Dark matter searches

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Material borrowed from: arXiv:1603.03797 (TASI lecture notes by M.Lisanti) and other sources

Literature

- Generic dark matter introduction:
  - TASI lecture notes by M. Lisanti (arXiv:1603.03797)
  - TASI lecture notes by Tongyan Lin (arXiv:1904.07915)
  - DM at colliders: Lectures by T. Tait
- Indirect detection:
  - Cargese lecture notes by P. Salati
  - Review article: Jennifer Gaskins (arXiv:1604.00014)
- Direct detection:
  - Large theory part covered in M. Lisanti TASI lecture notes
  - Experimental overview: Lecture notes by L. Baudis
  - Talk by E. Aprile
- Books:
  - Kolb and Turner

Plan

- What do we know about dark matter?

More than you would think

- What do we not know about dark matter?

Less than we want to know

- How do we know what we know?

Experiments and theory

- Why do we not know what we don't know?

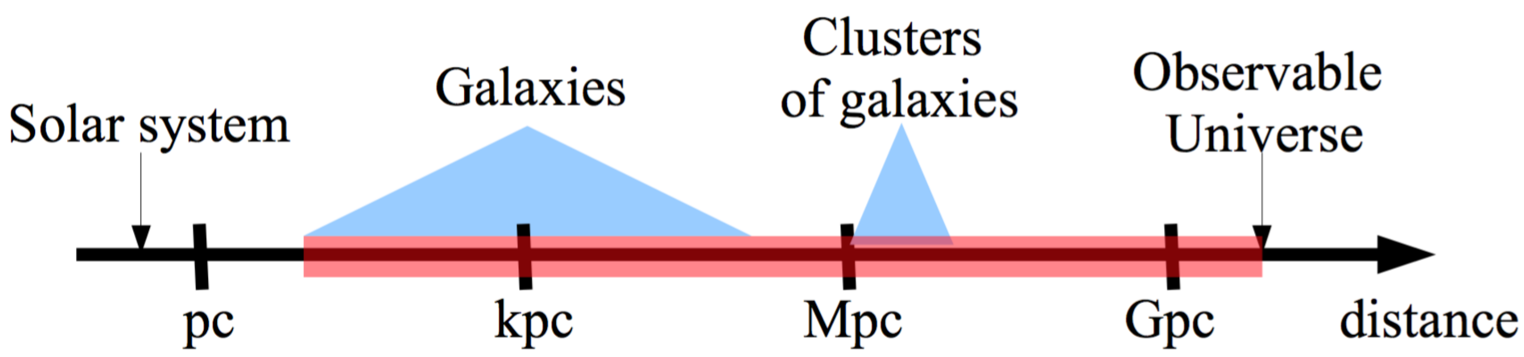
That is the most frustrating question today

- Is WIMP the final story?

We wish it was!!!

Evidence - galactic scale

- Strong evidence on all scales



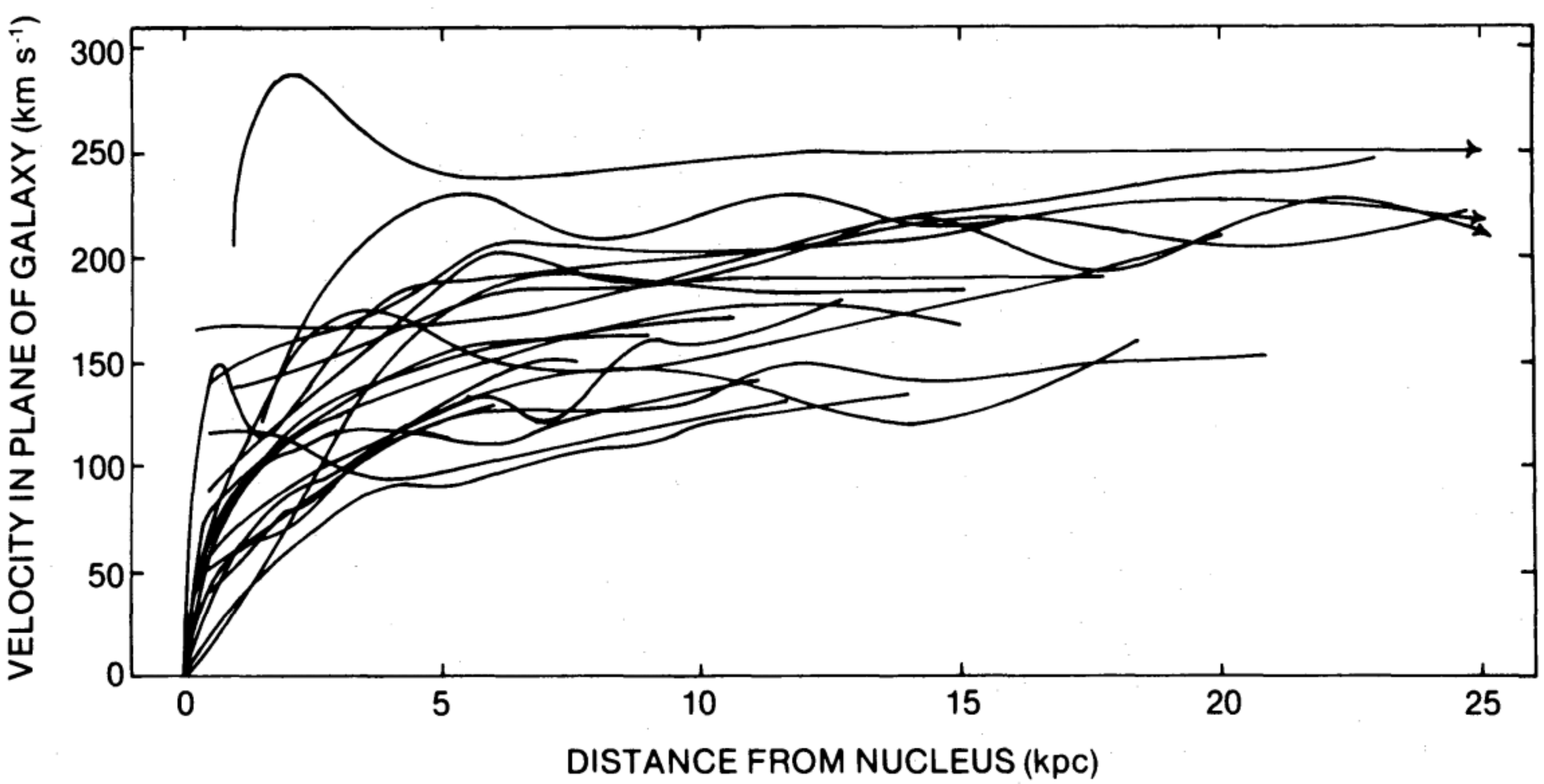
$$v_c(r) = \sqrt{\frac{GM}{r}}$$

$$\rho(r) \propto \frac{M(r)}{r^3} \sim \frac{1}{r^2}$$

Local halo $\quad M_{\text{halo}} \sim 10^{12} M_{\odot}$

$$M_{\text{halo}} \sim 4\pi \int_0^{R_{\text{halo}}} dr\, r^2\, \rho(r)$$

$$\rightarrow R_{\text{halo}} \sim 100\,\text{kpc}$$



$$\boxed{\langle v \rangle \sim \sqrt{\frac{G M_{\text{halo}}}{R_{\text{halo}}}} \sim 200 \ \ \text{km/s}}$$

DM is non-relativistic today!

Evidence - galactic scale

$$\langle v \rangle \sim \sqrt{\frac{GM_{\text{halo}}}{R_{\text{halo}}}} \sim 200 \quad \text{km/s}\,.$$

$$M_{\text{halo}} \sim 10^{12} M_{\odot}$$
$$R_{\text{halo}} \sim 100\,\text{kpc}$$

G = 6.67 X 10^{-11} m^3 kg^{-1} s^{-2}

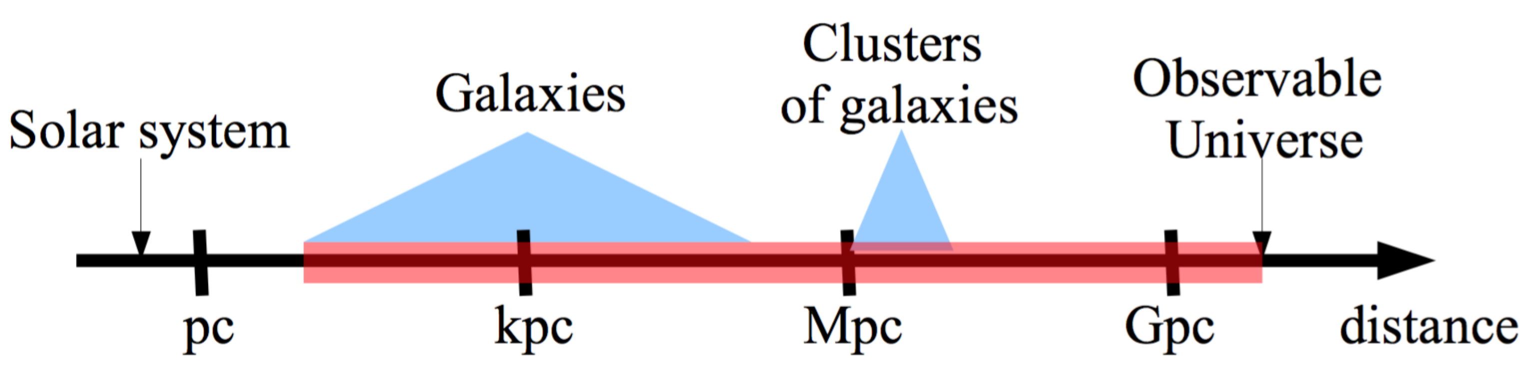
1 kpc = 3.086 X 10^{19} m

1 solar mass = 1.989 X 10^{30} kg

Verify that velocity is 200 km/s

Evidence - cluster scale

- Strong evidence on all scales



$$\frac{1}{2}m(3\sigma^2) \rightarrow 2\langle T\rangle = -\langle V\rangle \leftarrow G\frac{M_{tot}(r)m}{r}$$

Velocities ~ 1000 km/s
R ~ Mpcs
Distance ~100 Mpc
(1 pc = 3.26 light yrs)

F. Zwicky, Astrophysical Journal, vol. 86, p.217 (1937):

$$\mathcal{M} > 9 \times 10^{46}\text{gr} . \qquad (35)$$

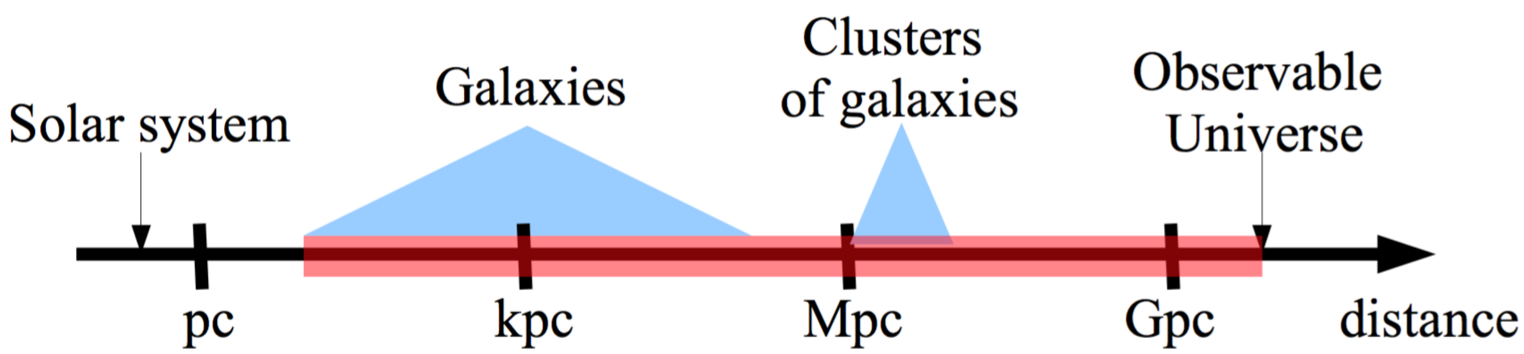
The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

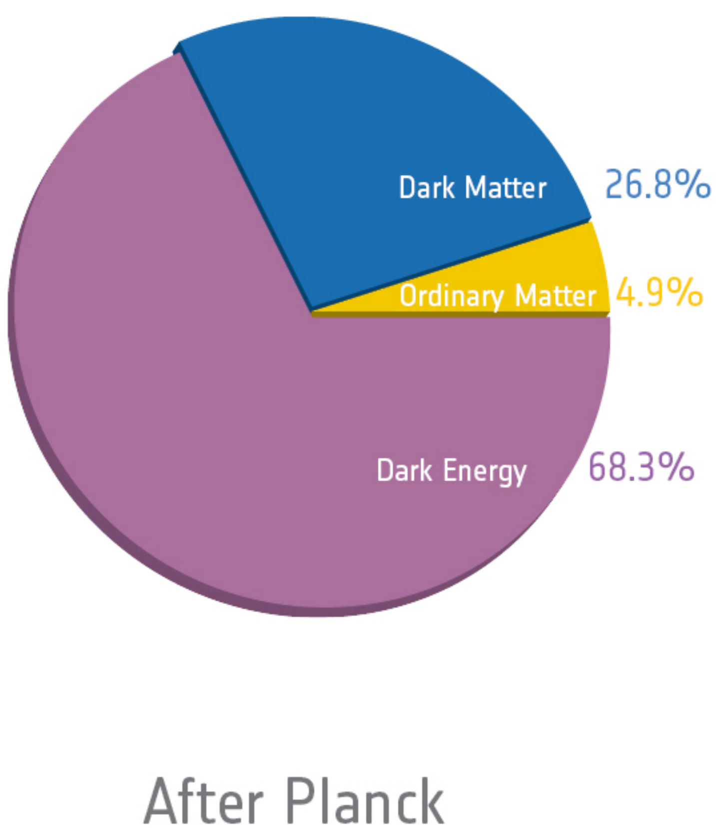
$$\overline{M} > 9 \times 10^{43}\ \text{gr} = 4.5 \times 10^{10}\ M_{\odot} . \qquad (36)$$

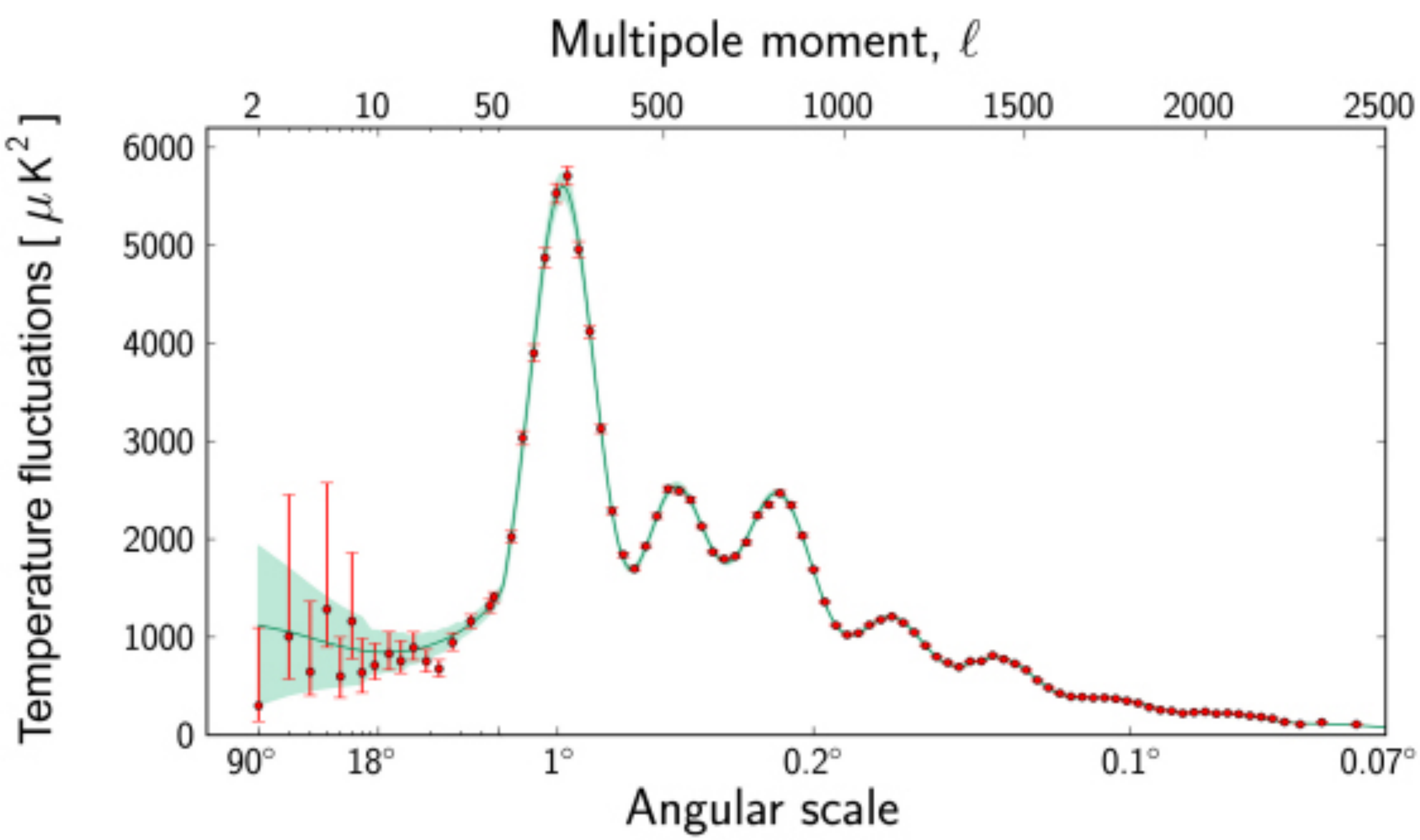
the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According

Evidence - observable Universe

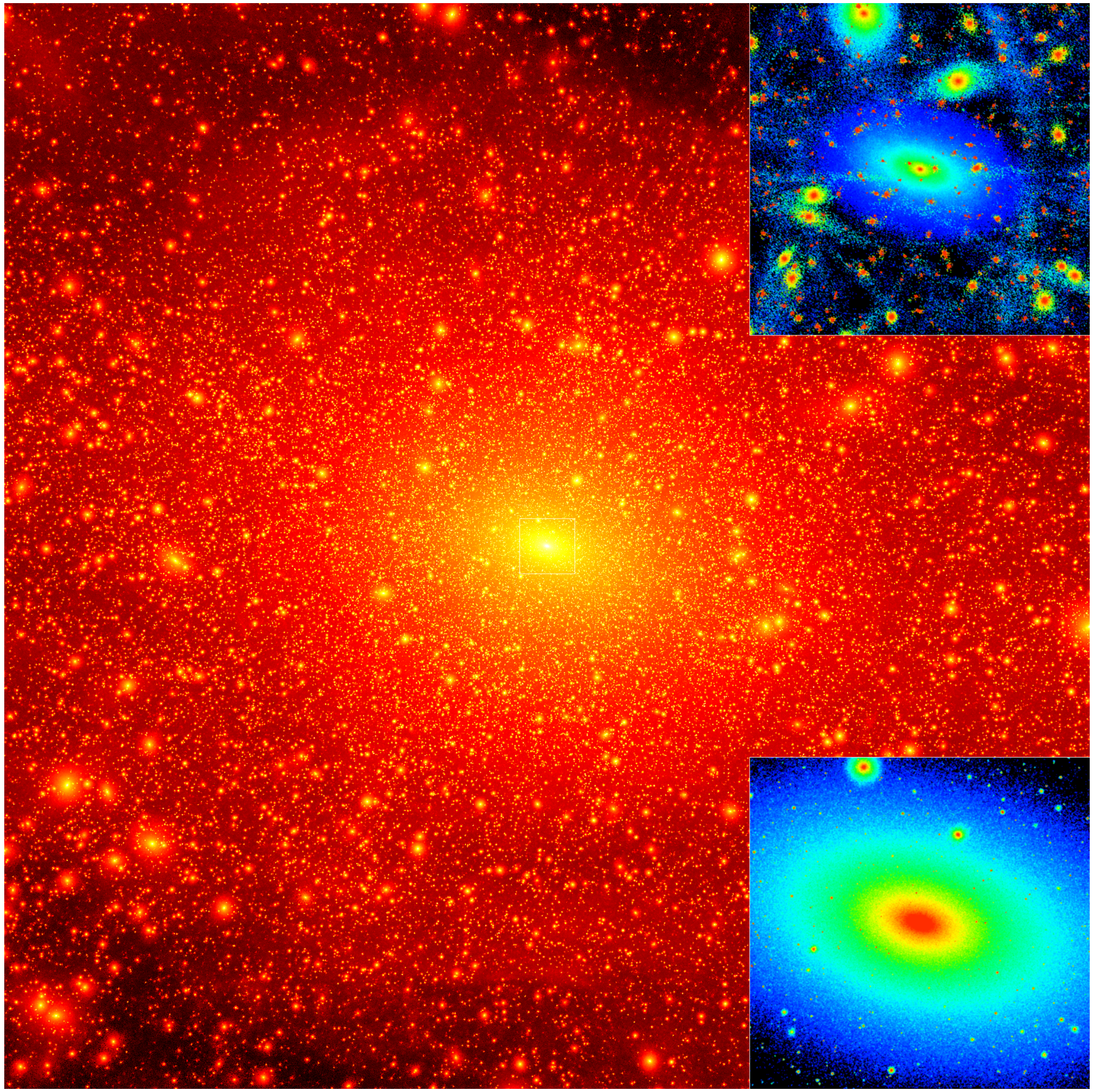
- Strong evidence on all scales







Lessons - simulations



- Need of ‘small scale’ simulations to understand dark matter properties at Galactic scale
- Millenium simulation large scale simulation, does not have good resolution for halo scales
- Simulation at the scale of Milky Way
- Primary inputs from Via Lactea II and Aquarius
- Image from Via Lactea II simulation
  - Dark matter density distribution in 800 kpc cube
  - (Remember we just said that the halo size is about 100 kpc)
  - Dense spot at the centre and presence of sub halos

Lessons - simulations

Preferred by DM only

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{r/r_s(1+r/r_s)^2}$$

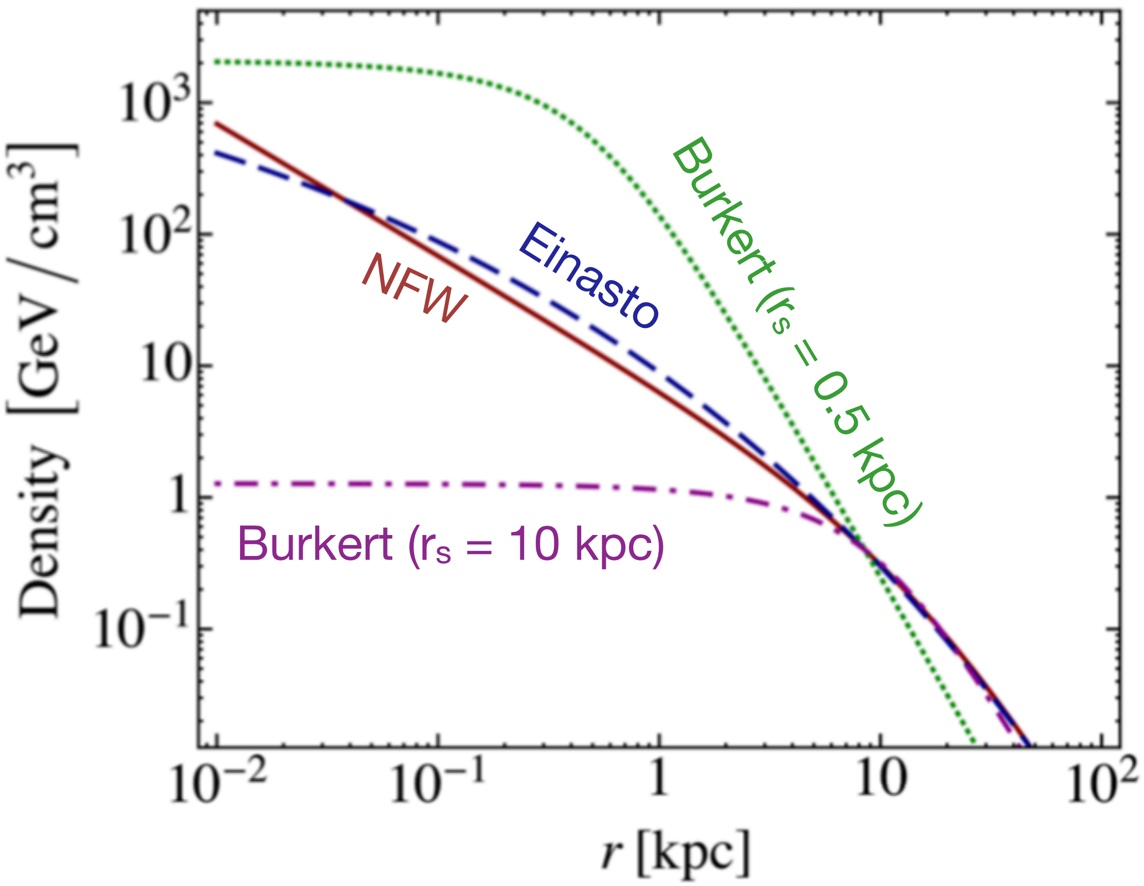
$$\rho_{\rm Ein}(r) = \rho_0 \exp\left[-\frac{2}{\gamma}\left(\left(\frac{r}{r_s}\right)^{\gamma}-1\right)\right]$$

Impact of baryons?

$$\rho_{\rm Burk}(r) = \frac{\rho_0}{(1+r/r_s)(1+(r/r_s)^2)}$$

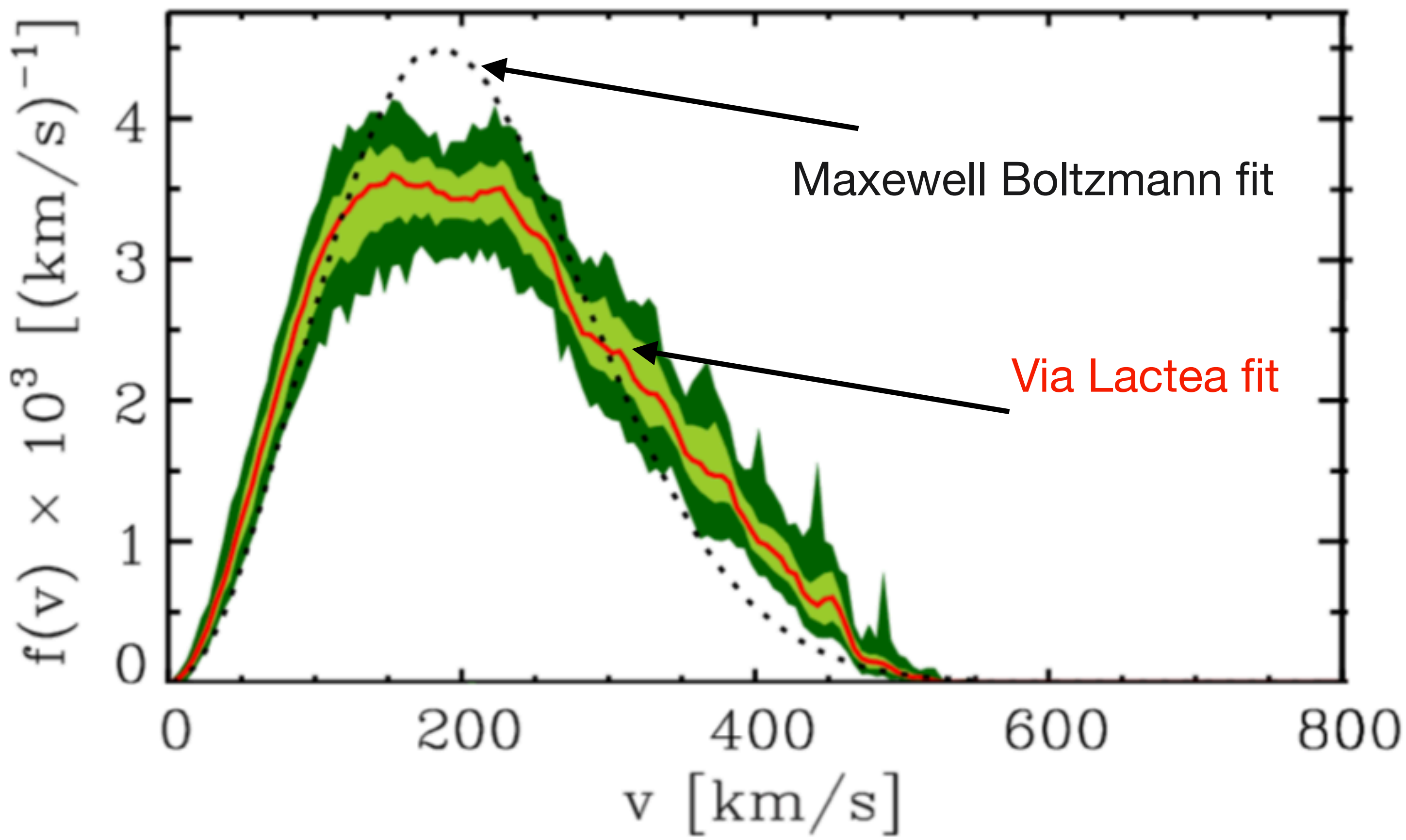
Enhancement due to central black hole

$$\rho_{\rm BH}(r) = \begin{cases} 0 & r < 4R_{\rm S} \\ \frac{\rho_{\rm sp}(r)\rho_{\rm pl}}{\rho_{\rm sp}(r)+\rho_{\rm pl}} & 4R_{\rm S} \le r < R_{\rm sp} \\ \rho_0\left(\frac{r}{r_0}\right)^{-\gamma}\left(1+\frac{r}{r_0}\right)^{-2} & r \ge R_{\rm sp}, \end{cases}$$



- Black hole enhancement profile not shown
- Considerable uncertainty about the DM density distribution at the centre of galaxy
- Impact on indirect detection experiments

Lessons - simulations



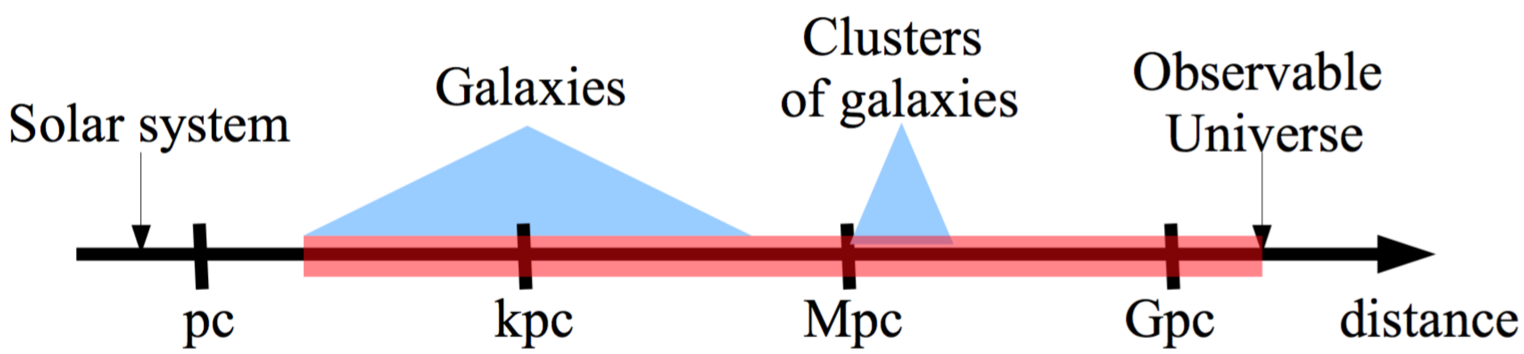
$$f(\mathbf{v}) = \begin{cases} \frac{1}{N_{esc}}\left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2} e^{-3\mathbf{v}^2/2\sigma_v^2} & : |\mathbf{v}| < v_{esc} \\ 0 & : \text{otherwise} \end{cases}$$

$$v_0 = \sqrt{2/3}\sigma_v \approx 235 \text{ km/s}$$

- We actually do not know the exact DM velocity distribution in Milky Way
- Our best estimates come from numerical simulations
- Recent data from Gaia satellite might have something to say here see this and this

Dark Matter - properties

- Strong evidence on all scales



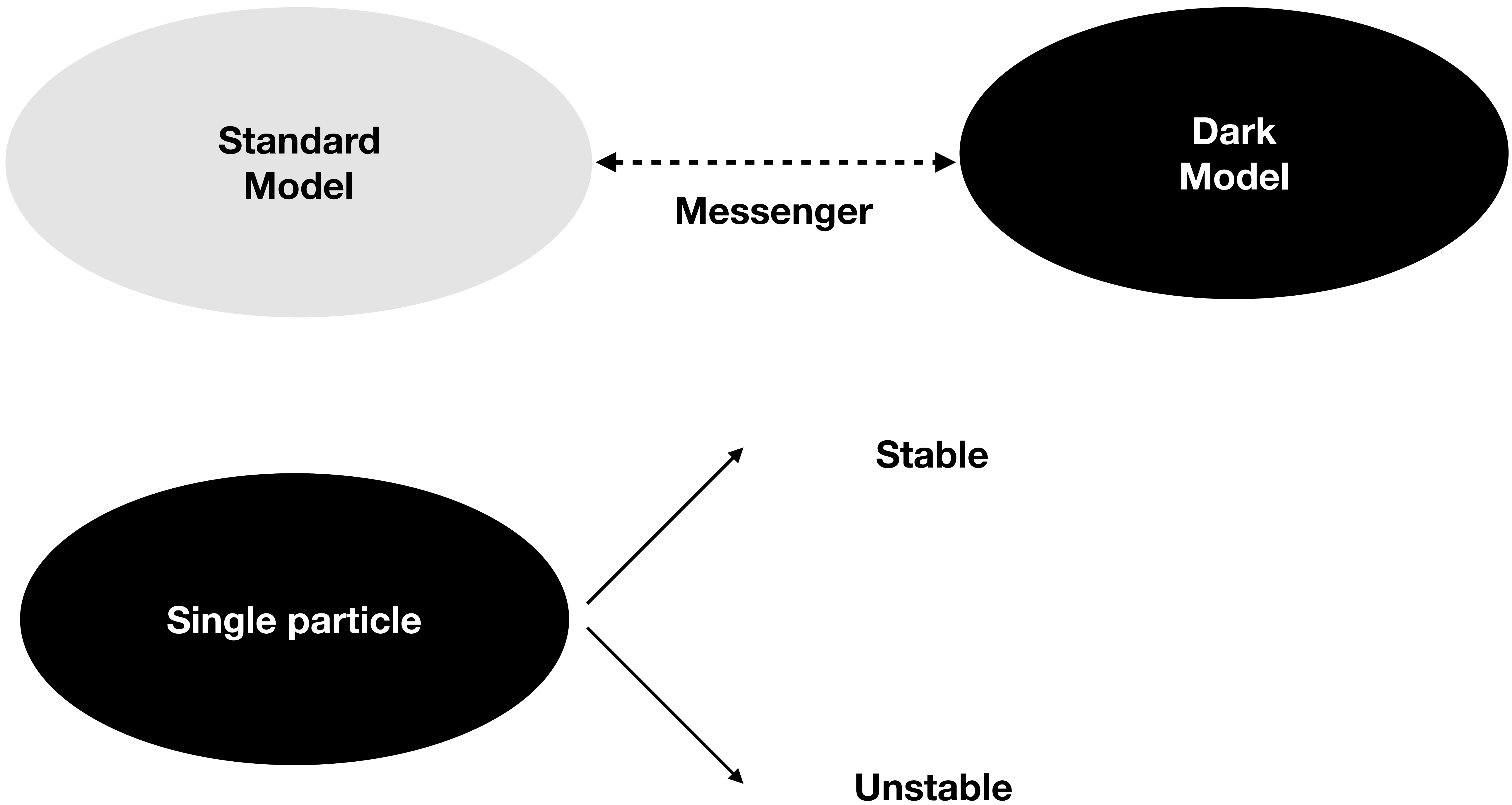
DM Today:
Believed to be

1) Neutral or milli-charged [Can have fractional charges]
2) Non-relativistic
3) Lifetime greater than the age of the Universe or Stable [Can decay]
4) Weak interactions with the SM particles [Can strongly interact with itself]
5) Massive (meaning has mass > 0 GeV) [Can be very light]

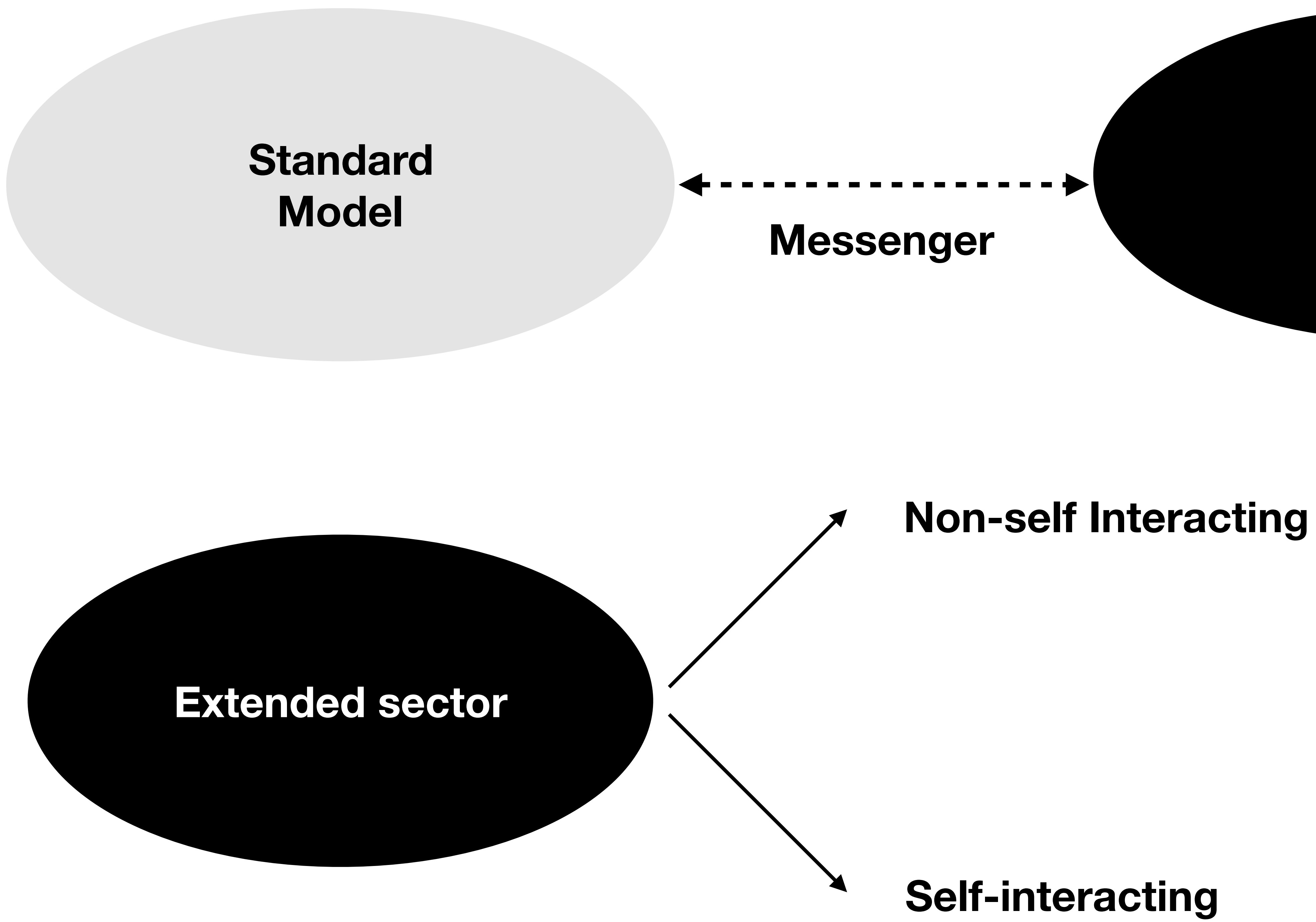
There is no such particle within the Standard Model

Neutrinos which come pretty close are relativistic species

Dark Matter - particle physics

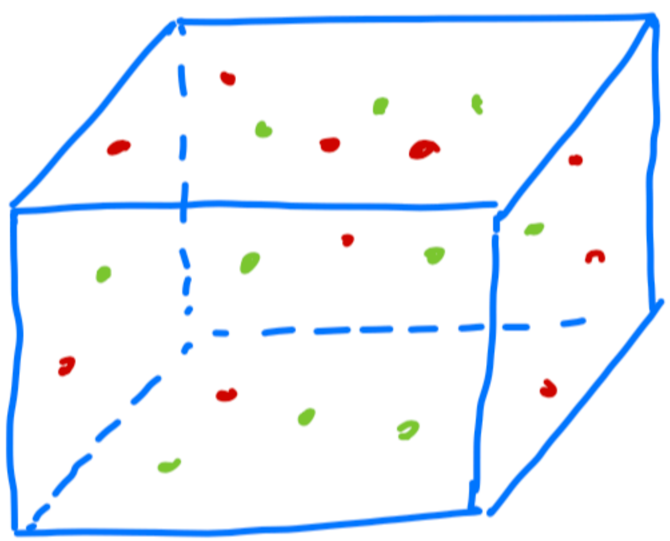


Dark Matter - particle physics



- How did dark matter originate?

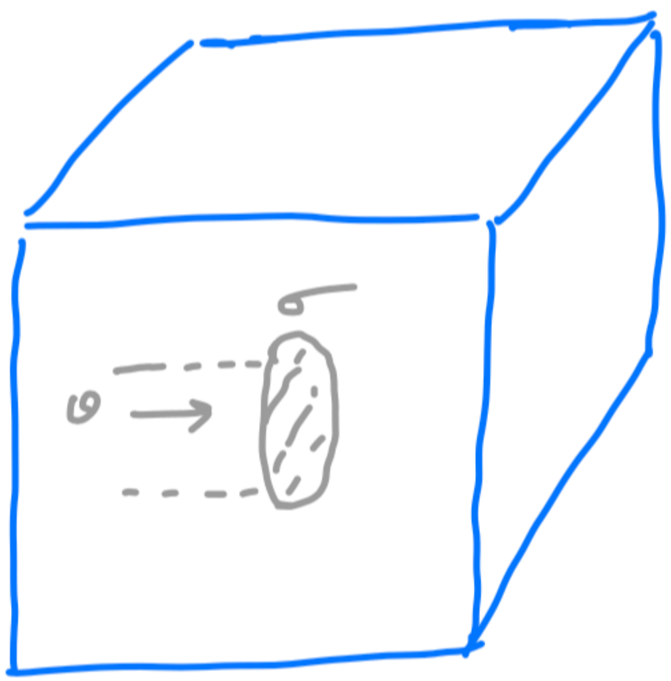
A thought experiment



- Consider Universe as a box of finite size, with finite temperature
- Consider particles of type A and B with $m_A > m_B$ in equillibrium, with constant velocities v_A and v_B
- Case I: Particles do not interact
  - Universe stays the same forever
- Case II: Interactions of the type A + A ➜ B + B are allowed therefore reverse interactions are not possible
  - All A convert to B, Universe has no A particles left

- Case III: A + A $\longleftrightarrow$ B + B are allowed, nothing else changes
  - Universe maintains equilibrium forever
- Case IV: A + A $\longleftrightarrow$ B + B but Universe cools down

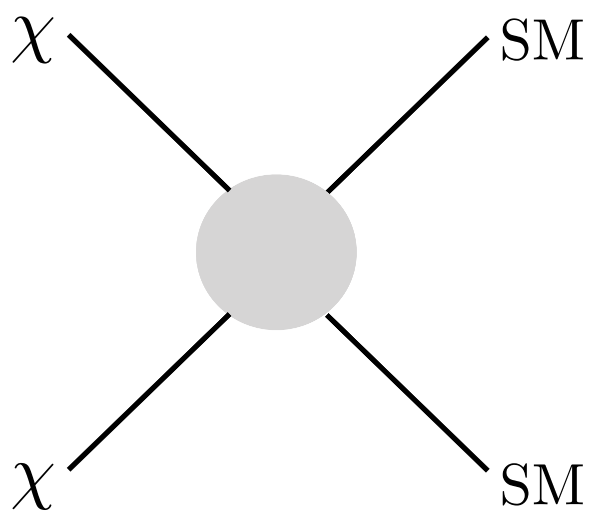
A thought experiment



- Case IV: A + A ⟷ B + B but Universe cools down
- Velocity of the particles reduces ($k_B T \sim 1/2\ mv^2$)
- Rate of interaction of particles σ
- Relative velocity between particles $| v_A - v_B |$
- Therefore flux of the particles $\sigma \times | v_A - v_B |$
- We know the number density of particles n_A
- Therefore characteristic time scale of the system = $n_A \times \sigma \times | v_A - v_B |$ [Check Units]
  - $n_A \times \sigma \times | v_A - v_B | = \mathrm{cm}^3/\mathrm{s} \times \mathrm{cm}^2 \times \mathrm{cm/s} = 1/\mathrm{s}$

- A = DM particles; B = SM particles
- Universe cools down because of expansion hence the only other time scale in the picture is the Hubble constant
- Freeze - out when $n_A \times \sigma \times | v_A - v_B | \sim H$ [Units of H = 1/s]
- In reality, one needs to consider particle distributions hence detailed thermodynamics

The WIMP paradigm



$\mathbf{L}[f] = \mathbf{C}[f]$ Liouville operator = collision operator

Covariant form of the Liouville operator

$$L[f] = E\frac{\partial f}{\partial t} - \frac{\dot{a}}{a}|\mathbf{p}|^2\frac{\partial f}{\partial E} \qquad n = g\int f(E,t)\,\frac{d^3p}{(2\pi)^3}$$

$$g\int L[f]\,\frac{d^3p}{(2\pi)^3} = \frac{1}{a^3}\frac{d}{dt}\left(na^3\right) = \frac{dn}{dt} + 3\,H\,n$$

$$g_1\int C[f_1]\,\frac{d^3p_1}{(2\pi)^3} = -\sum_{\text{spins}}\int\left[f_1f_2(1\pm f_3)(1\pm f_4)|\mathcal{M}_{12\to 34}|^2 - f_3f_4(1\pm f_1)(1\pm f_2)|\mathcal{M}_{34\to 12}|^2\right]$$
$$\times(2\pi)^4\delta^4(p_1+p_2-p_3-p_4)\,d\Pi_1\,d\Pi_2\,d\Pi_3\,d\Pi_4$$

$$\dot{n} + 3Hn = \langle\sigma v\rangle\left(n_{\text{eq}}^2 - n^2\right)$$

$$\boxed{\Omega_\chi = \frac{m\,s_{\text{today}}\,Y_{\text{today}}}{\rho_{\text{cr}}} \longrightarrow \Omega_\chi h^2 \sim \frac{10^{-26}\ \text{cm}^3/\text{s}}{\langle\sigma v\rangle} \simeq 0.1\left(\frac{0.01}{\alpha}\right)^2\left(\frac{m}{100\ \text{GeV}}\right)^2}$$

The WIMP paradigm

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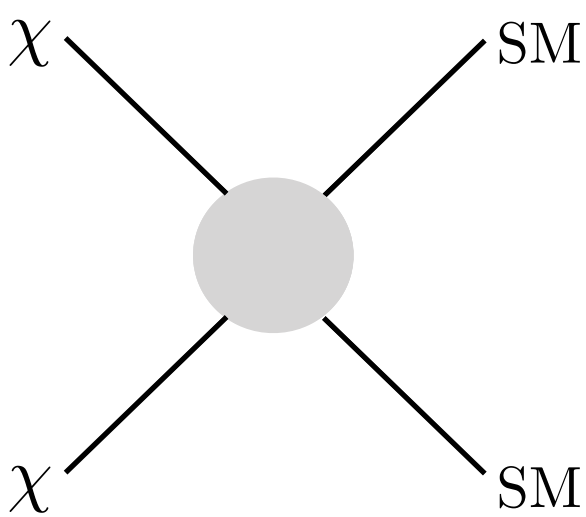
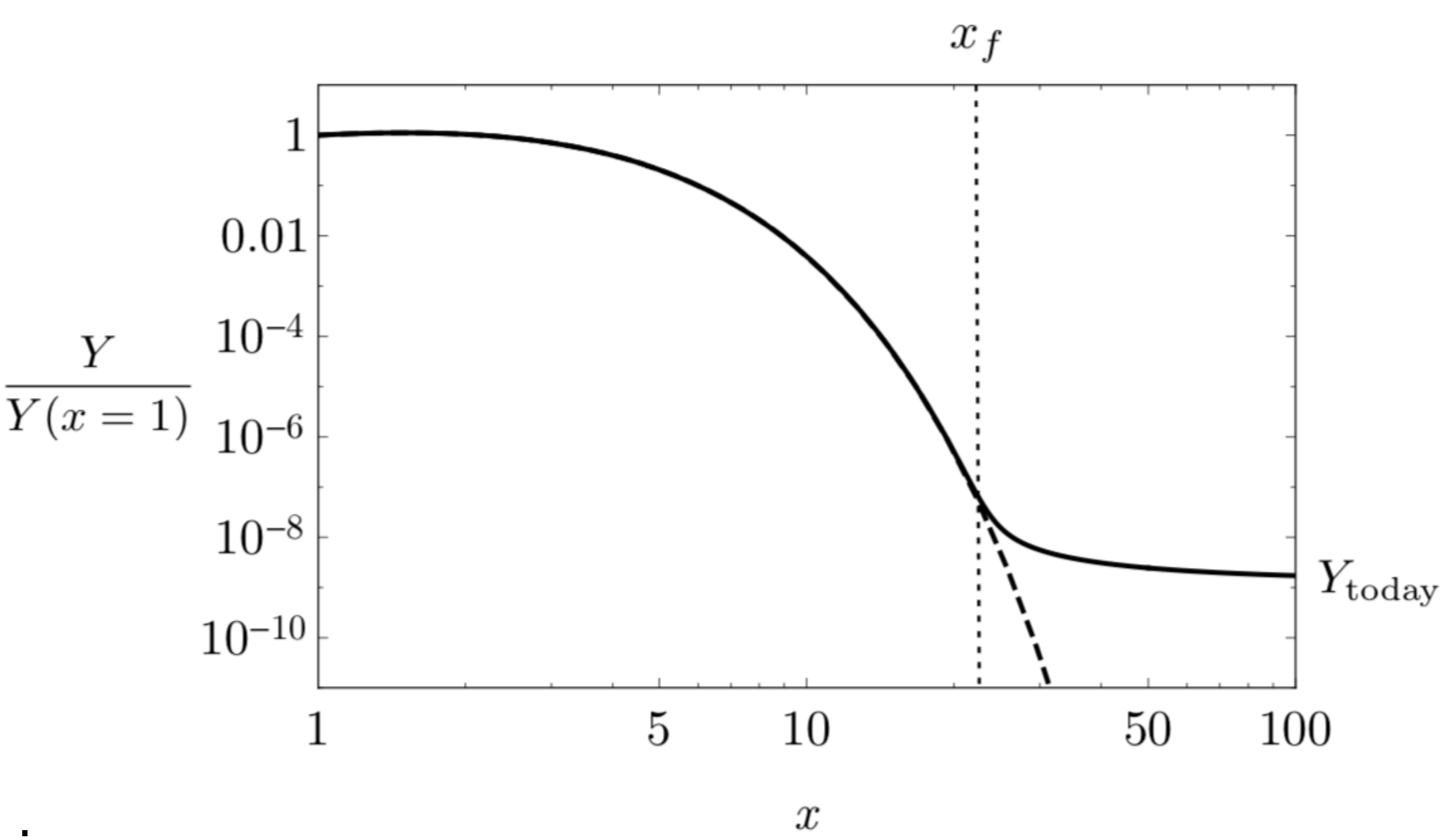
Weak scale coupling

Weak scale mass





- Popular ‘WIMP Miracle’ mechanism

The WIMP paradigm

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Weak scale coupling

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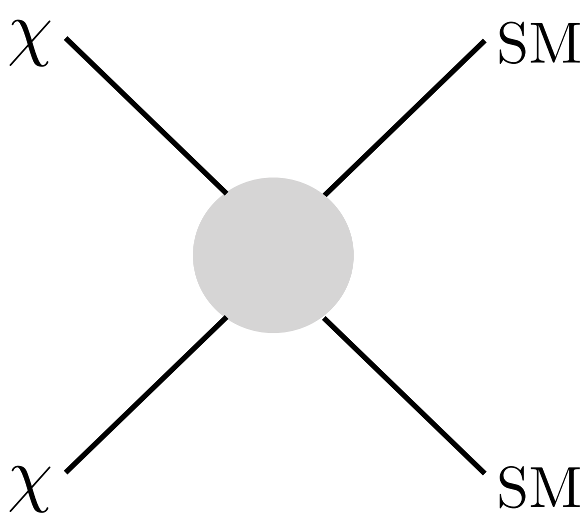

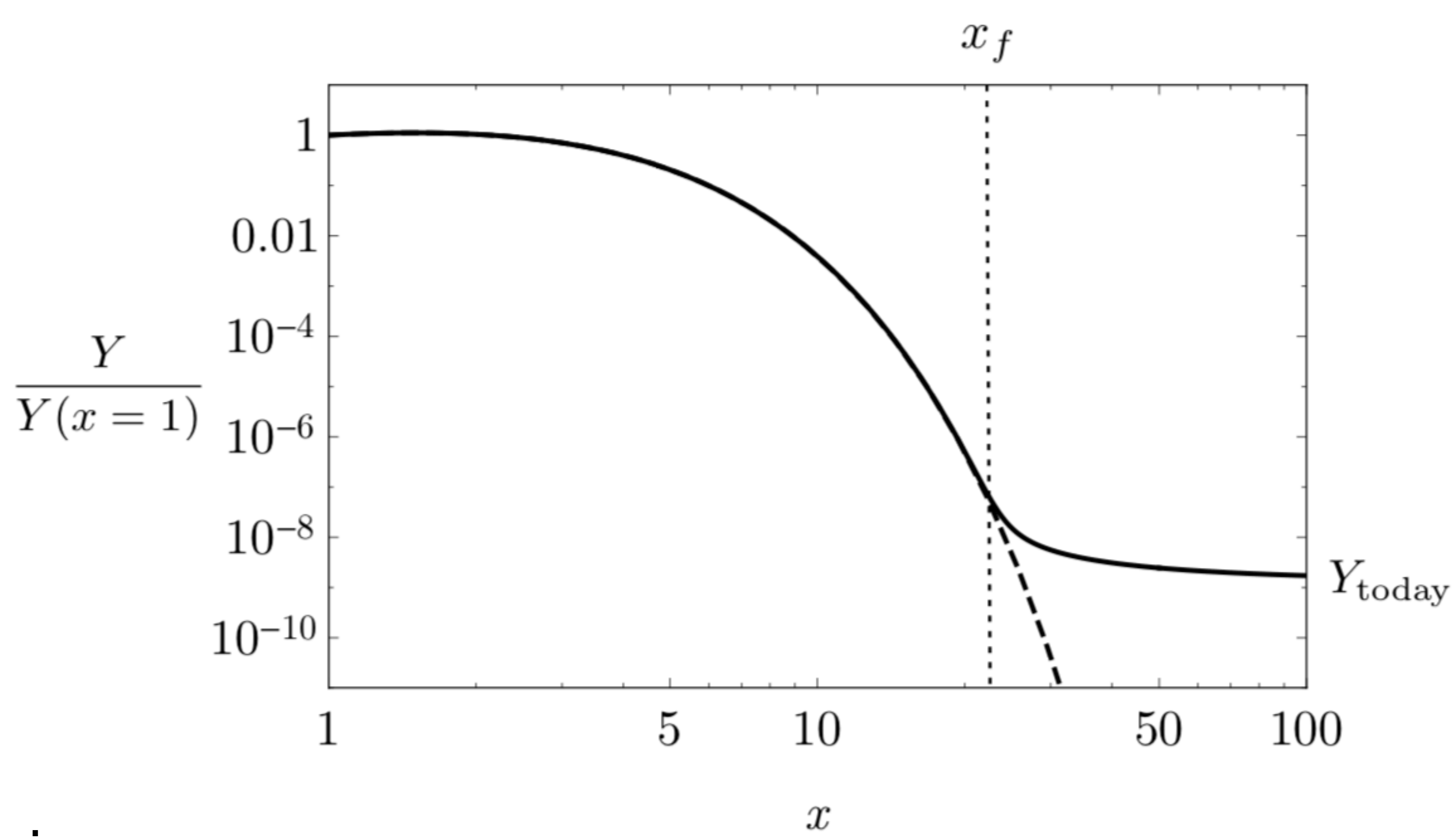

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Weak scale coupling

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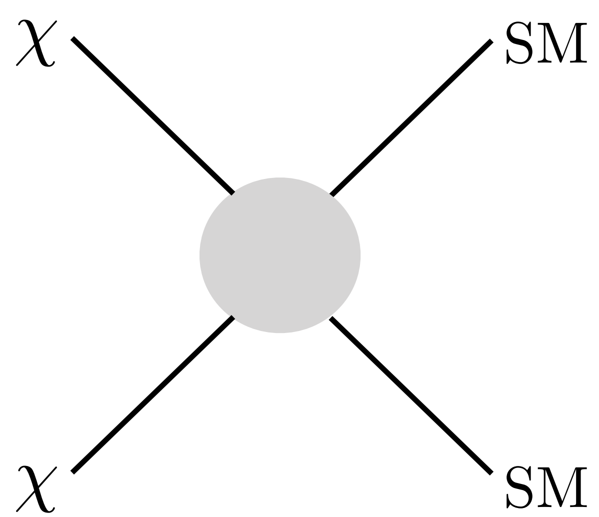
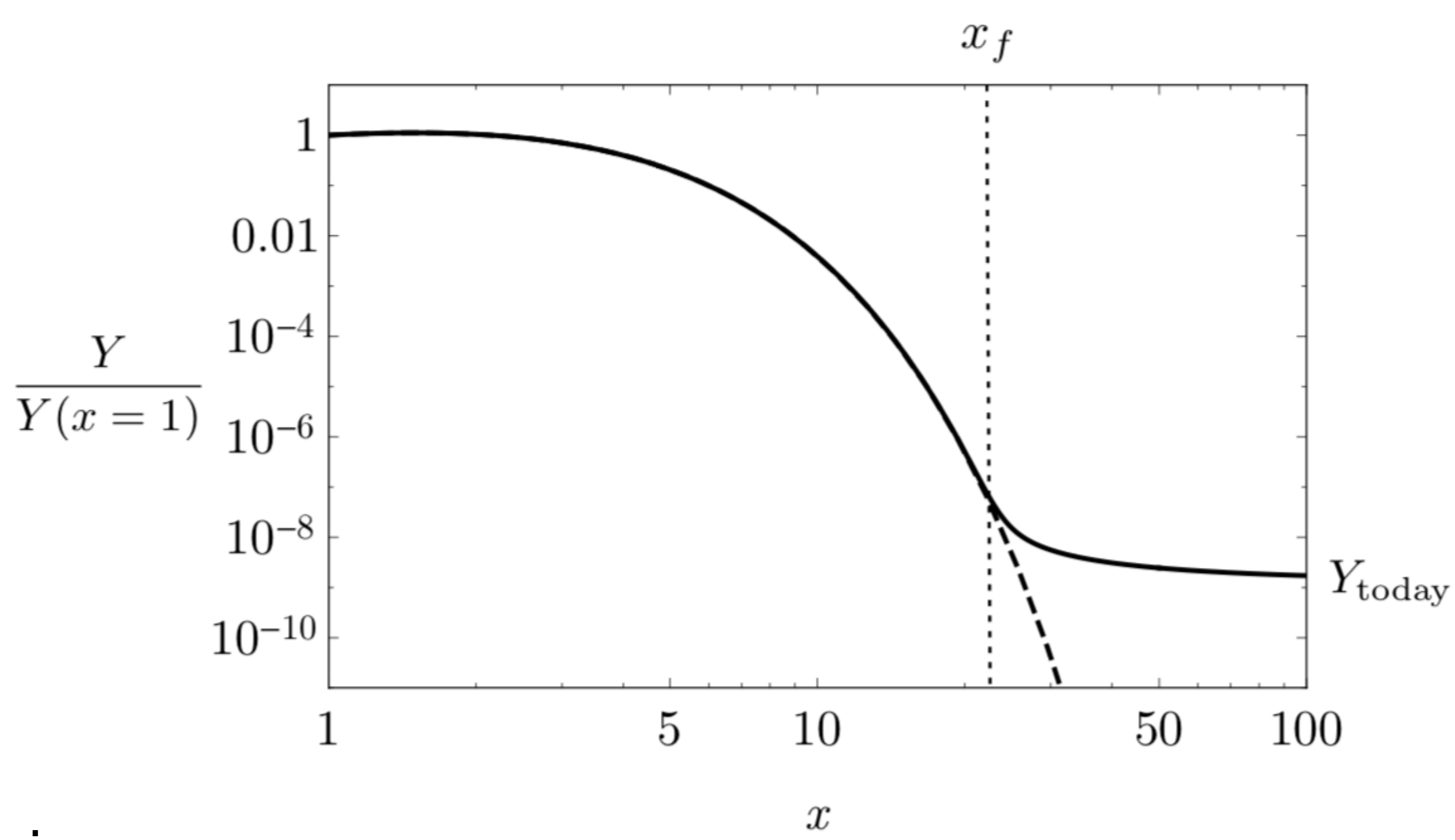




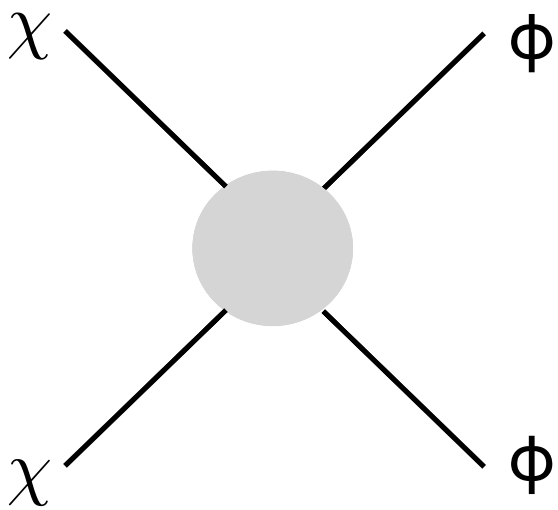
- Popular ‘WIMP Miracle’ mechanism

The WIMP - less scenario

D'Agnolo, arXiv:1505.07107

$$\Omega_\chi = \frac{m\, s_{\rm today}\, Y_{\rm today}}{\rho_{\rm cr}} \longrightarrow \Omega_\chi h^2 \sim \frac{10^{-26}\ {\rm cm}^3/{\rm s}}{\langle \sigma v \rangle} \simeq 0.1 \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m}{100\ {\rm GeV}}\right)^2$$

Is the WIMP miracle really a miracle?



$$\chi\chi \to \phi\phi \qquad \text{with} \qquad m_\phi > m_\chi$$

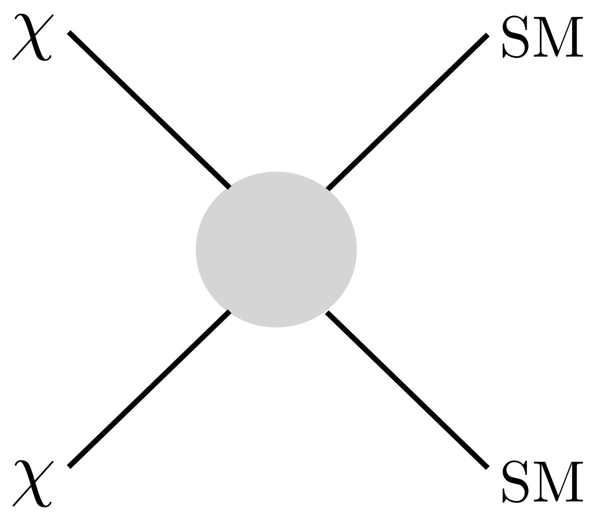
$$\dot{n} + 3Hn = -\langle \sigma v \rangle_{\chi\chi}\, n_\chi^2 + \langle \sigma v \rangle_{\phi\phi}\, (n_\phi^{\rm eq})^2$$

$$\langle \sigma v \rangle_{\chi\chi} = \langle \sigma v \rangle_{\phi\phi} \left(\frac{n_\phi^{\rm eq}}{n_\chi^{\rm eq}}\right)^2 \sim \frac{\alpha^2}{m_\phi^2}\, e^{-(m_\phi - m_\chi)/T}$$

- Exponential suppression of thermally averaged cross section in forward direction
- Relic density enhances exponentially if mass difference increases [remember inverse dependence between relic and cross section]

Simple alternative scenario with 2 ➜ 2 interactions but no WIMP

The WIMP miracle?

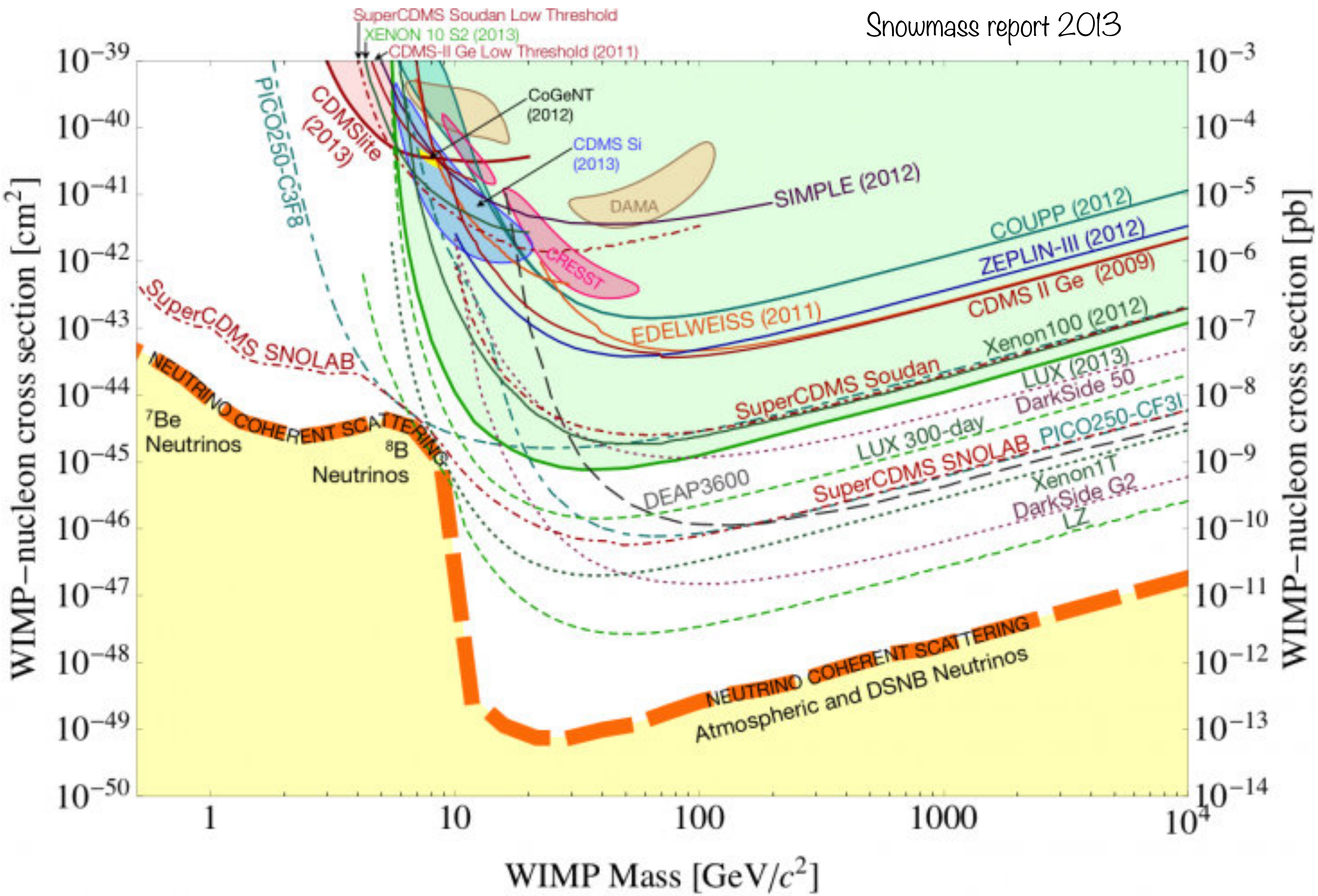


- Not so much a 'miracle' but carefully arranged particle physics and cosmology scenario, albeit simplest
- The temperature of the box decreases smoothly ➜ comoving entropy remains constant [Entropy does not have to be constant]
- Cross section constant throughout freeze-out ➜ resonant annihilation can lead strong dependence on temperature and correspondingly large changes in the freeze-out process

- A + A $\longleftrightarrow$ B + B processes dominate
  - Can have process of type A + C $\longleftrightarrow$ B + B
  - Can have processes of the type A + A $\longleftrightarrow$ A + A + A ➜ Strongly Interacting Massive Particles
- Scattering interactions are strong enough to achieve thermal equilibrium i.e. same rate of forward and backward processes ➜ Feebly Interacting Massive Particles

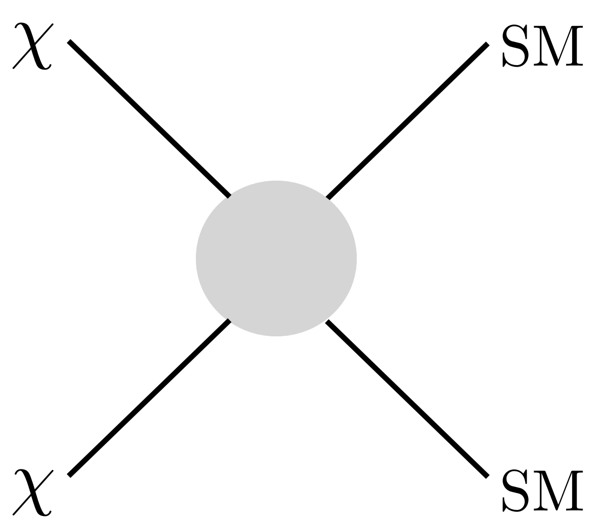
2 ➜ 2 interactions can be a generic SM - DM interaction mechanism but may not generate relic density

DM direct detection



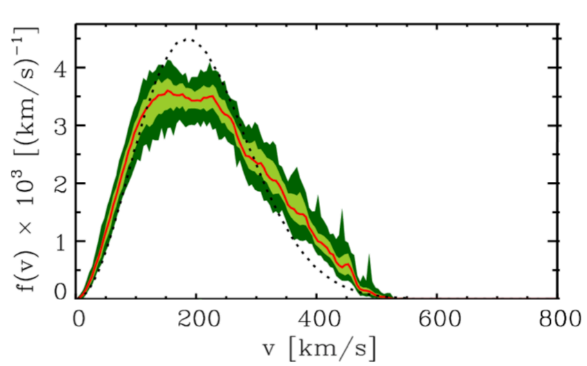
DM direct detection

- Despite all the caveats mentioned, WIMP paradigm motivated some great ways to look for DM particles, today these experimental avenues constrain non-WIMP scenarios as well



- SM = quarks; dark matter can scatter with nucleus
- One of the very powerful dark matter search
- Depends on particle physics and astrophysical parameters
- Particle physics: How does dark matter interact with the nucleus?

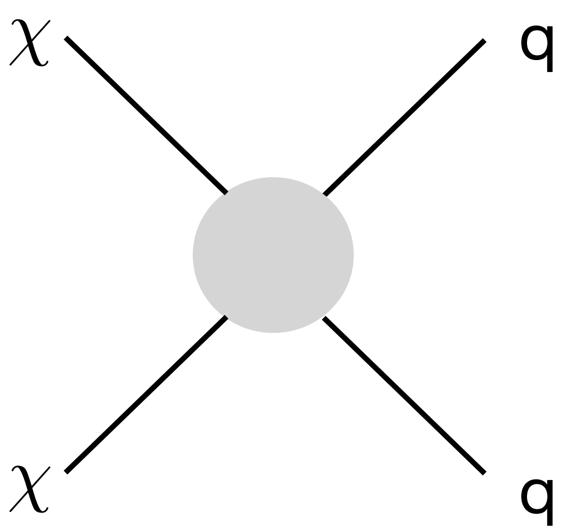
- Astrophysics: How much dark matter is really present in the solar system/around the Earth and how is it distributed



- Talked about the velocity distribution on slide 8

DM direct detection

- Let us consider how to deal with particle physics quantities
- Inherently depends on the interaction Lagrangian
- Case 1: 4 point effective operator



$$\mathcal{L}_{\text{eff}} = g_\phi \, \bar{\chi} \, \chi \, \bar{Q} \, Q$$

Note: g_ϕ dimension full in general

$$g_\phi = \frac{g_{\text{DM}} g_{\text{SM}}}{M_{\text{med}}^2}$$

Similar to Fermi interaction

- Our job is as follows:
  - Write partonic amplitude for this process
  - Translate to coupling to **neutrons** and **protons** from coupling to quarks
  - Translate to coupling to **nucleus**
  - Take non-relativistic limit of scattering amplitude
  - Relate to differential cross section by averaging/ summing initial and final state spins

DM direct detection

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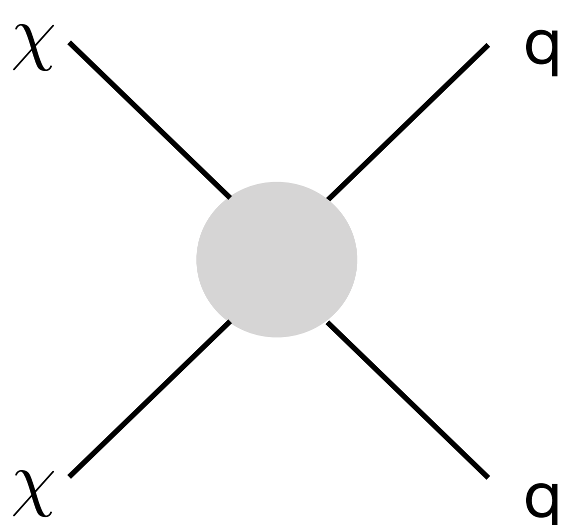
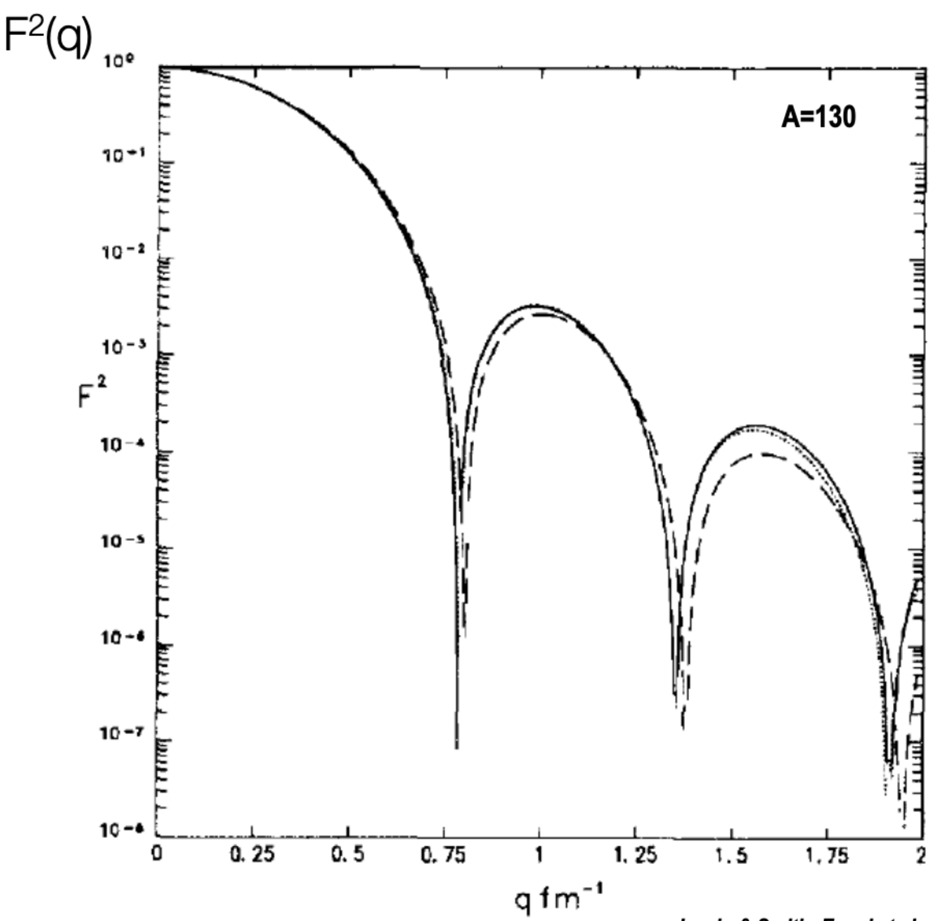




Lewin & Smith; Engel et al

- Coupling to proton expressed as function couplings to quark and gluon $m_p f^p_{T_q} \equiv \langle p \,|m_q \bar{Q} Q|\, p\rangle$

$$f_p = \sum_{q=u,d,s} m_p \frac{g_\phi}{m_q} f^p_{T_q} + \frac{2}{27} f^p_{TG} \sum_{q=c,b,t} m_p \frac{g_\phi}{m_q}$$

- Small momentum transfer ➜ no form factors for neutron or proton

$$\mathcal{M} = f_p \, \bar{\chi} \, \chi \, \bar{p} \, p + f_n \, \bar{\chi} \, \chi \, \bar{n} \, n \, .$$

- Convert to coupling to nucleon

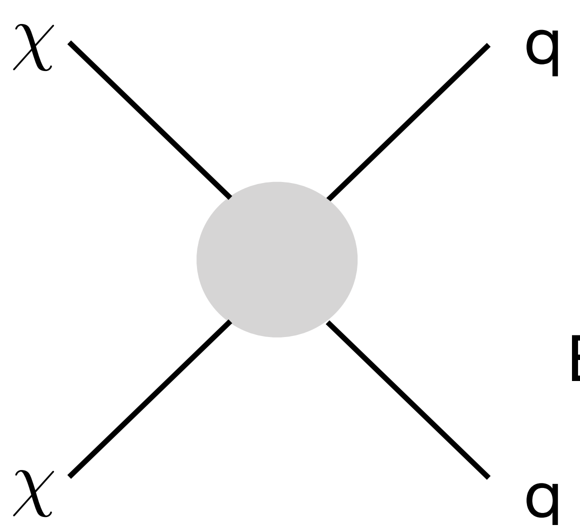
$$\mathcal{M} = [Z f_p + (A - Z) f_n] \, \bar{\chi} \, \chi \, \bar{N} \, N \, F(q)$$

- Form factor, usually one uses Helm form factor

$$F(q) = 3 e^{-q^2 s^2/2} \, \frac{\sin(q \, r_n) - q \, r_n \cos(q \, r_n)}{(q \, r_n)^3}$$

DM direct detection

$$\mathcal{L}_{\text{eff}} = g_\phi \, \bar{\chi} \, \chi \, \bar{Q} \, Q$$



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Experimental input

- Small momentum transfer ➜ no form factors for neutron or proton

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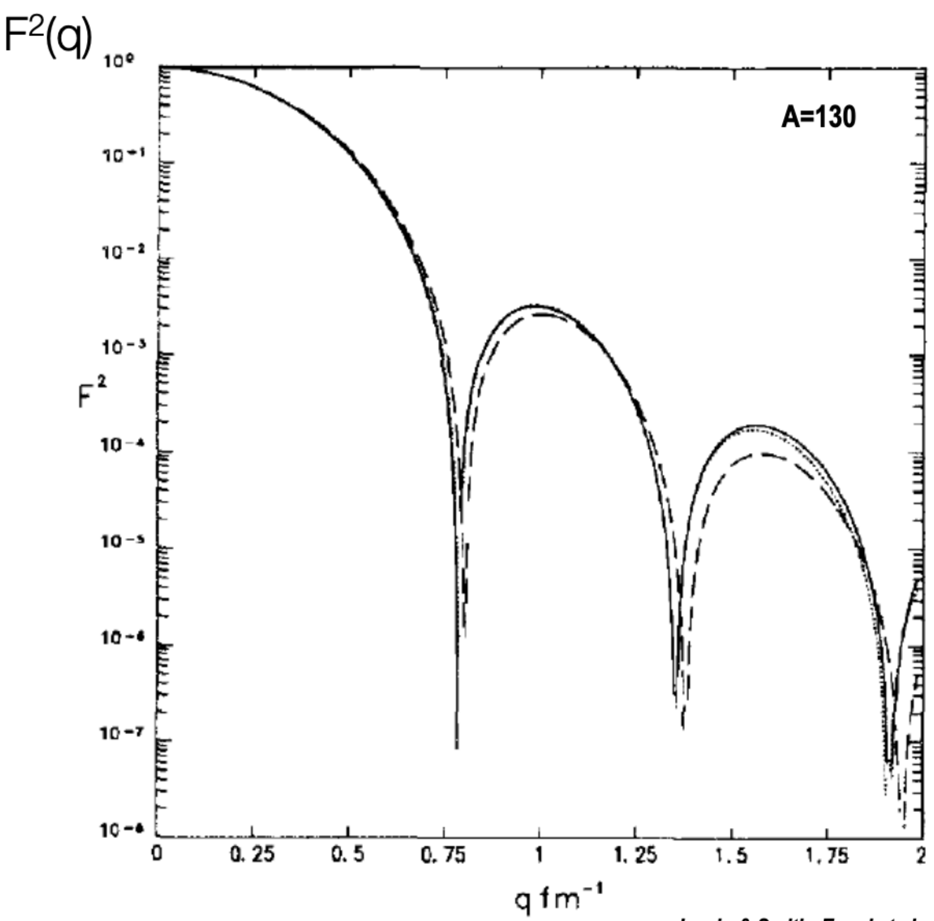

Lewin & Smith; Engel et al

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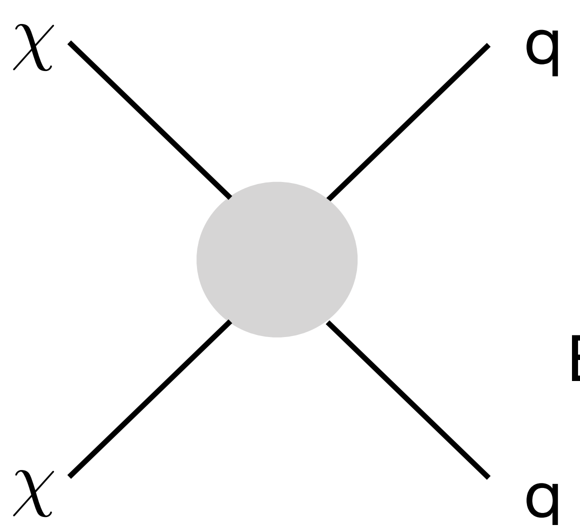

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Experimental input

Note this

- Small momentum transfer ➜ no form factors for neutron or proton

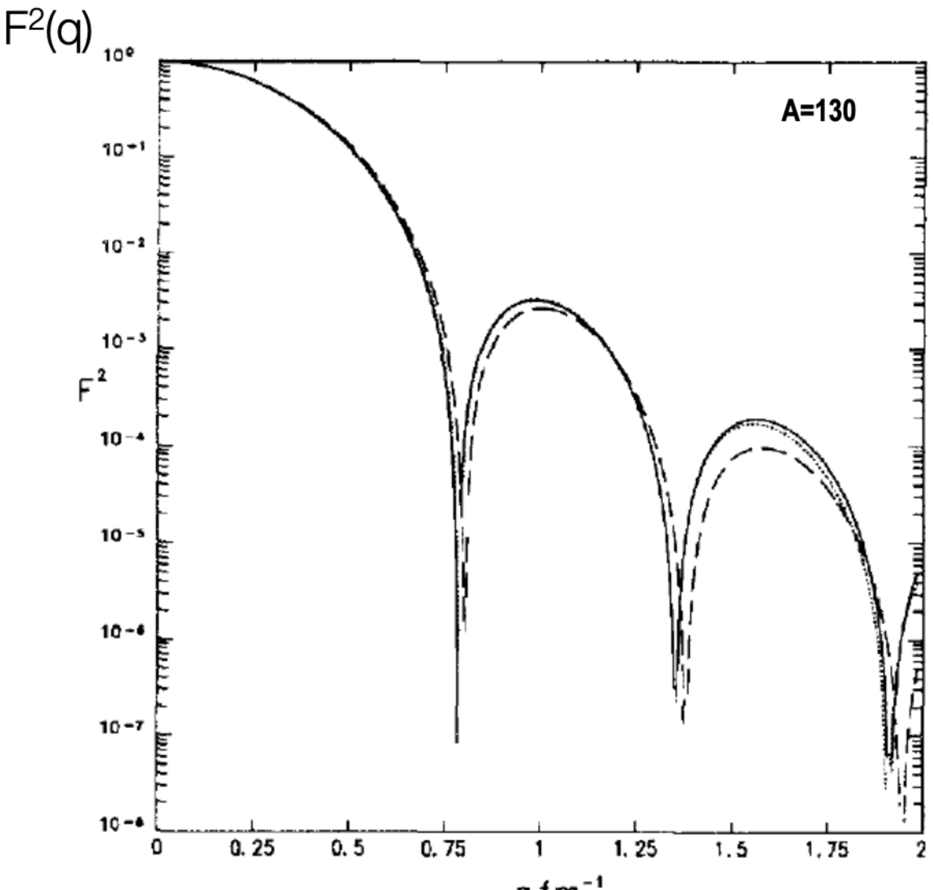
$$\mathcal{M} = f_p\, \bar\chi\, \chi\, \bar p\, p + f_n\, \bar\chi\, \chi\, \bar n\, n\,.$$

- Convert to coupling to nucleon

$$\mathcal{M} = [Z f_p + (A - Z) f_n]\; \bar\chi\, \chi\, \bar N\, N\, F(q)$$

- Form factor, usually one uses Helm form factor

$$F(q) = 3 e^{-q^2 s^2/2}\, \frac{\sin(q\, r_n) - q\, r_n \cos(q\, r_n)}{(q\, r_n)^3}$$



Lewin & Smith; Engel et al

DM direct detection

$$N^s(p) = \begin{pmatrix} \sqrt{p\cdot\sigma}\,\xi^s \\ \sqrt{p\cdot\bar{\sigma}}\,\xi^s \end{pmatrix} \qquad \sqrt{p\cdot\sigma} \approx \sqrt{m_N - \mathbf{p}\cdot\sigma} \approx \sqrt{m_N}\left(1 - \frac{\mathbf{p}\cdot\sigma}{2m_N}\right)$$

$$\frac{d\sigma}{dE_R} = \frac{2m_N}{\pi v^2}\frac{1}{(2J+1)(2s_\chi+1)}\sum_{\text{spins}}\left[Zf_p + (A-Z)f_n\right]^2 \; F^2(q)\left|\xi^{s'\dagger}\xi^s\right|^2\left|\xi^{r'\dagger}\xi^r\right|^2$$

$$\frac{1}{2s_\chi+1}\sum_{r',r=1,2}\left|\xi^{r'\dagger}\xi^r\right|^2 = \frac{1}{2s_\chi+1}\sum_{r',r}\mathrm{tr}\left[\xi^{r'}\xi^{r'\dagger}\xi^r\xi^{r\dagger}\right] = \frac{1}{2}\mathrm{tr}\,[1] = 1$$

$$\frac{d\sigma}{dE_R} = \frac{2m_N}{\pi v^2}\left[Zf_p + (A-Z)f_n\right]^2 \; F^2(q)$$

- For $f_p = f_n$, amplitude proportional to A^2, popular A^2 enhancement factor for Spin-Independent direct detection
- Can be physically understood as the DM has larger wavelength than the size of the nucleus

DM direct detection

$$\frac{d\sigma}{dE_R} = \frac{2m_N}{\pi v^2}\left[Z f_p + (A - Z) f_n\right]^2 \; F^2(q)$$

- Where is the relationship to the mediator mass and the σ_{SI} plotted on direct detection plots?
- Assume $f_p = f_n$

$$\frac{d\sigma}{d\,E_R} = \frac{2m_N}{\pi\,v^2} A^2\, f_p\, F^2(q)$$

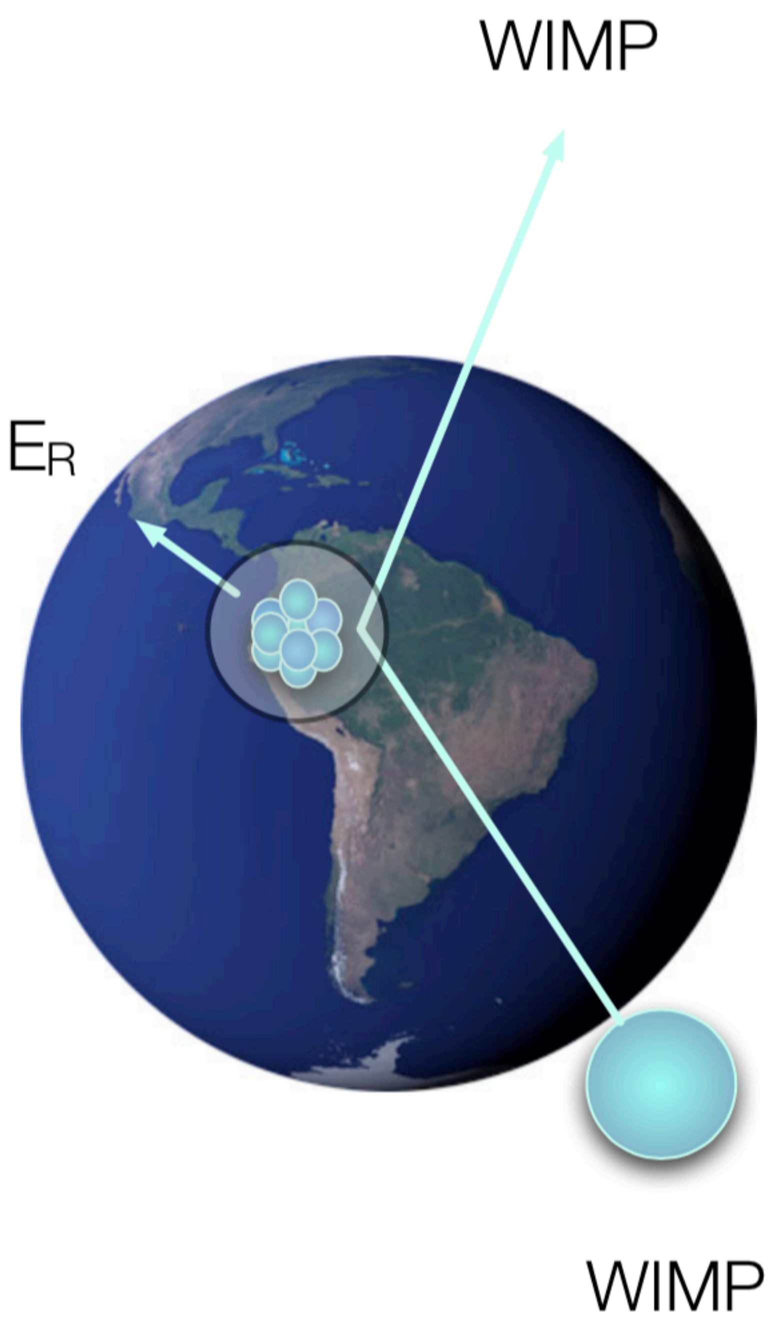
$$\frac{d\sigma}{d\,E_R} = \frac{2m_N}{\pi\,v^2} A^2\, F^2(q)\, f'_p \left(\frac{g^2_{\mathrm{DM}} g^2_{\mathrm{SM}}}{M^4_{med}}\right)$$

$$= \frac{2m_N}{\pi\, m_r^2\, v^2} A^2 F^2(q) f'_p \left(\frac{g^2_{\mathrm{DM}} g^2_{\mathrm{SM}}}{M^4_{\mathrm{med}}} m_r^2\right)$$

$$f_p = \sum_{q=u,d,s} m_p \frac{g_\phi}{m_q} f^p_{T_q} + \frac{2}{27} f^p_{T_G} \sum_{q=c,b,t} m_p \frac{g_\phi}{m_q}$$

- Pull out g_ϕ define remaining to be f'_p

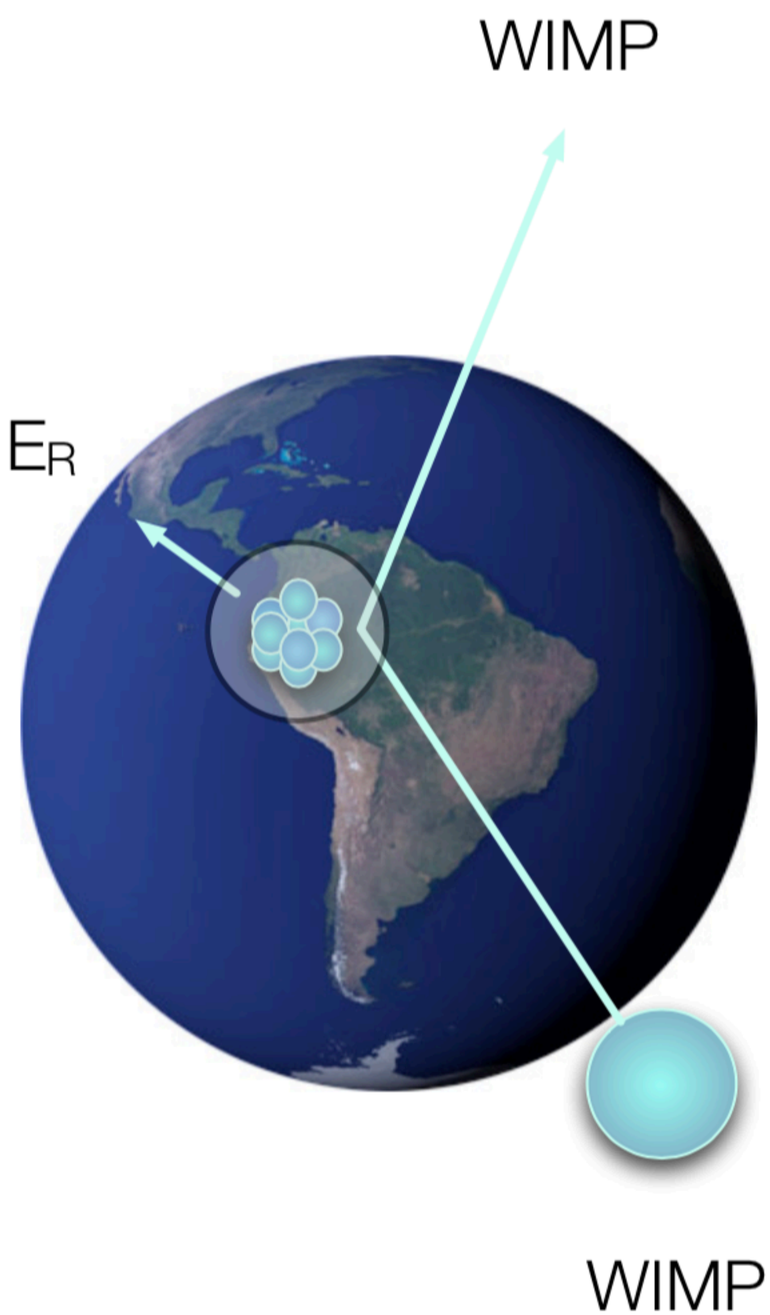
DM direct detection



- Experiment: We want to observe the “kick” induced by a non-relativistic dark matter particle in target made of composite system i.e. nucleus

- Few questions:
  - **‘Scale’ of this process** - i.e. what is the energy at which this process can be observed (determines threshold of the experiment)
  - **Shape of the processes** - how big an apparatus should this be?
  - **Rate of the processes** - how big an apparatus should this be?
  - **Backgrounds**

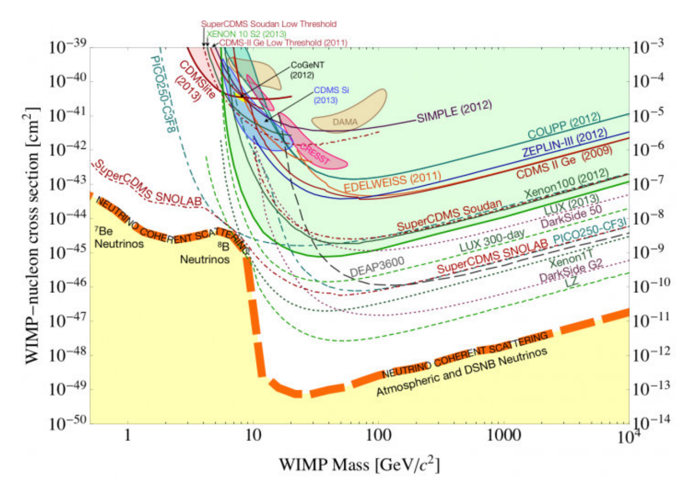
DD - Scale of the process



- Elastic collision between WIMPs and target nuclei

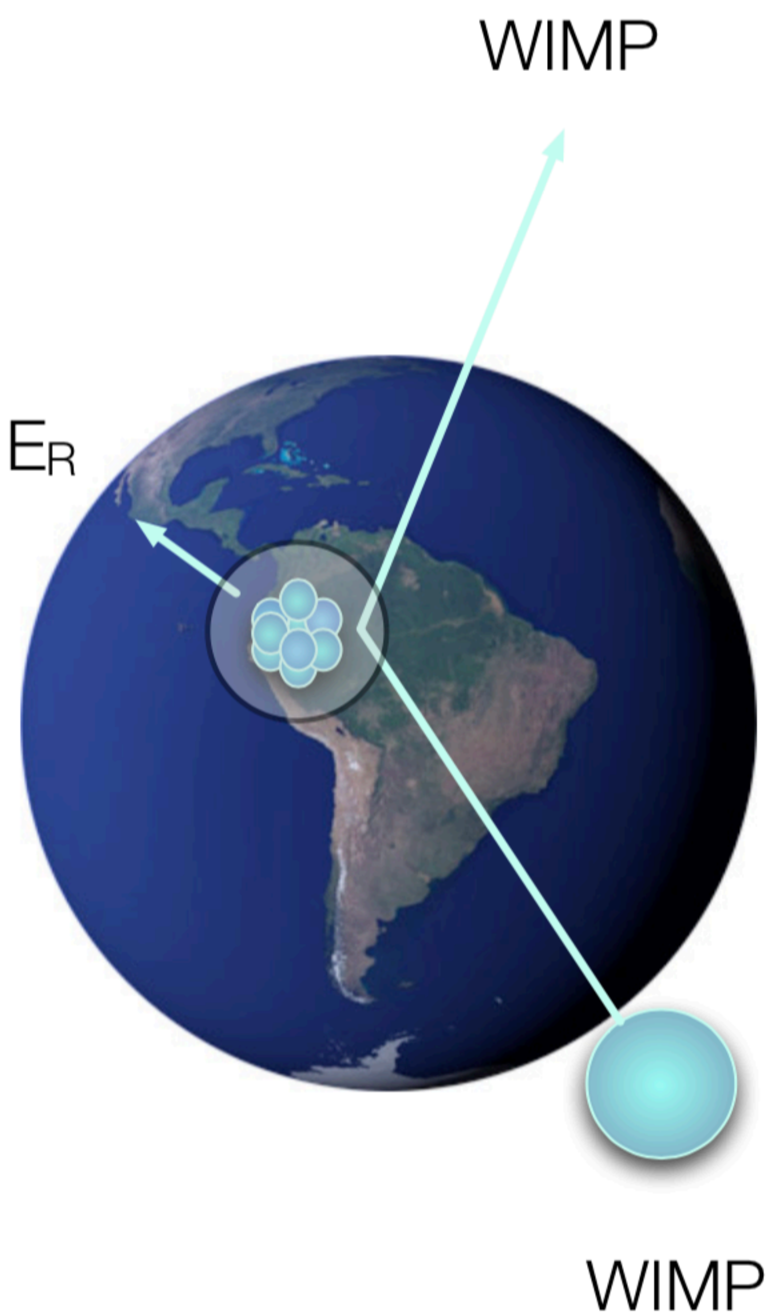
$$E_r = \left(\frac{m_\chi}{2} v^2\right) \times \frac{4\, m_N\, m_\chi}{(m_N + m_\chi)^2} \times \cos^2\theta_r$$

- Mean WIMP velocity relative to target: v~ 200km/s
- Scattering angle in center of mass system: θ_r
- WIMP mass = m_χ = 1 - 1000 GeV
- Nucleus mass = A * m_p = 100 GeV (e.g. Xenon)
- Typical recoil energies : 1 - 100 keV [Verify]
- If mediator > MeV, interactions are effective at direct detection experiments
- Limits on cross sections are only a function of dark matter mass



DD - Shape of the process

Applies to SI interactions only



- Typically used parametrisation

Interaction between on DM and one nucleus

$$\frac{d\sigma}{dE_R} = \frac{2m_N}{\pi v^2}\left[Zf_p + (A-Z)f_n\right]^2 F^2(q)$$

For a given DM particle velocity

- Reduced mass of the system: m_r
- Form factor, describes structure of the nucleus: F(q), F(0) = 1, target dependent, for multi-target experiments, one can sum over
- DM - nucleus cross section: σ_0 (for F(q) = 1)
- Two more questions arise:
  - How many target nuclei and DM particles are there ?
  - What is the velocity distribution of dark matter particles?

DD - Shape of the process

- Number of dark matter particles around us: $\frac{\rho_0}{m_{\rm DM}}$
- Velocity distribution of dark matter particles: $f(v)\,dv$

- Facts:
  - We do not precisely know the local density of dark matter, our **best measurement has 50% error** [see e.g this]
  - We do not precisely know the velocity distribution of dark matter particles in galaxy, we use **Maxwell-Boltzmann**

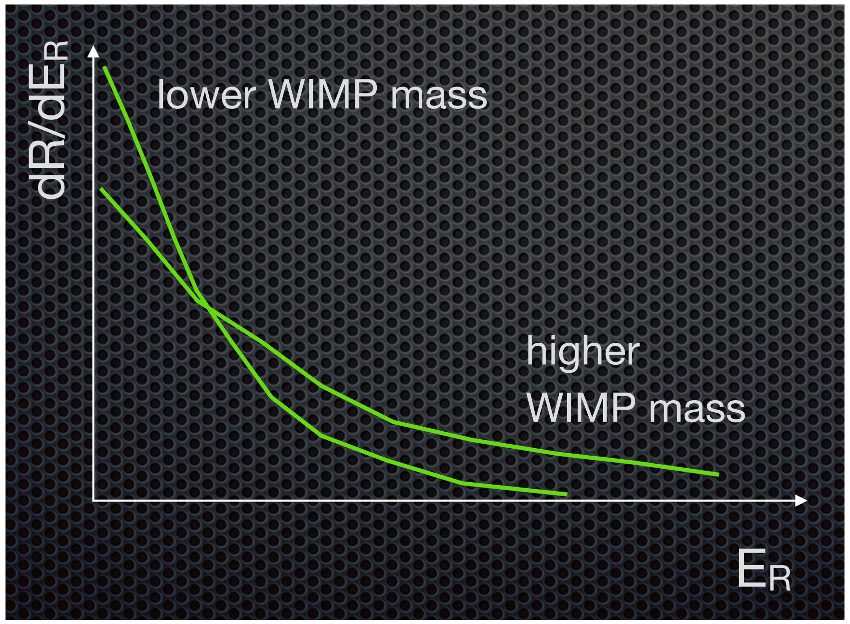
- Total rate

$$\frac{dR}{dE_R} = \frac{N_A}{A}\frac{\rho_0}{m_{\rm DM}}\int_{v_{min}}^{v_{max}} f(v)\,dv\,v\,\frac{d\sigma}{dE_R}$$

- Recoil rate per unit target mass (assuming σ α 1/v^2 as shown before)

$$\frac{dR}{dE_R} = \frac{N_A}{A}\frac{\rho_0}{m_{\rm DM}}\frac{\sigma_0}{2\,m_r^2}F^2(q)\int_{v_{\rm min}}^{v_{\rm max}} dv\,\frac{f(v)}{v}$$

DD - Shape of the process



- Facts:
  - No sharp feature e.g. peak
  - Most of the signal at low recoil energies
    - Need detectors with low threshold
    - Reason for low threshold detectors

- Recoil rate per unit target mass

$$\frac{dR}{dE_R} = \frac{N_A}{A}\frac{\rho_0}{m_{\rm DM}}\frac{\sigma_0}{2\,m_r^2}F^2(q)\int_{v_{\rm min}}^{v_{\rm max}} dv\,\frac{f(v)}{v}$$

- Assuming:

$$f(v) \sim exp(-v^2/v_0^2)$$

- Shape of DM recoil spectra:

$$\frac{dR}{dE_R} = exp\Big(-\frac{m_N\,E_R}{2m_r^2\,v_0^2}\Big)$$

Fast falling exponential

DD - Rate of the process

- Recoil rate per unit target mass

$$\frac{dR}{dE_R} = \frac{N_A}{A}\frac{\rho_0}{m_{\mathrm{DM}}}\frac{\sigma_0}{2m_r^2}F^2(q)\int_{v_{\min}}^{v_{\max}}\frac{f(v)}{v}dv$$

- Expected recoil rates from DM detectors

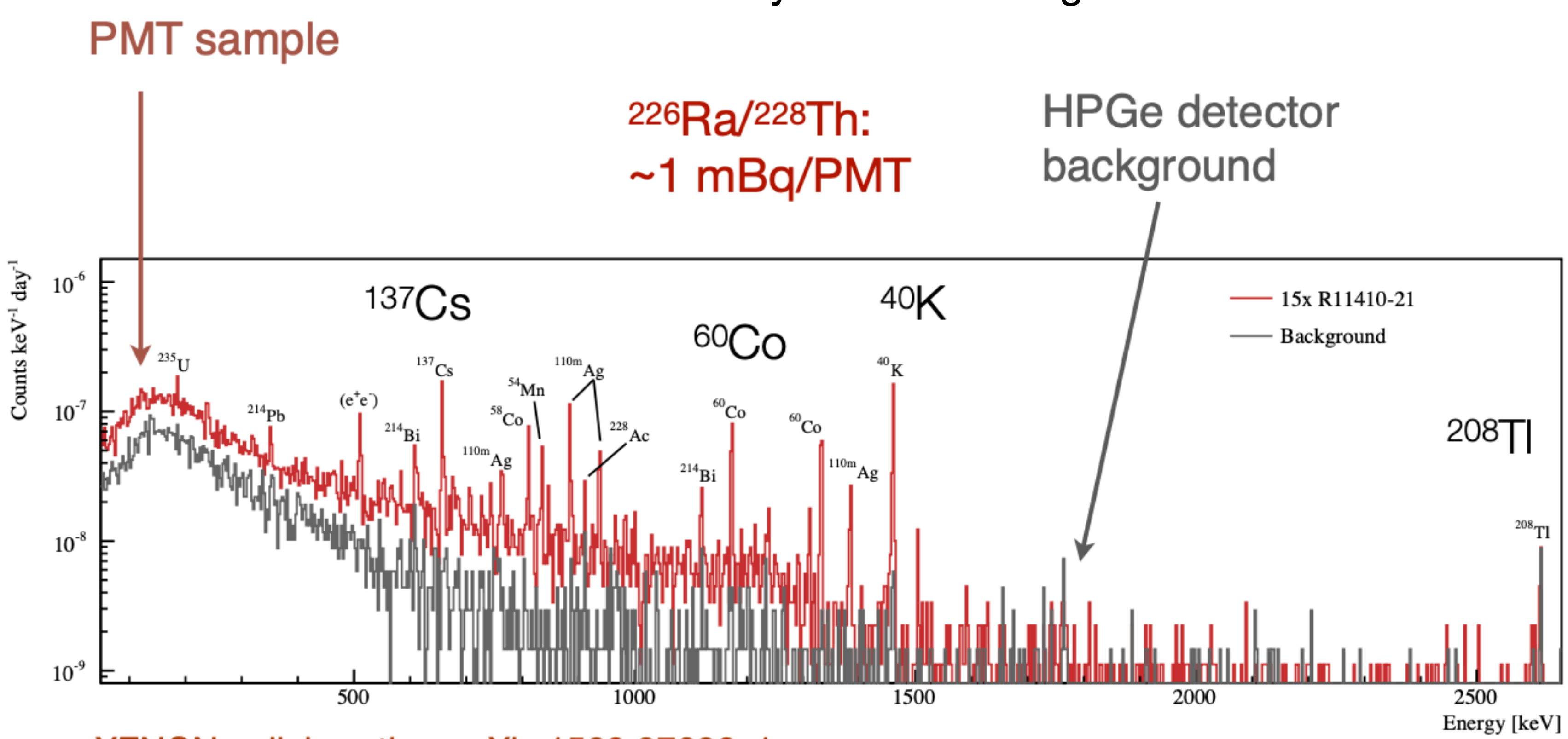
$$R \sim 0.13\frac{\text{events}}{\text{kg year}}\left[\frac{A}{100}\times\frac{\sigma_0}{10^{-38}\text{cm}^2}\frac{\langle v\rangle}{220\text{km s}^{-1}}\times\frac{\rho_0}{0.3\text{GeV cm}^{-3}}\right]$$

- Reason for going for large detectors and larger exposures

DD - Backgrounds

- **External, natural radioactivity**: ^{238}U, ^{238}Th, ^{40}K decays in rock and concrete walls of the laboratory [use shielding]
- **Internal radioactivity**: ^{238}U, ^{238}Th, ^{40}K, ^{137}Cs, ^{60}Co, ^{39}Ar, ^{85}Kr, ... decays in the detector materials, target medium and shields
- **Cosmic rays and secondary/tertiary particles**: go underground
- **Hadronic component (n, p)**: reduced by few meter water equivalent

Internal radioactivity for Xenon target



XENON collaboration, arXiv:1503.07698v1

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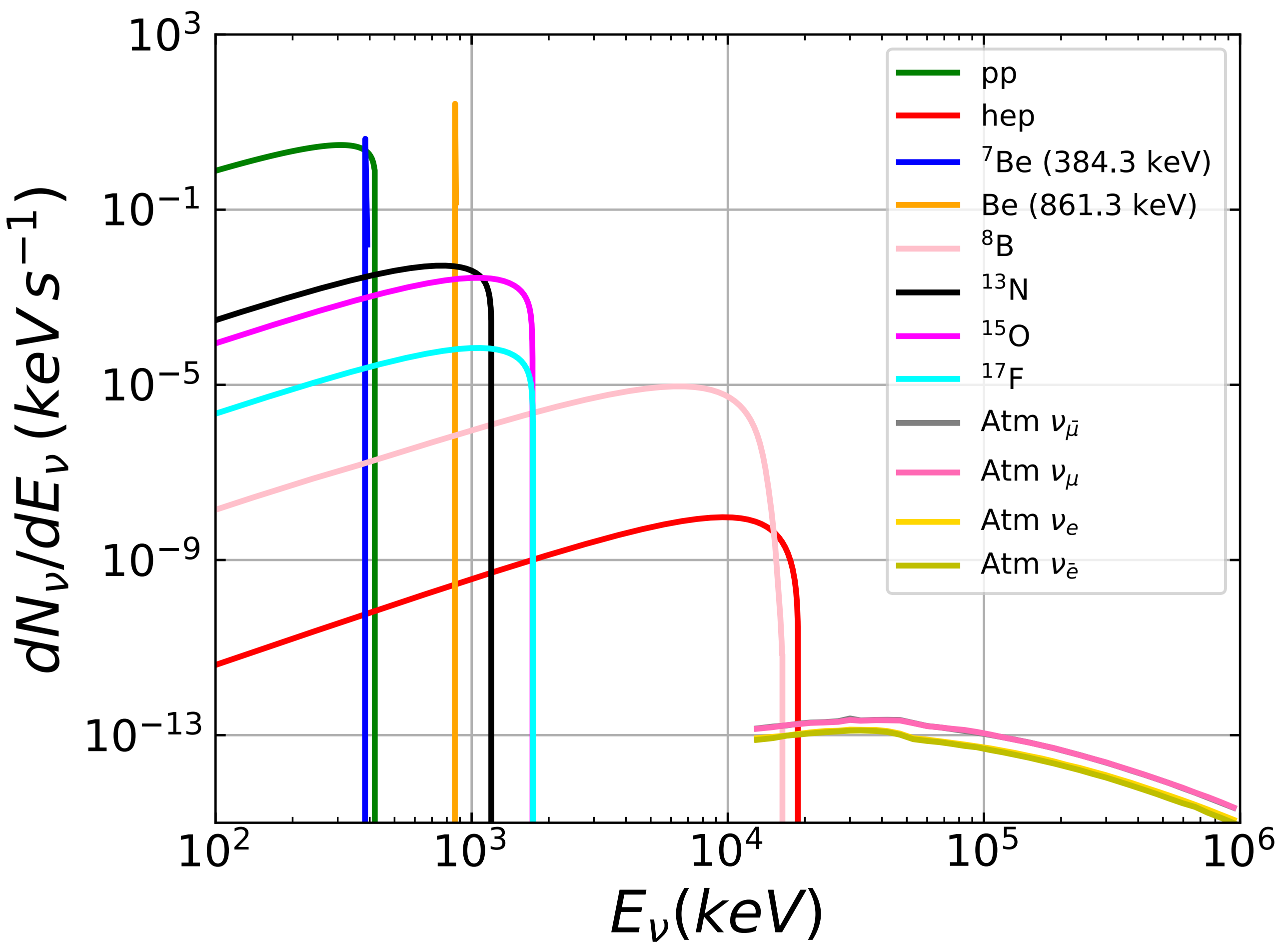
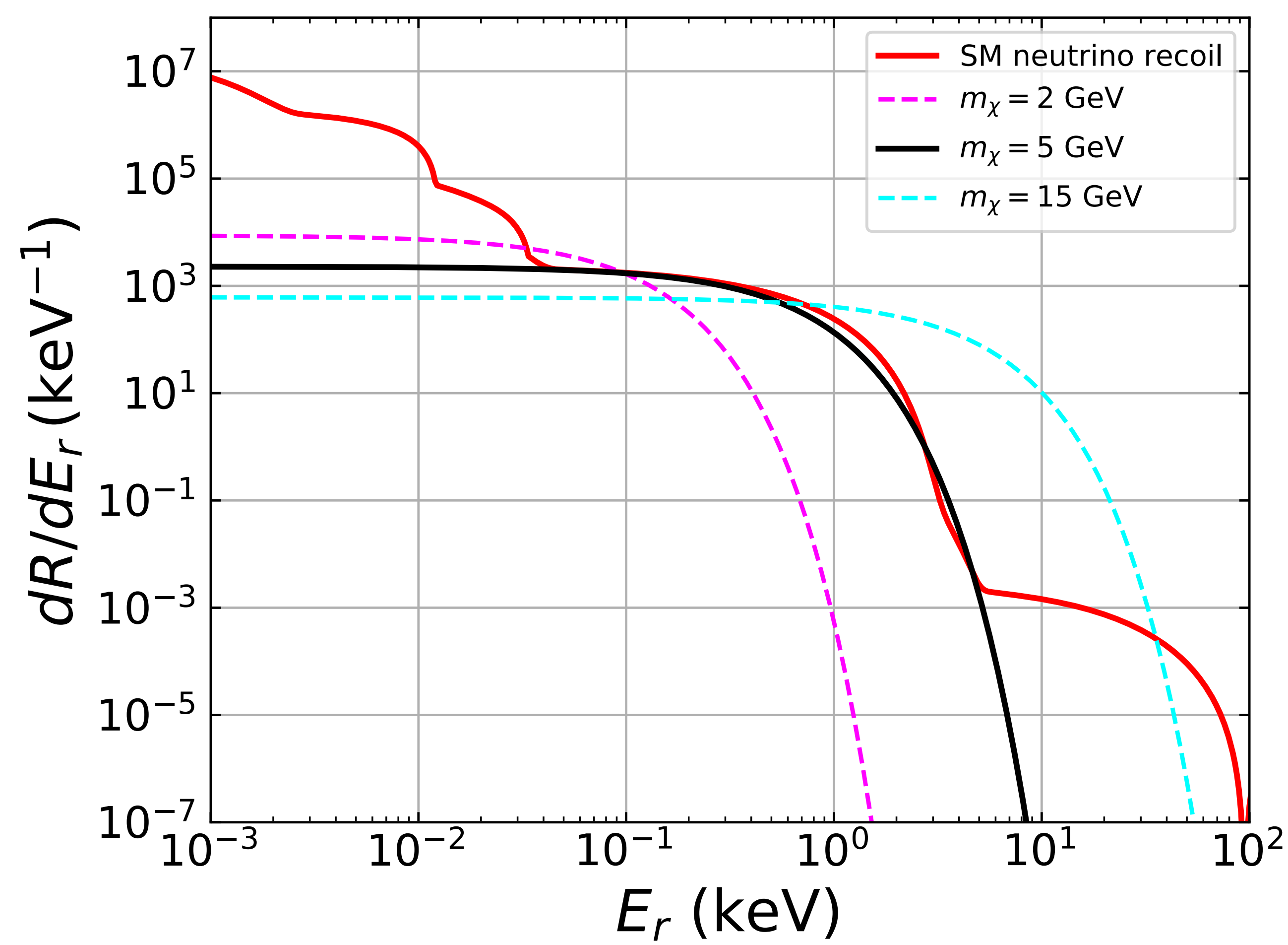
DD - Irreducible backgrounds

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

- Neutrinos are a natural and irreducible source of backgrounds for direct detection experiments
- Several sources of neutrino fluxes: solar neutrinos, atmospheric neutrinos, supernova neutrinos and anomalous neutrino fluxes
- Mimic the DM recoil at direct detection experiments
- Have not been a problem so far because the neutrino - nucleus coherent scattering is far too small compared to experimental sensitivities





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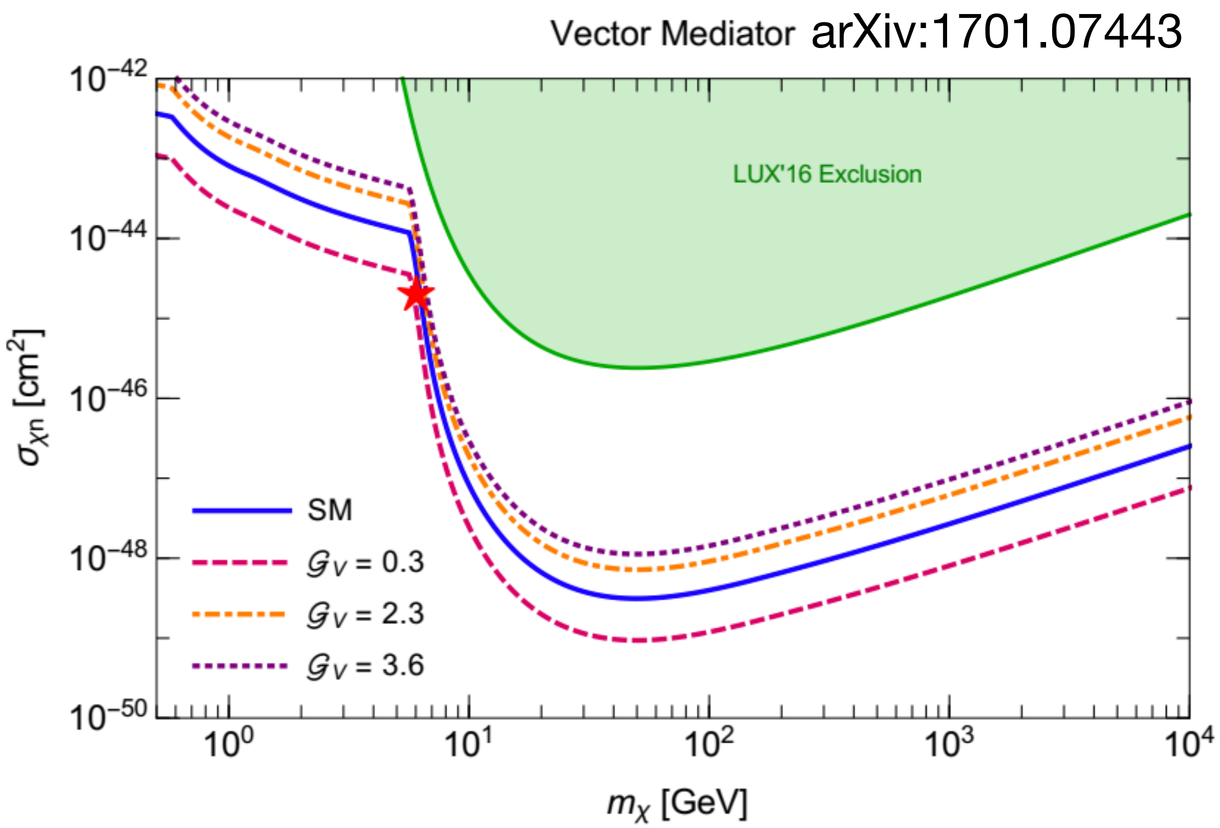
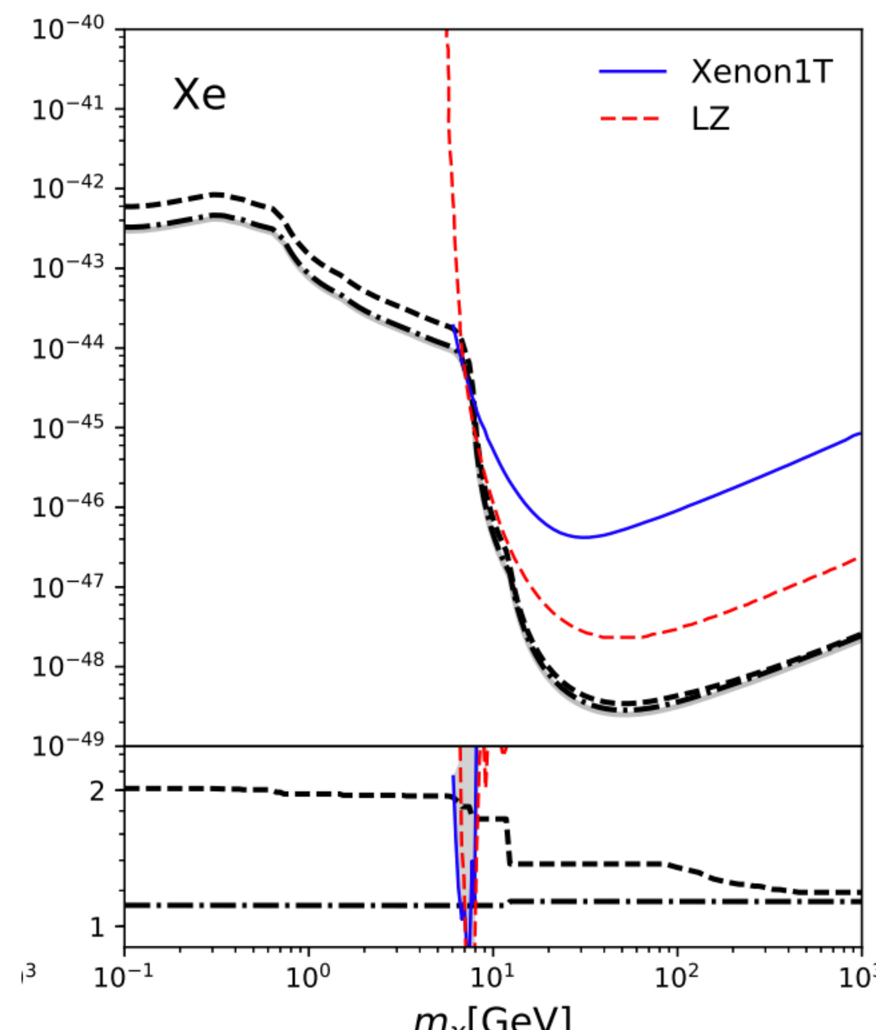
Neutrino physics at direct detection

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

- BSM physics can change neutrino coherent interaction rates at direct detection experiments
- Can change neutrino floor i.e. we may see neutrino events sooner or later than expected sensitivity from SM processes only
- Neutrino coherent scattering experiments constrain the BSM interaction strength
- We must also constrain cosmic neutrino fluxes to get exact predictions

arXiv:1701.07443





arXiv:1809.06385

Direct detection beyond EFT

- Dark matter event rate at direct detection experiment for heavy mediators

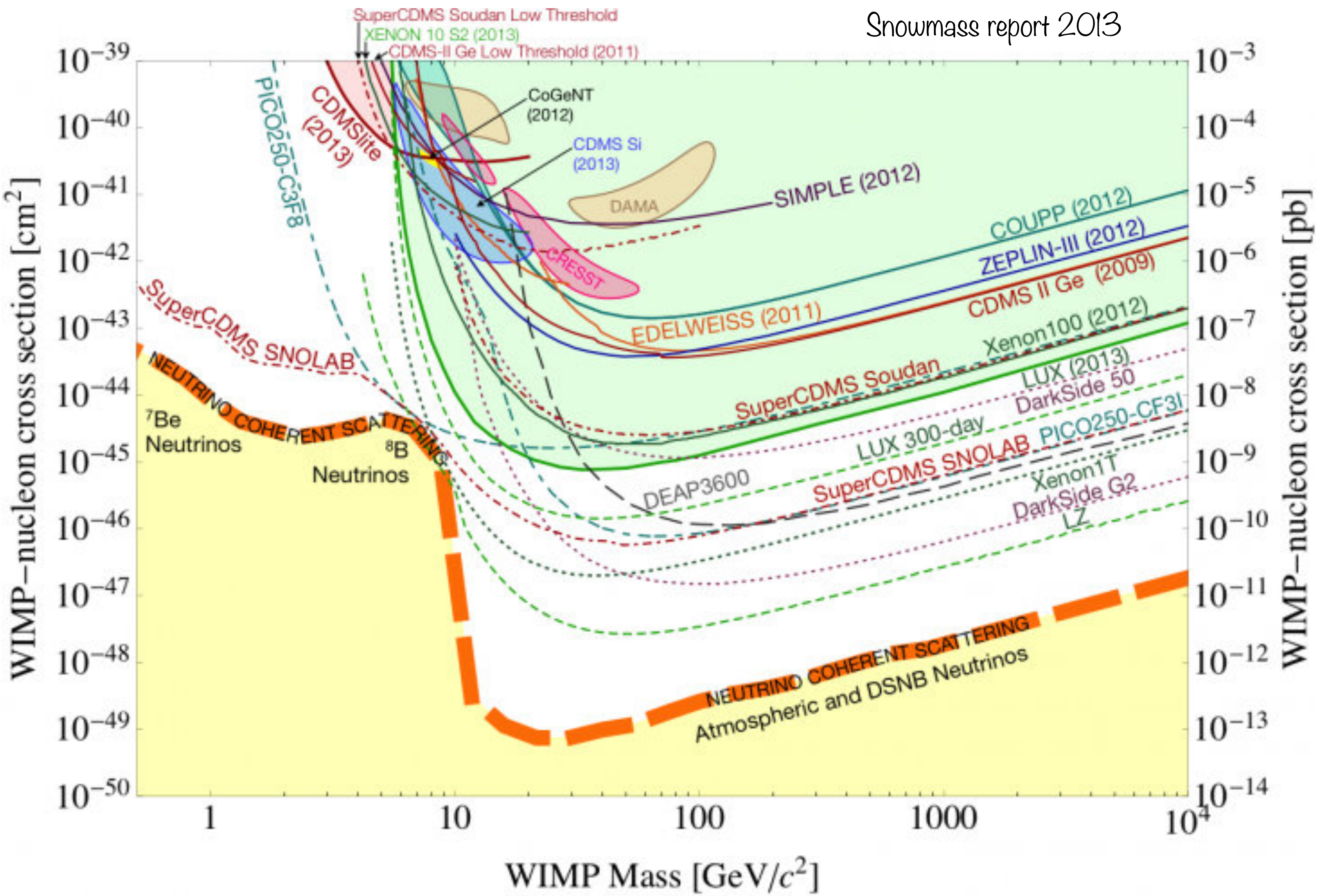
$$\frac{dR}{dE_R} = \frac{\rho_0}{m_{\rm dm}} \frac{2m_N}{m_r^2} A^2 f_p'^{} F^2(q) \Big(\frac{g_{\rm DM}^2 g_{\rm SM}^2}{M_{\rm med}^4} m_r^2 \Big) \int_{v_{\rm min}}^{v_{\rm max}} \frac{f(v)}{v} dv$$

- Dark matter event rate at direct detection experiment for light mediators

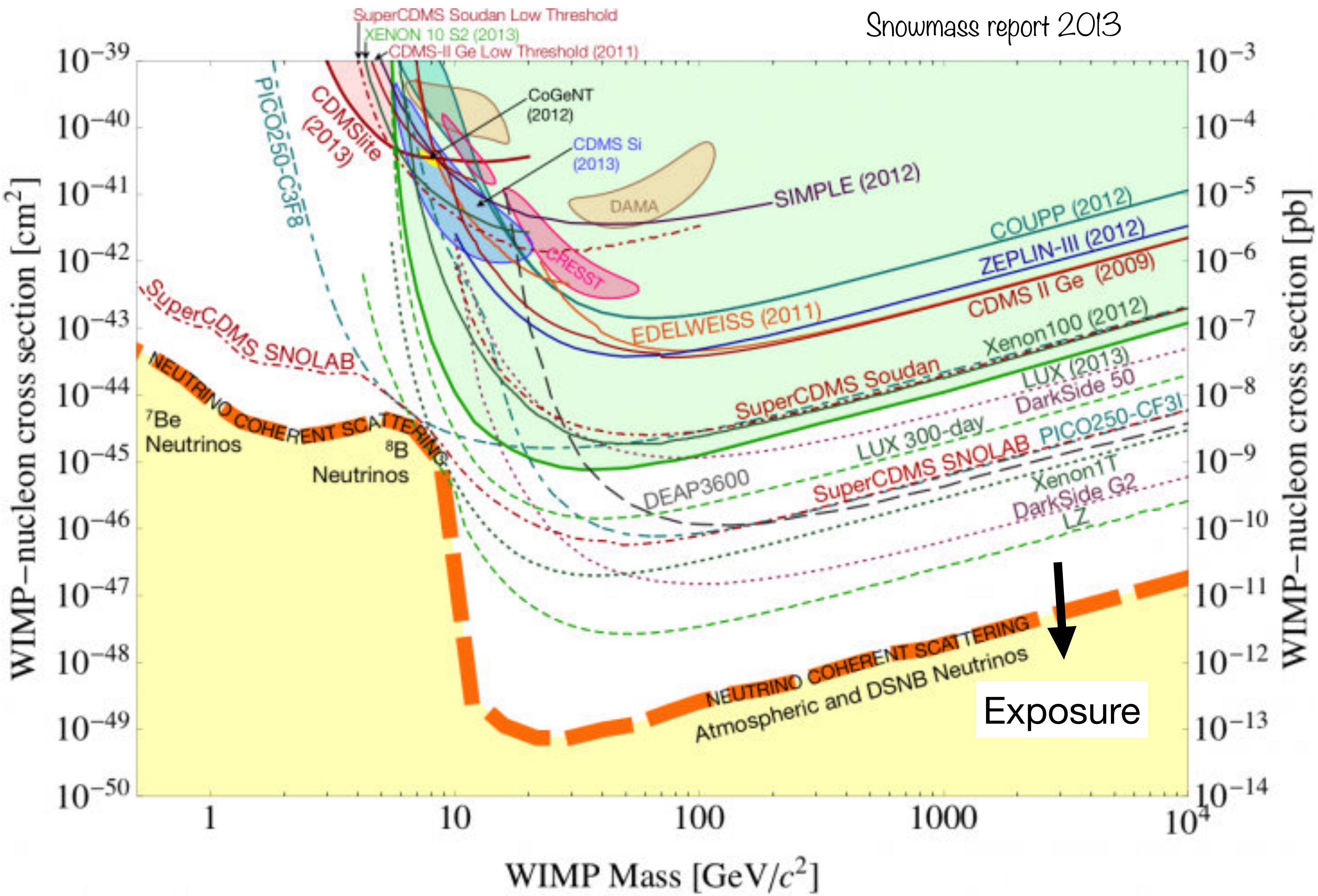
$$\frac{dR}{dE_R} = \frac{\rho_0}{m_{\rm dm}} \frac{2m_N}{m_r^2} A^2 f_p' F^2(q) \Big(\frac{g_{\rm DM}^2 g_{\rm SM}^2}{(2m_N E_R + M_{\rm med}^2)^2} m_r^2 \Big) \int_{v_{\rm min}}^{v_{\rm max}} \frac{f(v)}{v} dv$$

- Shape of differential event rate changes as soon as mediator mass is comparable to momentum transfer
- Usual limits are not applicable

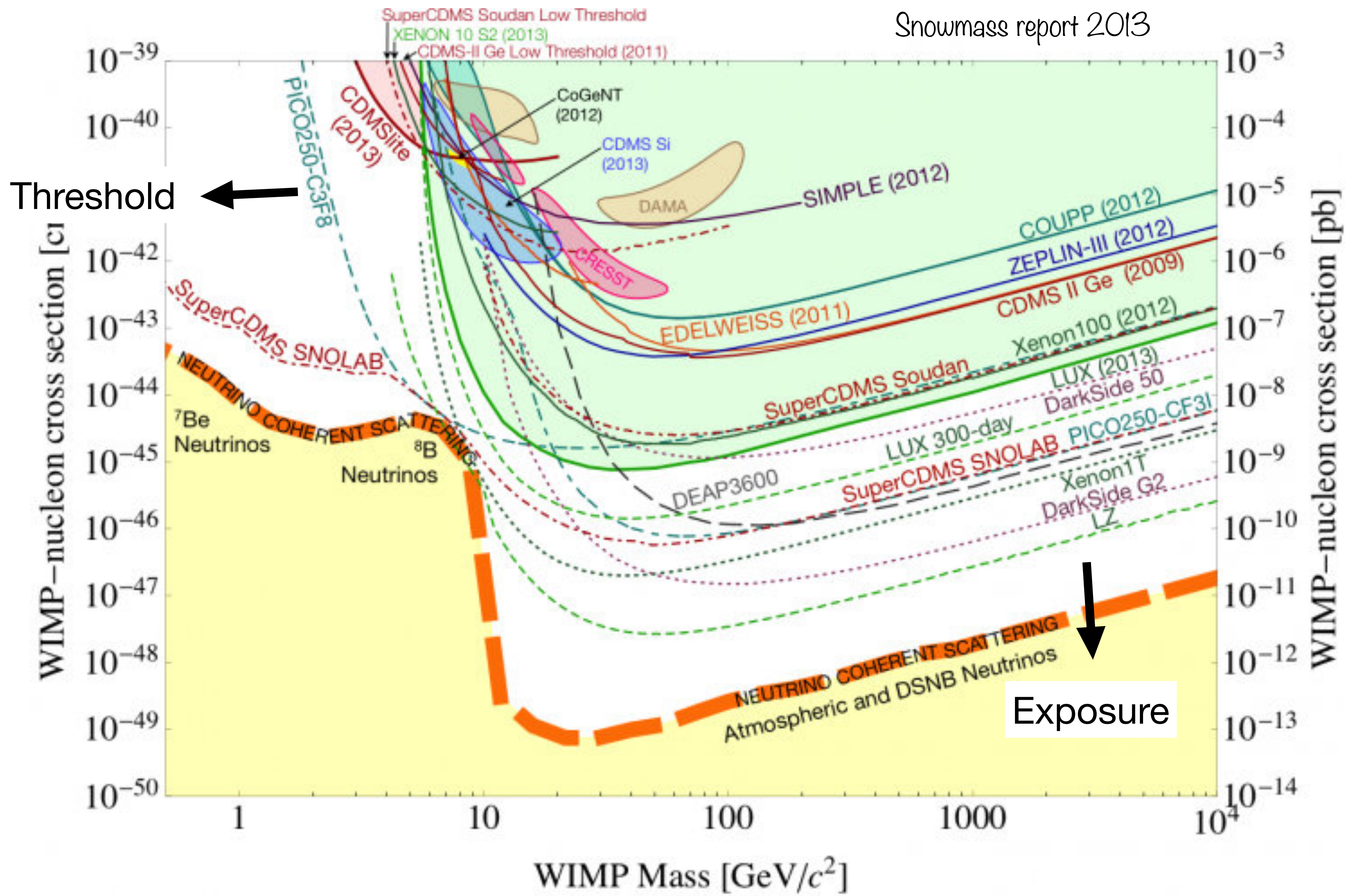
DM direct detection



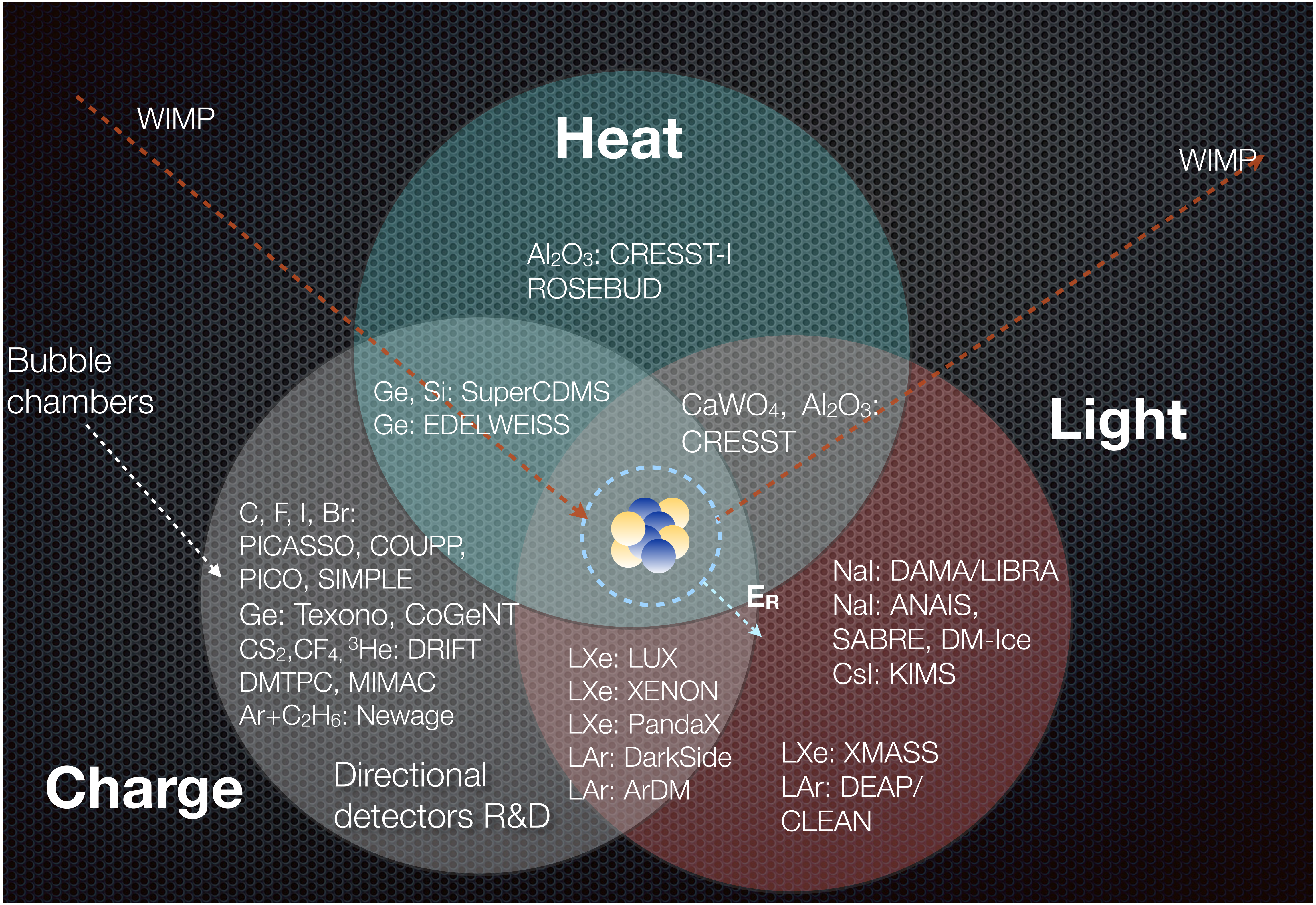
DM direct detection



DM direct detection

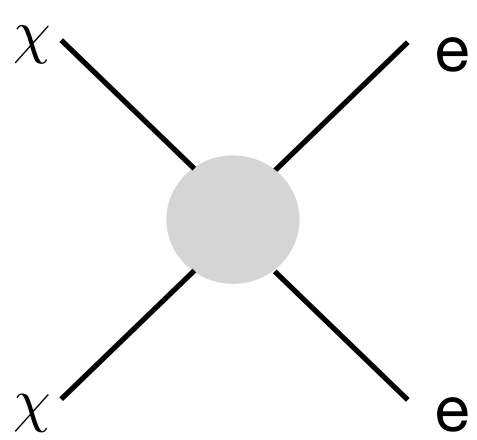


DM direct detection



Shamelessly stolen from talk by L. Baudis

Beyond DM - nucleus scattering



- What if DM scatters off electrons?
- Usually electron recoils are discarded by experiments
- New and exciting field
- Probes extremely light dark matter
- Requires computation of atomic wave functions

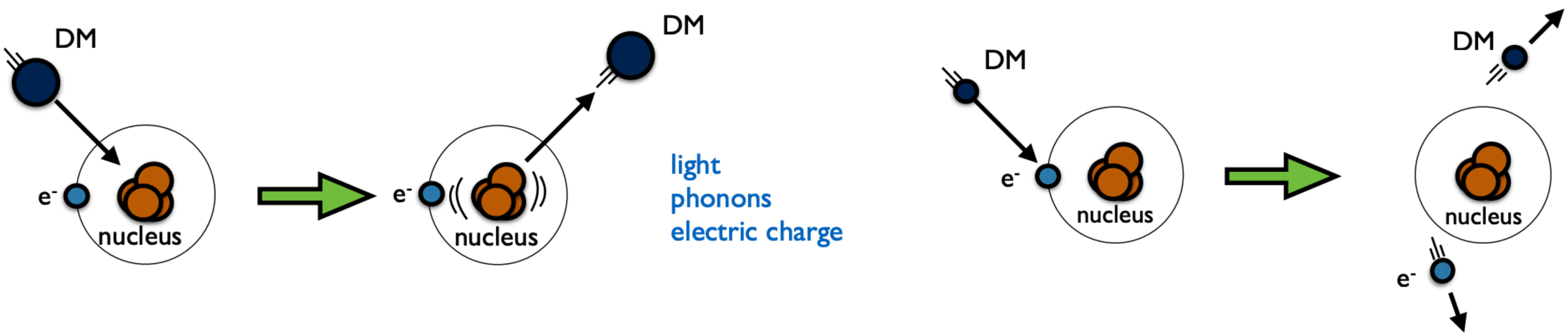
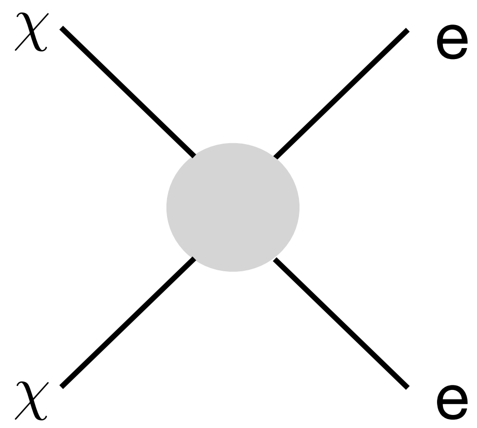


Diagram by R. Essig

Beyond DM - nucleus scattering



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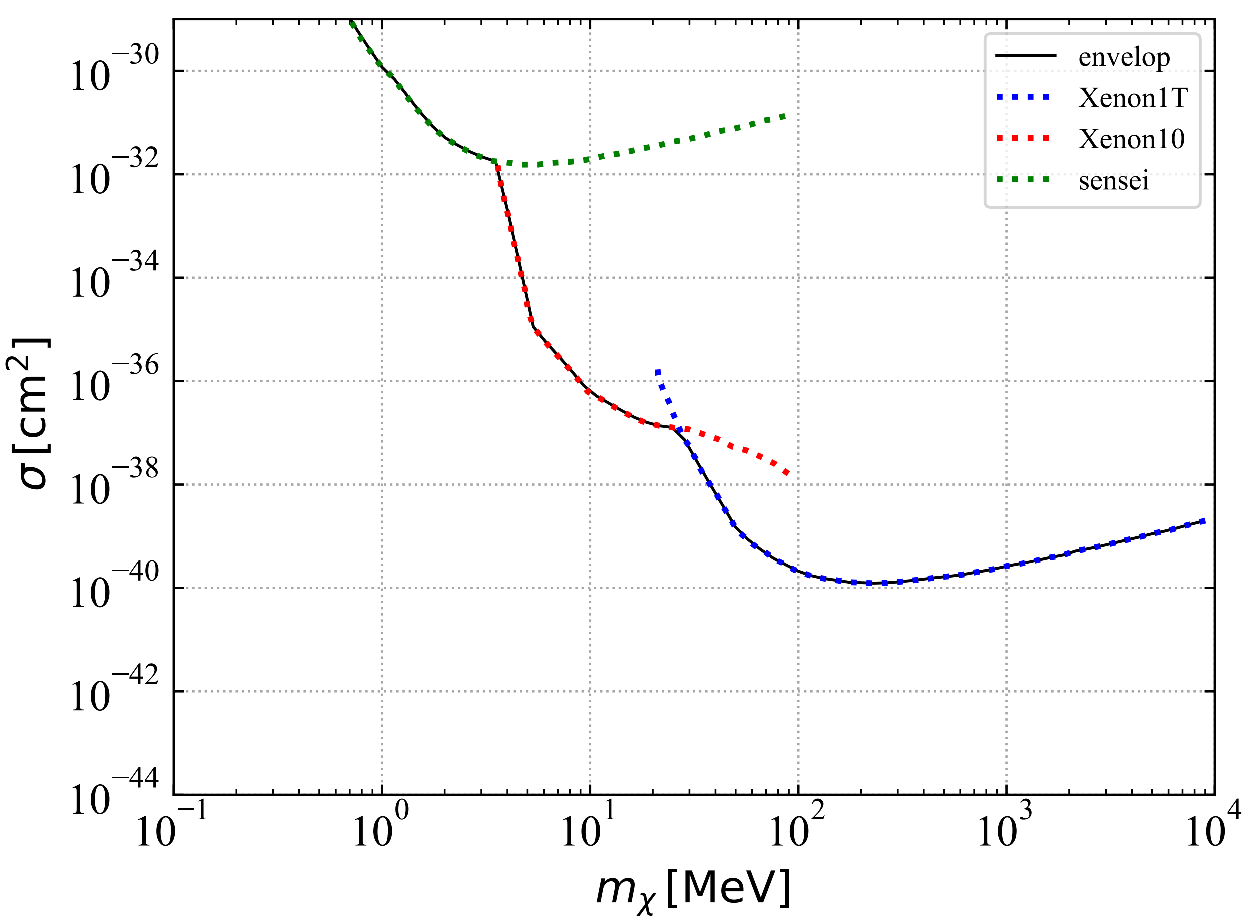
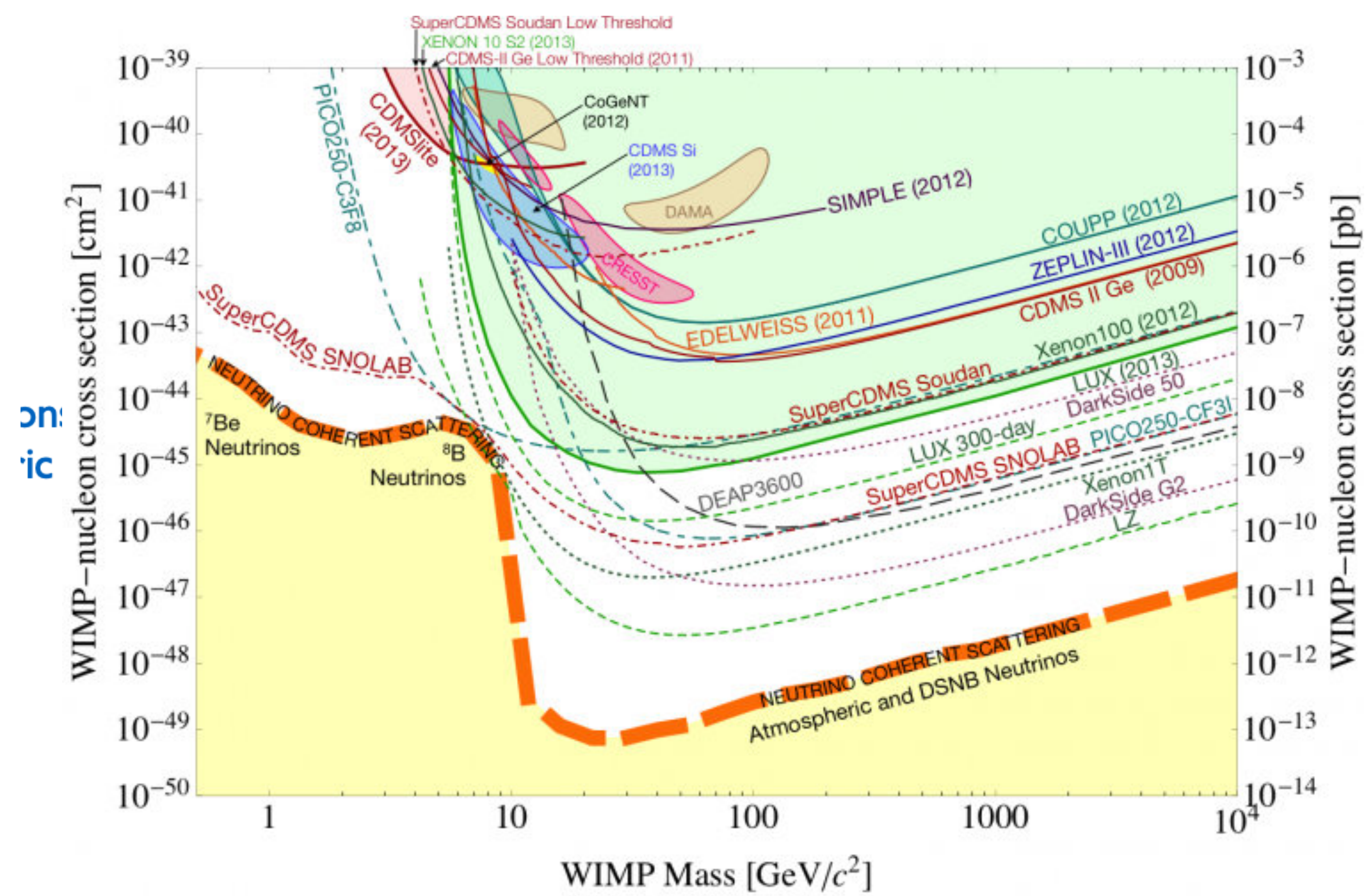
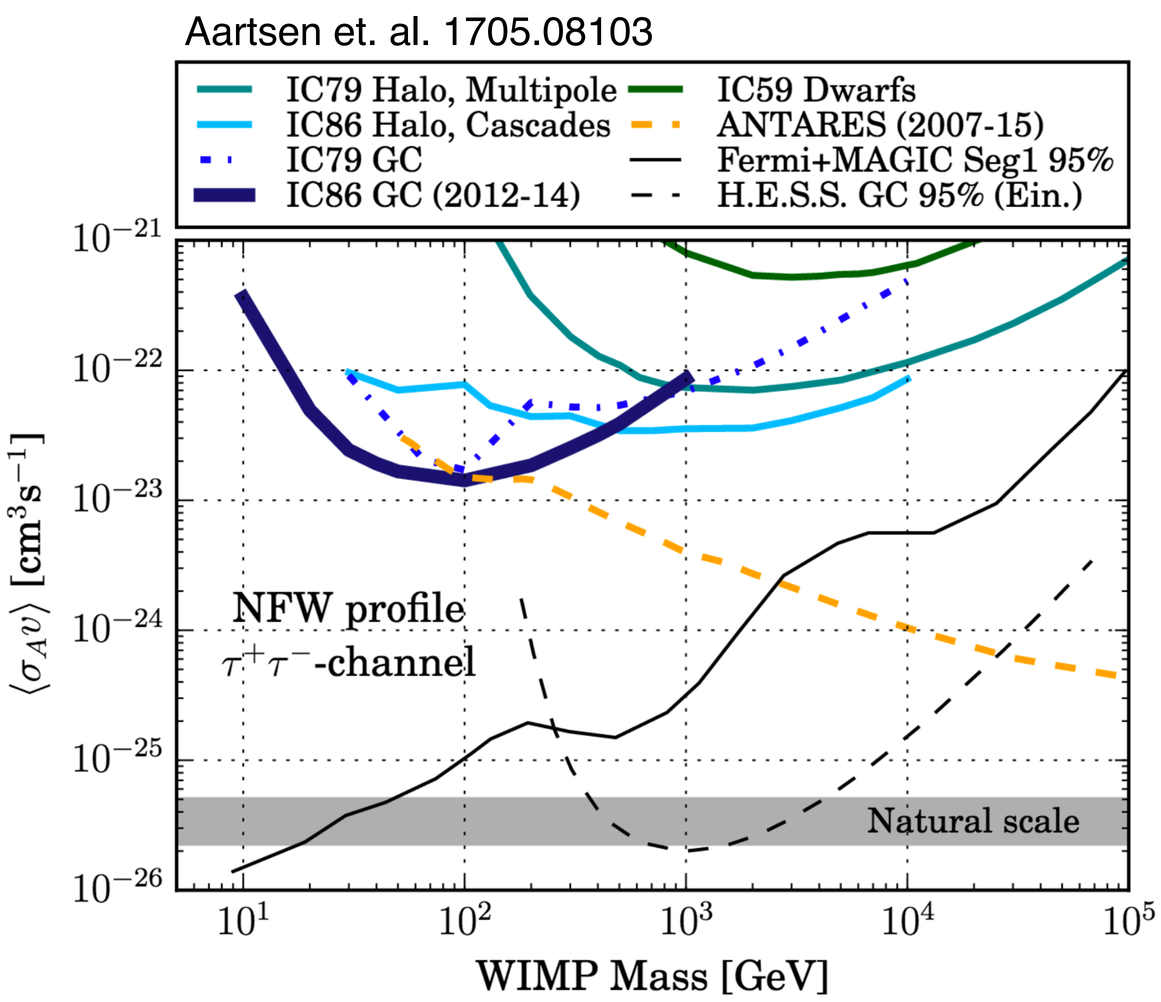
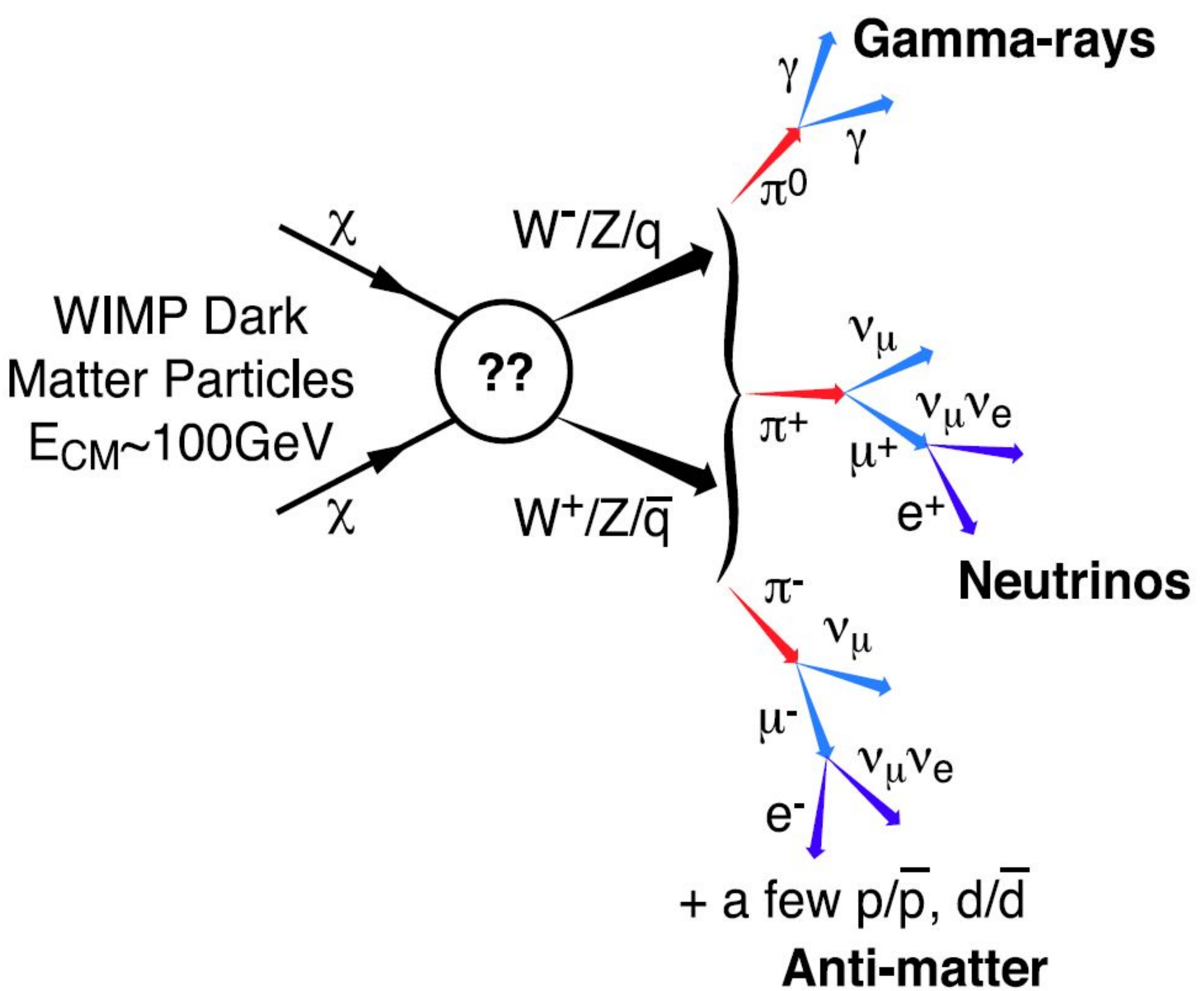




Indirect detection

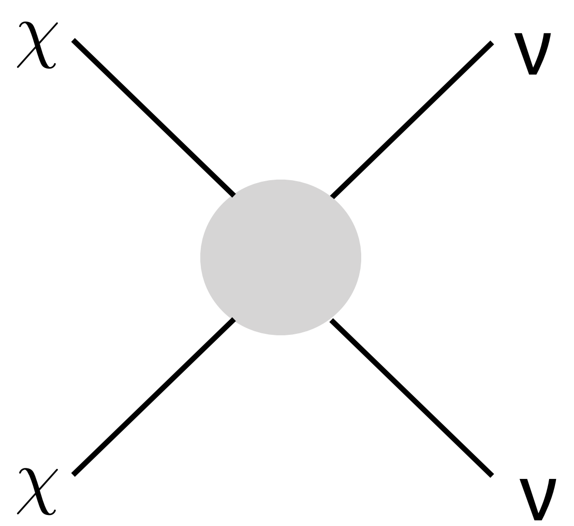




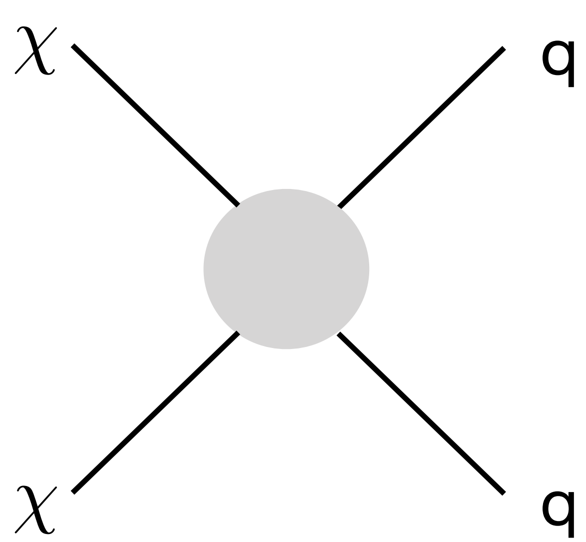
- One can look for neutrinos, photons, matter, anti-matter resulting from DM to SM interactions
- Basic principle: take a telescope (ground or space based) observe a target for finite amount of time for a specific final state and look for excess over astrophysical backgrounds

Indirect detection

- Example: Let us assume we have a telescope which can observe neutrinos (and only neutrinos)



- $E_\nu = m_\chi$: a line at the energy of mass of dark matter can be observed
- Neutrinos interact weakly, travel without deflection due to magnetic field or additional interactions
- Can point back to source
- Same principles apply to photons



- $E_q = m_\chi$: Quarks will hadronize and the charged particles resulting from hadronization will be deflected due to galactic magnetic field, we will lose initial correlation between DM mass and energy but can still see a broad excess
- Neutrinos form a part of quark hadronization and hence our neutrino telescope might observe them

Targets

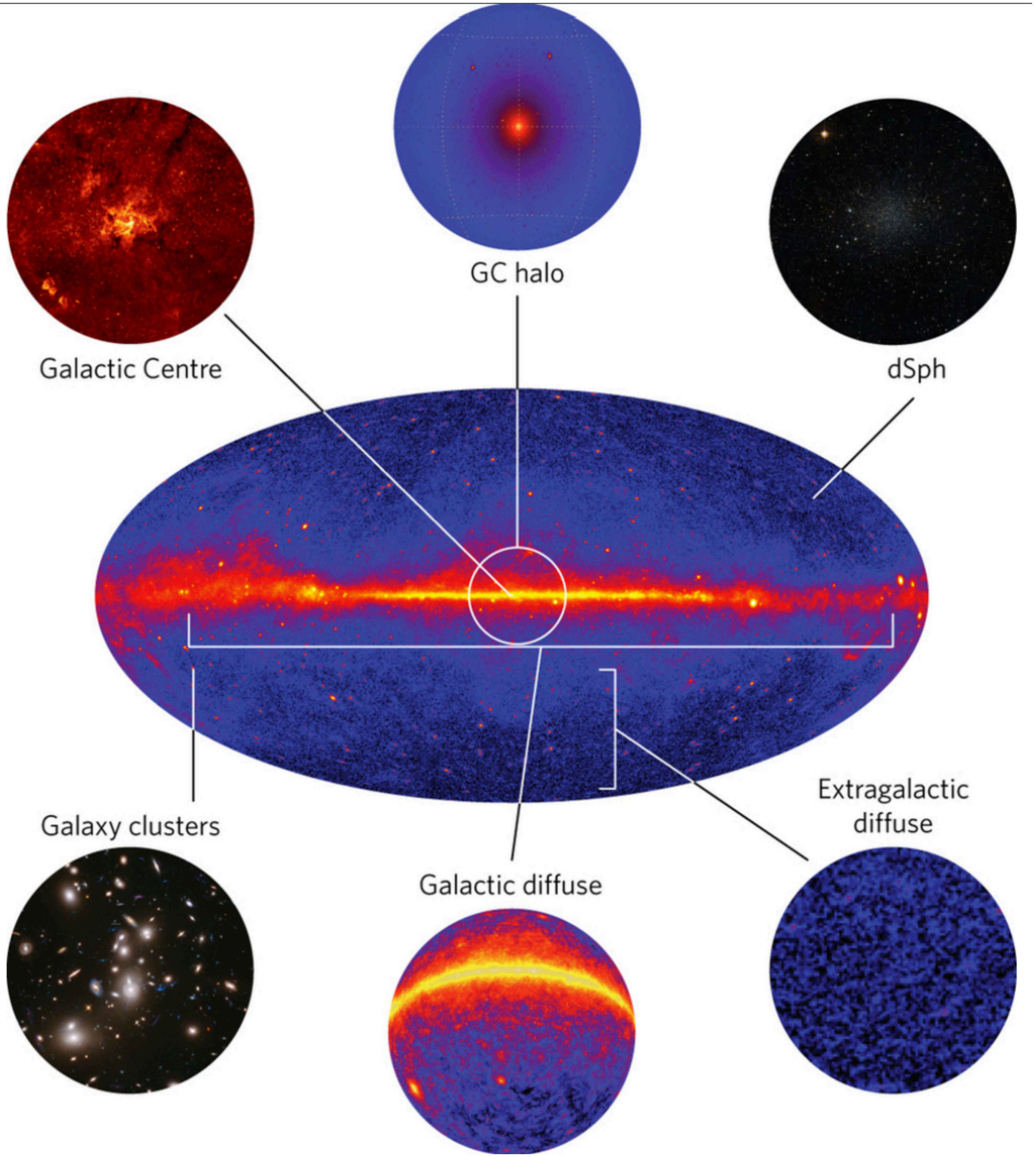
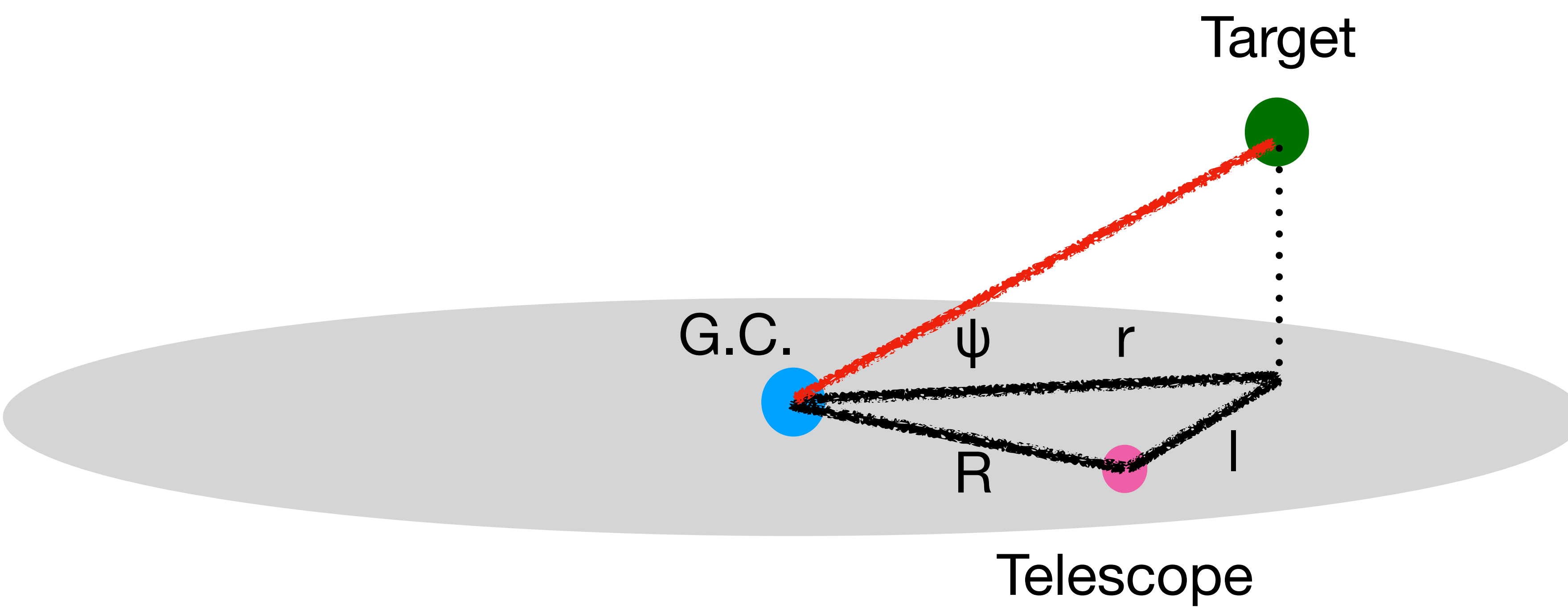


Diagram by F. Calore

Indirect detection - neutral states

- Discussion below applies to both photon and neutrino final states
- We first need to know how many DM particles annihilate



- Annihilation rate per particle

$$\sum_i \frac{\rho\left[r(\ell,\psi)\right]}{m_\chi} \times \langle \sigma_i v \rangle$$

Indirect detection - neutral states

- Discussion below applies to both photon and neutrino final states
- We first need to know how many DM particles annihilate
- Annihilation rate per particle $$\sum_i \frac{\rho\left[r(\ell,\psi)\right]}{m_\chi} \times \langle\sigma_i v\rangle$$
- DM number density in volume dV $$\left(\frac{\rho\left[r(\ell,\psi)\right]}{2\,m_\chi}\,dV\right)$$
- Total number of particles in volume $$\left(\sum_i \frac{\rho\left[r(\ell,\psi)\right]}{m_\chi}\,\langle\sigma_i v\rangle\right) \times \left(\frac{\rho\left[r(\ell,\psi)\right]}{2\,m_\chi}\,dV\right)$$
- Differential flux

$$\frac{d\Phi}{dE_\gamma}(E_\gamma,\psi) = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{\mathrm{l.o.s.}} d\ell\,\rho\left[r(\ell,\psi)\right]^2 \sum_i \frac{\langle\sigma_i v\rangle}{2m_\chi^2}\,\frac{dN_i}{dE_\gamma}$$

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- Factor out astrophysics

$$J = \frac{1}{\Delta\Omega}\int d\Omega \int_{\mathrm{l.o.s.}} d\ell\,\rho\left[r(\ell,\psi)\right]^2$$

- Some example J-factors

Target	$\log_{10}(J_{\mathrm{ann}})$
Galactic Center	21.5
Dwarf galaxies (best)	19
Galaxy clusters (best)	18

Indirect detection - neutral states

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AstroPhysics

$$\frac{d\Phi}{dE_\gamma}(E_\gamma,\psi) = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{\mathrm{l.o.s.}} d\ell\,\rho\left[r(\ell,\psi)\right]^2 \sum_i \frac{\langle\sigma_i v\rangle}{2m_\chi^2}\frac{dN_i}{dE_\gamma}$$

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AstroPhysics

Particle Physics

$$\frac{d\Phi}{dE_\gamma}(E_\gamma,\psi) = \frac{1}{4\pi} \int_{\Delta\Omega} d\Omega \int_{\mathrm{l.o.s.}} d\ell\, \rho\left[r(\ell,\psi)\right]^2 \sum_i \frac{\langle \sigma_i v \rangle}{2 m_\chi^2} \frac{dN_i}{dE_\gamma}$$

- Factor out astrophysics

$$J = \frac{1}{\Delta\Omega} \int d\Omega \int_{\mathrm{l.o.s.}} d\ell\, \rho\left[r(\ell,\psi)\right]^2$$

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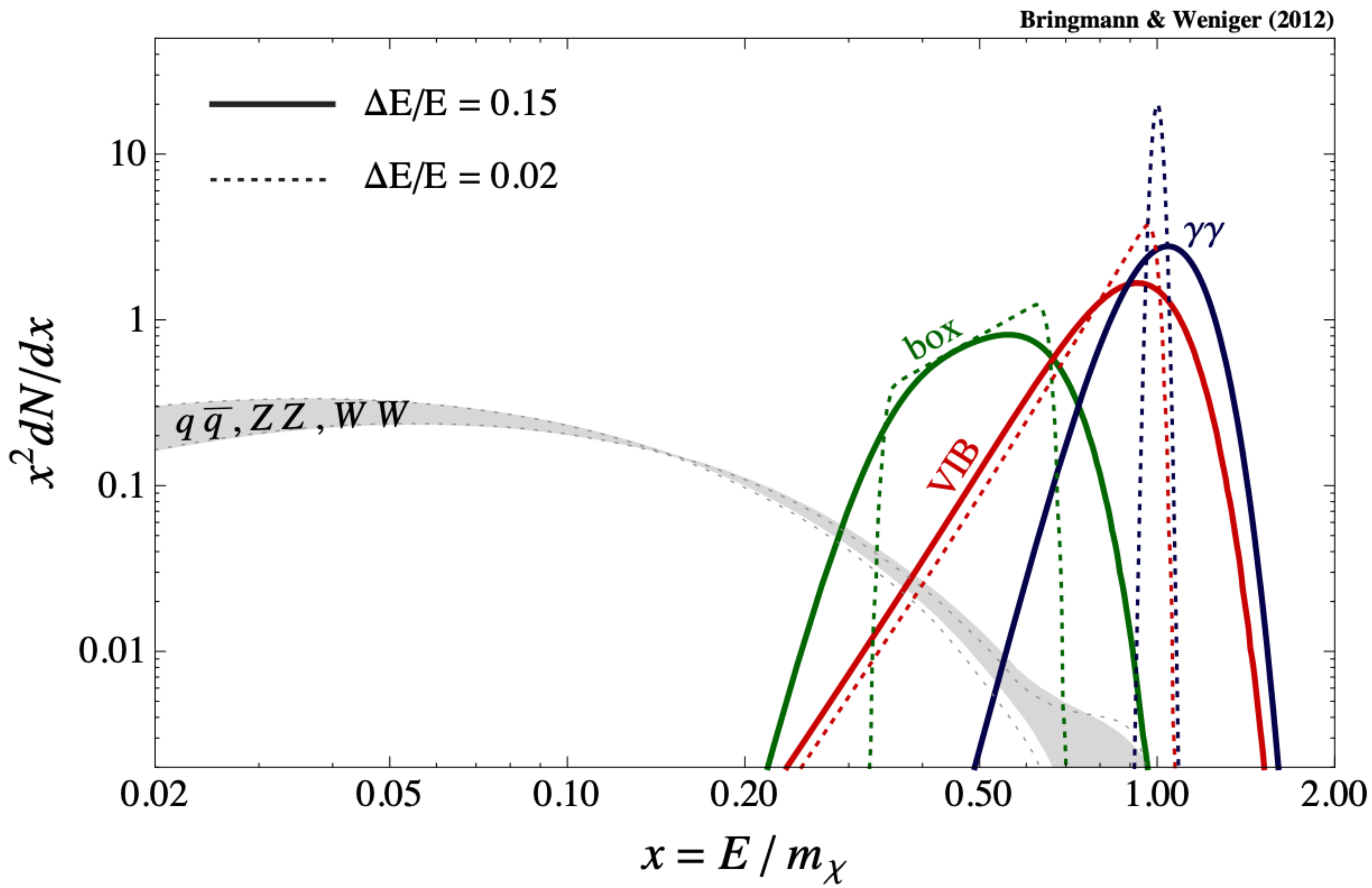
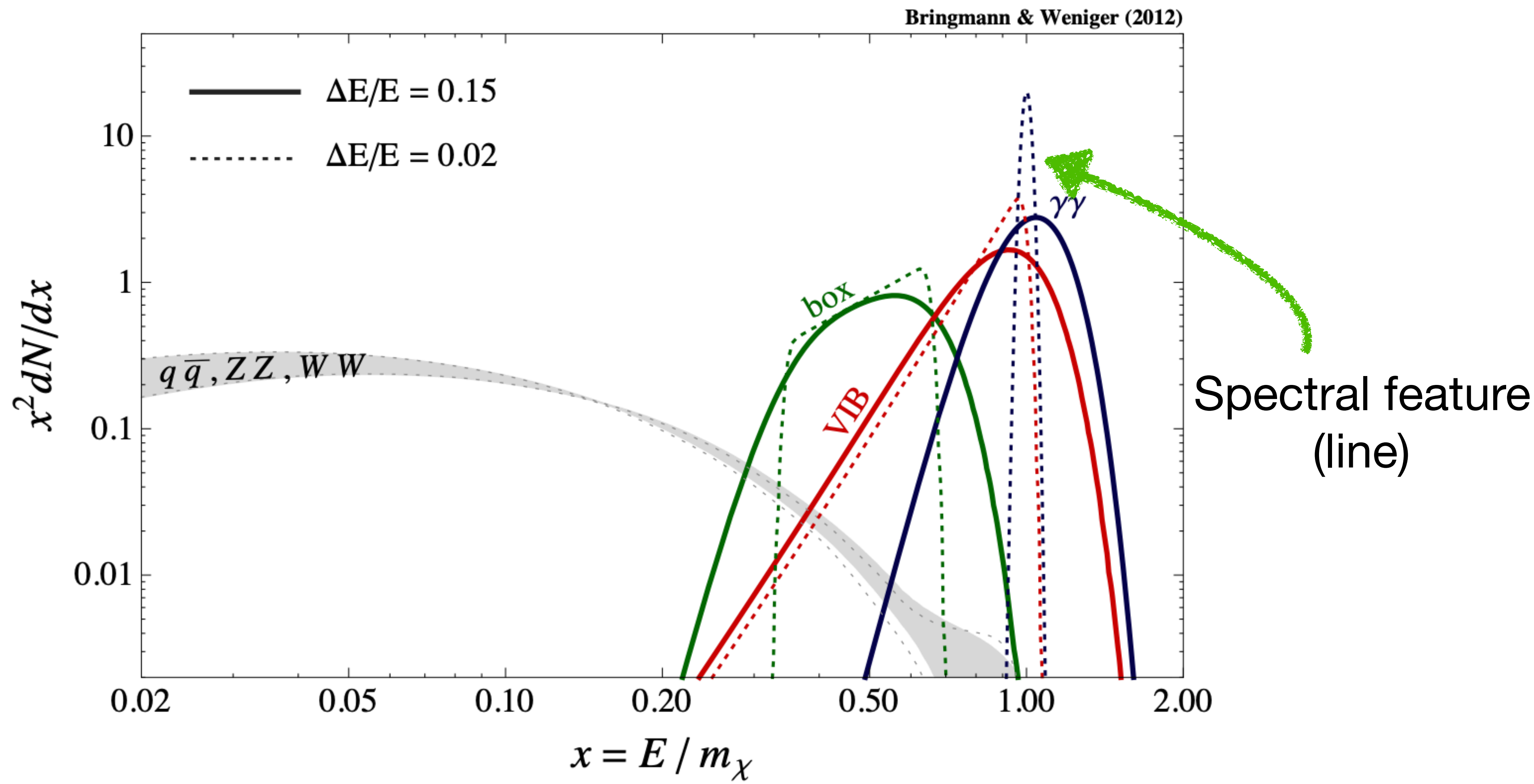
Indirect detection



- Two primary avenues
  - Search for primary decay products (spectral feature e.g. line)
  - Search for secondary decay products (continuum)

Indirect detection



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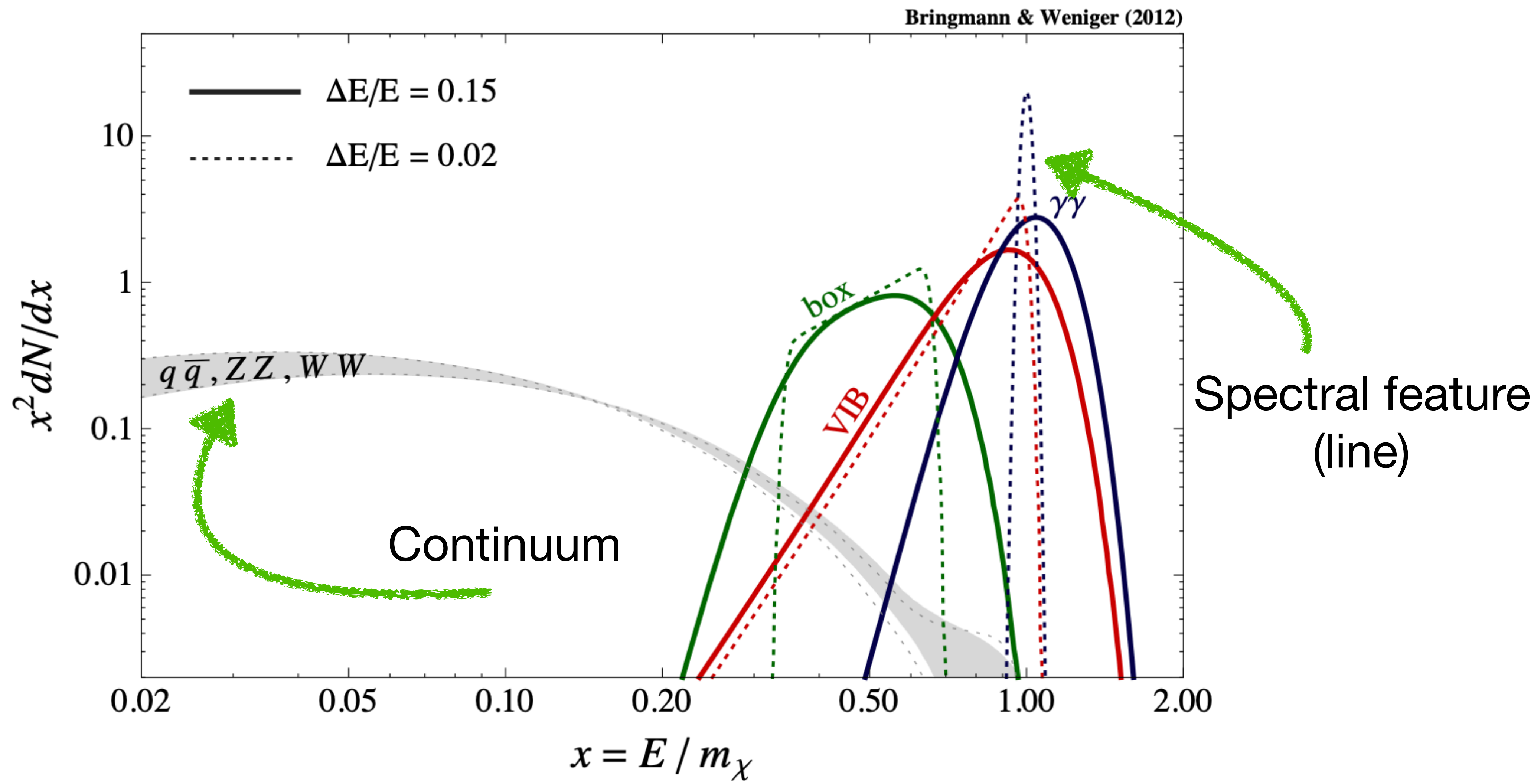
Indirect detection



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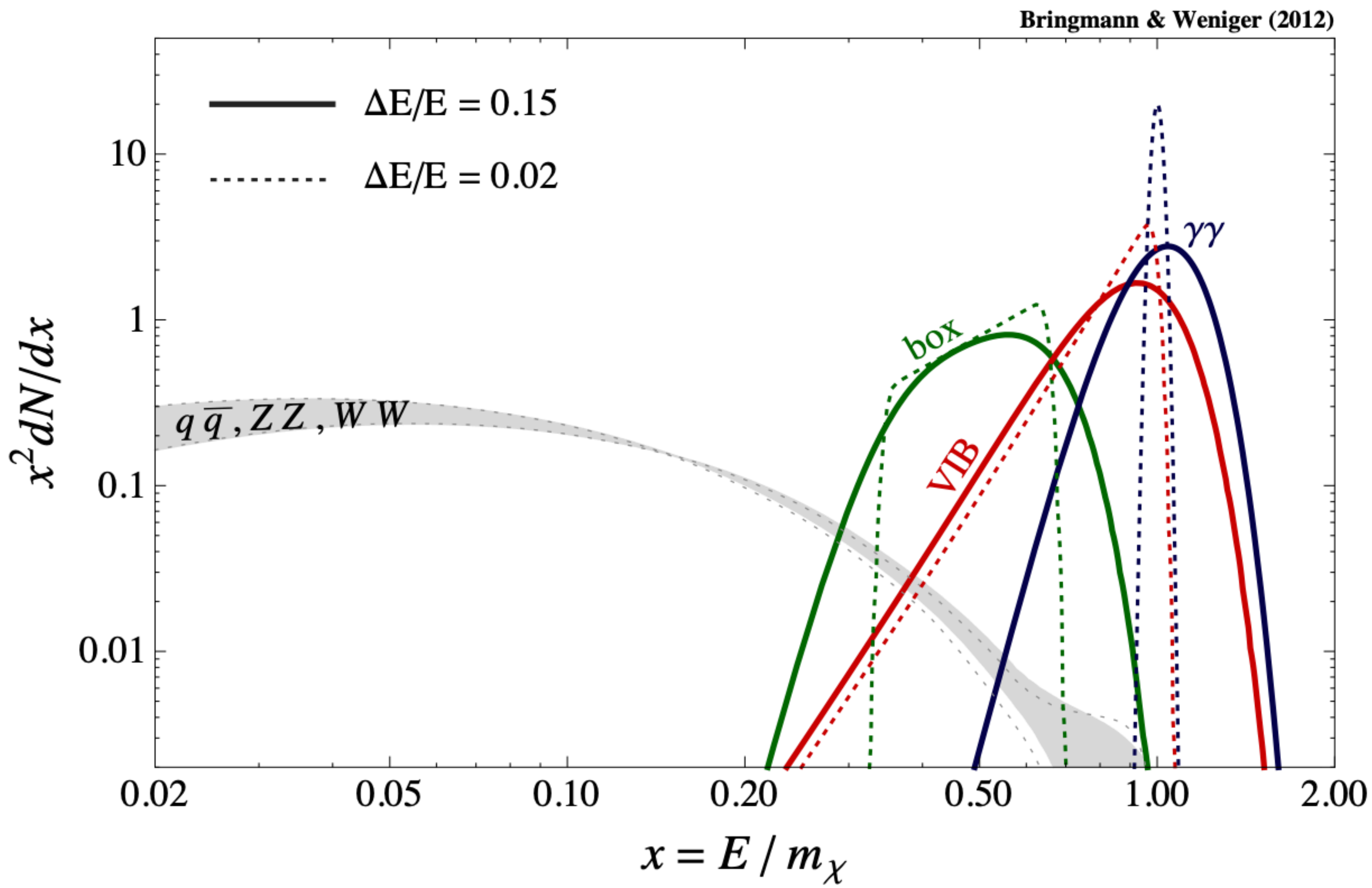

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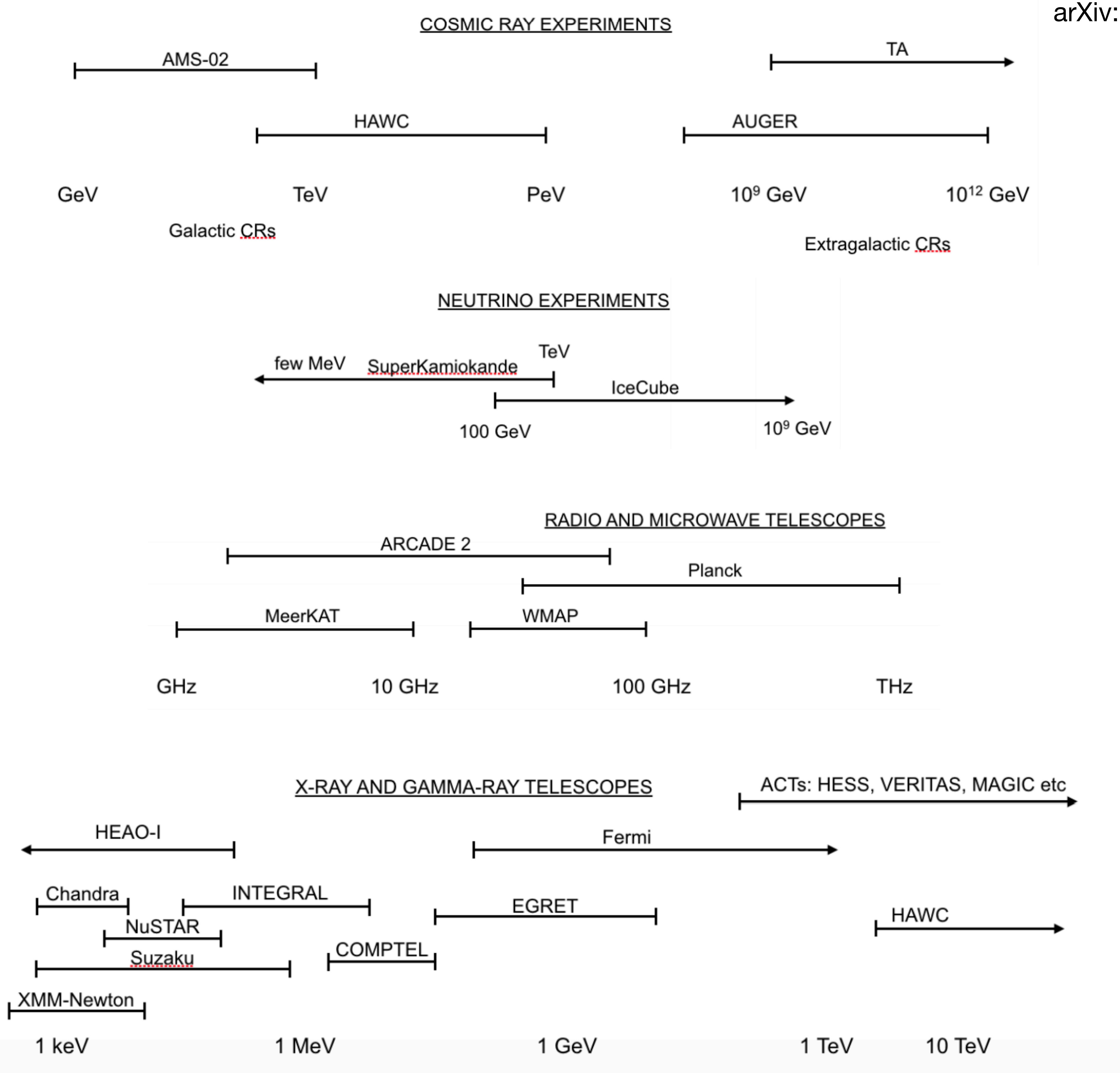
  - Search for primary decay products (spectral feature e.g. line)
  - Search for secondary decay products (continuum)


COSMIC RAY EXPERIMENTS
AMS-02
TA
HAWC
AUGER
GeV
TeV
PeV
10^9 GeV
10^12 GeV
Galactic CRs
Extragalactic CRs
NEUTRINO EXPERIMENTS
few MeV
SuperKamiokande
TeV
IceCube
100 GeV
10^9 GeV
RADIO AND MICROWAVE TELESCOPES
ARCADE 2
Planck
MeerKAT
WMAP
GHz
10 GHz
100 GHz
THz
X-RAY AND GAMMA-RAY TELESCOPES
ACTs: HESS, VERITAS, MAGIC etc
HEAO-I
Fermi
Chandra
INTEGRAL
EGRET
HAWC
NuSTAR
COMPTEL
Suzaku
XMM-Newton
1 keV
1 MeV
1 GeV
1 TeV
10 TeV

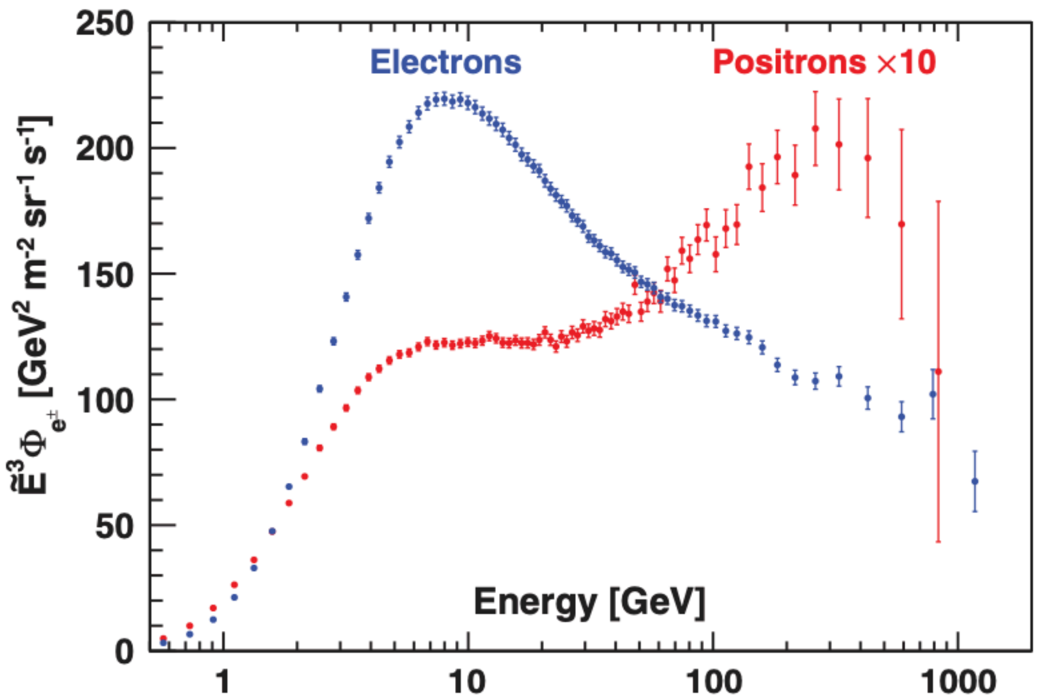
Current status

- Indirect detection searches in several final states
- Gamma-ray, x-ray, neutrinos, charged particles (positrons)
- Astrophysical targets: dwarf galaxies, centre of Milky Way, dark matter capture in the Sun
- Today multi-messenger astrophysics is a great avenue to explore dark matter at indirect detection experiments

Particle	Experiments	Advantages	Challenges
Gamma-ray† photons	Fermi LAT, GAMMA-400, H.E.S.S.(-II), MAGIC, VERITAS, HAWC, CTA	point back to sources, spectral signatures	backgrounds, attenuation
Neutrinos	IceCube/DeepCore/PINGU, ANTARES/KM3NET, BAIKAL-GVD, Super-Kamiokande/Hyper-Kamiokande	point back to sources, spectral signatures	backgrounds, low statistics
Cosmic rays	PAMELA, AMS-02, ATIC, IACTs, Fermi LAT, Auger, CTA, GAPS	spectral signatures, low backgrounds for antimatter searches	diffusion, do not point back to sources

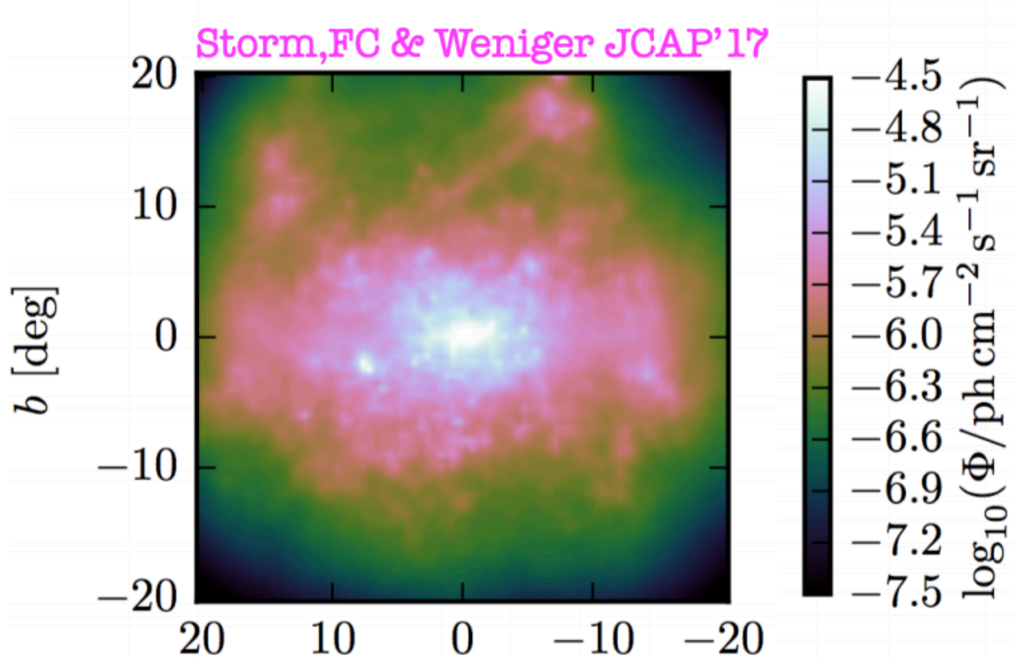
Current status

- AMS positron excess

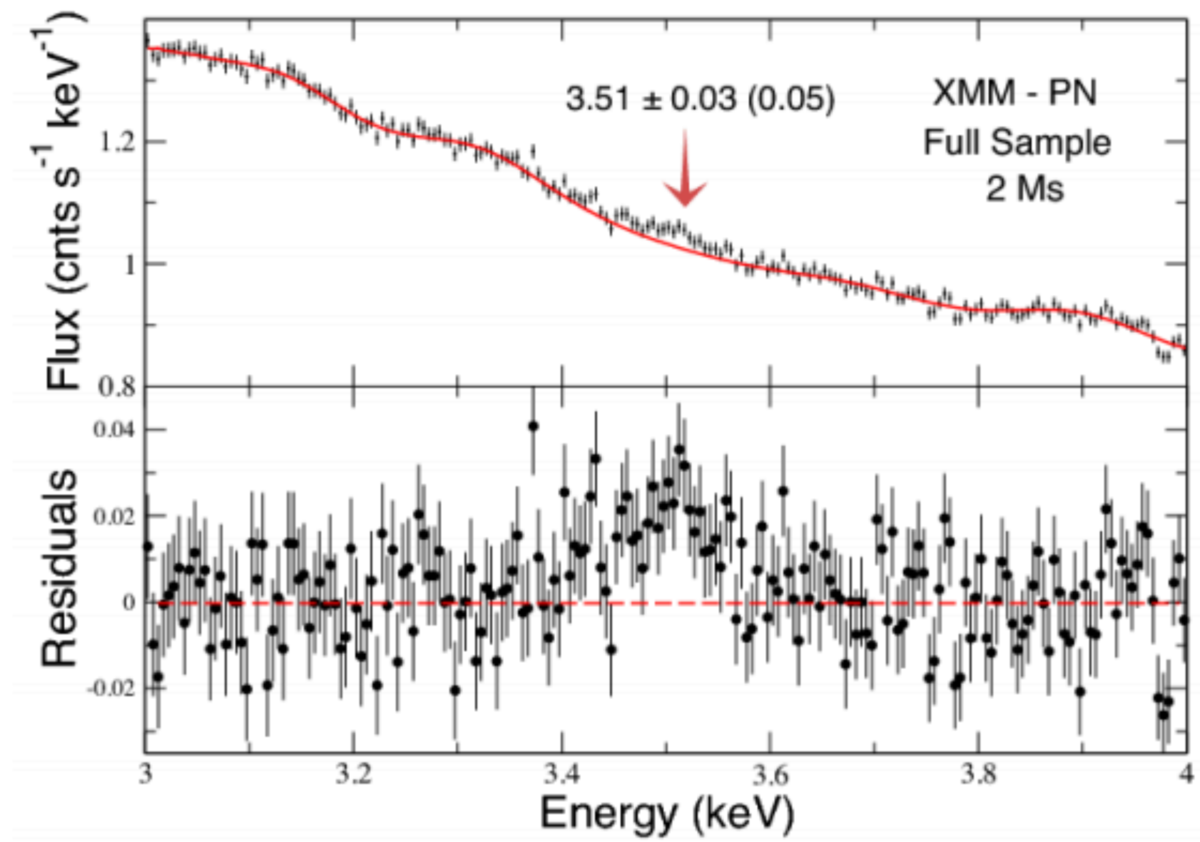


PhysRevLett.122.101101

- Fermi-LAT galactic center excess



- 3.5 keV line



Bulbul et al 1402.2301

- Not mentioning IceCube here; all about it in another lecture tomorrow

Indirect detection

- Extremely exciting avenue
- Close connection with progress in astrophysics
- Great prospects for understanding dark matter properties at large scales
- Discovery still illusive and challenging
- Many unresolved mysteries which need further data

Dark matter - conclusions

- One of the greatest challenges of 21st century physics
- WIMP paradigm no longer considered ‘miracle’, many many alternative models on the market
- Make most of data, observational evidences for progress
- Think of alternative, non-standard models
- Relic density still a golden number

Don’t shoot for the stars, we already know what’s in there. Shoot for the space in between because that’s where the real mystery lies.

- Vera Rubin