中微子、暗物质及其关联研究

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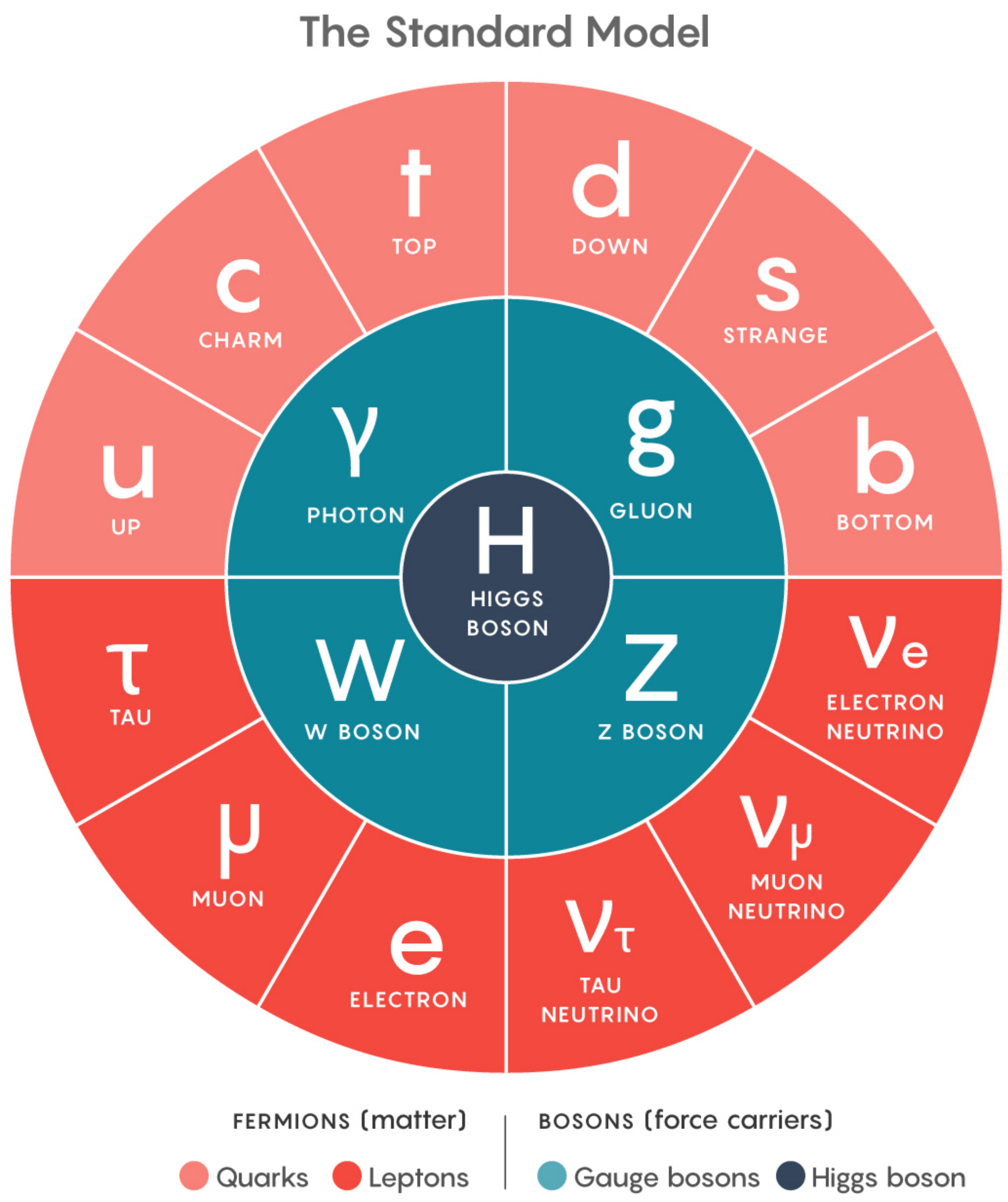
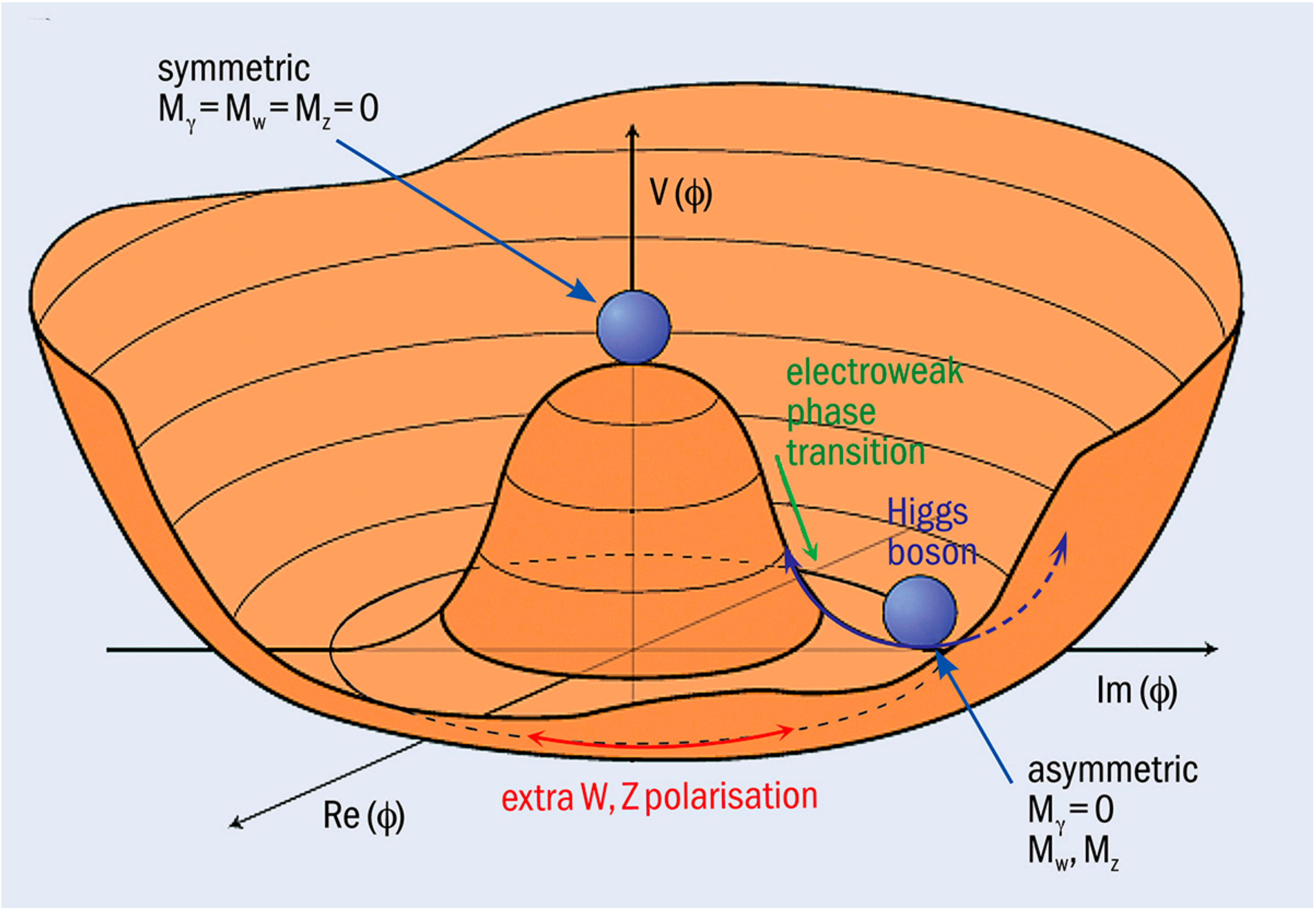
粒子物理标准模型精确检验与新物理前沿讲习班 — 山东大学

二零二三年八月十一日

粒子物理标准模型

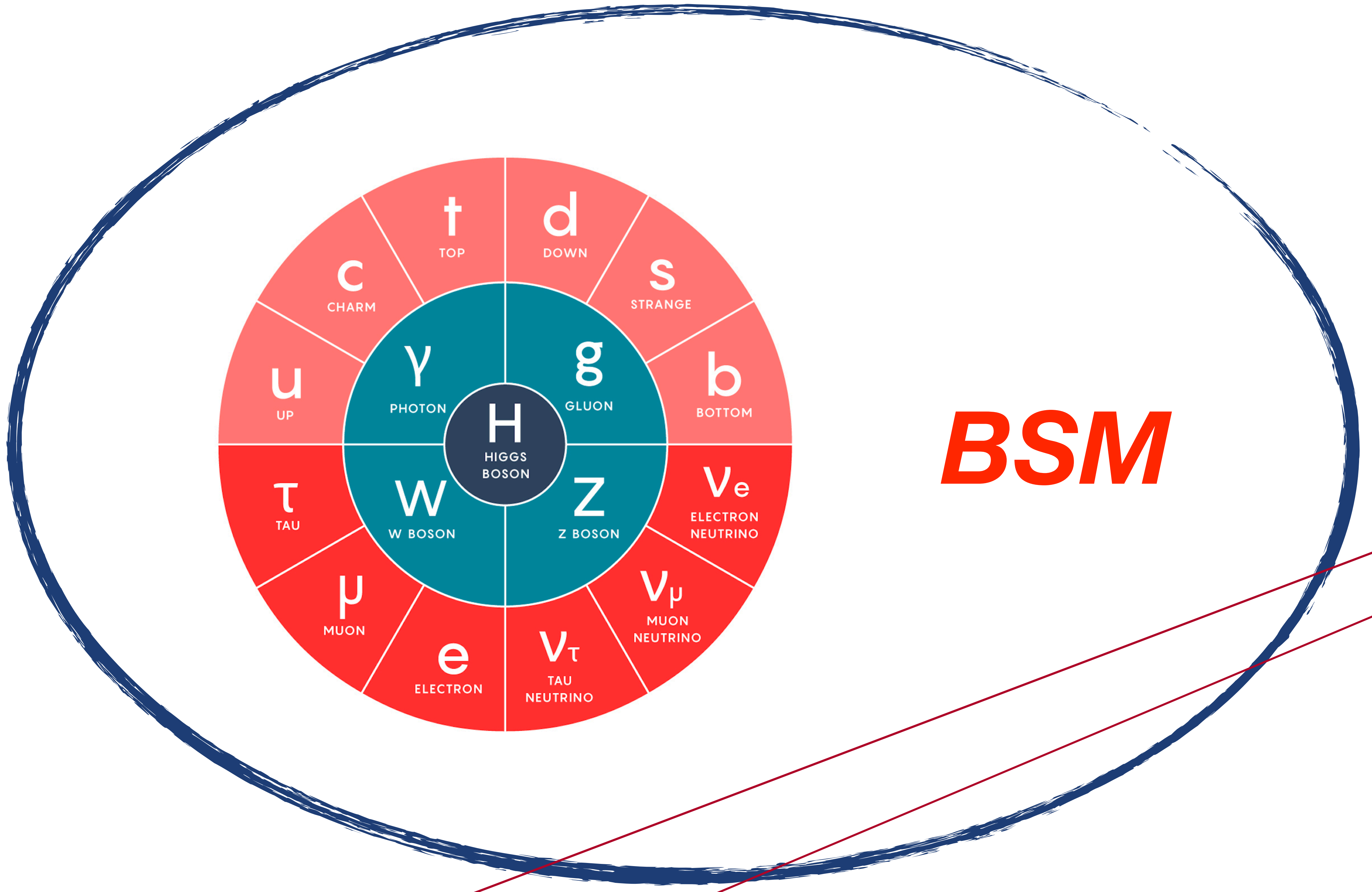


$$SU(3)_C \times SU(2)_L \times U(1)_Y$$



- 夸克、轻子、规范玻色子和希格斯粒子
- 电弱相互作用和强相互作用
- 包含的基本粒子均已被发现
- 被实验“精确”检验

寻找新物理 New Physics beyond the SM



- 其它的夸克?
- 其它的带电轻子?
- 其它的中微子?
- 其它的希格斯粒子?
- 其它的规范玻色子?
- 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)?
- 宇宙物质起源、中微子质量和混合起源、暗物质本质

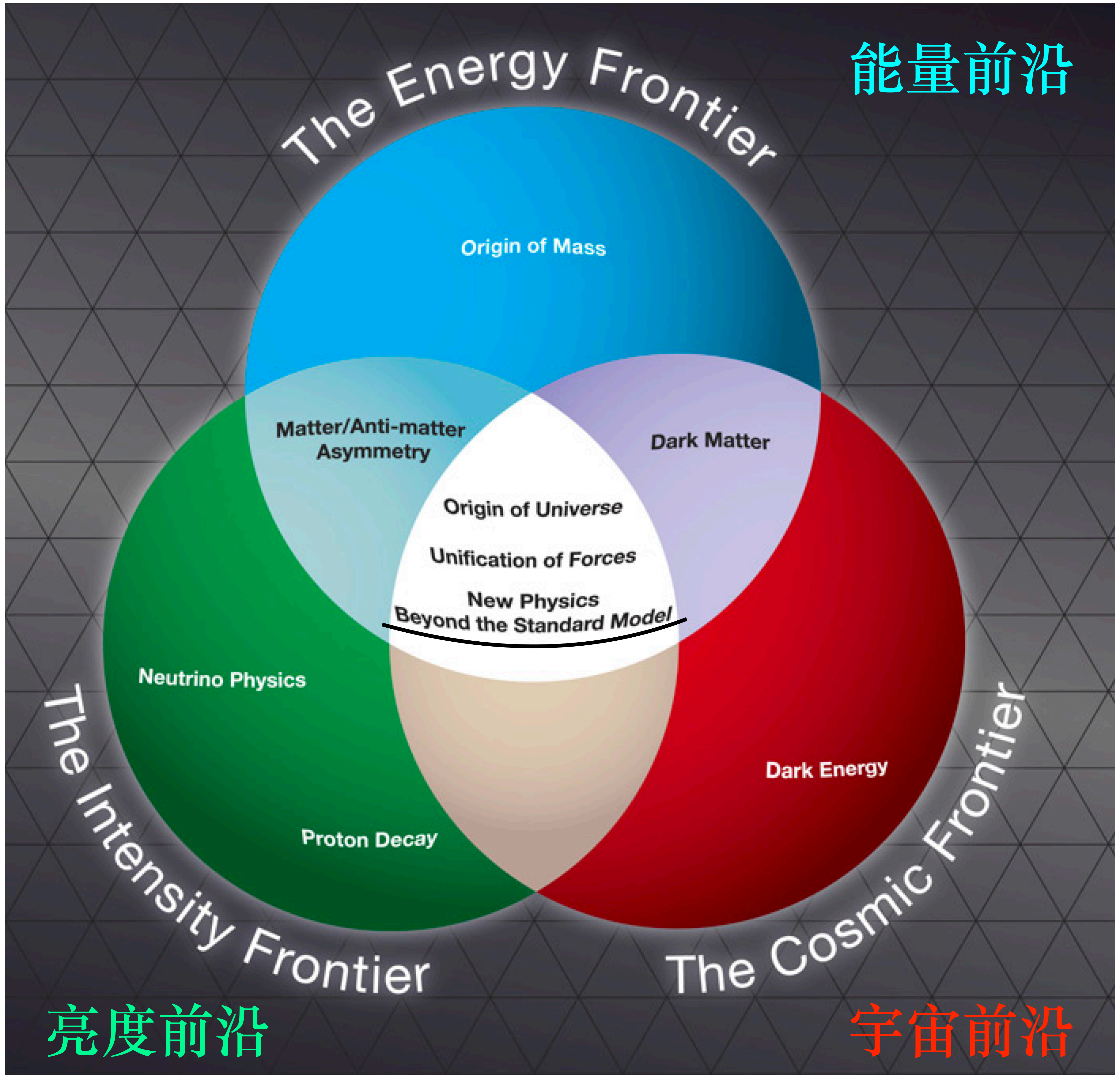
超出标准模型新物理：中微子质量起源 暗物质本质 正反物质不对称 …

探索新物理

质量起源

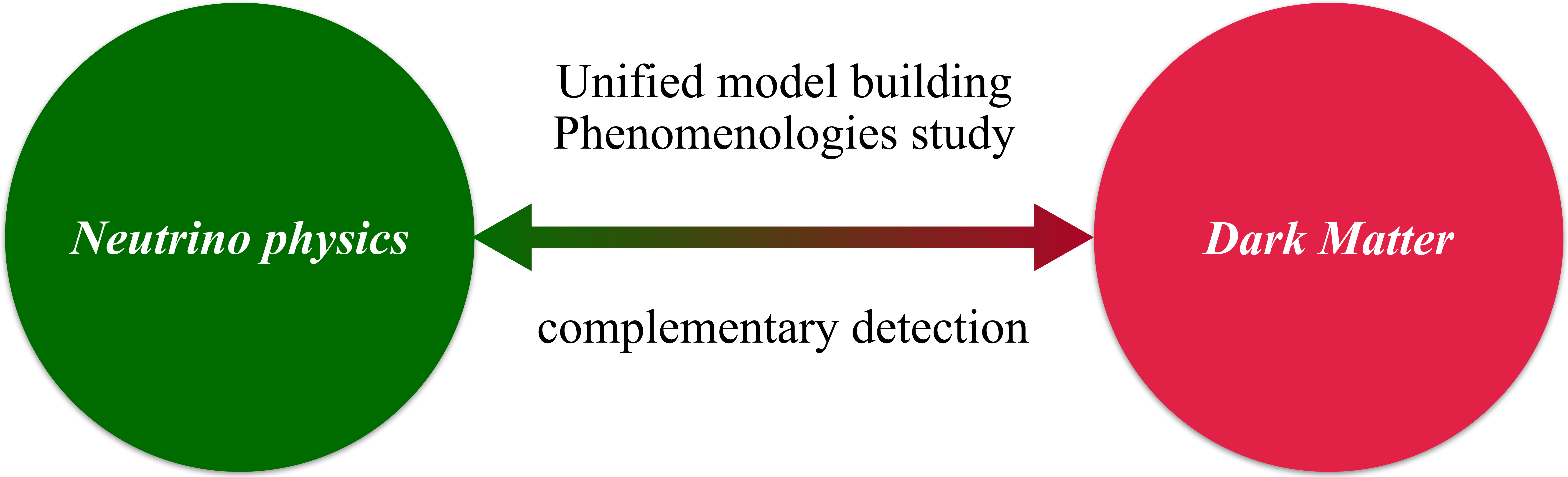
正反物质不对称

中微子物理



暗物质本质

The bridge between Dark matter and Neutrino



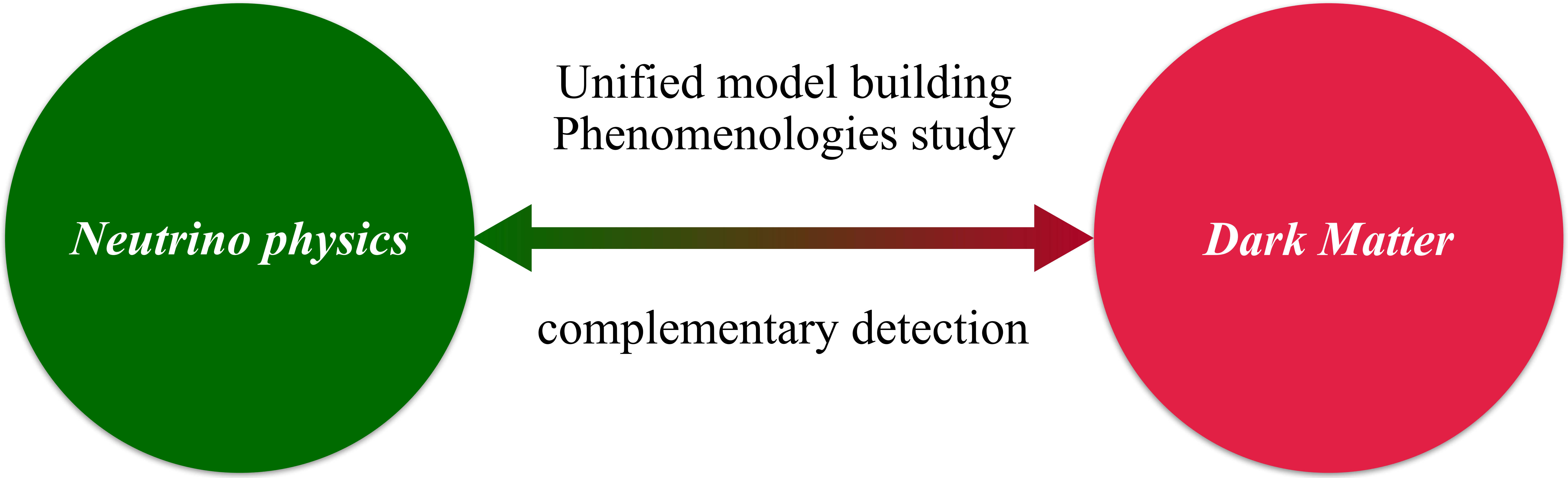
Neutrino physics

Unified model building
Phenomenologies study

complementary detection

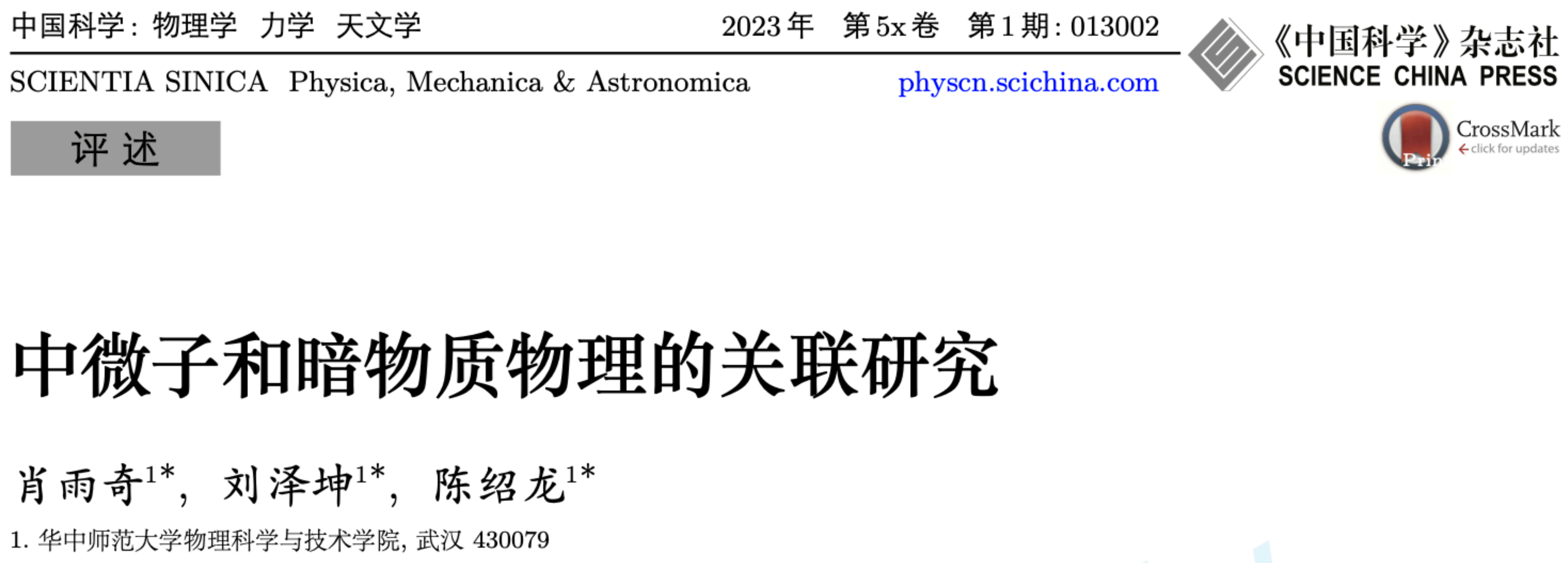
Dark Matter

The bridge between Dark matter and Neutrino



Unified model building
Phenomenologies study

complementary detection



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评 述

中微子和暗物质物理的关联研究

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A brief history on neutrino and dark matter physics

Discovery of the radioactivity (Becquerel)

1896

the missing energy

… the beta decay spectrum is *continuous* (Chadwick, Ellis and Wooster)

1910s-1920s

- “new particle” by Pauli
- neutron discovered (Chadwick)
- “neutrino” named by Fermi and Fermi theory on beta decay

1930-1933

the missing matter

Coma cluster “大”质光比 (Zwicky 1933)
“dark matter” proposed

“Is neutrino its own antiparticle” (Majorana)

1937

“great mass of internebular material” in Virgo cluster (Smith)

中微子和暗物质简史

- theory of solar fusion (Bethe)
- Neutrinos produced by supernova explosions (Gamow)

Proposals to detect neutrino (Pontecorvo)

Neutrino discovered (Reines and Cowan)

- Parity violation (Lee and Yang)
- Left-handed Neutrinos
- Neutrino oscillation idea ($\nu - \bar{\nu}$) (Pontecorvo)

1939/1941 1946 1956 1957

中微子和暗物质简史

1959

- Second family of neutrino? How to detect? (Pontecorvo, Schwartz)

1962

- Proposal of flavor mixing of neutrinos (Maki, Nakagawa and Sakata)
- Muon-neutrino discovered (Lederman, Schwartz and Steinberger)

1964

Prediction for Solar neutrinos (Bachall, Davis)

1967

Neutrino flavor oscillation (Pontecorvo)

Neutrino (as thermal relics) roles in cosmology (Gershtein and Zeldovich)

中微子和暗物质简史

1968

- Solar neutrino deficit (Davis)

1970

- M31 flat optical rotational curve (Rubin and Ford)

mid-1970s

- neutral currents (Gargamelle at CERN 1974)
- tau-lepton discovered (Perl at SLAC 1975)

- Neutrinos as (particle) dark matter
- N-body simulations became possible
- dark matter annihilation to gamma rays
- SUSY gravitino dark matter

1979

- The seesaw mechanism (Yanagida, Gell-Mann, Romond, Slansky...)
- Weinberg operator

中微子和暗物质简史

1980

- axion as dark matter (…)
- Hot dark matter theory (Zeldovich)

1983

- simulations rules out hot dark matter
- SUSY neutralino as DM

1984

- ν-N coherent scattering proposed (Drukier and Stodolsky)
  - first observation in 2017 (COHERENT)

- cold non-baryonic DM concepts well accepted (WIMPs)
- using cosmic-ray (anti-protons, positrons) to indirect detect DM (Silk and Srednicki)

1985

the MSW effect (Mikheyev, Smirnov, Wolfenstein)

- dark matter-nuclei elastic scattering (Goodman and Witten)
- searching neutrinos from DM annihilation in the Sun (Krauss, Freese, Spergel)

中微子和暗物质简史

- first observation of a possible atmospheric neutrino deficit (IMB, Kamiokande)

1986

- first expt at Homestake Mine, Germanium 33kg-days
- Annual modulation measurement proposed (Drukier, Freese and Spergel)

- neutrinos from SN1987 (Kamiokande)

1987

3 generations of neutrinos (LEP at CERN)

1989

1990

- DM section firstly appeared in PDG

中微子和暗物质简史

- atmospheric neutrino oscillation (SuperK)

- Observation of tau neutrino
- Solar neutrino deficit explained by oscillation and MSW effect (SNO)

- Solar neutrino oscillation confirmed by the deficit of reactor neutrinos (KamLAND)

1992 1998 2001 2002

- 1992 COBE satellite: CMB
- 1990s: liquid noble target proposal (CDMS, EDELWEISS, CRESST, XENON, LUX, CoGeNT, …)

中微子和暗物质简史

2000s

- 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.

2008/9

- PAMELA positron excess
- PLANCK satellite
- 锦屏地下实验室

2010s

- theta-13 measurement (Daya Bay, T2K, Double Chooz, Reno)
- High energy astrophysical neutrinos (IceCube)
- pp Solar neutrinos

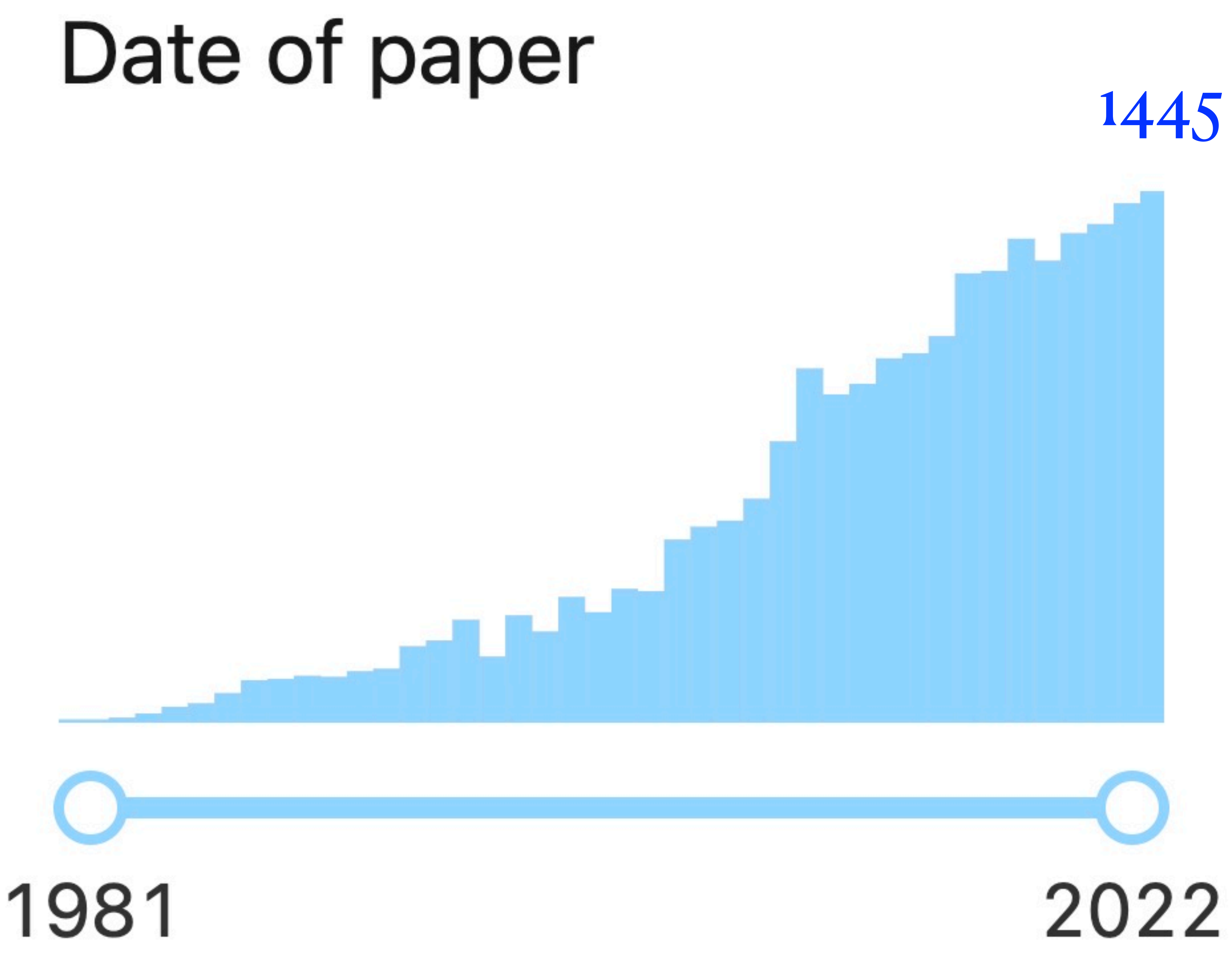
- Fermi LAT electron excess (2010-)
- AMS 02 electron excess (2013-)
- DM direct detection expts

2020s

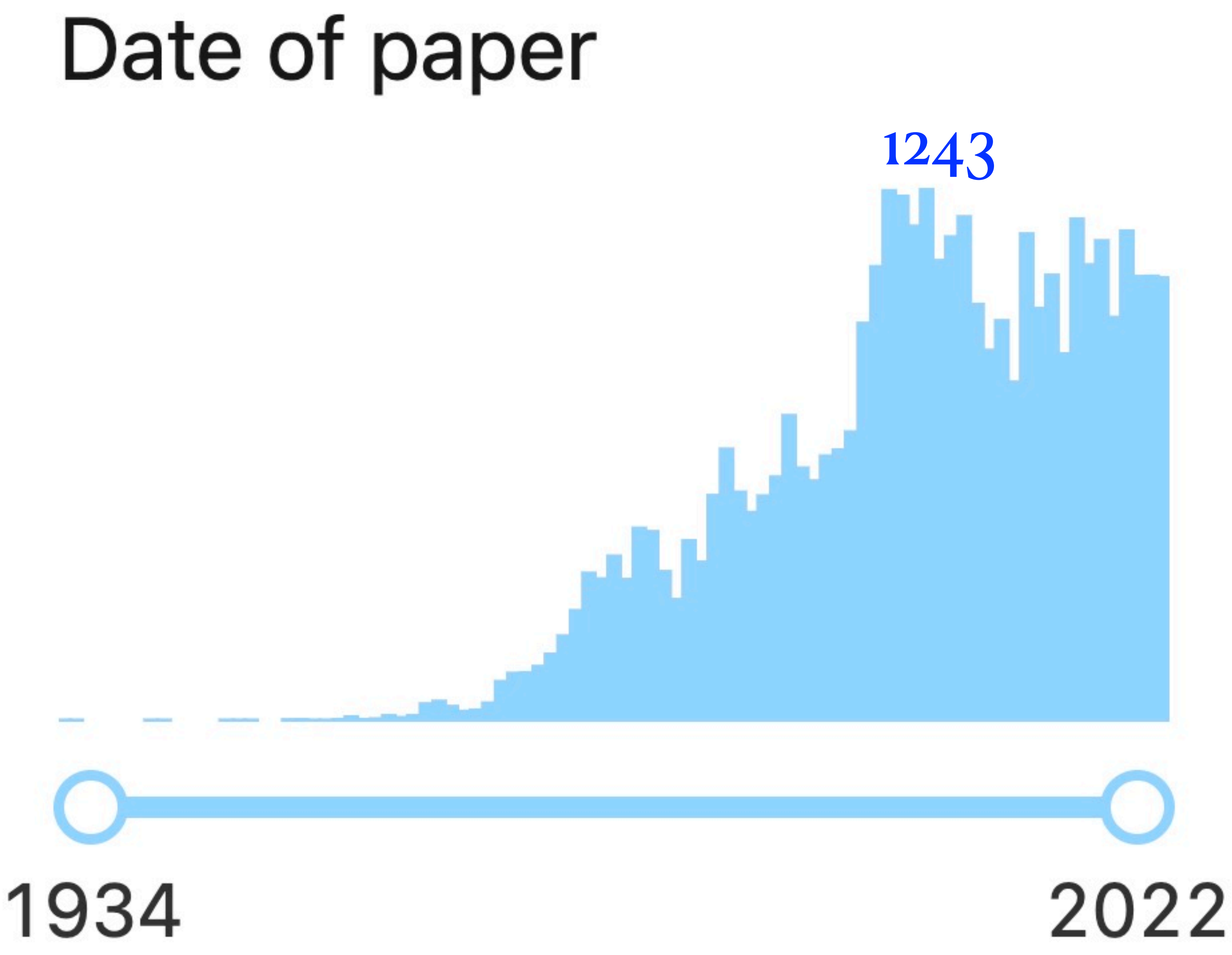
- mass hierarchy, CP violation ? … …
- $0\nu\beta\beta$? … …

- more sensitive detector … …
- more detection ways … …

中微子和暗物质物理：前沿热点

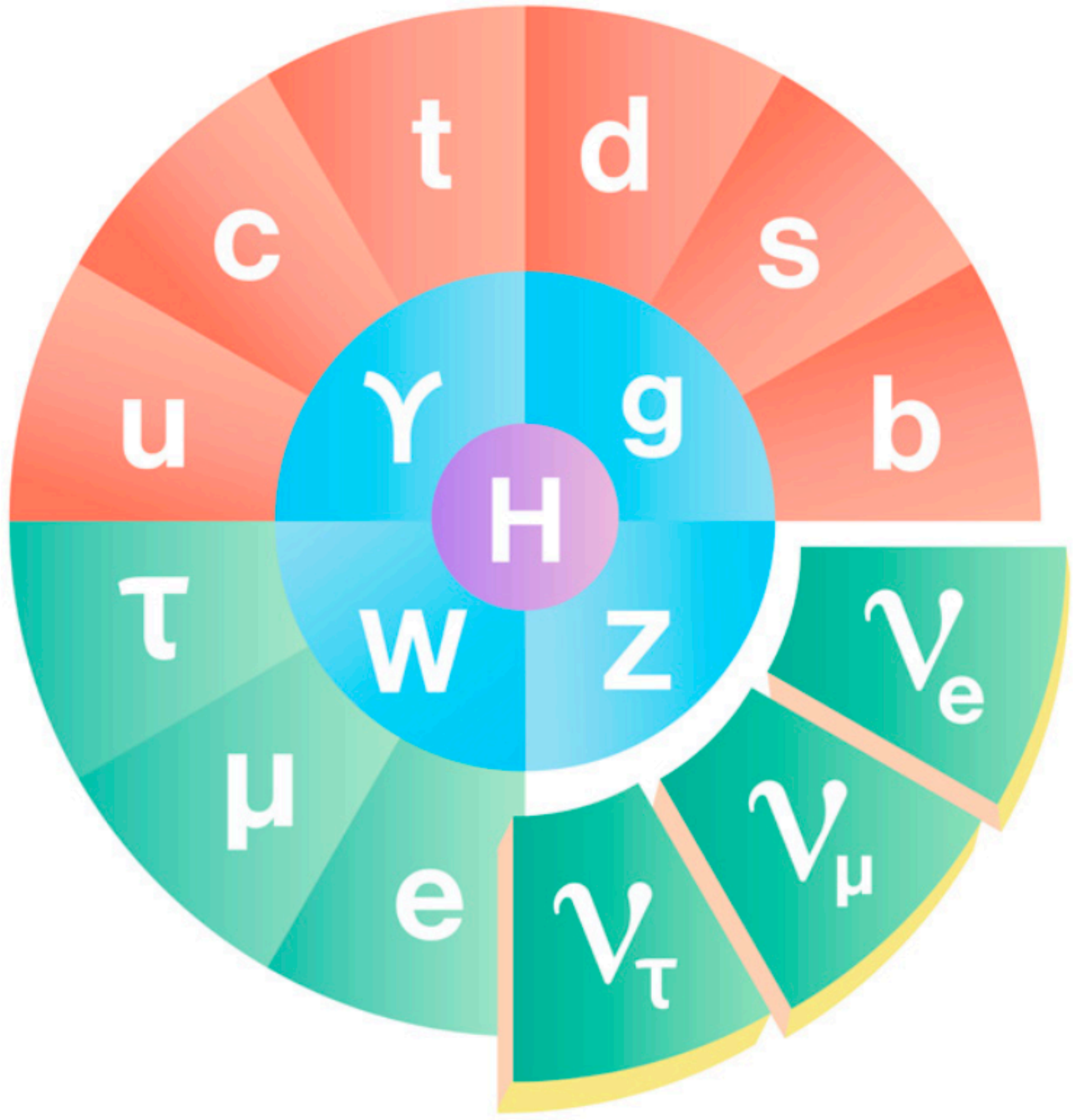


INSPIREHEP t dark matter and date <2023



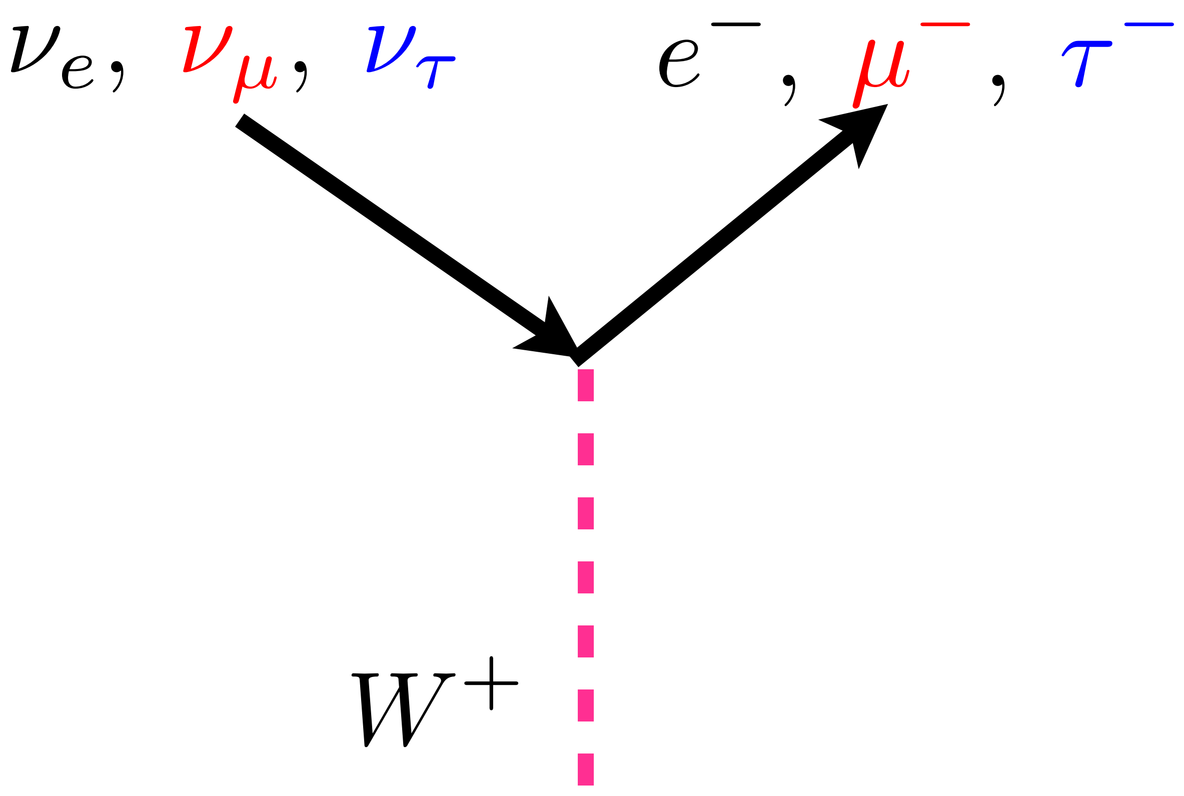
INSPIREHEP t neutrino and date <2023

Neutrinos in SM　(3 families)



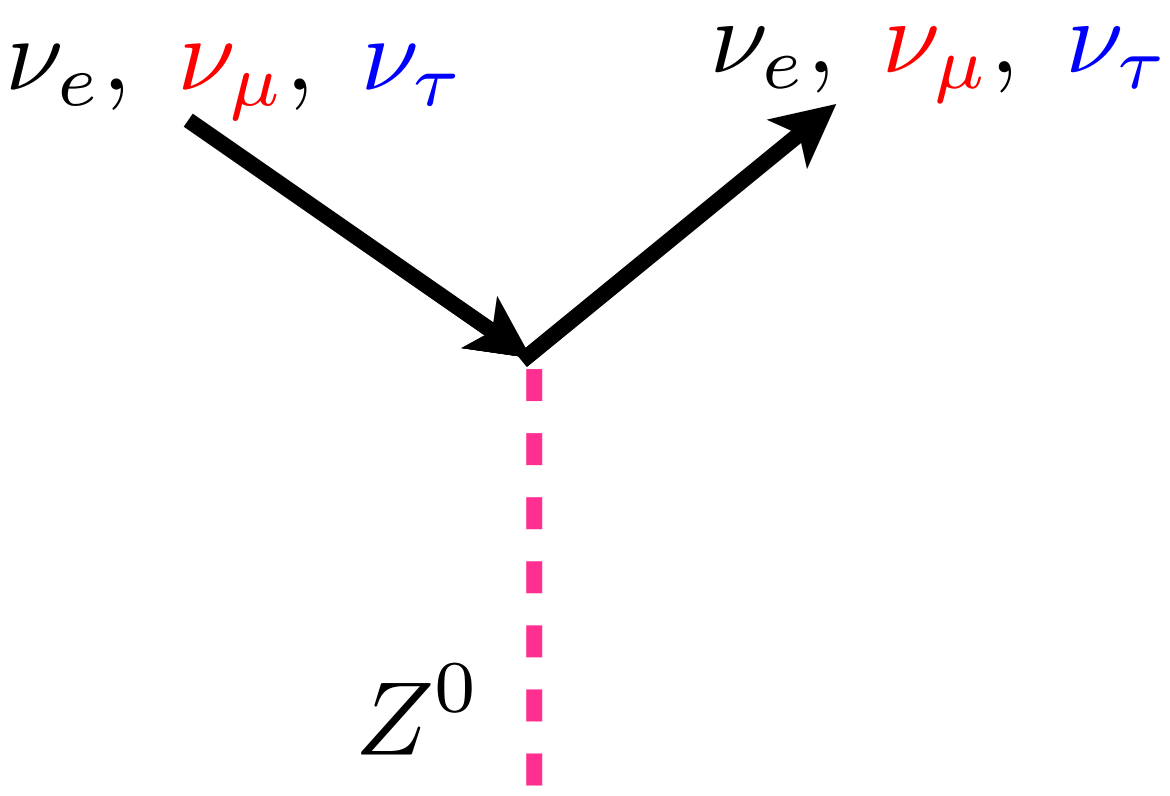
$$\mathcal{L} = -\frac{g}{2\cos\theta_W}\overline{\nu_L^\alpha}\gamma^\mu\nu_L^\alpha Z_\mu - \frac{g}{\sqrt{2}}\overline{\nu_L^\alpha}\gamma^\mu\ell_L^\alpha W_\mu^+ + \text{h.c.}$$

带电流



$M_W = 80\text{GeV}$

中性流

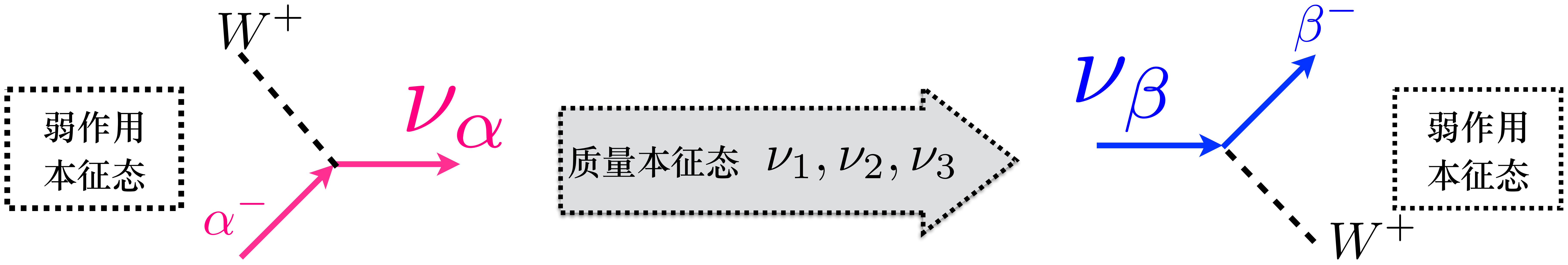


$M_Z = 91\text{GeV}$

低能：“弱”作用
相对于电磁力

$$\frac{Q^2}{M_W^2} \sim \frac{(\text{MeV} - \text{GeV})^2}{(100\ \text{GeV})^2} \sim 10^{-10} - 10^{-4}$$

Neutrino Oscillation



弱作用本征态

W^+

α^-

ν_α

质量本征态 ν_1, ν_2, ν_3

ν_β

β^-

W^+

弱作用本征态

中微子源

中微子探测器

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

产生实验 $$\mathcal{P}\left(\nu_e \to \nu_\mu\right) = \left|\langle \nu_\mu | \nu_e(t) \rangle\right|^2 = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})}$$

消失实验 $$\mathcal{P}\left(\nu_e \to \nu_e\right) = 1 - \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})}$$

若中微子源和探测器距离、中微子束流能量固定，振荡几率由质量平方差绝对值以及混合角决定。

Neutrinos in SM （3 families）

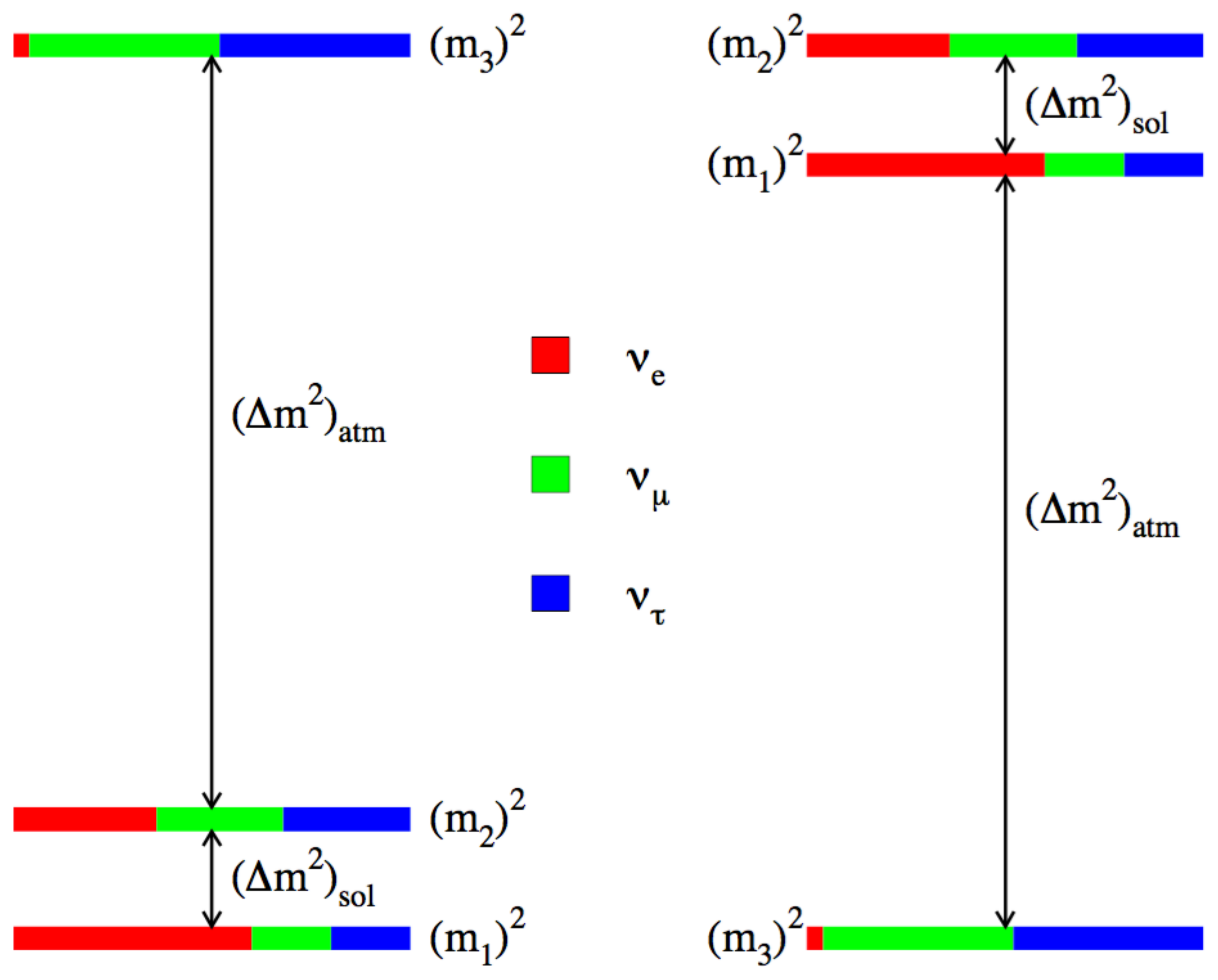
三个混合角，一个 Dirac CP 相位 （两个 Majorana 相位）

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

NuFIT 5.2 (2022)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
$\delta_{\rm CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

三个质量 m_1, m_2, m_3



正常秩序 反常秩序

Mass origin: Dirac or Majorana?

— 类似带电费米子，加入右手中微子，获得 Dirac 质量

$$-\mathscr{L}_D = Y_\nu \overline{L}_L \tilde{H} \nu_R + \text{h.c.} \Rightarrow m_\nu \overline{\nu}_L \nu_R + \text{h.c.}$$

Tiny Yukawa couplings $Y_\nu \langle H \rangle \sim 0.1\ \text{eV}$

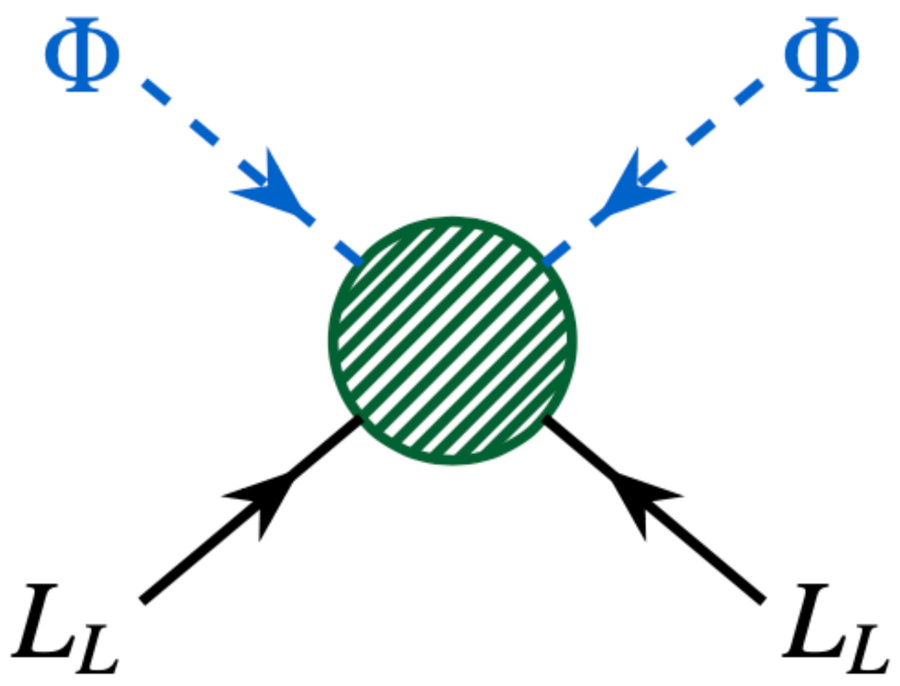
— 中微子为中性粒子，可以是自己的反粒子，轻子数不守恒，可以有 Majorana 质量

$$-\mathscr{L}_M = \frac{1}{2} m_\nu \overline{\nu_L^c} \nu_L$$

Seesaw mechanism: tree level

seesaw mechanism

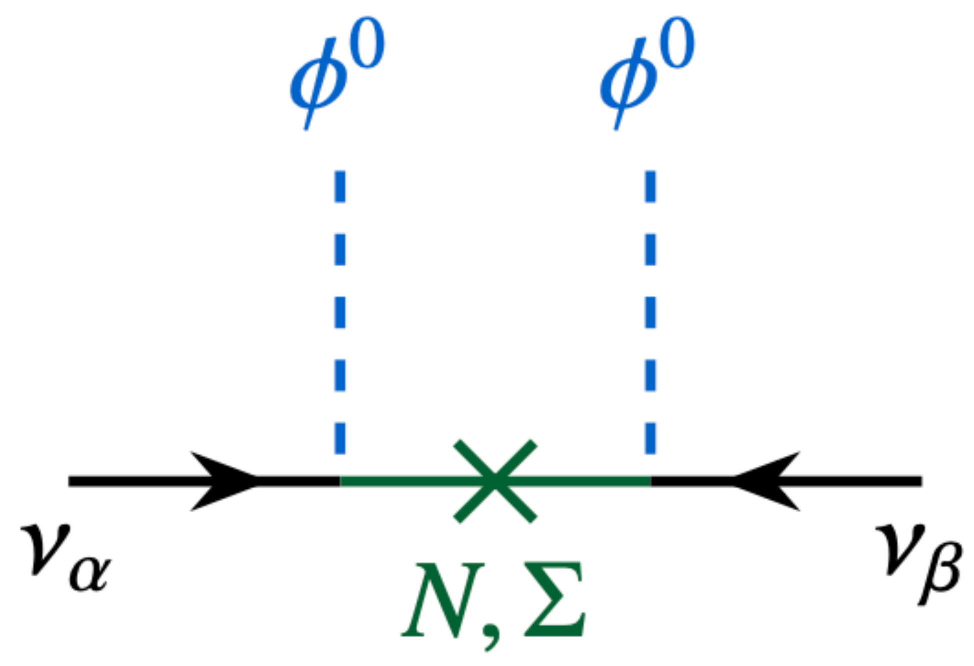
跷跷板机制



Weinberg 五维算符

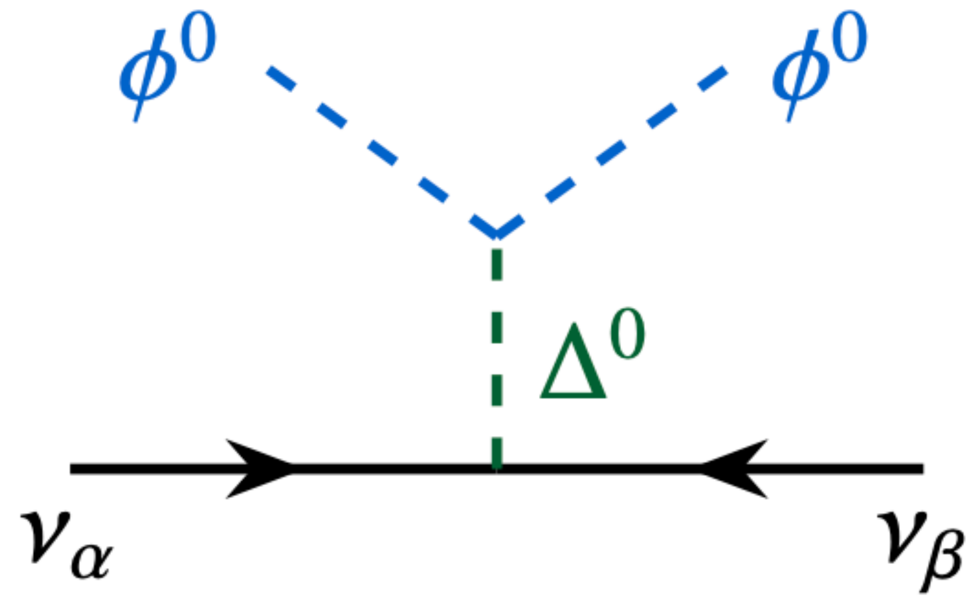
$$\frac{f_{ij}}{\Lambda}(\overline{L_L^{ic}} i\sigma_2 \Phi)(\Phi^T i\sigma_2 L_L^j)$$

=



第一、第三类跷跷板

+



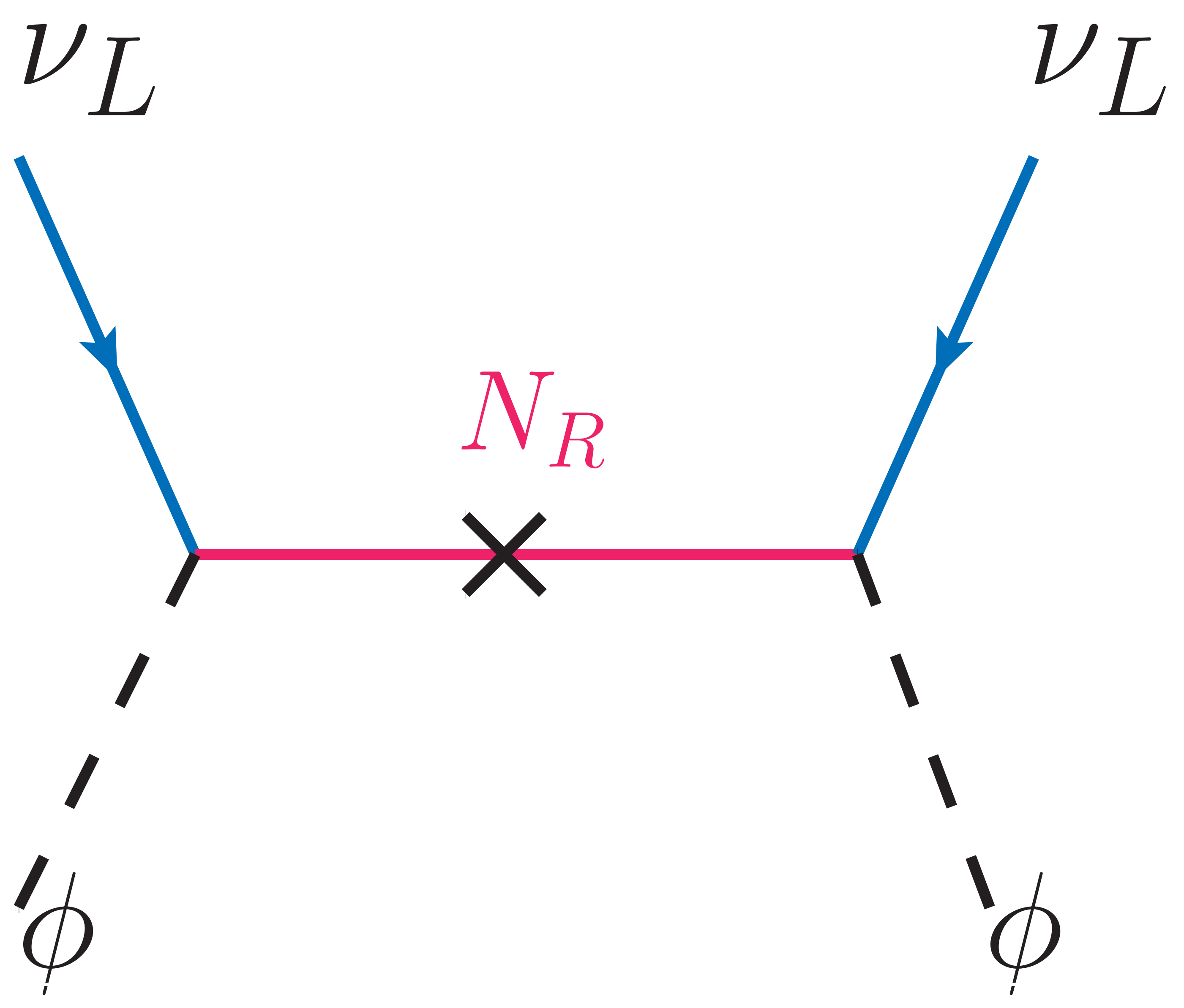
第二类跷跷板

E. Ma PRL 81(1998) 1171

- Type I: Right-handed singlet fermion N_R
- Type II: Triplet Higgs Δ
- Type III: Right-handed triplet fermion Σ

第一类型跷跷板机制

加入三代单态右手中微子 N_R^i (至少两代)



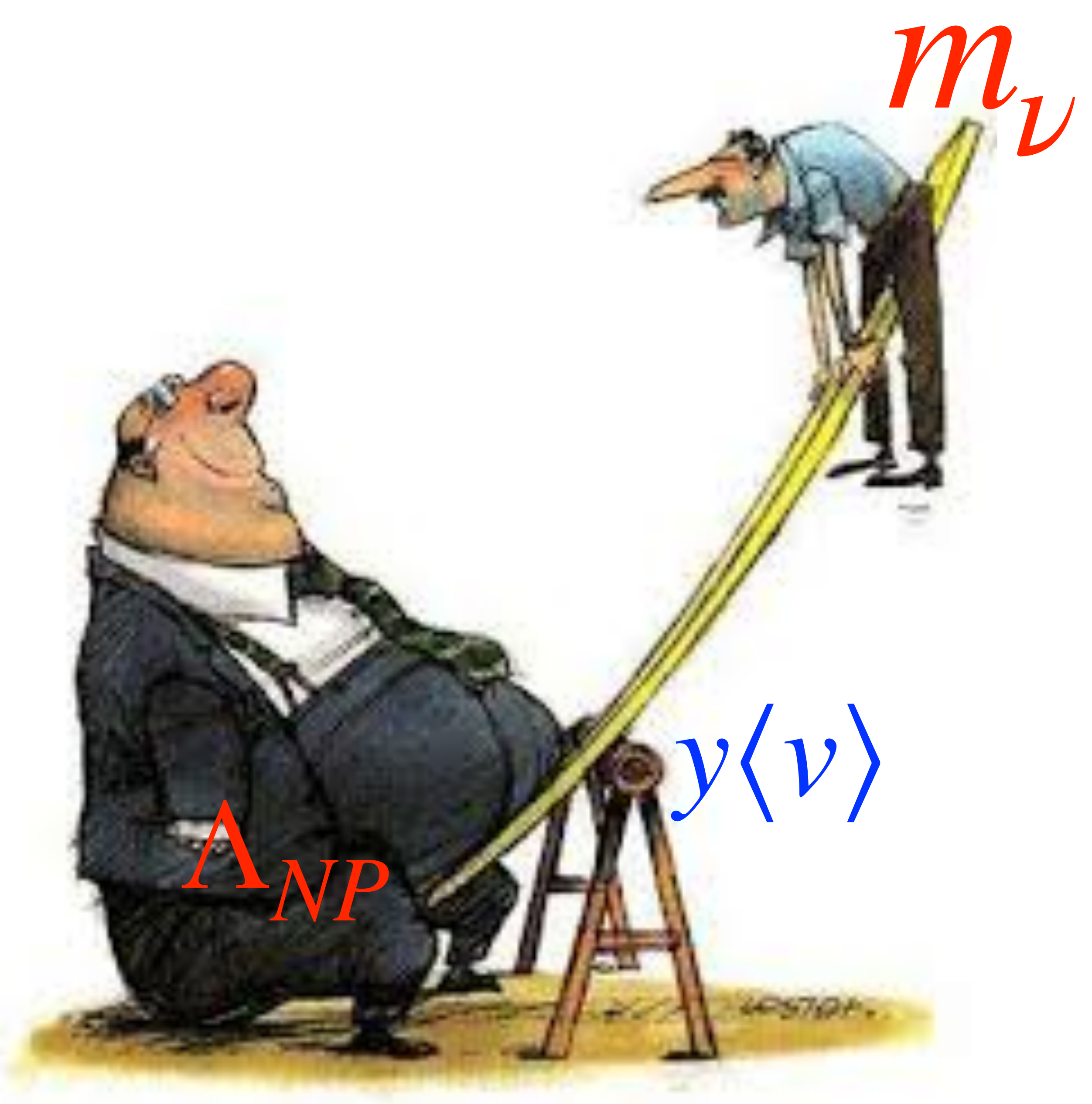
Type I seesaw mechanism

$$-\mathcal{L} = y\bar{L}_L\tilde{\Phi}N_R + \frac{1}{2}M_N\bar{N}_R^c N_R + h.c$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix}$$

$$m_\nu \sim \frac{m_D m_D}{M_N} \sim \frac{y^2\langle\phi\rangle^2}{M_N}$$

$$y^2 \sim 10^{-14}\frac{M_N}{\text{GeV}}$$

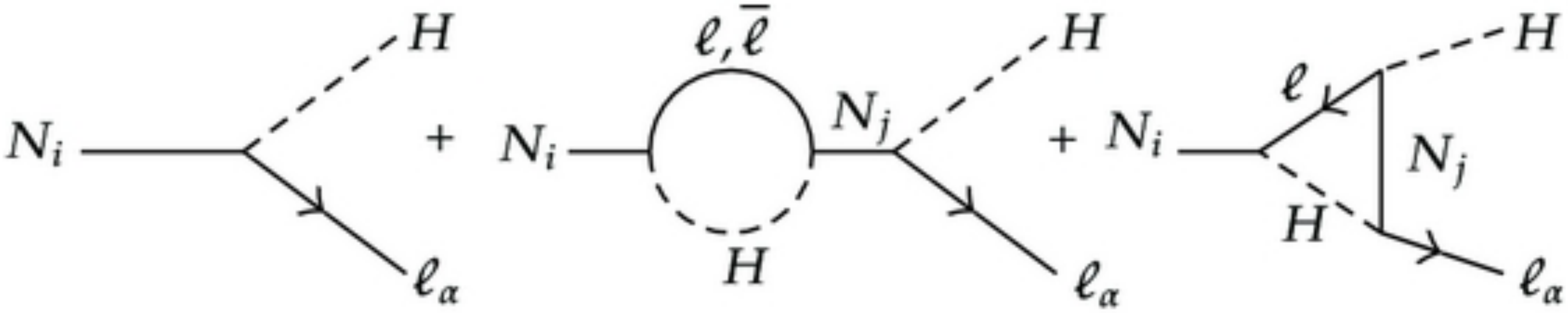


轻子生成机制 Leptogenesis

Baryon asymmetry in the Universe

$$\eta_B = \frac{n_{B-\bar{B}}}{n_\gamma} \sim 10^{-10}$$

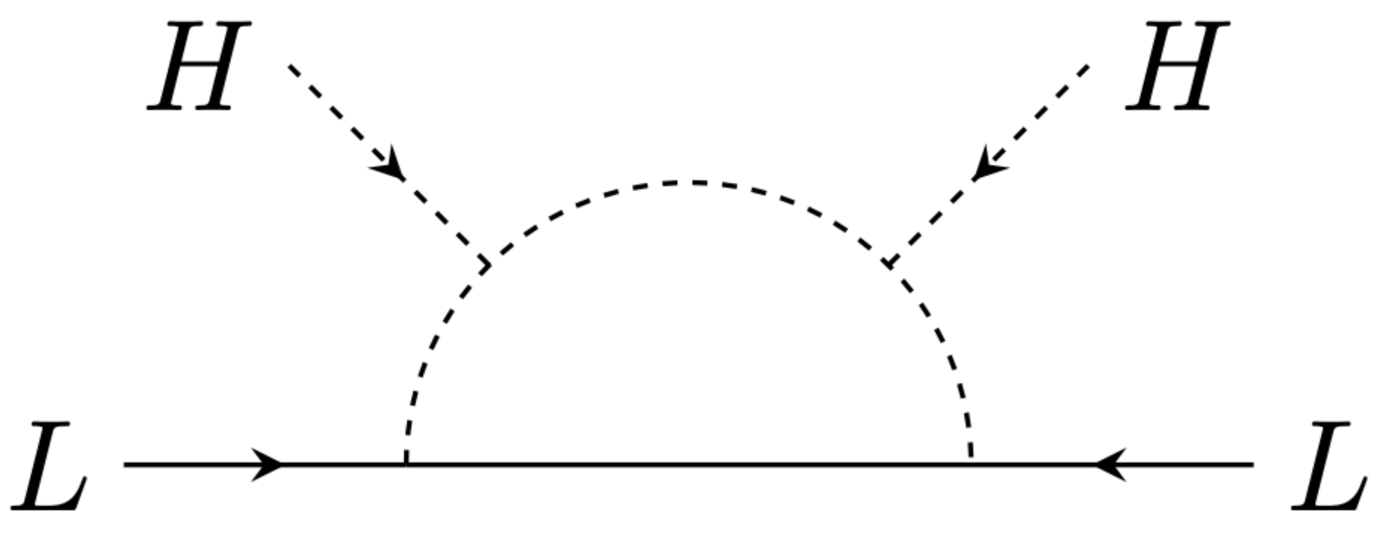
Leptogenesis



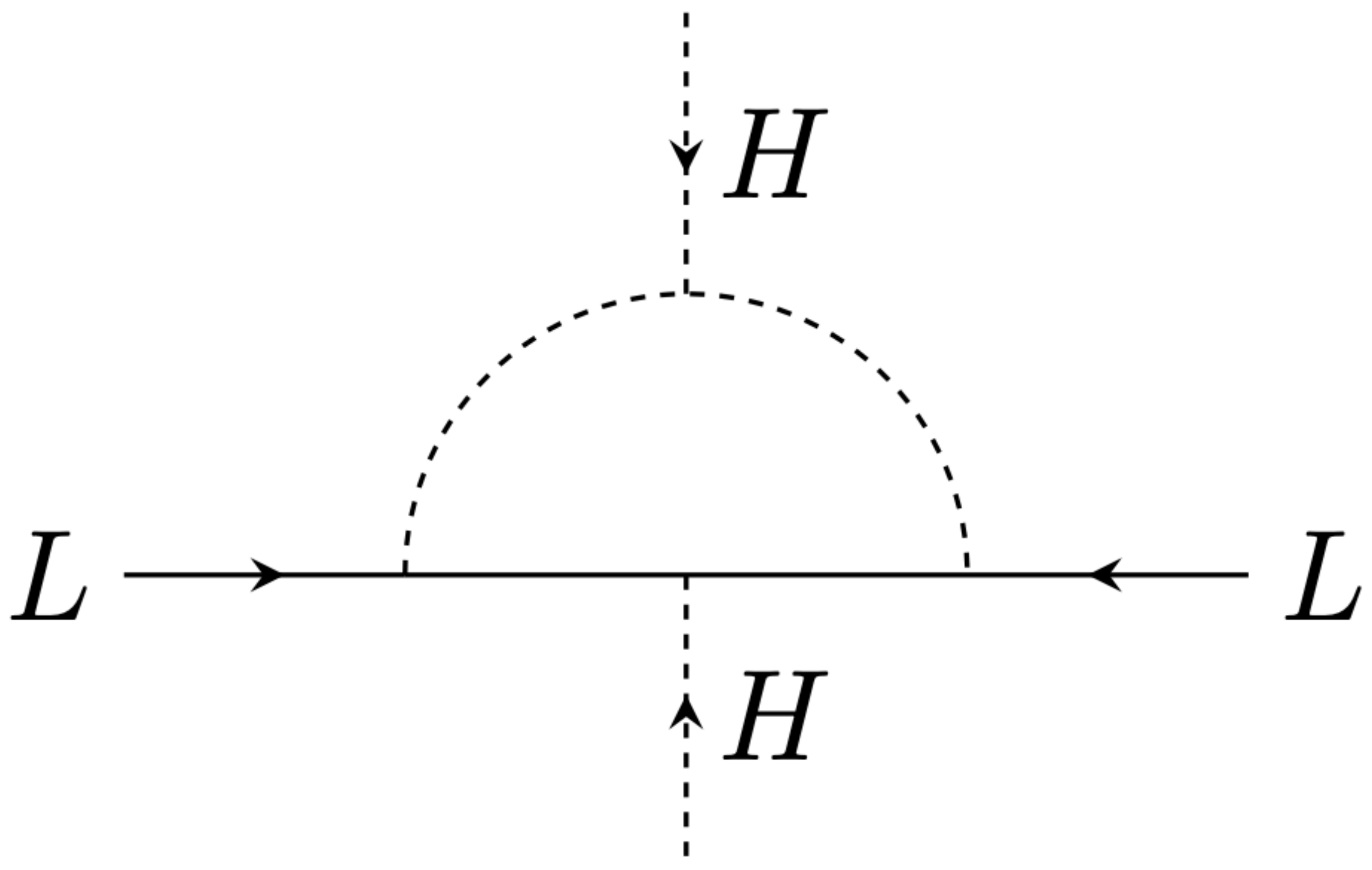
通过重的右手中微子衰变退耦产生轻子数，并转化为重子数，解释重子起源

one stone two birds

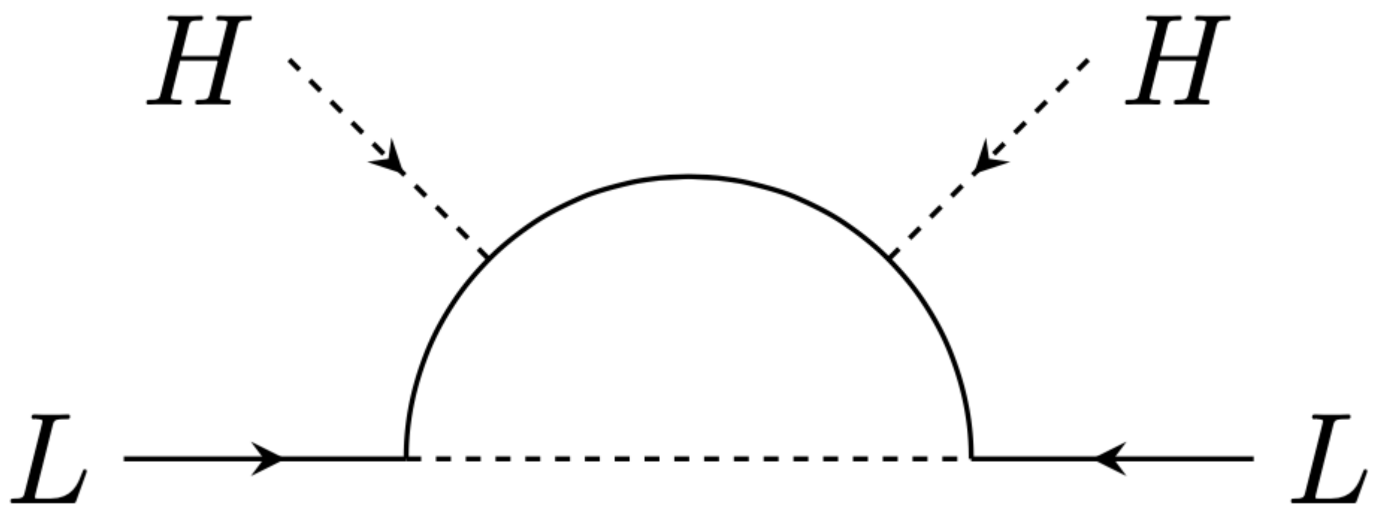
Seesaw mechanism: one-loop level



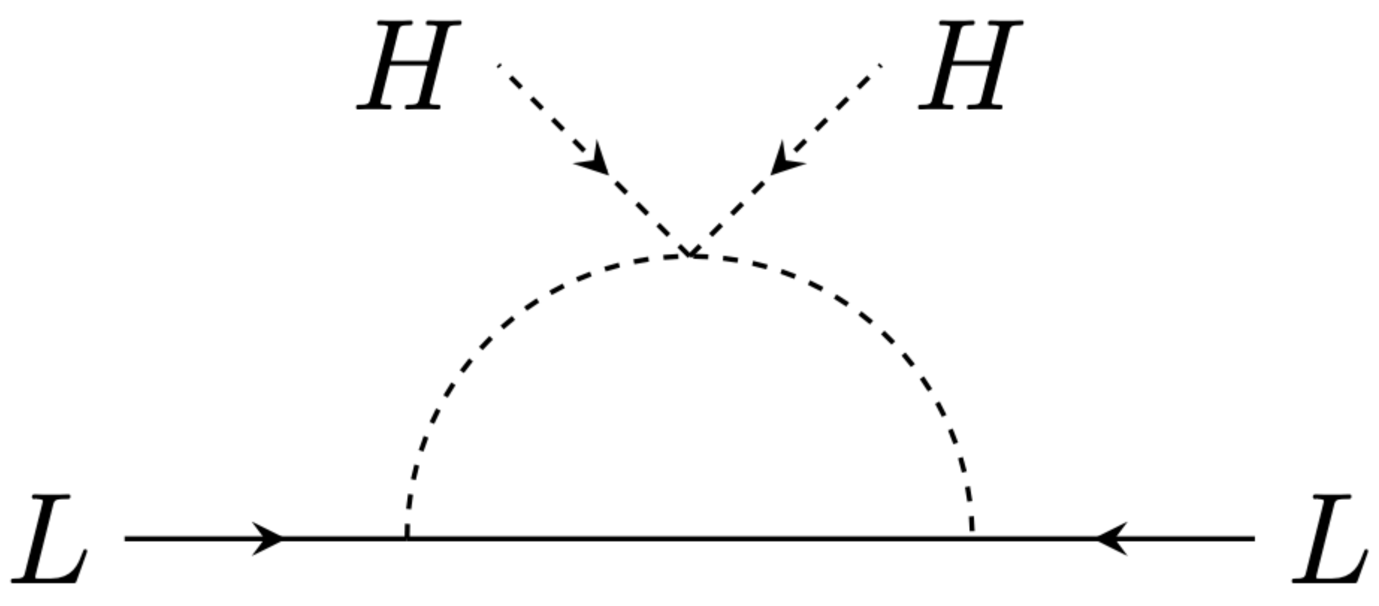
T-1-i



T-1-ii

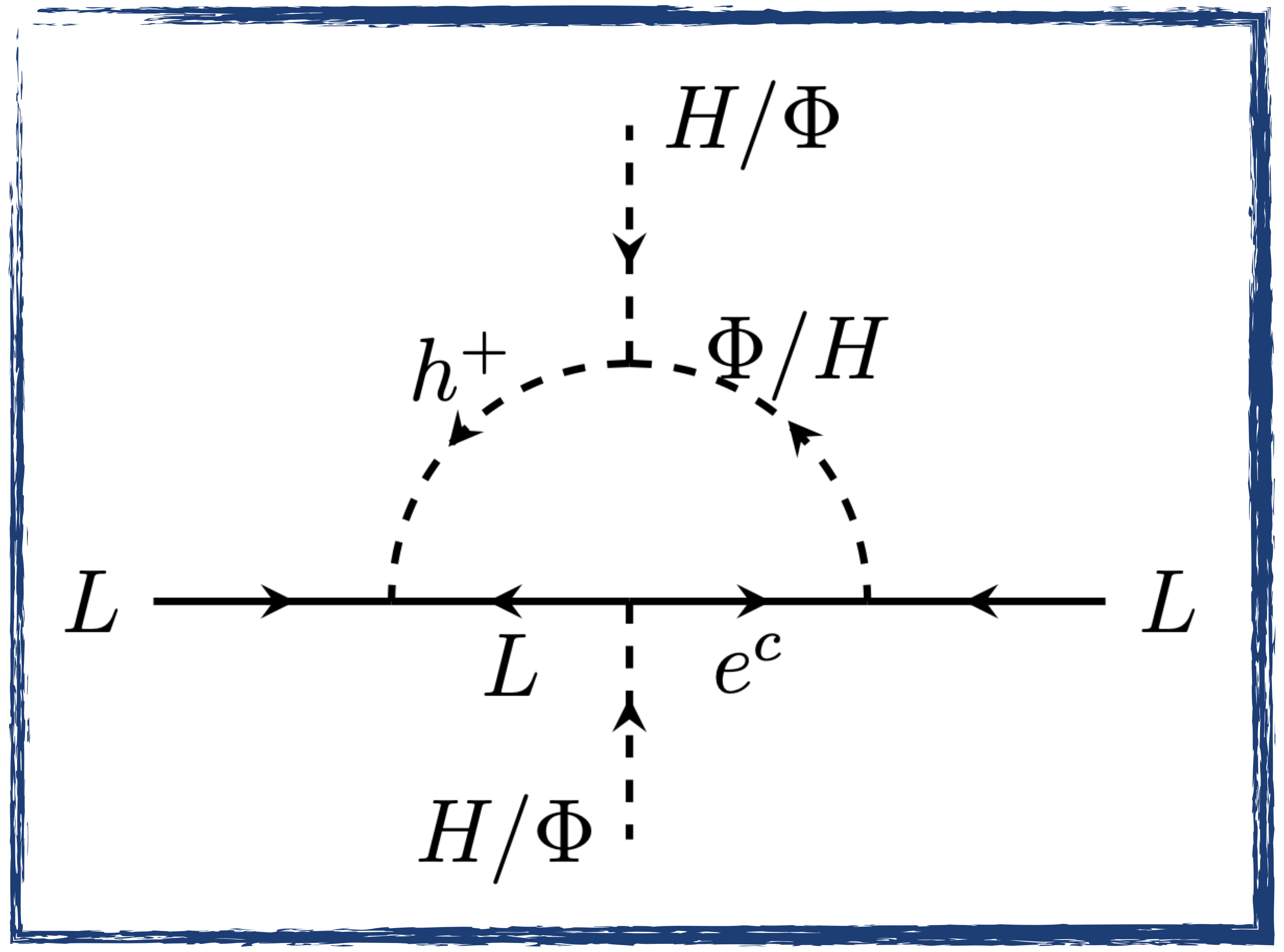


T-1-iii

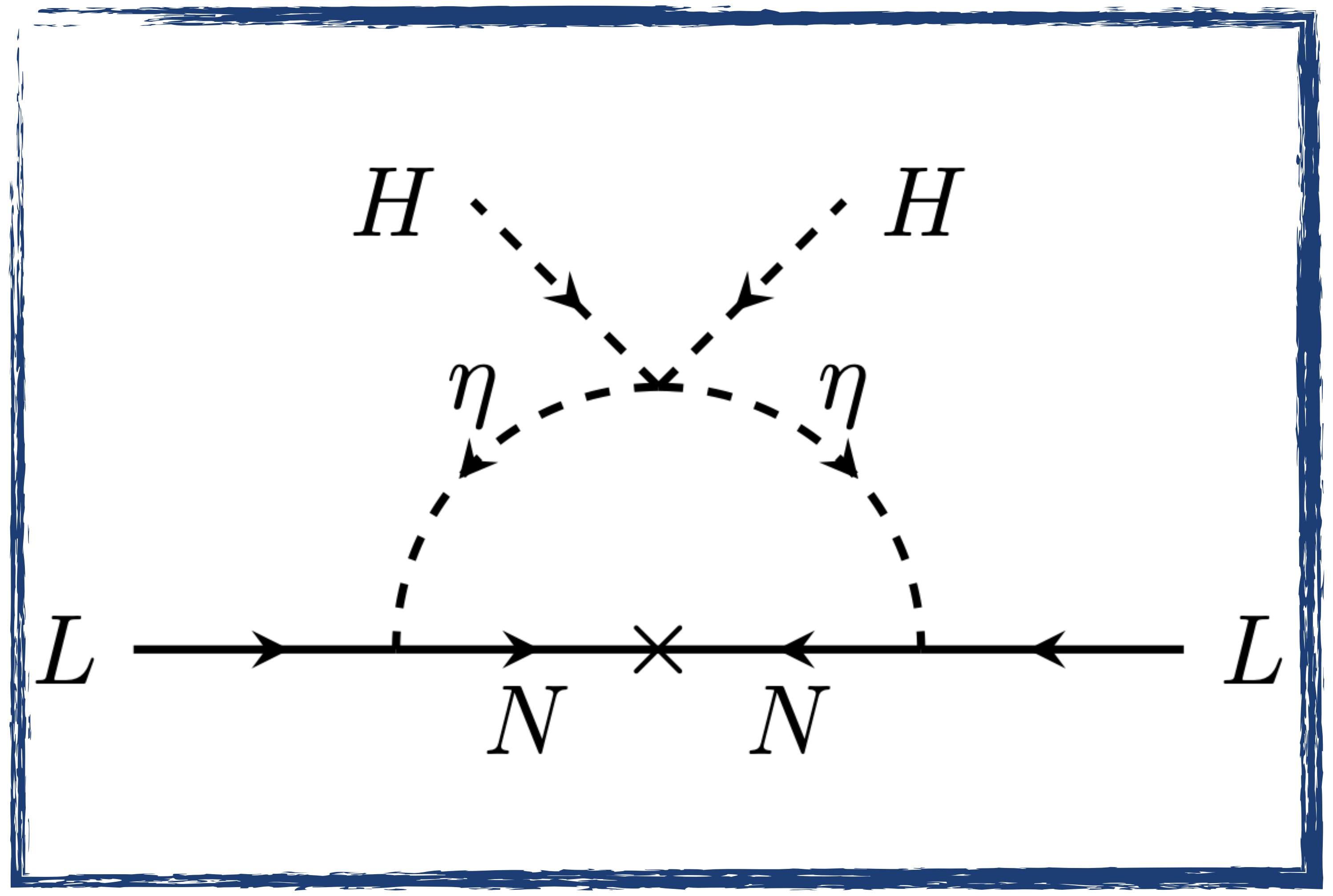


T-3

1204.5862 2105.01896



Zee model



Ma/scotogenic model

Seesaw mechanism: two-loop level

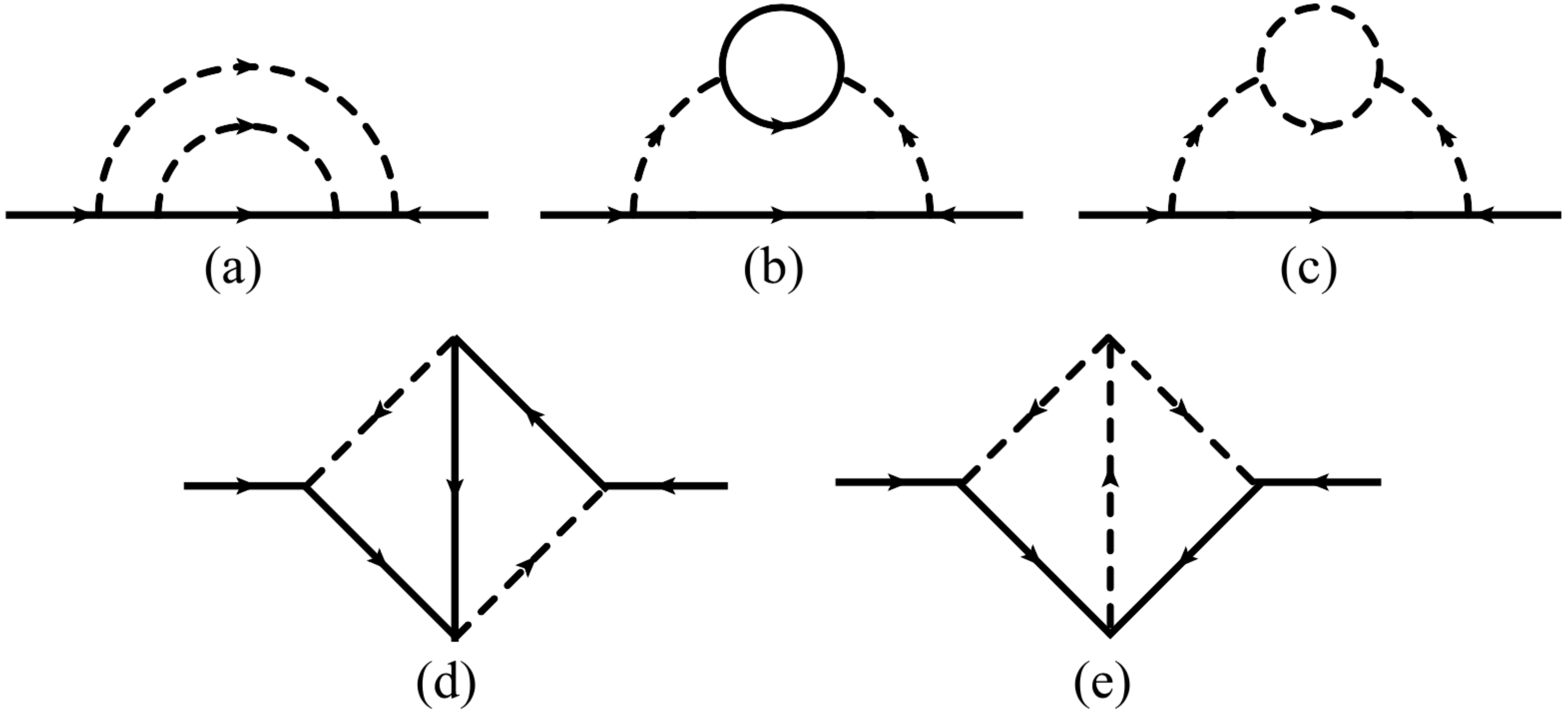
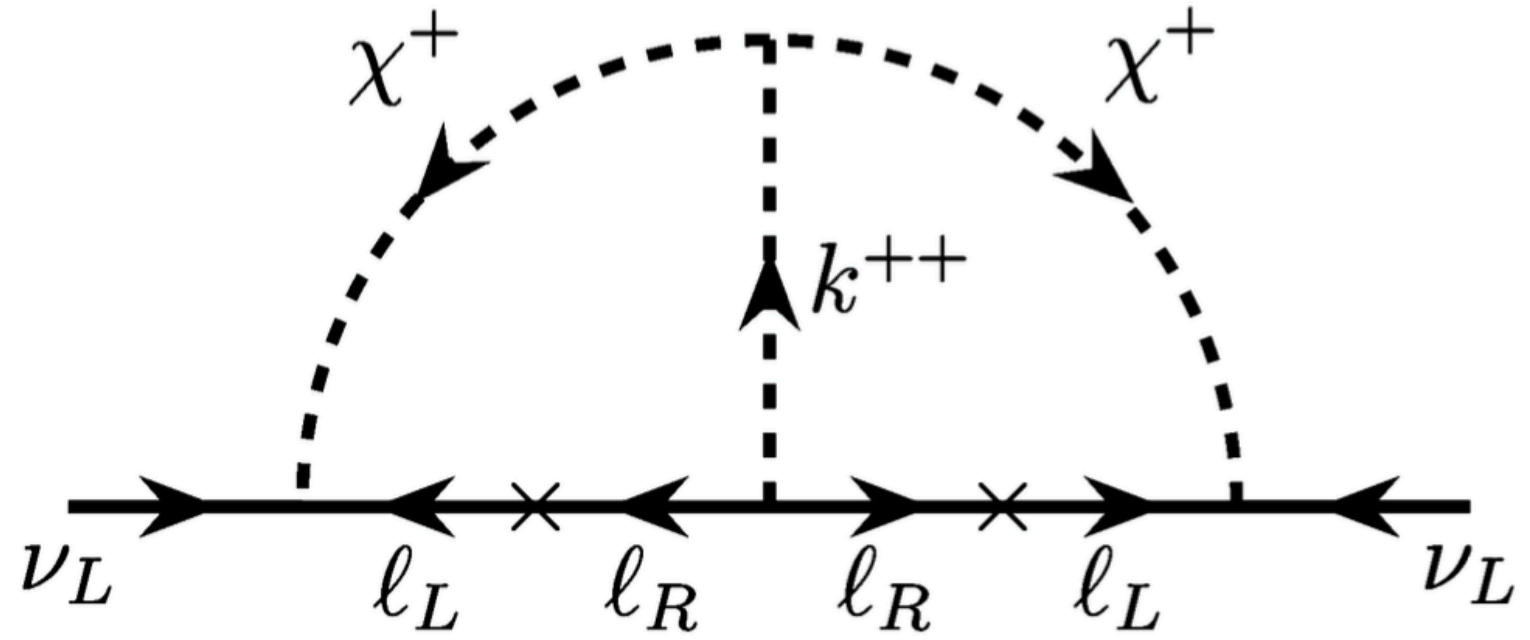


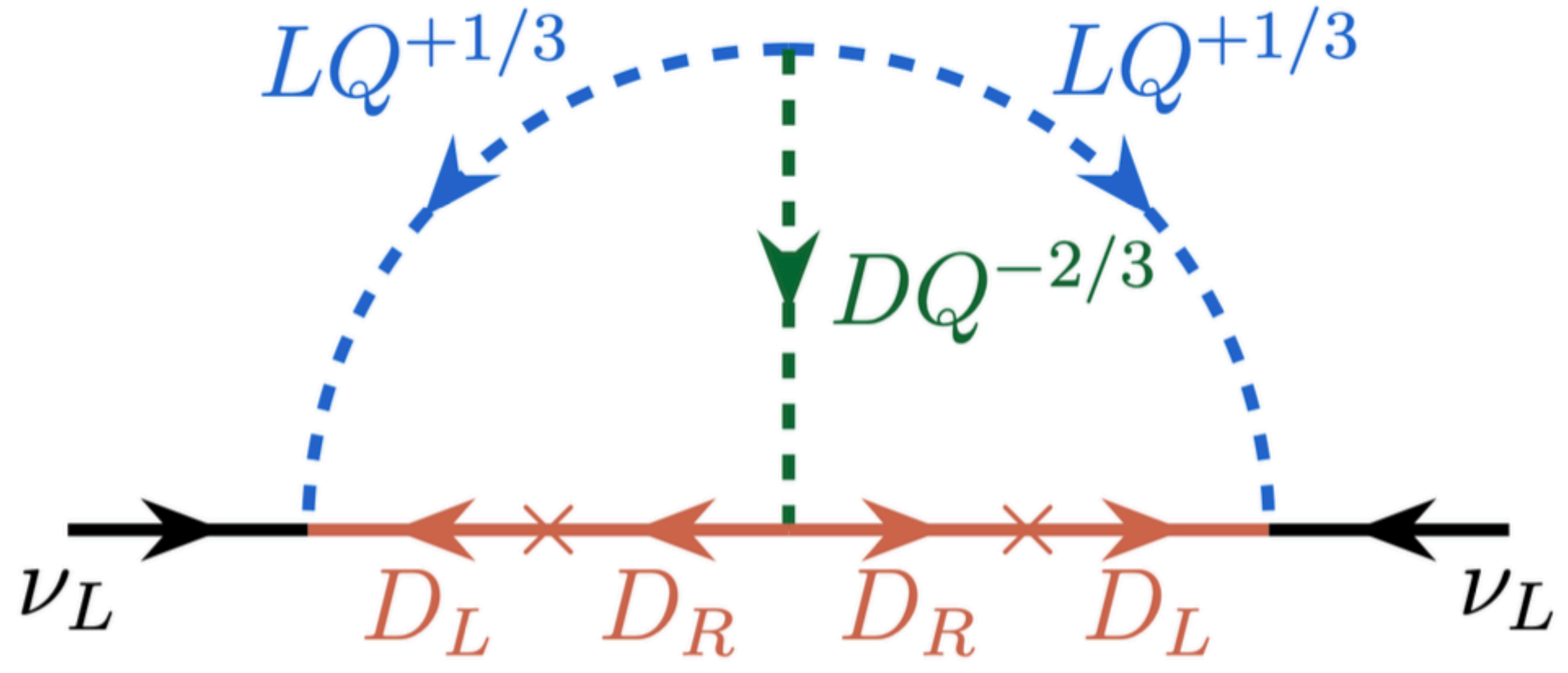
Fig. 1. Two-loop skeleton diagrams for neutrino mass before the Higgs insertions.

PLB779(2018)430

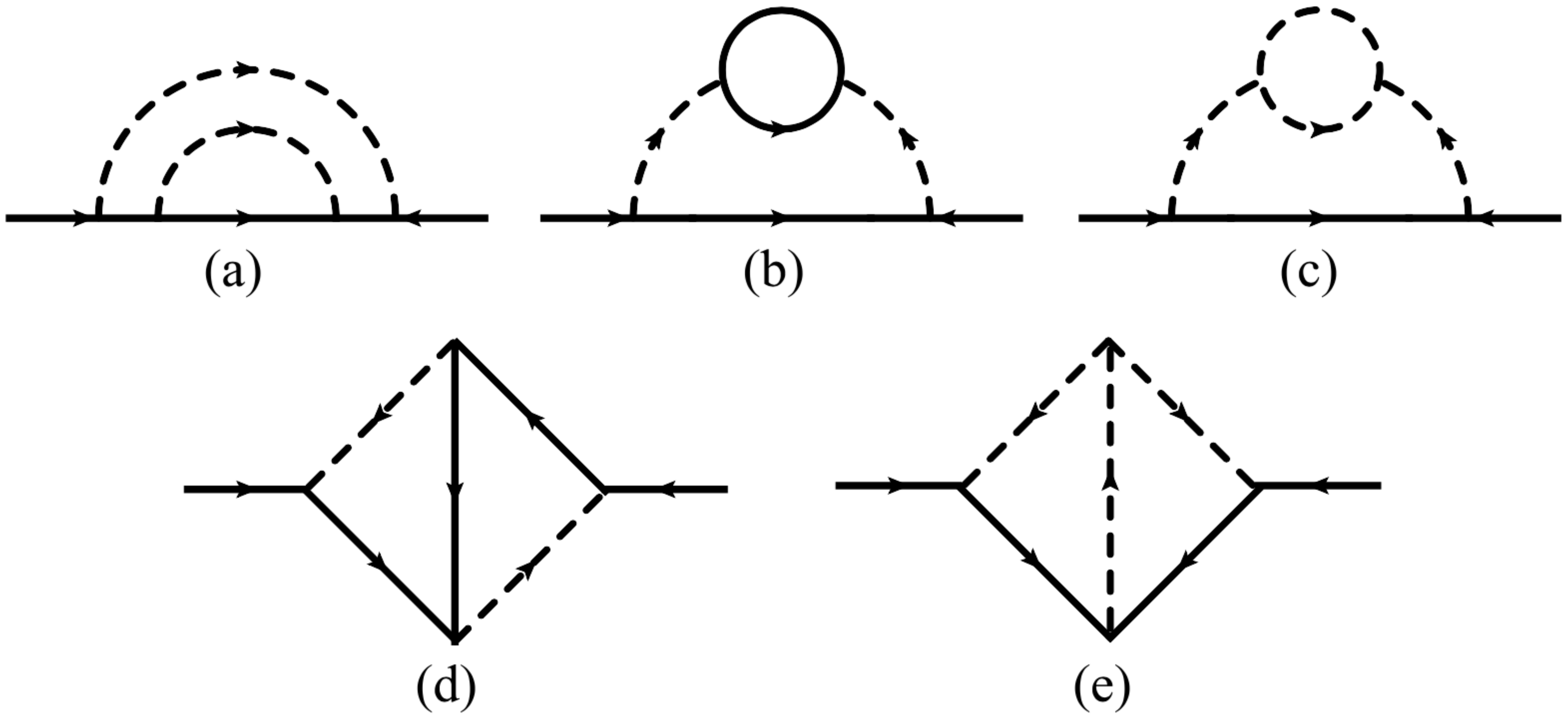
Zee, 1986; Babu, 1988



M. Kohda, H. Sugiyama,
K. Tsumura. 2012.5622



Seesaw mechanism: two-loop level



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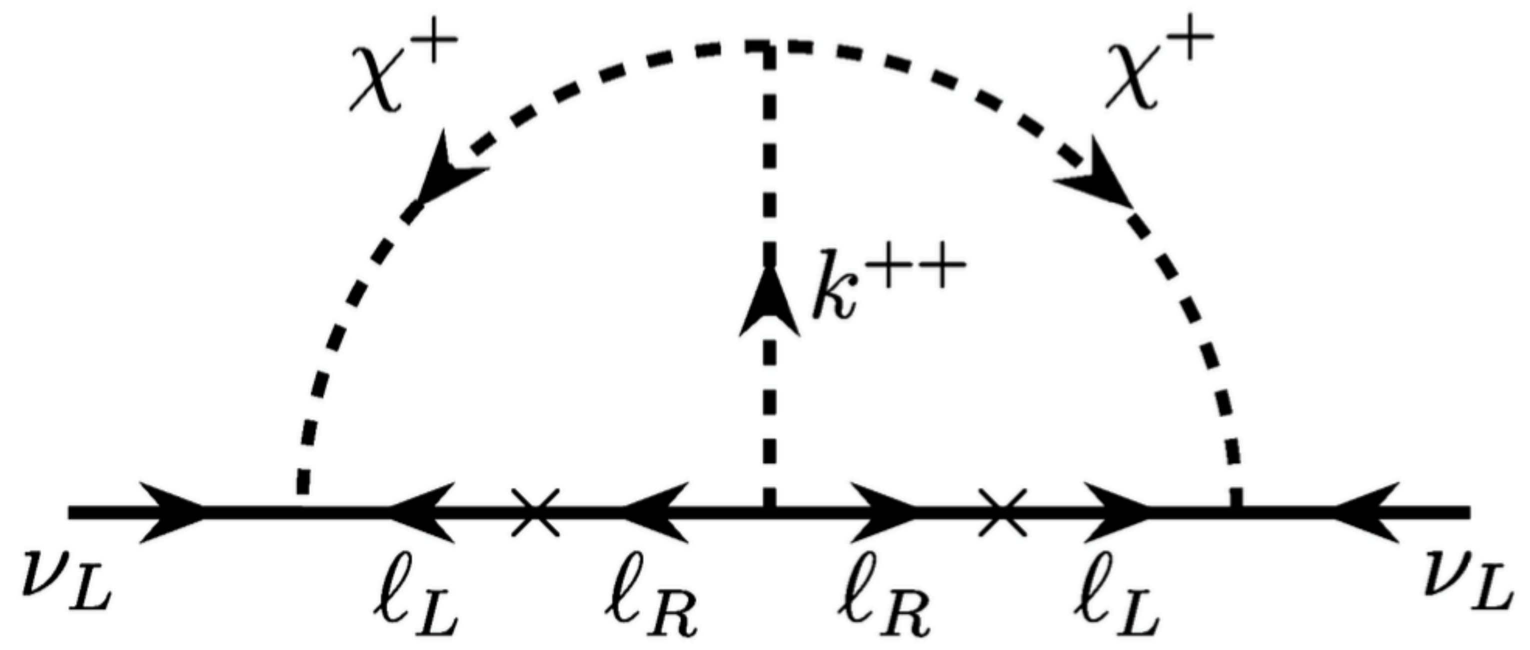

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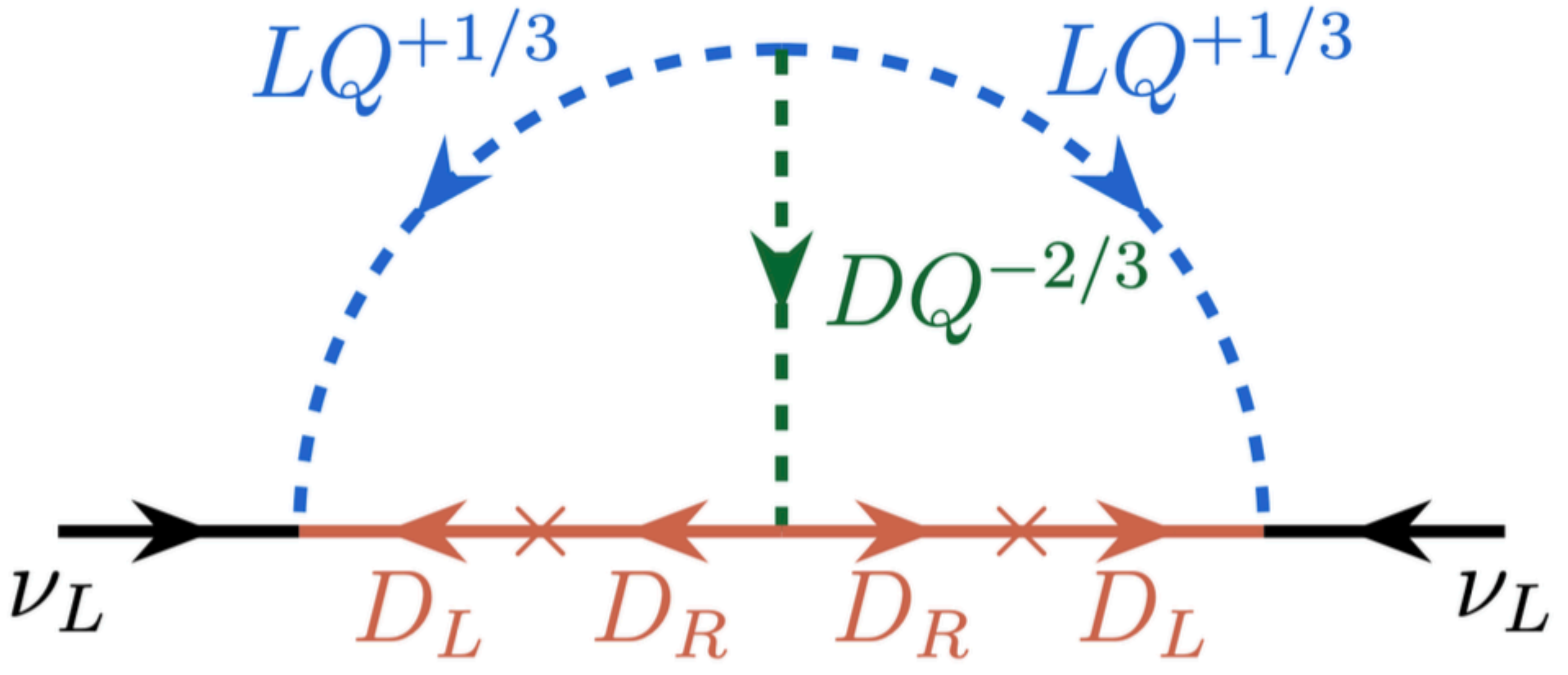
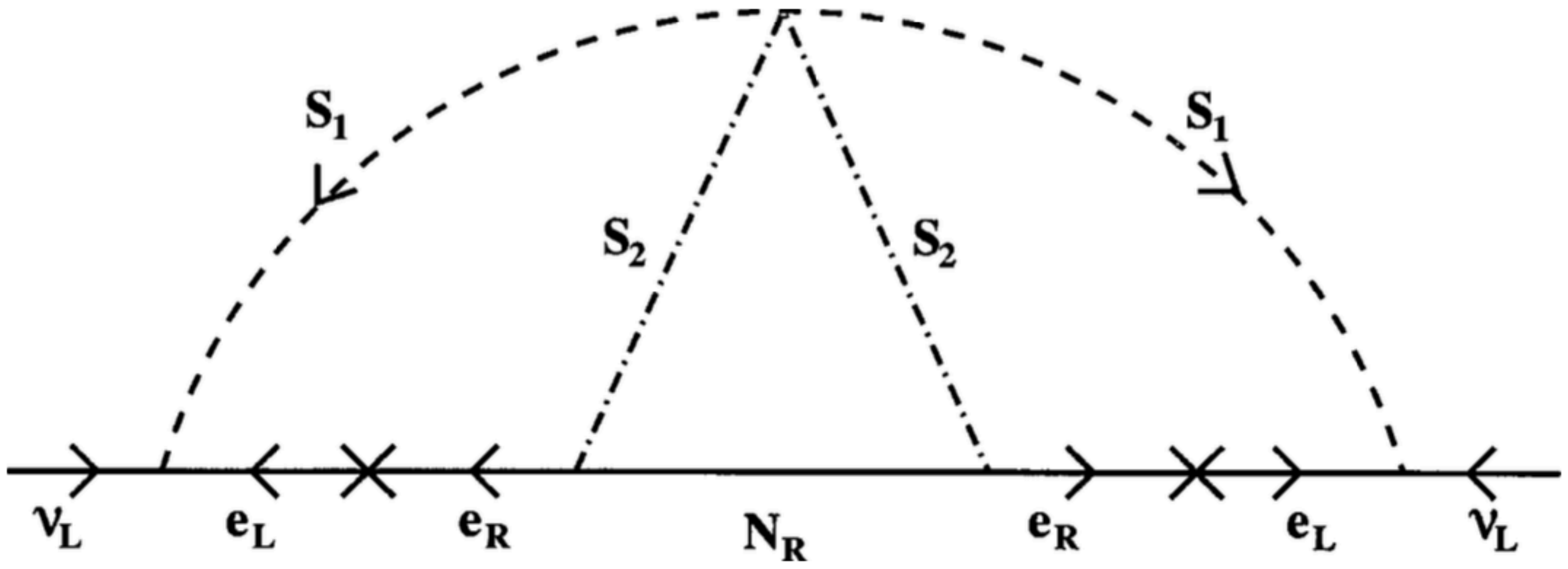
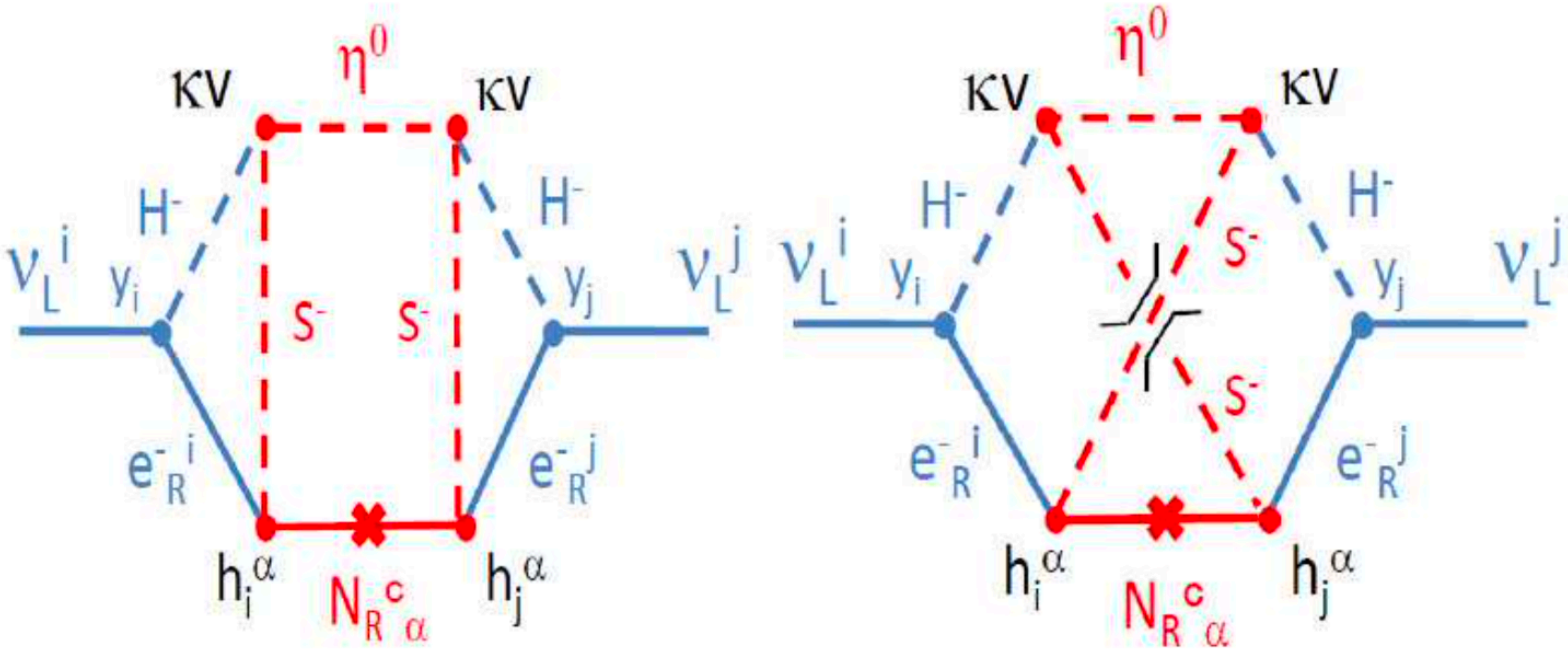


seesaw mechanism: three-loop level



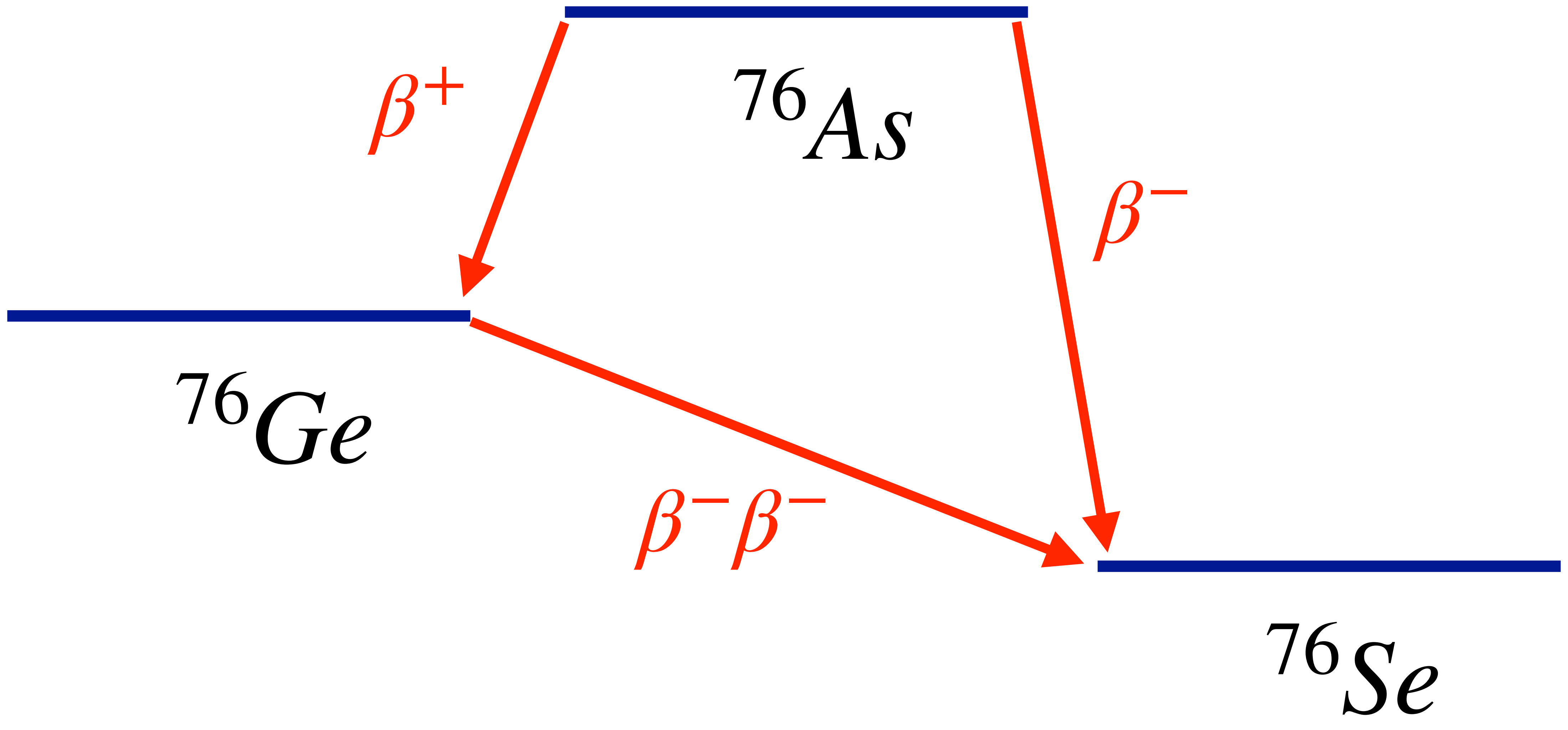
KNT model PRD 67 (2003) 085002

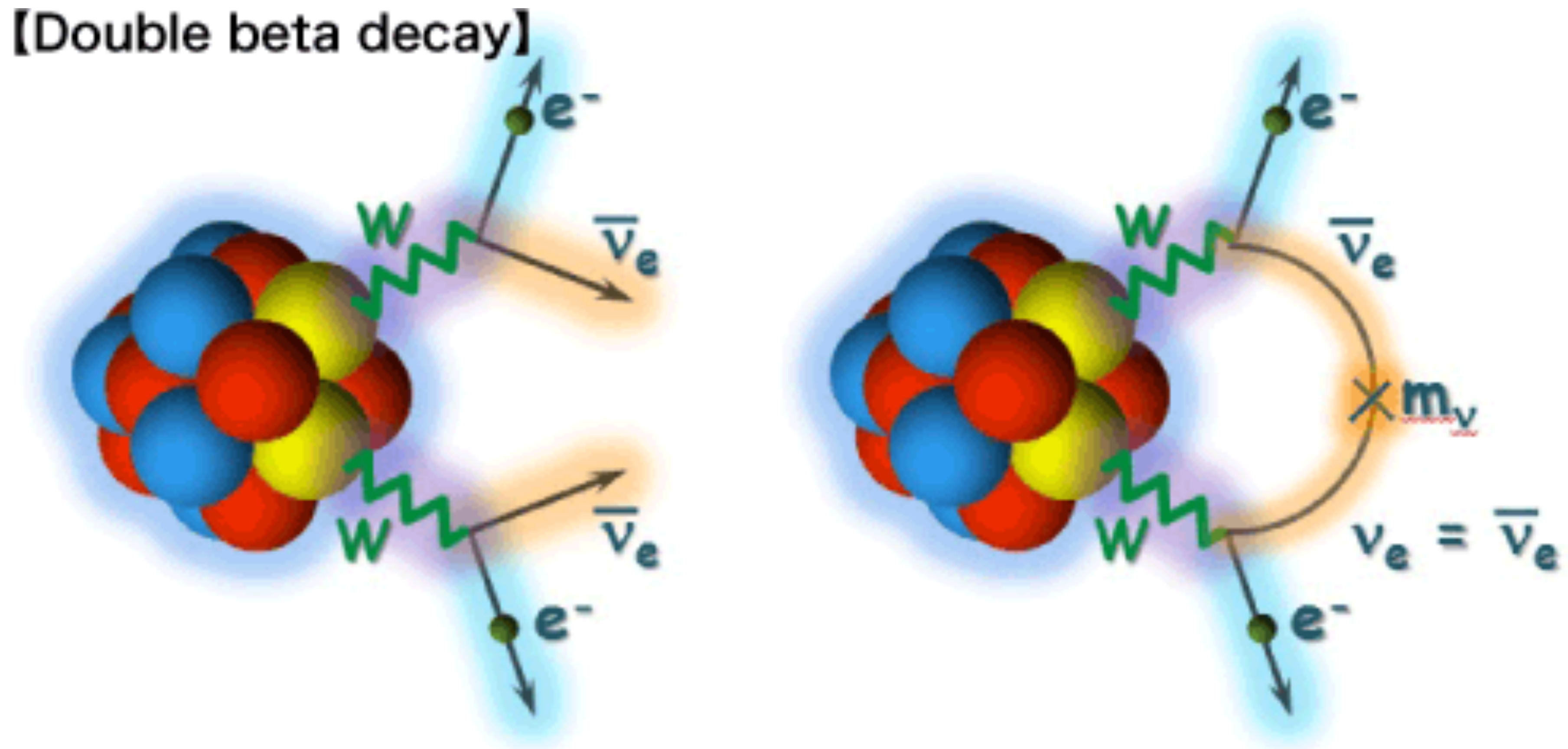


	Q^i	u_R^i	d_R^i	L^i	e_R^i	Φ_1	Φ_2	$S^\pm$	η	N_R^α
Z_2 (exact)	+	+	+	+	+	+	+	−	−	−
$\tilde{Z}_2$ (softly broken)	+	−	−	+	+	+	−	+	−	+

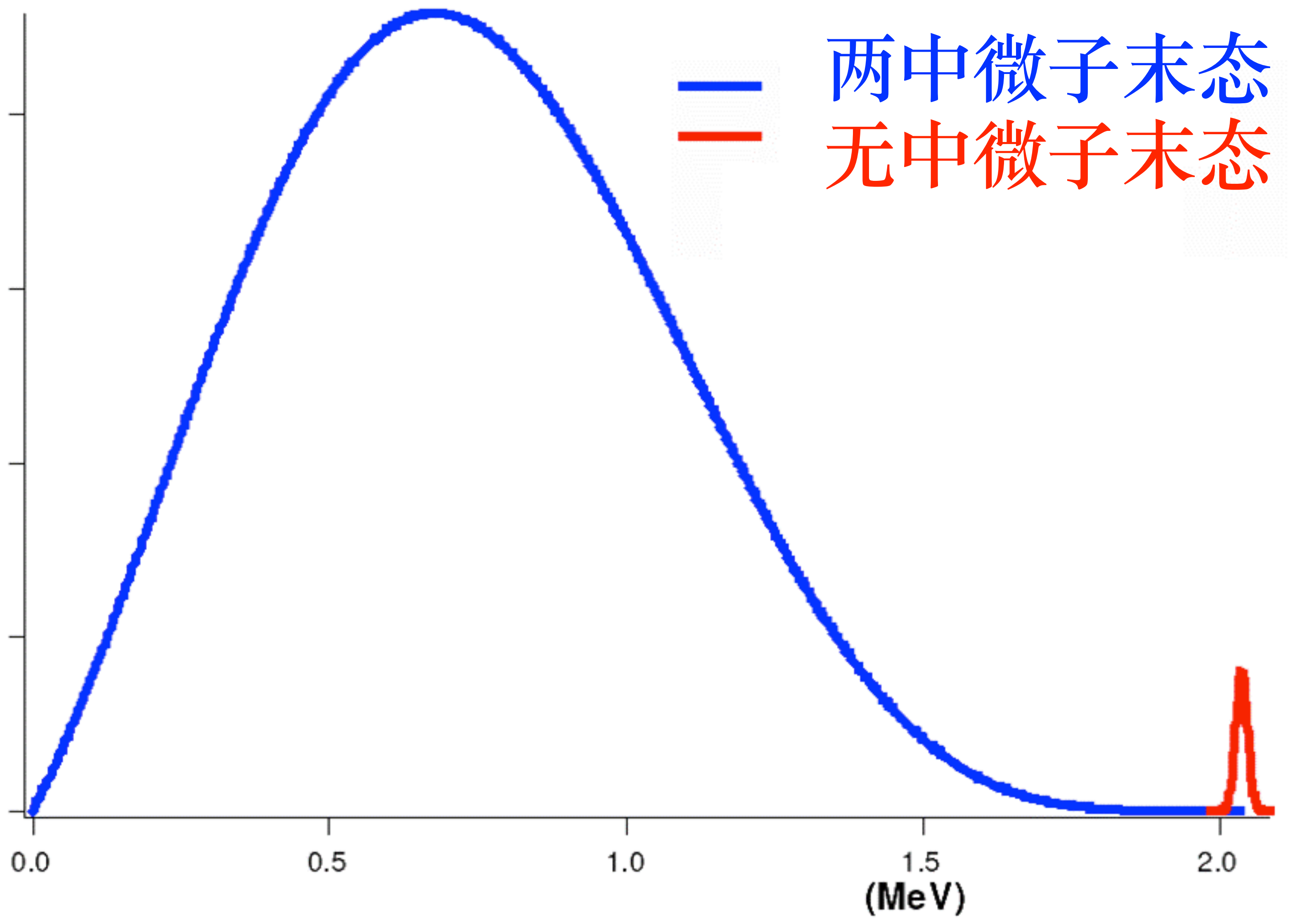
AKS model PRL 102 (2009) 051805

Neutrinoless double beta decay



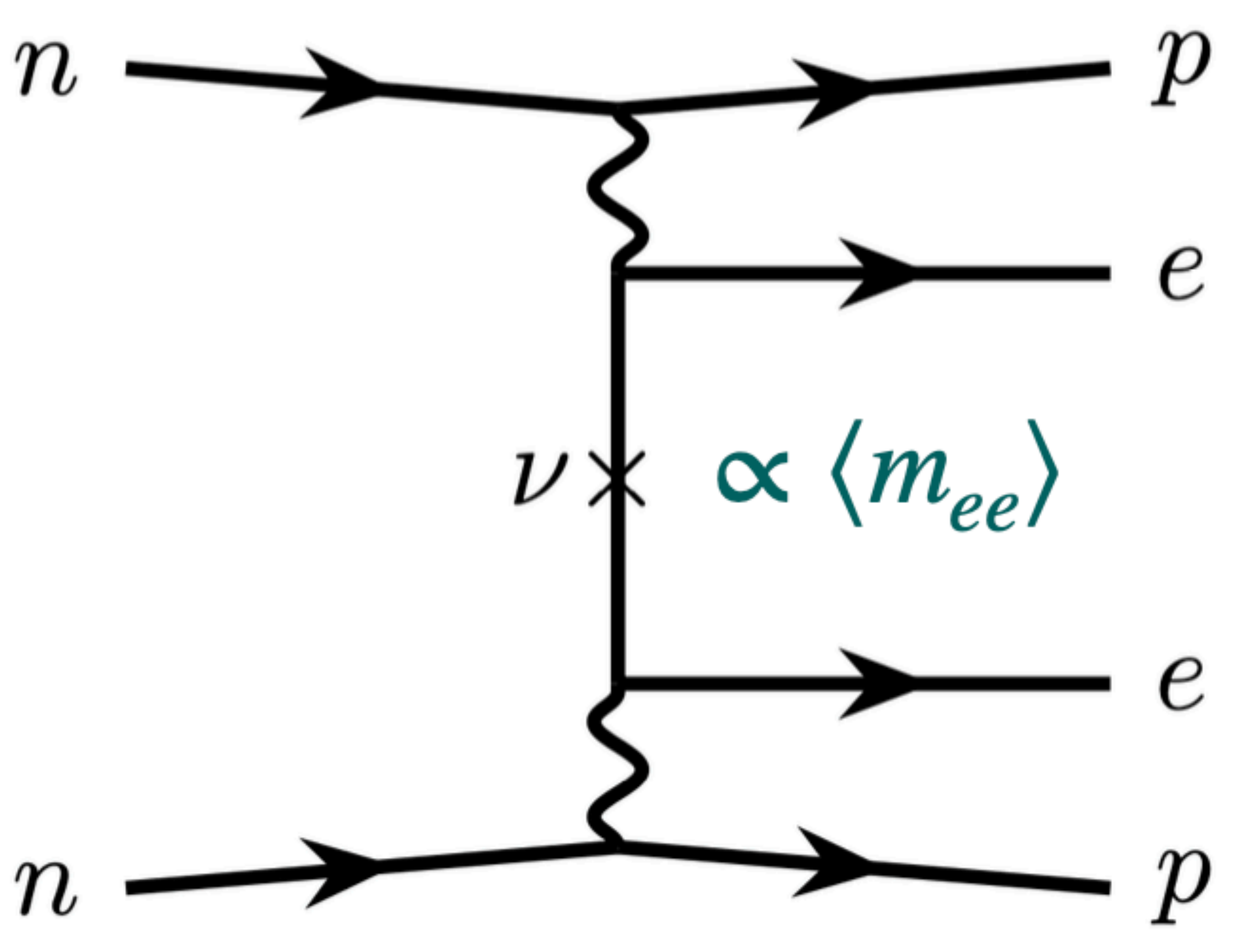


有中微子双beta衰变　　无中微子双beta衰变



两个电子能量总和

Neutrinoless double beta decay

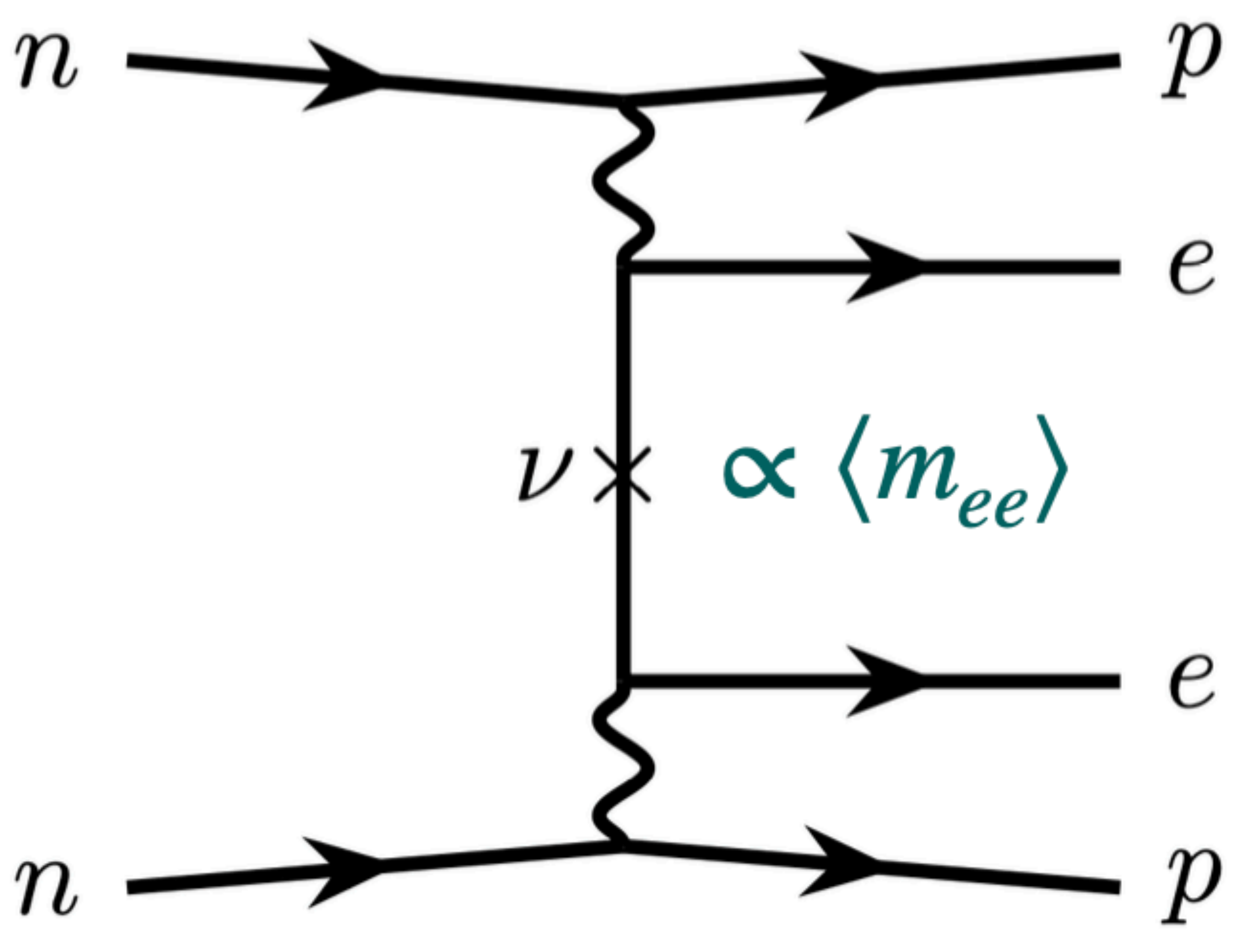


standard neutrino exchange

$$(T_{1/2}^{0\nu\beta\beta})^{-1} = G_{0\nu}\,|M_{0\nu}|^2 \frac{|\langle m_{ee}\rangle|}{m_e^2}$$

$$|\langle m_{ee}\rangle| = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$

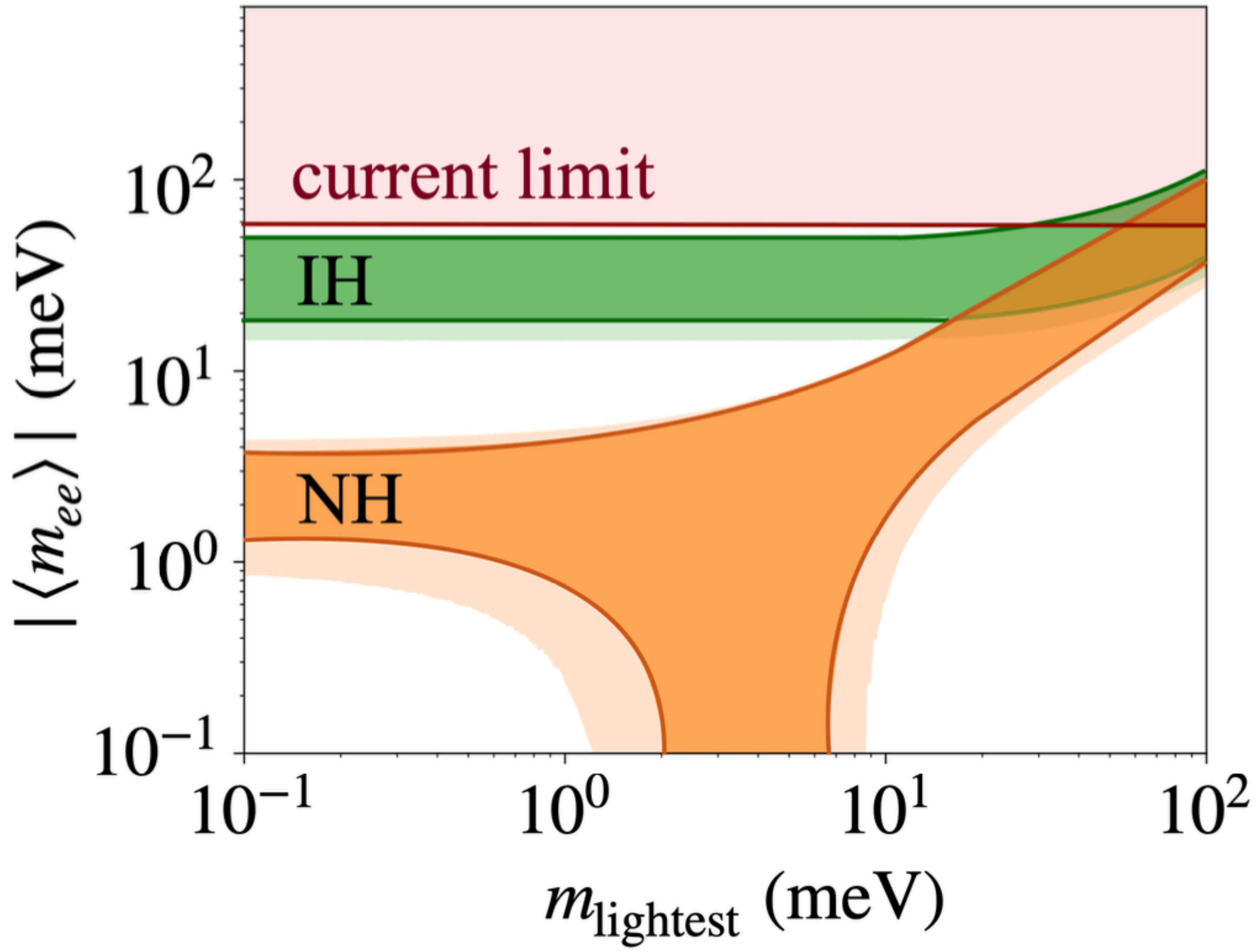
Neutrinoless double beta decay



standard neutrino exchange

$$(T_{1/2}^{0\nu\beta\beta})^{-1} = G_{0\nu} |M_{0\nu}|^2 \frac{|\langle m_{ee} \rangle|}{m_e^2}$$

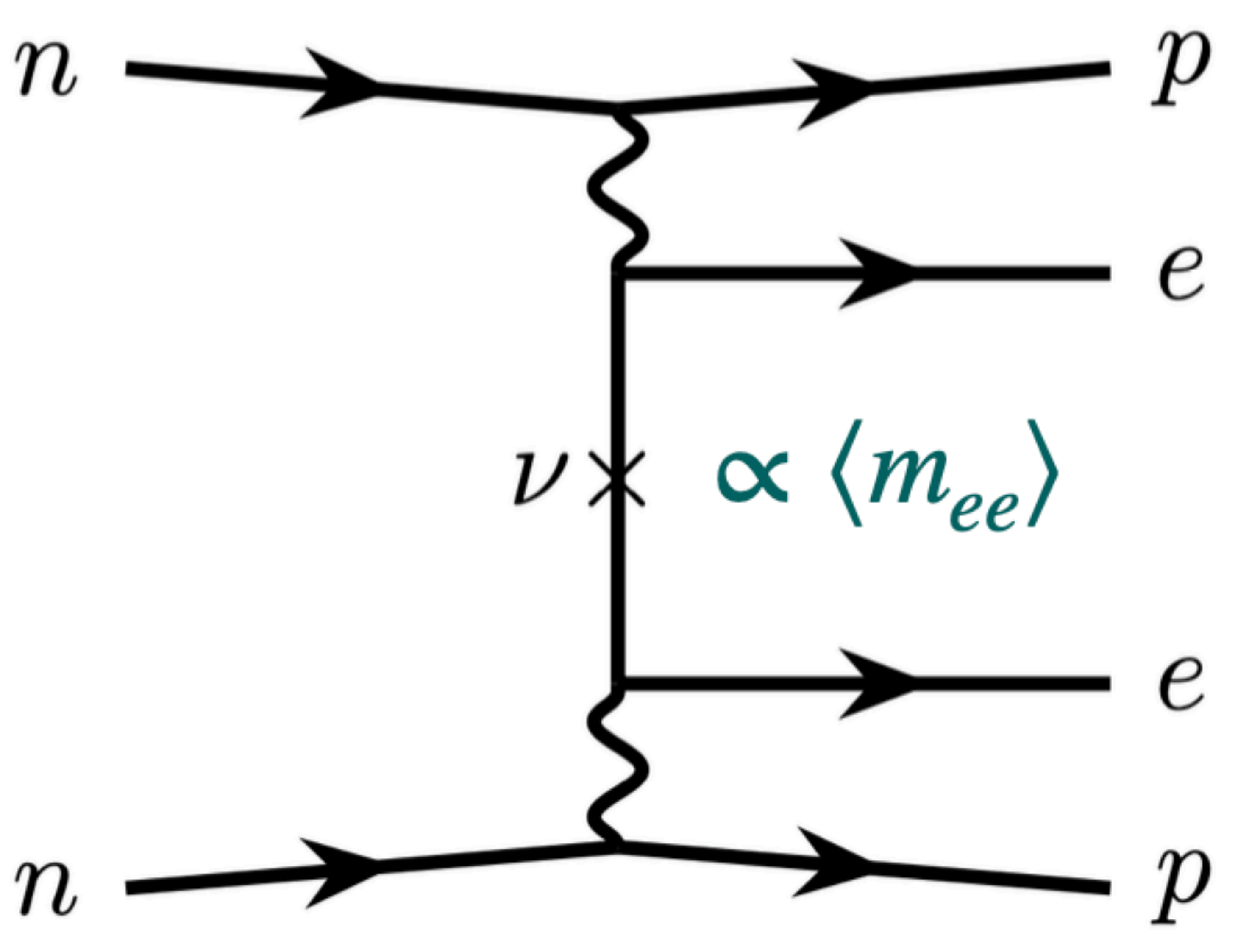
$$|\langle m_{ee} \rangle| = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$



KamLAND-Zen (^{136}Xe) $T_{1/2}^{0\nu\beta\beta} > 1.07 \times 10^{26}$ yrs

GERDA (^{76}Ge) $T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{26}$ yrs

Neutrinoless double beta decay



standard neutrino exchange

$$(T_{1/2}^{0\nu\beta\beta})^{-1} = G_{0\nu}\,|M_{0\nu}|^2 \frac{|\langle m_{ee}\rangle|}{m_e^2}$$

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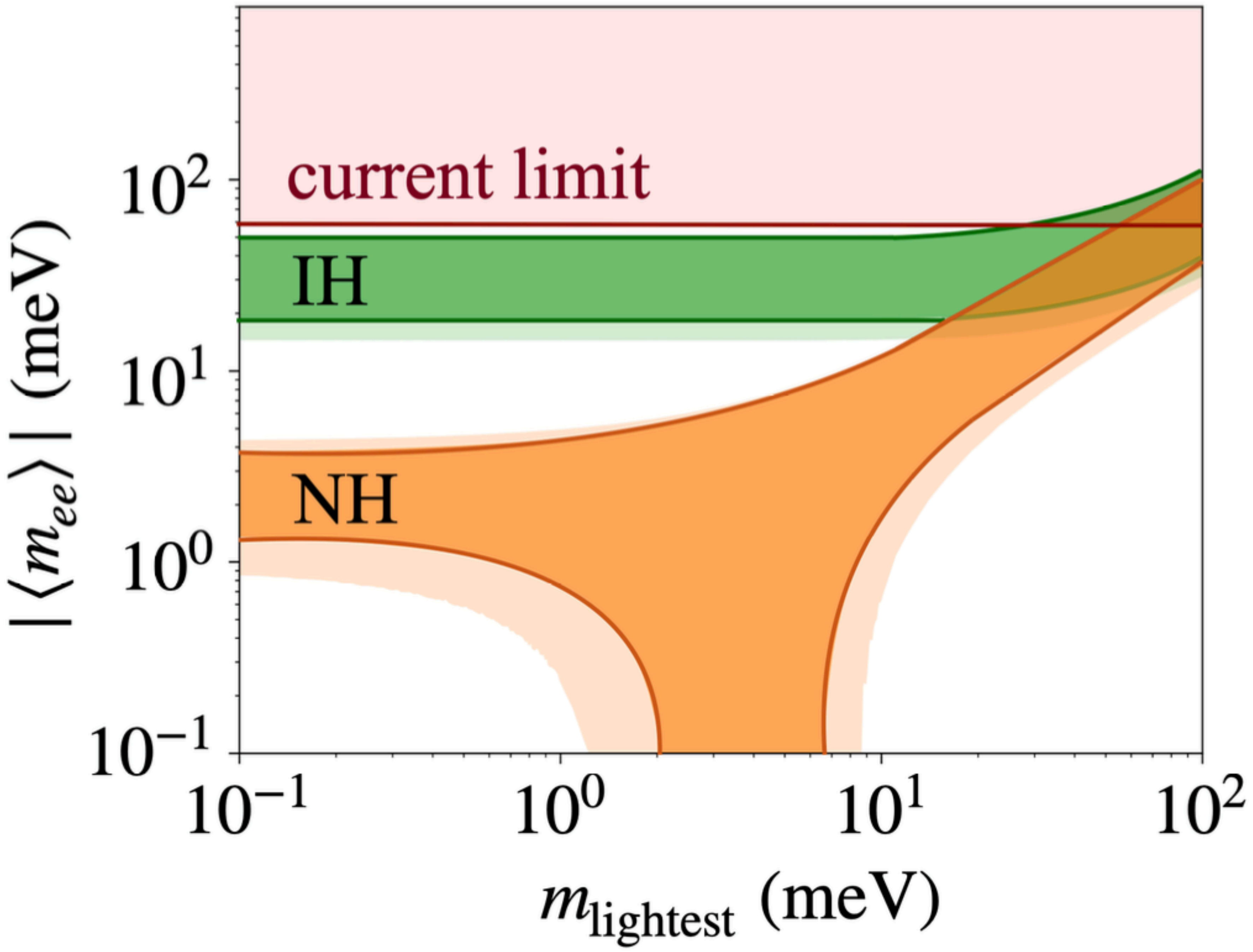

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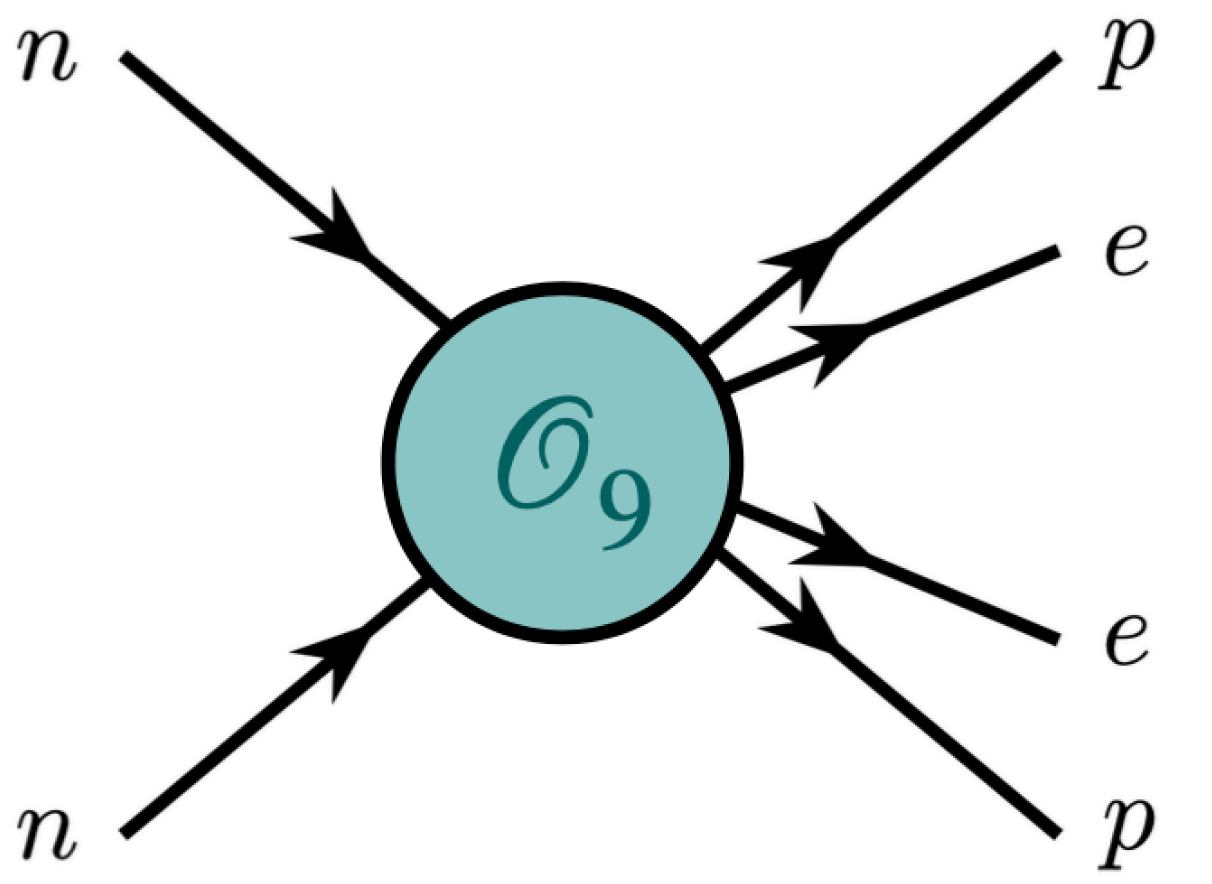
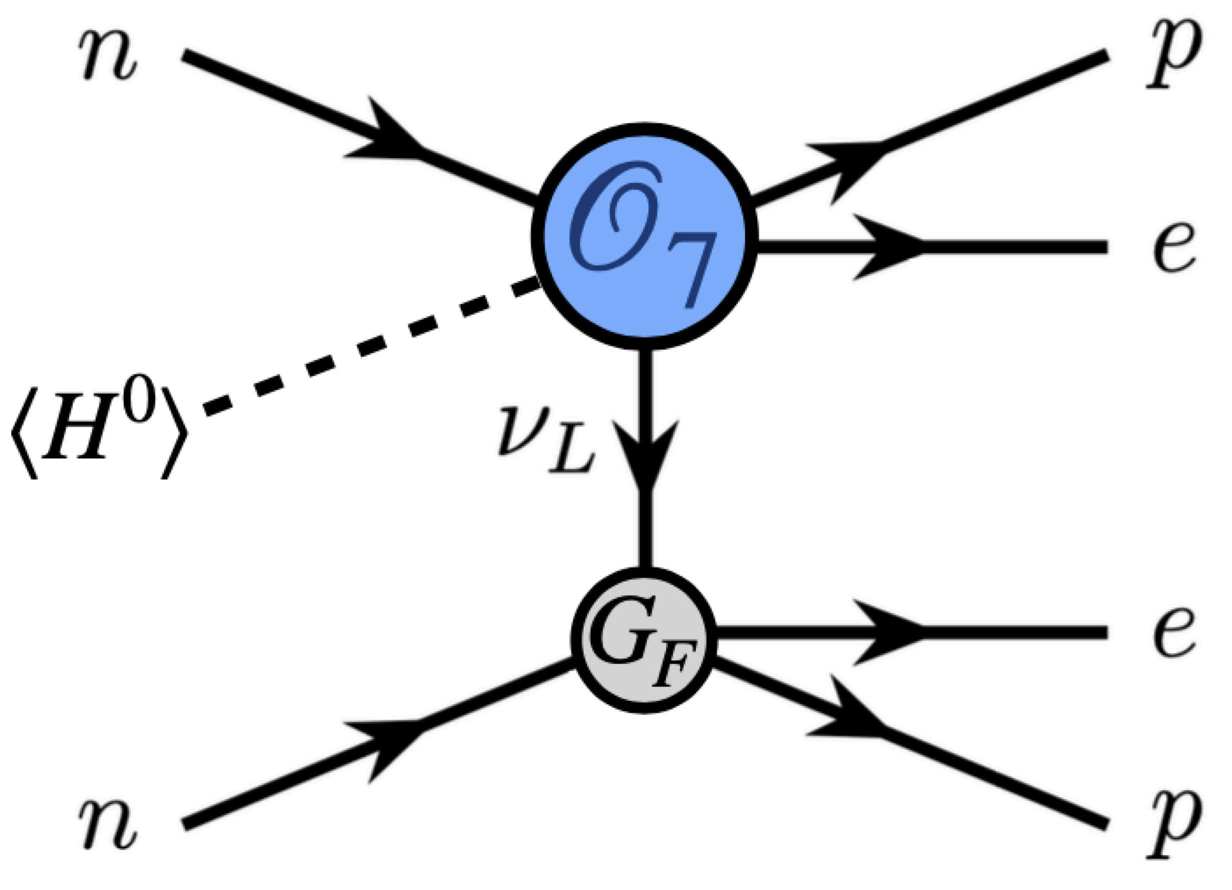


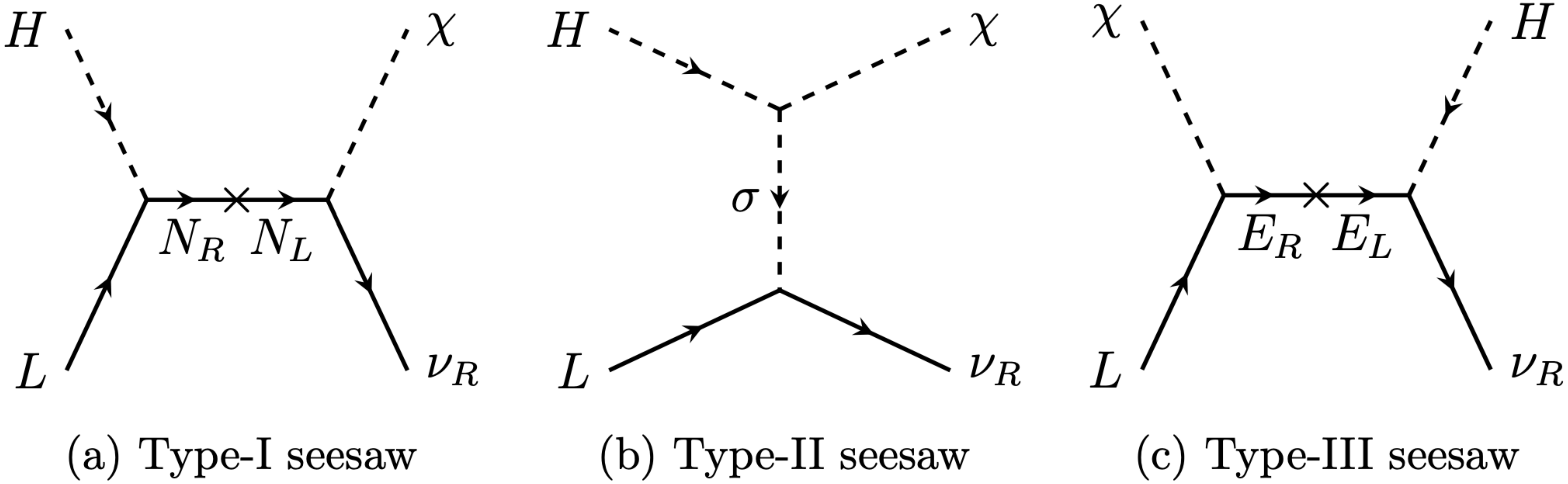
short-range



long-range

Dirac mass: seesaw

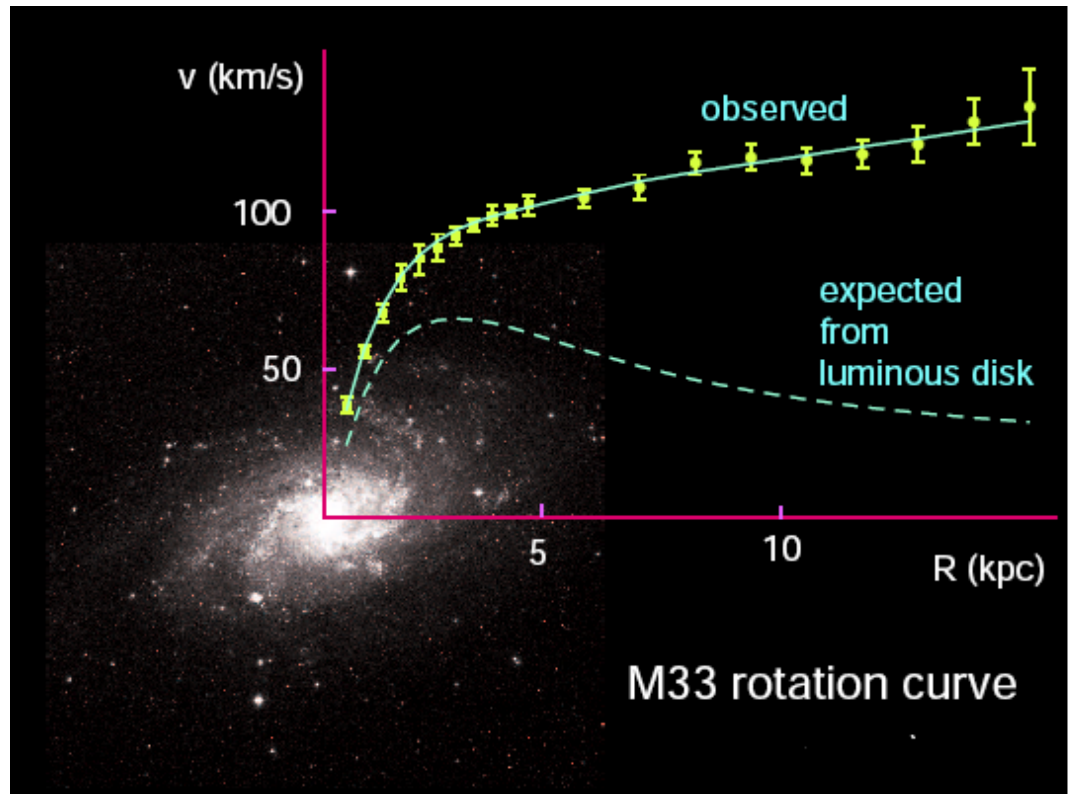
In general, need extra symmetry to allow $\bar{L}H\nu_R\chi$ but broken to generate the Dirac mass term $\bar{L}H\nu_R$



(a) Type-I seesaw (b) Type-II seesaw (c) Type-III seesaw

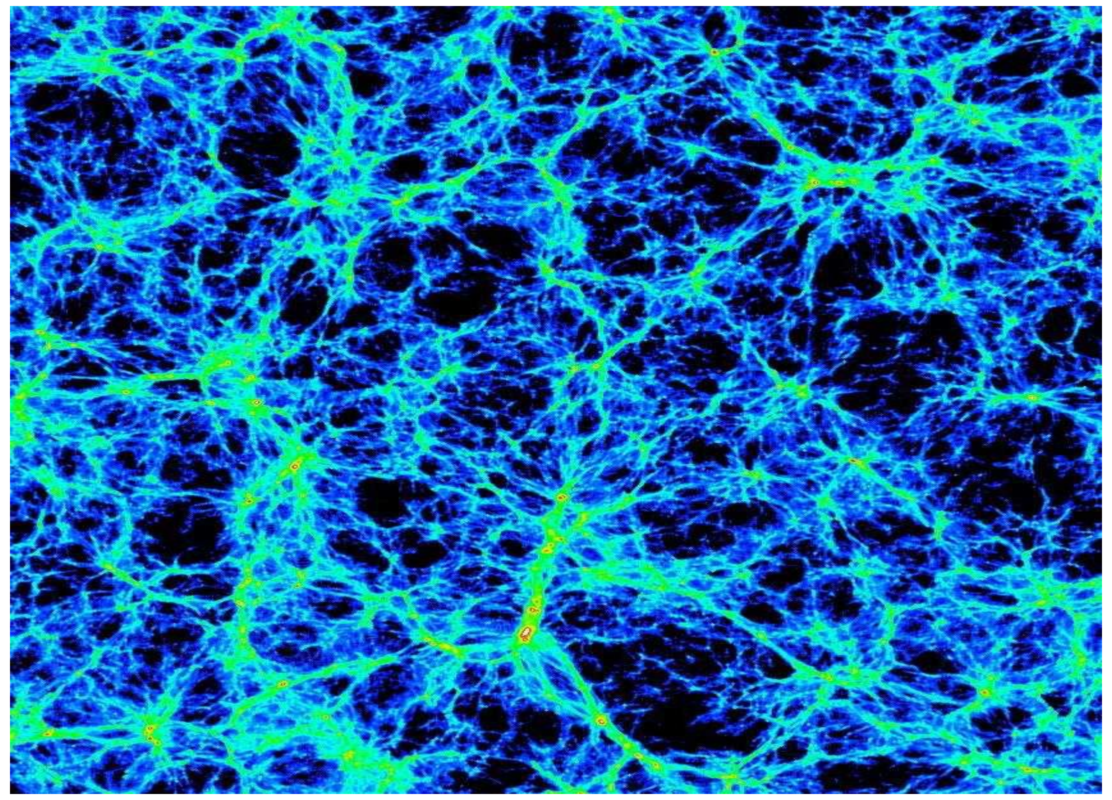
暗物质

All evidence in favor of particle DM thus far comes from observations of its gravitational effects on baryonic matter.

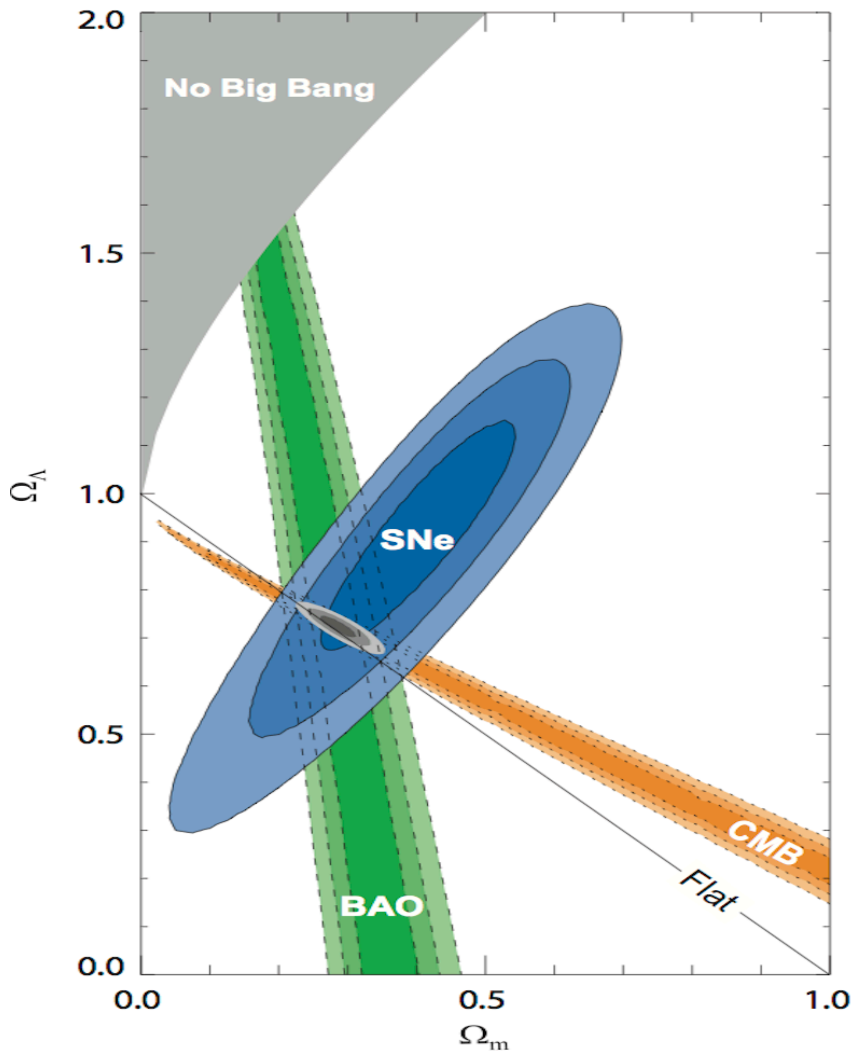


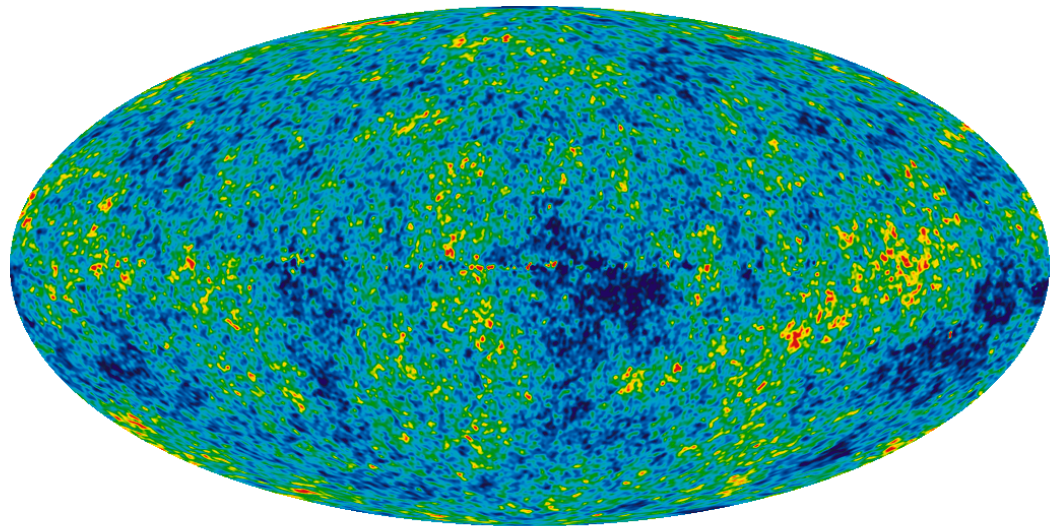
rotation curve

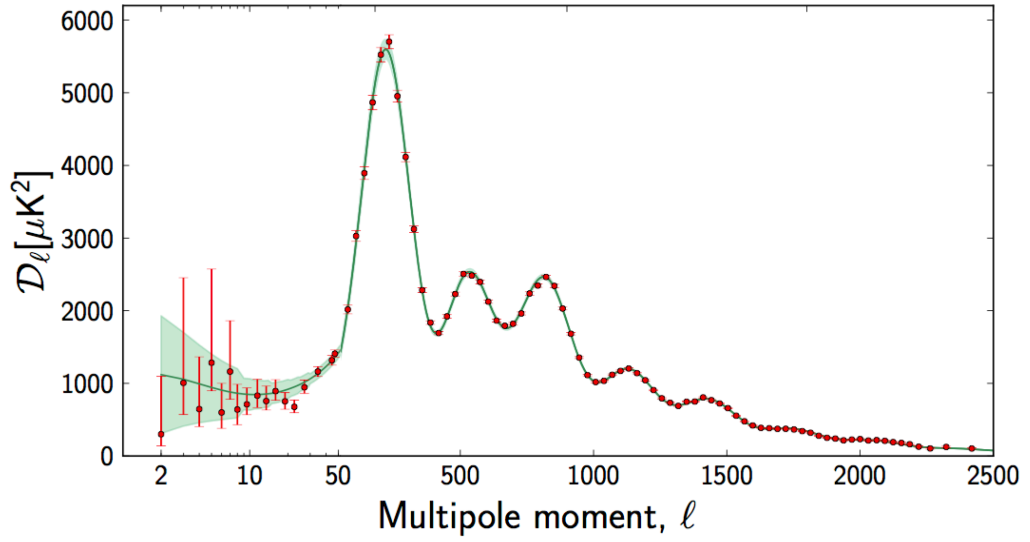
bullet cluster

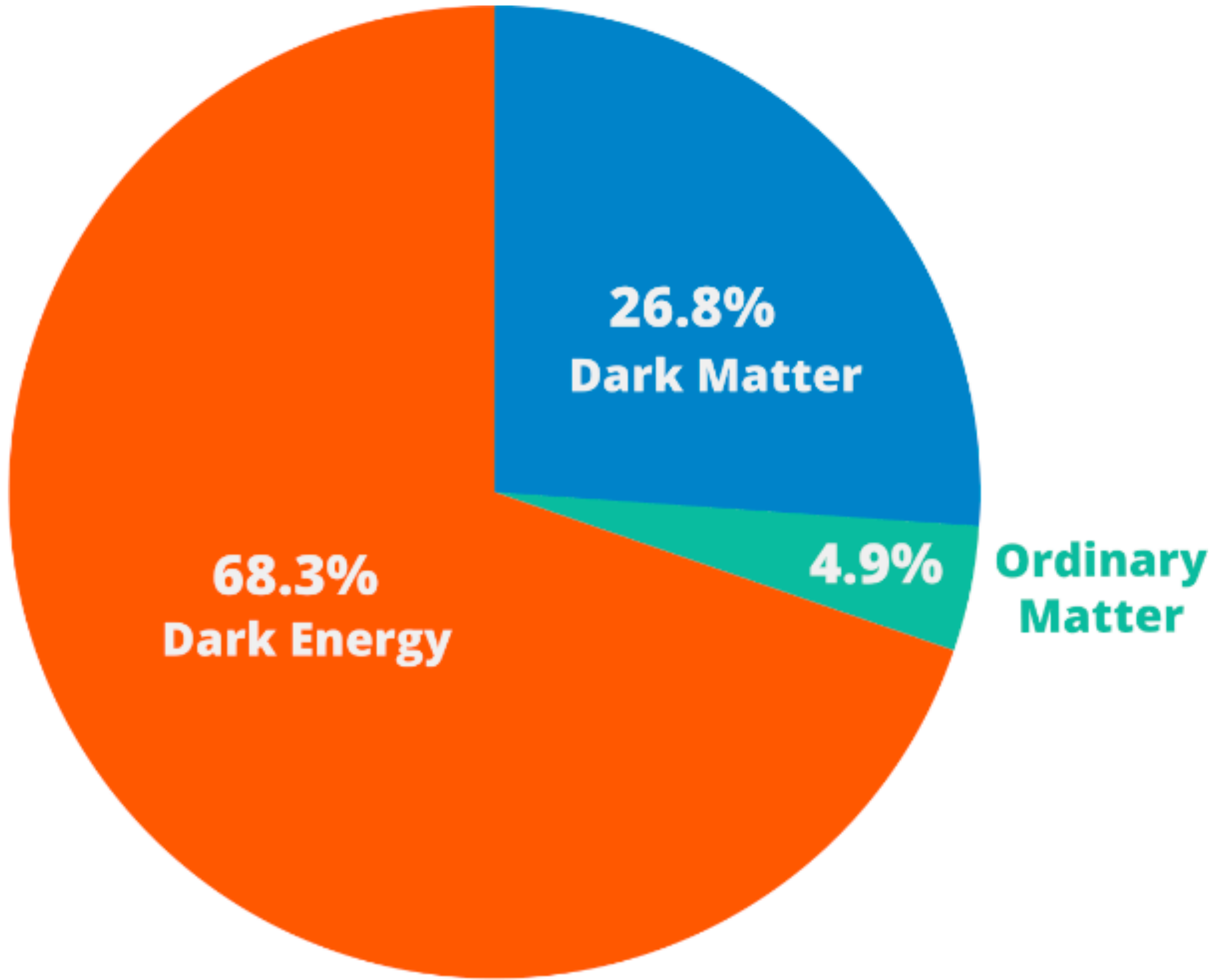


large structure formation

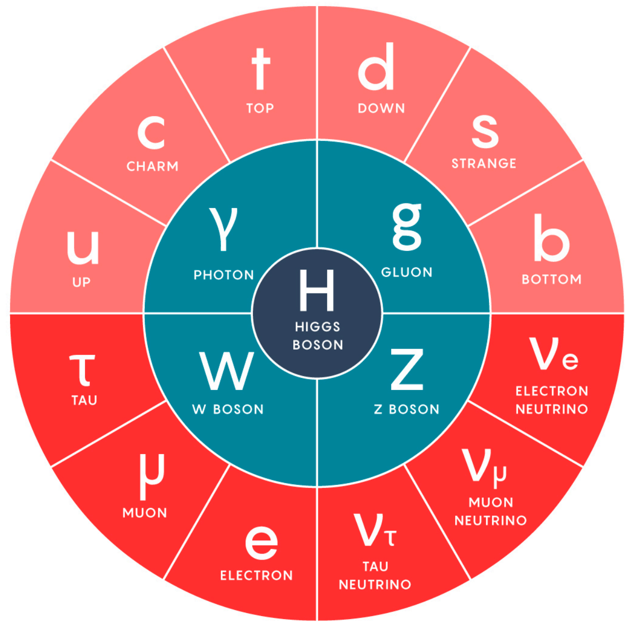








暗物质粒子



- 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.

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

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

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

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；

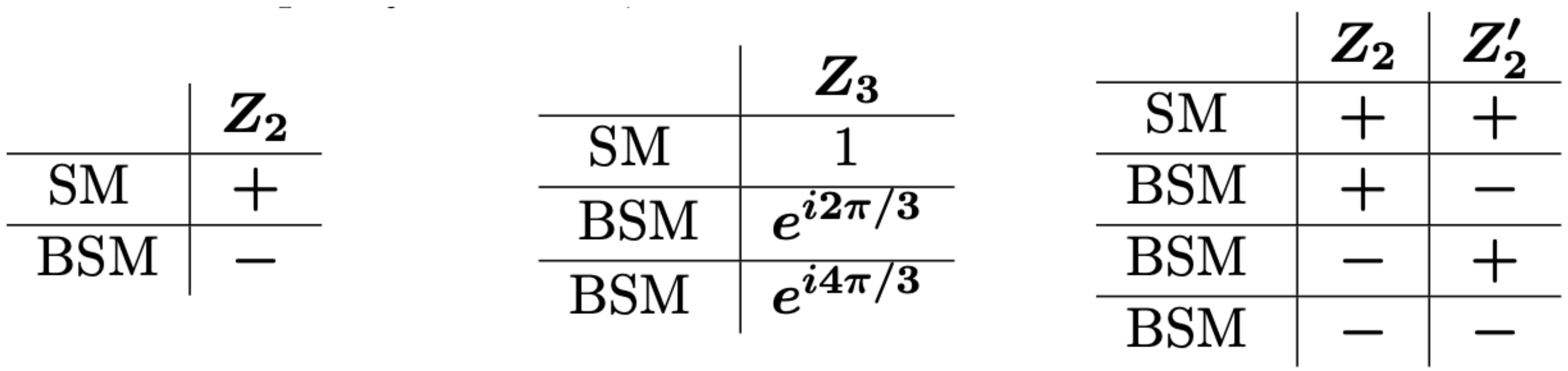
（3）电子：最轻的带电粒子，电荷守恒；$U(1)_Q$ 对称性

（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
SM	+
BSM	−

	Z_3
SM	1
BSM	$e^{i2\pi/3}$
BSM	$e^{i4\pi/3}$

	Z_2	Z_2'
SM	+	+
BSM	+	−
BSM	−	+
BSM	−	−

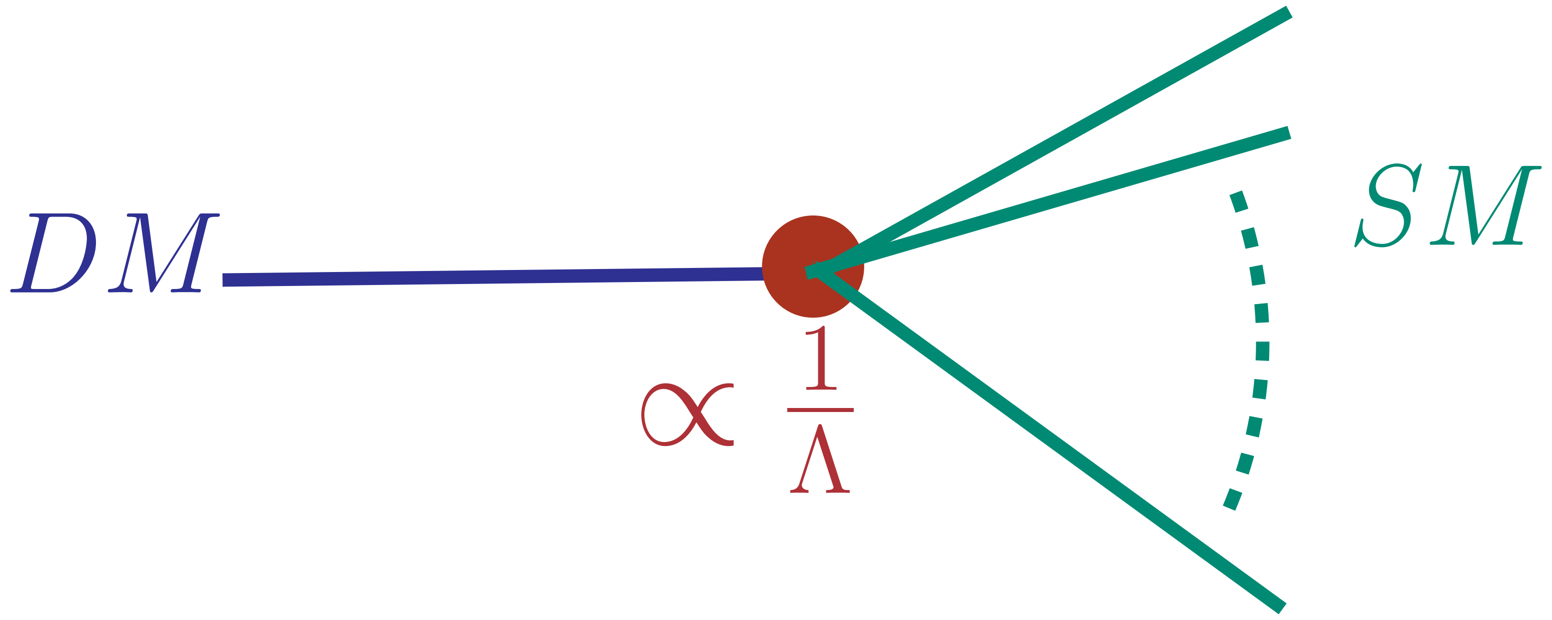
暗物质粒子

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, suppressed by GUT scale… …

Canonical Production Mechanism: Freeze out thermal relics

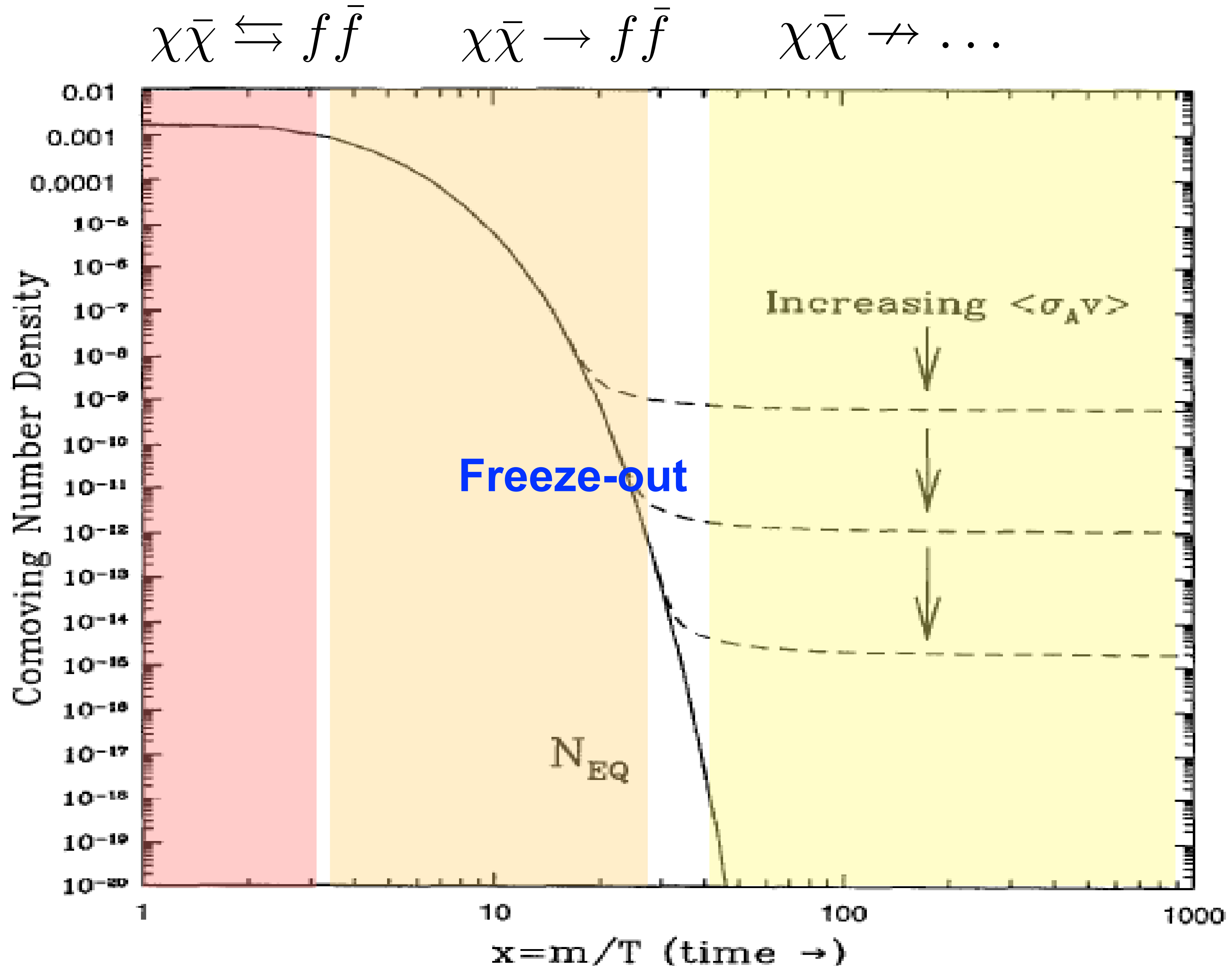
- Thermal freeze-out: the relic density connects to the “annihilation” cross section

$$\mathrm{DM} + \mathrm{DM} \longleftrightarrow \mathrm{SM} + \mathrm{SM}$$

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

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

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



WIMPs thermal relics: a rough estimate

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

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

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

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

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

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

“WIMP Miracle”

- Typical “weak scale” cross section

$\Omega_{\rm cdm} = 0.1198 \pm 0.0026$ Cosmology

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

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

WIMPy DM detection era! 😺 😺 😺

LHC + Direct Direction + Indirect Detection

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

Thermal relics

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

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

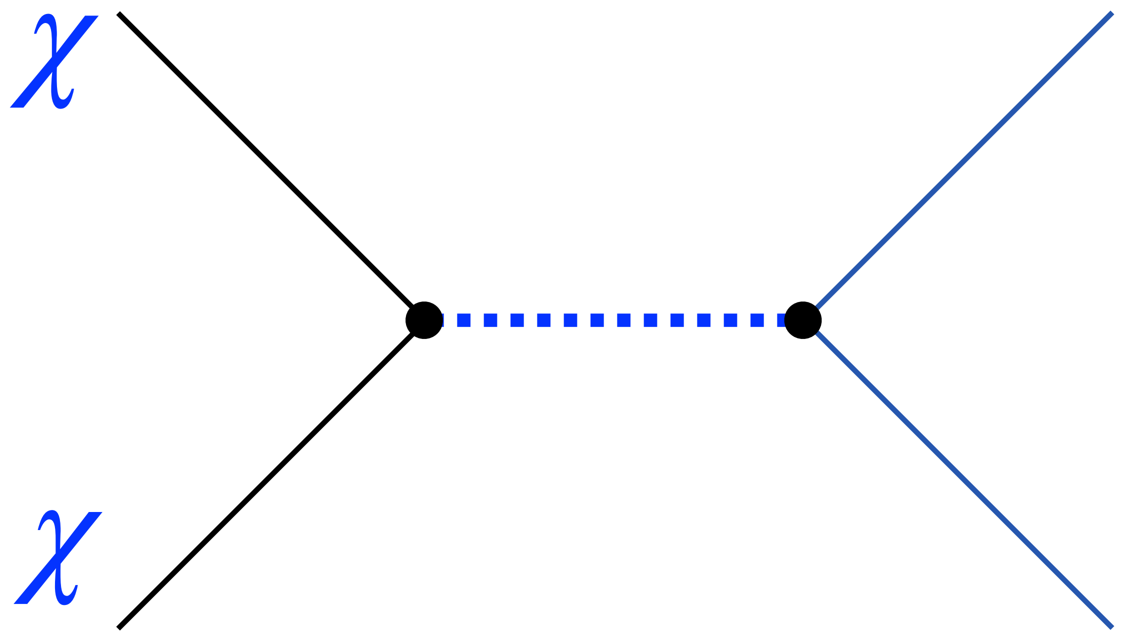
in terms of $x = m/T, Y \equiv n/s$

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

Thermal relics

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

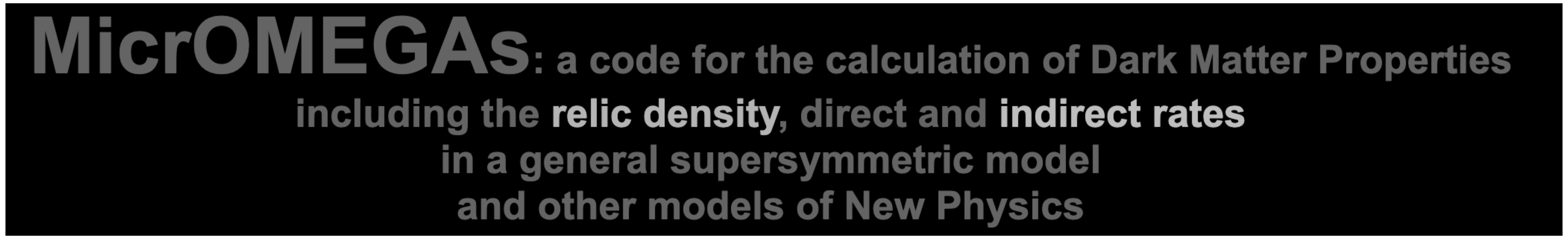
- Hybrid freeze-out processes:
  - self-annihilation;
  - co-annihilation;
  - resonance effects;
  - 2 to 2, 2 to 3, 3 to 2, 4 to 2 $\cdots$
  - $\cdots\ \cdots$



Complicated Boltzmann equation.

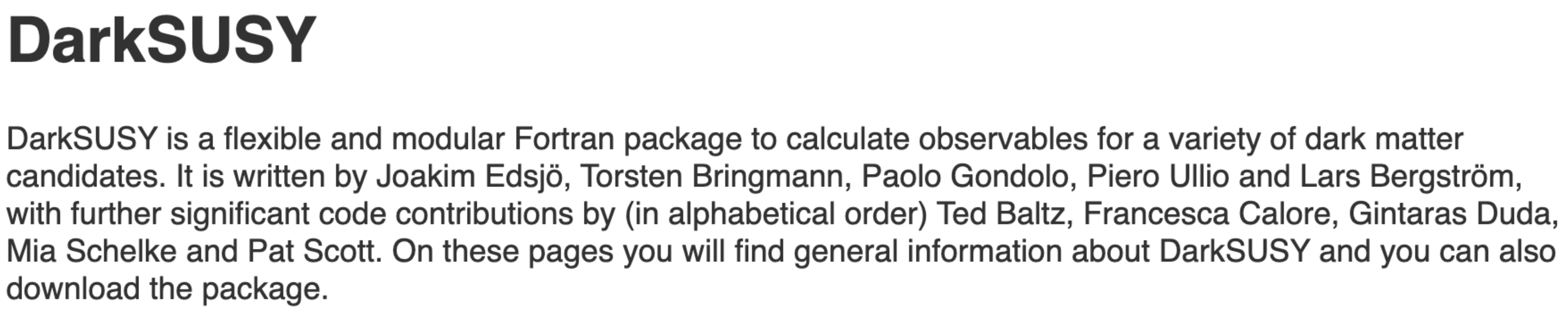
Computing Package

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

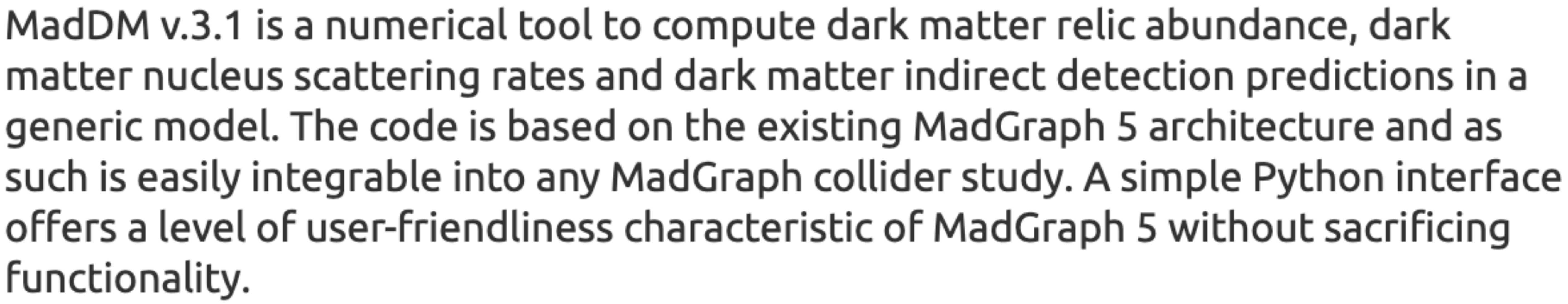
DarkSUSY https://darksusy.hepforge.org/



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

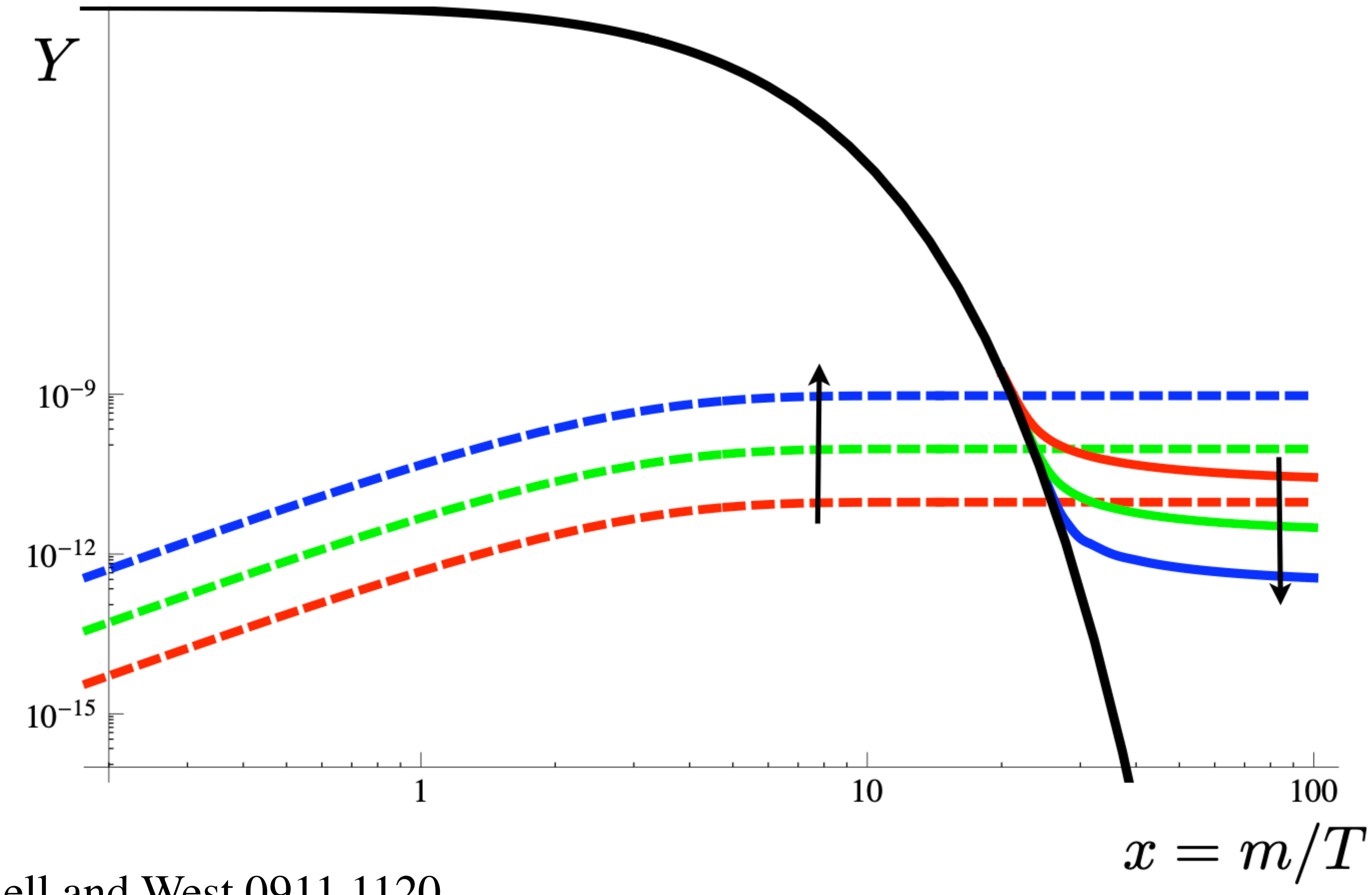


MadDM v.3.1 is a numerical tool to compute dark matter relic abundance, dark matter nucleus scattering rates and dark matter indirect detection predictions in a generic model. The code is based on the existing MadGraph 5 architecture and as such is easily integrable into any MadGraph collider study.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

… …

Non-thermal relics: Freeze-in Mechanism

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



Hall, Jedamzik, March-Russell and West 0911.1120

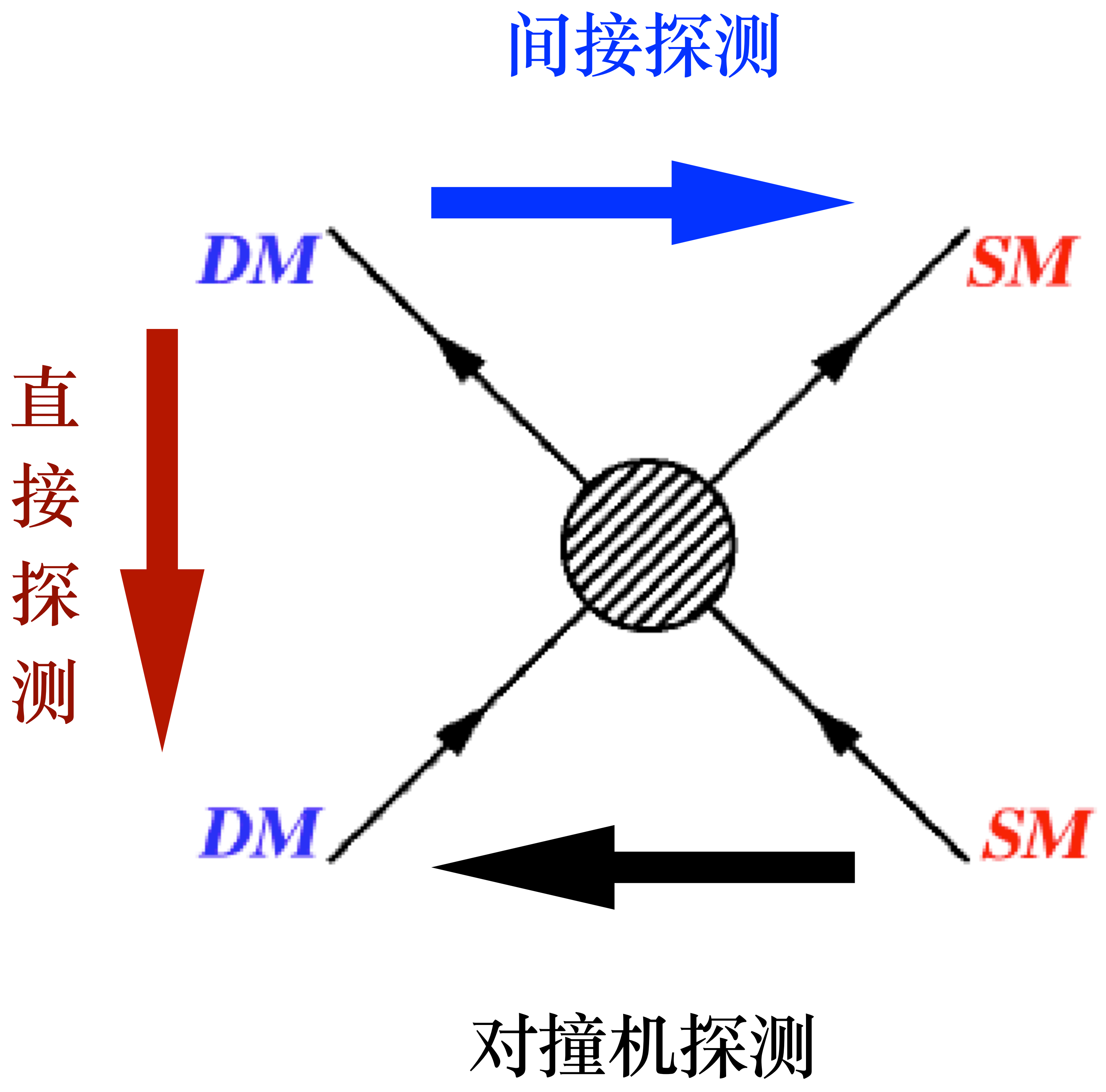
暗物质粒子探测

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；

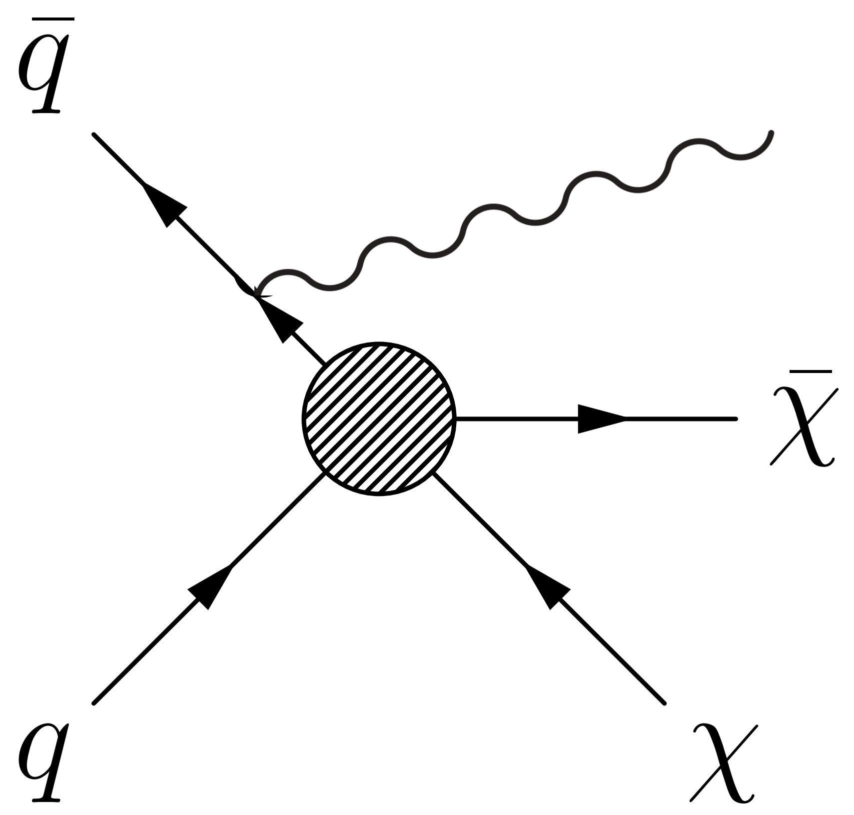
3. 对撞机探测，在对撞机上产生暗物质，暗物质表现为“消失的能动量”，类似于中微子。



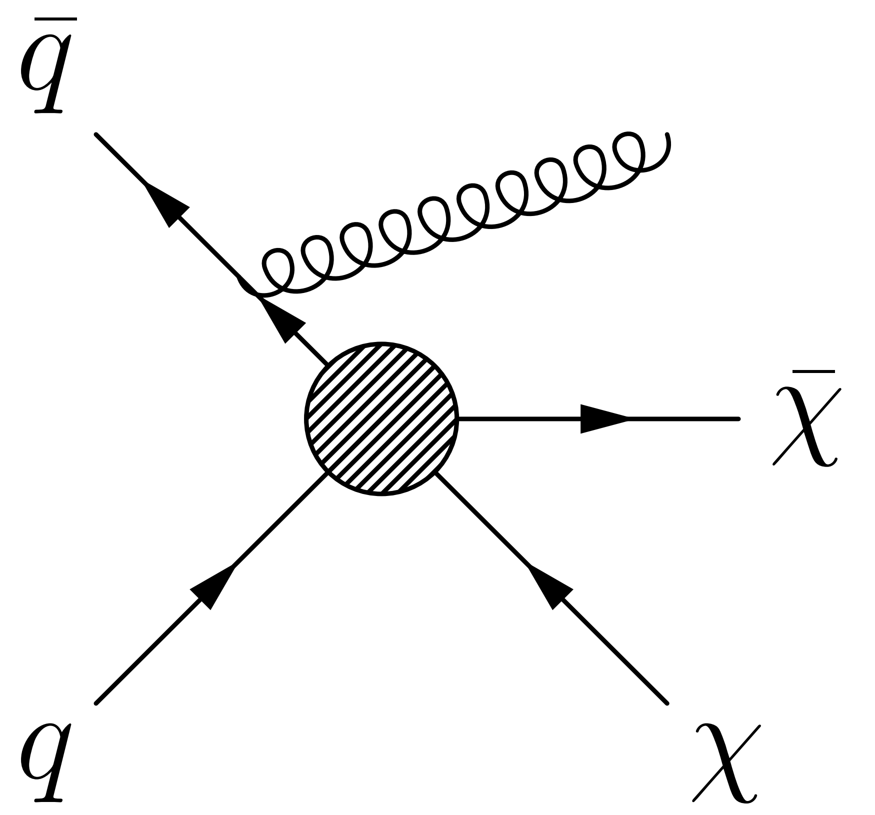
暗物质对撞机探测

- 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

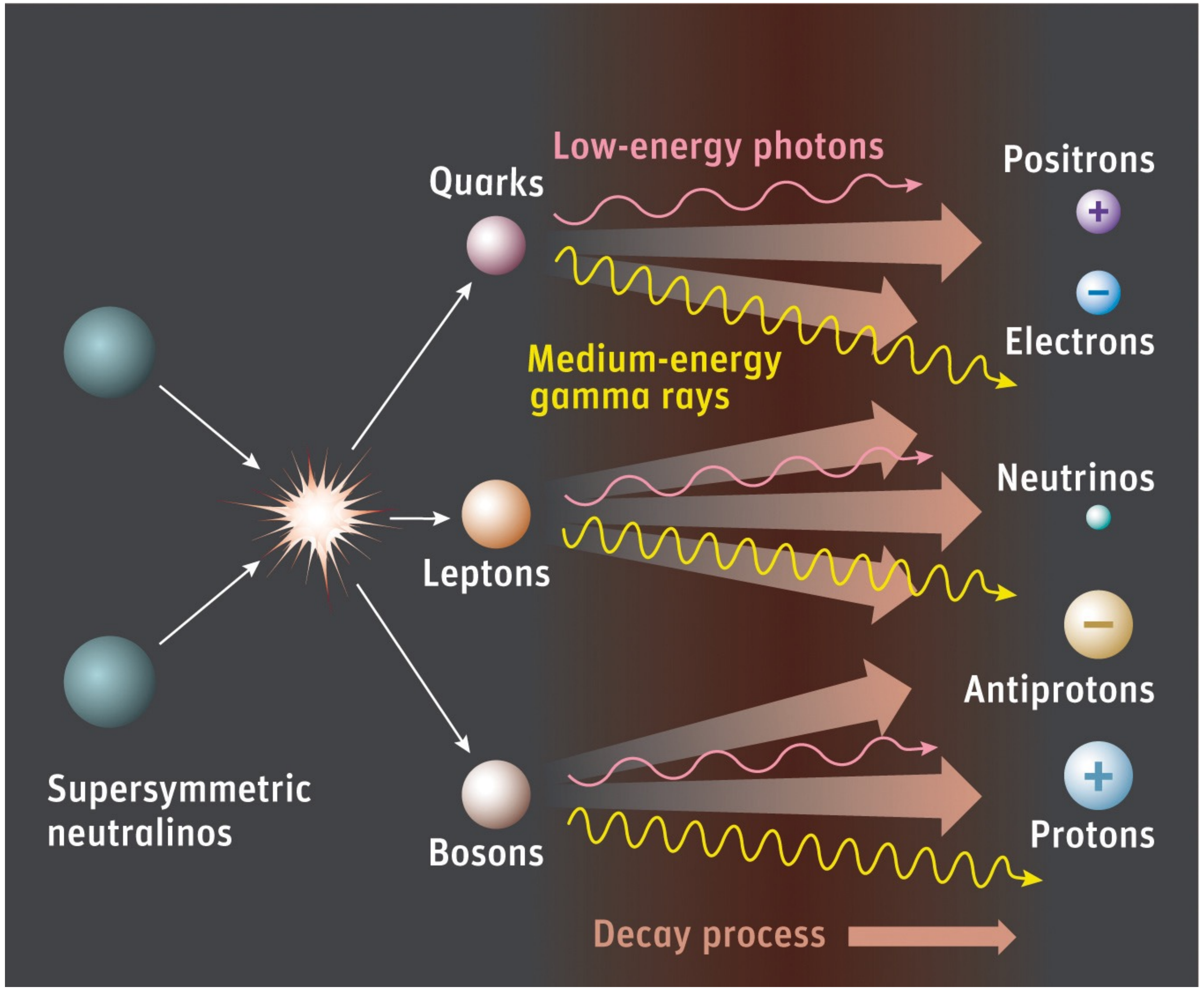


Monojet + MET

（2）multi-jets/leptons + missing ET

（3）Particle invisible decay

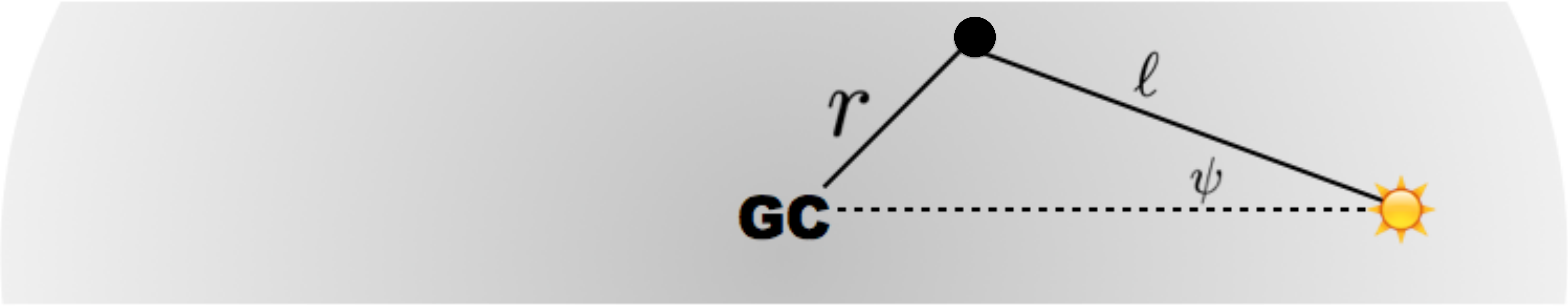
暗物质间接探测



探测暗物质在密度高区域自湮灭或衰变产物

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



Eg. Photon flux spectrum from annihilations

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

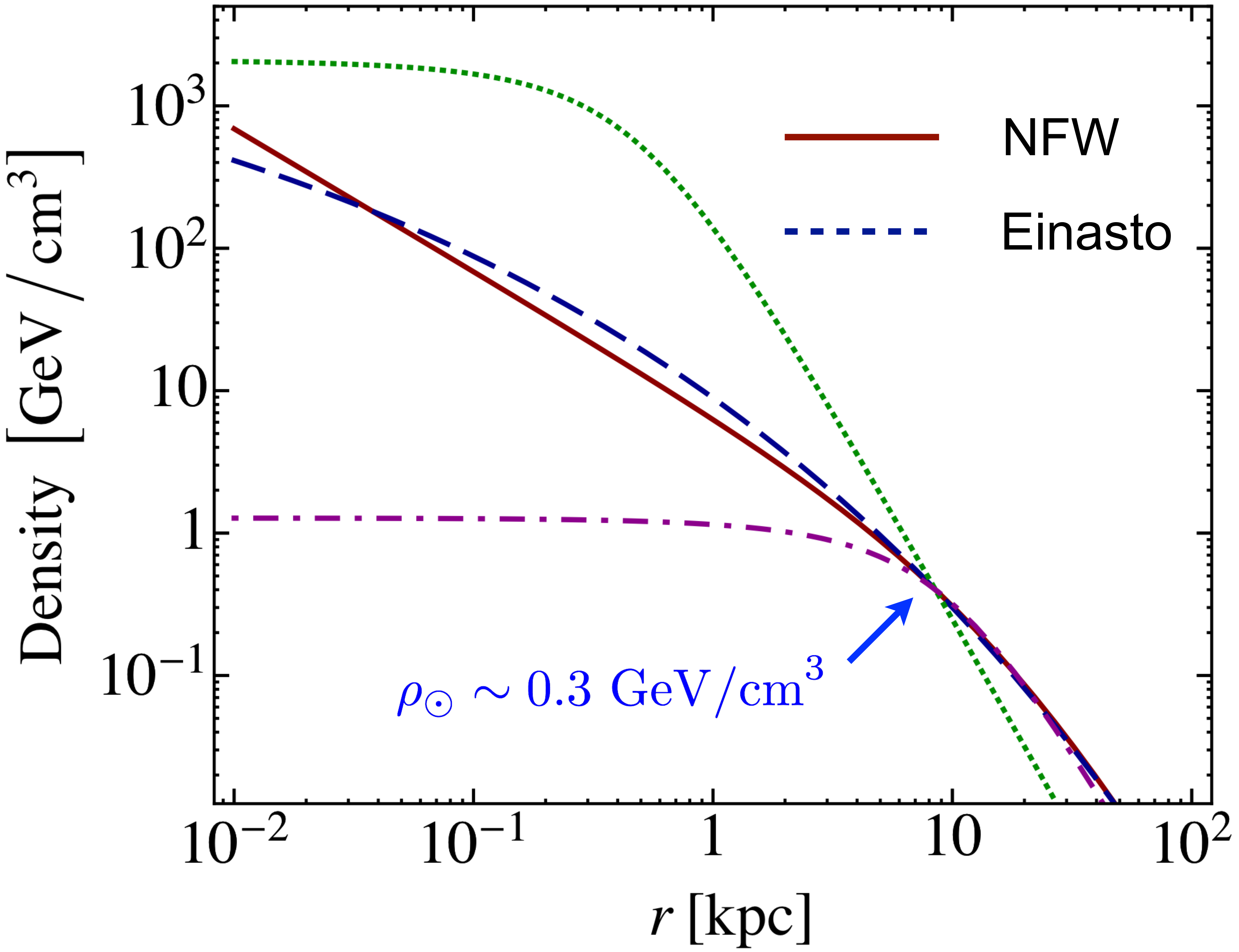
实验：

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

Neutrino telescopes

暗物质晕分布

From N-body simulations and rotation curves



1307.4082

DM density profile

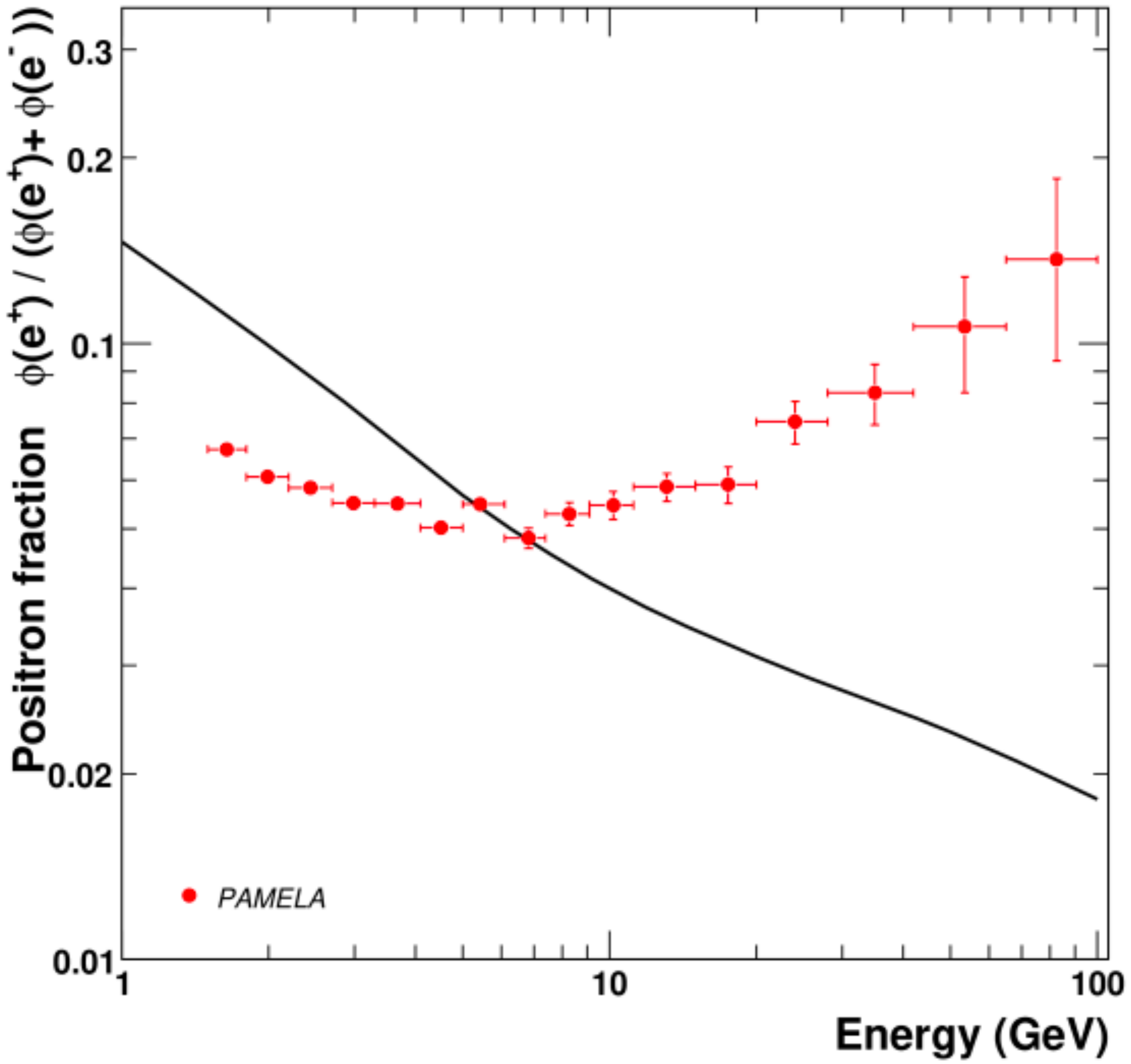
NFW profile

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

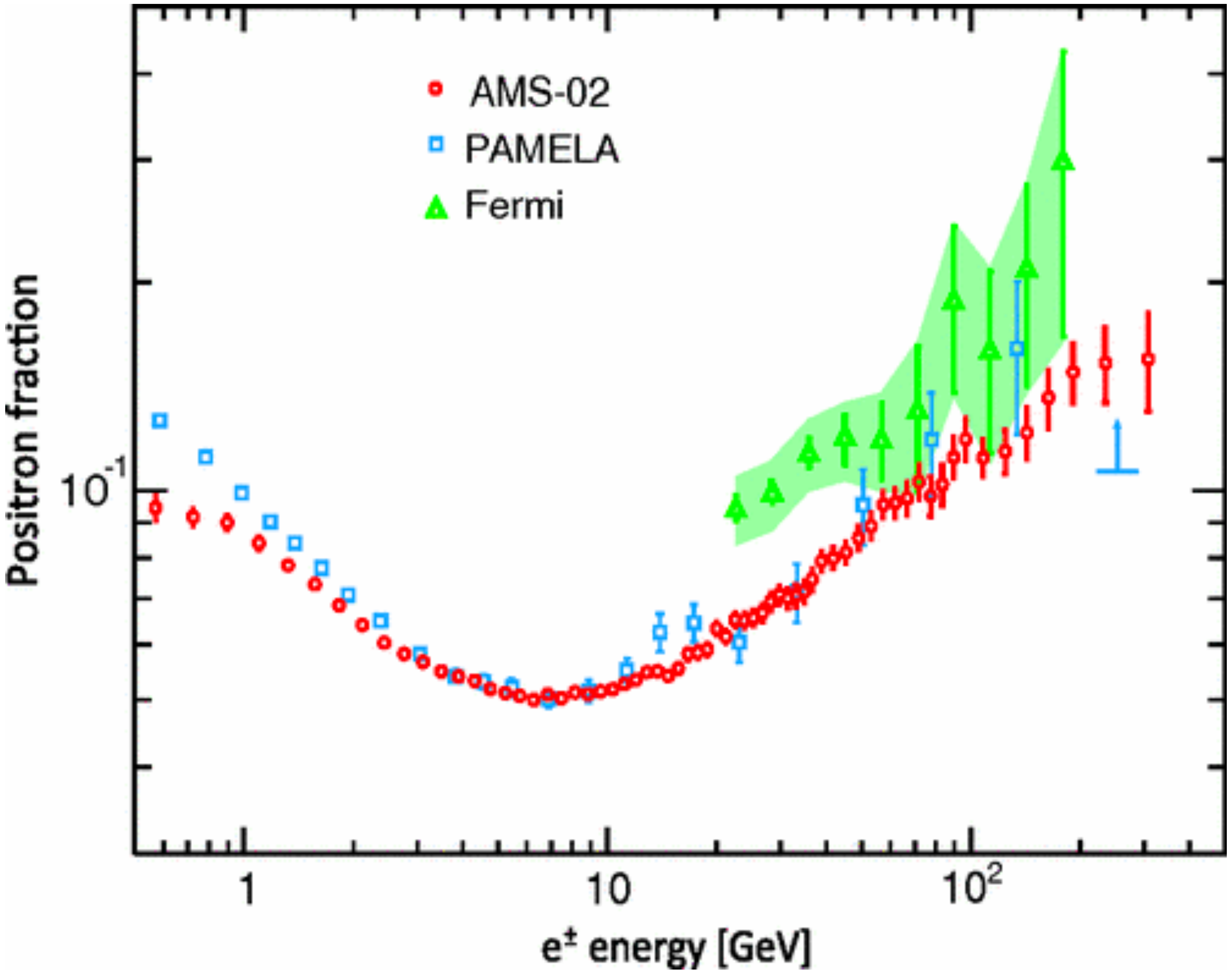
Einasto profile

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

宇宙射线电子正电子超出



PAMELA 2009

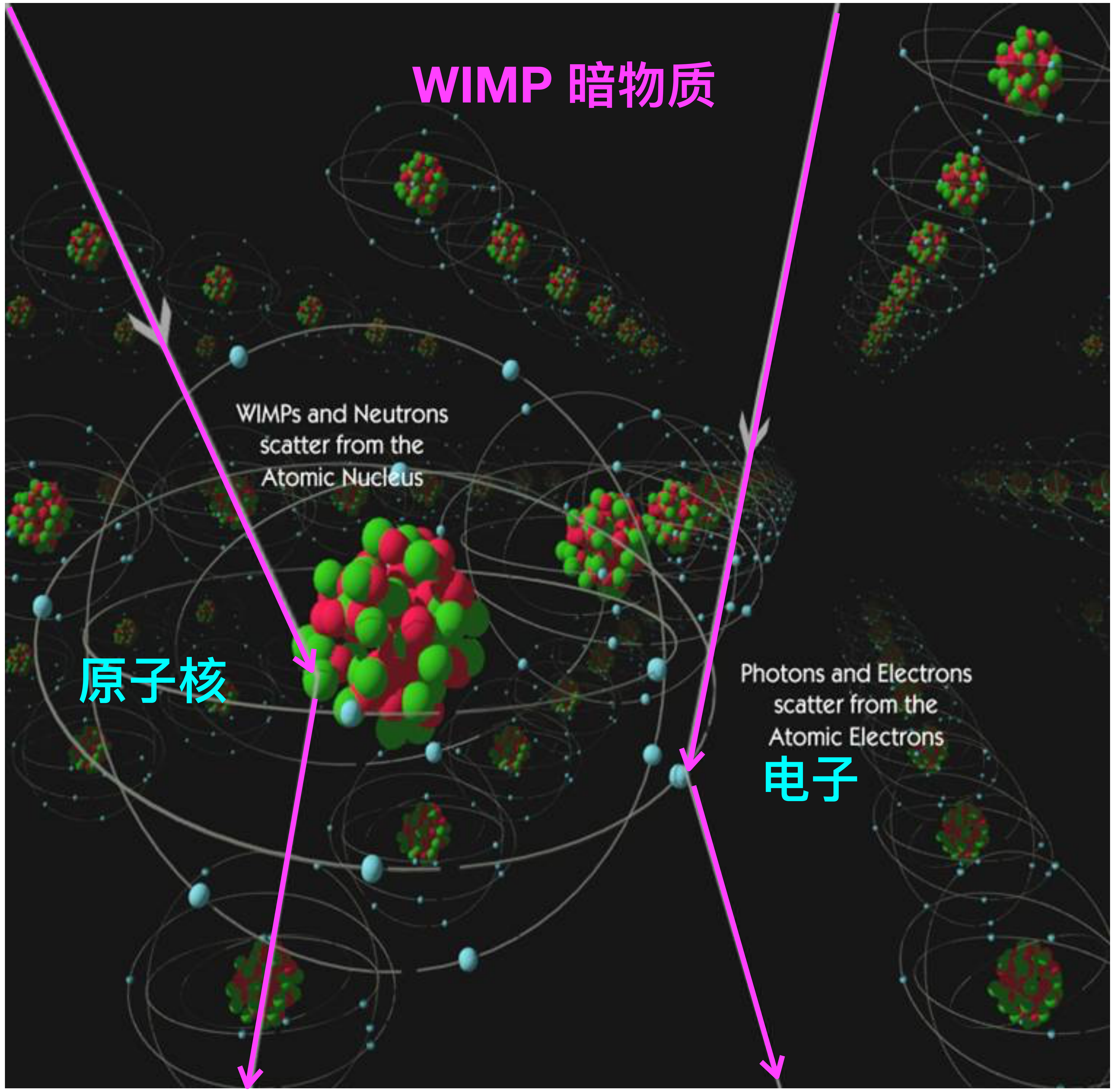


AMS-02 2013

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



暗物质直接探测实验：
CDMS, XENON, LUX,
CDEX, PandaX, ⋯ ⋯

暗物质直接探测

- 寻找原子核受到暗物质散射后的反冲：

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

- 事例数： $N_{\mathrm{Target}} \cdot n_\chi \cdot \sigma_{\chi N} v \cdot \mathrm{Time}$ (需要足够大的探测器)
- 能谱： counts/kg/keV/date

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

$v_{\min} = \sqrt{m_N E_r/(2\mu^2)}$	minimal velocity to create recoil E_r
$\rho_0 \sim 0.3\mathrm{GeV/cm}^3$	local DM density
$f_\oplus(\vec{v},t)$	velocity distribution

粒子物理、核物理、天体物理、宇宙学

暗物质直接探测

In the NR limit, the DM-nucleus interactions:

$$\bar{\chi}\chi\bar{N}N \Rightarrow 4m_\chi m_N \mathbf{1}_\chi \mathbf{1}_N$$

$$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}\gamma_\mu\gamma_5 N \Rightarrow 16 m_\chi m_N \vec{S}_\chi \cdot \vec{S}_N$$

- 自旋无关: $S \otimes S, V \otimes V$

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

$f_p = f_n \quad \Rightarrow \sigma \propto A^2$ (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

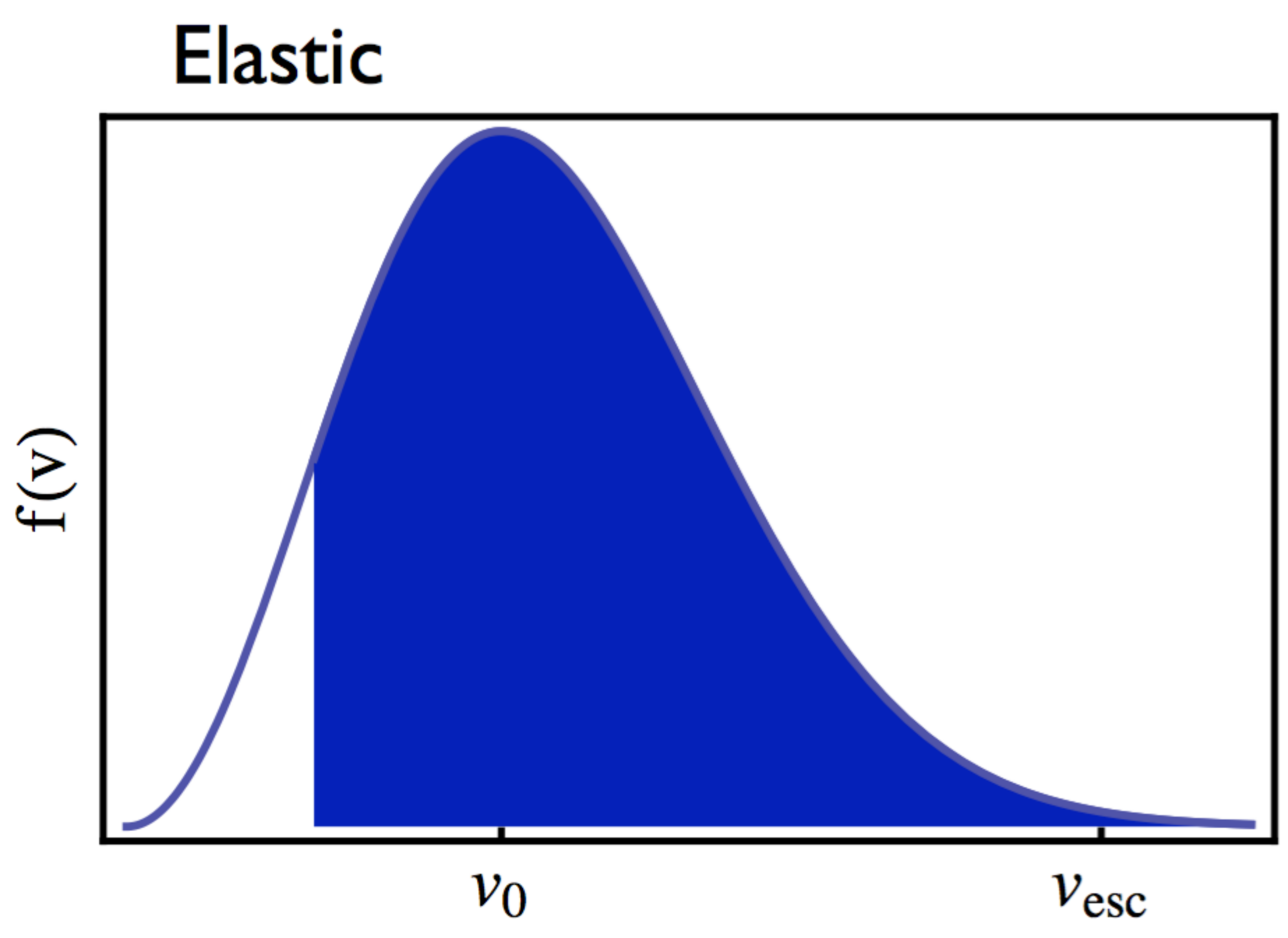
elastic scattering

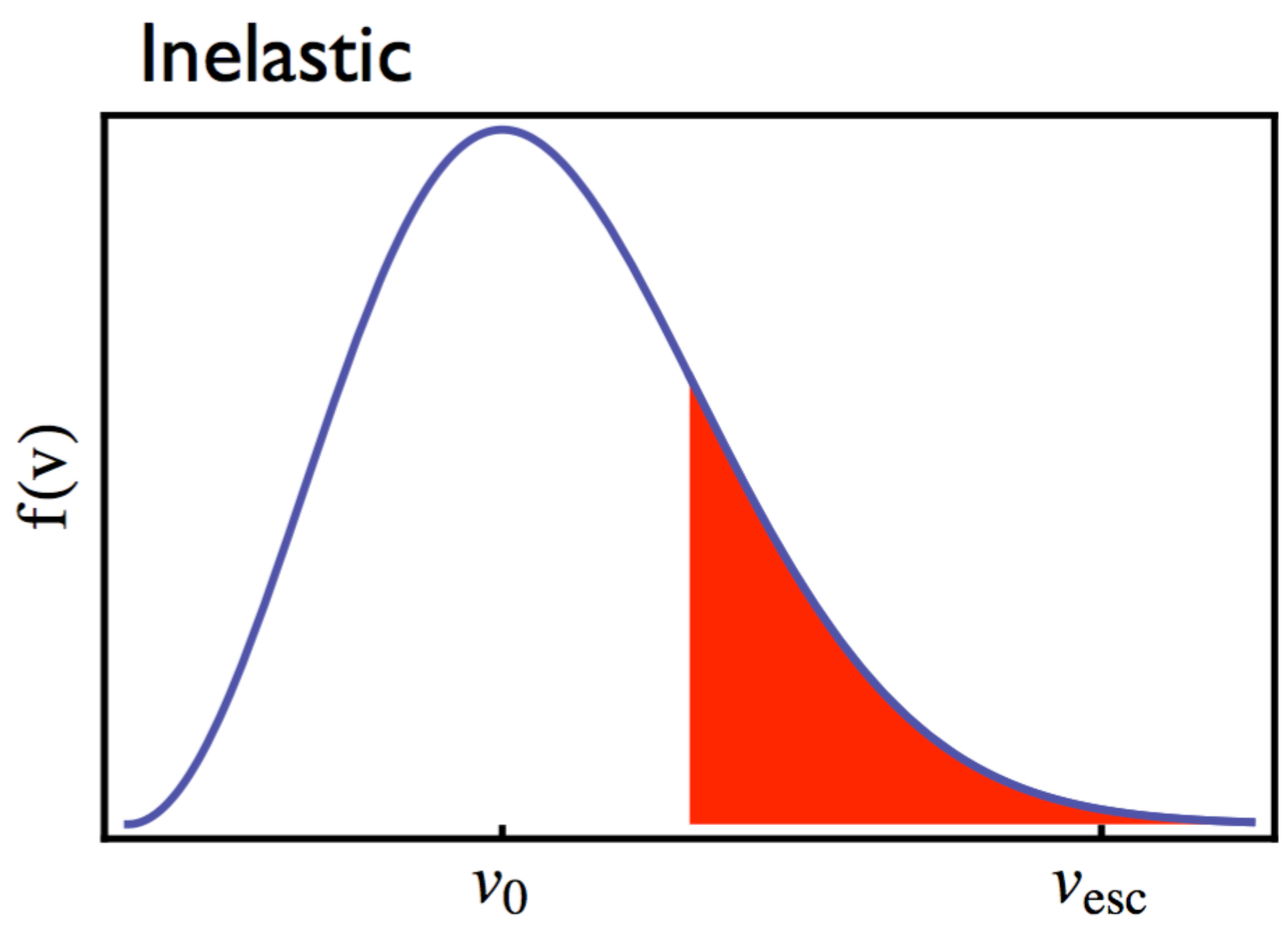
$$\chi + N \to \chi + N$$

inelastic scattering

$$\chi + N \to \chi^* + N$$

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





暗物质直接探测年调制效应

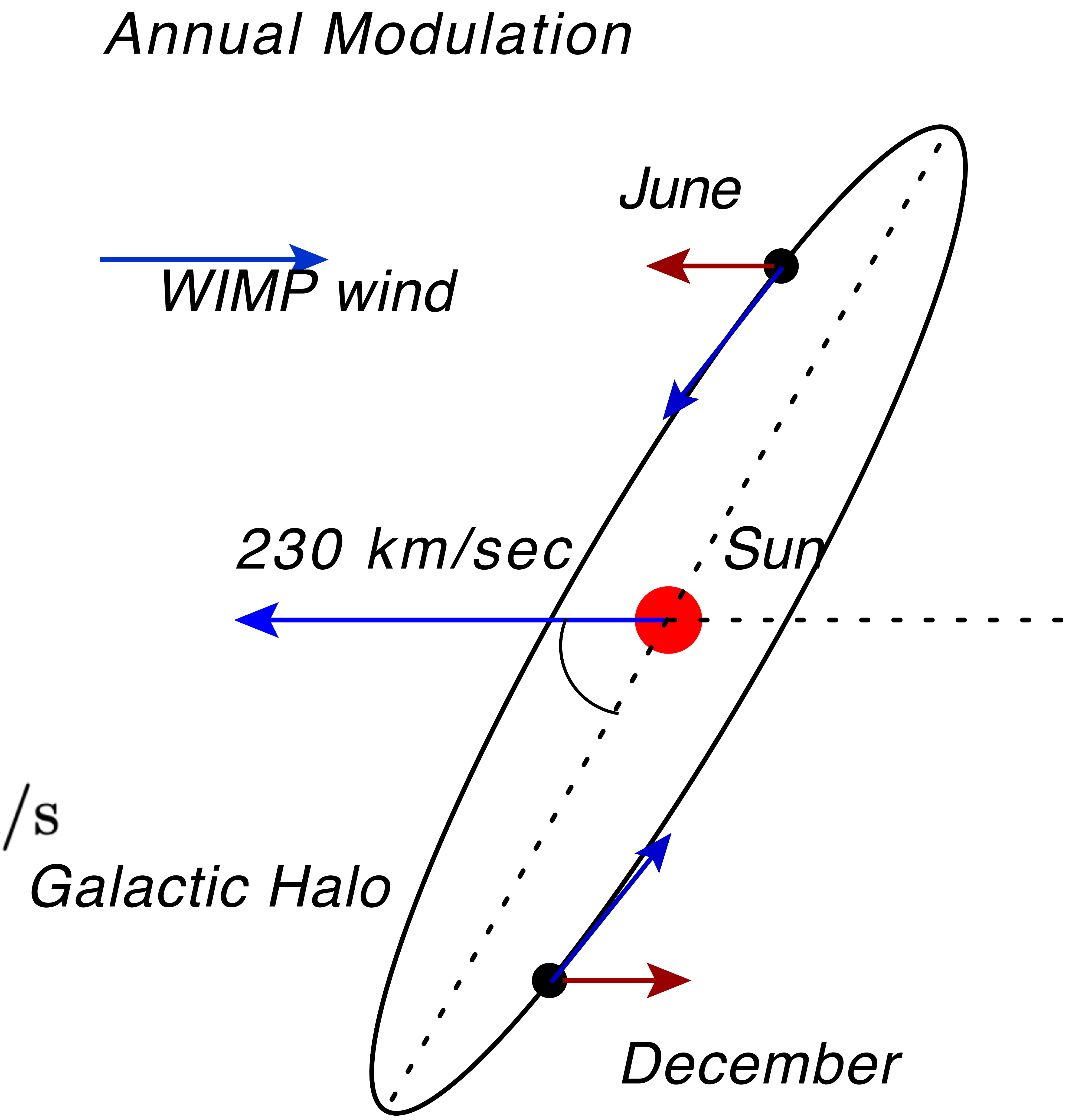
$\boldsymbol{f_\oplus(\vec{v},t)}$: DM velocity distribution in earth frame.

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

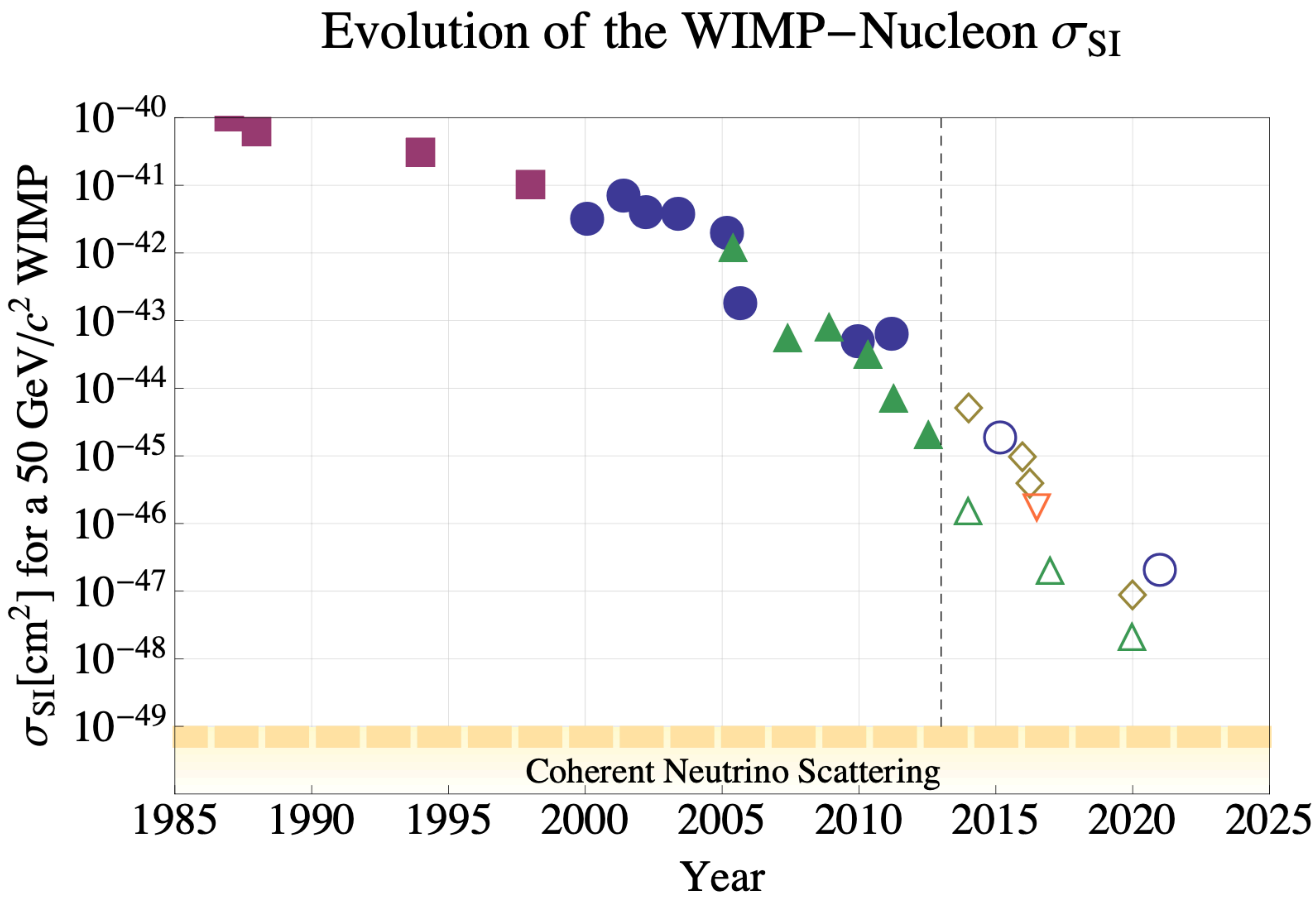
Maxwellian velocity distribution in dark halo frame

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

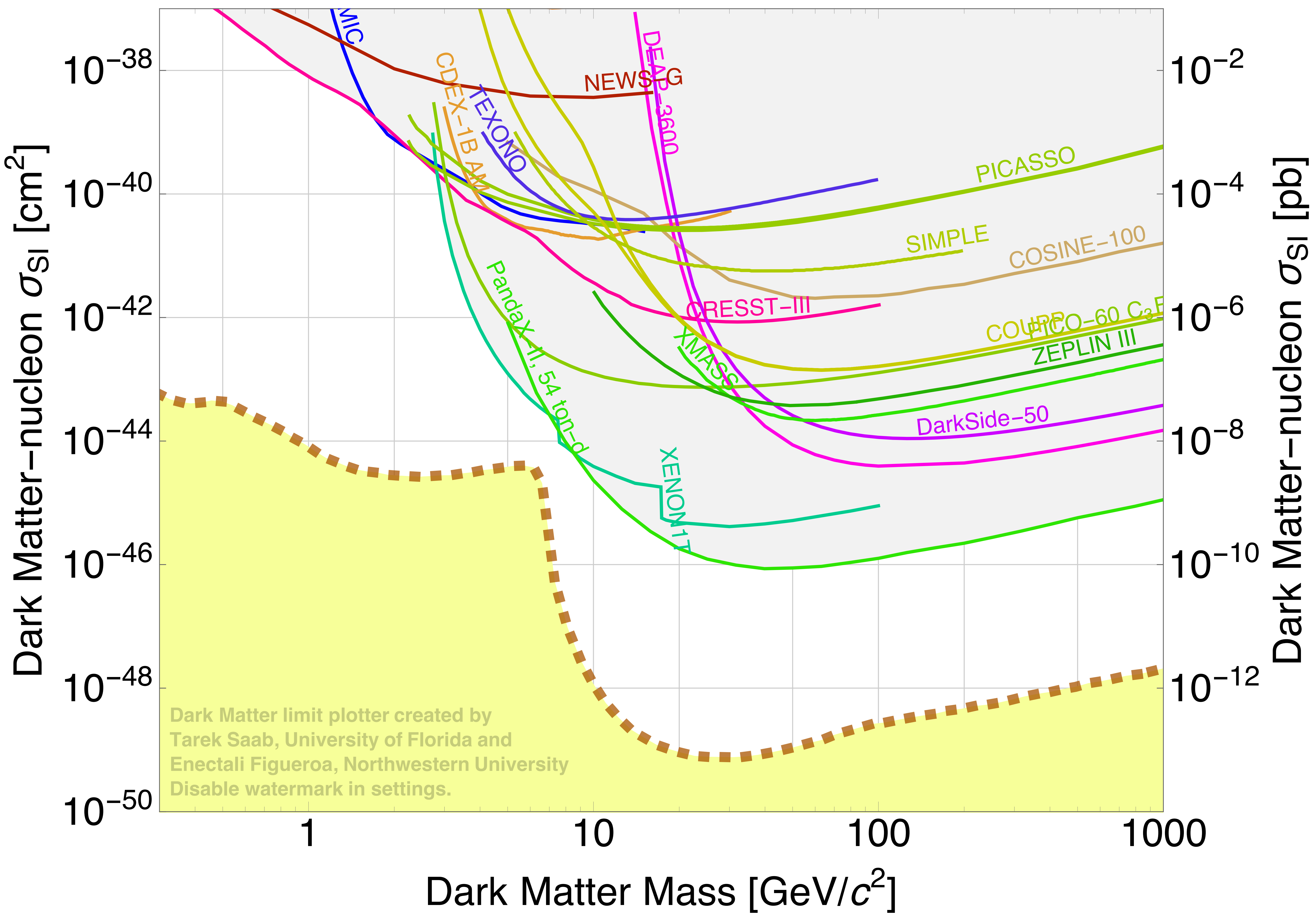
with $v_0 \simeq 220$ km/s, $v_{esc} \simeq 550$ km/s, $v_\oplus = 30$ km/s



暗物质直接探测

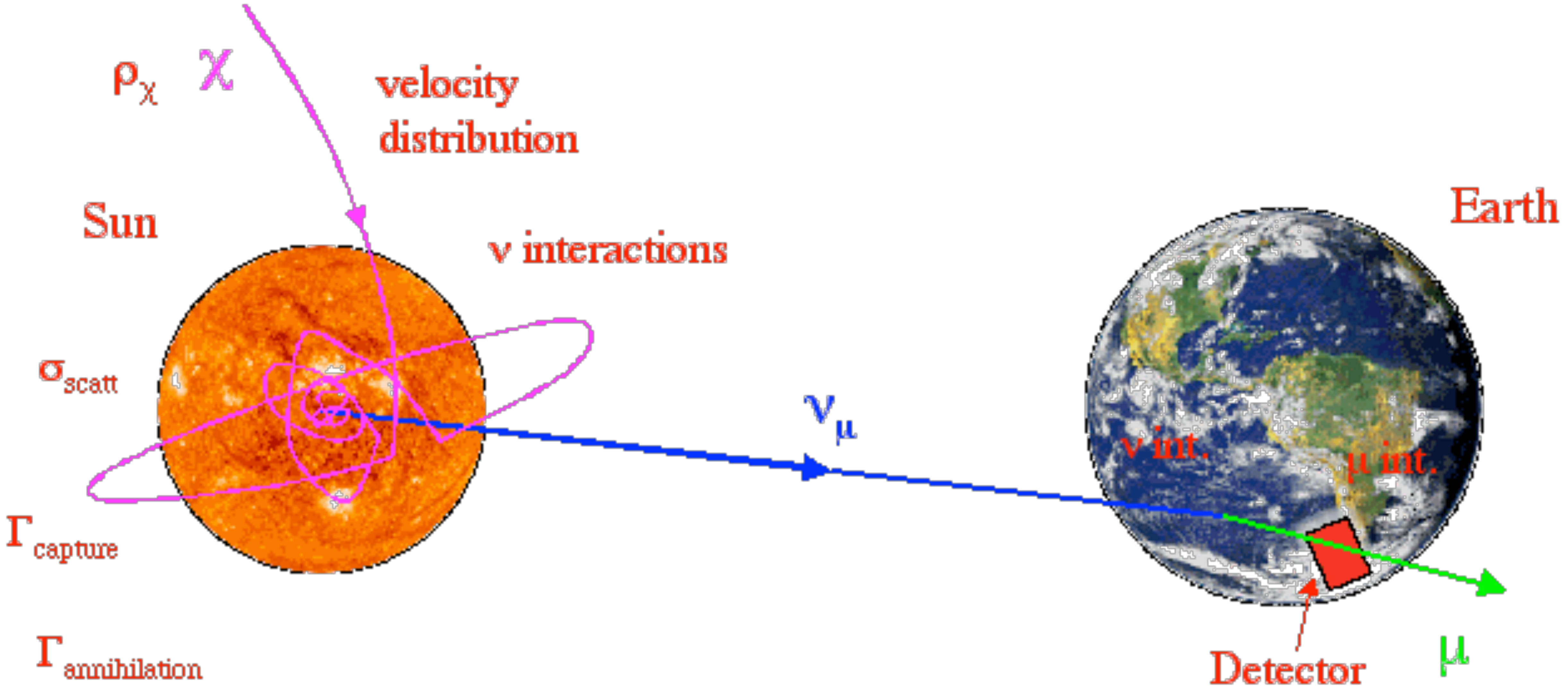

Evolution of the WIMP−Nucleon σ_{SI}
σ_{SI}[cm^2] for a 50 GeV/c^2 WIMP
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
Coherent Neutrino Scattering
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year

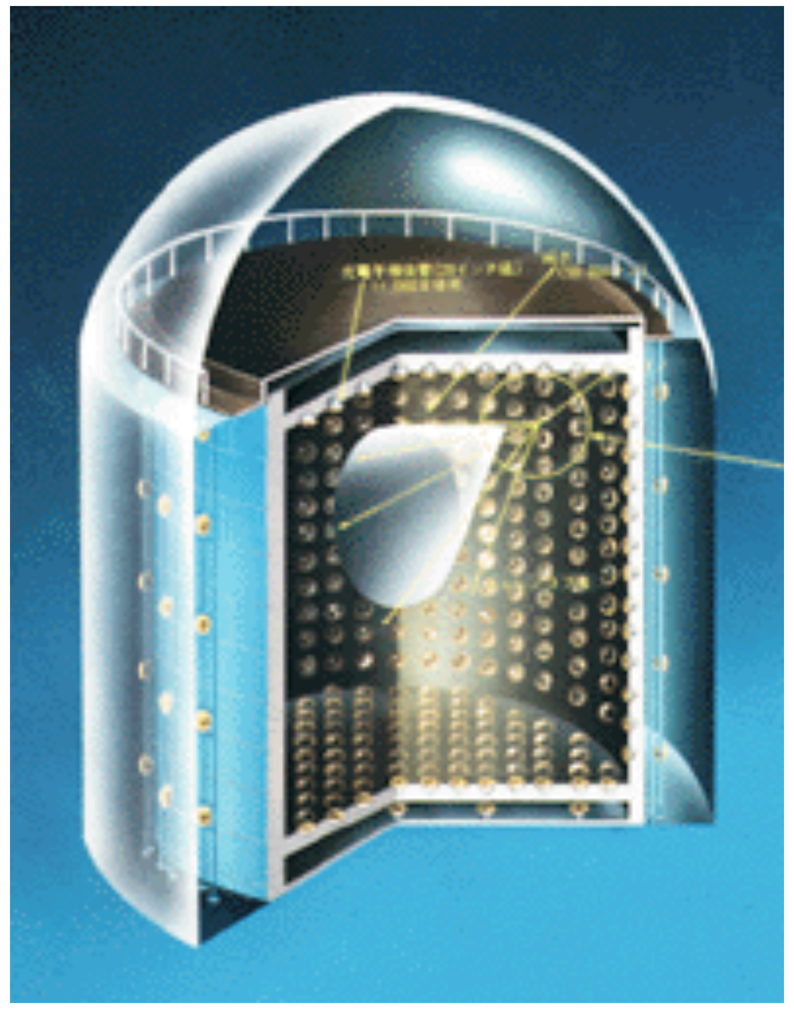
暗物质直接探测



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

来自星体的暗物质信号





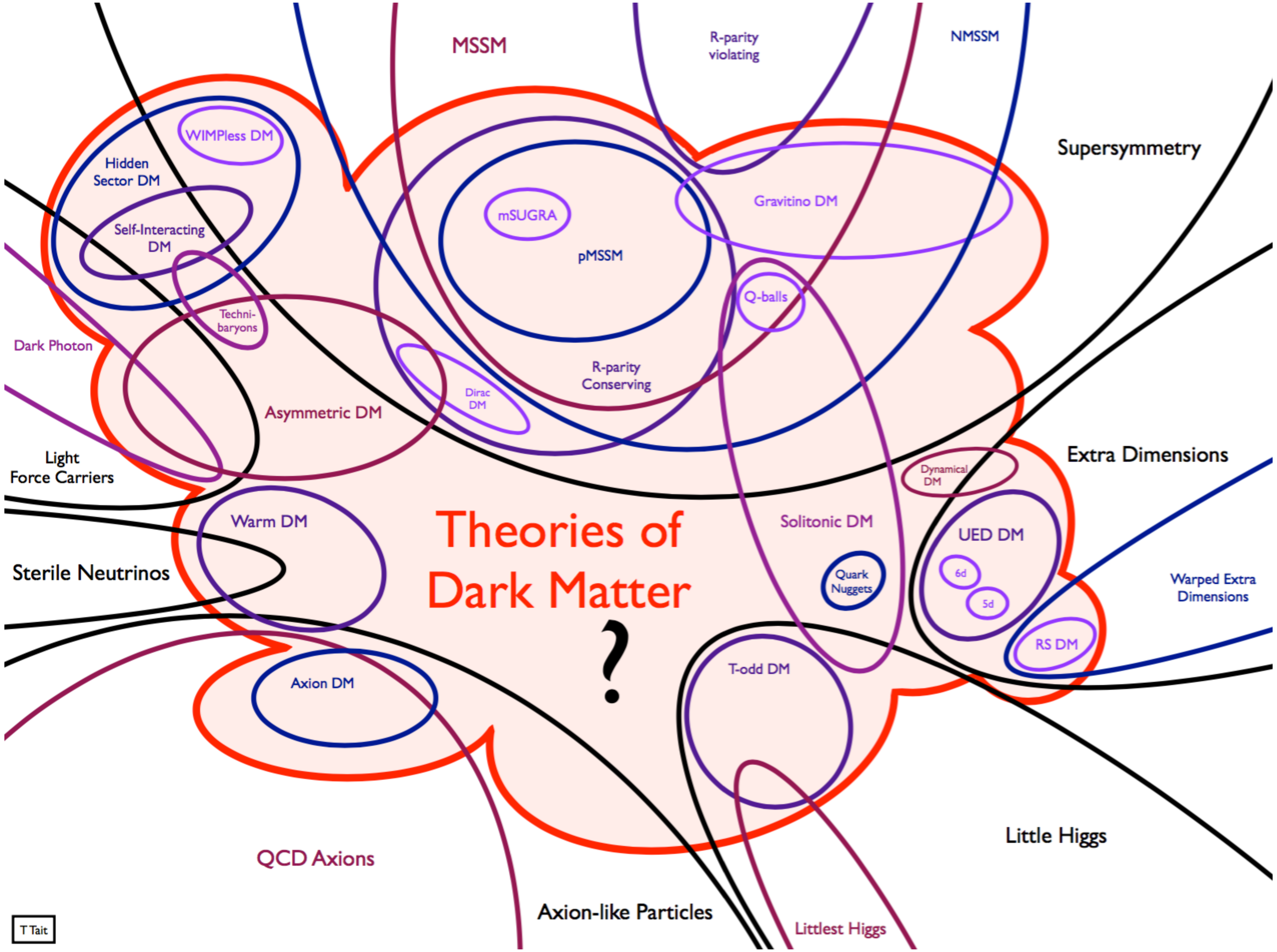
暗物质被太阳俘获积聚并自湮灭

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

若俘获过程和自湮灭达到平衡

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

暗物质理论模型：Call for new physics beyond the SM



Dark Matter Candidates Zoo

- 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, …)
- Multiple dark matter, mirror dark matter
- Hidden dark matter, self-interacting DM, composite DM, …
- axion-like, dark photon, very light or very heavy DM, boosted DM, …

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: $\sim \mathbf{10^{26}}$ sec lifetime
3. Good candidate: Gravitino with R-parity violation in SUSY. Due to the factor $\mathbf{1/M_{pl}}$ suppression, gravitino has very long lifetime to be dark matter.
4. candidate in some GUT theories, suppressed by the $\mathbf{1/\Lambda_{GUT}}$ scale.

Asymmetric Dark Matter

- DM density arises from DM matter-antimatter asymmetry;
- The fact $\Omega_{\rm dm} \sim \Omega_{\rm baryon}$;
- 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,

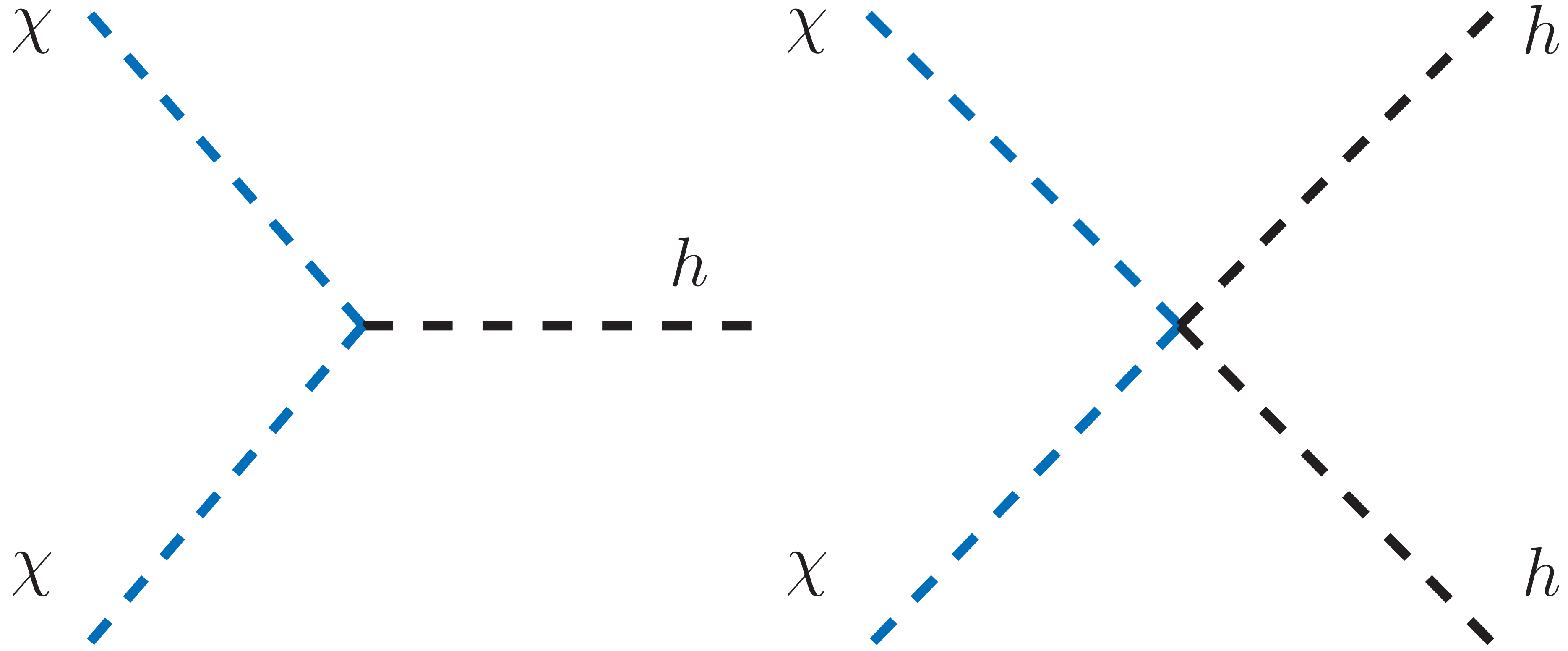
$$q n_{b-\bar{b}} = -Q n_{dm-\bar{dm}}$$

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

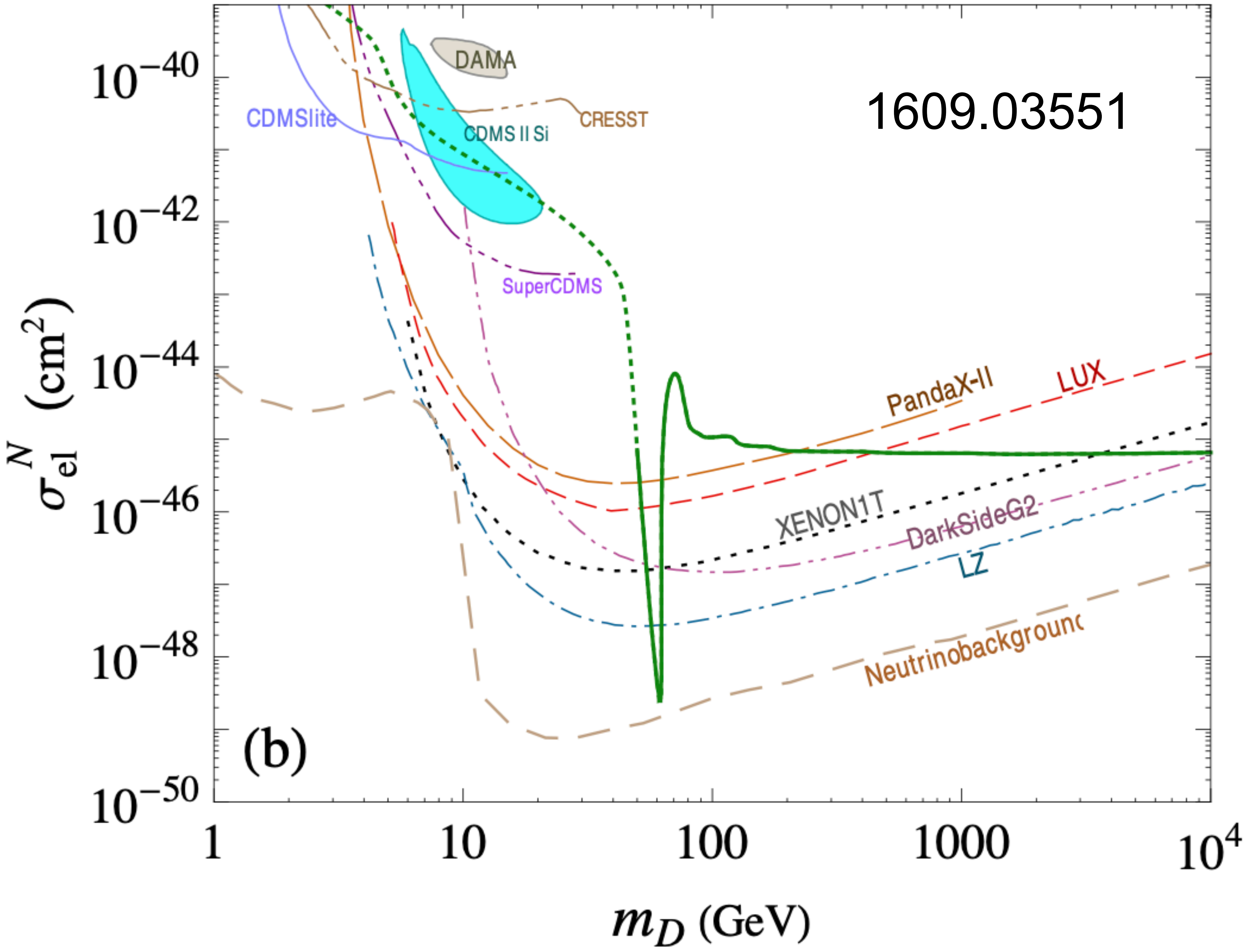
“最简”模型：Singlet scalar DM

- 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

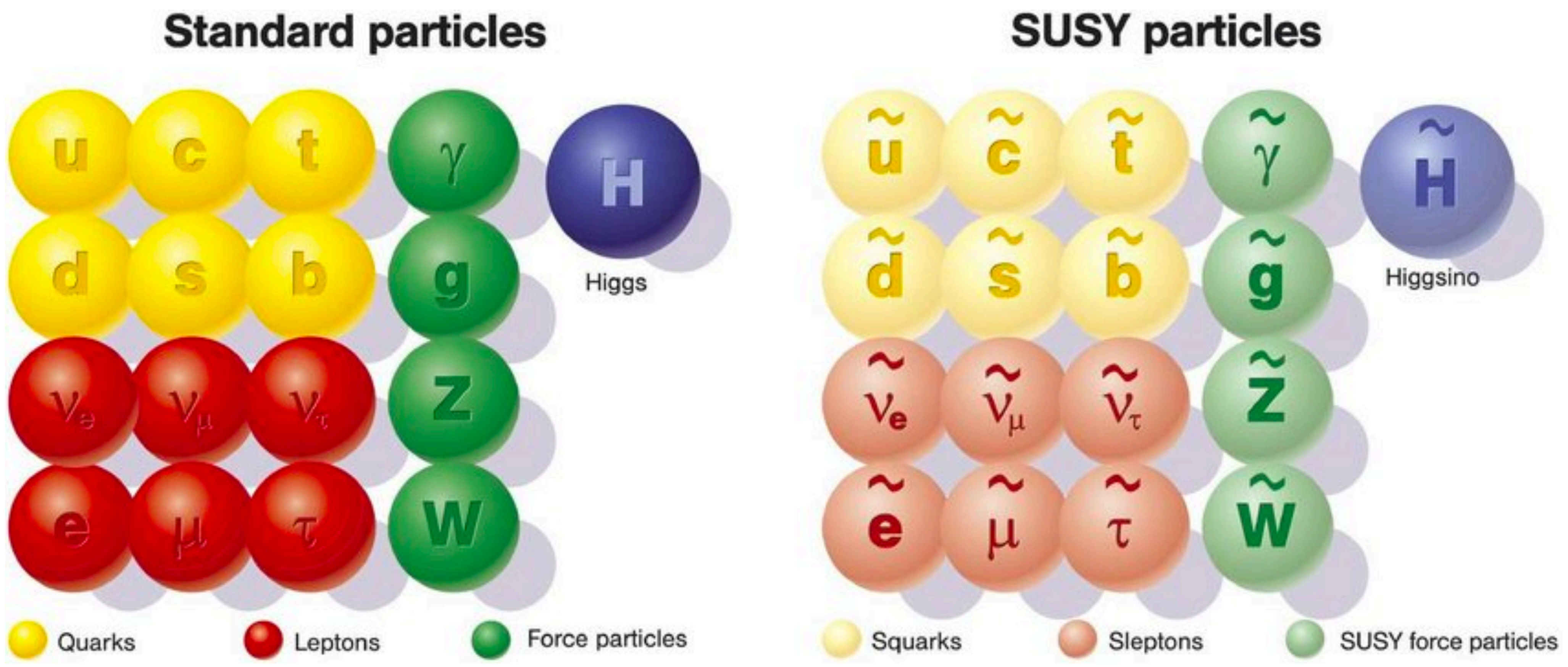
❶ Supersymmetry: A possible solution to the "hierarchy problem"

❷ Each SM particle has its own superpartner and vice versa

❸ R-parity

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

❹ 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

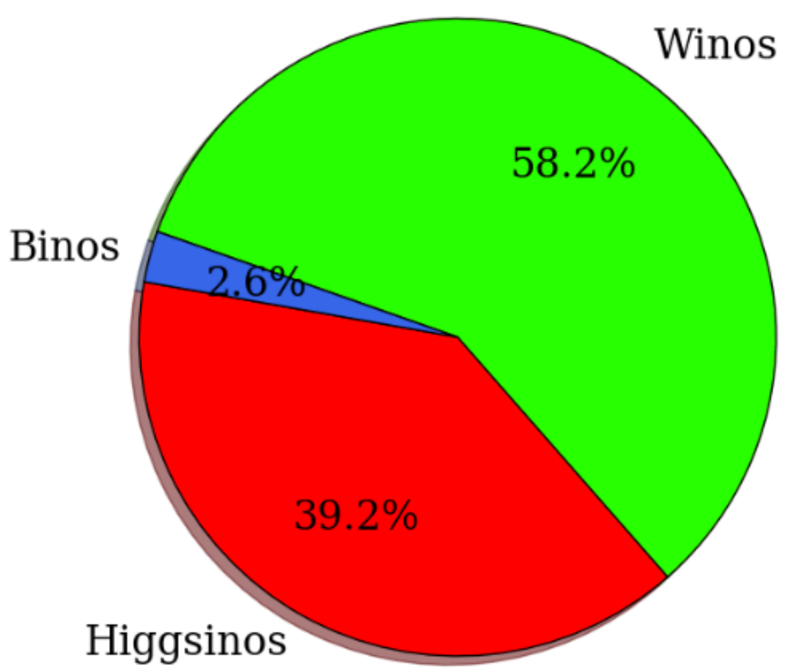
⑥ neutralino annihilation

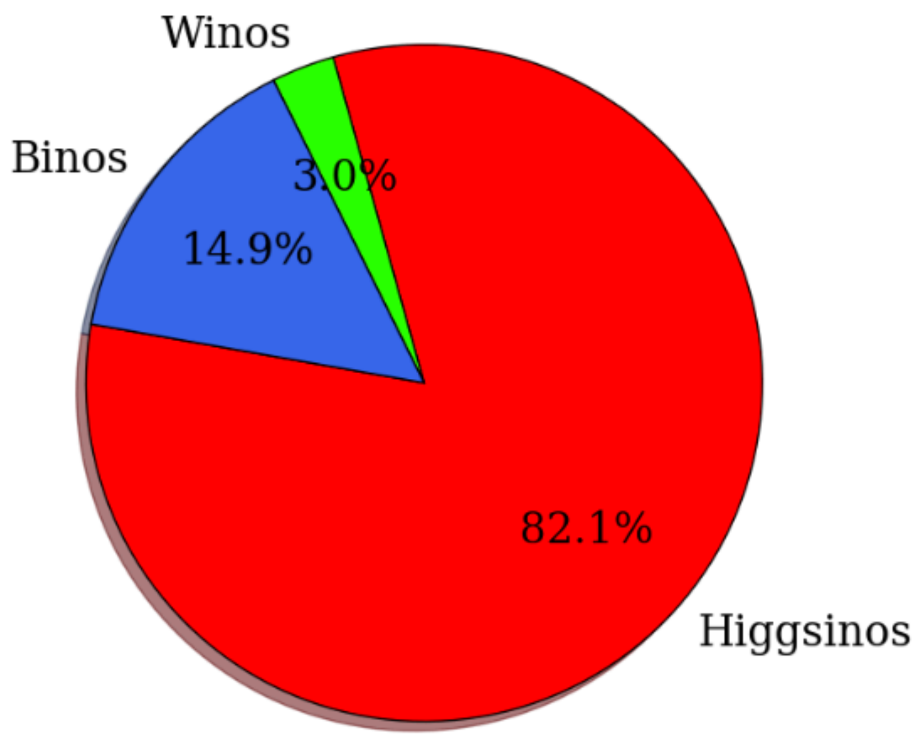
$$\chi + \chi \to f\bar{f}, \text{Higgs, gauge bosons}$$

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

$|\alpha_i|^2 \to 1$ (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

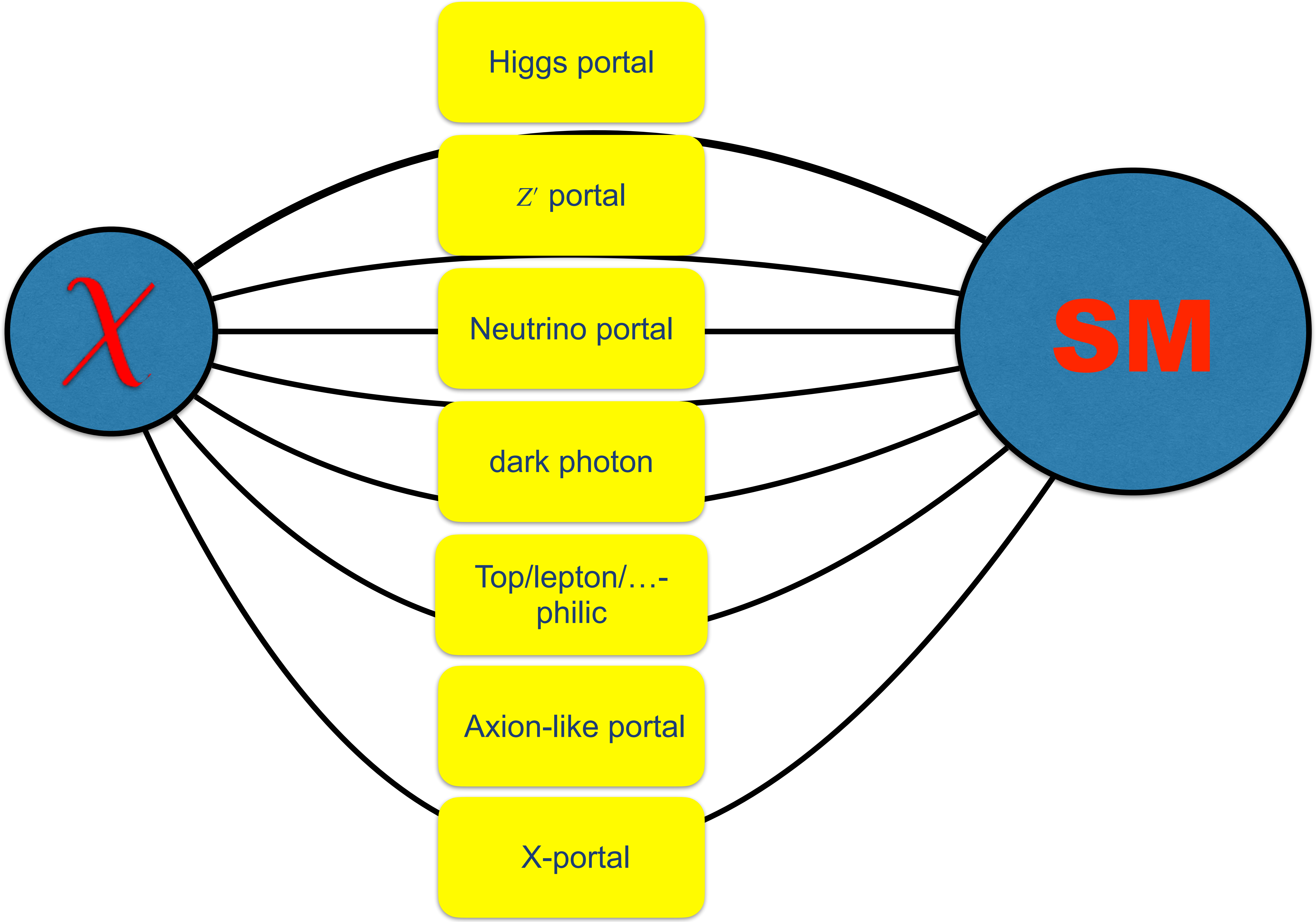
SUSY LSP

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, …

Simplified model



χ

Higgs portal

Z' portal

Neutrino portal

dark photon

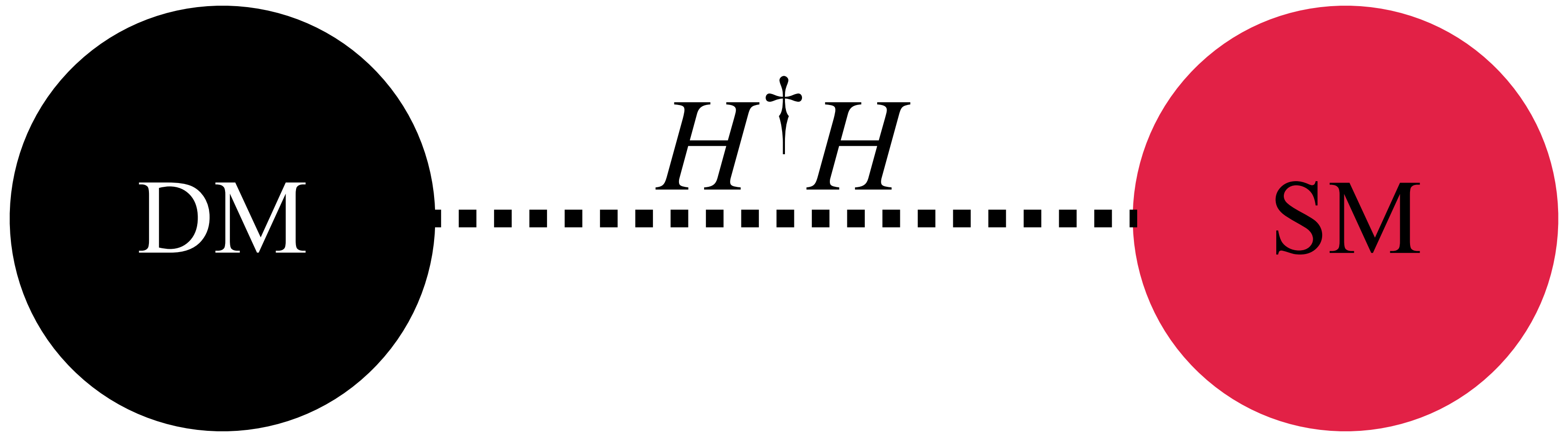
Top/lepton/…-philic

Axion-like portal

X-portal

SM

Simplified model: Higgs portal



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

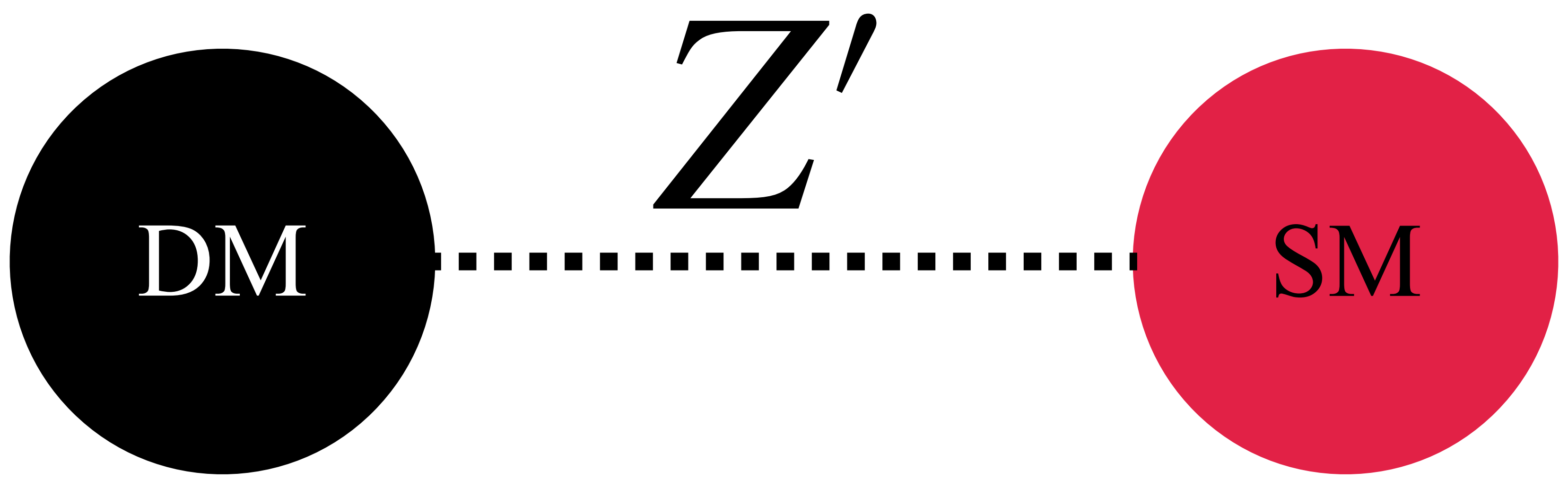
$$\mathcal{L}_V = \mathcal{L}_{\rm SM} - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} + \frac{1}{2}\mu_V^2 V_\mu V^\mu - \frac{1}{4!}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{hV}\, V_\mu V^\mu H^\dagger H,$$

$$\mathcal{L}_\chi = \mathcal{L}_{\rm SM} + \frac{1}{2}\overline{\chi}\left(i\partial\!\!\!/ - \mu_\chi\right)\chi - \frac{1}{2}\frac{\lambda_{h\chi}}{\Lambda_\chi}\left(\cos\theta\,\overline{\chi}\chi + \sin\theta\,\overline{\chi}i\gamma_5\chi\right)H^\dagger H,$$

$$\mathcal{L}_\psi = \mathcal{L}_{\rm SM} + \overline{\psi}\left(i\partial\!\!\!/ - \mu_\psi\right)\psi - \frac{\lambda_{h\psi}}{\Lambda_\psi}\left(\cos\theta\,\overline{\psi}\psi + \sin\theta\,\overline{\psi}i\gamma_5\psi\right)H^\dagger H,$$

1512.06458

Simplified model: Z prime portal



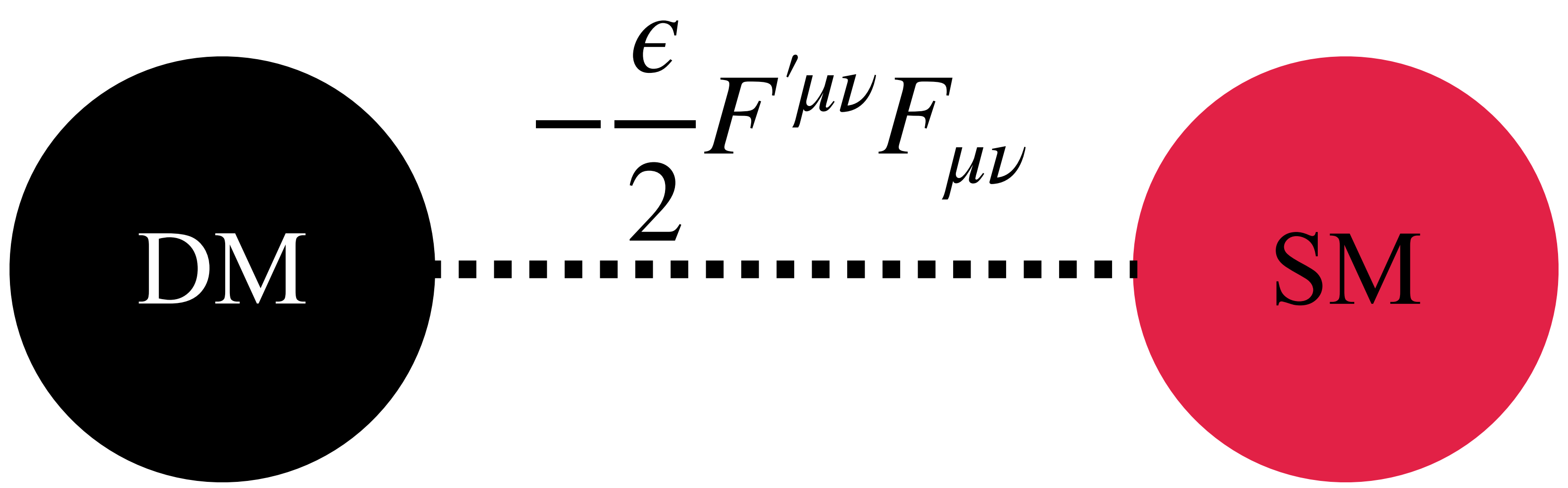
$$\mathcal{L} = Z'_\mu[(g_{Z'}\bar{q}\gamma^\mu q + g_{Z'5}\bar{q}\gamma^\mu\gamma_5 q) + (g_D\bar{\chi}\gamma^\mu\chi + g_{D5}\bar{\chi}\gamma^\mu\gamma_5\chi)]$$

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

1202.2894

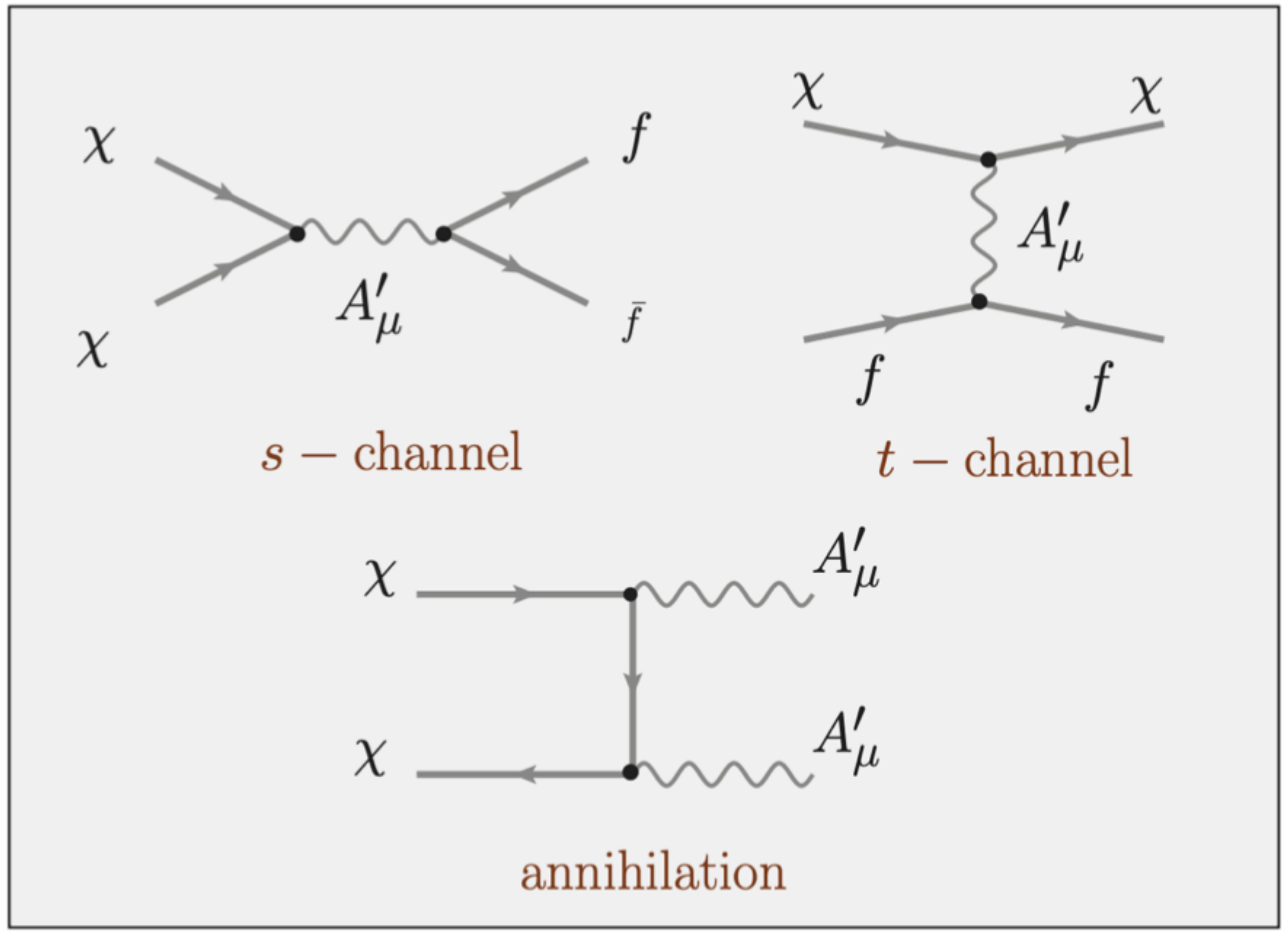
U(1)’-portal

- Massive dark photon



$$-\frac{\epsilon}{2}F'^{\mu\nu}F_{\mu\nu}$$

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



See 2005.01515, 2105.04565 for review on dark photon

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

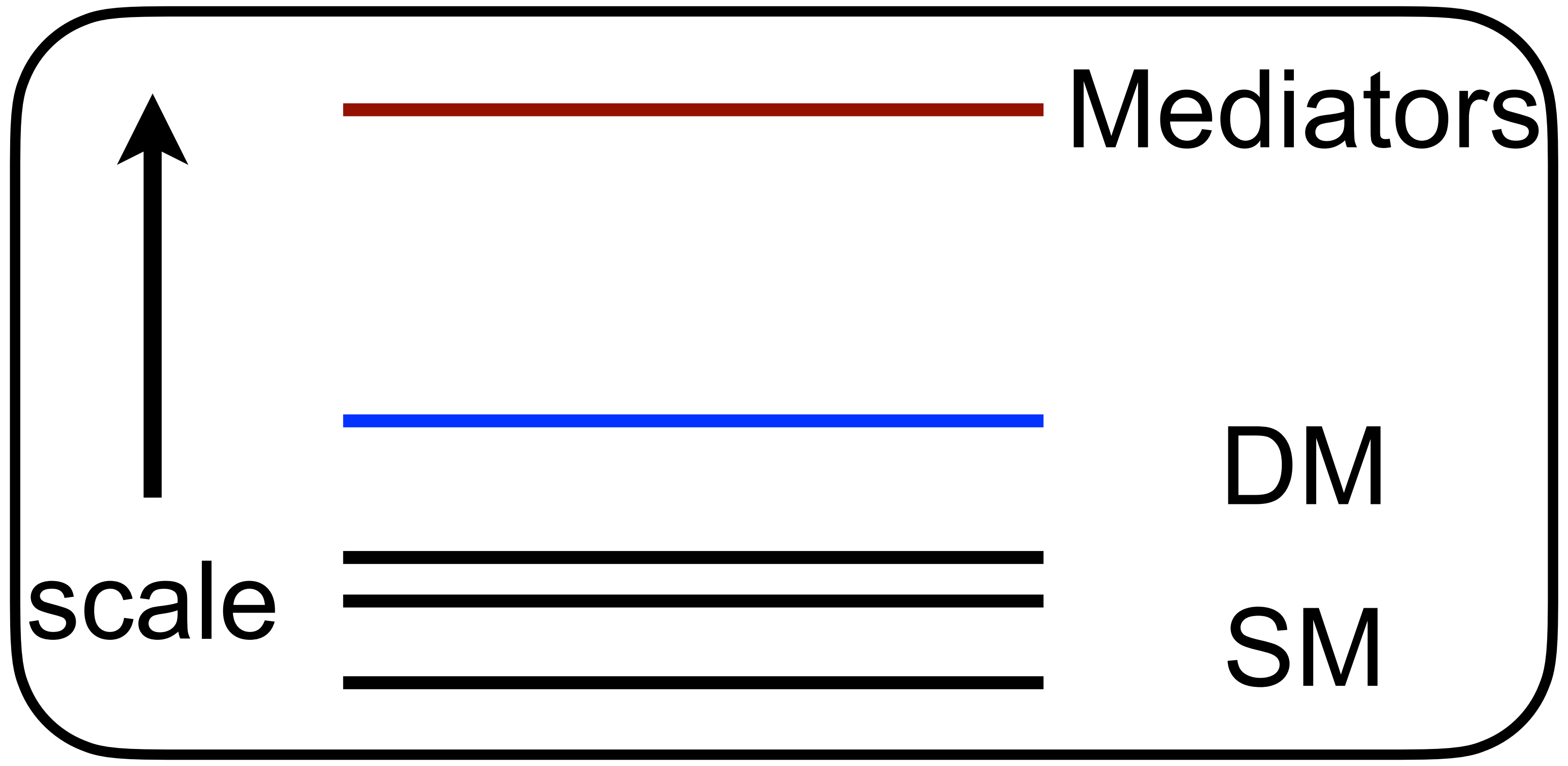
$$\mathscr{L} \supset \epsilon e' A_\mu \bar{\chi}\gamma^\mu \chi$$

milli-charged Dark Matter

有效算符 (Effective Field Theory)

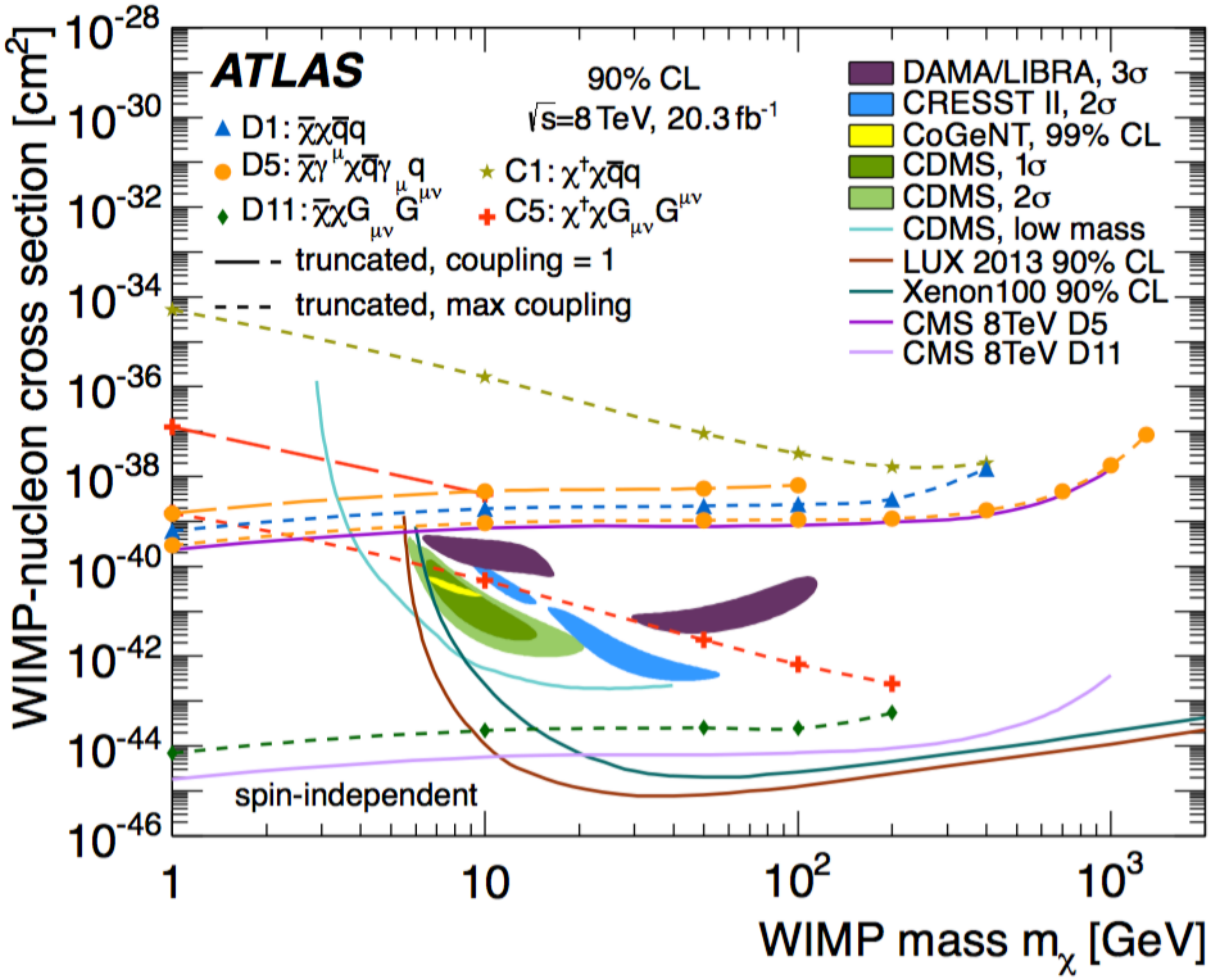
- The mediator is integrated out.
- few parameters: DM mass, effective scale

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	$\bar{\chi}\gamma^5\chi\bar{q}q$	$im_q/2M_*^3$
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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$



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

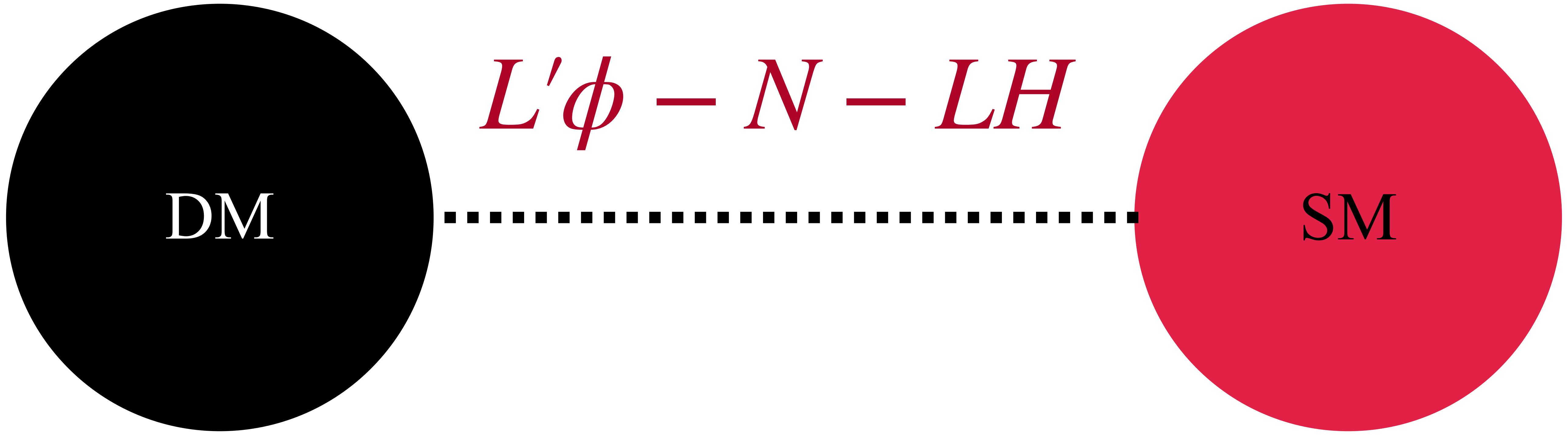
有效算符



1502.01518

Right-handed neutrino portal

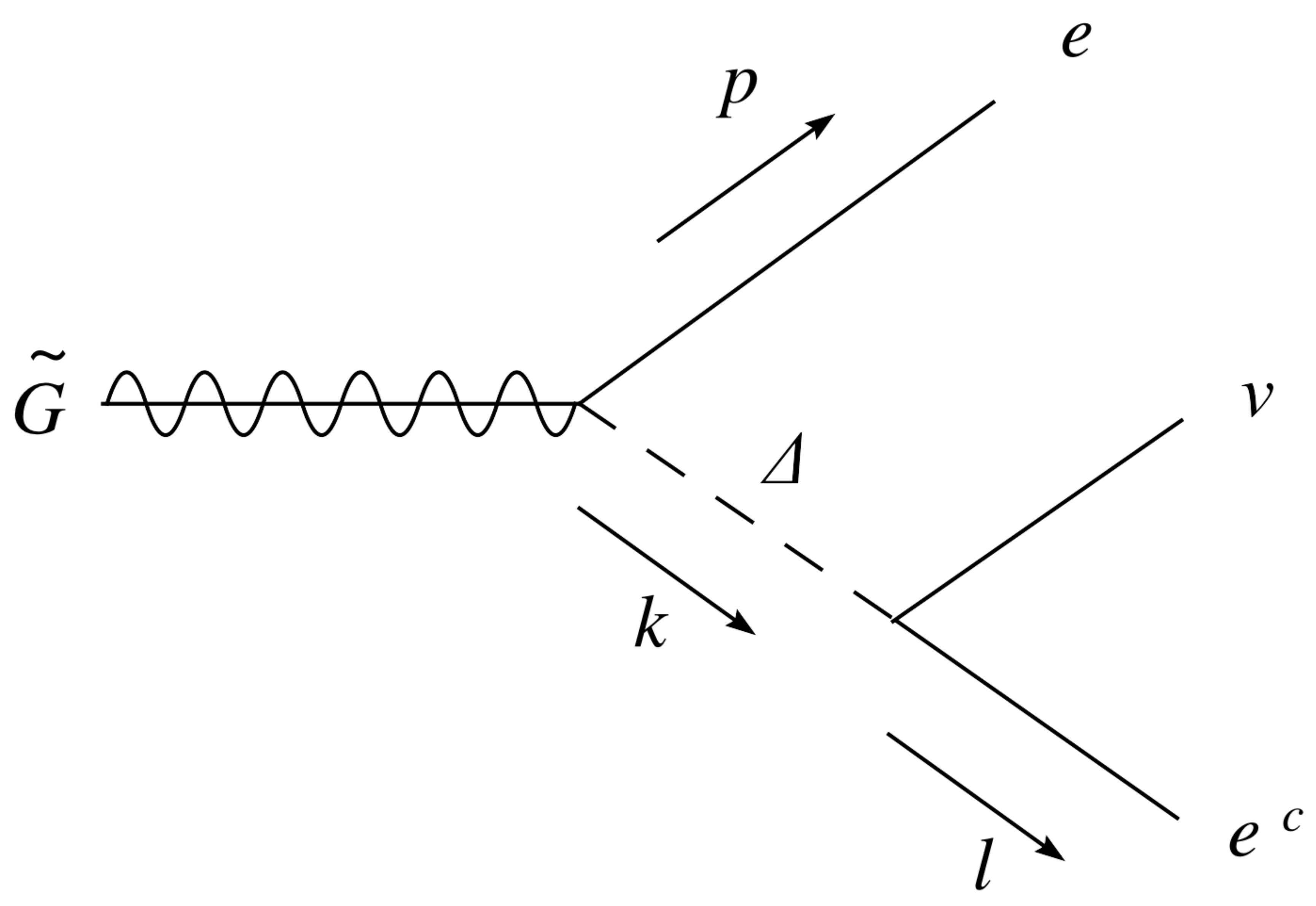
- Seesaw mechanism - origin of neutrino mass and mixing
- Leptogenesis - baryon asymmetry in the Universe
- mediator between dark sector and the SM
- Provide connection between the origins of DM and Baryonic matter.



0911.4463 *one stone three birds*

Triplet Higgs portal

Triplet Higgs generate neutrino mass (Type II seesaw), exclusively couples to leptons



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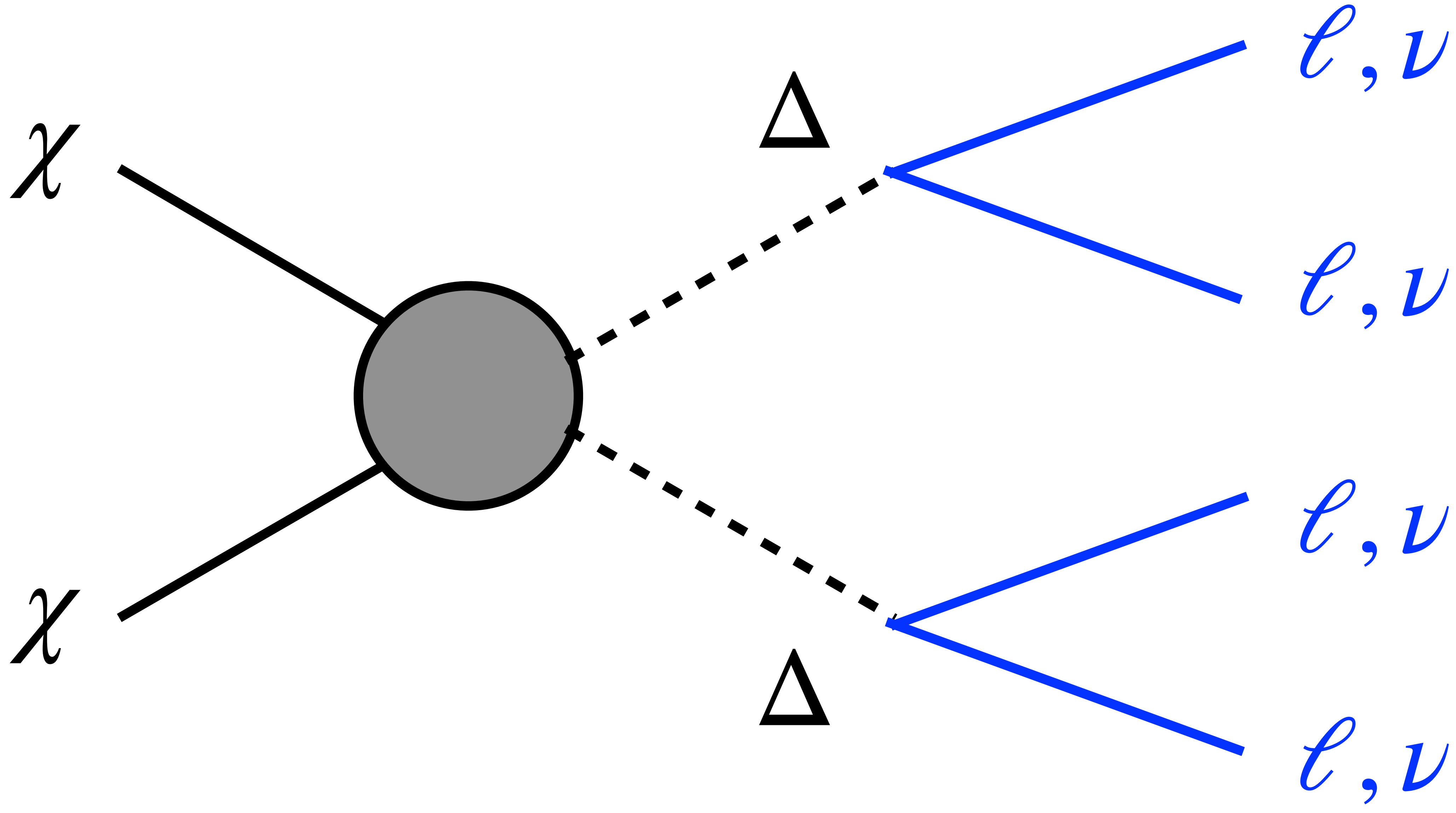


1712.00869, 1804.09835, …

to explain the electron/positron excess observed by PAMELA, Fermi-LAT , AMS02 , DAMPE…

Sneutrino Dark Matter

Sneutrino

- LH Sneutrino as DM candidate, ruled out by direct detection
- SM+ RH neutrino for neutrino mass generation
- RH sneutrino non-thermal DM (Freeze-in)
- RH sneutrino + LH sneutrino mixing state as (thermal) DM candidate

keV Sterile Neutrino as Dark Matter

- 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)

- The sterile neutrino:

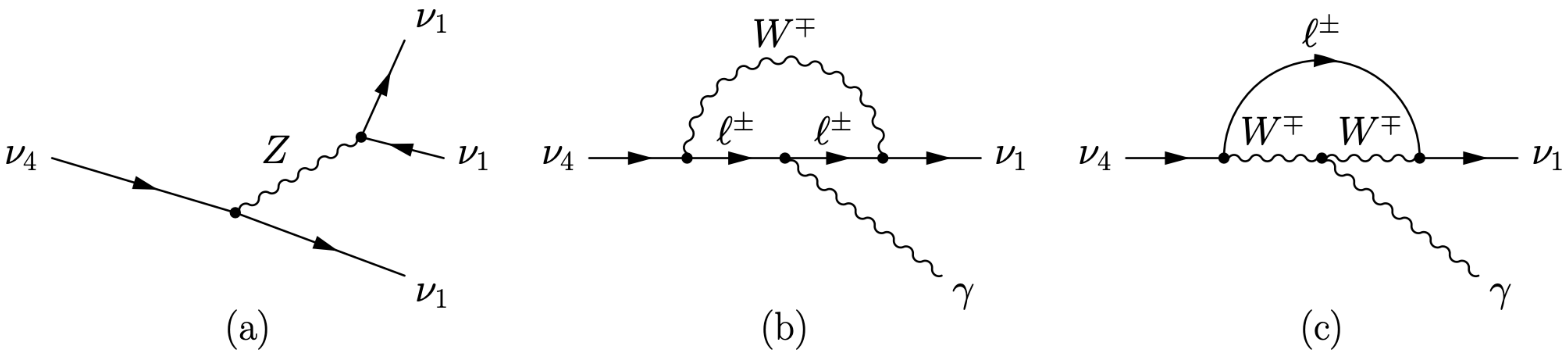
$$\nu_s = \cos\theta N_R + \sin\theta \nu_L$$

produced by oscillations, the abundance of ν_s : Freeze-in non-thermal relics

$$\Omega_s h^2 \sim 0.1 \frac{\sin^2 2\theta}{10^{-8}} \left(\frac{m_s}{3\mathrm{keV}}\right)^{1.8}$$

Phys. Rept. 481,1

keV Sterile Neutrino



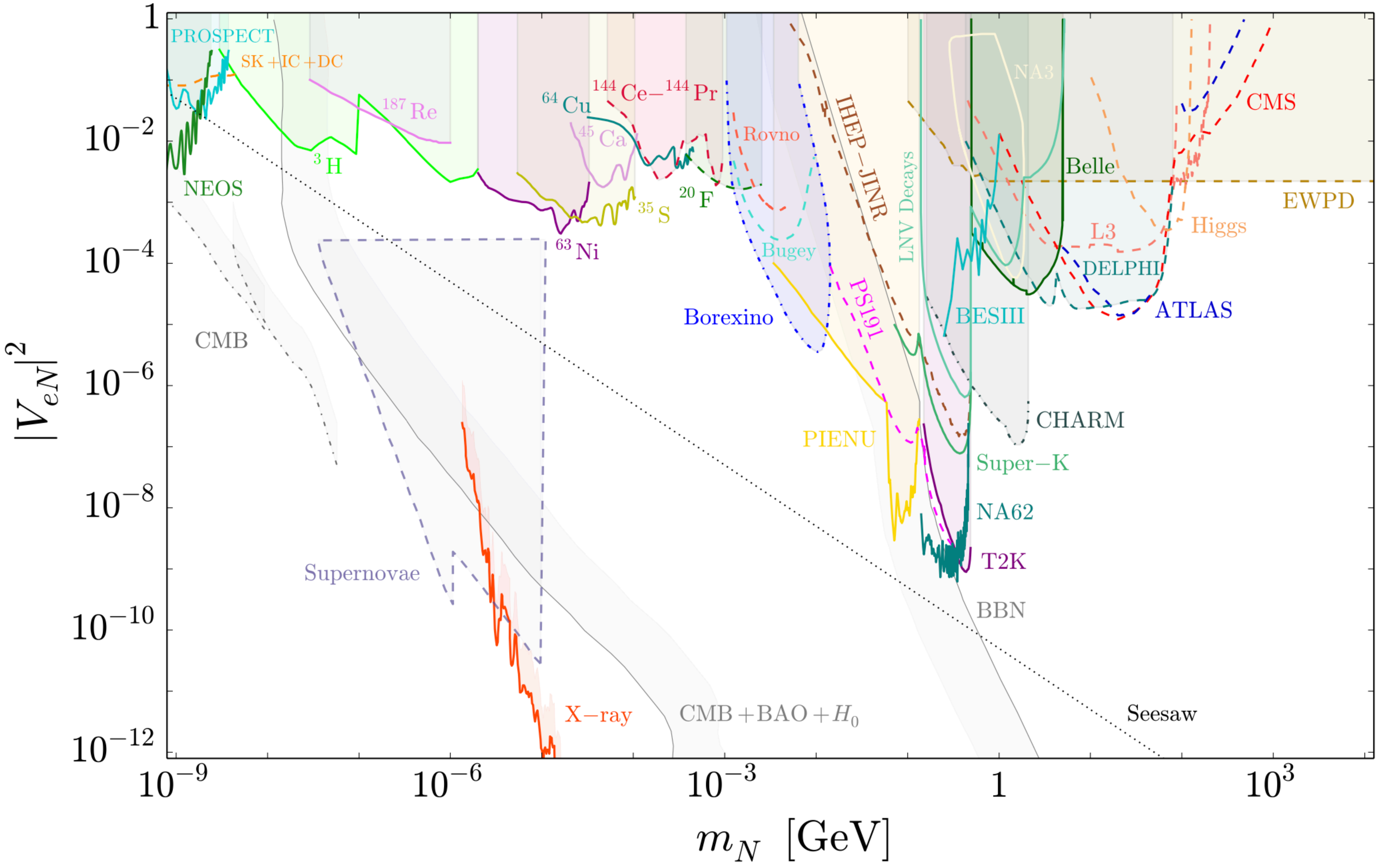
The lifetime:

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

$$\nu_s \to \nu + \gamma$$

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

keV Sterile Neutrino



Scotogenic Neutrino mass models

Neutrino radiative Majorana mass and dark matter

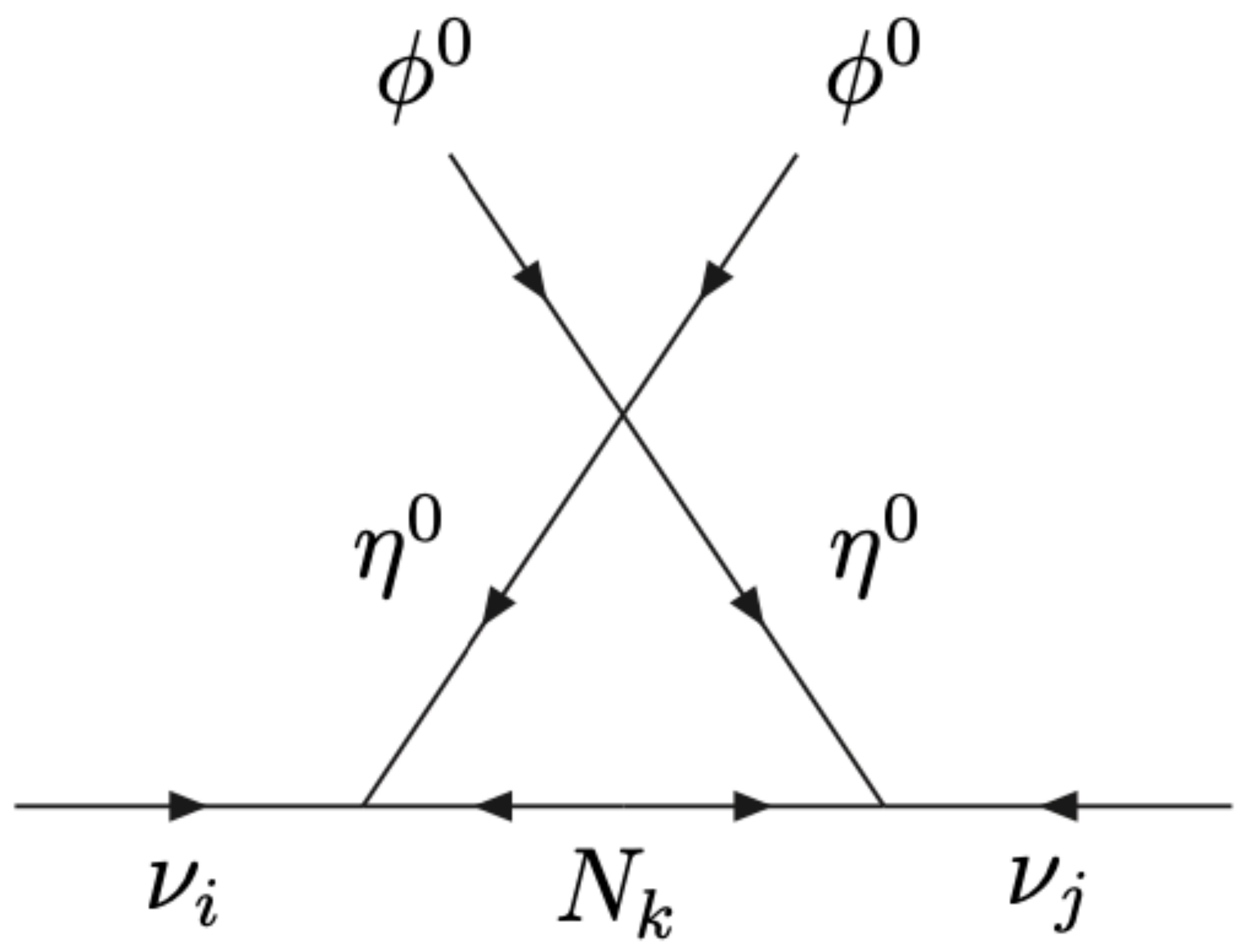


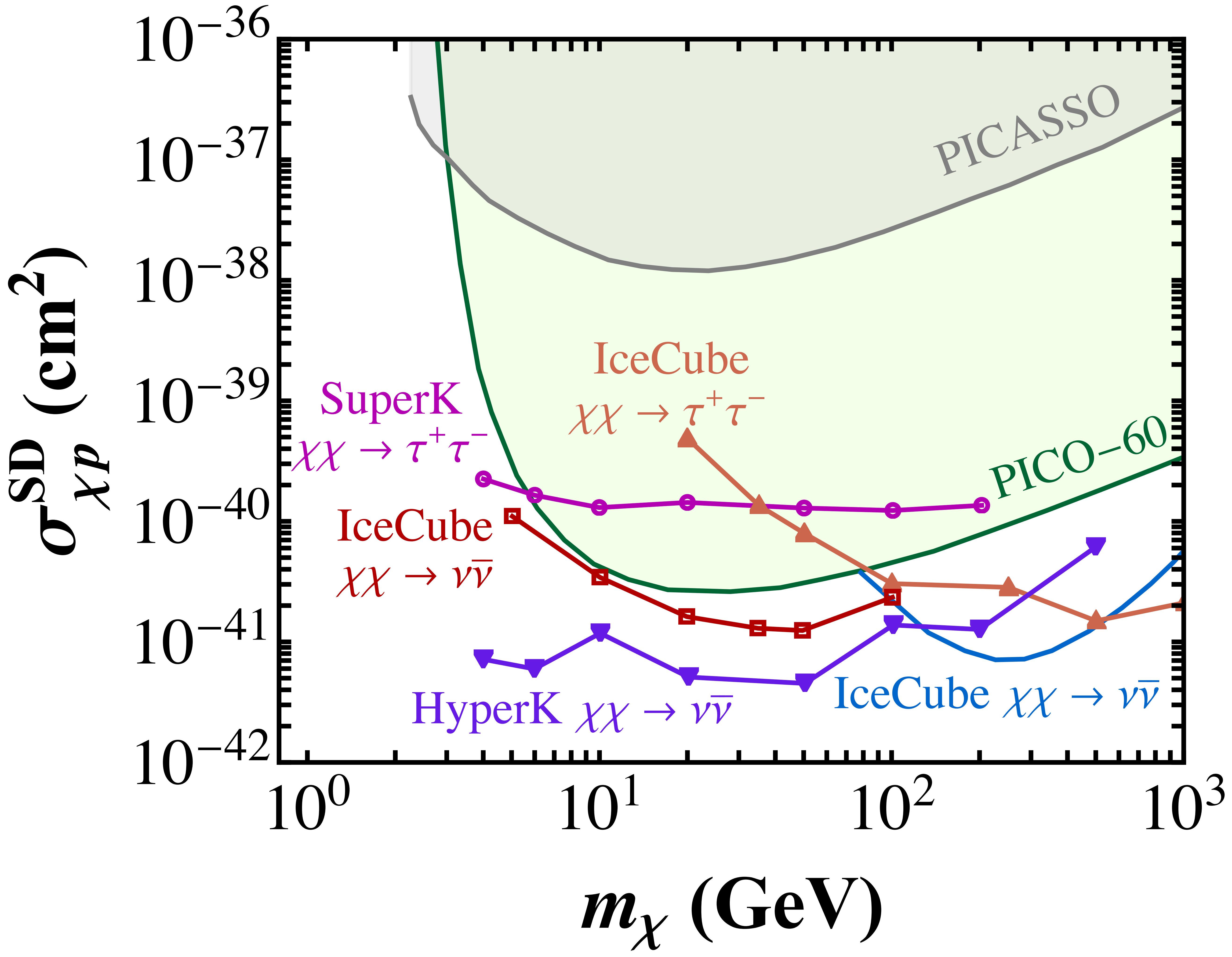
Figure 1: One-loop generation of neutrino mass.

N_k, η (singlet, doublet) are odd under a new Z_2 symmetry, forbid tree level seesaw and provide stable dark matter

Ma Model hep-ph/0601225 1400+ citations

中微子+暗物质实验

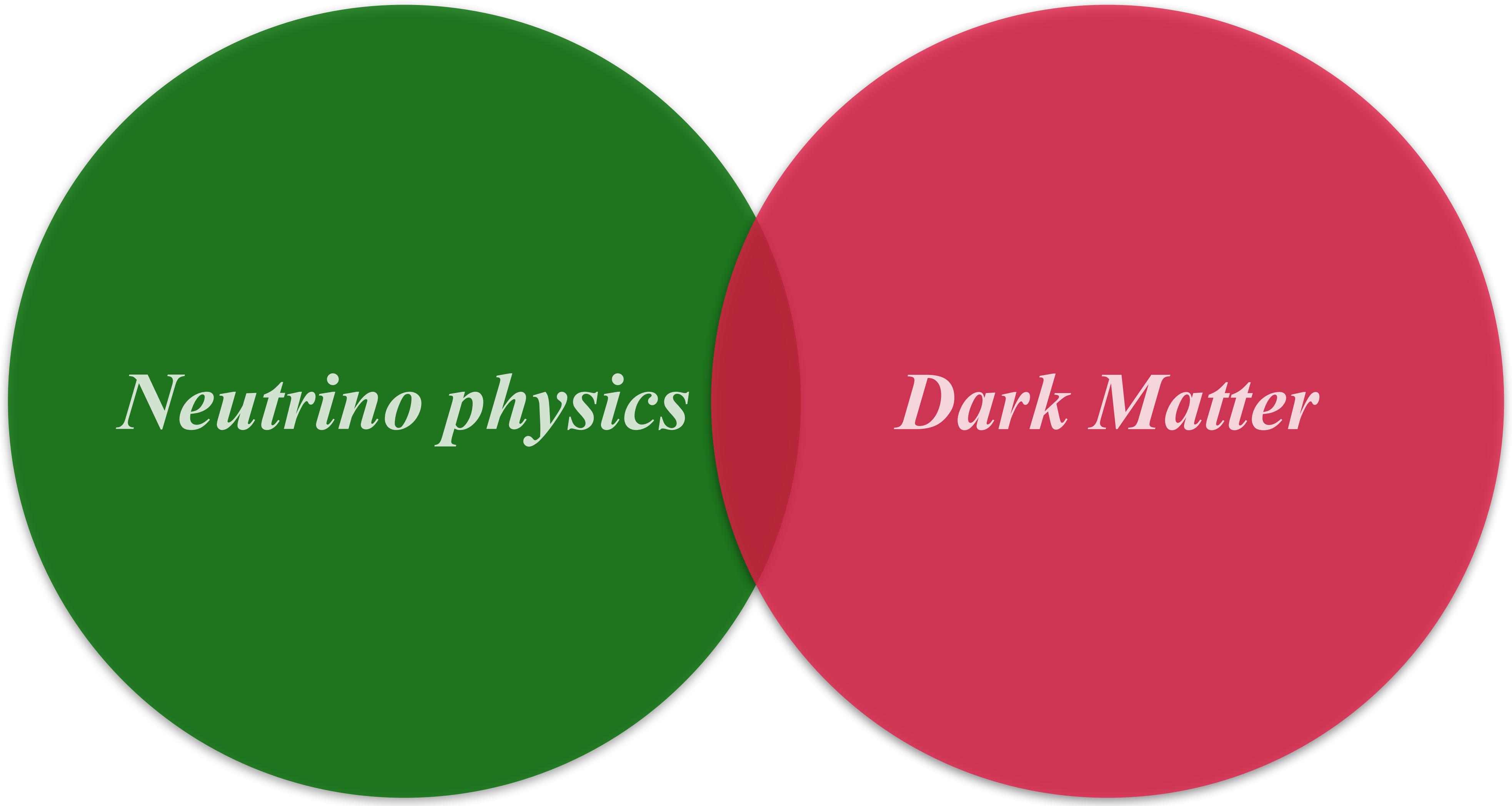
宇宙射线中的高能中微子信号，如太阳内部暗物质湮灭产生的中微子信号



中微子+暗物质实验

- 银心暗物质源中微子信号 (Super-Kamiokande, IceCube, Antares, Hyper-Kamiokande, JUNO, DUNE, KM3NeT, IceCube-Gen2 ⋯)
- 中微子实验上探测轻暗物质
- 超重暗物质和高能中微子信号
- 暗物质直接探测实验探测中微子

中微子和暗物质物理将持续作为活跃的研究领域，需要更多的想法和努力，将带来更多有趣的物理。



Neutrino physics

Dark Matter