Nordic conference on Particle Physics: Dark matter I

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Outline

- **DM Motivation**
- **WIMPS**
    - Freeze-out
    - Direct Detection
    - Indirect Detection
    - LHC searches for DM
- **(Some) Alternatives to WIMPs (tomorrow)**

Books and Reviews

- ## Books

Kolb and Turner, The Early Universe, (1990)

Bertone et al, Particle dark matter, (2013)

Bergström and Goobar, Cosmology and particle Astrophysics, (2006)

- ## Reviews (+ Lectures)

Bertone, Hooper, Silk, Particle dark matter: Evidence, candidates and constraints, hep-ph/0404175, Phys.Rept. 405 (2005) 279-390

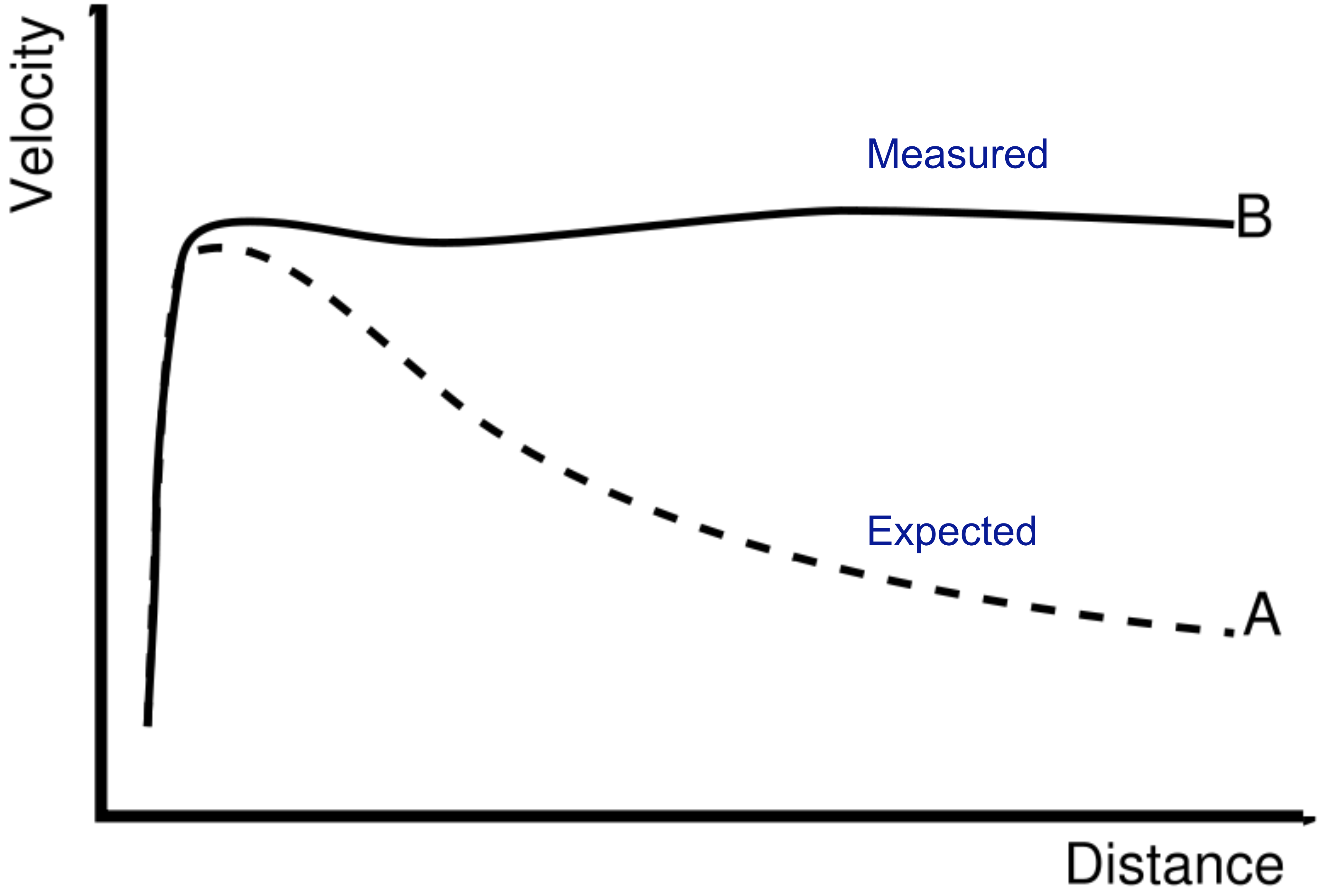
Conrad, Indirect Detection of WIMP Dark Matter: a compact review, arXiv:1411.1925

Gelmini, TASI 2014 Lectures: The Hunt for Dark Matter, arXiv:1502.01320

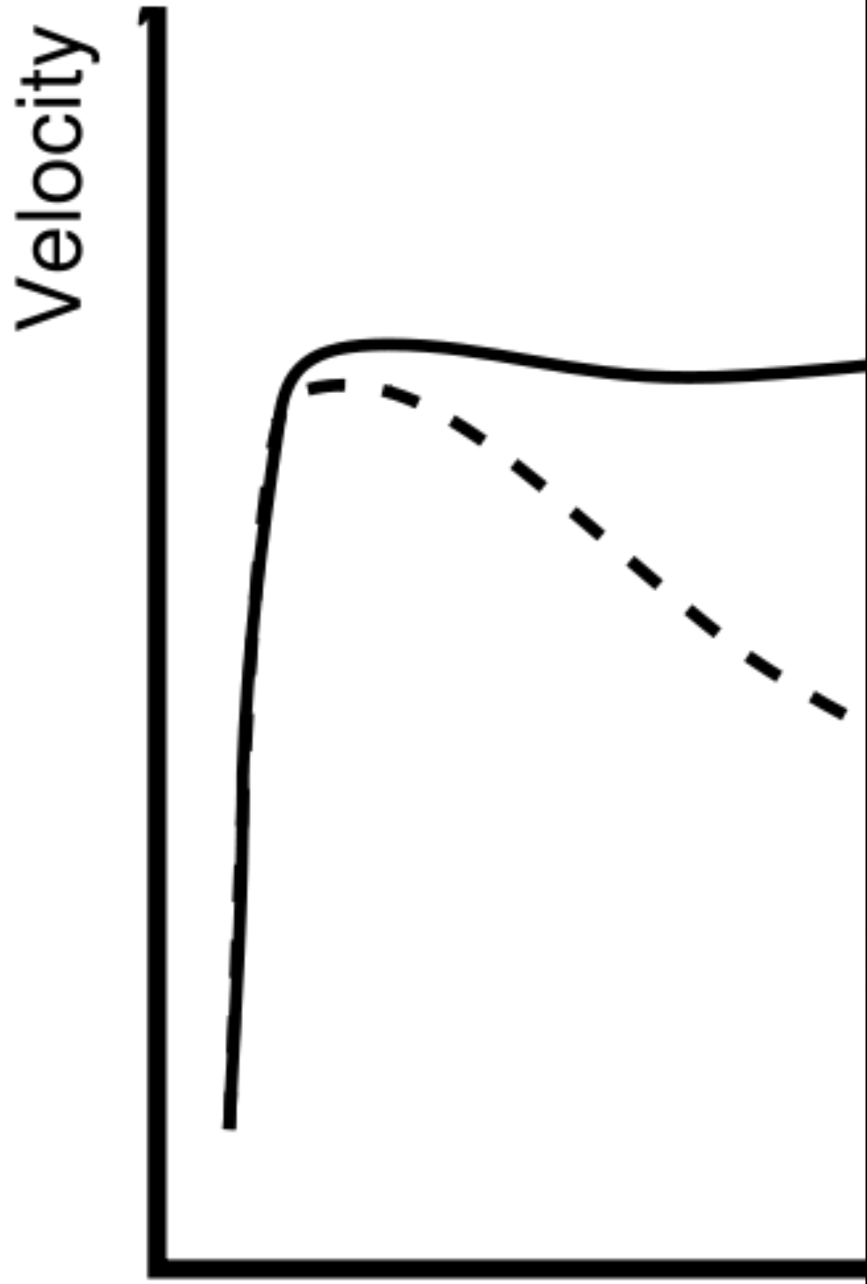
Baer, Choi, Kim, Roszkowski, Dark matter production in the early Universe: beyond the thermal WIMP paradigm, arXiv:1407.0017, Phys.Rept. 555 (2014) 1-60

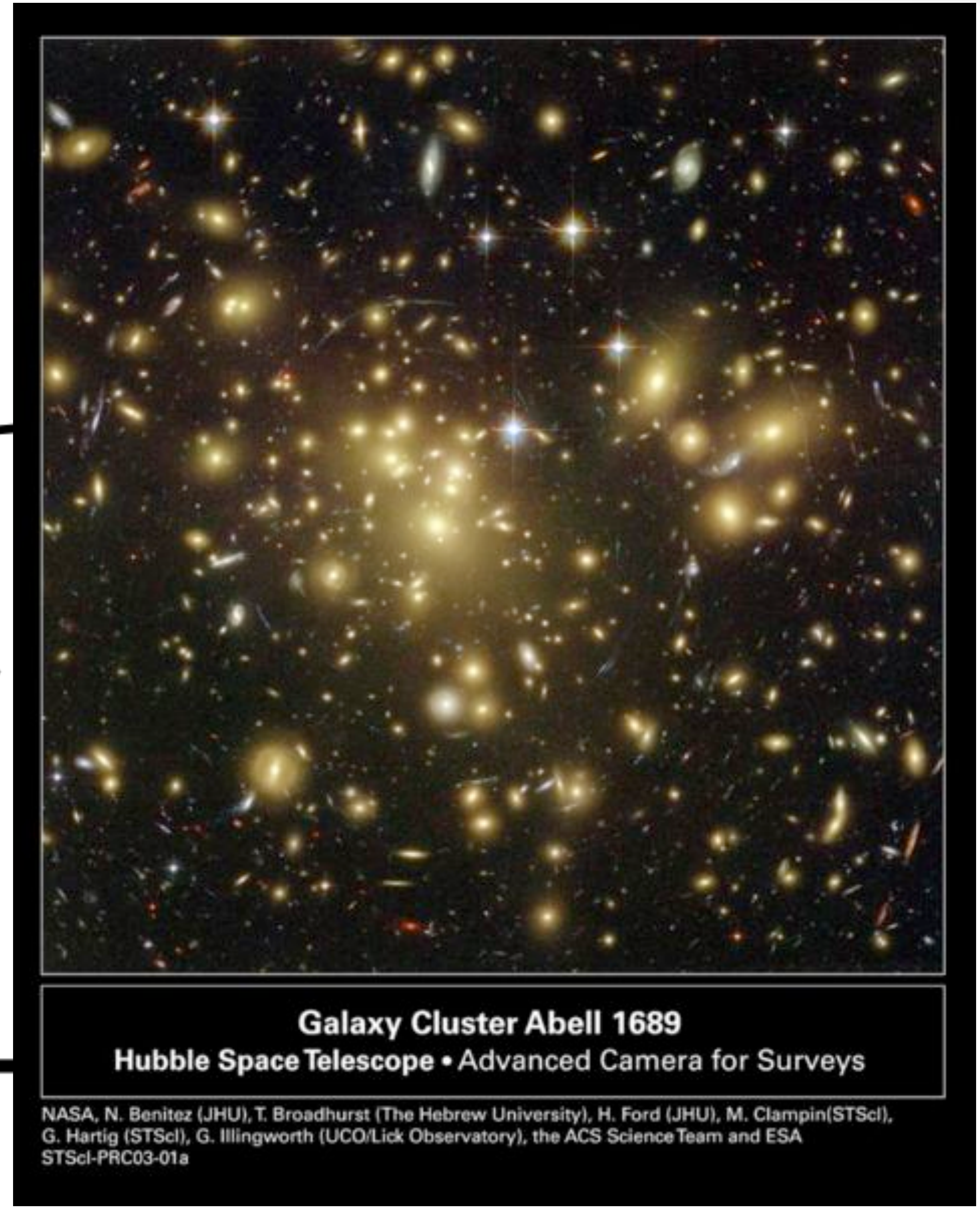
Many more available…

Dark Matter Motivation



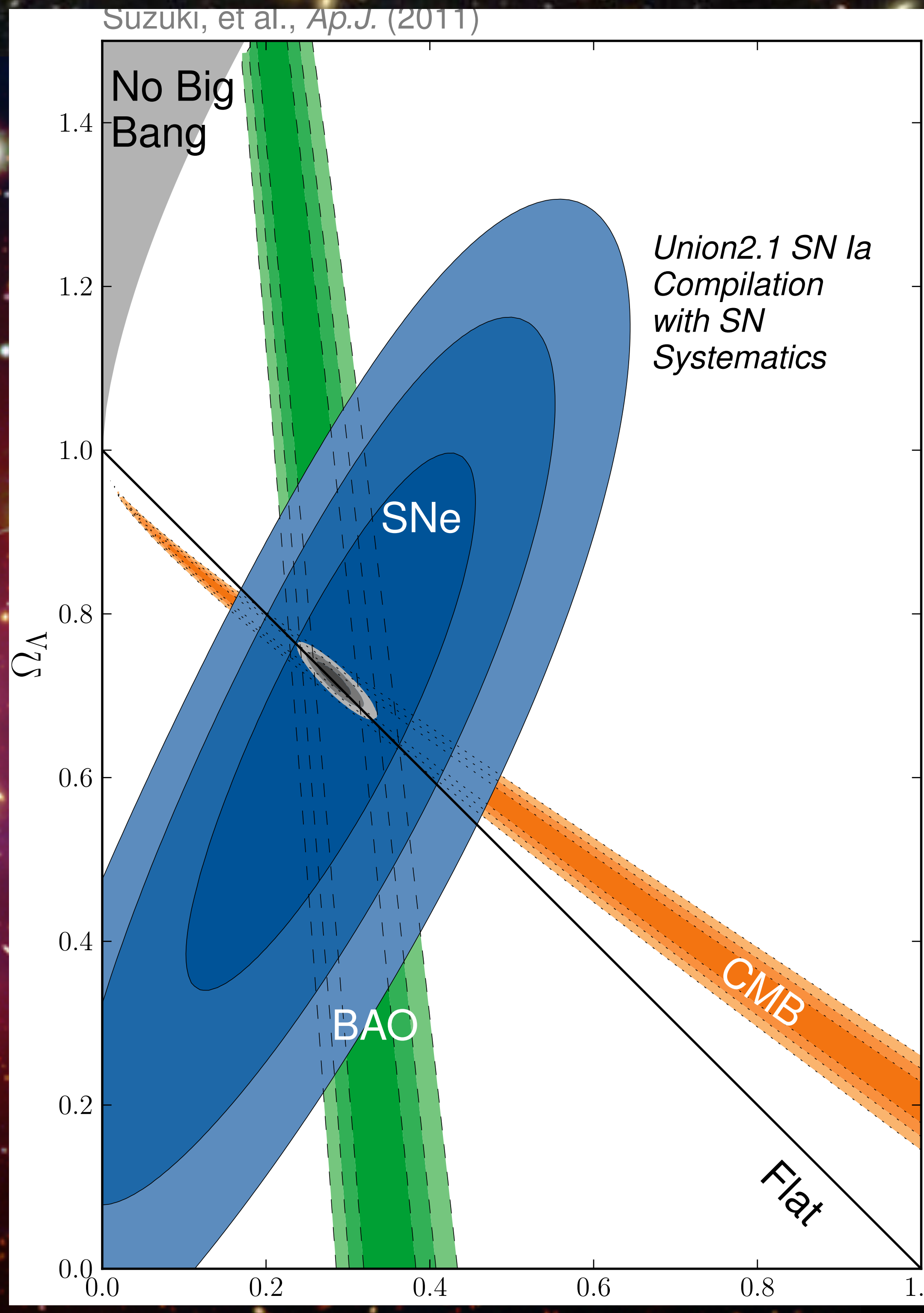
Dark Matter Motivation



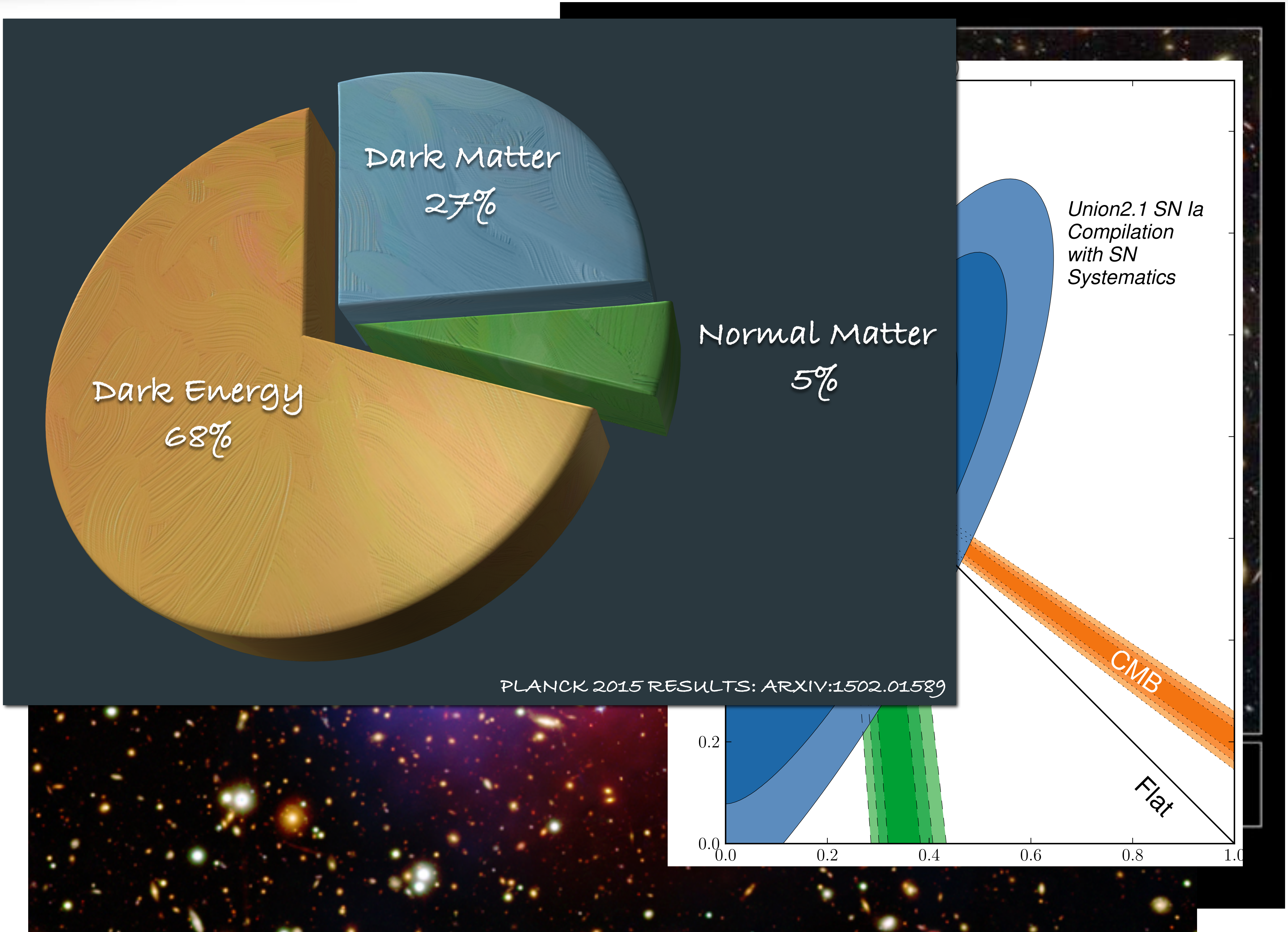


Dark Matter Motivation

Dark Matter Motivation



Dark Matter Motivation



What do we know?

- DM has attractive gravitational interactions and is either stable or has a lifetime $\gg \tau_U$
- DM is not observed to interact with light or gluons
- Bulk of the DM is Cold or Warm, thus particle DM requires physics beyond the SM
- Mass of major component of DM only constrained within some 80 orders of magnitude
- Dominant component of the DM must be dissipation-less, but part of it could be
- DM assumed to be collision-less, however the upper limit on DM self-interactions is actually very large

How was dark matter produced?

- Many ideas/models on the market - start with the most studied

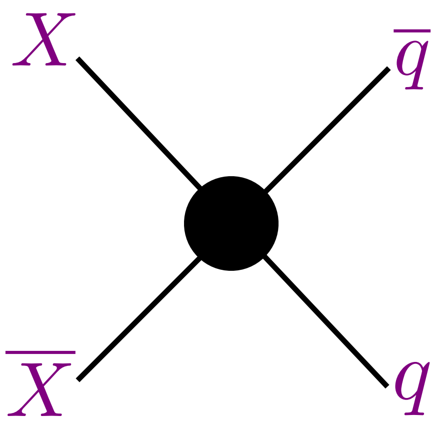
Freeze-out

- Seen this already in Mark Hindmarsh's lectures - quick recap

Dark matter from freeze-out

- Simplest set-up relies on a connection between DM states and SM states, e.g.

$$\mathcal{L} = \bar{X} X \bar{q} q \qquad \Rightarrow$$



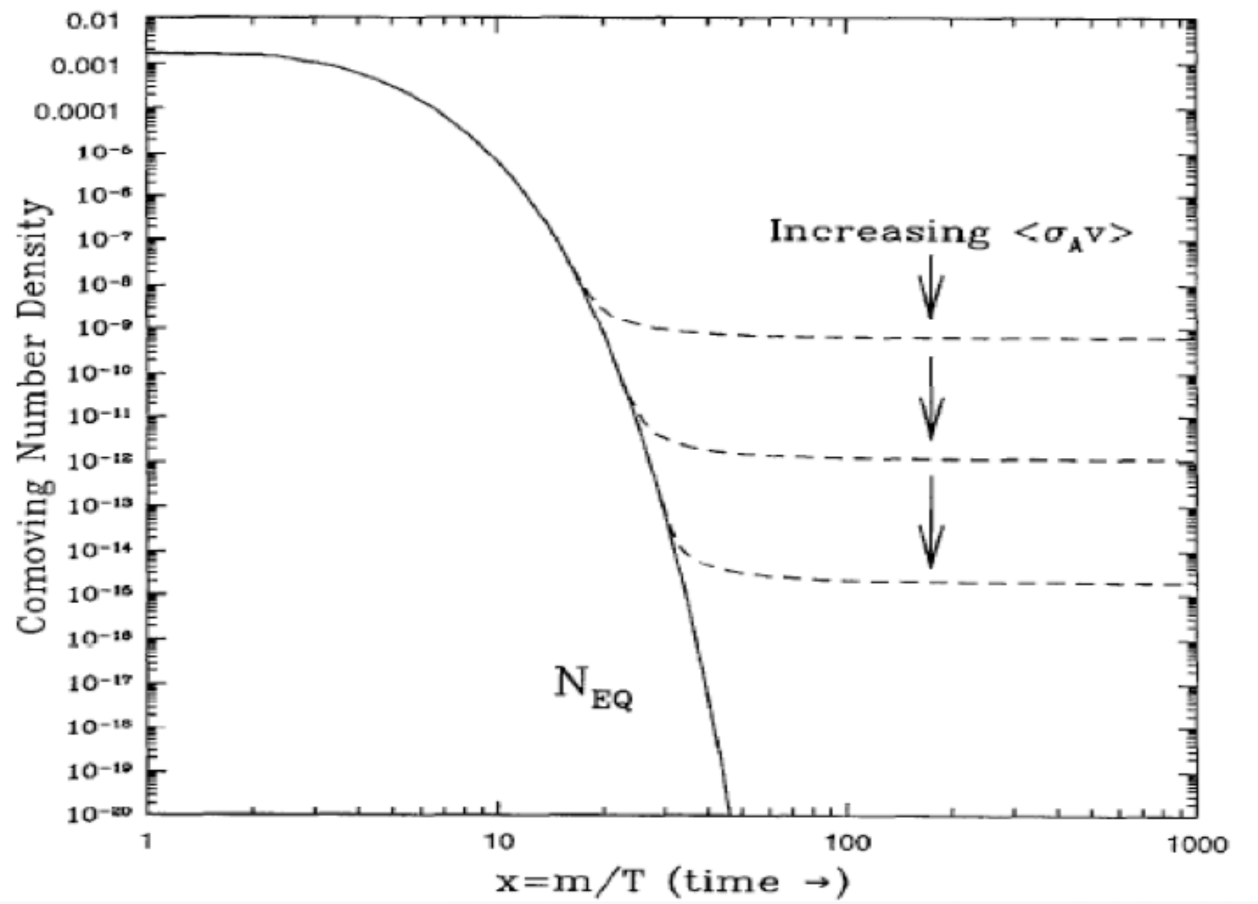
- The strength of interaction determines whether the DM state is in thermal equilibrium (chemical)

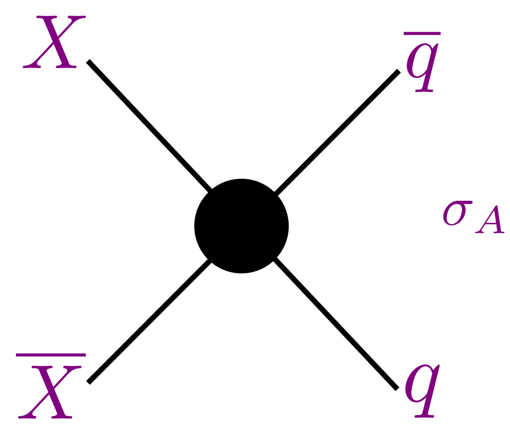
Dark matter from freeze-out

- Assumptions for standard freeze-out
  - Single species of dark matter
  - Radiation dominated universe
  - DM interactions with the SM states large enough to be in thermal equilibrium at $T > m_X$

Standard Freeze-out

- Standard scenario for WIMP DM…



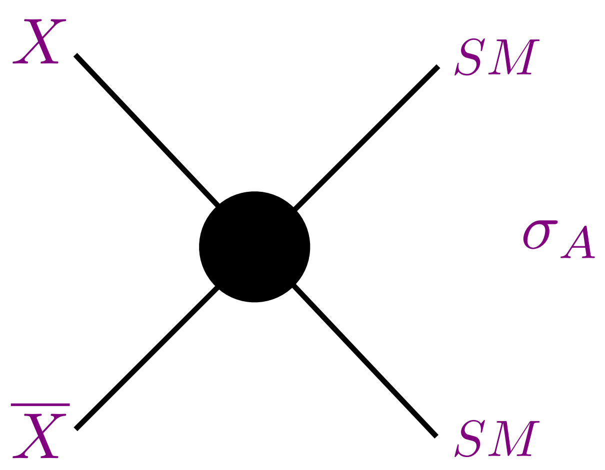


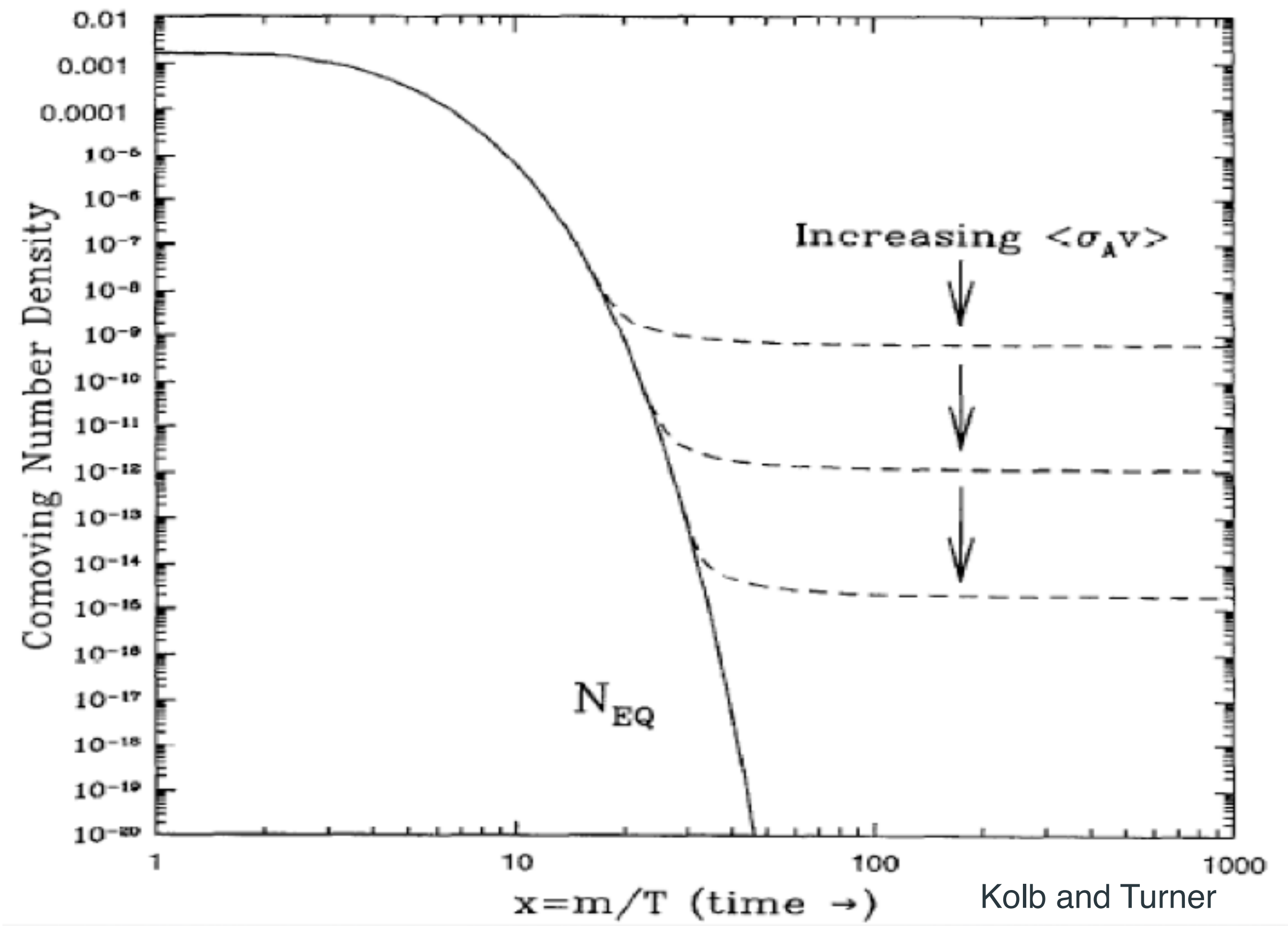
- Initially in thermal equilibrium $T > m_X$
- As the temp decreases $T < m_X$ creation of X becomes exponentially suppressed
- Annihilation of X still proceeds, number density of X given by

$$\mathrm{N_{EQ}} \approx g_X \left(\frac{m_X T}{2\pi} \right)^{3/2} e^{-m_X/T}$$

$n_{X,eq} \to 0$ as $T \to 0$

Standard Freeze-out





- Due to expansion, dark matter number density freezes-out when: $\Gamma = n_X \langle \sigma_A v \rangle < H$

- Number density of dark matter determined by Boltzmann Equation

$$\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma_A v \rangle \left(n_X^2 - n_{X,eq}^2 \right)$$

Standard Freeze-out

- Boltzmann equations usually solved numerically for most models but an analytic solution can be constructed.

- Non-relativistic expansion of the cross section, (temp of universe is below the mass of the DM).

$$\sigma v = a + b v^2 + \ldots \qquad \rightarrow \qquad \langle \sigma v \rangle = a + 6b \frac{T}{m_{\rm dm}} + \ldots$$

$$\Omega h^2 \approx \frac{1.04 \times 10^9}{M_{\rm pl}} \frac{x_f}{\sqrt{g_*}} \frac{1}{a + 3b/x_F}$$

$$x_F = \ln\left(c(c+2)\sqrt{\frac{45}{8}} \frac{g}{2\pi^3} \frac{m_{\rm dm} M_{\rm pl}(a + 6b/x_F)}{\sqrt{g_* x_F}} \right)$$

Kolb and Turner

WHERE

$$\sqrt{g_*} = \frac{g_*^s}{\sqrt{g_*^\rho}} \left[1 + \frac{1}{3} \frac{d g_*^s}{dT} \right] \qquad S = g_*^s \frac{2\pi^2}{45} T^3 \quad H = 2\sqrt{\frac{\pi^3}{45}} \frac{\sqrt{g_*^\rho} T^2}{M_{\rm pl}}$$

Standard Freeze-out

- Yield set at freeze-out gives final dark matter abundance.

$$\Omega h^2 \sim 0.1 \frac{3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_A v \rangle}$$

Approx. weak scale cross section $\longrightarrow$ WIMPs

- Freeze-out abundance determined but annihilation cross-section

WIMP Candidates

- LSP in a SUSY model e.g. neutralino, sneutrino
- LKP in ED model E.g. KK excitation of the hyper-charge gauge boson
- Singlet scalar/fermion extension to the Standard Model
- Extra scalar states in the Inert Higgs Doublet model and variants
- Basically anything with an approx weak scale mass and couplings…

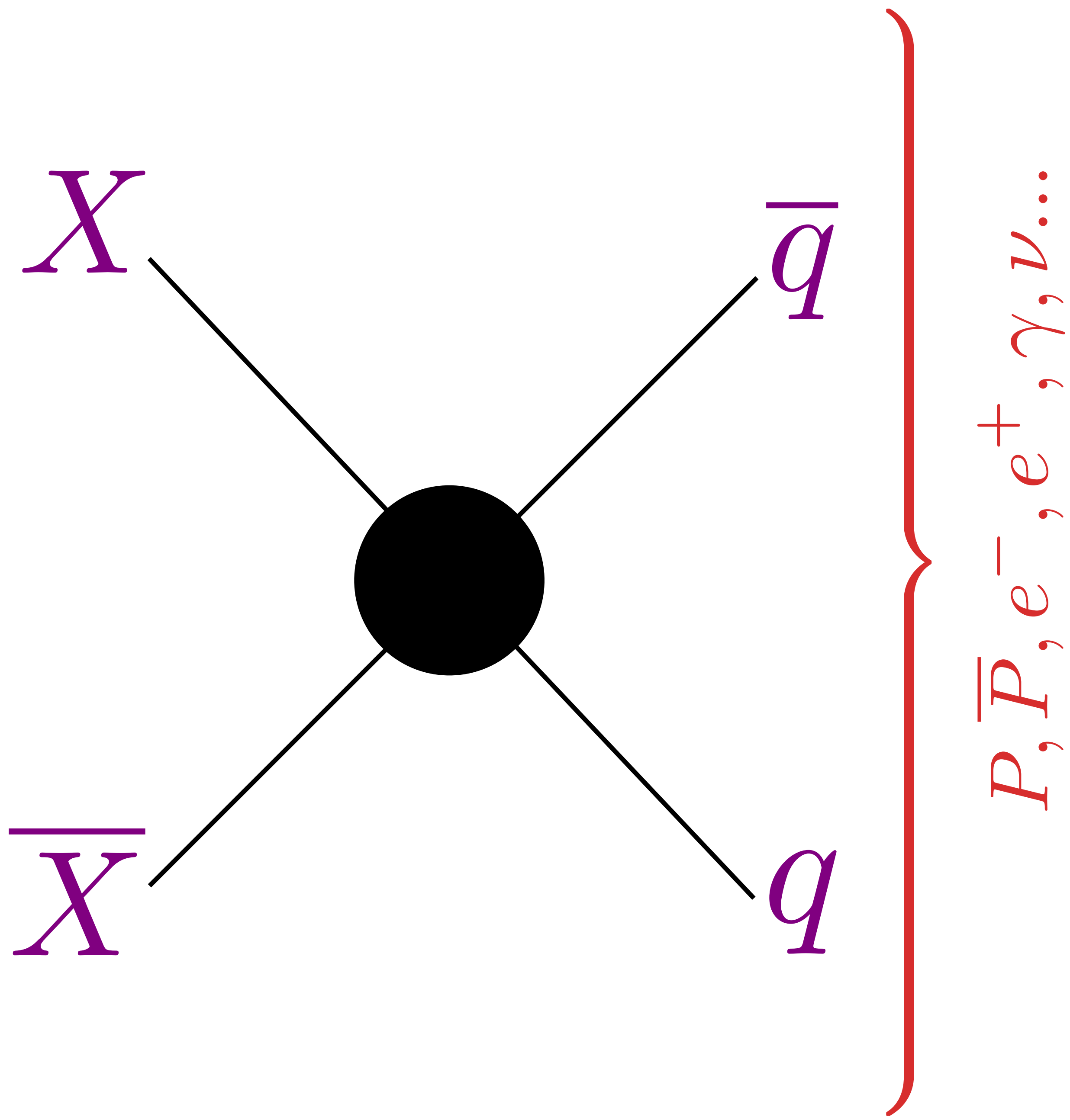
Standard Freeze-out

- Beyond generating the dm abundance, freeze-out points to ways in which dm can be probed

$$\mathcal{L} = \bar{X} X \bar{q} q$$

Interaction leads to annihilation - as we have already seen in freeze-out

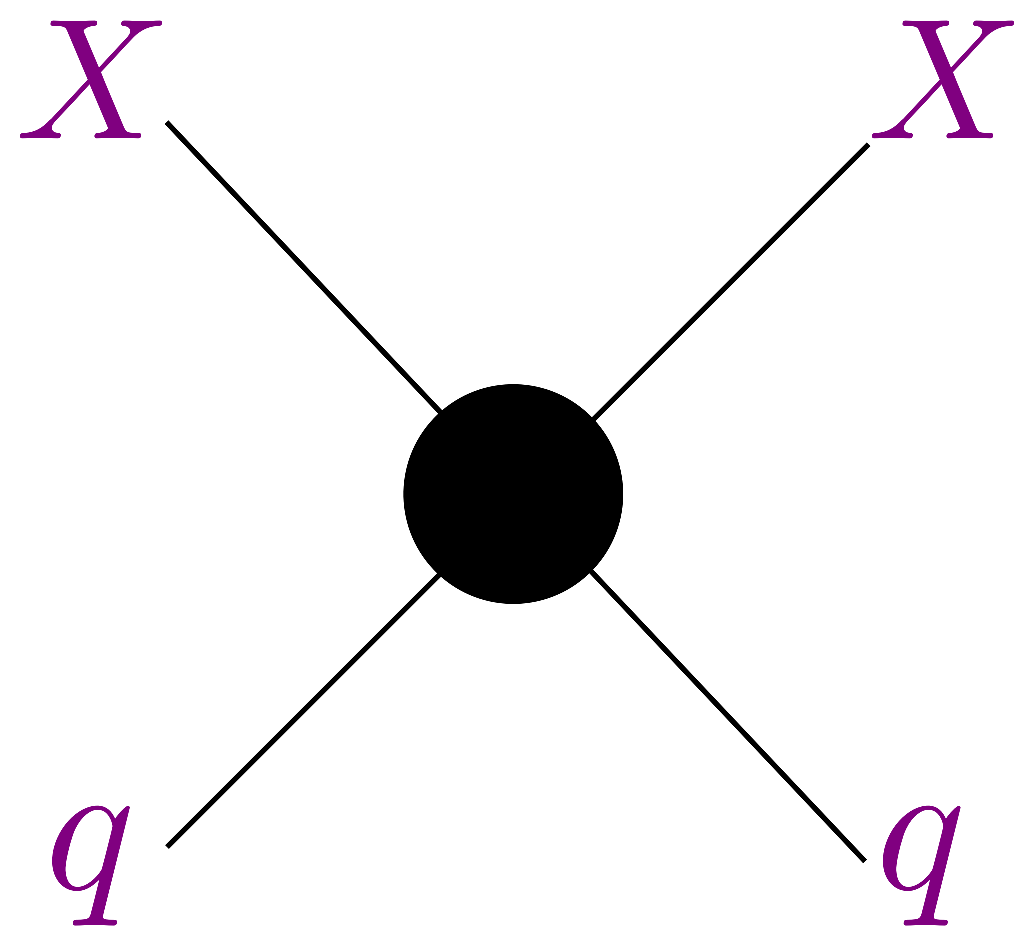
DM annihilation today can lead to indirect signals



Standard Freeze-out

- We can also turn the diagram on its side

$$\mathcal{L} = \bar{X} X \bar{q} q$$

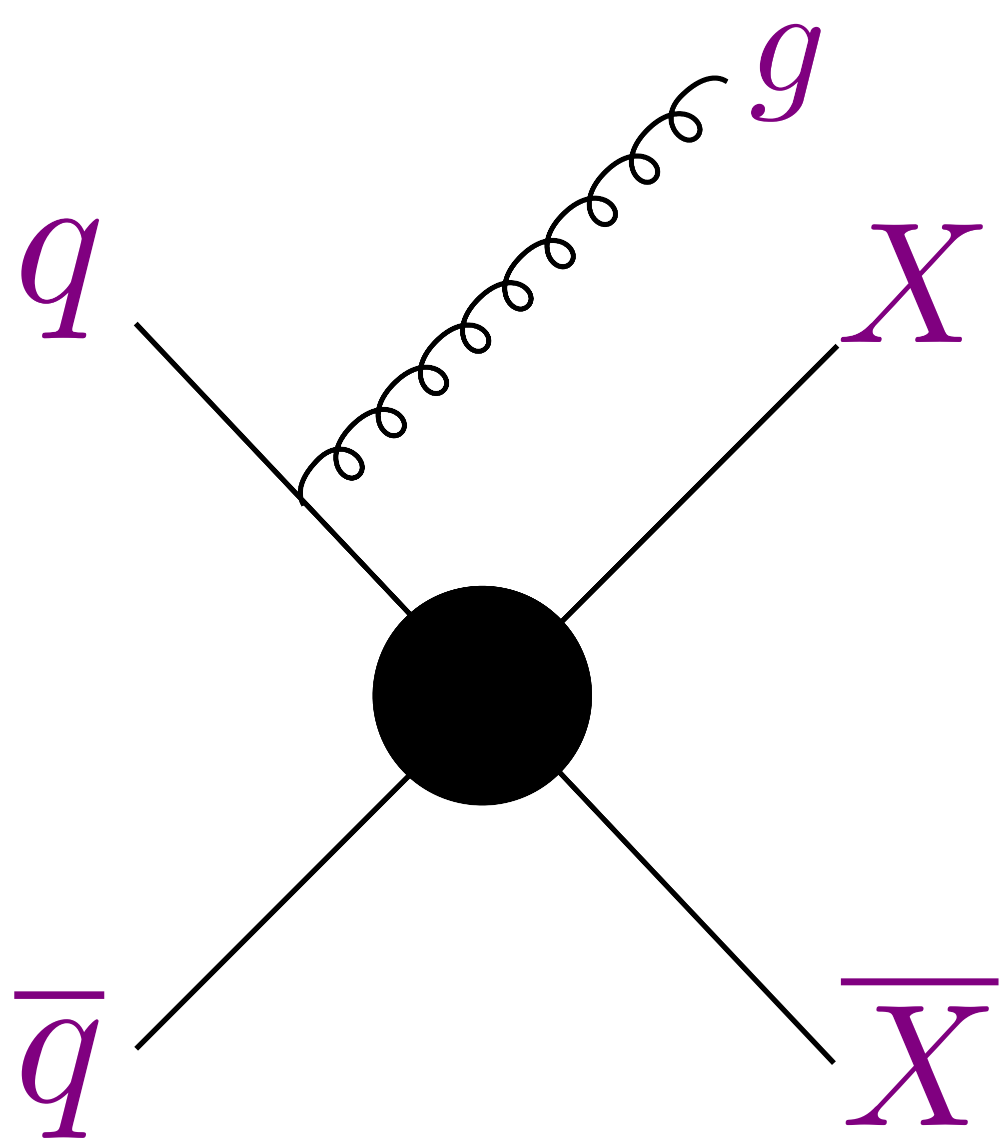


Leads to possibility of direct detection

Standard Freeze-out

- Turning the diagram once more

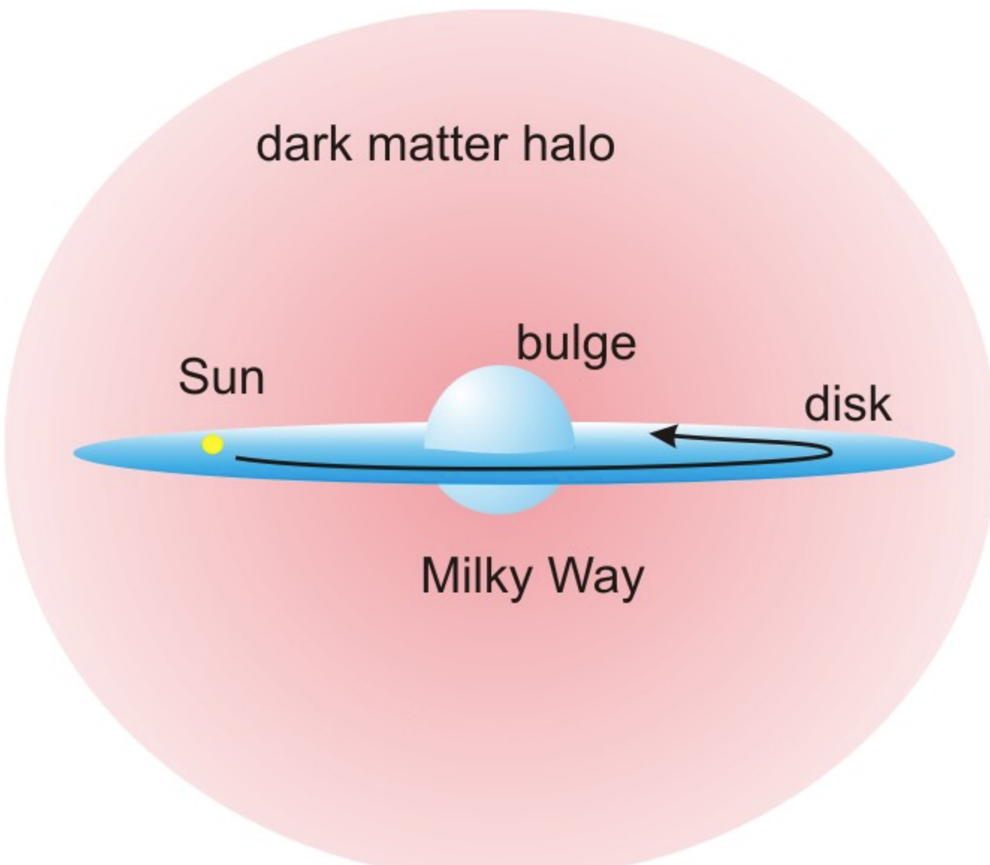
$$\mathcal{L} = \bar{X} X \bar{q} q$$



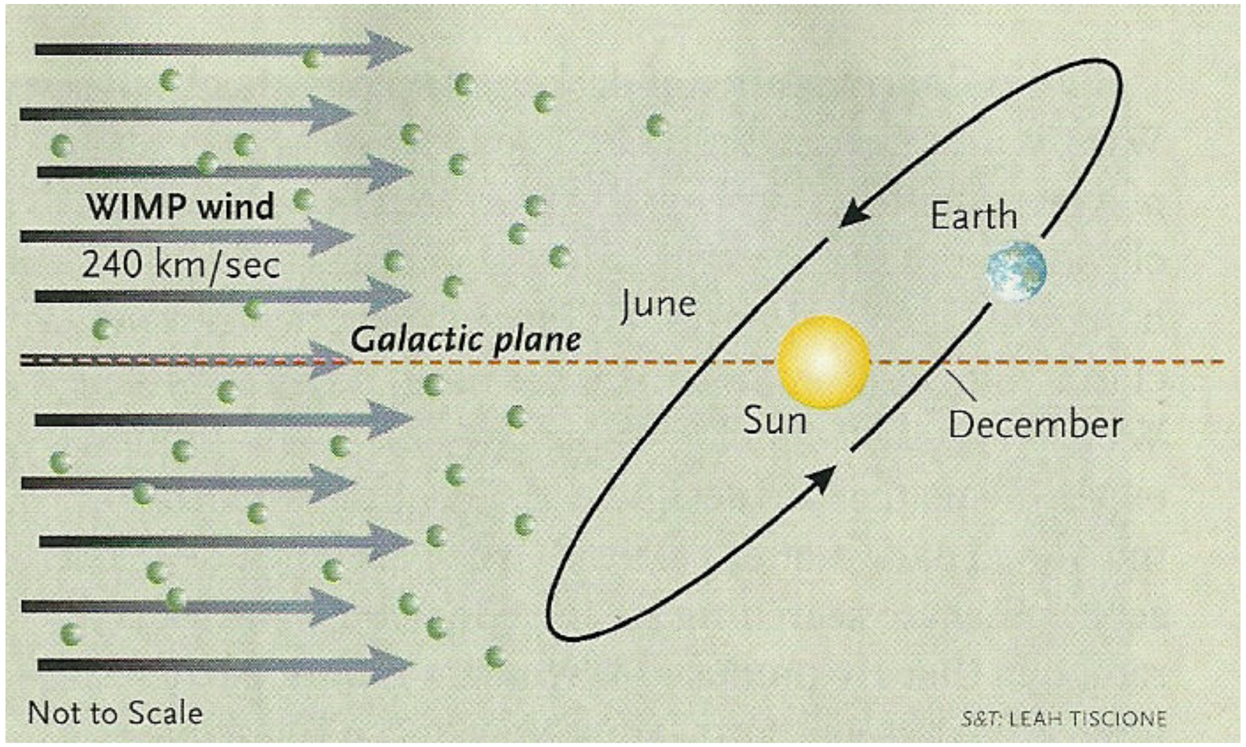
Leads to possibility of producing DM at the LHC…more later in the week with Mads

Direct Detection

- Principles of direct detection: The Earth moves thorough a “Dark matter wind”

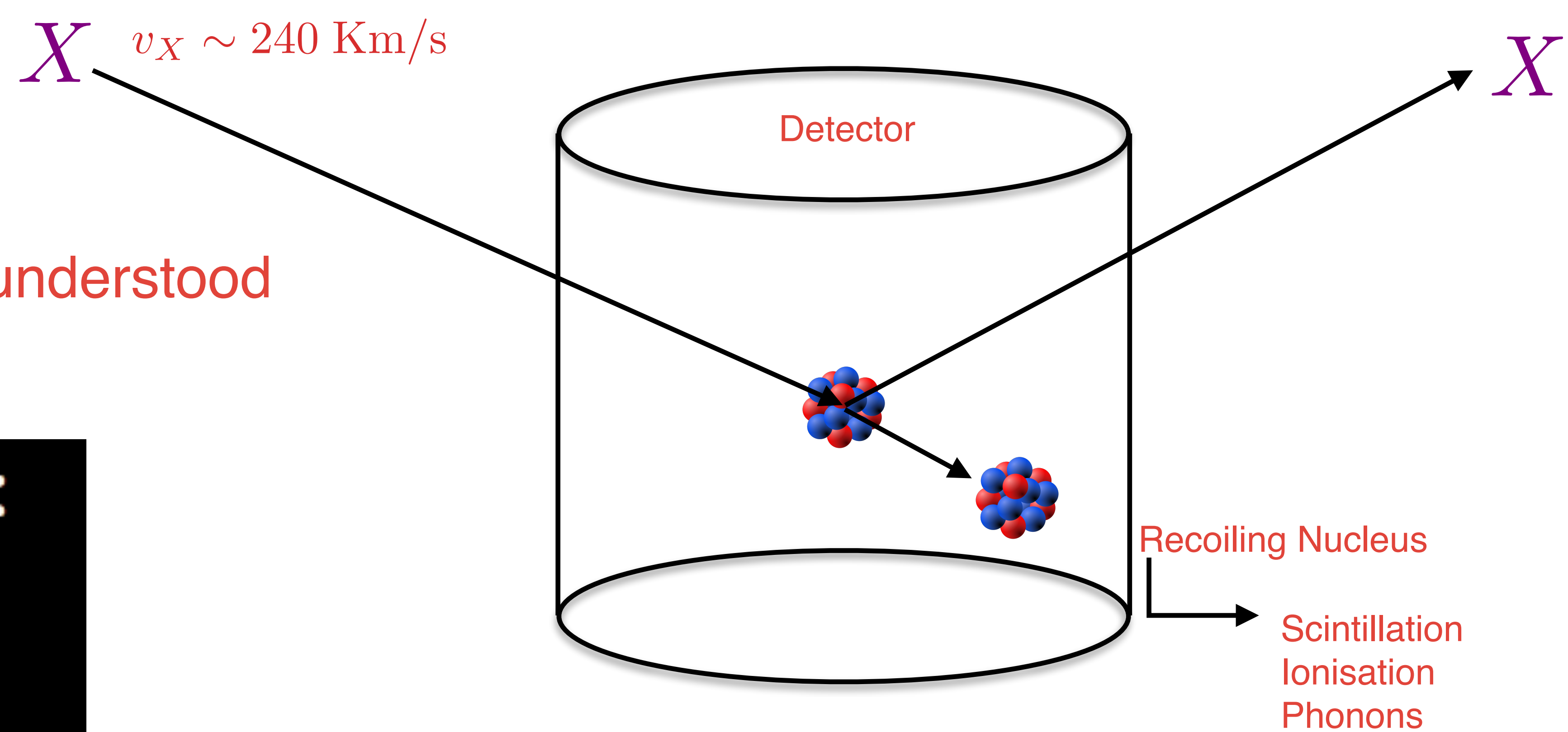


credit: Sabine Hossenfelder



Direct Detection

- Look for DM scattering off Standard Model nuclei



- Need very low and well understood backgrounds

Backgrounds:

$\gamma\, e^- \rightarrow \gamma\, e^-$

$n\, N \rightarrow n\, N$

$N \rightarrow N' + \alpha, e^-$

$\nu\, N \rightarrow \nu\, N$

DM-Nucleus Reduced mass

Scattering angle

$$E_{\mathrm{recoil}} = \frac{\mu_{XN}^2 v_X^2}{M_N}(1 - \cos\theta)$$

$$E_{\mathrm{recoil}} \sim 1 - 100\ \mathrm{KeV}$$

- Detectors located deep underground

Direct Detection

- Event rate:

Particle Physics	Nuclear structure	Local Astrophysics

$$\frac{dR}{dE_R} = \frac{\sigma_{XN}(0)}{m_X} \frac{F_N(q)^2}{\mu_{XN}^2} \rho_X g(v_{\min})$$

$\sigma_{XN}(0)$ .... DM-Nucleus zero-momentum-transfer cross section

$F_N(q)$ .... Nuclear form factor, q =momentum transfer

$g(v_{\min}) \equiv \frac{1}{2} \int_{v>v_{\min}} d^3\mathbf{v} \, \frac{f(\mathbf{v})}{v}$ .... Integral over local WIMP velocity distribution

$v_{\min} = \sqrt{E_R M_N / 2\mu_r^2}$ .... Minimum WIMP velocity for given E_R

Direct Detection

- Two main ways for DM to scatter:

Spin Independent

$$\sigma^{\rm SI}_{XN}(0) = A^2 \frac{\mu^2_{XN}}{\mu^2_{Xp}} \sigma^{\rm SI}_{Xp}$$

(Assuming DM-p and DM-n interactions are equal)

Spin Dependent

$$\sigma^{\rm SD}_{XN}(0) = \frac{4\mu^2_{XN}}{\pi} \frac{J+1}{J} \times |\langle S_p \rangle G^p_a + \langle S_n \rangle G^n_a|^2$$

A = Atomic number of target nucleus

$\langle S_p \rangle, \langle S_n \rangle$ = expectation value of spin of p and n in nucleus

J = nuclear spin

G^p_a, G^n_a = axial four-fermion couplings of the WIMP with point-like protons and neutrons

See astro-ph/0406204v1 for a nice summary and more details

Direct Detection

For Spin independent scattering

- Form Factor: reflects the loss of coherence with increasing momentum transfer

$$F_N^2(q) = \left(\frac{3j_1(qR_1)}{qR_1}\right)^2 e^{-q^2 s^2}$$

Essentially the Fourier transform of the nucleon density, where

s, R_1 = Describe the size and the form of the nucleus

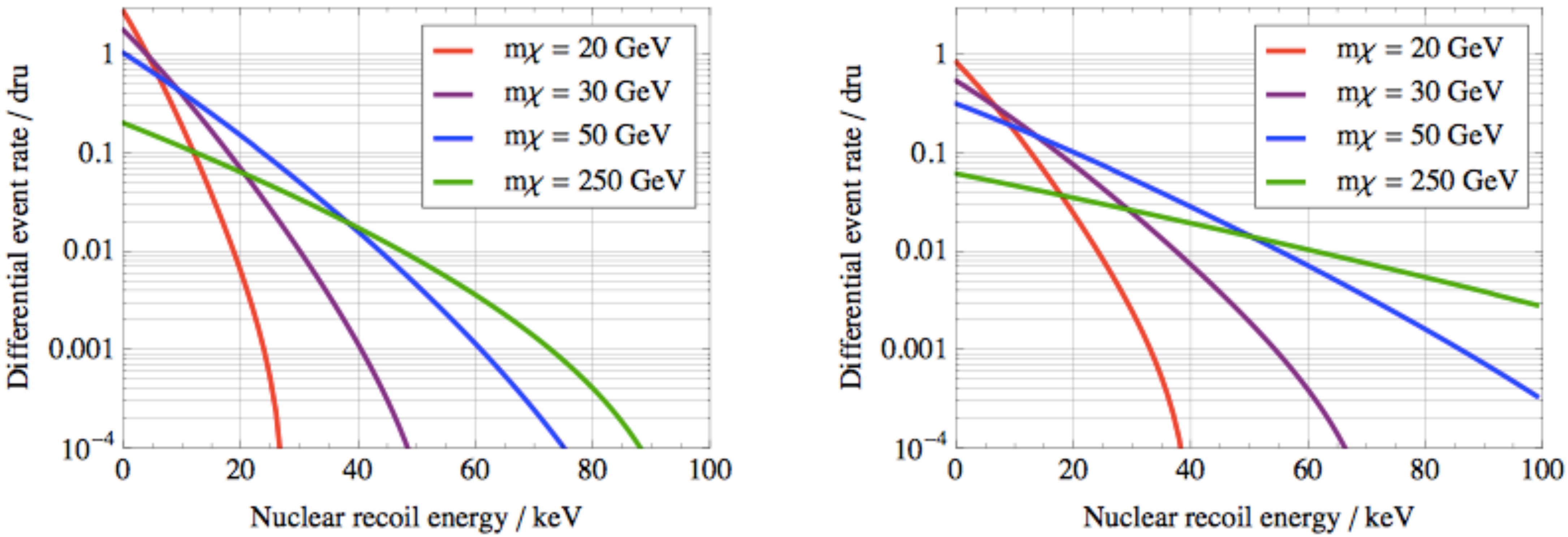
(See McCabe, arXiv:1005.0579 for nice discussion of this)

$q = \sqrt{2m_N E_r}$ = momentum transfer of scattering

Direct Detection

- Event rate - DM mass and nuclear target dependence

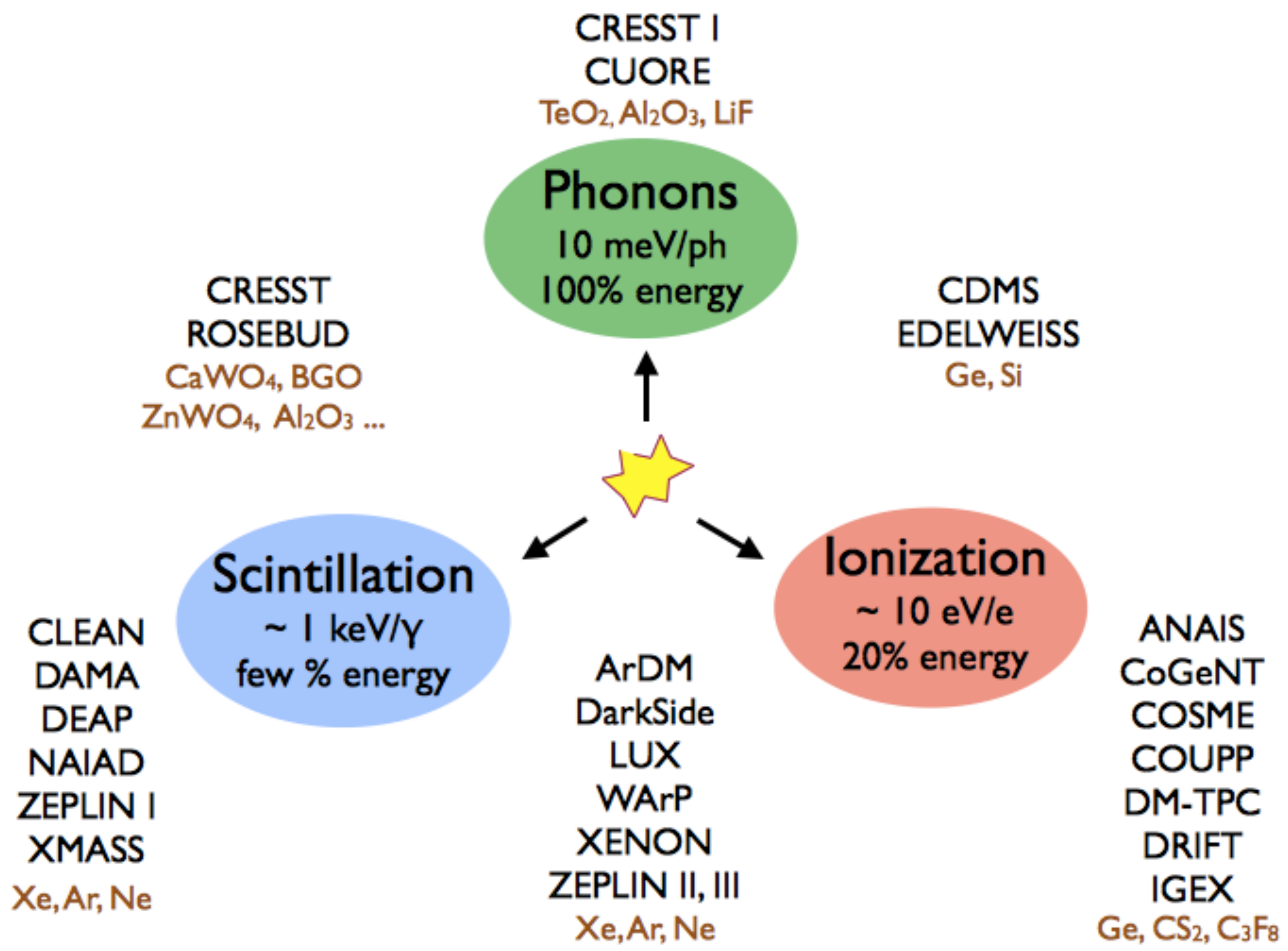
Credit: Felix Kahlhöfer



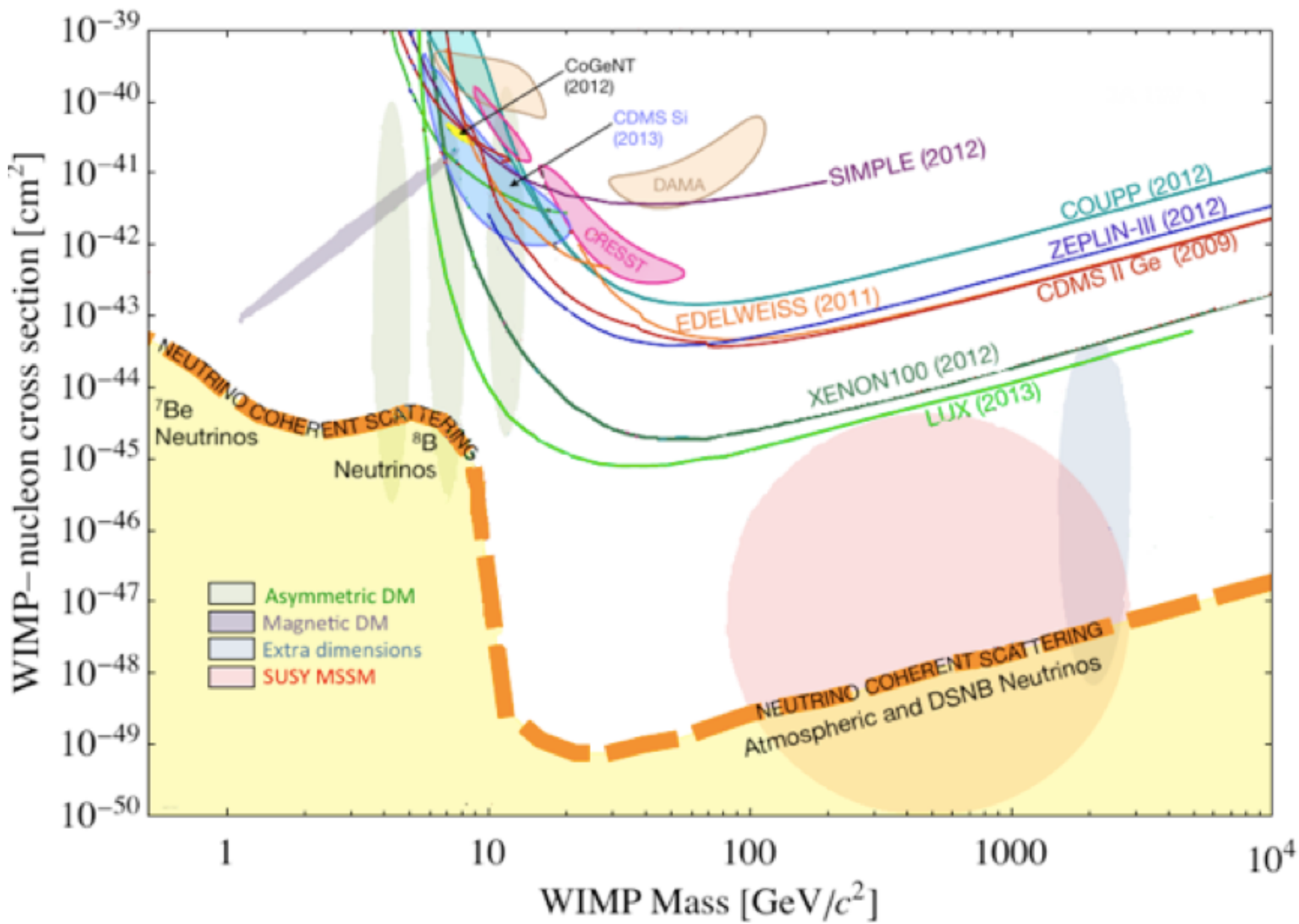
(a) A xenon target with $m_N = 131.3$ u. (b) A germanium target with $m_N = 72.6$ u.

Direct Detection: The Experiments

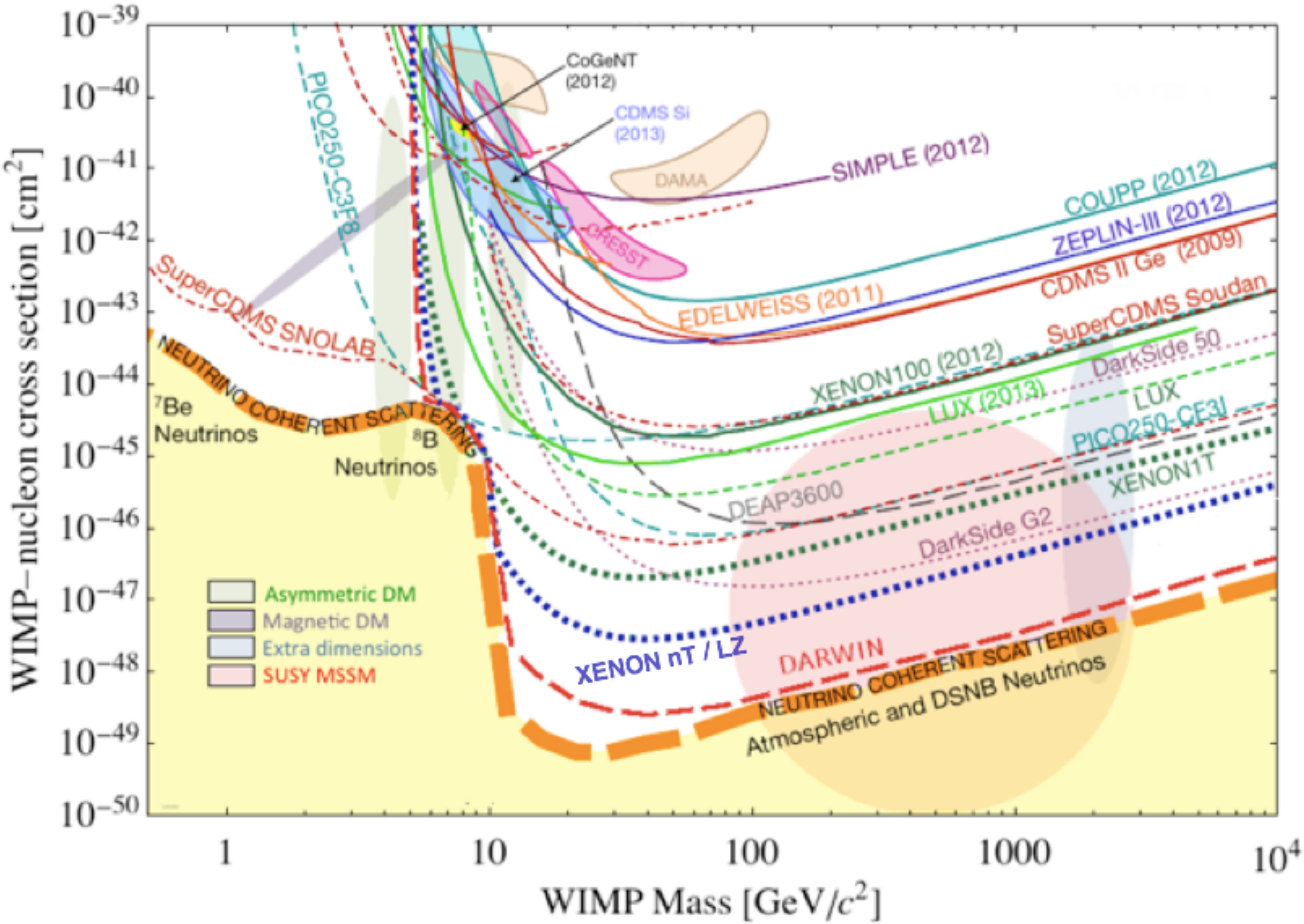
Credit: Enectali Figueroa-Feliciano



Direct Detection: Current status



Direct Detection: Future Prospects



SO FAR: ~3 YEARS/ORDER OF MAGNITUDE

Indirect Detection

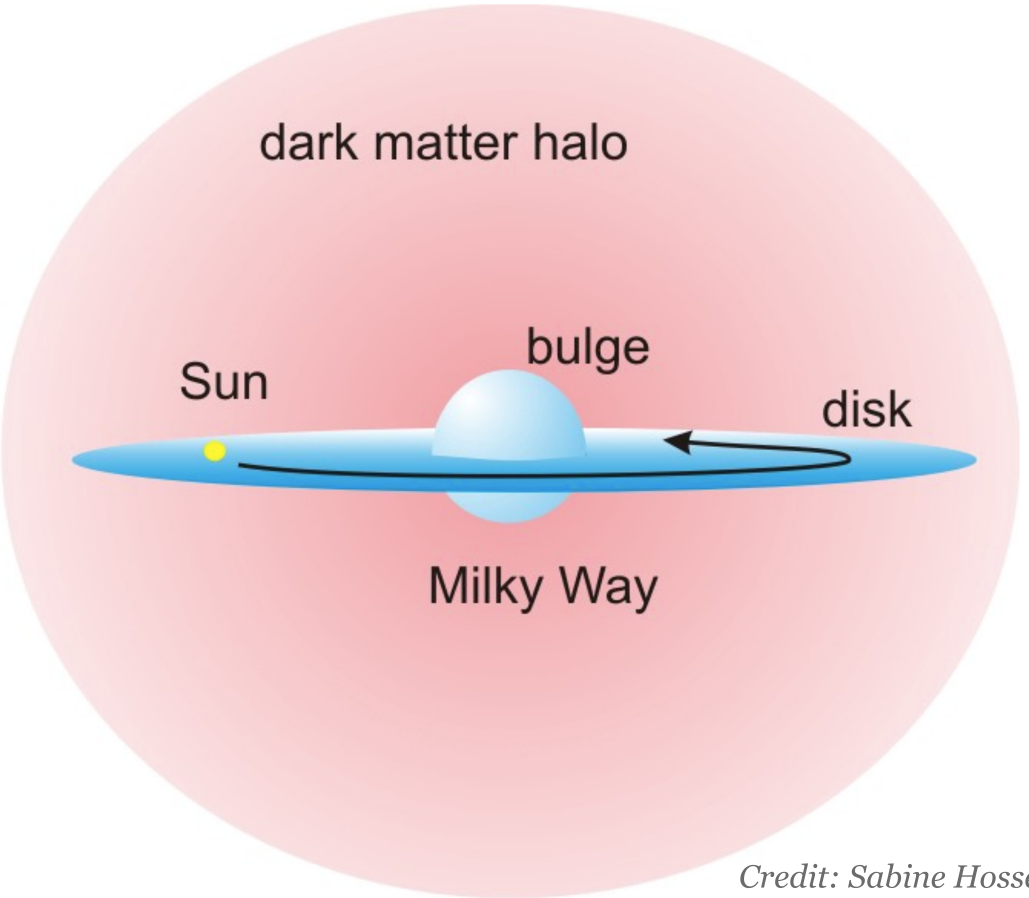
- Looking for SM states from DM annihilations
  - Sources:

Galactic centre/halo

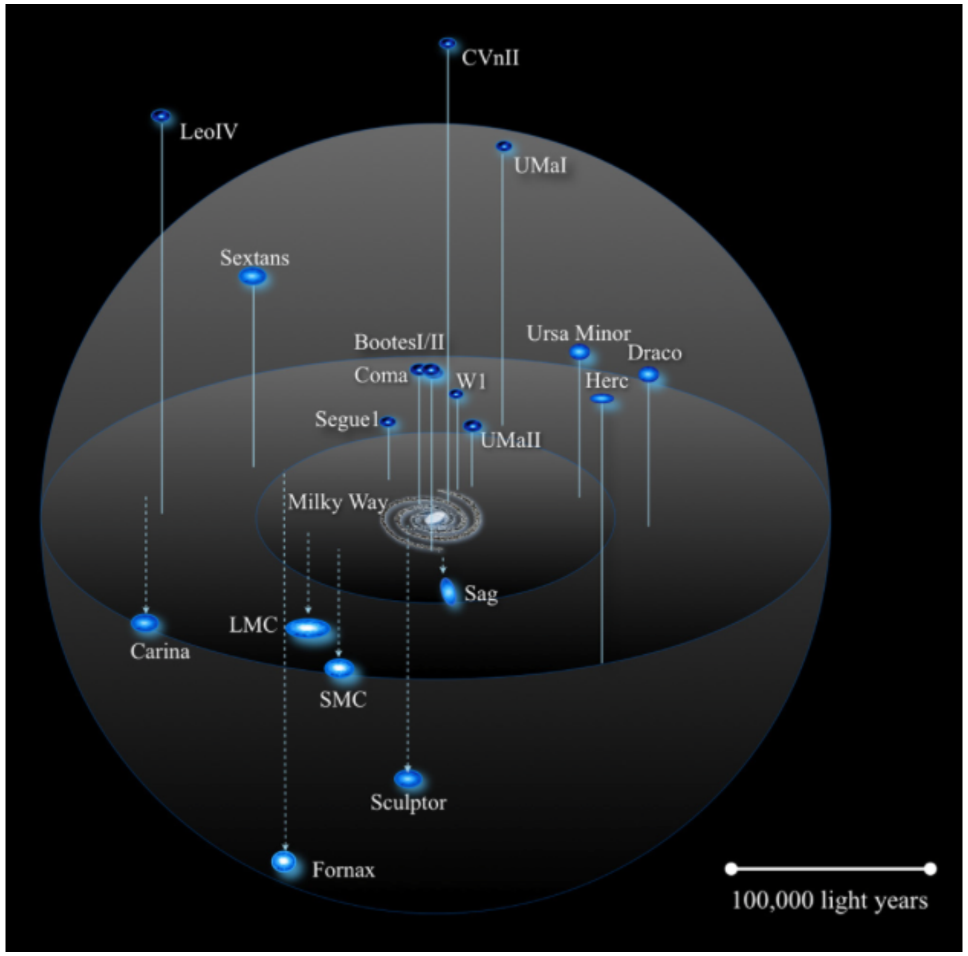
Dwarf Spheroidal galaxies

The Sun The Earth

Credit: J. Bullock, M. Geha, R. Powell

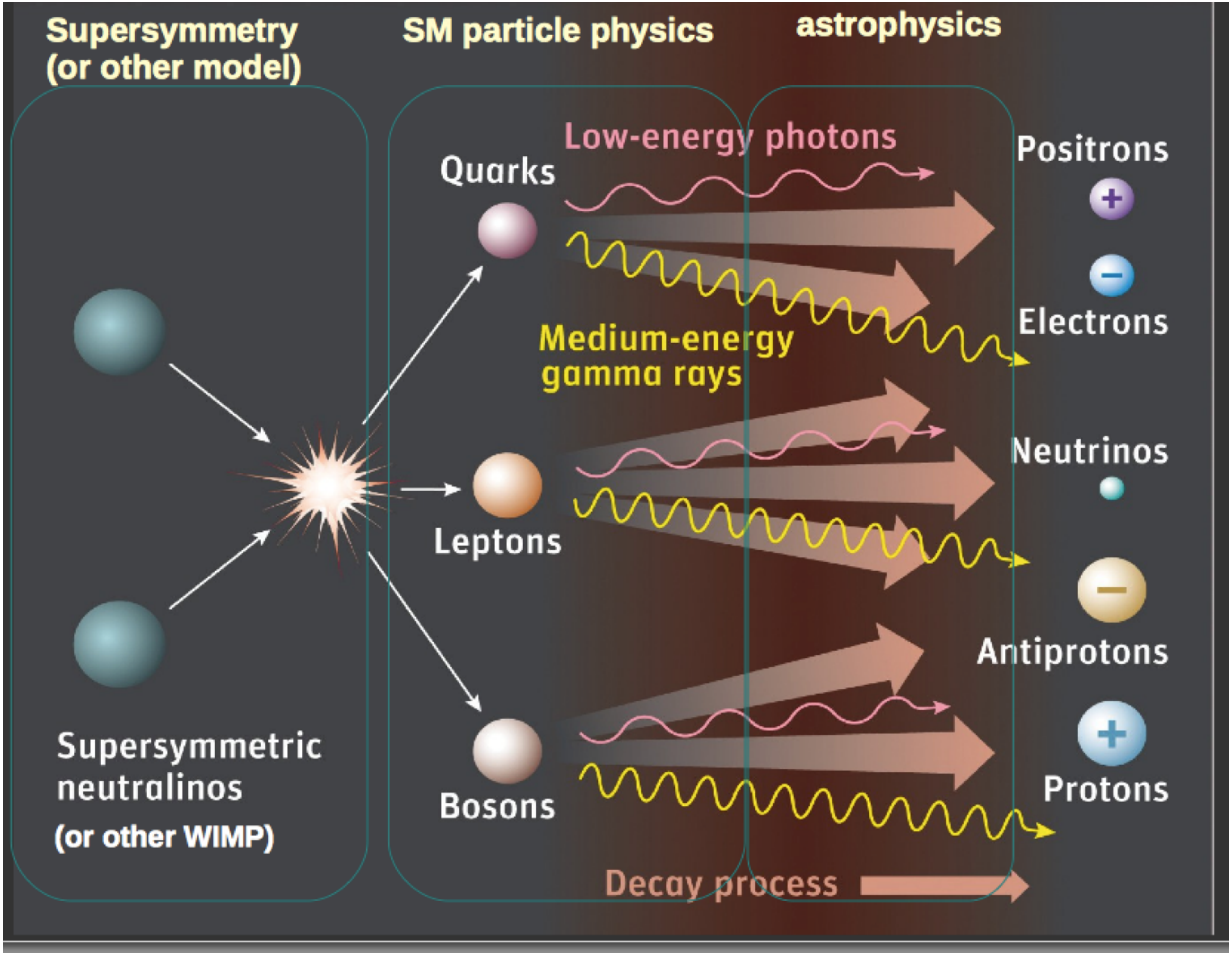


Credit: Sabine Hossenfelder



Indirect Detection

Credit: Carlos de los Heros



Indirect Detection

- Indirect dark matter searches through three 'signatures':

1) $\gamma - \mathrm{rays}$ 2) $e^+, e^-, \bar{p}, p$ 3) ν

- Detectors:

1) $\gamma - \mathrm{rays}$ Cherenkov Telescopes (Earth's Surface) and Satellites

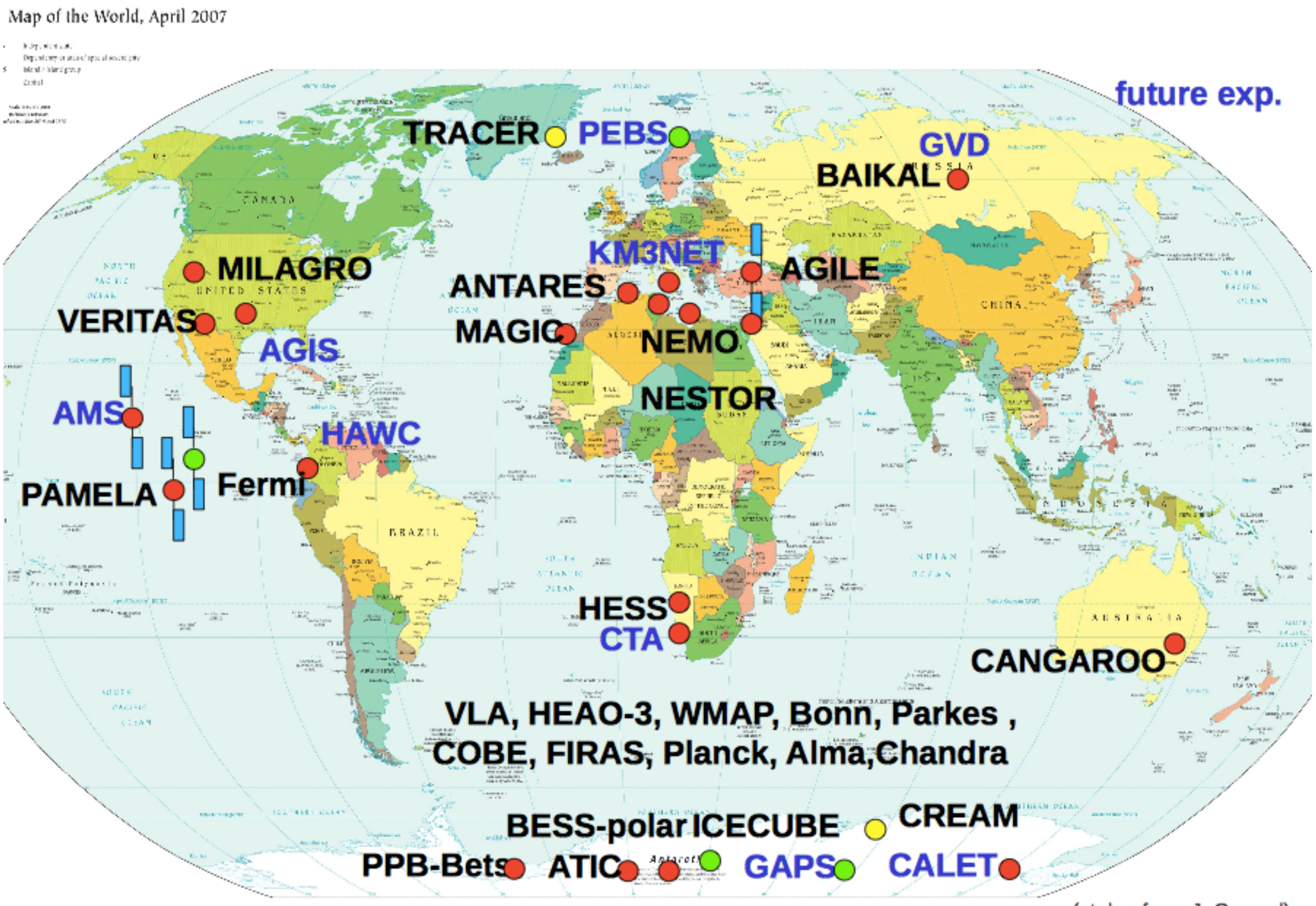
   e.g. HESS, MAGIC, VERITAS… e.g. FERMI-LAT, INTEGRAL, …

2) $e^+, e^-, \bar{p}, p$ Satellites e.g. PAMELA, AMS, …

3) ν Neutrino telescopes (underground/water/ice)

   e.g. ICECUBE, …

Indirect Detection



(stolen from J. Conrad)

Indirect Detection

- Features of a Gamma ray spectrum

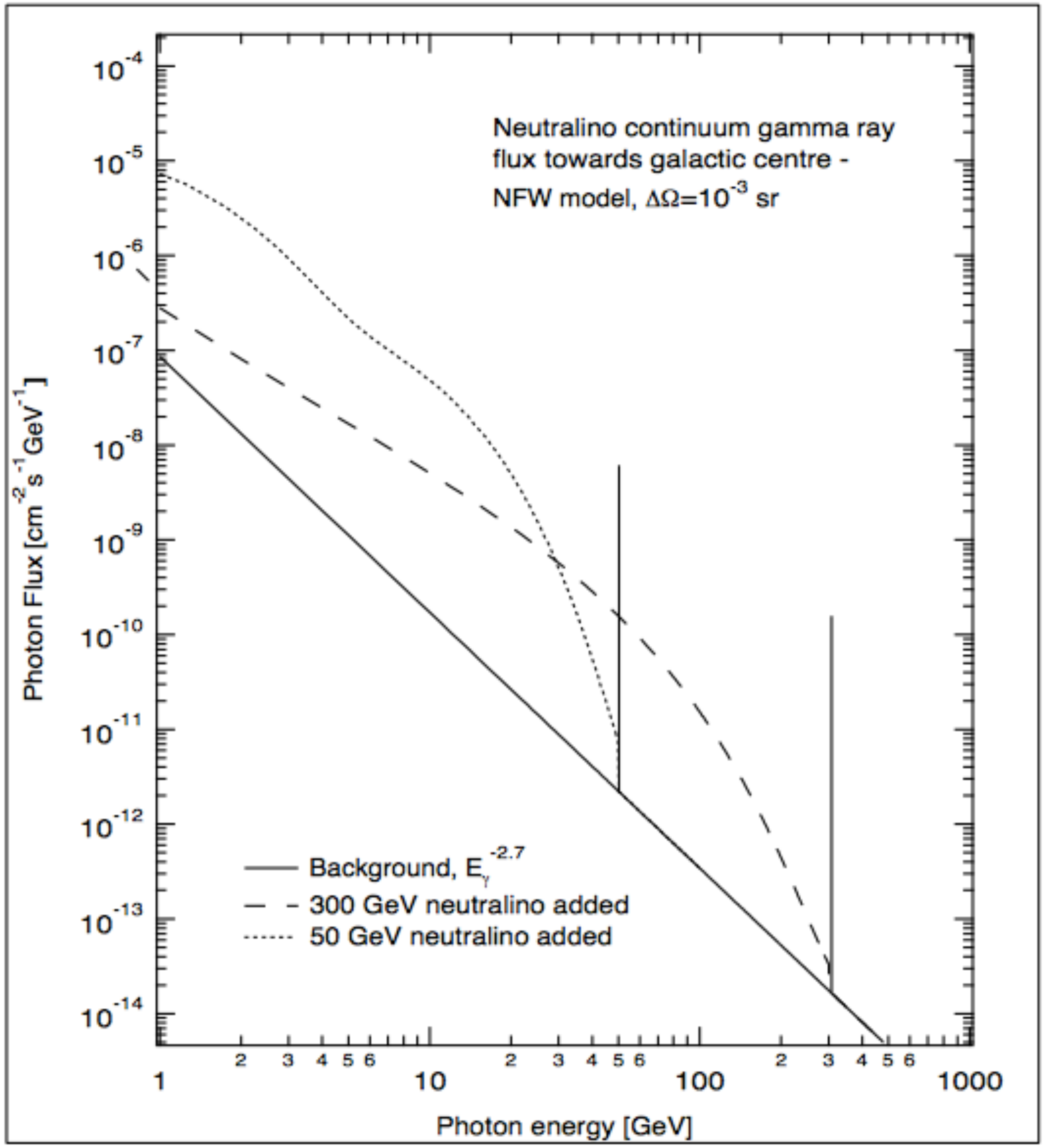
Bergström, Ullio, Buckley '98

Continuous spectrum -

Large rate but at lower energies difficult to see above background

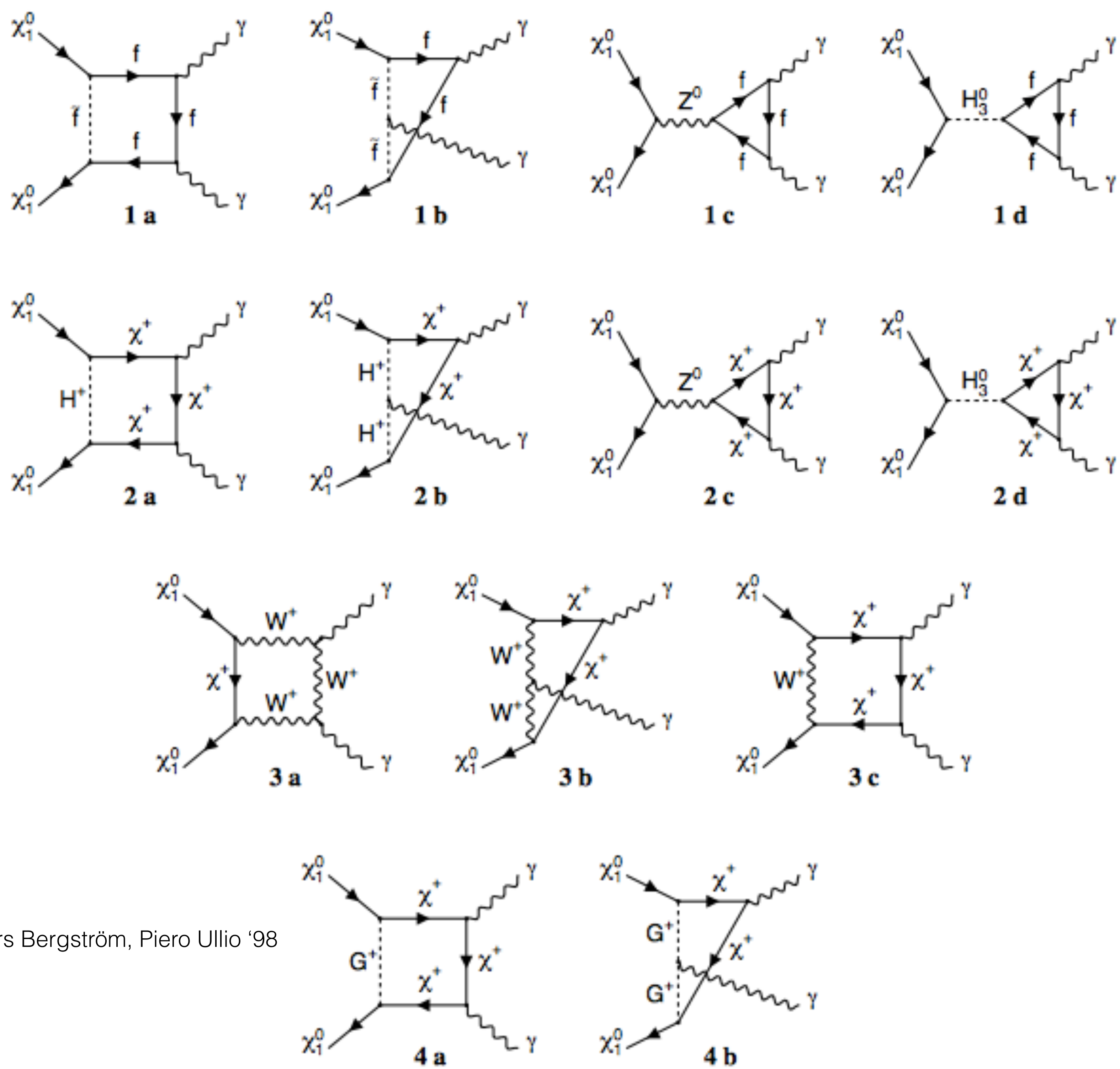
Mono-energetic gamma ray lines -

Often small rate but at highest energy ; "smoking gun"



Indirect Detection

- Loop induced annihilation to photons



Lars Bergström, Piero Ullio '98

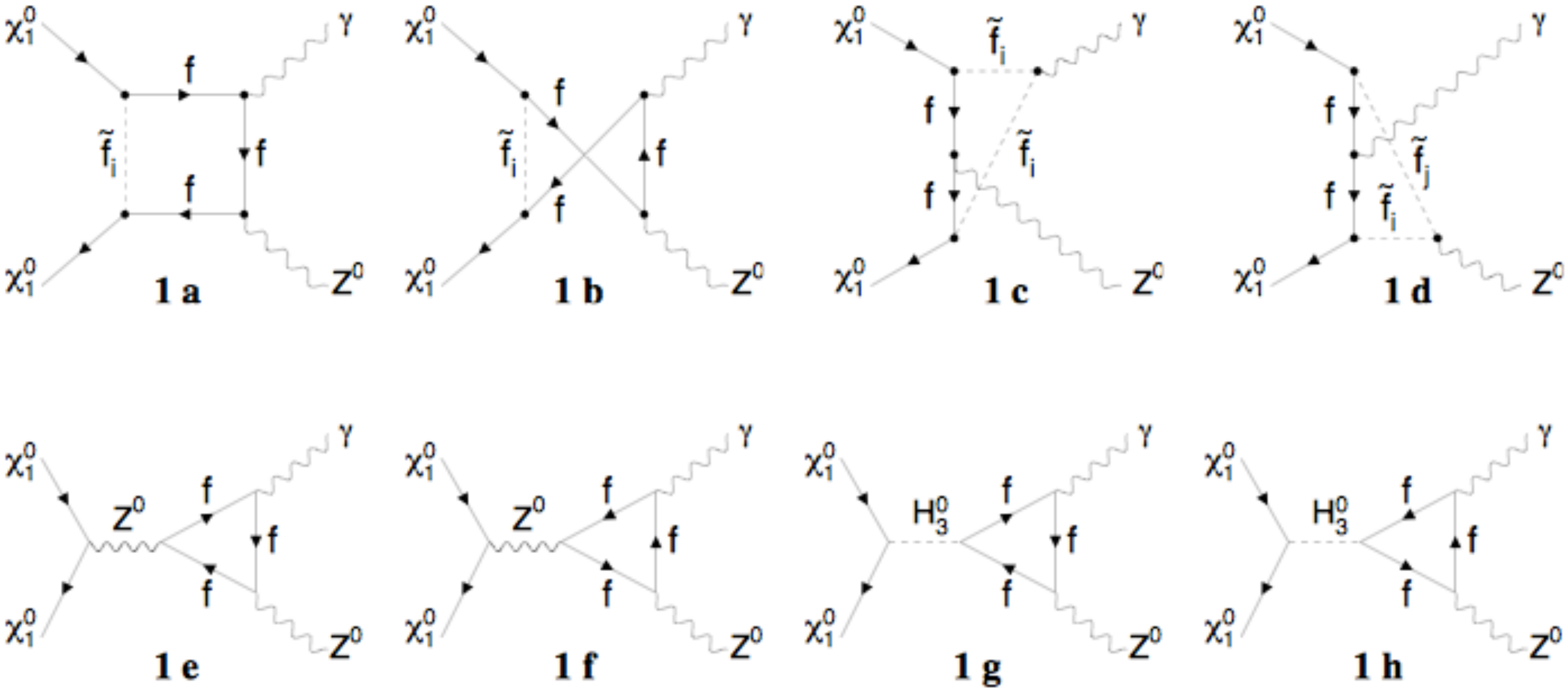
Non-relativistic annihilation

$$\frac{v_{\rm dm}}{c} \sim 10^{-3}$$

$$\Rightarrow \quad E_\gamma \approx m_{\rm dm}$$

Produces a line in gamma ray spectrum

Indirect Detection



$+\ldots$

Lars Bergström, Piero Ullio '98

Annihilation to $Z^0 + \gamma$
also generates gamma ray line
with energy

$$E_\gamma \approx m_{\rm dm}\left(1 - \frac{m_z^2}{4\, m_{\rm dm}^2}\right)$$

Indirect Detection

- Rates for indirect detection of SM species $j = \gamma, e^+, e^-, \bar{p}, p, \nu$

Particle Physics

Astro part

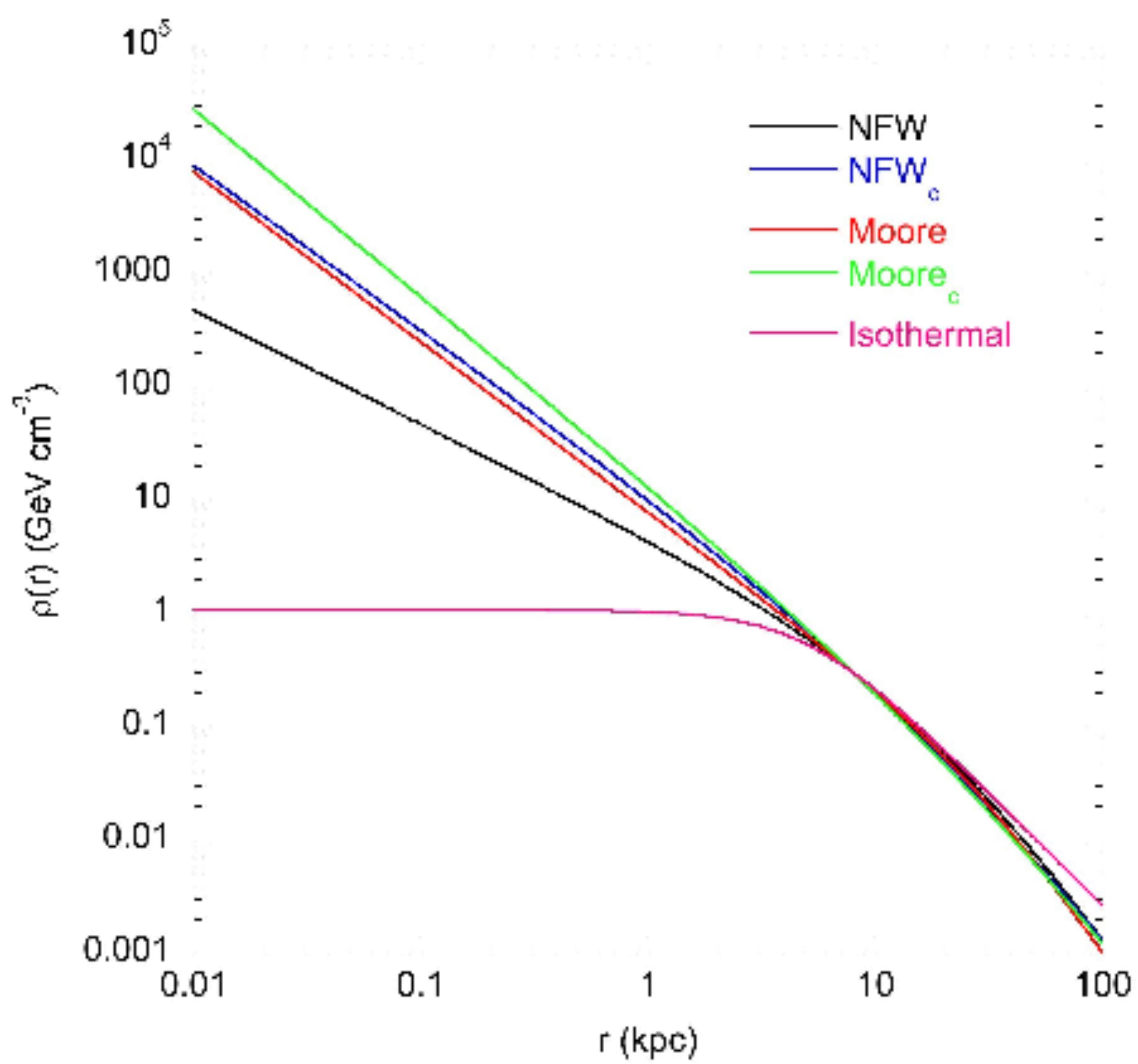
$$\frac{d\phi(\Delta\Omega, E_j)}{dE_j} = \frac{\langle \sigma v \rangle}{2m_{\rm dm}^2}\frac{dN_j}{dE_j} J(\Delta\Omega)$$

$$J(\Delta\Omega) = \frac{1}{4\pi}\int_{\Delta\Omega}\int_{\rm l.o.s.} \rho_{\rm dm}^2(\mathbf{r})\, dl\, d\Omega'$$ .... Line-of-sight (l.o.s.) integral through DM distribution integrated over a solid angle, ΔΩ.

$$\frac{dN_j}{dE_j}$$ .... Differential yield per annihilation

Indirect Detection

- Major uncertainties over dark matter density distribution - uncertainty appears in “J-factor”



$$\rho_{\text{Moore}}(r) = \frac{c}{r^{3/2}(a^{3/2} + r^{3/2})};$$

$$\rho_{\text{NFW}}(r) = \frac{c}{r(a+r)^2};$$

$$\rho_{\text{Burkert}}(r) = \frac{c}{(r+a)(a^2+r^2)};$$

$$+\ldots$$

Indirect Detection

- Uncertainties in the way SM final states propagate through the interstellar medium

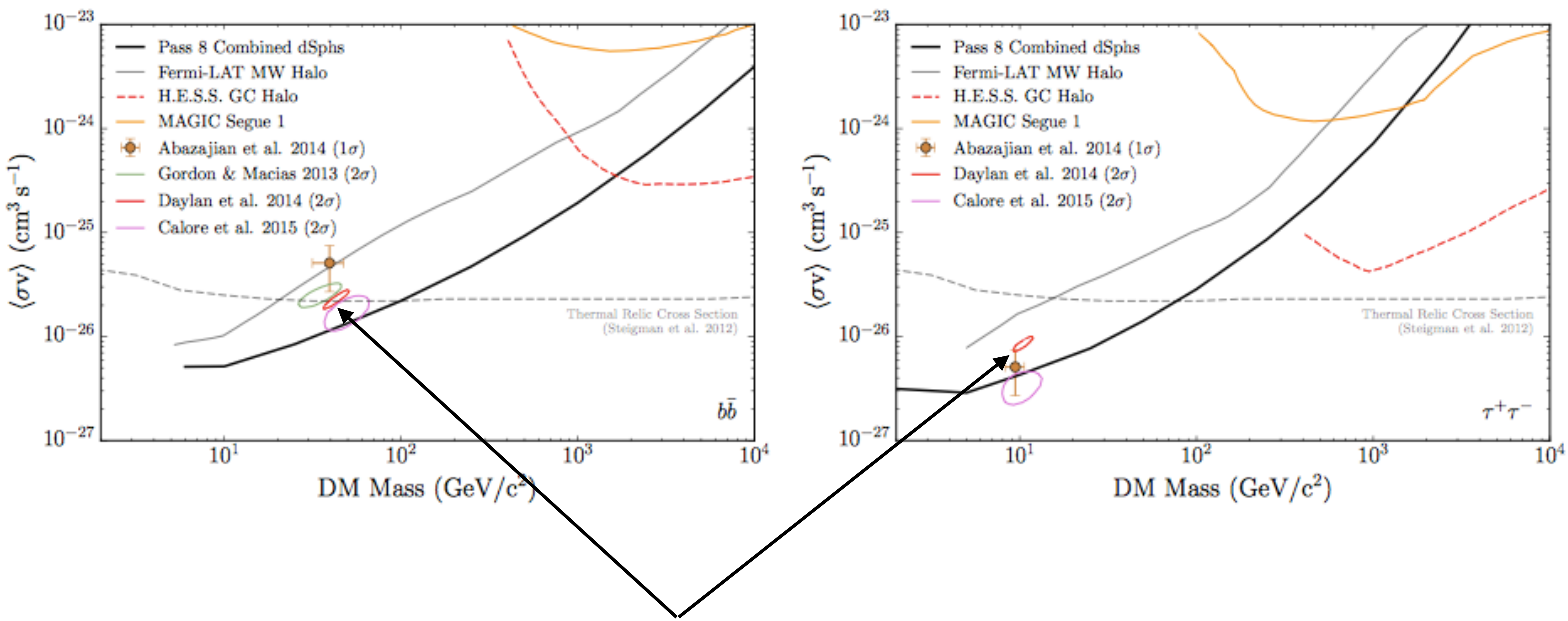
- Uncertainties in what we predict for the annihilation cross sections

- Large and uncertain backgrounds - E.g. Pulsars

Indirect Detection

- Gamma ray limits: dSphs excellent place to look - good mass to light ratio

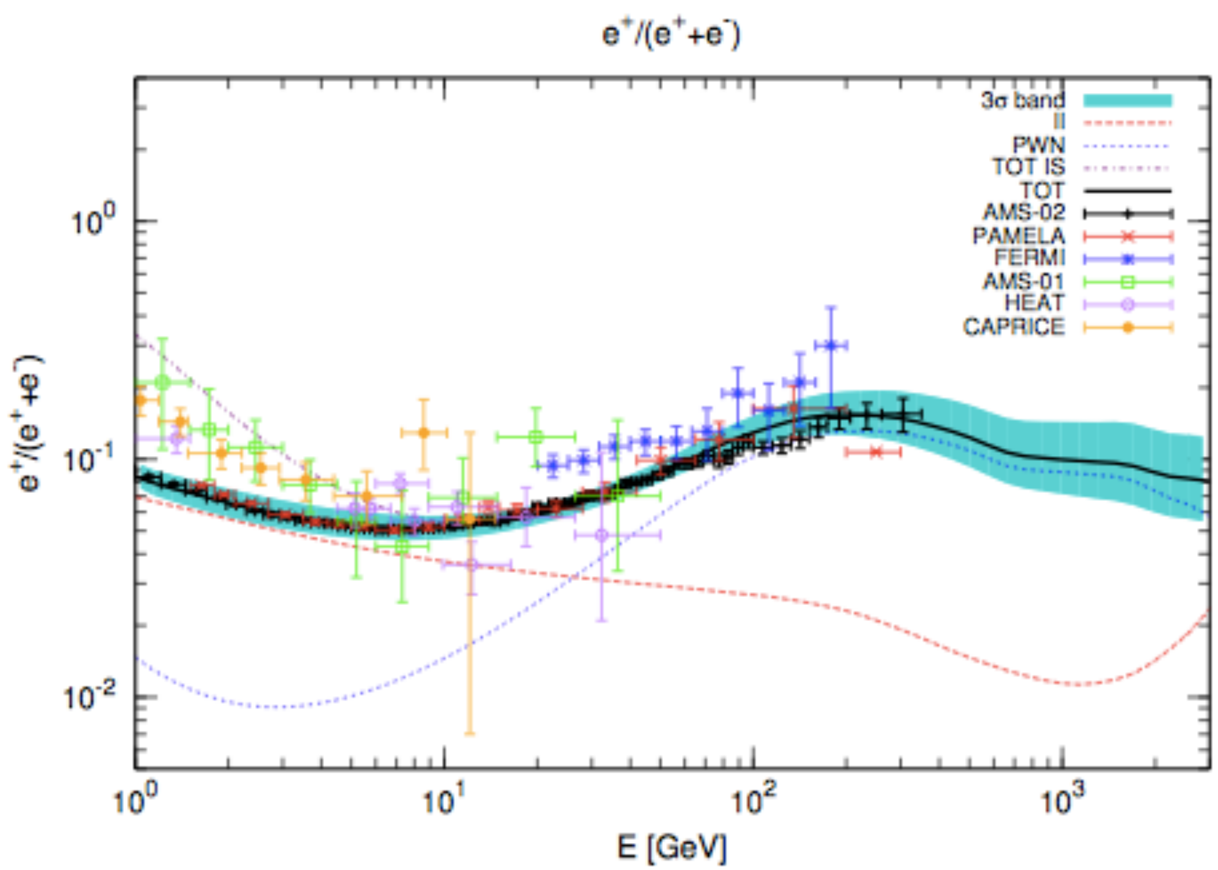
Fermi 2015

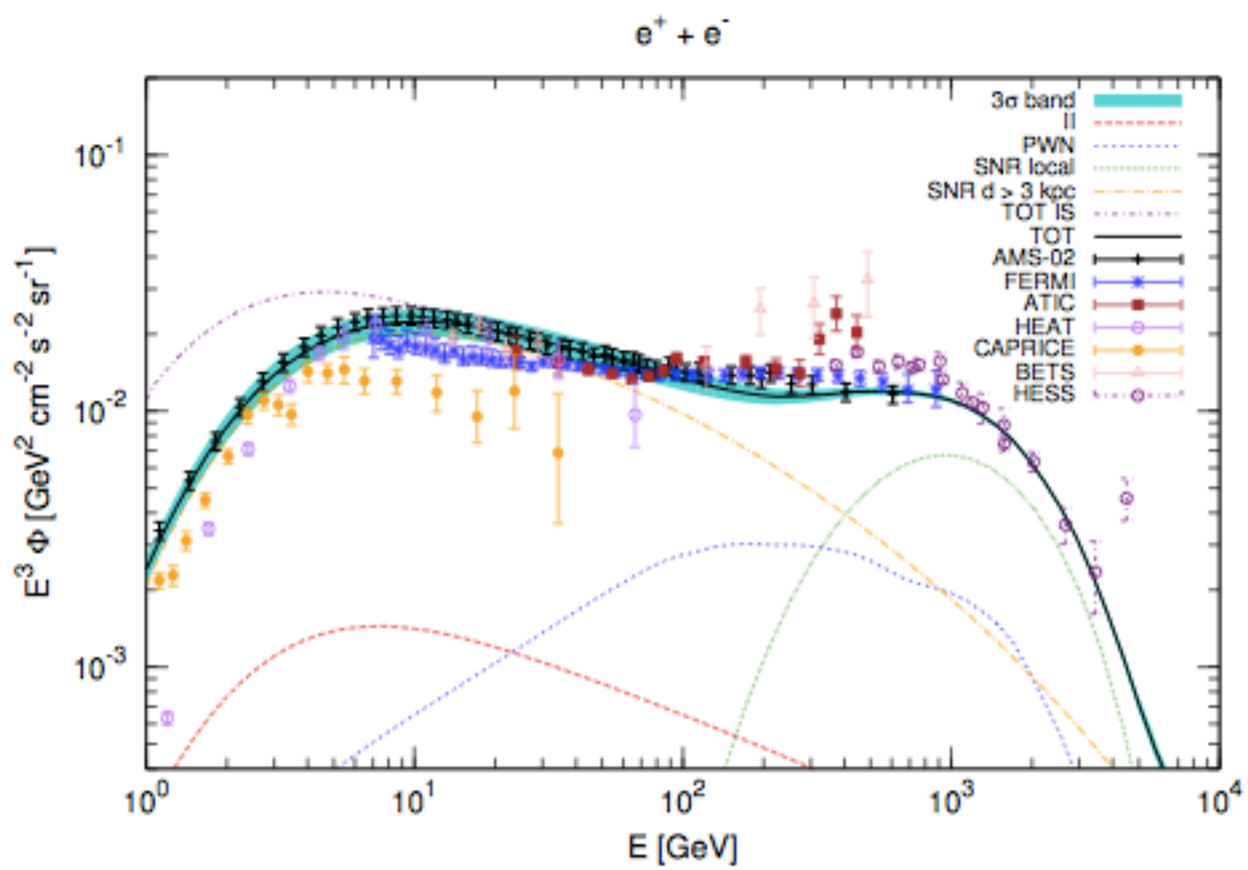


Galactic center excess best fit …T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden,
S. K. N. Portillo (2014) and others

Indirect Detection

- Measurements of cosmic rays - increasing positron fraction…
- Conventional picture: Positrons produced in local collisions of cosmic rays with interstellar medium - energy spectrum should decrease in region of interest



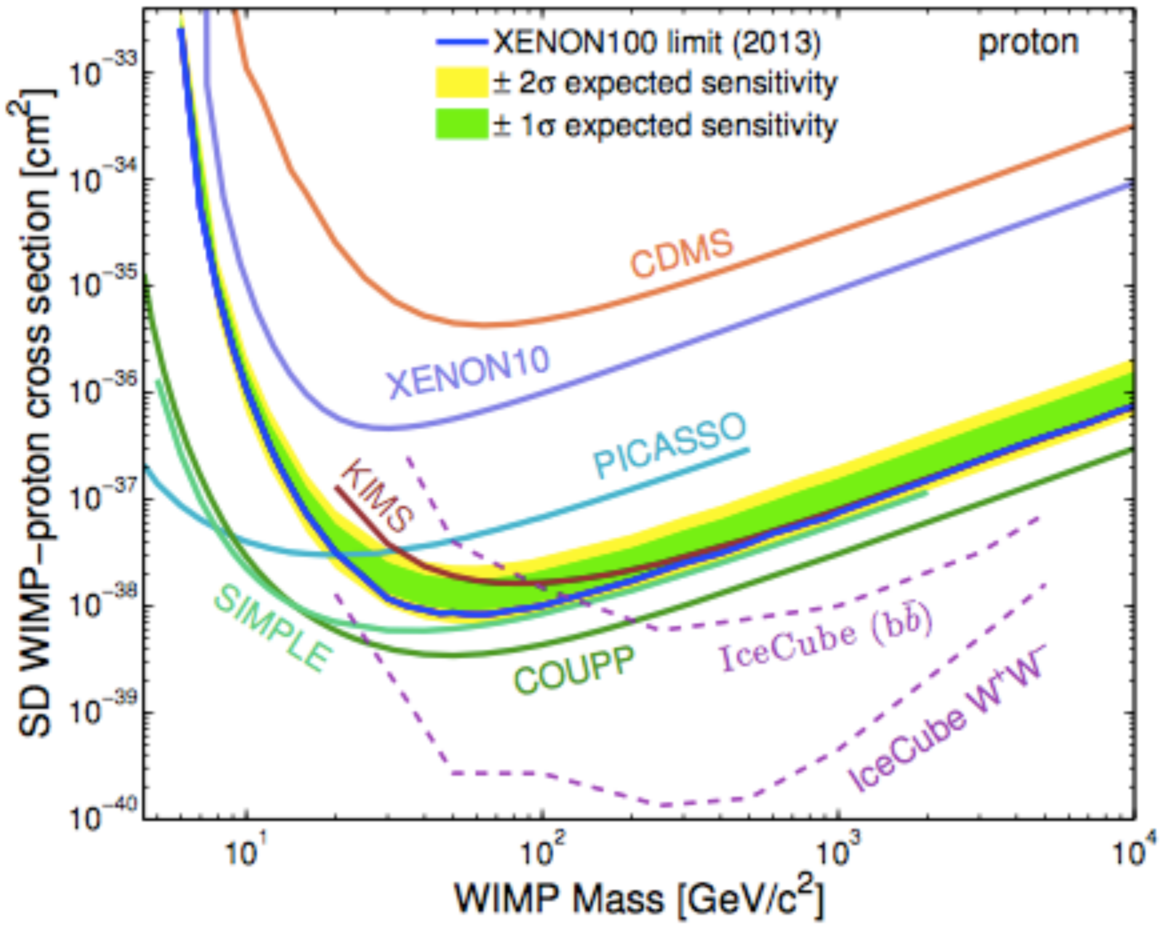


- Can potentially explain with Pulsars or other astro background - - but dark matter interpretation is intriguing but difficult with no excess found in anti-protons

Indirect Detection

- Using neutrinos to constrain DM elastic scattering
  - DM states collide with protons in the sun - get gravitationally captured
  - DM states in Sun can annihilate producing neutrinos - look for these

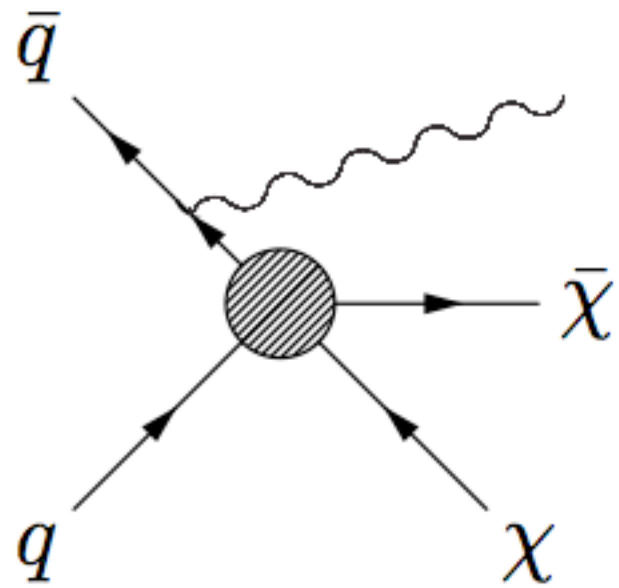
From Klasen, Pohlb, Sigl, (2015)



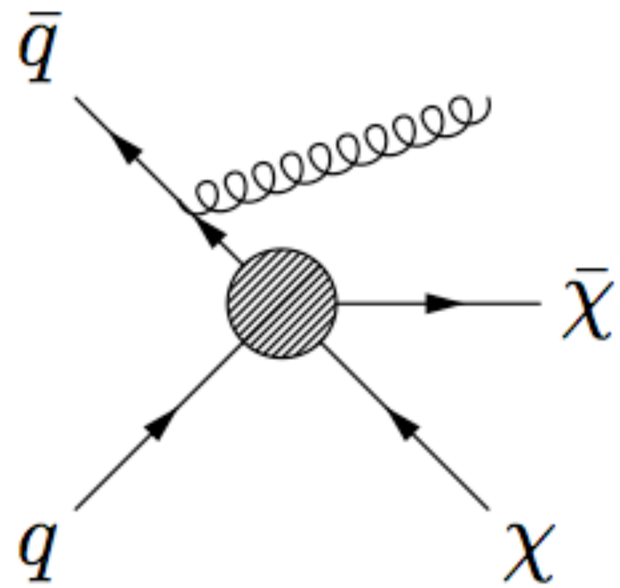
Depends on to what the DM annihilates

LHC Searches

- Look for processes of the type:



Monophoton + MET



Monojet + MET

- Searches now in many channels of the form “mono-x” plus missing

- Excellent complimentary search strategy - more from Mads later in the week

Summary so far...

- Evidence points towards a missing mass component of the Universe which is dark

- Most studied candidate is the WIMP produced via freeze-out

- Many candidate WIMPS: SUSY LSP, ED LKP, anything with weak couplings and electroweak scala mass

- Can probe WIMPs in a number of ways

    - Directly in labs - looking for DM scattering of SM nuclei

    - Indirectly - looking for SM final states in DM annihilations in astrophysical environments

    - In colliders - “looking” at direct production in collisions in association with some SM states

Summary so far…

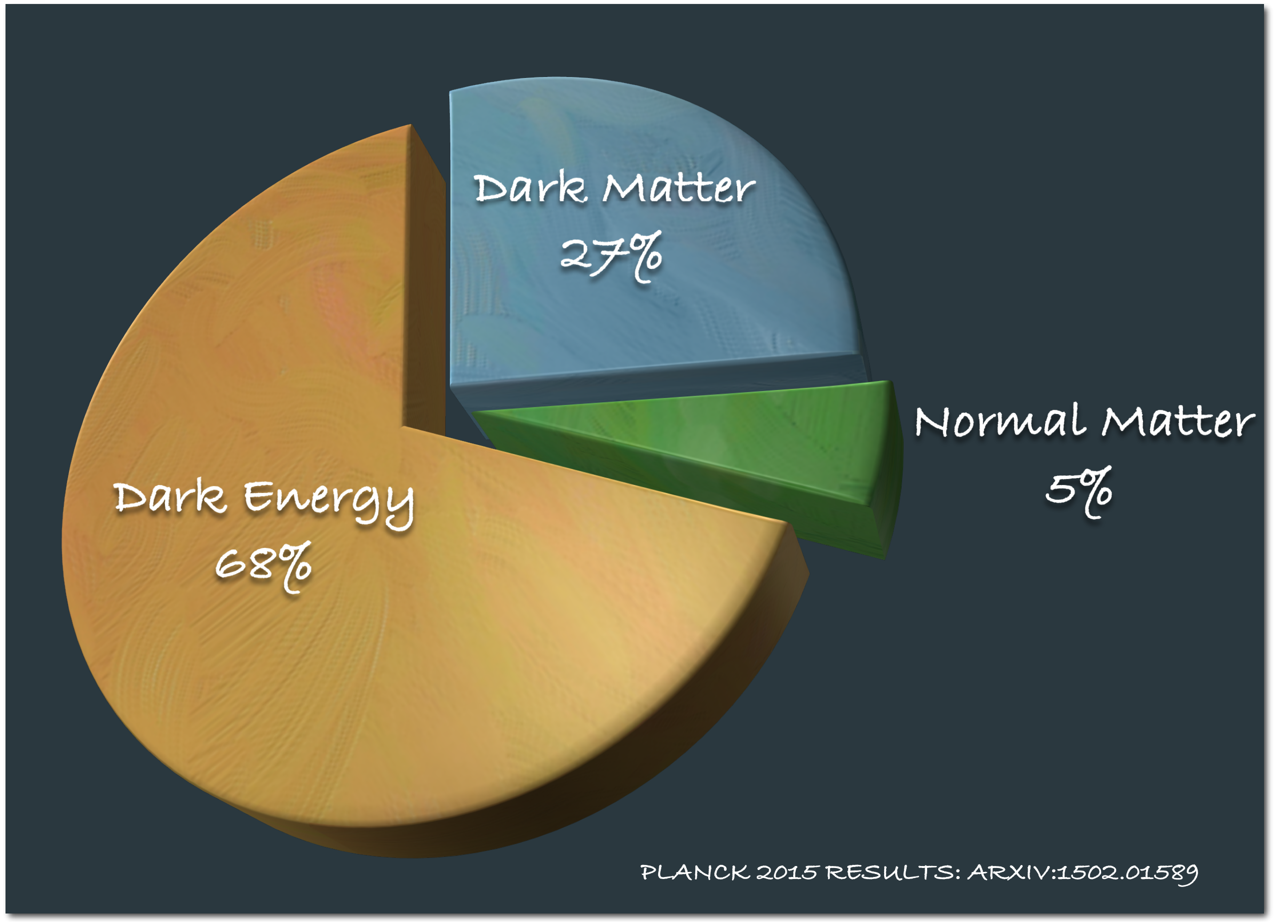
- So far no confirmed DM signal…
    - Maybe this simple picture is not correct - modifications and alternatives…

Alternatives to Standard Freeze-out

- So far we have described one particular class of DM model - there is a huge range of alternatives

- Asymmetric Dark matter
- Non-thermally produced states
- Strongly interacting dark matter - SIMPs
- WIMPless models
- WIMPzillas
- Superwimps
- Frozen-in dark matter - FIMPs
- Axions or axion like particles - misalignment mechanism
- WIMPonium
- Self-interacting dark matter
- Nuclear Dark matter
- + many many more…

Motivation for Asymmetric DM



$$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim 5$$

- Standard picture:

$\Omega_{\rm dm}$ WIMP freeze-out - set when $\Gamma_{\rm ann} \lesssim H$

$\Omega_{\rm B}$ Set by CP-violating, baryon number violating out of equilibrium processes.

- Given the physics generating each quantity, ratio is a surprise
- If not a coincidence - need to explain the closeness

$\Rightarrow$ Asymmetric Dark Matter

ADM Basics

$$\eta_{\rm dm} = n_{\rm dm} - n_{\overline{\rm dm}} \neq 0$$

or

$$\eta_{\rm B} = n_{\rm B} - n_{\overline{\rm B}} \neq 0$$

or both

- Relate this DM asymmetry to the baryon asymmetry (or vice versa)
- Leading to: $n_{\rm dm} - n_{\overline{\rm dm}} \propto n_{\rm B} - n_{\overline{\rm B}} \Rightarrow \eta_{\rm dm} = C\eta_{\rm B}$

$$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim \frac{(n_{\rm dm} + n_{\overline{\rm dm}})m_{\rm dm}}{(n_{\rm B} + n_{\overline{\rm B}})m_{\rm B}}$$

ADM Basics

$$\eta_{\rm dm} = n_{\rm dm} - n_{\overline{\rm dm}} \neq 0$$

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- Leading to: $n_{\rm dm} - n_{\overline{\rm dm}} \propto n_{\rm B} - n_{\overline{\rm B}} \Rightarrow \eta_{\rm dm} = C\eta_{\rm B}$

$$n_{\rm dm} \gg n_{\overline{\rm dm}}$$

$$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim \frac{(n_{\rm dm} + n_{\overline{\rm dm}})m_{\rm dm}}{(n_{\rm B} + n_{\overline{\rm B}})m_{\rm B}} \sim \frac{(n_{\rm dm} - n_{\overline{\rm dm}})m_{\rm dm}}{(n_{\rm B} - n_{\overline{\rm B}})m_{\rm B}}$$

ADM Basics

$$\eta_{\rm dm} = n_{\rm dm} - n_{\overline{\rm dm}} \neq 0$$

or

$$\eta_{\rm B} = n_{\rm B} - n_{\overline{\rm B}} \neq 0$$

or both

- Relate this DM asymmetry to the baryon asymmetry (or vice versa)
- Leading to:

$$n_{\rm dm} - n_{\overline{\rm dm}} \propto n_{\rm B} - n_{\overline{\rm B}} \Rightarrow \eta_{\rm dm} = C\eta_{\rm B}$$

$$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim \frac{(n_{\rm dm} - n_{\overline{\rm dm}})m_{\rm dm}}{(n_{\rm B} - n_{\overline{\rm B}})m_{\rm B}} \sim \frac{\eta_{\rm dm}}{\eta_{\rm B}} \frac{m_{\rm dm}}{m_{\rm B}}$$

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$$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim \frac{\eta_{\rm dm}}{\eta_{\rm B}}\frac{m_{\rm dm}}{m_{\rm B}} \sim C\frac{m_{\rm dm}}{m_{\rm B}}$$

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$$\eta_{\rm dm} = n_{\rm dm} - n_{\overline{\rm dm}} \neq 0$$

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$$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim \frac{\eta_{\rm dm}}{\eta_{\rm B}}\frac{m_{\rm dm}}{m_{\rm B}} \sim C\frac{m_{\rm dm}}{m_{\rm B}}$$

- Value of C is determined by how the asymmetries are shared between the two sectors

ADM Basics

- In many models, symmetries are introduced that link the baryon and dark matter sectors

- In the dark sector: $U(1)_X$
- In the SM sector: $U(1)_{B-L}$

- Require "sharing" operators that are in thermal equilibrium at $T > m_X$

$$\mathcal{L} \supset \frac{1}{M^{d-4}} \mathcal{O}_{\mathrm{B-L}} \mathcal{O}_X$$

Break symms to subgroup $U(1)_{B-L+X}$

- Operators transmit the asymmetry from one sector to another

- Drop out of thermal equilibrium leaving $U(1)_X$ and $U(1)_{B-L}$

- They can also lead to signals. e.g. at the LHC

ADM Basics

$$\frac{\Omega_{dm}}{\Omega_B} \sim \frac{\eta_{dm}}{\eta_B}\frac{m_{dm}}{m_B}$$

If $\eta_{\rm dm} \sim \eta_{\rm B}$

- Then we get a prediction for the mass of the dark matter

$$\boxed{m_{\rm dm} \sim 5 m_{\rm B} \sim 5 \text{ GeV}}$$

- This is the "natural" dark matter mass for ADM models.
- This is true if the sharing operator decouples before the DM becomes non-relativistic
- If not, then the relationship is more complicated

$\Rightarrow$ Can get different predictions for the DM mass

Heavy ADM

See e.g. Barr 91; Buckely, Randall '11

- Can have ADM with heavy masses
- Sharing processes only decouple after DM has become non-relativistic

$\Rightarrow$ Dark matter asymmetry gets Boltzmann suppressed

$$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \approx \frac{m_{\rm dm}}{m_{\rm B}} x^{3/2} e^{-x}$$

WITH $x = \dfrac{m_{\rm dm}}{T_d}$

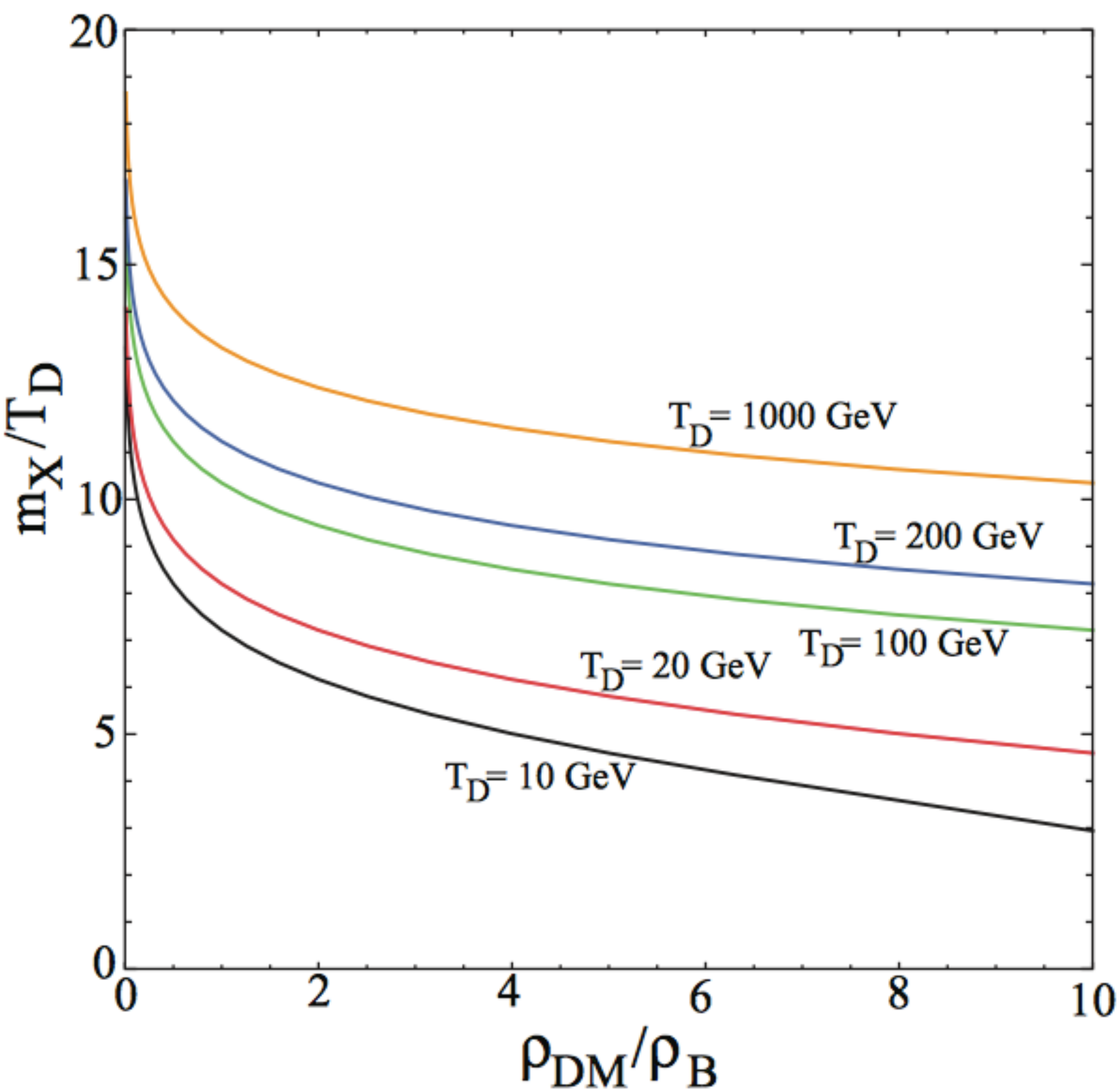
T_d Decoupling temp of X-number violating interactions

- Actual suppression is more complicated - see Barr '91

Heavy ADM

Buckley, Randall; (2010)

- Large range of possible masses



Asymmetric Freeze-out

Iminniyaz, Drees, Chen 2011;
Graesser, Shoemaker, Vecchi, 2011

- Already seen what happens in the standard freeze-out scenario, what happens if

$$n_{\rm dm} - n_{\overline{\rm dm}} \neq 0$$

- Assuming there is this asymmetry in the dark mater states, this changes details of freeze-out.

- Using again $\sigma v = a + b v^2 + \ldots$

$$Y_{\bar\chi}(x \to \infty) = \frac{C}{\exp\left[C(4\pi/\sqrt{90})\, m_\chi M_{\rm Pl}\, \sqrt{g_*}\, (a\ \bar{x}_F^{-1} + 3b\ \bar{x}_F^{-2})\right] - 1}$$

$$Y_{\chi}(x \to \infty) = \frac{C}{1 - \exp\left[-C(4\pi/\sqrt{90})\, m_\chi M_{\rm Pl}\, \sqrt{g_*}\, (a x_F^{-1} + 3b x_F^{-2})\right]}$$

- Here C is the asymmetry in dark matter number
- Take limit as $C \to 0$ we get back to the symmetric result $\Omega h^2 \approx \frac{1.04 \times 10^9}{M_{\rm pl}} \frac{x_f}{\sqrt{g_*}} \frac{1}{a + 3b/x_F}$

Asymmetric Freeze-out

Compare cases of symmetric and asymmetric freeze-out.

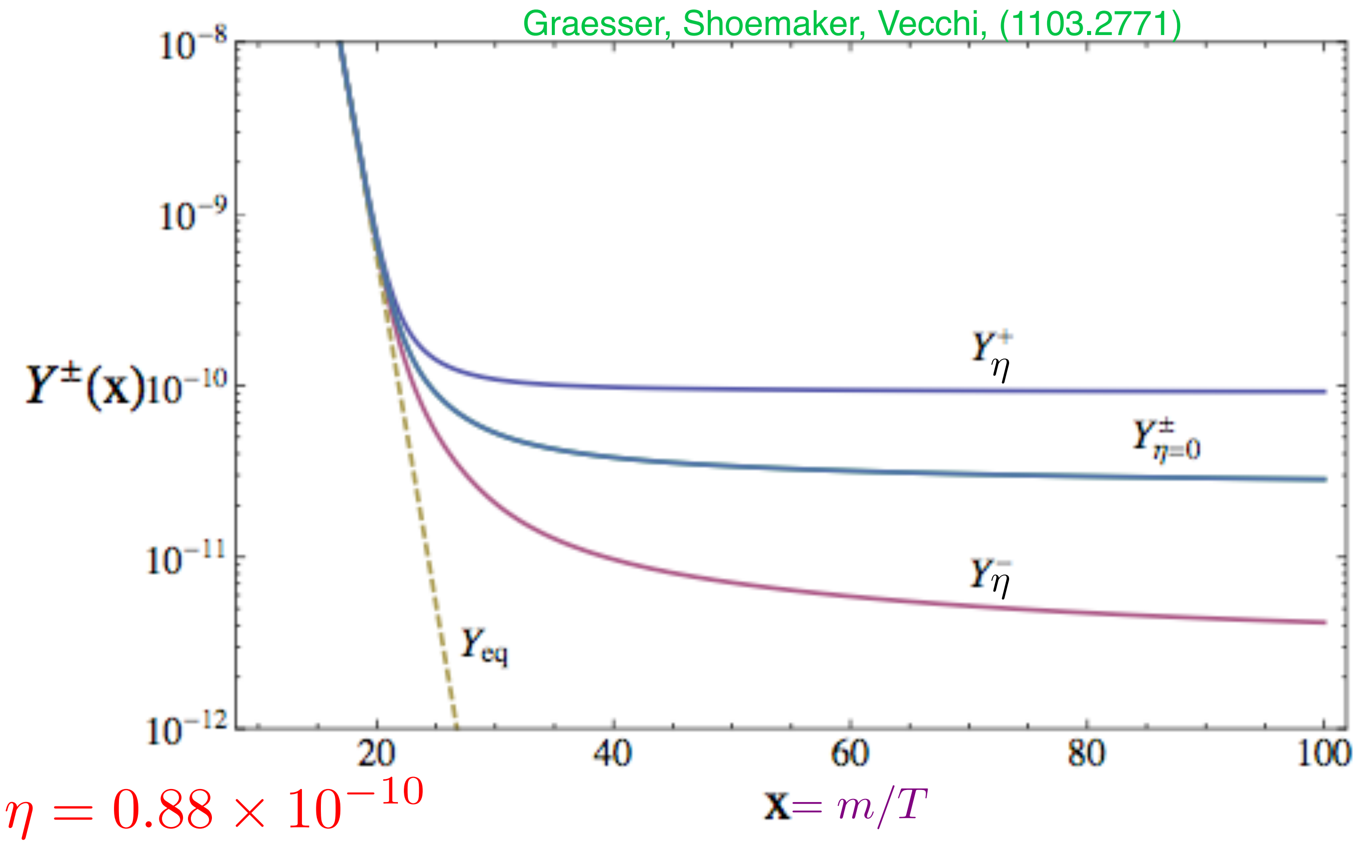
All lines are plotted for the same model parameters - same cross section and masses of dark matter states

η = asymmetry in DM

Y^{+} =Yield for DM states in asymmetric case

Y^{-} =Yield for anti-DM states in asymmetric case

$Y^{\pm}_{\eta=0}$ = Yield for DM and anti dm states in symmetric case



It is clear that this asymmetry can lead to a large difference in the final dark matter number density.

Need annihilation rate to be approx factor of 2-3 larger than for symmetric case

Probing ADM

- Indirect detection: In most models there is no indirect detection as there are no anti-DM for DM to annihilate with
    - Some more complicated models predict late time regeneration of a small amount of anti-dm through DM-AntiDM oscillations

- Direct detection is the same as for the symmetric case

- Limits from capture in stars are more constraining

- As annihilation cross-section for asymmetric freeze-out needs to be larger than the symmetric case, limits from the LHC and direct detection are more constraining

Quick ADM Summary

- Potential to explain ratio of DM to normal matter densities

- More sophisticated models can not only explain ratio but also generate the asymmetries in the first place - co-generating the DM and baryon asymmetries - one possible baryogenesis mechanism

Freeze-out Assumptions - Revisited

- Single species of dark matter
- Radiation dominated universe
- DM interactions with the SM states large enough to be in thermal equilibrium at $T > m_X$

Freeze-out Assumptions - Revisited

- Single species of dark matter

- Radiation dominated universe

- ~~DM interactions with the SM states large enough to be in thermal equilibrium at $T > m_X$~~

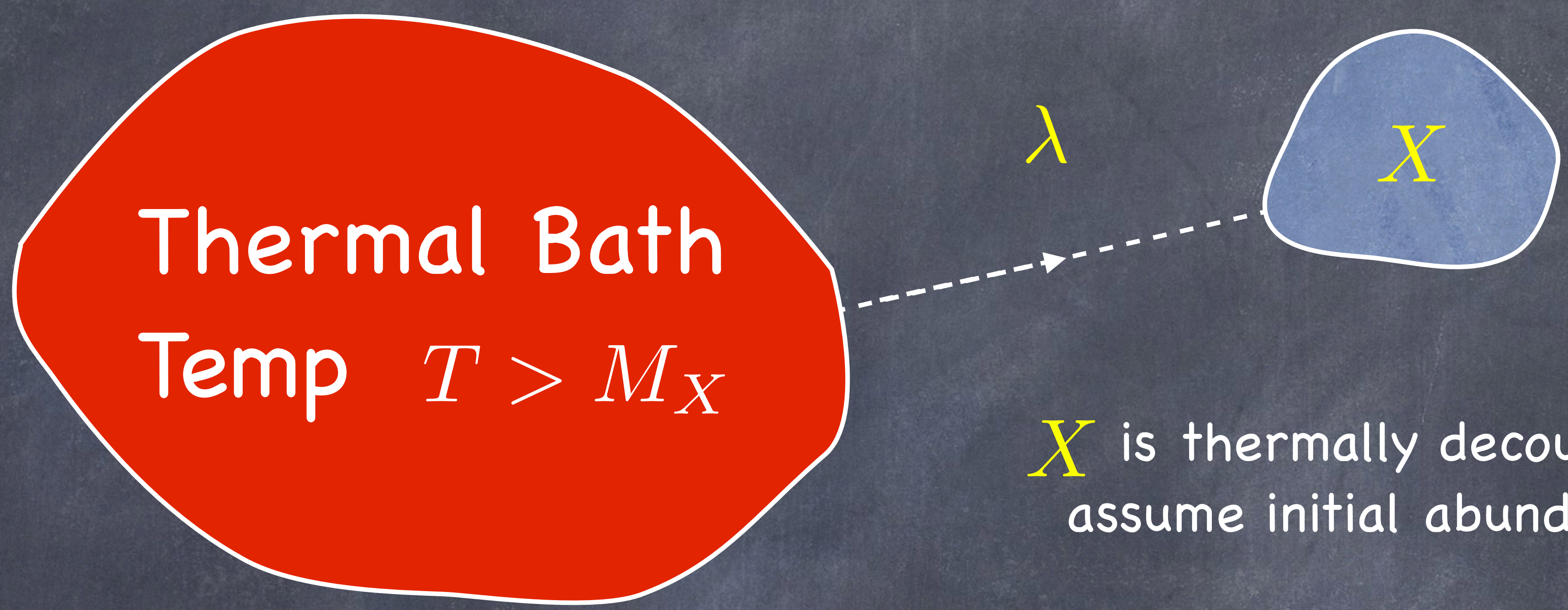
  - Assume now this is not the case…

$\Rightarrow$ Leads to the possibility of “Freeze-in”

Freeze-in overview

- Freeze-in is relevant for particles that are feebly coupled (Via renormalisable couplings) - λ

  Frozen Interacting Massive Particles (FIMPs) X



X is thermally decoupled and we assume initial abundance negligible

- Although interactions are feeble they lead to some X production
- Dominant production of X occurs at $T \sim M_X$ IR dominant
- Increasing the interaction strength increases the yield

opposite to Freeze-out...

Freeze-out vs Freeze-in

$$Y_{FO} \sim \frac{1}{\langle \sigma v \rangle \, M_{Pl} \, m'}$$

Using $\langle \sigma v \rangle \sim \lambda'^2 / m'^2$

$$Y_{FO} \sim \frac{1}{\lambda'^2} \left(\frac{m'}{M_{Pl}} \right)$$

Freeze-in via, decays, inverse decays or 2-2 scattering

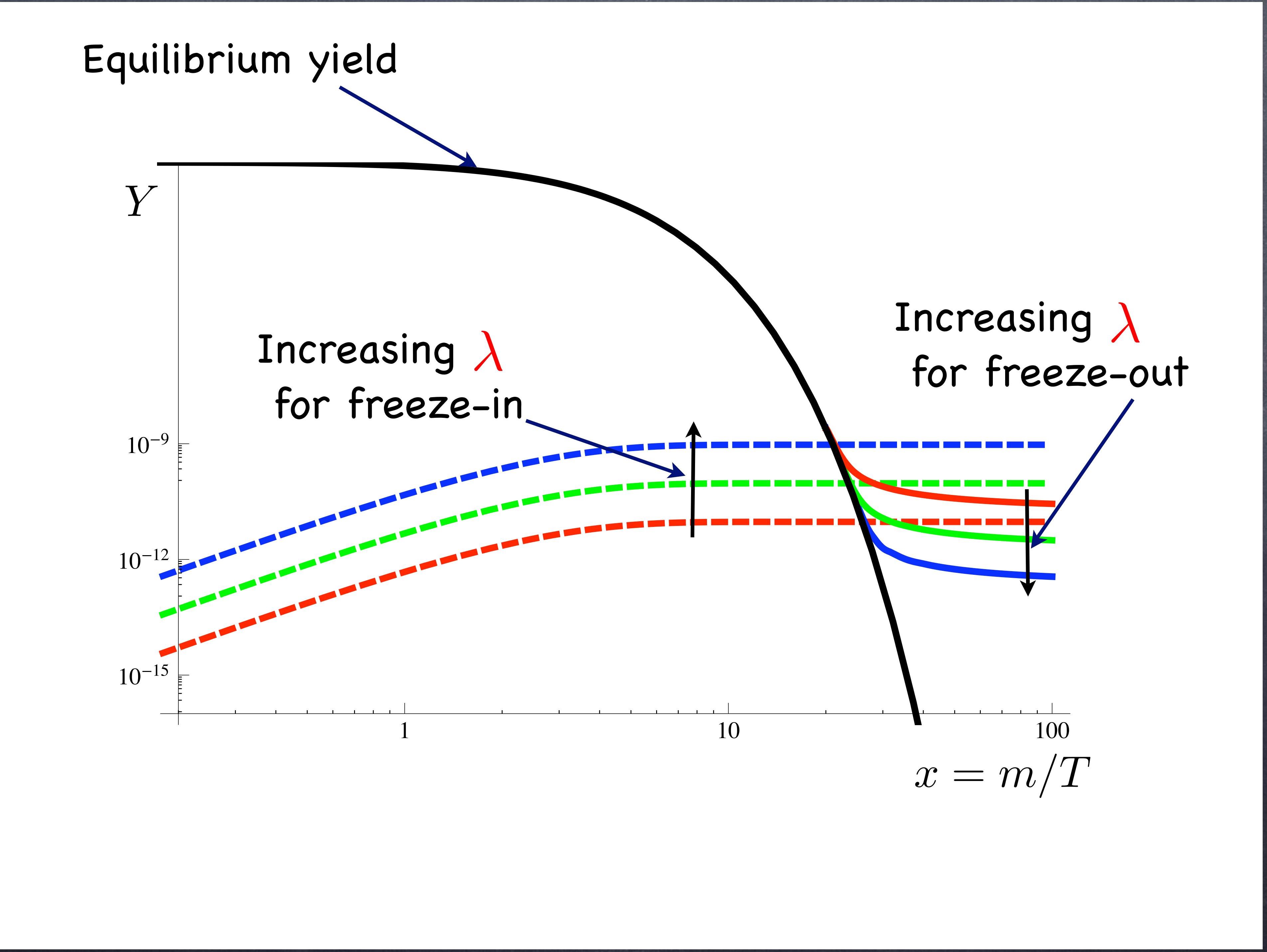
Coupling strength λ

m mass of heaviest particle in interaction

$$Y_{FI} \sim \lambda^2 \left(\frac{M_{Pl}}{m} \right)$$

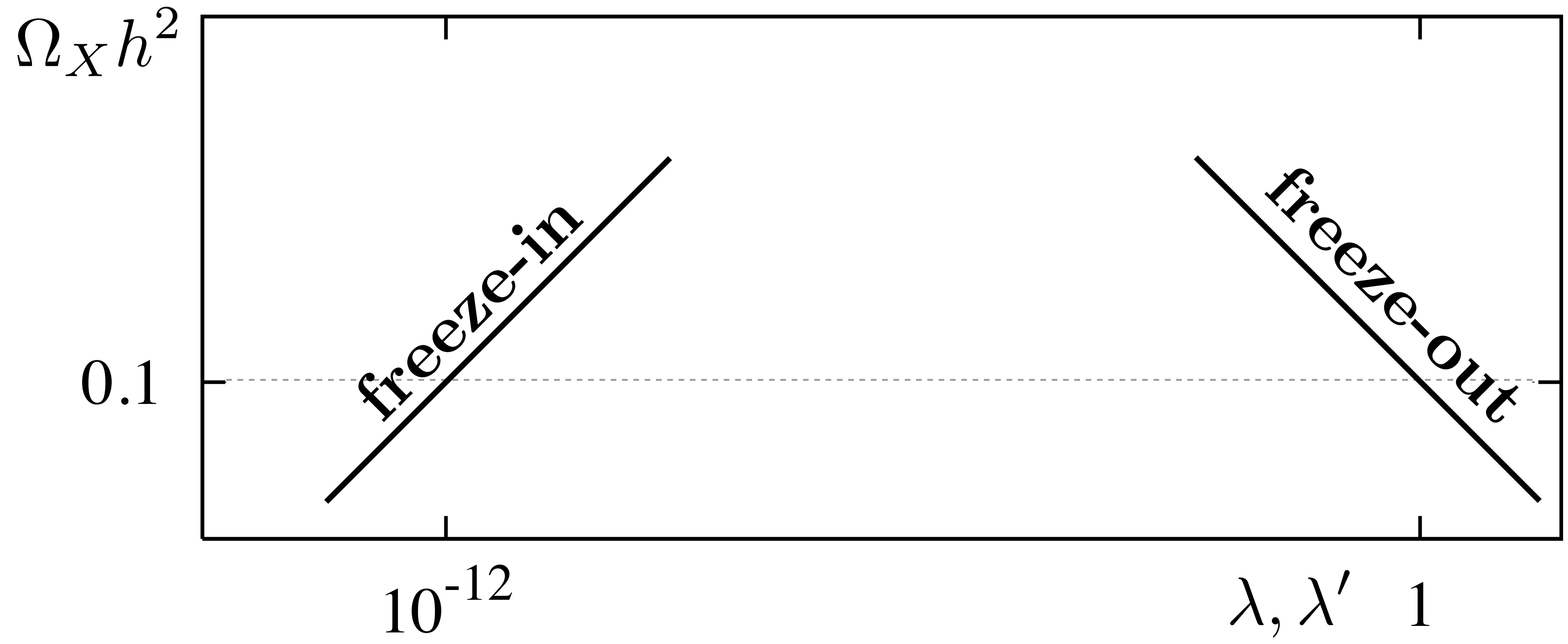
Freeze-in vs Freeze-out

- As T drops below mass of relevant particle, DM abundance is heading towards (freeze-in) or away from (freeze-out) thermal equilibrium



Freeze-in vs Freeze-out

- For a TeV scale mass particle we have the following picture.



FIMP miracle vs WIMP miracle

- WIMP miracle is that for $m' \sim v \quad \lambda' \sim 1$

$$Y_{FO} \sim \frac{1}{\lambda'^2}\left(\frac{m'}{M_{Pl}}\right) \sim \frac{v}{M_{Pl}}$$

- FIMP miracle is that for $m \sim v \quad \lambda \sim v/M_{Pl}$

$$Y_{FI} \sim \lambda^2\left(\frac{M_{Pl}}{m}\right) \sim \frac{v}{M_{Pl}}$$

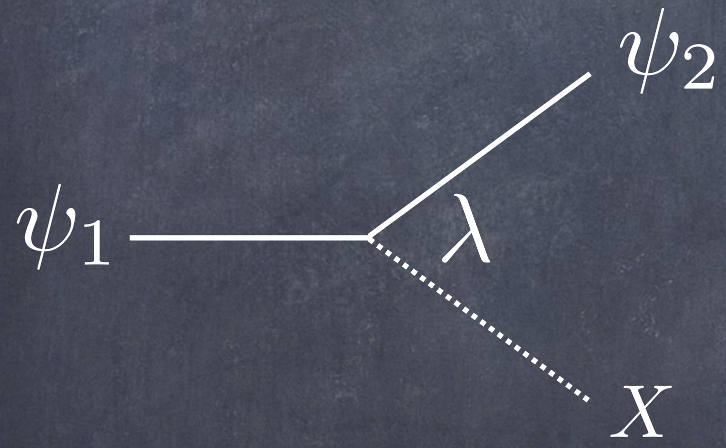
Example Toy Model I

- FIMPs can be DM or can lead to an abundance of the Lightest Ordinary Supersymmetric Particle (LOSP)
- Consider FIMP X coupled to two bath fermions ψ_1 and ψ_2

$$L_Y = \lambda \psi_1 \psi_2 X$$

- Let ψ_1 be the LOSP

- First case FIMP DM: $m_{\psi_1} > m_X + m_{\psi_2}$



$$\Omega_X h^2 \sim 10^{24} \frac{m_X \Gamma_{\psi_1}}{m_{\psi_1}^2}$$

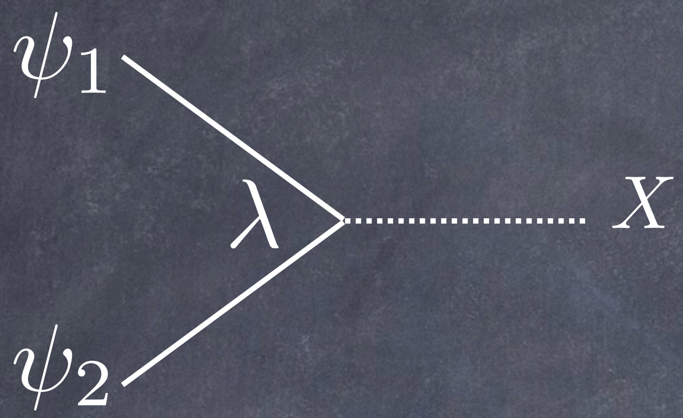
Using $\Gamma_{\psi_1} \sim \frac{\lambda^2 m_{\psi_1}}{8\pi} \Rightarrow$

$$\Omega_X h^2 \sim 10^{23} \lambda^2 \frac{m_X}{m_{\psi_1}}$$

For $\frac{m_X}{m_{\psi_1}} \sim 1$ need $\lambda \sim 10^{-12}$ for correct DM abundance

Toy Model continued...

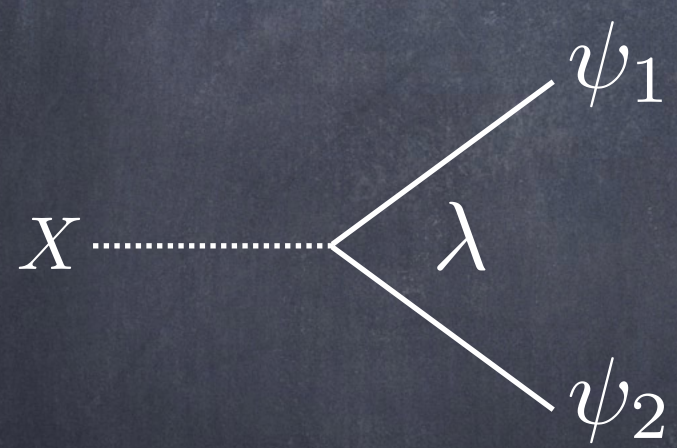
- Second case LOSP (=LSP) DM: $m_X > m_{\psi_1} + m_{\psi_2}$



$$\Omega_X h^2 \sim 10^{24} \frac{\Gamma_X}{m_X} \sim 10^{23} \lambda^2$$

Using $\Gamma_X \sim \frac{\lambda^2 m_X}{8\pi}$

- BUT X is unstable...



giving

$$\Omega_{\psi_1} h^2 = \frac{m_{\psi_1} \Omega_X h^2}{m_X} \sim 10^{23} \lambda^2 \frac{m_{\psi_1}}{m_X}$$

Again for $\frac{m_X}{m_{\psi_1}} \sim 1$ need $\lambda \sim 10^{-12}$ for correct DM abundance

- X lifetime can be long - implications for BBN, indirect DM detection

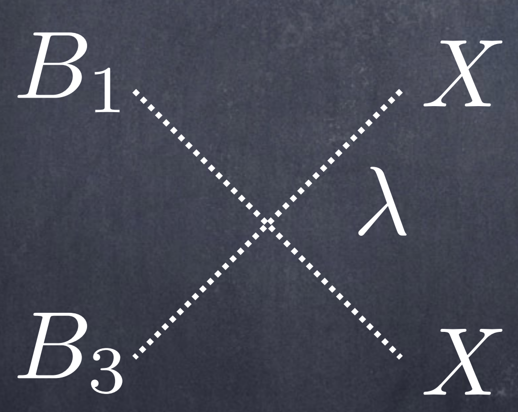
Example Model II

- Many applications and variations of the Freeze-in mechanism
- Assume FIMP is lightest particle carrying some stabilising symmetry - FIMP is the DM
- Consider quartic coupling of FIMP with two bath scalars

$$\mathcal{L}_Q = \lambda X^2 B_1 B_2$$

Assuming

$$m_X \gg m_{B_1}, m_{B_2}$$



$$\Omega h^2_X \approx 10^{21} \lambda^2$$

For correct DM abundance $\Rightarrow \lambda \sim 10^{-11}$

- NOTE: Abundance in this case is independent of the FIMP mass

FIMP Candidates and generating tiny λ

- Any long lived particle that is coupled to the thermal bath with a feeble coupling - needs to be a SM gauge singlet

- Hidden sector feebly coupled to MSSM

- Moduli and Modulinos associated with SUSY breaking

$$m_{susy}^2(T)\,\phi^\dagger\phi = m_{susy}^2\left(1+\frac{T}{M}\right)\phi^\dagger\phi \qquad \lambda\sim\frac{m_{susy}}{M}$$

- Dirac neutrino masses with SUSY - RH sneutrino FIMPs

$$\mathcal{L}_{\rm Dirac}=\lambda_\nu L H_u N \qquad \lambda_\nu\sim 10^{-12}$$

See Moroi *et al* for related

- FIMPs from kinetic mixing: hidden sector particles coupling to the MSSM via mixing of $U(1)_Y$ and hidden U(1) feeble mixing feeble coupling
- Others...Gravitino, RH neutrino, axino..

Experimental Signatures

- Long lived LOSPs at the LHC: FIMPs frozen in by decay of LOSP

- The LOSP is unstable, it decays to the FIMP and only the FIMP

- The LOSP is therefore long lived

- Every SUSY event will produce two LOSP each will have long lived decays

- LOSP could be charged electronically or even coloured

$$\tau_{\rm LOSP} = 7.7 \times 10^{-3}{\rm sec} \left(\frac{m_X}{100\,{\rm GeV}}\right) \left(\frac{300\,{\rm GeV}}{m_{\rm LOSP}}\right)^2 \left(\frac{10^2}{g_*(m_{\rm LOSP})}\right)^{3/2}$$

Implications for Big Bang Nucleosynthesis

- Signals for BBN: FIMPs or LOSPs decaying late could have implications for BBN

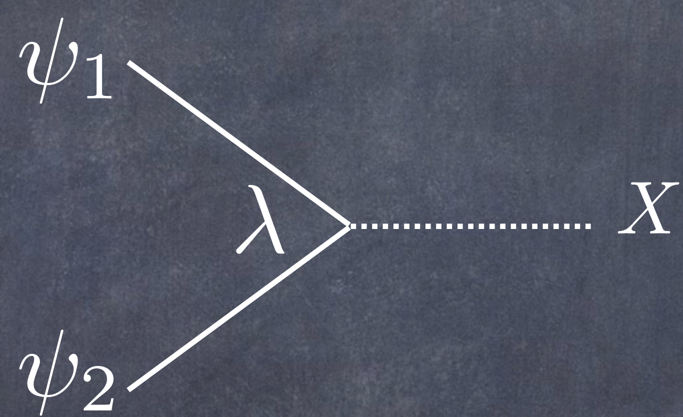
- After Freeze-in, either the LOSP or FIMP is unstable, can live for a second or more - decays during BBN era

- Depending on the details of these decays, an injection of hadrons during BBN can change the abundances of some elements

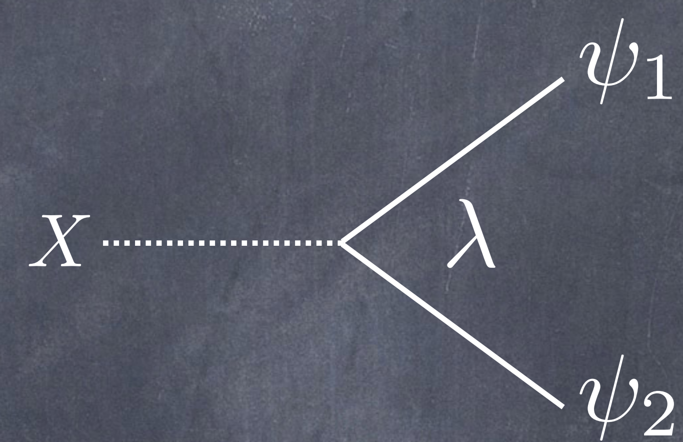
Implications for indirect and direct DM detection

- Enhanced indirect and direct detection: LOSP DM relic abundance and LOSP DM annihilation cross section no longer related.

- Case where an abundance of unstable FIMPs are frozen-in, these then decay back to the LOSPs



then



- If Freeze-in dominantly produces DM abundance annihilation cross section must be large - freeze-out abundance is small

- The annihilation cross section for the DM LOSP will be greater than the canonical value needed for freeze-out - BOOST FACTORS

Freeze-in Summary

- Freeze-in can provide attractive alternative to Freeze-out

- It is an IR dominated process and in simple scenarios relic abundance can be found analytically

- Experimental implications of Freeze-in include: long lived states at the LHC, modifications to predictions at BBN and changes in predictions for indirect and direct DM detection

Hidden Sector DM

Visible sector

$q, e, W, Z, H, \tilde{q}, \ldots$

Portal

Hidden sector

$\chi, \chi', \chi''_\mu \cdots$

- Hidden sector states have no SM gauge interactions
- Hidden sector may be linked, beyond gravity, to the visible sector

Portals: higgs - $|H|^2|\chi|^2$ or $|H|^2|\chi'|^2$ etc

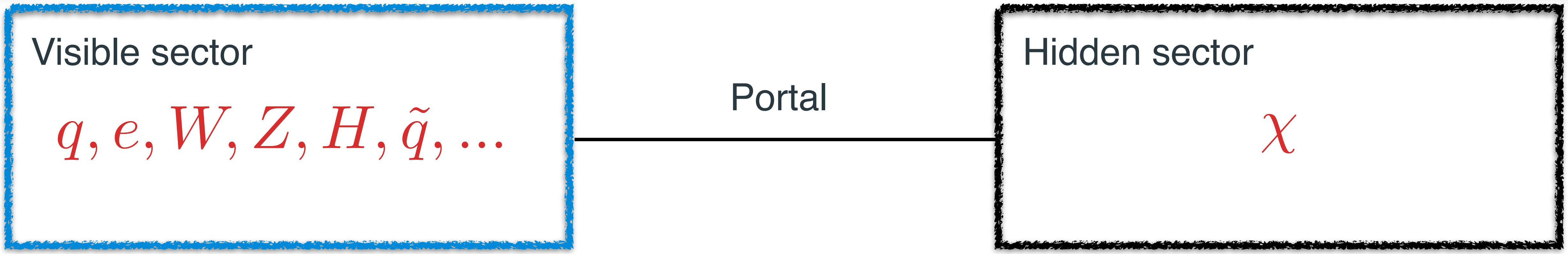
neutrino - $LH\chi$ or $LH\chi'$

kinetic mixing - $(\partial_\mu \chi''_\nu - \partial_\nu \chi''_\mu) F_Y^{\mu\nu}$ if χ''_μ is a $U(1)'$ Gauge boson

plus D>4 operators $\frac{1}{M^{n-4}} \mathcal{O}_{\rm sm} \mathcal{O}_{\rm hs}$

- The form of this portal can play a major role in DM genesis

SuperWIMPS



- If the portal interactions are only gravitational - still have options
- SuperWIMPS: Feng, Rajaraman, Takayama '03
  - DM state never in thermal equilibrium
  - Abundance is generated by late decay of another particle that has frozen-out
  - Prime example - gravitino dm with LOSP freezing out and decaying to gravitino
  - Implications for BBN + long lived states at colliders
- See also WIMPzillas Kolb, Chung, Riotto '98

Multi-state hidden sectors

Visible Sector

$q, e, W, Z, H, \tilde{q}, \ldots$

Portal

Hidden sector

$\chi, \chi', \chi''_\mu \cdots$

- In particular the idea of self interacting dark matter (SIDM)

  Carlson, Machacek, Hall '92

  - Motivated by small scale structure problems e.g.

    Spergel, Steinhardt '99

    - "Cusps vs cores"
    - "Too big to fail"

For self interacting DM to solve, requires $$\frac{\sigma}{m_\chi} \sim \frac{1\text{barn}}{\text{GeV}}$$

Rocha et al '12, Peter et al '12, Vogelsberger '12, Zavala et al '12

$\Rightarrow$ Suggests some strongly interacting theory

$\Rightarrow$ Confining non-abelian gauge theory

Self-interacting dark matter

Visible sector

$q, e, W, Z, H, \tilde{q}, \ldots$

Portal

Hidden sector

$\chi, \chi', \chi''_\mu \cdots$

$SU(N_D)$

- Many models of non-abelian theories in hidden sectors e.g.
  - Glueball dark matter: Pure Yang-mills + susy version with glueballinos — Boddy, Feng, Kaplinghat, Shadmi, Tait '14
    - makes use of wimpless miracle — Feng, Kumar '08

$$\Omega h^2 \sim \frac{m_\chi^2}{g_\chi^4}$$

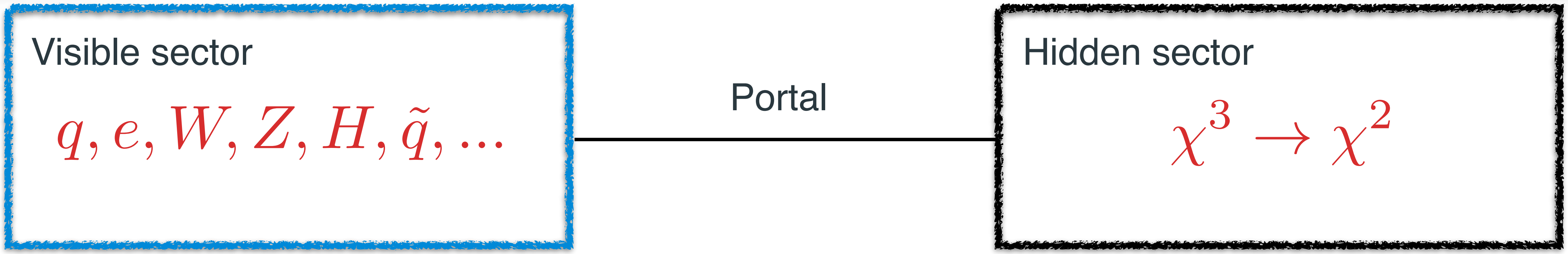
if $m_\chi \propto g_\chi^2$ we get correct size

$\rightarrow$ large range of possibilities including qcd-like interactions and masses

Lots of other earlier examples e.g. Falkowski, Kuknevich, Shelton '09, Alves, Bebnahani, Schuster, Wacker '09, Kribs, Roy, Terning, Zurek '09, Lisanti, Wacker '09, Buckley, Neil '12+…

Simp Miracle

Hochberg, Kuflik, Volansky, Wacker '14
Hochberg, Kuflik, Murayama, Volansky, Wacker '14



- Inspiration from the cannibalistic model of Carlson, Machacek, Hall '92

- Freeze-out of dark matter dominated by $3 \to 2$ processes

- Crucial portal interaction to visible sector allows excess energy from cannibalisation of DM states to be redistributed throughout thermal bath.

- Allows for a Strongly Interacting Massive Particle with Gev or below mass - application to small scale structure problem

Summary

- WIMP DM generated via the freeze-out mechanism is simple, in many case predictive scenario to explain DM
- Many experimental efforts to detect DM: direct detection, indirect detection, LHC searches.
- Maybe this simple picture is not right? Maybe the WIMP has had its day?
- Maybe DM is related to the matter-antimatter asymmetry?
- Maybe DM has no significant coupling to the SM and direct dark matter detection will never see it?!
- Lots of fun investigating the possibilities though!