Dark Matter

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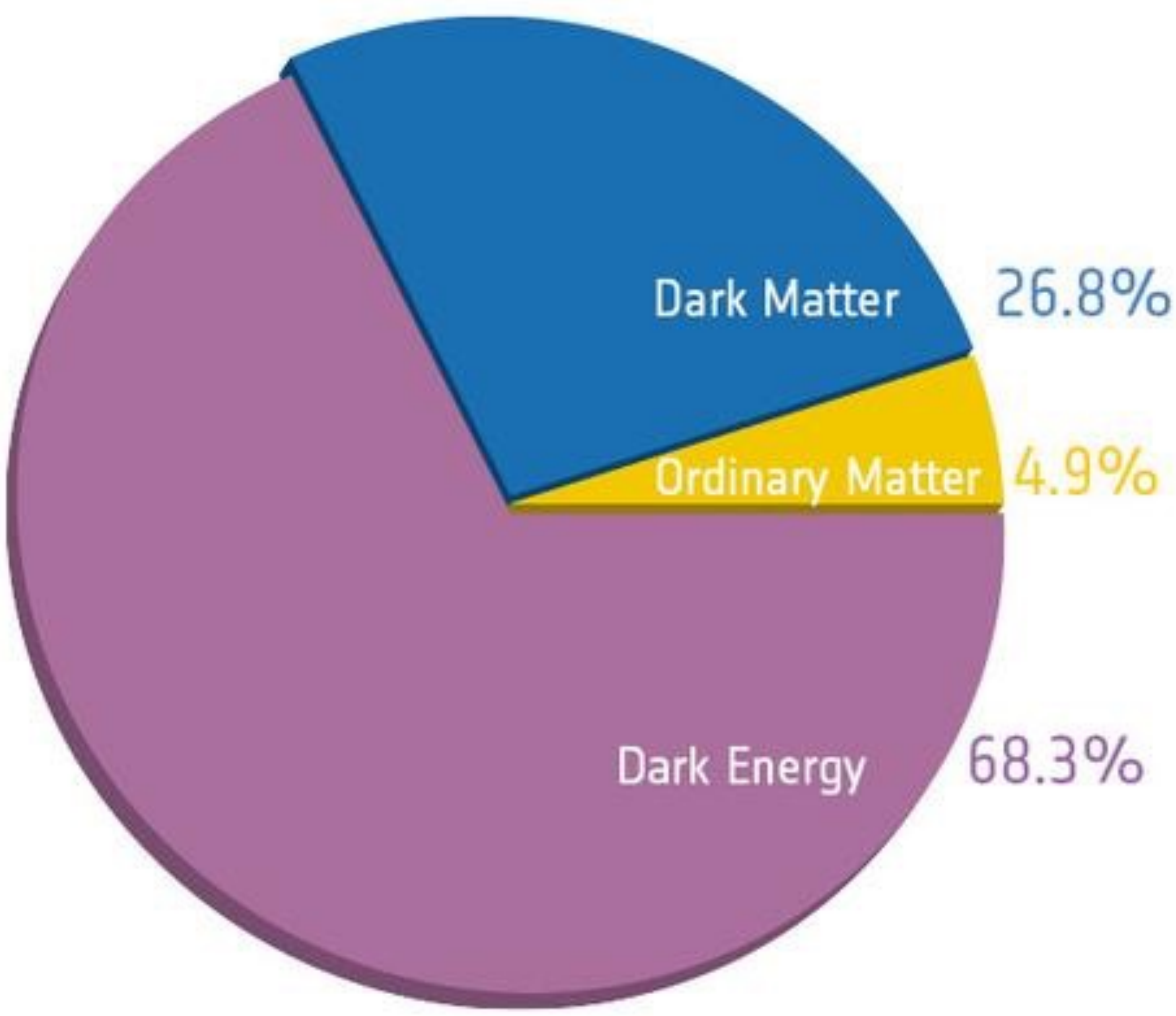
MC4BSM workshop 2016, Beijing

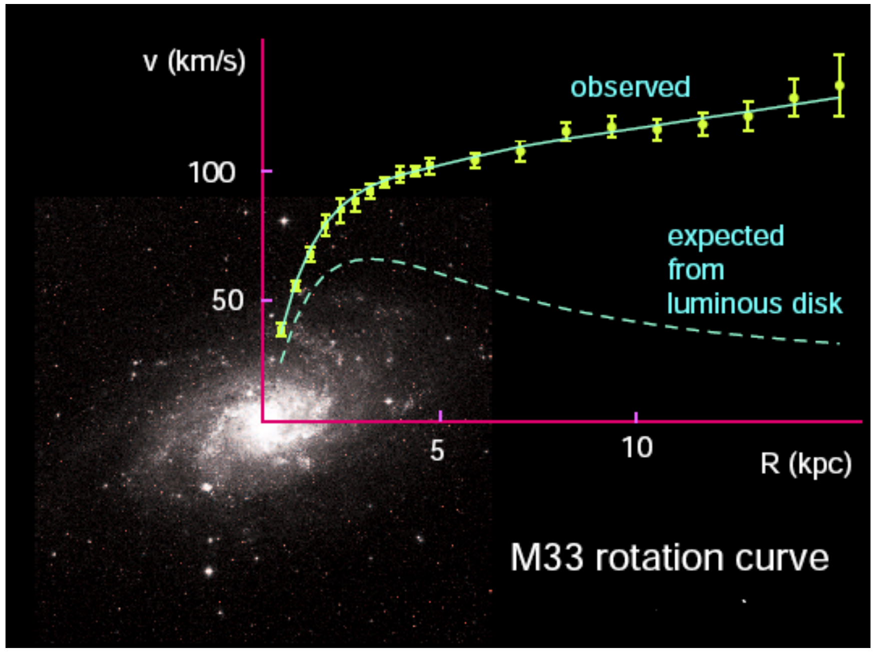
The Big Question

What is the Universe made of?

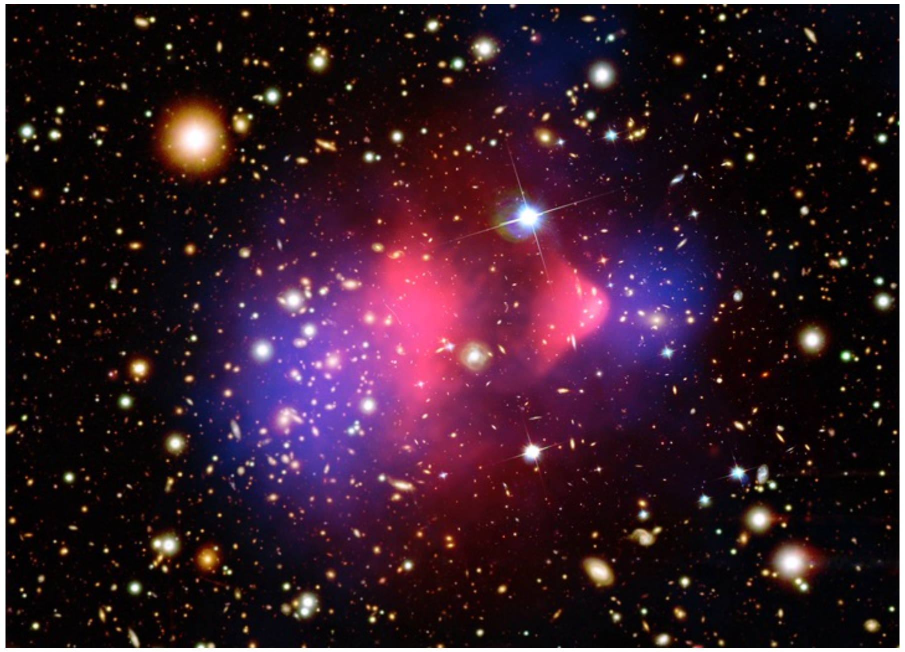


Dark matter dominates in Matter.

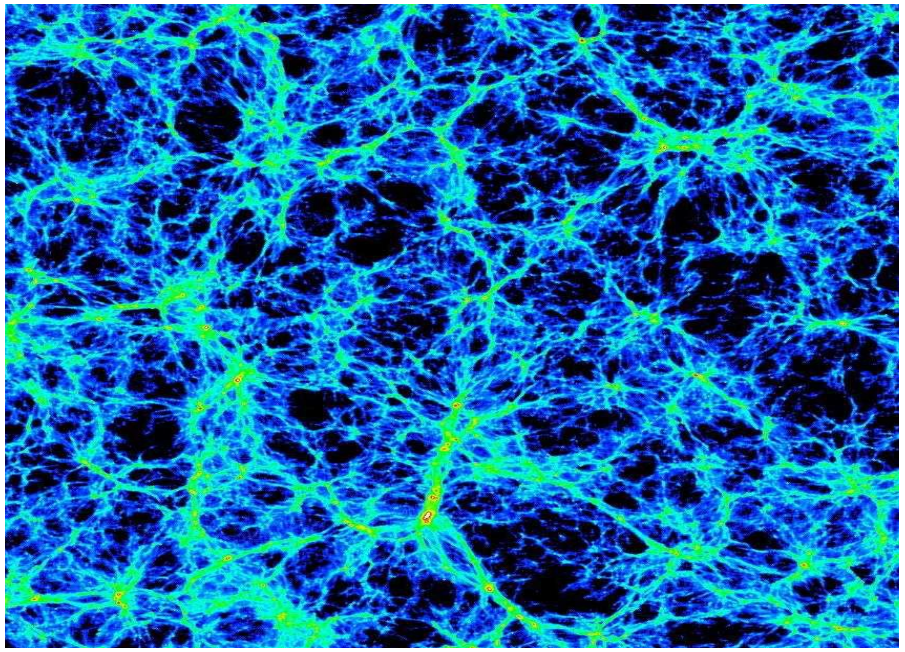
Evidence of dark matter



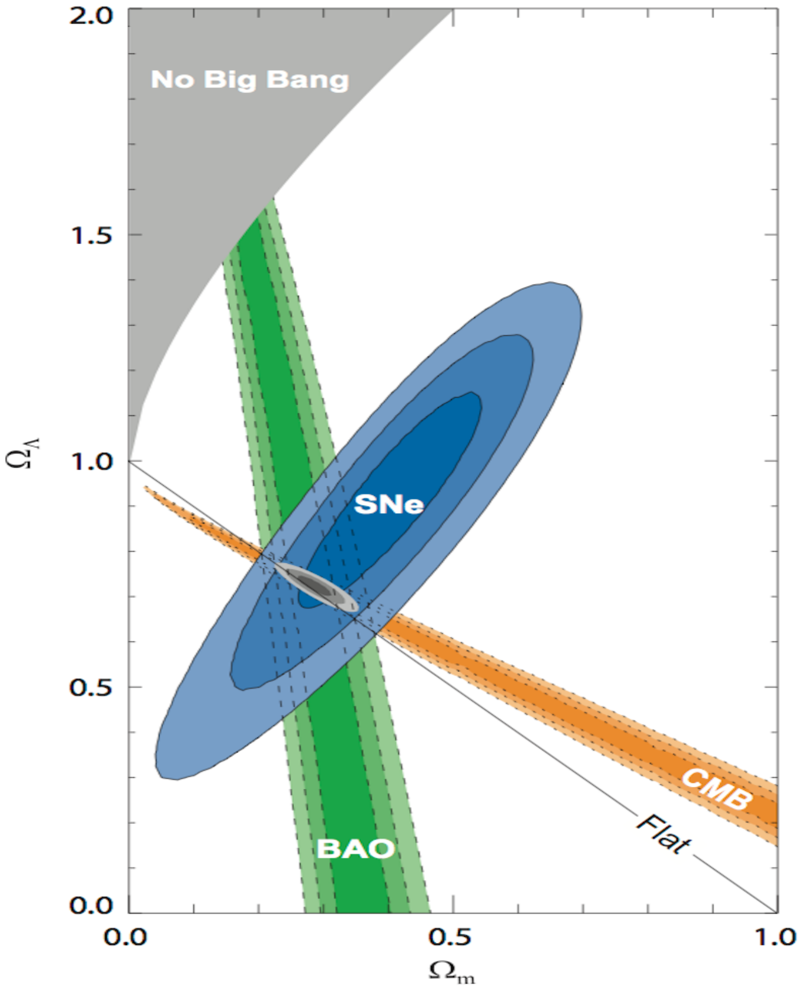
rotation curve

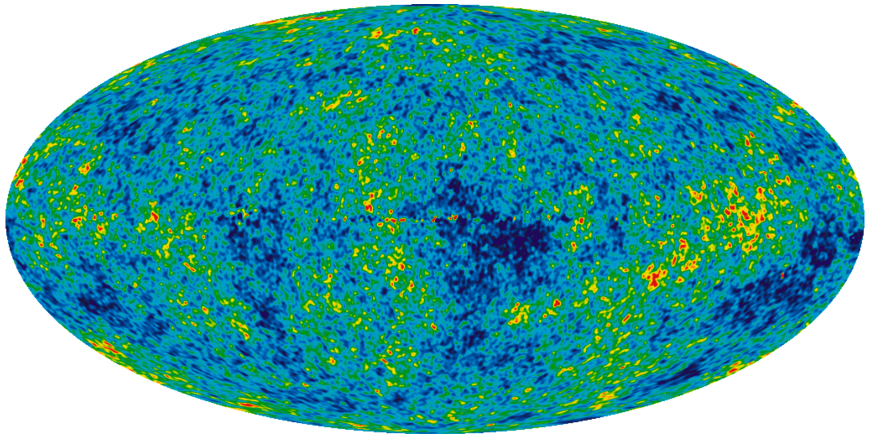


bullet cluster



large structure formation





CMB

$$\Omega_{\rm cdm} = 0.265(11)$$
$$\Omega_b = 0.0499(22)$$
$$\Omega_\Lambda = 0.685(16)$$

PDG 2015

Dark matter

1. The existence of dark matter is well established (by gravitational effects).

2. The relic density of dark matter is known with precision:

$$\Omega_{\rm cdm} h^2 = 0.1198(26)$$

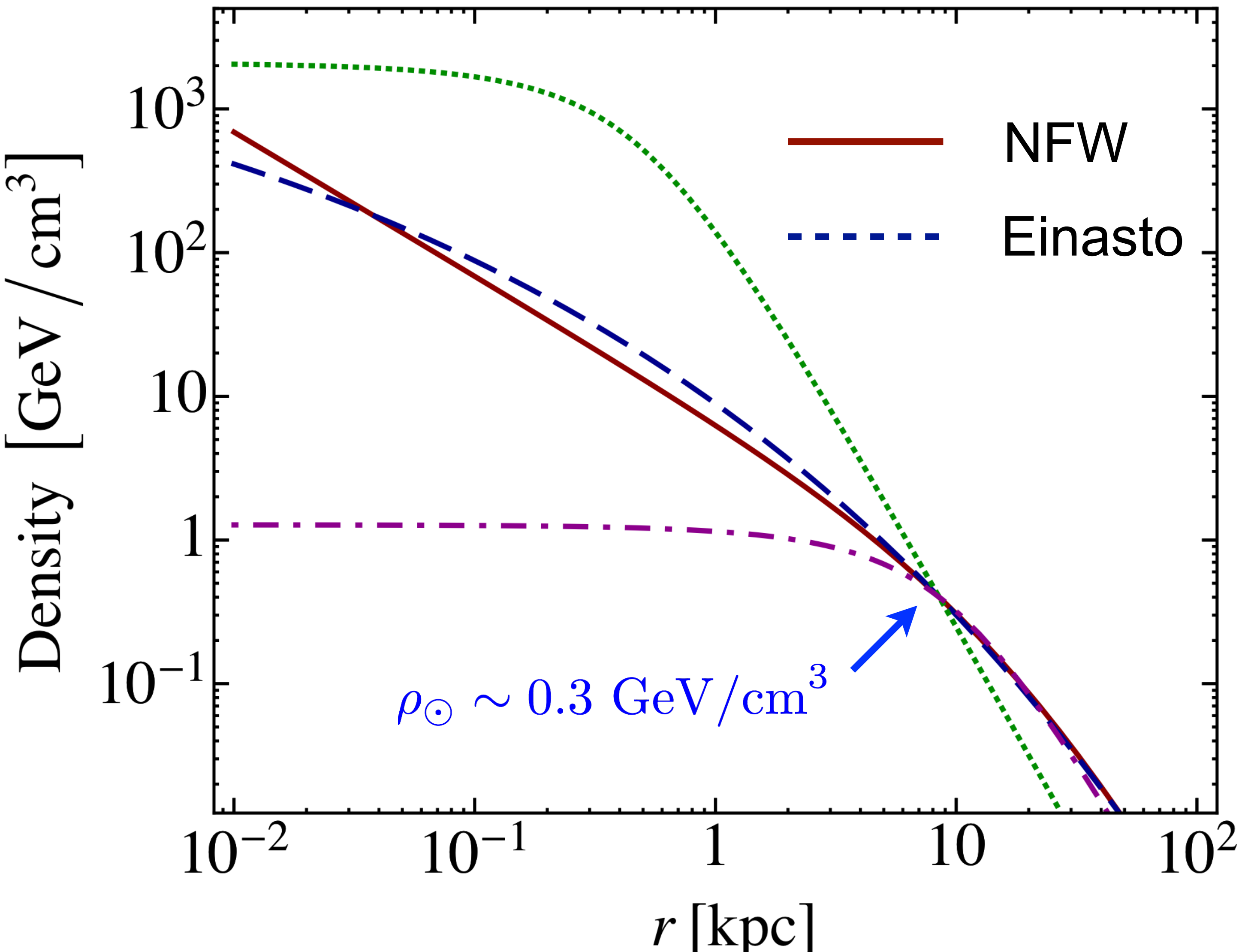
3. The identity of dark matter is still a mystery.

4. Particle Dark Matter basic properties:

   - (Electrically) neutral or milli-charged;
   - Non-Baryonic;
   - Weakly interacting;
   - “Cold” or “Warm”;
   - Stable on the cosmological scale.

Dark matter profile

From N-body simulations and rotation curves



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DM density profile

NFW profile

$$\rho_{\mathrm{NFW}}(r) = \frac{4\rho_s}{(r/r_s)(1+r/r_s)^2}$$

Einasto profile

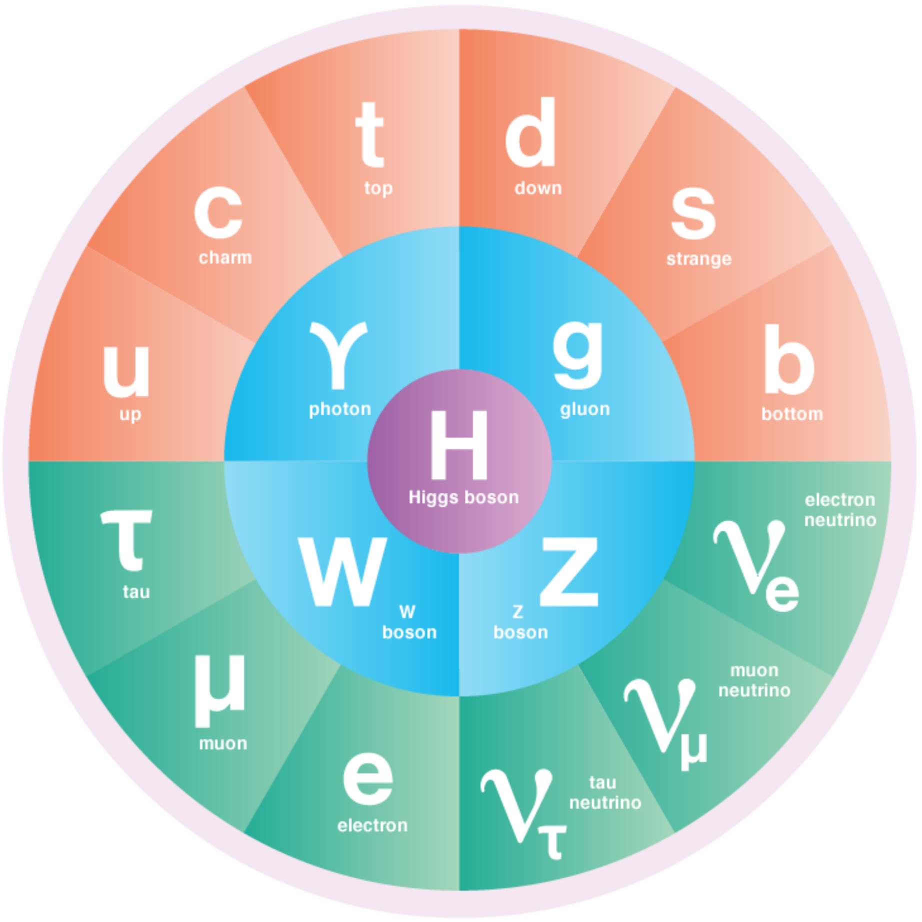
$$\rho_{\mathrm{Ein}}(r) = \rho_s \exp\left[-\frac{2}{\gamma}\left((r/r_s)^2 - 1\right)\right]$$

Beyond the SM

- The relic abundance of active (massive) Neutrinos is:

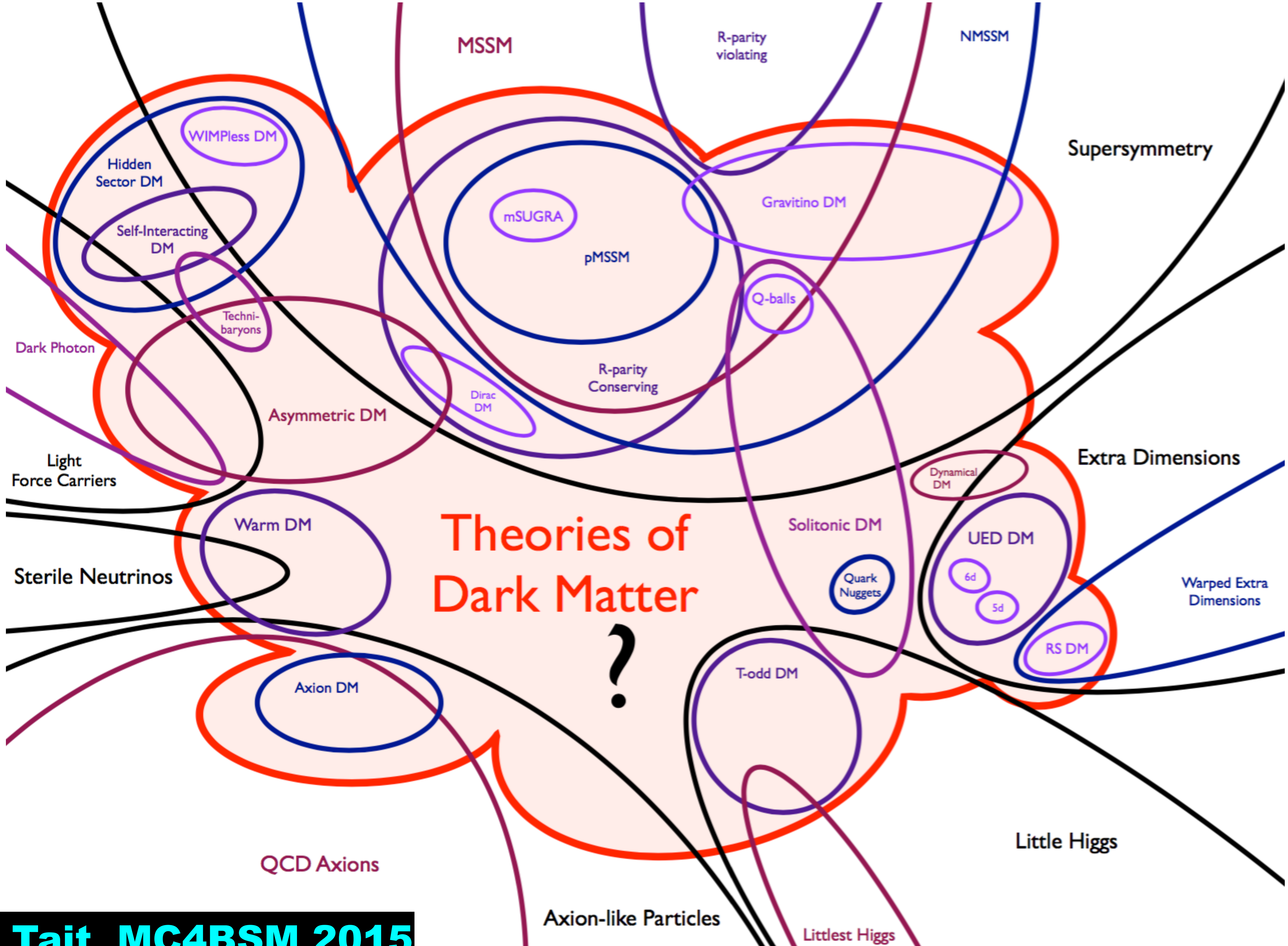
$$\Omega_\nu h^2 \approx \frac{\sum m_\nu}{93\text{eV}} \lesssim 0.01$$

- Neutrinos are too "hot" to be dark matter.



Go beyond the Standard Model!

Dark matter zoo



T. Tait MC4BSM 2015

WIMPs (Weakly interacting massive particles)

- Popular candidates: **weakly interacting massive particles;**

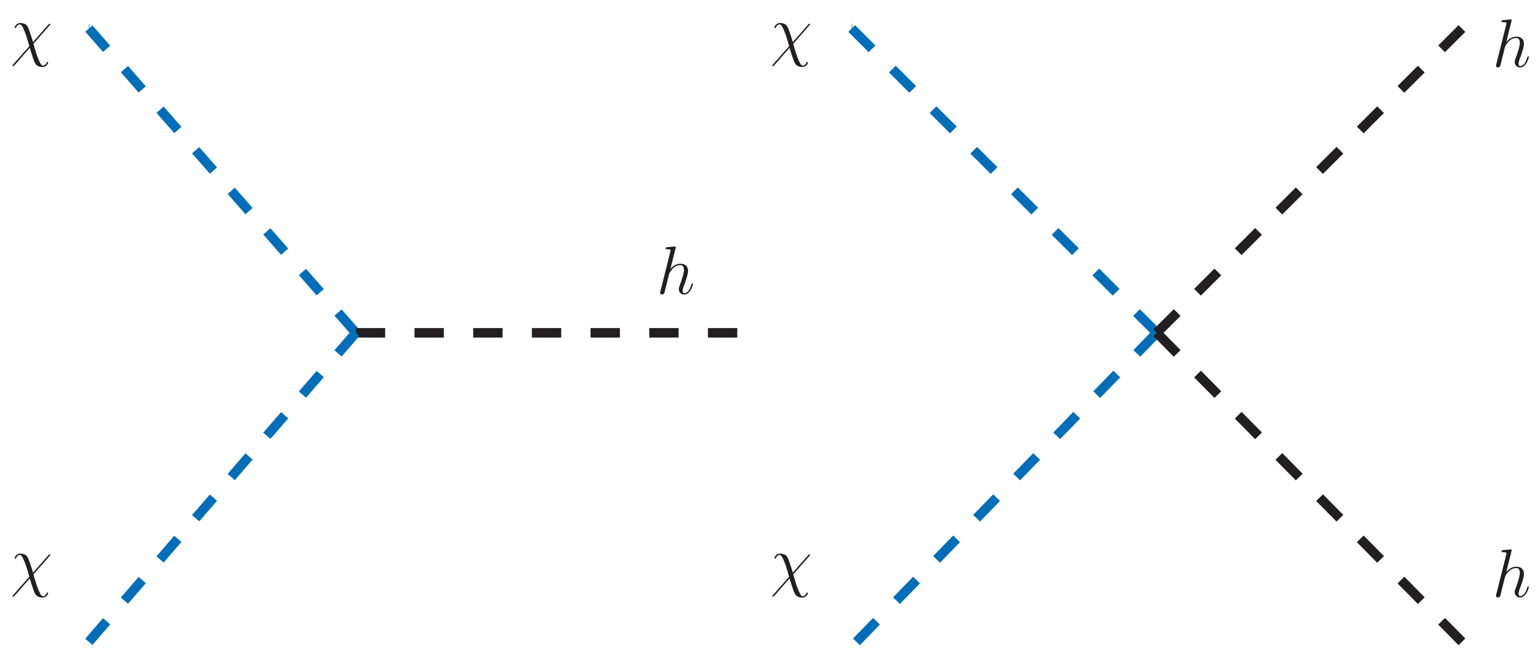
- Stabilization mechanism: an ad hoc Z2 symmetry, such as the R-parity in SUSY theories.

- Show up as byproducts in many models BSM addressing the hierarchy problem. (neutralinos in SUSY, …)

The simplest DM model

- Real singlet scalar with Z2 odd symmetry added into SM.

$$\mathcal{L}_\chi = \frac{1}{2}\partial^\mu\chi\partial_\mu\chi - \frac{1}{4}\lambda\chi^4 - \frac{1}{2}m_0^2\chi^2 - \lambda\chi^2 H^\dagger H$$



Tools to generate interactions (Feynman rules)
FeynRules, LanHEP, …

‘canonical’ WIMPs: Thermal relics

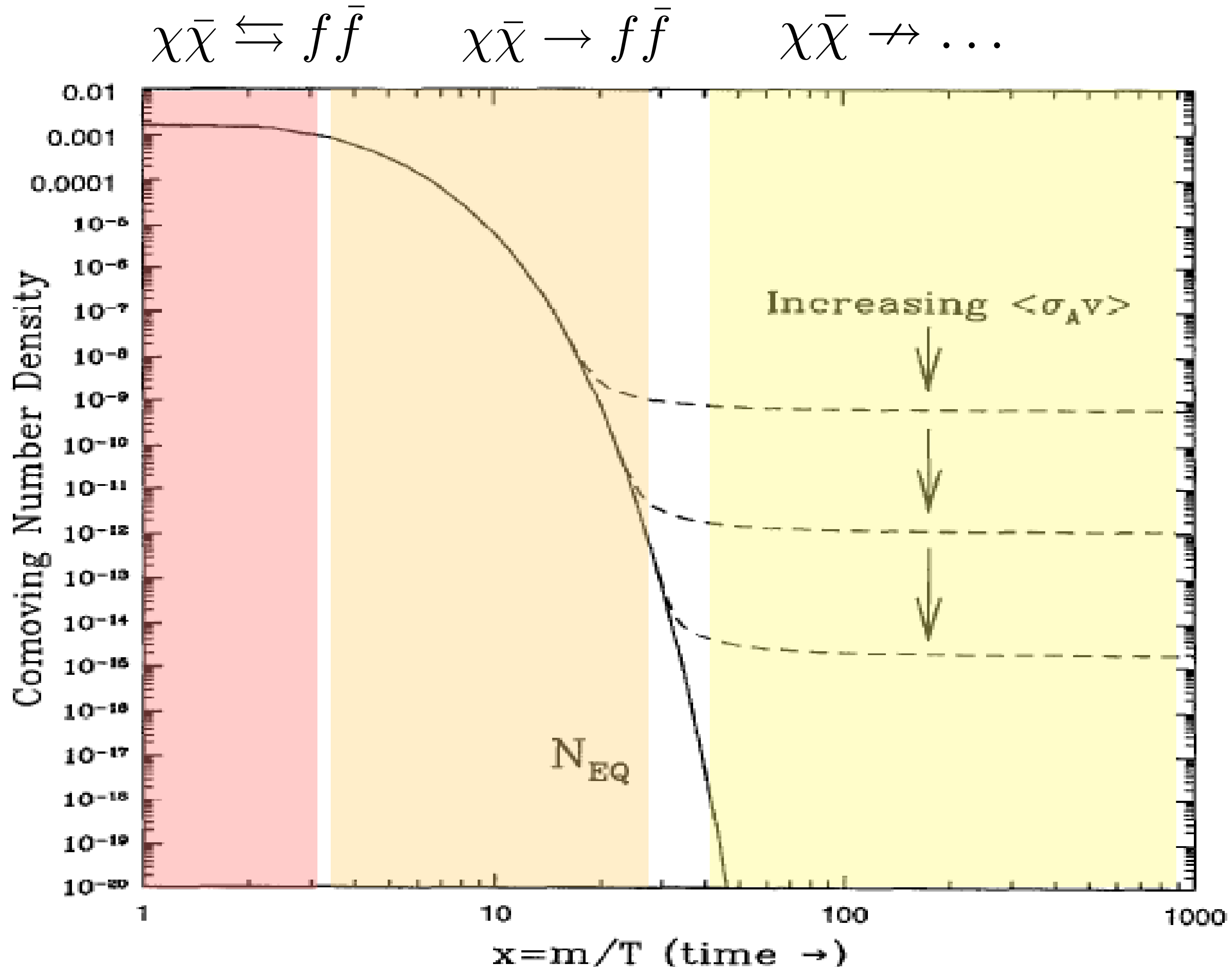
- Thermal freeze-out: the relic density connects to the “annihilation” cross section

DM + DM ⟷ SM + SM

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

- Thermal freeze-out while annihilation rate comparable to the Hubble constant.

$$\Gamma_{\rm anni} = n_\chi \langle\sigma_A v\rangle \sim H(T_f)$$



'canonical' WIMP relics

- For homogeneous and isotropic PDFs, the Boltzmann equation of self-conjugated particles is

$$\dot{n} + \underbrace{3Hn}_{\text{dilution}} = \langle \sigma_A v \rangle (\underbrace{n_{eq}^2}_{\text{creation}} - \underbrace{n^2}_{\text{annihilation}})$$

in terms of $x = m/T, Y \equiv n/s$

$$\frac{dY}{dx} = -\sqrt{\frac{\pi g_*}{45 G_N}} \frac{m_\chi}{x^2} \langle \sigma_A v \rangle (Y^2 - Y_{eq}^2)$$

‘canonical’ WIMP relics

neglect Y_{eq} for $x \gg x_f$

$$\frac{1}{Y_\infty} \sim \frac{1}{Y(x_f)} + \sqrt{\frac{\pi}{45 G_N}} m_\chi \int_{x_f}^{\infty} dx \sqrt{g_*(x)} \frac{\langle \sigma_A v \rangle}{x^2}$$

neglect $1/Y(x_f)$ and assume $\langle \sigma_A v \rangle \approx$ const.

$$Y_\infty \sim \sqrt{\frac{45 G_N}{\pi g_*(x_f)}} \frac{x_f}{m_\chi} \frac{1}{\langle \sigma_A v \rangle}$$

The relic density is

$$\Omega_\chi h^2 = \frac{s_0 Y_\infty m_\chi h^2}{\rho_c} \sim \frac{3 \times 10^{-38} \text{cm}^2}{\langle \sigma_A v \rangle} \frac{x_f}{\sqrt{g_*(x_f)}}$$

general WIMP relics

- For general case, the dark matter model may include multiple dark matter candidates.

- Hybrid freeze-out processes:
  - self-annihilation;
  - co-annihilation;
  - threshold effects;
  - resonance effects;
  - 2 to 2, 2 to 3, …

general WIMP relics

- For general case, the dark matter model may include multiple dark matter candidates.

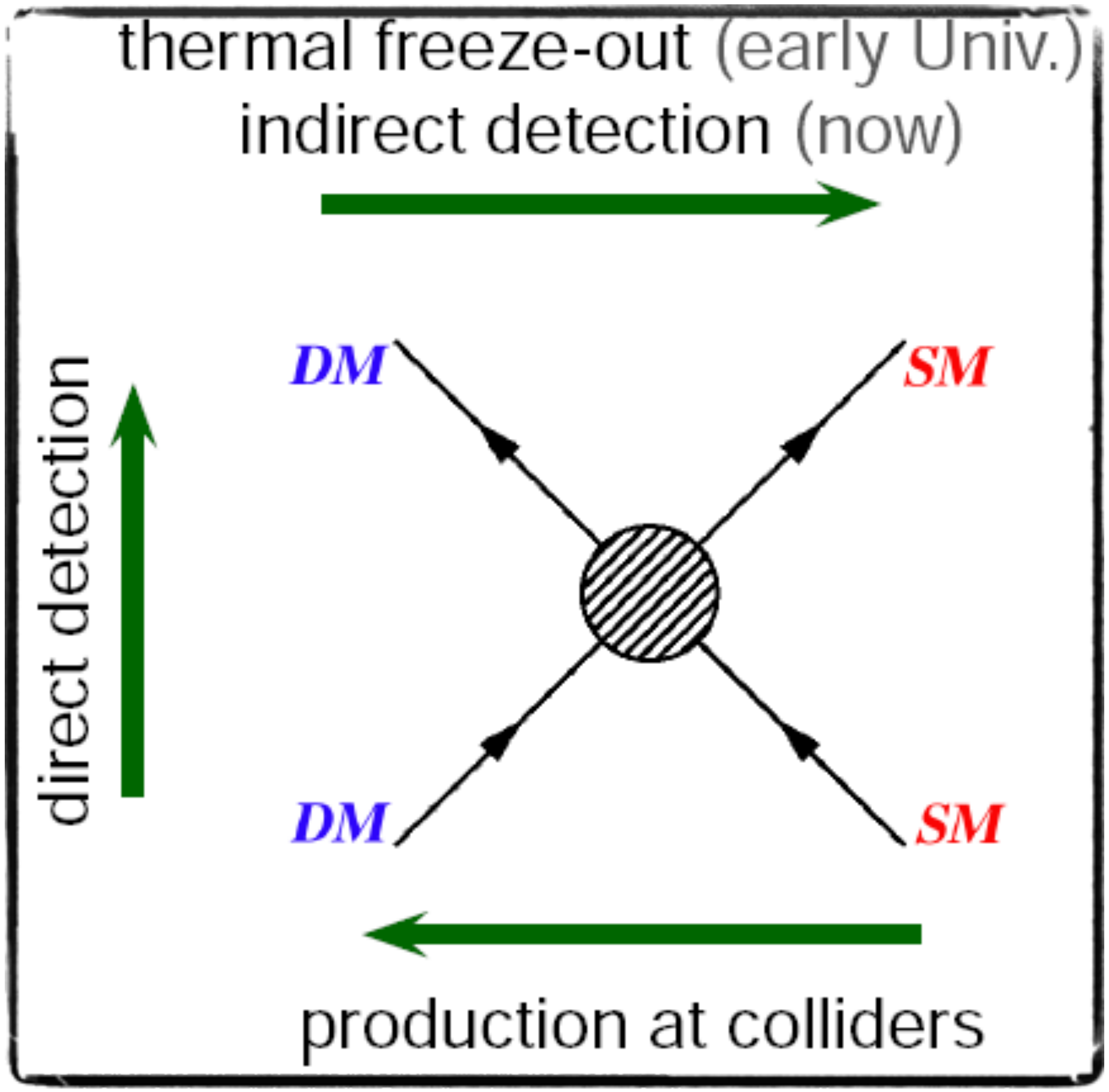
- Hybrid freeze-out processes:
  - self-annihilation;
  - co-annihilation;
  - threshold effects;
  - resonance effects;
  - 2 to 2, 2 to 3, …

The Boltzmann equation involves more terms and becomes more complicated.

micrOMEGAs
MadDM
……

Dark matter (WIMP) detections

- **WIMPs: weakly interacting massive particles**



1) direct detection: nuclear recoil

2) indirect detection: annihilation products

3) search at the colliders: Missing ET

Direct detection

- Searching for nuclear recoil of DM-nucleus (elastic) scattering

Recoil energy: $$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2 (1 - \cos\theta_{cm})}{m_N}$$

Interaction rate: $$R = N_T n_\chi \sigma v$$

- Rate spectral: (counts/day/kg/keV)

$$\boxed{\frac{dR}{dE_r} = \frac{1}{m_N}\frac{\rho_0}{m_\chi}\int_{v_{\min}}^{v_{\rm esc}} \frac{d\sigma}{dE_r} v f_\oplus(\vec{v},t) d^3\mathbf{v}}$$

$v_{\min} = \sqrt{m_N E_r/(2\mu^2)}$ minimal velocity to create recoil E_r

$\rho_0 \sim 0.3\mathrm{GeV}/\mathrm{cm}^3$ local DM density

$f_\oplus(\vec{v},t)$ velocity distribution

DM velocity distribution

$f_\oplus(\vec{v},t)$: DM velocity distribution in earth frame.

$$f_\oplus(\vec{v},t) = f_{\rm gal}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t))$$

- Maxwellian velocity distribution in dark halo frame

$$f_{\rm gal}(\vec{v}) = \begin{cases} \propto e^{-v^2/v_0^2} & v < v_{esc} \\ 0 & v > v_{esc} \end{cases}$$

with $v_0 \simeq 220$ km/s, $v_{esc} \sim 550$ km/s, $v_\oplus = 30$ km/s

In the NR limit, the DM-nucleus interactions:

- spin-independent interactions: $S \otimes S, V \otimes V$

coherent interactions: $\sigma \propto [Z f_p + (A-Z) f_n]^2$

$f_p = f_n \quad \Rightarrow \sigma \propto A^2 \quad (A^2 \text{ enhancement})$

$f_p \neq f_n \quad \text{isospin-violating dark matter}$

- spin-dependent interactons: $A \otimes A, T \otimes T$

couple to the nucleus with spin (unpaired proton and/or neutron)

elastic and inelastic scattering

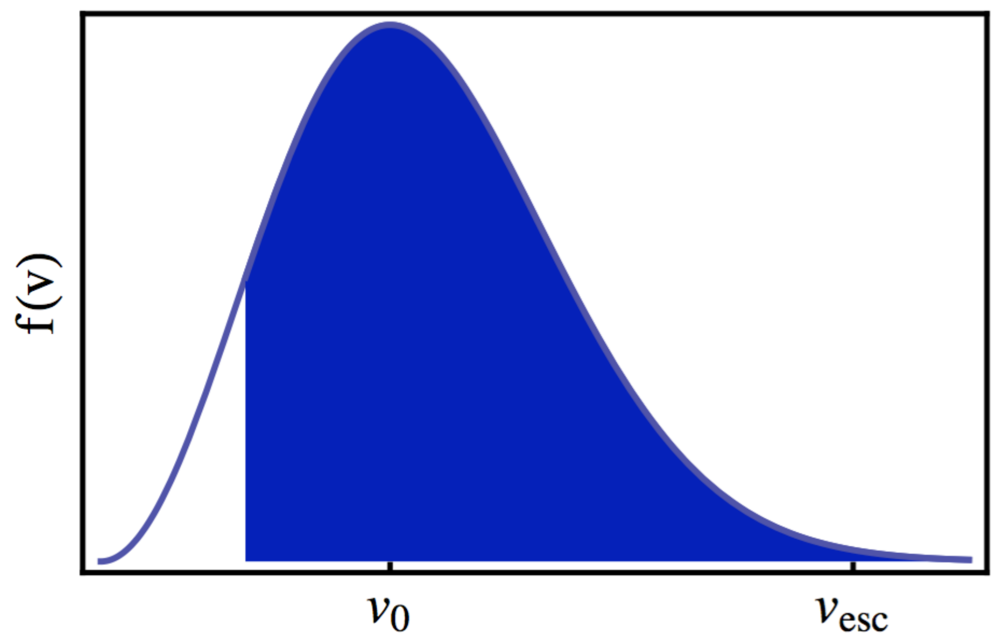
DM is multiplet system

$$\chi + N \rightarrow \chi + N$$

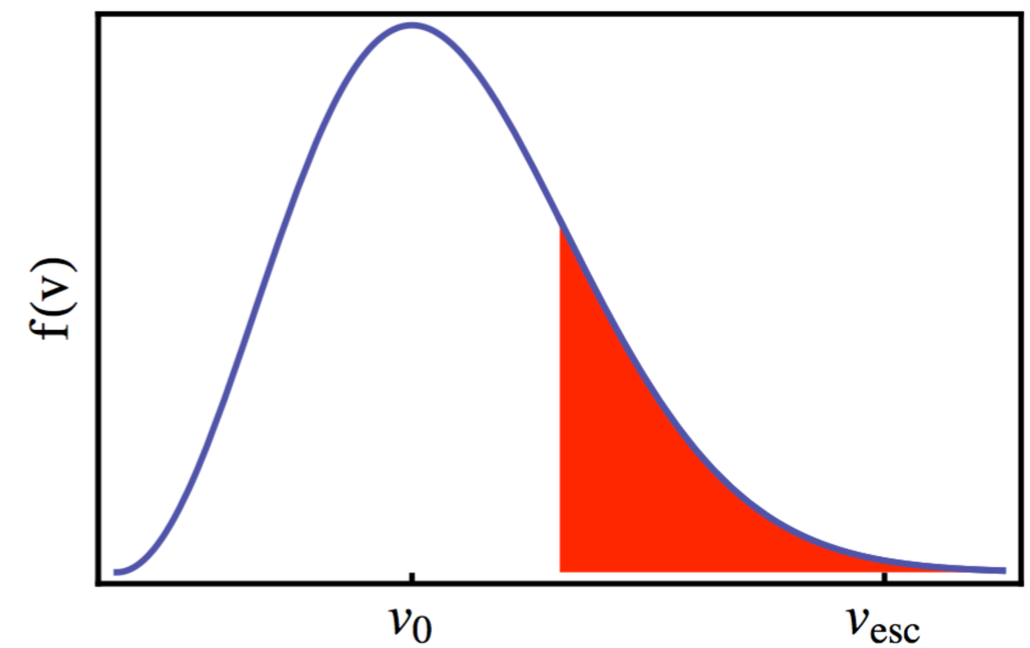
$$\chi + N \rightarrow \chi^* + N$$

$$v_{min} = \frac{1}{\sqrt{2 m_N E_r}} \left(\frac{m_N E_r}{\mu} + \delta_\chi \right)$$

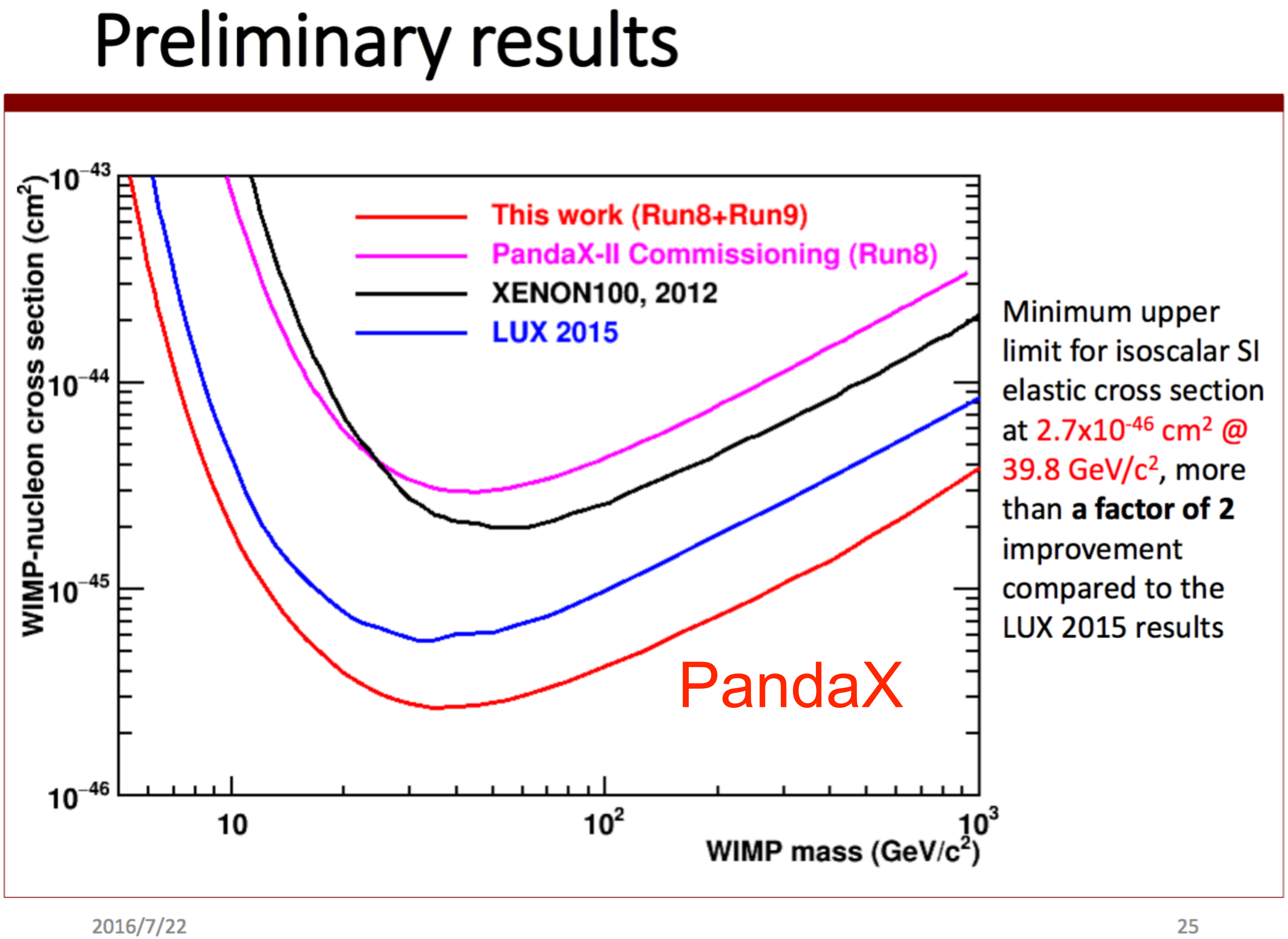
Elastic



Inelastic

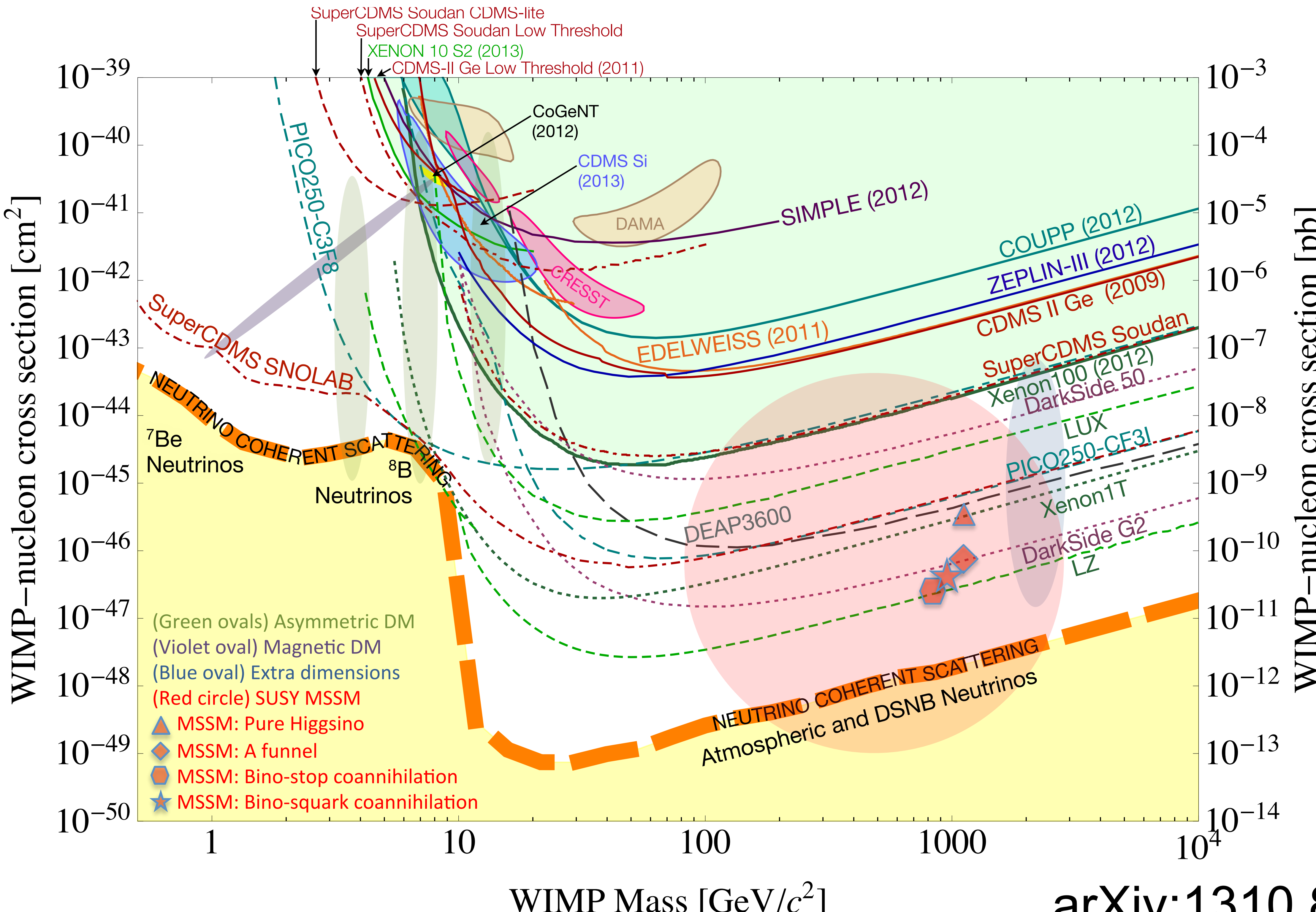


Spin-independent Xsection



We don't 'see' dark matter yet from DM direct detection.

Spin-independent Xsection

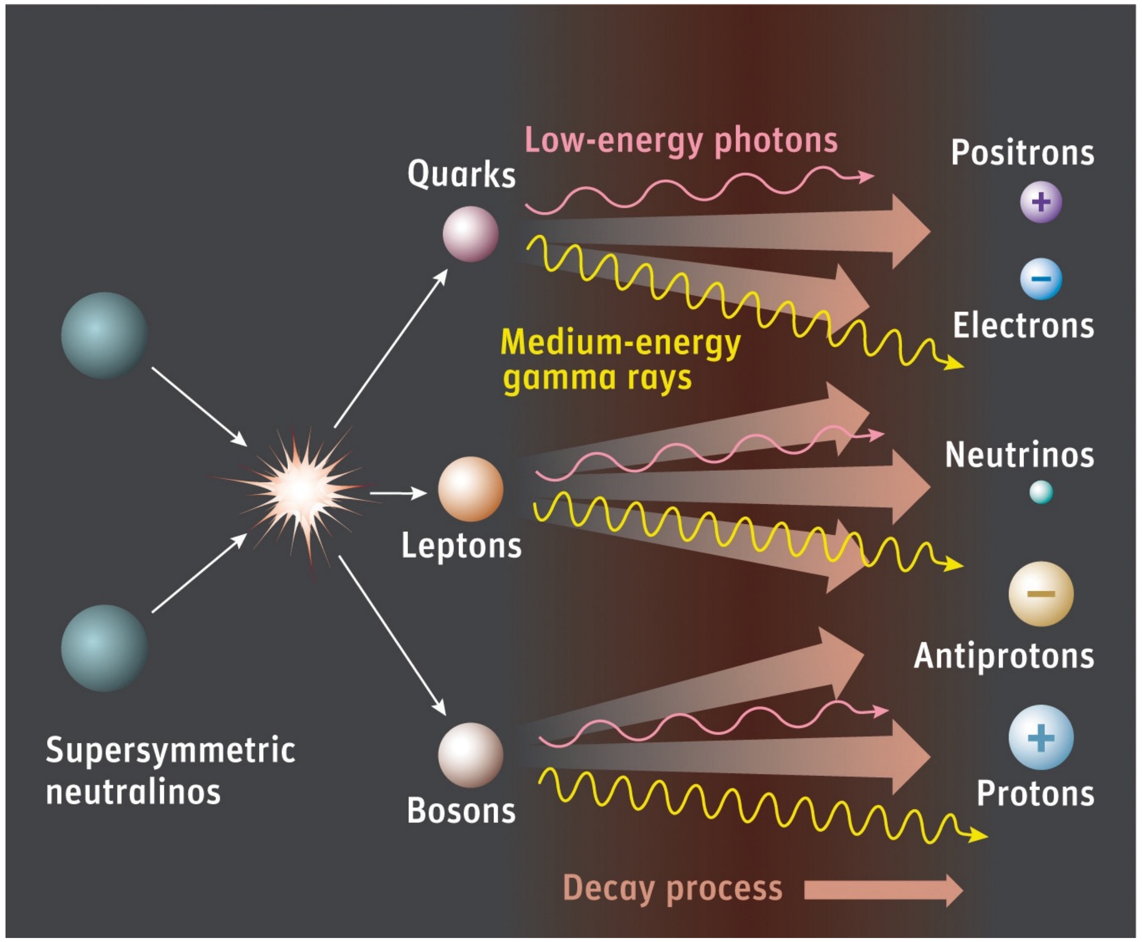


arXiv:1310.8327

low mass region signals are mostly gone.

Indirect detection

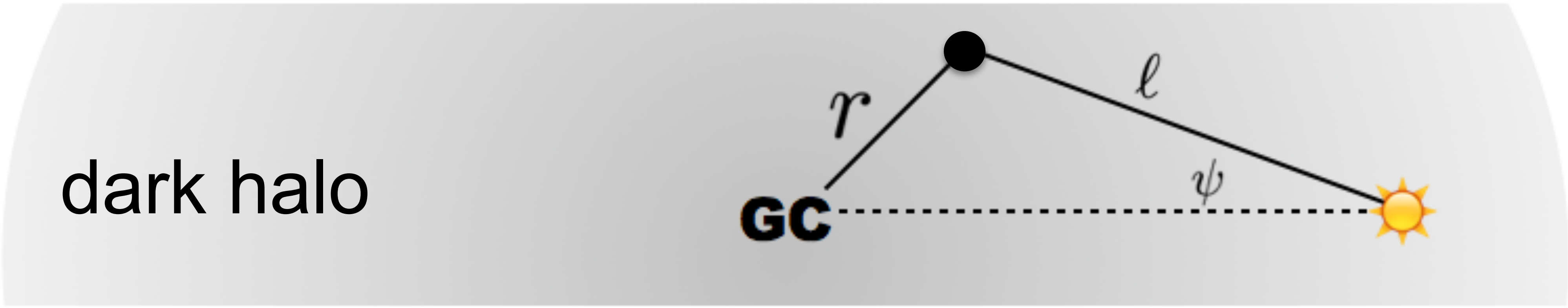
- Search for the products of DM annihilation in the region with high density.



1. gamma rays from galactic center, dwarf galaxies, …
2. positron, electron, antiproton, proton cosmic ray signals
3. neutrinos from stellar objects, e.g. Sun, earth, …

Indirect detection

- Photon flux spectrum from annihilations



$$\Phi(E,\psi) = \frac{\langle \sigma v \rangle}{m_\chi^2} \frac{dN}{dE_\gamma} \frac{1}{4\pi} \int d\Omega \int_{l.o.s.} d\ell \rho [r(\ell,\psi)]^2$$

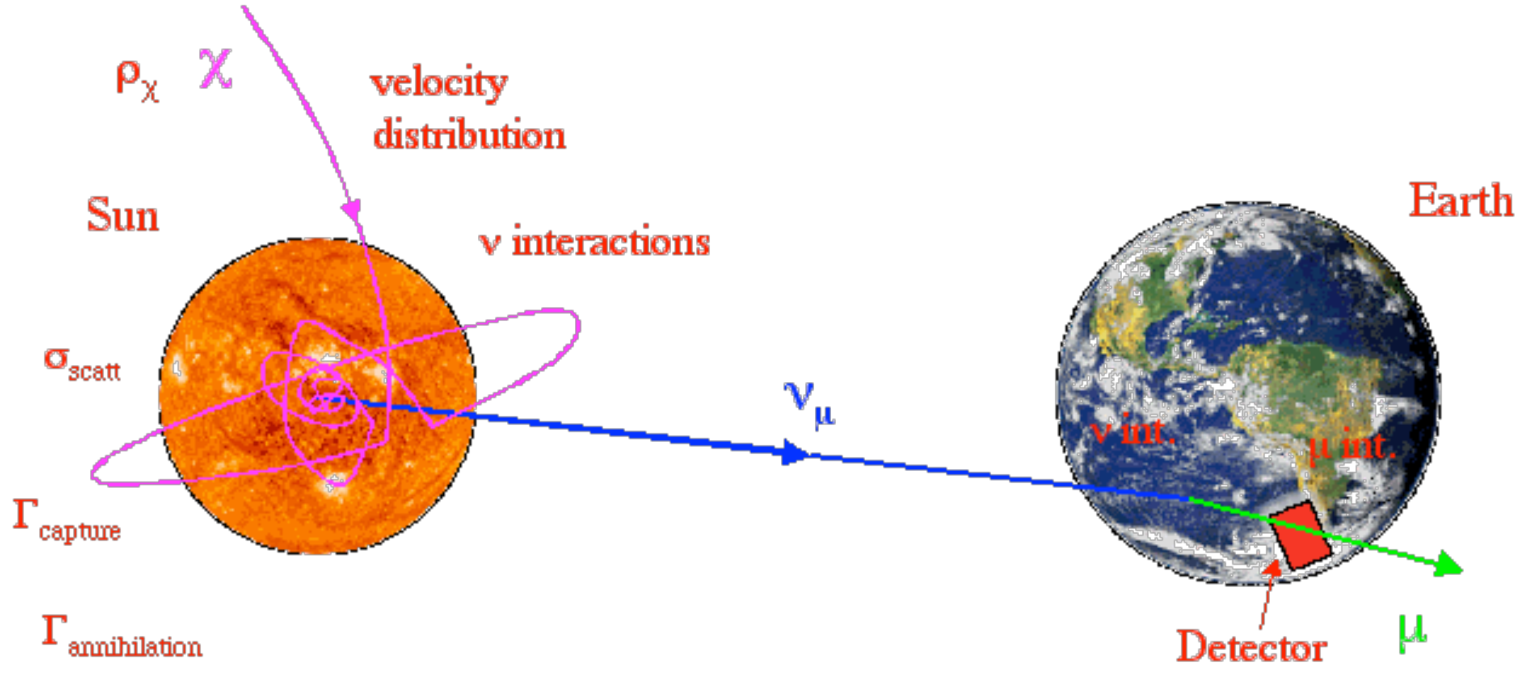
Fermi LAT, HESS, …

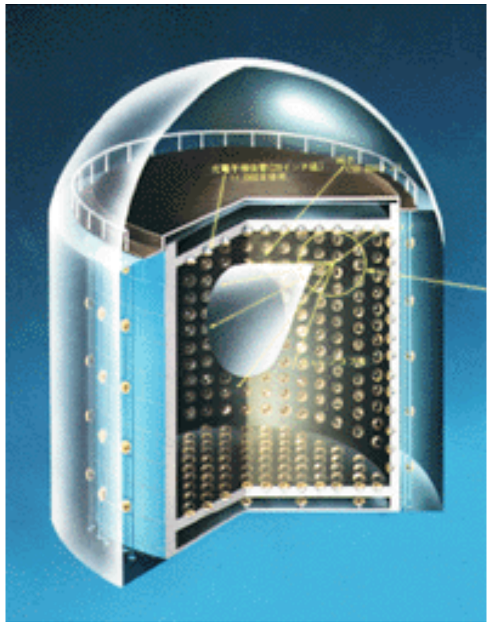
- Charged products (electrons/protons) from annihilations

  Solve the transportation equation

PAMELA, AMS02, …

DM capture in the Sun





DM capture and self-annihilation in the Sun

$$\frac{dN}{dt} = C_\odot - C_A N^2 \quad \Rightarrow \quad N(t) = \sqrt{\frac{C_\odot}{C_A}} \tanh(\sqrt{C_\odot C_A} \cdot t)$$

Capture and self-annihilation in equilibrium:

$$\Gamma_A = C_\odot / 2$$

DM capture in the Sun

The Sun is a natural detector for DM direct detection.

The capture rate

$$C_{\odot,i} = \sum_i 4\pi \int_0^{R_\odot} r^2 dr \frac{\rho_\chi \rho_{\odot,i}(r)}{2 m_\chi \mu_i^2} \sigma_i \int_0^\infty du \frac{f(u)}{u}$$

$$\times \int_{E_{R,\mathrm{cap}}}^{E_{R,\mathrm{max}}} dE_R F^2(E_R)$$

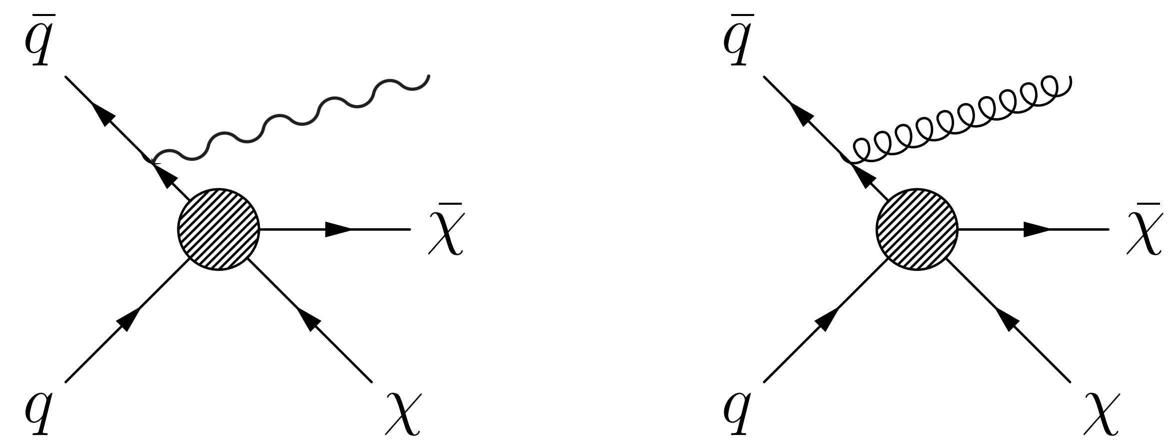
Constraints/detection from Super-Kamionkande, IceCube from the neutrino signals.

Missing ET at the collider

- DM's stability enforced by Z2 symmetry: DM produced in pairs. (Z3 dark matter, …)

- DM appears as missing transverse energy at the collider.

- Simplest case: Monojet/monophoton + missing ET;



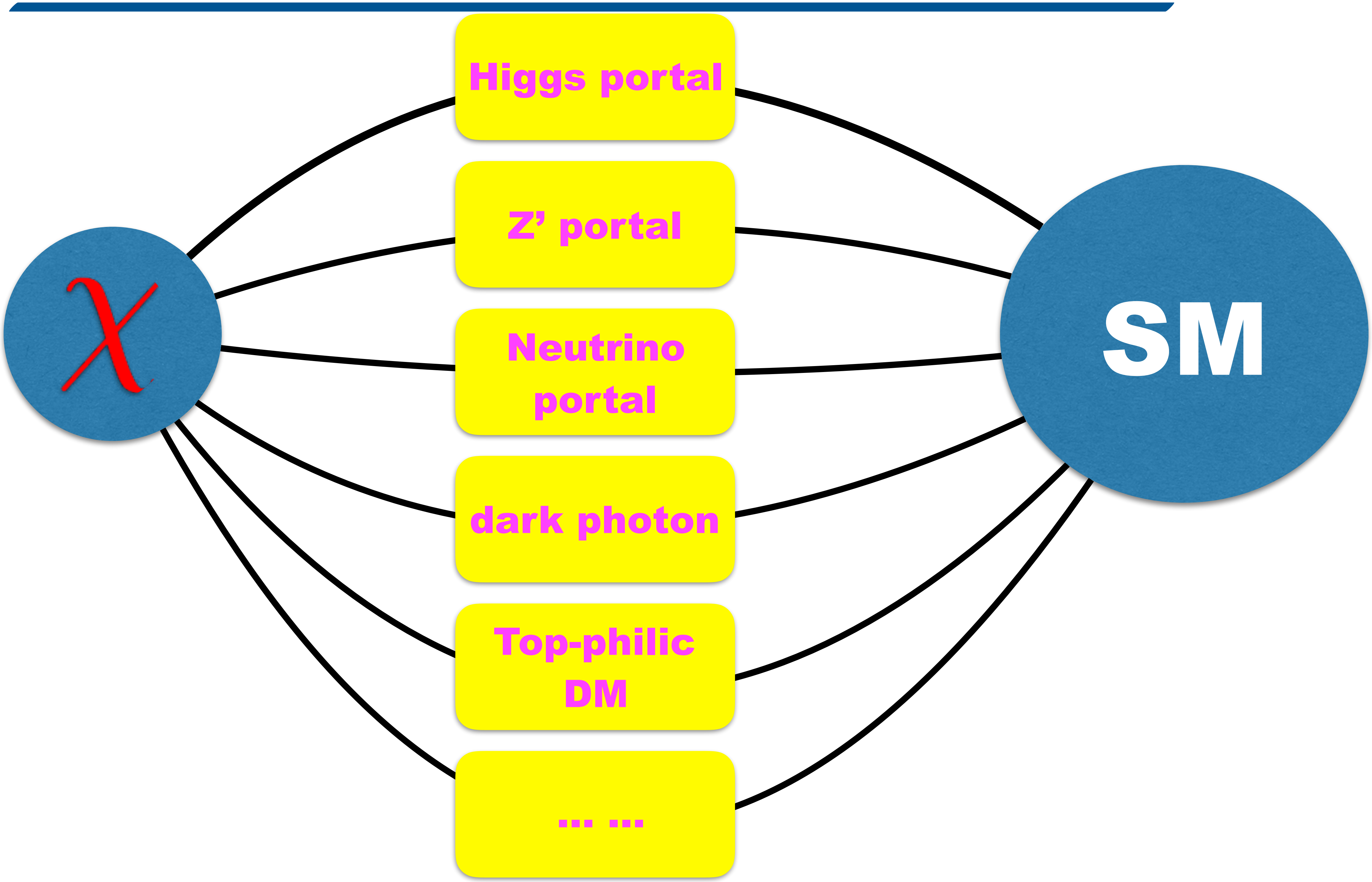
Monophoton + MET   *Monojet + MET*

- Multi-jets/leptons + missing ET;

Dark Matter models

- BSM theory with natural DM candidate;
- Alternative DM product mechanisms (freeze in, non-thermal…)
- DM and neutrino mass correlated (sterile neutrino, “scotogenic” neutrino mass, …)
- Baryogenesis and darkogenesis (Asymmetric DM, …)
- Phenomenology motivated (inelastic DM, isospin-violating DM, resonant DM, …)
- Various mediator DM (Higgs portal, U(1)’ portal, neutrino portal , …)
- Various interactions DM (form factor, momentum dependent, …)
- composite DM, …

Simplified models

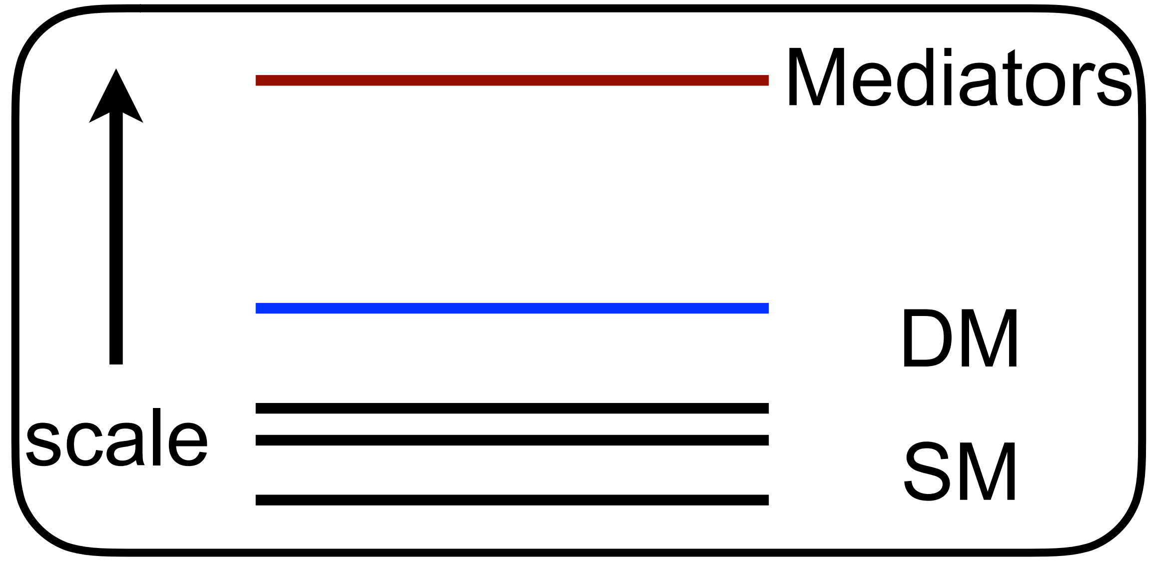


Start from a 'simple' Lagrangian

Effective field theories approach

Name	Operator	Coefficient
D1	$\bar\chi\chi\bar q q$	m_q/M_*^3
D2	$\bar\chi\gamma^5\chi\bar q q$	im_q/M_*^3
D3	$\bar\chi\chi\bar q\gamma^5 q$	im_q/M_*^3
D4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	m_q/M_*^3
D5	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	$1/M_*^2$
D6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/M_*^2$
D7	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi\bar q\sigma_{\mu\nu} q$	i/M_*^2
D11	$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar\chi\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D
M1	$\bar\chi\chi\bar q q$	$m_q/2M_*^3$
M2	$\bar\chi\gamma^5\chi\bar q q$	$im_q/2M_*^3$

Name	Operator	Coefficient
M3	$\bar\chi\chi\bar q\gamma^5 q$	$im_q/2M_*^3$
M4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	$m_q/2M_*^3$
M5	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/2M_*^2$
M6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/2M_*^2$
M7	$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^3$
M8	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M9	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M10	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/8M_*^3$
C1	$\chi^\dagger\chi\bar q q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar q\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar q\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar q\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar q q$	$m_q/2M_*^2$
R2	$\chi^2\bar q\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/8M_*^2$

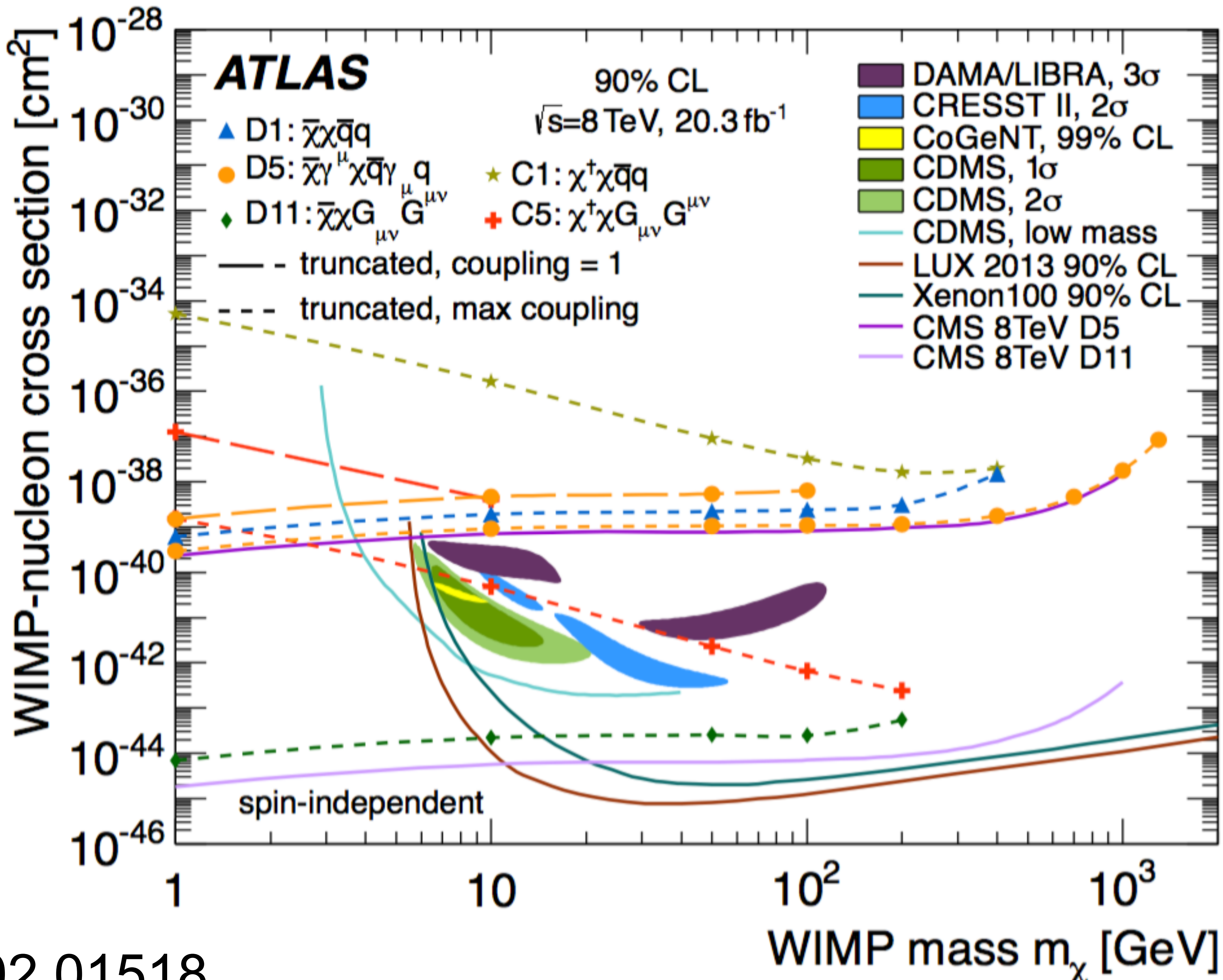


- The mediator is integrated out.
- few parameters: DM mass, effective scale

EFT approach is useful for complementary analysis for various detection ways.

1009.0008

LHC monojet



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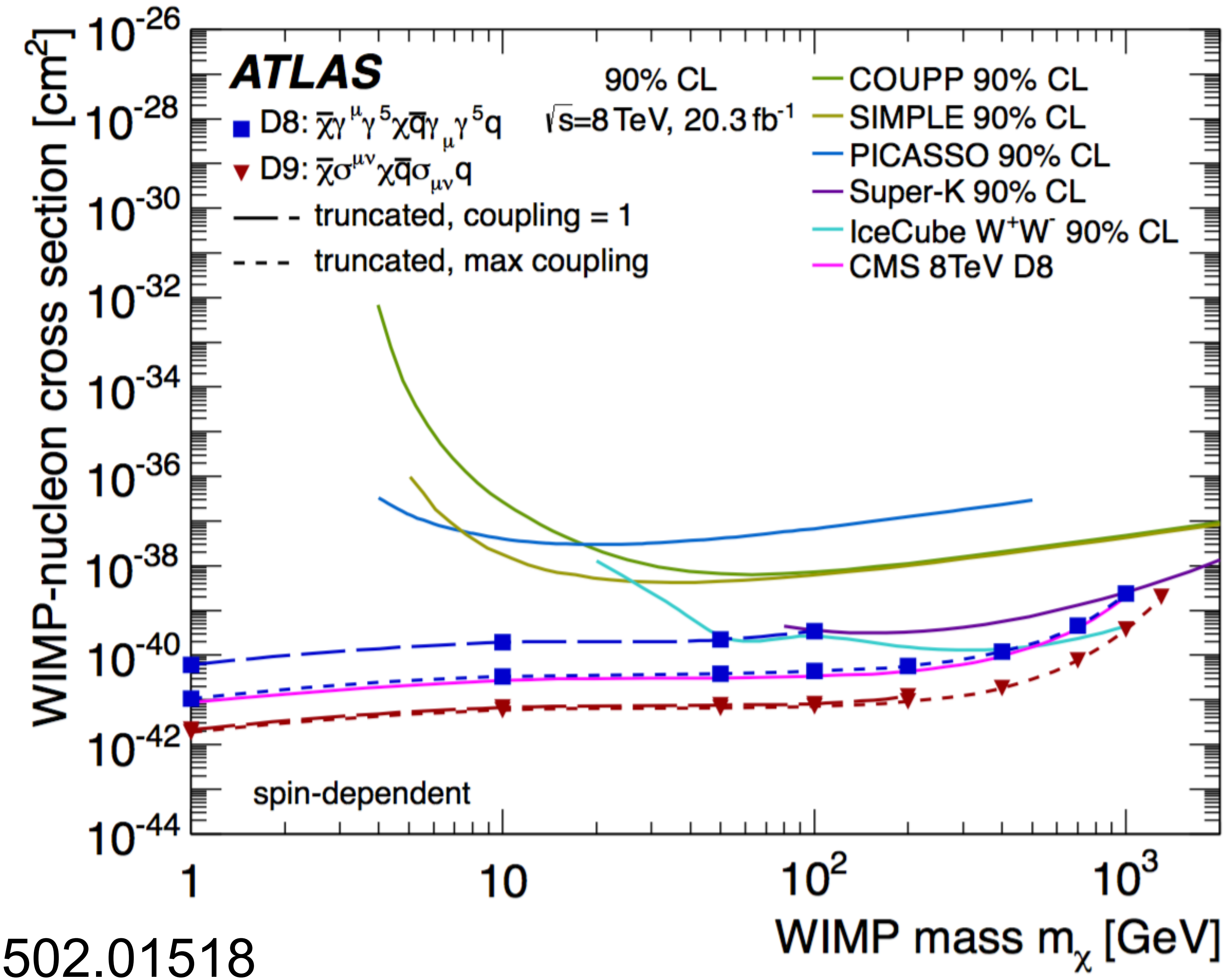
LHC monojet



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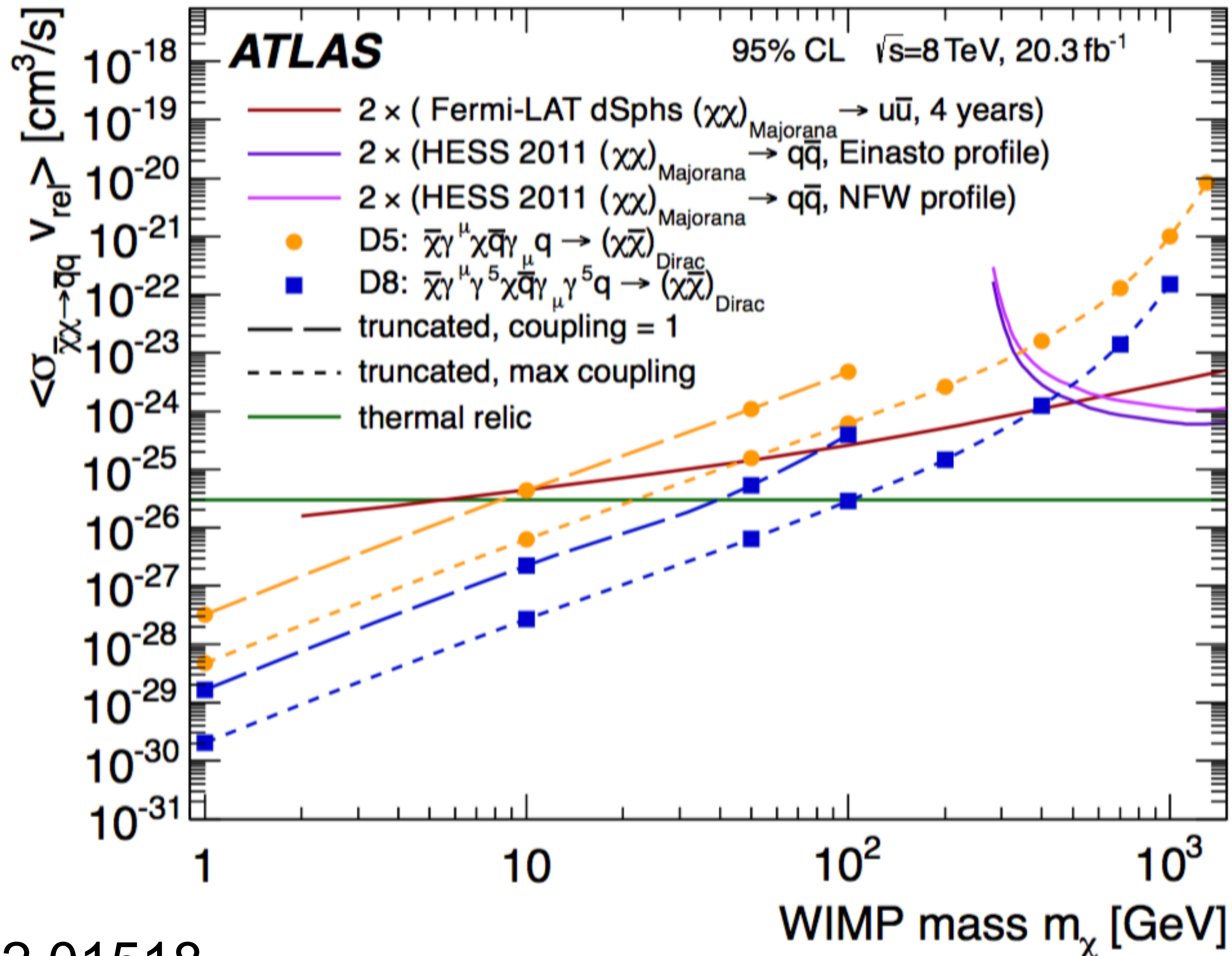
LHC monojet



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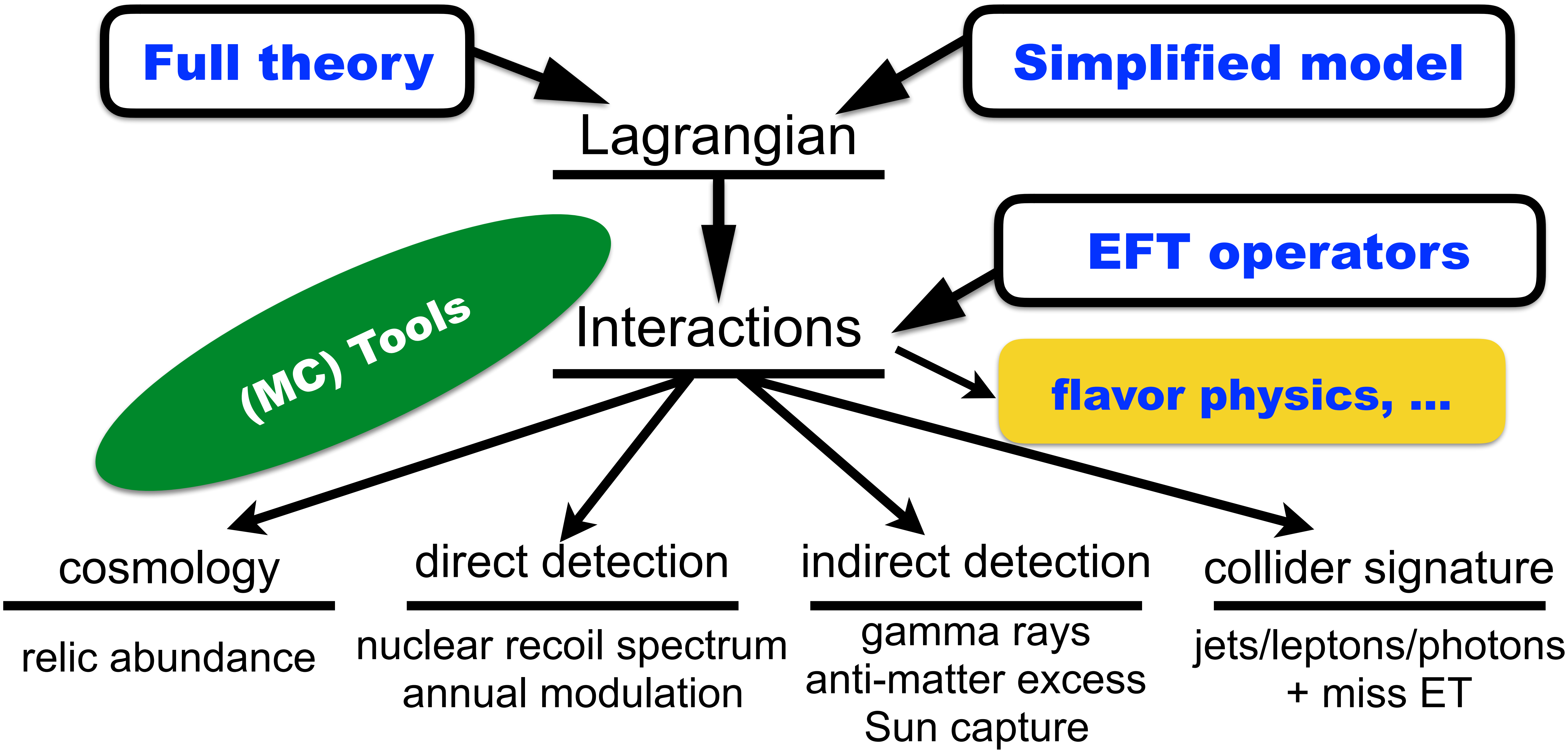
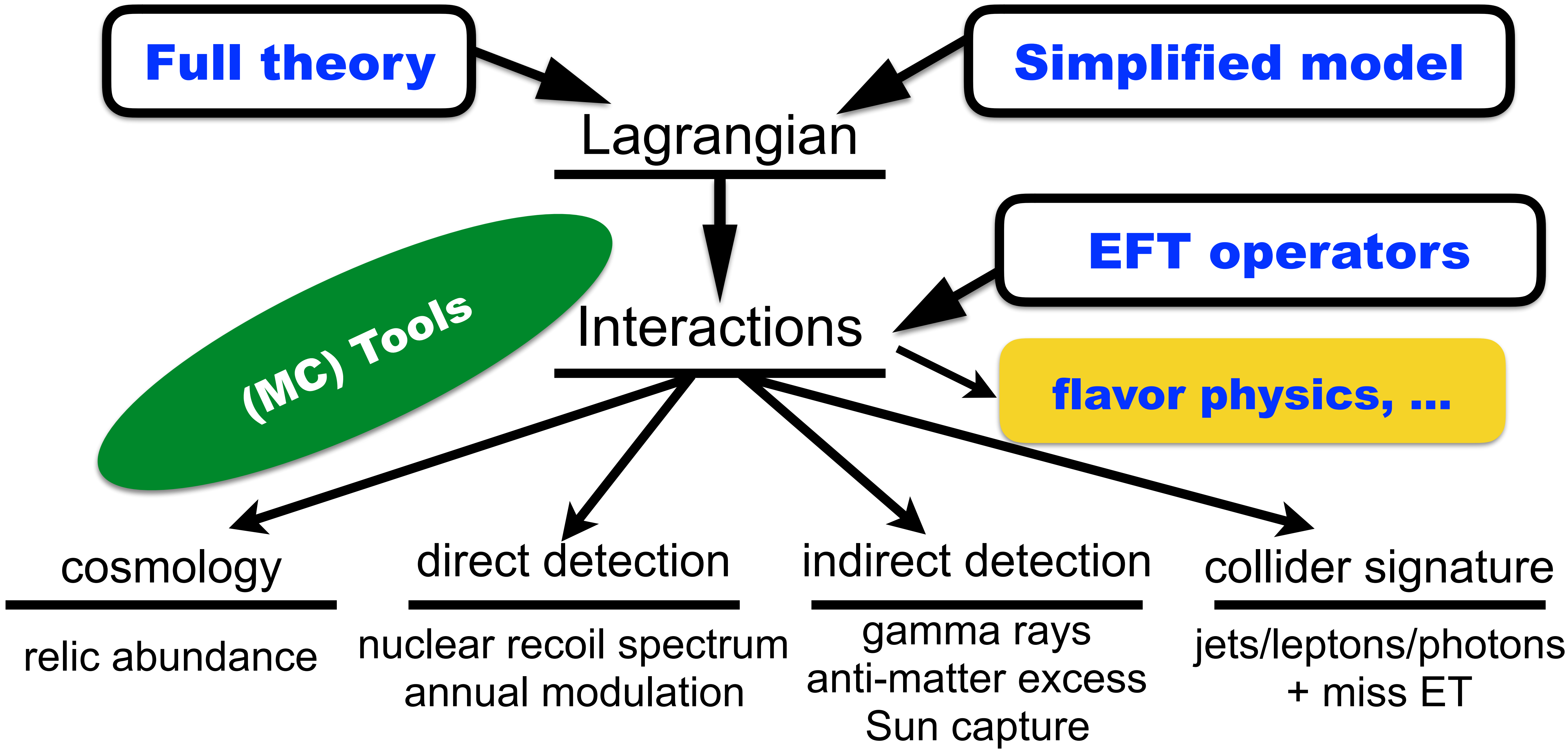
Decoding the dark matter



Decoding the dark matter



MCTools play important roles in the studying of DM.

Thank you.