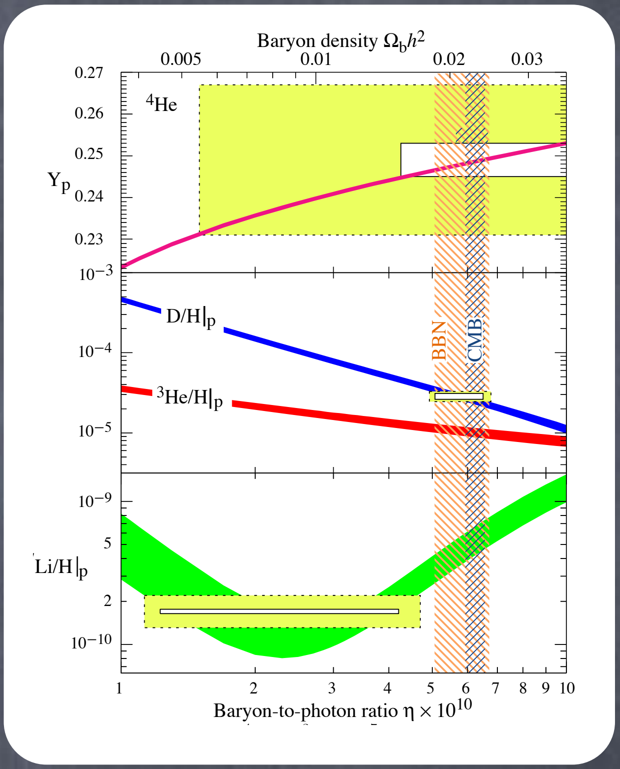
BBN (baryons) | CMB (curvature) | LSS (matter) | Supernovae (DE) | Galaxy curves (matter)

1. BBN

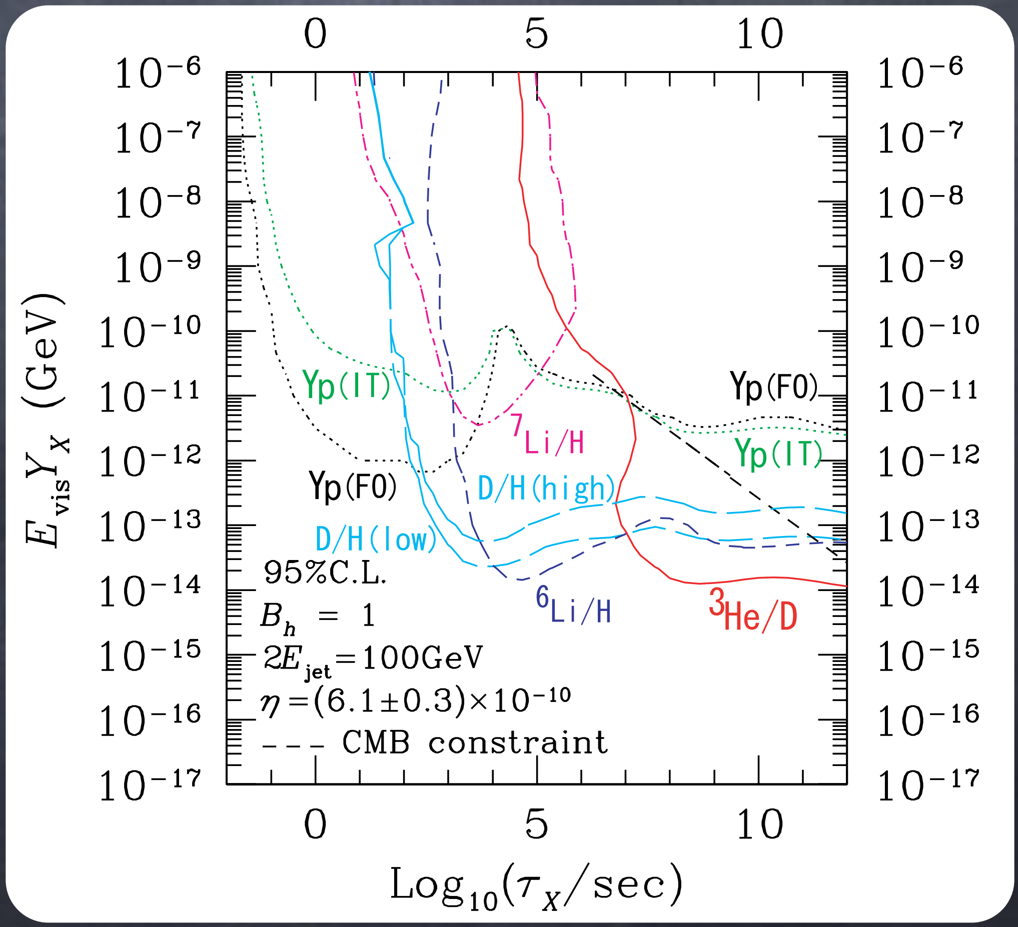
- Late-decaying or annihilating DM can ionize nuclei and change the predictions of BBN

- BBN occurs at T ~ 1 MeV or t ~ 1 sec

- Particularly relevant for decay to gravitinos or for MeV mass (or lighter) DM



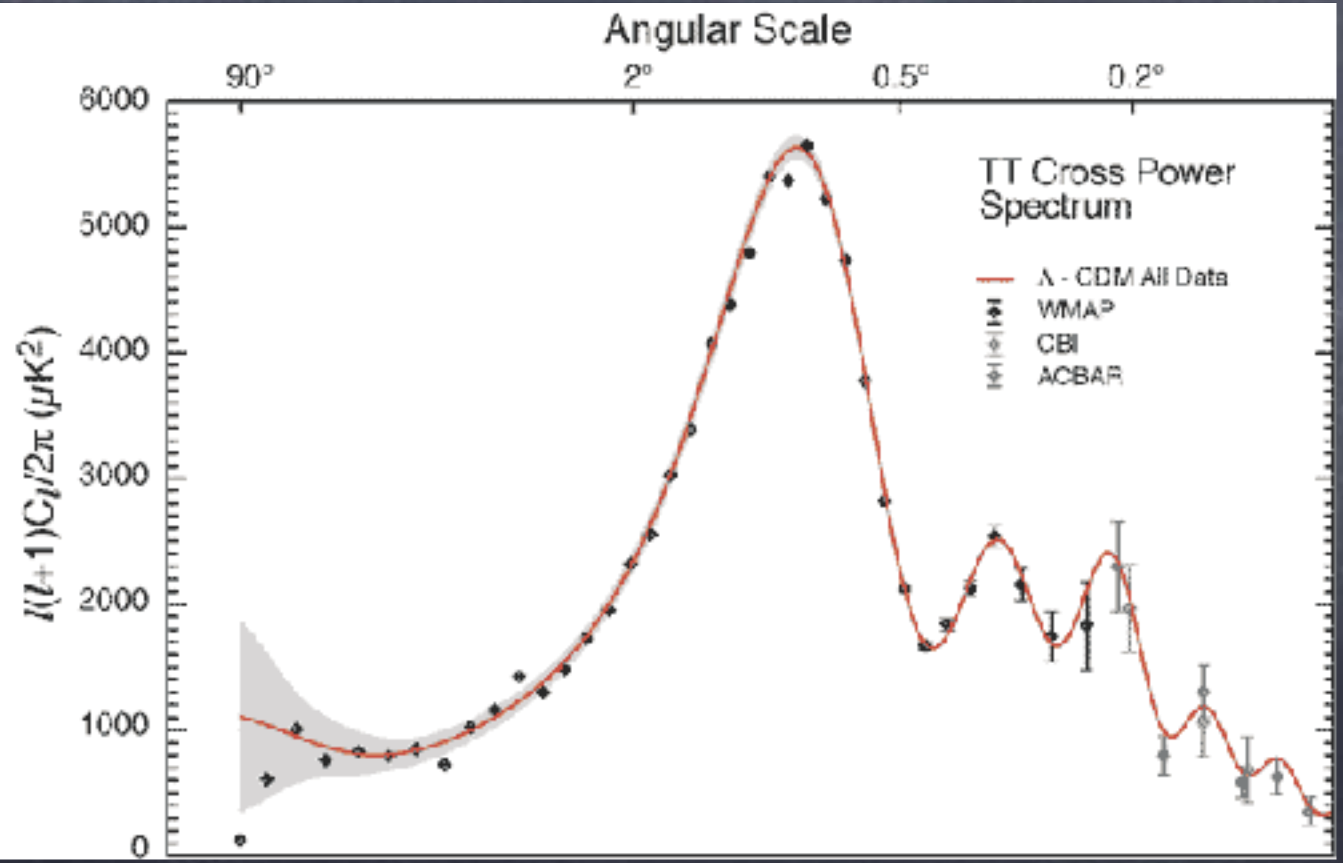
Kawasaki, Kohri, Moroi, hep-ph/0408426



2. CMB epoch

- CMB multipoles + LSS are consistent with baryon-photon fluid plus non-interacting matter

matter-radiation equality --> measurement of matter density



Baryon density

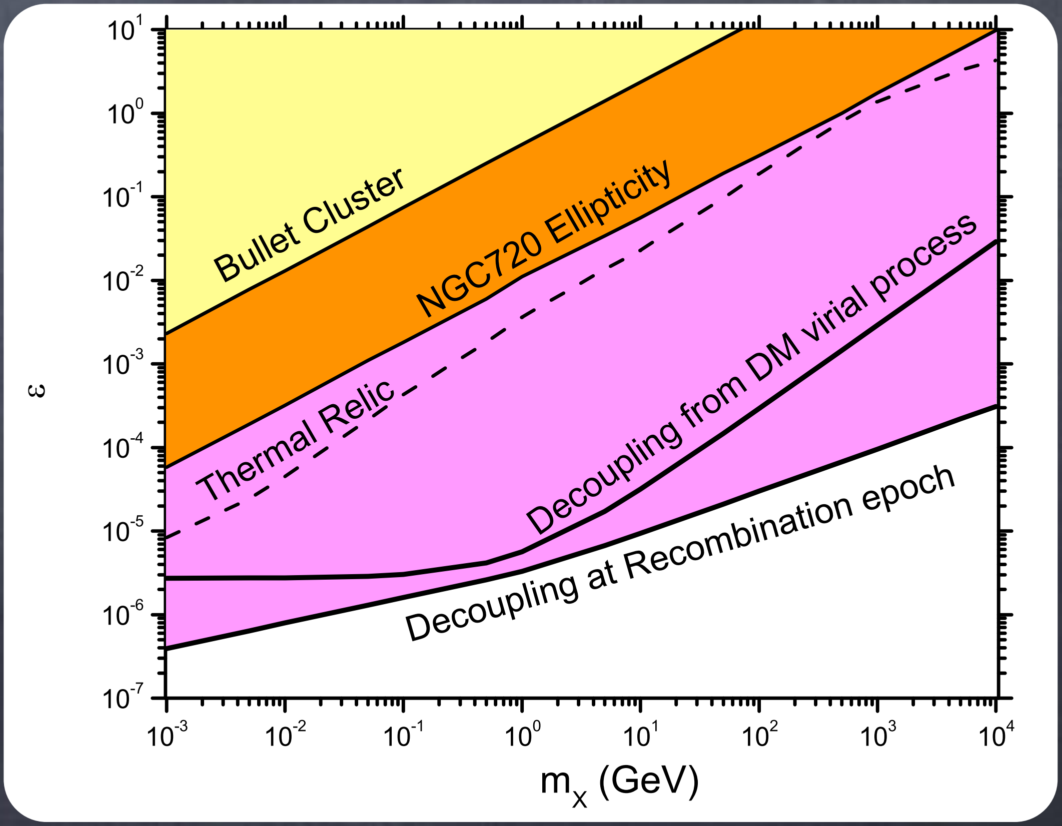
sound speed = baryon to photon ratio

2. CMB epoch

- DM interactions with baryo-photon fluid would damage agreement with observations of CMB

Rutherford scattering:

$$\frac{d\sigma_{Xb}}{d\Omega_*} = \frac{\alpha_{em}^2 \epsilon^2}{4\mu_b^2 v_{rel}^4 \sin^4(\theta_*/2)}$$

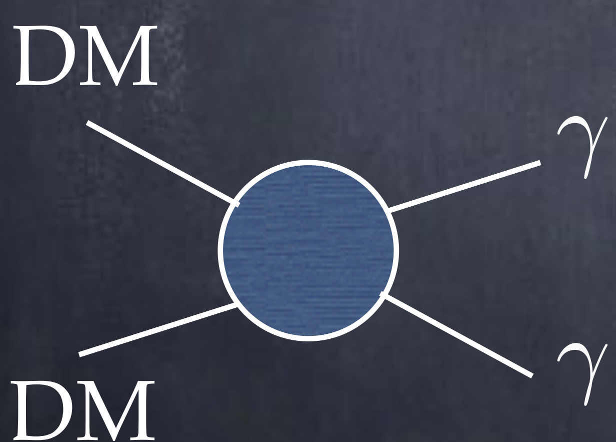


McDermott, Yu, KZ
1011.2907

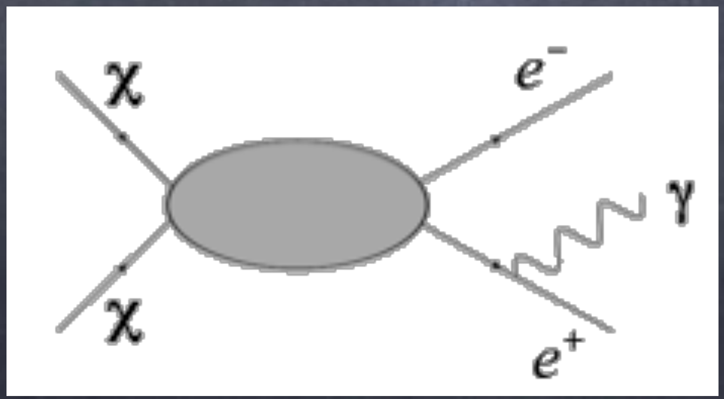
- This constrains DM milli-charge

3. DM Annihilations and CMB epoch

- A high rate of DM annihilations would inject ionizing photons into the CMB
- Epoch of *re*combination, not de-combination

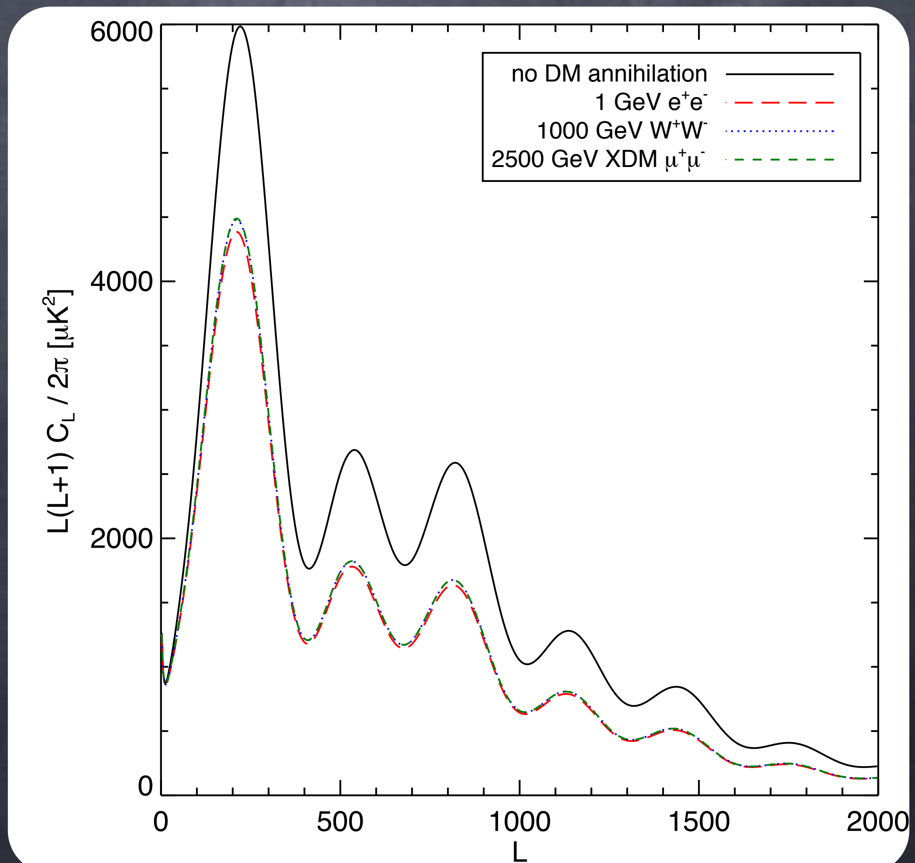


Direct photons



Final State Radiation

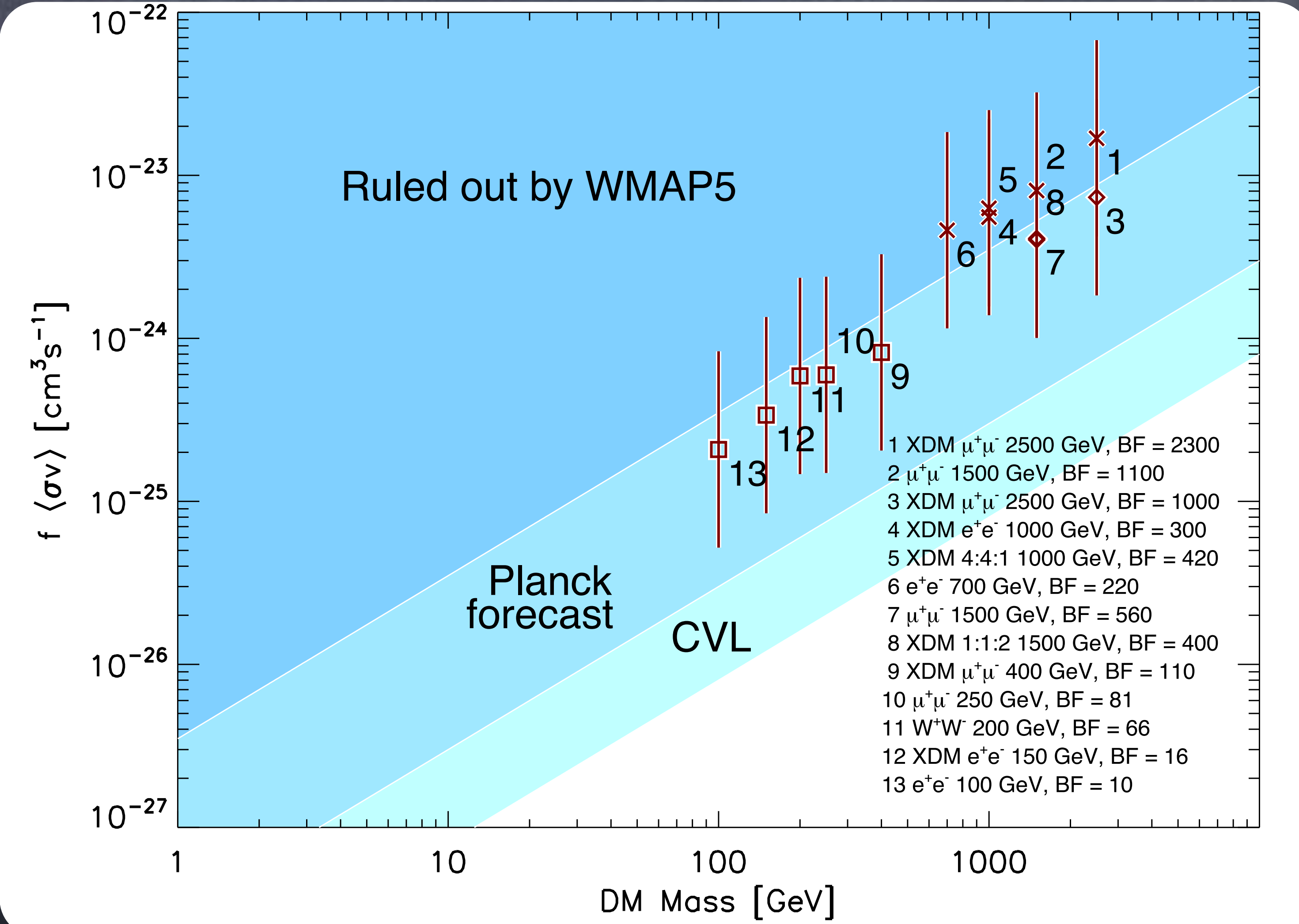
Finkbeiner, Padmanabhan, Slatyer 0906.1197



3. DM Annihilations and CMB epoch

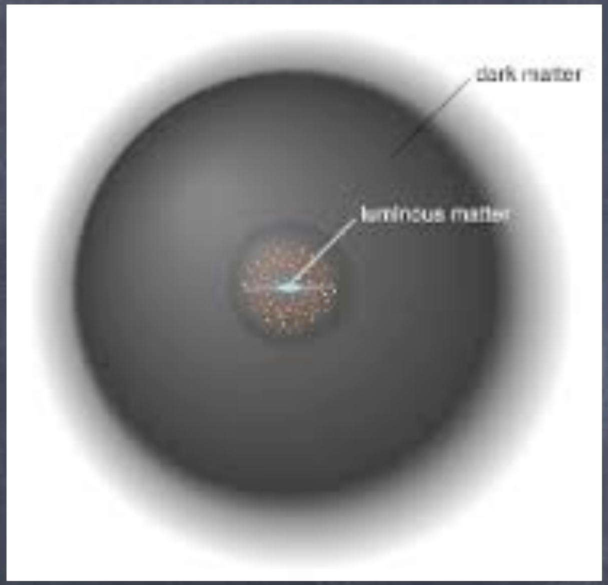
- Powerful constraint on ionizing radiation injection rate = annihilation rate

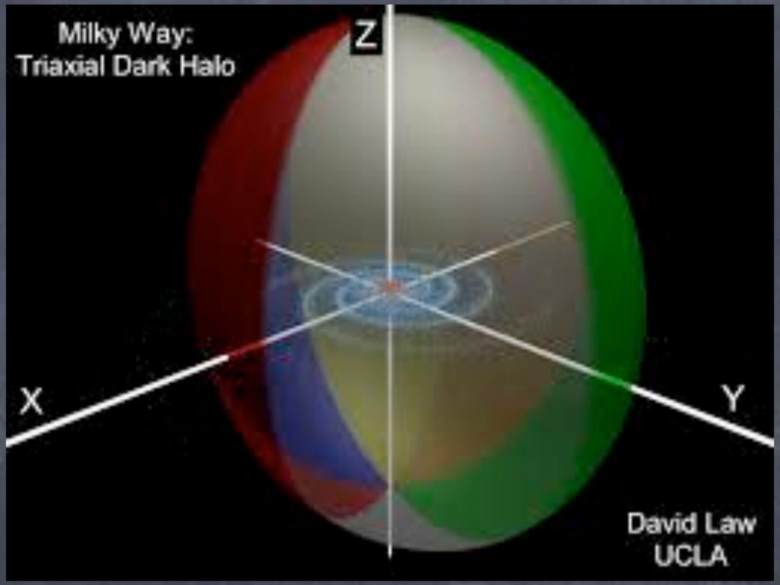
Finkbeiner, Padmanabhan, Slatyer 0906.1197



4. Large Scale Structure

- Dark matter halos are not exactly spherical!





- If DM had strong self-interactions, the resulting halo would be approx spherical

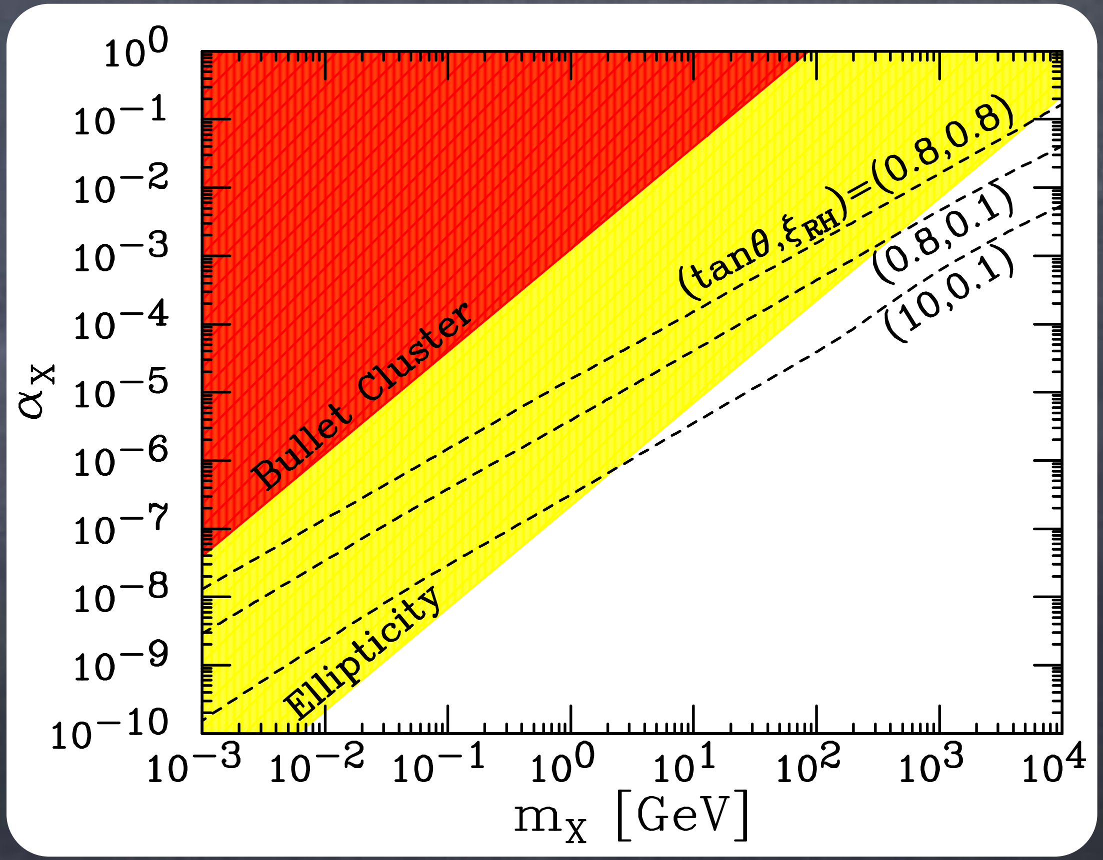
4. Large Scale Structure

- Places constraint on DM self-interactions

- Require one scattering or fewer per DM particle over the age of the halo

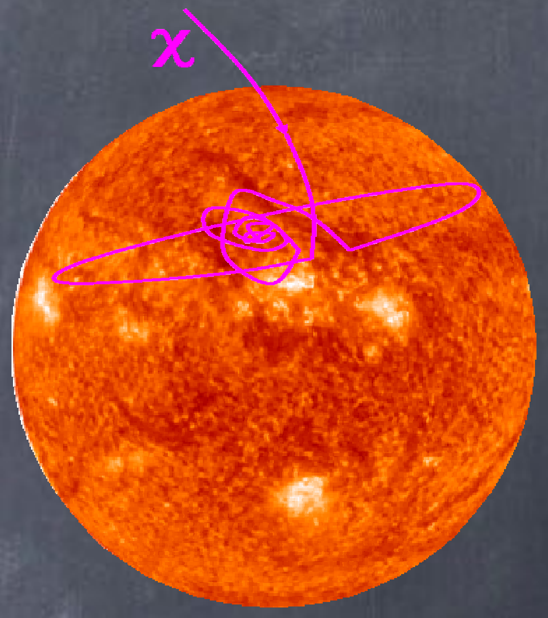
$$\frac{d\sigma_{XX}}{d\Omega_*} = \frac{\alpha_{em}^2 \epsilon^4}{m_X^2 v_{rel}^4 \sin^4(\theta_*/2)}$$

$$n_X \sigma_{XX} v \lesssim \tau_{halo}^{-1}$$



Feng et al, 0905.3039

4. Astrophysical objects



- If DM interacts with nucleons in object, it can scatter, lose energy and become trapped
- DM slowly thermalizes with object and sinks to center

Annihilation Inside

- Equilibrium achieved when capture and annihilation balance $\dot{N} = C - AN^2 = 0$
- As long as capture and annihilation rate is large enough, this is achieved

$$AN^2 = C \tanh^2(t_\odot/\tau_E) \qquad \tau_E = \sqrt{CA}$$

- Capture rate prop to scattering rate

$$C^\odot \simeq 1.3 \times 10^{25}\,\mathrm{s}^{-1} \left(\frac{\rho_{\mathrm{DM}}}{0.3\,\mathrm{GeV/cm^3}}\right) \left(\frac{270\,\mathrm{km/s}}{\bar{v}}\right) \left(\frac{1\,\mathrm{GeV}}{m_{\mathrm{DM}}}\right)$$
$$\times \left[\left(\frac{\sigma_{\mathrm{H}}}{10^{-40}\,\mathrm{cm}^2}\right) S(m_{\mathrm{DM}}/m_{\mathrm{H}}) + 1.1 \left(\frac{\sigma_{\mathrm{He}}}{16 \times 10^{-40}\,\mathrm{cm}^2}\right) S(m_{\mathrm{DM}}/m_{\mathrm{He}})\right]$$

Gould, ApJ **388**, 338 (1991)

Collection Inside

- What if annihilation does not occur? (ADM)
- Then only collection occurs $N = Ct$

$$N_X \simeq 2.3 \times 10^{44} \left(\frac{100\ \mathrm{GeV}}{m_X}\right)\left(\frac{\rho_X}{10^3\ \mathrm{GeV/cm^3}}\right)\left(\frac{\sigma_{XB}}{2.1 \times 10^{-45}\ \mathrm{cm^2}}\right)\left(\frac{t}{10^{10}\ \mathrm{years}}\right)$$

- Not very much mass, but if x-sect large enough, may have impact $\sim 10^{57}\ \mathrm{GeV}/M_\odot$
- Scalar DM may form black hole; fermion DM may alter stellar evolution

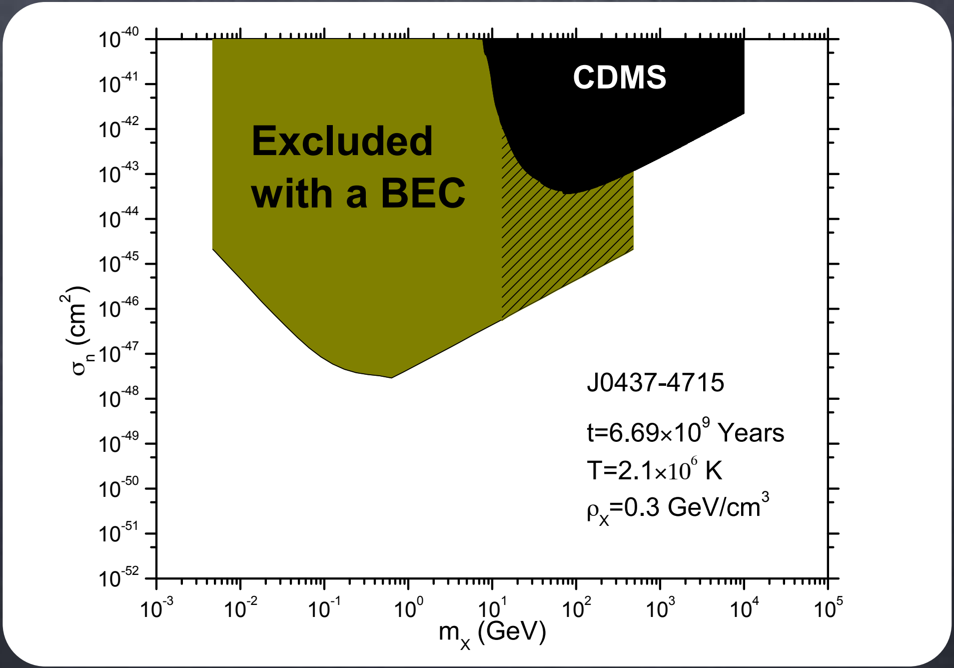
Black Hole Formation

- When collected DM a) self-gravitates AND b) exceeds Chrandrasekhar number, then form a black hole

$$E \sim -\frac{GNm^2}{R} + \frac{1}{R} \qquad N_{Cha}^{boson} \simeq \left(\frac{M_{pl}}{m}\right)^2 \simeq 1.5 \times 10^{34} \left(\frac{100 \text{ GeV}}{m}\right)^2$$

$$N_X \simeq 2.3 \times 10^{44} \left(\frac{100 \text{ GeV}}{m_X}\right) \left(\frac{\rho_X}{10^3 \text{ GeV/cm}^3}\right) \left(\frac{\sigma_{XB}}{2.1 \times 10^{-45} \text{ cm}^2}\right) \left(\frac{t}{10^{10} \text{ years}}\right)$$

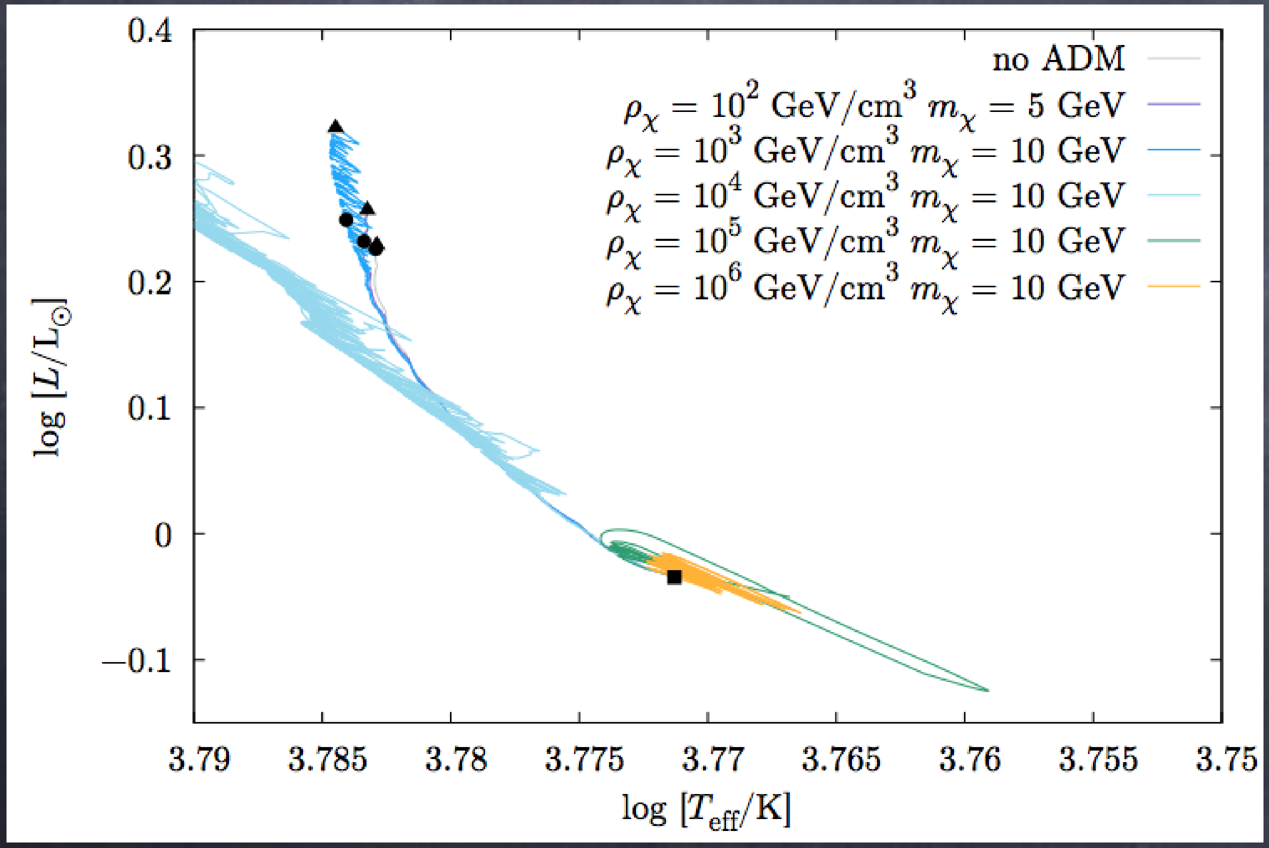
- Black hole would eat neutron star



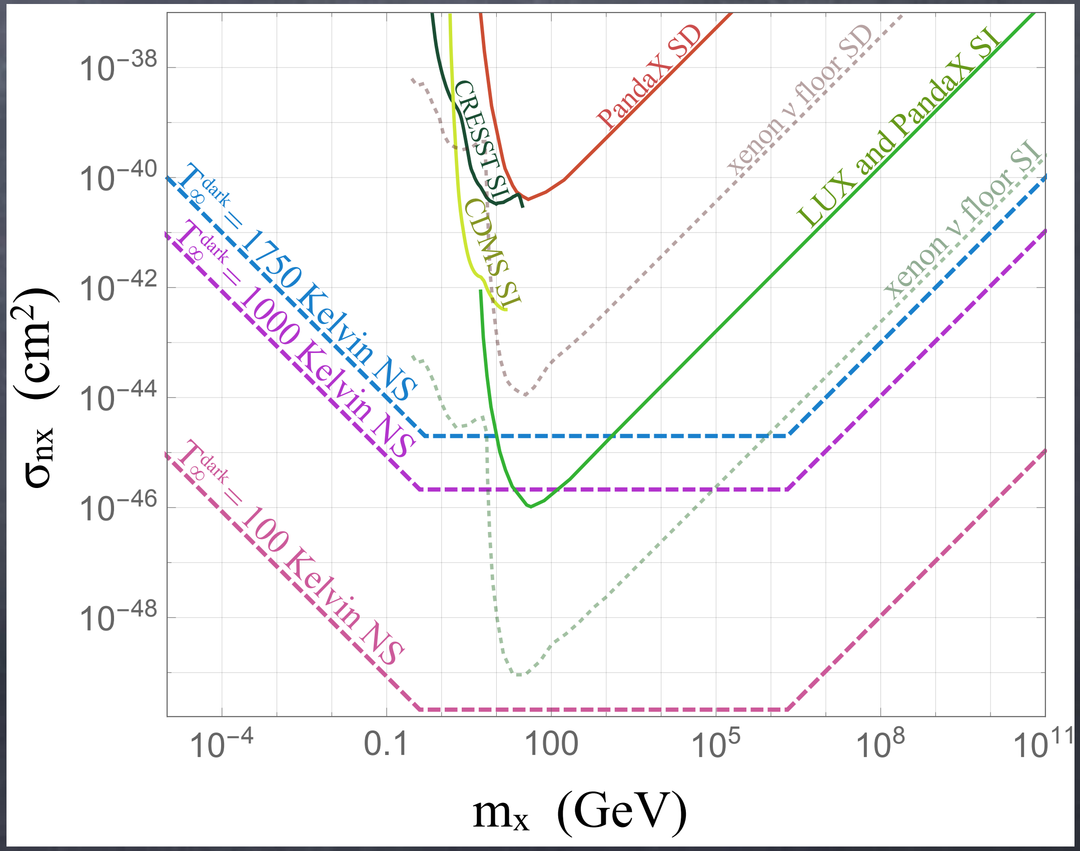
McDermott, Yu, KZ 1103.5472

Stellar Constraints

- Disrupt main sequence evolution
- Heat neutron stars



Taoso et al, 1005.5711



Baryakhtar et al, 1704.01577

Dark Matter Model Dynamics

(Looking beyond the vanilla WIMP paradigm)

DM Paradigm: recap

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

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 .....

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

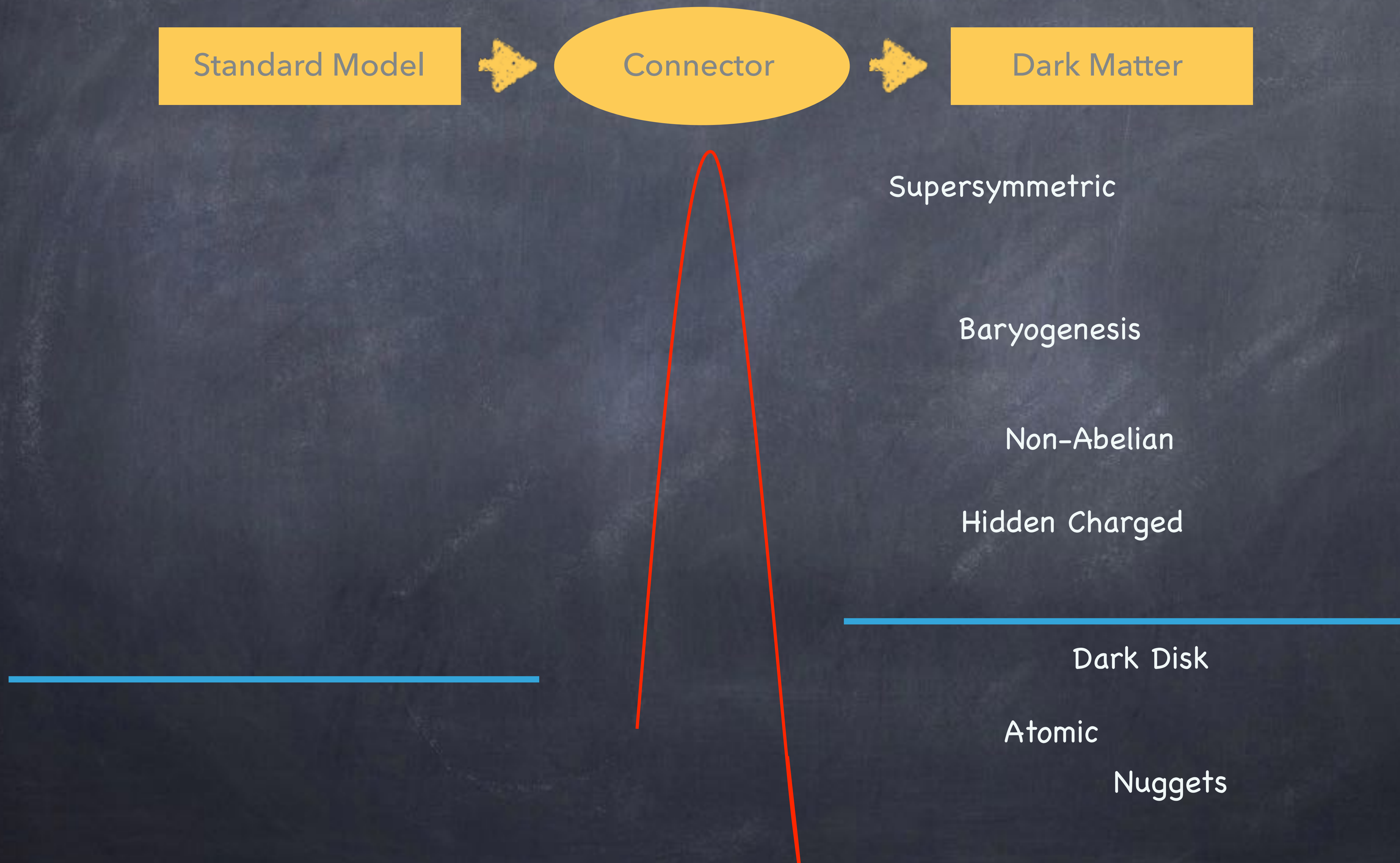
Standard Model

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

Our Thinking Has Shifted: Why?

- Perhaps overly influenced by only a couple of paradigms? Overly single minded focus?

Broad Range of Models



Broad Range of Models

Standard Model → Connector → Dark Matter

Supersymmetric

Hooper, KZ 2008, Feng and Kumar 2008

Arkani-Hamed, Weiner 2008

Baumgart, Cheung et al 2009 ...

Baryogenesis

Buckley & Randall 2010, Cheung & KZ 2011

Fileviez-Perez & Wise 2010, 2013 ...

Non-Abelian

Kribs, Roy, Terning, KZ 2009 ...

Hidden Charged

Pospelov & Ritz 2007, Feng et al 2009 ...

Dark Disk

Fan, Katz, Randall, Reece 2013 ...

Atomic Kaplan et al 2009 ...

Nuggets

Wise, Zhang 2014 ...

Broad Range of Models

Standard Model → Connector → Dark Matter

pure glue, light flavors, heavy flavors, quirky asymmetric dark matter, Strongly Interacting Massive Particle (SIMP), Wess-Zumino-Witten SIMP

MeV DM, WIMPless, Anomalies: PAMELA, ATIC, Fermi I, Fermi II, Fermi III, DAMA, CDMS, Cogent

Darkogenesis, Xogenesis, Hylogenesis, Cladogenesis, ADM from Leptogenesis, Dark Affleck-Dine

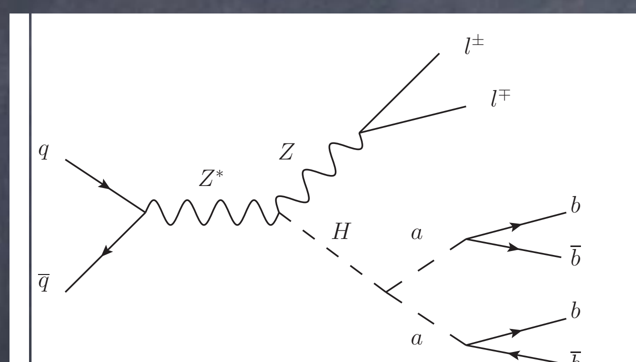
Dark photons, Freeze-in, WIMPless miracle

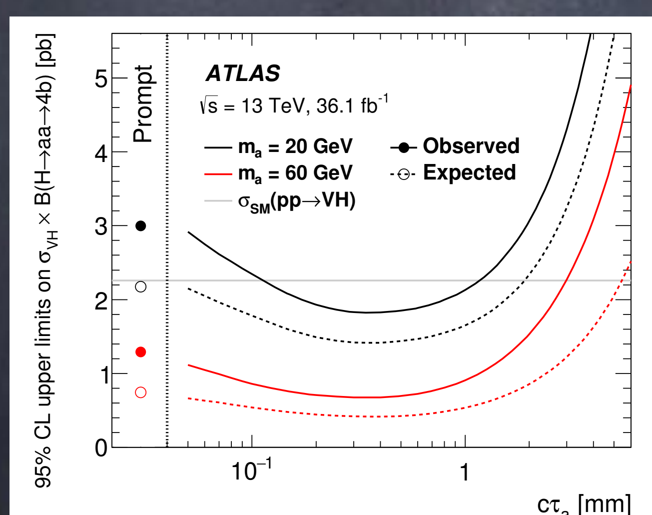
Mirror Matter, Atomic Matter, Self-Interacting Dark Matter, Magentic, Dark Anapole and EDMs

Dark Disk — Killing the Dinosaurs

Broad Range of Models

Standard Model → Connector → Dark Matter





GUT

Weak

Light

Supersymmetric

Baryogenesis

Non-Abelian

Hidden Charged

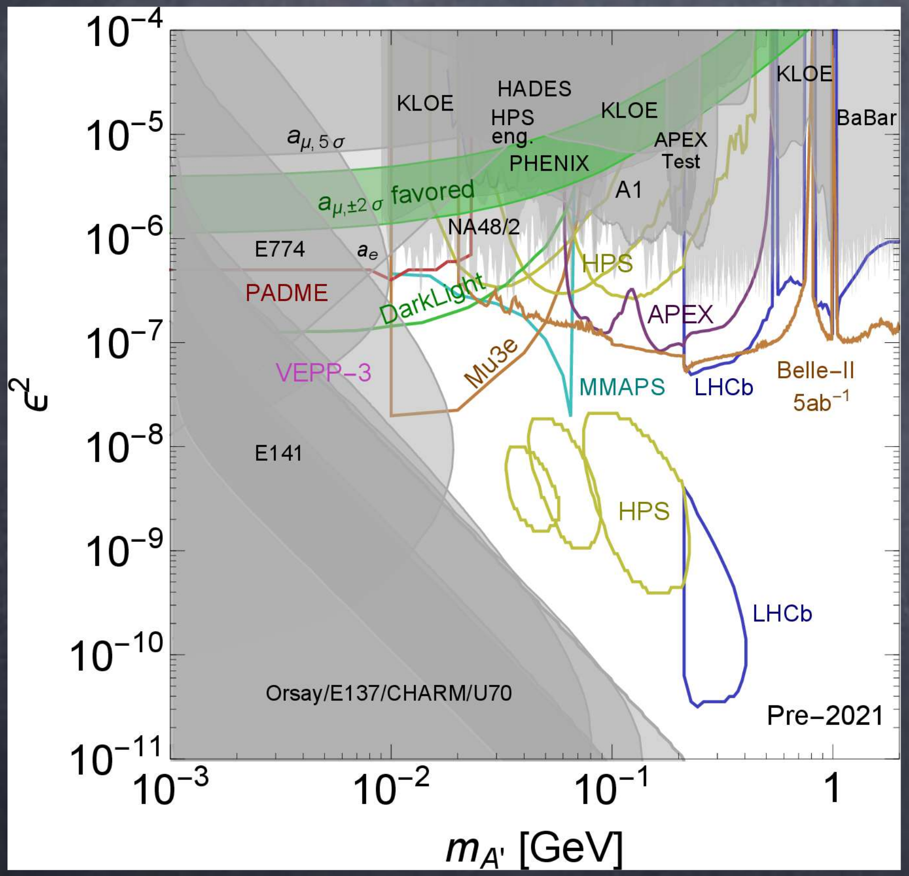
Dark Disk

Atomic

Nuggets

Broad Range of Models

Standard Model → Connector → Dark Matter



GUT

Weak

Light

Supersymmetric

Baryogenesis

Non-Abelian

Hidden Charged

Dark Disk

Atomic

Nuggets

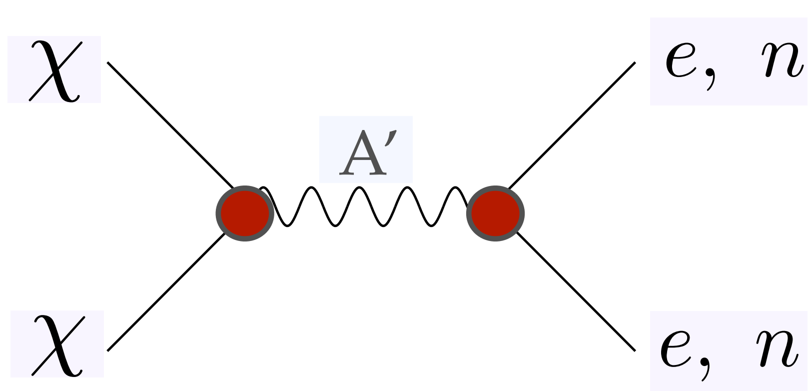
Experimental Implications of Dark Sectors and Forces

Exp. Implications of Dark Sectors ....

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

Direct Detection

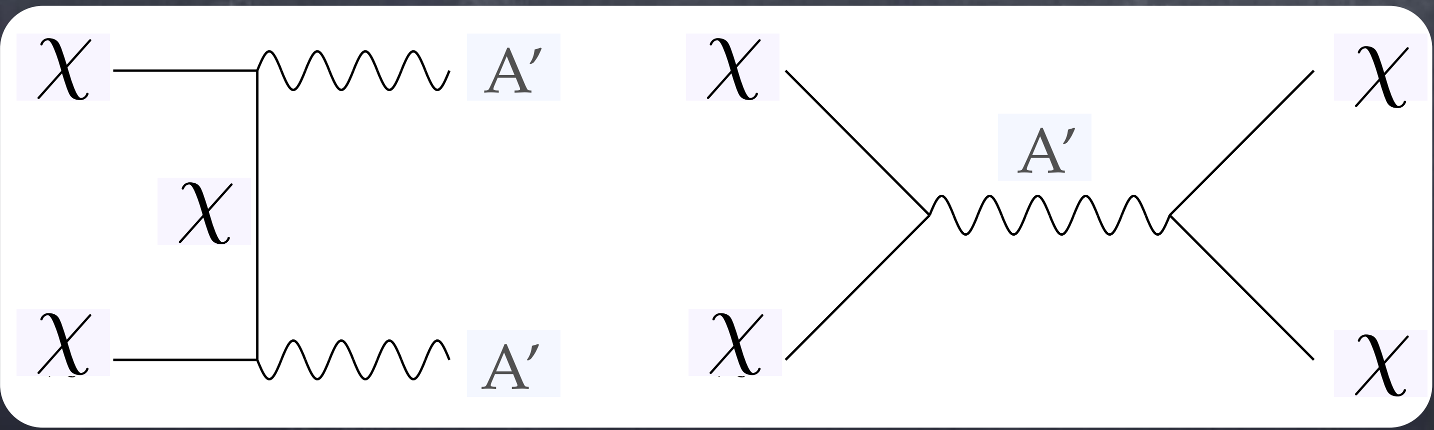
- Mediates _large_ scattering cross-sections



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

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

- Simplified model gives rise to many effects

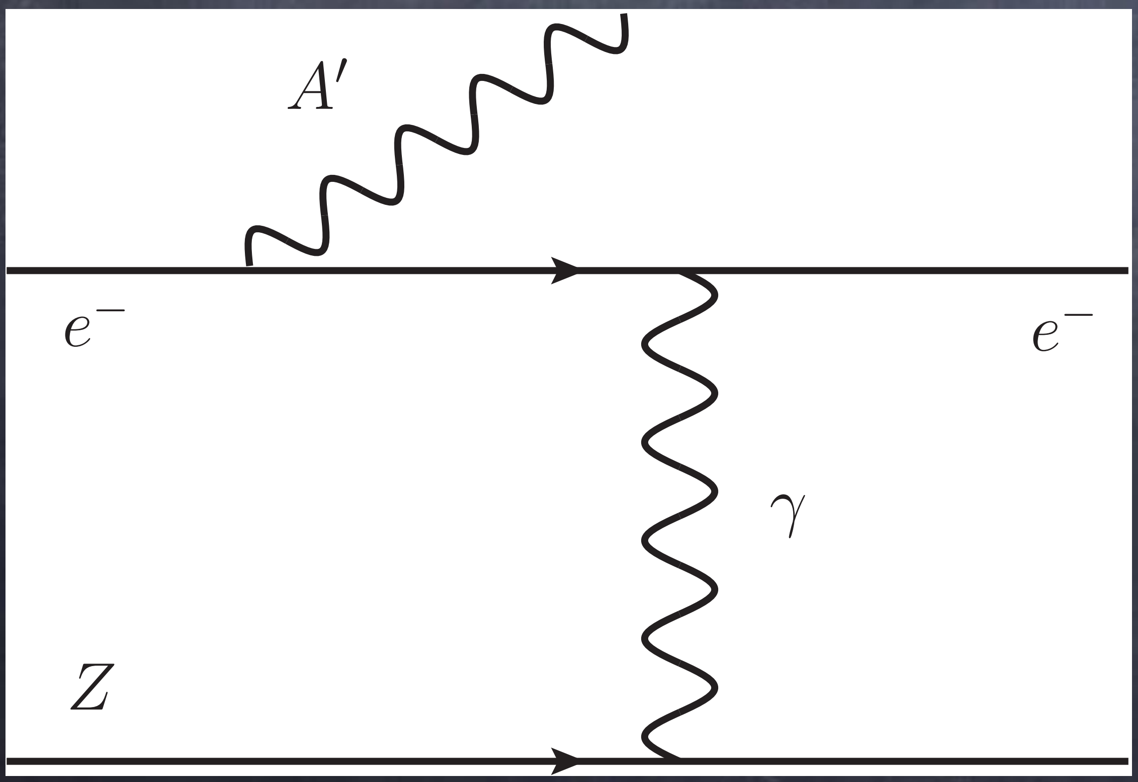


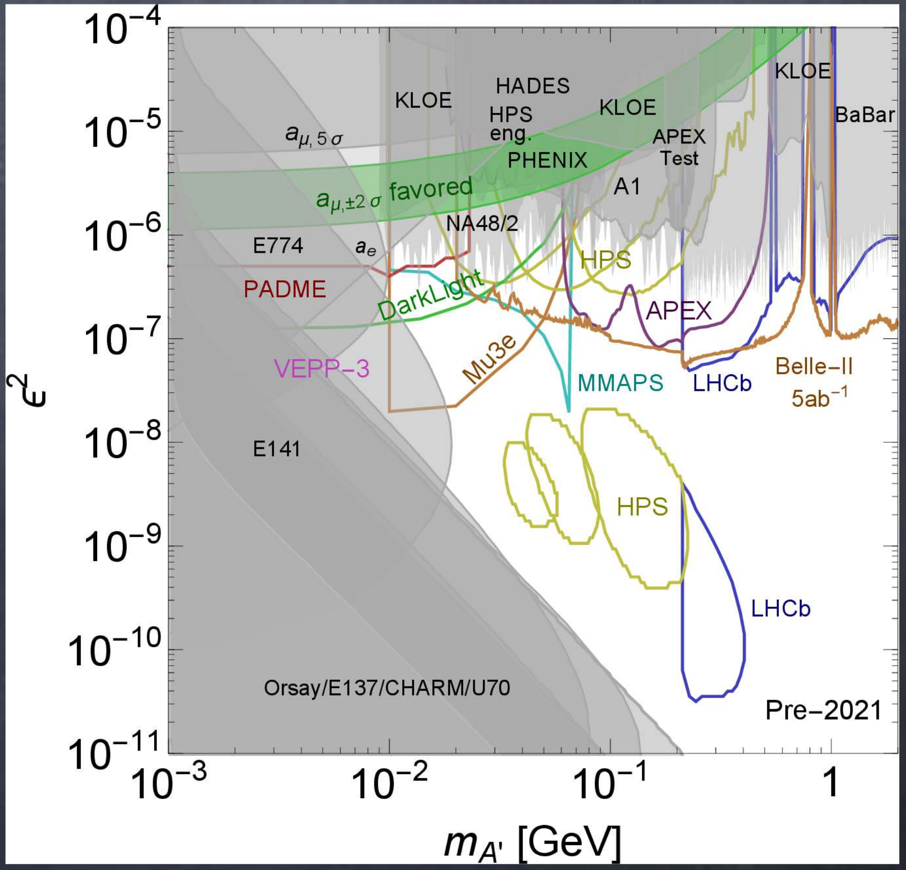
Connection to Intensity Experiments

- 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

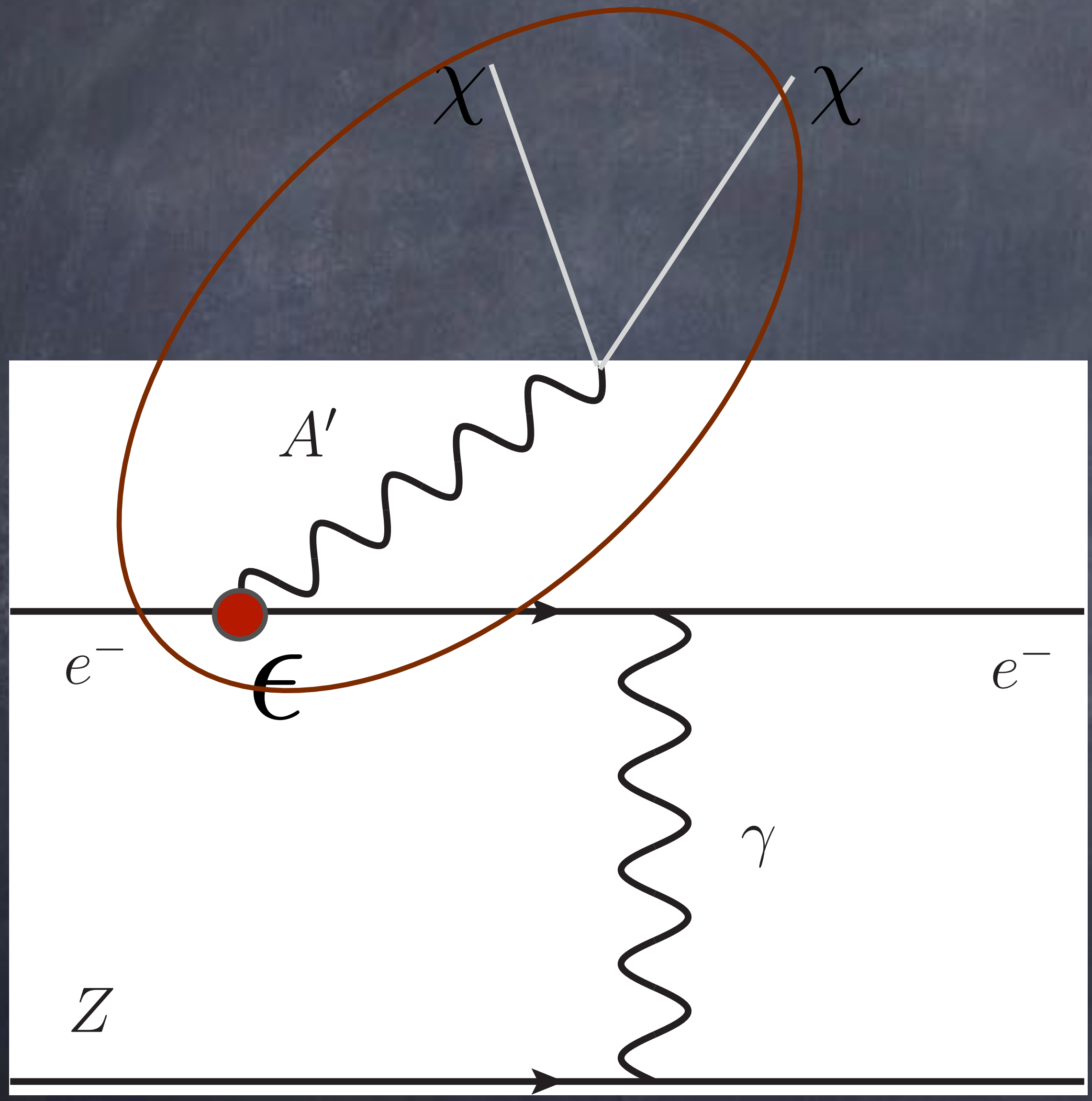
- Dark sectors may be more efficiently produced in low energy intensity experiments

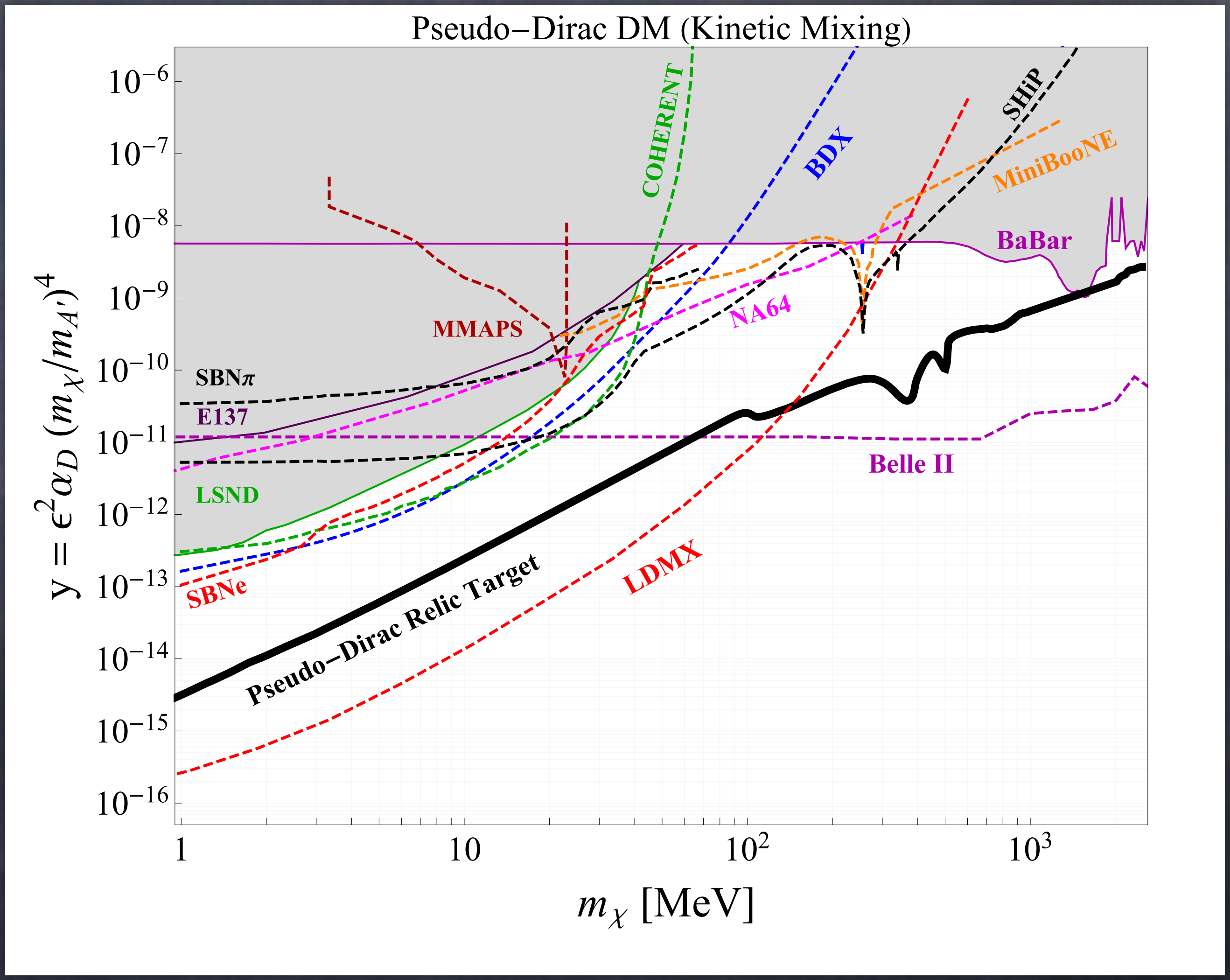




Cosmic Visions, 1707.04591

Translate to Direct Detection Bounds

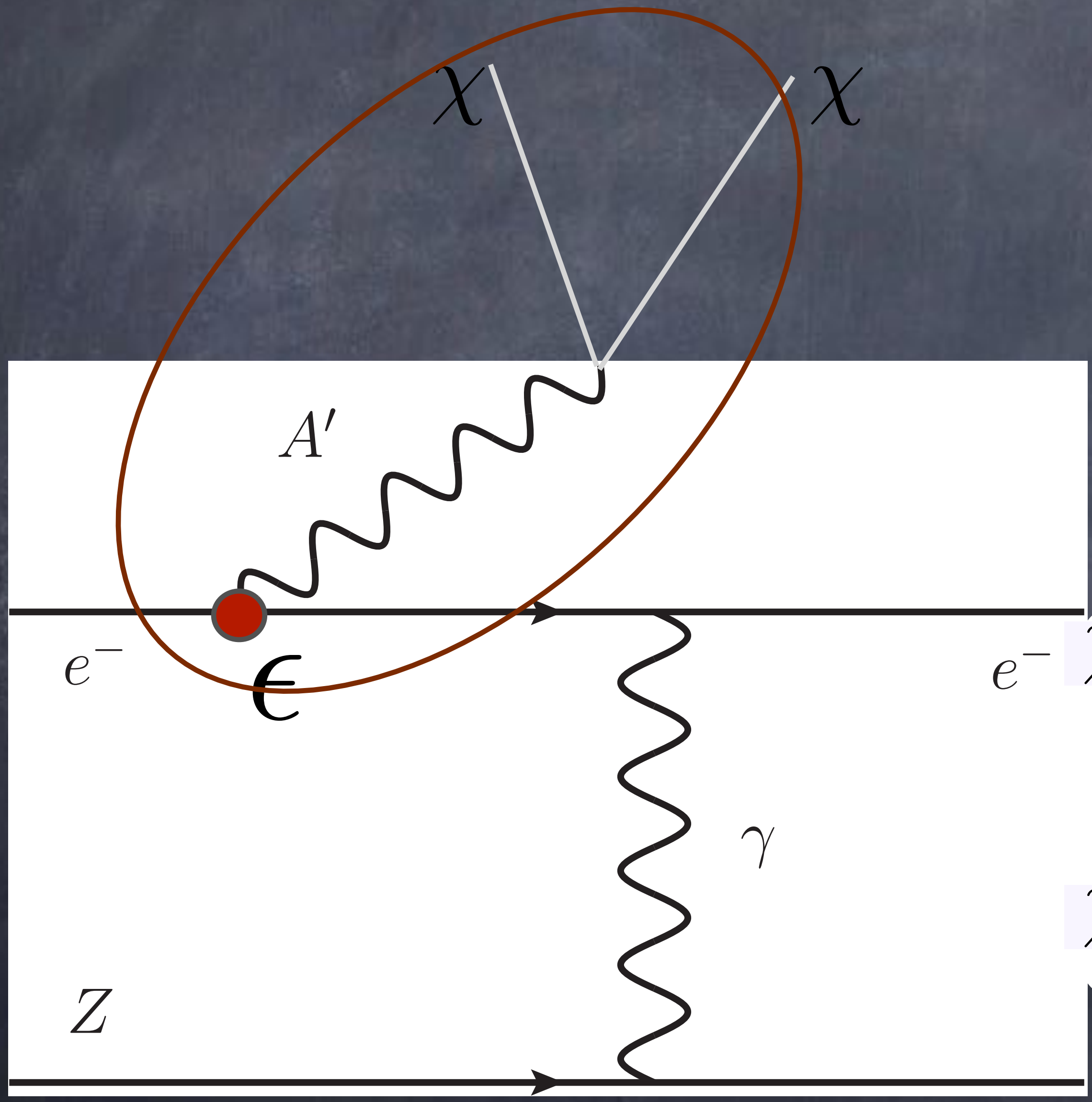


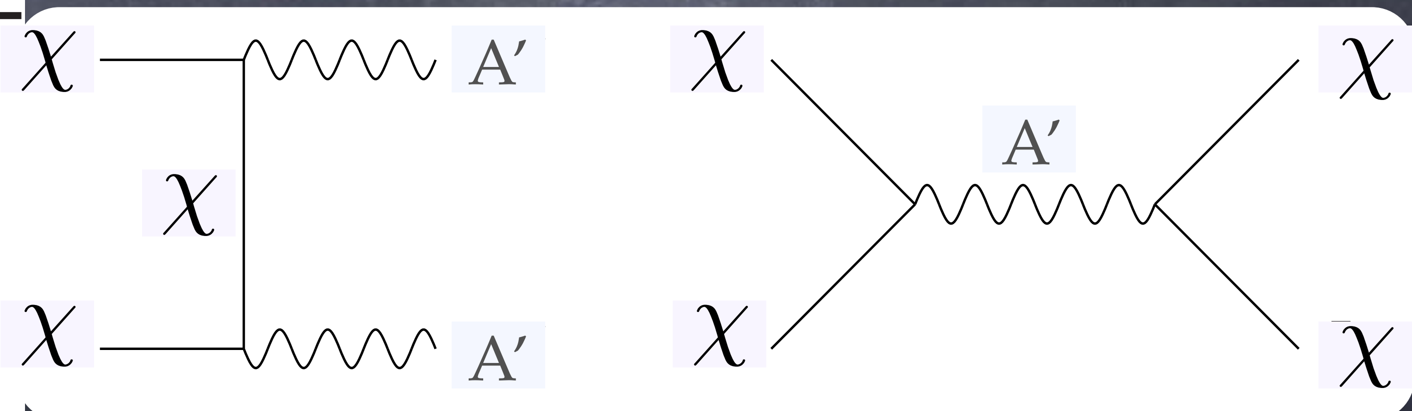


Cosmic Visions, 1707.04591

Translate to Direct Detection Bounds

$$m_\chi, \; m_{A'}, \; g_e, \; g_\chi$$



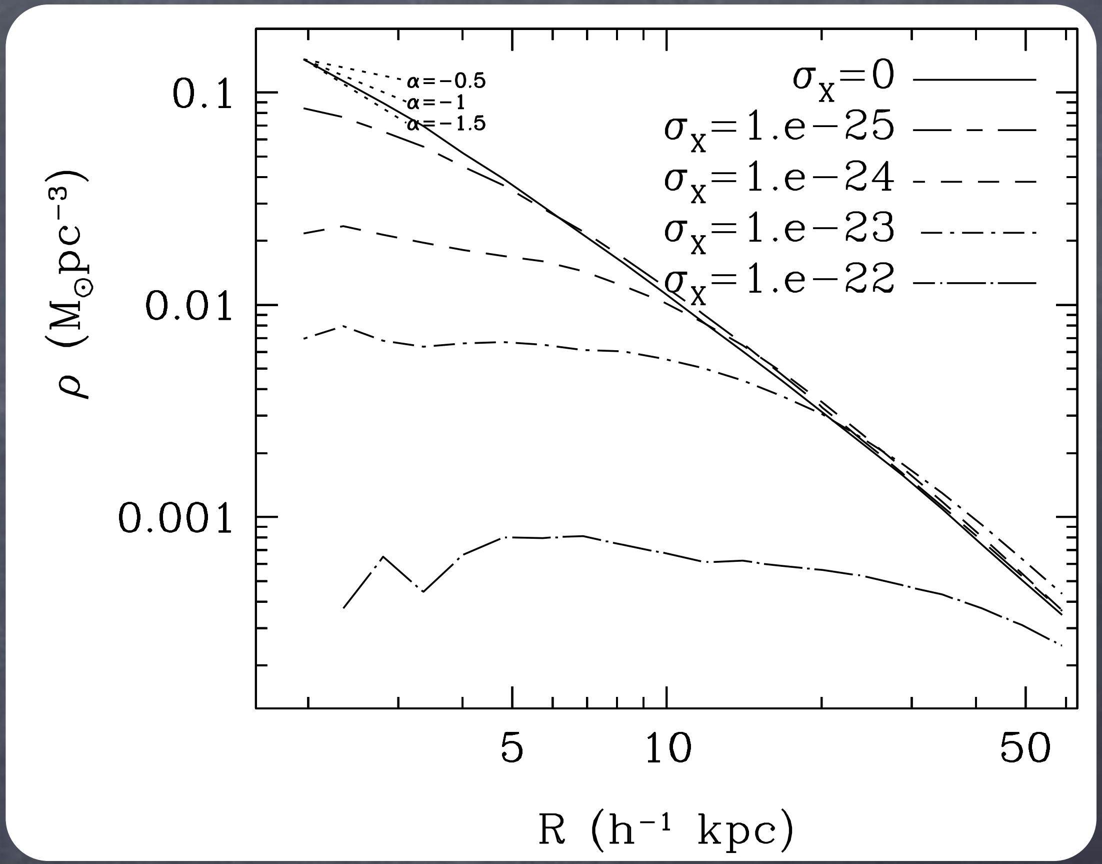


DM relic abundance

DM self-scattering

DM Interactions and DM Halos

Dave, Spergel, Steinhardt, Wandelt



- 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)

Implies Dark Forces!

- Very **big** scattering cross-sections

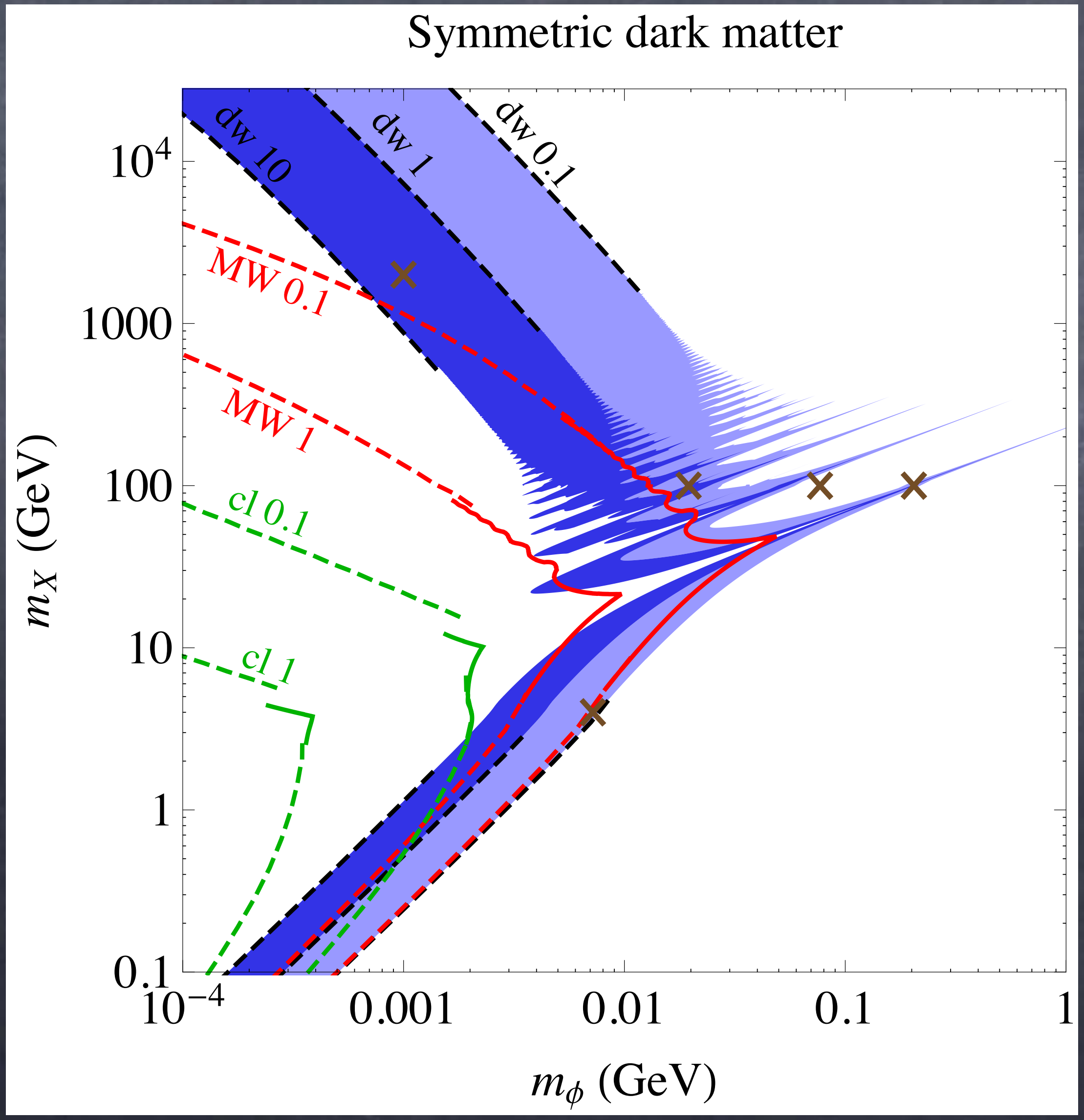
$$\sigma/m_X \sim 0.1\ \mathrm{cm}^2/\mathrm{g} \simeq 0.2 \times 10^{-24}\ \mathrm{cm}^2/\ \mathrm{GeV} \quad (\sigma_{weak} \sim 10^{-39}\ \mathrm{cm}^2)$$

- Fits well with new models of DM!

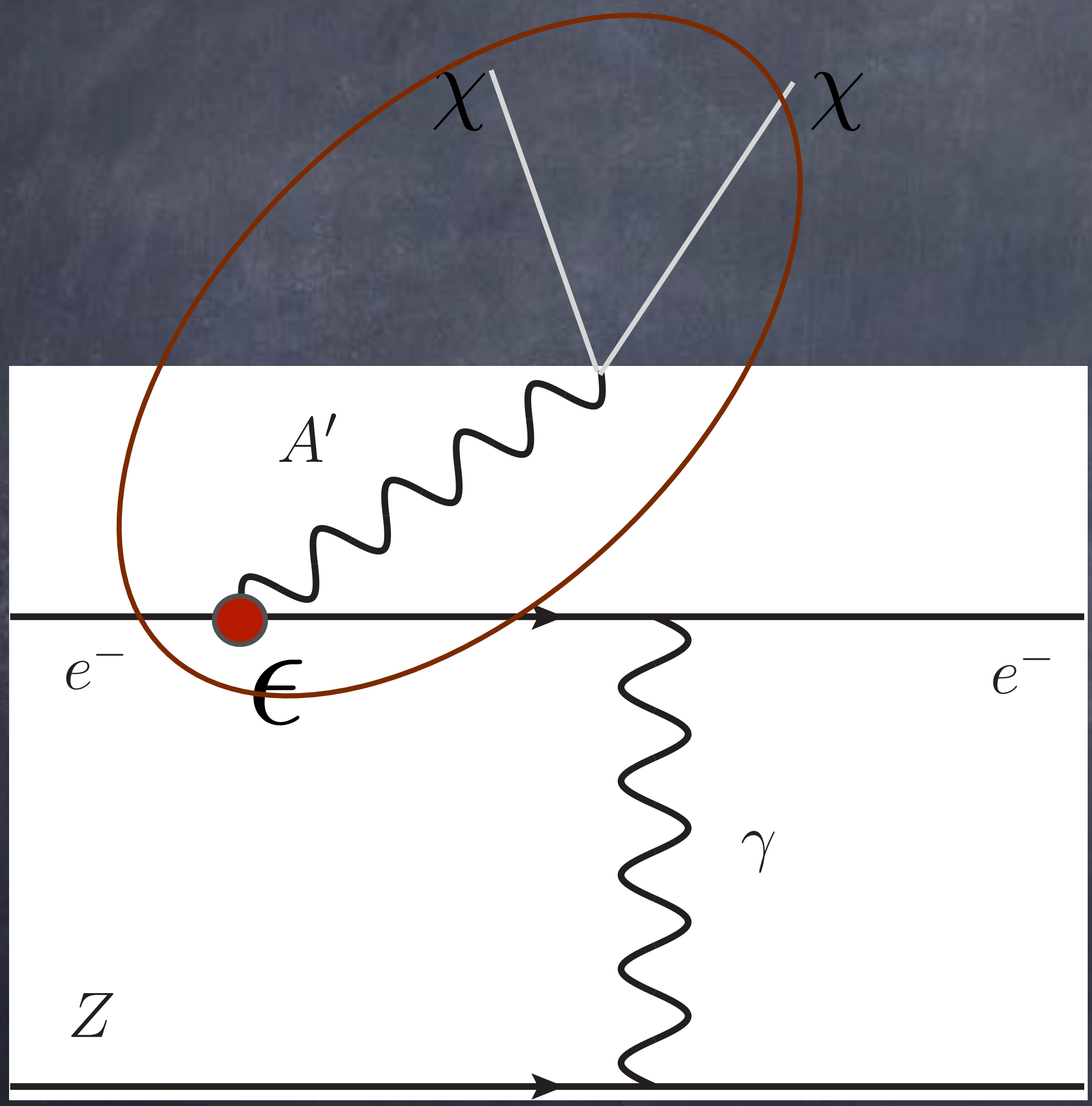
$$\sigma_T \approx 5 \times 10^{-23}\ \mathrm{cm}^2 \left(\frac{\alpha_X}{0.01}\right)^2 \left(\frac{m_X}{10\ \mathrm{GeV}}\right)^2 \left(\frac{10\ \mathrm{MeV}}{m_\phi}\right)^4$$

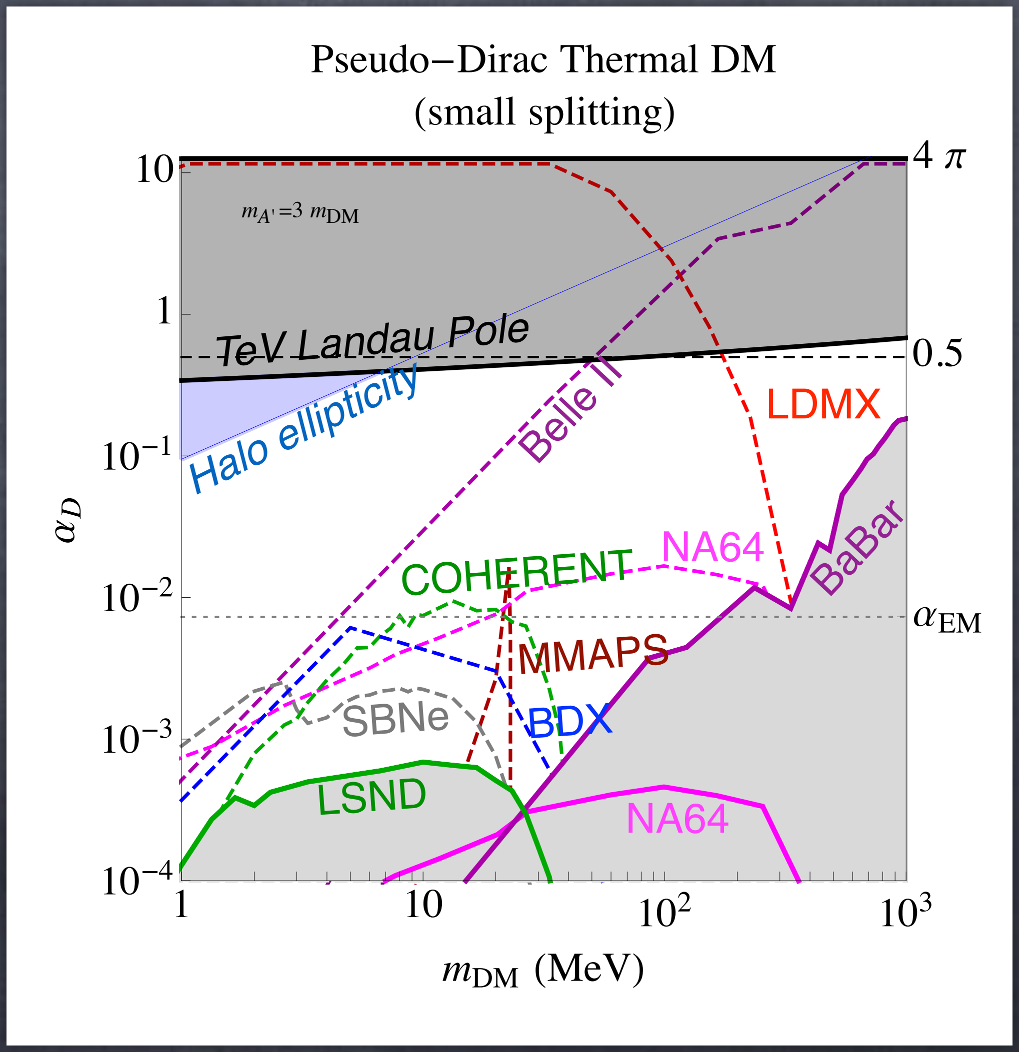
- Range of dynamics much bigger than previously thought

DM self-scattering is generic in hidden sector



Translate to Direct Detection Bounds

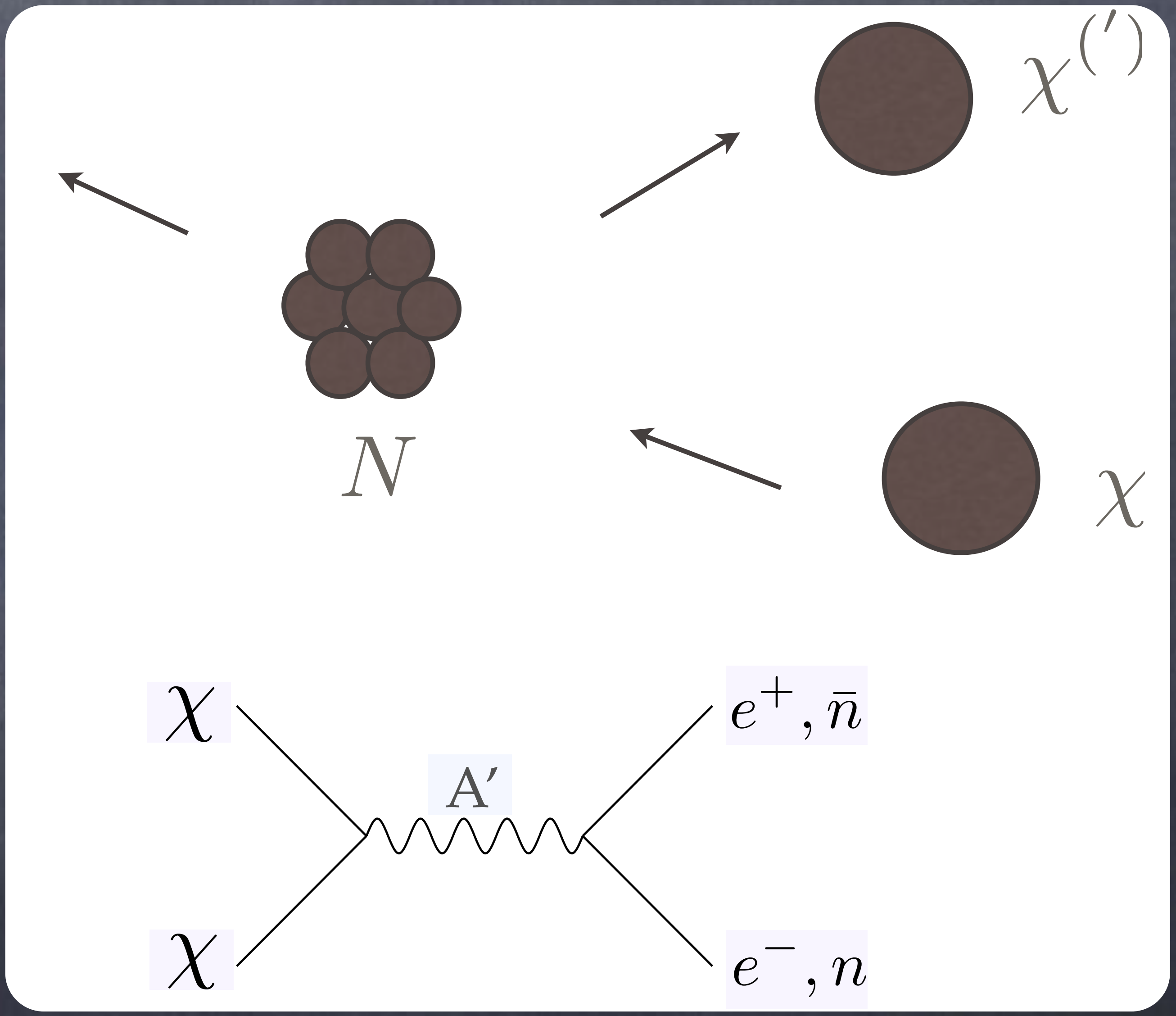




Cosmic Visions, 1707.04591

Connection to Direct Detection

Can now take constraints from heavy photon searches + halo shapes to map to direct detection experiments

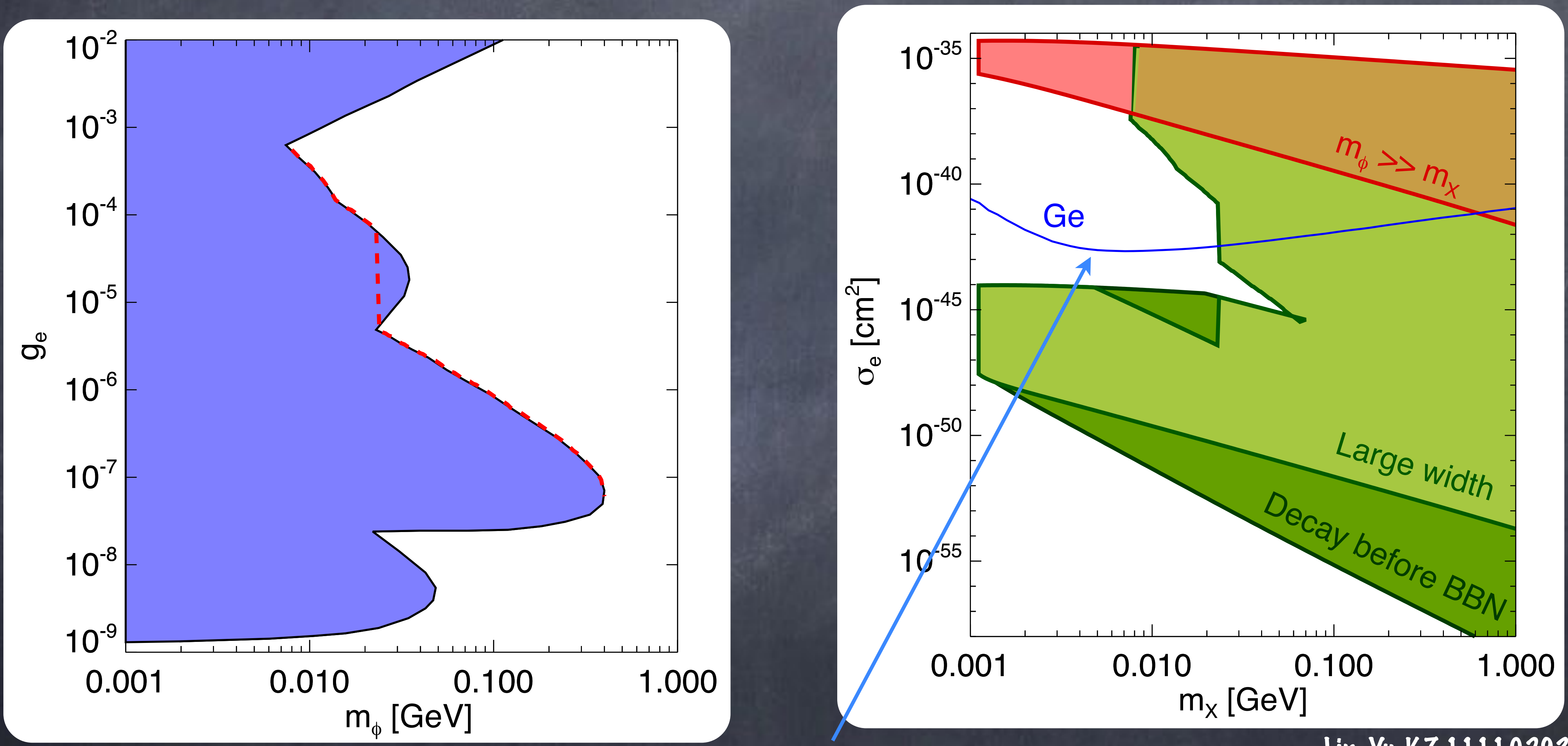


Constrained by halo shapes

$$\sigma_n \approx \frac{g_\chi^2 g_n^2 \mu_n^2}{\pi m_{A'}^4} \qquad \sigma_e \approx \frac{g_\chi^2 g_e^2 \mu_e^2}{\pi m_{A'}^4}$$

Constrained by intensity experiments

Map into Direct Detection Plane

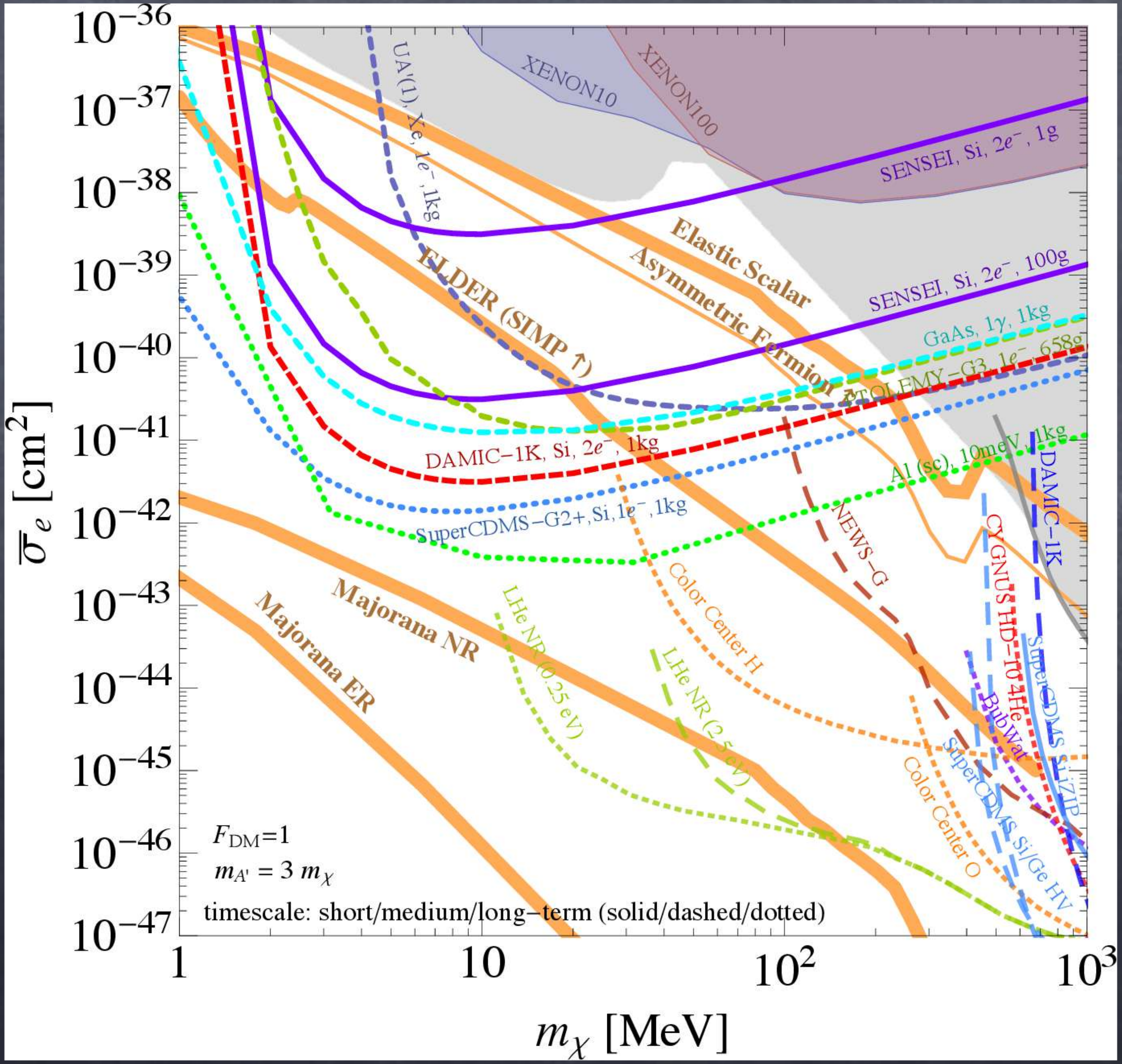


Lin, Yu, KZ 1111.0293

Projected maximum sensitivity of direct detection experiment

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

Direct Detection Prospects

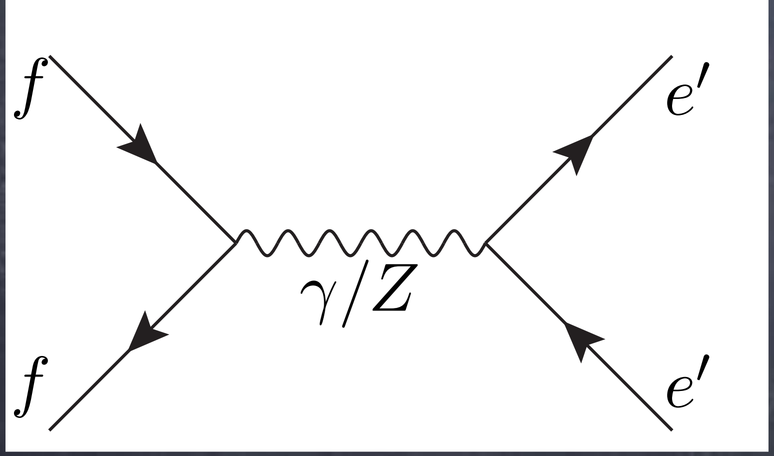


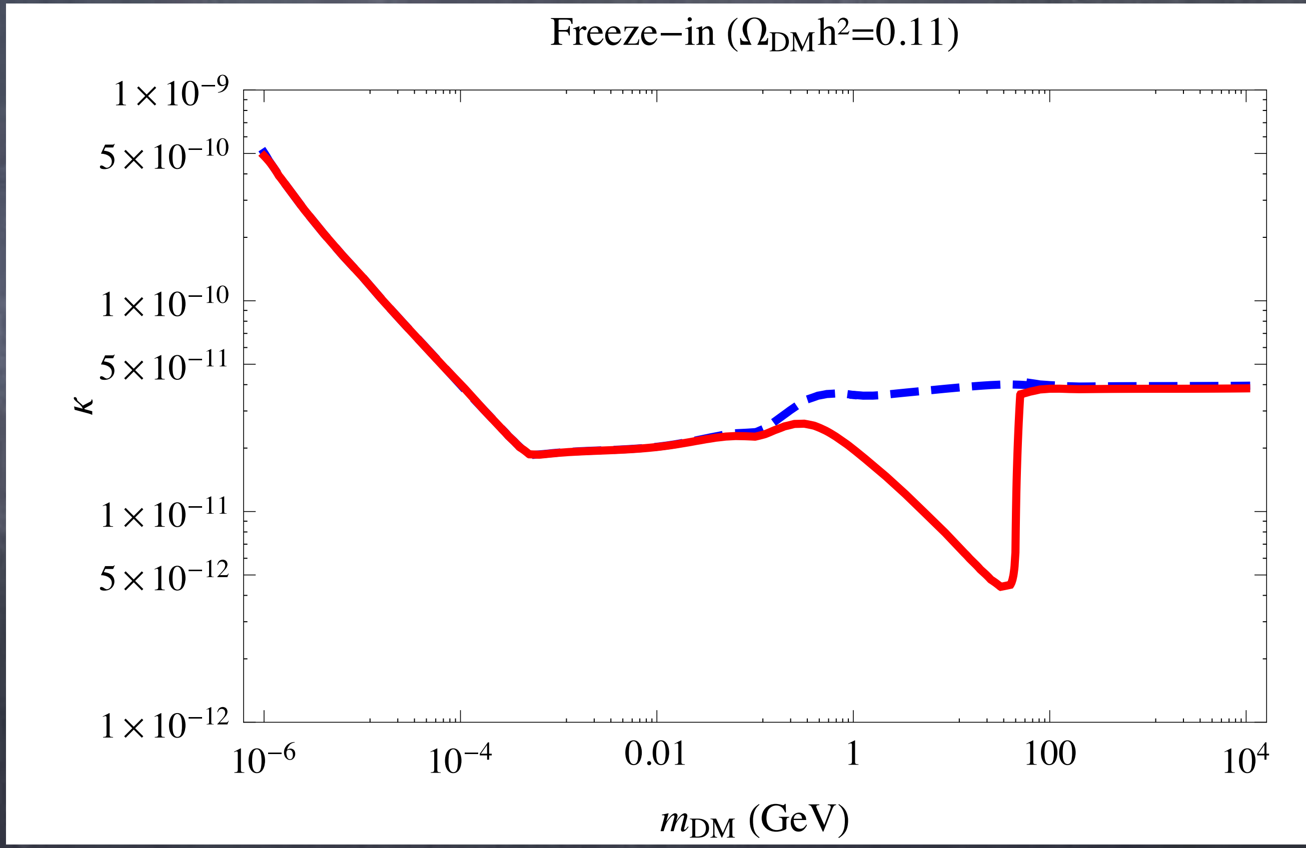
Cosmic Visions, 1707.04591

What about benchmarks?

- Two examples: Freeze-in

Production Process



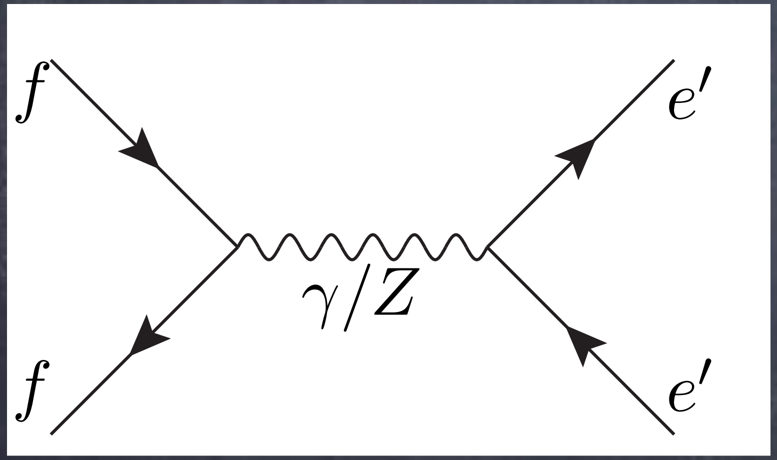


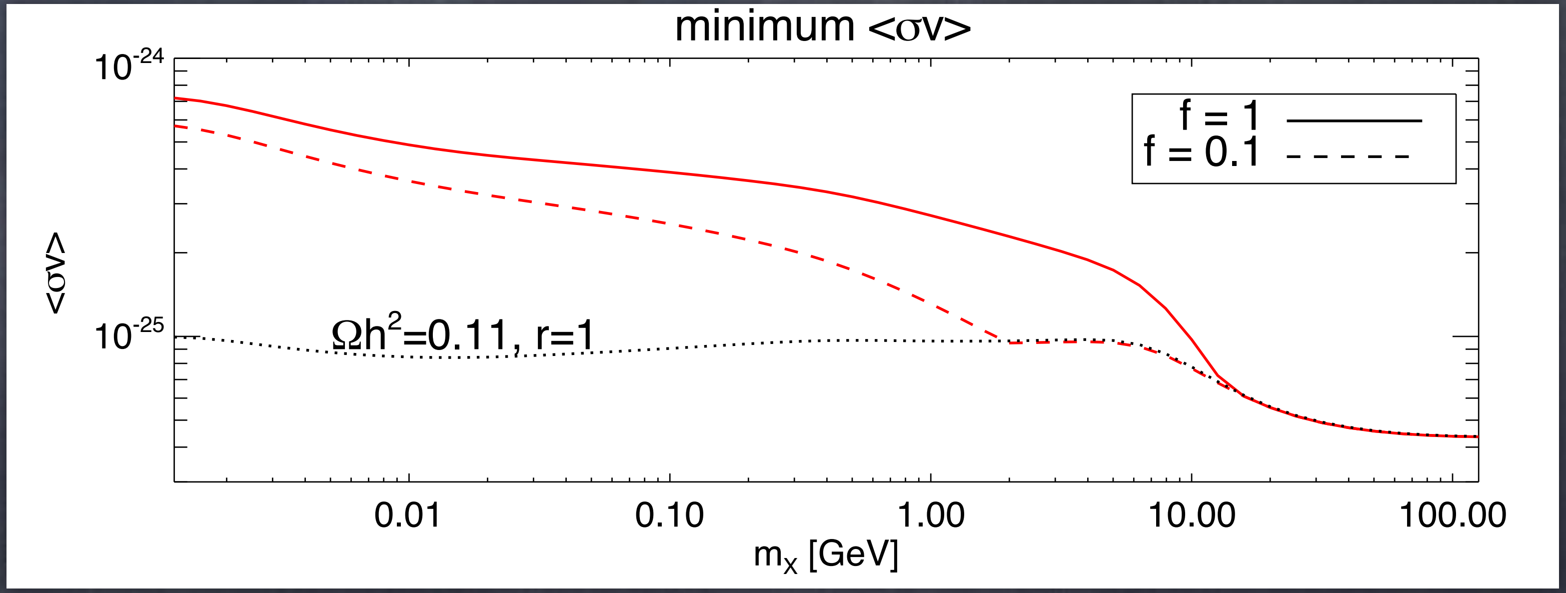
Hambye et al 1112.0493

What about benchmarks?

- Two examples: Asymmetric Dark Matter

Annihilation Process

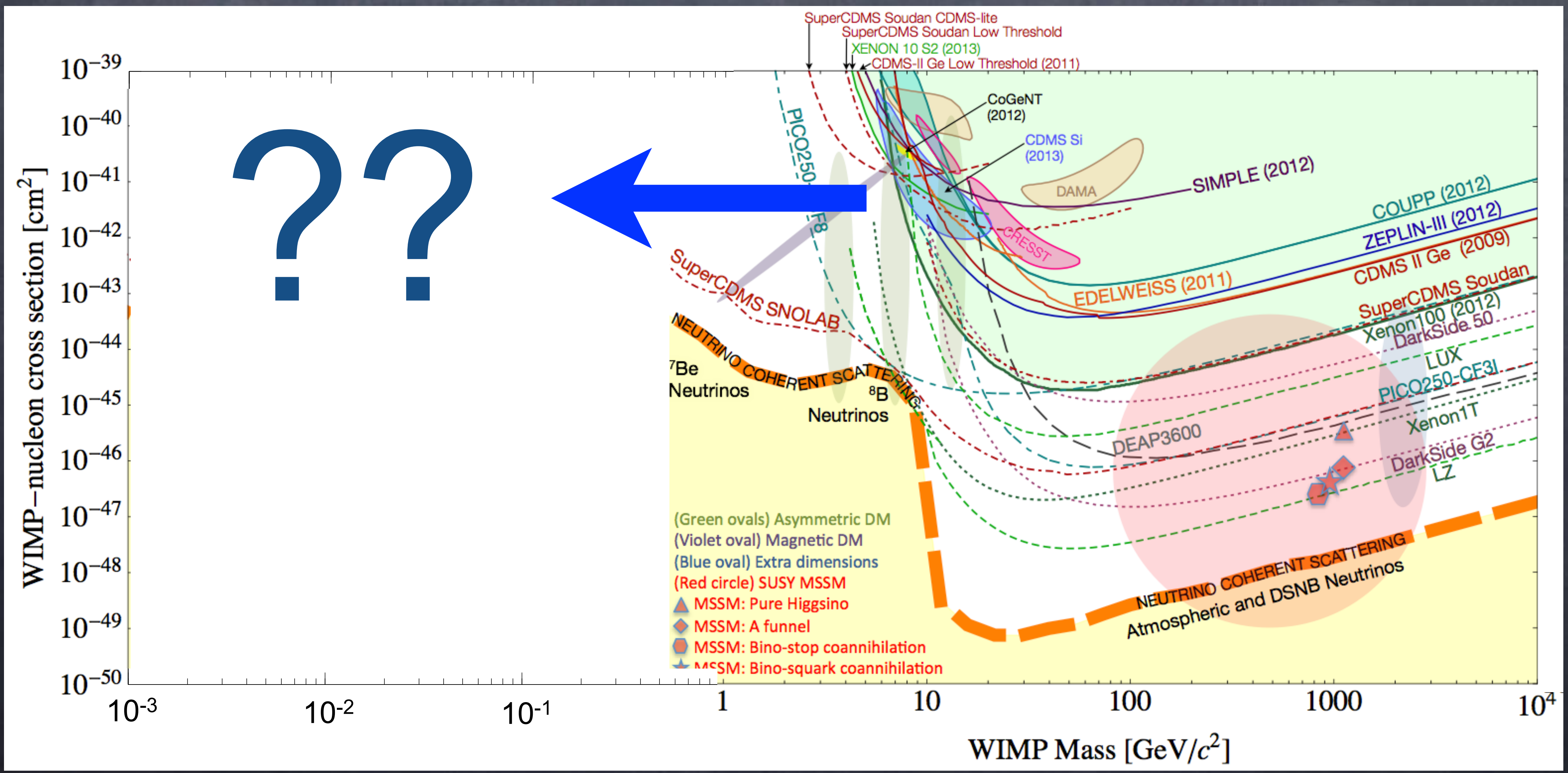




Lin, Yu, KZ 1111.0293

Electron scattering

- Use atomic ionization or excitation energies to get signal and extend searches down to 1 MeV?



Nuclear Recoils

- Kinematic penalty when DM mass drops below nucleus mass

$$E_D = \frac{q^2}{2m_N} \qquad q_{\rm max} = 2m_X v$$

$$E_D \gtrsim \text{ eV} \leftrightarrow m_X = 300 \text{ MeV}$$

even though $E_{\rm kin} \gtrsim 300 \text{ eV}$

Next up: electron

- More bang for the buck if DM lighter than 1 GeV

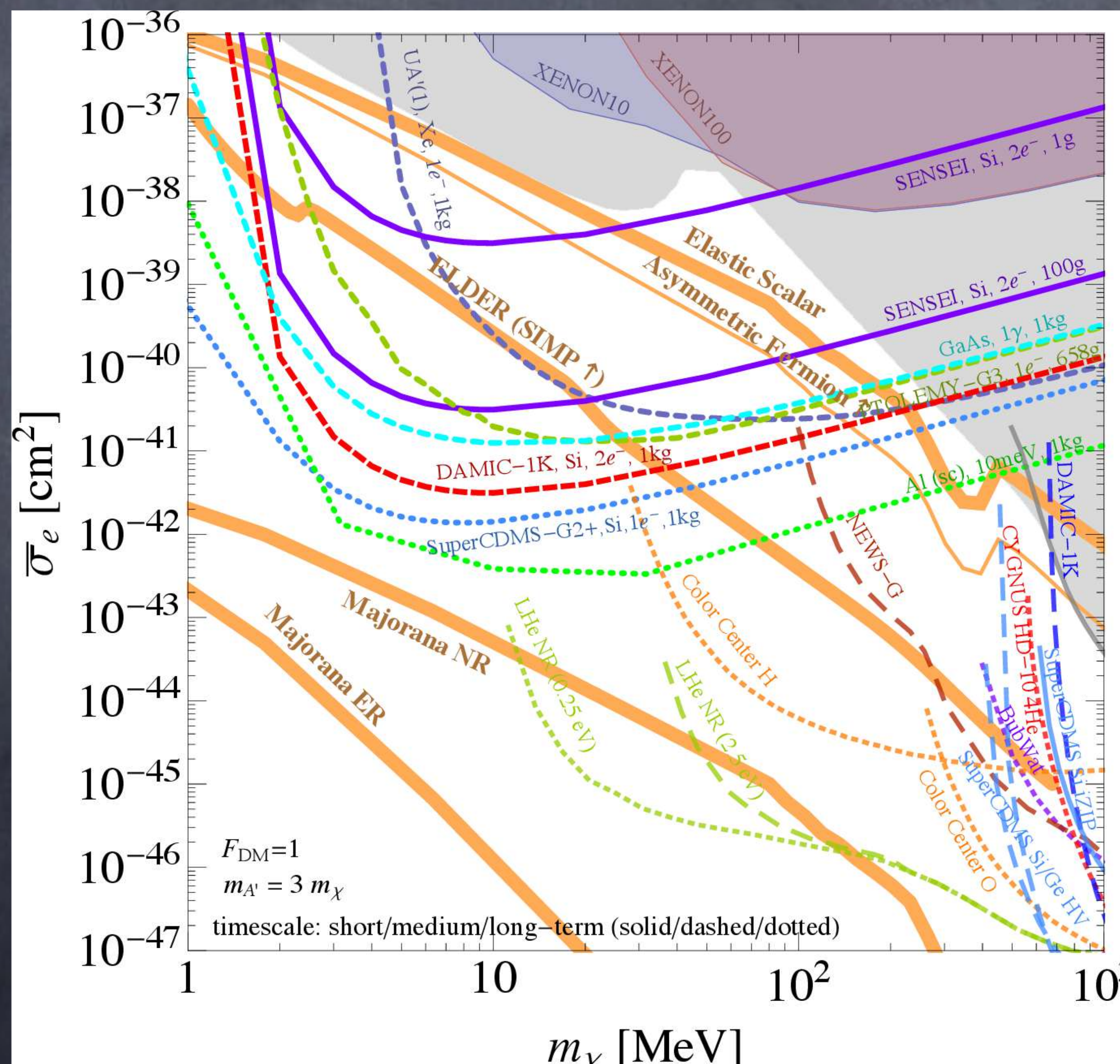
$$E_D = \frac{q^2}{2m_e} \qquad\qquad q_{\max} = 2m_X v$$

- Allows to extract all of DM kinetic energy for DM MeV and heavier

$$E_D \gtrsim \text{ eV} \leftrightarrow m_X = 1 \text{ MeV}$$

Electron excitation experimental proposals

ADM Benchmark



Cosmic Visions, 1707.04591

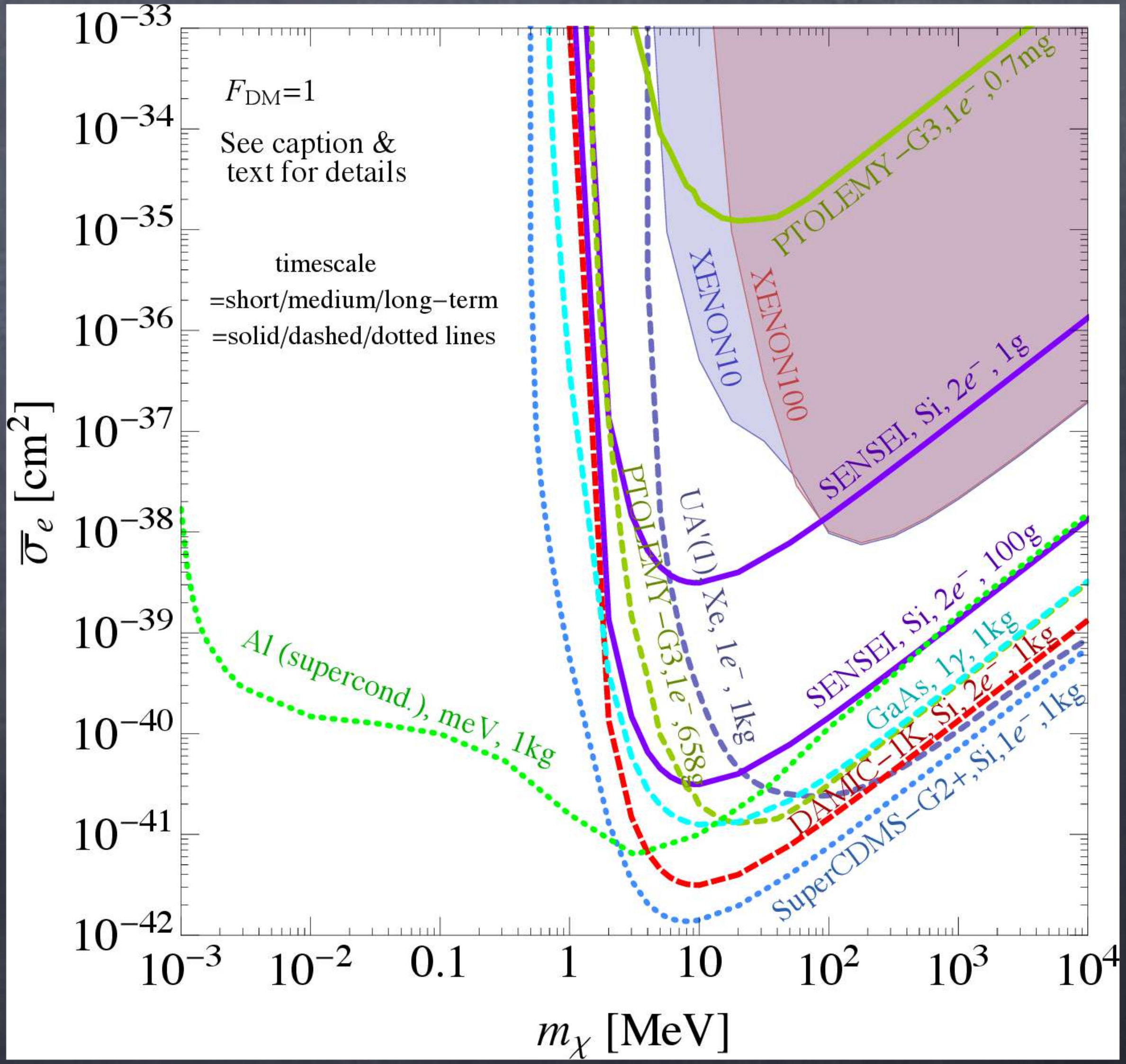
Electron excitation experimental proposals

- Superconductors and Dirac materials — examples of small gap

$$\Delta \simeq 0.3 \text{ meV}$$

- Utilize Fermi velocity when mX < me

$$\omega = \frac{q^2}{2m_e} + \vec{v}_F \cdot \vec{q}$$



Cosmic Visions, 1707.04591

Utilizing Coherent Modes

- When the momentum transfer becomes small enough, coherent modes become visible
- Sub-MeV DM <—> sub-keV momentum transfer <—> q ~ inverse angstrom <—> inter-particle spacing in typical materials
- Coherent modes — phonons — acoustic and optical — rotons, maxons

Superconductors: 1604.06800

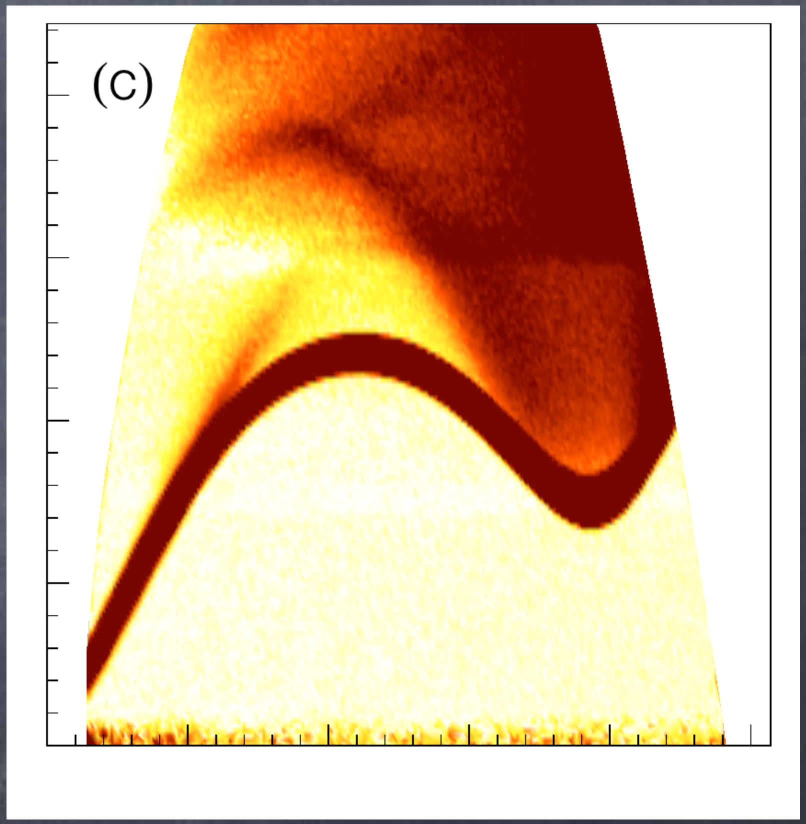
Dirac or Weyl Materials: 1708.08929

Polar Materials: 1612.06598

Superfluid Helium: 1604.08206

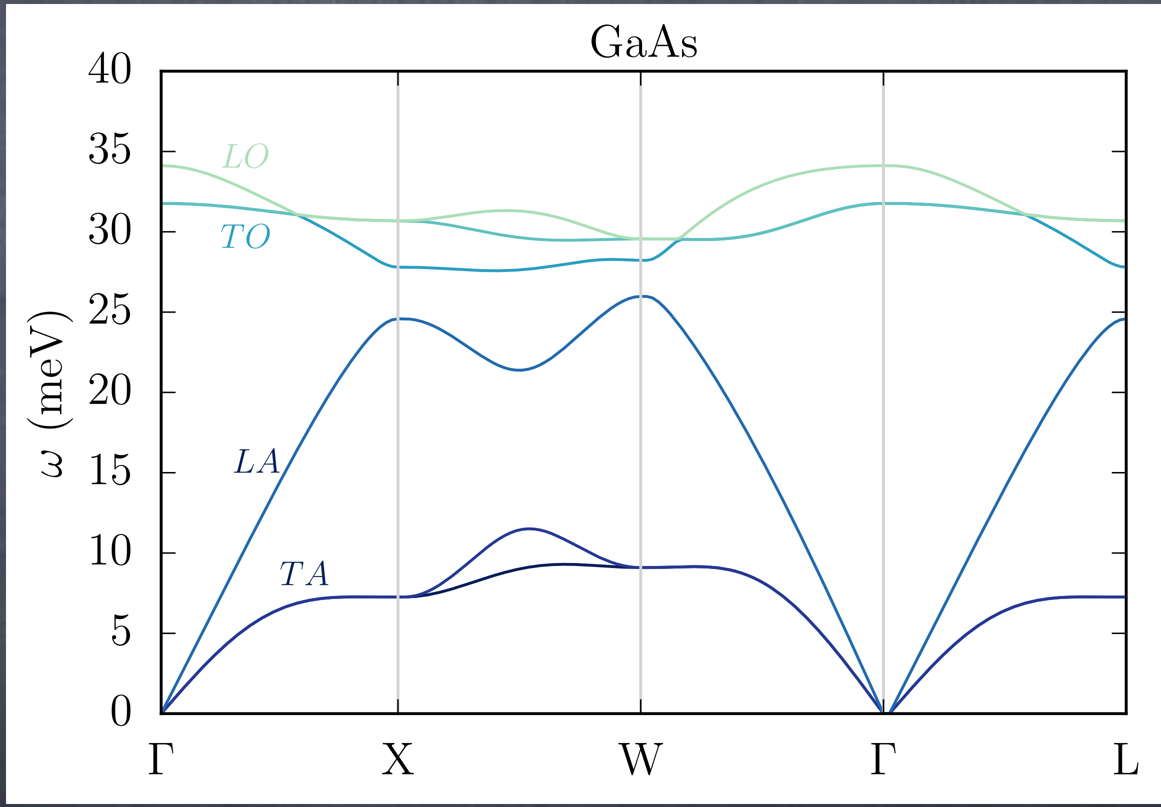
Utilizing Coherent Modes

- Material is characterized by the dispersion
- Amplitude of response = "Dynamic Structure Factor"



Utilizing Coherent Modes

- Different materials have different kinds of coherent modes
- All materials have acoustic phonons
- Superfluid helium also has rotons and maxons
- Materials with more complex crystal structures have optical phonons



Utilizing Coherent Modes

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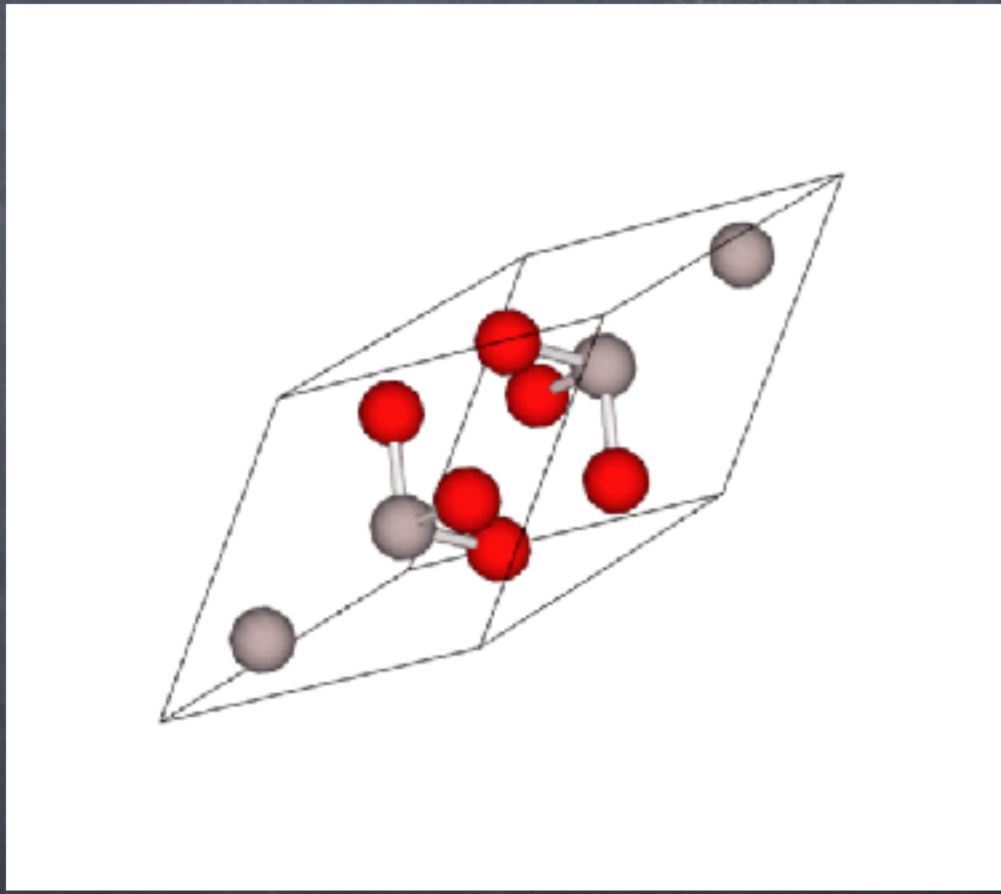


Characterizing Dark Matter Scattering

$$R = \frac{\rho_X}{m_X} \frac{n_T}{\rho_T} \frac{\bar{\sigma}}{2\mu_X^2} \int dv f(v) \int d^3q |F(q)|^2 S(q,\omega)$$

DM velocity distribution

Momentum dependence of cross-section

Material response

- e.g. Nuclear recoils:

$$S(q,\omega) = A^2 |F_N(q)|^2 \delta\left(\omega - \frac{q^2}{2m_N}\right)$$

- e.g. Single acoustic phonon

$$S(q,\omega) = \frac{q}{2m_{\mathrm{He}} c_s} \delta(\omega - c_s q)$$

Characterizing Dark Matter Scattering

$$R = \frac{\rho_X}{m_X}\frac{n_T}{\rho_T}\frac{\bar{\sigma}}{2\mu_X^2}\int dv f(v) \int d^3q |F(q)|^2 S(q,\omega)$$

DM velocity distribution

Momentum dependence of cross-section

Material response

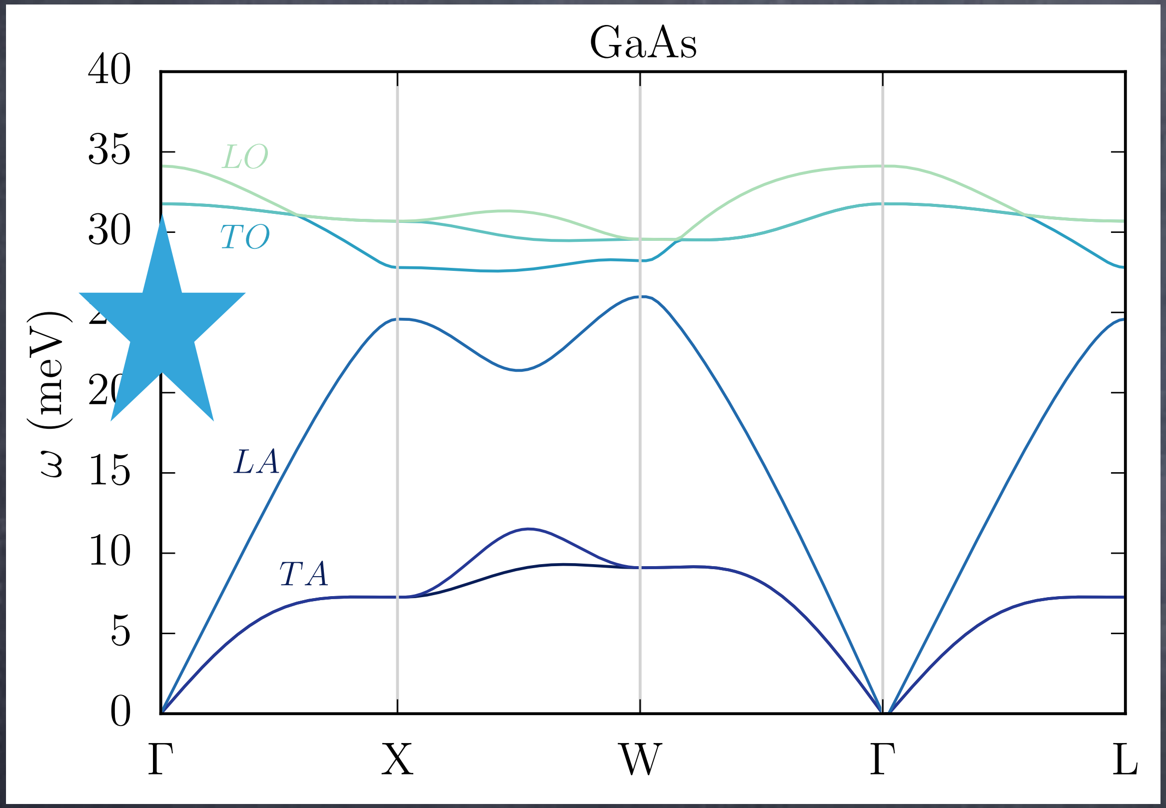
- e.g. Single optical phonon:

$$S(q,\omega) \sim \frac{q^2}{2m_T\omega_{\rm ph}}\delta(\omega-\omega_{\rm ph})$$

- e.g. Two phonons:

$$S(q,\omega) \sim \frac{7m_{\rm H}^{5/2}}{60\pi^2}\frac{c_s^4 q^4}{\omega^{7/2}}$$

Kinematic Matching



$$E_D \sim v_X q$$

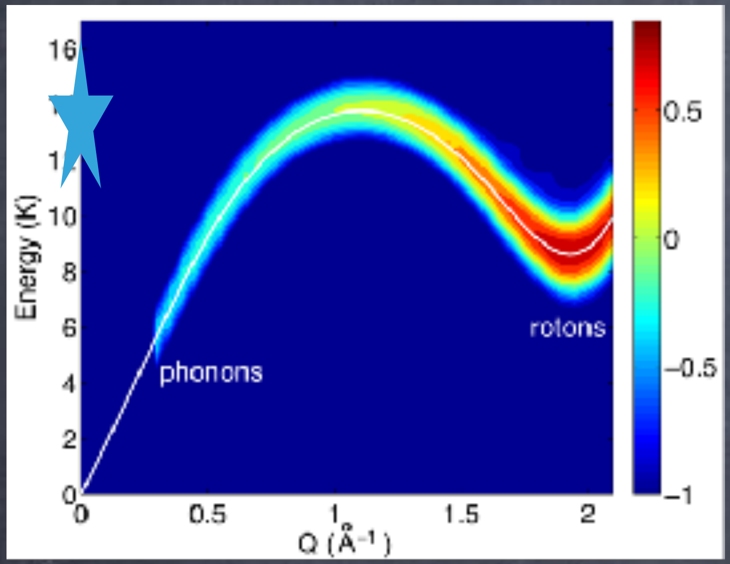
vs

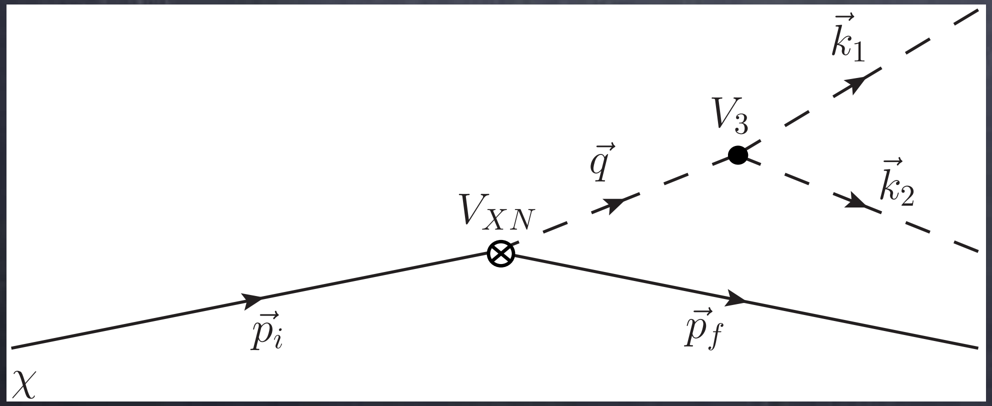
$$E_D \sim c_s q$$

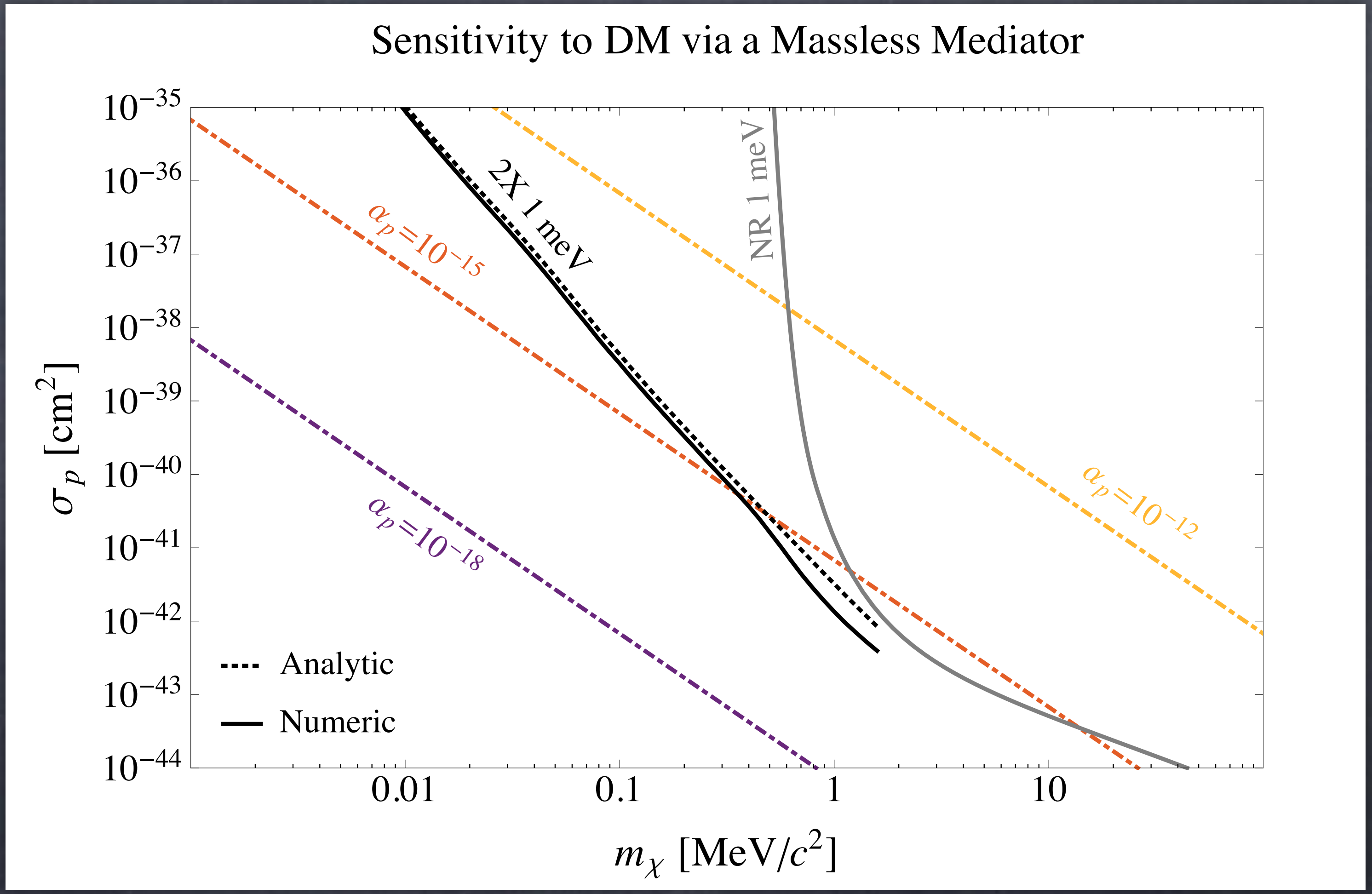
$$c_s \ll v_X$$

Reach

Superfluid Helium: Schutz, KZ 1604.08206



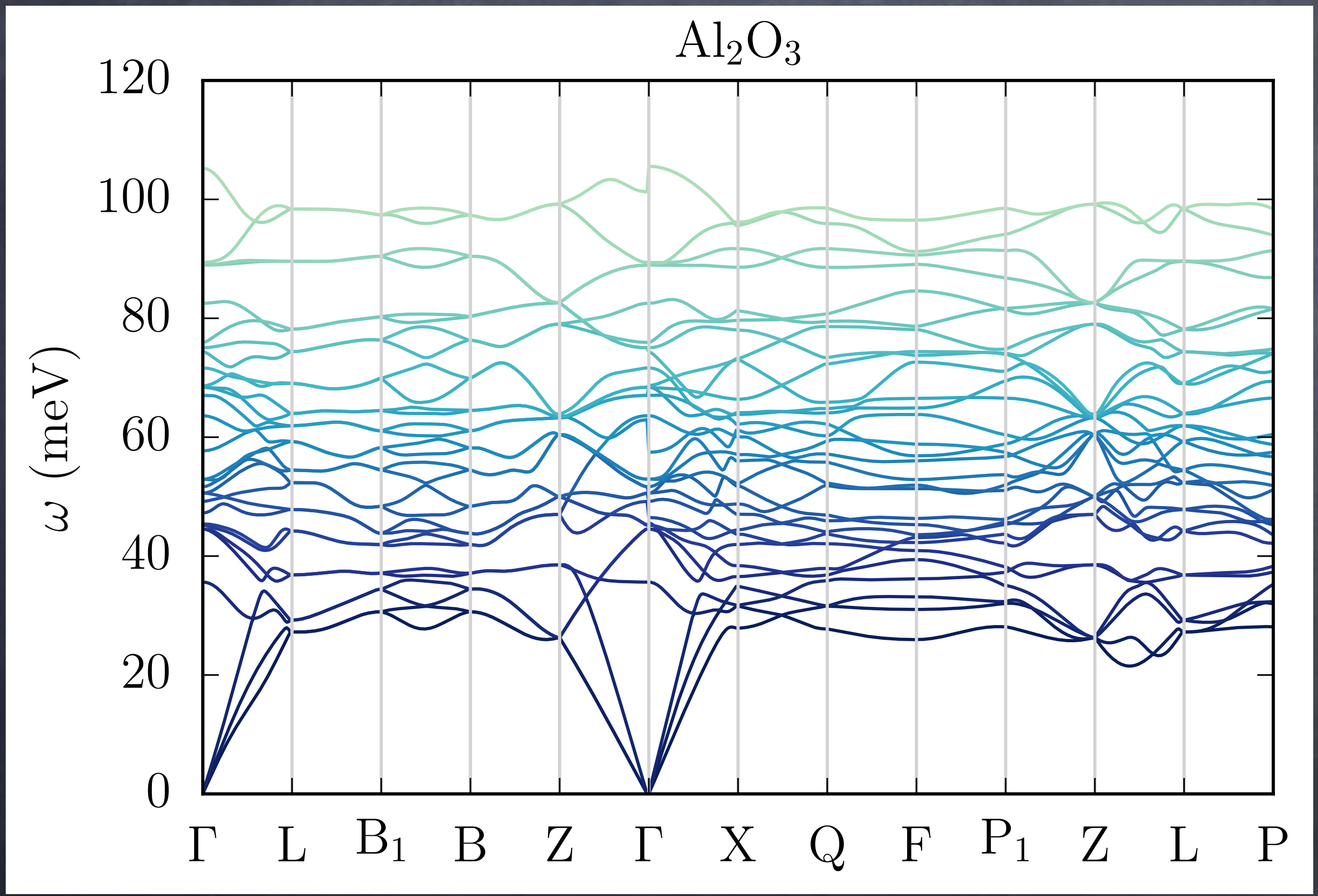


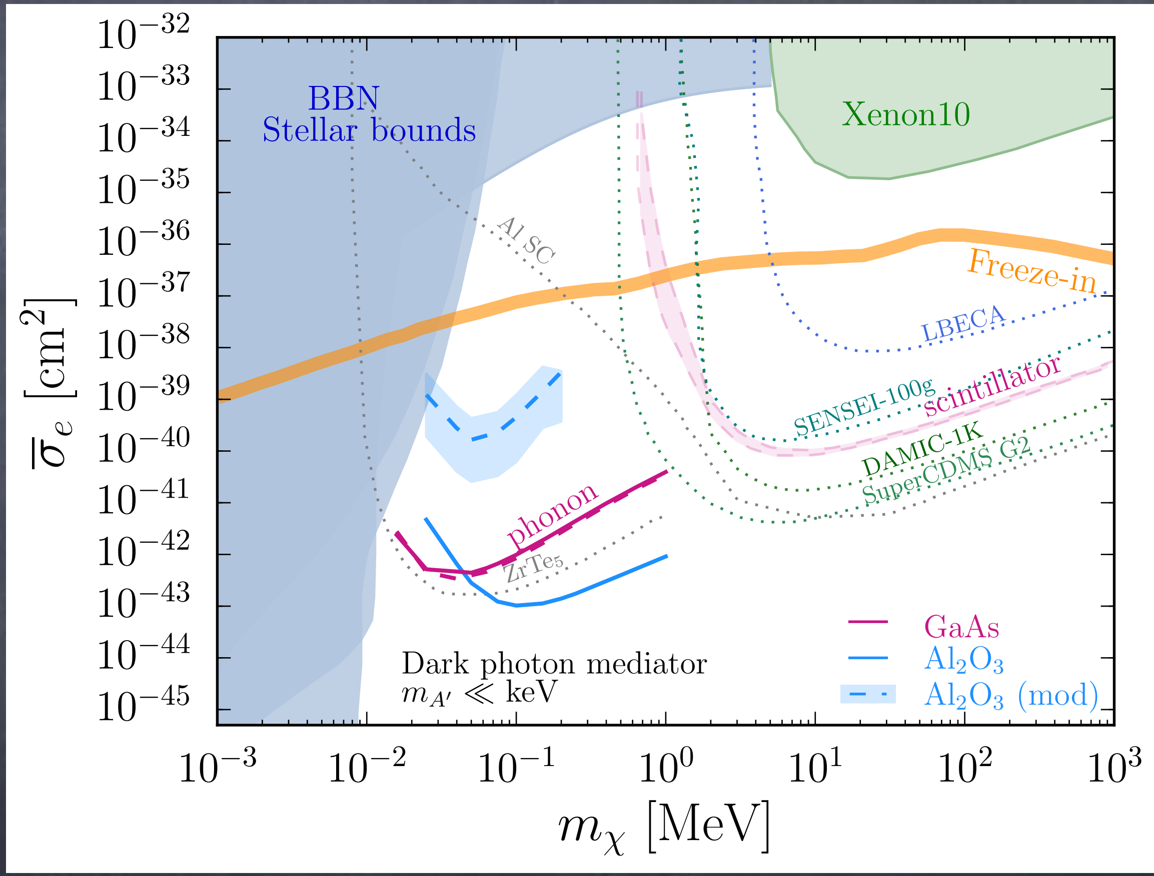


Multiple Acoustic Phonon

Reach

Polar Materials: Lin, Knapen, Pyle, KZ 1612.06598

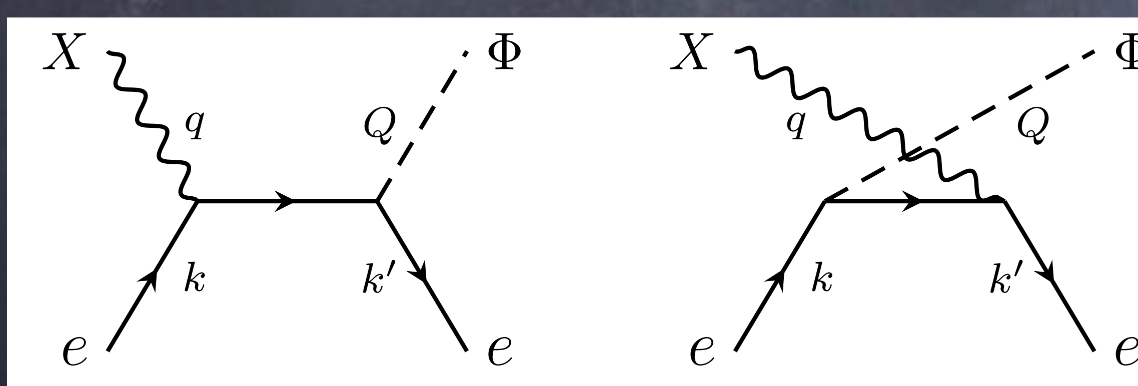


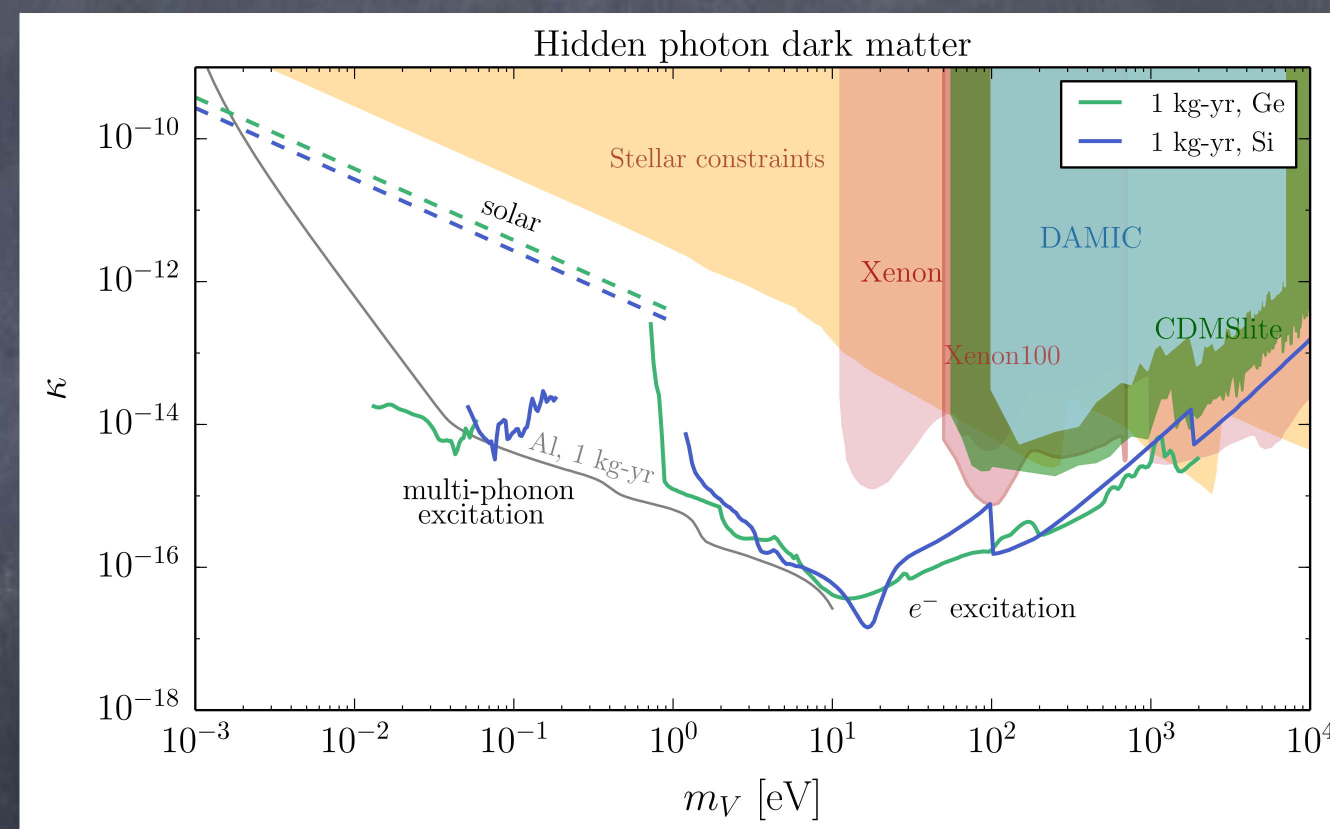


Single Optical Phonon, Single Acoustic Phonon

Reach

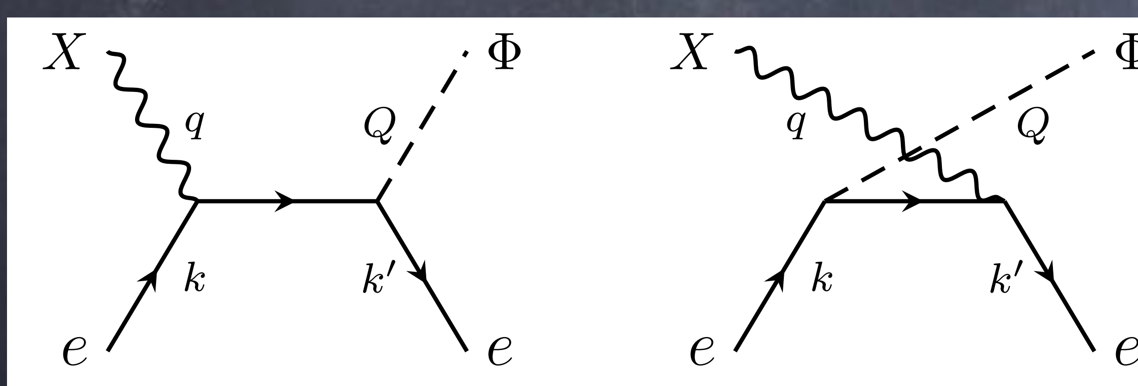
$$\langle n_e \sigma_{\rm abs} v_{\rm rel} \rangle_\gamma = -\frac{\mathrm{Im}\ \Pi(\omega)}{\omega}$$

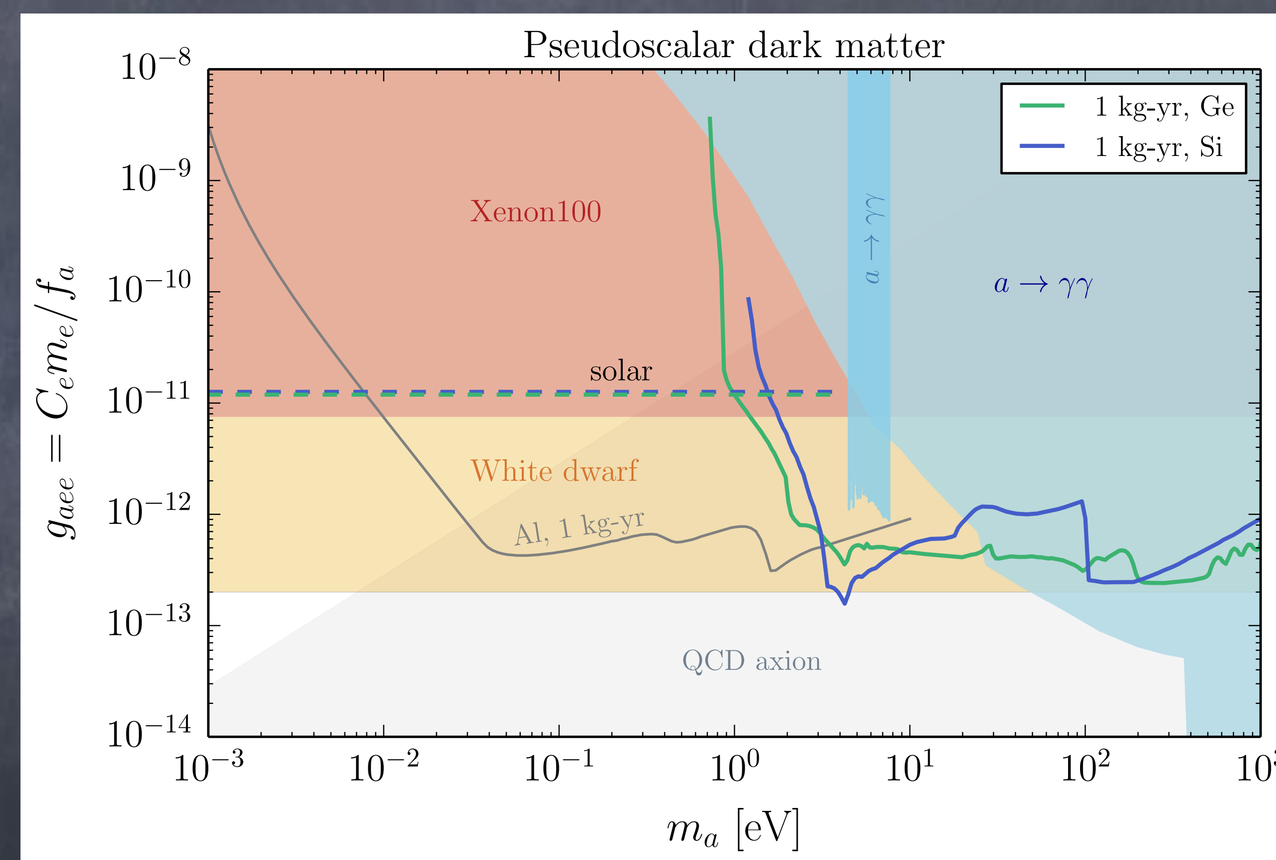




Reach

$$\langle n_e \sigma_{\rm abs} v_{\rm rel} \rangle_\gamma = - \frac{{\rm Im}\ \Pi(\omega)}{\omega}$$





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 have developed.
- 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
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