Dark Matter

II. (some) Candidates and detection

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Forewords to the second class:

The slides of these classes have been put together by looting the excellent ones created by some of the teachers of the “School on Dark Matter”, held at ICTP-SAIFR in São Paulo in 2016.

For this second class I have used material from
P.D. Serpico, N. Bozorgnia, and F. Calore.

The complete material can be found at this address
http://www.ictp-saifr.org/school-on-dark-matter-2/

and I strongly encourage you to download and study them to have a broader view on the subject. As you will remember most of this class was held at a board, and this slides summarize the content to the introduction to WIMP searches, direct and indirect.

RECAP & PLAN

Recent determination (Planck 2015, 68% CL)

$\Omega_c h^2$=0.1188±0.0010, i.e. Ω_c~0.26

$$\Omega_X h^2 = 2.74 \times 10^8 \left(\frac{M_X}{\mathrm{GeV}}\right) Y_0$$

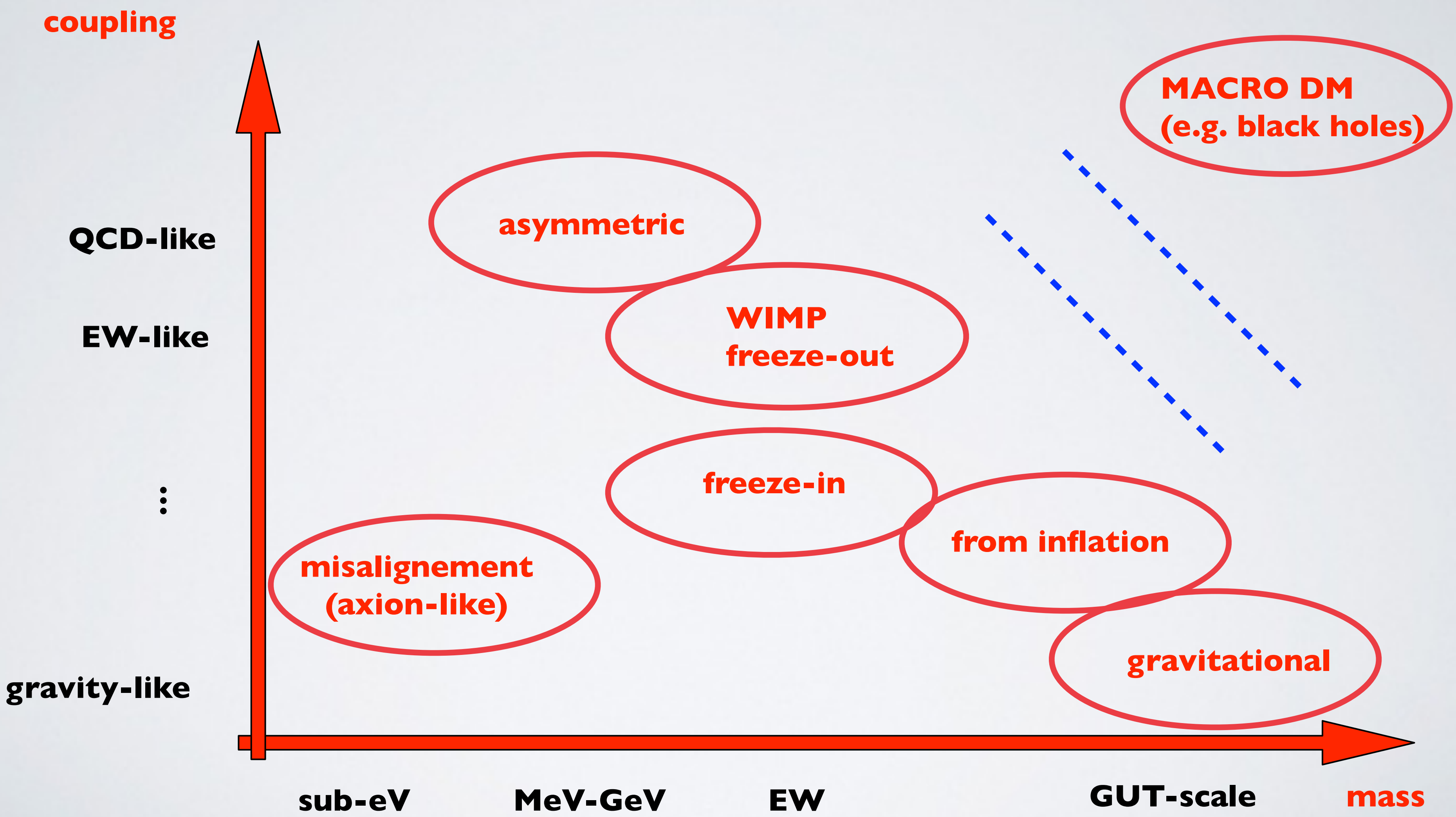
[Main] Goal: *compute value of number to entropy density ratio, Y_0*

- We shall first provide a heuristic argument for the simplest (yet powerful!) toy-model evolution equation for *Y*
- We shall use this equation in different regimes to elucidate a couple of classes (not all!) of DM candidates
- Some generalizations will be briefly discussed.
- Later (Lec. 4, most likely) we'll come back to sketch a "microscopic" derivation/interpretation of the equation we started with

Caveat: *matching Ω_X is one condition for a good DM candidate, not the only one! Remember lecture 2 (collisionless, right properties for LSS structures...)*

DM CLASSIFICATION / PARAMETER SPACE

Will discuss different classes based on production mechanisms. However, these are typically linked with masses and couplings as well!



BOLTZMANN EQ. FOR DM DENSITY CALCULATION

Assume that binary interactions of our particle *X* are present with species of the thermal bath

$$X\,X \leftrightarrow \text{(thermal bath particles)}$$

If interaction rate **Γ=n σ v** very slow wrt Hubble rate **H**, # of particles conserved covariantly, i.e.

$$\frac{dn}{dt} + 3H\,n = 0 \Rightarrow n \propto a^{-3}$$

If interaction rate **Γ>> H**, # of particles follows equilibrium, e.g. for non-relativistic particles

$$n_{\text{eq}} = g\left(\frac{m\,T}{2\pi}\right)^{3/2} \exp\left(-\frac{m}{T}\right)$$

The following equation has the right limiting behaviours

$$\frac{dn}{dt} + 3H\,n = -\langle\sigma v\rangle[n^2 - n_{\text{eq}}^2]$$

must be quadratic, for binary processes

for now, symbolic only

REWRITING IN TERMS OF Y AND x

$$\frac{dn}{dt} + 3H\,n = -\langle\sigma v\rangle[n^2 - n_{\rm eq}^2] \qquad \frac{dY}{dt} = -s\langle\sigma v\rangle[Y^2 - Y_{\rm eq}^2]$$

$$\frac{dY}{dt} = \frac{d}{dt}\left(\frac{n}{s}\right) = \frac{d}{dt}\left(\frac{n\,a^3}{s\,a^3}\right) = \frac{1}{s\,a^3}\frac{d}{dt}\left(n\,a^3\right) = \frac{1}{s\,a^3}\left(a^3\frac{dn}{dt} + 3a^2\dot{a}\,n\right) = \frac{1}{s}\left(\frac{dn}{dt} + 3H\,n\right)$$

Define *x=m/T* (*m arbitrary mass, either* M_X *or not*); for an iso-entropic expansion one has

$$\frac{d}{dt}(a^3 s) = 0 \Longrightarrow \frac{d}{dt}(a\,T) = 0 \Longrightarrow \frac{d}{dt}(a/x) = \frac{\dot{a}}{x} - \frac{a}{x^2}\dot{x} = 0 \Longrightarrow \frac{dx}{dt} = H\,x$$

$$\frac{dY}{dx} = -\frac{x\,s\langle\sigma v\rangle}{H(T=m)}[Y^2 - Y_{\rm eq}^2]$$

radiation-dominated period

More in general (arbitrary *s(t)* and *H(t)*):

$$\frac{dY}{dx} = -\sqrt{45\pi}M_{\rm Pl}\,m\frac{h_{\rm eff}(x)\langle\sigma v\rangle}{\sqrt{g_{\rm eff}(x)}\,x^2}\left(1 - \frac{1}{3}\frac{d\log h_{\rm eff}}{d\log x}\right)(Y^2 - Y_{\rm eq}^2)$$

M. Srednicki, R. Watkins and K. A. Olive,
"Calculations of Relic Densities in the Early Universe,"
Nucl. Phys. B 310, 693 (1988)

P. Gondolo and G. Gelmini,
"Cosmic abundances of stable particles: Improved analysis,"
Nucl. Phys. B 360, 145 (1991).

FREEZE-OUT CONDITION

The previous equation is a *Riccati equation*: no closed form solution exist!

Approximate analytical solutions exist for different hypotheses/regimes

(In the following, we shall assume the choice $m=M_X$)

For h_{eff} ~ const., we can re-write

$$\frac{x}{Y_{\rm eq}}\frac{dY}{dx} = -\frac{\Gamma_{\rm eq}}{H}\left[\left(\frac{Y}{Y_{\rm eq}}\right)^2 - 1\right] \quad \text{with} \quad \Gamma_{\rm eq} = \langle \sigma v \rangle n_{\rm eq}$$

If $\Gamma_{eq} >> H$ the particle starts from equilibrium condition at sufficiently small x (high-T), when relativistic. Crucial variable to determine the Y_{final} is the freeze-out epoch x_F from condition

$$\Gamma_{\rm eq}(x_F) = H(x_F)$$

RELATIVISTIC FREEZE-OUT

$$\Gamma_{\rm eq}(x_F) = H(x_F)$$

If the solution to this condition yields x_F<<*1*, then *(Lecture 1)*

$$n = g\frac{\zeta(3)}{\pi^2}T^3 \times \left\{1(\text{B}), \frac{3}{4}(\text{F})\right\}$$

comoving abundance stays constant, and independent of *x (if dof do not change)*

$$Y(x_F) = 0.28\frac{g \times \{1(\text{B}), 3/4(\text{F})\}}{h_{\rm eff}(x_F)}$$

Today's abundance of such a relativistic freeze-out relic is thus

$$\Omega_X h^2 = 0.0762 \times \left(\frac{M_X}{\text{eV}}\right)\frac{g \times \{1(\text{B}), 3/4(\text{F})\}}{h_{\rm eff}(x_F)}$$

For the neutrino case, $h_{\rm eff}$=10.75, g×{ }=3/2, thus

$$\Omega_\nu h^2 \simeq \frac{\sum m_\nu}{94\,\text{eV}}$$

Inconsistent with DM for current upper limits!

NON-RELATIVISTIC FREEZE-OUT

to determine x_F

$$\Gamma_{\rm eq}(x_F) = H(x_F)$$

$$\frac{g\langle\sigma v\rangle}{(2\pi)^{3/2}} M_X^3\, x_F^{-3/2} e^{-x_F} = \sqrt{\frac{4\pi^3}{45} g_{\rm eff}}\, \frac{M_X^2}{x_F^2\, M_{\rm Pl}}$$

$$x_F^{1/2} e^{-x_F} = \sqrt{\frac{4\pi^3}{45} g_{\rm eff}}\, \frac{(2\pi)^{3/2}}{M_{\rm Pl} M_X\, g\, \langle\sigma v\rangle}$$

Thus one obtains

$$Y(x_F) = \frac{n(x_F)}{s(x_F)} = \frac{g}{h_{\rm eff}} \frac{45}{2\pi^2 (2\pi)^{3/2}} x_F^{3/2} e^{-x_F}$$

which also writes

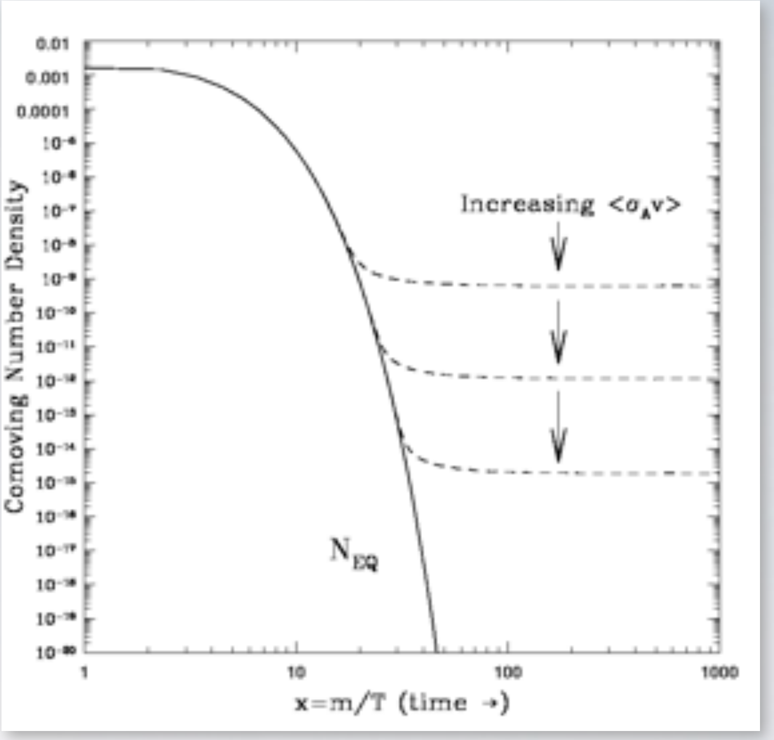
(Note the important result ***Y(x*** —

$$Y(x_F) = \sqrt{\frac{45\, g_{\rm eff}}{\pi}}\, \frac{x_F}{h_{\rm eff} M_{\rm Pl}\, M_X\, \langle\sigma v\rangle} = \mathcal{O}(1)\, \frac{x_F}{M_{\rm Pl}\, M_X\, \langle\sigma v\rangle}$$

NON-RELATIVISTIC FREEZE-OUT: INTERPRETATION

$$Y(x_F) \simeq \mathcal{O}(1) \frac{x_F}{M_{\rm Pl}\, M_X\, \langle \sigma v \rangle}$$

makes sense, in the Boltzmann suppressed tail: The more it interacts, the later it decouples, the fewer particles around.



Also, plugging numbers (typically x_F~30), one has

$$\Longrightarrow \Omega_X h^2 \simeq \frac{0.1\,\mathrm{pb}}{\langle \sigma v \rangle}$$

dimensionally, for electroweak scale masses and couplings, one gets the right value!

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m^2} \simeq 1\,\mathrm{pb} \left(\frac{200\,\mathrm{GeV}}{m} \right)^2$$

But the pre-factor depends from widely different cosmological parameters (Hubble parameter, CMB temperature) and the Planck scale. Is this match simply a coincidence?

Dubbed sometimes "Weakly Interacting Massive Particle" (WIMP) Miracle

ASYMMETRIC DM?

$$\frac{\Omega_{dm}}{\Omega_b} \simeq 5$$

Not in WIMP paradigm! DM result of thermal freeze-out, baryons from some unknown **baryogenesis** mechanism. A nice avenue would be some similar process happening in the dark sector, too!

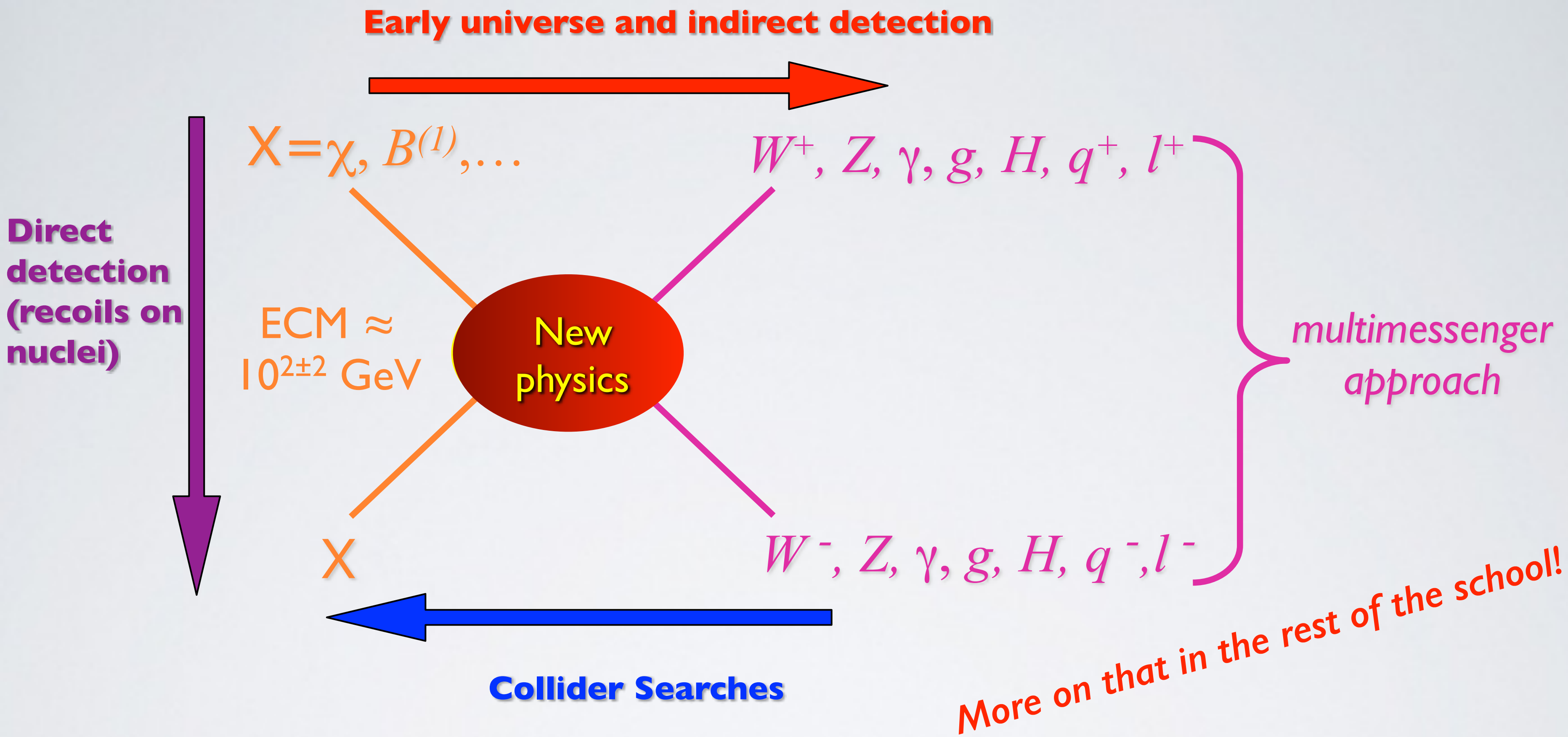
Is this relation suggestive of a common origin (co-genesis)?

Theoretically, not hard: all classes of models considered for baryogenesis can be considered (actually more, since phenomenologically more freedom in dark sector...)

K. Zurek "Asymmetric Dark Matter: Theories, Signatures, and Constraints," Phys. Rept. 537 91 (2014) 1308.0338

- Introduce a DM candidate which is not self-conjugated, allowing for asymmetry in number density $$n_{dm} - \bar{n}_{dm} \neq 0$$
- Use dynamics to relate it to the baryon asymmetry $$n_{dm} - \bar{n}_{dm} \propto n_b - \bar{n}_b$$
- Generically one has (κ model dependent!) $$\frac{\Omega_{dm}}{\Omega_b} = \frac{|n_{dm} - \bar{n}_{dm}| m_{dm}}{n_b\, m_b} \simeq \kappa \frac{m_{dm}}{m_N}$$

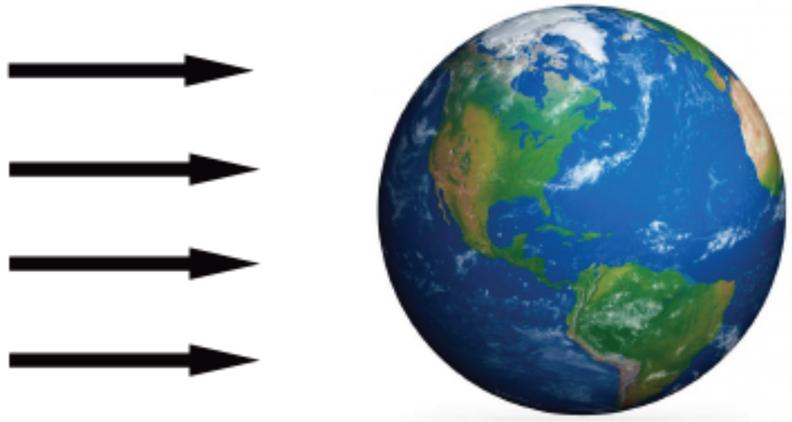
WIMP (NOT GENERIC DM!) SEARCH PROGRAM



- ✓ demonstrate that astrophysical DM is made of particles (locally, via DD; remotely, via ID)
- ✓ Possibly, create DM candidates in the controlled environments of accelerators
- ✓ Find a consistency between properties of the two classes of particles. Ideally, we would like to calculate abundance and DD/ID signatures → link with cosmology/test of production

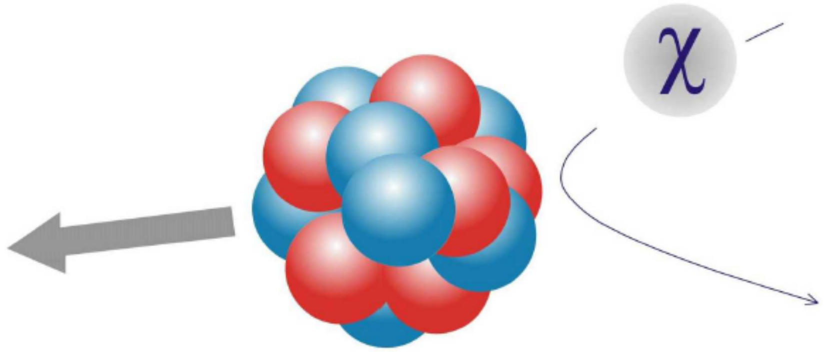
Direct detection of WIMPs

Billions of WIMPs may be passing through the Earth each second, but they very rarely interact.



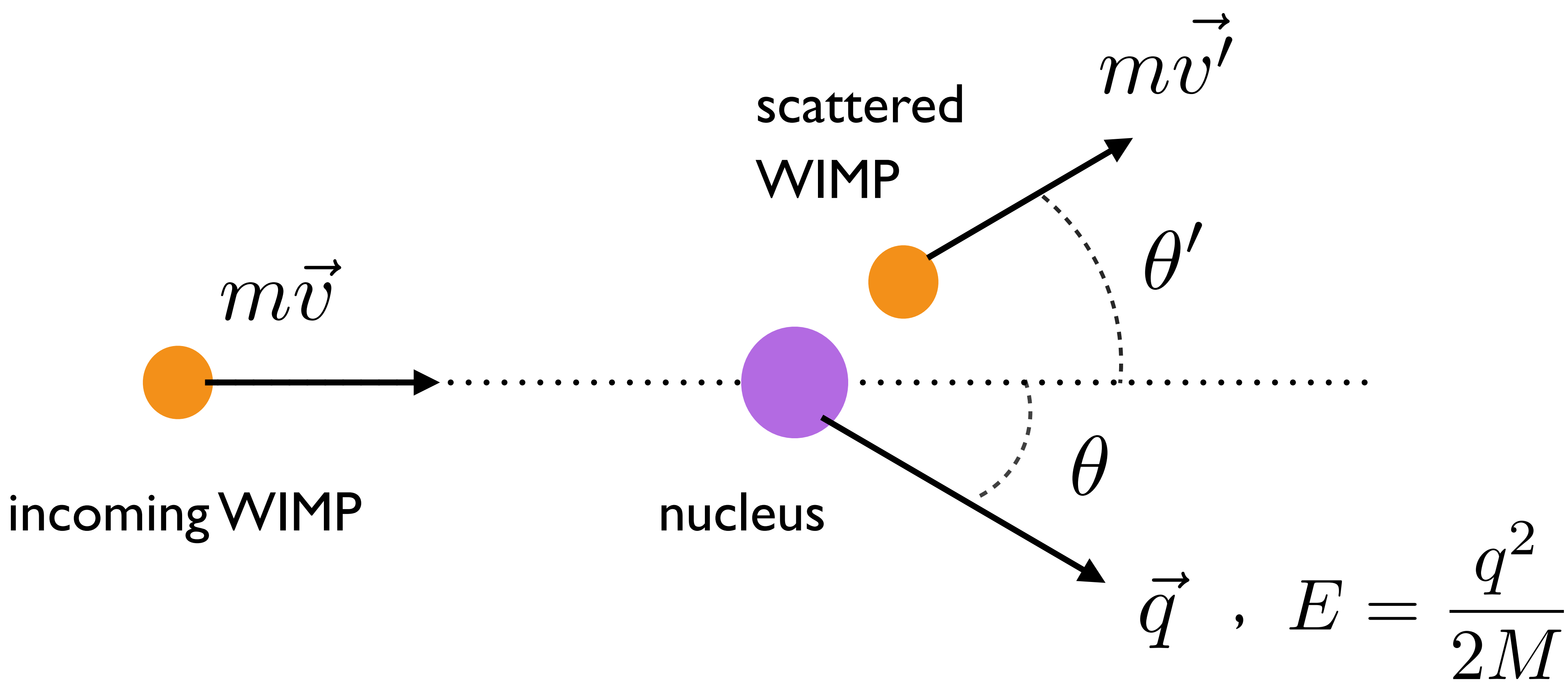
- Direct detection experiments operate underground and search for WIMPs via their scattering with atomic nuclei in the detector.

- WIMP velocity ~10^{-3} c → non-relativistic
- Expected recoil energies ~ 10 keV
- Expect < 1 event/kg/year



WIMP-nucleus interaction

- WIMP-nucleus *elastic* collision:



m : mass of WIMP
M : mass of nucleus

Direct detection of WIMPs

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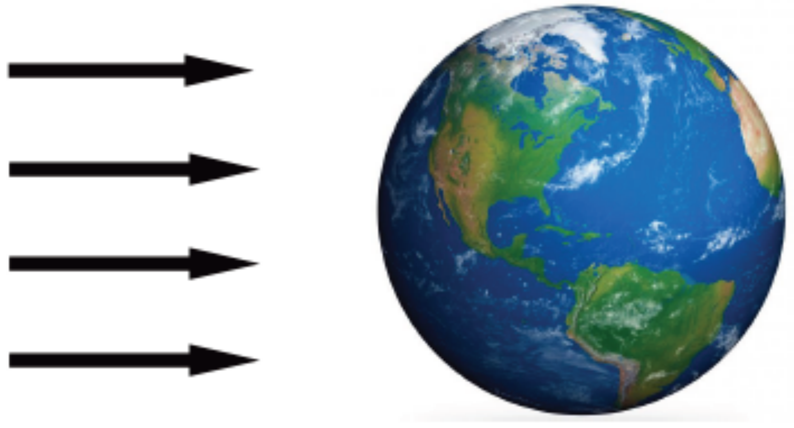

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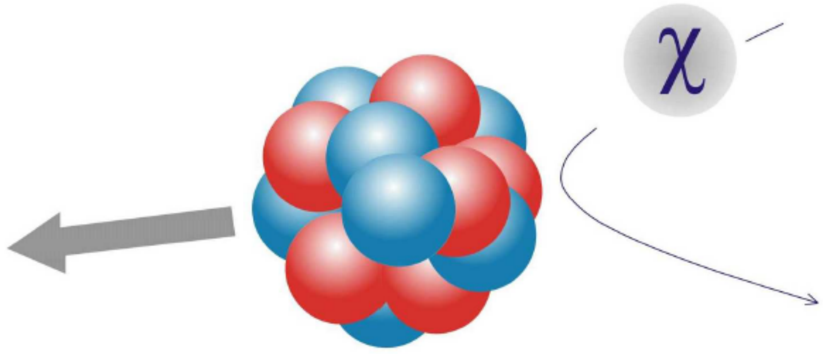


The expected event rate

- The **strongly simplified** expected event rate:

$$R \propto N \Phi_\chi \sigma$$

- N: number of target nuclei in the detector
- Φ_χ: flux of WIMPs
- σ: WIMP-nucleus scattering cross section

$$\Phi_\chi = n \langle v \rangle$$

- $\langle v \rangle$: average WIMP velocity with respect to the detector
- n : WIMP number density $\quad n = \dfrac{\rho}{m}$
- ρ : local DM mass density

The differential event rate

$$\frac{dR}{dE} = \frac{\rho}{m}\frac{1}{M}\int_{v>v_m} d^3v\ \frac{d\sigma}{dE}\ v\ f(\mathbf{v})$$

- Many unknowns enter the event rate:
  - DM mass
  - Local DM density
  - Local DM velocity distribution
  - DM-nucleus cross section

The differential event rate

$$\frac{dR}{dE} = \frac{\rho}{m}\frac{1}{M}\int_{v>v_m} d^3v \, \frac{d\sigma}{dE} v \; f(\mathbf{v})$$

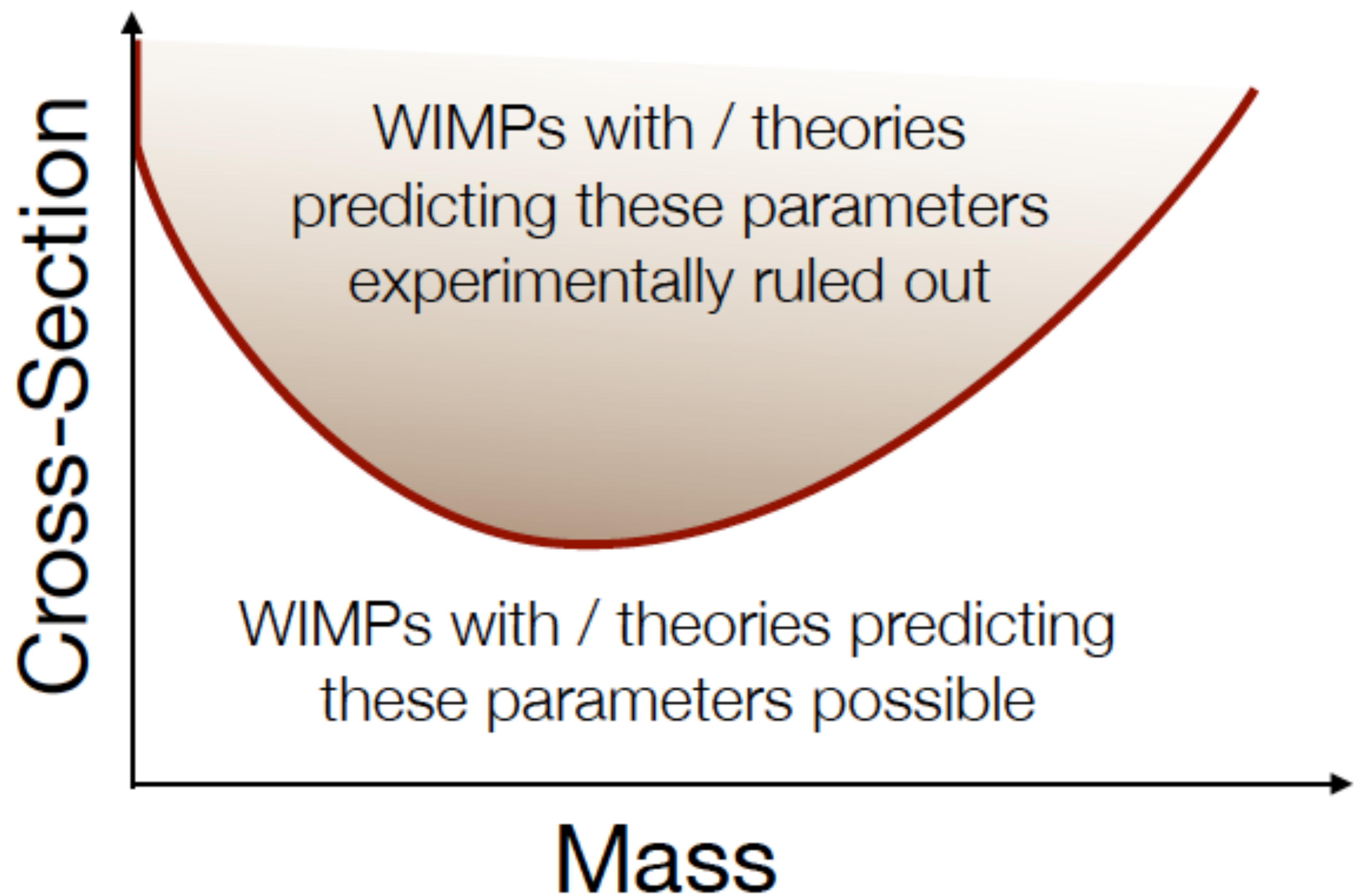
$$\frac{d\sigma}{dE} = \frac{M}{2\mu^2 v^2}\sigma_0 F^2(E)$$

$$\frac{dR}{dE} = \frac{\rho \, \sigma_0 \; F^2(E)}{2m\mu^2} \int_{v>v_m} d^3v \; \frac{f(\mathbf{v})}{v}$$

particle physics

astrophysics

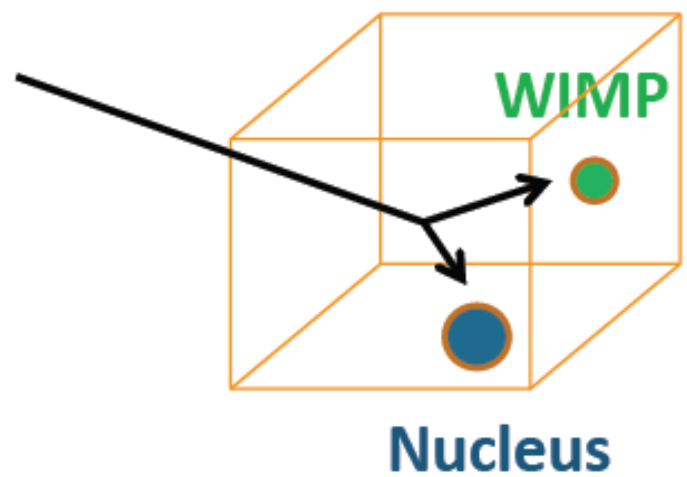
Exclusion limit



Direct detection techniques

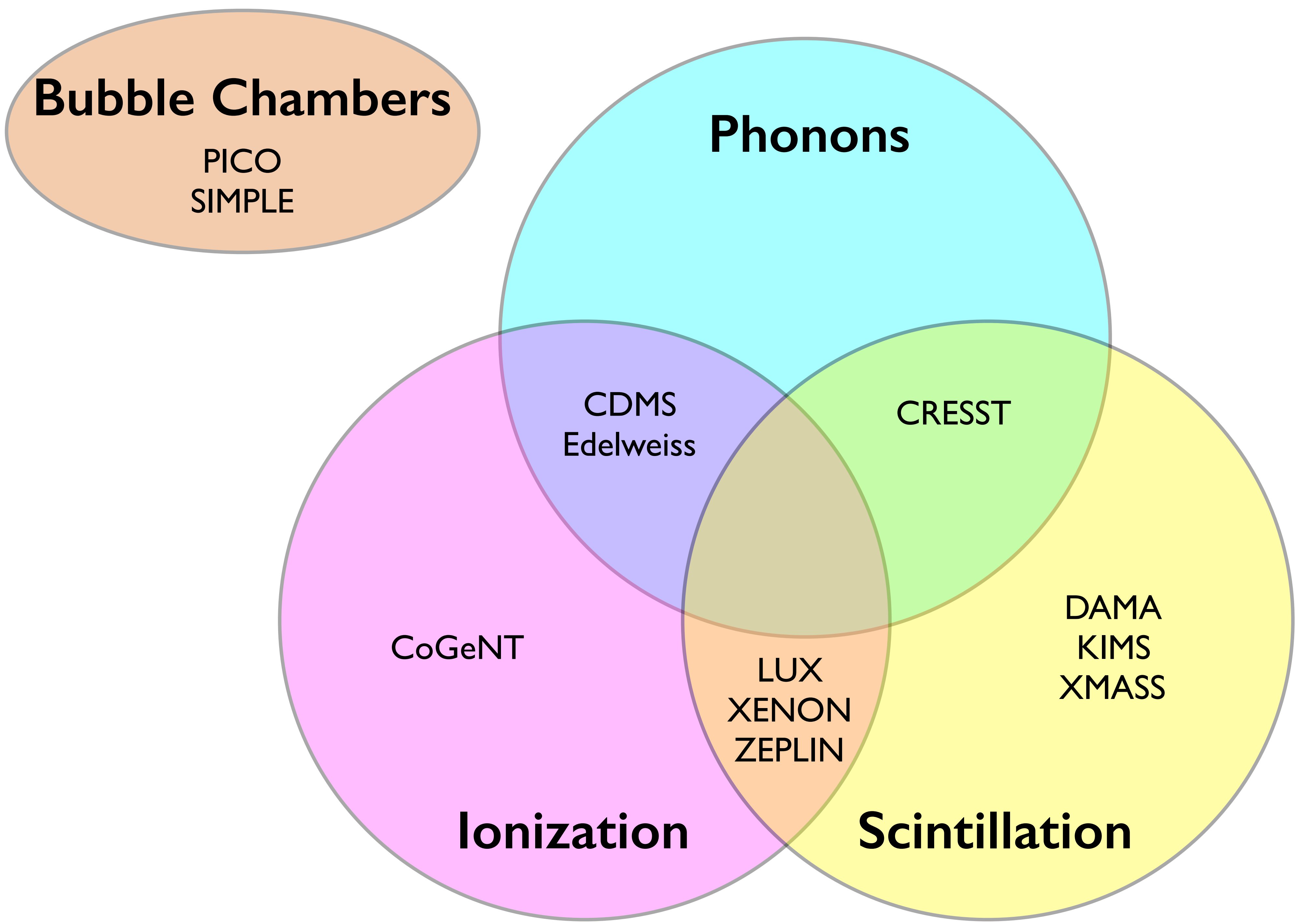
- The majority of direct detection experiments are *direction-insensitive*, and they measure the recoil energy of the nucleus.

- Signals in direct detection experiments:
  - phonons (heat)
  - scintillation (light)
  - ionization (charge)



- Different types of detectors:
  - crystalline detectors operating at very low temperatures (mK), crystals at room temperature, noble liquid detectors, …

Direct detection techniques

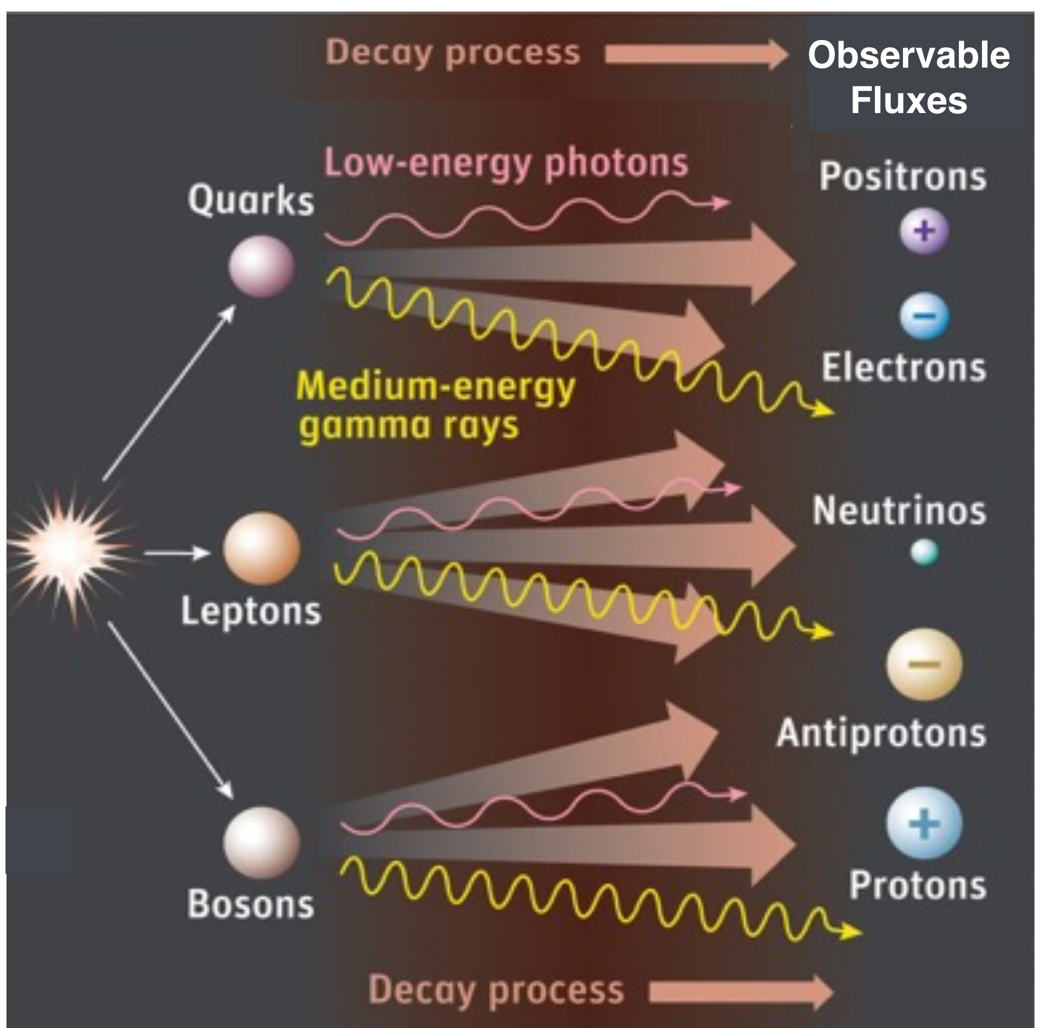


Indirect dark matter detection

Two key-assumptions:

1) **Dark matter exists** and is the main responsible for the gravitational potential inferred in galaxies, clusters and cosmo.
2) **Dark matter is non-gravitationally coupled** to standard matter.

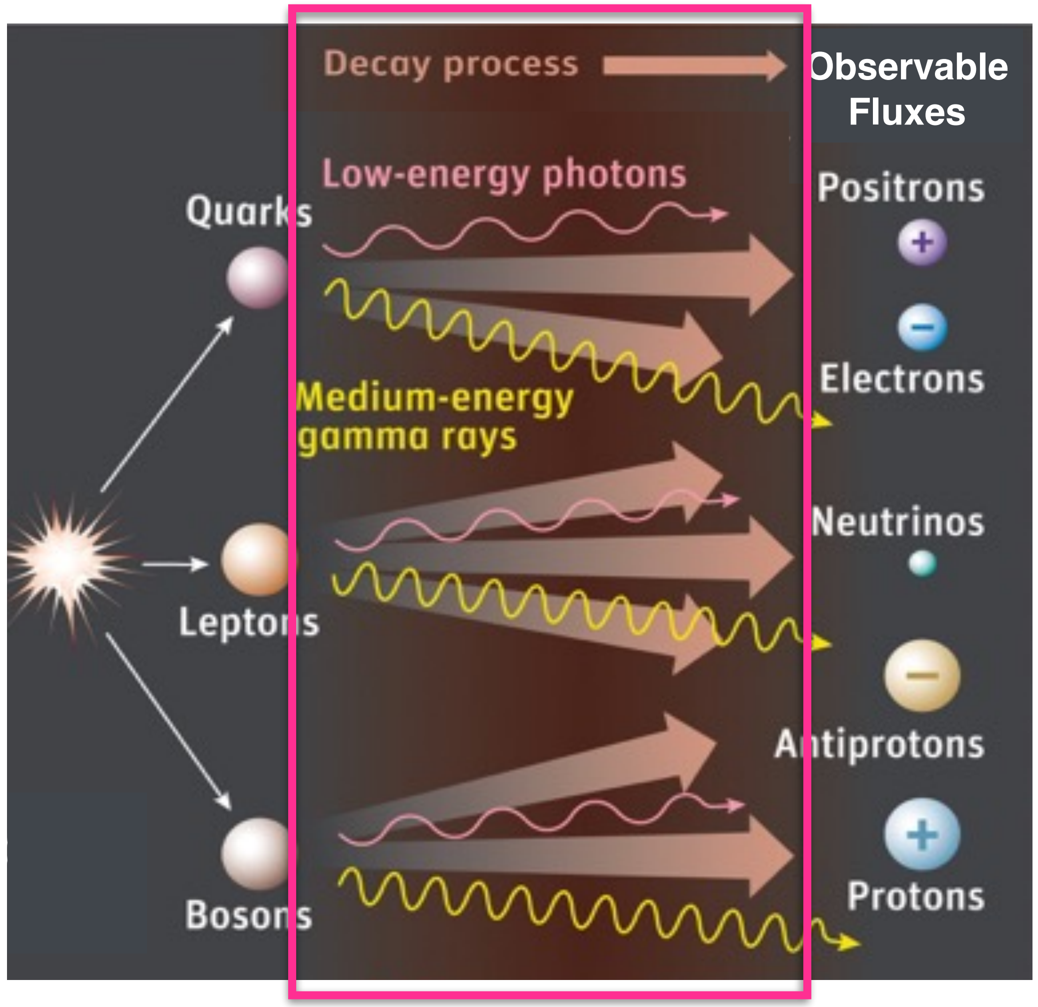
DM annihilation/decay

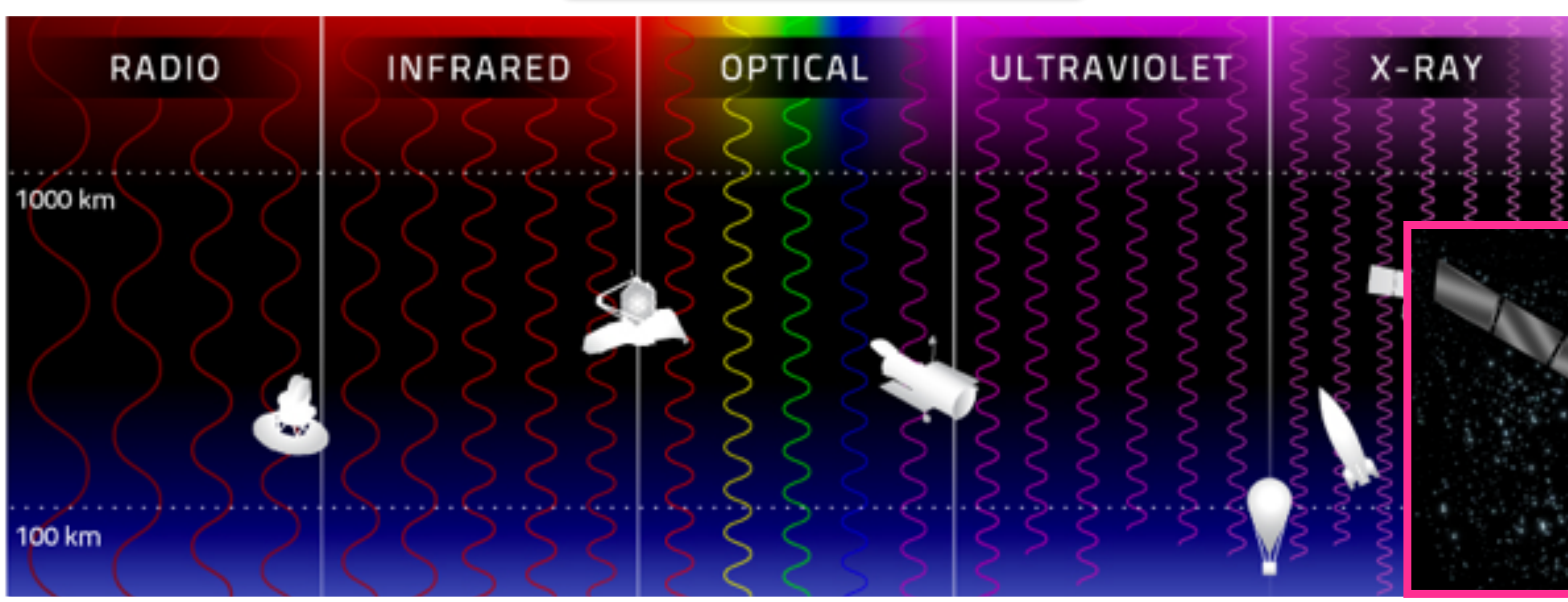


DM annihilation/ decay leads to production of **observable fluxes** of stable particles.

Indirect dark matter detection

DM annihilation/decay

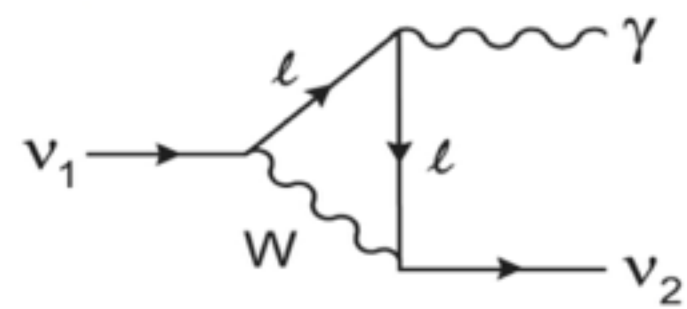




Dark matter signals

Annihilation

Decay



Velocity averaged DM annihilation cross-section

$$\frac{dN_{\text{ann}}}{dA\,dt\,d\Omega\,dE} = \frac{\langle \sigma v \rangle}{2m_\chi^2}\frac{dN_x}{dE}\frac{1}{4\pi}J_{\text{ann}}(\psi)$$

DM mass; DM spectrum

$$J_{\text{ann}}(\psi) = \int_{\text{los}} \rho^2(\psi, l)dl$$

DM spatial profile

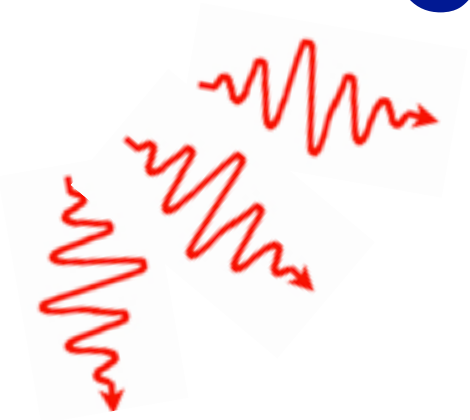
$$\frac{dN_{\text{dec}}}{dA\,dt\,d\Omega\,dE} = \frac{1}{m_\chi \tau}\frac{dN_x}{dE}\frac{1}{4\pi}J_{\text{dec}}(\psi)$$

DM decay rate

$$J_{\text{dec}}(\psi) = \int_{\text{los}} \rho(\psi, l)dl$$

Reviews: Bringmann & Weniger, PDU'15; Ibarra+, Int. J. of Modern Physics A'13

General about DM searches

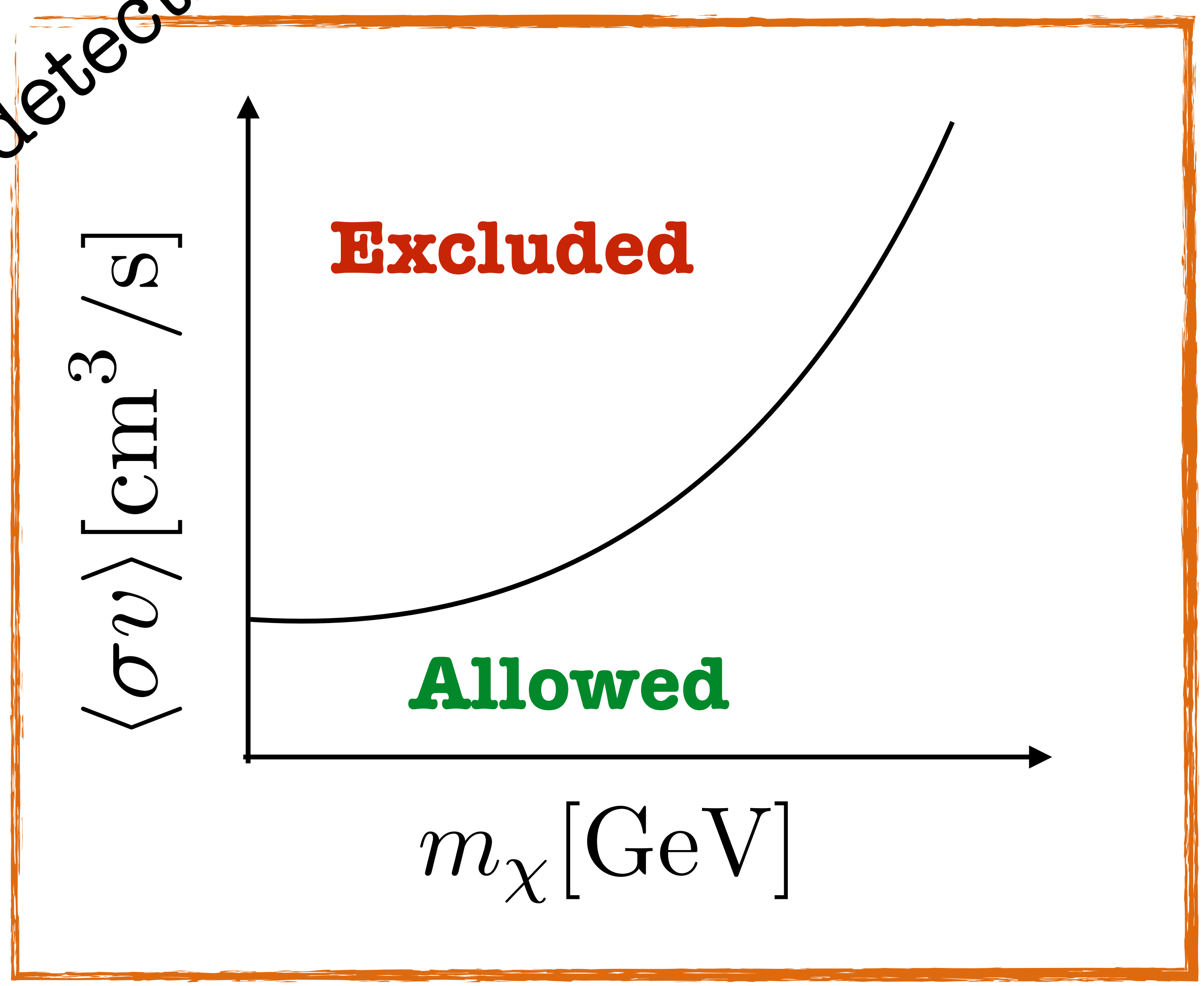


Observed Flux

Expected Flux

$$\Phi_{\rm Obs} \qquad \Phi_{\rm Th}$$

No signal detection

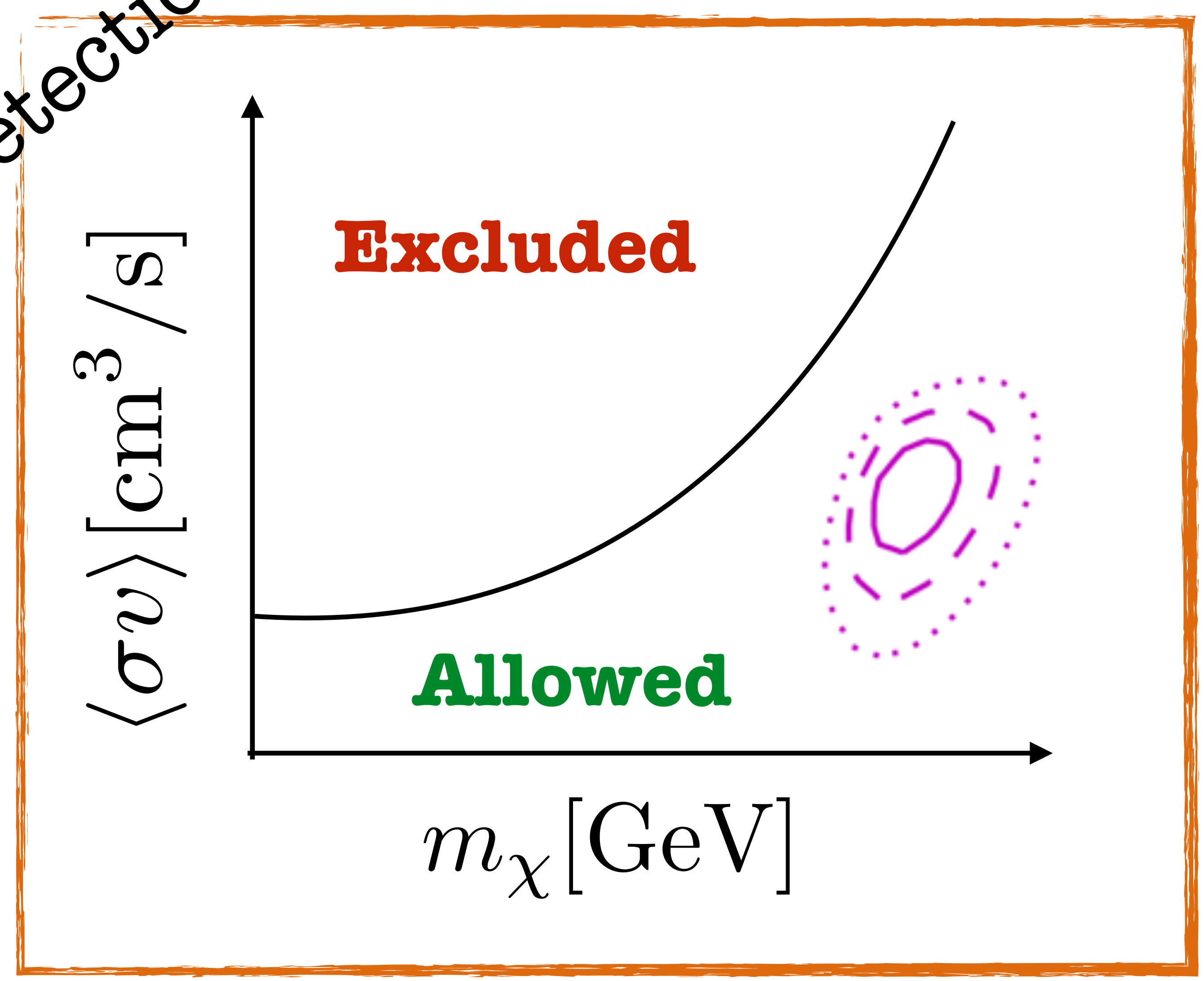


General about DM searches

Observed Flux — Expected Flux

$$\Phi_{\mathrm{Obs}} \qquad \Phi_{\mathrm{Th}}$$

Signal detection



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