Direct and Indirect Probes for Dark Matter : from Recoil Electrons to Gravitational Waves

Soroush Shakeri

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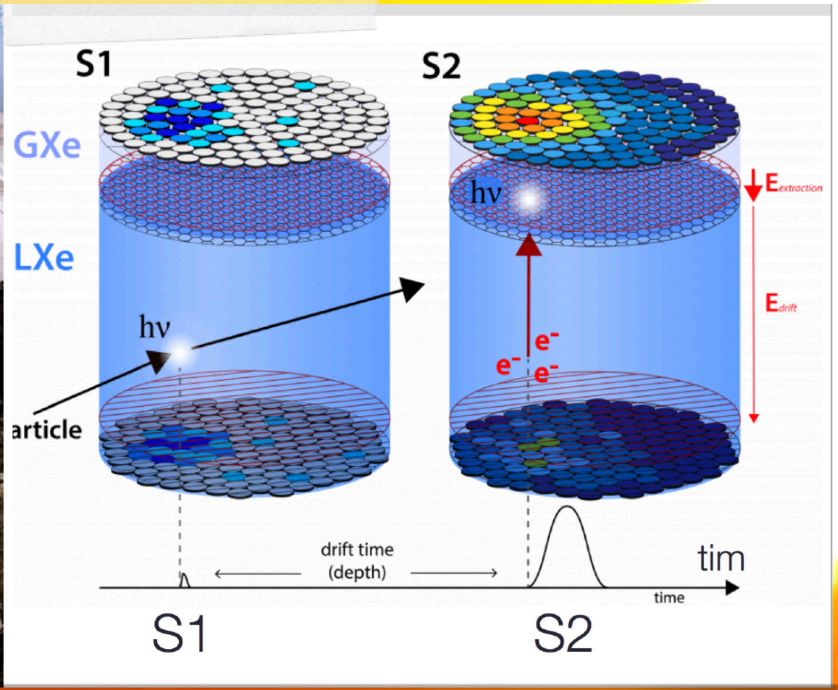
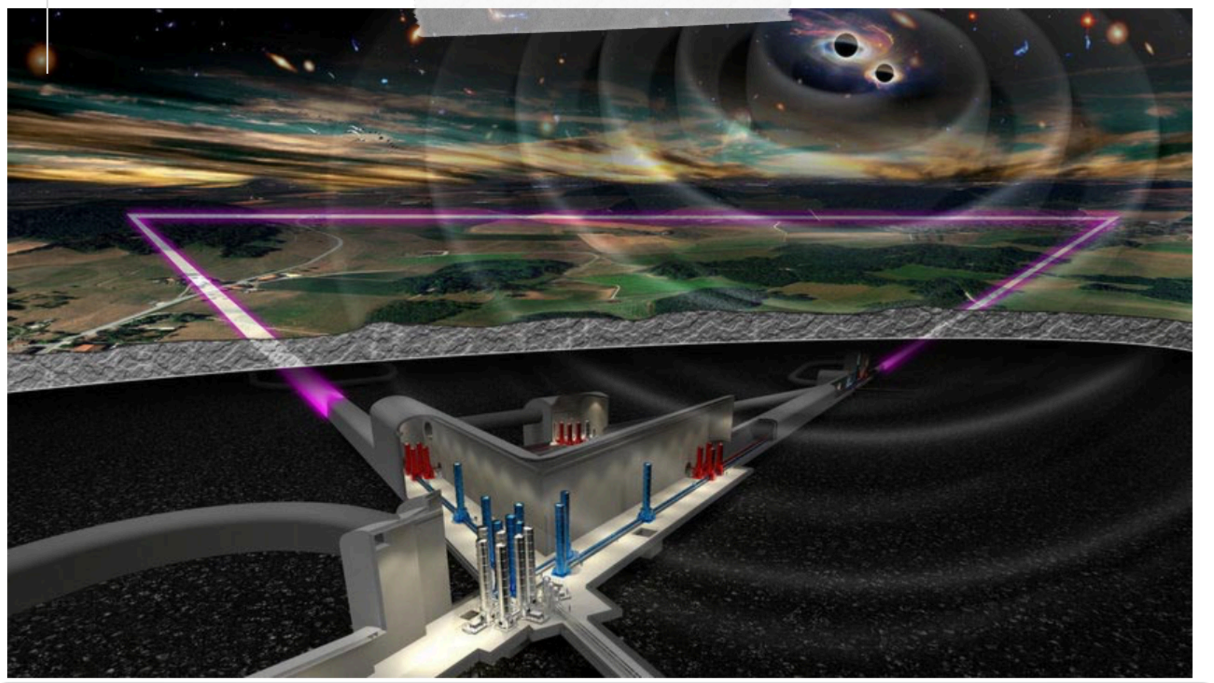
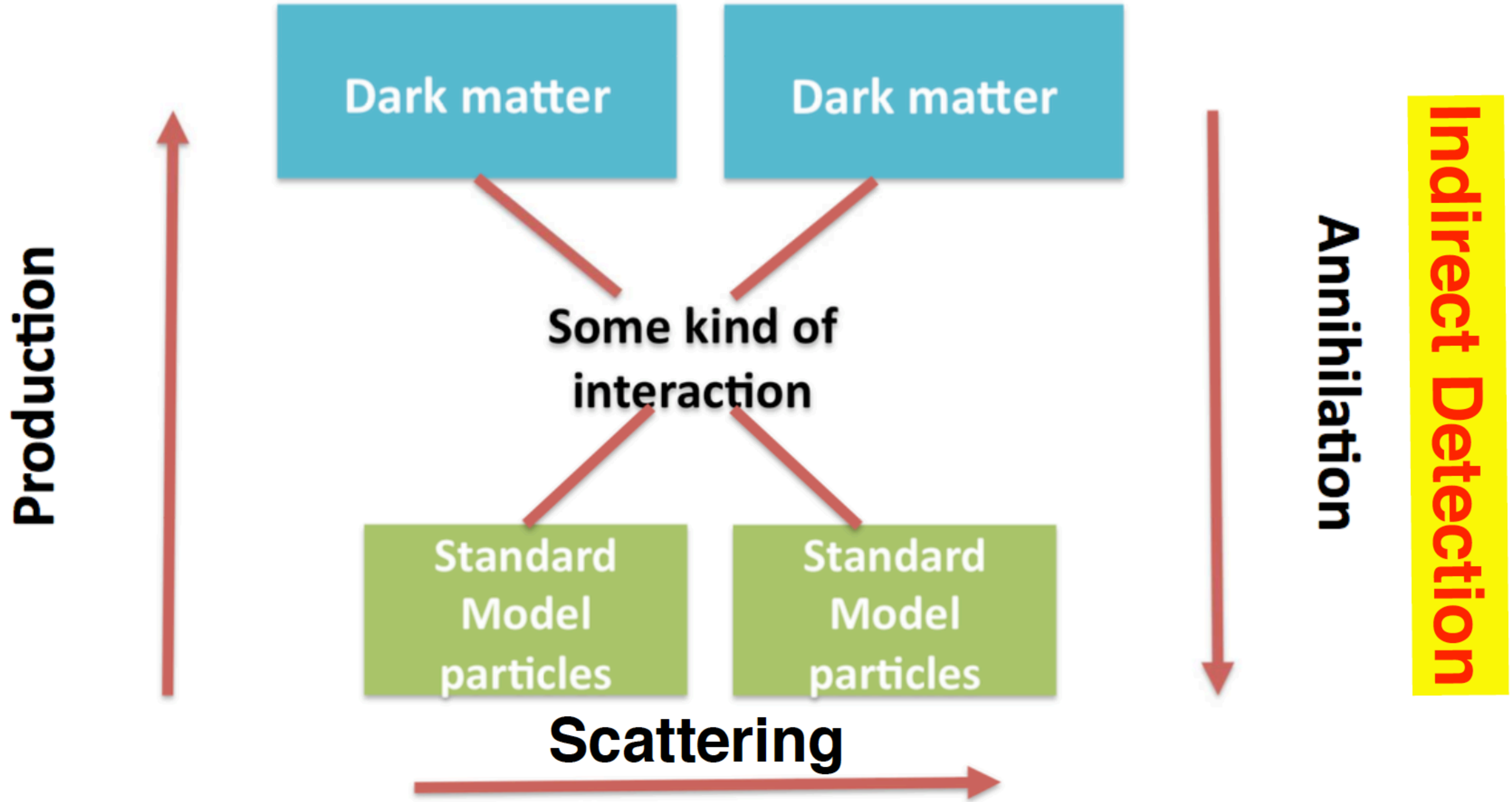




S. Shakeri, F. Hajkarim, and S.-S. Xue, **JHEP12(2020)194.**

D.R. Karkevandi, **S. Shakeri**, V. Sagun, O. Ivanytskyi, [**ArxiV: 2109.03801]. To be appeared in PRD soon**

Dark Matter Search Strategies



Dark matter

Dark matter

Some kind of interaction

Standard Model particles

Standard Model particles

Production

Annihilation

Indirect Detection

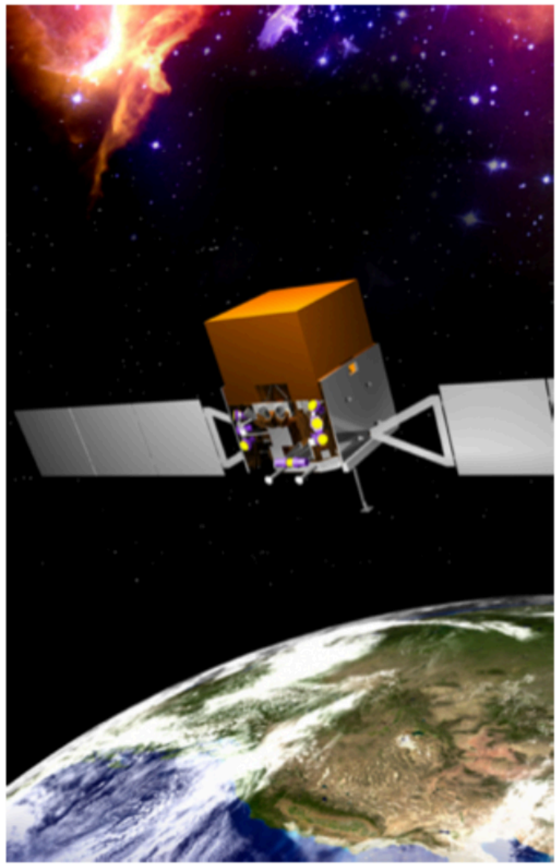
Scattering

Direct Detection

Dark Matter Search Strategies

Indirect detection

DM->GW, M(R)



$\chi\bar{\chi} \rightarrow \gamma\gamma, q\bar{q}, \ldots$

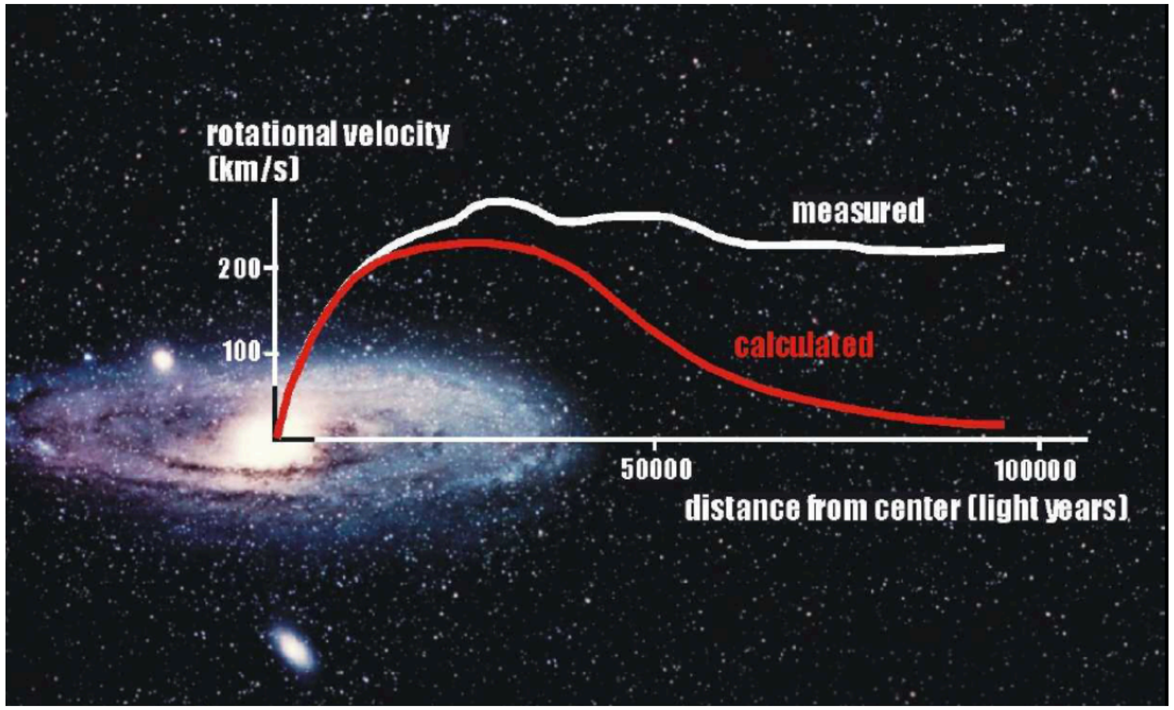
Direct detection

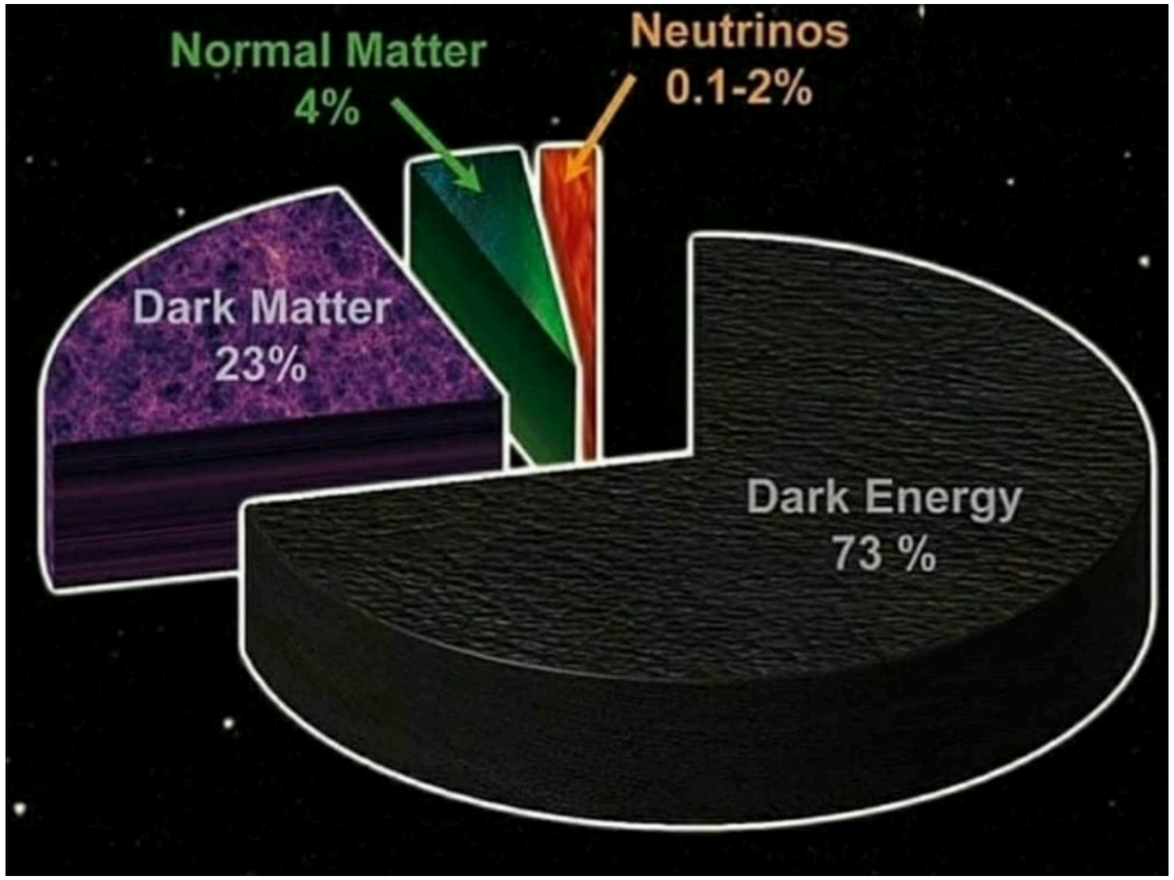
$\chi\,\mathrm{N} \rightarrow \chi\,\mathrm{N}$

Production at LHC

$\mathrm{p} + \mathrm{p} \rightarrow \chi\bar{\chi} + \mathrm{X}$

Nature volume 562, pages51–56(2018)





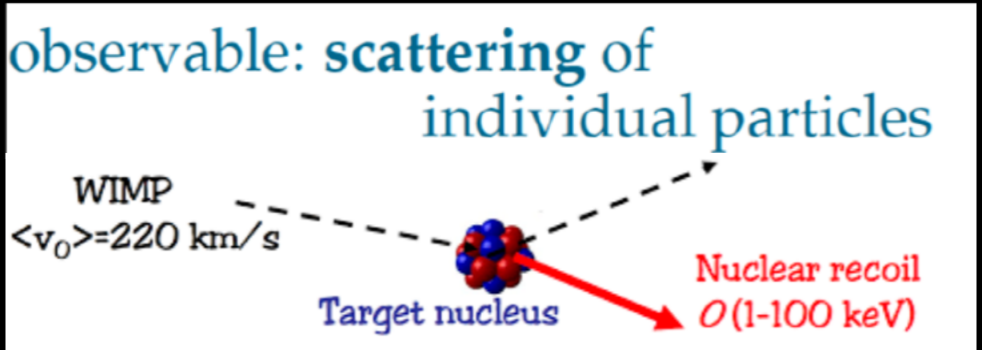
- The existence of dark matter is confirmed via multiple independent observations:
  - Galactic rotation curves and velocity dispersions.
  - Gravitational lensing of galaxy clusters.
  - CMB power spectrum.
  - Structure formation.
- All of these observations are based on the **gravitational** interactions between DM and visible matter.

Dark Matter particle mass range

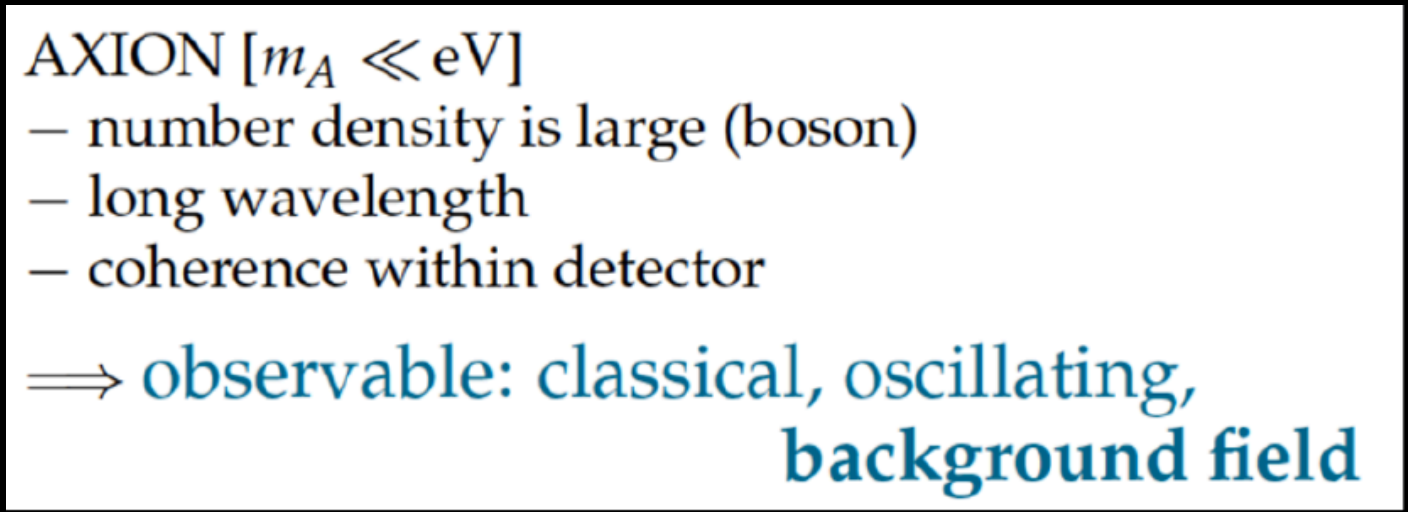
Weakly Interacting Massive Particle (WIMP)

WIMP range: $m_{\text{proton}} < m < 1$ TeV

- Thermally produced in the early universe
- Interactions only through weak nuclear force and gravity
- tiny de Brogli-wavelength - (Particle behavior)
- Cold Dark Matter


observable: **scattering** of individual particles

Axion Dark Matter


AXION [$m_A \ll$ eV]

– number density is large (boson)

– long wavelength

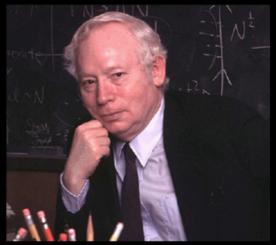
– coherence within detector

$\Longrightarrow$ observable: classical, oscillating, **background field**

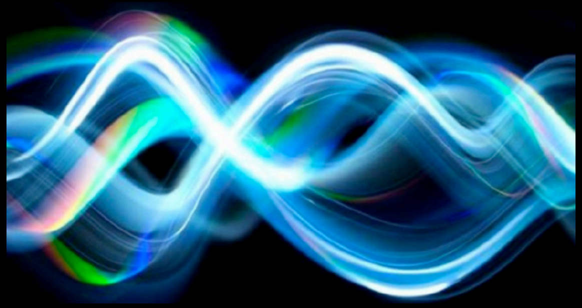

Frank Wilczek


Roberto Peccei

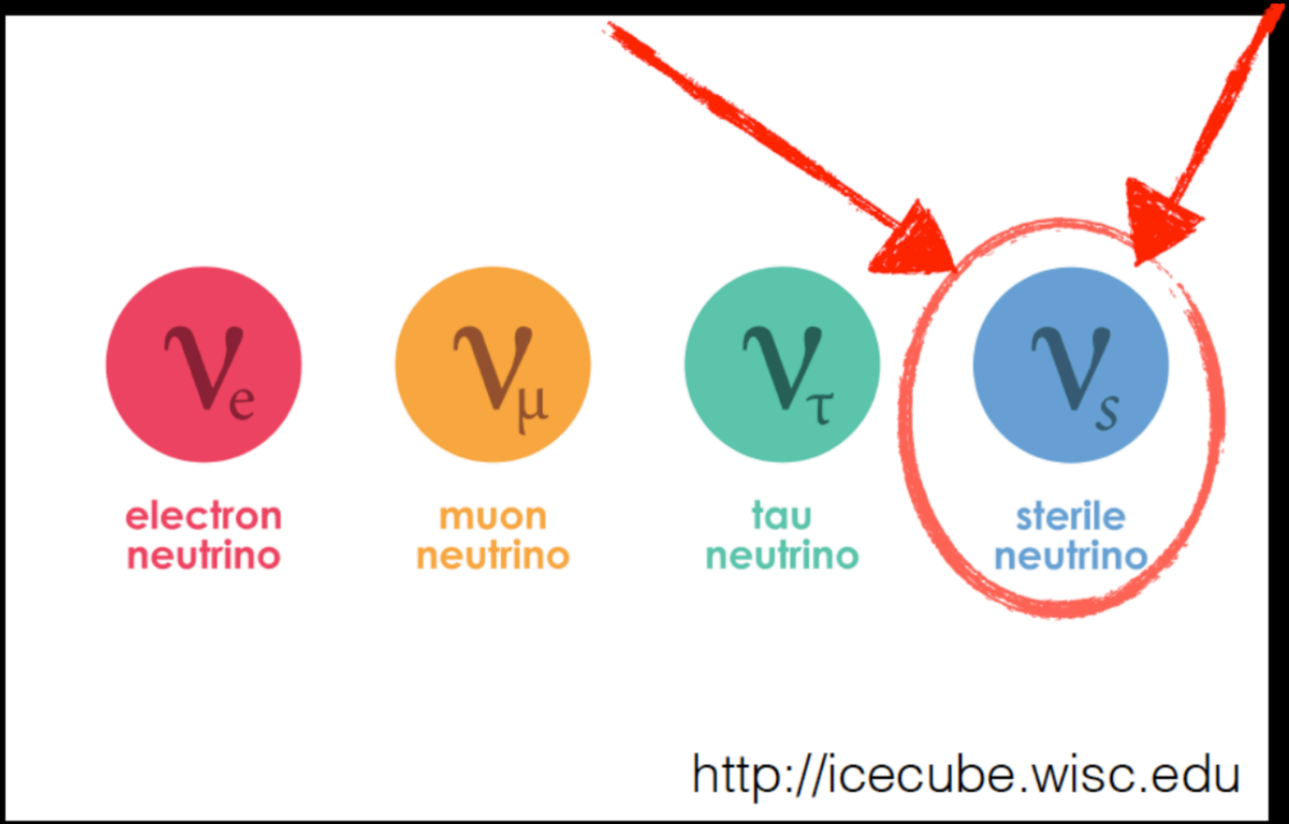

Helen Quinn


Steven Weinberg

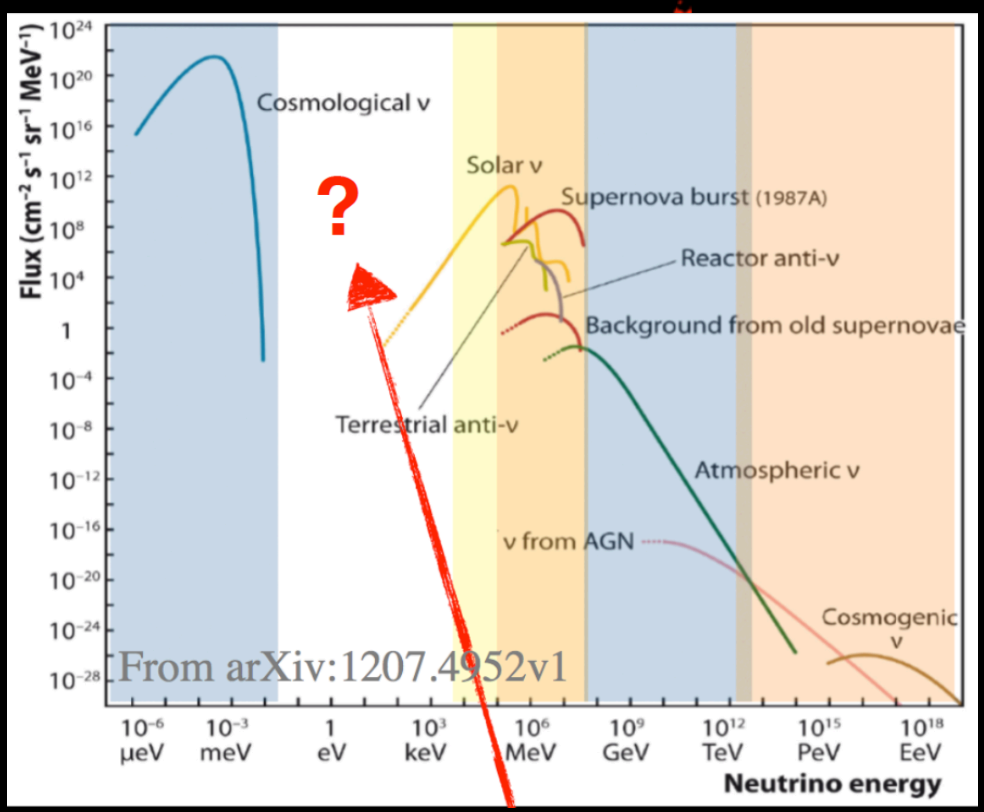
Peccei & Quinn 1977
Wilczek 1978
Weinberg 1978



Warm Dark Matter Sterile Neutrino



http://icecube.wisc.edu



From arXiv:1207.4952v1

The neutrino spectrum at all energies

- Thermally produced in the early universe
- few keV < m < GeV
- Mixing with SM neutrinos in extension of SM
- keV mass sterile neutrinos are over produced in early universe

?? Come back to this !!!!

Sterile Neutrino DM

S. Dodelson and L. M. Widrow, Phys. Rev. Lett. 72, 17 (1994), arXiv:hep-ph/9303287 [hep-ph].

J. R. Bond, A. S. Szalay, and M. S. Turner, Phys. Rev. Lett. 48, 1636 (1982).

I. Z. Rothstein, K. S. Babu, and D. Seckel [Nucl. Phys. B403, 725 (1993)

Lee B.W.; Weinberg S. (1977). "Cosmological Lower Bound on Heavy-Neutrino Masses". Physical Review Letters. 39 (4): 165–168.

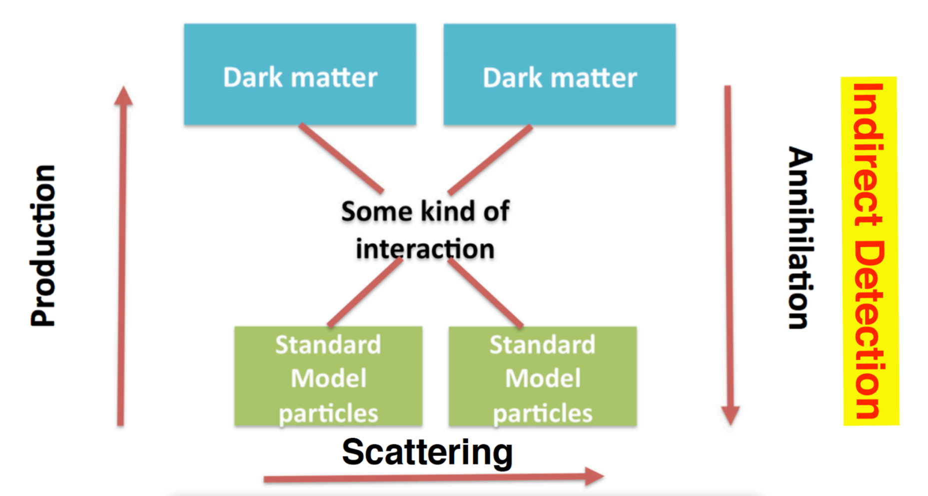
Direct Detection Experiments

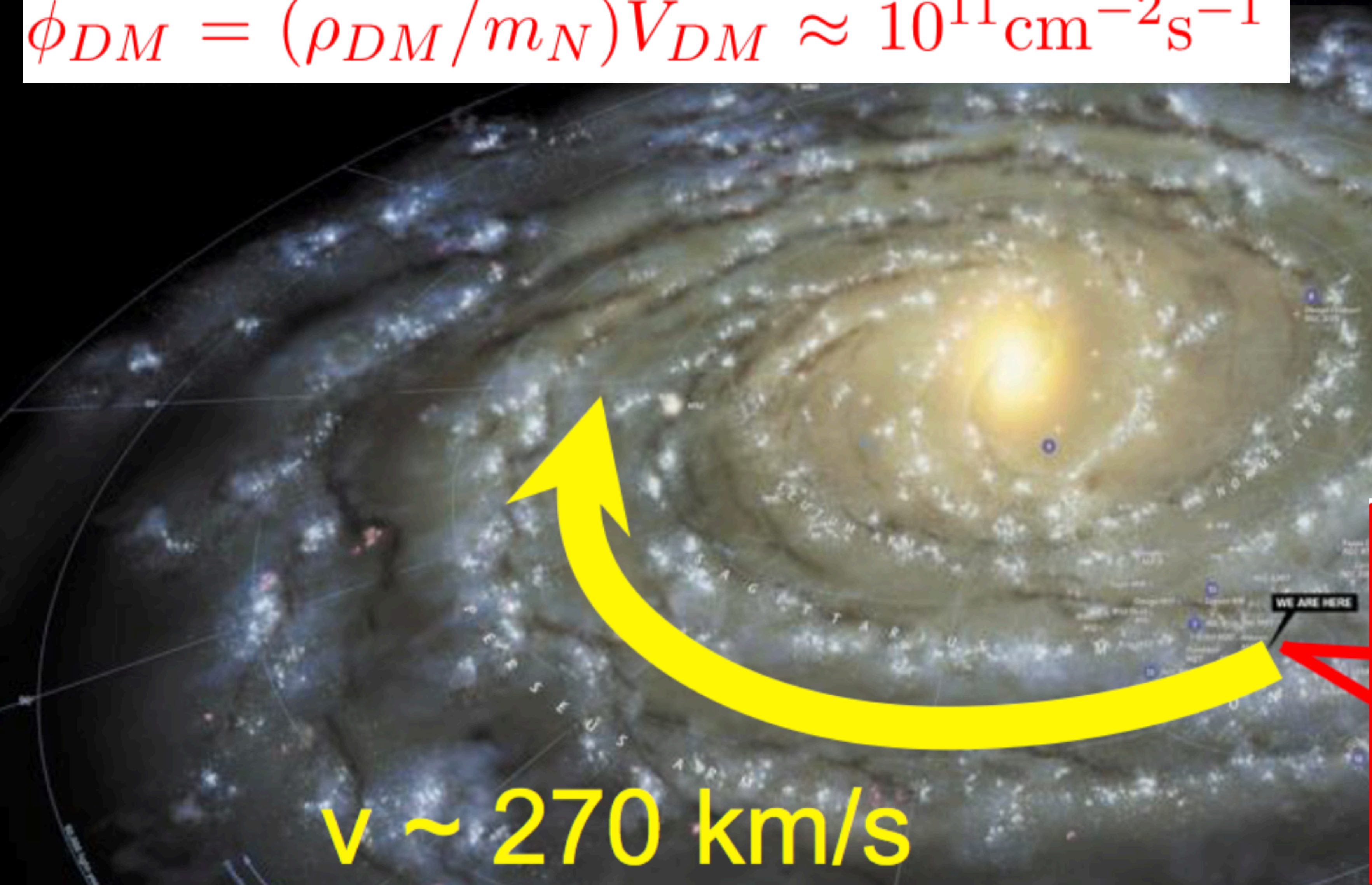
DM Local Density

$$\rho_{DM} \sim 0.4 \frac{GeV}{cm^3}$$

$$m_{DM} \approx 100\,\mathrm{keV}$$

$$\phi_{DM} = (\rho_{DM}/m_N)V_{DM} \approx 10^{11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

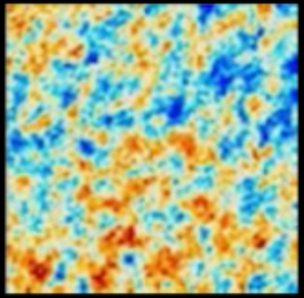




v ~ 270 km/s

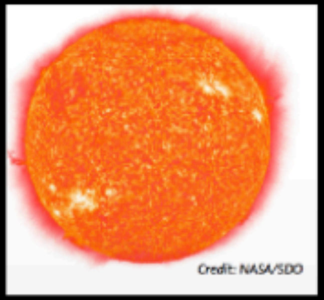
CMB flux

$$\phi_{CMB} \approx 1.23 \times 10^{13}\, cm^{-2} s^{-1}$$



Neutrino flux from the proton-proton fusion inside the sun

$$\phi_{\nu,pp} \approx 6 \times 10^{10}\ \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$$



Credit: NASA/SDO

Billard with invisible Balls

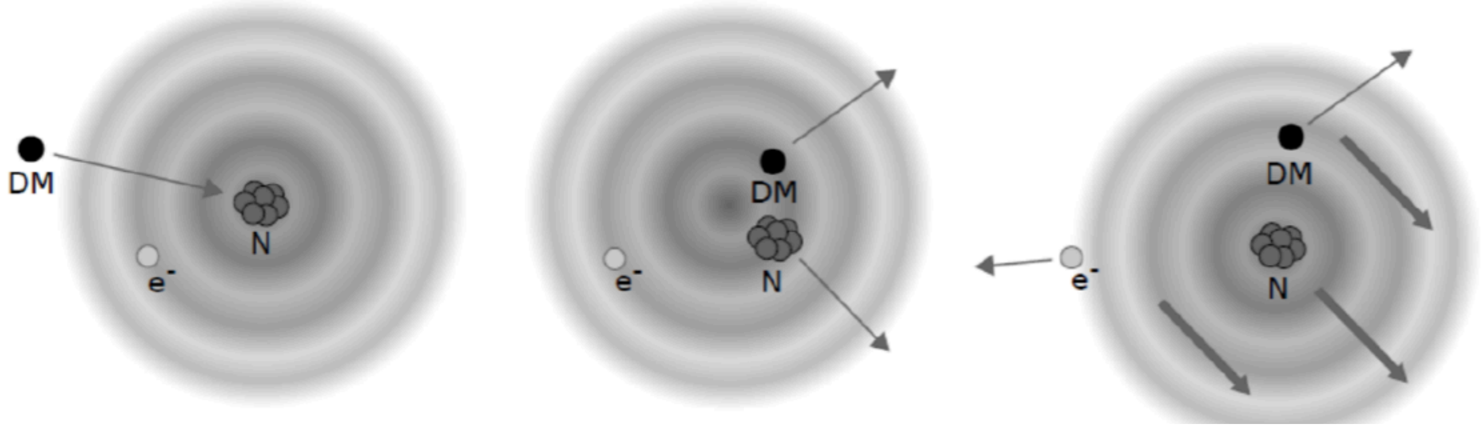
Elastic Scattering

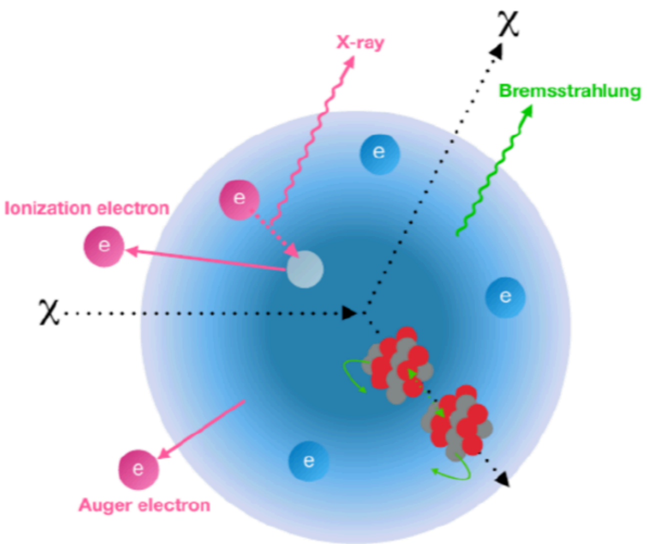
$$\Delta E_k = \frac{1}{2} M_D (v_f^2 - v_i^2) \approx 0.5 \times 10^{-6} M_D c^2$$

$m_D = 2$ MeV $\Rightarrow \Delta E_k \approx 2$ eV

Technological Challenges in Low-mass region

Inelastic Scattering



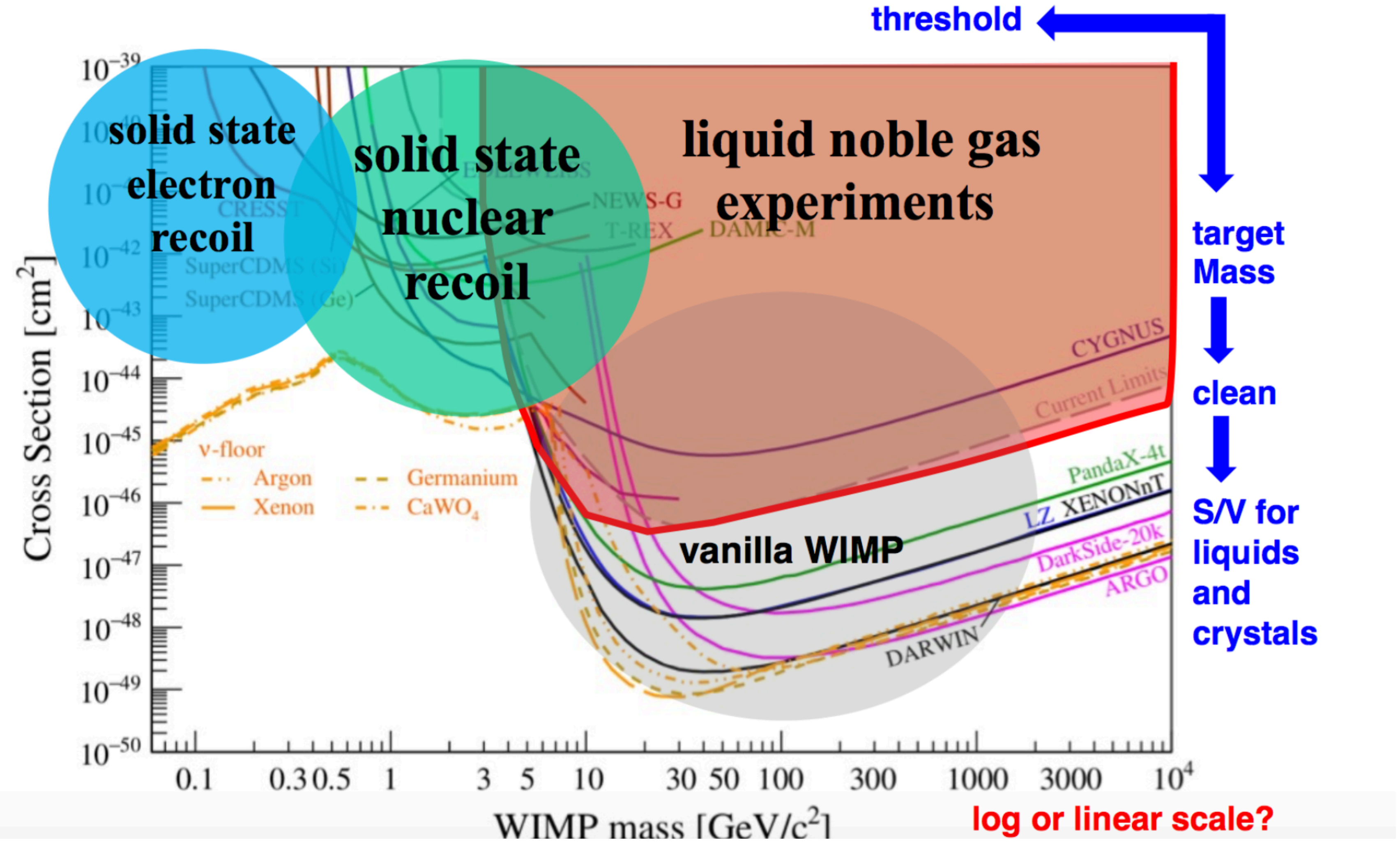


Recoil energy

e^- recoil due to the absorption of DM by e^-

$$T_e \approx m_{DM}^2 / 2m_e = 2.45 \text{ keV} (m_{DM}/50 \text{ keV})^2$$

Low-mass (Sub-GeV) DM detectors



threshold

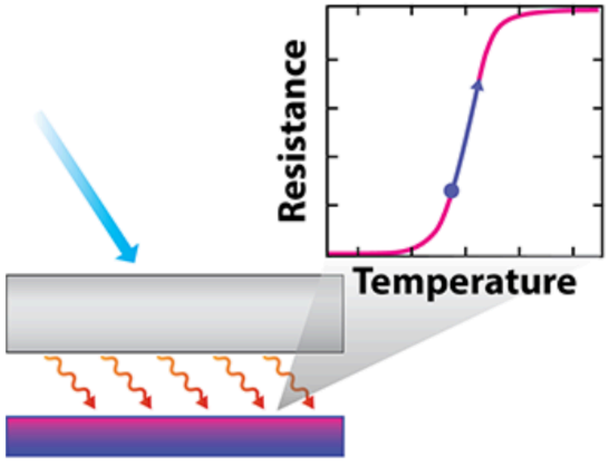
target Mass

clean

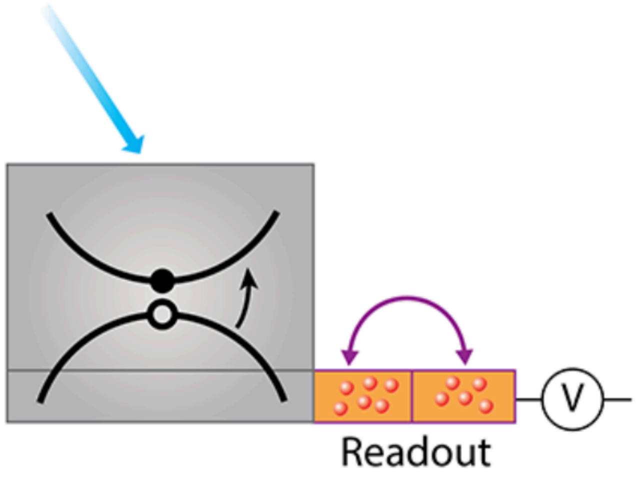
S/V for liquids and crystals

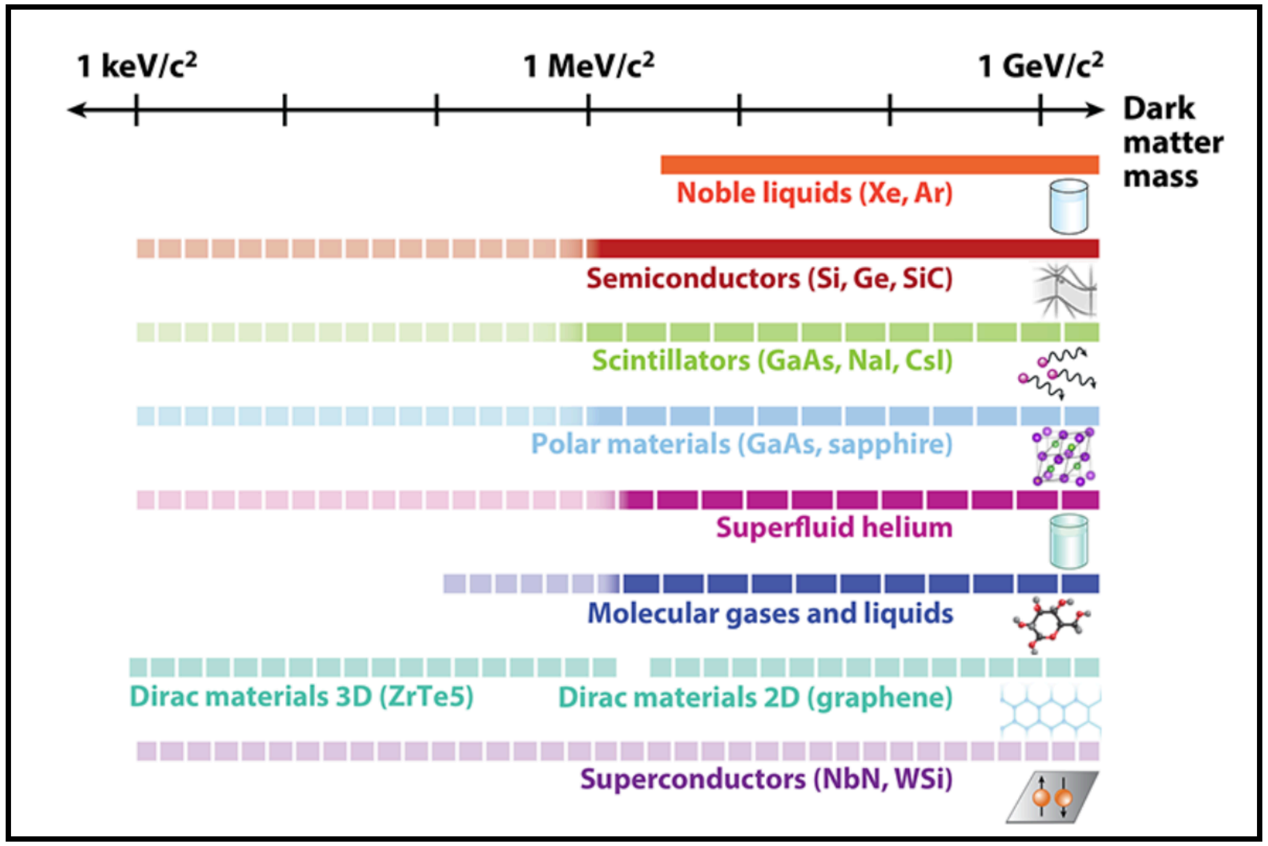
log or linear scale?

superconducting nanowire single-photon detector (SNSPD)

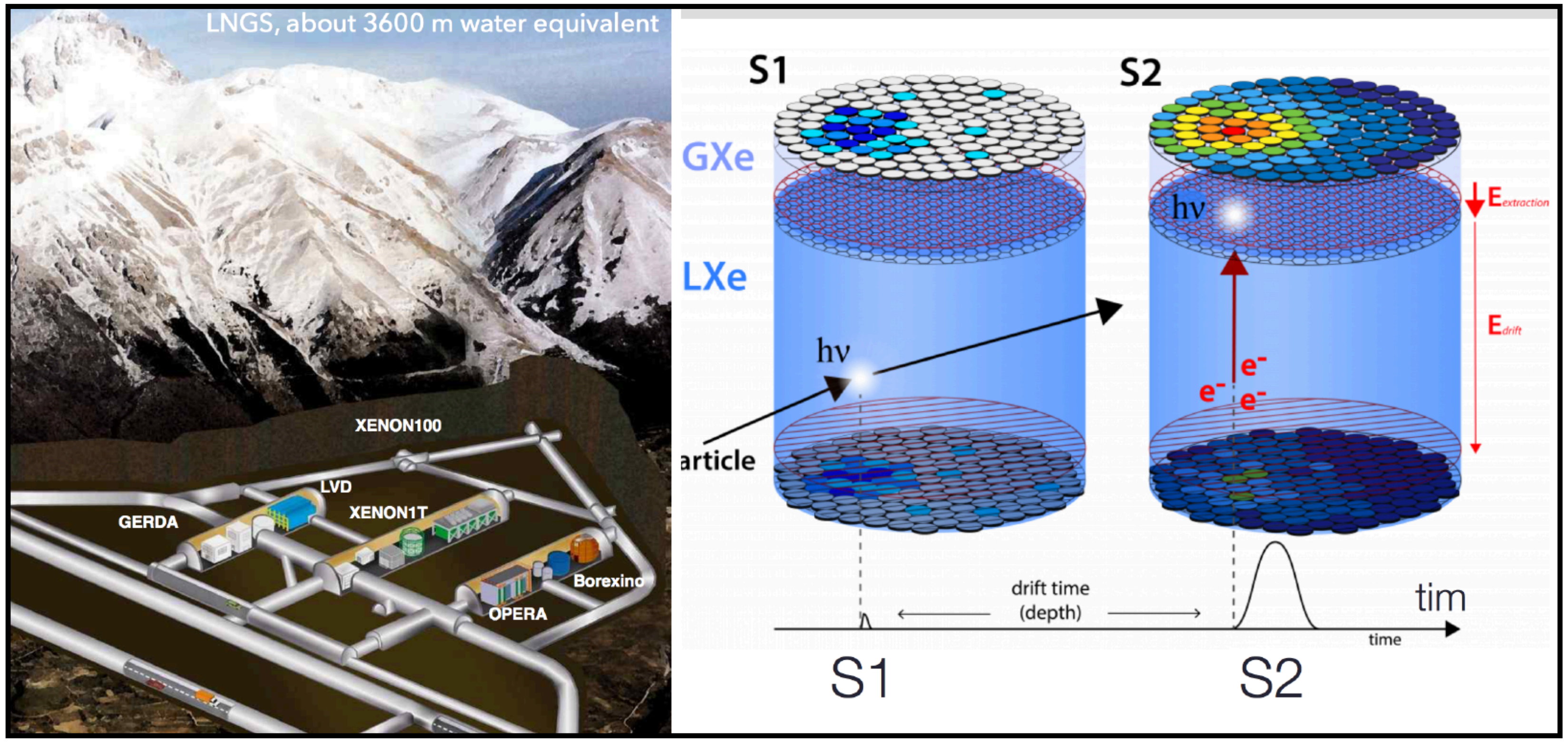


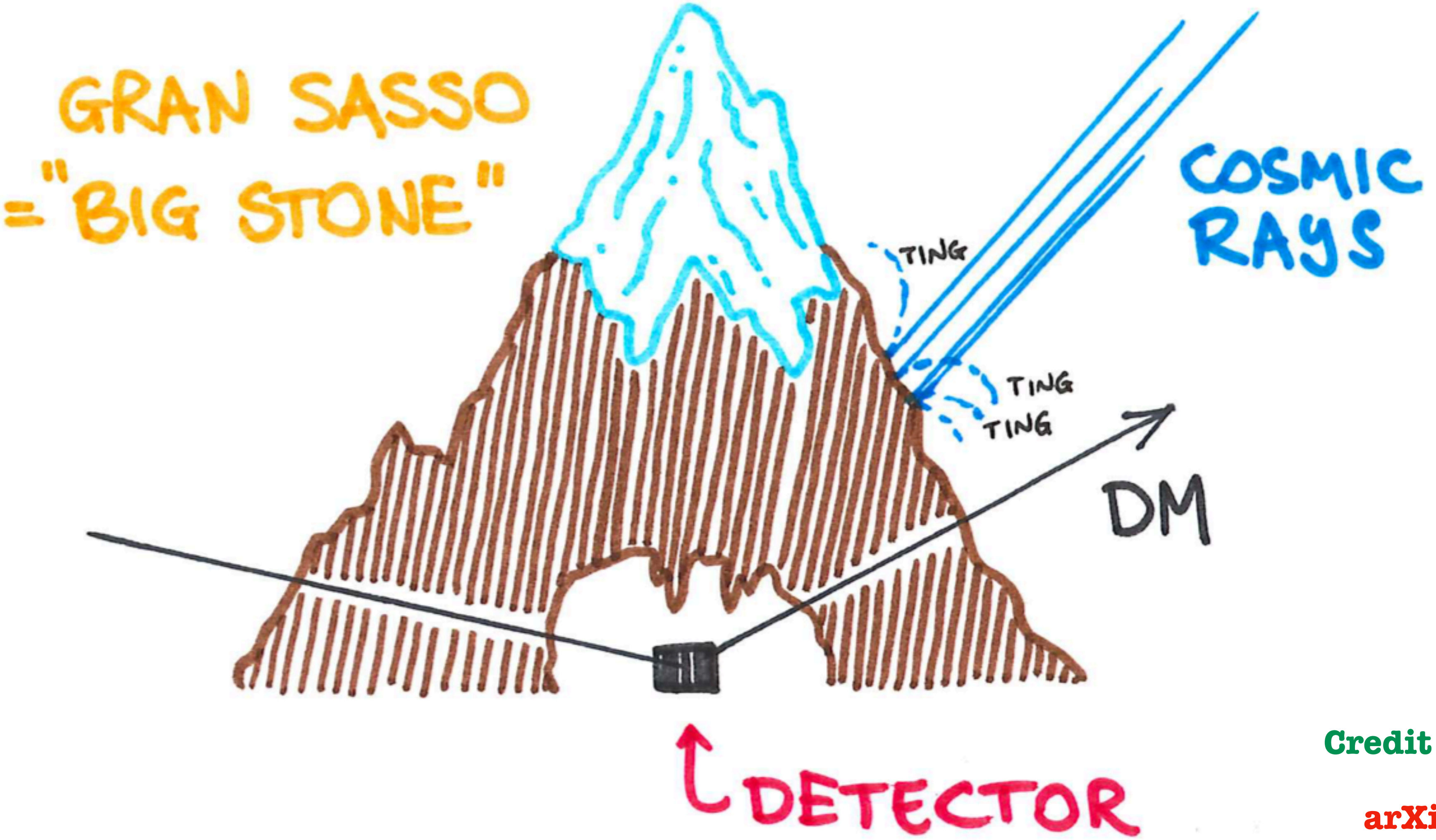
silicon-based charge-coupled device

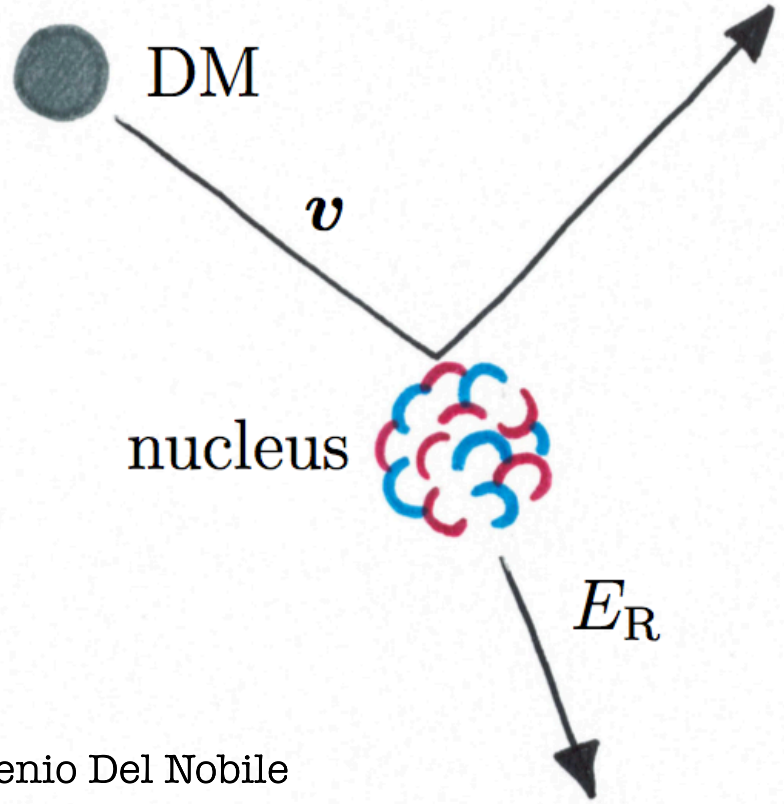




XENON Experiment



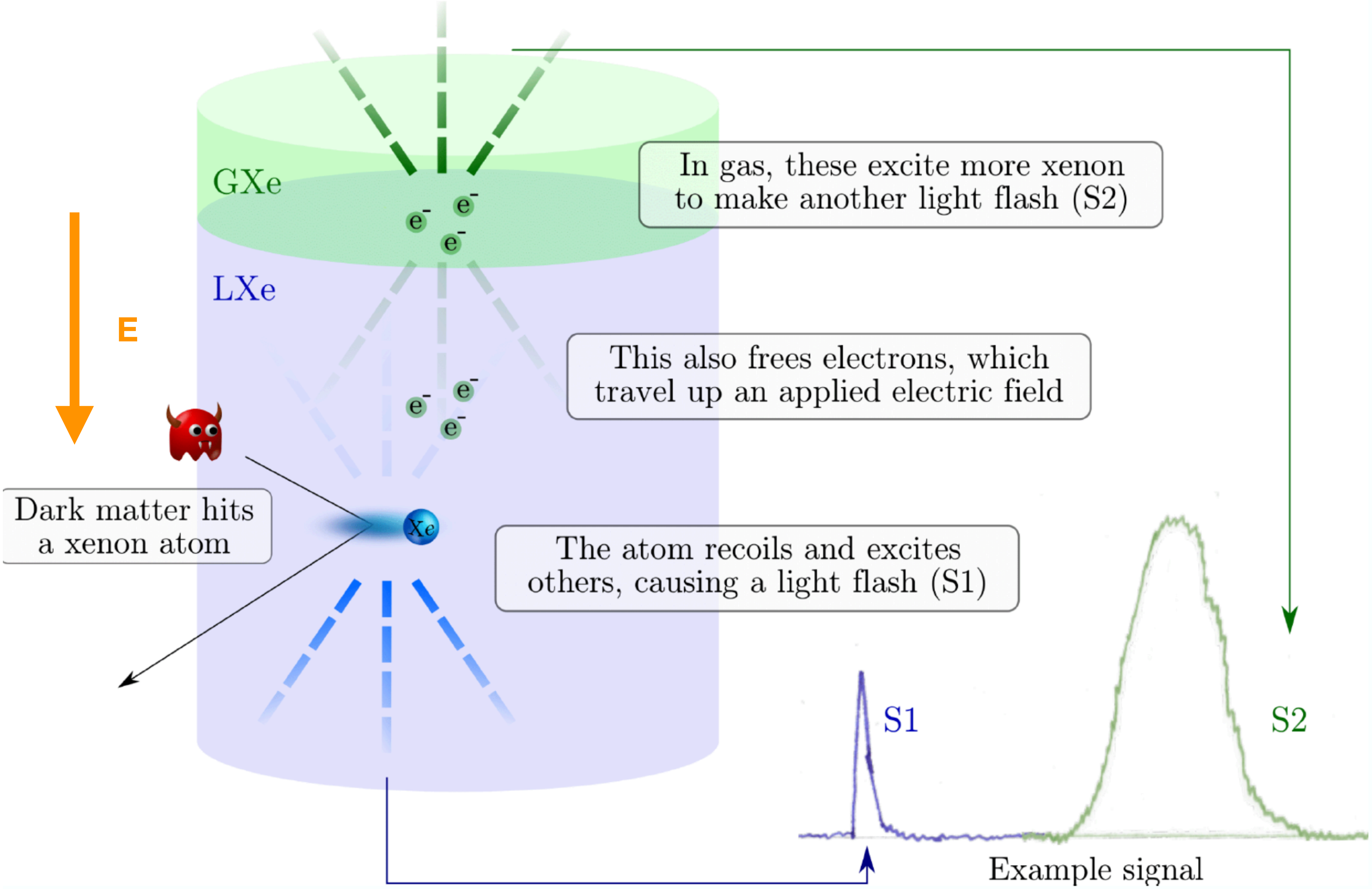




Credit : Eugenio Del Nobile

arXiv:2104.12785v1

Detection Method in XENON Experiment



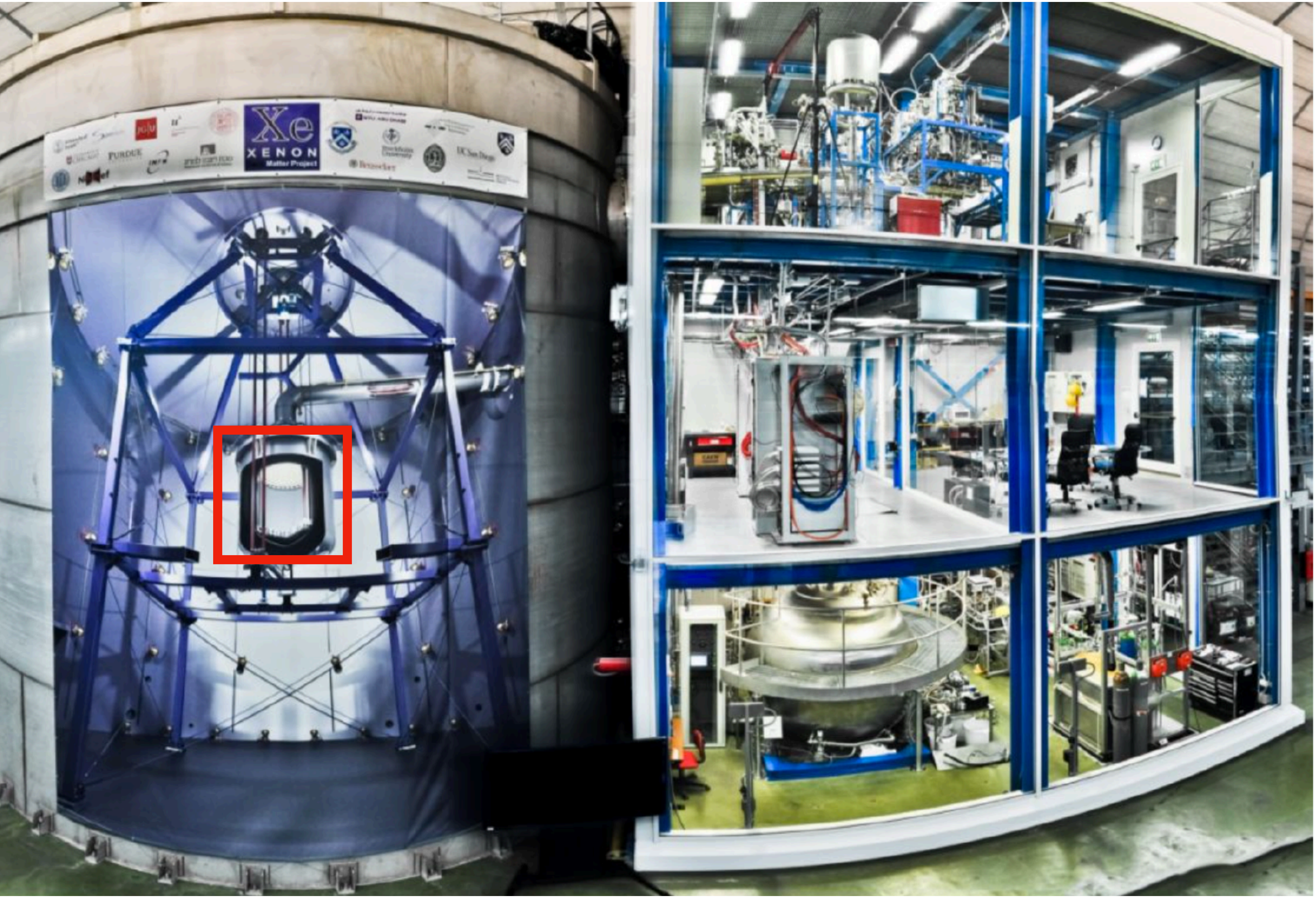
In gas, these excite more xenon to make another light flash (S2)

This also frees electrons, which travel up an applied electric field

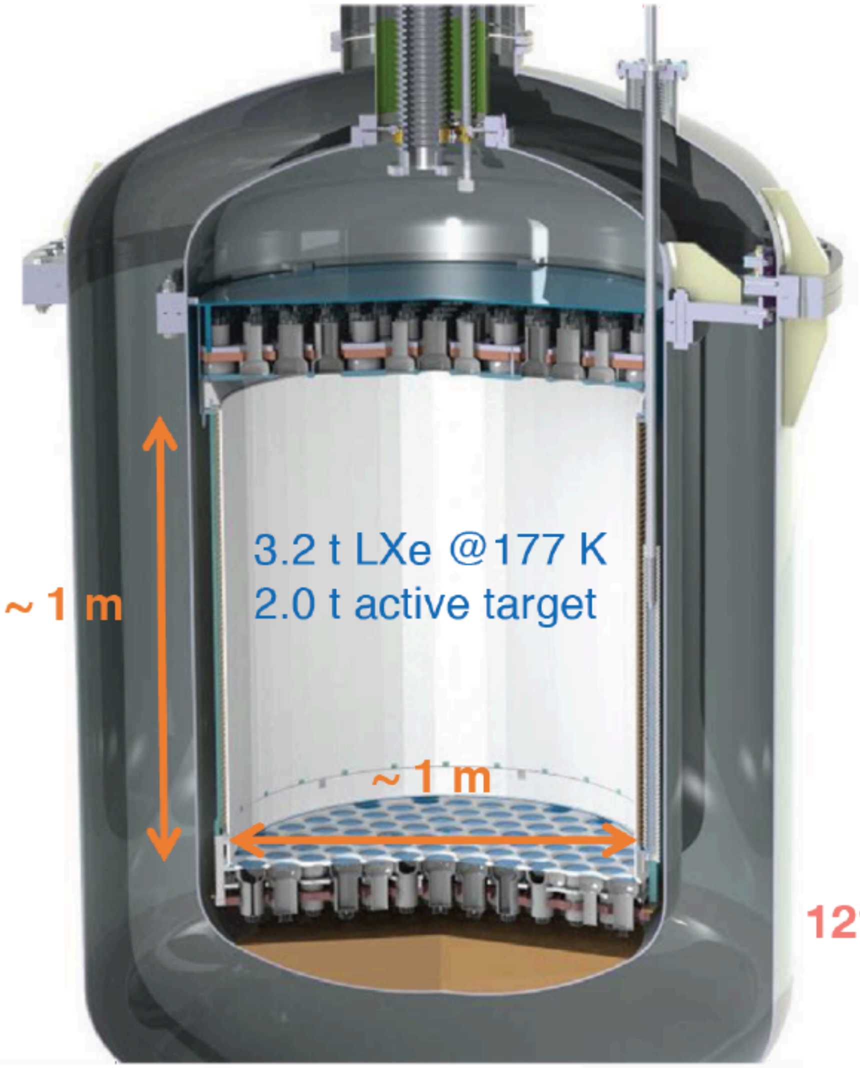
Dark matter hits a xenon atom

The atom recoils and excites others, causing a light flash (S1)

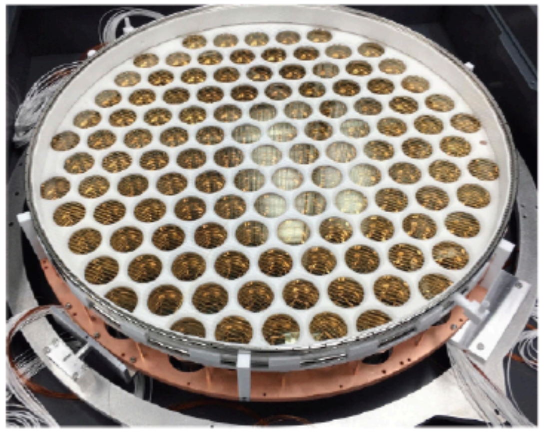
Example signal


Xe
XENON
Dark Matter Project
PURDUE
Stockholm University
UC San Diego
Rensselaer

The XENON1T Time Projection Chamber (TPC)



127 3” PMTs in the top array



121 3” PMTs in the bottom array

https://science.purdue.edu/xenon1t/

Event Rate and Exclusion region

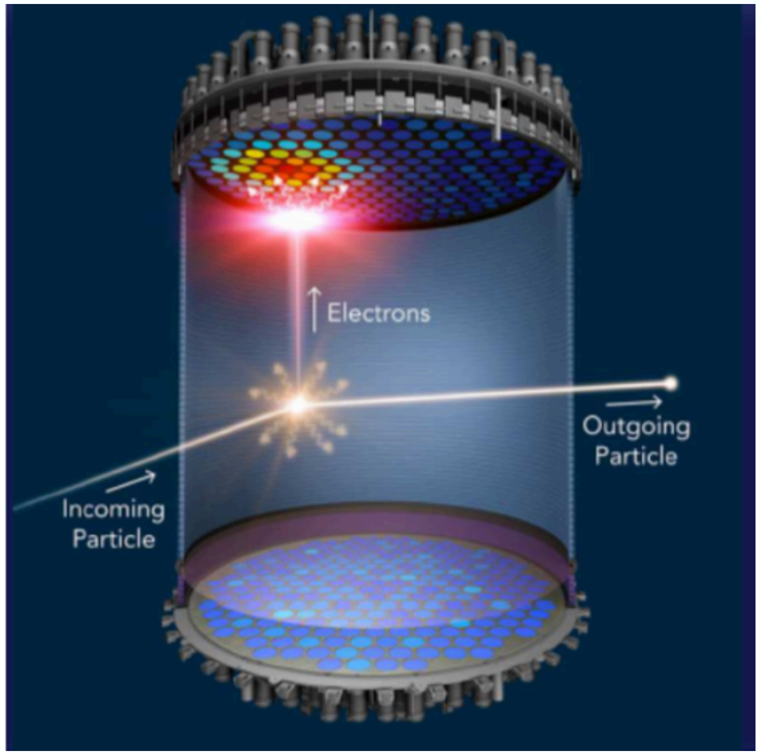
Event rate in a terrestrial detector

Detector physics — N_N, E_{th}

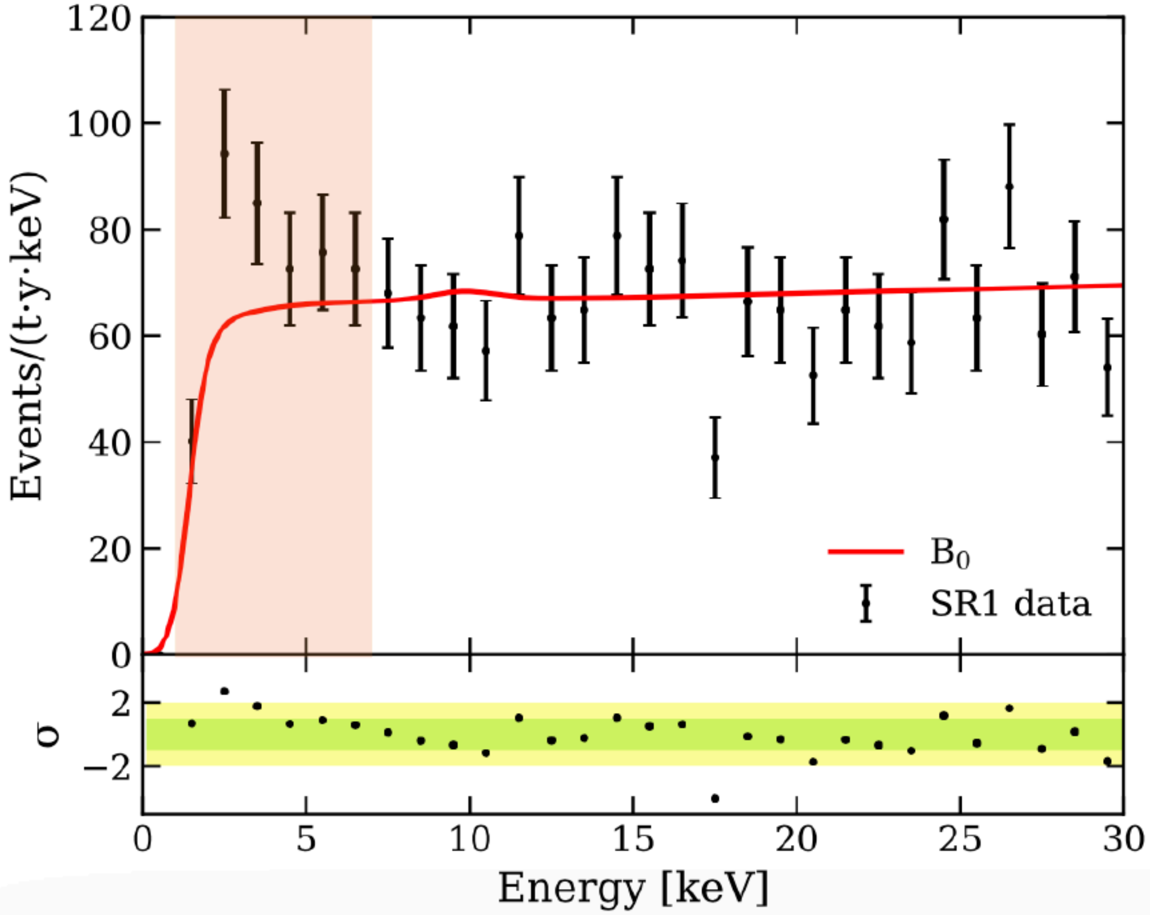
Particle/nuclear physics — $m_{\rm DM}\ d\sigma/dE_R$

Astrophysics — $\rho_0, f(v)$

$$R \sim N_N \times \frac{\rho_{\rm DM}}{m_{\rm DM}} \times \langle v \rangle \times \sigma_{\rm DM}$$



Observation of Excess Electronic Recoil Events in XENON1T



Between 1 and 7 keV

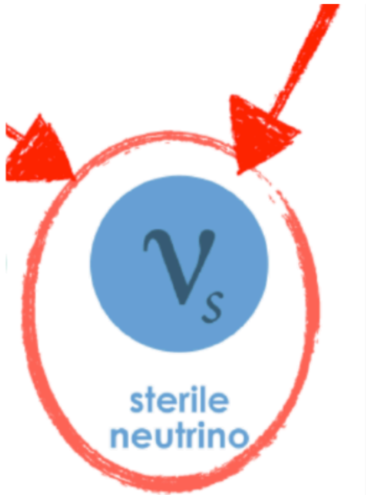
Expected: 232 ± 15 events

Observed: 285 events

$76 \pm 2_{\text{stat}}$ events/(tonne × year × keV) between 1–30 keV,

XENON collaboration, Phys. Rev. D 102, 072004 (2020)

HINT OF DM?



?

Statistical fluke?

"Five sixes"
Axions at 3.5σ global

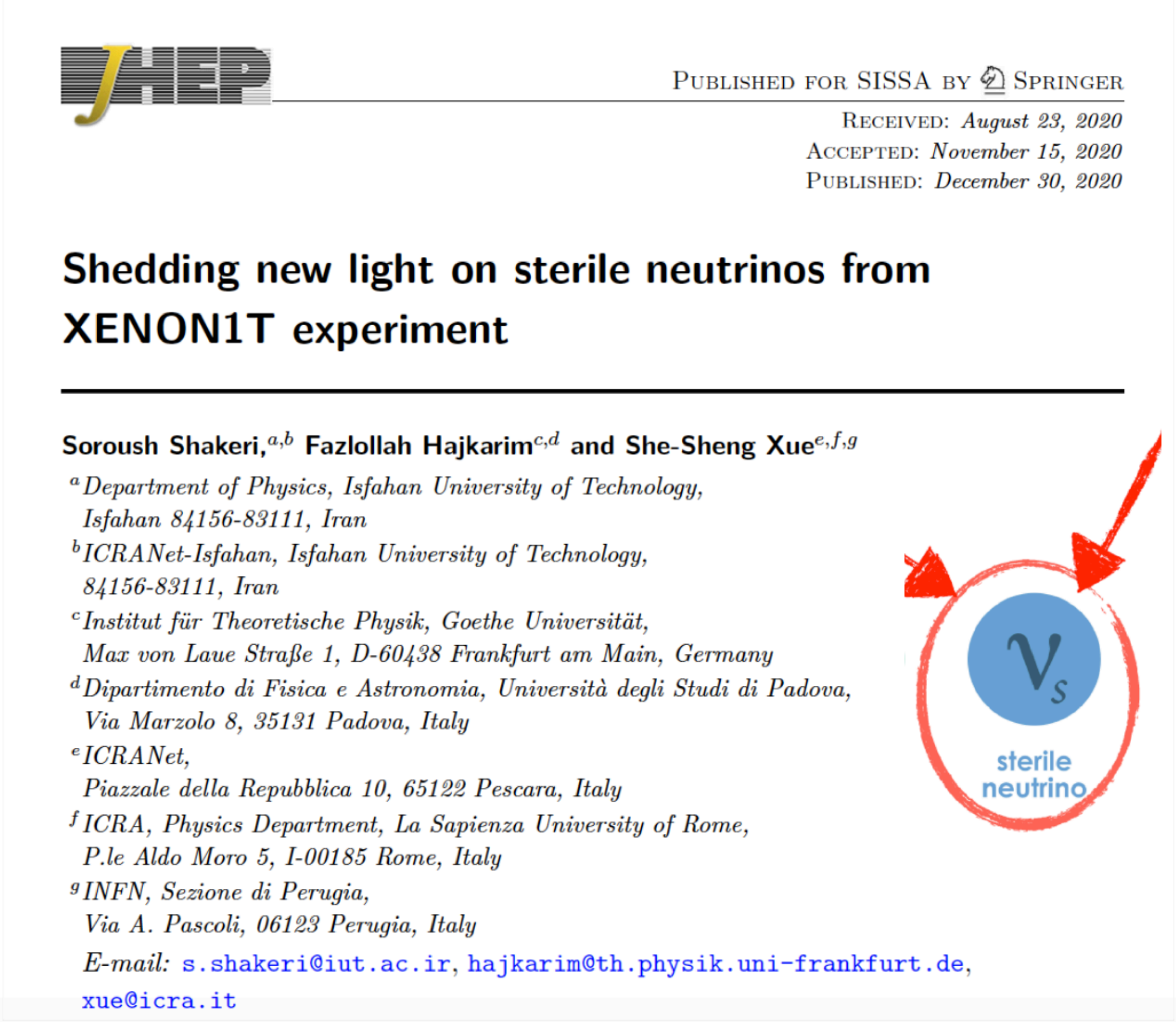
New background?

Systematic error?

Not right at the threshold
Strong calibration constraints

?

New physics?



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Shedding new light on sterile neutrinos from XENON1T experiment

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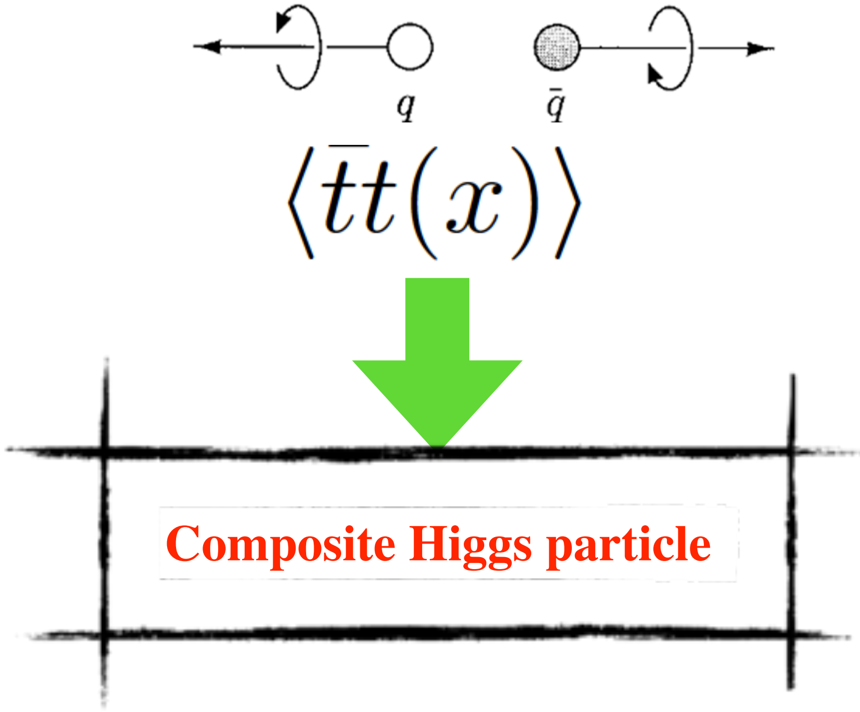
Minimal dynamical symmetry breaking of the standard model

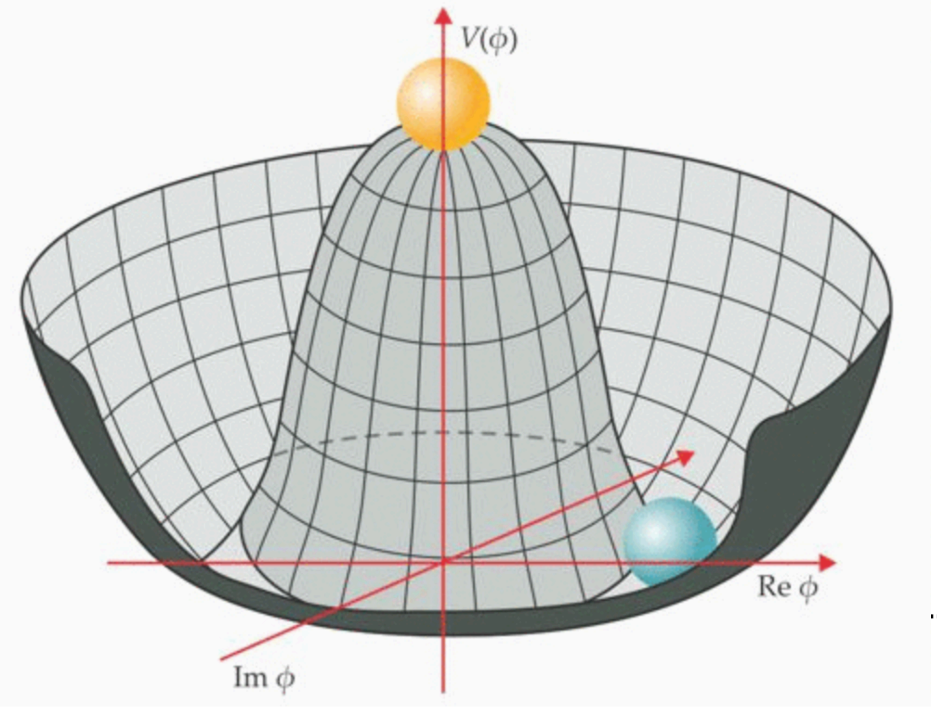
$$L = L_{\text{kinetic}} + G(\bar{\Psi}_L^{ia} t_{Ra})(\bar{t}_R^{b} \Psi_{Lib})$$



$$\langle \bar{t}t(x) \rangle$$

Composite Higgs particle

-Top quark mass is generated by the spontaneous breaking of SM gauge symmetries.



Dynamical Breaking of $SU(2) \times U(1)$

- Analogy to BCS Theory and Quark condensate similar to Cooper Pairs

W. A. Bardeen, C. T. Hill and M. Lindner,, **Phys. Rev. D 41 (1990) 1647.**

Yoichiro Nambu and G.jona-lasinio. Phys Rev. 122, 345-358 (1961).

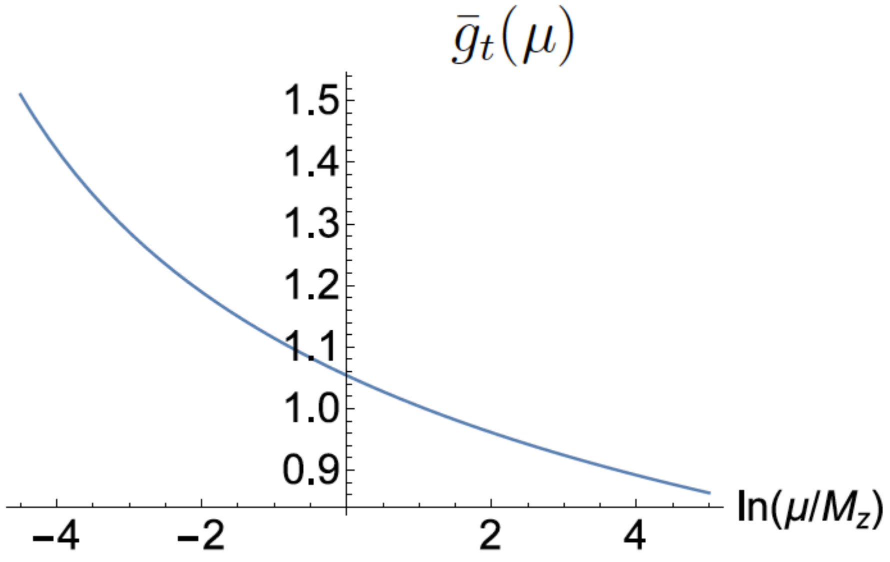
New Physics at TeV Scale

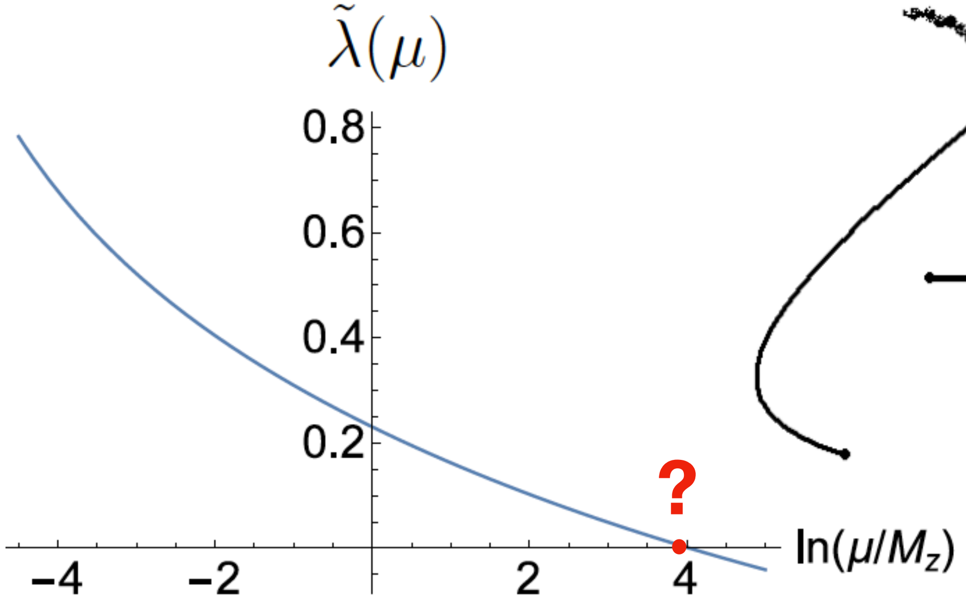
The effective SM Lagrangian with the bilinear top-quark mass term and Yukawa coupling to the composite Higgs boson at the low-energy scale

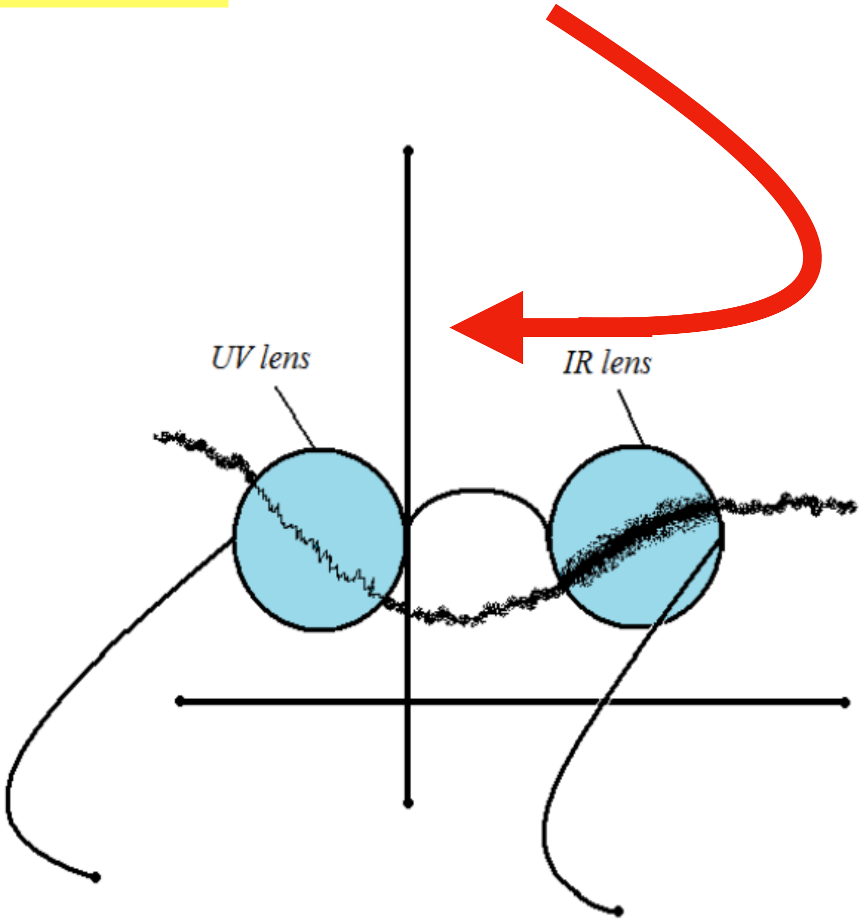
$m_t \approx 173$ GeV

$m_H \approx 126$ GeV

$$L = L_{\text{kinetic}} + g_{t0}(\bar{\Psi}_L t_R H + \text{h.c.}) + Z_H |D_\mu H|^2 - m_H^2 H^\dagger H - \frac{\lambda_0}{2}(H^\dagger H)^2$$







$\mu > \mathcal{E} \approx 5$ TeV, $\lambda(\mu) < 0$ that would imply new physics beyond SM at TeV scales

S.-S. Xue, **Phys. Lett. B 721 (2013) 347,** S.-S. Xue, **Phys. Lett. B 727 (2013) 308,**
S.-S. Xue, **JHEP 05 (2017) 146** **,** S.-S. Xue, **Phys. Lett. B 737 (2014) 172**
R. Leonardi, O. Panella, F. Romeo, A. Gurrola, H. Sun and S.-S. Xue,, Eur. Phys. J. C 80 (2020)
S.-S. Xue, **JHEP (2016) 2016: 72** [1605.01266].

Spontaneous breaking of sterile neutrino PQ symmetry

$G(\bar{\nu}_R^{\ell c}\nu_R^{\ell})(\bar{\nu}_R^{\ell}\nu_R^{\ell c})$ Respect to Global PQ chiral symmetry $U^{\rm PQ}_{\rm lepton}(1)$

$$\nu_R^{\ell}\ (\ell = e, \mu, \tau)$$

Only sterile neutrinos carry PQ charge

$$\nu_R^{\ell} \to e^{i\alpha_{\rm PQ}}\nu_R^{\ell}$$

The SSB of $U^{PQ}_{\rm lepton}(1)$

leads to the generation of

Pseudoscalar Axion,

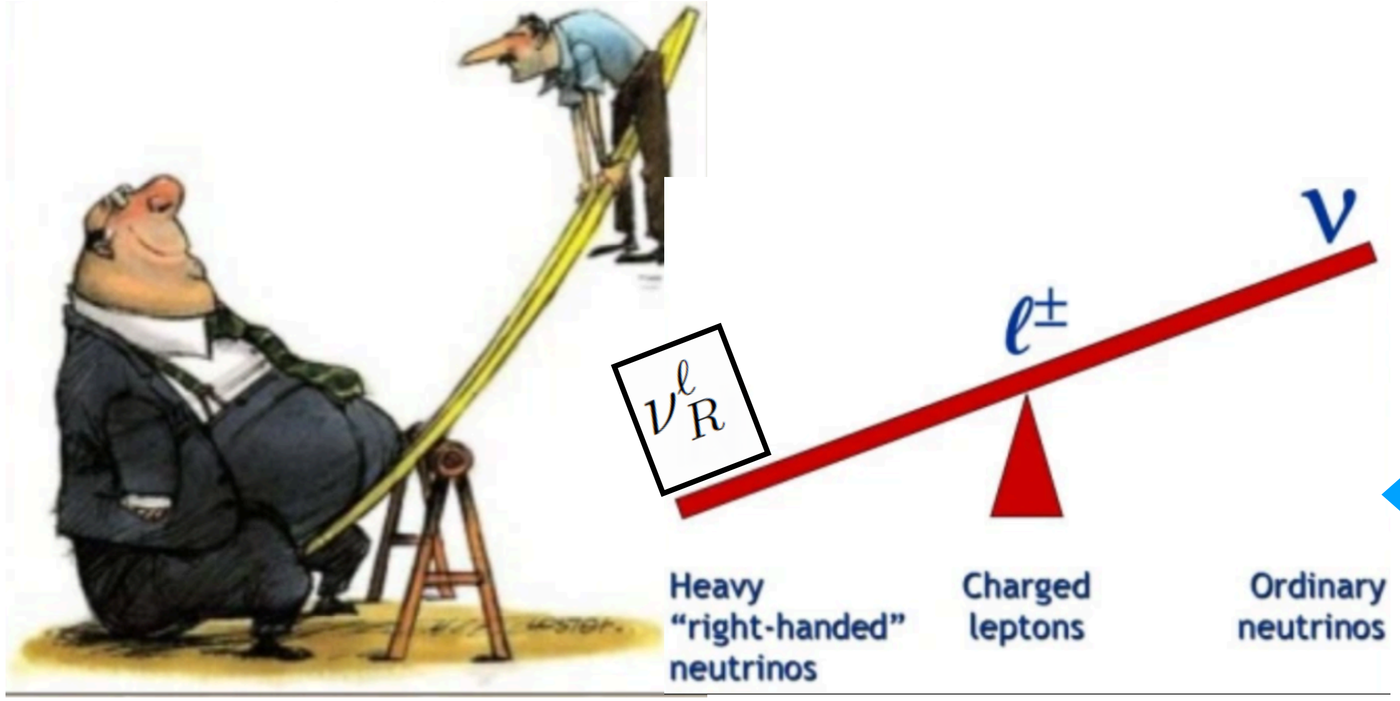
$$\phi^M = \sum_{f=1,2,3} \langle \bar{\nu}_R^{f,c}\gamma_5\nu_R^{f}\rangle$$

Massive Scalar Boson

$$\phi^M_H = \sum_{f=1,2,3} \langle \bar{\nu}_R^{f,c}\nu_R^{f}\rangle$$

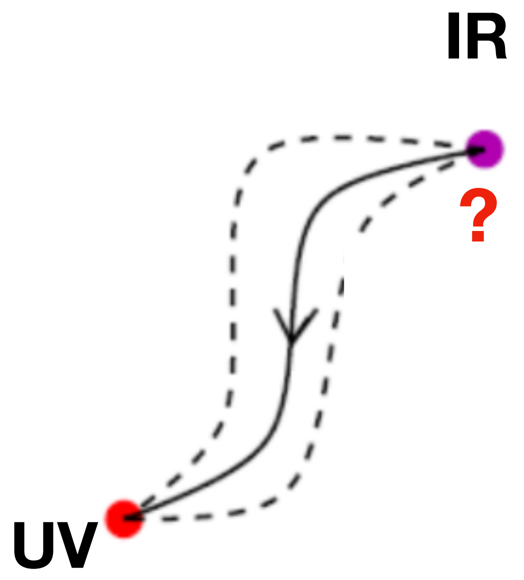
Sterile Neutrino Majorana Masses

$$m^M = -G\sum_{f=1,2,3} \langle \bar{\nu}_R^{f\,c}\nu_R^{f}\rangle$$

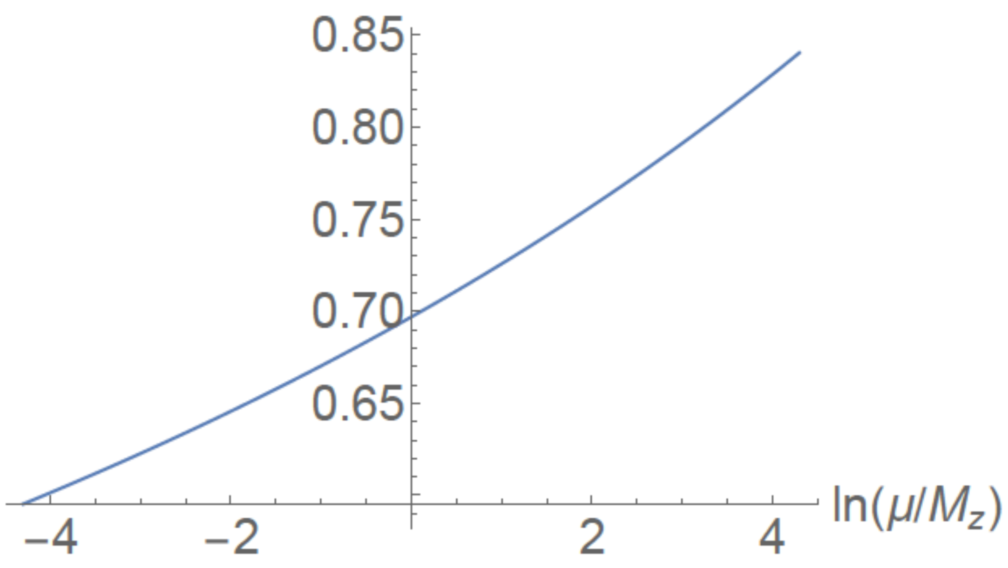


Sterile Neutrino Condensate and Composite Bosons (Axion and WIMP)

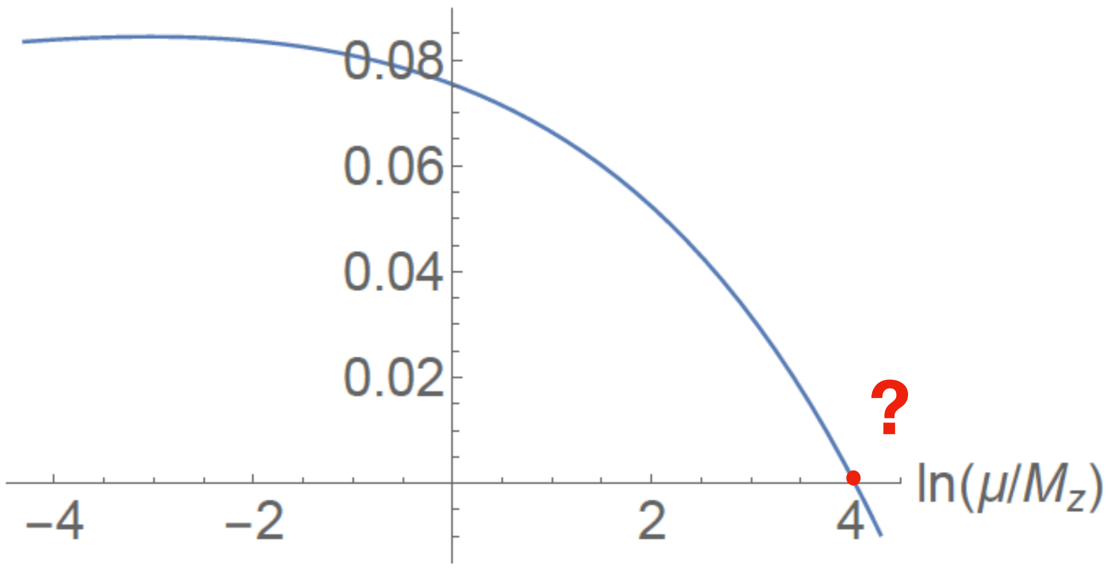
$$\begin{aligned} L^S_{\rm eff} &= L^S_{\rm kinetic} + g_{t0}(\bar{\nu}_R^{\ell,c}\nu_R^{\ell}\phi_H^M + {\rm h.c.}) \\ &+ Z_\phi|\partial_\mu\phi_H^M|^2 - m_\phi^2\phi_H^{M\dagger}\phi_H^M - \frac{\lambda_0}{2}(\phi_H^{M\dagger}\phi_H^M)^2 \\ &+ Z_\phi|\partial_\mu\phi^M|^2 + \Delta L^S_{\rm gauge}, \end{aligned}$$



$\bar{g}_s(\mu)$



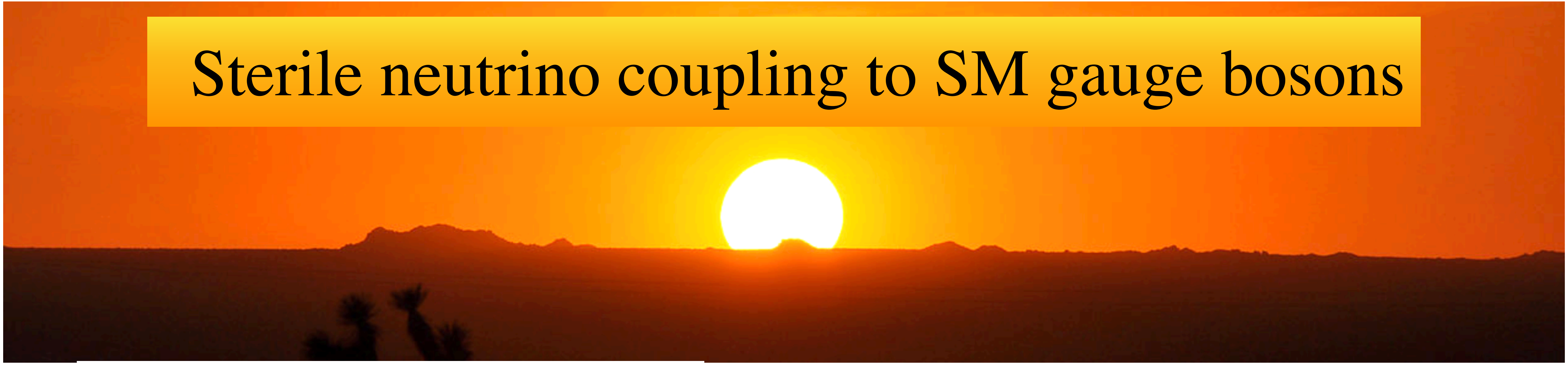
$\tilde{\lambda}_s(\mu)$

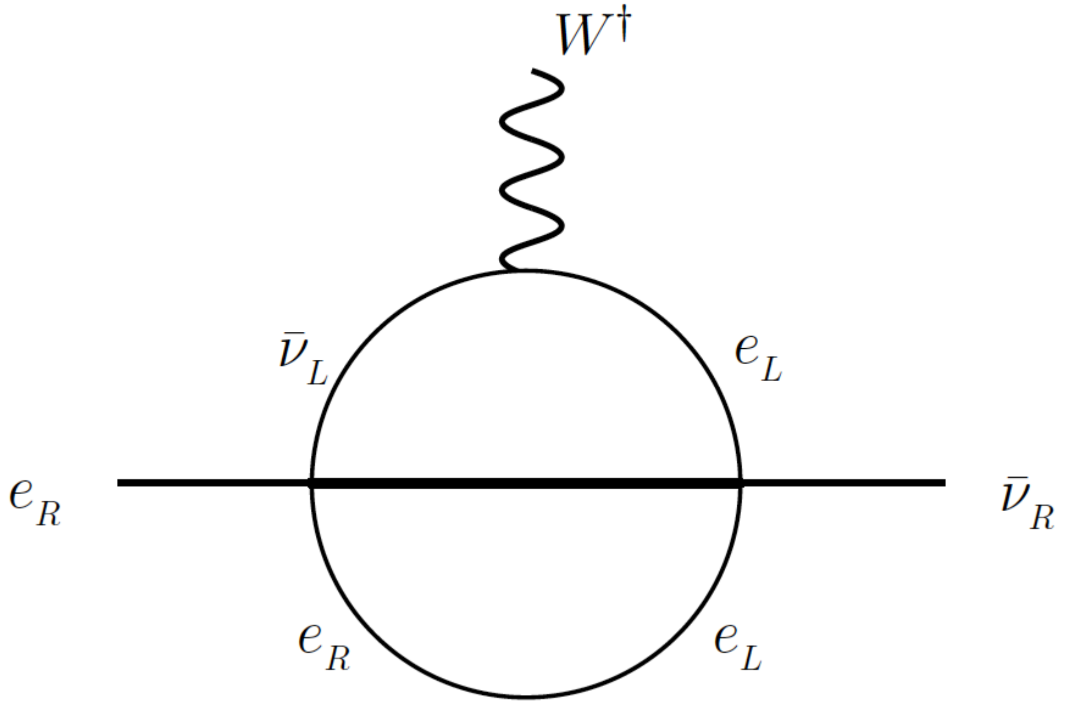


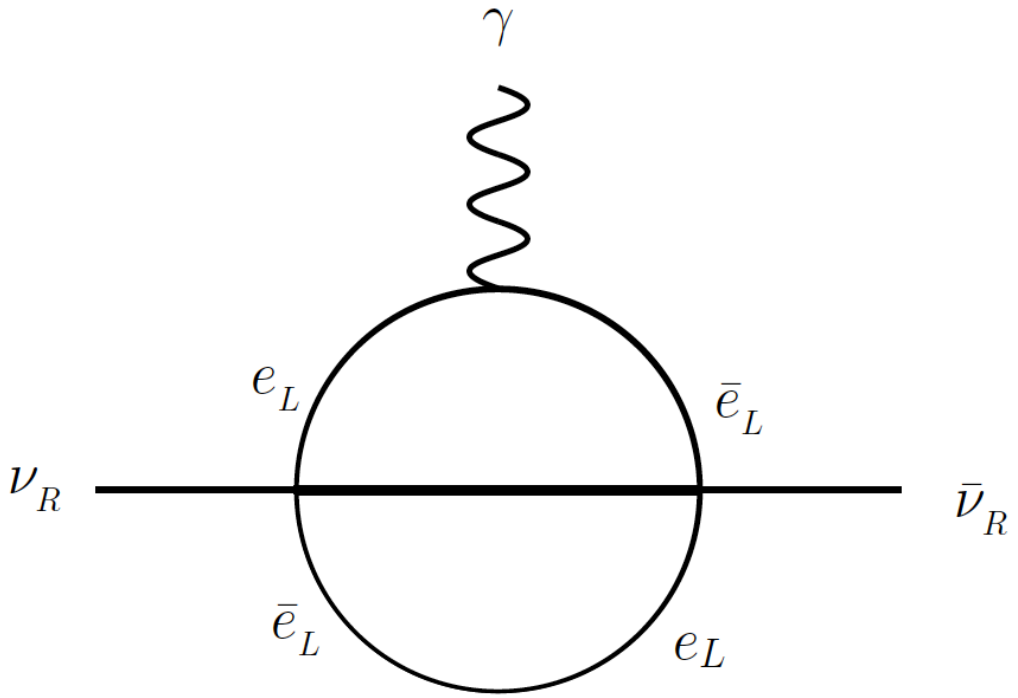
S.-S. Xue, Hierarchy spectrum of SM fermions: from top quark to electron neutrino, **JHEP 11 (2016) 072**

S.-S. Xue, Spontaneous Peccei-Quinn symmetry breaking renders sterile neutrino, axion and boson to be candidates for dark matter particles, **[ArXiv:2012.04648]**

Sterile neutrino coupling to SM gauge bosons





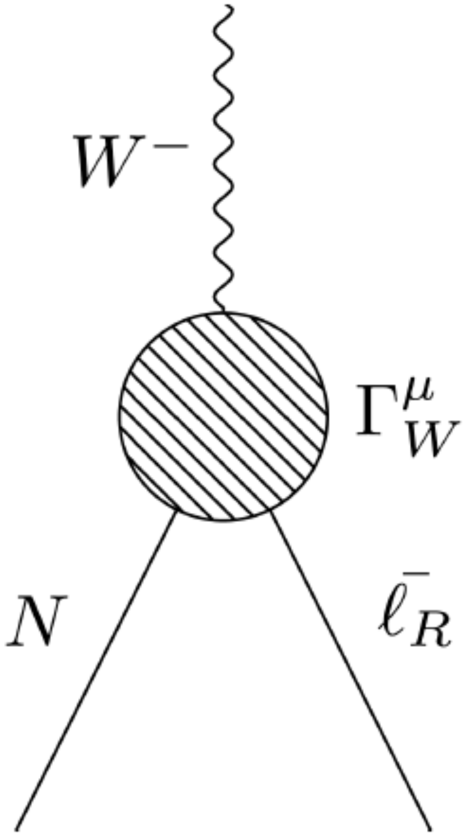


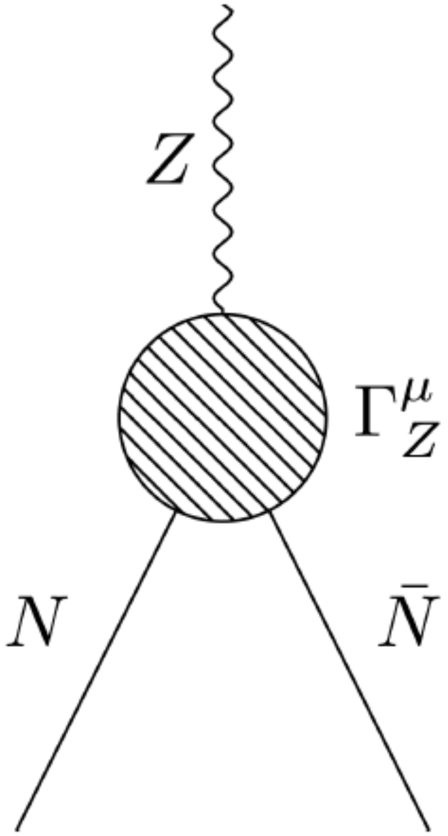
Sunset diagrams from four-fermion interactions lead to effective SM gauge boson couplings to right-handed neutrinos

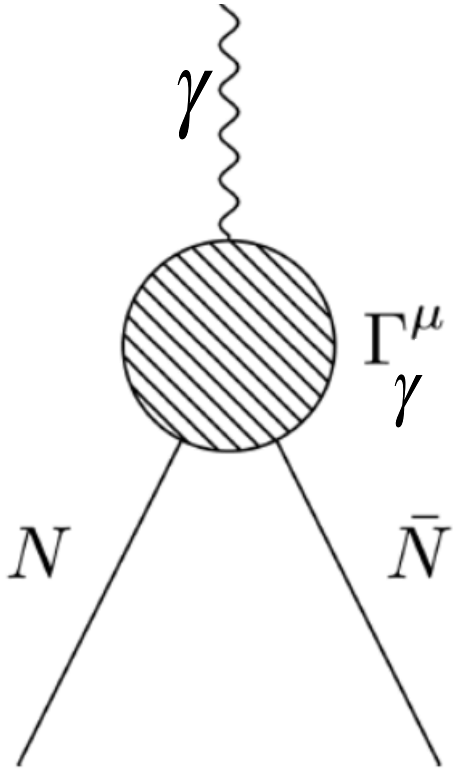
$$\mathcal{L} \supset -G \sum_f \left(\bar{\psi}_L^f \psi_R^f \bar{\psi}_R^f \psi_L^f + \bar{\nu}_R^{fc} \psi_R^f \bar{\psi}_R^f \nu_R^{fc} \right) + \text{h.c.}$$

Sterile neutrino and charged lepton couplings

$$\mathcal{L} \supset \mathcal{G}_R^W \ (g_w/\sqrt{2})\bar{\ell}_R\gamma^\mu\nu_R^\ell W_\mu^- + \mathcal{G}_R^Z \ (g_w/\sqrt{2})\bar{\nu}_R^\ell\gamma^\mu\nu_R^\ell Z_\mu^0 \ + \ \mathcal{G}_R^\gamma \ (e)\bar{\nu}_R^\ell\gamma^\mu\nu_R^\ell A_\mu + \text{h.c.}$$







$$\boxed{\Gamma_W^\mu = i\frac{\mathcal{G}_R^W(p_1,p_2)}{\sqrt{2}}\gamma^\mu g_w P_R}$$

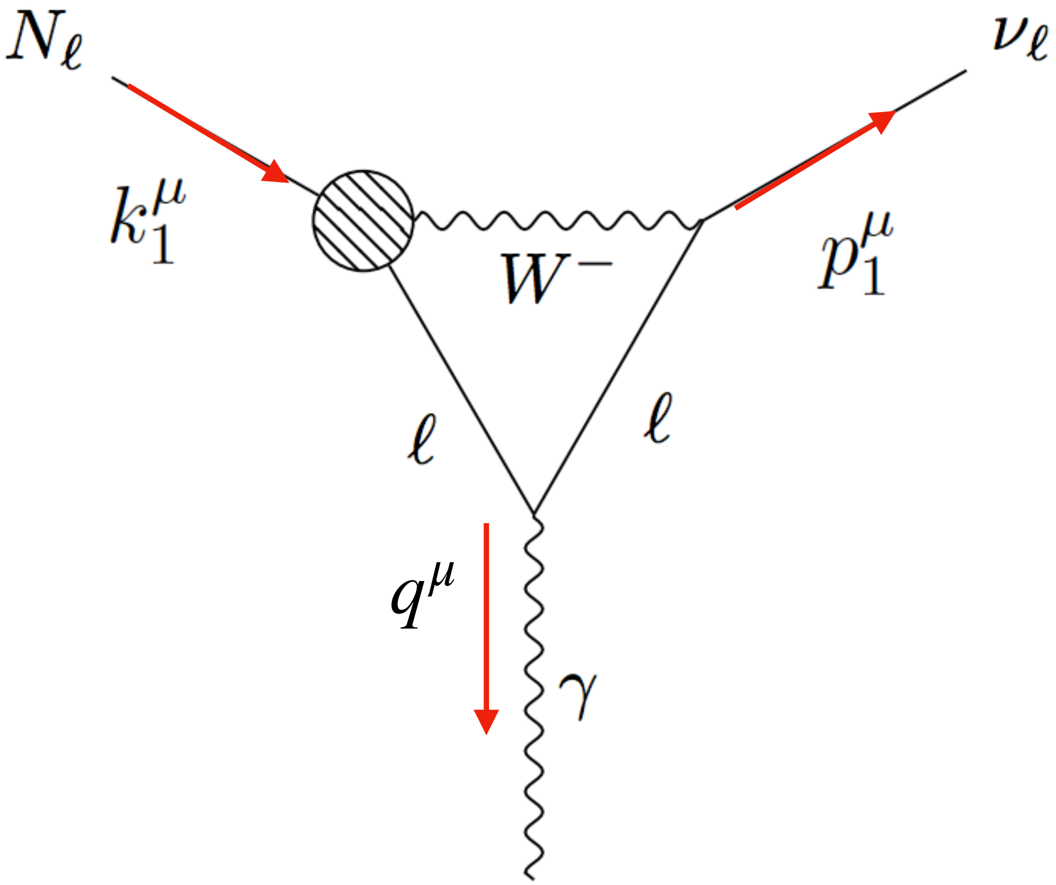
$$\boxed{\Gamma_W^\mu = i\frac{\mathcal{G}_R^Z(p_1,p_2)}{\sqrt{2}}\gamma^\mu g_w P_R}$$

$$\boxed{\Gamma_\gamma^\mu = i\mathcal{G}_R^\gamma(p_1,p_2)\gamma^\mu e}$$

At the electroweak scale $v = (G_F\sqrt{2})^{-1/2} \approx 246 \text{ GeV},$ $\quad \mathcal{G}_R^Z \approx \mathcal{G}_R^W \approx \mathcal{G}_R^\gamma \propto (v/\Lambda_{\text{cut}})^2$

3 Generation Sterile Neutrinos N_e, N_μ, N_τ $\mathcal{G}_R$

Introducing a New EM Effective vertex for Sterile Neutrino - SM Neutrino



1PI vertex

$$\boxed{\Lambda^\mu_{l'}(q) = i\frac{eg_w^2\mathcal{G}_R m_{l'}}{16\pi^2}\left[(C_0+2C_1)p_1^\mu + (C_0+2C_2)k_1^\mu\right]}$$

Passarino-Veltman functions $C_i \equiv C_i(m_N^2, q^2, m_\nu^2; m_W, m_l, m_l) \xrightarrow{q^2\to 0} C_i(m_N^2, 0, m_\nu^2; m_W, m_l, m_l) \propto m_W^{-2}$

Sterile Neutrino Radiative Decay Process

$$N_R^l \rightarrow \nu_L^l + \gamma$$

$$\Gamma(N_R^l \rightarrow \nu_L^l + \gamma) = \left(\frac{\alpha\, g_w^4}{1024\, \pi^4}\right) m_l^2 (m_N^l)^3 \mathcal{G}_R^2 \left[(C_0 + 2C_1)^2 + (C_0 + 2C_2)(C_0 + 2C_1)\right]$$

At low energy scale (Zero momentum transfer limit)

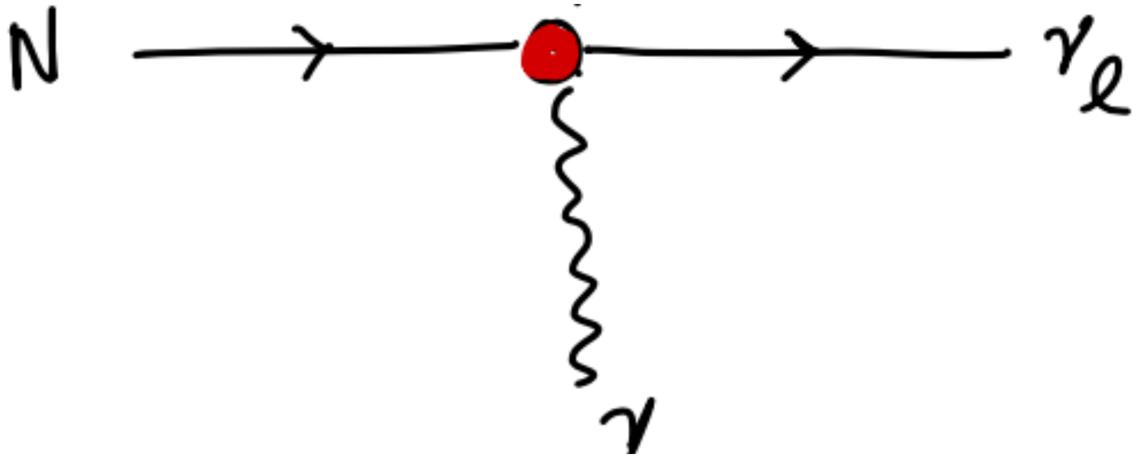
$$\Gamma(N_R^e \rightarrow \nu_L^e + \gamma) = 1.57 \times 10^{-19} s^{-1} \left(\frac{\mathcal{G}_R}{10^{-4}}\right)^2 \left(\frac{m_e}{511\,\mathrm{keV}}\right)^2 \left(\frac{M_N^e}{100\,\mathrm{keV}}\right)^3$$

$$\Gamma(N_R^\mu \rightarrow \nu_L^\mu + \gamma) = 6.70 \times 10^{-15} s^{-1} \left(\frac{\mathcal{G}_R}{10^{-4}}\right)^2 \left(\frac{m_\mu}{106\,\mathrm{MeV}}\right)^2 \left(\frac{M_N^\mu}{100\,\mathrm{keV}}\right)^3$$

$$\Gamma(N_R^\tau \rightarrow \nu_L^\tau + \gamma) = 1.87 \times 10^{-12} s^{-1} \left(\frac{\mathcal{G}_R}{10^{-4}}\right)^2 \left(\frac{m_\tau}{1.77\,\mathrm{GeV}}\right)^2 \left(\frac{M_N^\tau}{100\,\mathrm{keV}}\right)^3$$

Active-Sterile Neutrino Transition Magnetic Moments

“Neutrino Dipole Portal”



$$\mathcal{L} \supset \frac{1}{2}\mu_\nu^{\alpha\beta}\,\bar{\nu}_L^\alpha\sigma^{\mu\nu}N_R^\beta F_{\mu\nu}$$

$$N_R^l \to \nu_L^l + \gamma \quad \Rightarrow \quad \Gamma_{\mu_{\rm eff}} = \mu_{\rm eff}^2 m_N^3/(16\pi)$$

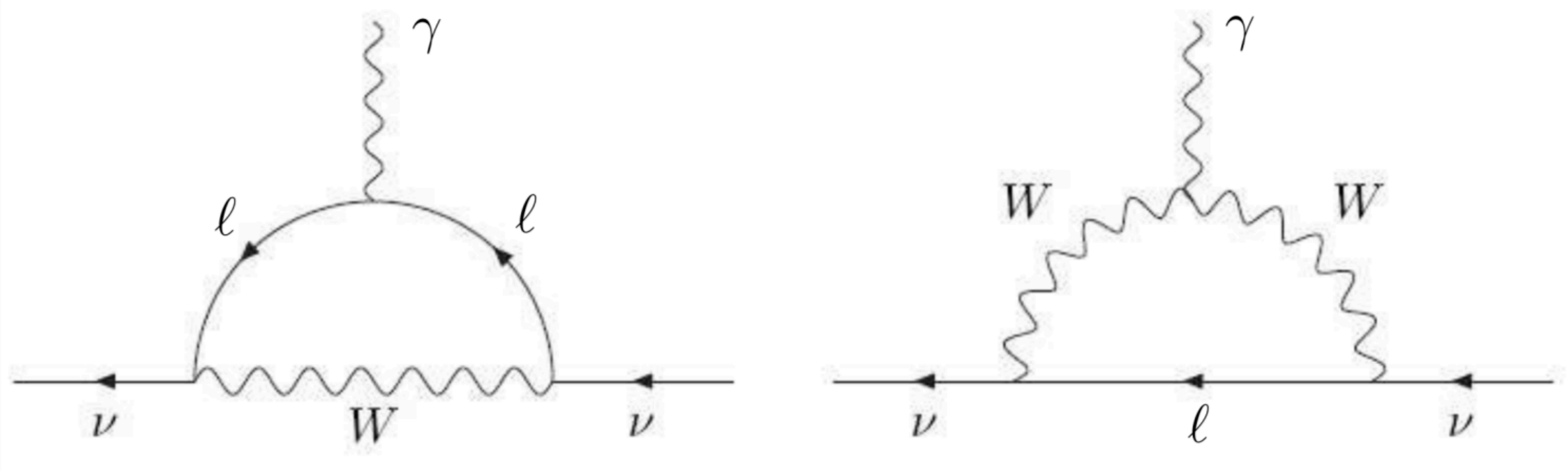
V. Brdar, A. Greljo, J. Kopp, and T. Opferkuch, **JCAP 01, 039, (2021)**

P. Coloma, P. A. Machado, I. Martinez-Soler and I. M. Shoemaker, **Physical Review Letters 119 (2017)** .

G. Magill, R. Plestid, M. Pospelov and Y.-D. Tsai, D, **Phys. Rev. D 98 (2018) 115015**

Neutrino Magnetic Moments is a Property of SM Neutrinos But Transition Magnetic Moment is **Not** !!

NOTE

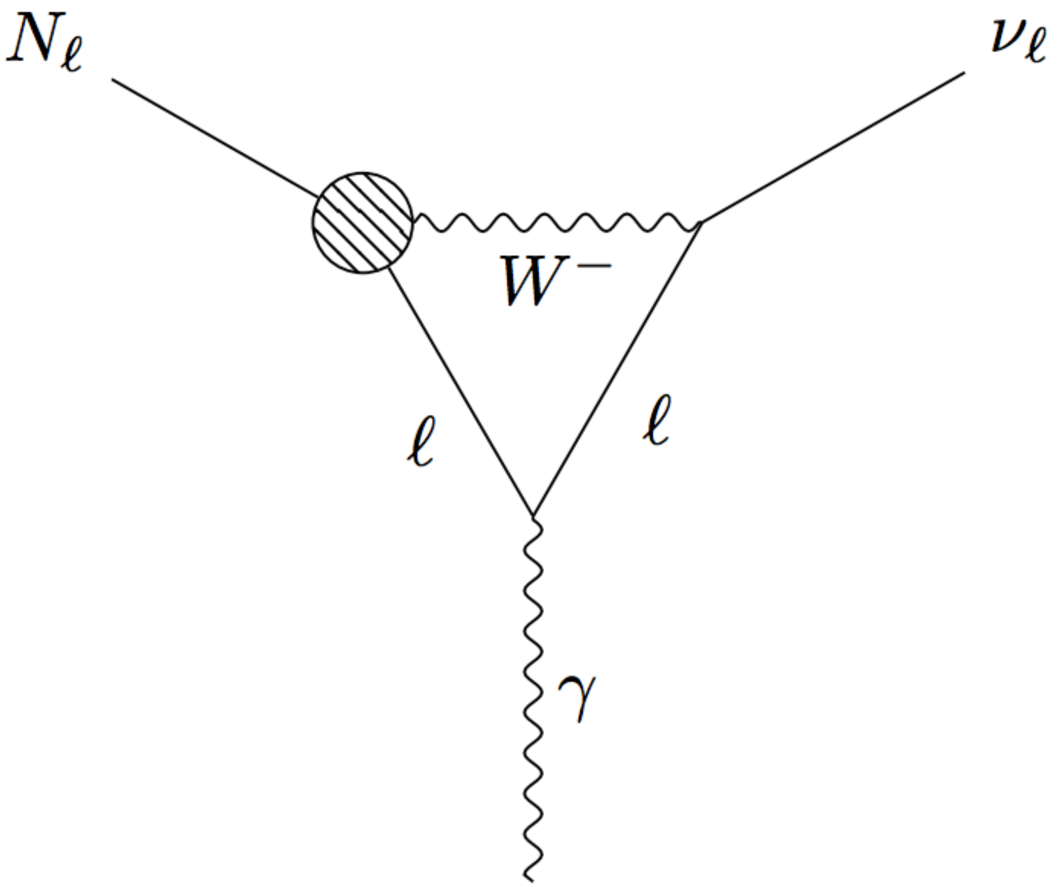


$$\mu_\nu = \frac{3eG_F m_\nu}{8\pi^2\sqrt{2}} = \frac{3G_F m_e m_\nu}{4\pi^2\sqrt{2}}\mu_B$$

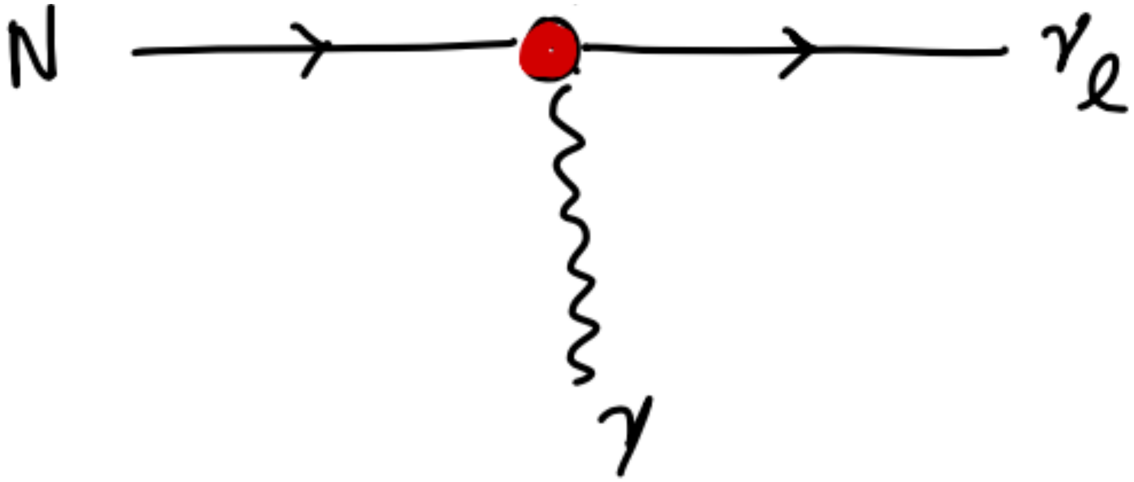
$$\boxed{\mu_\nu = 3 \times 10^{-19}\,(m_\nu/1\mathrm{eV})\,\mu_B}$$

S.T. Petcov1976
Kazuo Fujikawa. Jun, 1980

Induce an Effective Transition Magnetic Moment



$$(U_L^\nu U_L^\ell)^{ll'}\,\bar\nu_L^l \Lambda^\mu_{l'} N_R^{l'} A_\mu + \text{h.c.},$$



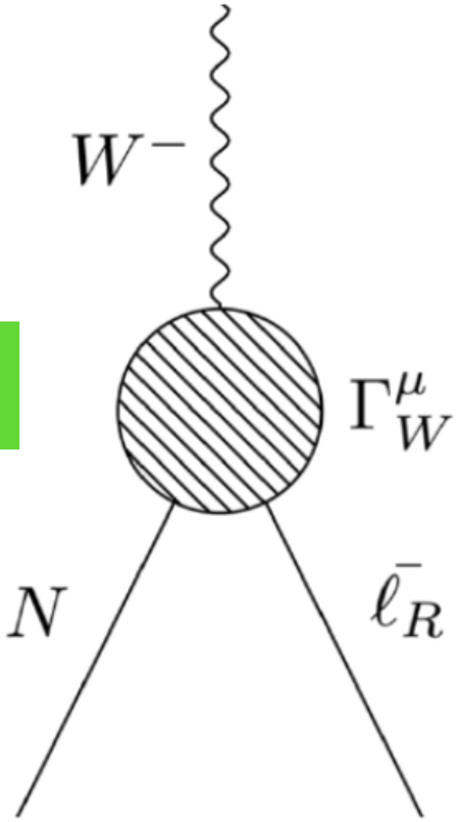
$(U_L^\nu U_L^\ell)$ is the PMNS mixing matrix

$$\boxed{\frac{\mu_{\rm eff}}{\mu_B} \sim \frac{G_F m_e}{4\sqrt{2}\pi^2}\mathcal{G}_R m_\ell \approx 1.87\times 10^{-12}\left(\frac{\mathcal{G}_R}{10^{-2}}\right)\left(\frac{m_\ell}{1.77\text{GeV}}\right)}$$

S. Shakeri, F. Hajkarim, and S.-S. Xue, **JHEP12(2020)194.**

Consistency with the SM Precision Measurements

W decay width



$$\Gamma_{\text{total}} = \Gamma_{\text{SM}} + \delta\Gamma$$

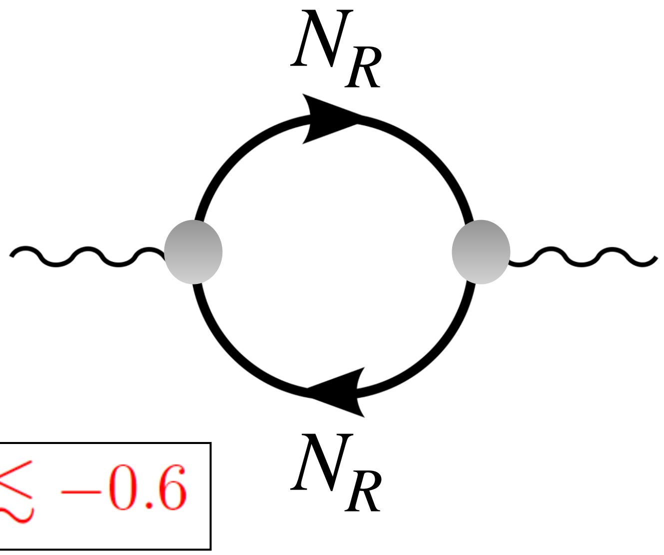
$$\delta\Gamma_W \leq 4.2 \times 10^{-2}\text{GeV}$$

$$\boxed{\mathcal{G}_R \lesssim 6 \times 10^{-3}}$$

S.-S. Xue, et al ,**Phys. Rev. D 101 (2020) 123016**

Contribution to the Photon Vacuum Polarization

SM Fine-Structure constant



$$\alpha \approx \alpha_{\text{sm}} \left(1 + (\mathcal{G}^{\gamma}_{R})^2 \frac{\alpha_{\text{sm}}}{15\pi} \frac{m_e^2}{(m^e_N)^2}\right)$$

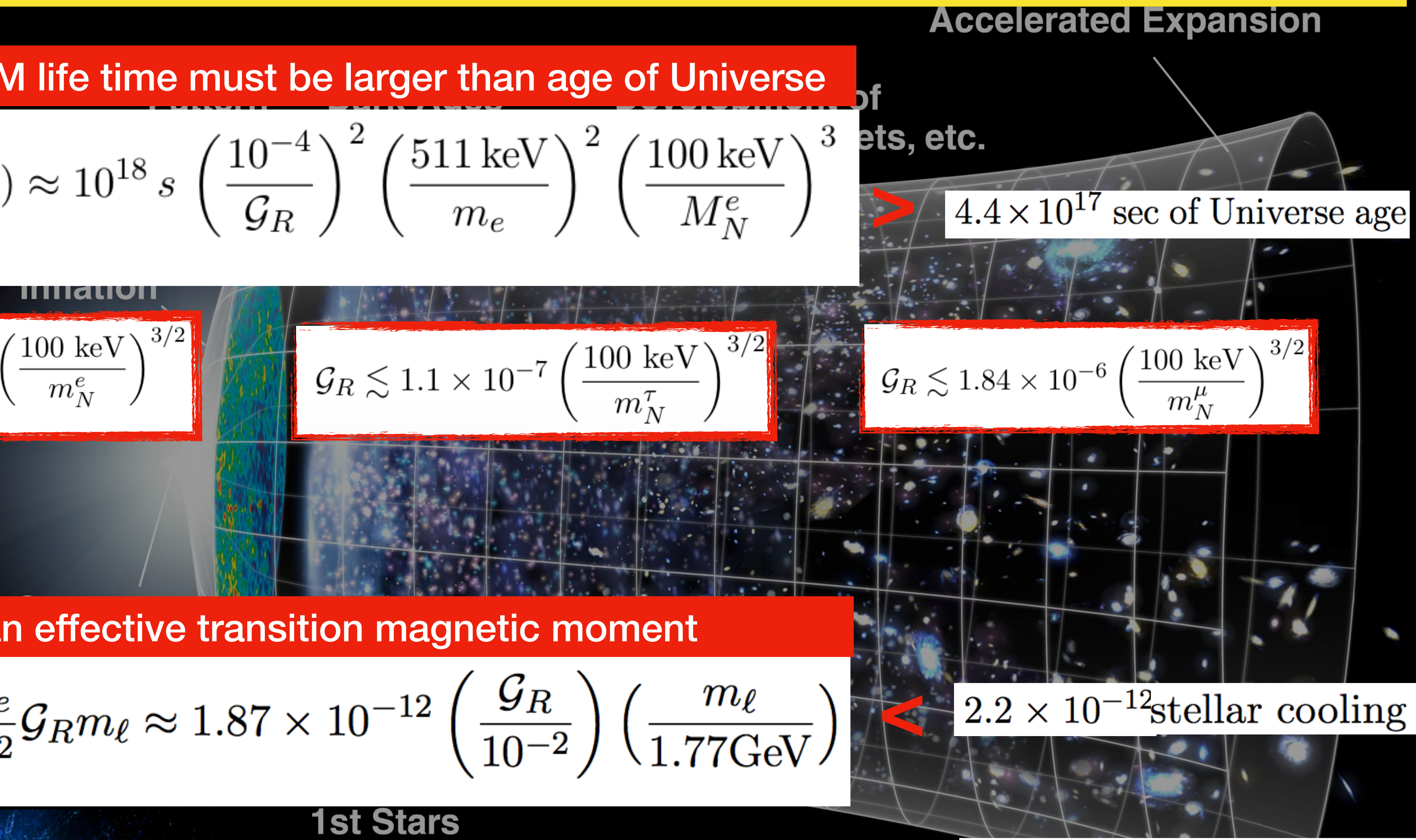
$$\boxed{(\alpha_{\text{sm}}/\alpha_{\text{exp}} - 1) \times 10^9 \lesssim -0.6}$$

R. H. Parker, et al. **Science 360 (2018) 191**

$$\boxed{\mathcal{G}^{\gamma}_{R} < 3.8 \times 10^{-4}}$$

S.-S. Xue,**[ArXiv:2012.04648]**

Preserving Astrophysical and Cosmological and Astrophysical Constraints



In order to be DM life time must be larger than age of Universe

$$\tau(N_R^e \to \gamma\,\nu^e) \approx 10^{18}\,s \left(\frac{10^{-4}}{\mathcal{G}_R}\right)^2 \left(\frac{511\,\mathrm{keV}}{m_e}\right)^2 \left(\frac{100\,\mathrm{keV}}{M_N^e}\right)^3$$

$>$ 4.4×10^{17} sec of Universe age

$$\mathcal{G}_R \lesssim 3.8\times 10^{-4}\left(\frac{100\ \mathrm{keV}}{m_N^e}\right)^{3/2}$$

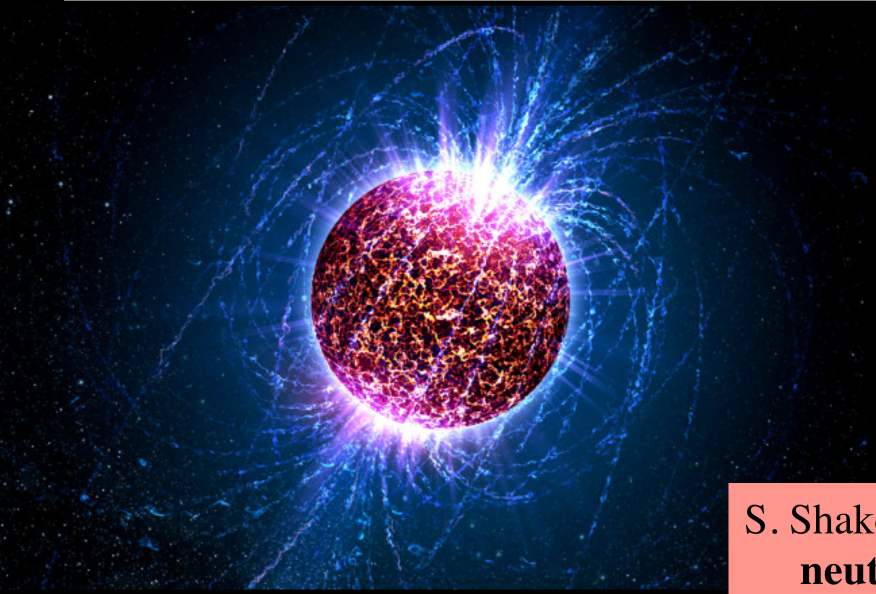
$$\mathcal{G}_R \lesssim 1.1\times 10^{-7}\left(\frac{100\ \mathrm{keV}}{m_N^\tau}\right)^{3/2}$$

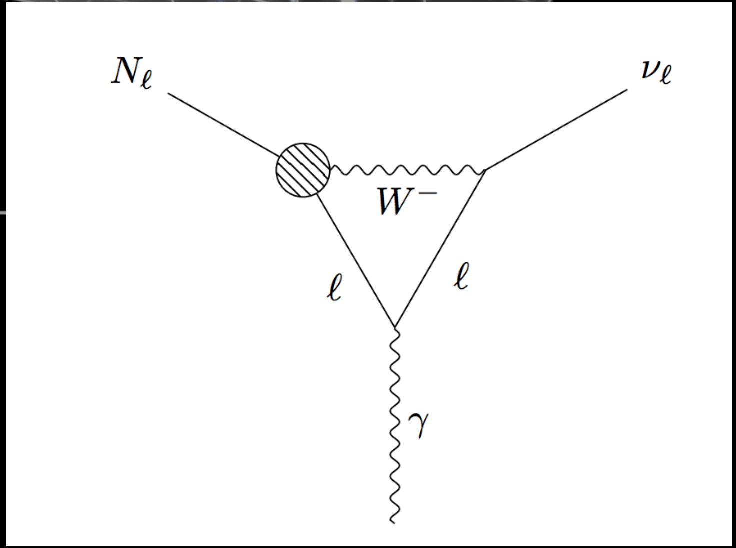
$$\mathcal{G}_R \lesssim 1.84\times 10^{-6}\left(\frac{100\ \mathrm{keV}}{m_N^\mu}\right)^{3/2}$$

Induce an effective transition magnetic moment

$$\frac{\mu_{\rm eff}}{\mu_B} \sim \frac{G_F m_e}{4\sqrt{2}\pi^2}\mathcal{G}_R m_\ell \approx 1.87\times 10^{-12}\left(\frac{\mathcal{G}_R}{10^{-2}}\right)\left(\frac{m_\ell}{1.77\mathrm{GeV}}\right)$$

$<$ 2.2×10^{-12} stellar cooling





S. Shakeri, F. Hajkarim, and S.-S. Xue, **Shedding new light on sterile neutrinos from xenon1t experiment**, JHEP 2020 (Dec, 2020).

Sterile Neutrino-Electron Scatterings

Incoming Sterile Neutrino

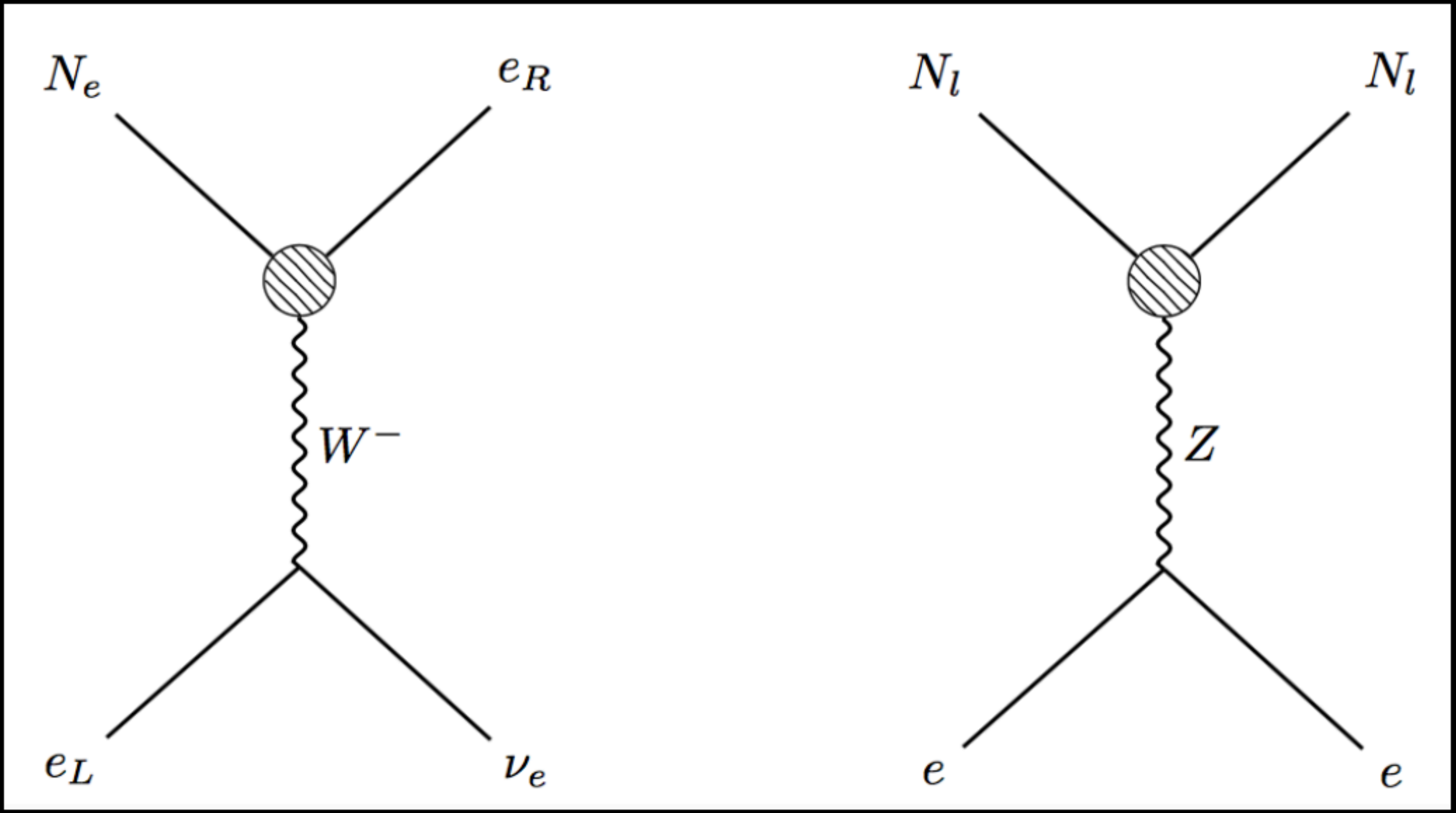
Inelastic $N_e e \to \nu_e e$

$N_\ell e \to N_\ell e$ Elastic

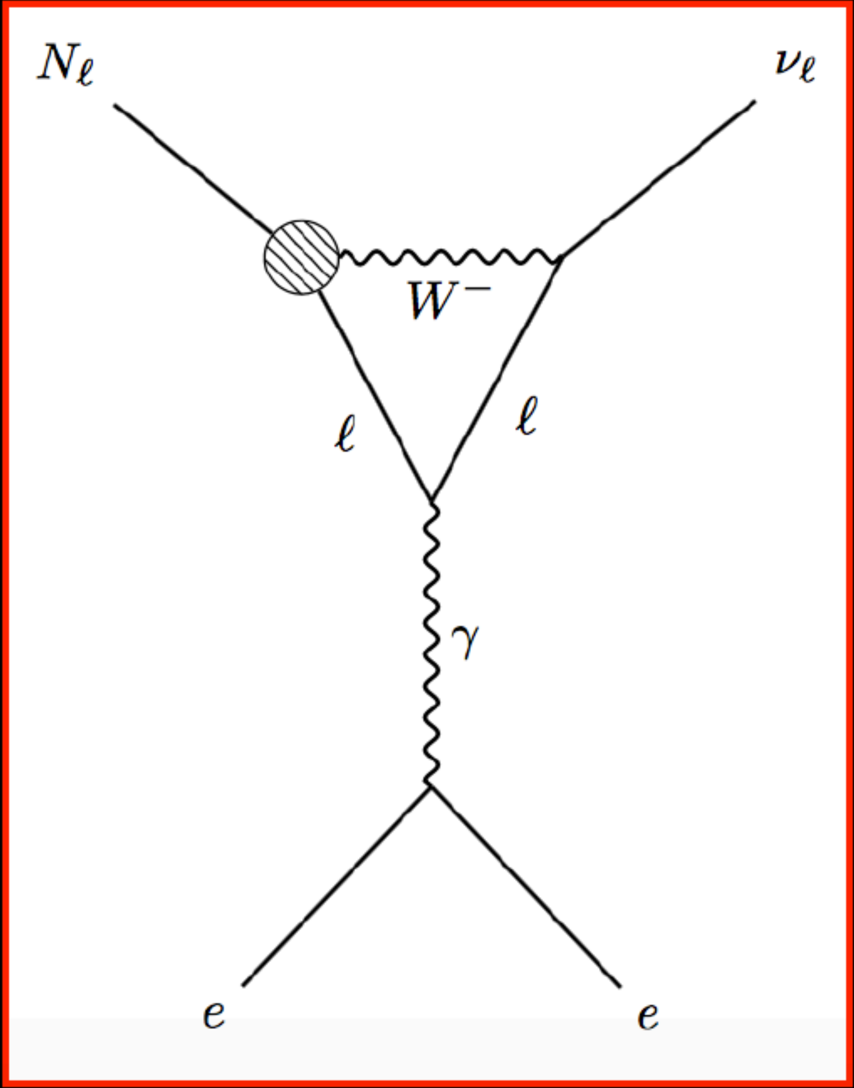
Inelastic $N_\ell e \to \nu_\ell e$ (EM Channel)

Outgoing Sterile Neutrino

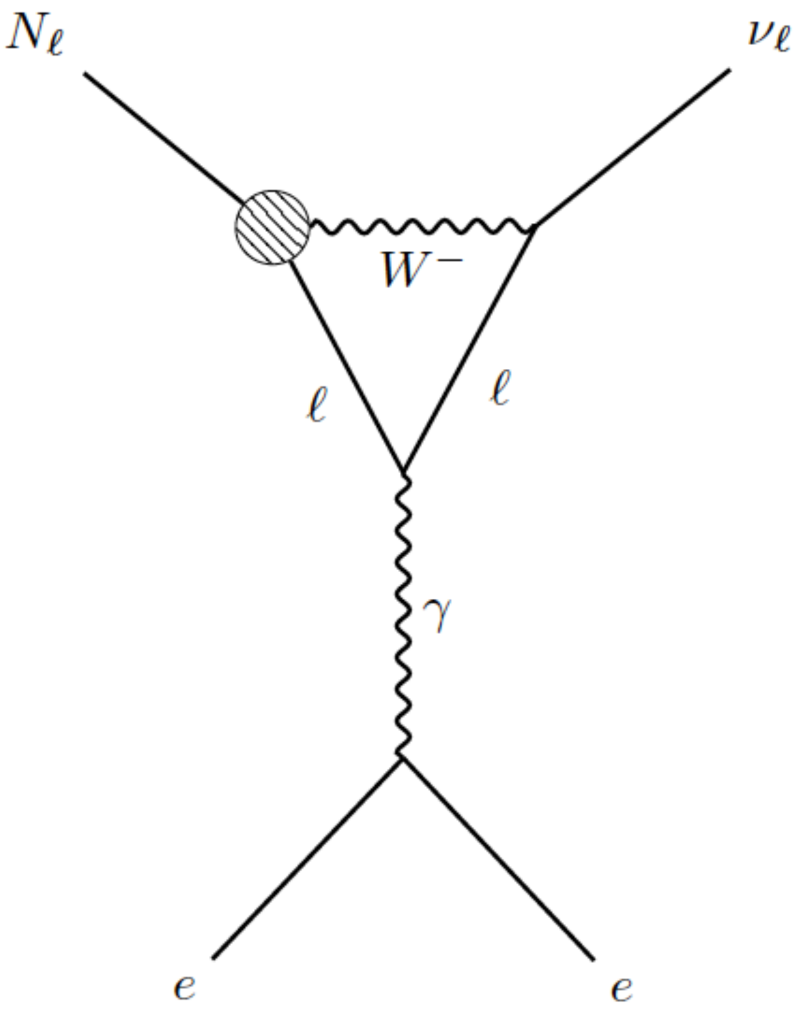
$\nu_e e \to N_e e$ Inelastic

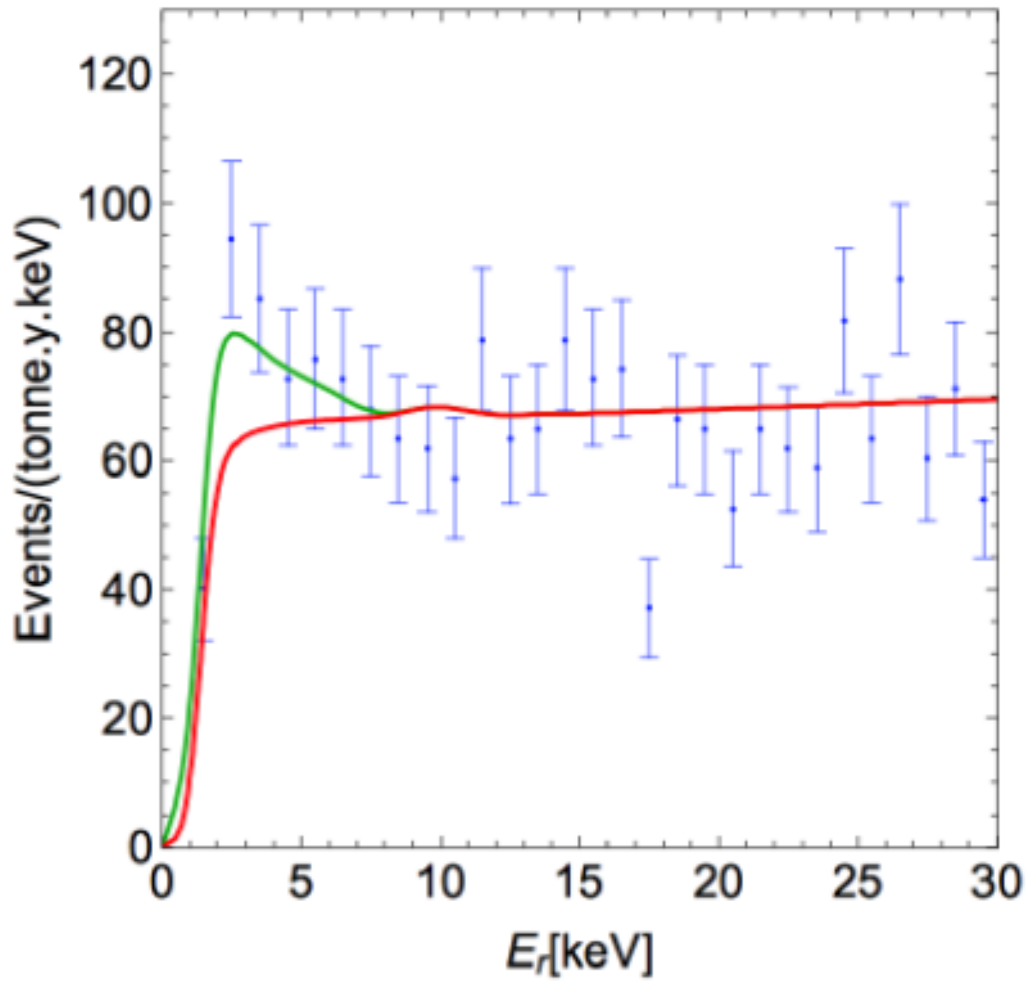


S. Shakeri, F. Hajkarim, and S.-S. Xue, **Shedding new light on sterile neutrinos from xenon1t experiment**, JHEP 2020 (Dec, 2020).



$N_\ell e \to \nu_\ell e$ (EM Channel)



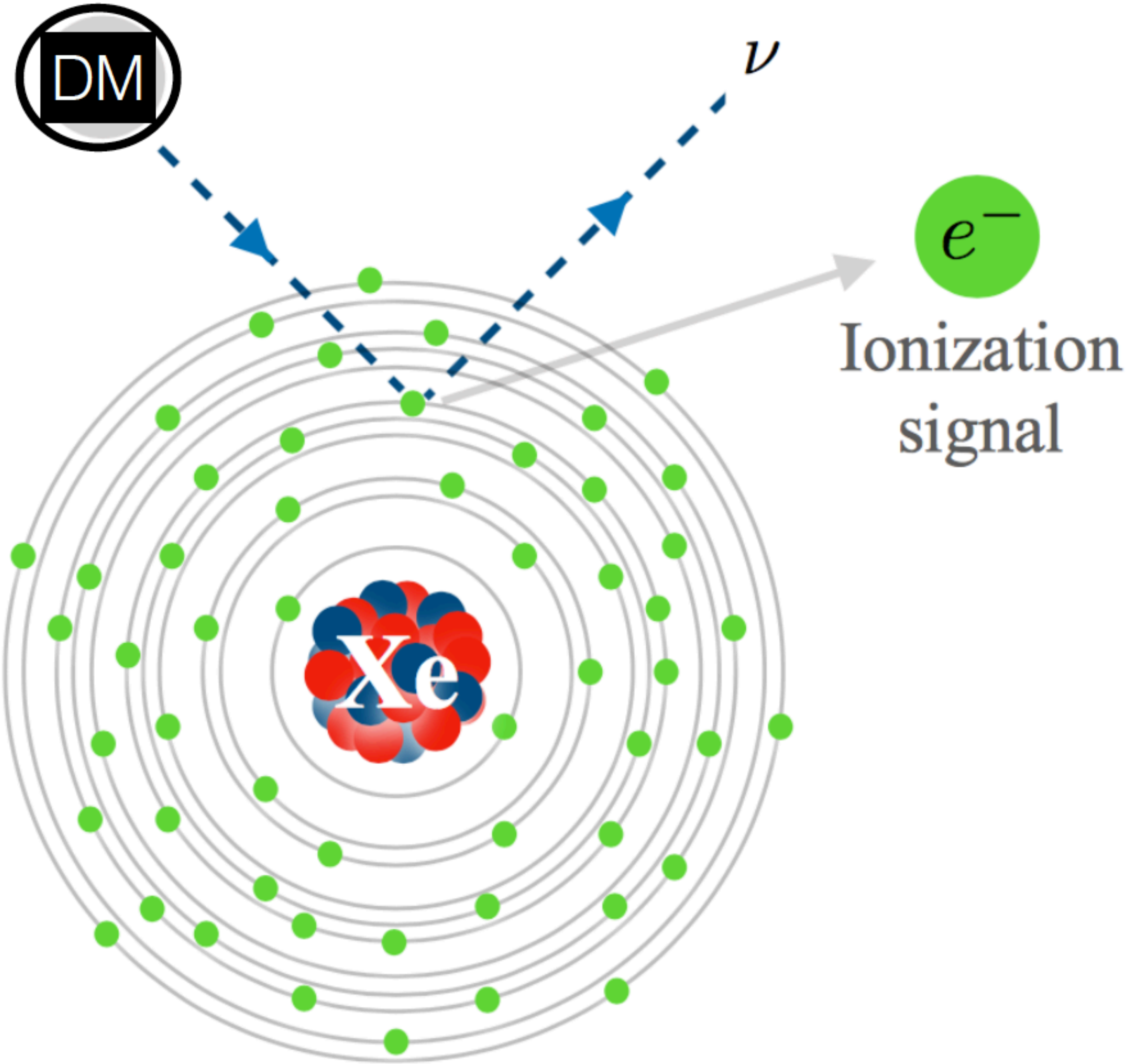


$$\frac{d\sigma_{N_\ell e\to\nu_l e}}{dE_r} \propto \left(\frac{\alpha G_F \mathcal{G}_R m_\ell}{4\pi^{3/2}\upsilon_N \underline{E_r} m_e^{1/2}}\right)^2 (M_N^2 + 2m_e E_r)$$

↓ E_r $\qquad$ $\frac{d\sigma_{N_\ell e\to\nu_l e}}{dE_r}$ ↑

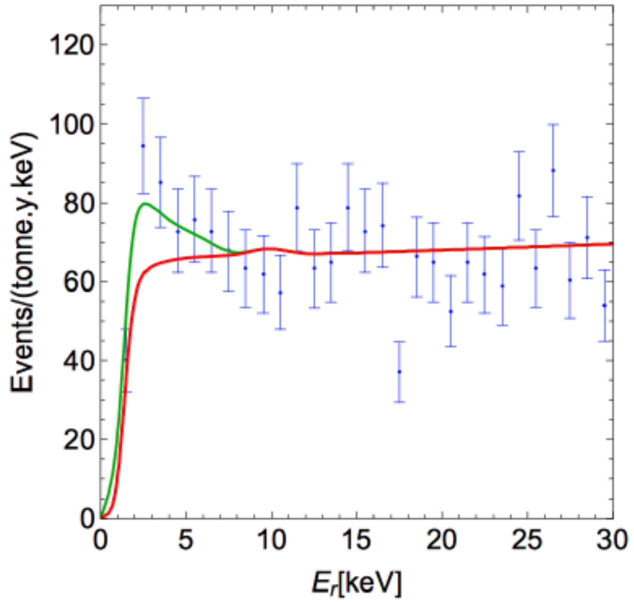
Inelastic scattering of DM from Xenon electrons

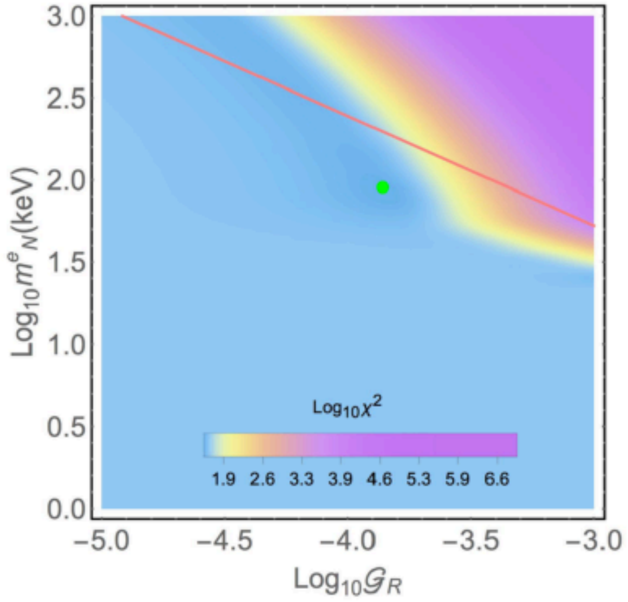
our main idea



Recoil energy

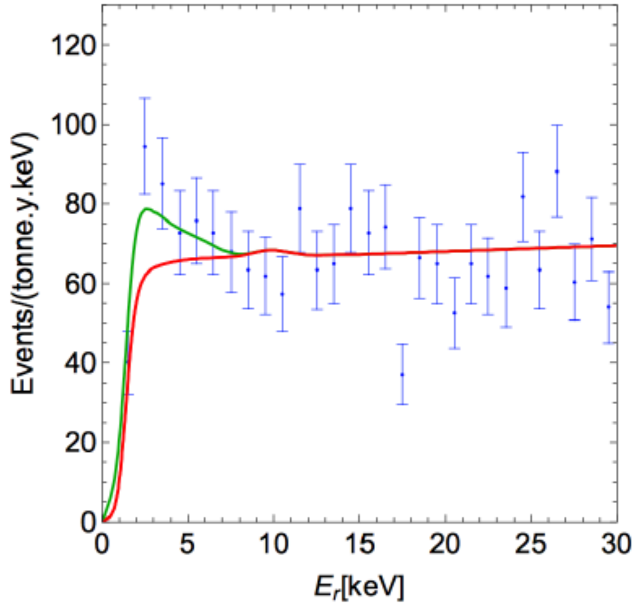
$$T_e \approx m_{DM}^2/2m_e = 2.45\ \text{keV}(m_{DM}/50\ \text{keV})^2$$

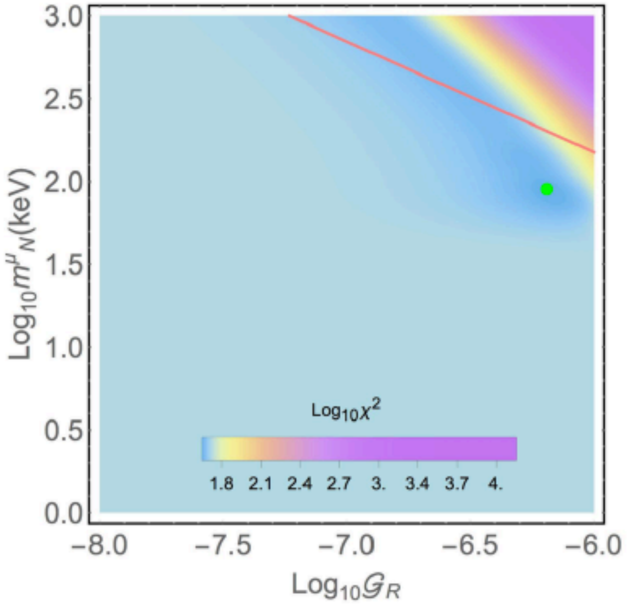




$$[\mathcal{G}_R, m^l_{N_e}]$$

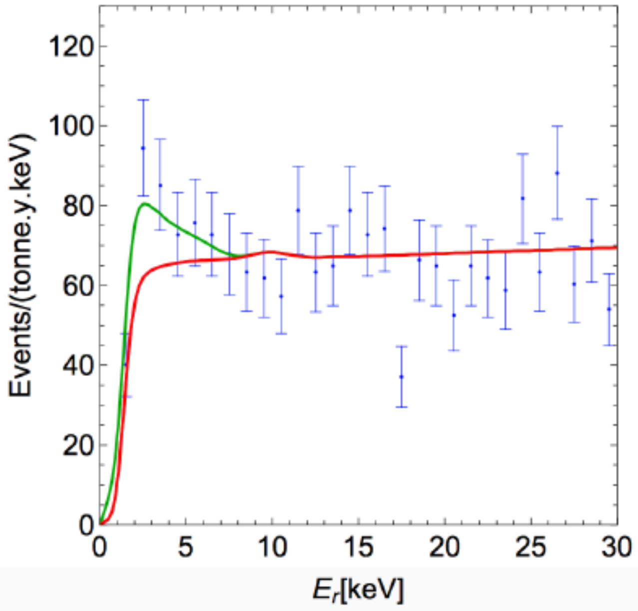
$$[1.4\times10^{-4}, 90.6\ \text{keV}]$$

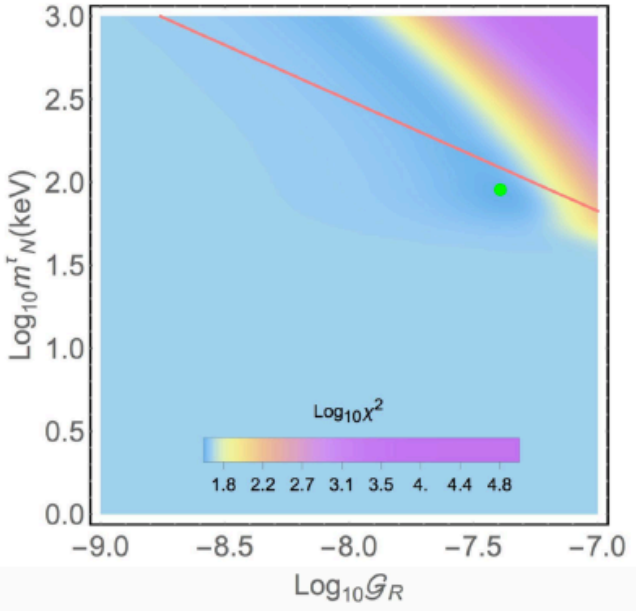




$$[\mathcal{G}_R, m^l_{N_\mu}]$$

$$[6.4\times10^{-7}, 90.6\ \text{keV}]$$





$$[\mathcal{G}_R, m^l_{N_\tau}]$$

$$[4.0\times10^{-8}, 90.6\ \text{keV}]$$

3 different scenarios

1) **DM :** N_e

$m_N^e \sim 90$

$\mathcal{G}_R \sim \mathcal{O}(10^{-4})$

N_μ

N_τ

Decay

SM

2) **DM :** N_R^e and N_R^μ

$m_N^\mu \sim 90$ keV

$\mathcal{G}_R \sim \mathcal{O}(10^{-6})$

N_τ

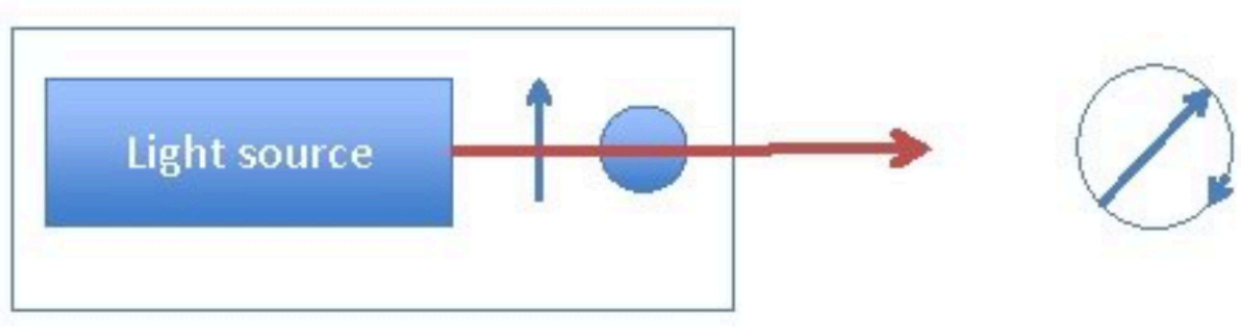
Decay

SM

3) **DM :** N_R^e, N_R^μ, and N_R^τ $\mathcal{G}_R \sim \mathcal{O}(10^{-7})$ $m_N^\tau \sim 90$ keV

Regarding the XENON1T electron recoil data, there is a degeneracy between three scenarios.

- **Polarization asymmetry between out going recoil electrons**



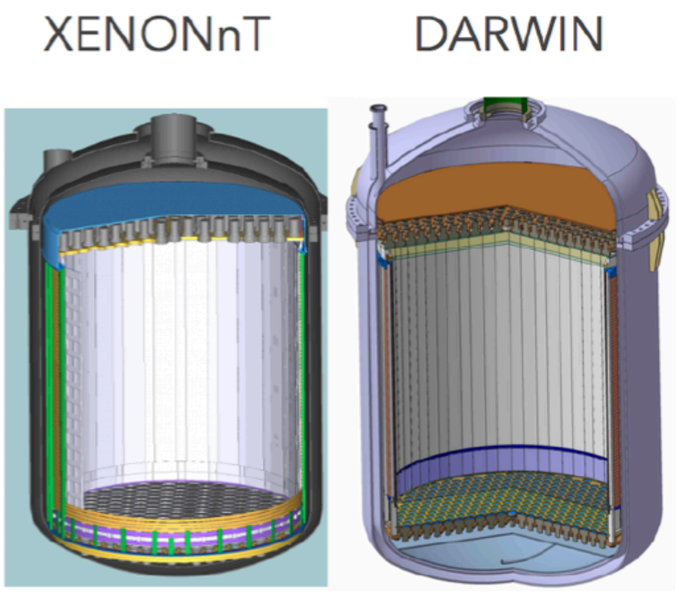
The scattering via charged lepton coupling leads to asymmetry between left- and right-handed recoil electrons

1)
$$N + e_{L/R} \to \nu + e_{L/R}$$
$$N + e_R \to \nu + e_L$$

2)
$$N + e_L \to \nu + e_R$$

$$\boxed{\mathcal{A} = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)}$$

Towards Ultimate DM detector



Sterile Neutrino DM Relic Density

Sterile Neutrinos in Thermal Equilibrium
$2 \longleftrightarrow 2$ Processes

$$N_\ell \bar{N}_\ell \longleftrightarrow \gamma\gamma$$

$$N_\ell \bar{N}_\ell \longleftrightarrow \ell^- \ell^+$$

$$N_\ell \ell^- \longleftrightarrow \ell^- \nu_\ell$$

Sterile Neutrinos Decay Process

$$N_\ell \to \gamma\nu$$

$$\Gamma_N = n_N \langle \sigma v \rangle \approx G_F^2 \mathcal{G}_R^2 T^5$$

$$H = \sqrt{\frac{4\pi^3 g_\star(T)}{45}}\, \frac{T^2}{M_{Pl}} \approx 1.66\ (g_\star(T))^{1/2} \frac{T^2}{M_{Pl}}$$

When $\Gamma_N \approx H$, sterile neutrinos decouple

$$T_{f_N} \approx 21.02\ \text{GeV} \left(\frac{10^{-6}}{\mathcal{G}_R}\right)^{2/3} \left(\frac{g_\star(T)}{86.25}\right)^{1/6}$$

S.Mahmoudi, S. Shakeri, and S.-S. Xue, **Relic Density of Sterile Neutrinos**, **In preparation 2021.**

DM Overproduction and Entropy Dilution

$$\Omega_N = \frac{Y_N m_N s}{\rho_c} \simeq \underset{?}{\underline{240}} \left(\frac{m_N}{90\,\mathrm{keV}}\right)\left(\frac{86.25}{g_*(T_{f_N})}\right)$$

$$\Omega_{\mathrm{DM}} = 0.228 \pm 0.039$$ **Planck 2018**

$N_1 = DM$

$$\boxed{\Omega_{N_1} \to \hat{\Omega}_{N_1} = \Omega_{N_1}/\mathcal{S}}$$

Entropy Dilution can be generated by Decaying N_2 **and/or** N_3

$$\mathcal{S} \equiv \frac{S_{\mathrm{after}}}{S_{\mathrm{before}}} \simeq 1.8\, g_*(T_r)^{1/4} \frac{Y_N\, m_N \tau_N^{1/2}}{M_{\mathrm{pl}}^{1/2}}$$

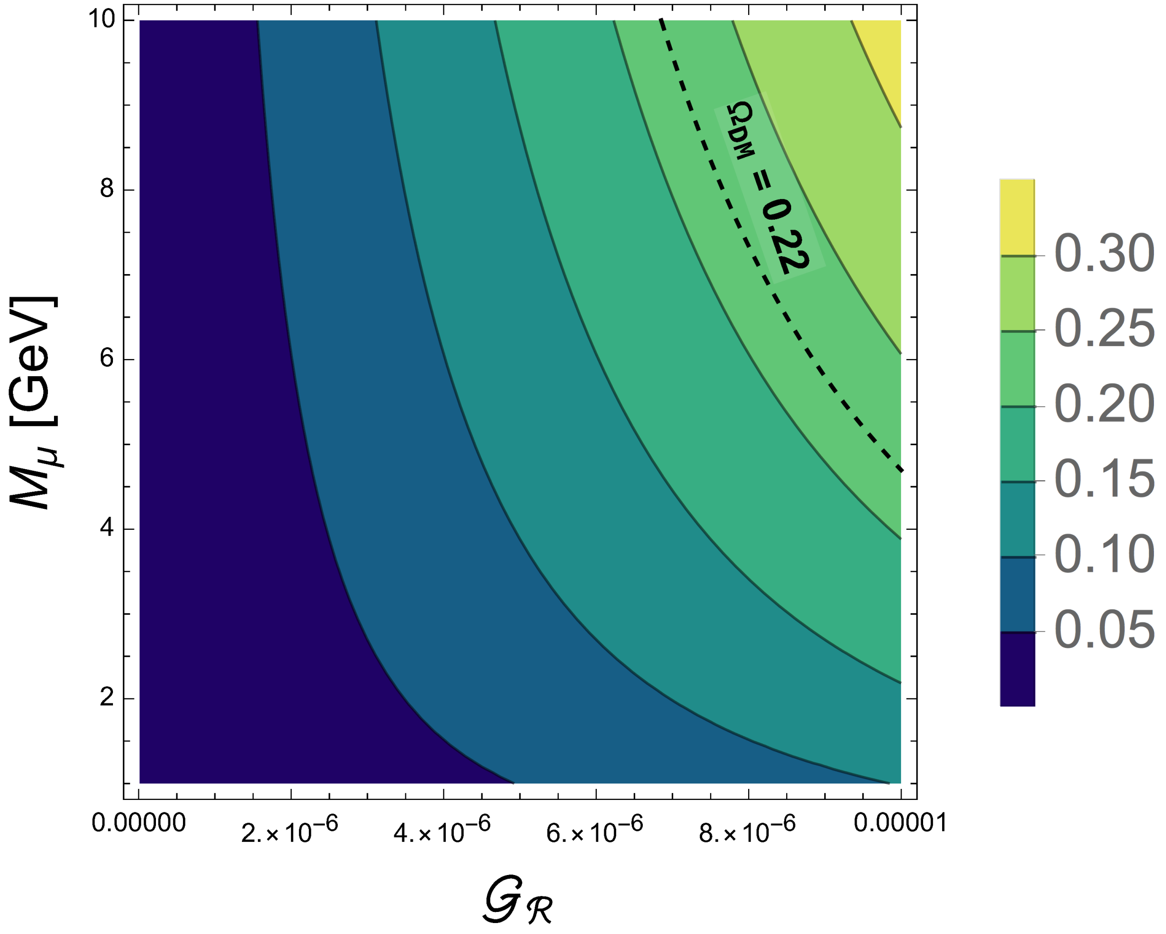
S.Mahmoudi, S. Shakeri, and S.-S. Xue, **Relic Density of Sterile Neutrinos**, **In preparation 2021.**

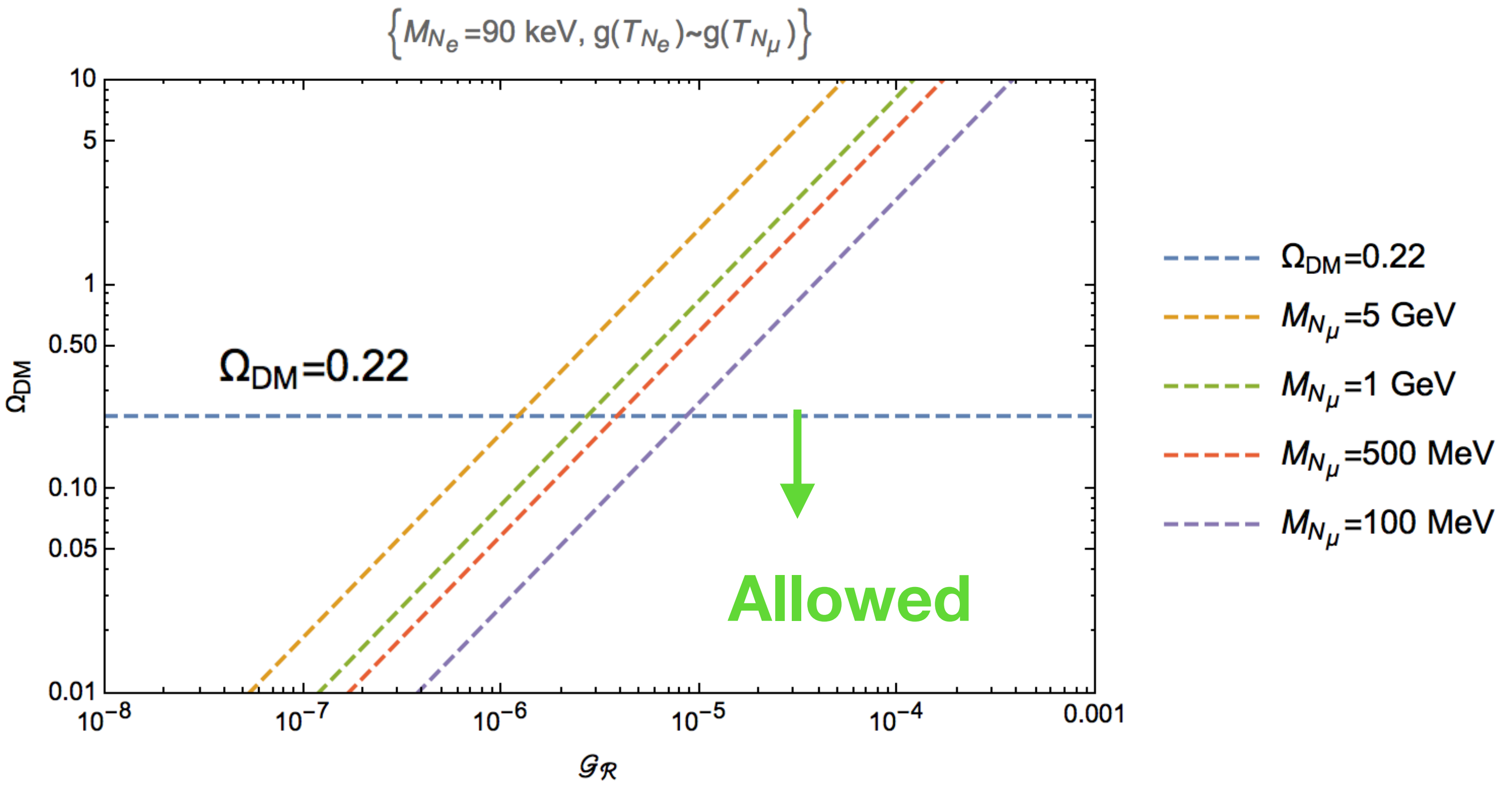
$N_e = DM$ $N_\mu =$ Diluter

$$\tau(N_R^\mu \to \gamma\, \nu^\mu) \simeq 1\, s \left(\frac{10^{-4}}{\mathcal{G}_R}\right)^2 \left(\frac{2.93\,\mathrm{GeV}}{M_{N_\mu}}\right)^3 \lesssim \mathcal{O}(1)s$$ **BBN Constraint**

$$\mathcal{S}_{N_\mu} \simeq 480 \left(\frac{g_*(T_r)^{1/4}}{g_*(T_{f_{N_\mu}})}\right) \left(\frac{1\mathrm{GeV}}{M_{N_\mu}}\right)^{1/2} \left(\frac{10^{-4}}{\mathcal{G}_R}\right)$$

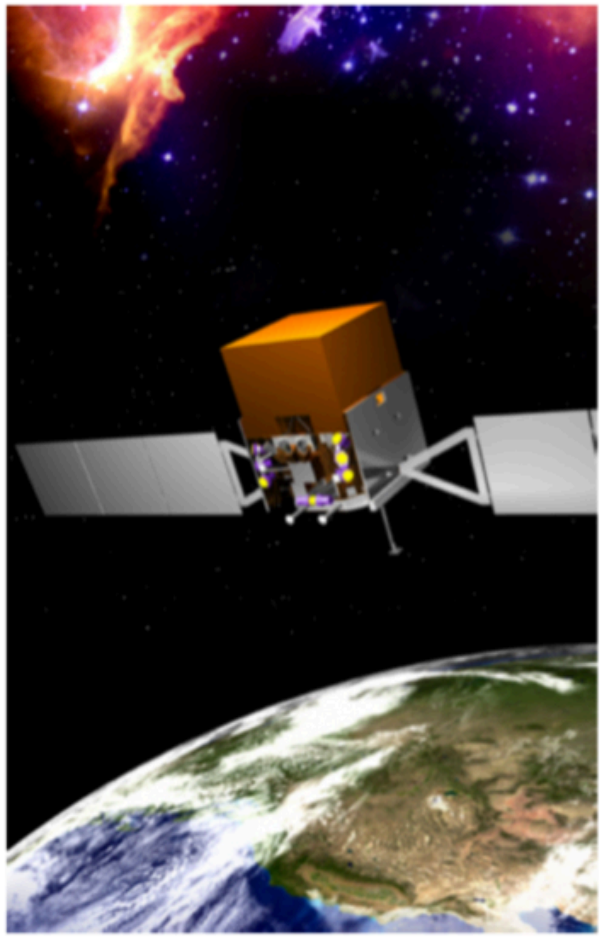
$$\boxed{\hat{\Omega}_{N_e} \simeq 0.47 \left(\frac{m_{N_e}}{1\mathrm{keV}}\right) \left(\frac{1\mathrm{GeV}}{m_{N_\mu}}\right) \left(\frac{g_*(T_{f_{N_\mu}})}{g_*(T_{f_{N_e}})}\right) \left(\frac{10.75}{g_*(T_r)}\right)^{1/4} \left(\frac{1\mathrm{s}}{\tau_{N\mu}}\right)^{1/2}}$$





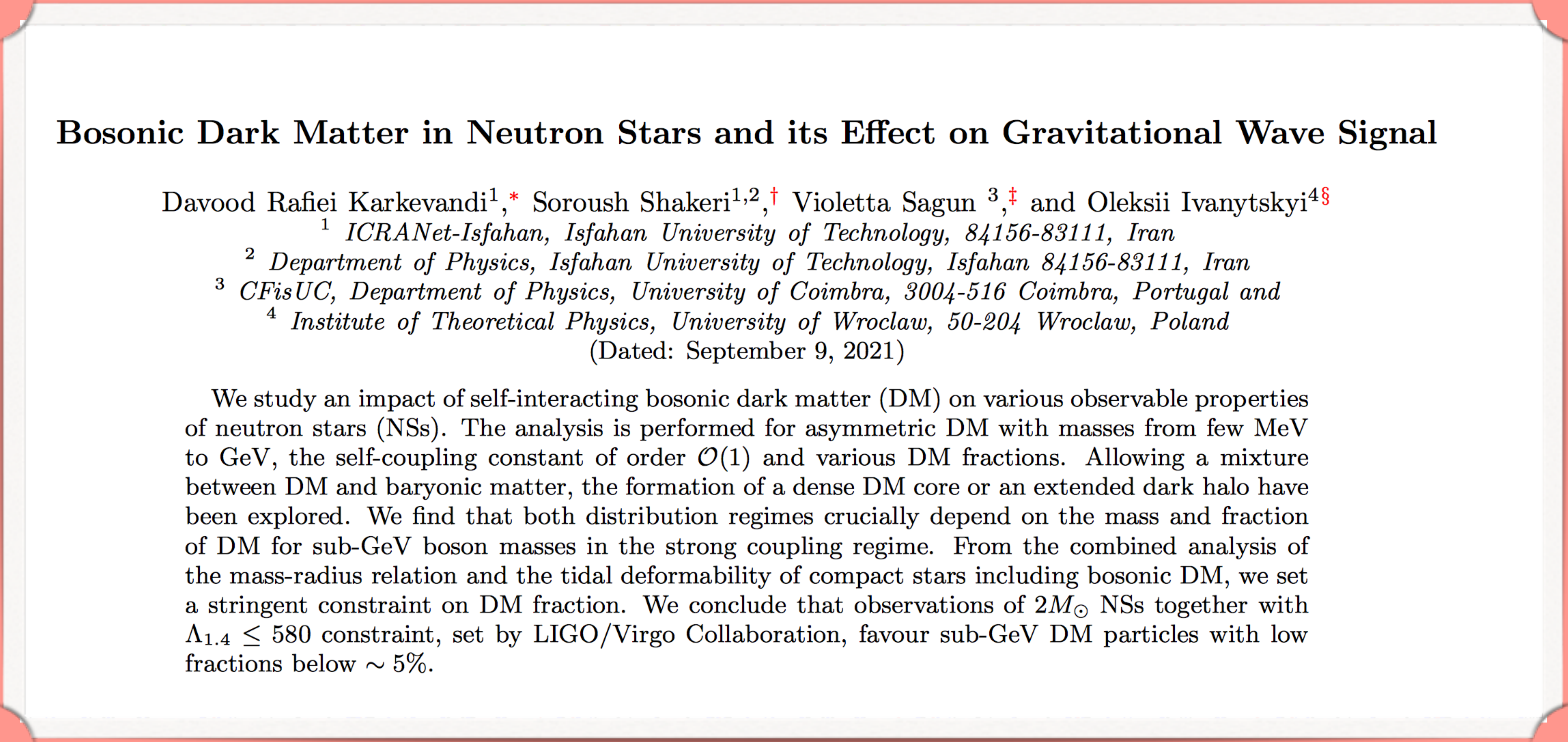
S.Mahmoudi, S. Shakeri, and S.-S. Xue, **Relic Density of Sterile Neutrinos**, **In preparation 2021.**

Indirect detection



DM->GW, M(R)

$\chi\bar{\chi} \to \gamma\gamma, q\bar{q}, \ldots$



Bosonic Dark Matter in Neutron Stars and its Effect on Gravitational Wave Signal

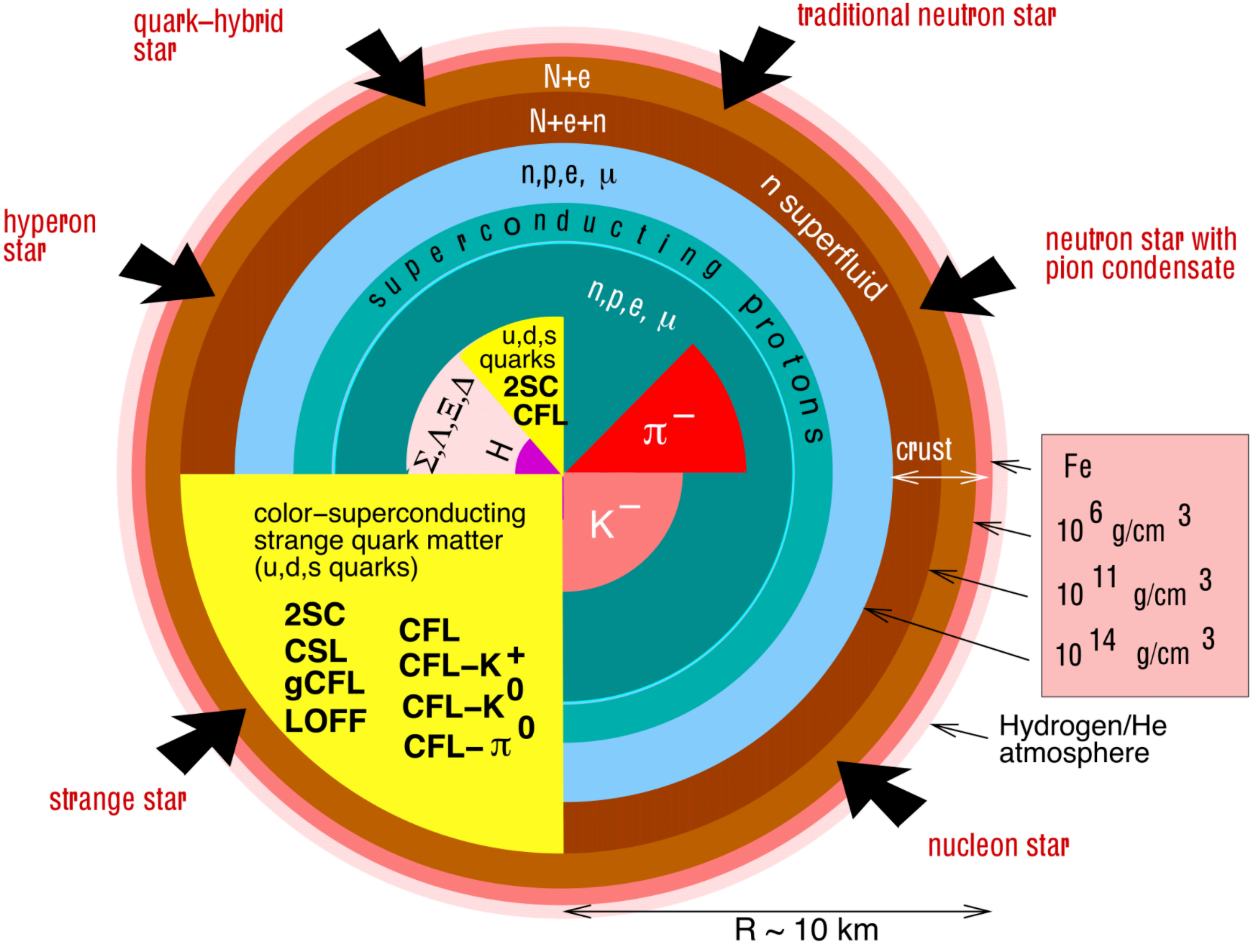
Davood Rafiei Karkevandi[1],[*] Soroush Shakeri[1,2],[†] Violetta Sagun [3],[‡] and Oleksii Ivanytskyi[4][§]
[1] *ICRANet-Isfahan, Isfahan University of Technology, 84156-83111, Iran*
[2] *Department of Physics, Isfahan University of Technology, Isfahan 84156-83111, Iran*
[3] *CFisUC, Department of Physics, University of Coimbra, 3004-516 Coimbra, Portugal and*
[4] *Institute of Theoretical Physics, University of Wroclaw, 50-204 Wroclaw, Poland*

(Dated: September 9, 2021)

We study an impact of self-interacting bosonic dark matter (DM) on various observable properties of neutron stars (NSs). The analysis is performed for asymmetric DM with masses from few MeV to GeV, the self-coupling constant of order $\mathcal{O}(1)$ and various DM fractions. Allowing a mixture between DM and baryonic matter, the formation of a dense DM core or an extended dark halo have been explored. We find that both distribution regimes crucially depend on the mass and fraction of DM for sub-GeV boson masses in the strong coupling regime. From the combined analysis of the mass-radius relation and the tidal deformability of compact stars including bosonic DM, we set a stringent constraint on DM fraction. We conclude that observations of $2M_{\odot}$ NSs together with $\Lambda_{1.4} \leq 580$ constraint, set by LIGO/Virgo Collaboration, favour sub-GeV DM particles with low fractions below $\sim 5\%$.

arXiv:2109.03801v1

Neutron Stars (NSs) as a Natural Laboratory to Test Fundamental Physics



$R \sim 10$ km

$M \sim 1.4 M_\odot$

$\rho_c \sim 2 - 10\rho_{\rm nuc}$

$(\rho_{\rm nuc} := 2 \times 10^{17}\,{\rm kg\,m^{-3}})$

[Weber, J. Phys. G 27, 465 (2001)]

The maximum mass for NS and its interior structure

Neutron Star Hydrostatic Equilibrium Equations

$$\frac{dP}{dr} = -G\frac{m(r)\rho(r)}{r^2}\left(1+\frac{P(r)}{c^2\rho(r)}\right)\left(1+4\pi\frac{r^3P(r)}{c^2}m(r)\right)\left[1-\frac{2Gm(r)}{c^2r}\right]^{-1}$$

$$\frac{dm}{dr} = 4\pi r^2\rho(r)$$

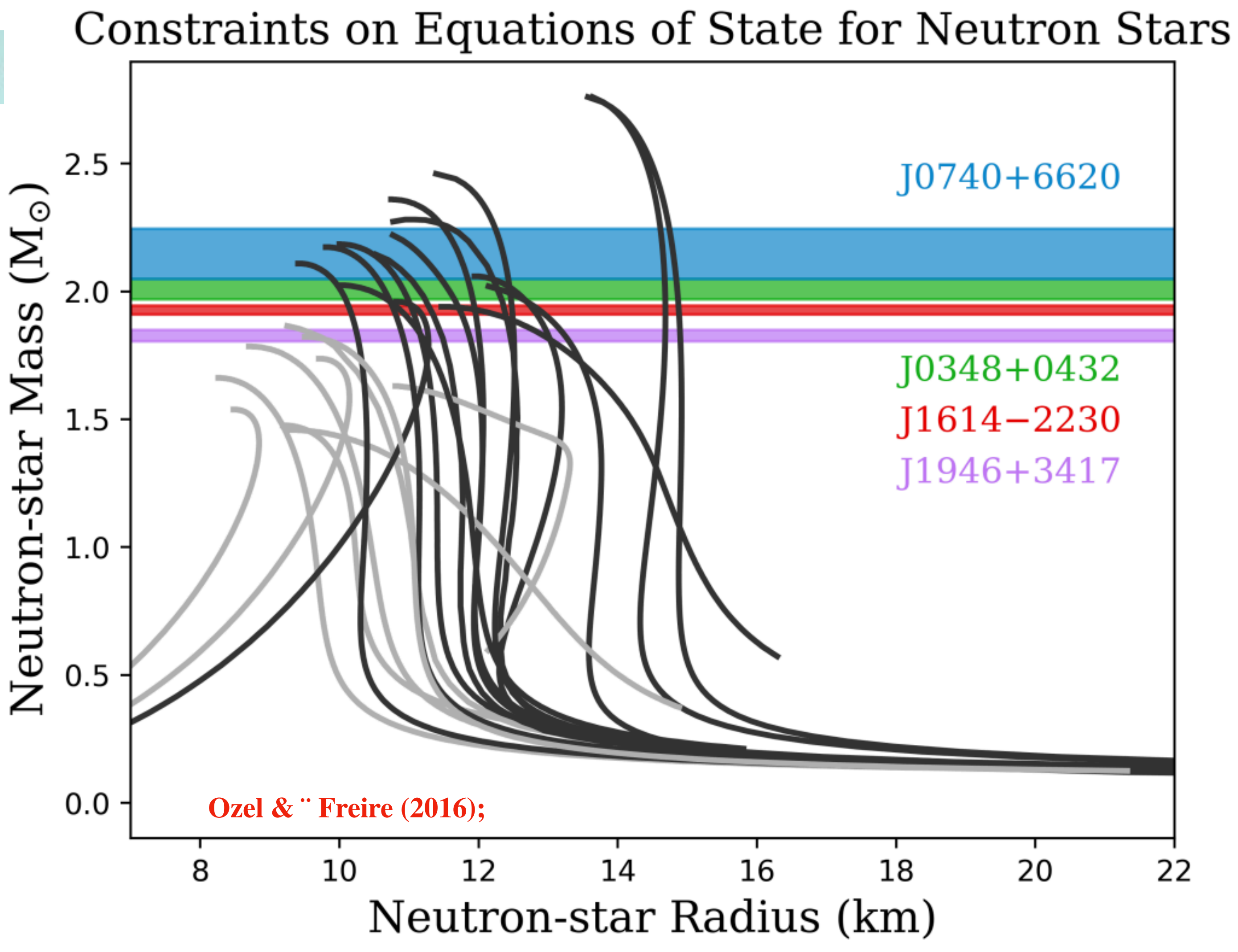
Tolman- Oppenheimer -Volkoff (TOV) Eqs.

Equation of State ?

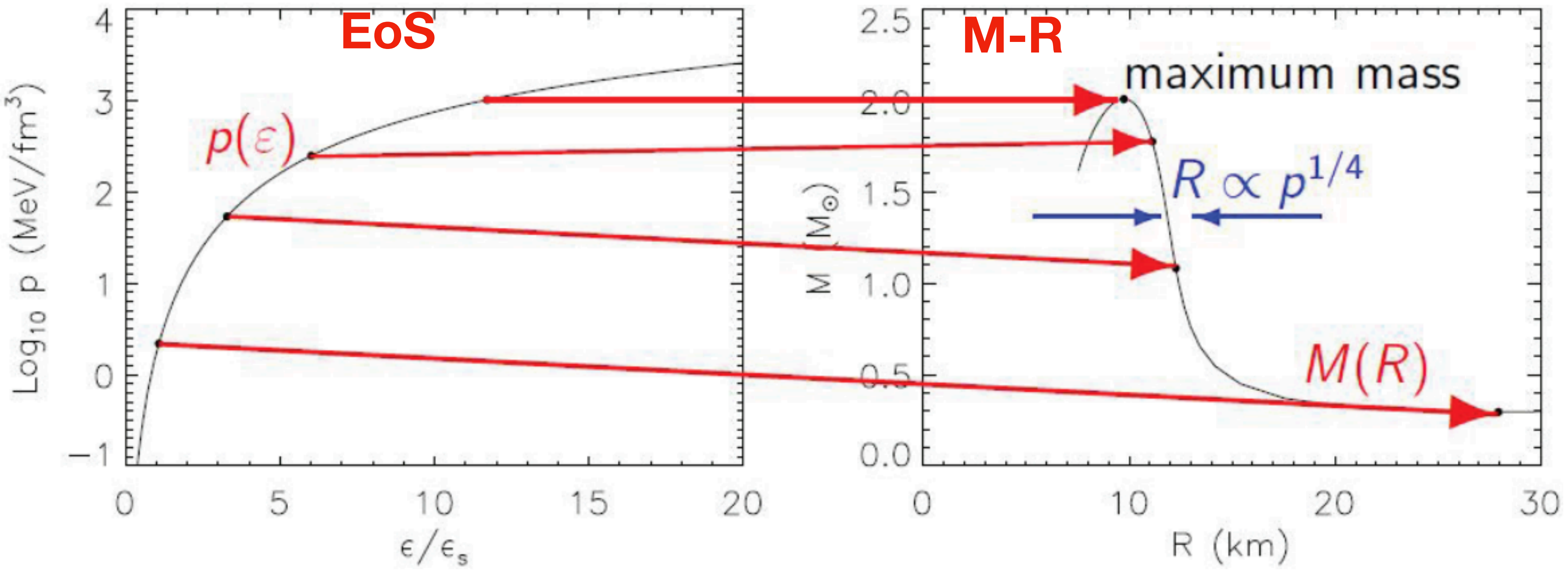
$$\boxed{\varepsilon(P)}$$

$$P_c \Longrightarrow m(r),\quad P(r),\quad \varepsilon(r)$$

$$P(R)=0 \Longrightarrow R,\quad m(R)=M$$

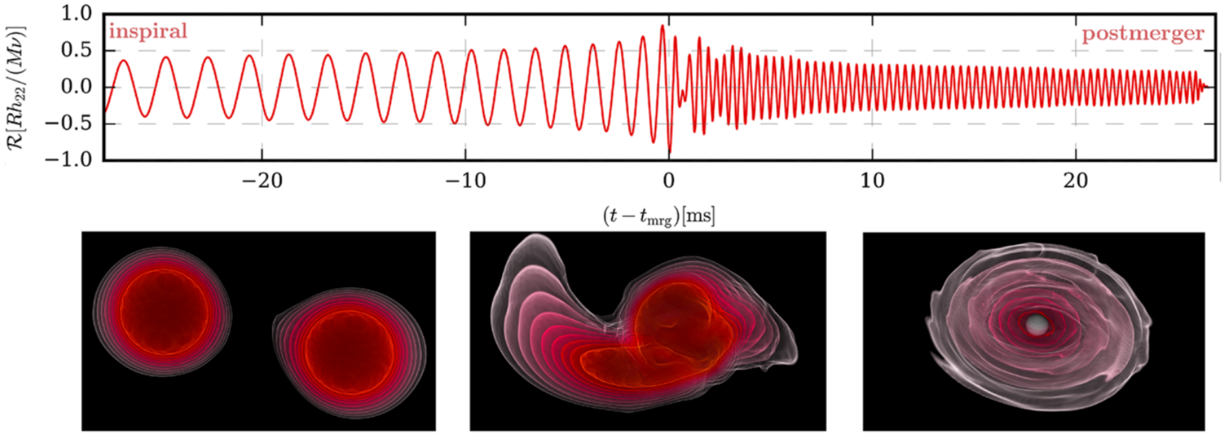


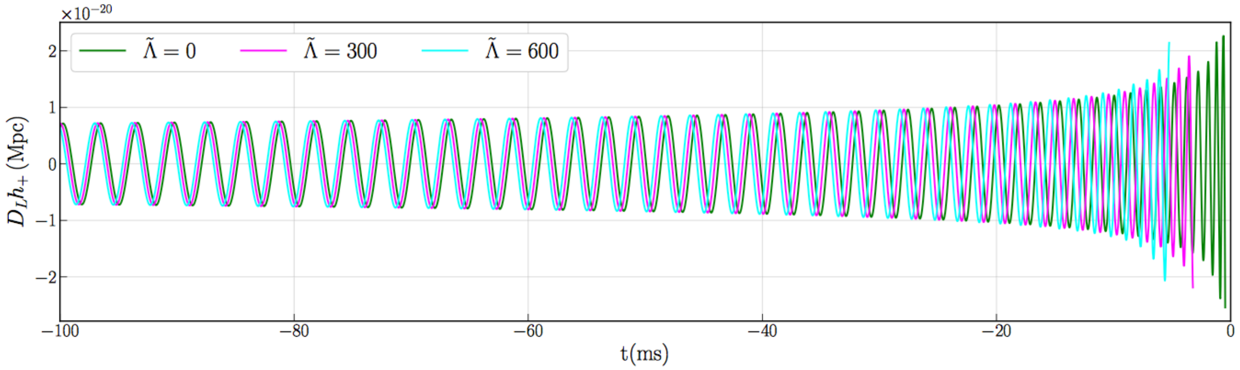
Ozel & ¨ Freire (2016);

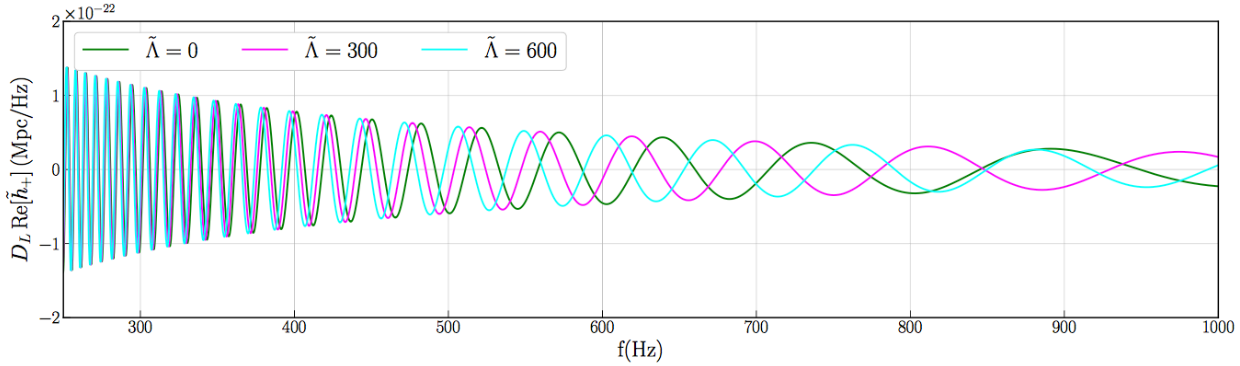


R. C. Tolman, Phys. Rev. 55, 364 (1939). ‚J. R. Oppenheimer and G. M. Volkoff, Phys. Rev. 55, 374 (1939).

Tidal Deformation and Gravitational Wave Signal

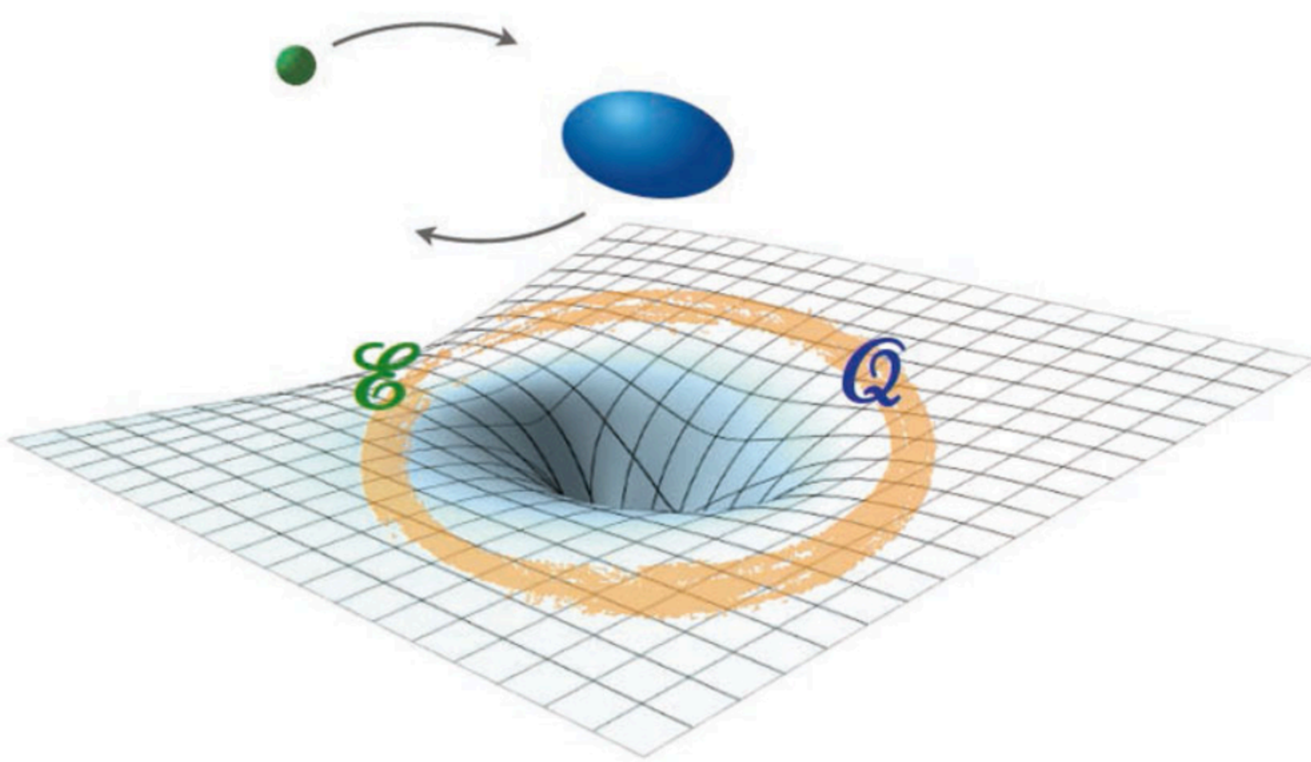






$$\Psi(f) = 2\pi f t_c + \phi_c - \frac{\pi}{4} + \frac{3}{128\eta u^5}\left\{1 + f(\eta)u^2 + (4\beta - 16\pi)u^3 + \left[g(\eta) + \sigma\right]u^4 + \ldots - \frac{39}{2}\tilde{\Lambda}u^{10} + \ldots\right\}.$$

Gravitational Wave Phase in Frequency Domain



$$Q_{ij} = \lambda_t \varepsilon_{ij}$$

Induced quadrupole moment

Tidal deformability

External tidal field

$$\lambda_t = \frac{2}{3}k_2 R^5$$

k_2: Dimensionless tidal love number

R: radius of star

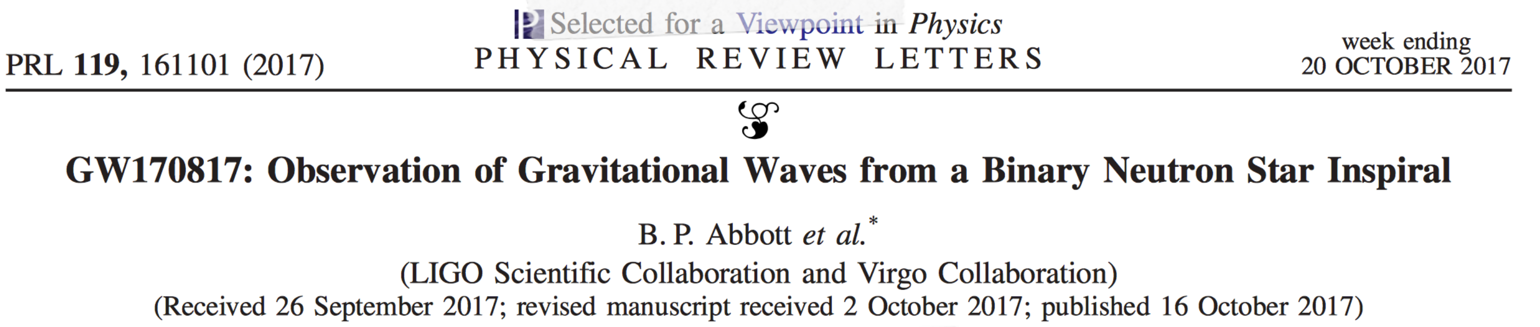
k_2 will be calculated by TOV equation, so it is related to the NS matter and the EoS

Tanja Hinderer
"Tidal Love Numbers of Neutron Stars"
Astrophys.J. 677 (2008) 1216-1220
Tanja Hinderer, et al.
Phys.Rev.D81:123016,2010
Sergey Postnikov, et al.
Phys.Rev.D 82 (2010) 024016
Gen.Rel.Grav. 53 (2021) 3, 27 2004.02527

Dimensionless tidal deformability: $\Lambda = \frac{\lambda_t}{M^5} = \frac{2}{3}k_2\left(\frac{R}{M}\right)^5$

R and M are the mass and radius of star

NS mass and Tidal Deformability for a Wide Variety of equation-of-state models.



Selected for a Viewpoint in *Physics*

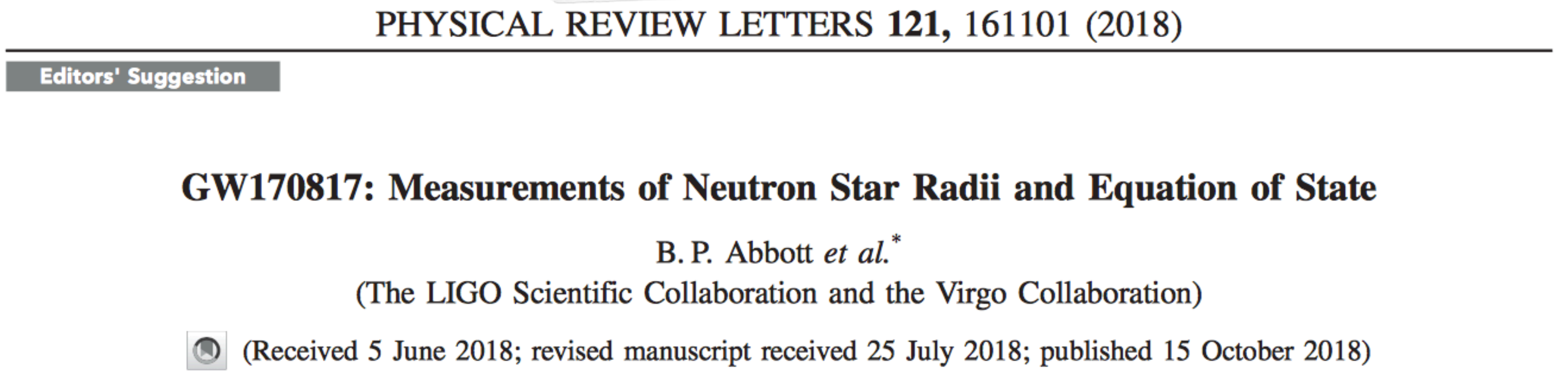
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)



PHYSICAL REVIEW LETTERS **121,** 161101 (2018)

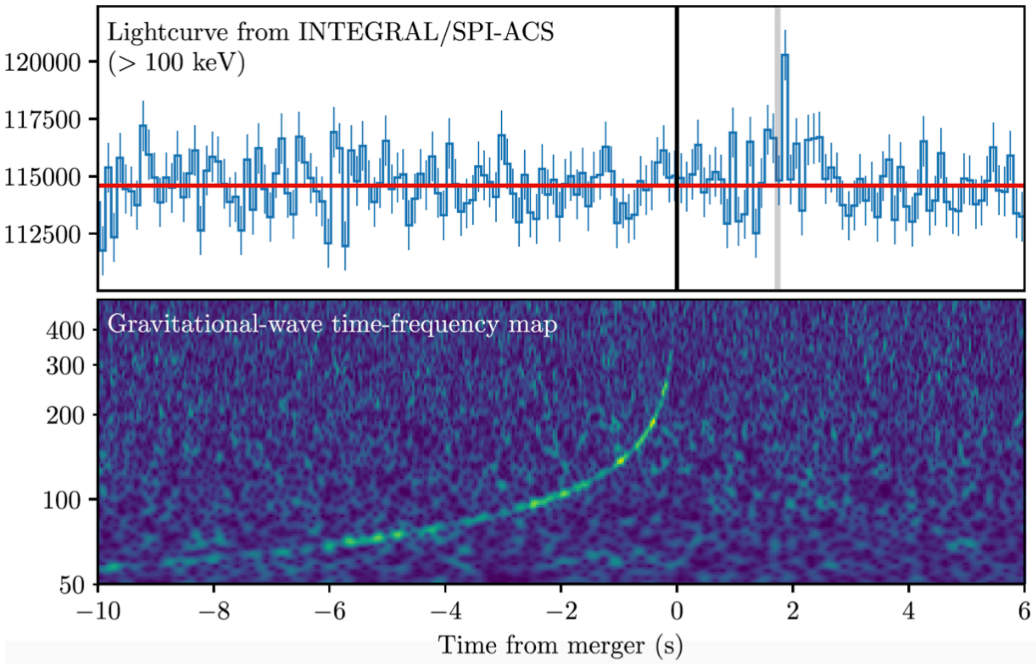
Editors' Suggestion

GW170817: Measurements of Neutron Star Radii and Equation of State

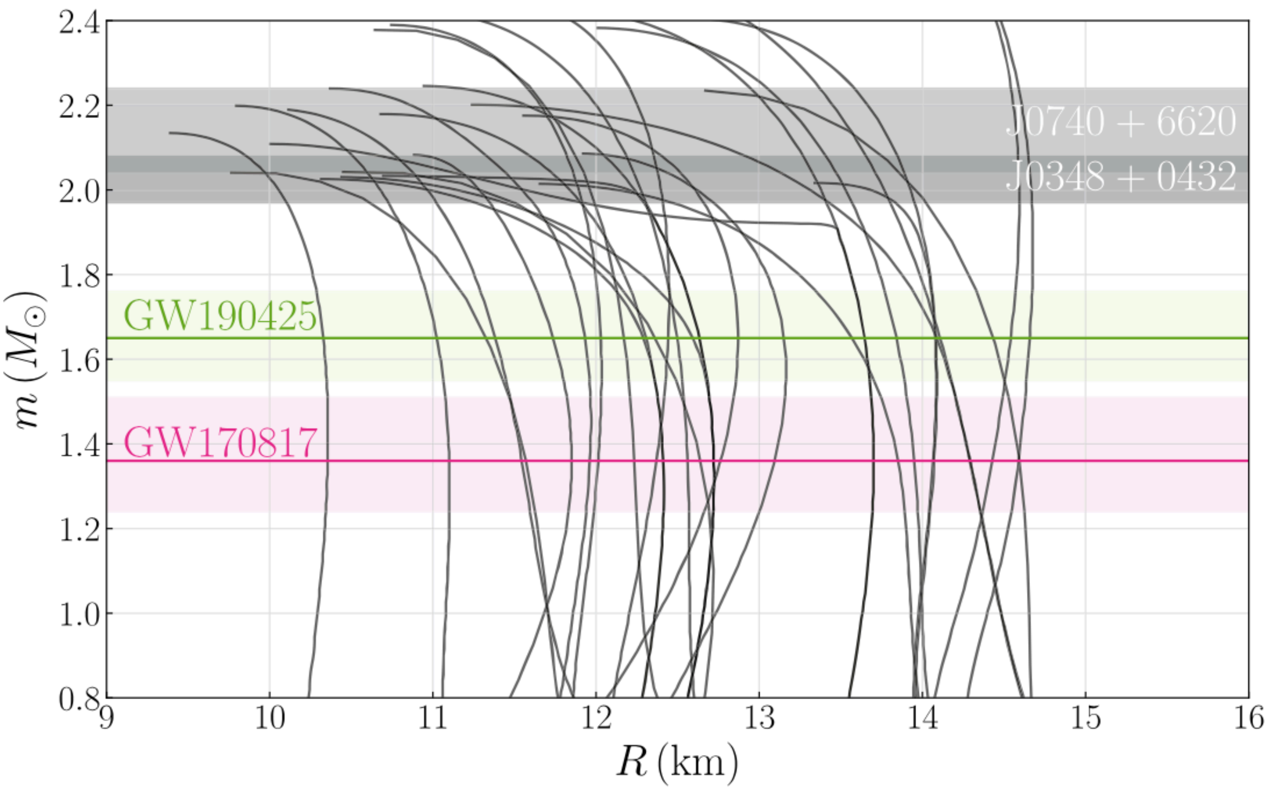
B. P. Abbott *et al.**

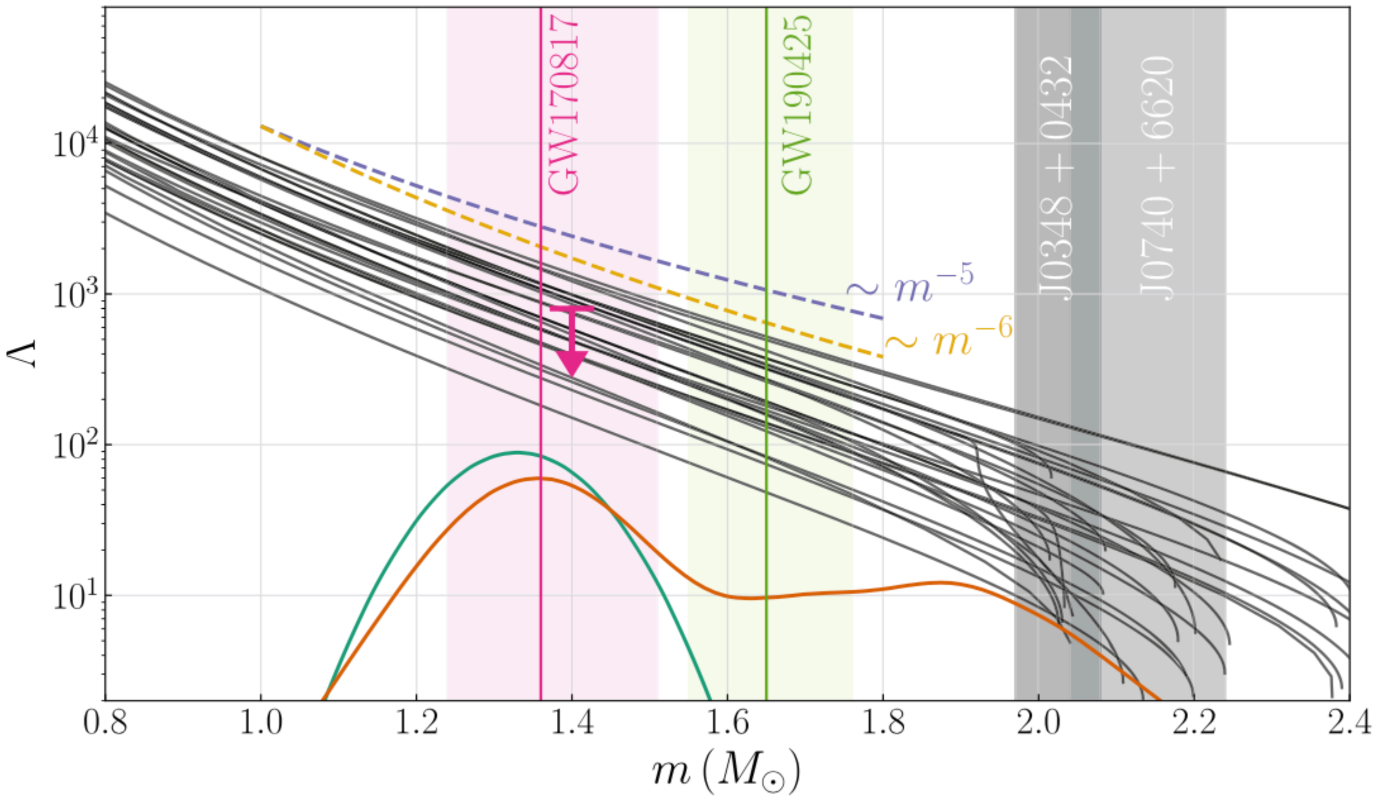
(The LIGO Scientific Collaboration and the Virgo Collaboration)

(Received 5 June 2018; revised manuscript received 25 July 2018; published 15 October 2018)



Dimensionless tidal deformability, $\Lambda \leq 580$ for $M = 1.4M_\odot$





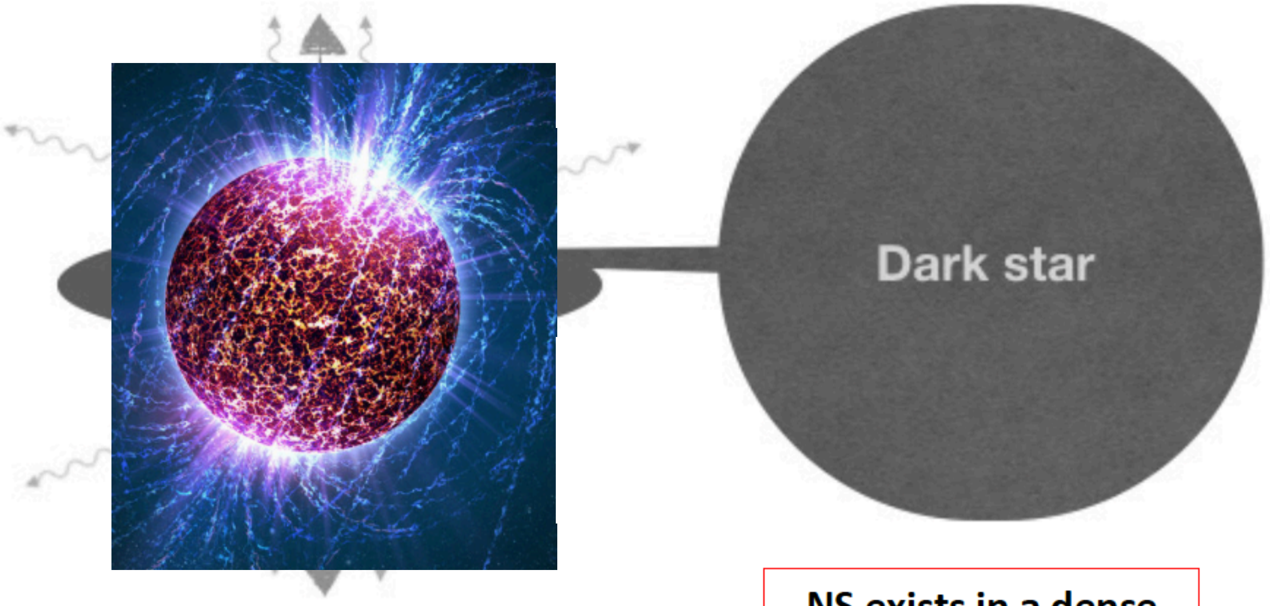
Gen.Rel.Grav. 53 (2021) 3, 27 • e-Print: 2004.02527

Dark Matter in Neutron Stars

DM capture by NS in a binary system including Dark star or Dark star – NS merger

I. Goldman, et al. Phys.Lett.B 725 (2013) 200-207
Moira I. Gresham, et al. Phys. Rev. D 99, 083008 (2019)
P. Ciarcelluti & F. Sandin. Phys.Lett. B695:19-21,2011
F. Sandin & P. Ciarcelluti. Astropart.Phys.32:278-284,2009

Accumulation of DM by a star or a NS during its life time



DM capture by NS in a binary system including Dark star or Dark star – NS merger

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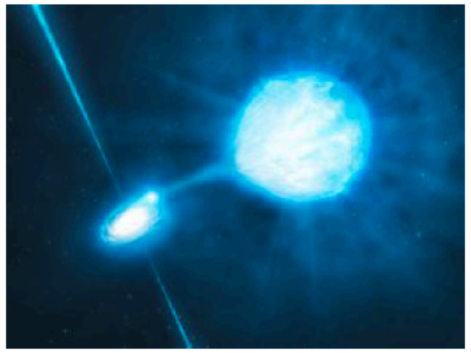
F. Sandin & P. Ciarcelluti. Astropart.Phys.32:278-284,2009

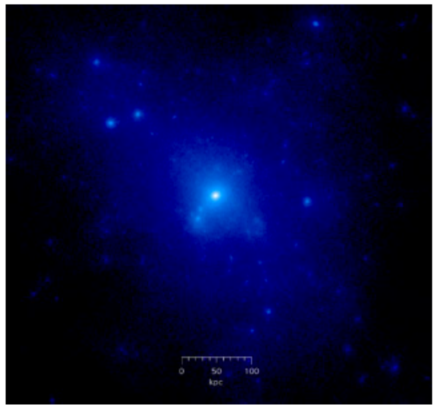
Dark star as an accretion center of baryonic matter



John Ellis, et al. Phys. Rev. D 97, 123007 (2018)
Qian-Fei Xiang,, et al. Physical Review C 89, 025803 (2014)
I.Goldman, et al. Phys.Lett.B 725 (2013) 200-207
P. Ciarcelluti & F. Sandin. Phys.Lett. B695:19-21,2011
F. Sandin & P. Ciarcelluti. Astropart.Phys.32:278-284,2009

NS exists in a dense halo or region of DM or passes through it

A. Del Popolo, et al. Universe 6 (2020) 12, 222
X. Y. Li, et al. JCAP10(2012)031
F. Sandin & P. Ciarcelluti. Astropart.Phys.32:278-284,20
Deliyergiyev, et.al. Phys. Rev. D 99, 063015 (2019)
Ang Li, et al. astropartphys.2012.07.006



DM production in the NS matter

John Ellis, et al. Phys. Rev. D 97, 123007 (2018)
A. Nelson, S. Reddy, D. Zhou, JCAP07(2019)012

Dark matter admixed neutron star

Dark matter admixed Neutron star

Asymmetric DM

Mass - Radius profile
Tidal deformability

Single fluid DM admixed NS

Two-fluid DM admixed NS

Equation of state by considering DM-Baryonic matter interaction

G. Panotopoulos and I. Lopes, Phys.Rev.D 96 (2017) 8, 083004
Abdul Quddus, et al. *J.Phys.G* 47 (2020) 9, 095202
Arpan Das, et al. Phys. Rev. D 99, 043016 (2019)

Chris Kouvaris, Phys.Rev.D77:023006,2008
M.A. Perez-Garcıa and J. Silk, Phys. Lett. B 711, 6 (2012).

Self-annihilating DM

Luminosity and the effective temperature

DM and BM interact only through gravitational force

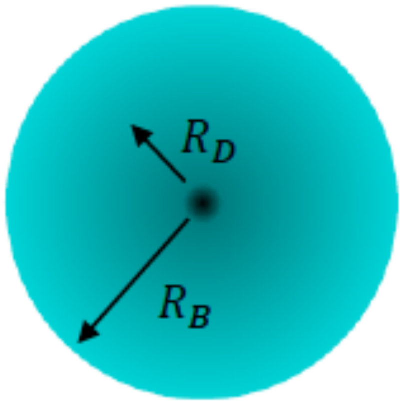
2 TOV equations:

$$\frac{dp_B}{dr} = -\frac{(\epsilon_B + p_B)(M + 4\pi r^3 p)}{r^2\,(1 - 2M/r)}$$

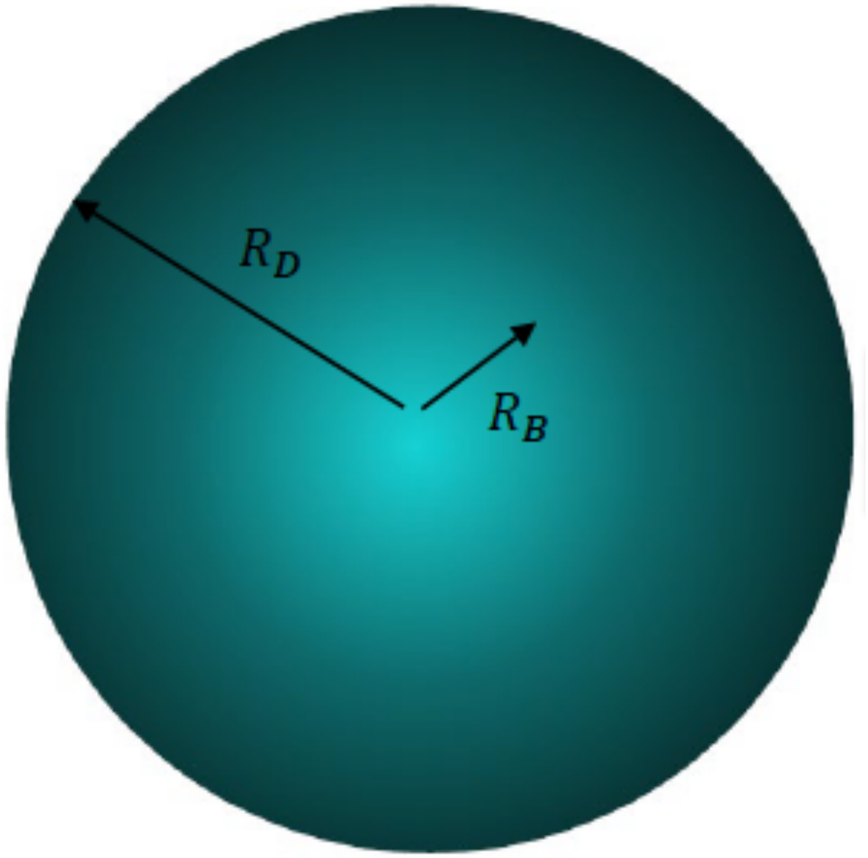
$$\frac{dp_D}{dr} = -\frac{(\epsilon_D + p_D)(M + 4\pi r^3 p)}{r^2\,(1 - 2M/r)}$$

EoS for BM and EoS for DM

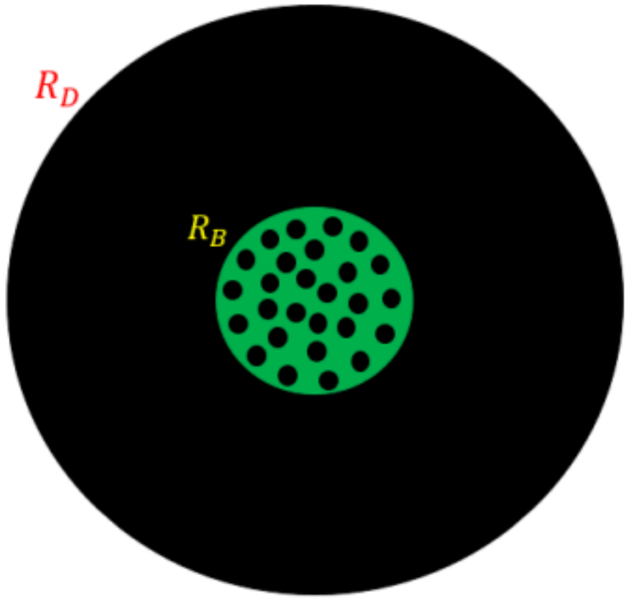
DM distribution in NS : DM core or DM halo



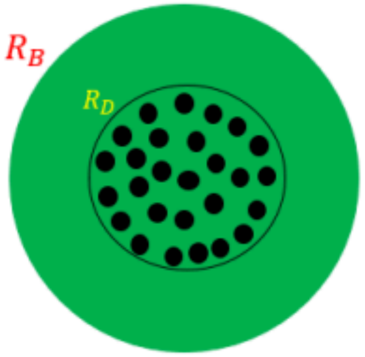
DM core



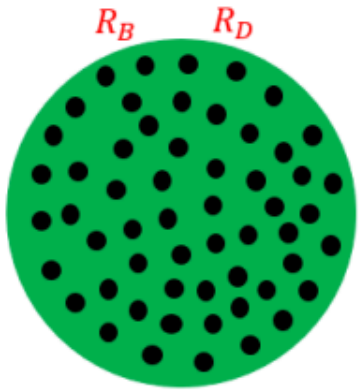
DM halo



$R_D > R_B$

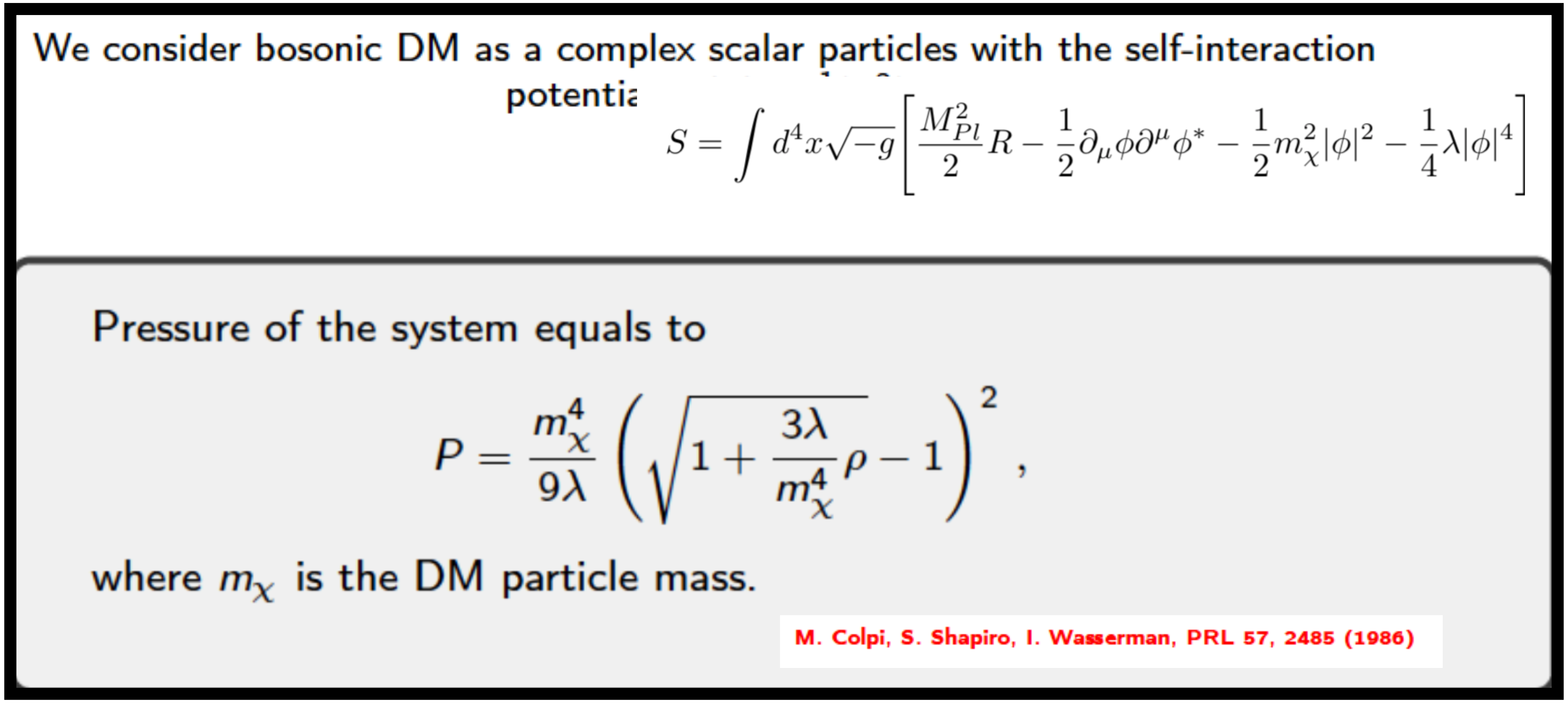


$R_B > R_D$



$R_B \approx R_D$

Bosonic Dark Matter and Baryonic Matter



We consider bosonic DM as a complex scalar particles with the self-interaction potenti

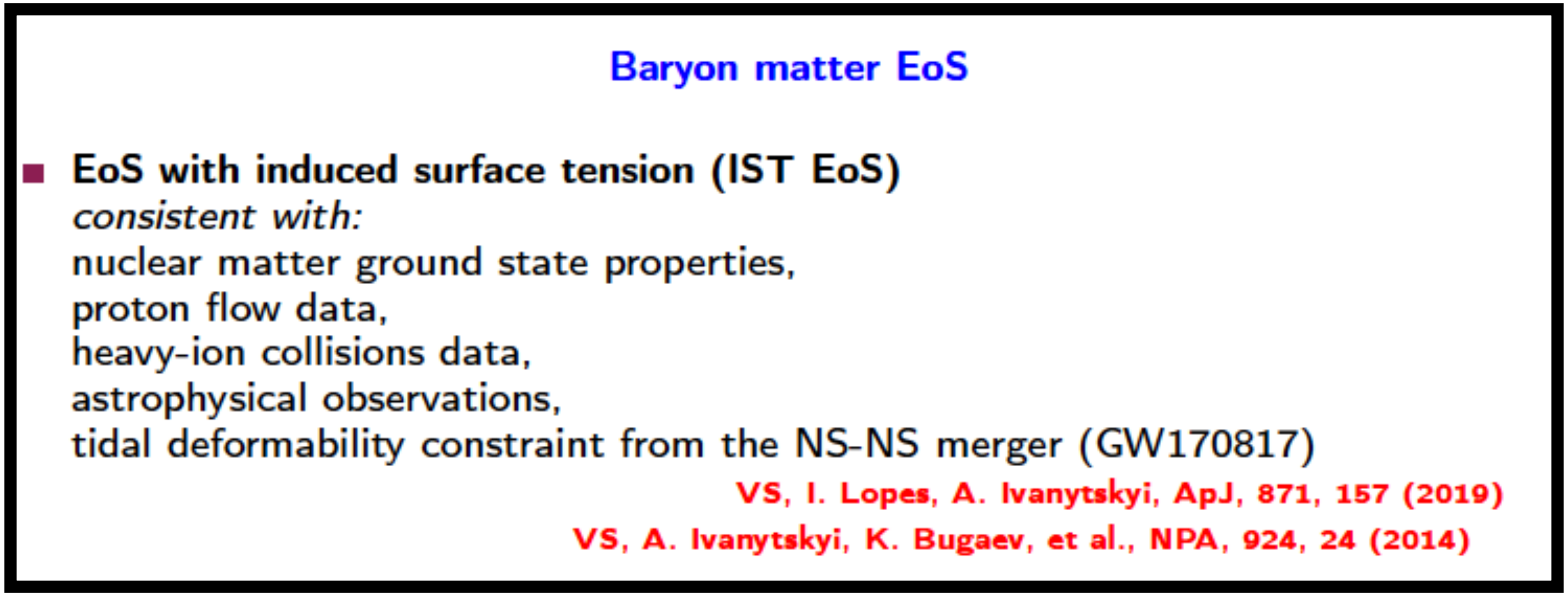
$$S = \int d^4x\sqrt{-g}\left[\frac{M_{Pl}^2}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi^* - \frac{1}{2}m_\chi^2|\phi|^2 - \frac{1}{4}\lambda|\phi|^4\right]$$

Pressure of the system equals to

$$P = \frac{m_\chi^4}{9\lambda}\left(\sqrt{1+\frac{3\lambda}{m_\chi^4}\rho} - 1\right)^2,$$

where m_χ is the DM particle mass.

M. Colpi, S. Shapiro, I. Wasserman, PRL 57, 2485 (1986)



Baryon matter EoS

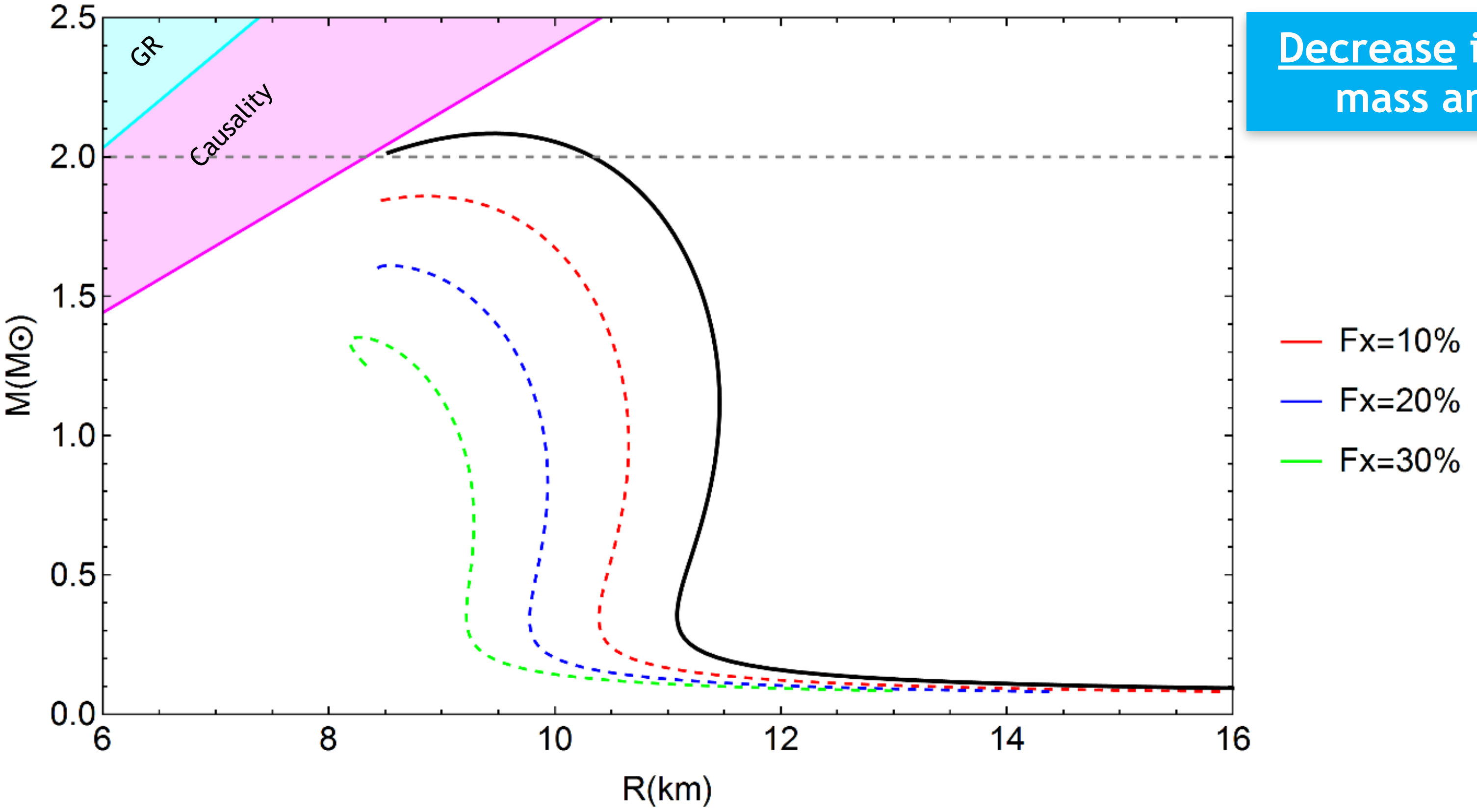
- **EoS with induced surface tension (IST EoS)**
  consistent with:
  nuclear matter ground state properties,
  proton flow data,
  heavy-ion collisions data,
  astrophysical observations,
  tidal deformability constraint from the NS-NS merger (GW170817)

VS, I. Lopes, A. Ivanytskyi, ApJ, 871, 157 (2019)
VS, A. Ivanytskyi, K. Bugaev, et al., NPA, 924, 24 (2014)

DM Core

m_D = 400 MeV
$\lambda = \pi$

<u>Decrease</u> in maximum mass and radius



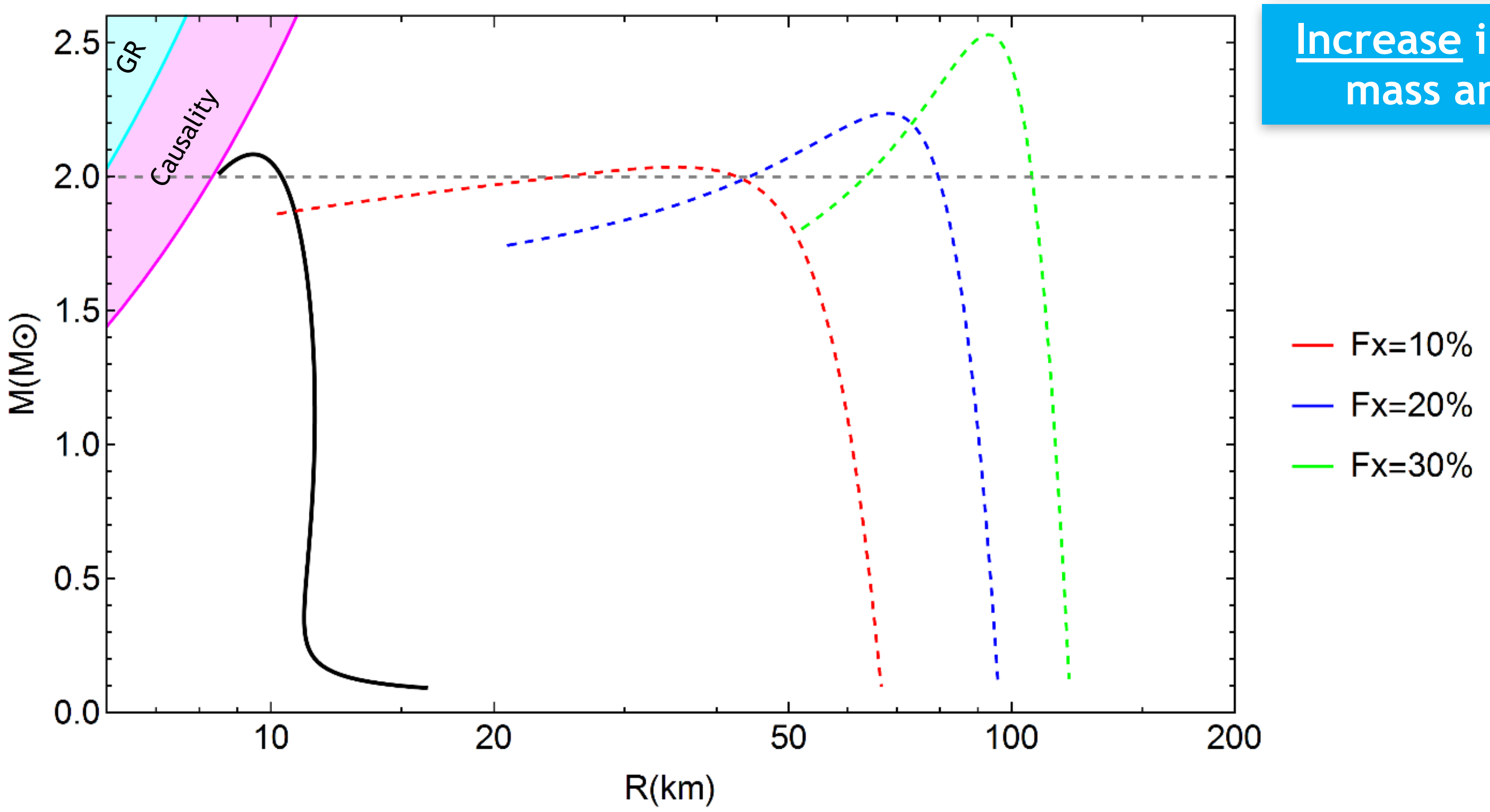
$M_T = M_B(R_B) + M_D(R_D)$
DM core: $\boldsymbol{R = R_B}$, DM halo: $\boldsymbol{R = R_D}$

Black solid line : Only BM (without DM)

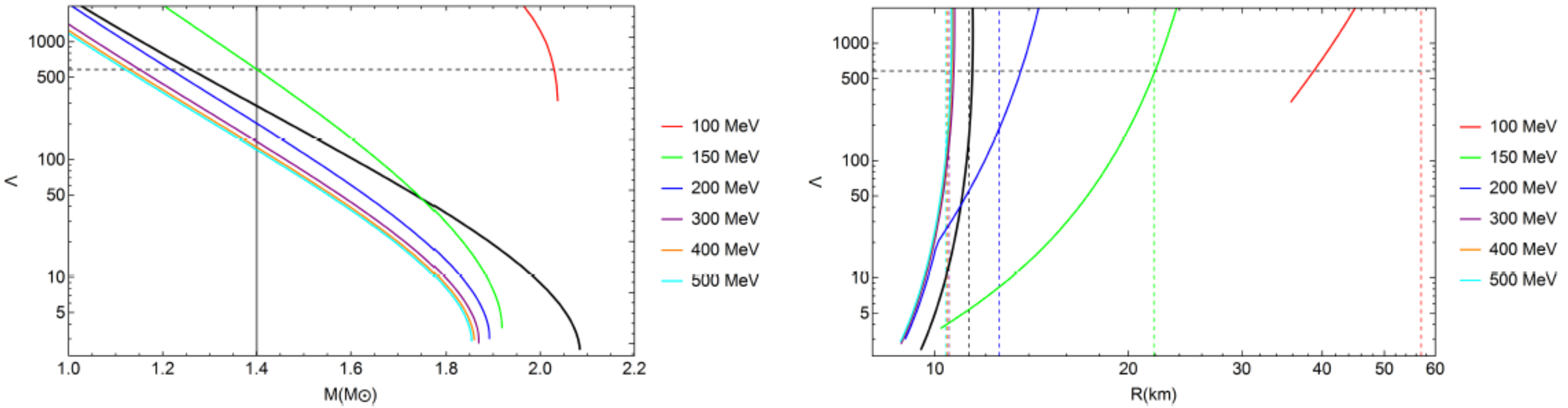
DM halo

m_D = 100 MeV
$\lambda = \pi$

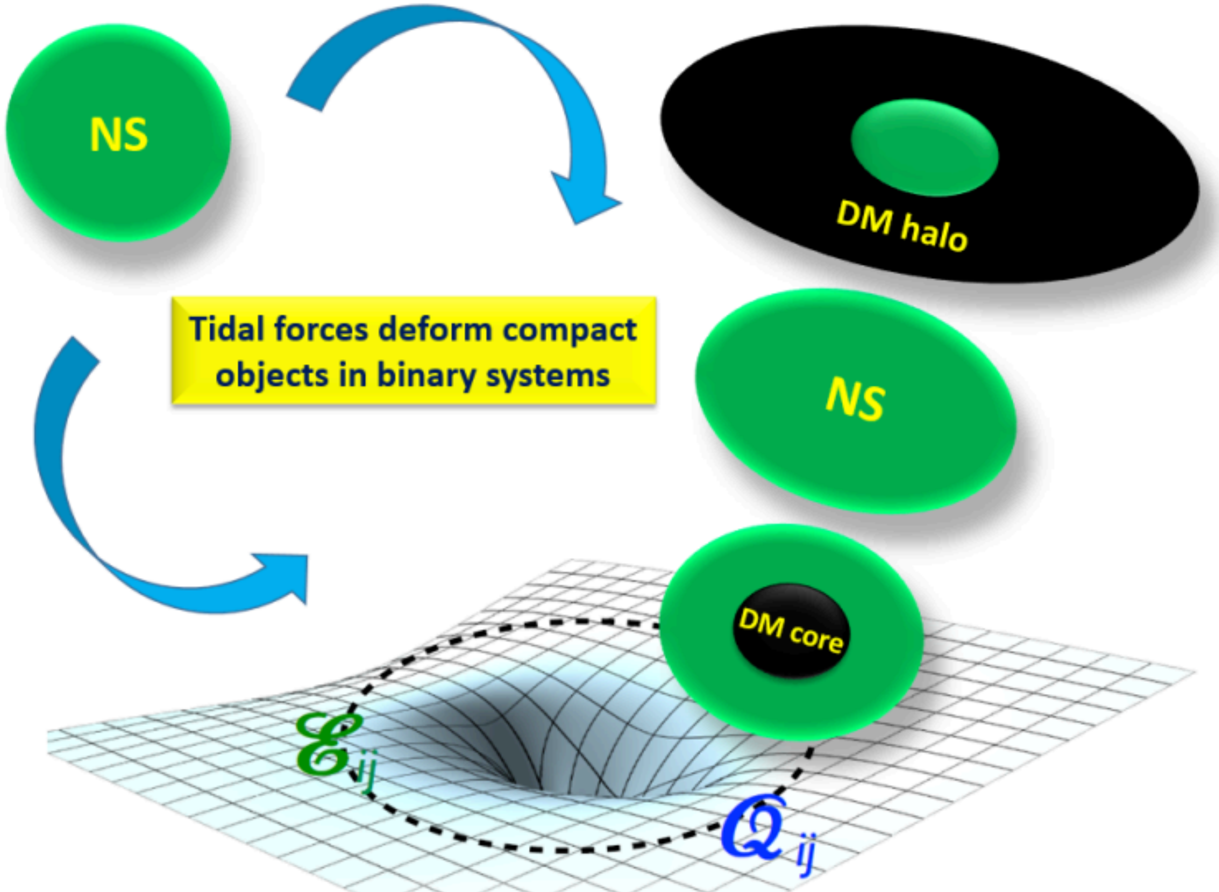
<u>Increase</u> in maximum mass and radius



Effect of DM on Tidal Deformability and GWs



coupling constant $\lambda = \pi$, **fraction** $f_\chi = 10\%$

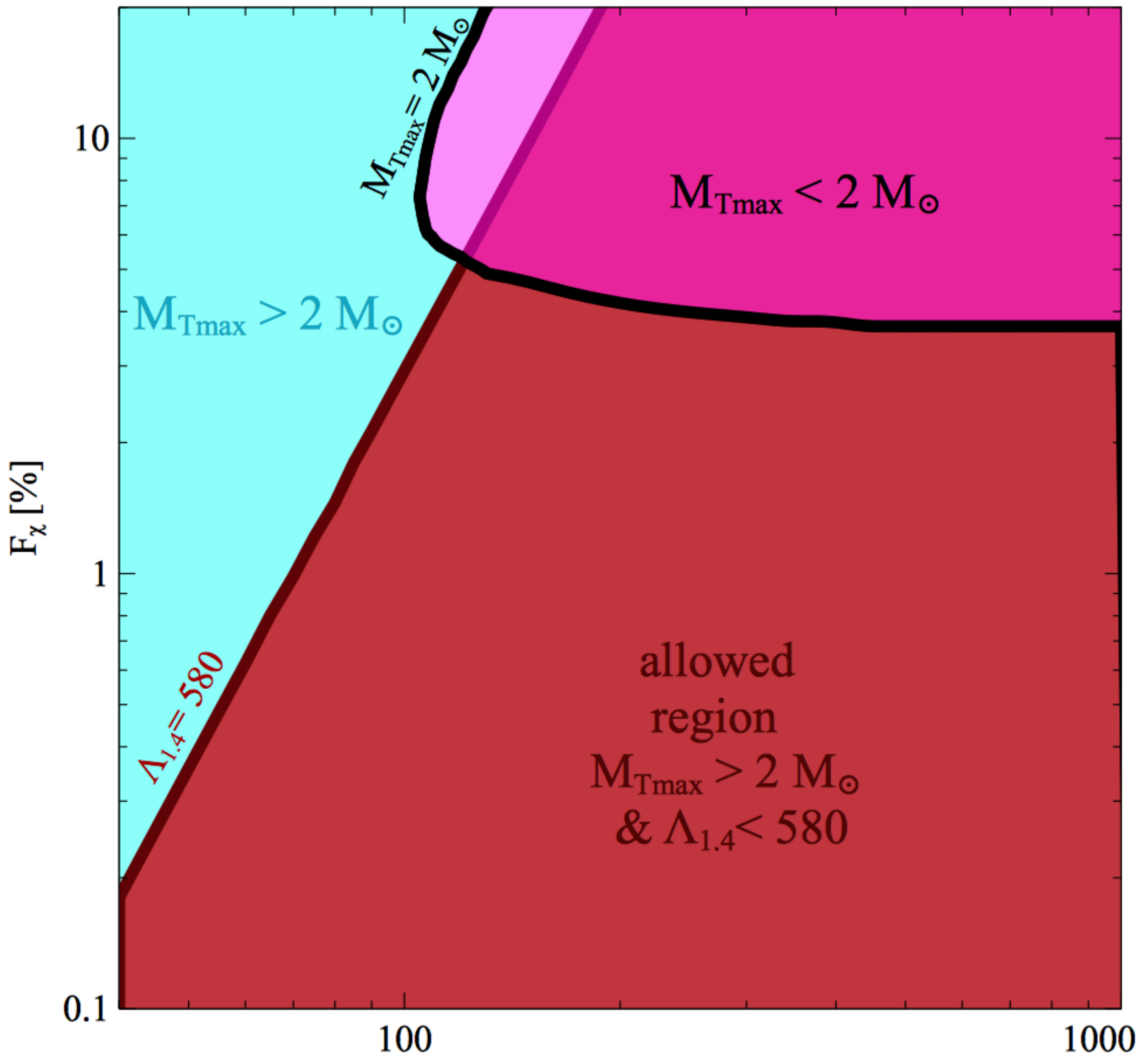


Tidal forces deform compact objects in binary systems

Deformation of spacetime away from spherical symmetry

D.R. Karkevandi, **S. Shakeri**, V. Sagun, O. Ivanytskyi, [ArxiV: **2109.03801**].
To be appeared in PRD soon

Constraint on the Fraction and Mass of Bosonic Dark Matter from combined $M_{Tmax} > 2\,M_\odot$ & $\Lambda_{1.4} < 580$



We conclude that observations of $2M_\odot$ NSs together with $\Lambda_{1.4} \leq 580$ constraint, set by LIGO/Virgo Collaboration, favour sub-GeV DM particles with low fractions below $\sim 5\%$.

D.R. Karkevandi, **S. Shakeri**, V. Sagun, O. Ivanytskyi, [ArxiV: **2109.03801**]. To be appeared in PRD soon

Big Questions !

- The mystery of particle generations
- The Origin of Neutrino Masses
- The Mass Hierarchy Problem
- The Fine-Tuning Problem
- The Strong CP problem
- The Particle Nature of DM

Recent Anomalies in Particle Physics

- XENON1T excess
- Muon (g-2)
- MiniBooNe Excess
- B-Meson Decay

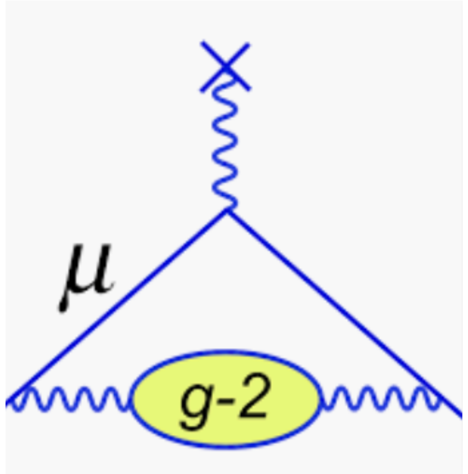
Occam's razor

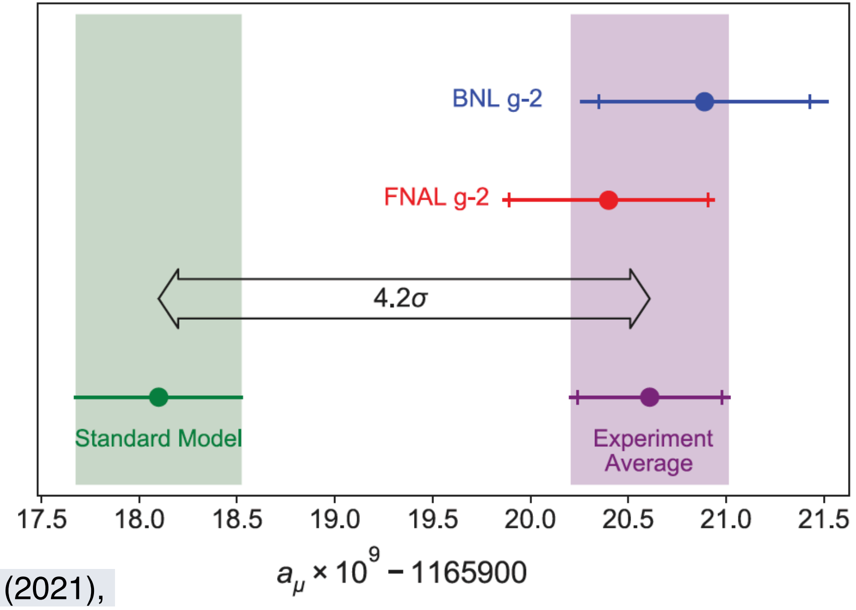
Among competing hypotheses, the one with the fewest assumptions should be selected

Physicists should be skeptical about models that add complexity for the sole reason of satisfying constraints from previous searches.

Different Anomalies in Particle Physics

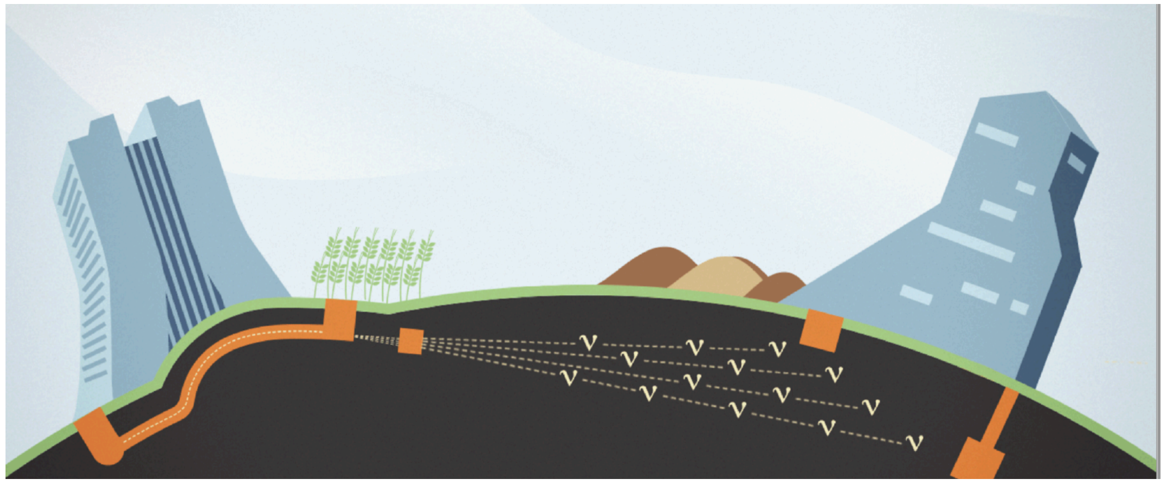
FermiLab : g-2 muon and

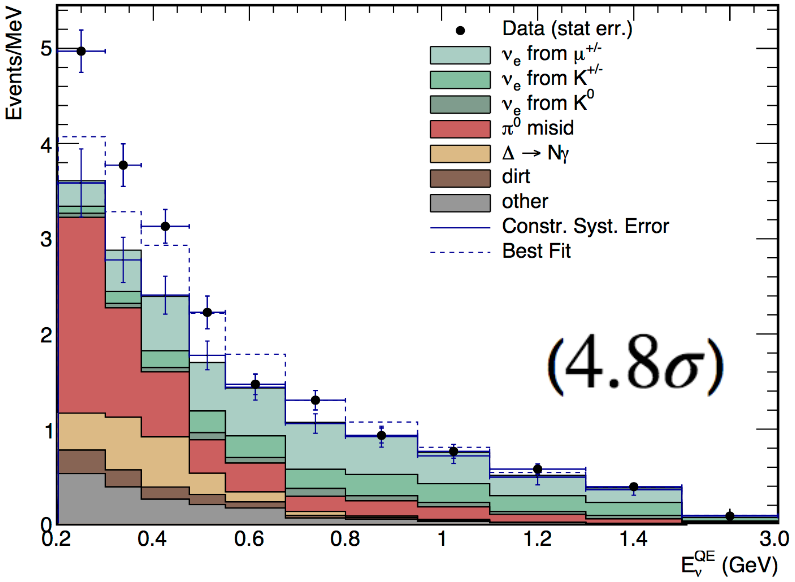




B. Abi et al. (Muon g-2), Phys. Rev. Lett. 126 , 141801 (2021),

FermiLab : MiniBooNe Anomaly





MiniBooNE collaboration, Phys. Rev. Lett. 121 (2018) 221801 [1805.12028].

B meson anomaly LHCb

$$(B \to K^* \mu^+ \mu^-)$$

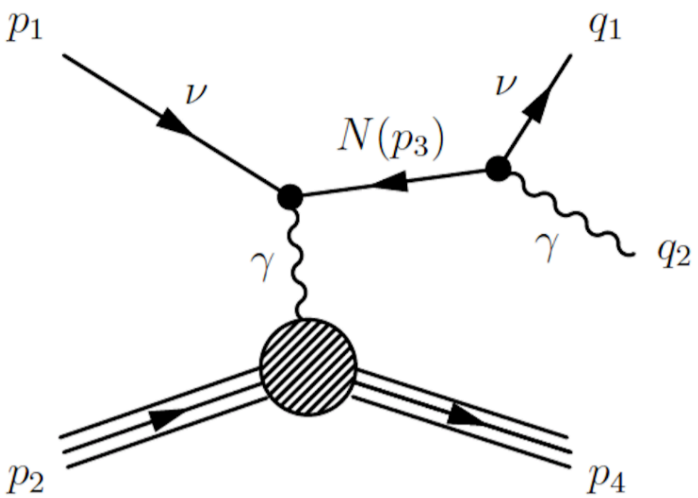
5σ

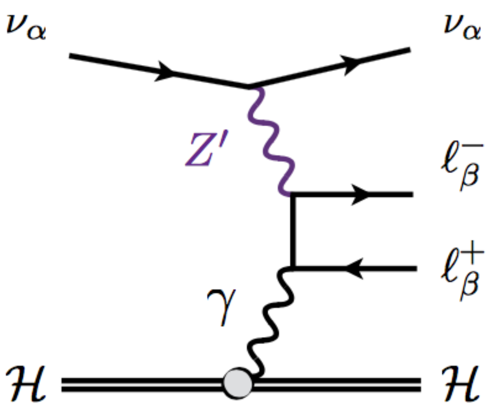
. R. Aaij et al. [LHCb], **[arXiv:2103.11769 [hep-ex]].**

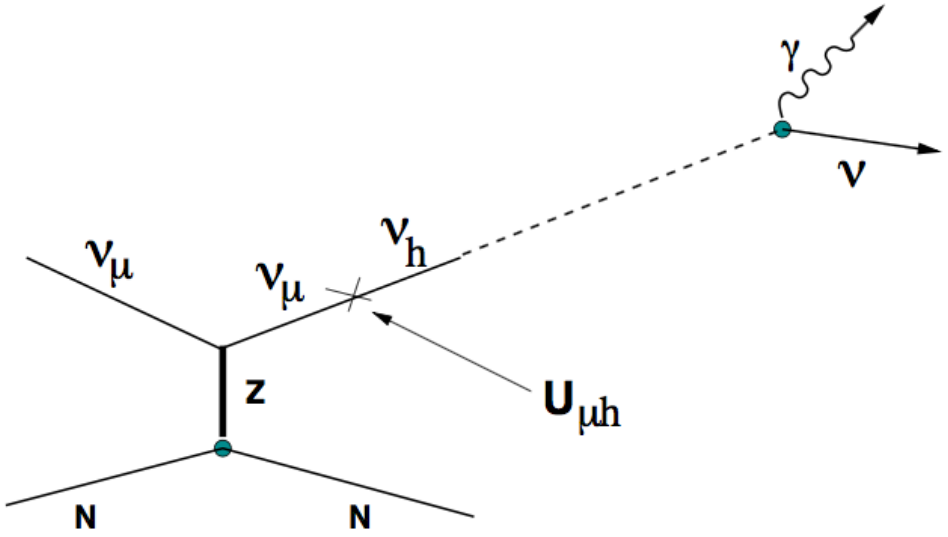
Thanks For Your Attention

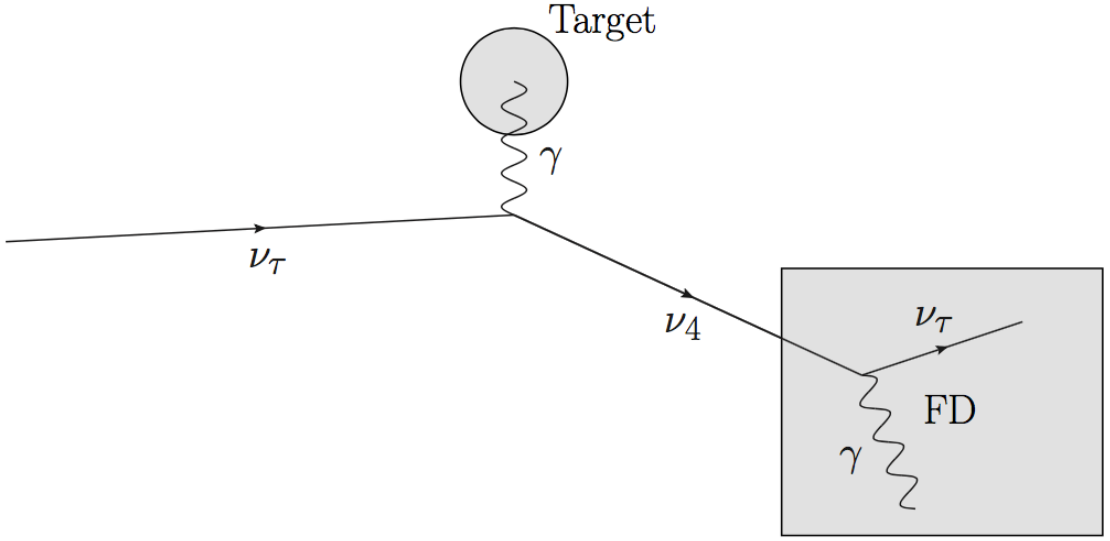
ISFAHAN-IRAN

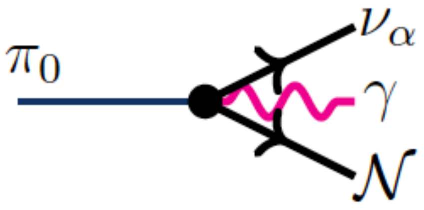
Revisiting the phenomenology of Sterile Neutrinos using our New Proposed EM vertex

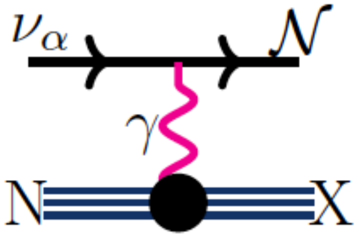


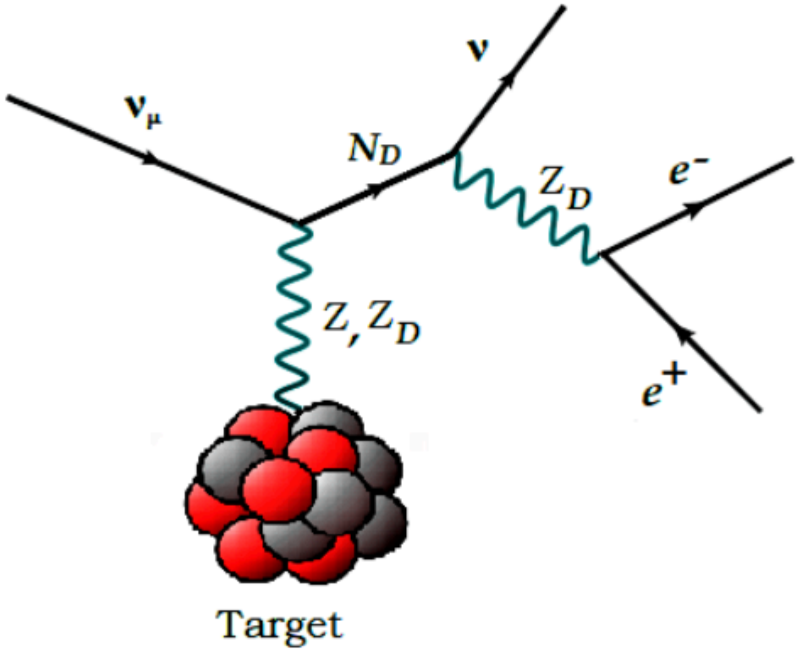












S. Gninenko,**Phys. Rev. Lett. 103 (2009) 241802**

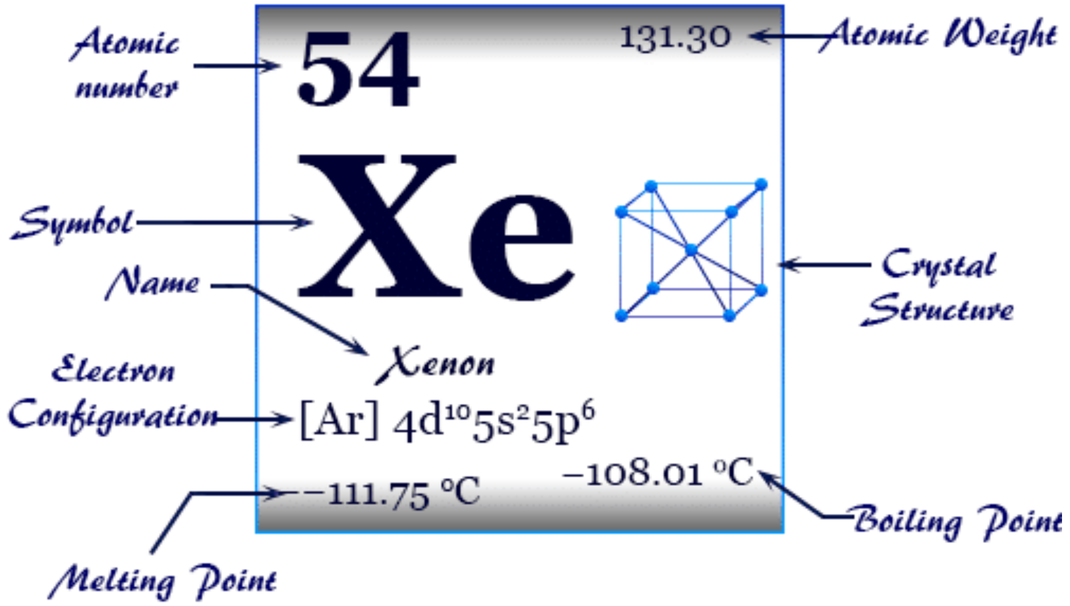
G. Magill, R. Plestid, M. Pospelov and Y.-D. Tsai, D, **Phys. Rev. D 98 (2018) 115015**

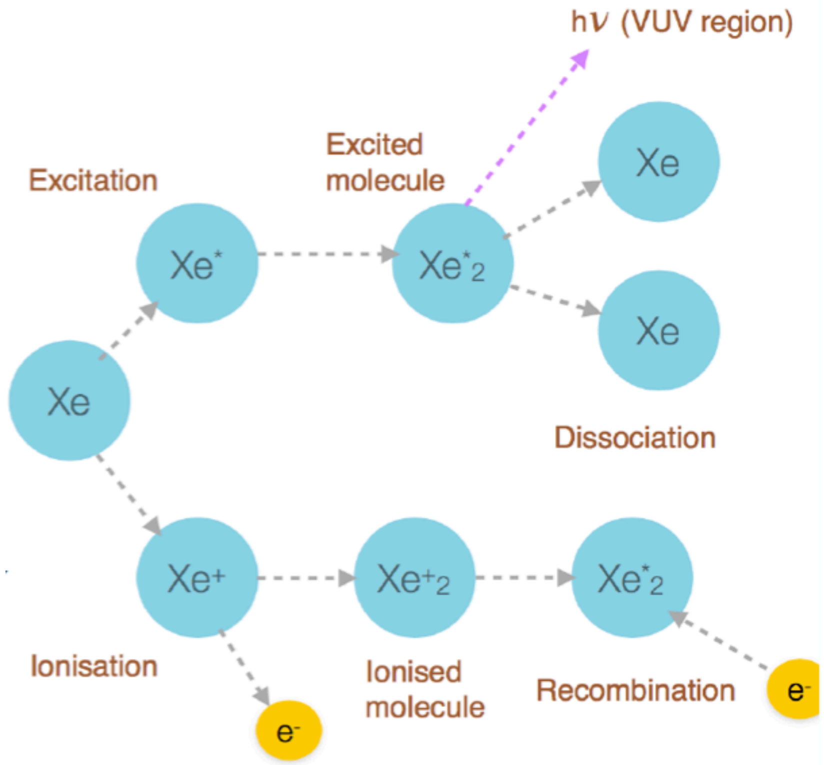
E. Bertuzzo, S. Jana, P. A. Machado and R. Zukanovich Funchal,, **Phys. Rev. Lett. 121 (2018) 241801**

Thomas Schwetz, Albert Zhou, Jing-Yu Zhu **J. High Energ. Phys. 2021, 200 (2021)**

Stefano Vergani, Nicholas W. Kamp, et al **arXiv:2105.06470v3**

Peter Ballett, Matheus Hostert, Silvia Pascoli, et al, **Phys. Rev. D 100, 055012 (2019)**





Xenon Binding Energies [eV]

$n \diagdown l$	s	p	d
5	25.7	12.4	–
4	213.8	163.5	75.6
3	1093.2	958.4	710.7
2	5152.19	4837.7	–
1	33317.4	–	–

TABLE I. Binding energies $|E_B^{nl}|$ [eV] of the electrons in xenon shells (n, l) calculated from