

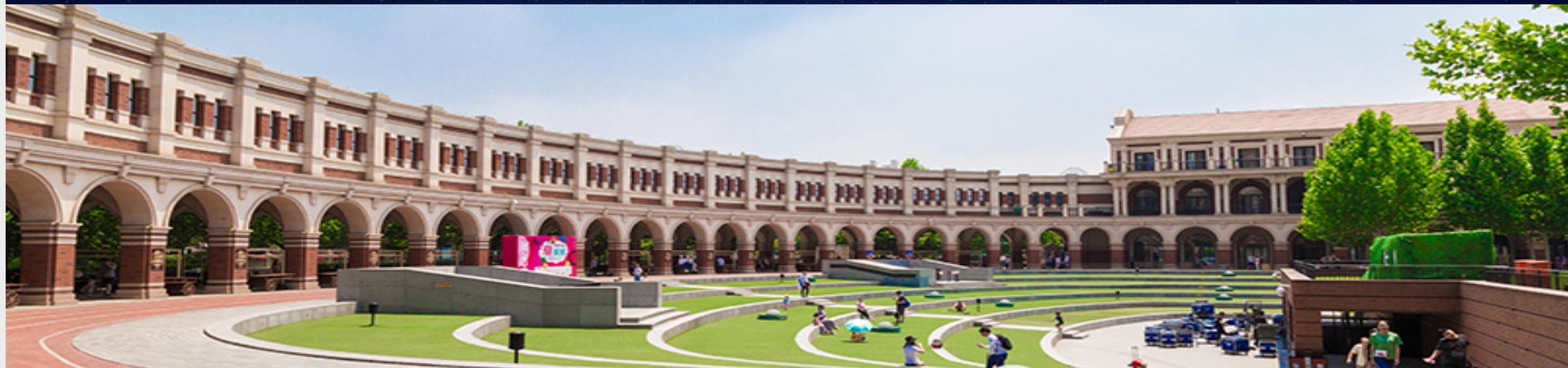
暗物质物理101

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华中师范大学

对撞机唯象学暑期学校 — 青岛

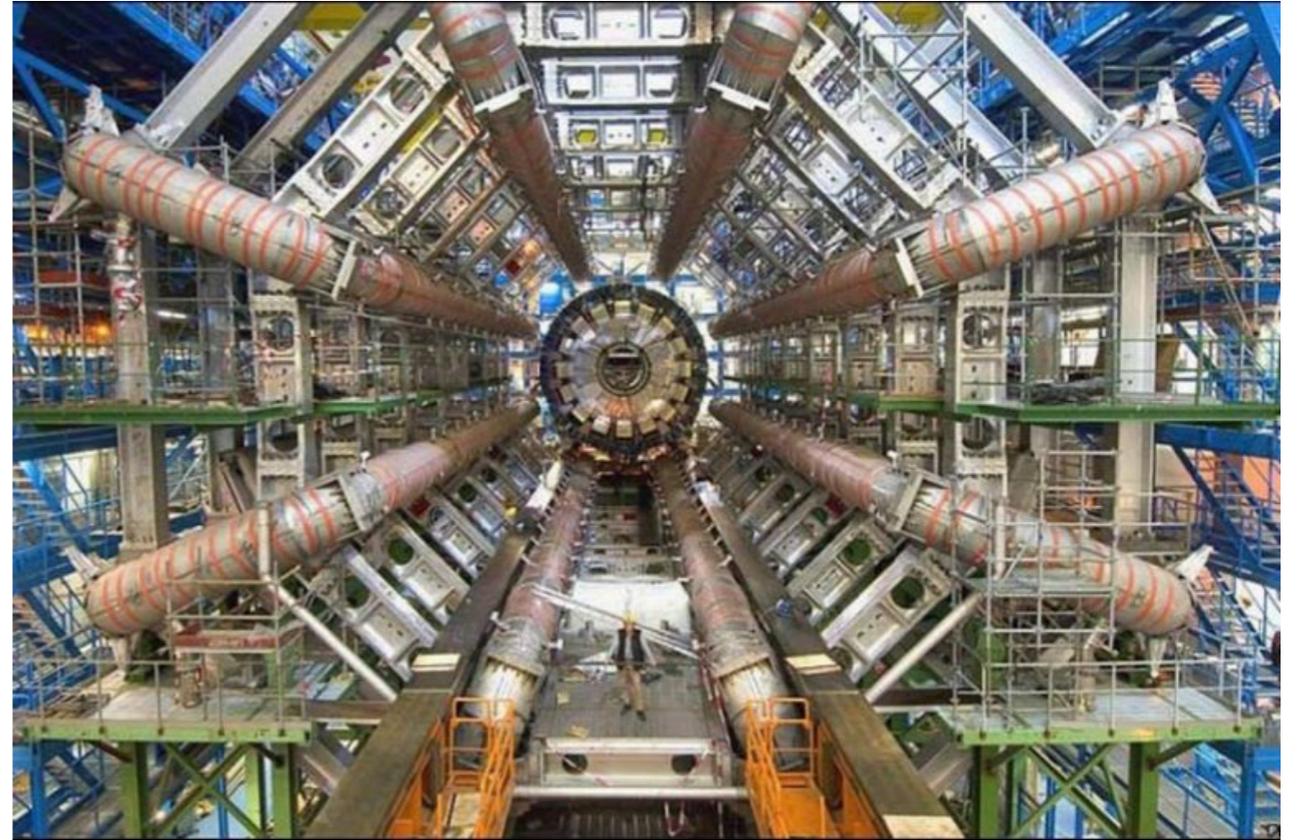
二零二一年七月五日



粒子物理

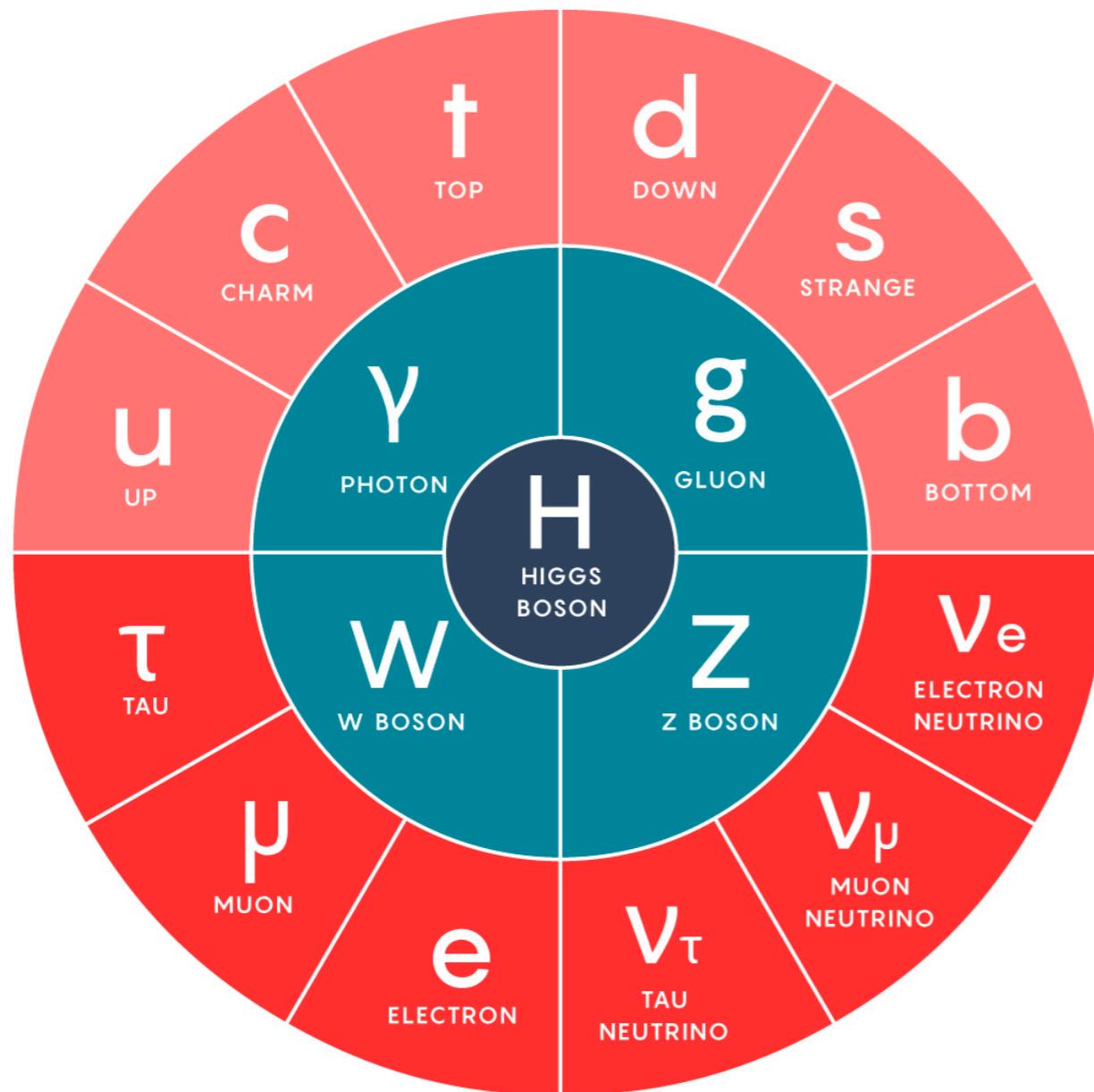


“运动形态”
“组成结构”
“相互作用”

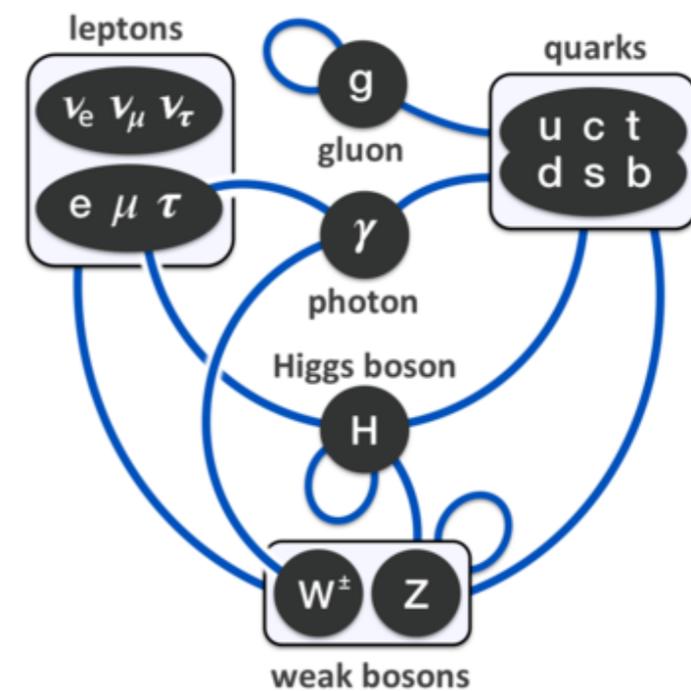
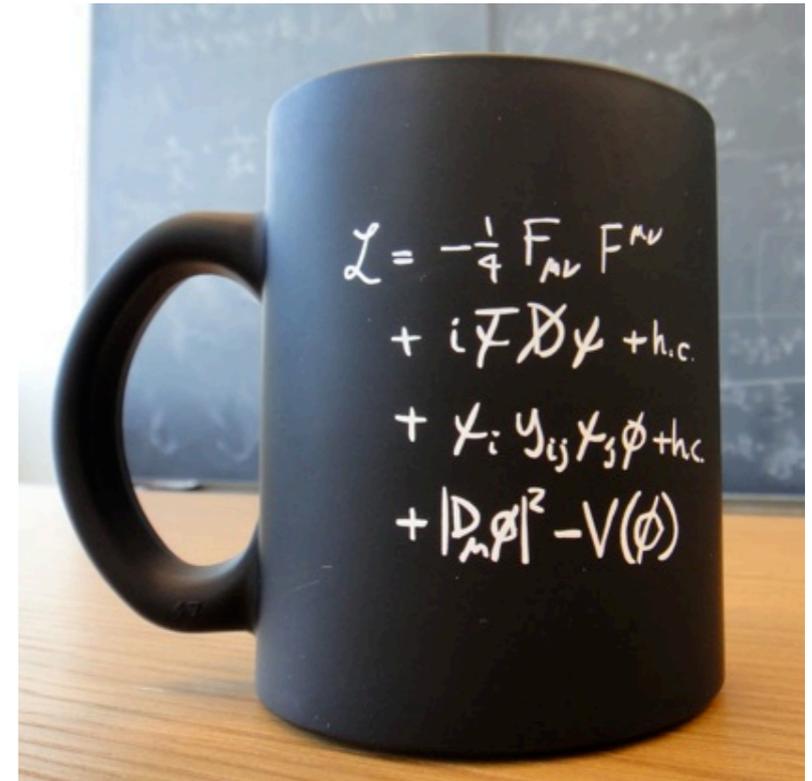


粒子物理标准模型

The Standard Model



FERMIONS (matter) | BOSONS (force carriers)
 ● Quarks ● Leptons | ● Gauge bosons ● Higgs boson

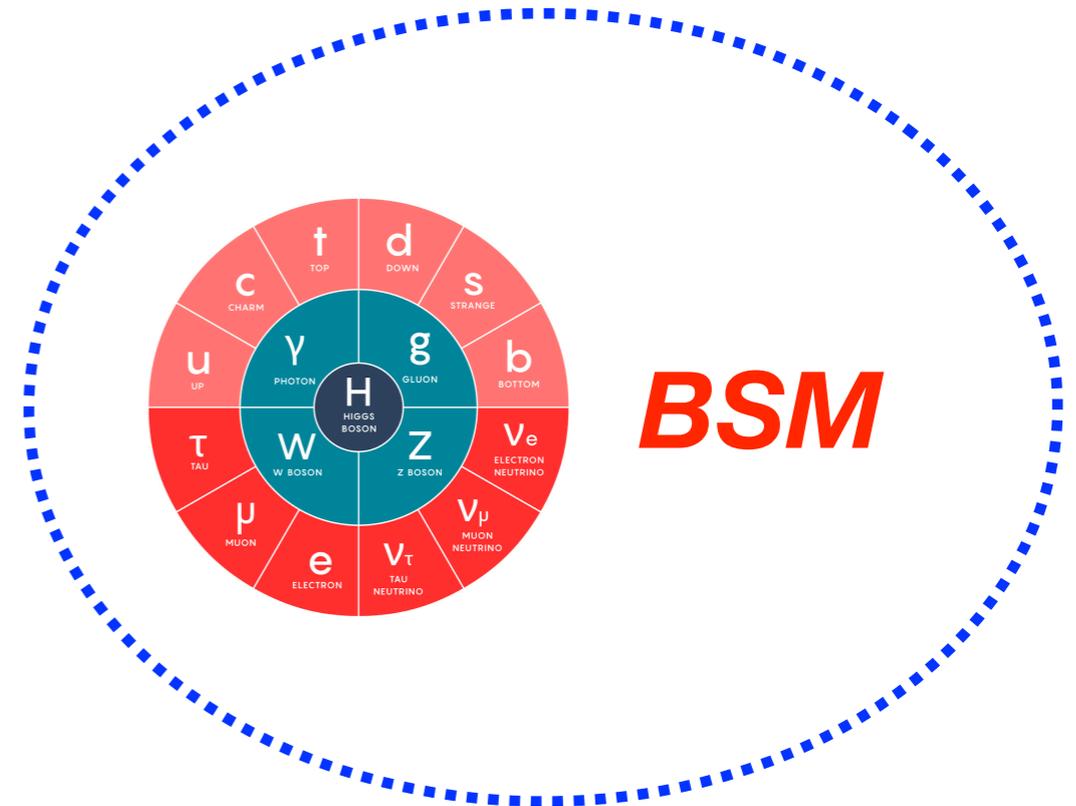


粒子物理标准模型

- 基于 $SU(3) \times SU(2) \times U(1)$ 规范对称性
- 三代夸克和轻子：6 味夸克，3 味带电轻子，3 味中微子
- 夸克和胶子禁闭于强子（介子、重子、…）中
- 夸克味混合：KM 机制，CP 破坏跟 CKM 混合矩阵中相位有关
- 基本粒子相互作用中重子数和轻子数守恒
- …

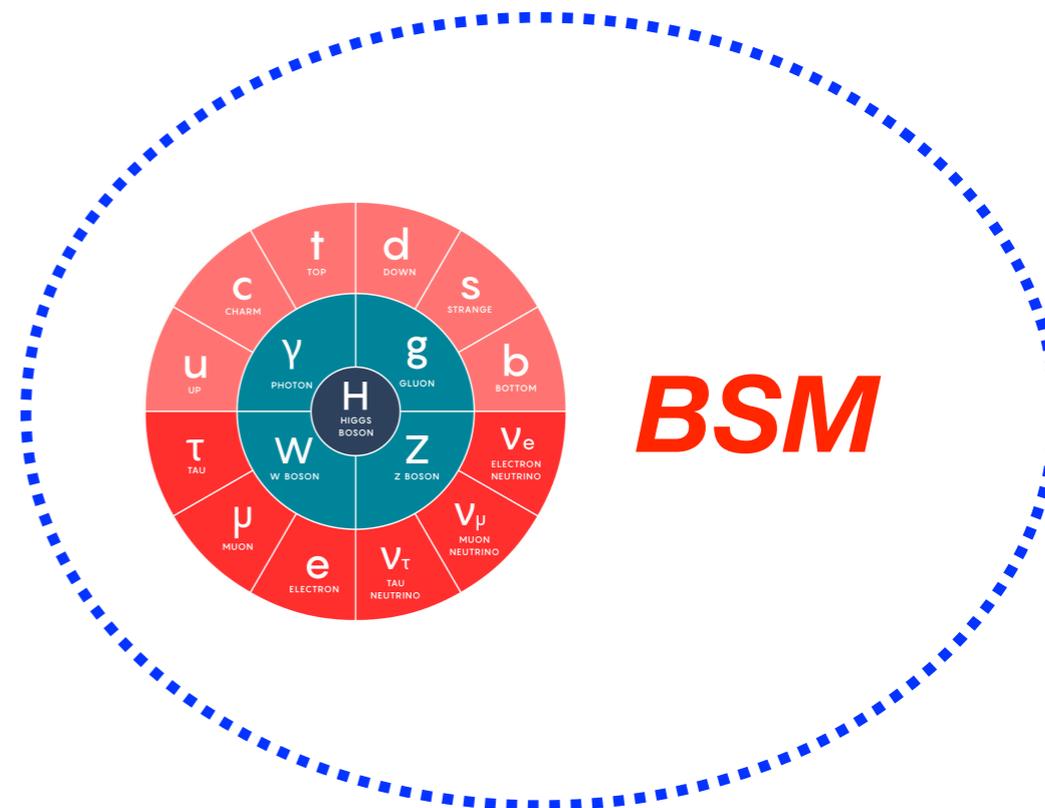
寻找超出已知的物理 *beyond the SM*

- 其它的夸克?
- 其它的带电轻子?
- 其它的规范玻色子?
- 其它的希格斯粒子?
- 其它的中微子?
- 其它的新形态基本粒子?
 - 如: 稳定、电中性、弱作用的粒子 (暗物质粒子)?
-

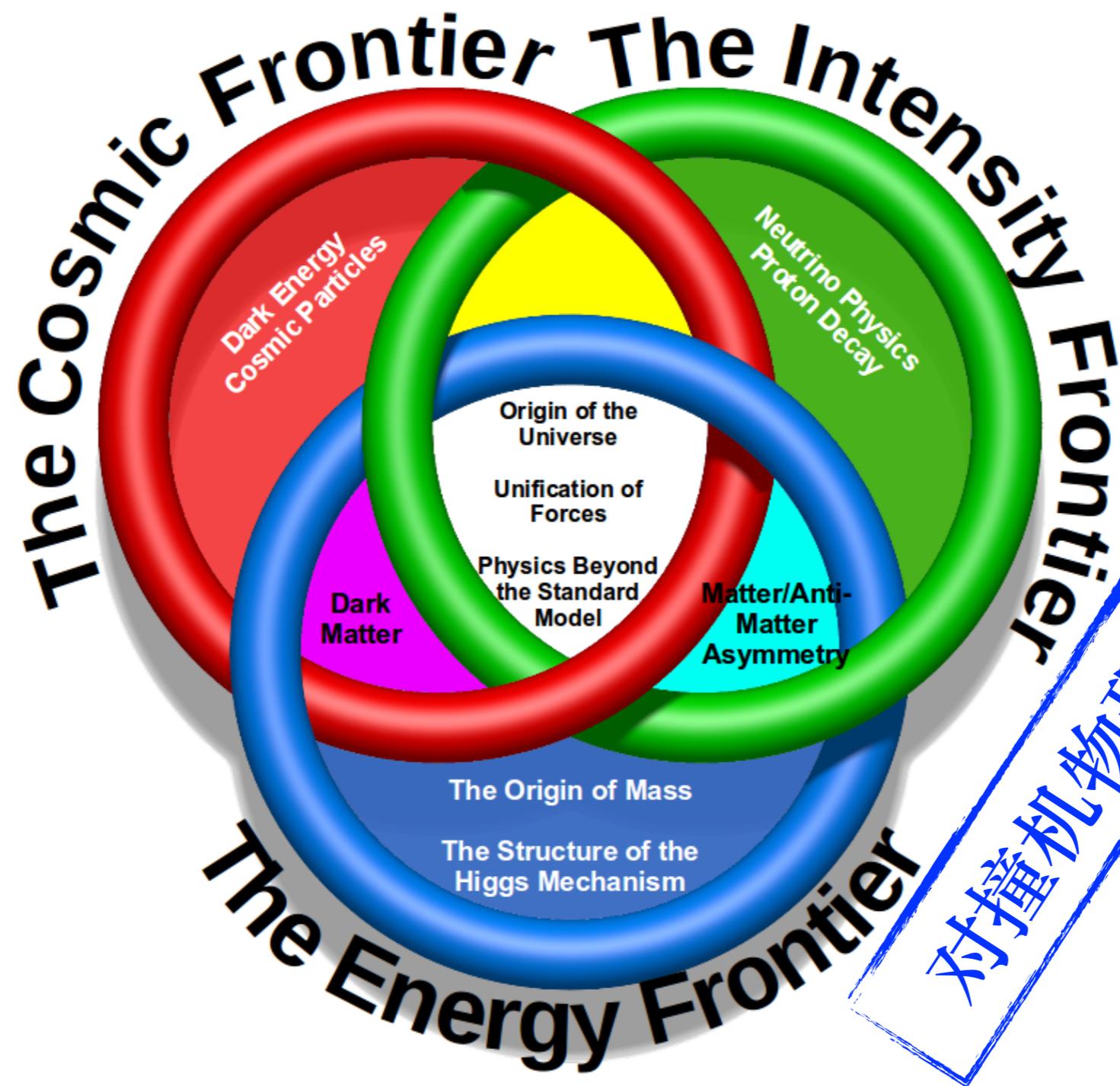


寻找超出已知的物理 *beyond the SM*

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-
- 宇宙物质起源、中微子质量和混合起源、暗物质本质



探索新物理



BES III
BELLE II
LHC-ATLAS
LHC-CMS
LHC-LHCb
EIC
CEPC
... ..

暗物质 Dark Matter

dark matter | dārĕk 'mædə |

noun *Astronomy*

(in some cosmological theories) **non-luminous material** that is postulated to exist in space and that could take any of **several forms** including weakly interacting particles (cold dark matter) or high-energy randomly moving particles created soon after the Big Bang (hot dark matter).

暗物质 ànwùzhì

名 指宇宙中**不发光的**天体和某些**非重子中性粒子**等。这些物质用光学方法观测不到，故称。

暗物质简史

mainly taken from “A history of dark matter” by G. Bertone, D. Hooper, arXiv:1605.04909

- 1930, Pauli 不可见的“中微子”假说
- 1933, Zwicky Coma cluster 质光比 “... *that dark matter is present in much greater amount than luminous matter.*”
- 1956, neutrino detected
- 1966, Gershtein and Zeldovich, Neutrino roles in cosmology; 1976 中微子暗物质
- 1970s, Rubin, Ford, Freeman... 旋转曲线
- 1974, Carr, Hawking 原初黑洞
- 1977, P. Hut cosmological bounds on the mass of SUSY gravitino
- 1960s-1970s, N-body simulations became possible
- 1978, dark matter annihilation to gamma rays (indirect detection)
- 1980, axion as dark matter
- 1982, 修改引力(MOND)
- 1983, hot DM cannot account for most dark matter
- 1983, SUSY neutralino as dark matter
- 1980s, cold non-baryonic DM widely accepted (WIMPs 1984)
- 1984, using cosmic-ray (anti-protons, positrons) to indirect detect DM (Silk and Srednicki)
- 1985, searching neutrinos from DM annihilation in the Sun (Krauss, Freese, Spergel)

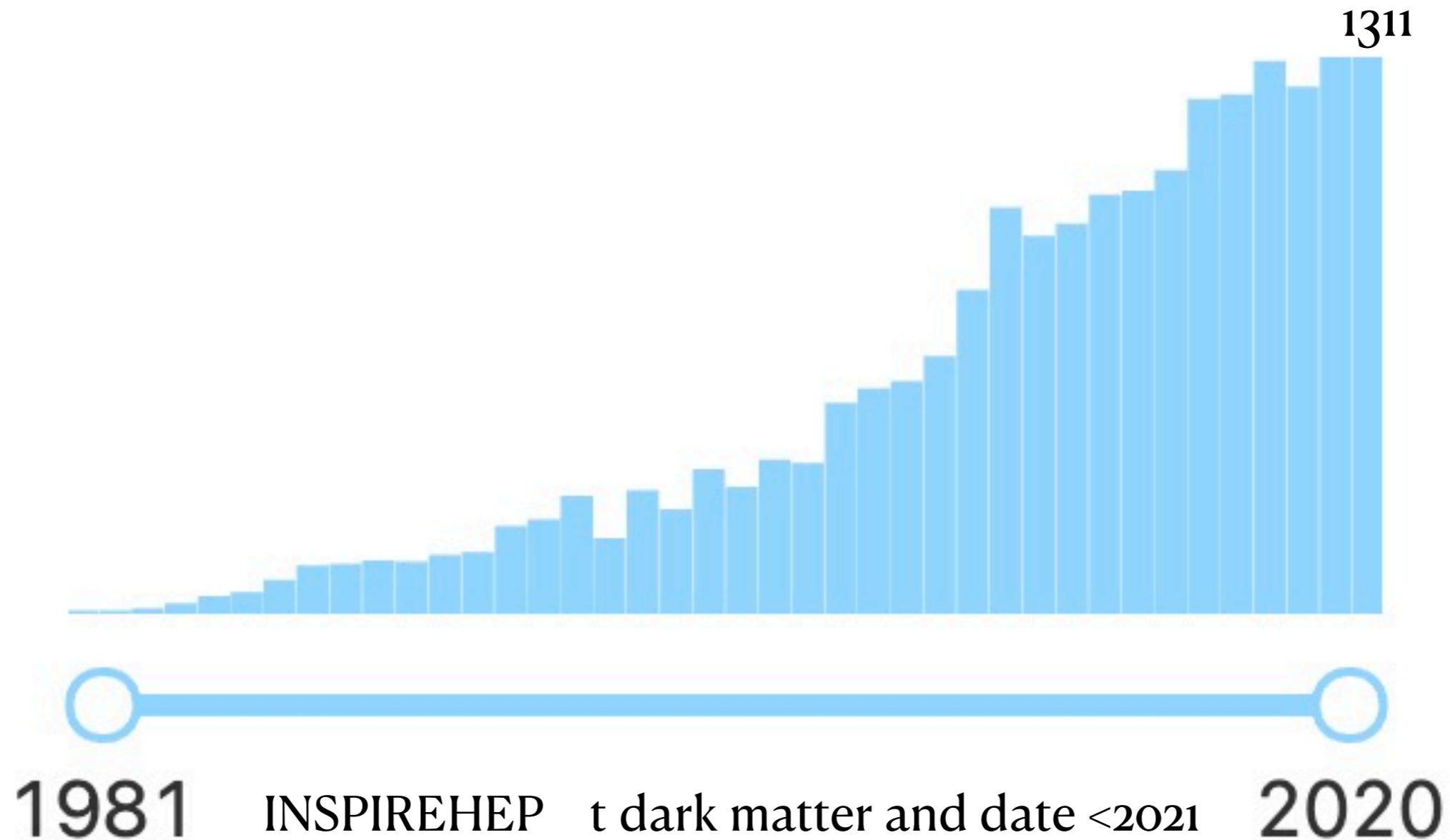
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- 1984, ν -N coherent scattering proposed (Drukier and Stodolsky)
 - detected by COHERENT in 2019.
- 1985, dark matter-nuclei elastic scattering (Goodman and Witten)
- 1986, 1st expt at Homestake Mine, Germanium 33kg-days
- 1986, Annual modulation measurement proposed (Drukier, Freese and Spergel)
 - 1998 **DAMA** first result
- 1980s, axion-gamma-gamma coupling expt proposal (2003, ADMX)
- 1990s, liquid noble target proposal
- 1990, DM section firstly appeared in PDG.
- 2003, WMAP first result released. 2004 PDG $\Omega_{nbm}h^2 = 0.111 \pm 0.006$, improved from $\Omega_m = 0.3 \pm 0.1$ in 2001.
- Direct detection expts: **CDMS**, EDELWEISS, **CRESST**, XENON, LUX, **CoGeNT**, CDEX, PandaX, ...
- Indirect detection expts: CAPRICE, AMS, AMS02, HESS, INTEGRAL, PAMELA, Fermi-LAT, HEAT, ATIC ...
- Neutrino telescope: AMANDA, Super-K, IceCube, ANTARES, JUNO...

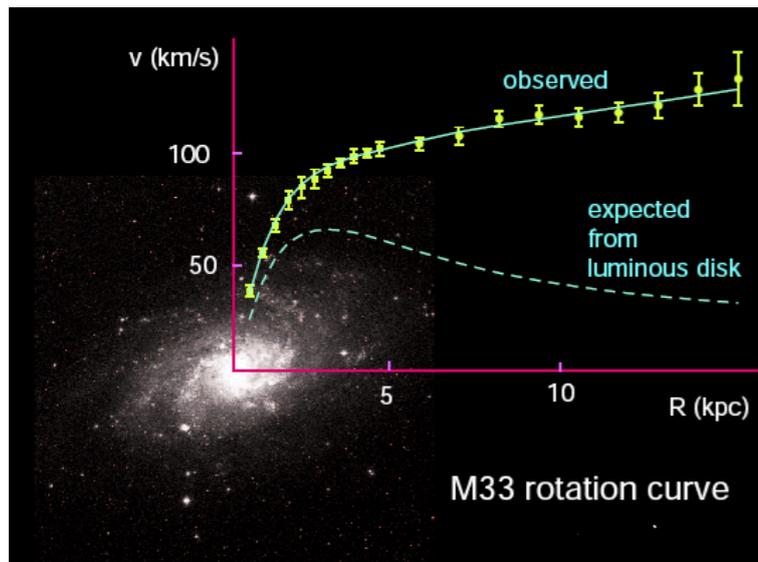
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- 2009-, 锦屏实验室, CDEX, PandaX, DAMPE, LHAASO

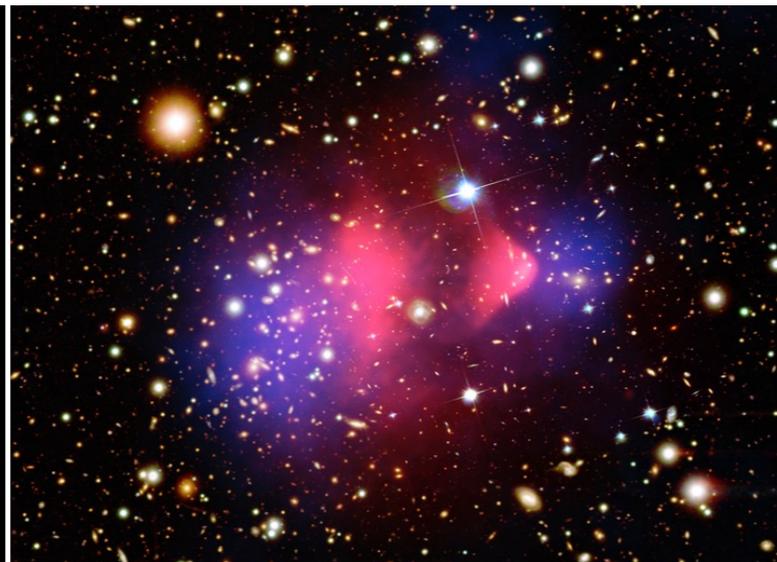
暗物质物理：前沿热点



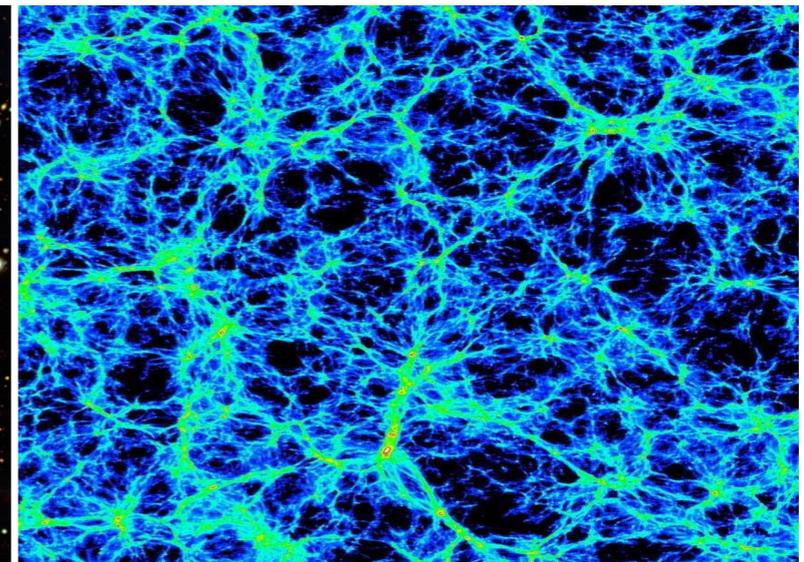
暗物质：引力效应



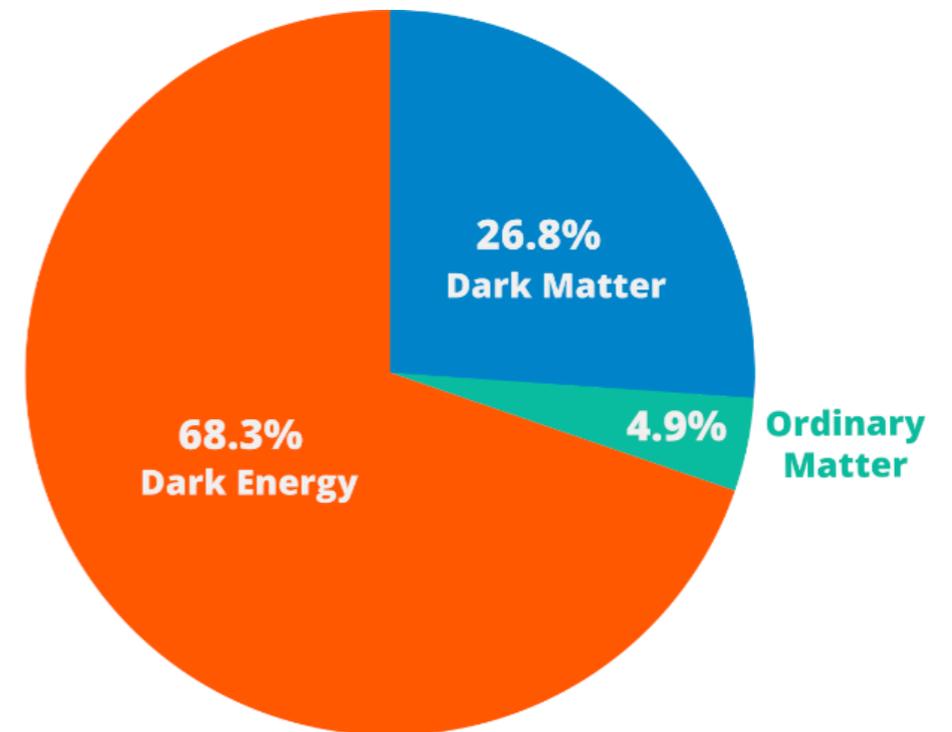
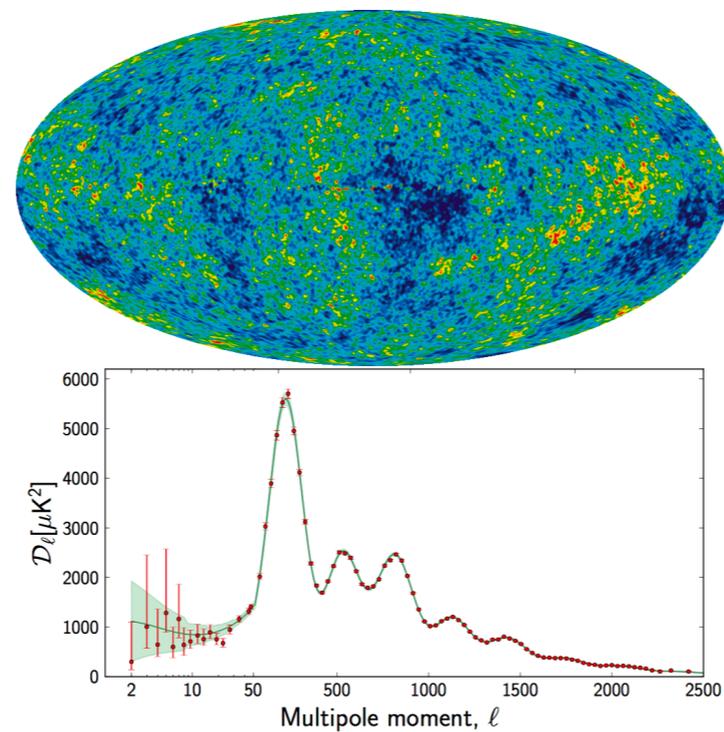
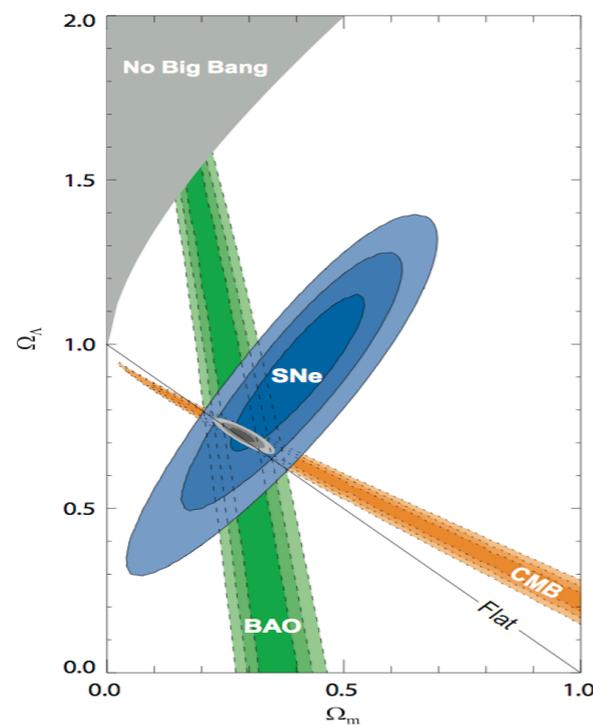
rotation curve



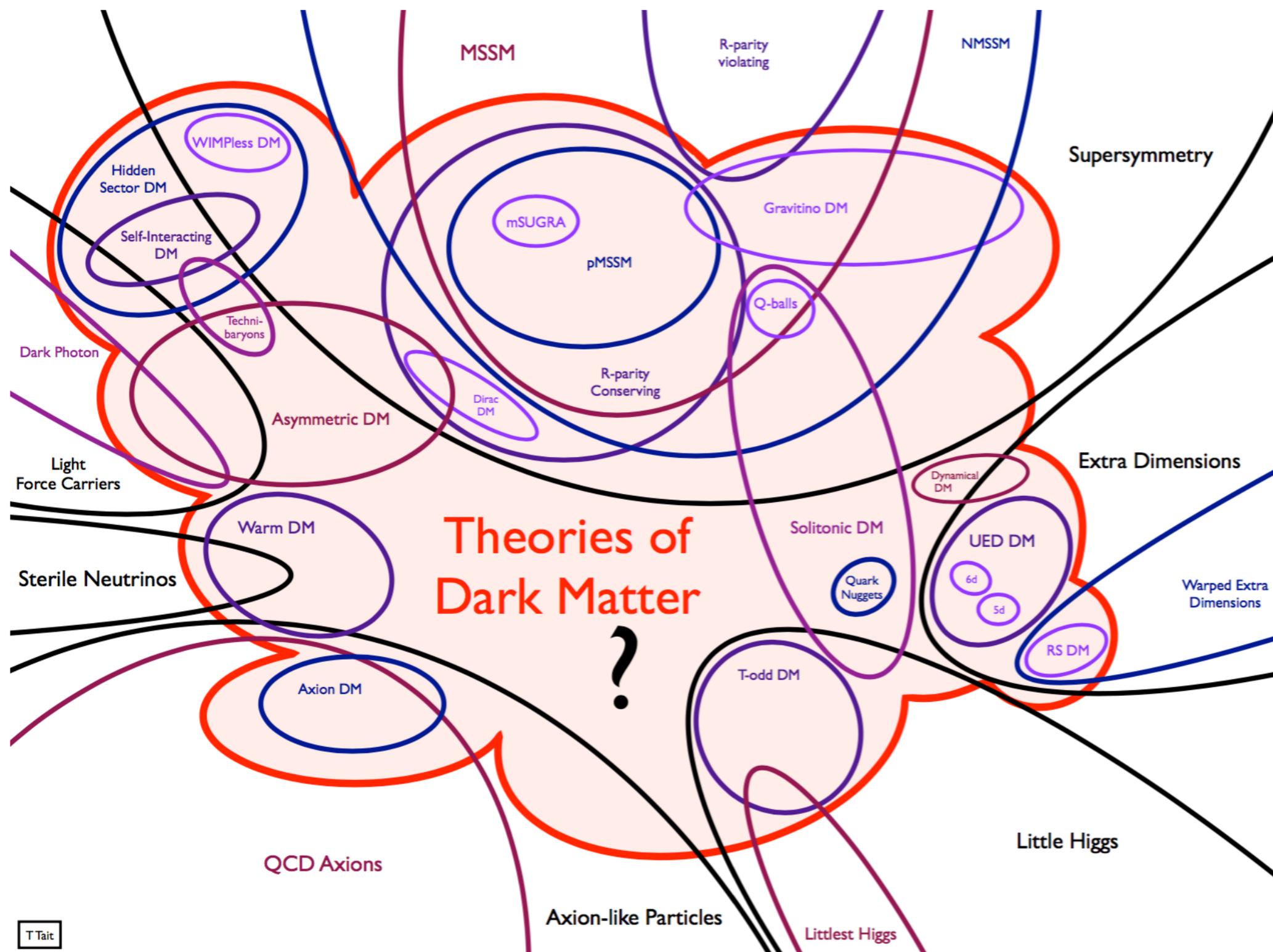
bullet cluster



large structure formation

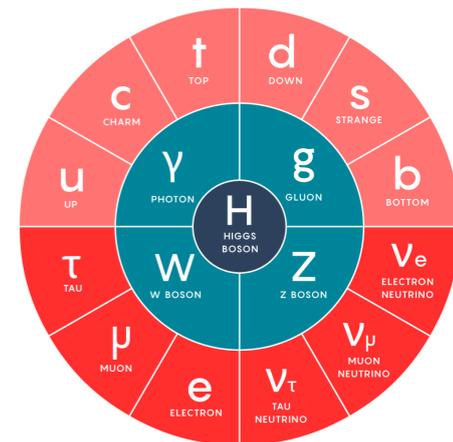


暗物质理论模型: Call for new physics bSM



暗物质粒子

- 暗物质具有中性、稳定（寿命长），非重子性质；
- 标准模型中无合适的暗物质粒子；
- Light neutrinos are “hot” relics, decoupled from thermal bath around MeV.



$$\Omega_\nu h^2 \approx \frac{\sum m_\nu}{93.14 \text{ eV}}$$

- Neutrinos are too “hot” to be dark matter, constrained by structure formation.

Relics bound

$$\Omega_\nu h^2 \lesssim 0.12 \longrightarrow \sum m_\nu \lesssim 10 \text{ eV} \quad (\text{Cowsik-McClelland limit})$$

$$\text{CMB + Large scale structure} \quad \sum m_\nu \lesssim (0.1 - 0.4) \text{ eV}$$

暗物质粒子

稳定性： 不衰变或者寿命长于宇宙年龄；

标准模型中粒子稳定性：

- (1) 光子：无质量，最轻的玻色子；
- (2) 中微子：最轻的费米子；
- (3) 电子：最轻的带电粒子，电荷守恒； $U(1)_Q$ 对称性
- (4) 质子：标准模型具有偶然的 $U(1)_B$ 对称性；

暗物质稳定机制：

(一) 稳定不衰变：

如加入额外对称性 Z_2 或具有残余 Z_2 对称性。

	Z_2		Z_3		Z_2	Z'_2
SM	+	SM	1	SM	+	+
BSM	-	BSM	$e^{i2\pi/3}$	BSM	+	-
		BSM	$e^{i4\pi/3}$	BSM	-	+
				BSM	-	-

暗物质粒子

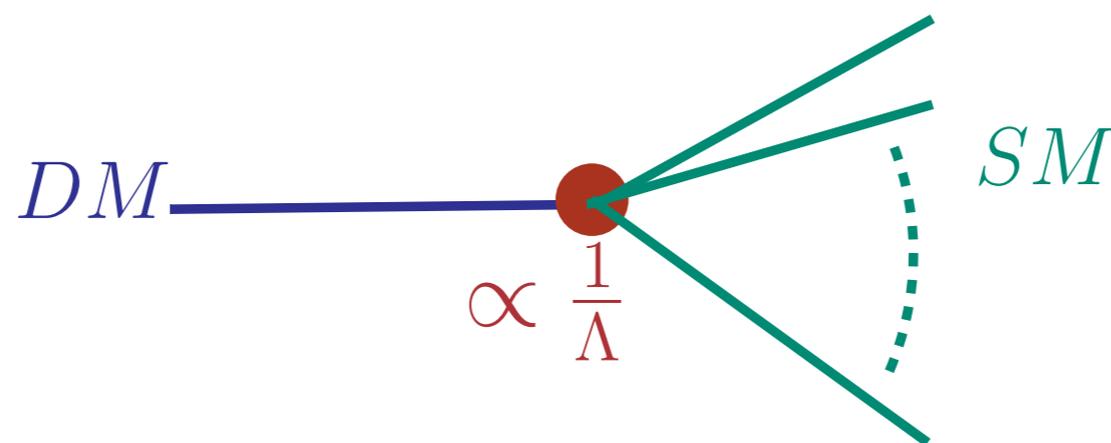
如：一类流行或常见的暗物质候选者，被称为 WIMPs (“未卜”粒子)
Weakly Interacting Massive Particles (GeV - 100 TeV scale)

- 1, Lightest Supersymmetric particle (LSP)
- 2, Lightest T-odd particle in the little Higgs theory (LTP)
- 3, Lightest KK particle in extra dimension (LKP)

... ..

(二) 长寿命衰变:

如：暗物质粒子和标准模型粒子相互作用极小或者被高能标压低，或质量较轻。



Sterile neutrino, Gravitino in R-parity violated SUSY,

Canonical Production Mechanism: Thermal relics

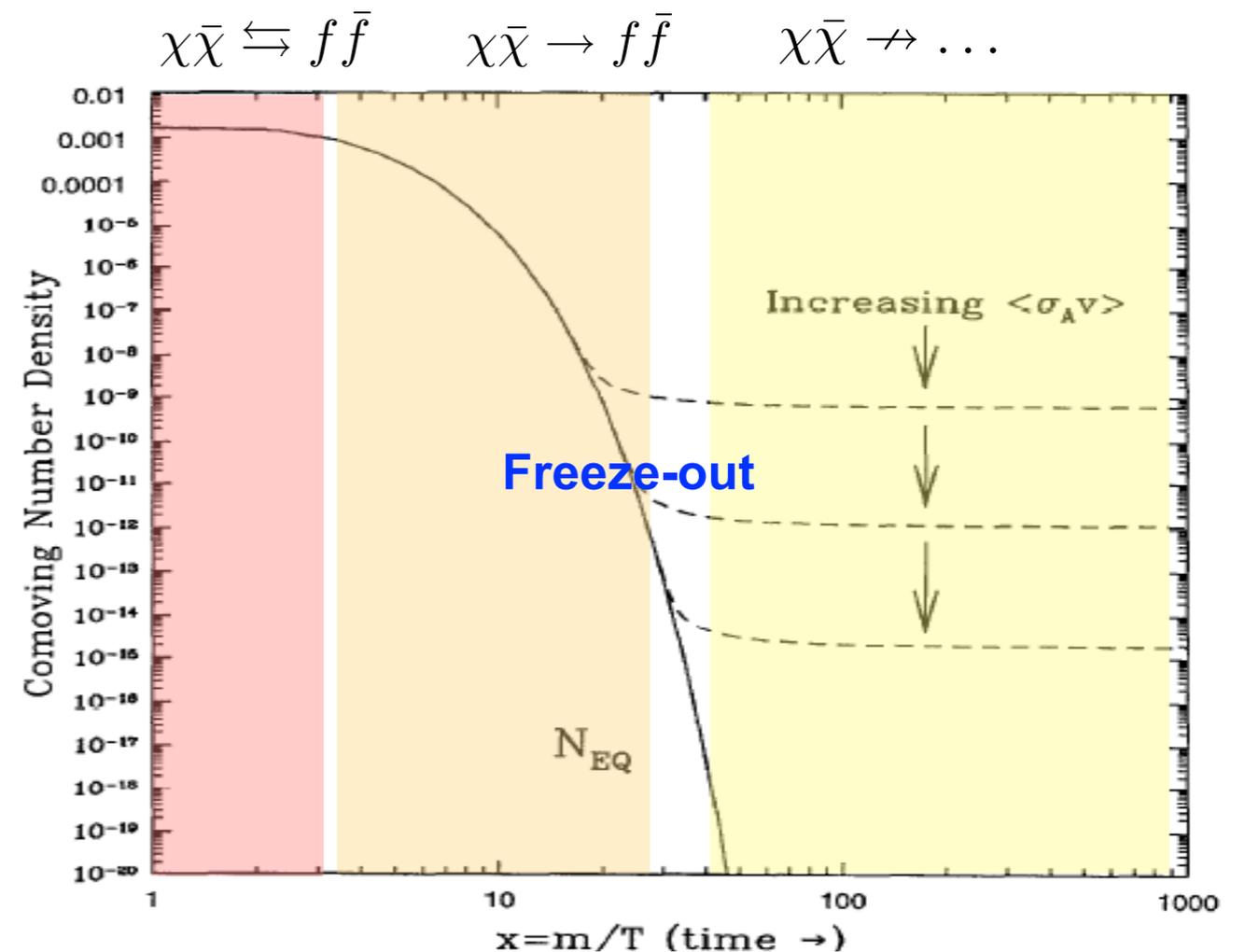
- Thermal freeze-out: the relic density connects to the “annihilation” cross section



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

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

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



WIMPs thermal relics: a rough estimate

- 1 Assume $\langle \sigma_A v \rangle$ energy independent at freezing-out
- 2 From $H(T_f) = \Gamma(T_f)$

$$1.66 \sqrt{g_*} T_f^2 / M_{\text{pl}} = g \left(\frac{m_\chi T_f}{2\pi} \right)^{3/2} e^{-m_\chi/T_f} \langle \sigma_A v \rangle$$

- 3 set at weak scale, $g_* \sim 100$, $g = 2$, $m_\chi \sim T \sim 100\text{GeV}$,
 $\langle \sigma_A v \rangle \sim 1\text{pb}$,

$$e^{-m_\chi/T_f} \sim 4 \times 10^{-11} \quad \Rightarrow \quad \frac{m_\chi}{T_f} \sim 24$$

- 4 Typical freeze-out temperature is

$$x_f \equiv \frac{m_\chi}{T_f} \sim 20$$

WIMPs thermal relics: a rough estimate

- After freeze-out, n_χ/s per comoving volume is constant.

$$s = \frac{2\pi^2}{45} g_{*s} T^3 \text{ is the entropy. } \quad (H(T_f) = 1.66\sqrt{g_*}T_f^2/M_{\text{pl}})$$

$$\left(\frac{n_\chi}{s}\right)_0 = \left(\frac{n_\chi}{s}\right)_f \sim \frac{1}{s_f} \cdot \frac{H(T_f)}{\langle\sigma_A v\rangle} \simeq \frac{75}{M_{\text{pl}}\langle\sigma_A v\rangle\sqrt{g_*}m_\chi}$$

- Today's abundance of WIMPs χ is given by

$$\Omega_\chi h^2 = \rho_\chi h^2 / \rho_c = m_\chi n_\chi^0 h^2 / \rho_c$$

- input $s_0 \sim 3000\text{cm}^{-3}$, $\rho_c \sim 10^{-5}h^2\text{GeV cm}^{-3}$, $g_* \sim 100$, we obtain

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\text{cm}^3\text{s}^{-1}}{\langle\sigma_A v\rangle}$$

“WIMP Miracle”

$$\Omega_{\text{cdm}} = 0.1198 \pm 0.0026 \quad \text{Cosmology}$$

$$\sigma v \sim 10^{-36} \text{cm}^2 = 1 \text{pb} \quad \text{For the right abundance}$$

- Typical “weak scale” cross section

$$\sigma \sim \frac{\alpha_w^2}{\Lambda_{\text{weak}}^2} \sim 1 \text{pb}$$

WIMPy DM detection era! 🐱 🐱 🐱

LHC + Direct Direction + Indirect Detection

WIMP mass range $\mathcal{O}(10) \text{ GeV} \lesssim m_\chi \lesssim 120 \text{ TeV}$

Thermal relics

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

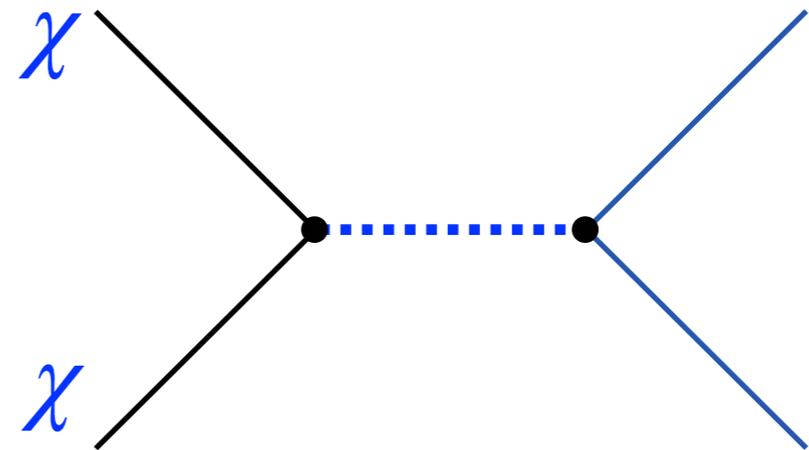
$$\dot{n} + \underbrace{3Hn}_{\text{dilution}} = \langle \sigma_{Av} \rangle \left(\underbrace{n_{eq}^2}_{\text{creation}} - \underbrace{n^2}_{\text{annihilation}} \right)$$

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

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

Thermal relics

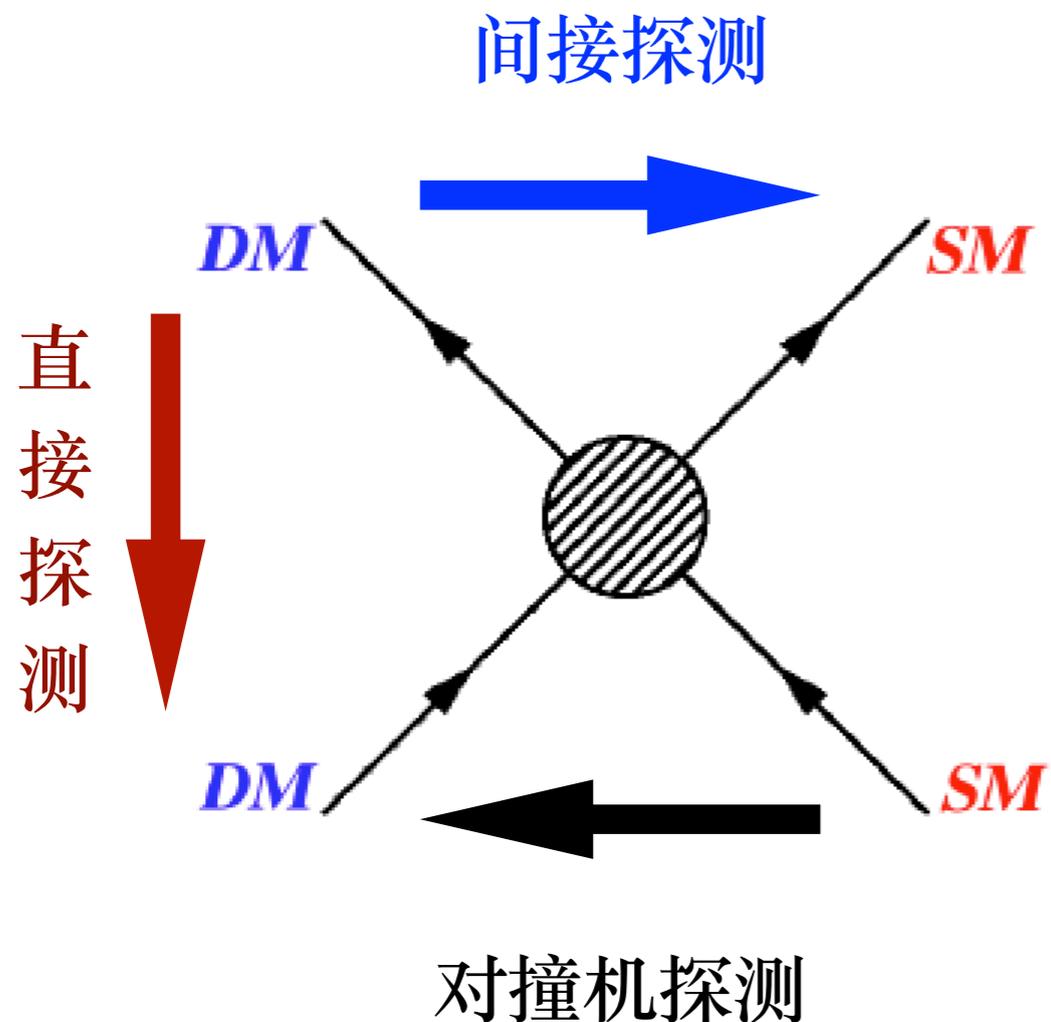
- For general case, the dark matter model may include multiple dark matter candidates.
- Hybrid freeze-out processes:
 - self-annihilation;
 - co-annihilation;
 - threshold effects;
 - resonance effects;
 - 2 to 2, 2 to 3, 3 to 2...
 -



Complicated Boltzmann equation.

暗物质粒子探测

暗物质探测一般分为三类：



1. 直接探测，暗物质和探测器材料发生弹性碰撞；

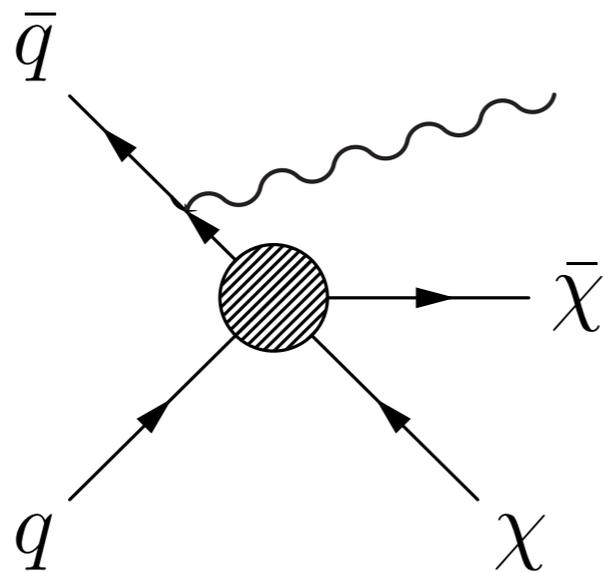
2. 间接探测，在暗物质密度高区域暗物质发生自湮灭，探测湮灭产物；

3. 对撞机探测，在对撞机上产生暗物质，暗物质表现为“消失的能动量”，类似于中微子。

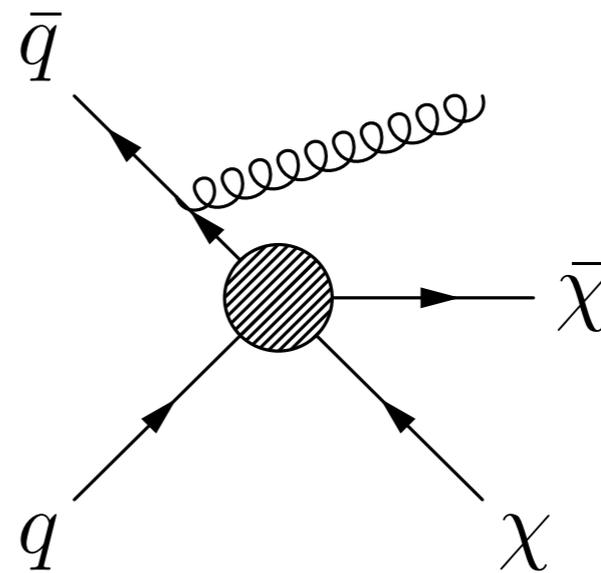
暗物质对撞机探测

- 在对撞机上产生暗物质，寻找消失的能动量。

(1) 简单情况: monojet/mono-photon/mono-Z + missing ET



Monophoton + MET

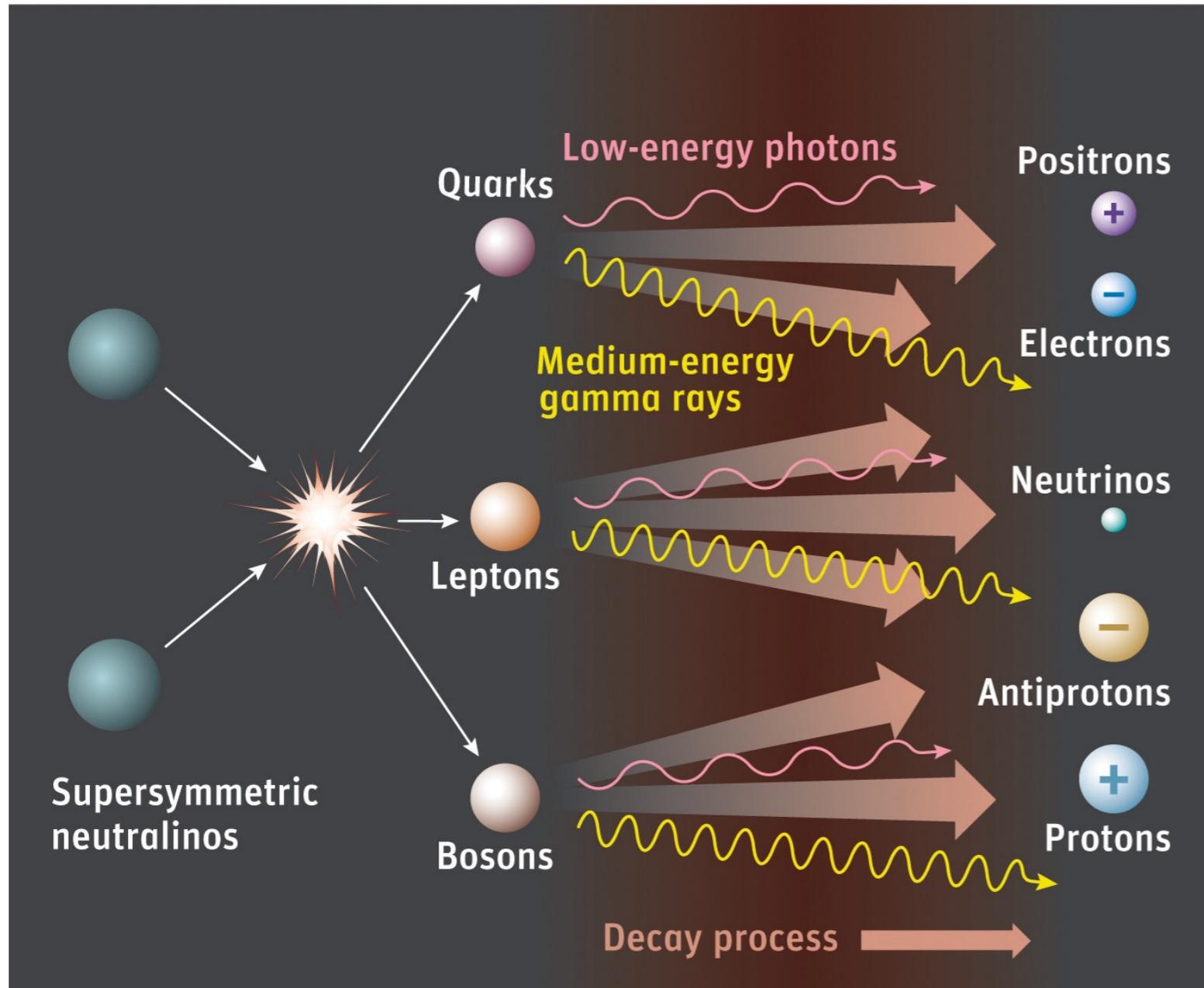


Monojet + MET

(2) multi-jets/leptons + missing ET

(3) Particle invisible decays

暗物质间接探测

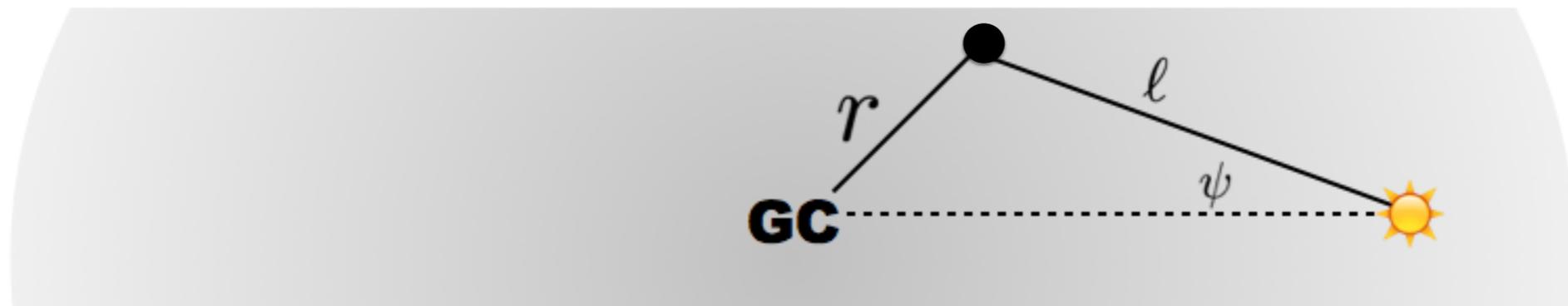


探测暗物质在密度高区域自湮灭产物；

1. 伽玛射线：从银心、矮星系…；
2. 正反电子、正反质子等宇宙射线
3. 从星体来的中微子，如太阳、地球等。

暗物质间接探测

例如：从暗物质湮灭过程产生的伽马射线



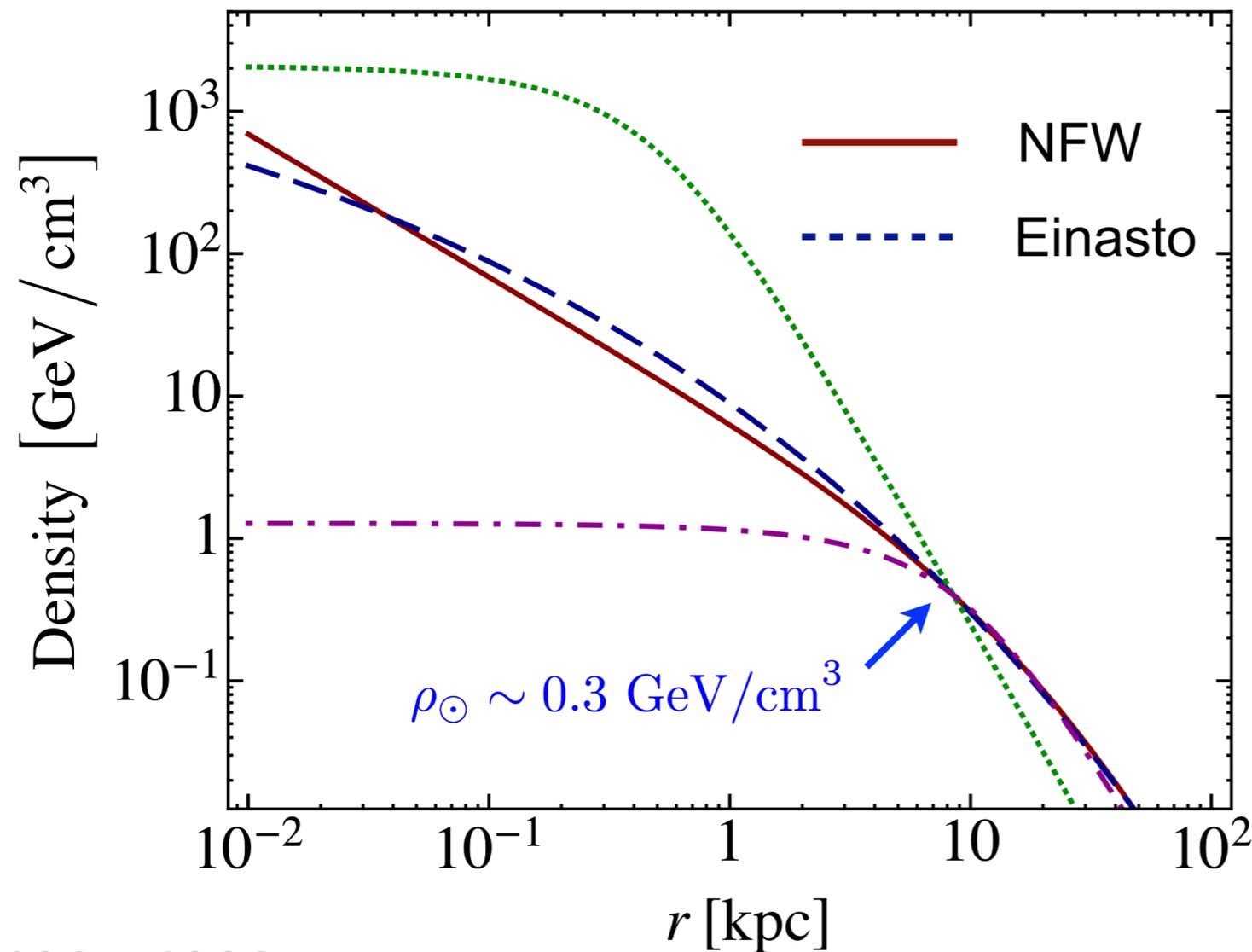
实验：

INTEGRAL, Fermi-LAT, PAMELA, AMS02,
DAMPE, HESS, CTA, LHAASO, ...

Neutrino telescopes

暗物质晕分布

From N-body simulations and rotation curves



NFW profile

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

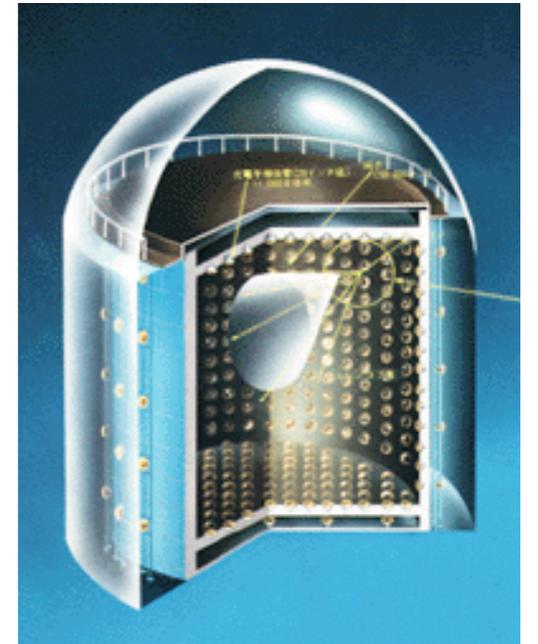
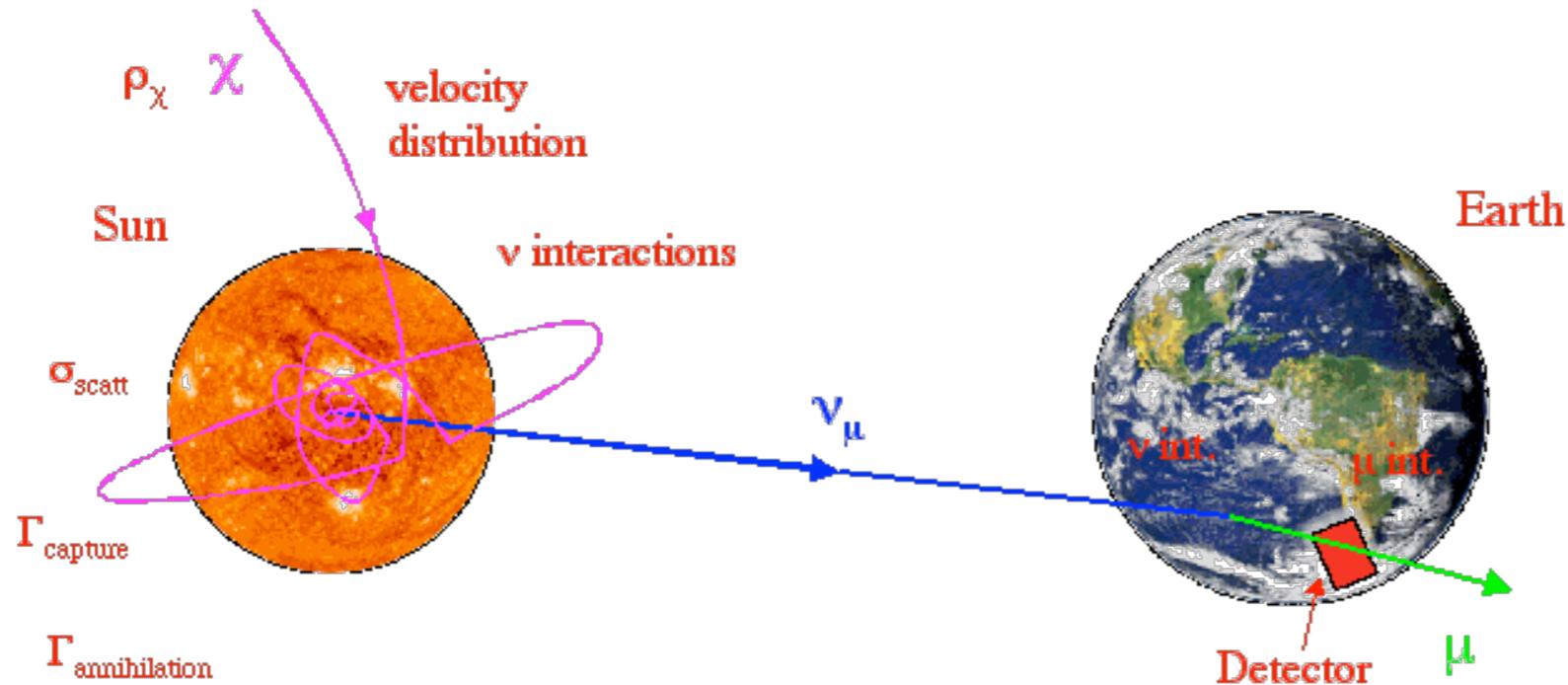
Einasto profile

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

1307.4082

DM density profile

来自星体的暗物质信号



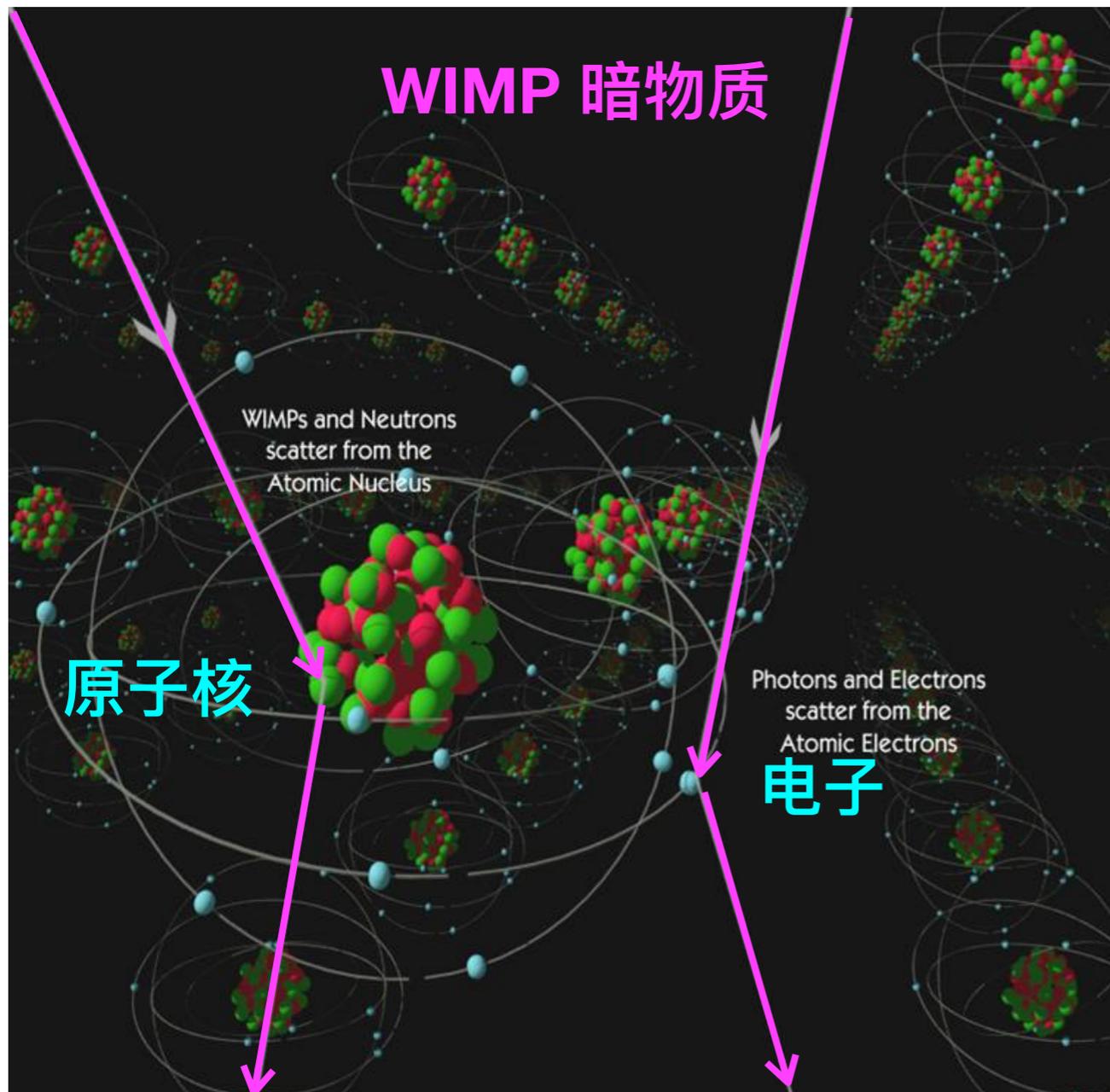
暗物质被太阳俘获积聚并自湮灭

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

若俘获过程和自湮灭达到平衡

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

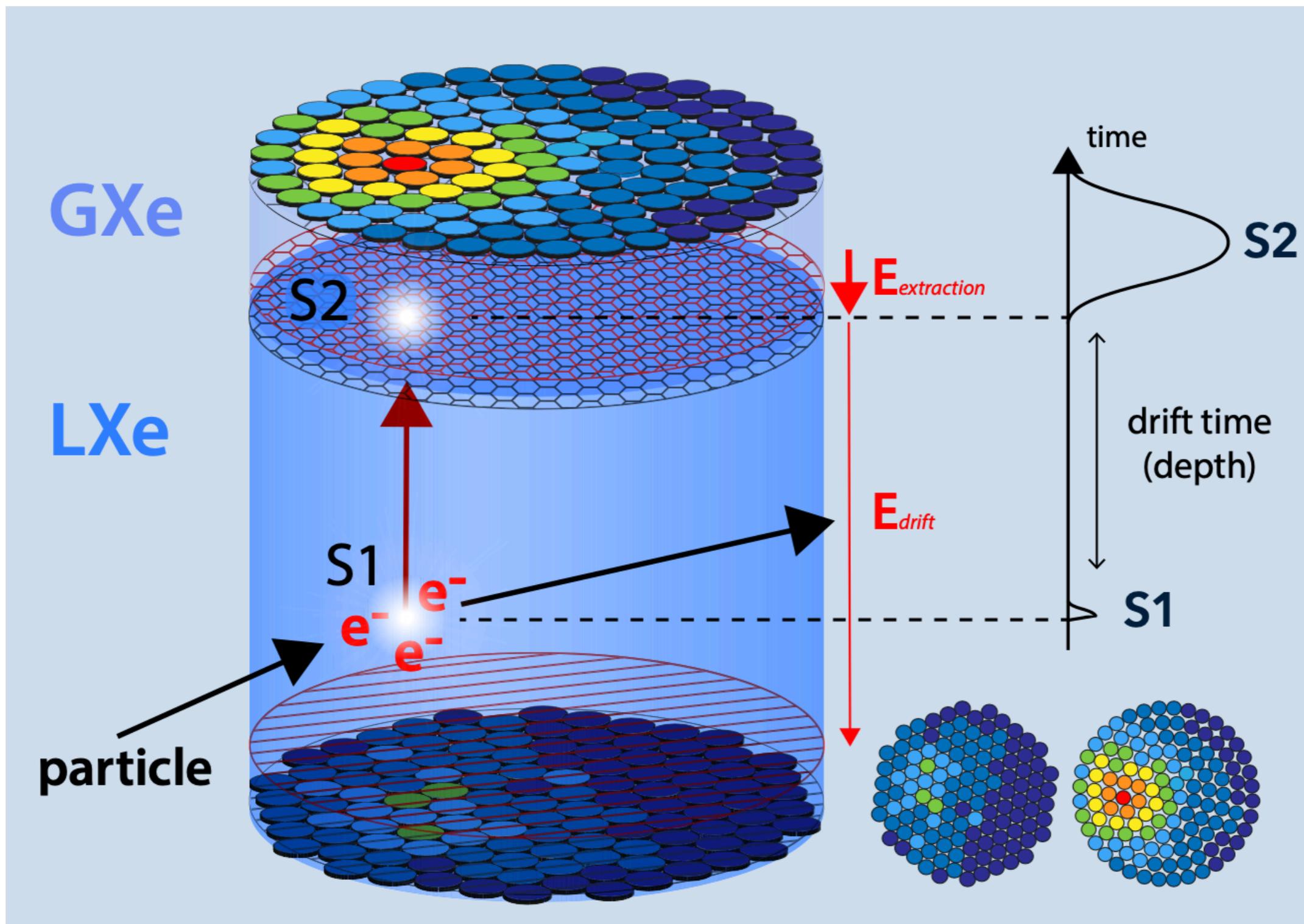
暗物质直接探测



暗物质和探测器原子（原子核或电子）发生弹性散射，原子得到额外动能，表现：

发热、发光、电离

暗物质直接探测



暗物质直接探测

- 寻找原子核受到暗物质散射后的反冲:

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2 (1 - \cos \theta)}{m_N} \lesssim (1 - 50) \text{KeV}$$

- 事例数: $N_{\text{Target}} \cdot n_\chi \cdot \sigma_{\chi N} v \cdot \text{Time}$ (需要足够大的探测器)

- 能谱: counts/kg/keV/date

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

$$v_{\min} = \sqrt{m_N E_r / (2\mu^2)}$$

$$\rho_0 \sim 0.3 \text{GeV/cm}^3$$

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

minimal velocity to create recoil E_r

local DM density

velocity distribution

粒子物理、核物理、天体物理、宇宙学

暗物质直接探测

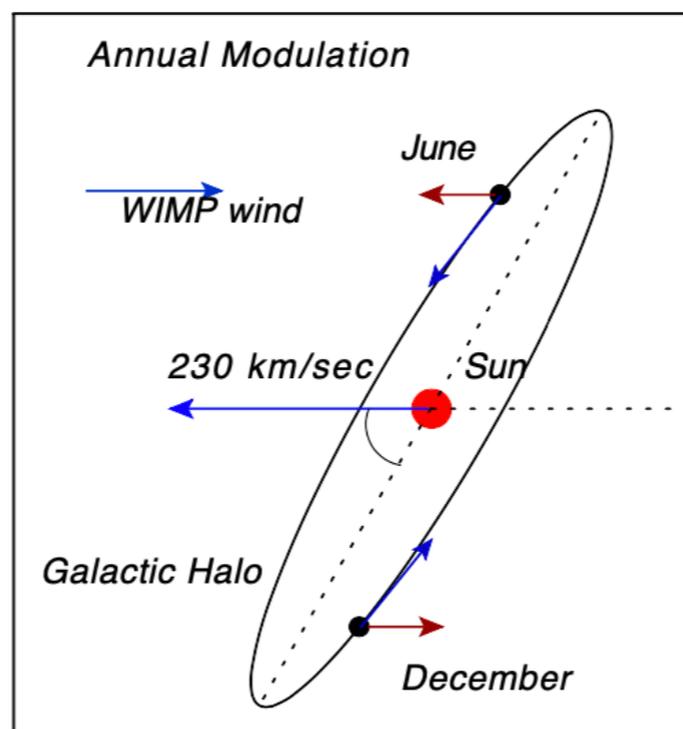
$f_{\oplus}(\vec{v}, t)$: DM velocity distribution in earth frame.

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

Maxwellian velocity distribution in dark halo frame

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

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



暗物质直接探测

In the NR limit, the DM-nucleus interactions:

$$\begin{aligned}\bar{\chi}\chi\bar{N}N &\Rightarrow 4m_\chi m_N \mathbf{1}_\chi \mathbf{1}_N \\ \bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}\gamma_\mu\gamma_5N &\Rightarrow 16m_\chi m_N \vec{S}_\chi \cdot \vec{S}_N\end{aligned}$$

- 自旋无关: $S \otimes S, V \otimes V$

coherent interactions: $\sigma \propto [Zf_p + (A - Z)f_n]^2$
 $f_p = f_n \Rightarrow \sigma \propto A^2$ (A^2 enhancement)
 $f_p \neq f_n$ isospin-violating dark matter

- 自旋相关: $A \otimes A, T \otimes T$

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

非弹性散射

elastic scattering

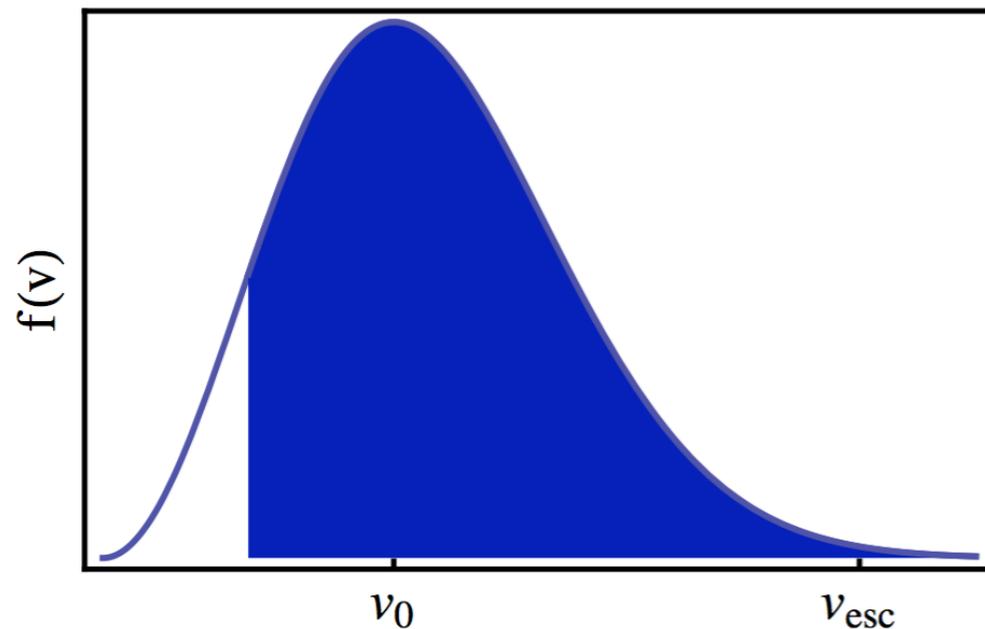


inelastic scattering

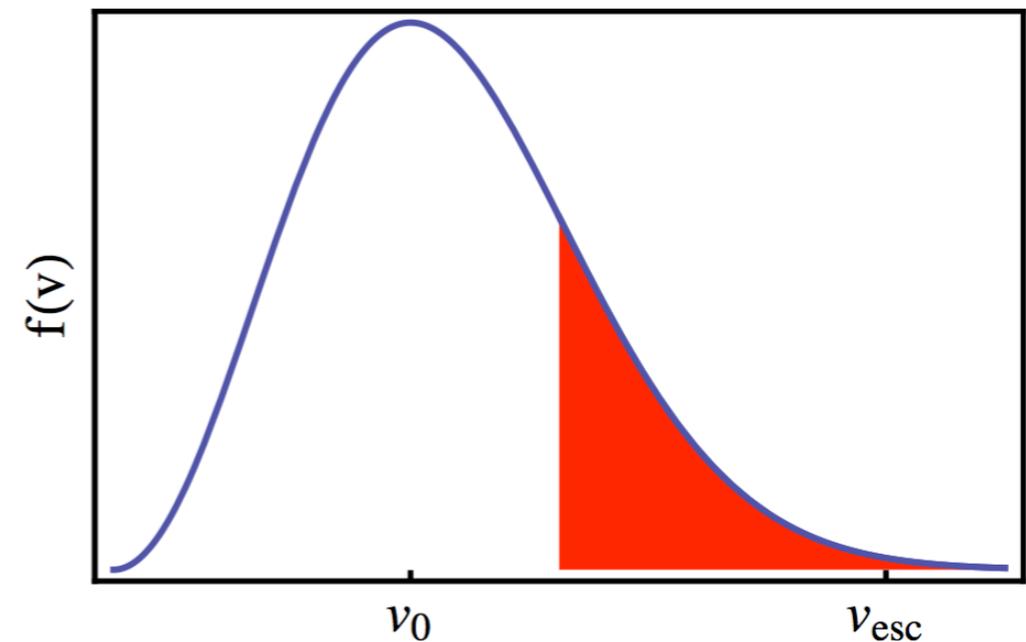


$$v_{min} = \frac{1}{\sqrt{2m_N E_r}} \left(\frac{m_N E_r}{\mu} + \delta_\chi \right)$$

Elastic

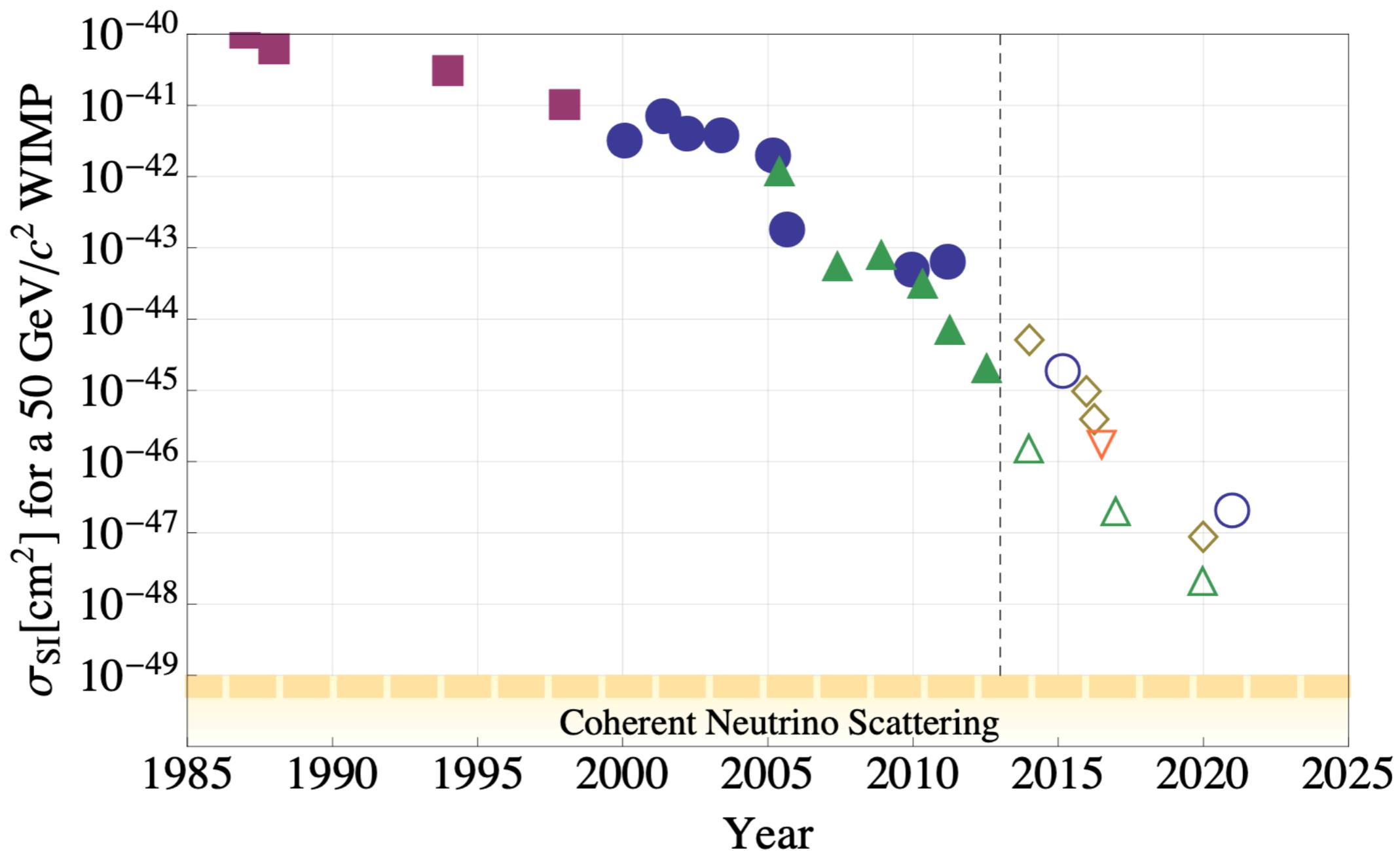


Inelastic

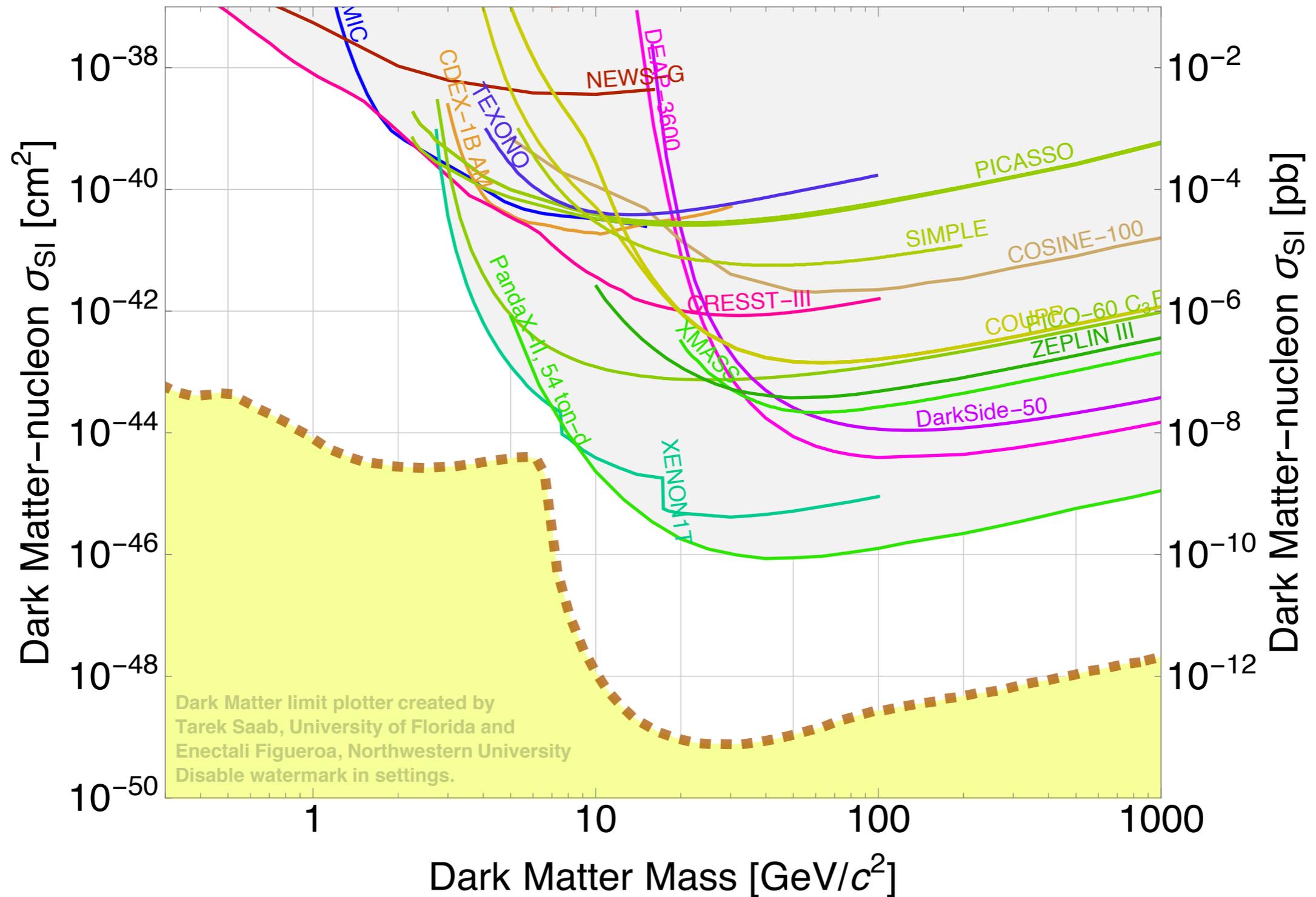


暗物质直接探测

Evolution of the WIMP–Nucleon σ_{SI}



暗物质直接探测

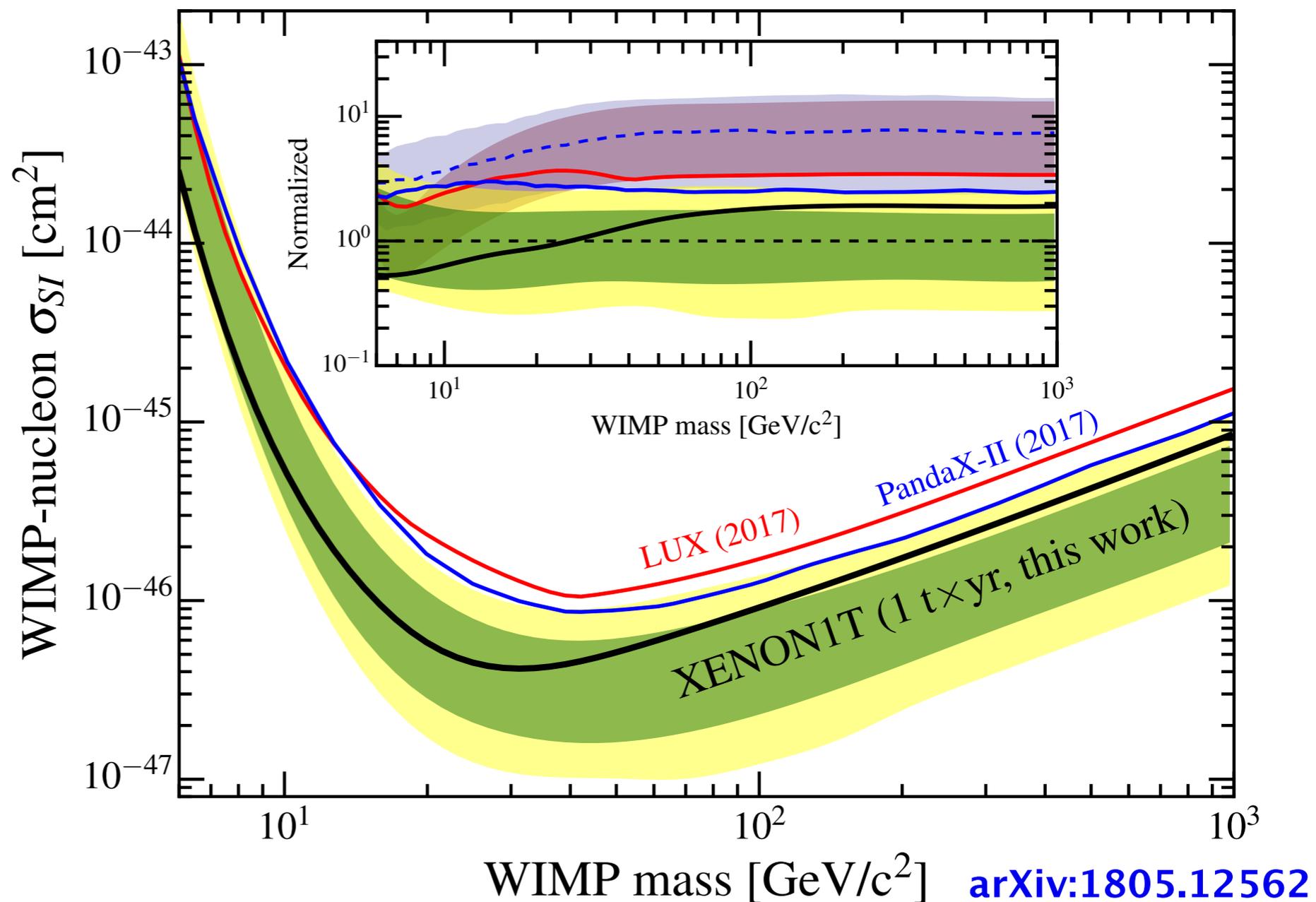


<https://supercdms.slac.stanford.edu/dark-matter-limit-plotter>

暗物质直接探测

还没有暗物质明确迹象。

实验给出对暗物质和原子核弹性散射截面大小的限制。

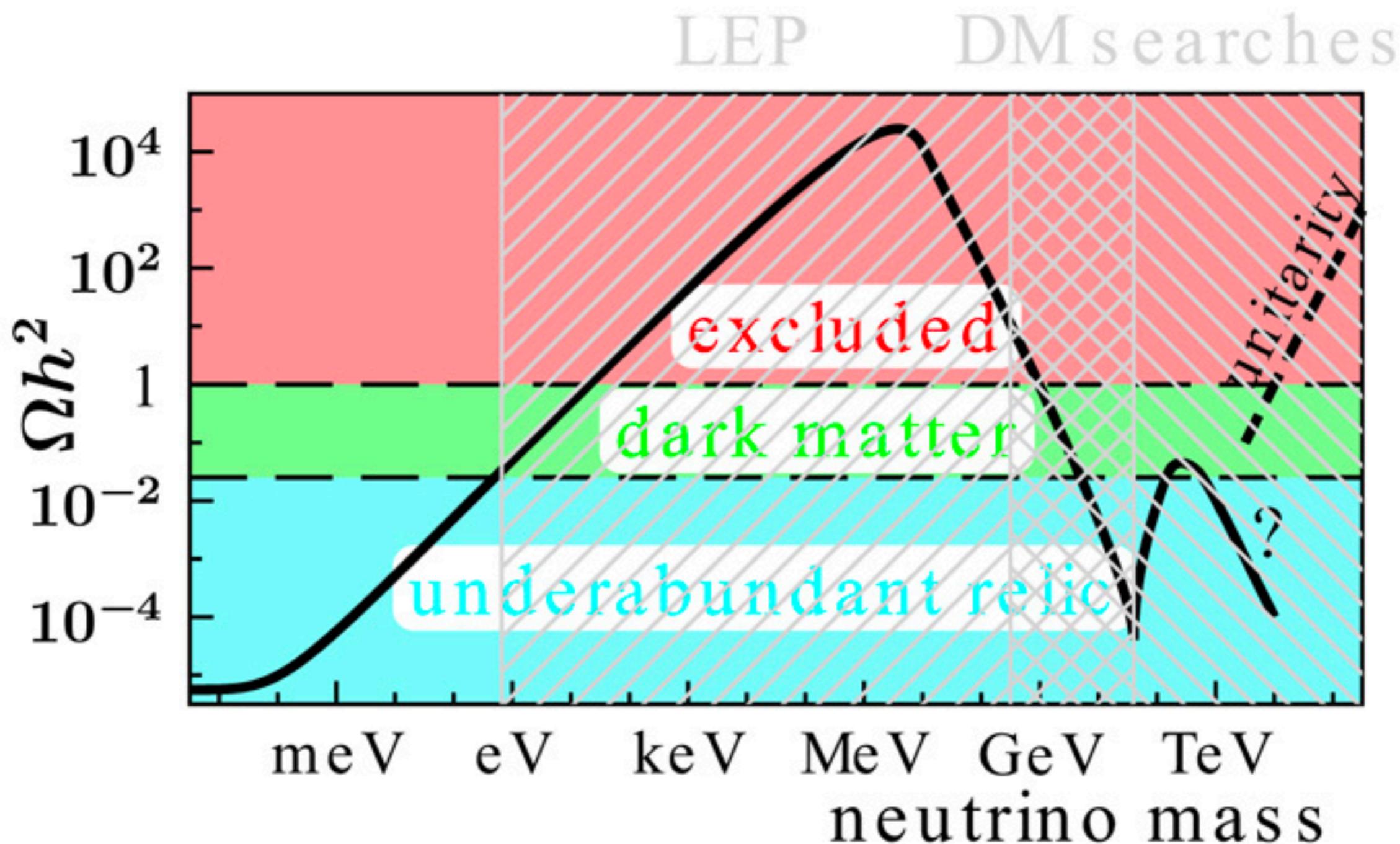


Dark Matter Candidates Zoo

- BSM theory with natural DM candidate;
- Alternative DM production 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, ...)
- Multiple dark matter, mirror dark matter
- Hidden dark matter, self-interacting DM, composite DM, ...

“最简”模型：Extra active neutrino

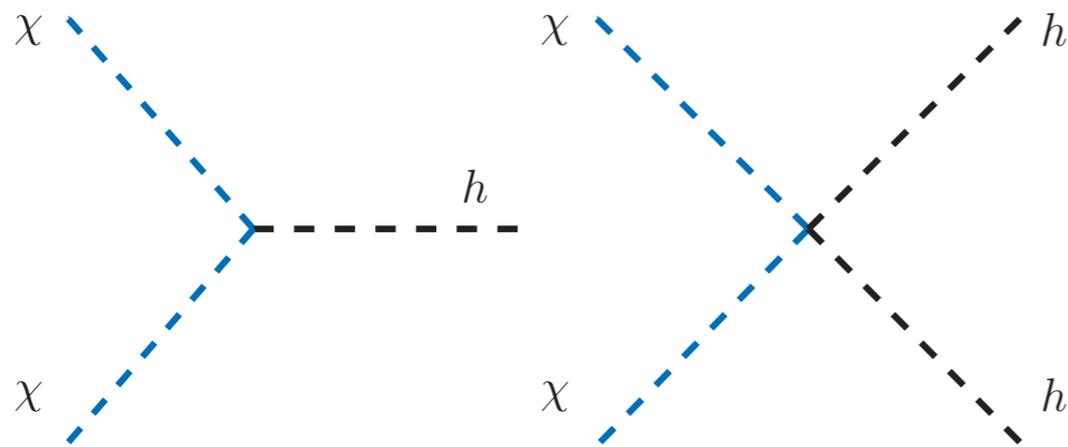
SM + active neutrino, e.g., 4th generation



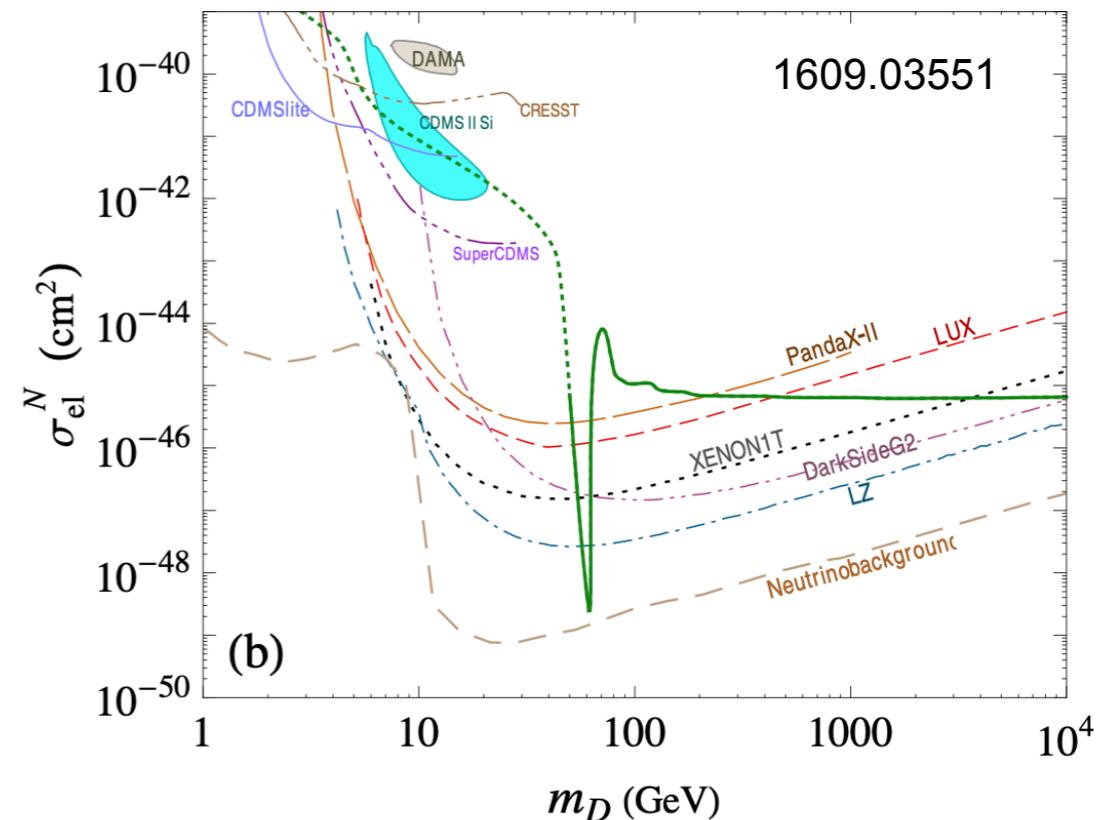
“最简”模型： Singlet scalar DM

- SM + Real singlet scalar with Z2 odd symmetry

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



Higgs portal singlet scalar dark matter

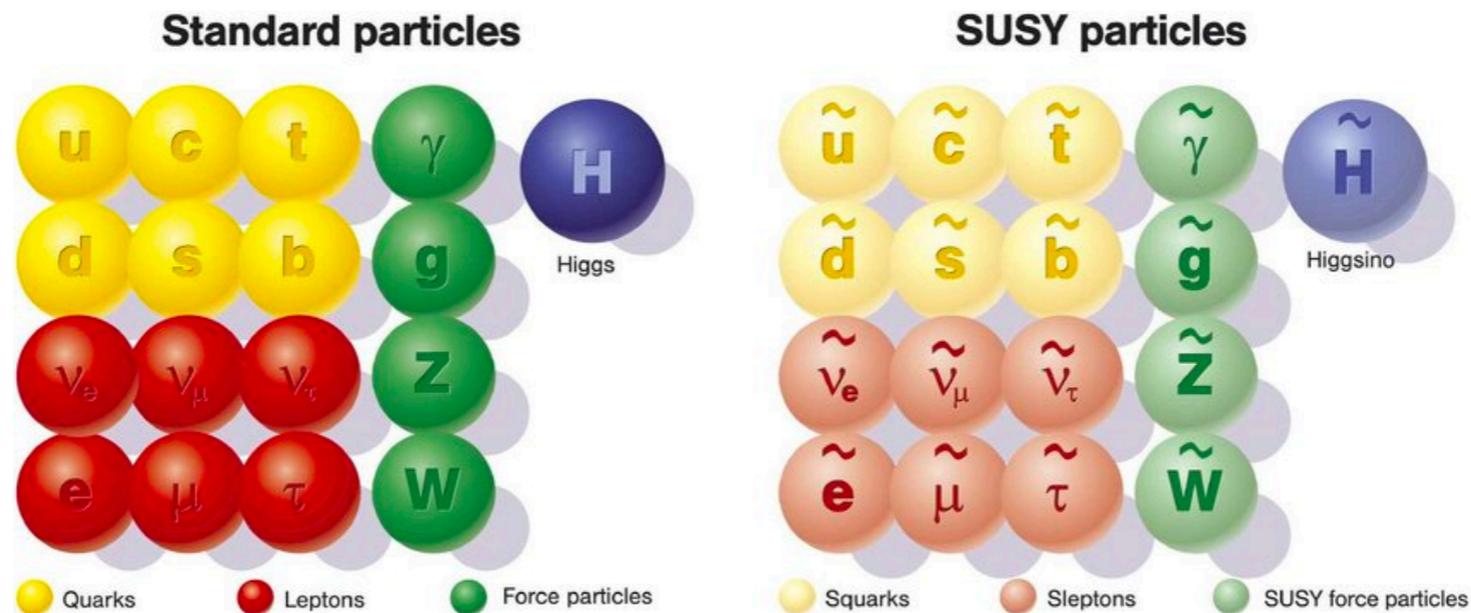


SUSY LSP: neutralino

- ① **Supersymmetry:** A possible solution to the “hierarchy problem”
- ② Each SM particle has its own superpartner and vice versa
- ③ R-parity

$$R = (-1)^{3(B-L)+2s} \Rightarrow \text{SM} : + \quad \text{SUSY} : -$$

- ④ the lightest supersymmetric is stable: **DM candidate!**



SUSY LSP: neutralino

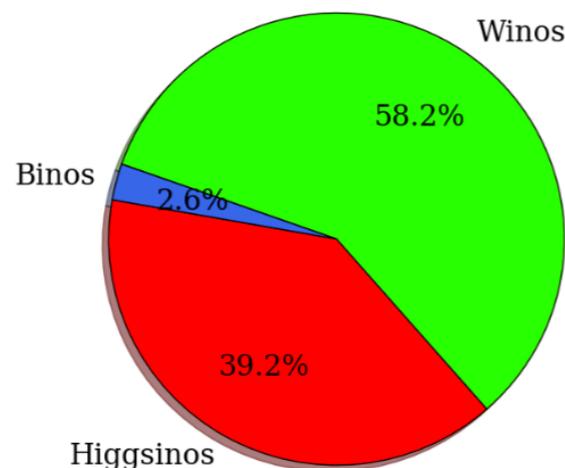
- ⑤ the neutralino χ , a linear combination of $\{\tilde{B}, \tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0\}$ was/is the leading candidate of DM
- ⑥ neutralino annihilation

$\chi + \chi \rightarrow f\bar{f}, \text{Higgs, gauge bosons}$

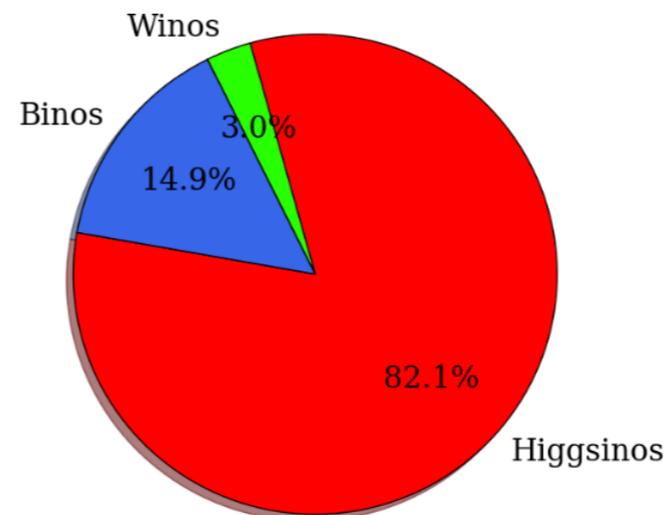
$$\tilde{\chi}_1 = \alpha_1 \tilde{B} + \alpha_2 \tilde{W}_3 + \alpha_3 \tilde{H}_1^0 + \alpha_4 \tilde{H}_2^0$$

$|\alpha_i|^2 \rightarrow 1$ (e.g. 90%) bino-like, wino-like, higgsino-like

w/ relic density
upper bound



w/ relic density
upper and lower limit



light Higgs mass, relic density, LEP and flavour, direct and indirect detections and LHC constraints

taken from pMSSM scan 1707.00426

SUSY LSP: Sneutrino/Gravitino

Sneutrino

- LH Sneutrino as DM candidate, ruled out by direct detection.
- SM+ RH neutrino for neutrino mass generation.
- RH Sneutrino + LH Sneutrino mixing state as DM candidate.

Gravitino

- Superpartner of Graviton.
- Non-thermal relics, produced from scattering from primordial thermal bath after inflation or decay by neutralino after freeze-out.
- highly suppressed coupling, hard to be detected. R-parity violated SUSY, it decays into neutrino + photon with long lifetime.

axinos, singlino, ...

keV Sterile Neutrino

- Connected to the origin of neutrino mass — Seesaw mechanism.
- Neutrino oscillation — active neutrinos are massive. (BSM)
- Tiny neutrino mass: seesaw mechanism (SM+Right-handed N_R)

$$M_\nu = \begin{pmatrix} 0 & M_D^T \\ M_D & M_R \end{pmatrix} \Rightarrow m_\nu = \frac{m_D m_D^T}{M_R}$$

- The sterile neutrino: $\nu_s = \cos \theta N_R + \sin \theta \nu_L$
- produced by oscillations, the abundance of ν_s : non-thermal relics

$$\Omega_s h^2 \sim 0.1 \frac{\sin^2 2\theta}{10^{-8}} \left(\frac{m_s}{3\text{keV}} \right)^{1.8} \quad \text{Phys. Rept. 481,1}$$

- The lifetime:

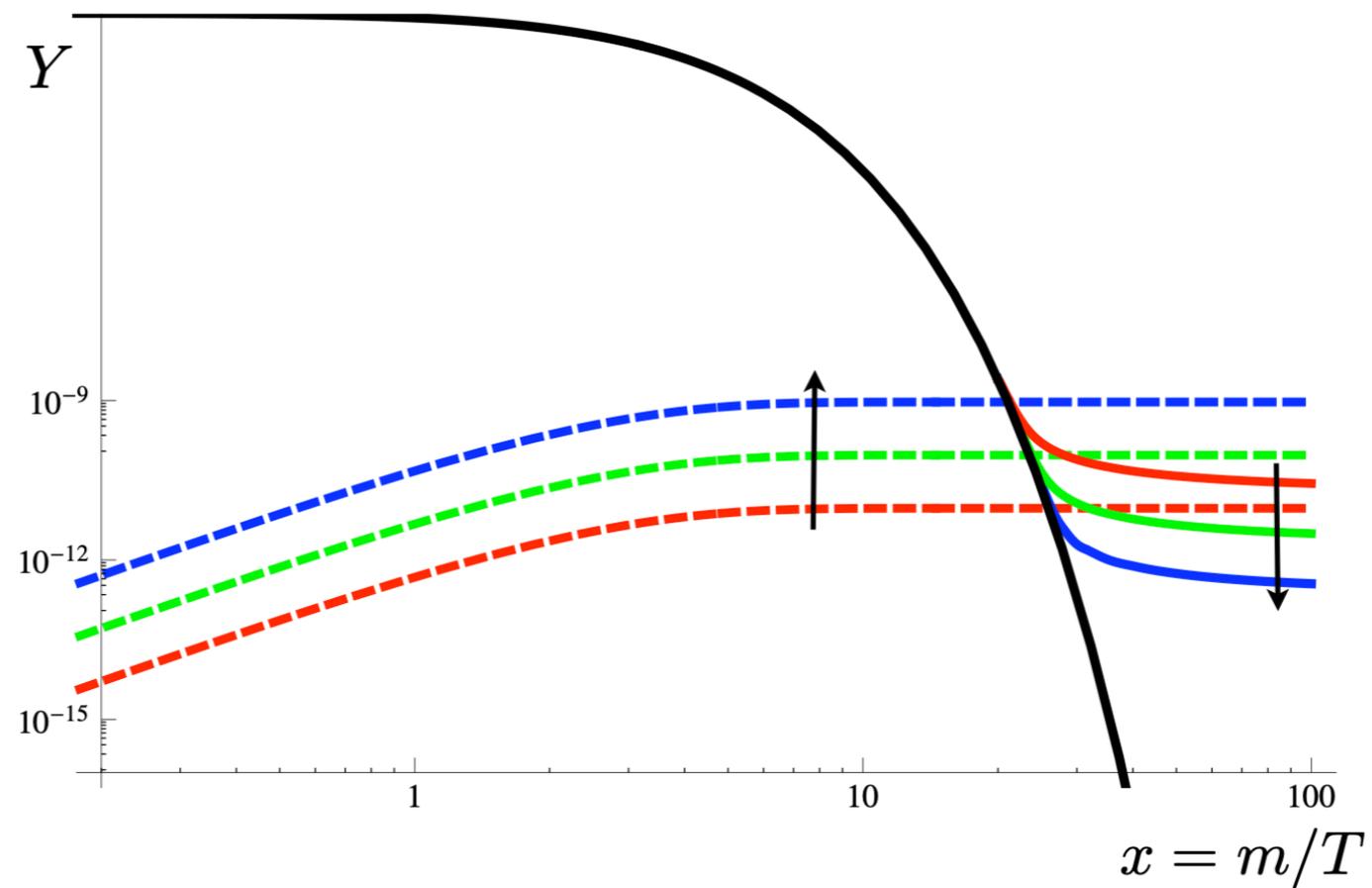
$$\tau_{3\nu} \sim 10^{24} \text{years} \left(\frac{10\text{keV}}{m_s} \right)^5 \left(\frac{10^{-8}}{\theta^2} \right)$$

- detection signals are mono-energetic X-rays: $E_\gamma = m_s/2$

Non-thermal relics: Freeze-in Mechanism

Hall, Jedamzik, March-Russell and West 0911.1120

- Feebly interacting massive particle (FIMP)
 - never attains thermal equilibrium



Decaying dark matter

- ① The lifetime is longer than universe's age
- ② To explain the PAMELA's/AMS 02 positron/electron data, decaying dark matter: $\sim 10^{26}$ sec lifetime
- ③ Good candidate: **Gravitino** with R-parity violation in SUSY. Due to the factor $1/M_{\text{Pl}}$ suppression, gravitino has very long lifetime to be dark matter.
- ④ candidate in some GUT theories, suppressed by the $1/\Lambda_{\text{GUT}}$ scale.

Asymmetric Dark Matter

- DM density arises from DM matter-antimatter asymmetry;
- The fact $\Omega_{\text{dm}} \sim \Omega_{\text{baryon}}$;
- Baryogenesis:

$$\eta_b = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6 \times 10^{-10}$$

- Assume there is conservation for SM global number q and hidden charge Q ,

$$qn_{b-\bar{b}} = -Qn_{\text{dm}-\bar{\text{dm}}}$$

- from $\Omega_b \propto m_b \eta_b$, $\Omega_{\text{DM}} \propto m_{\text{DM}} \eta_{\text{DM}}$, the masses are related;
- Possible to unify the origin of the baryon and Dark matter abundance.

Self Interacting Dark Matter (SIDM)

- To affect the macroscopic properties of dark matter halo.

$$\frac{\sigma_{\chi\chi}\rho_{\chi}v/m_{\chi}}{H_0} \sim 1$$

$$\Rightarrow \left(\frac{\sigma_{\chi\chi}}{m_{\chi}}\right) \sim 1.3 \frac{\text{cm}^2}{\text{g}} \left(\frac{1\text{GeV}/\text{cm}^3}{\rho_{\chi}}\right) \left(\frac{10\text{ km/s}}{v}\right)$$

$$\frac{\text{cm}^2}{\text{g}} \sim 1.8 \frac{\text{barn}}{\text{GeV}}$$

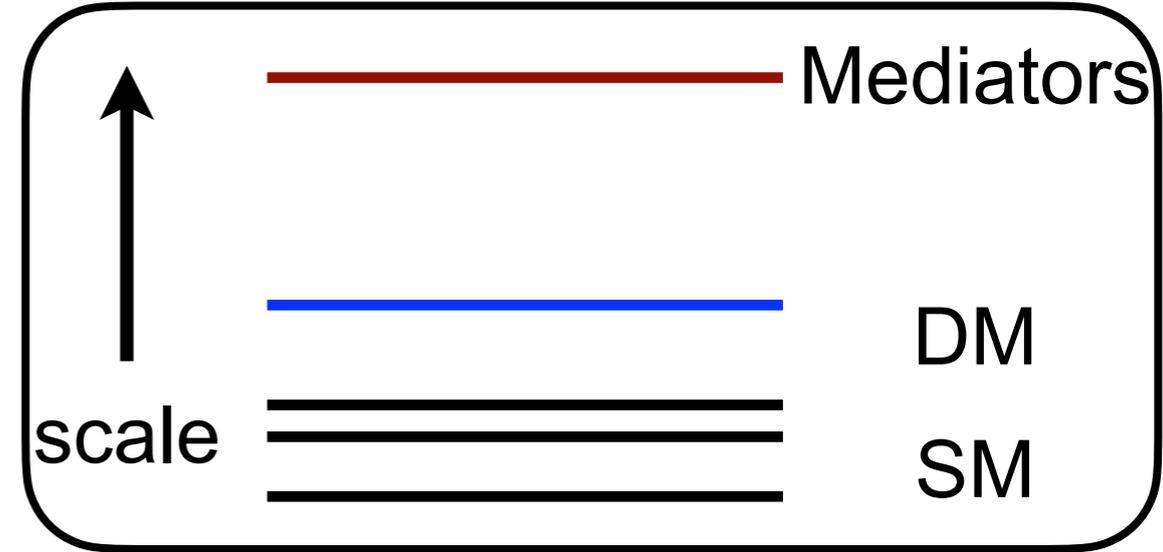
Strong interacting dark sector

- Self interacting DM helps to suppress the central density of dark matter halo, and affect the formation of sub-halos the way favored by the observations.

有效算符 (Effective Field Theory)

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	$\bar{\chi}\chi\bar{q}\gamma^5q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	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	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
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	$\bar{\chi}\gamma^5\chi\bar{q}q$	$im_q/2M_*^3$

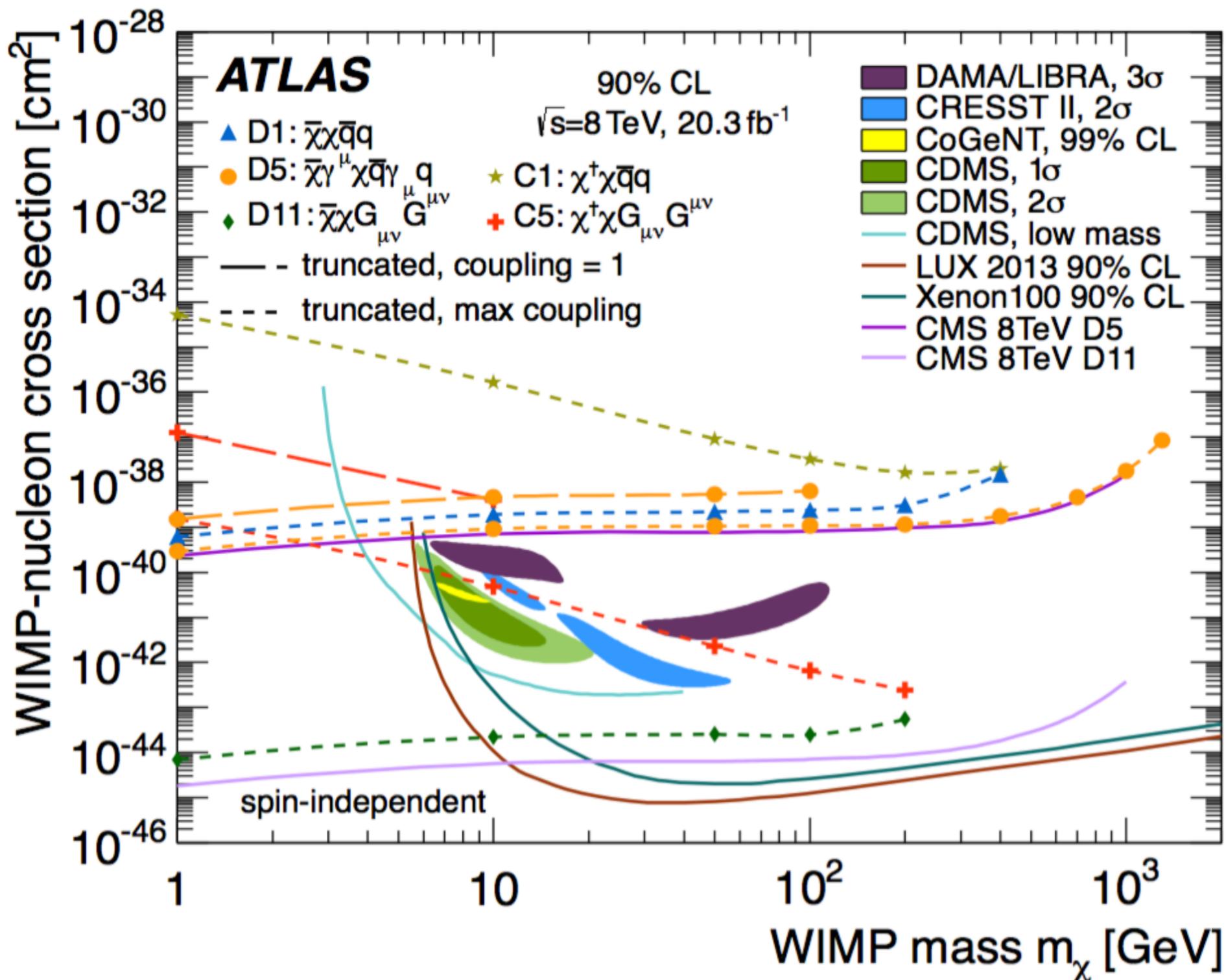
Name	Operator	Coefficient
M3	$\bar{\chi}\chi\bar{q}\gamma^5q$	$im_q/2M_*^3$
M4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	$m_q/2M_*^3$
M5	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/2M_*^2$
M6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$	$1/2M_*^2$
M7	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^3$
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	$\chi^\dagger\chi\bar{q}\gamma^5q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5q$	$1/M_*^2$
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	$\chi^2\bar{q}\gamma^5q$	$im_q/2M_*^2$
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

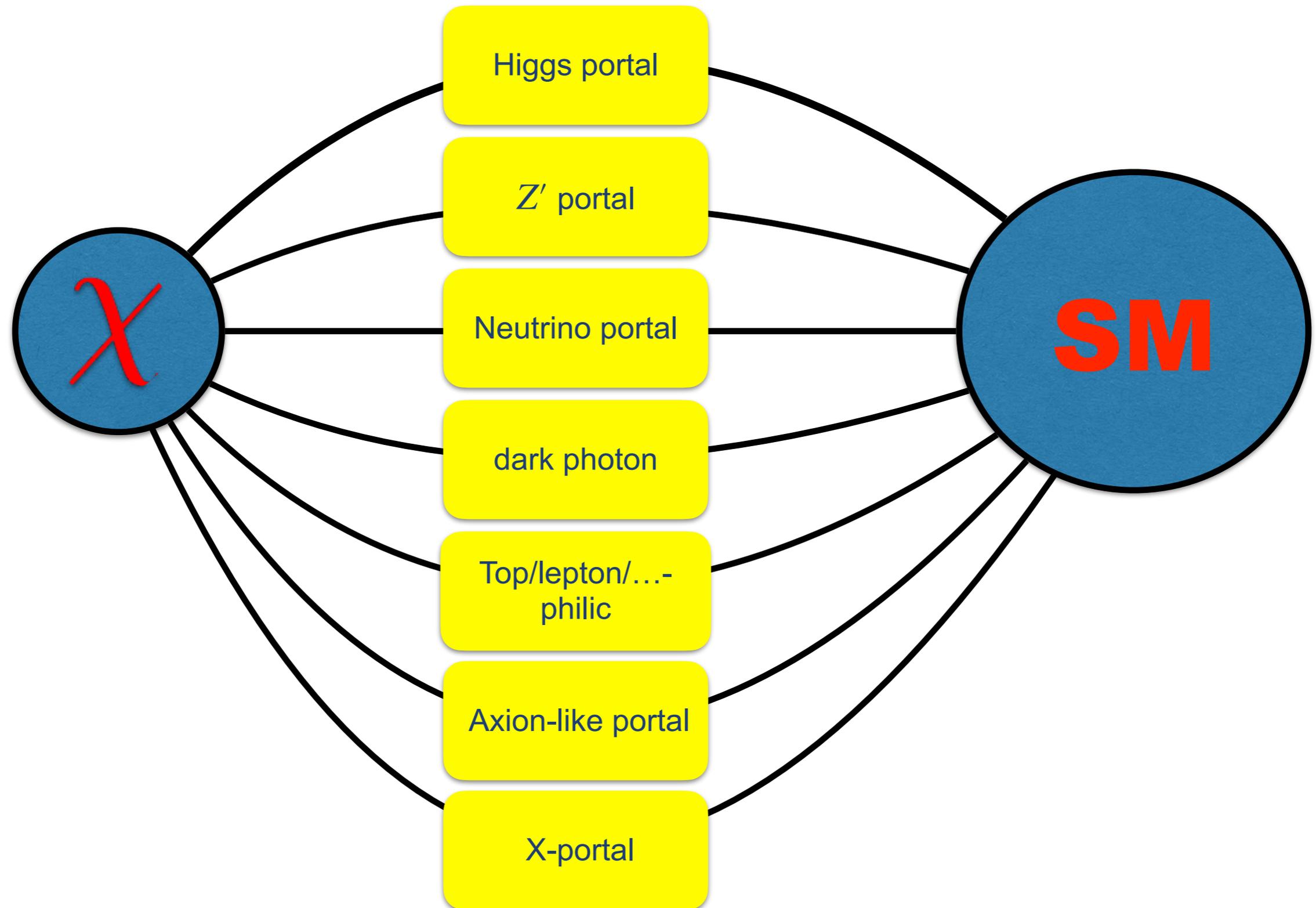
EFT approach is useful for complementary analysis for various detection ways.

有效算符

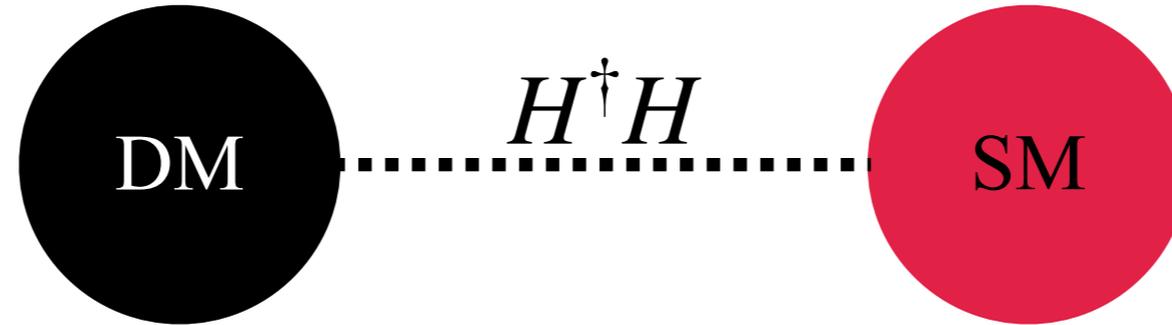


1502.01518

Simplified model



Simplified model: Higgs portal



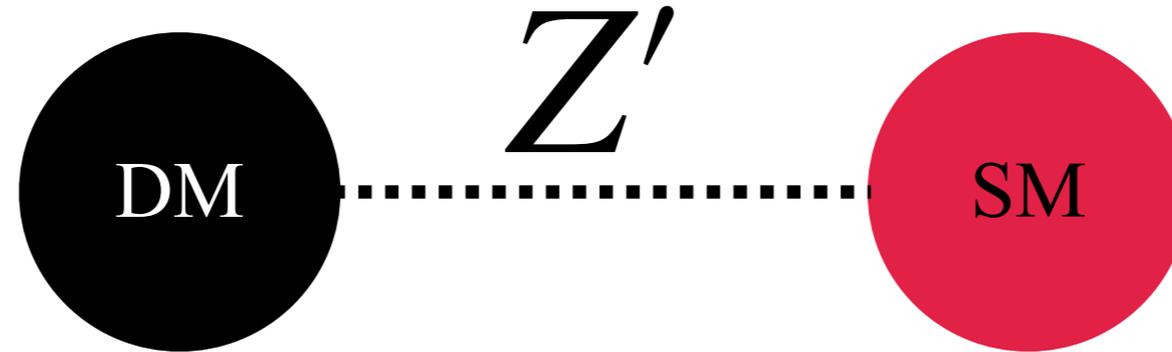
$$\mathcal{L}_S = \mathcal{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{1}{2}\mu_S^2 S^2 - \frac{1}{4!}\lambda_S S^4 - \frac{1}{2}\lambda_{hS} S^2 H^\dagger H,$$

$$\mathcal{L}_V = \mathcal{L}_{\text{SM}} - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} + \frac{1}{2}\mu_V^2 V_\mu V^\mu - \frac{1}{4!}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{hV} V_\mu V^\mu H^\dagger H,$$

$$\mathcal{L}_\chi = \mathcal{L}_{\text{SM}} + \frac{1}{2}\bar{\chi}(i\not{\partial} - \mu_\chi)\chi - \frac{1}{2}\frac{\lambda_{h\chi}}{\Lambda_\chi} \left(\cos\theta \bar{\chi}\chi + \sin\theta \bar{\chi}i\gamma_5\chi \right) H^\dagger H,$$

$$\mathcal{L}_\psi = \mathcal{L}_{\text{SM}} + \bar{\psi}(i\not{\partial} - \mu_\psi)\psi - \frac{\lambda_{h\psi}}{\Lambda_\psi} \left(\cos\theta \bar{\psi}\psi + \sin\theta \bar{\psi}i\gamma_5\psi \right) H^\dagger H, \quad 1512.06458$$

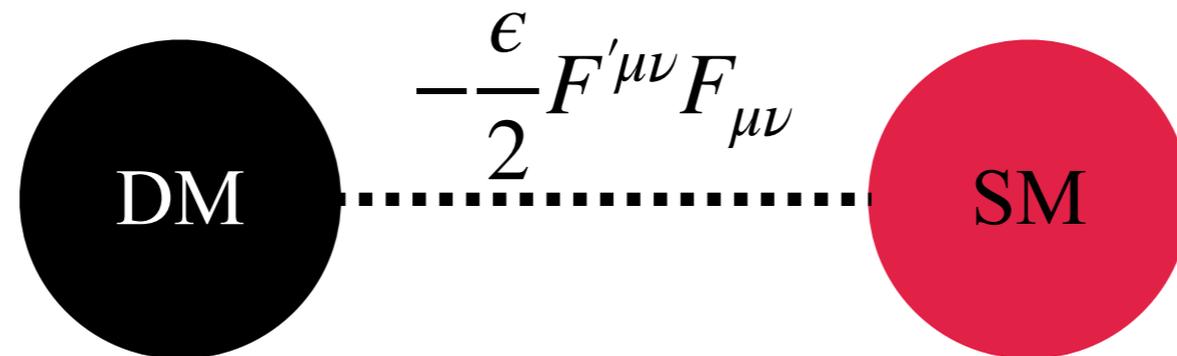
Simplified model: Z' prime portal



$$\mathcal{L} = Z'_\mu [(g_{Z'} \bar{q} \gamma^\mu q + g_{Z'5} \bar{q} \gamma^\mu \gamma_5 q) + (g_D \bar{\chi} \gamma^\mu \chi + g_{D5} \bar{\chi} \gamma^\mu \gamma_5 \chi)]$$

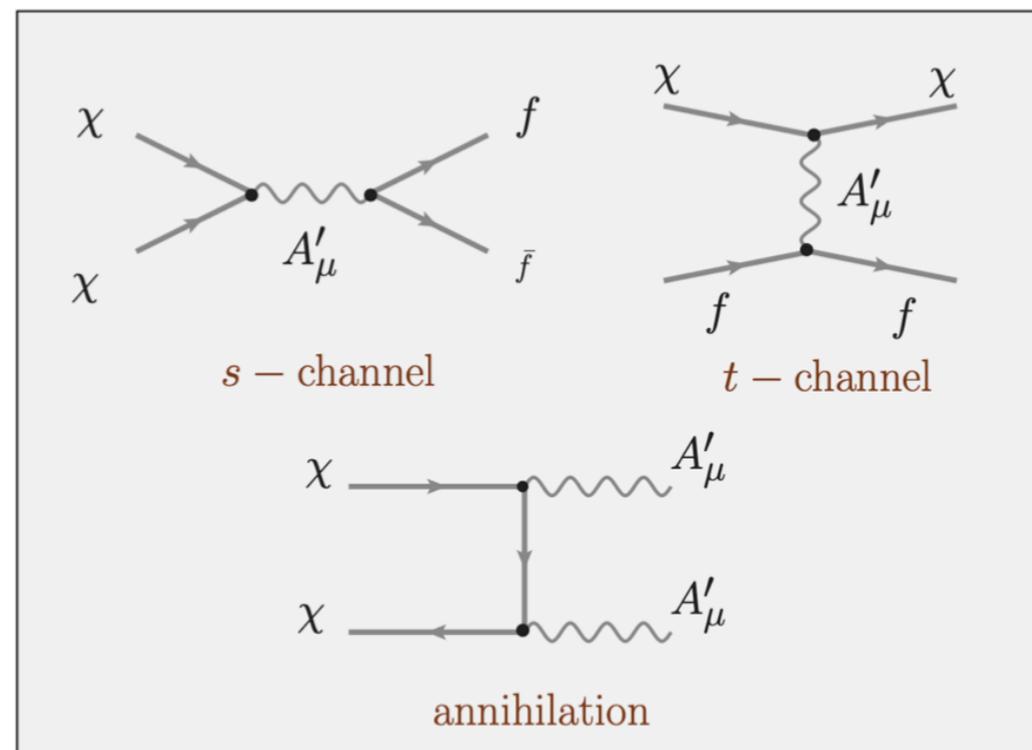
	Operator	Structure	DM-nucleon Cross Section	
O_1	$\bar{q} \gamma^\mu q \bar{\chi} \gamma_\mu \chi$	SI, MI	$\frac{9g_{Z'}^2 g_D^2 M_N^2 M_\chi^2}{\pi M_{Z'}^4 (M_N + M_\chi)^2}$	1202.2894
O_2	$\bar{q} \gamma^\mu q \bar{\chi} \gamma_\mu \gamma_5 \chi$	SI, MD	$\sim v^2$	
O_3	$\bar{q} \gamma^\mu \gamma_5 q \bar{\chi} \gamma_\mu \chi$	SD, MD	$\sim v^2$	
O_4	$\bar{q} \gamma^\mu \gamma_5 q \bar{\chi} \gamma_\mu \gamma_5 \chi$	SD, MI	$\frac{3g_{Z'5}^2 g_{D5}^2 (\Delta\Sigma)^2 M_N^2 M_\chi^2}{\pi M_{Z'}^4 (M_N + M_\chi)^2}$	

Simplified model: U(1)'-portal



- Massive dark photon

$$\mathcal{L} \supset e\epsilon A'_\mu J^\mu + e' A'_\mu J'^\mu$$



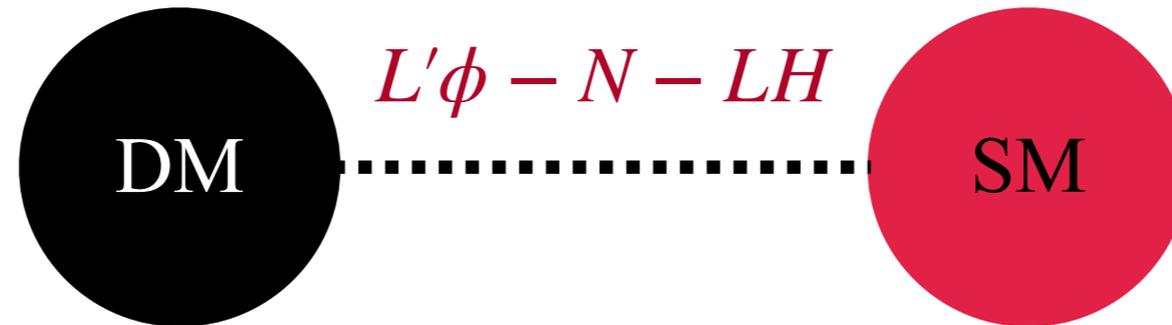
See 2005.01515,
2105.04565 for
review on dark
photon

- There is a rotation way of dark U(1) and SM U(1) to lead the following interaction.

$$\mathcal{L} \supset \epsilon e' A'_\mu \bar{\chi} \gamma^\mu \chi$$

milli-charged Dark Matter

Simplified model: Neutrino portal



- Seesaw mechanism - origin of neutrino mass and mixing
- Leptogenesis - baryon asymmetry in the Universe
- mediator between dark sector and the SM
- Provide connection between the origins of DM and Baryonic matter.

Computing Package

MicrOMEGAs <https://lapth.cnrs.fr/micromegas/>

MicrOMEGAs: a code for the calculation of Dark Matter Properties including the relic density, direct and indirect rates in a general supersymmetric model and other models of New Physics

DarkSUSY <https://darksusy.hepforge.org/>

DarkSUSY

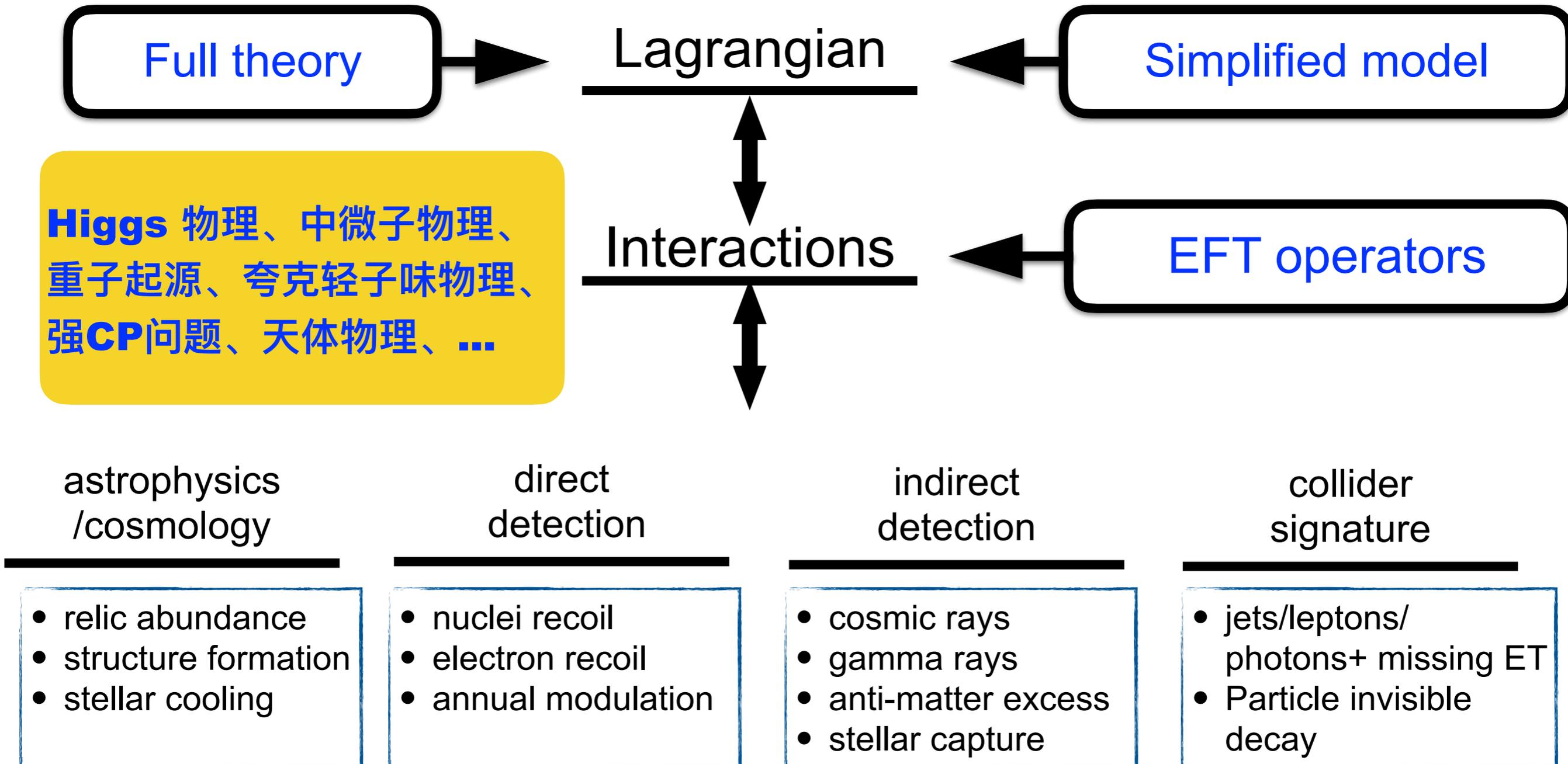
DarkSUSY is a flexible and modular Fortran package to calculate observables for a variety of dark matter candidates. It is written by Joakim Edsjö, Torsten Bringmann, Paolo Gondolo, Piero Ullio and Lars Bergström, with further significant code contributions by (in alphabetical order) Ted Baltz, Francesca Calore, Gintaras Duda, Mia Schelke and Pat Scott. On these pages you will find general information about DarkSUSY and you can also download the package.

MadDM <https://launchpad.net/maddm>

MadDM v.3.1 is a numerical tool to compute dark matter relic abundance, dark matter nucleus scattering rates and dark matter indirect detection predictions in a generic model. The code is based on the existing MadGraph 5 architecture and as such is easily integrable into any MadGraph collider study. A simple Python interface offers a level of user-friendliness characteristic of MadGraph 5 without sacrificing functionality.

....

Decoding the particle dark matter



DM candidates: A Ten-point test [\[arXiv:0711.4996\]](#)

1. Does it match the appropriate relic density?
2. Is it cold?
3. Is it neutral?
4. Is it consistent with BBN?
5. Does it leave stellar evolution unchanged?
6. Is it compatible with constraints on self-interactions?
7. Is it consistent with direct DM searches?
8. Is it compatible with gamma-ray constraints?
9. Is it compatible with other astrophysical bounds?
10. Can it be probed experimentally?

探索暗物质踪迹

更多的相关问题

质量、自旋、种类、相互作用、产生机制、媒介粒子、探测信号、宇宙演化、星体演化、模型构造、探测原理、探测技术、……

暗物质物理是一个活跃、丰富的交叉前沿研究领域。

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谢谢！祝学习顺利。

