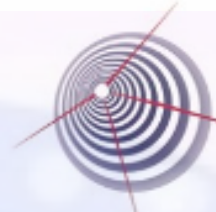
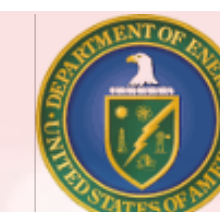




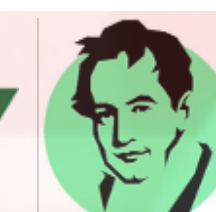
WashU



MCDONNELL CENTER
FOR THE SPACE SCIENCES



U.S. DEPARTMENT OF
ENERGY



Alexander von
HUMBOLDT
STIFTUNG

Open Questions in Neutrino Physics and How (Not) to Answer Them

Bhupal Dev (bdev@wustl.edu)

Washington University in St. Louis

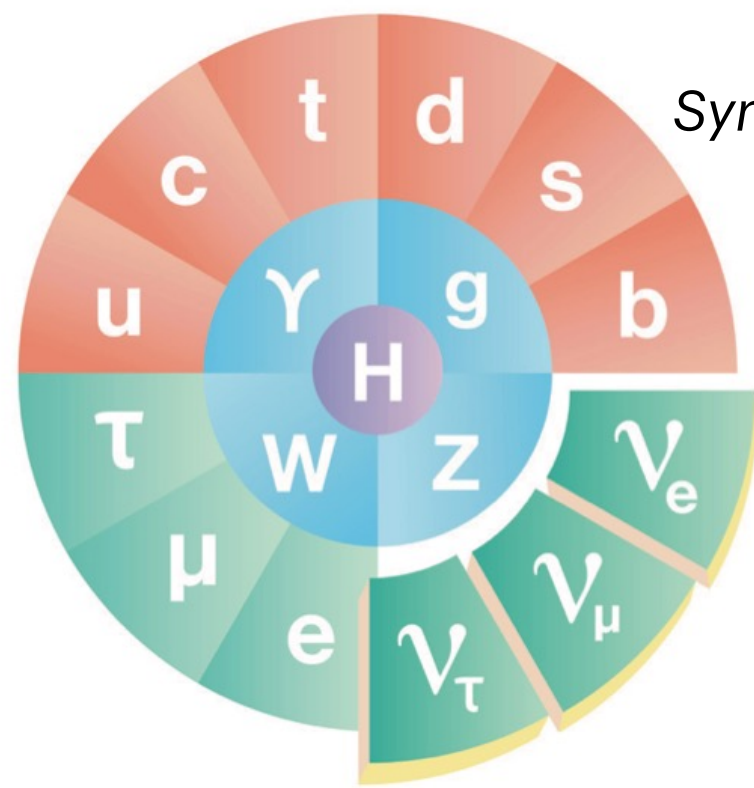
Brookhaven Forum 2025

Launching the
Second Century of
Quantum Physics

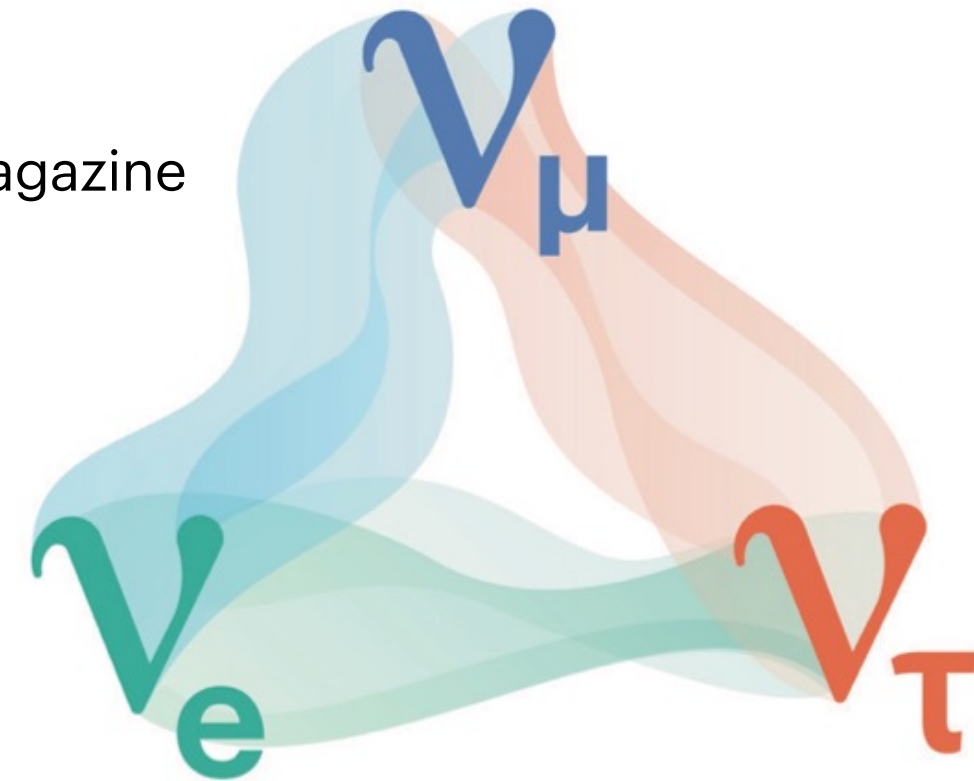
October 22–24, 2025

Hosted by Brookhaven National Laboratory

Neutrinos: The Least Known Sector of the SM

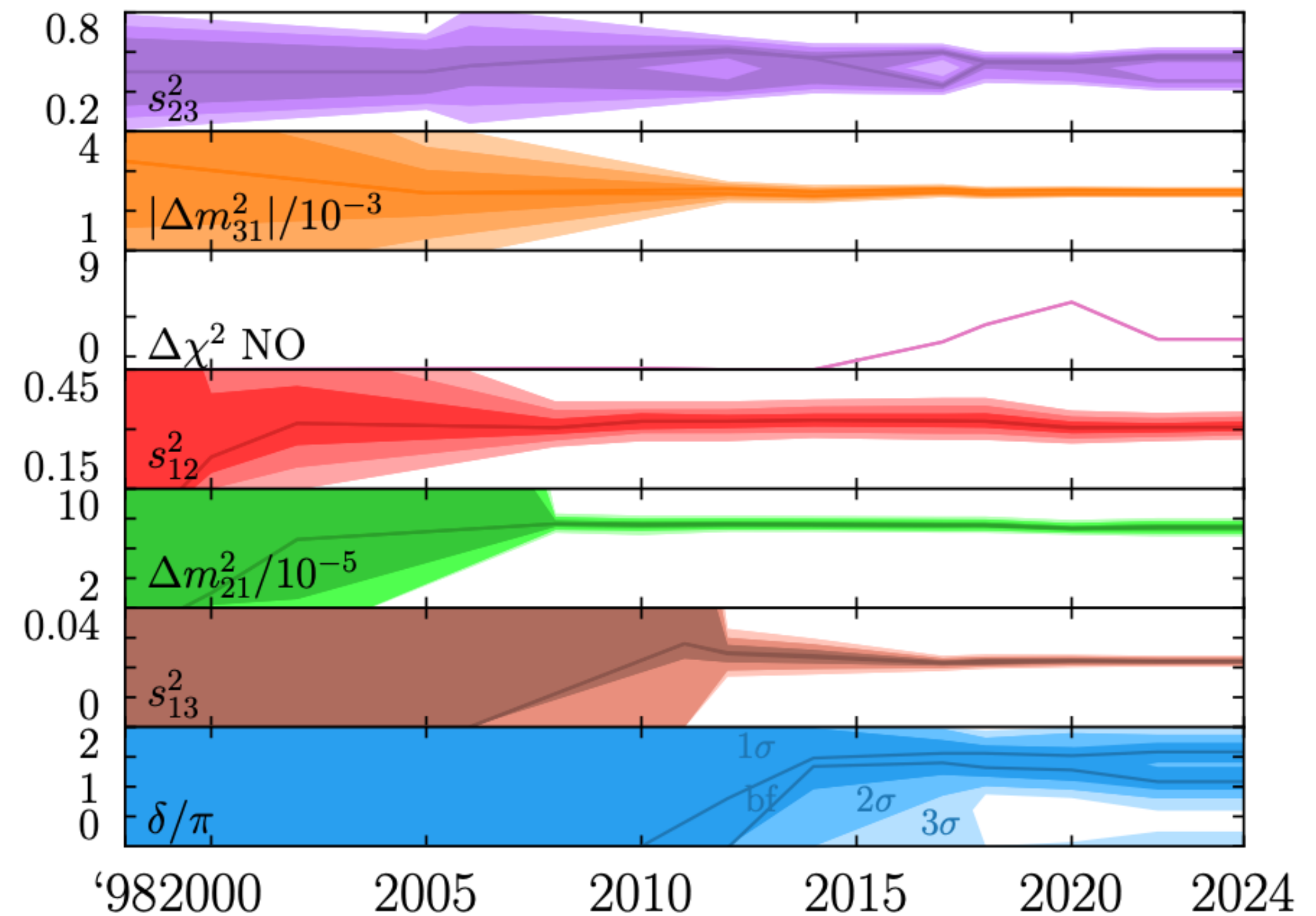


Symmetry Magazine



- Flavor eigenstates $\neq$ Mass eigenstates
- Oscillation Probability:

$$P_{\alpha\beta} \simeq \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$
- $P_{\alpha\beta} \neq 0 \implies$ Nonzero masses and mixing
- Evidence of BSM Physics.



Denton, [2501.08374](#)

Are there any more surprises?

Open Questions in Neutrino Physics

1. What is the neutrino mass ordering? Normal or inverted?
2. In which octant is the atmospheric mixing angle?
3. Is there leptonic CP violation?
4. What is the absolute neutrino mass scale?
5. Are there other species of (sterile) neutrinos?
6. How do neutrinos get mass? Is it Dirac or Majorana?
7. Why neutrino mixing is so different from quark mixing?
8. Do neutrinos decay? What is their lifetime?
9. Do neutrinos have non-standard interactions?
10. Are neutrinos responsible for the observed baryon asymmetry?
11. Do neutrinos have anything to do with Dark Matter (DM)?

BD, [2503.21212](#)



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BD, [2503.21212](#)



Known Unknowns

Snowmass NF01 Report: [2212.00809](#)

		Atmospheric Mass Ordering	θ_{23} Octant	$\sin \delta \neq 0$ for 50% of δ
JUNO	Optimistic Conservative	2030: 3σ 2030: 2.5σ	- -	- -
DUNE	Optimistic Conservative	2030: 5σ 2032: 5σ	2036: 3σ , 2040: 5σ 2040: 2σ	2035: 3σ , 2039: 5σ 2037: 3σ
HK	Optimistic Conservative	2033: 5σ 2032: 3σ	2033: 5σ 2034: 3σ	2029: 3σ , 2032: 5σ 2029: 3σ , 2037: 5σ
IceCube	Optimistic Conservative	2030: 3σ , 2033: 4σ 2033: 2σ	- -	- -
KM3NeT	Optimistic Conservative	2026: 3σ , 2029 5σ 2030: 3σ , 2032: 4σ	- -	- -



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What do we learn from these precision measurements?



Known Unknowns

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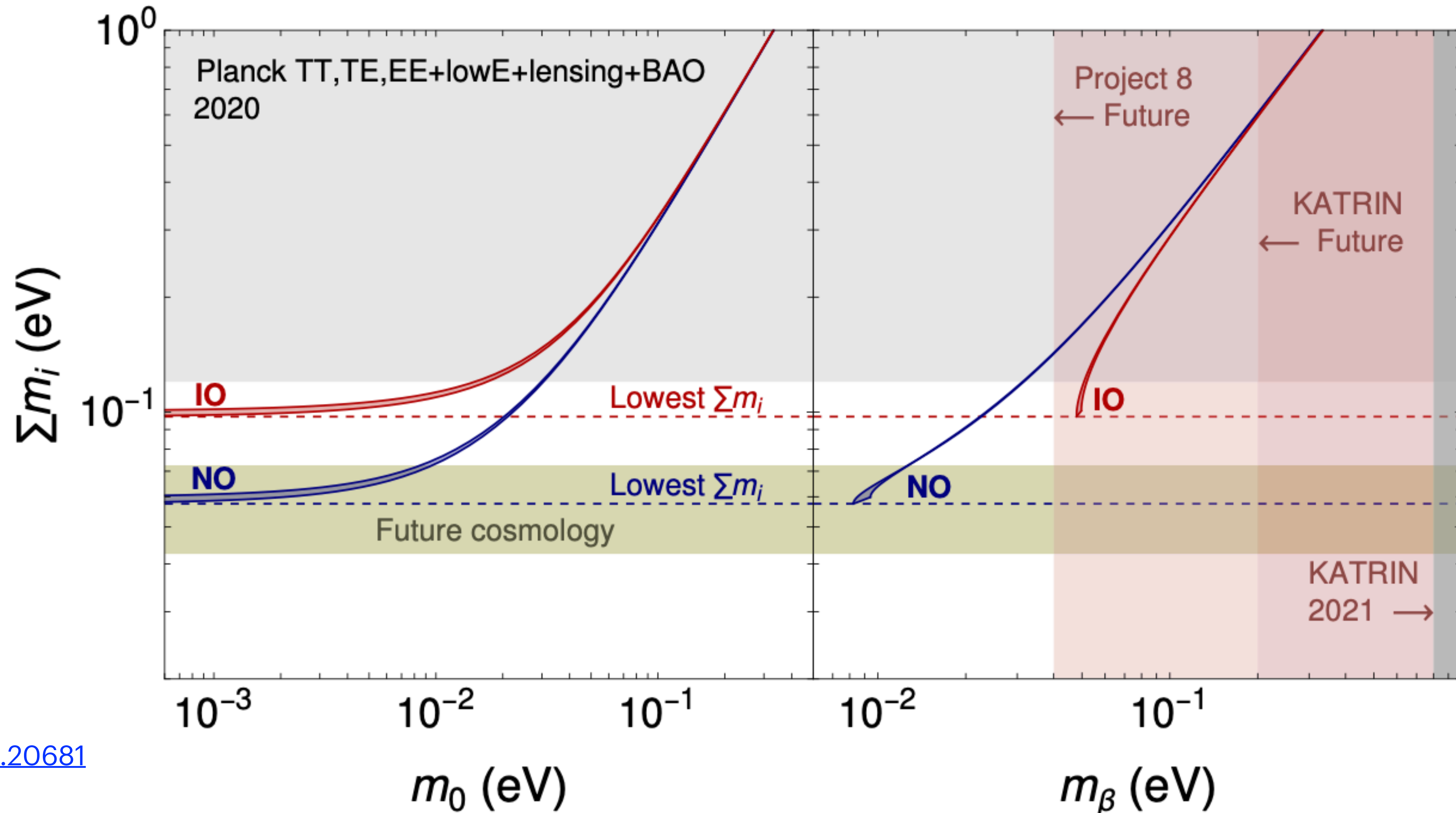
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What do we learn from these precision measurements?

- ‘ ν SM’ parameters — Must be measured as accurately as possible.
- Possible implications for leptonic unitarity triangle, flavor puzzle, leptogenesis, ...

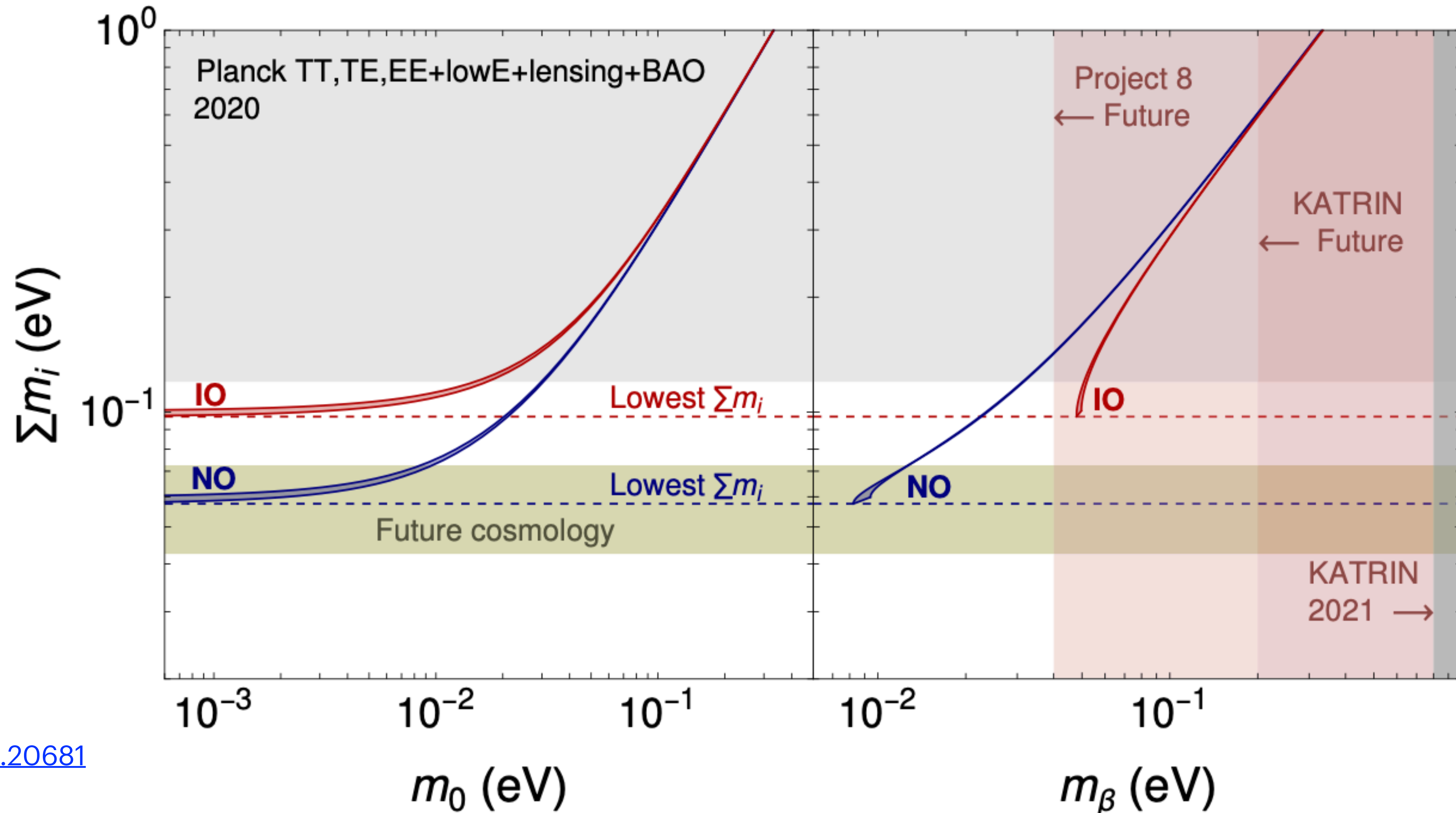


Absolute Neutrino Mass Scale



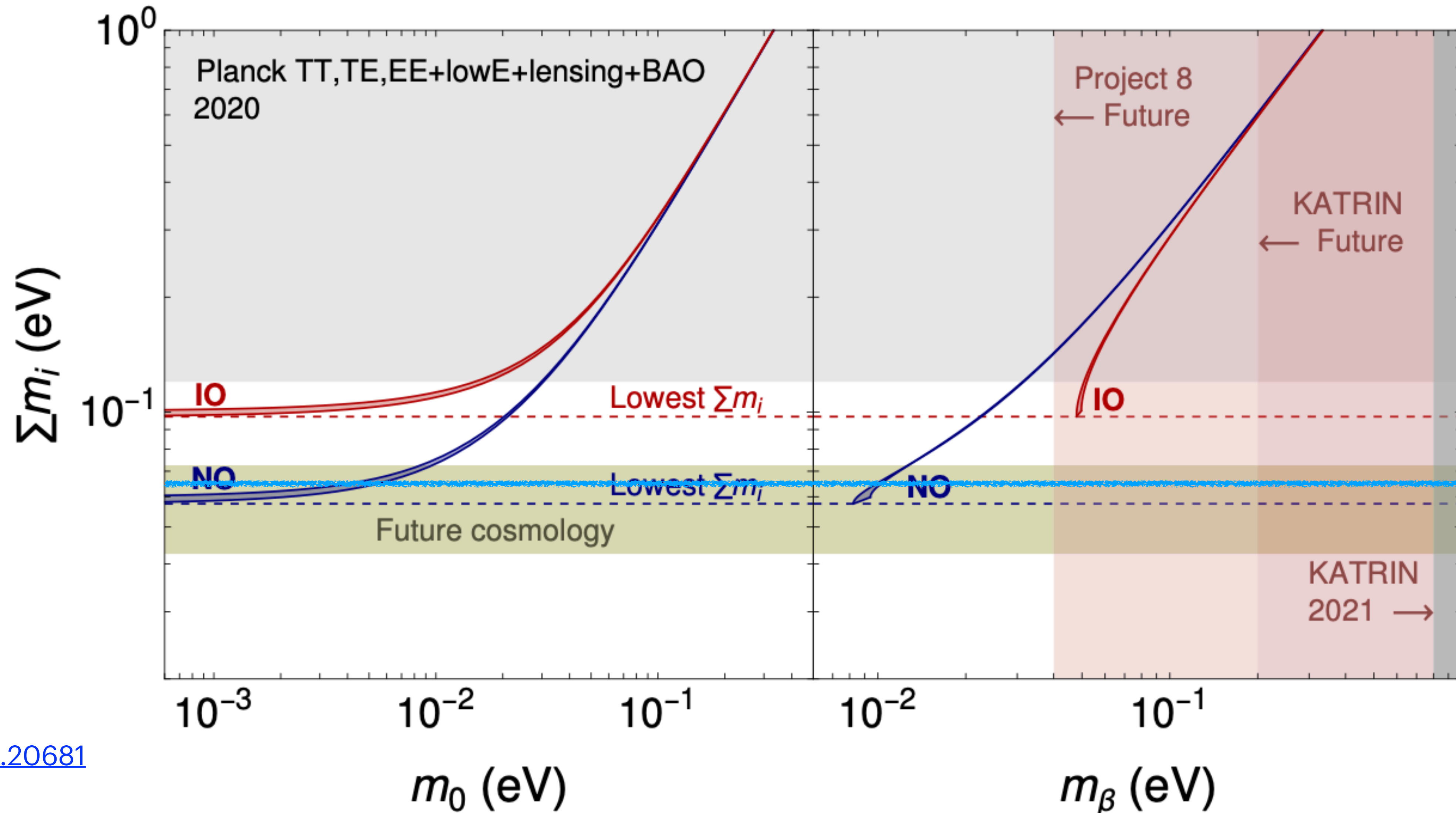
[2310.20681](#)

Absolute Neutrino Mass Scale



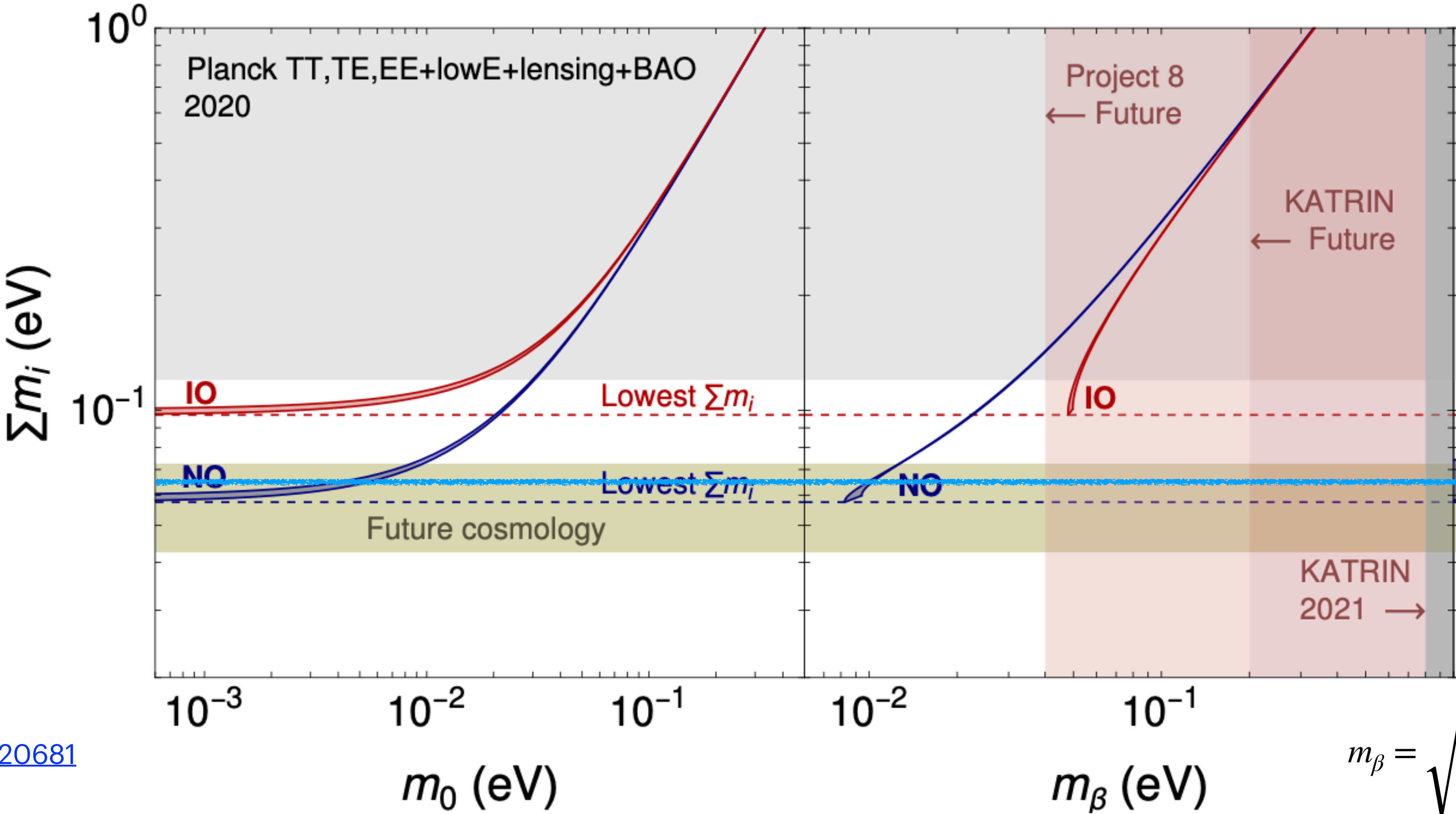
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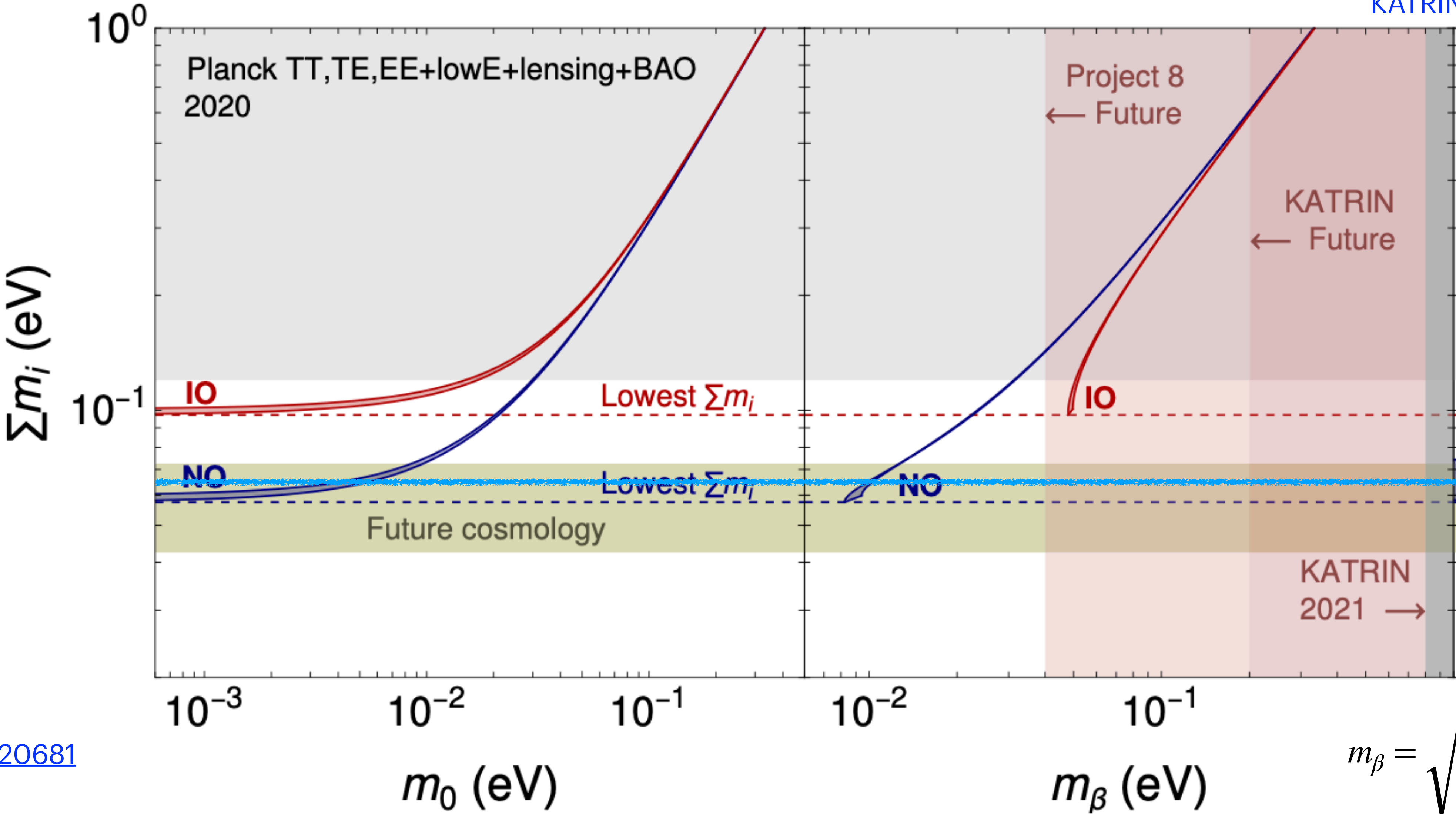
$$m_\beta = \sqrt{\sum_i m_i^2 |U_{ei}|^2}$$

[2310.20681](#)



Absolute Neutrino Mass Scale

KATRIN, [2406.13516](#)



DESI, [2503.14744](#)

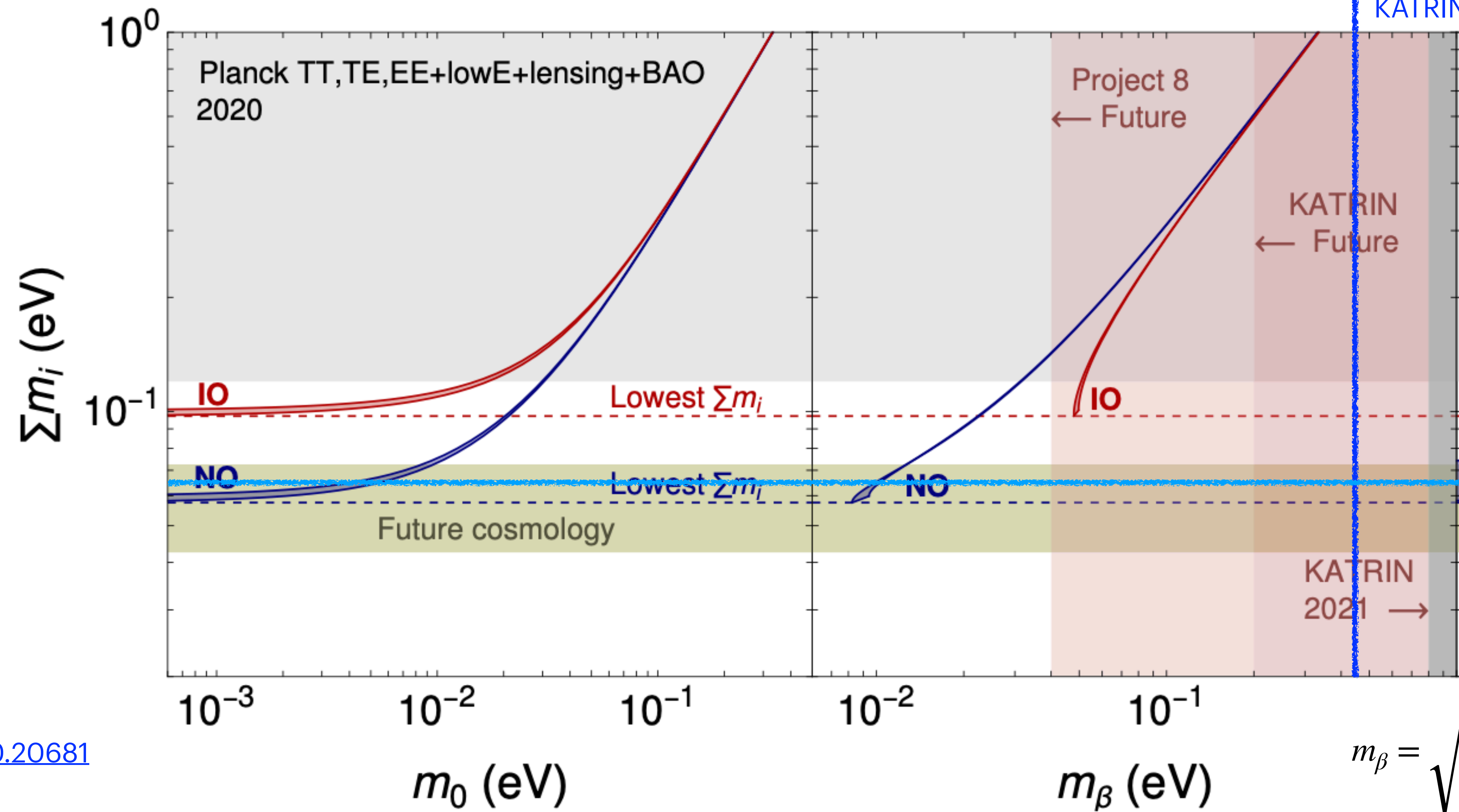
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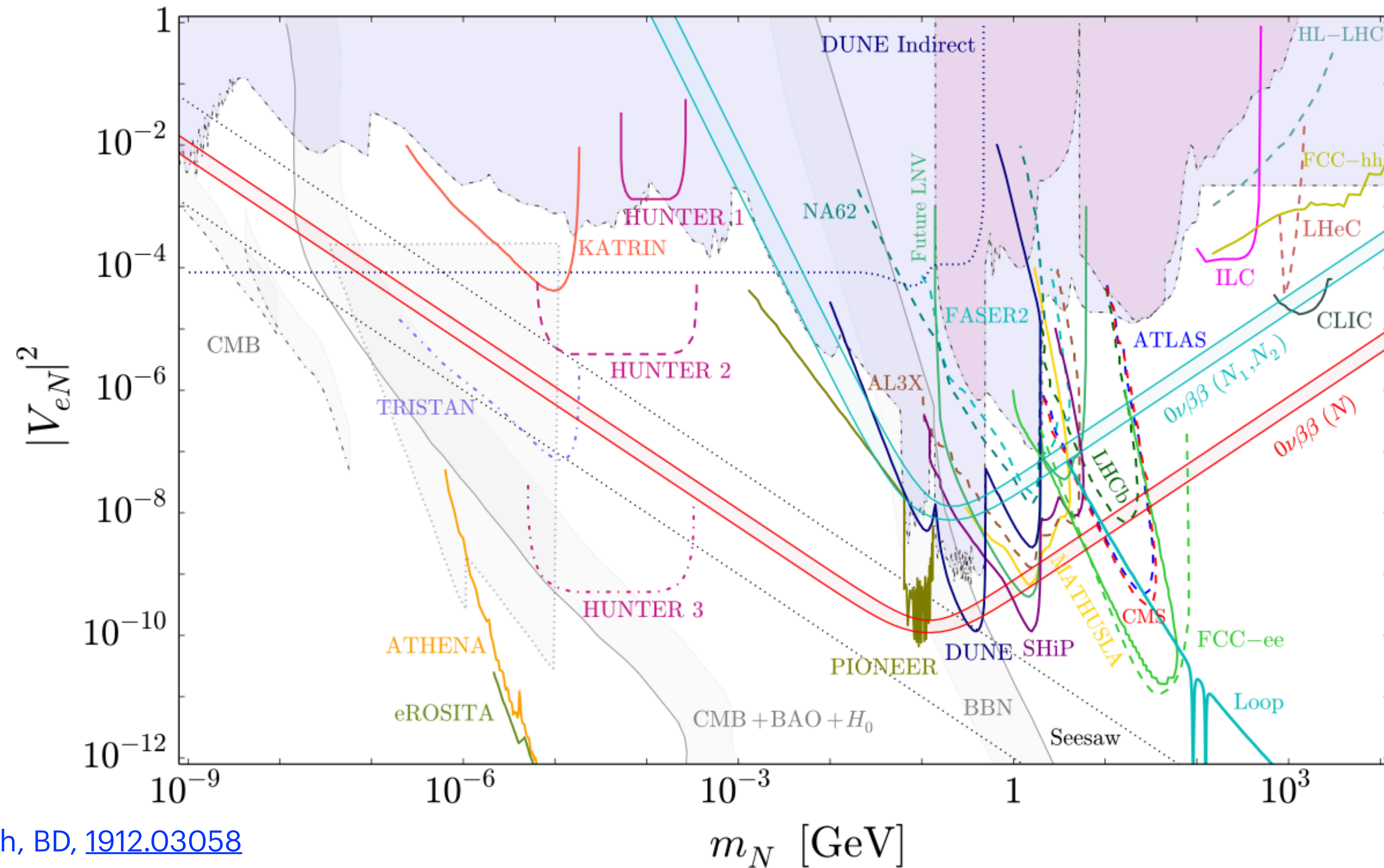
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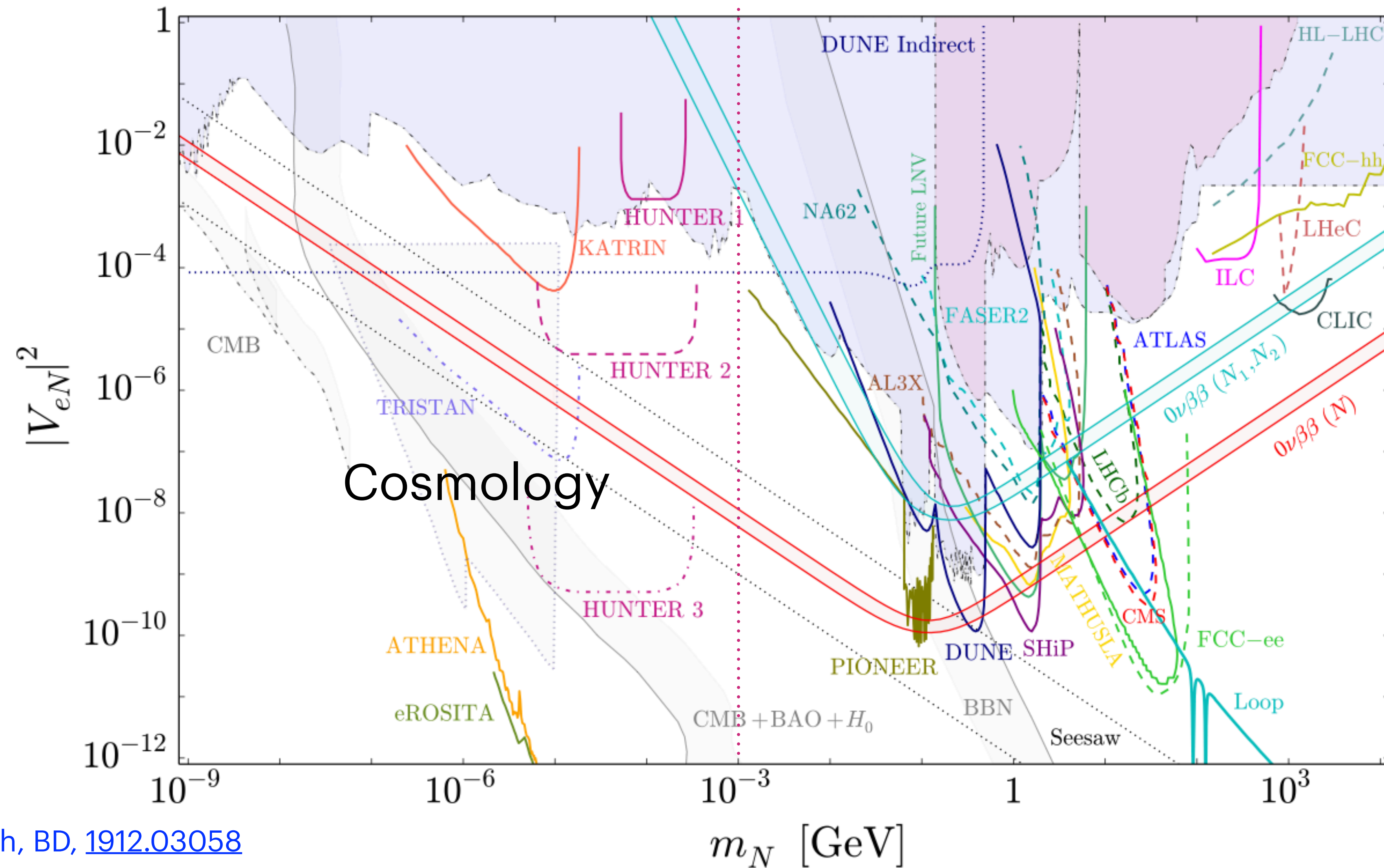


Additional Neutrino Species



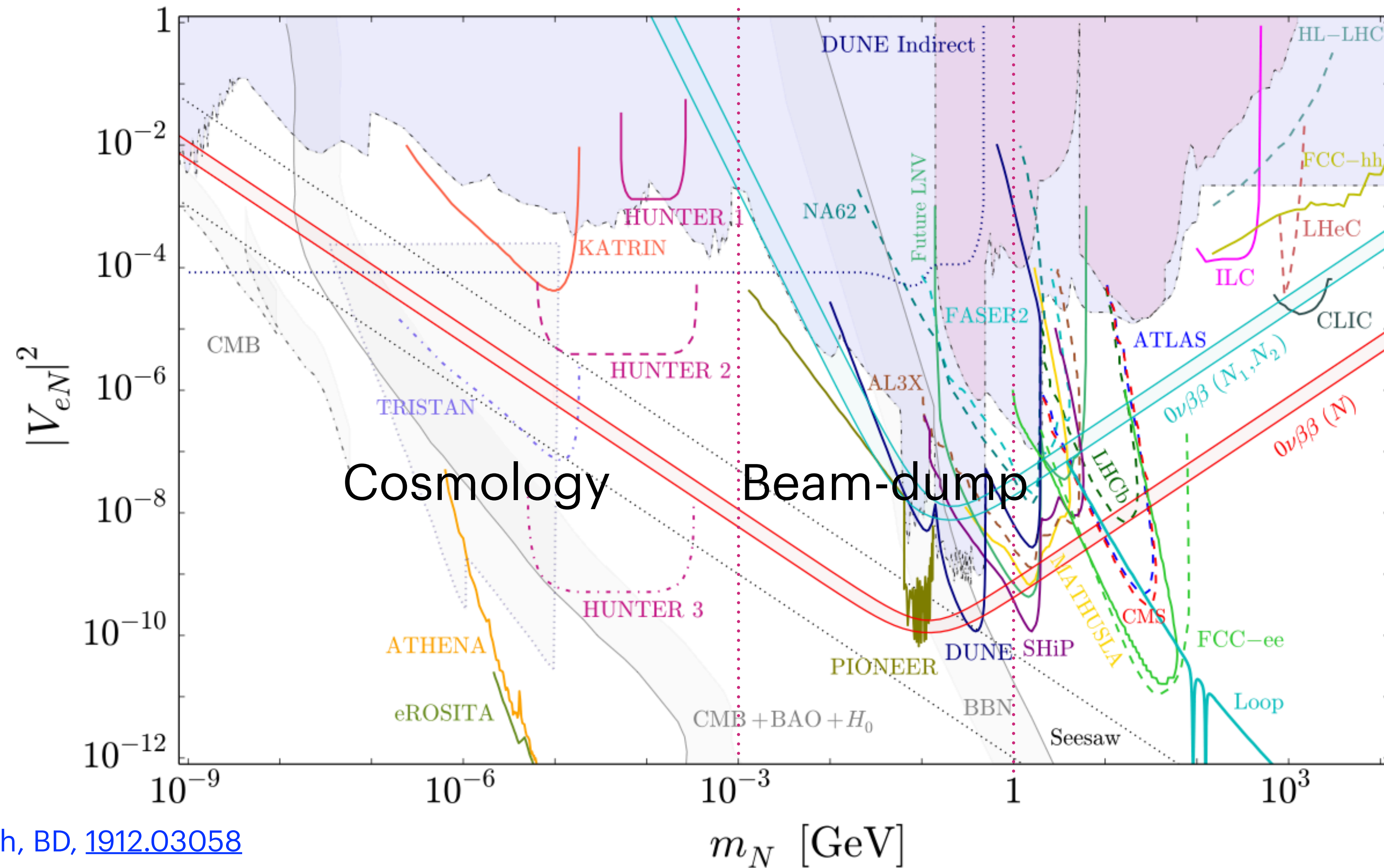
Bolton, Deppisch, BD, [1912.03058](#)

Additional Neutrino Species



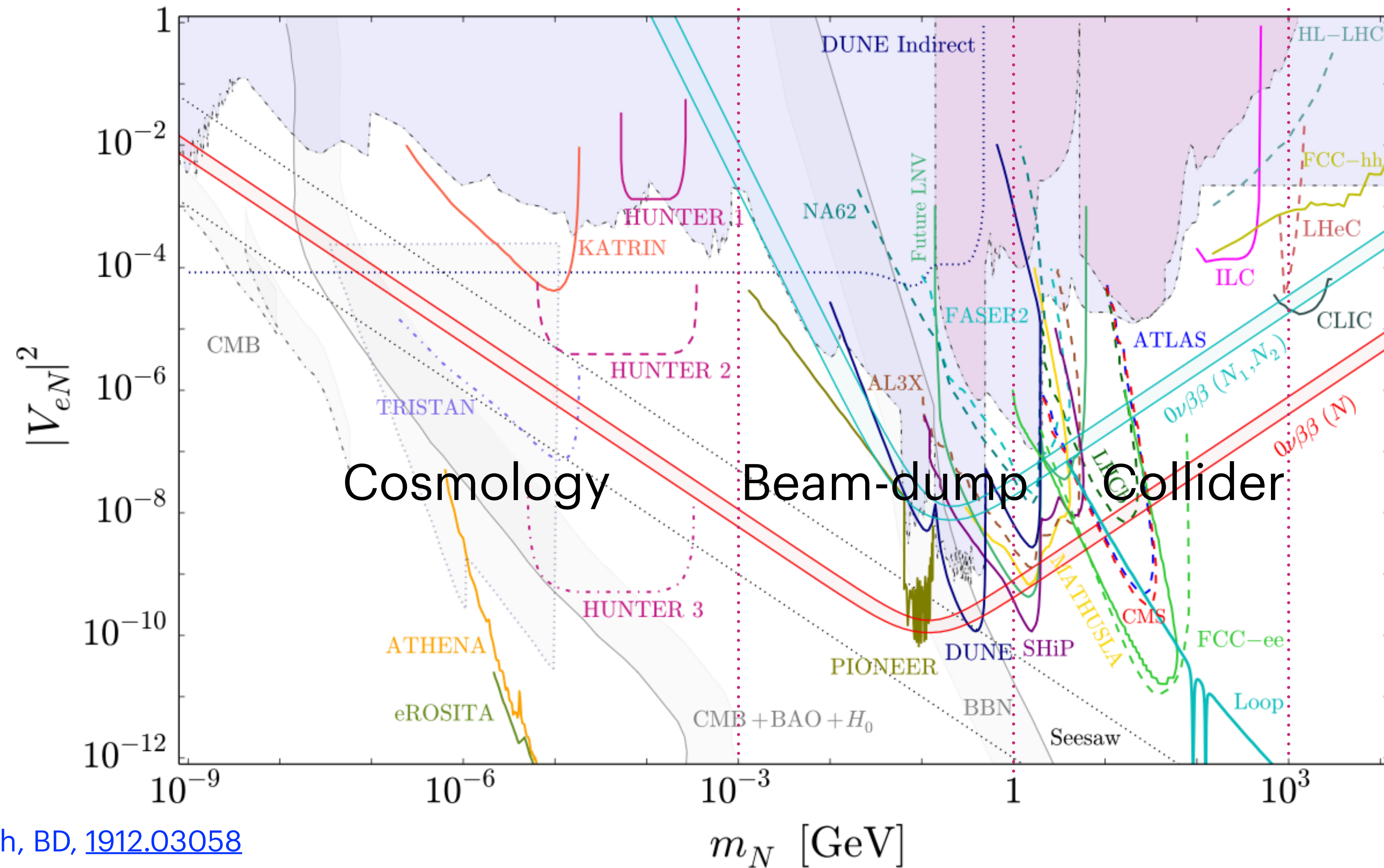
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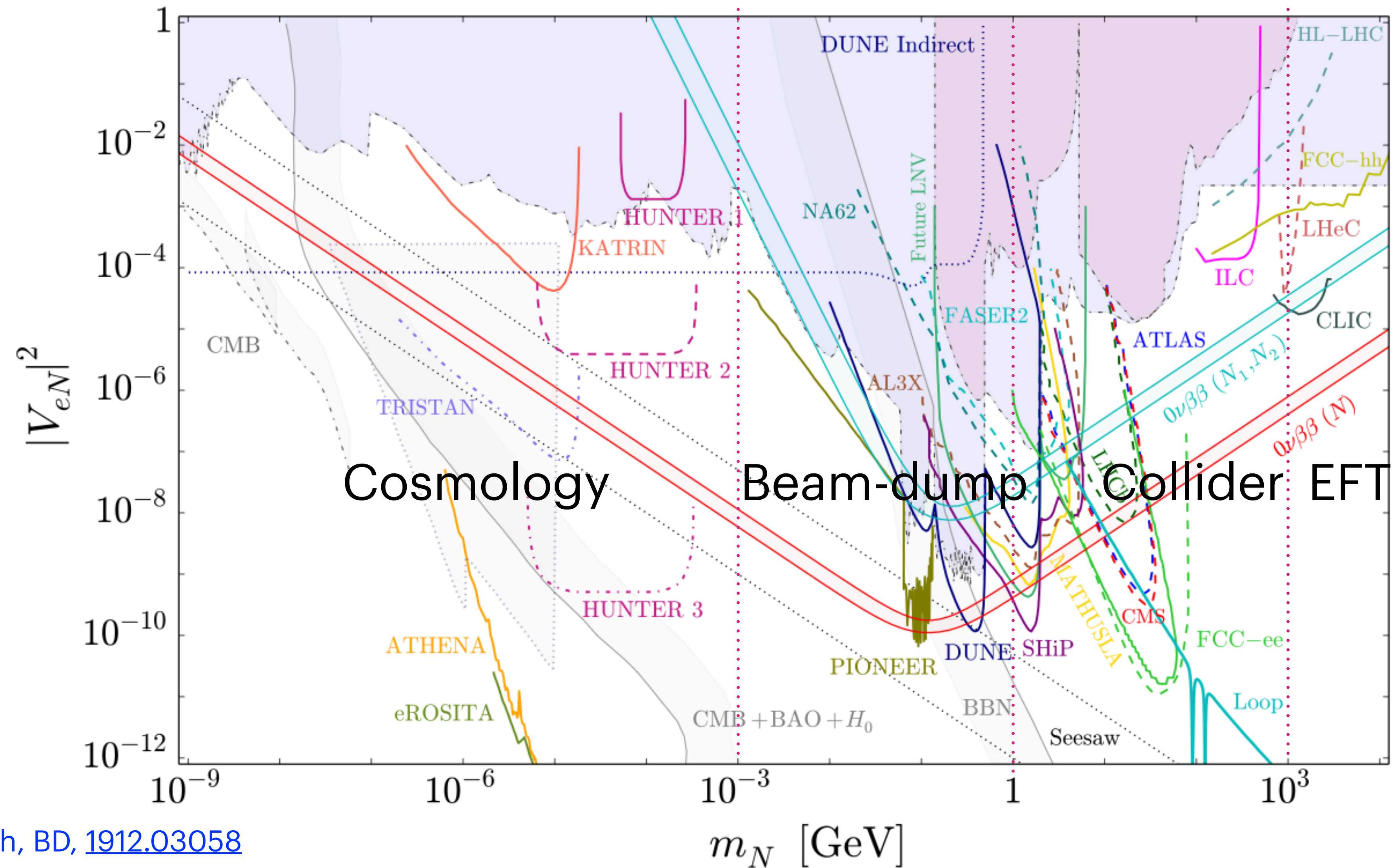
Bolton, Deppisch, BD, [1912.03058](#)

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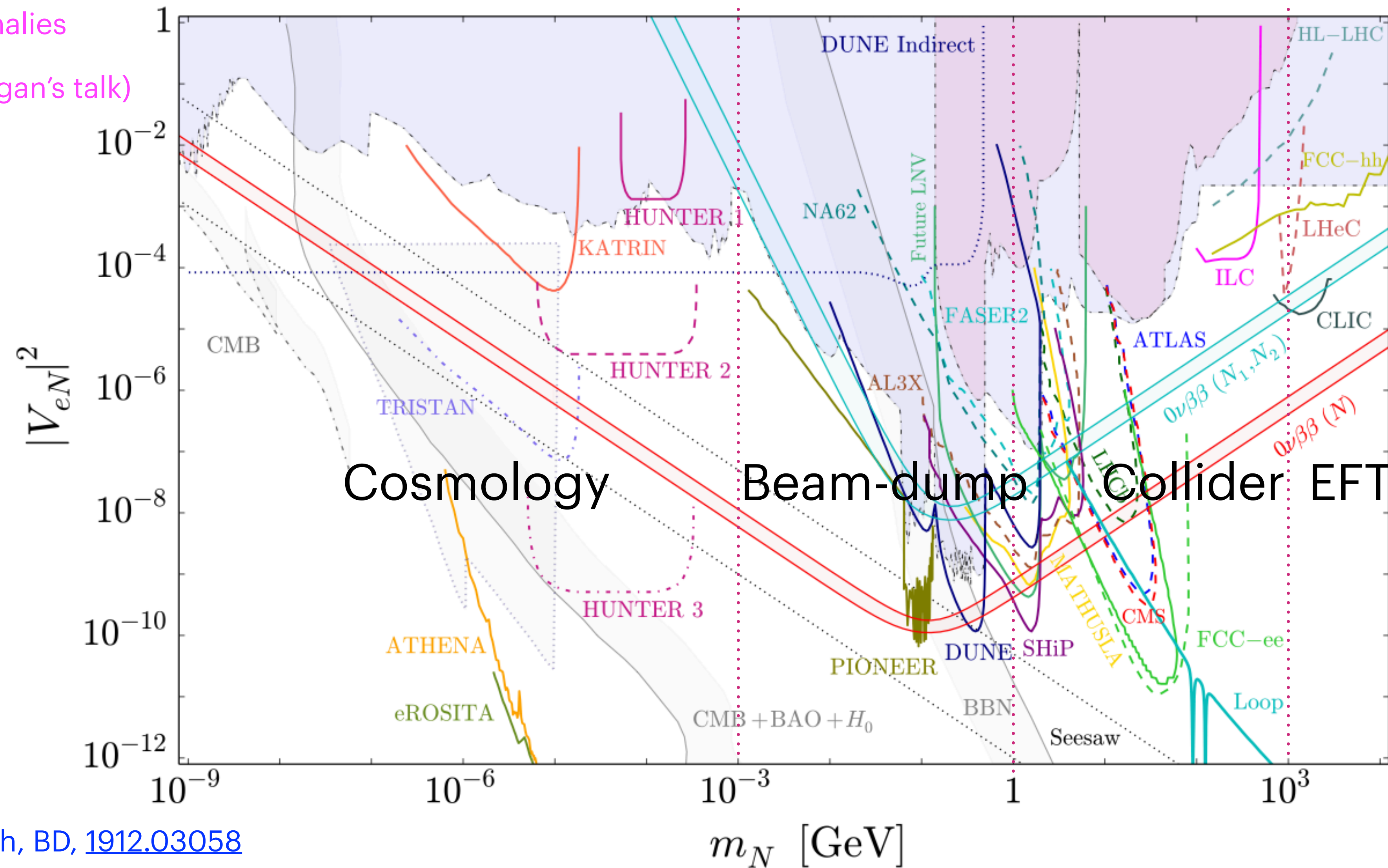


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Additional Neutrino Species

SBN Anomalies

(M. Ross-Lonergan's talk)

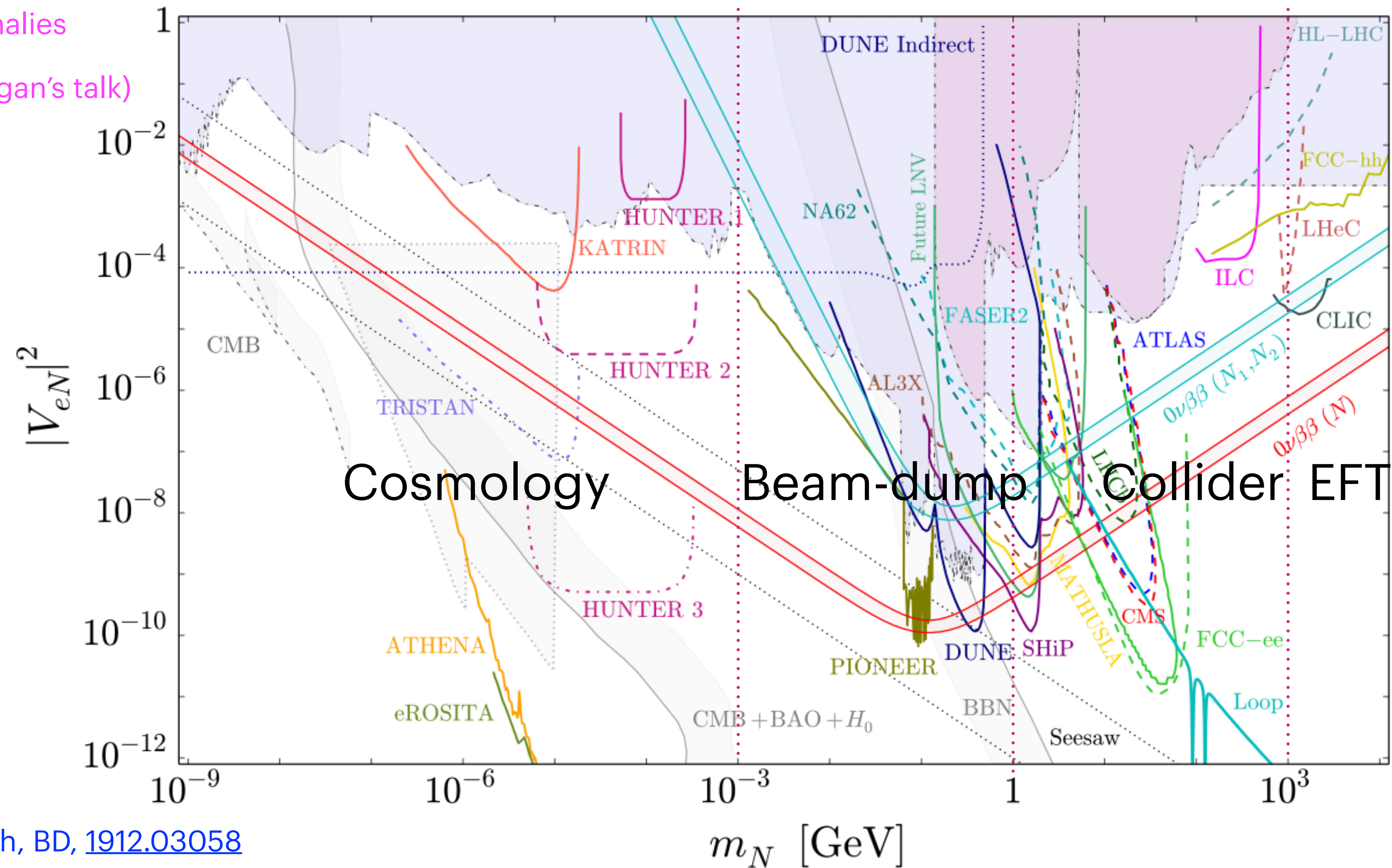


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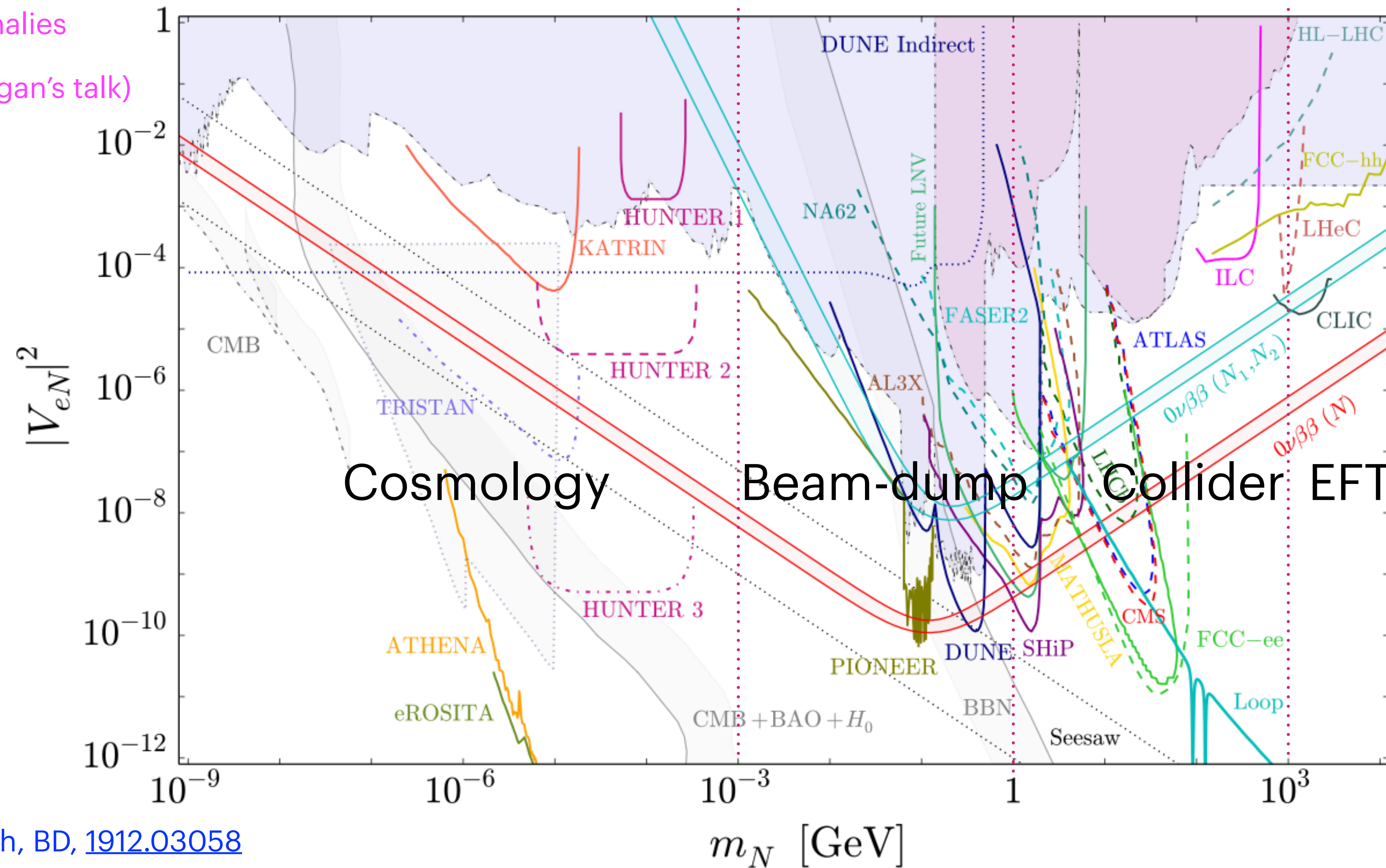


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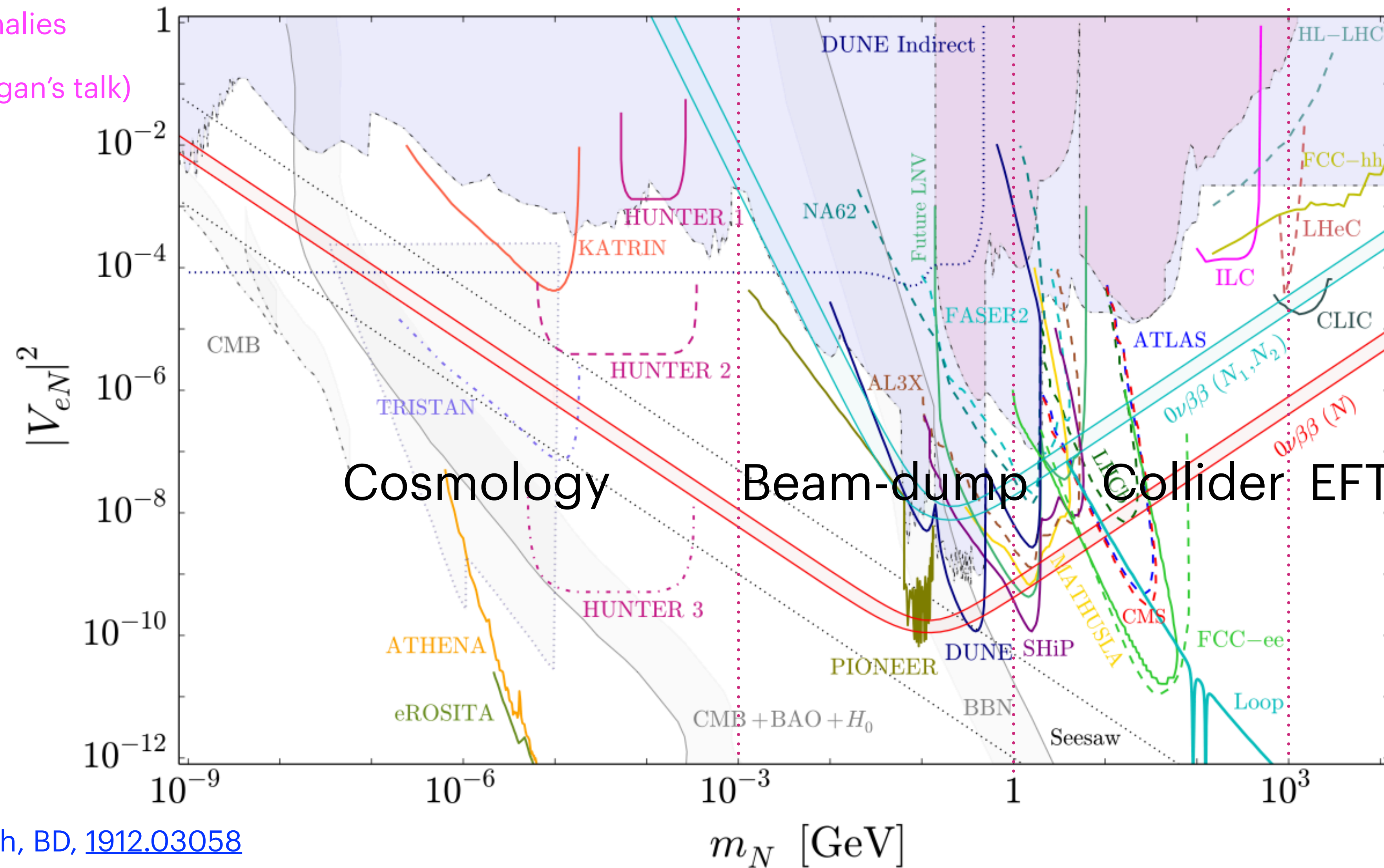
EIC Prospects
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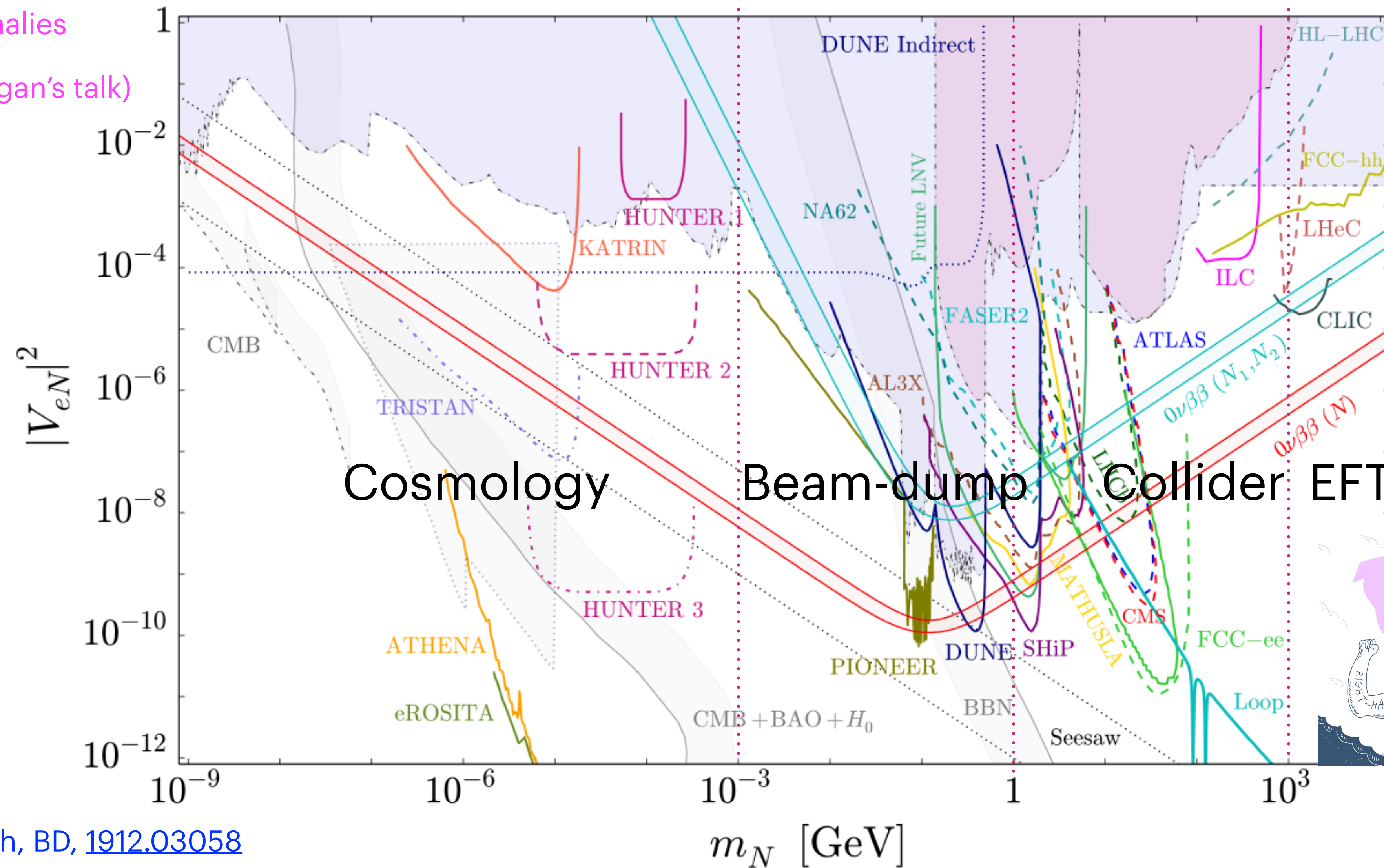
Motivated by seesaw

Bolton, Deppisch, BD, [1912.03058](#)

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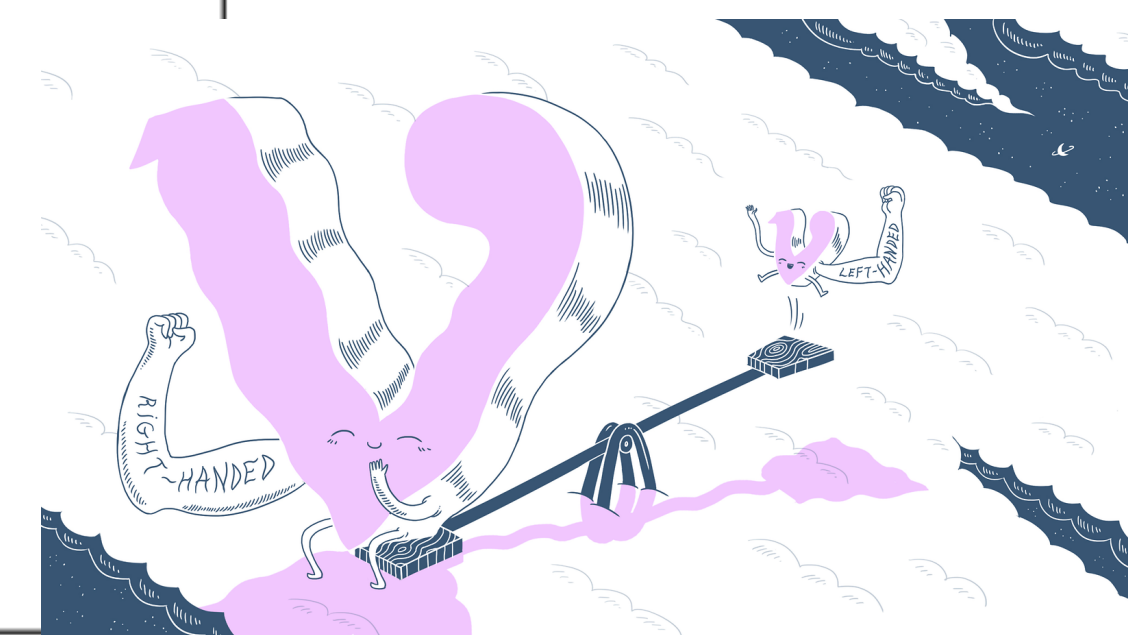
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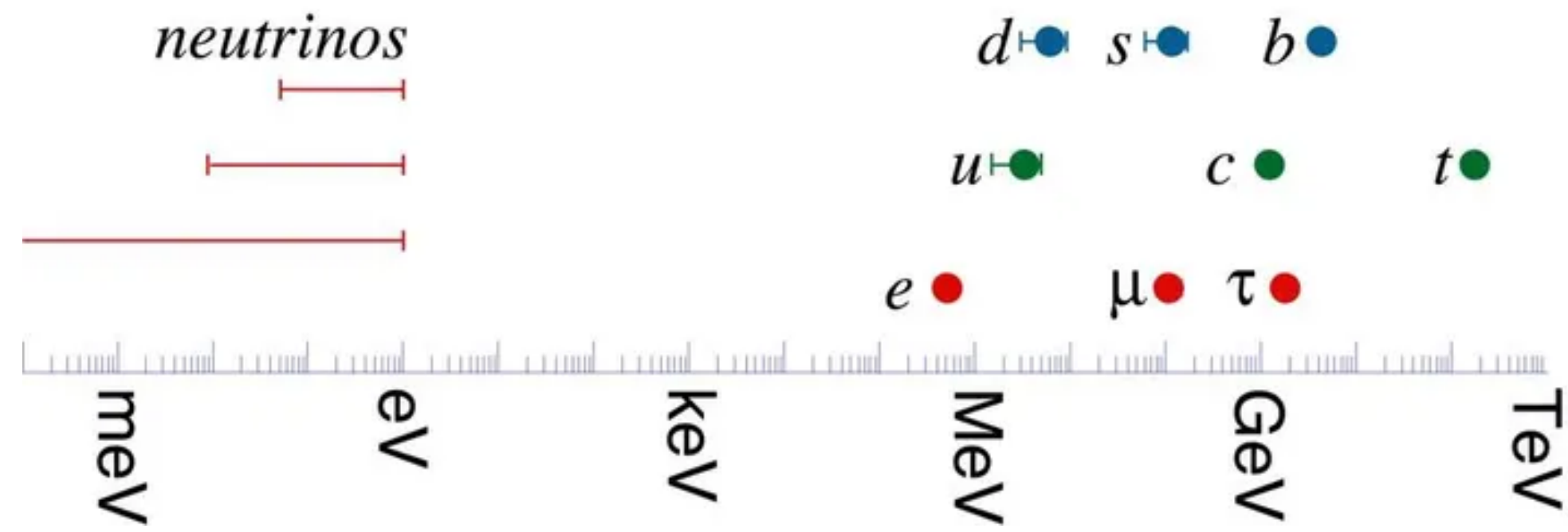
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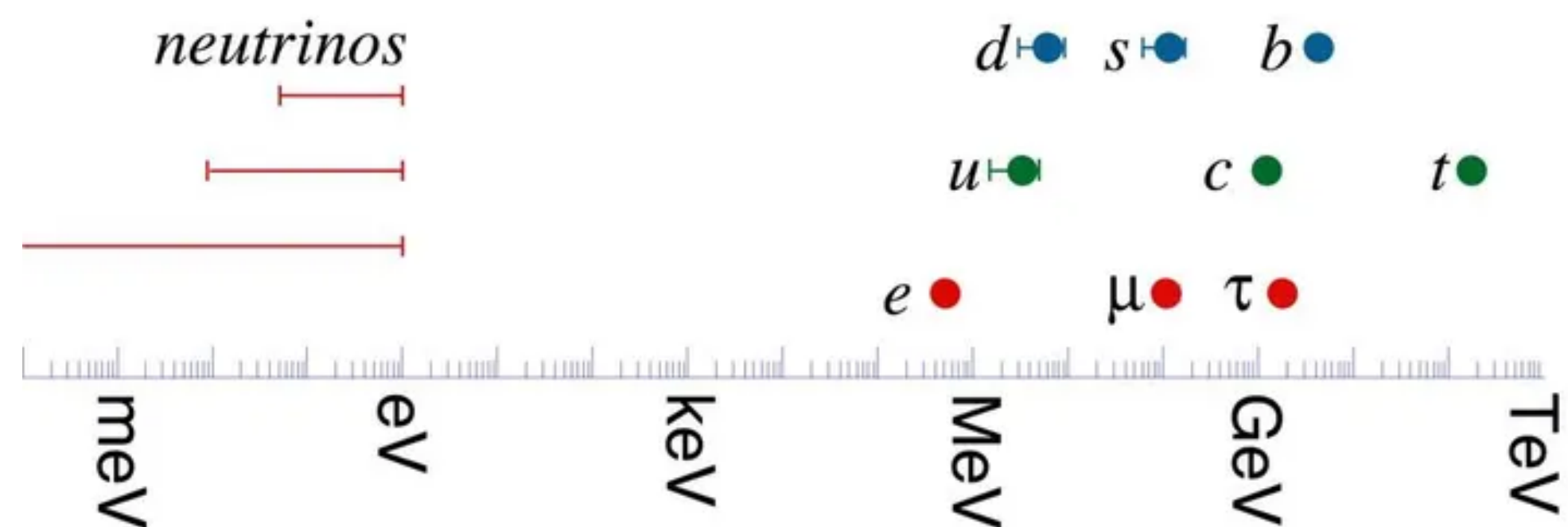


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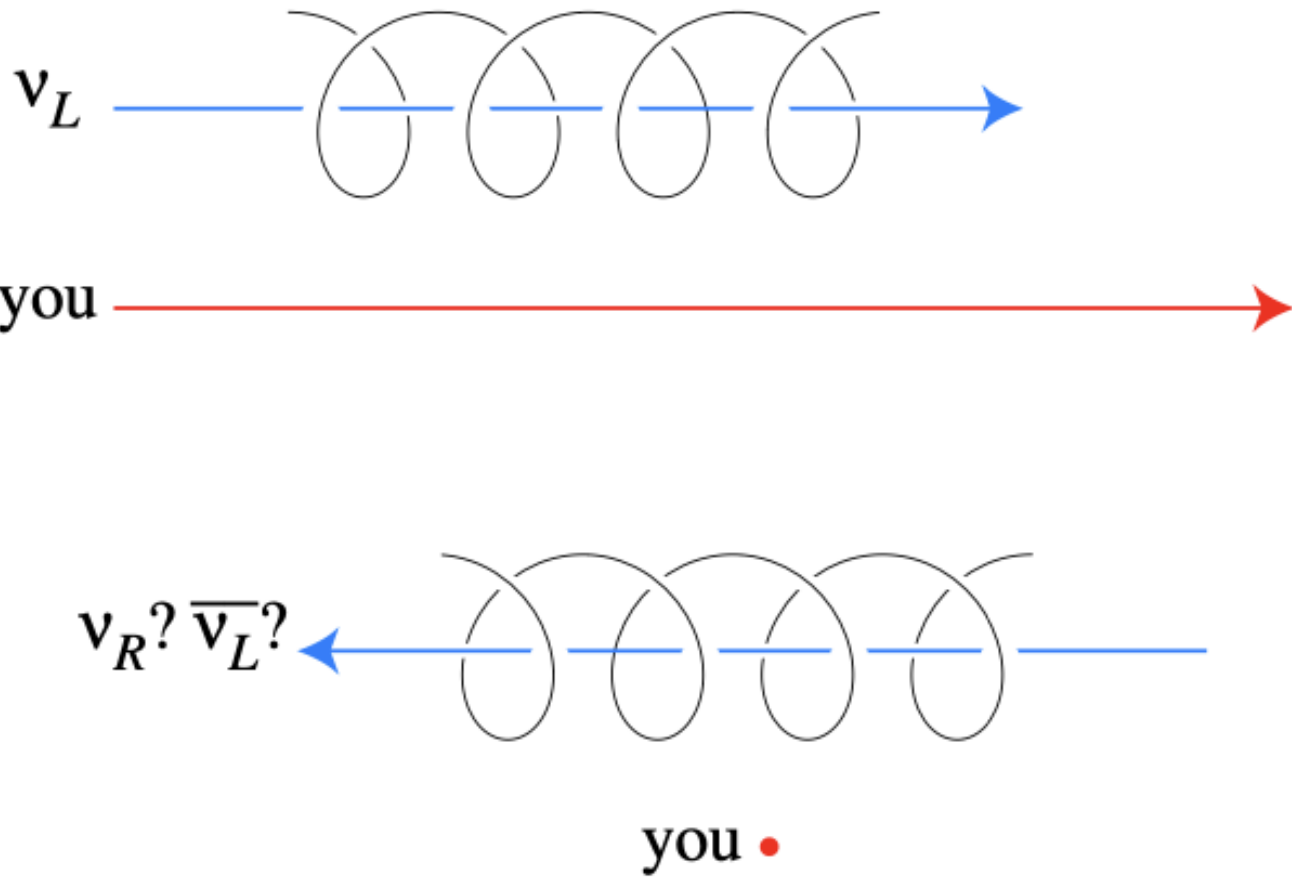
Nature of Neutrino Mass



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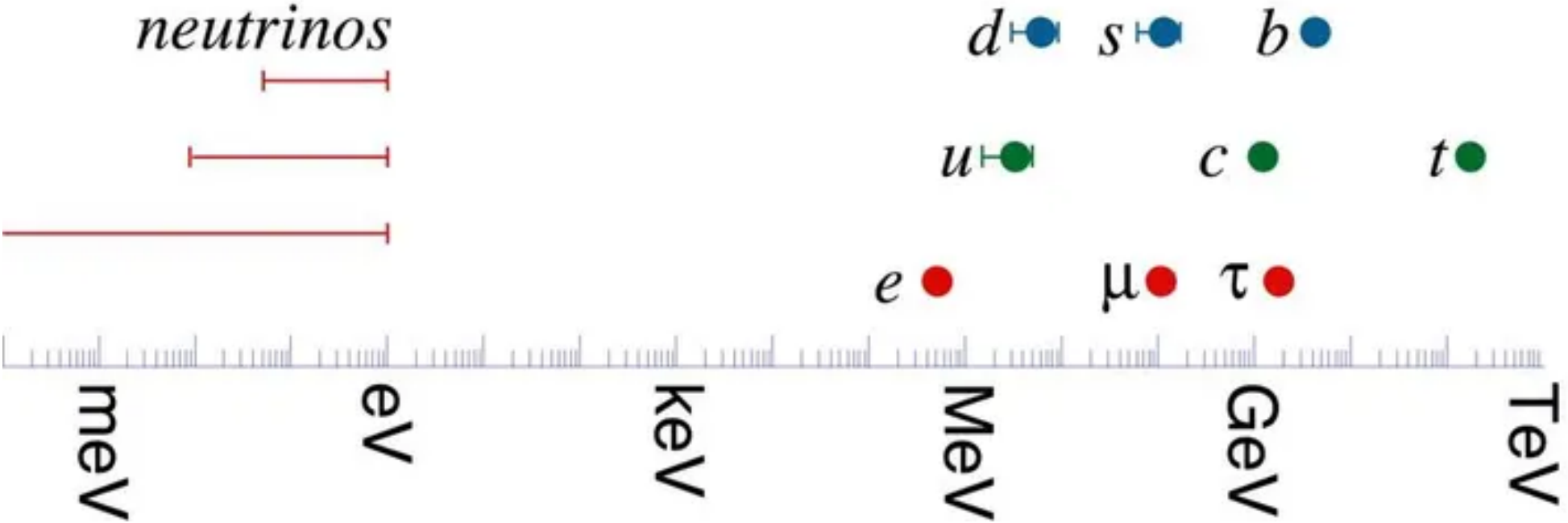
From A. de Gouvea



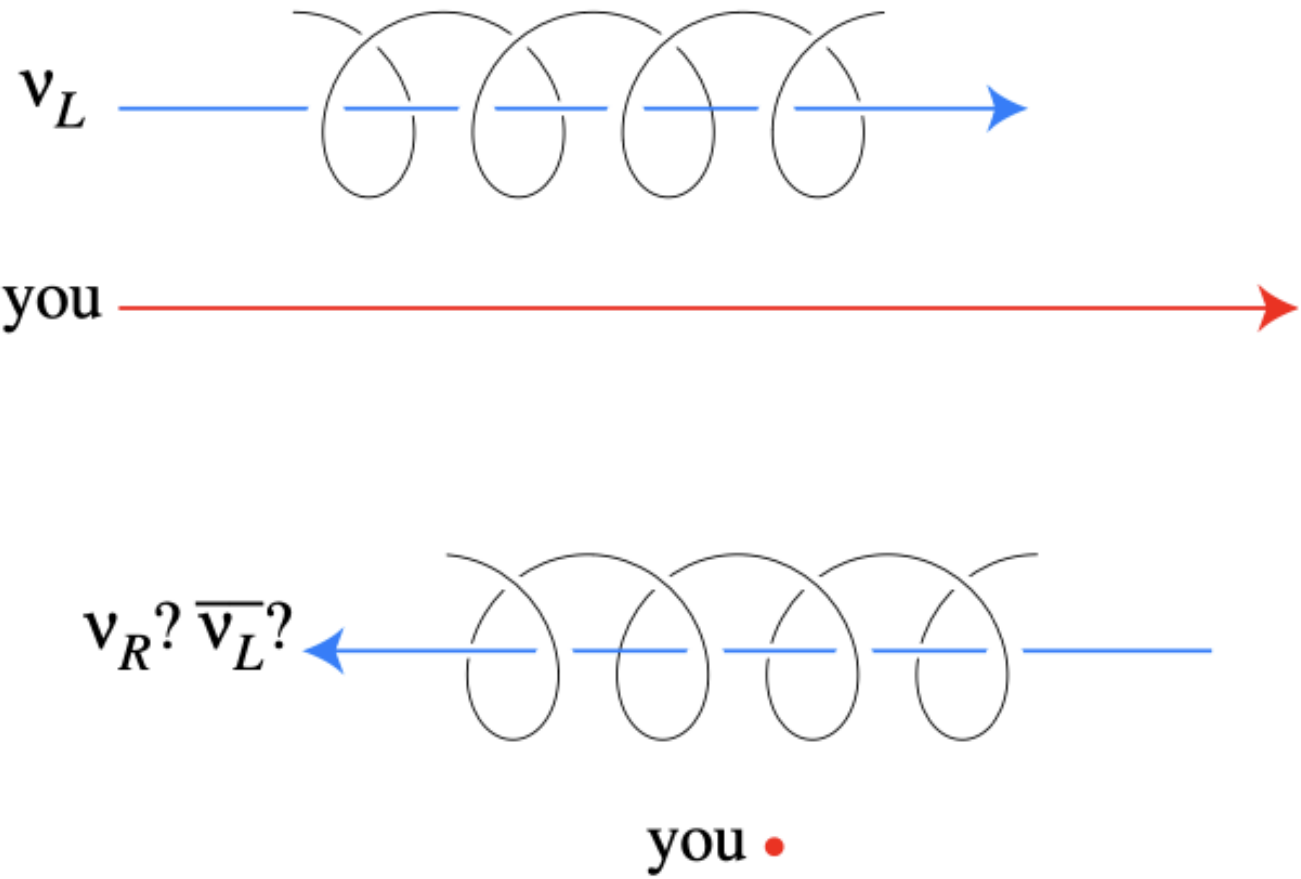
How many degrees of freedom are required to describe massive neutrinos?



Nature of Neutrino Mass



From A. de Gouvea



A massive neutral fermion ($s=1/2$) is described by 4 or 2 degrees of freedom:

$$\begin{aligned} (\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R) \\ \updownarrow \text{"Lorentz"} \quad \text{'DIRAC'} \\ (\nu_R \leftarrow \text{CPT} \rightarrow \bar{\nu}_L) \end{aligned}$$

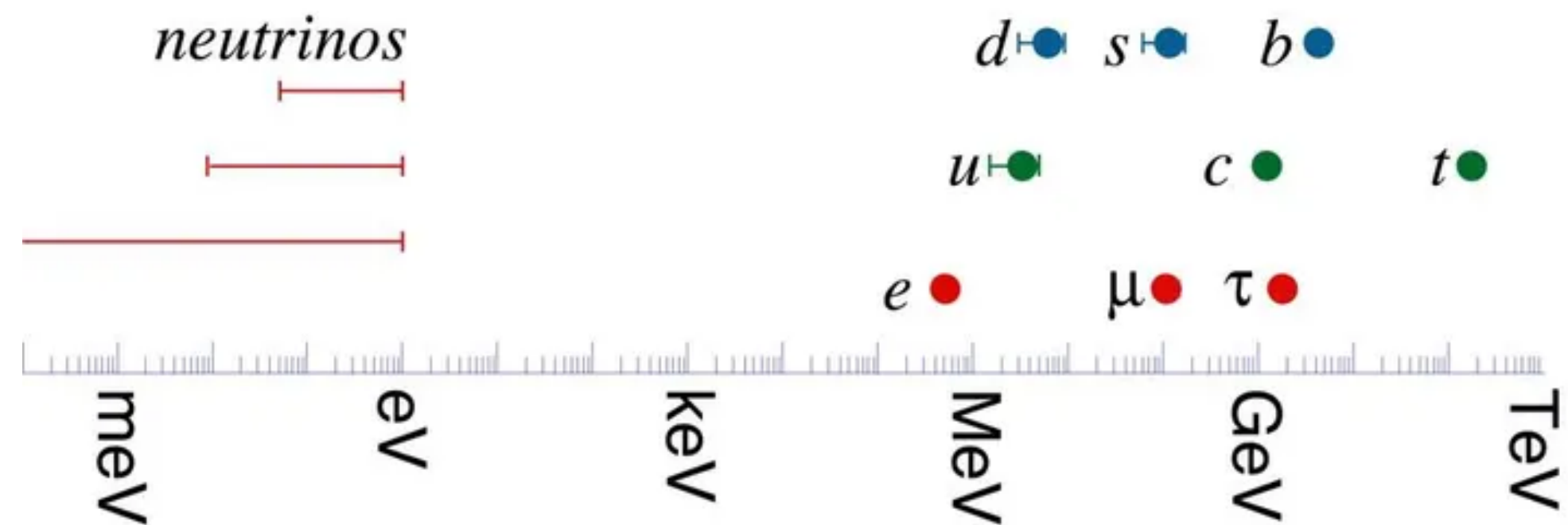
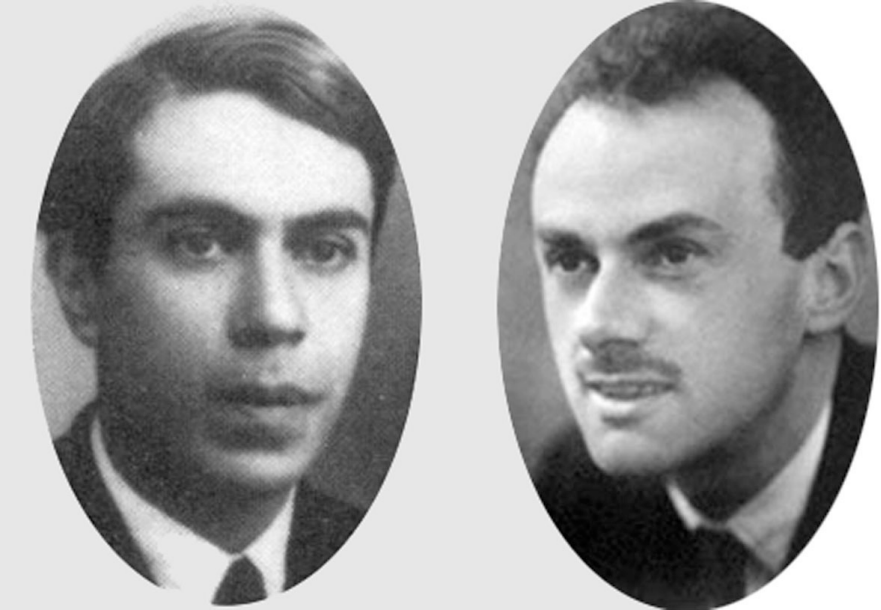
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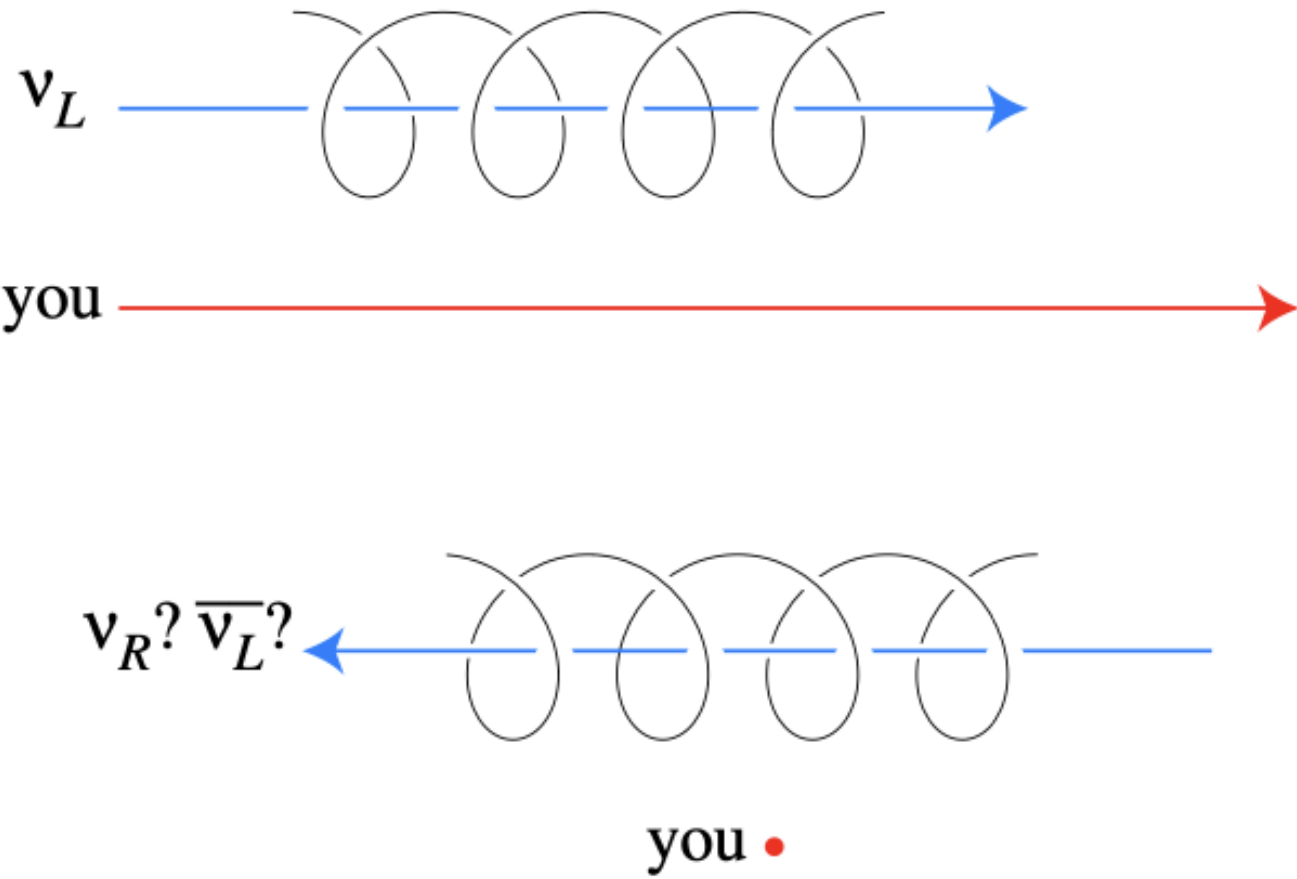
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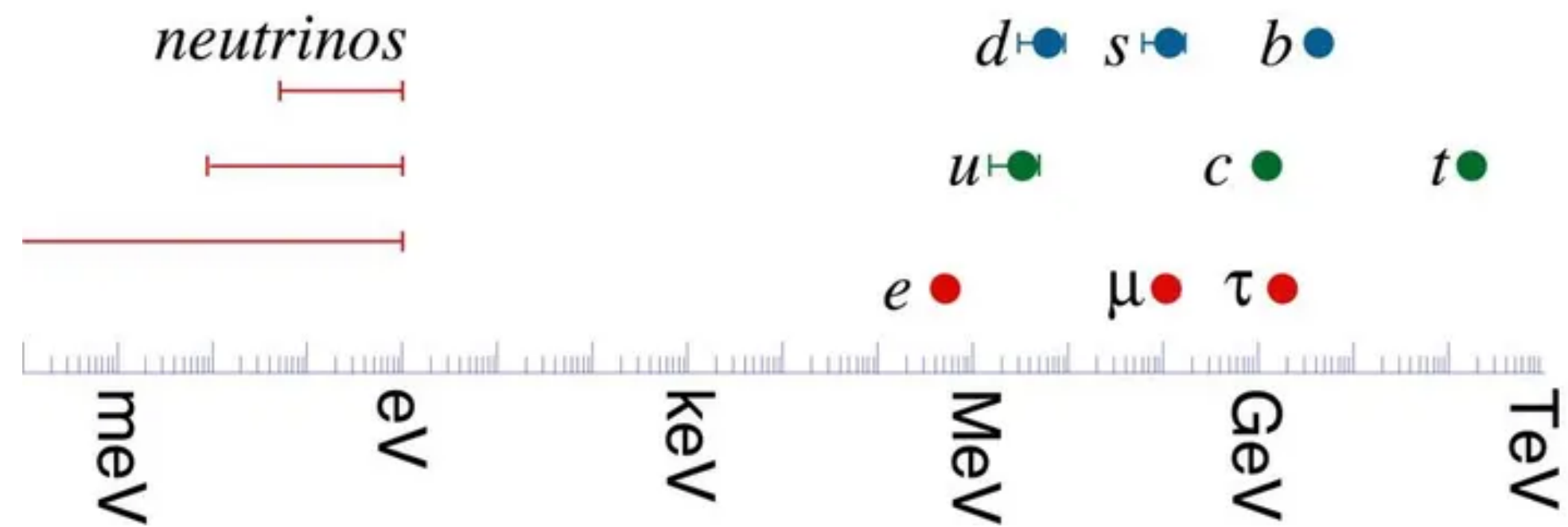
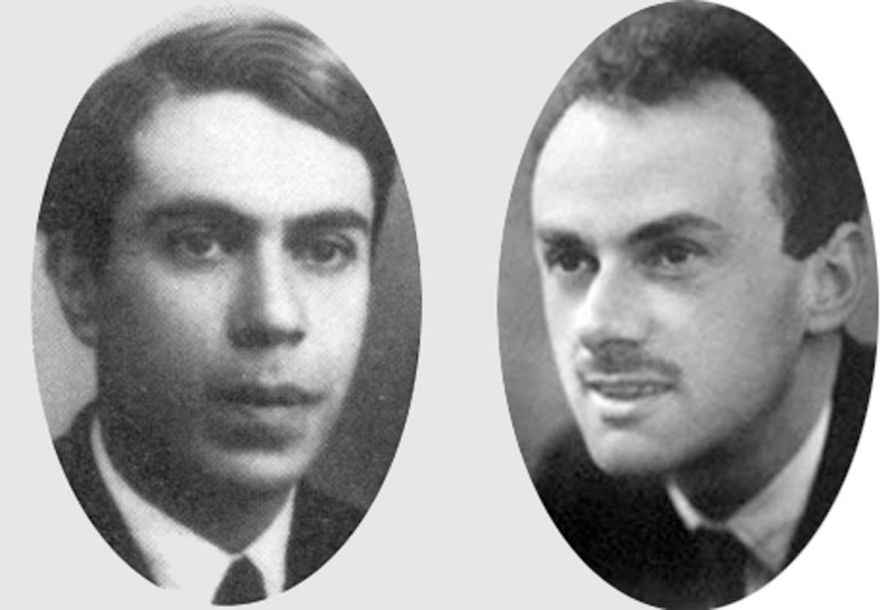
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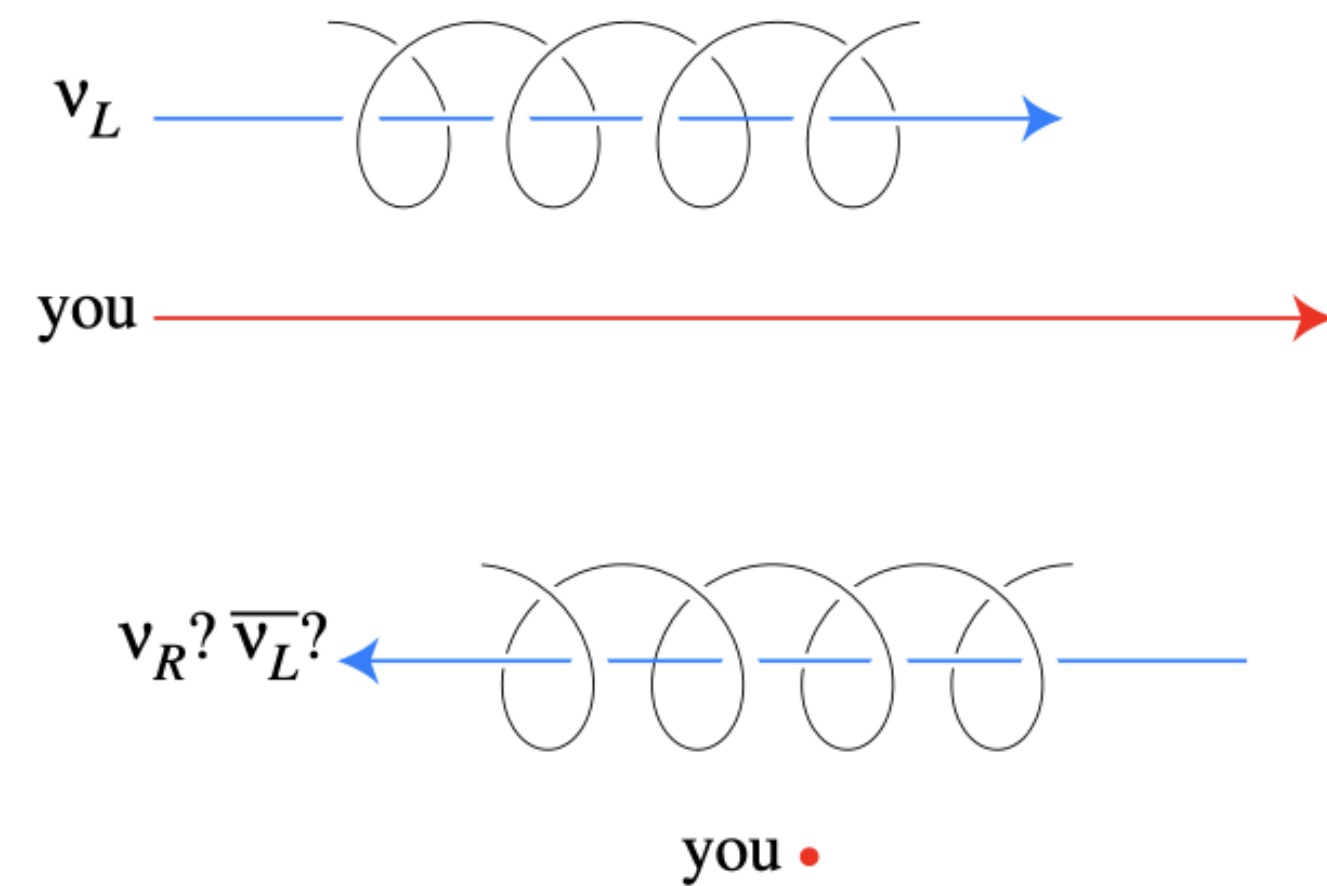


Nature of Neutrino Mass



Majorana or Dirac?

From A. de Gouvea



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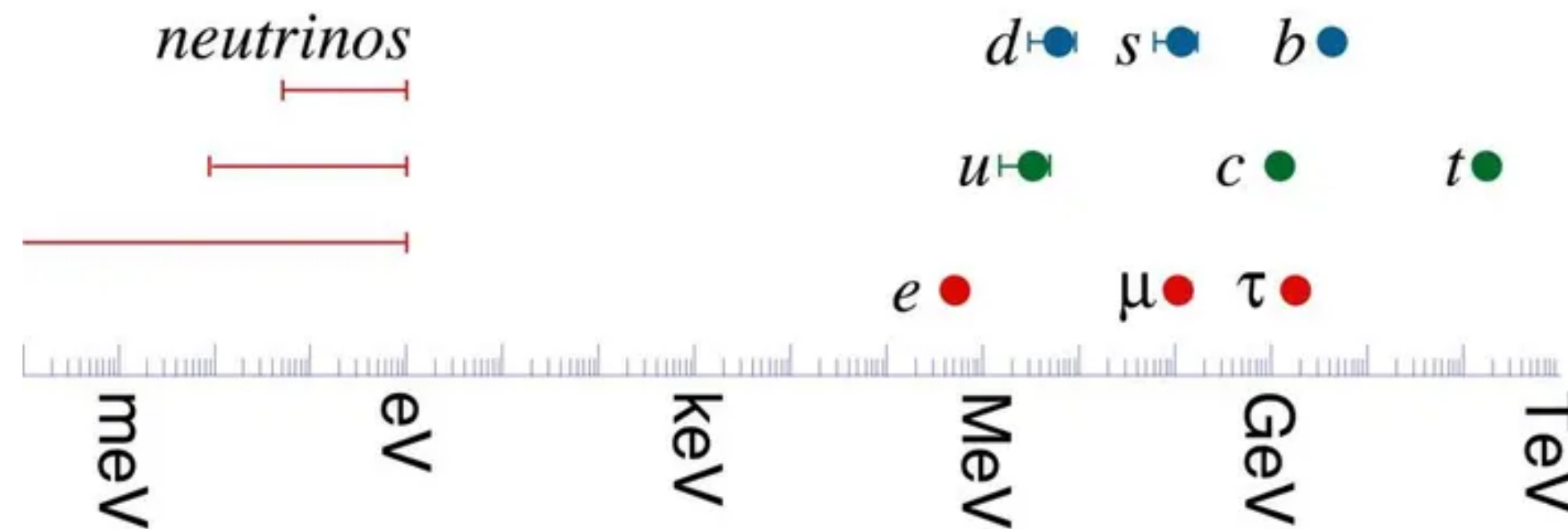
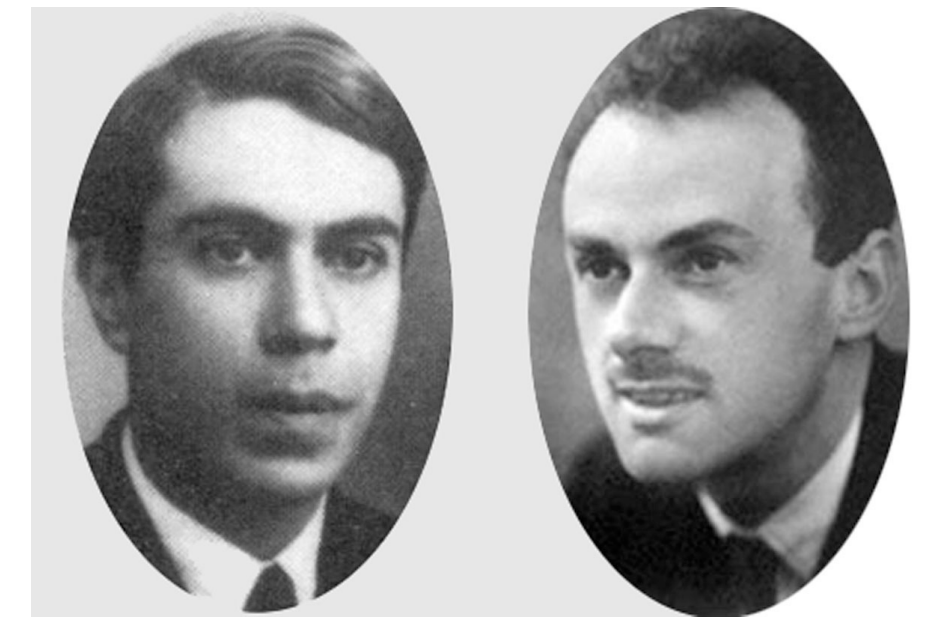
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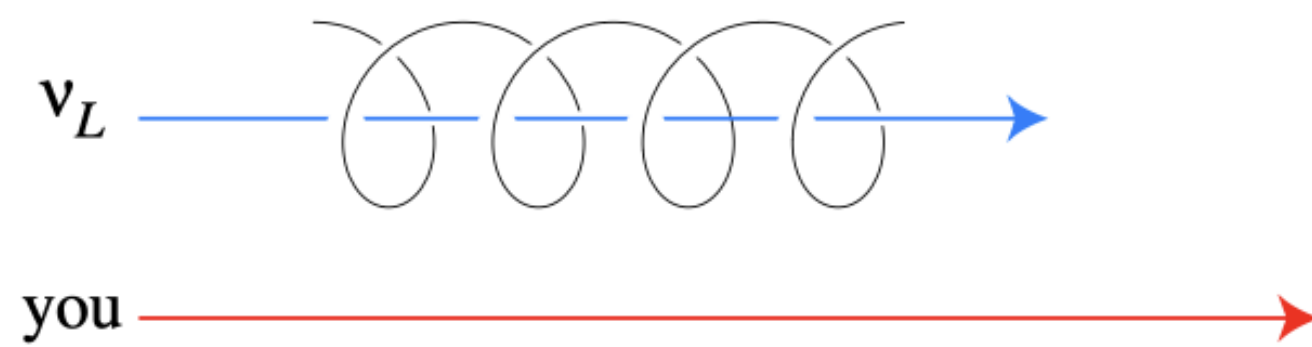
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Nature of Neutrino Mass



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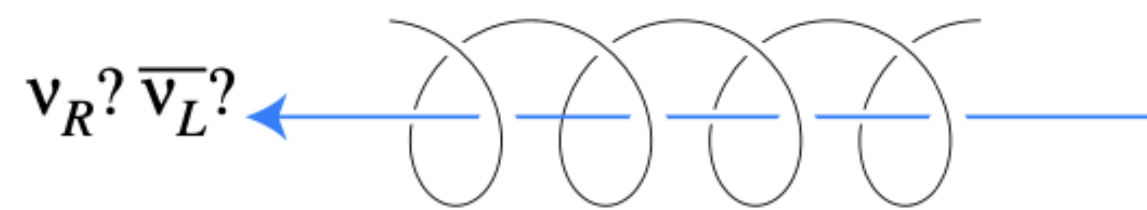
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you •

'MAJORANA'

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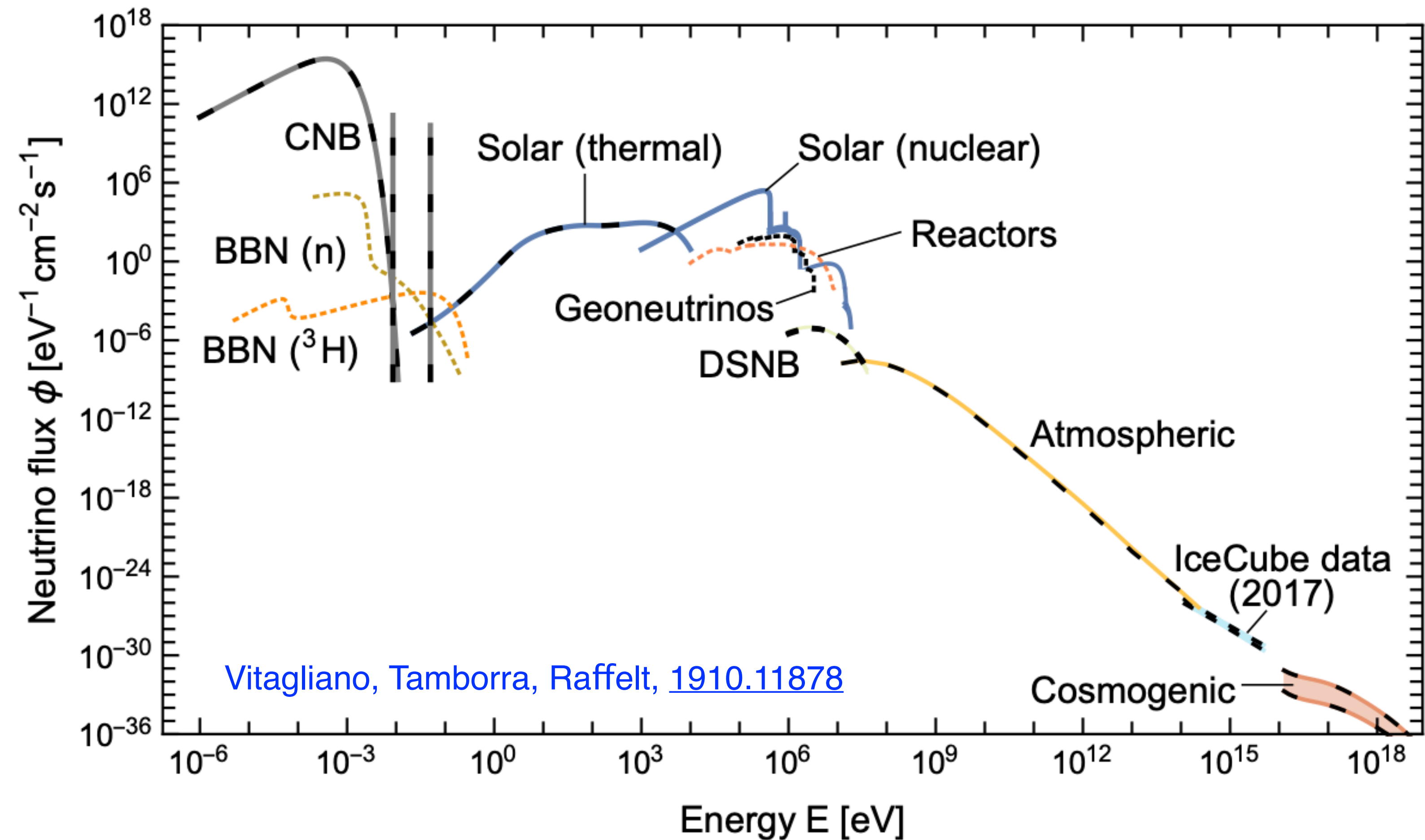
Majorana or Dirac?

- Why is it a difficult question?
- The Majorana nature is usually suppressed by the tiny neutrino mass itself: $\mathcal{M} \propto (m_\nu/E)^2$.
- Two ways around:
 - Find non-relativistic neutrinos.
 - Find a process that violates lepton number (or enhances the effect).

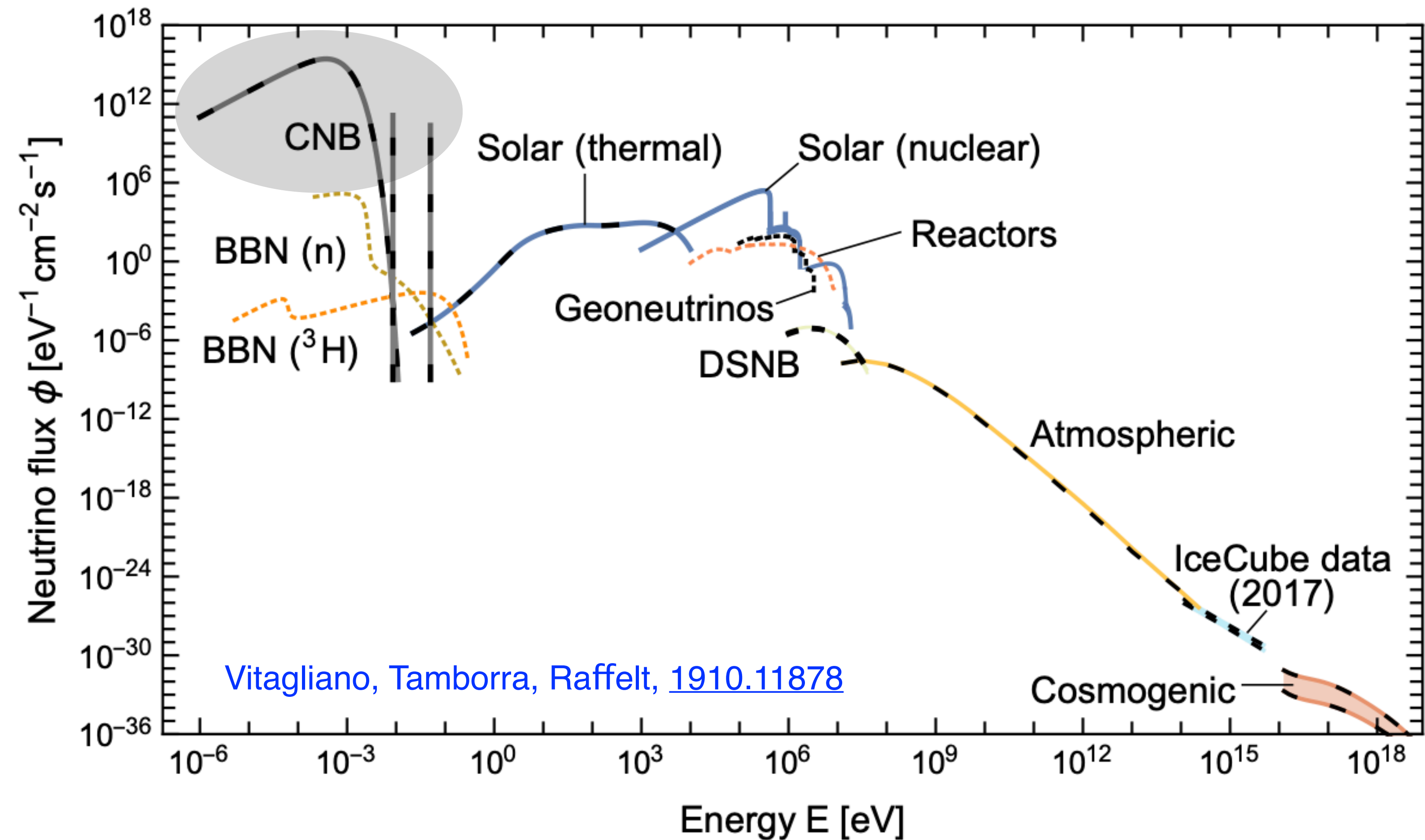
Both are difficult.



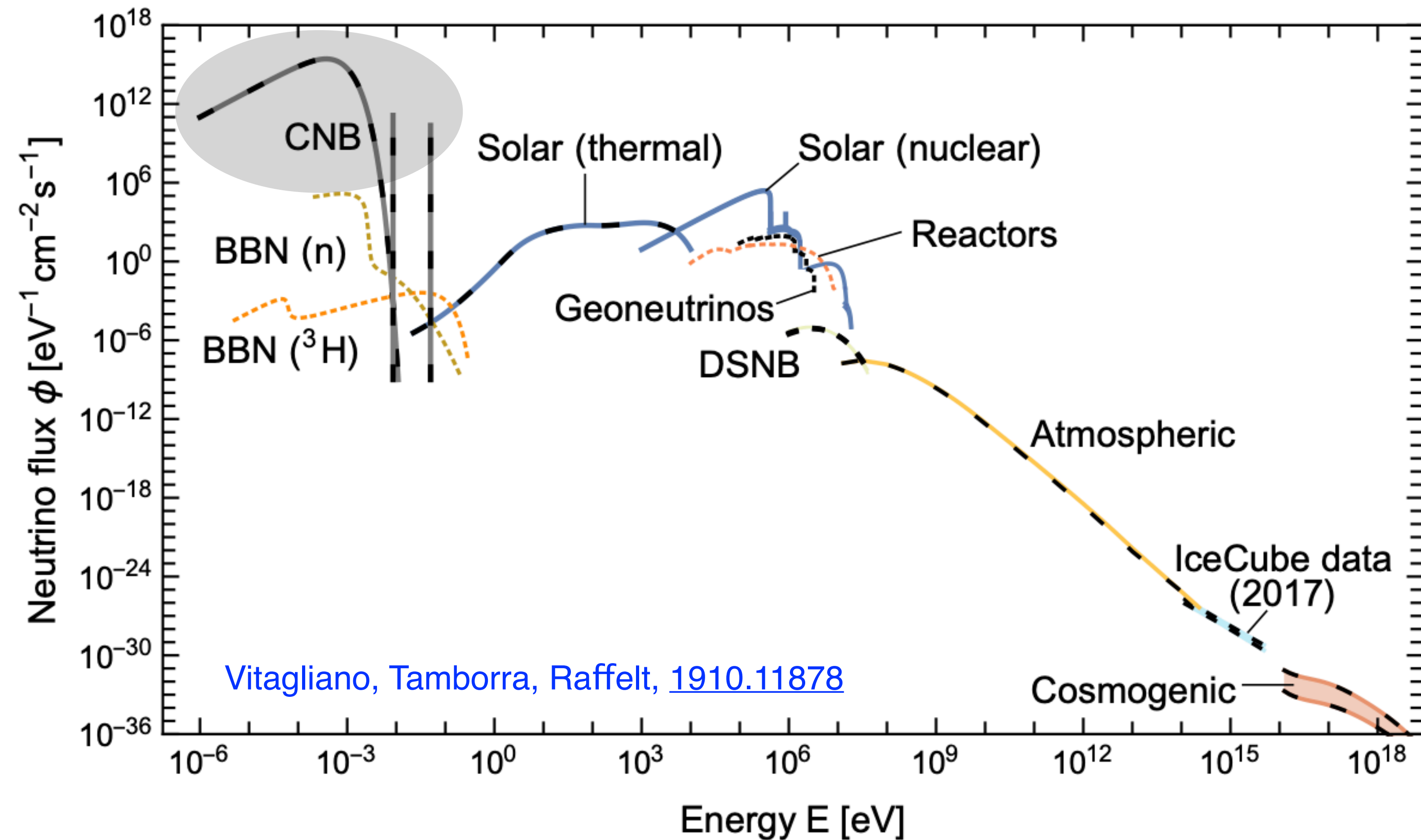
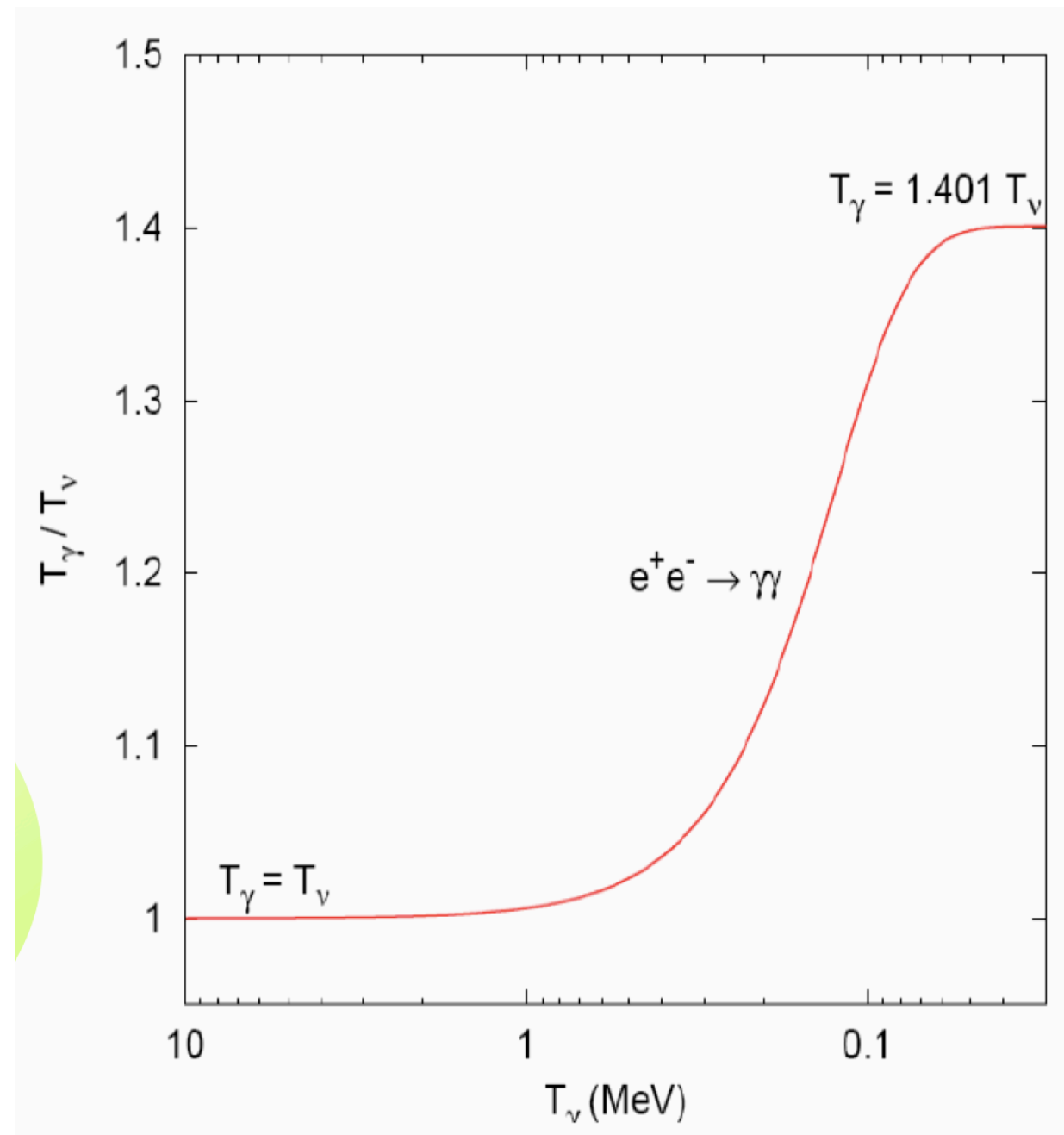
Relic Neutrino Background



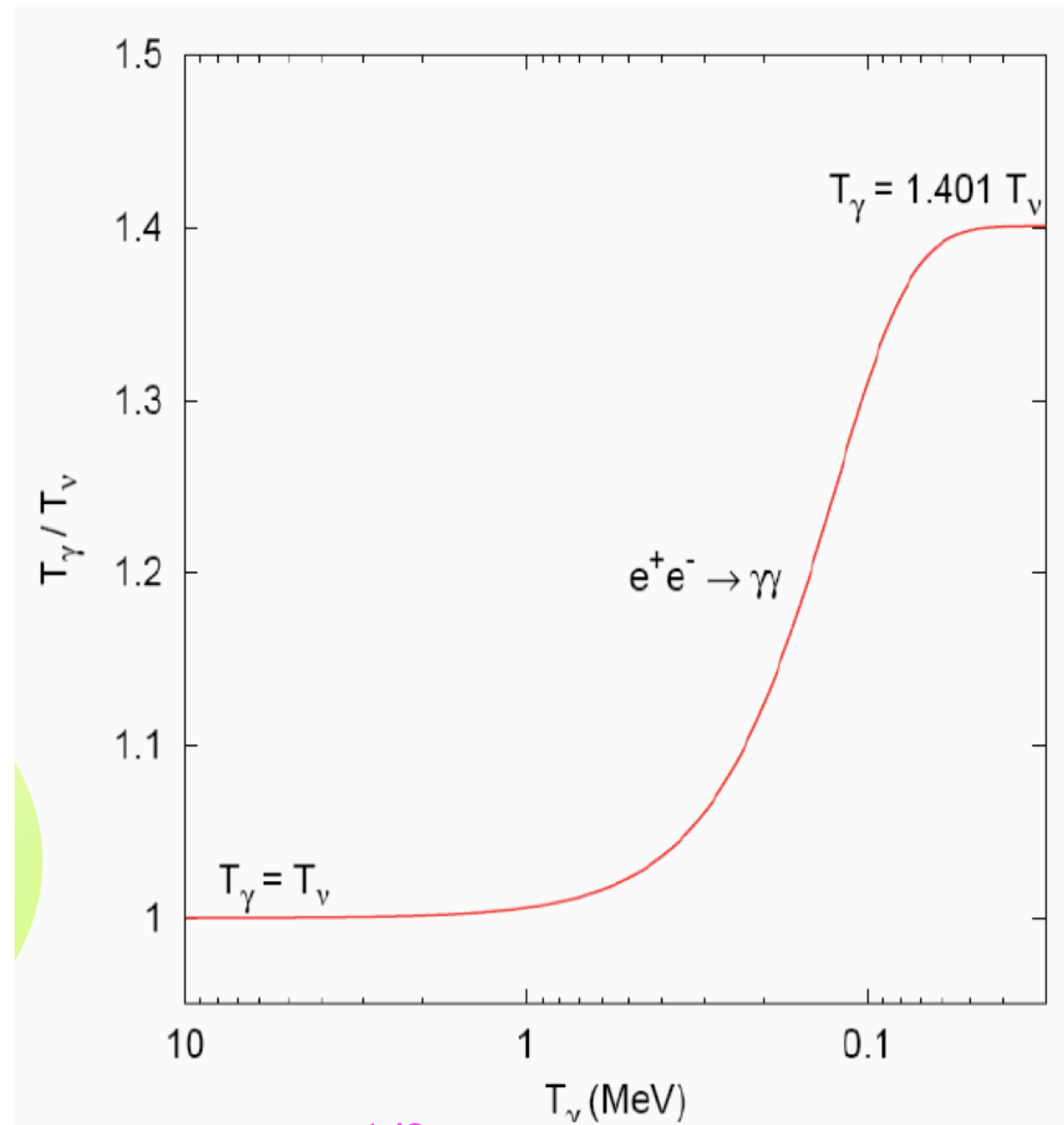
Relic Neutrino Background



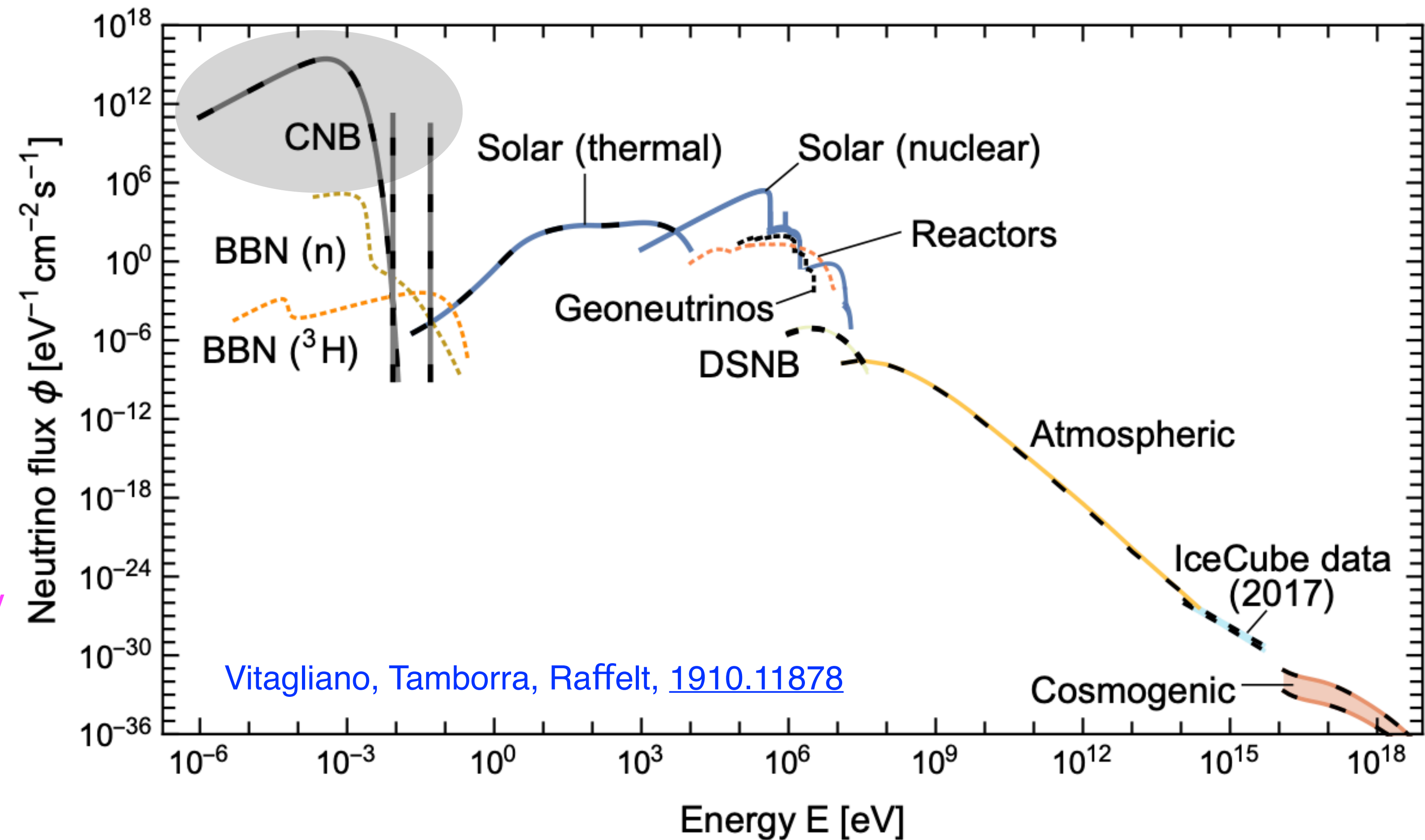
Relic Neutrino Background



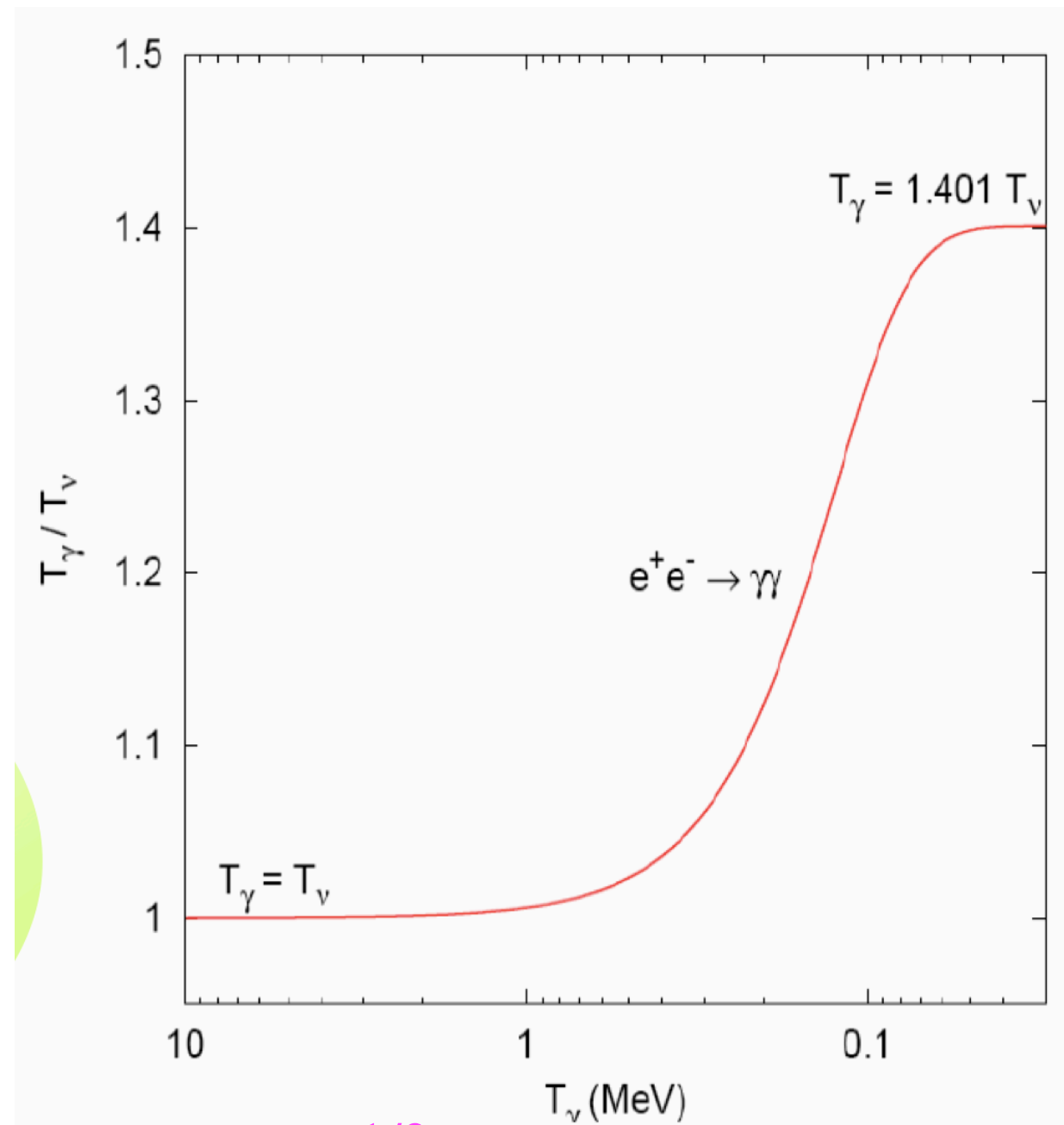
Relic Neutrino Background



$$T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma,0} = 1.945 \text{ K} = 1.7 \times 10^{-4} \text{ eV}$$

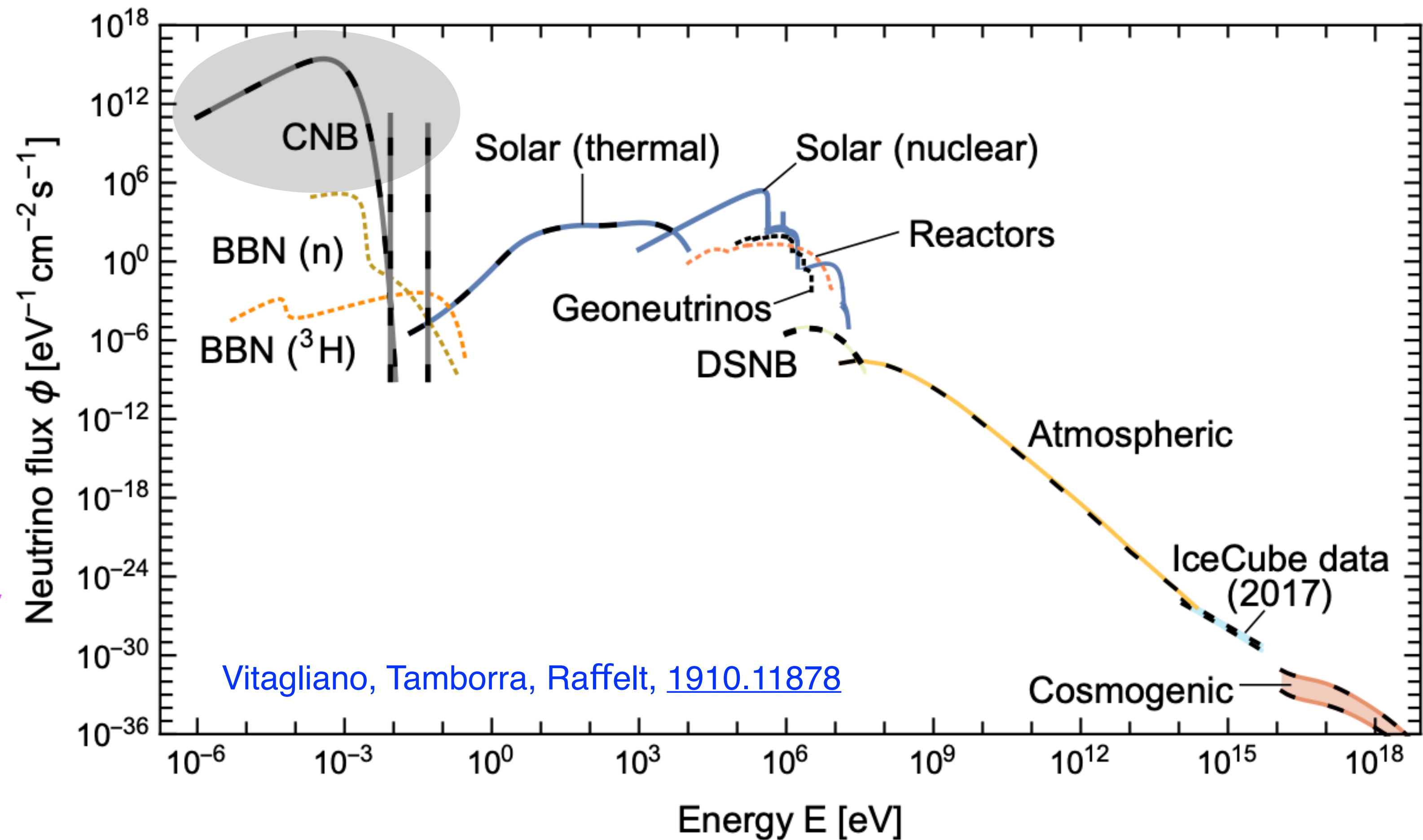


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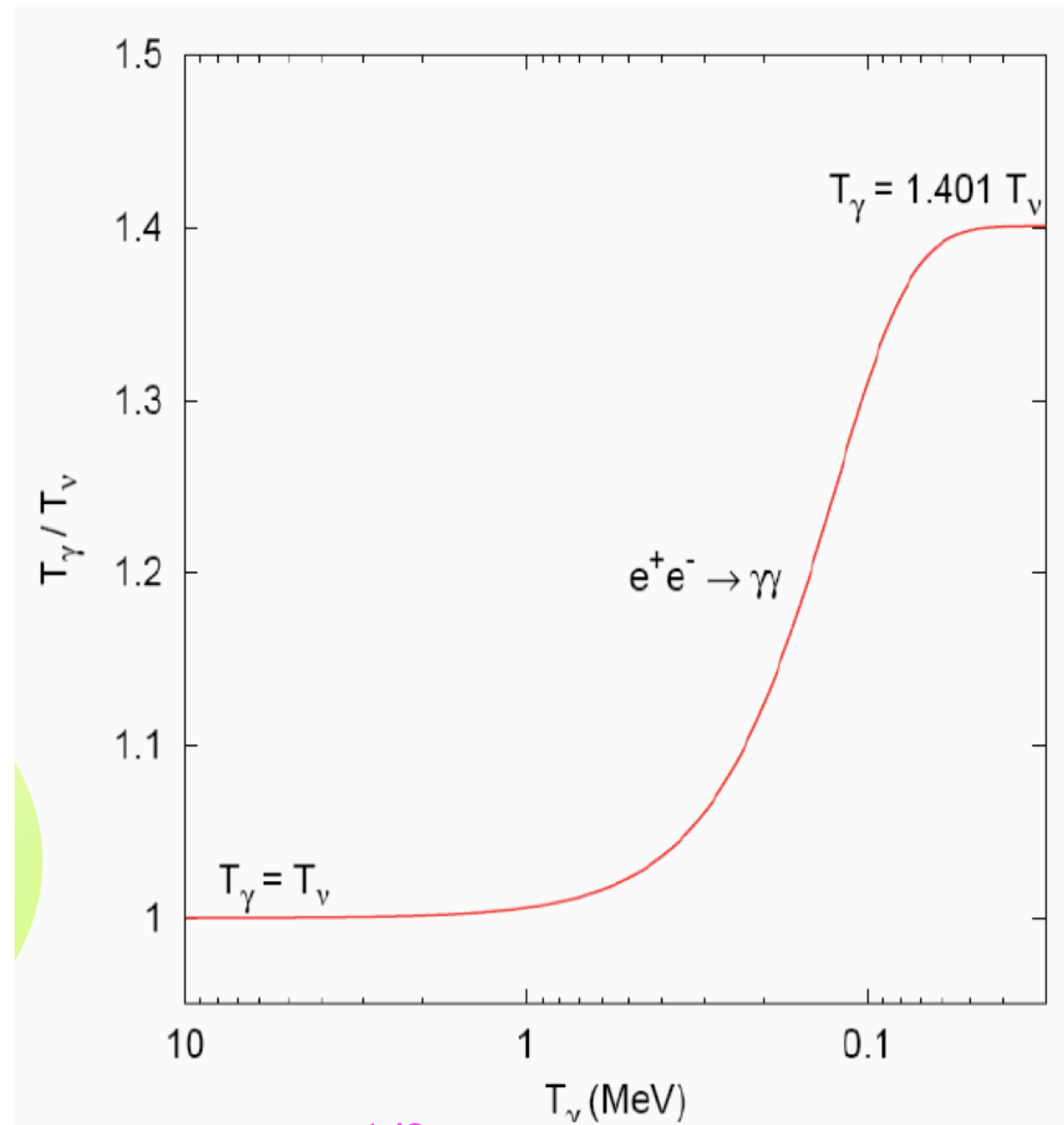


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(Non)relativistic Fermi gas

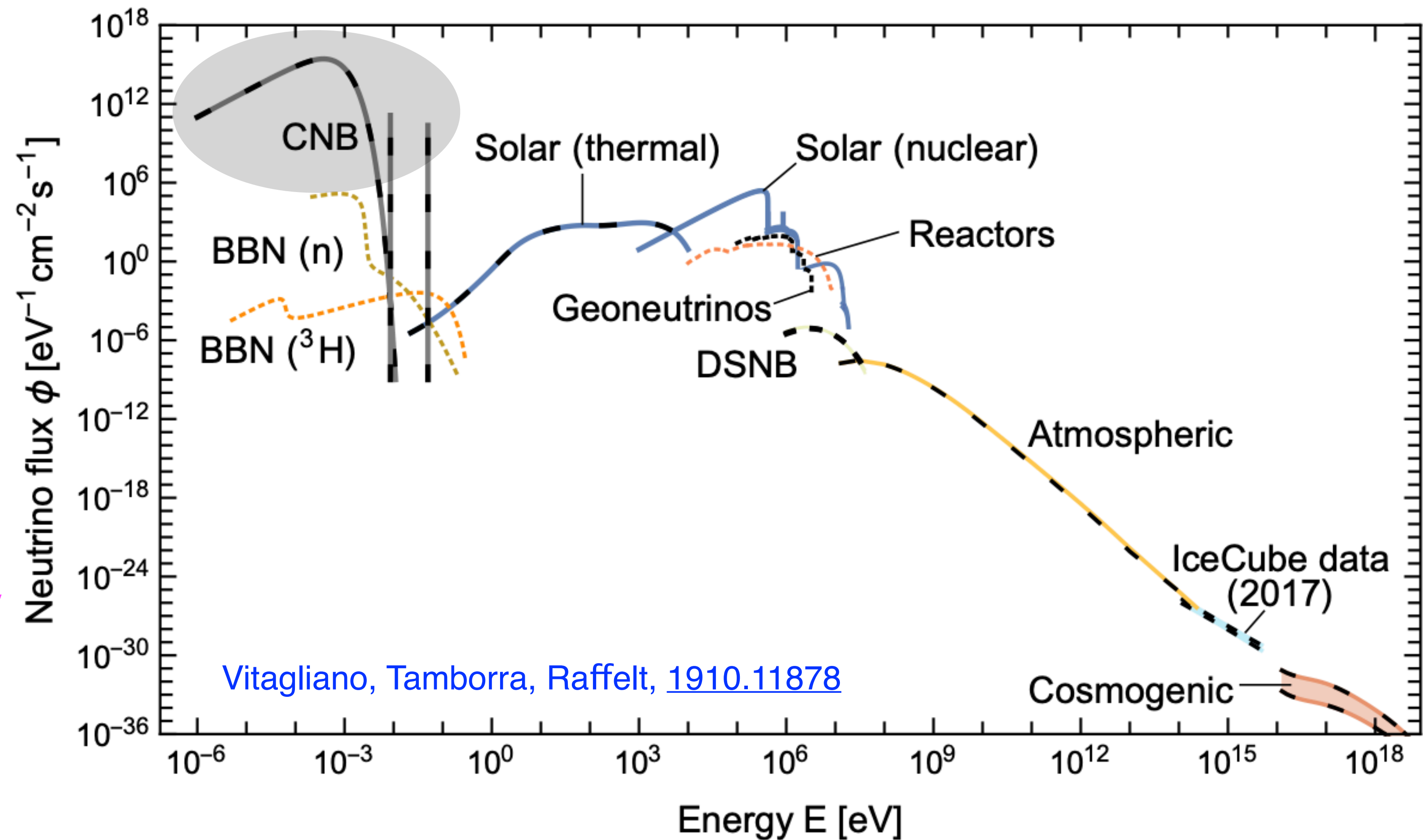
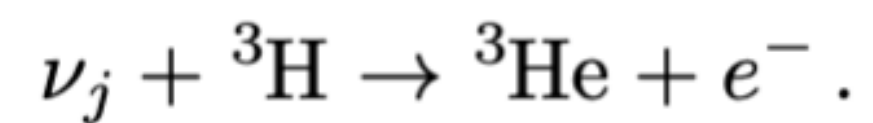


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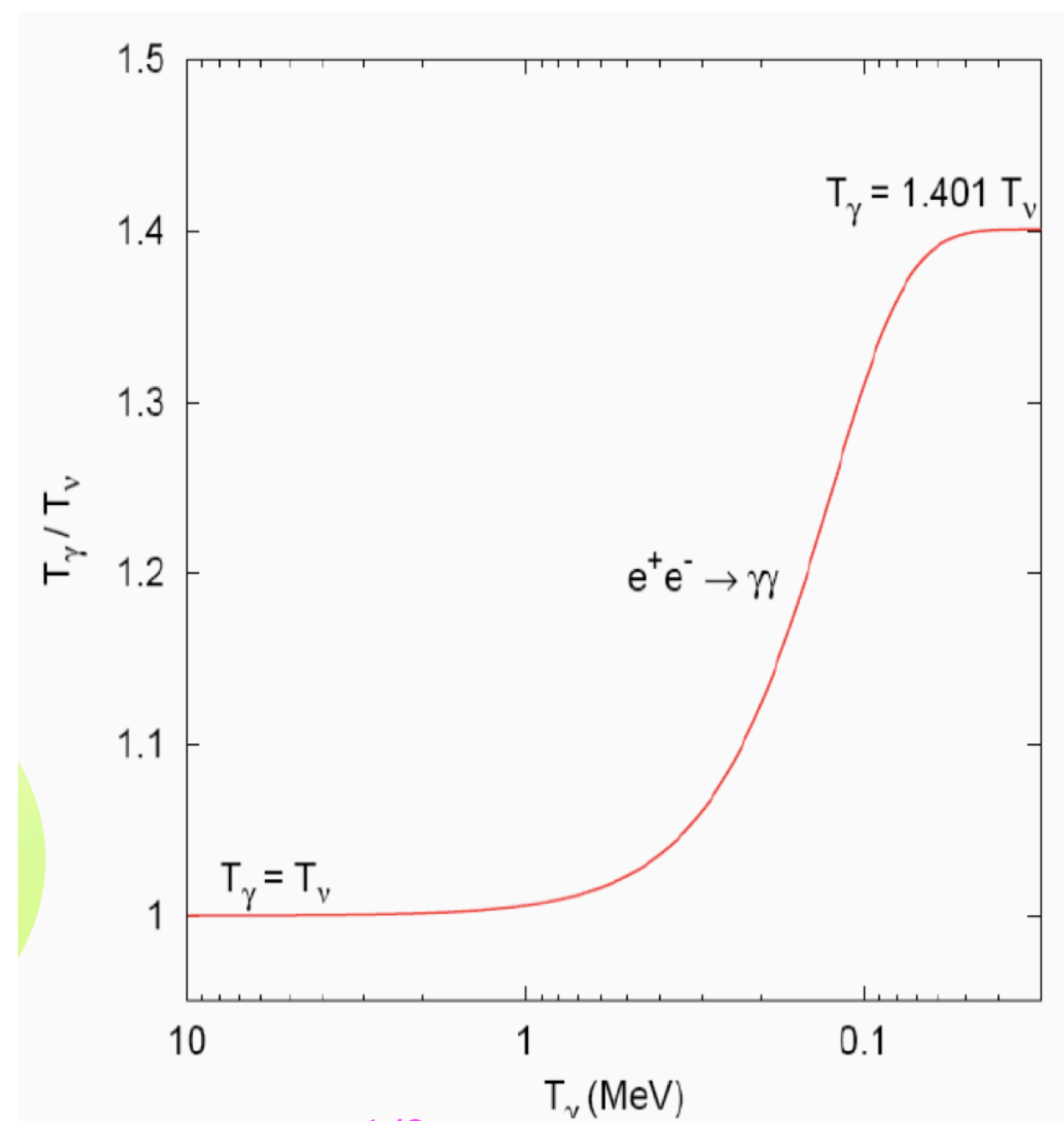
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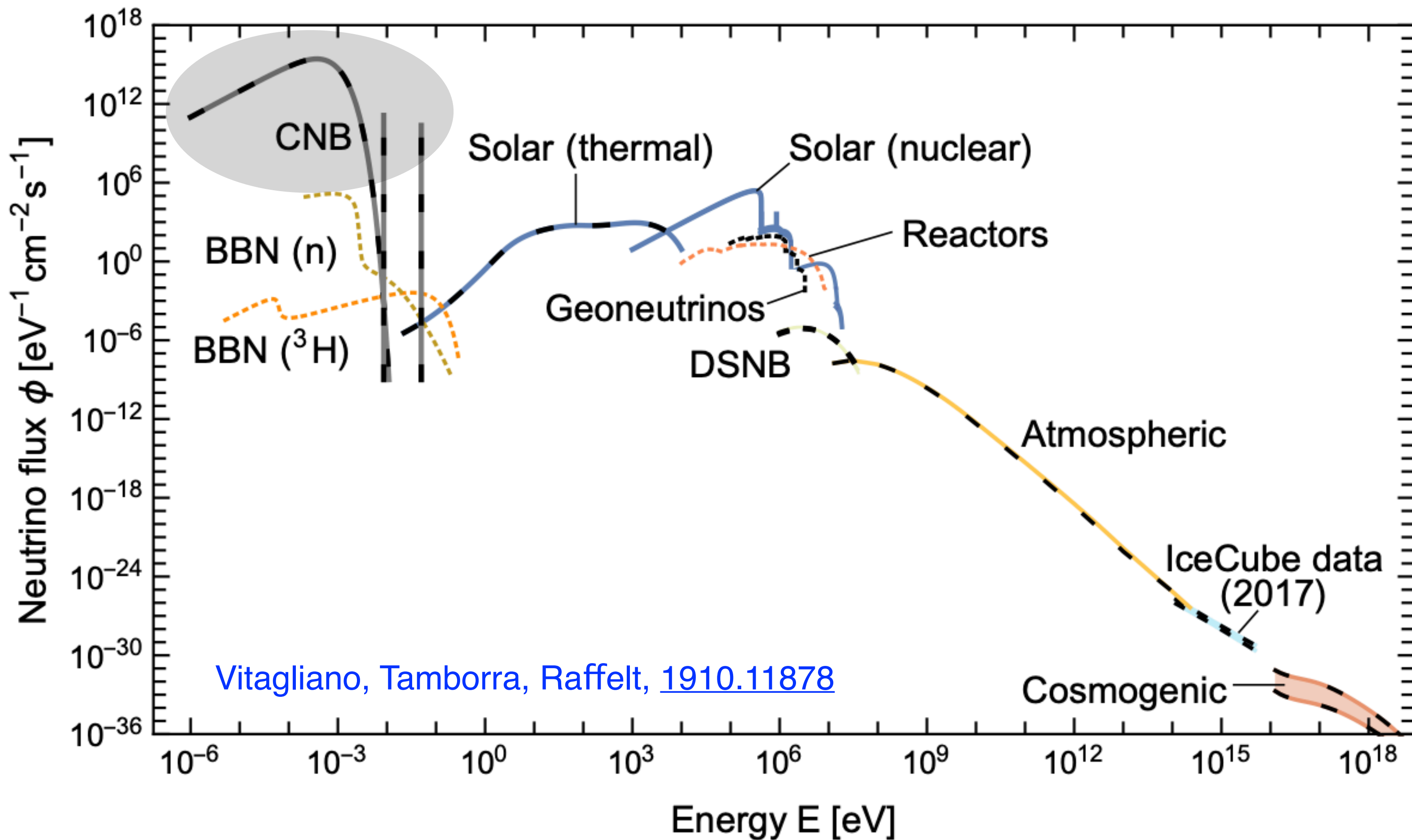
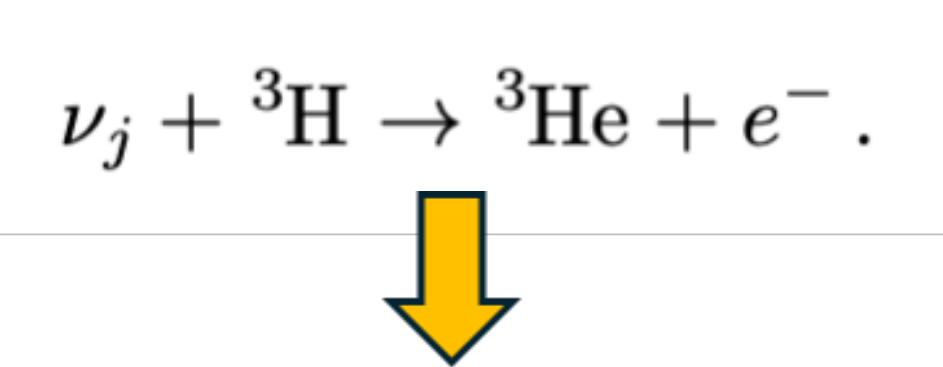
Vitagliano, Tamborra, Raffelt, [1910.11878](#)

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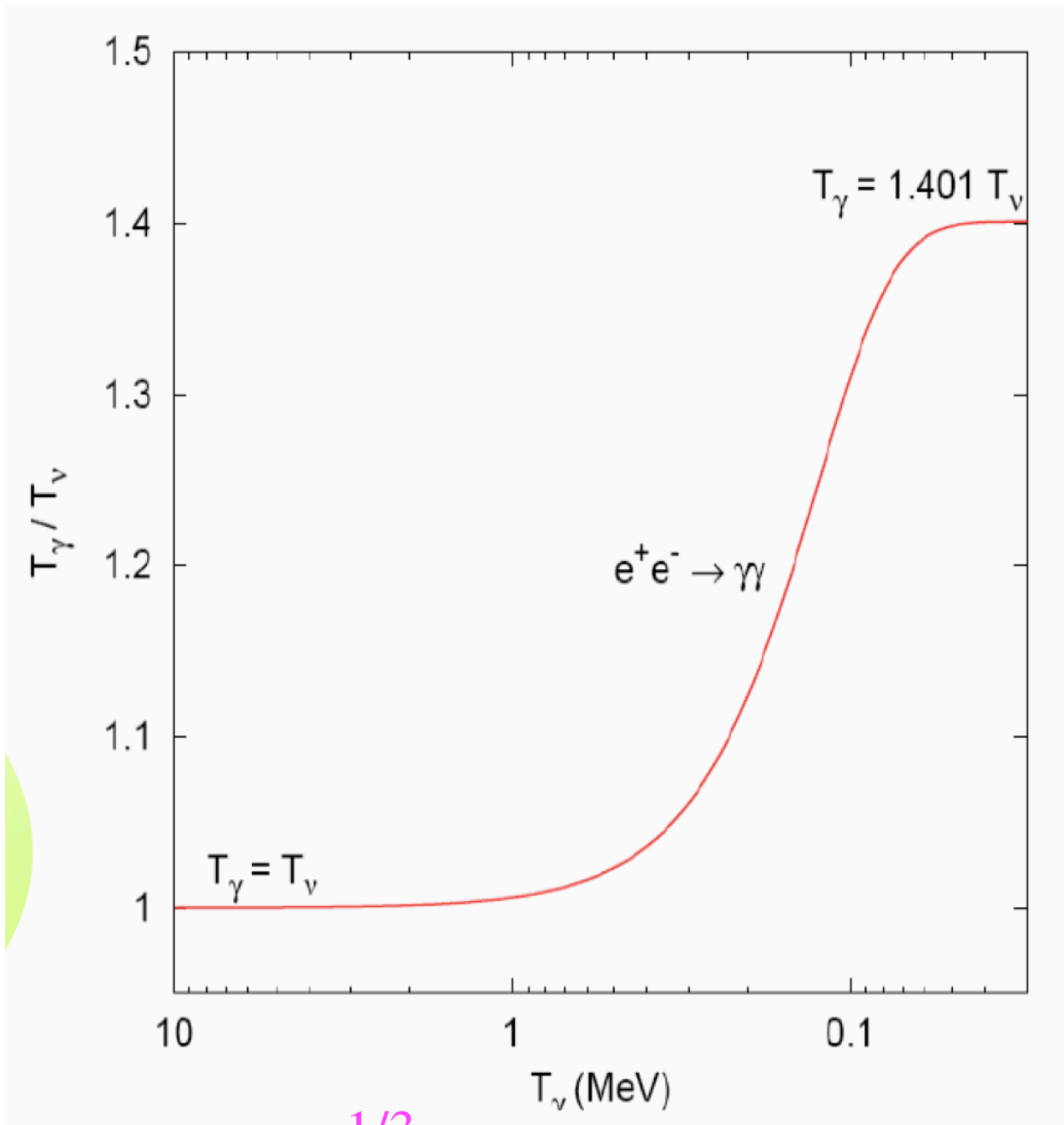
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(Non)relativistic Fermi gas



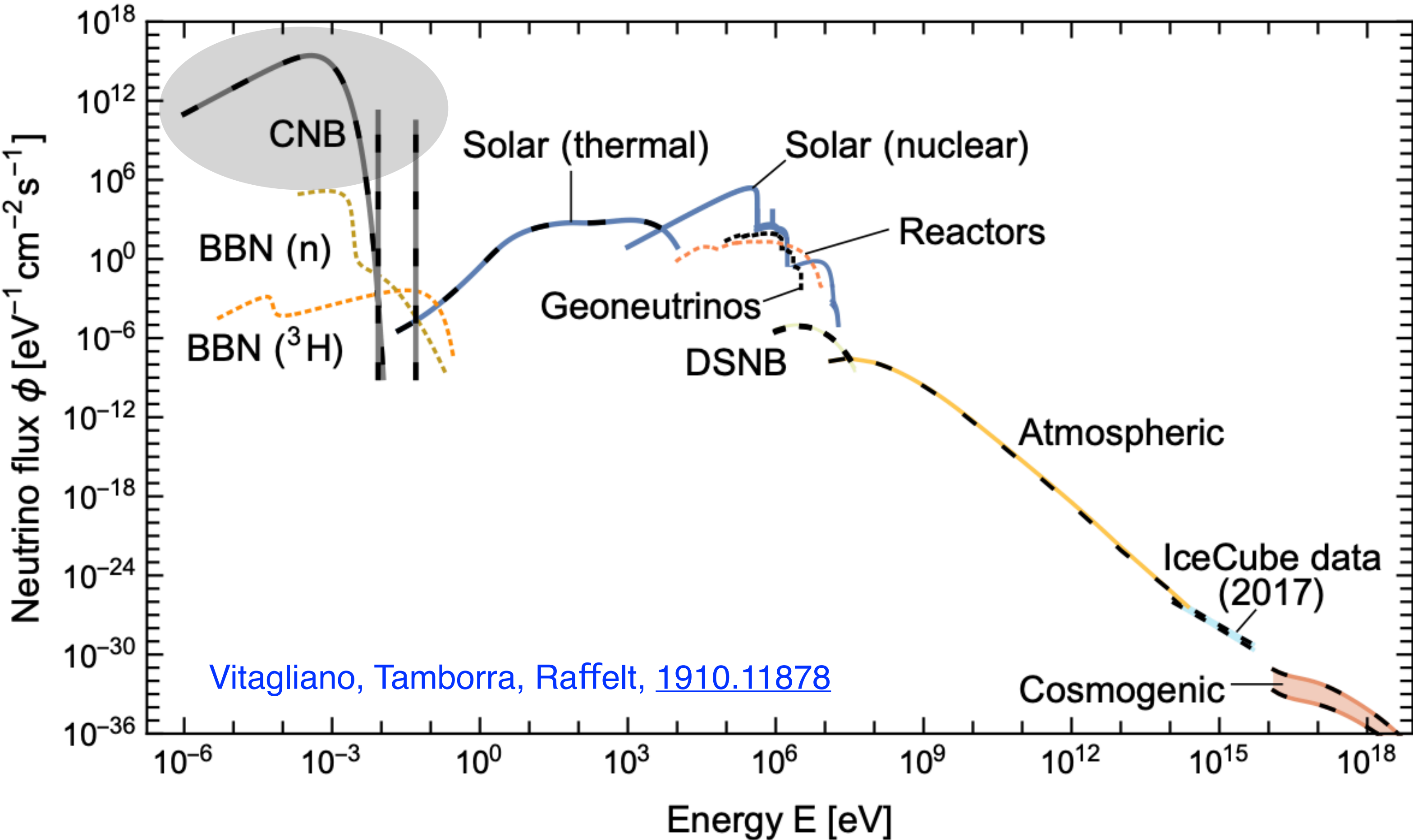
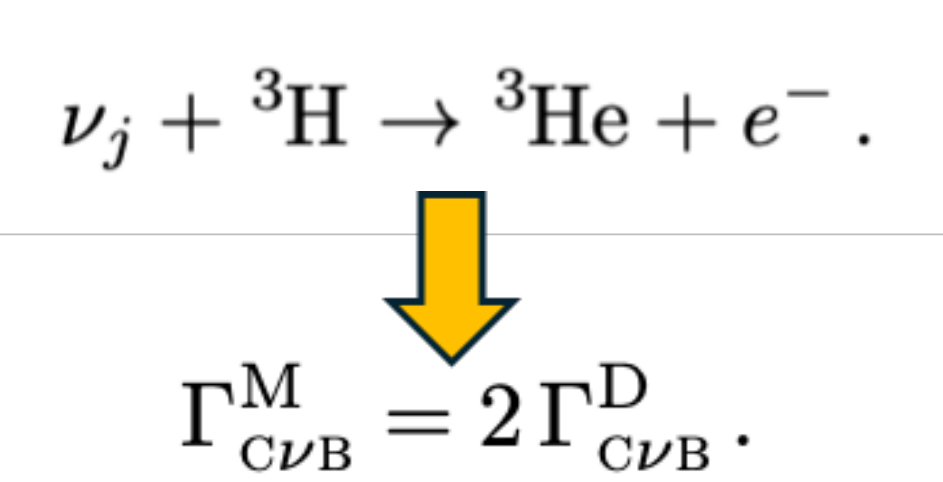
Vitagliano, Tamborra, Raffelt, [1910.11878](#)

Relic Neutrino Background

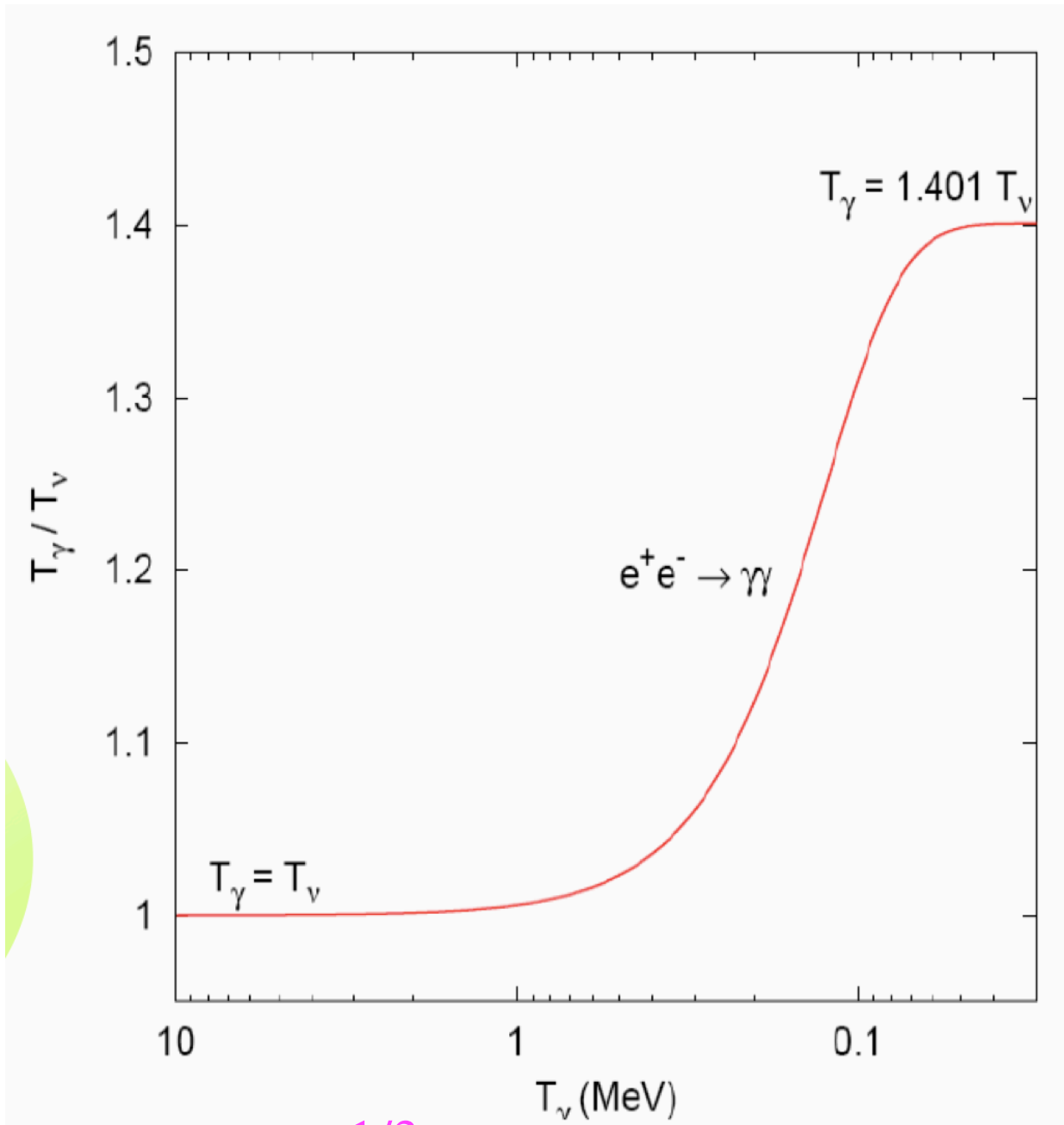


$$T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma,0} = 1.945 \text{ K} = 1.7 \times 10^{-4} \text{ eV}$$

(Non)relativistic Fermi gas

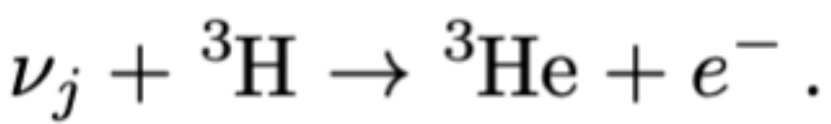


Relic Neutrino Background



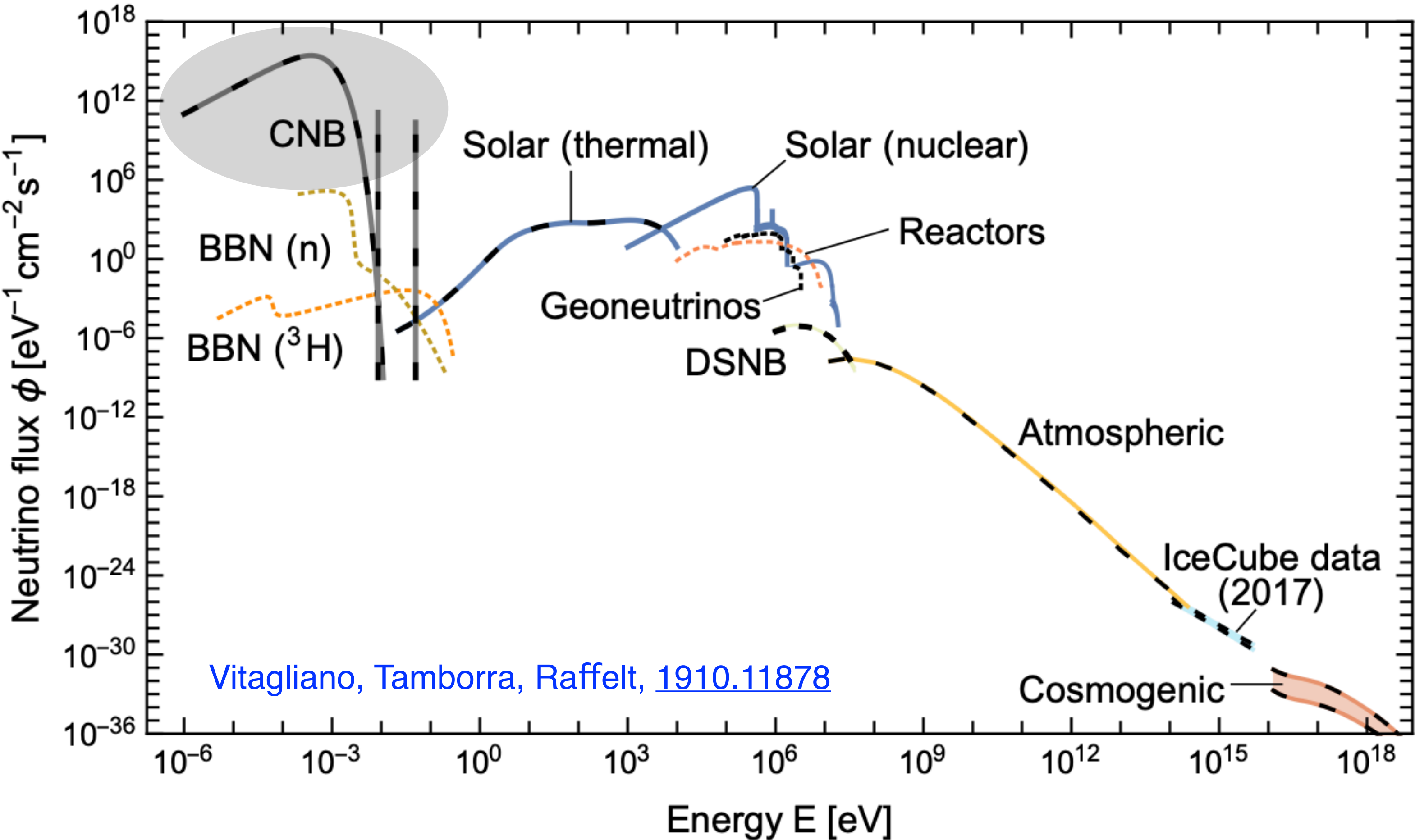
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(Non)relativistic Fermi gas



$$\Gamma_{C\nu B}^M = 2 \Gamma_{C\nu B}^D.$$

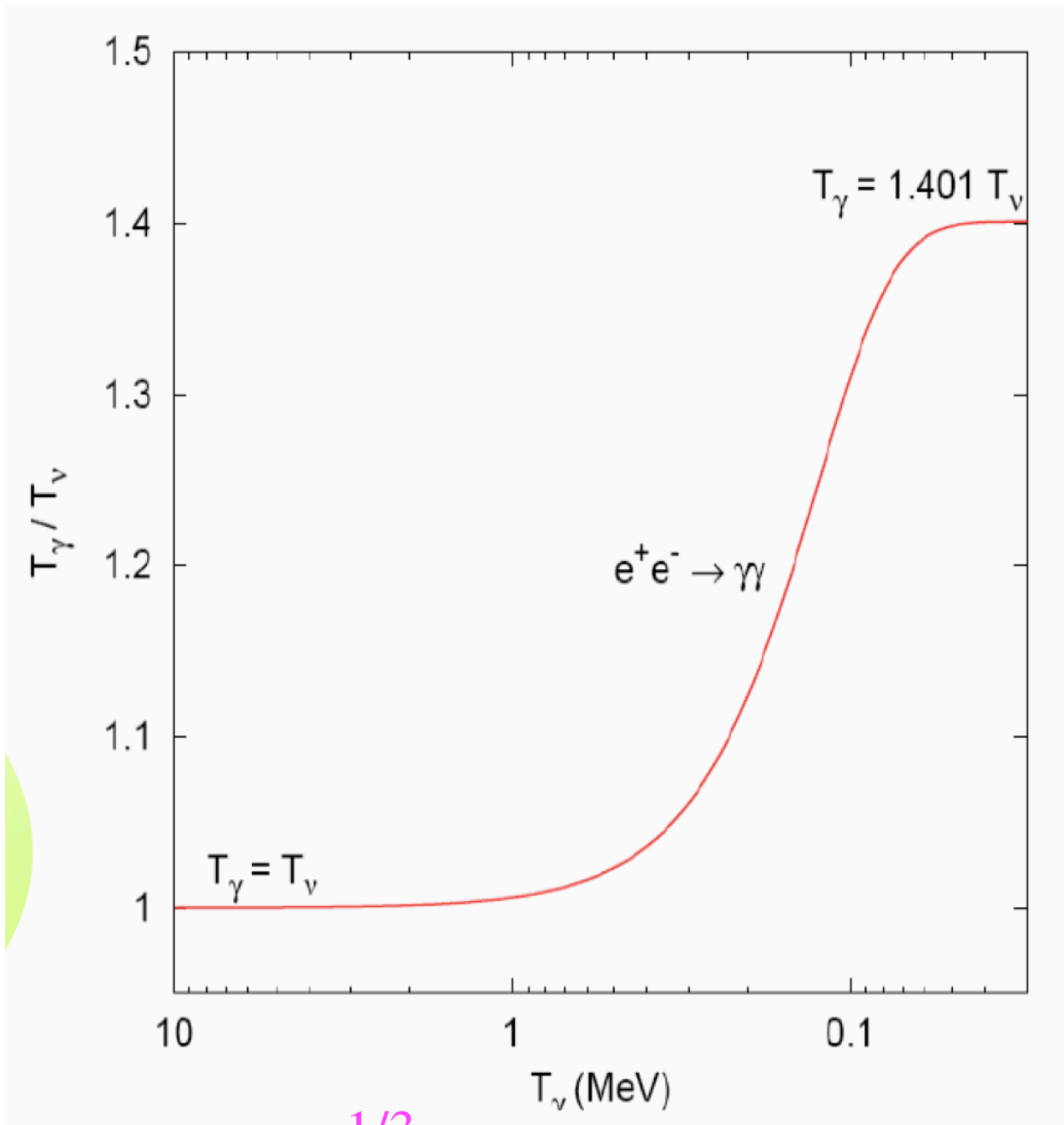
Long, Lunardini, Sabancilar, [1405.7654](#)
PTOLEMY, [1902.05508](#)



Vitagliano, Tamborra, Raffelt, [1910.11878](#)

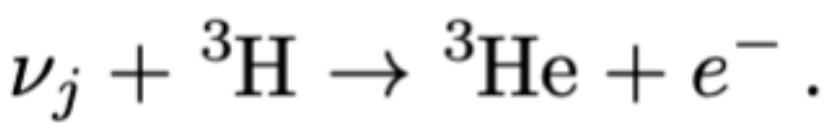


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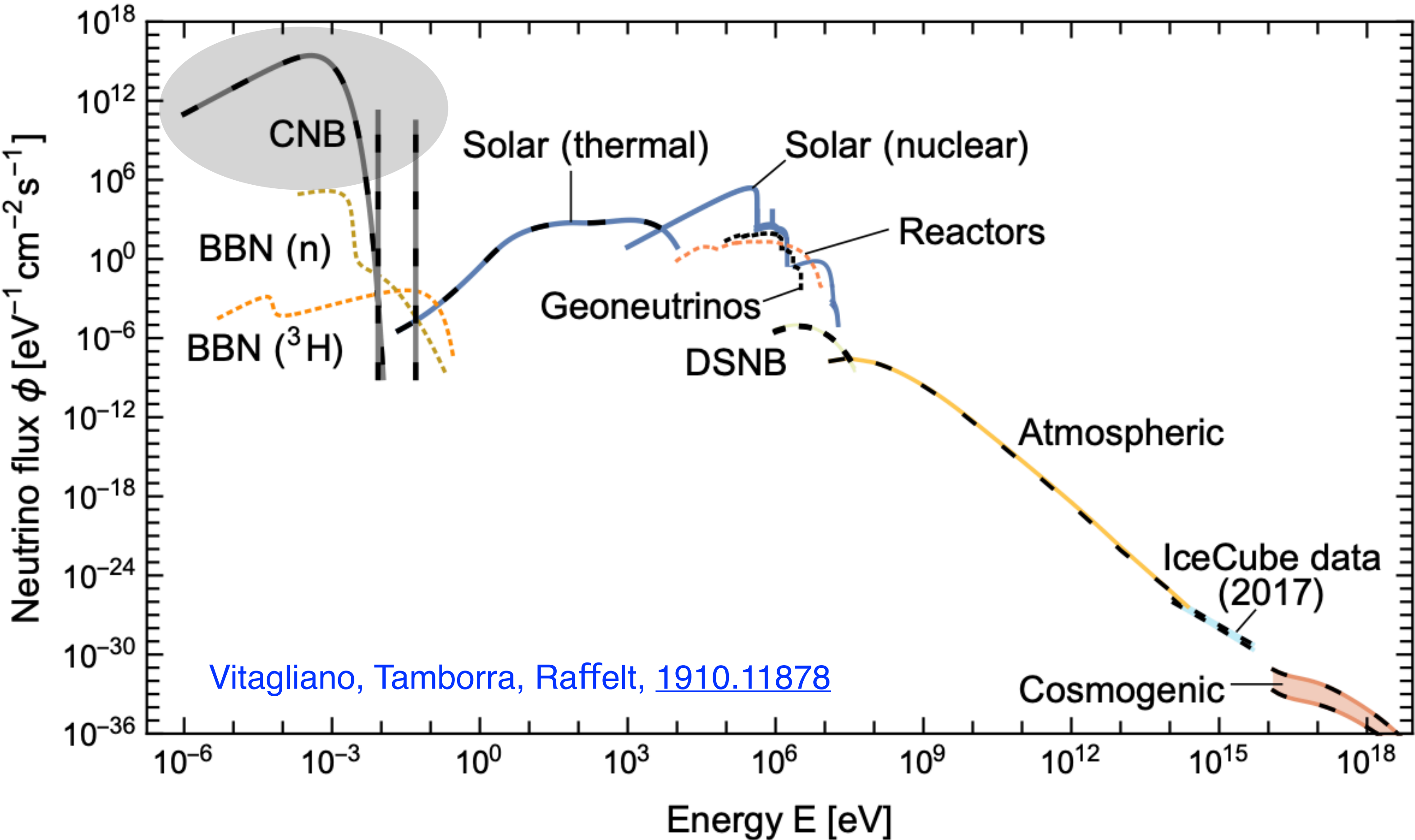
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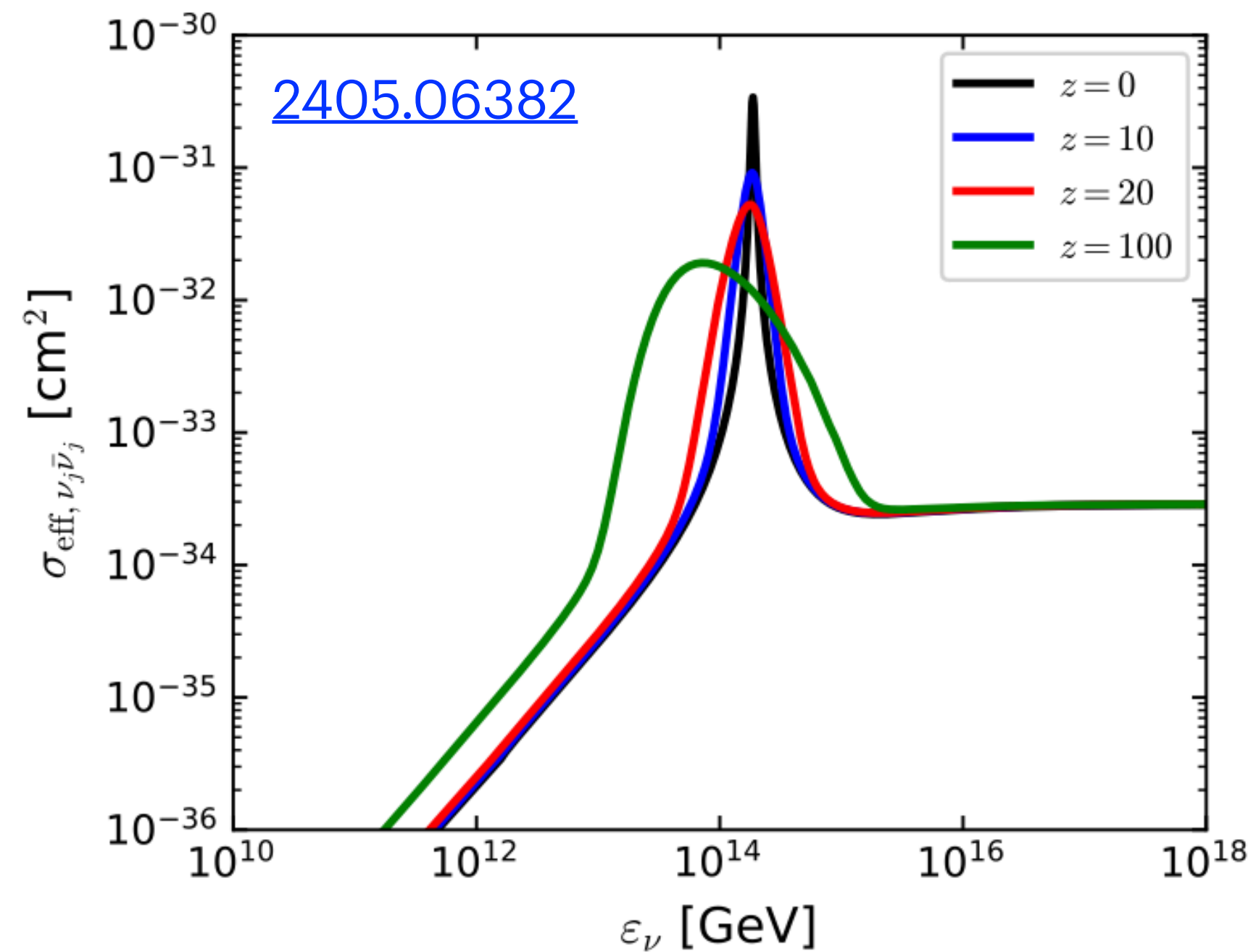
Direct detection of CνB could (in principle) answer the Dirac vs. Majorana question.

Long, Lunardini, Sabancilar, [1405.7654](#)
PTOLEMY, [1902.05508](#)



Interlude: Indirect Detection of $C\nu B$

Weiler (PRL '82) **Z-burst:** $\nu_{\text{UHE}} \bar{\nu}_{\text{relic}} \rightarrow Z \rightarrow f\bar{f}$

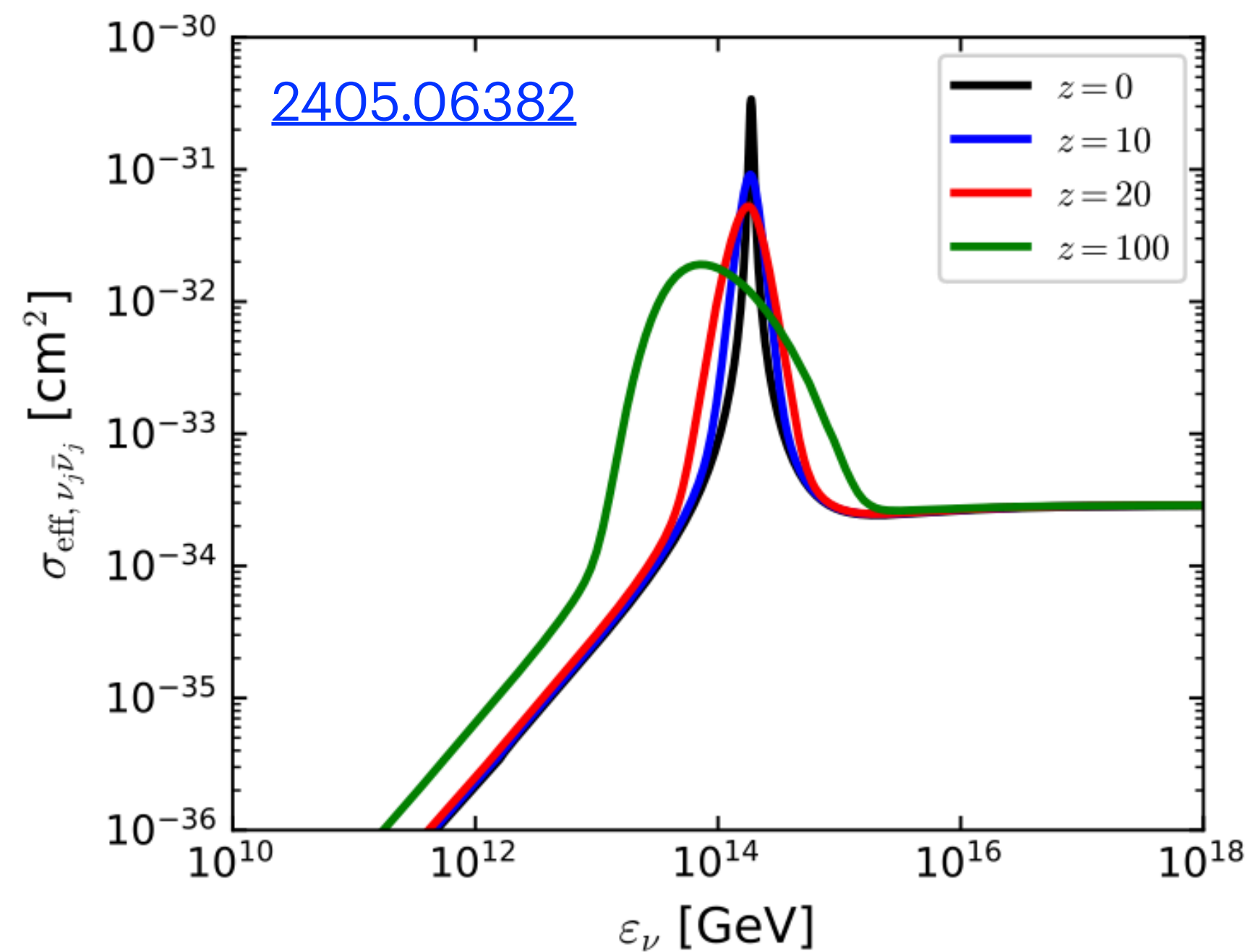


$$E_\nu^{\text{res}} = \frac{m_Z^2}{2m_\nu(1+z)} = \frac{(4.2 \times 10^{22} \text{ eV})}{(1+z)} \left(\frac{0.1 \text{ eV}}{m_\nu} \right)$$

Beyond the GZK cut-off!

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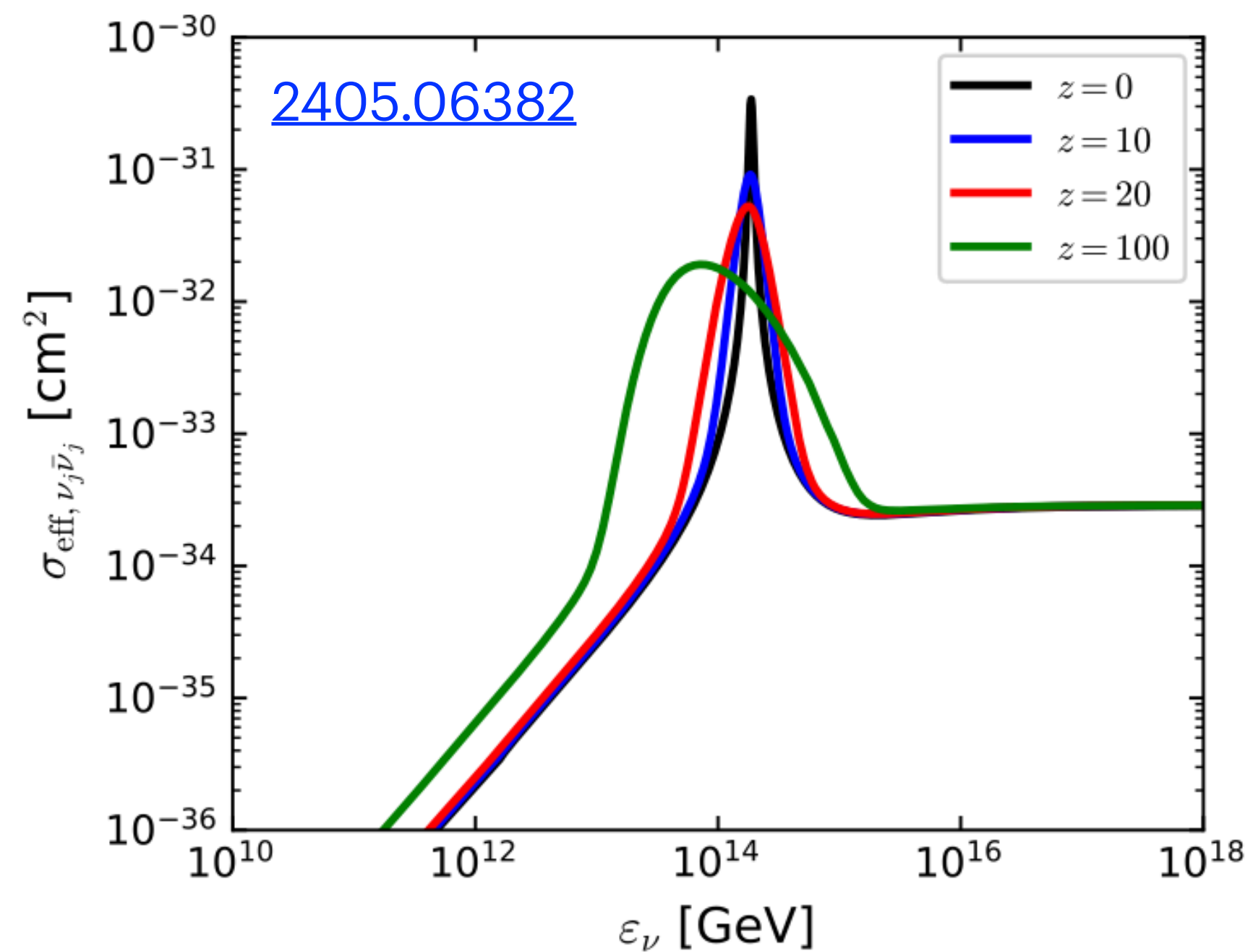
Beyond the GZK cut-off!

Possible in presence of new (BSM) source of UHE neutrinos, e.g.
heavy dark matter decay: [Maitra, Suliga, Brdar, BD, 2508.21034](#)

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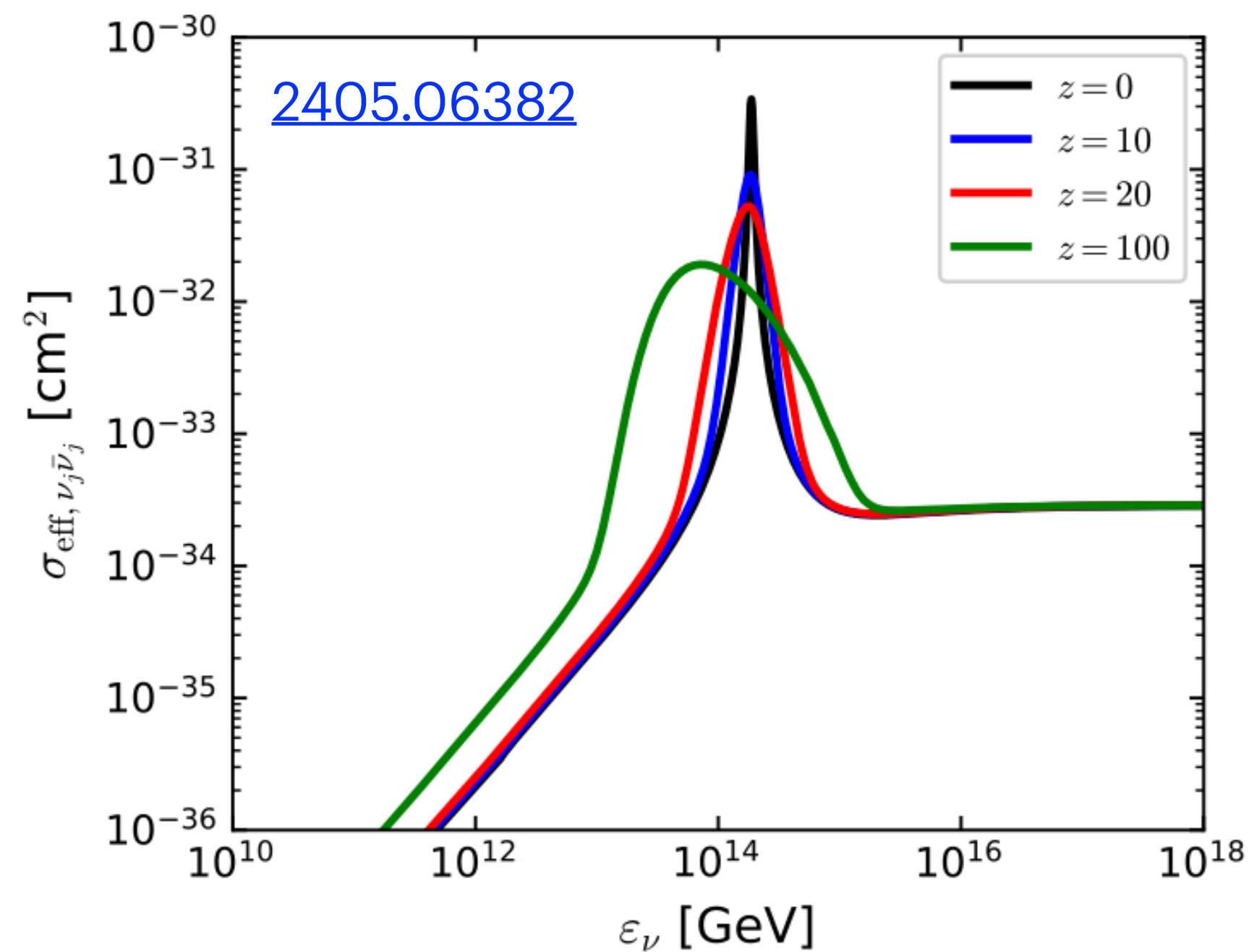


Paschos, Lalakulich, [0206273](#);

BD, Soni, [2112.01424](#);

Brdar, BD, Plestid, Soni, [2207.02860](#)

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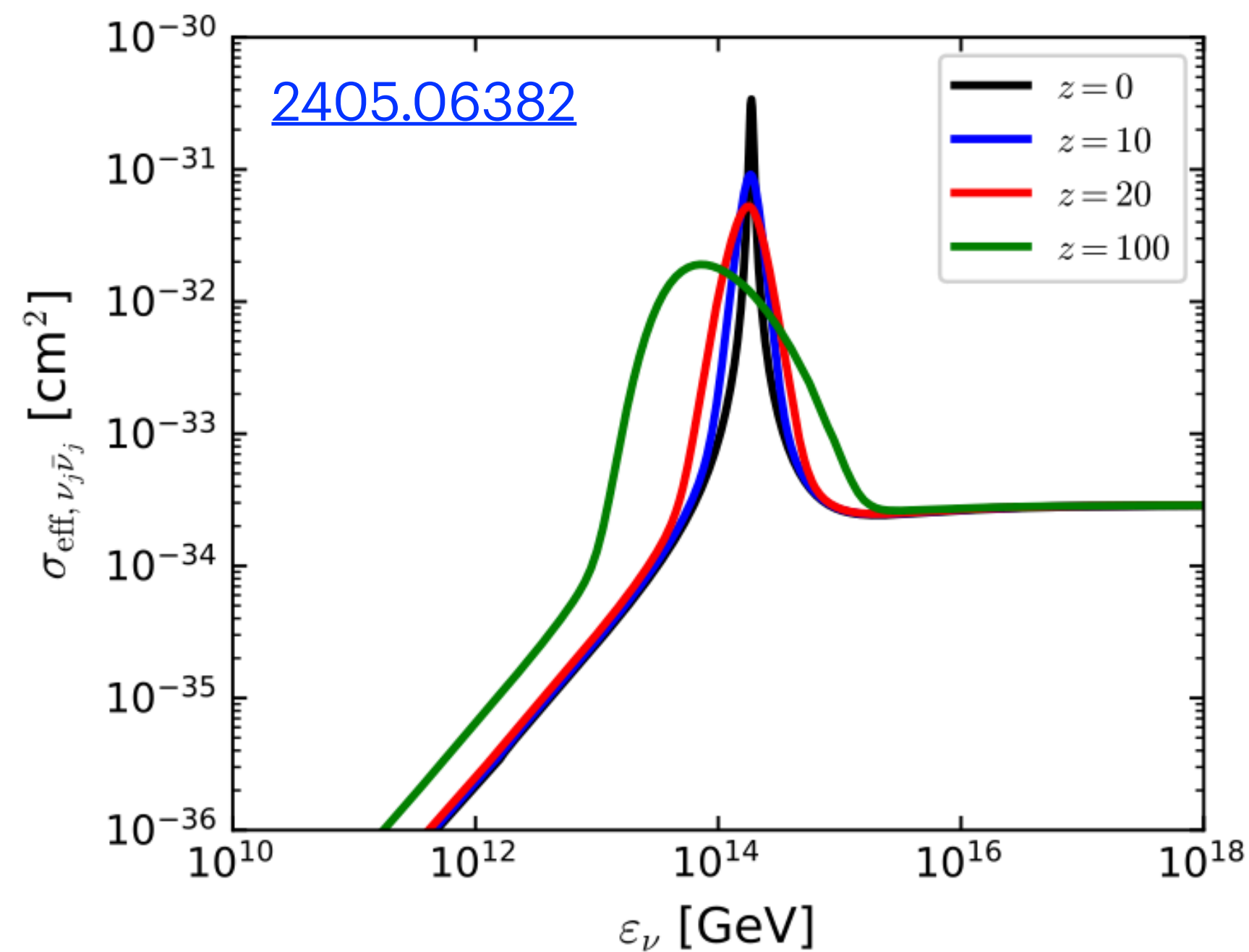
Paschos, Lalakulich, [0206273](#);

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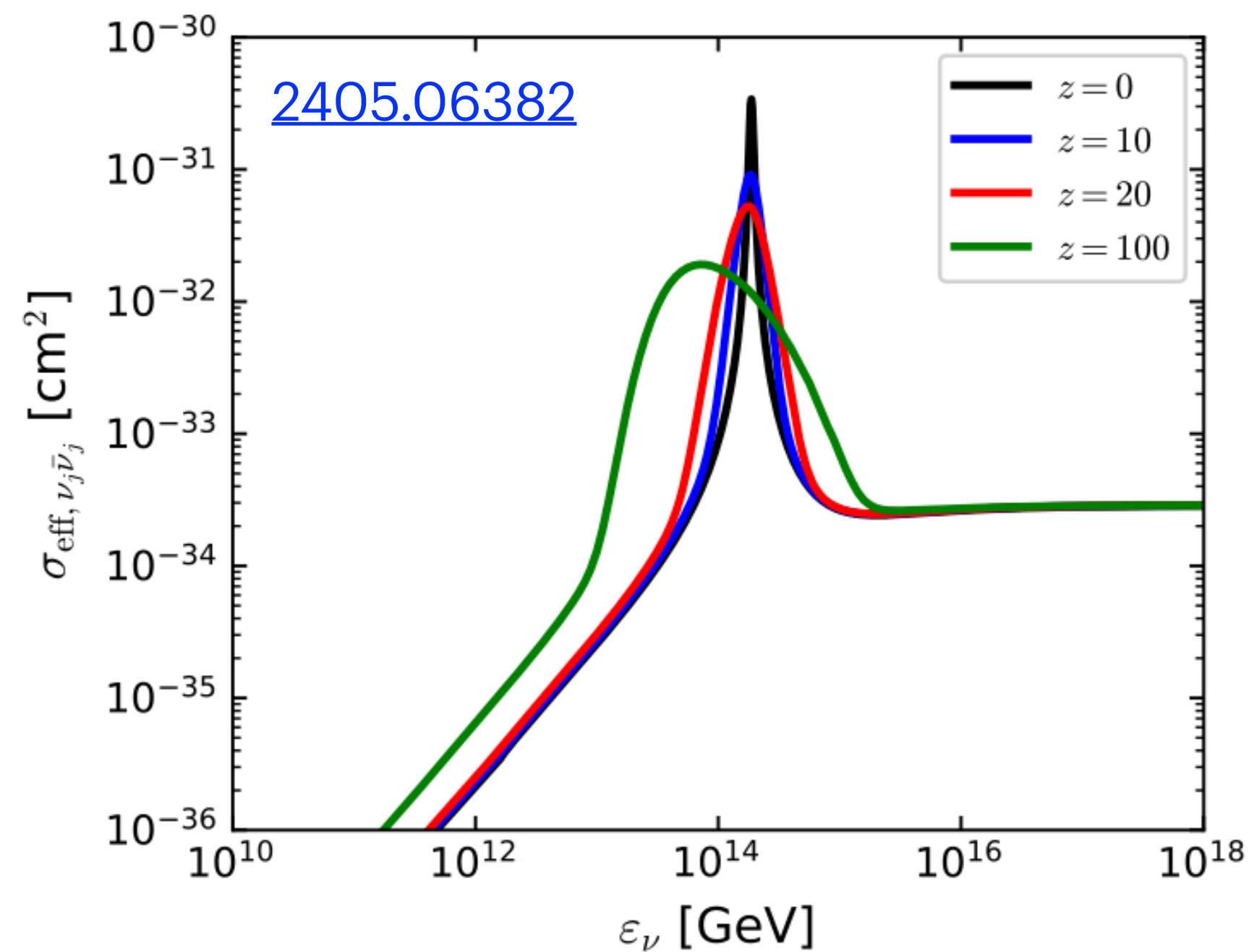


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Vector Meson Resonance:

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Interlude: Indirect Detection of $C\nu B$

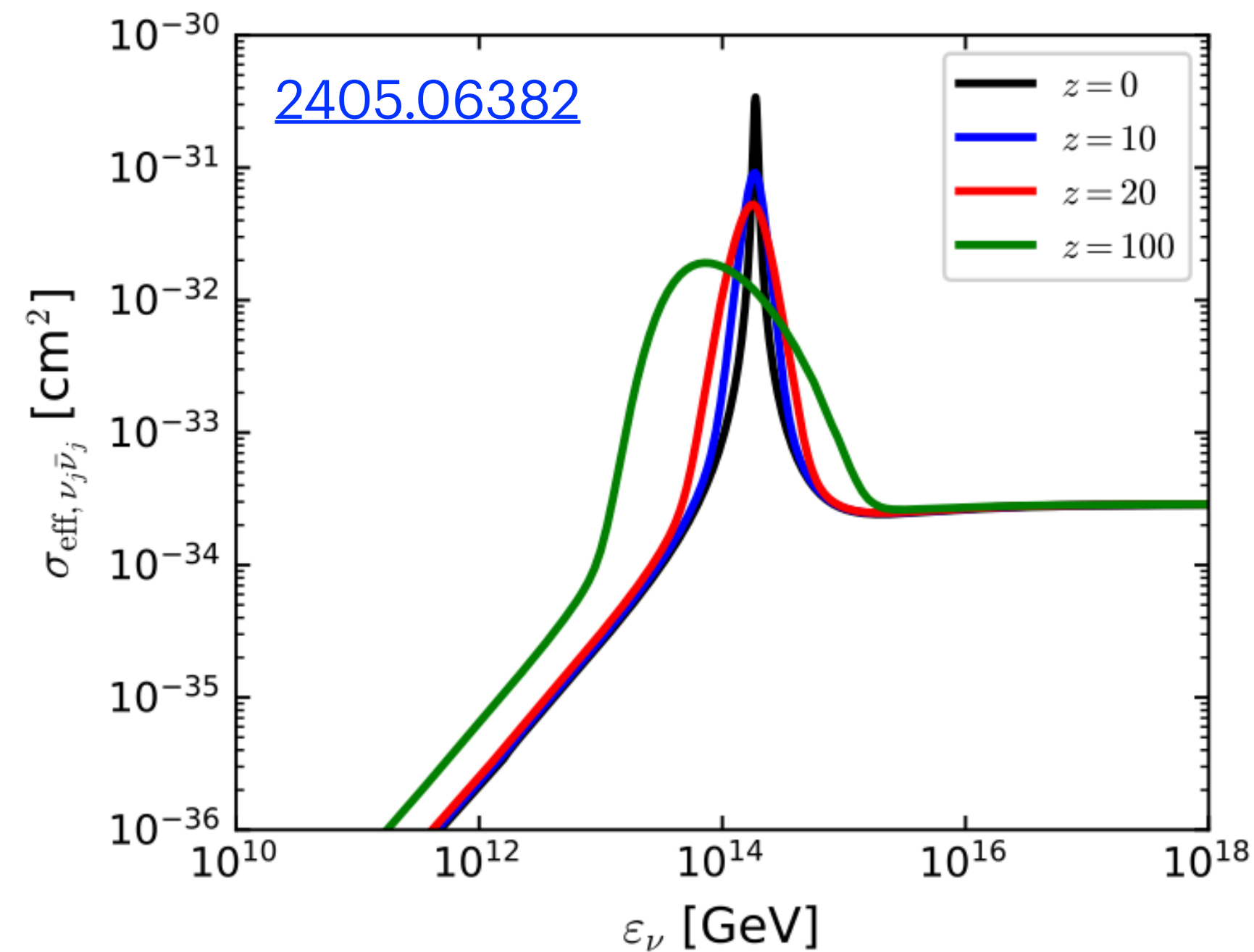
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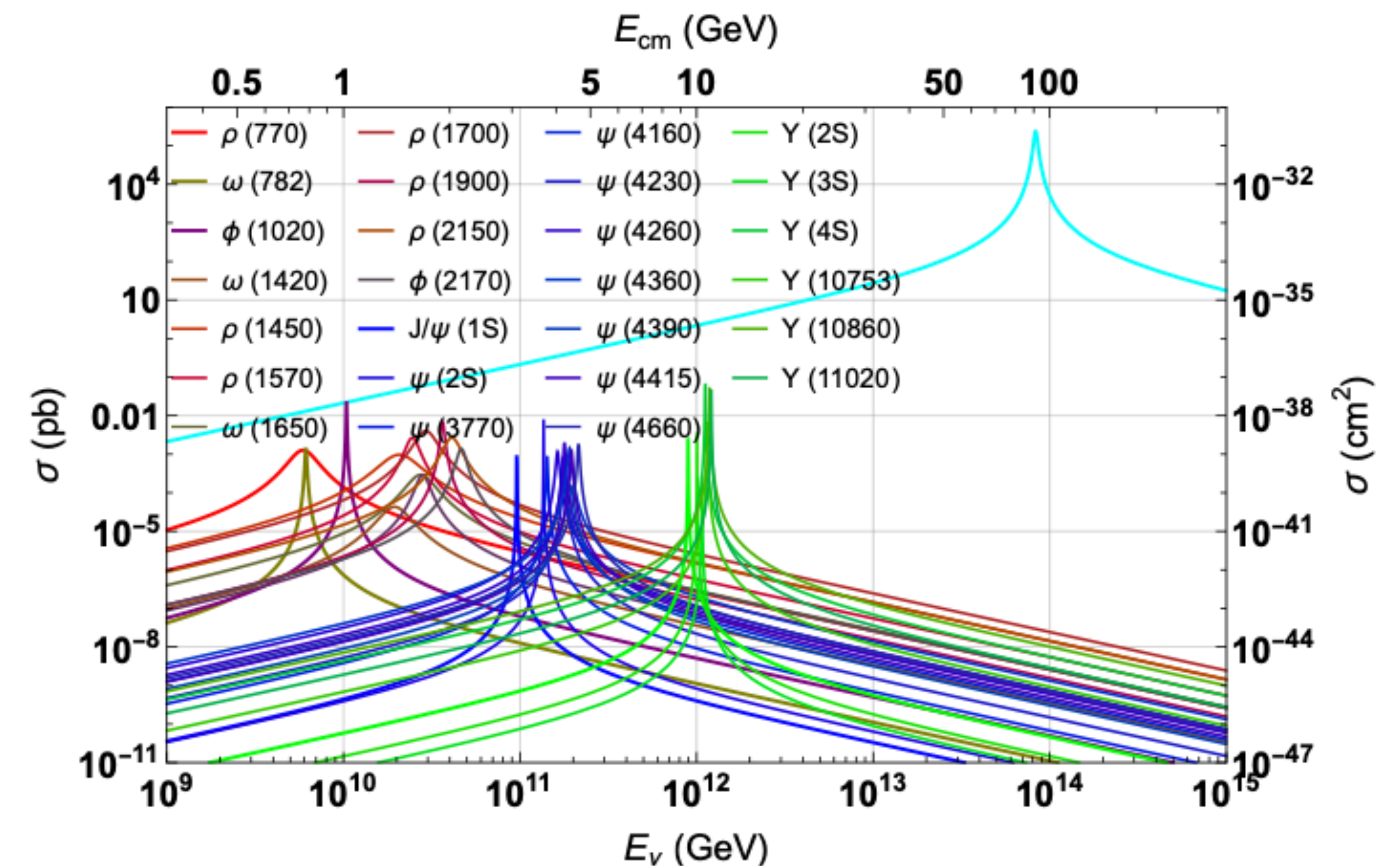
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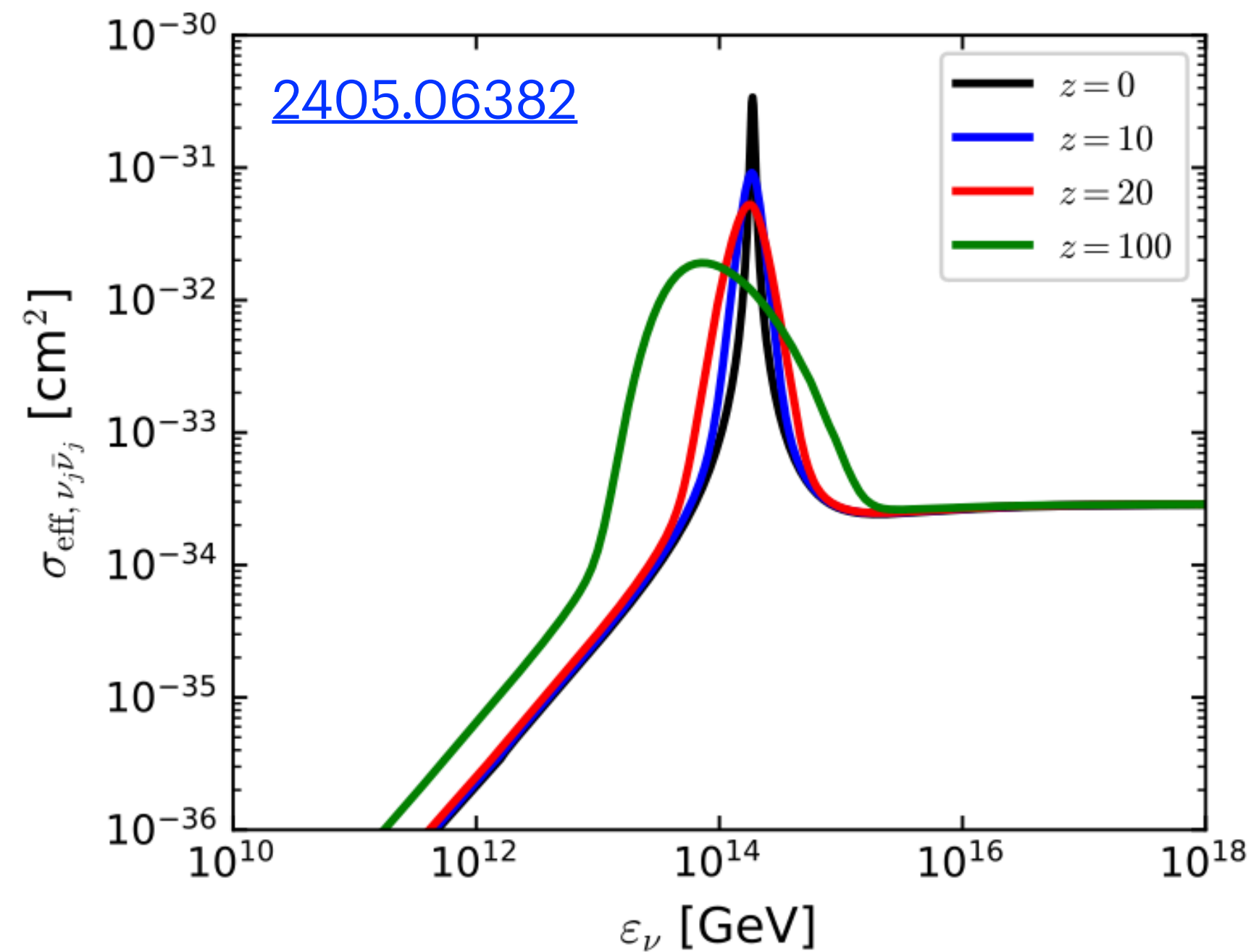
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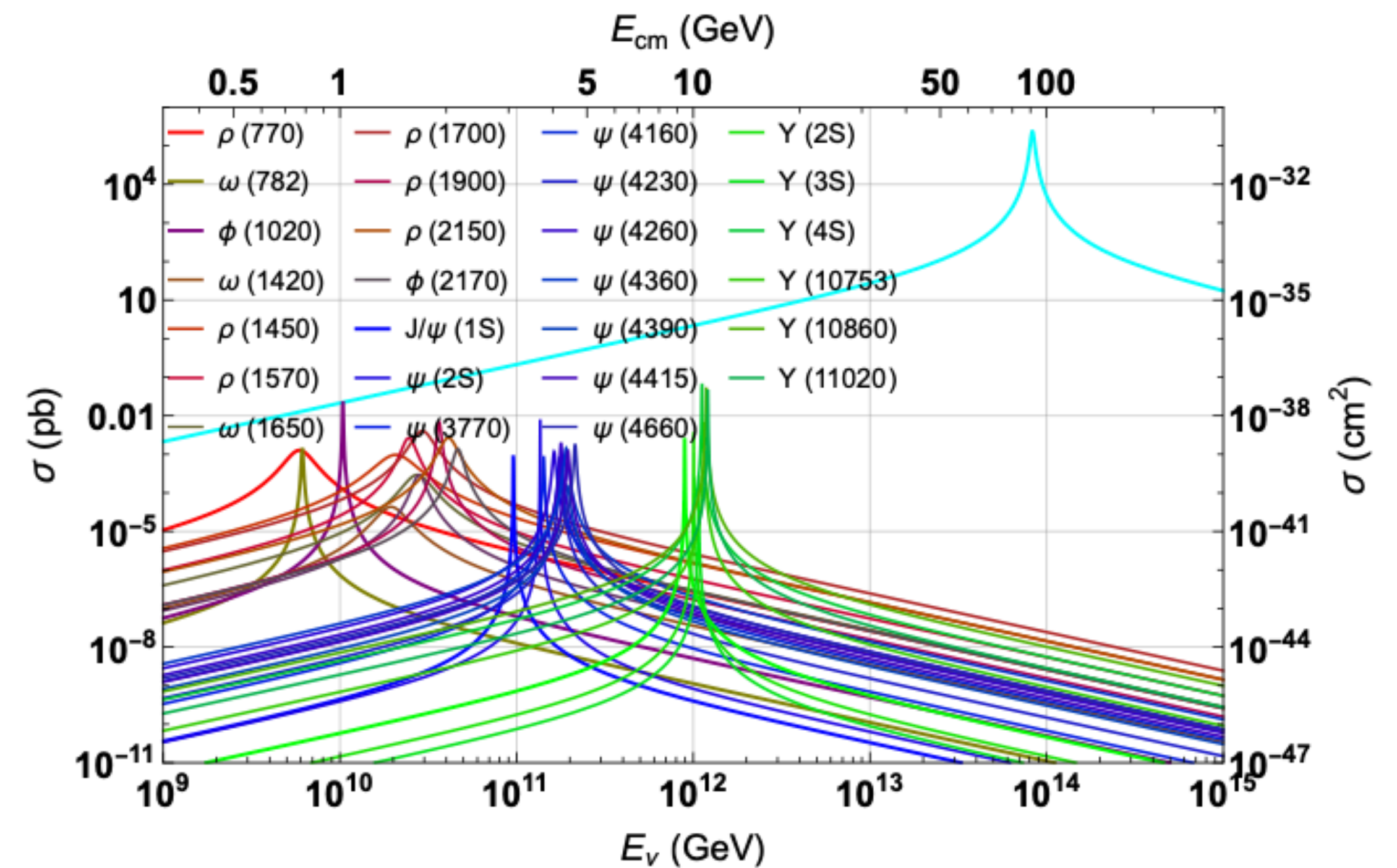
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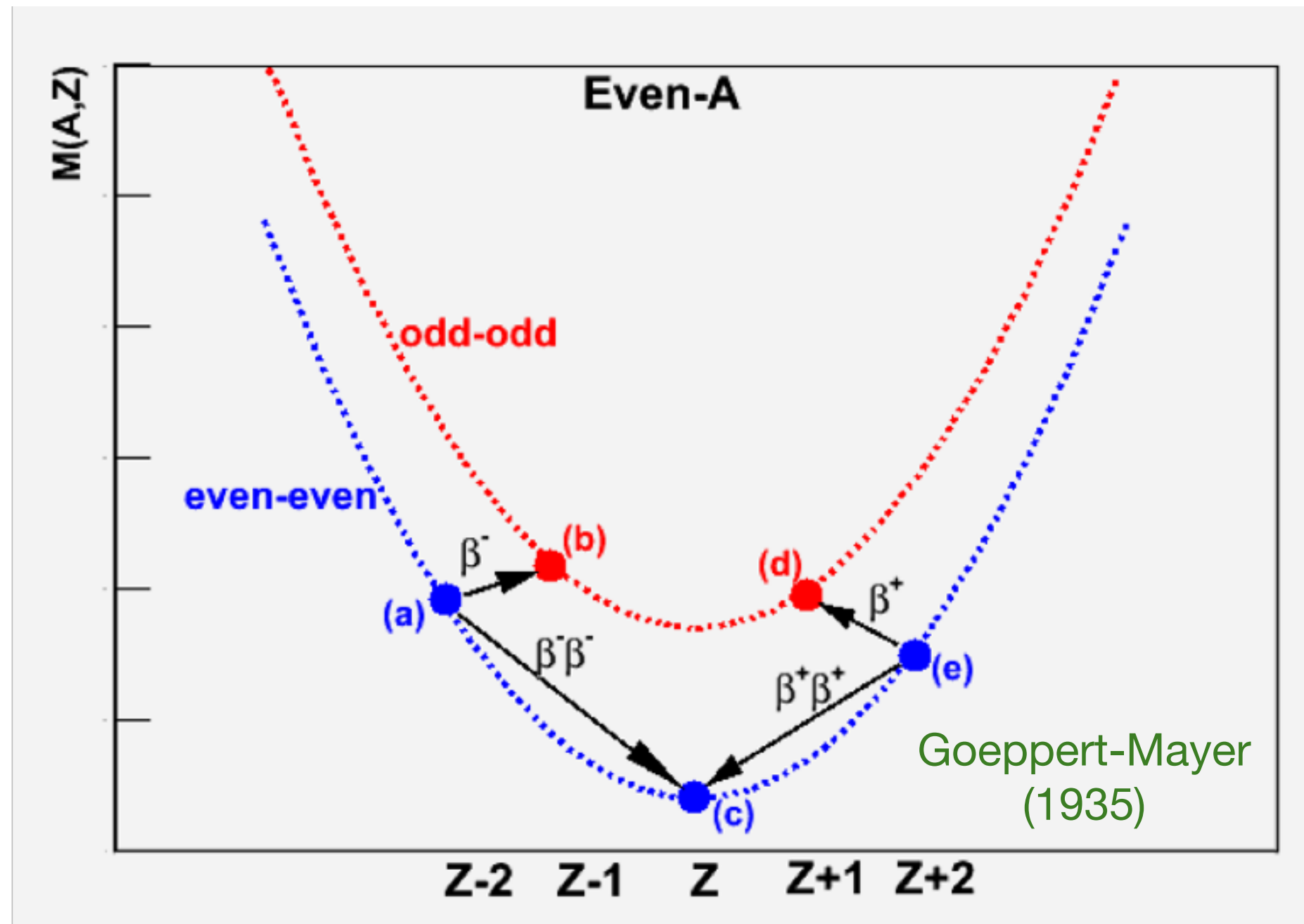
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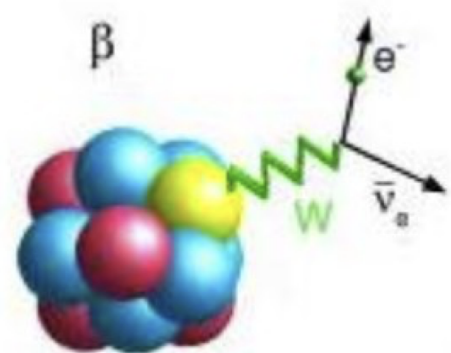


$$E_{\nu}^{\text{res}} = \frac{m_{\rho}^2}{2m_{\nu}(1+z)} = \frac{(3.0 \times 10^{18} \text{ eV})}{(1+z)} \left(\frac{0.1 \text{ eV}}{m_{\nu}} \right)$$

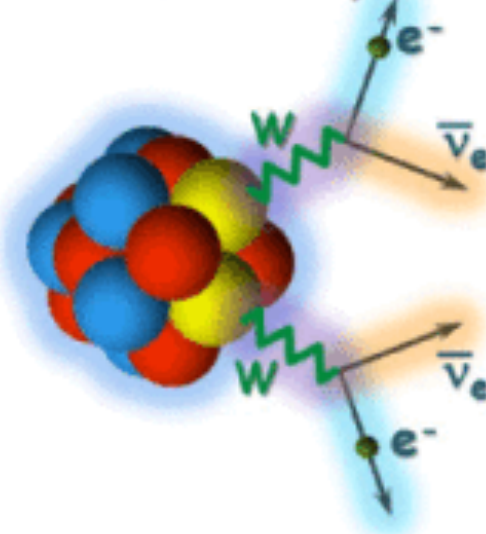
'Smoking Gun' Signal of Majorana Neutrinos



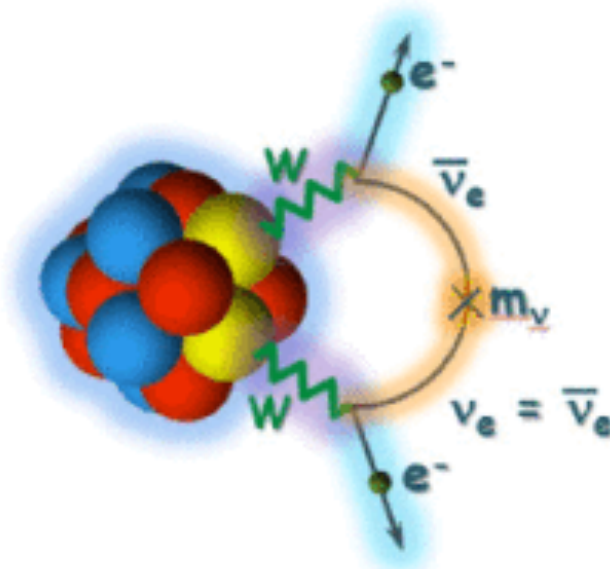
Racah (1937); Furry (1939);
Schechter, Valle (1982)



[Double beta decay]



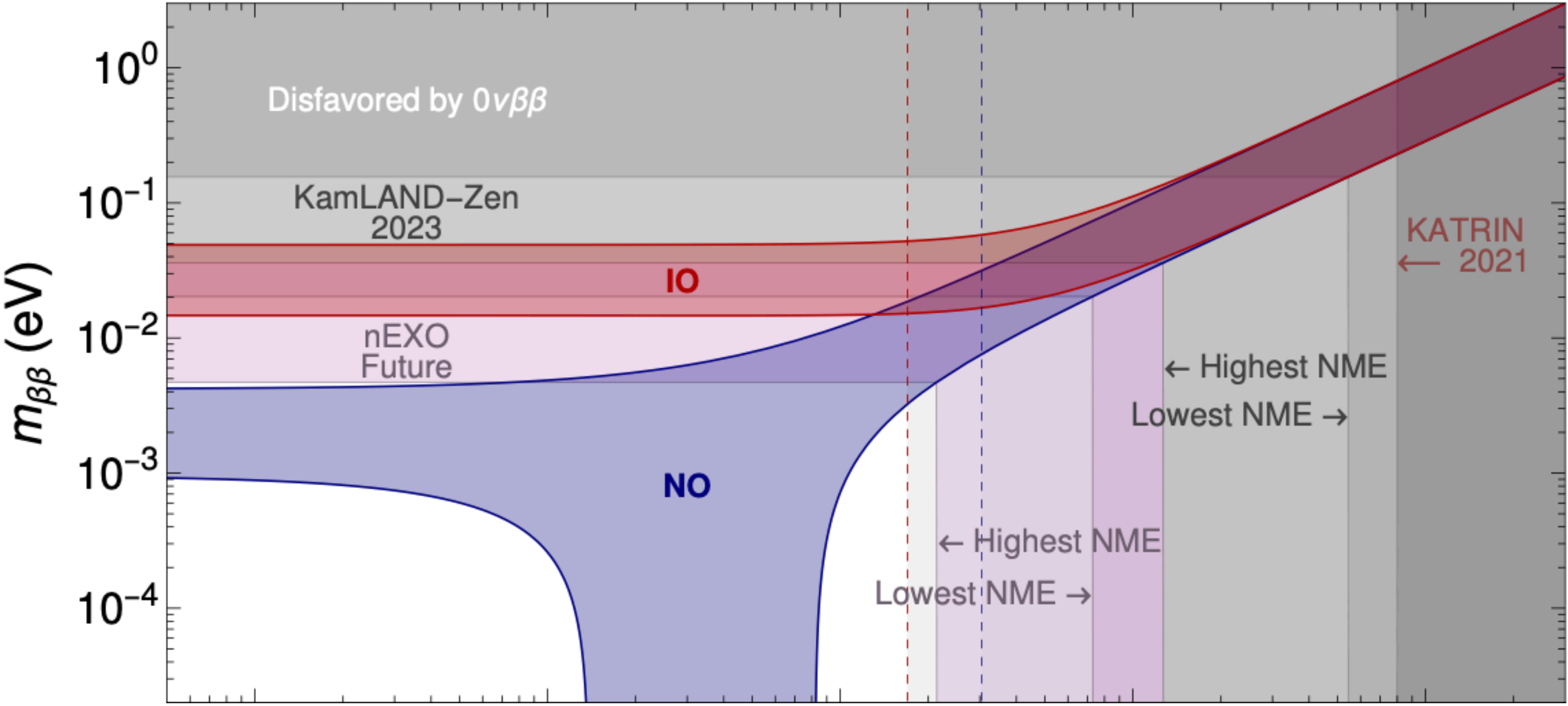
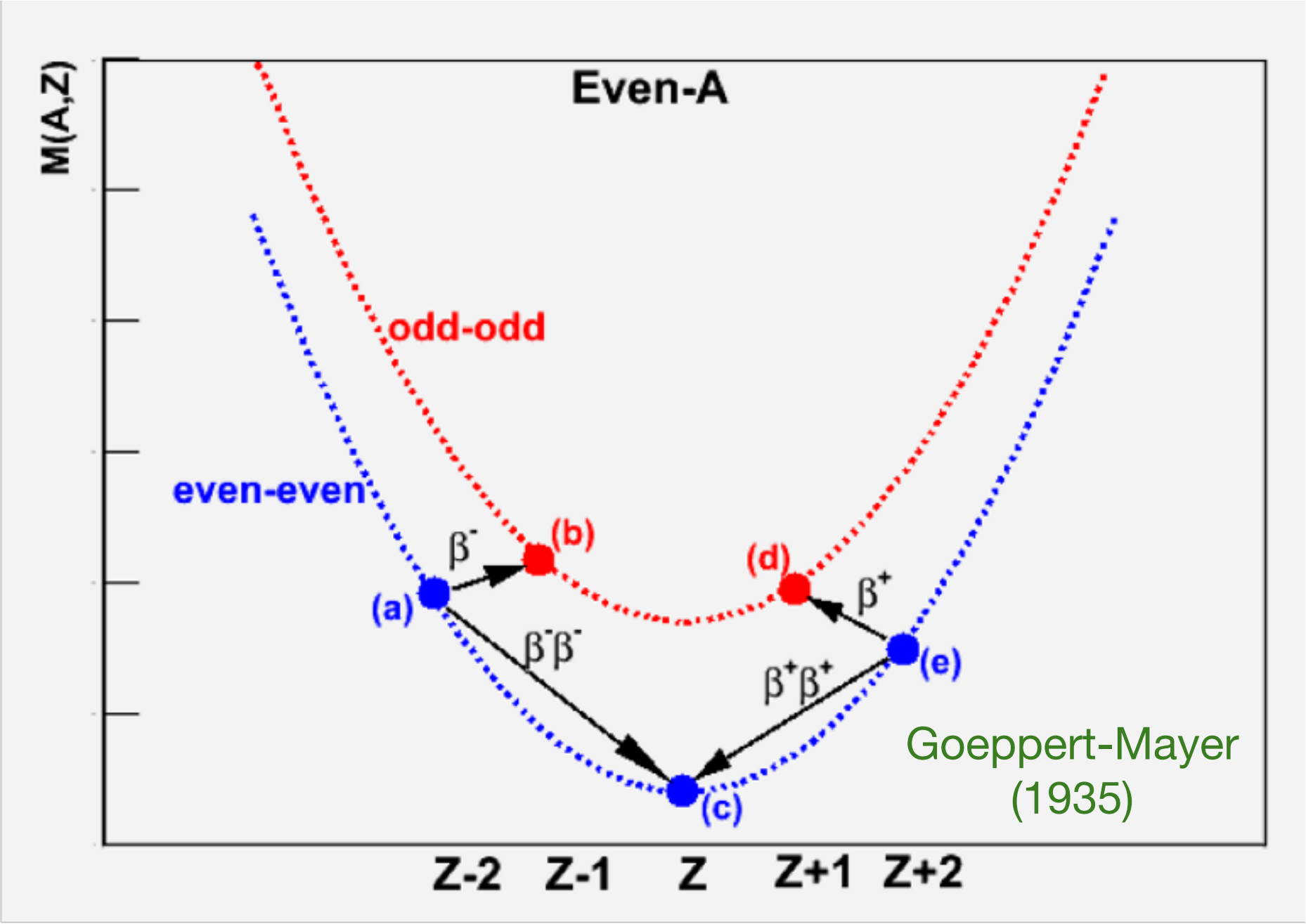
Double beta decay
which emits anti-neutrinos



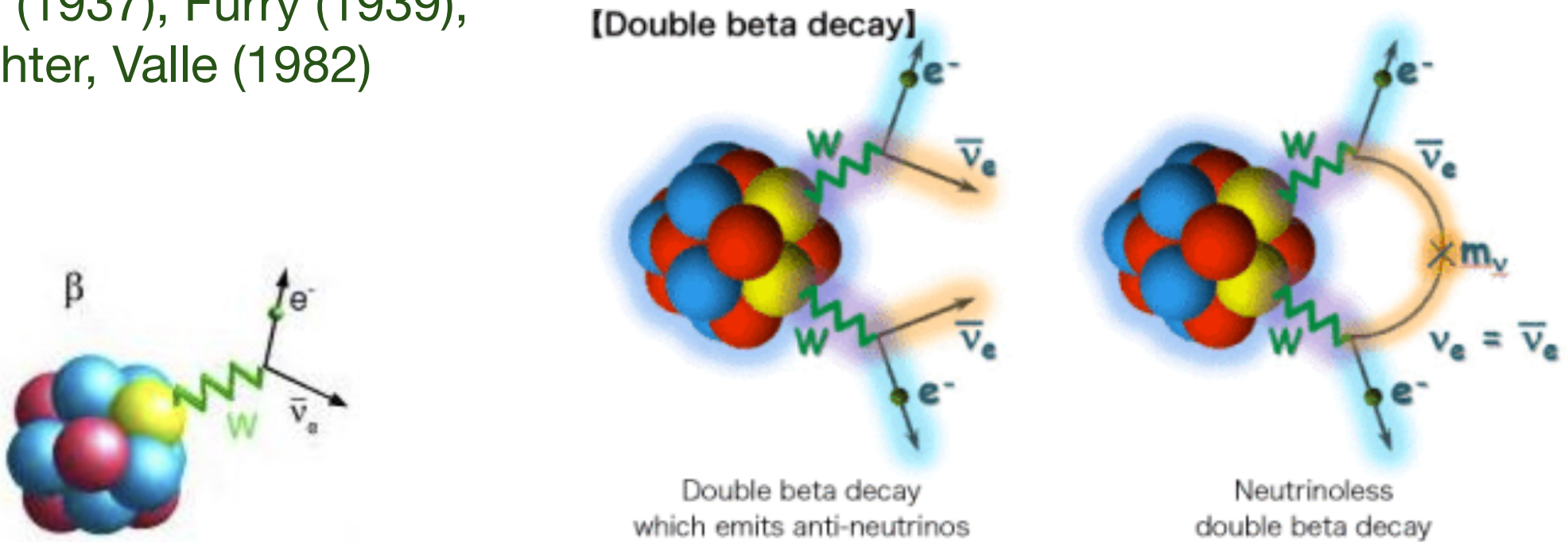
Neutrinoless
double beta decay

Experimentally feasible in about 10 nuclei.

'Smoking Gun' Signal of Majorana Neutrinos



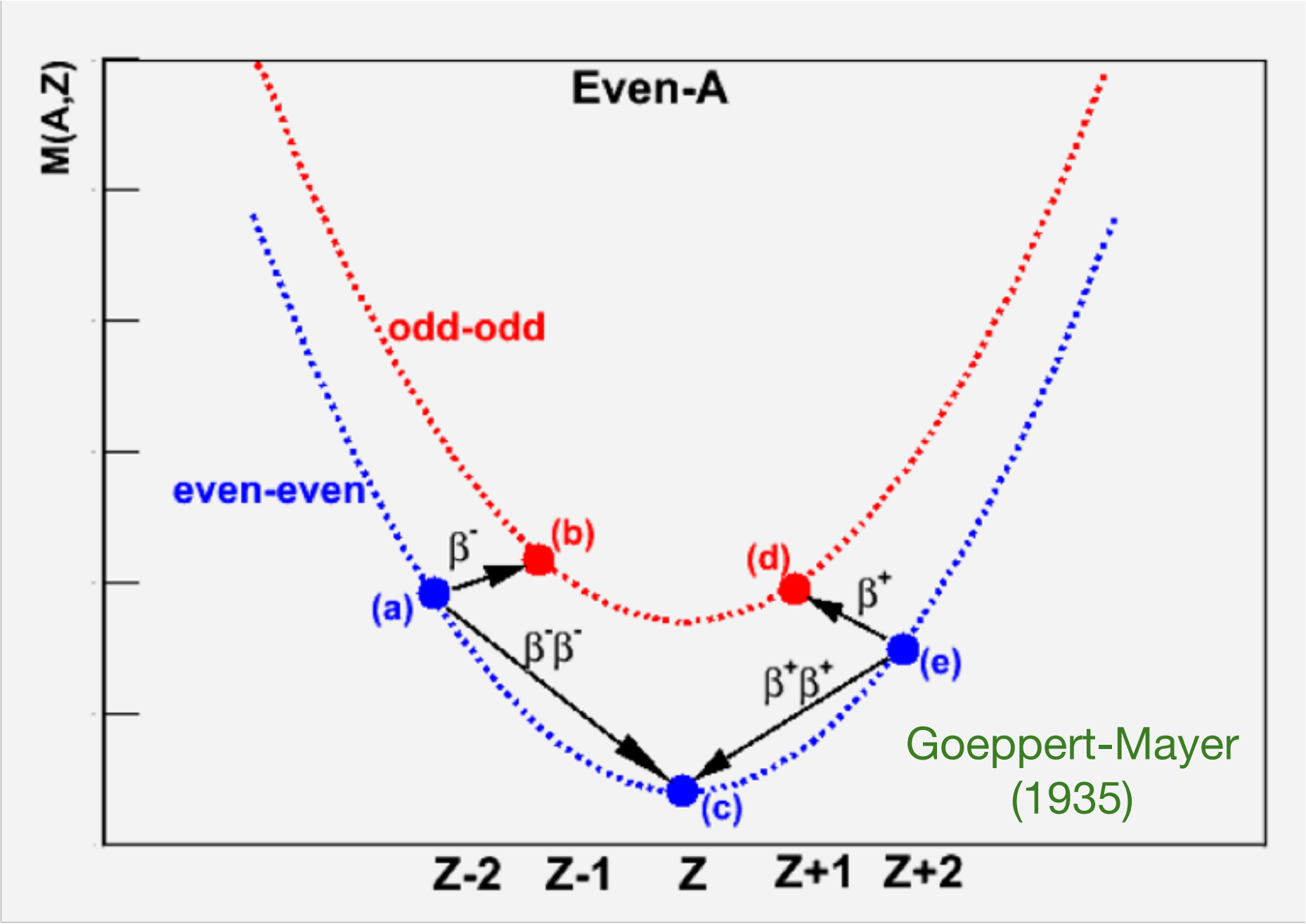
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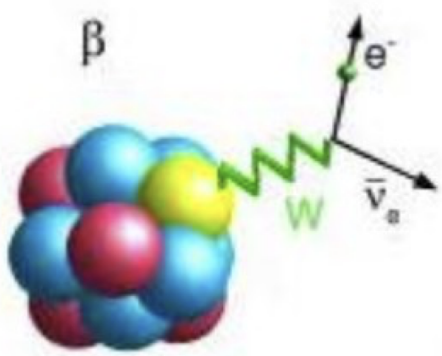
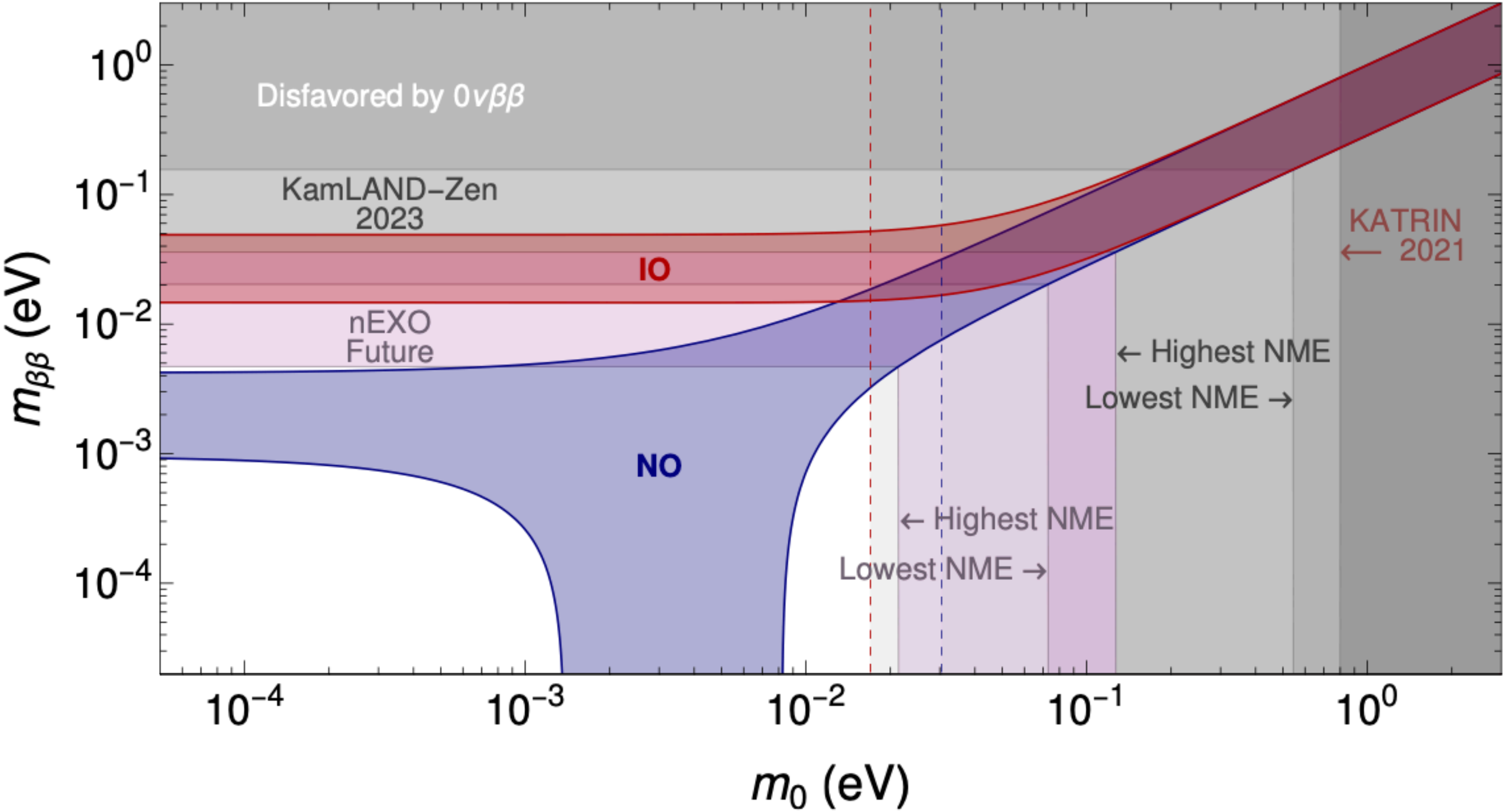
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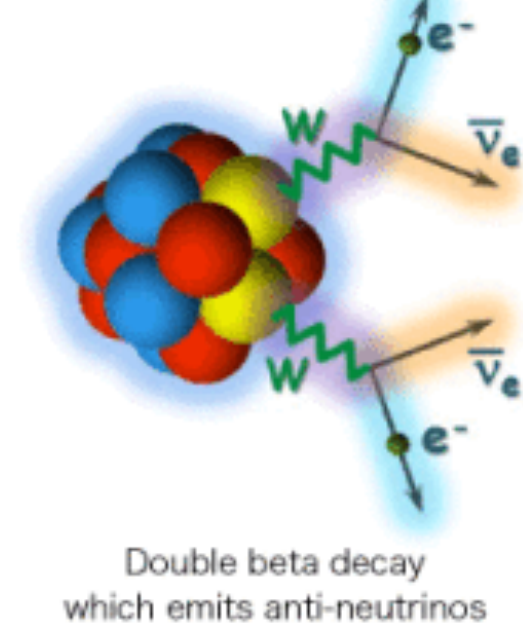
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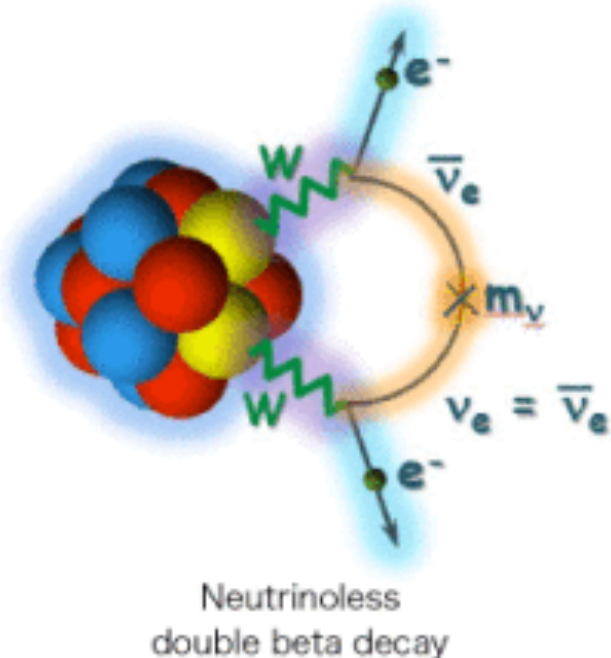
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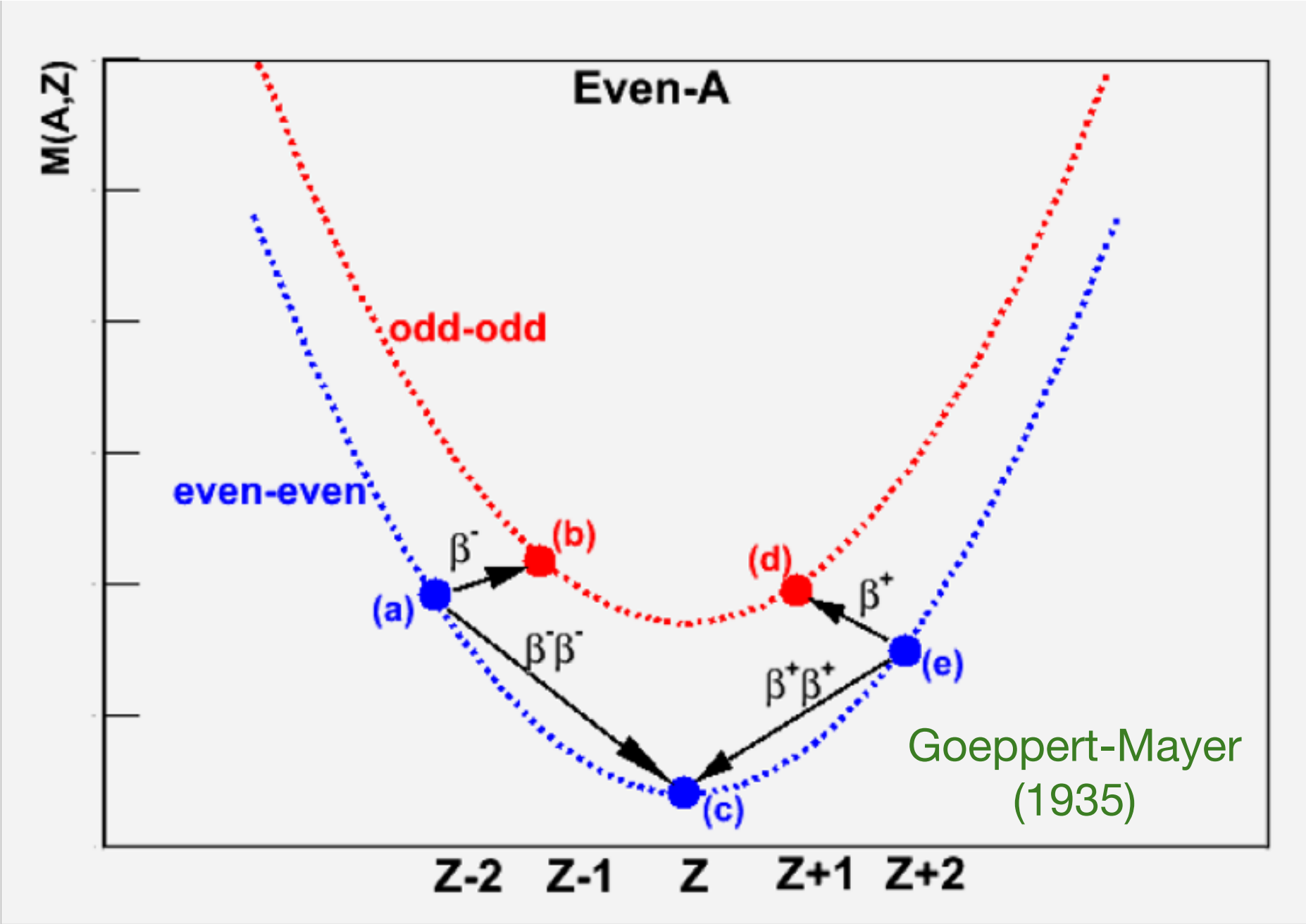


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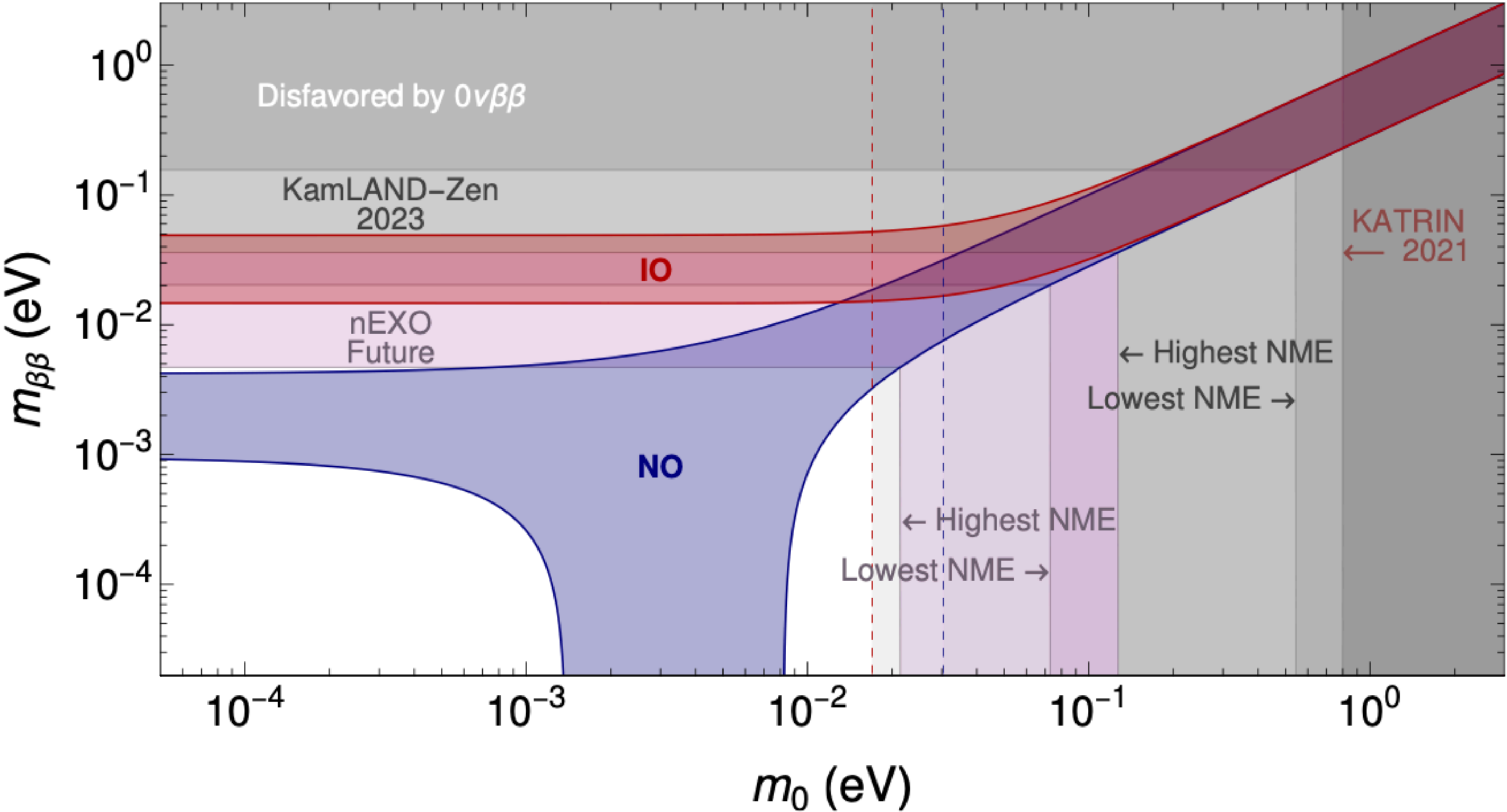
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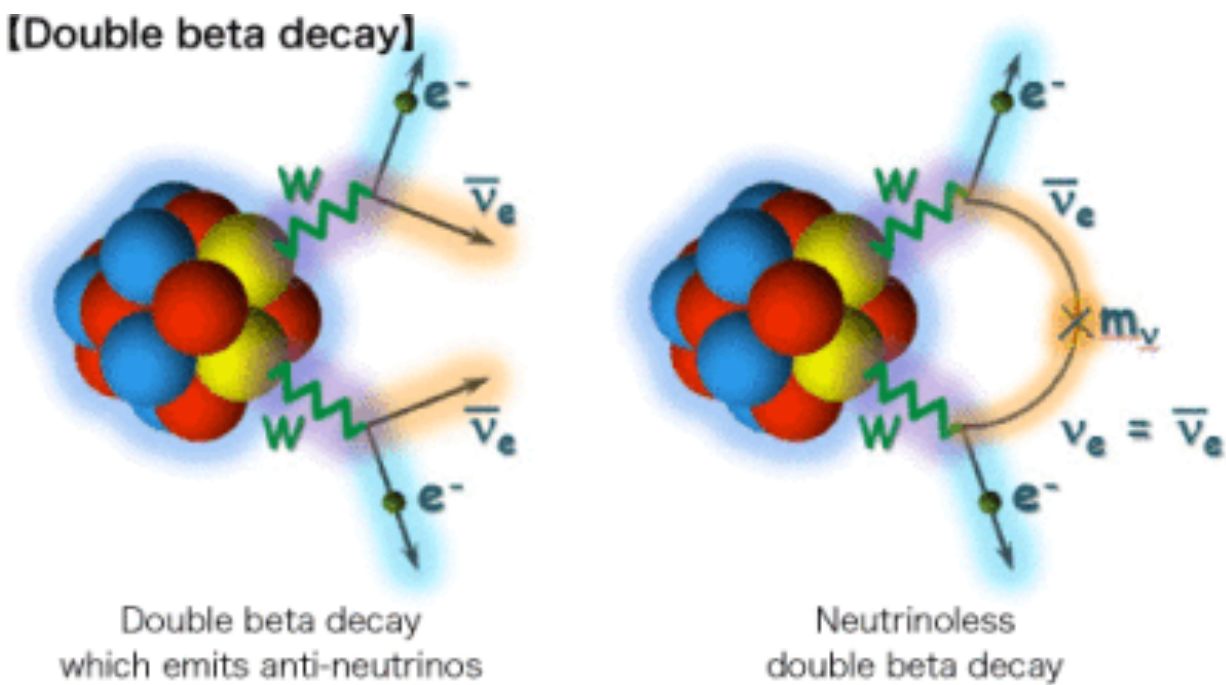
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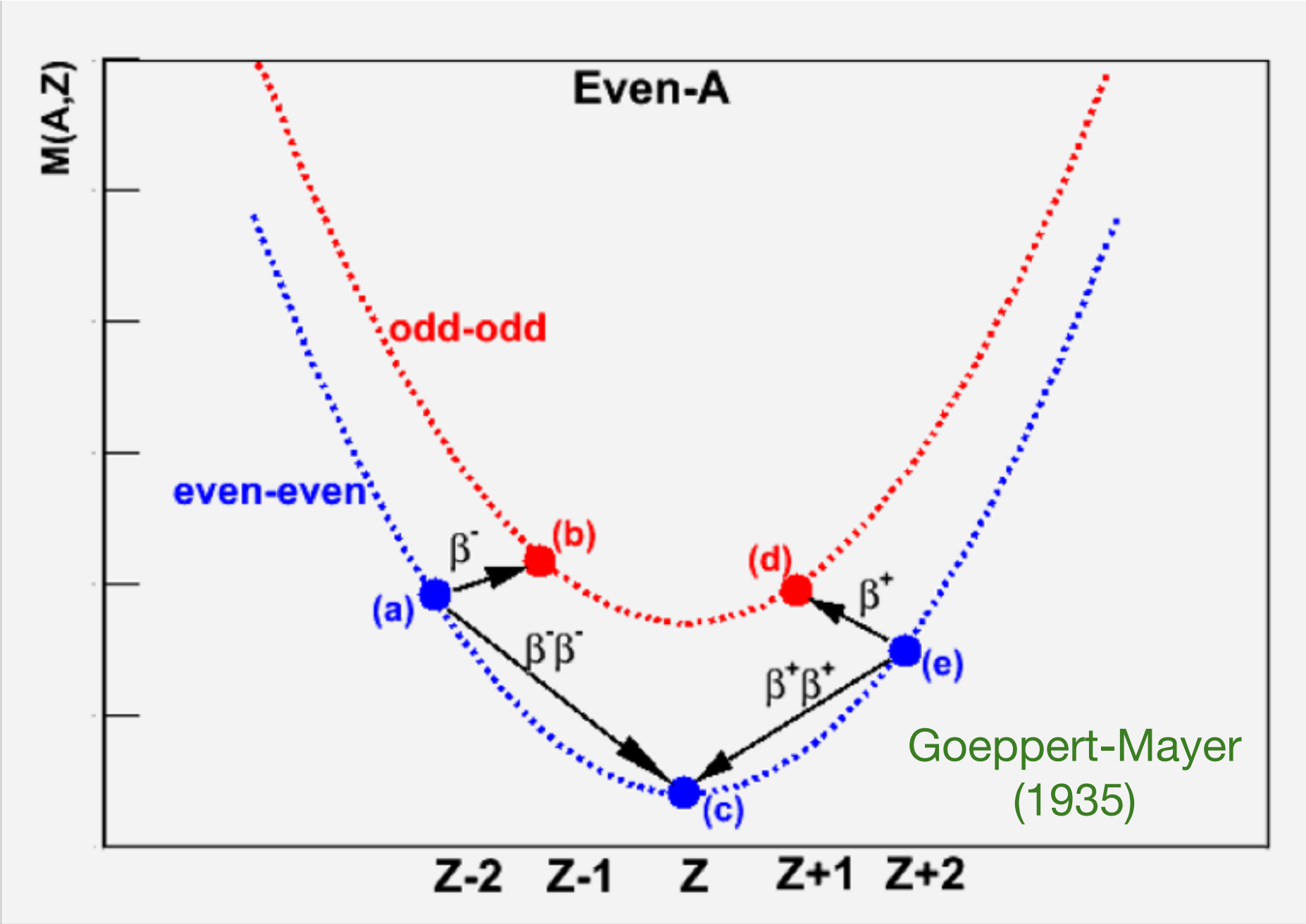
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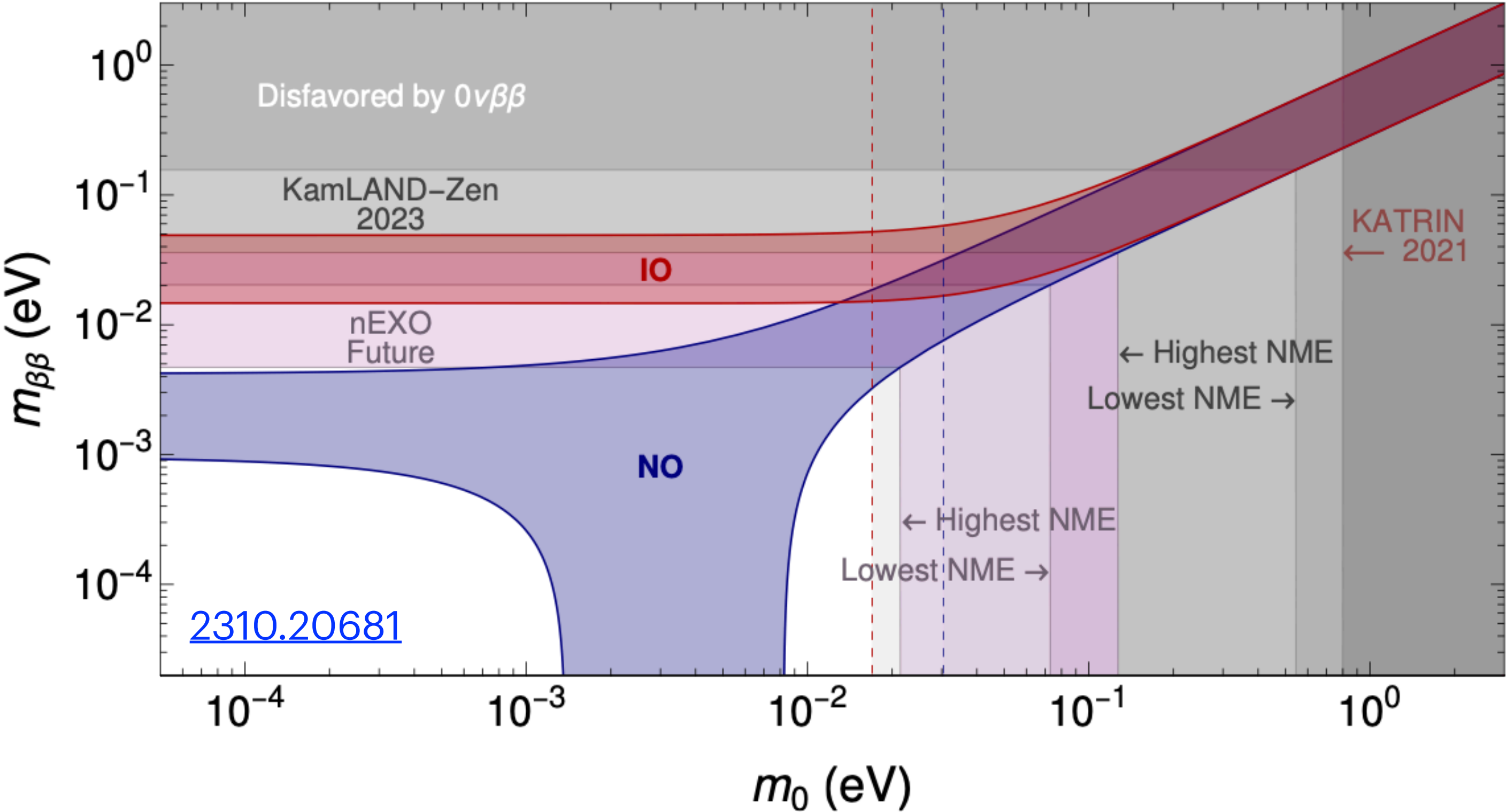
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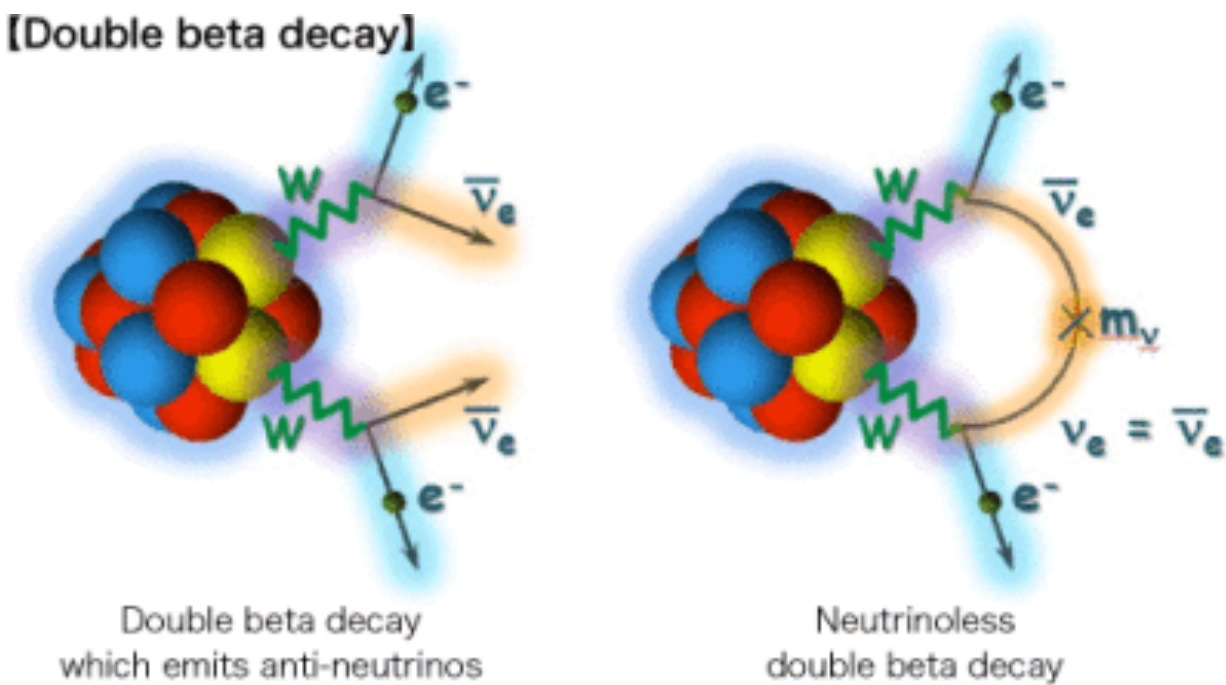
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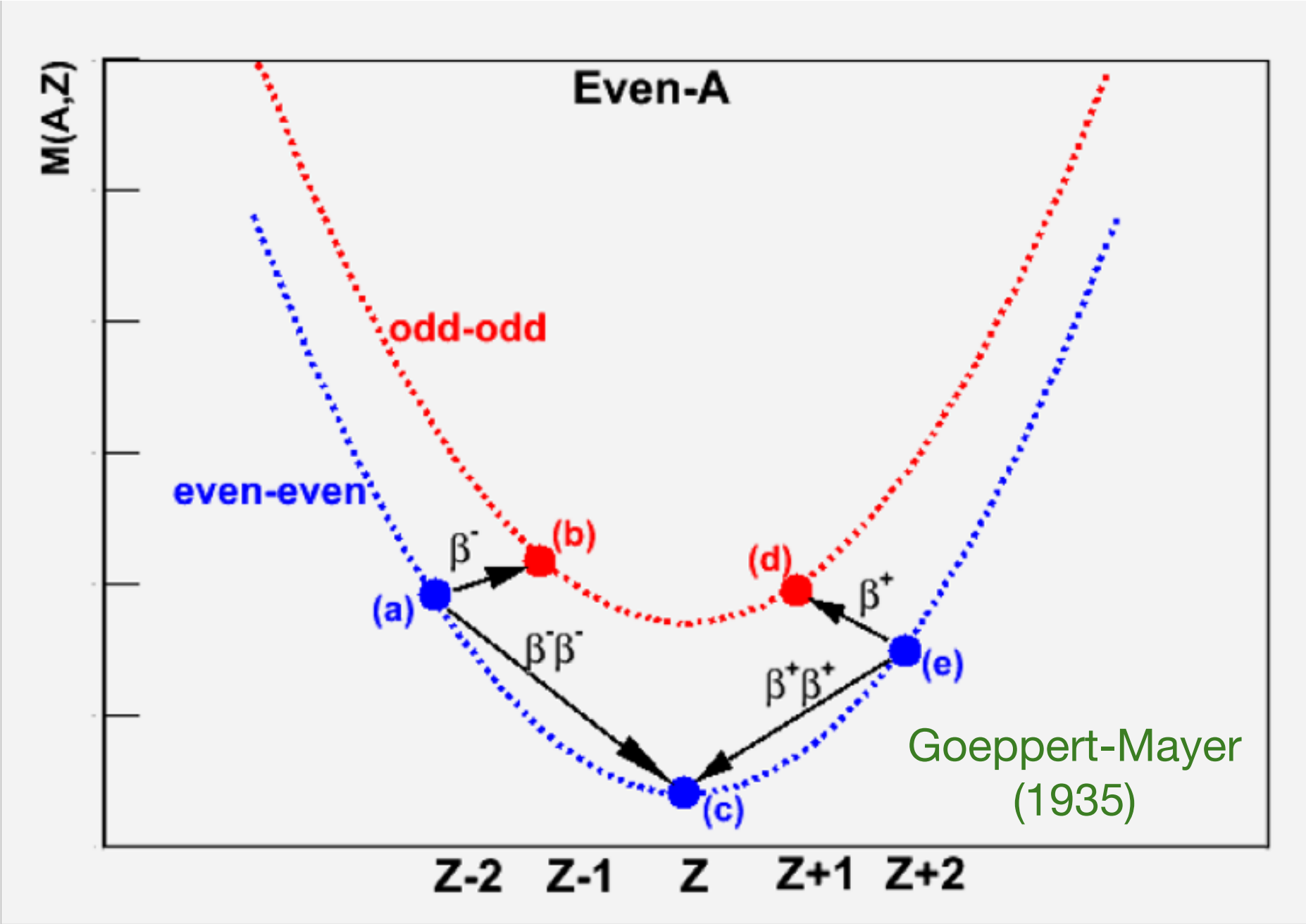


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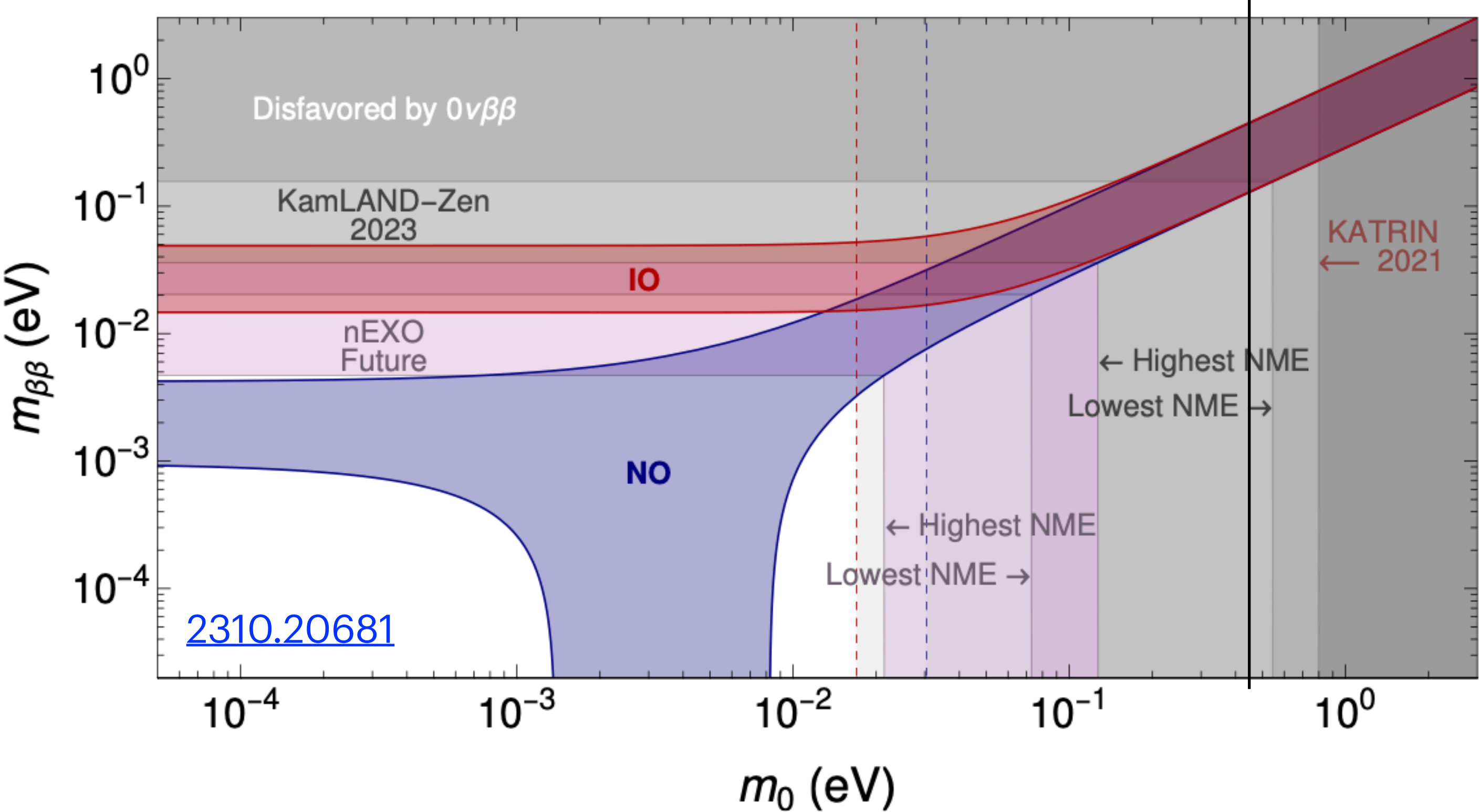


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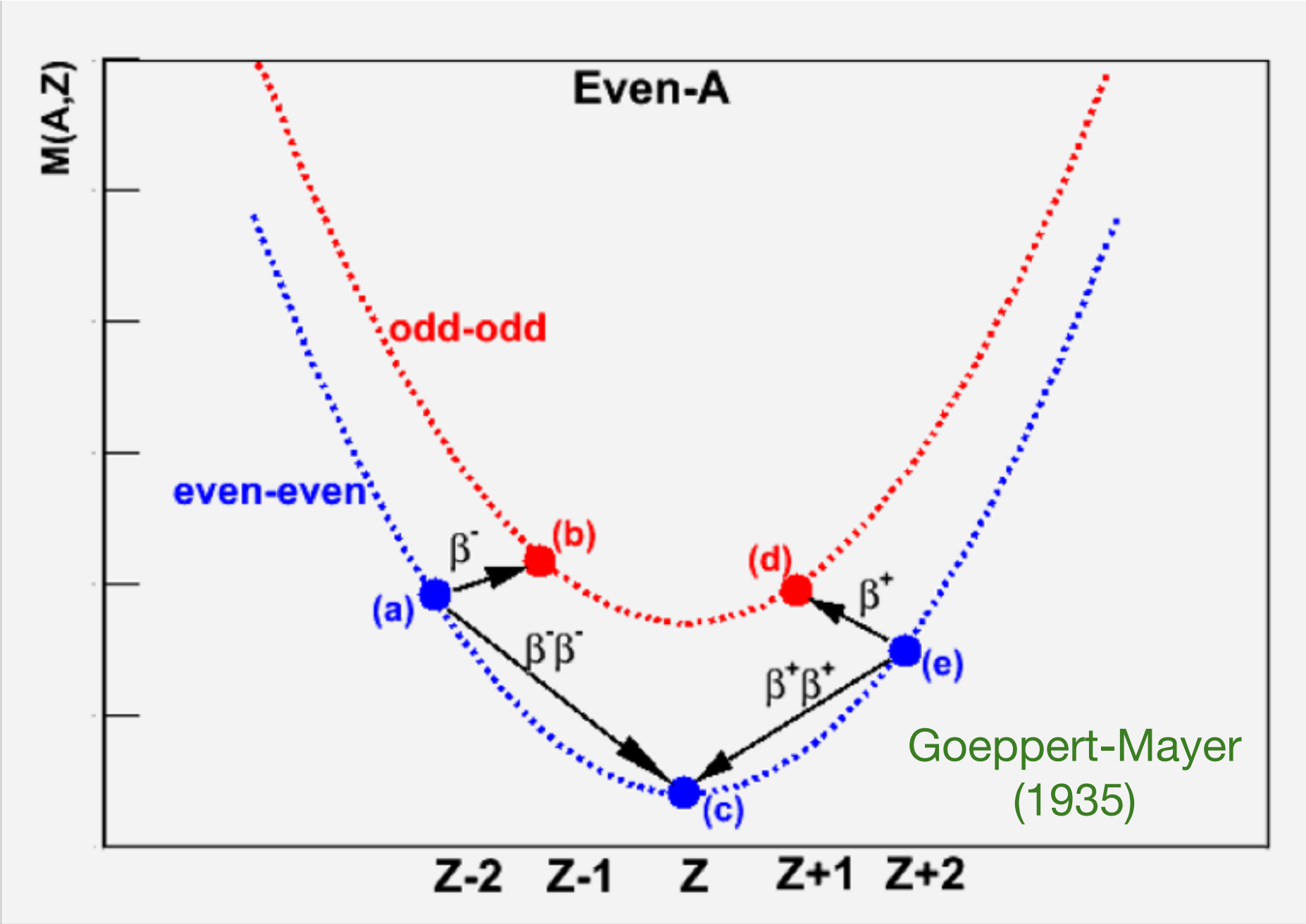
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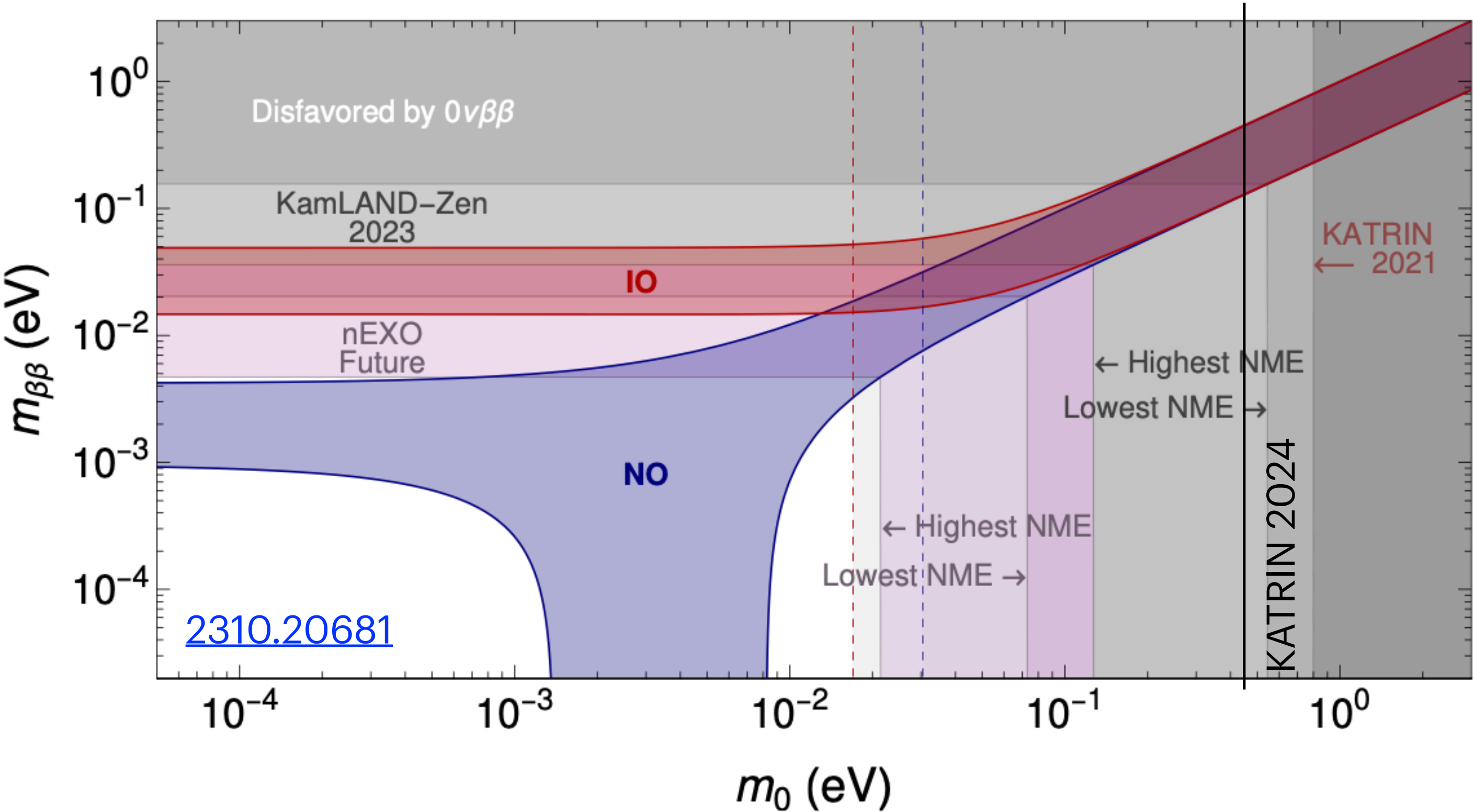
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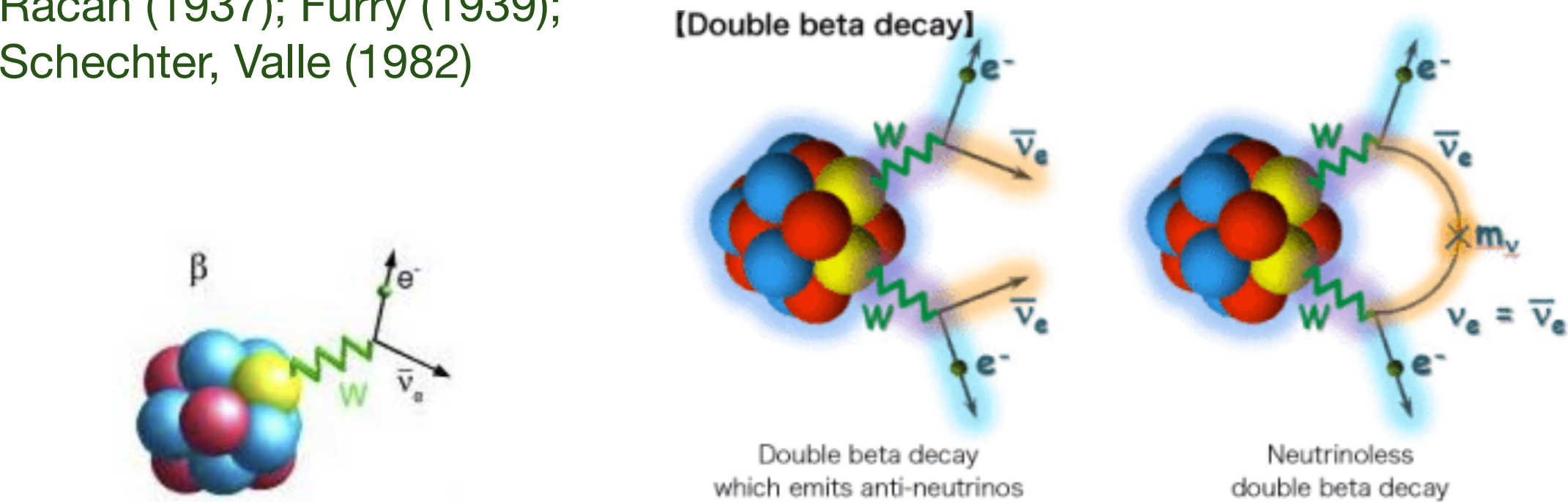
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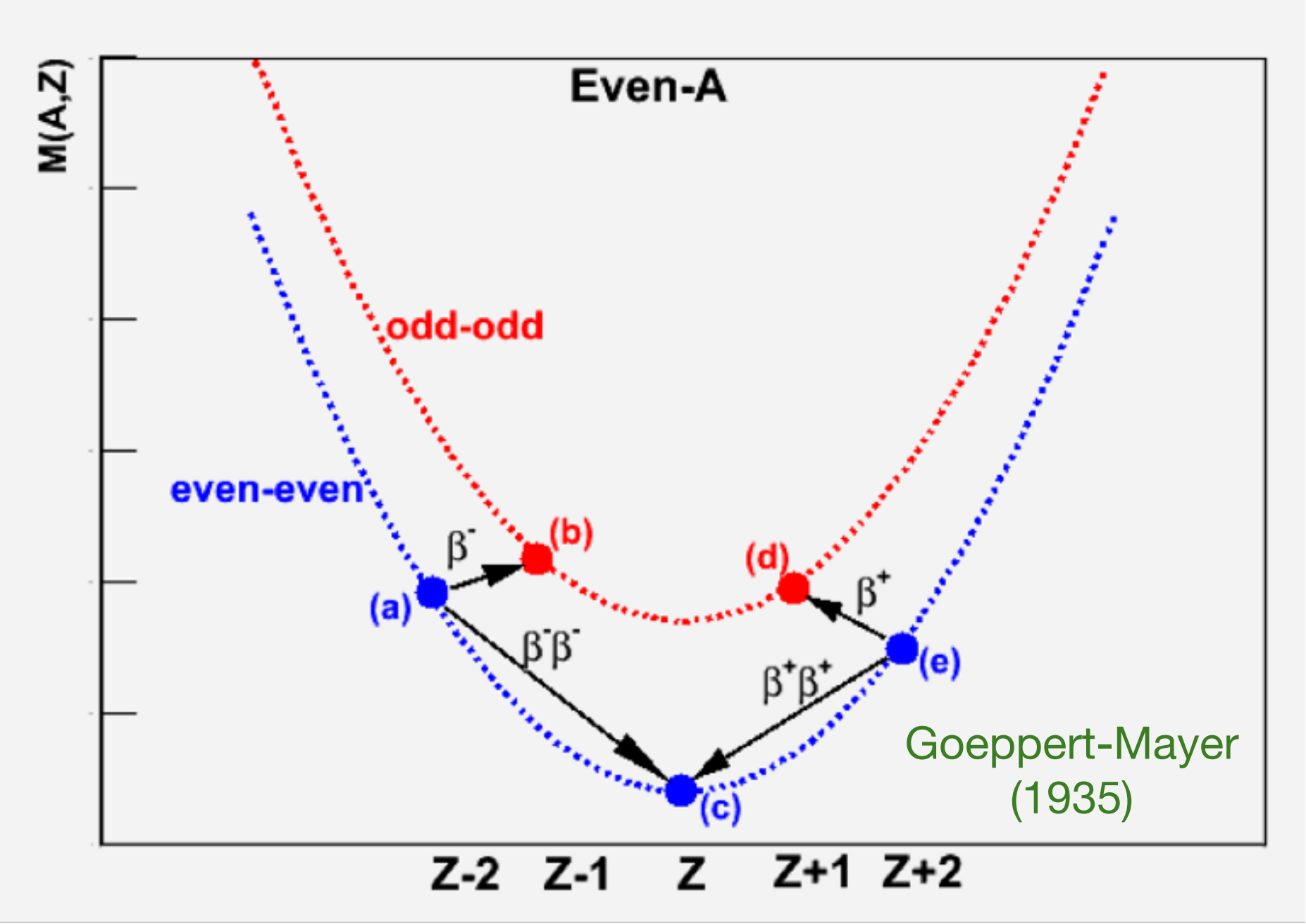


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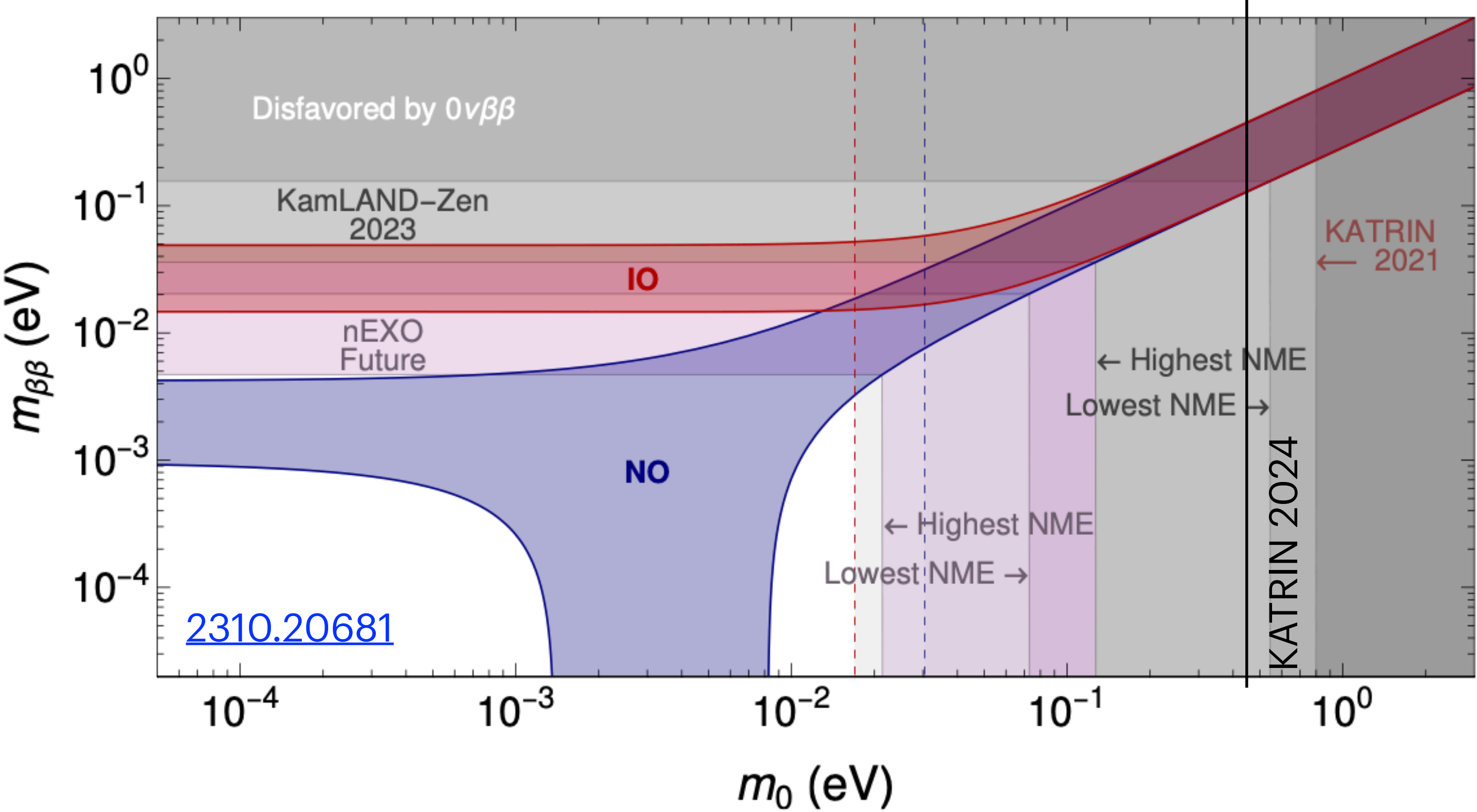


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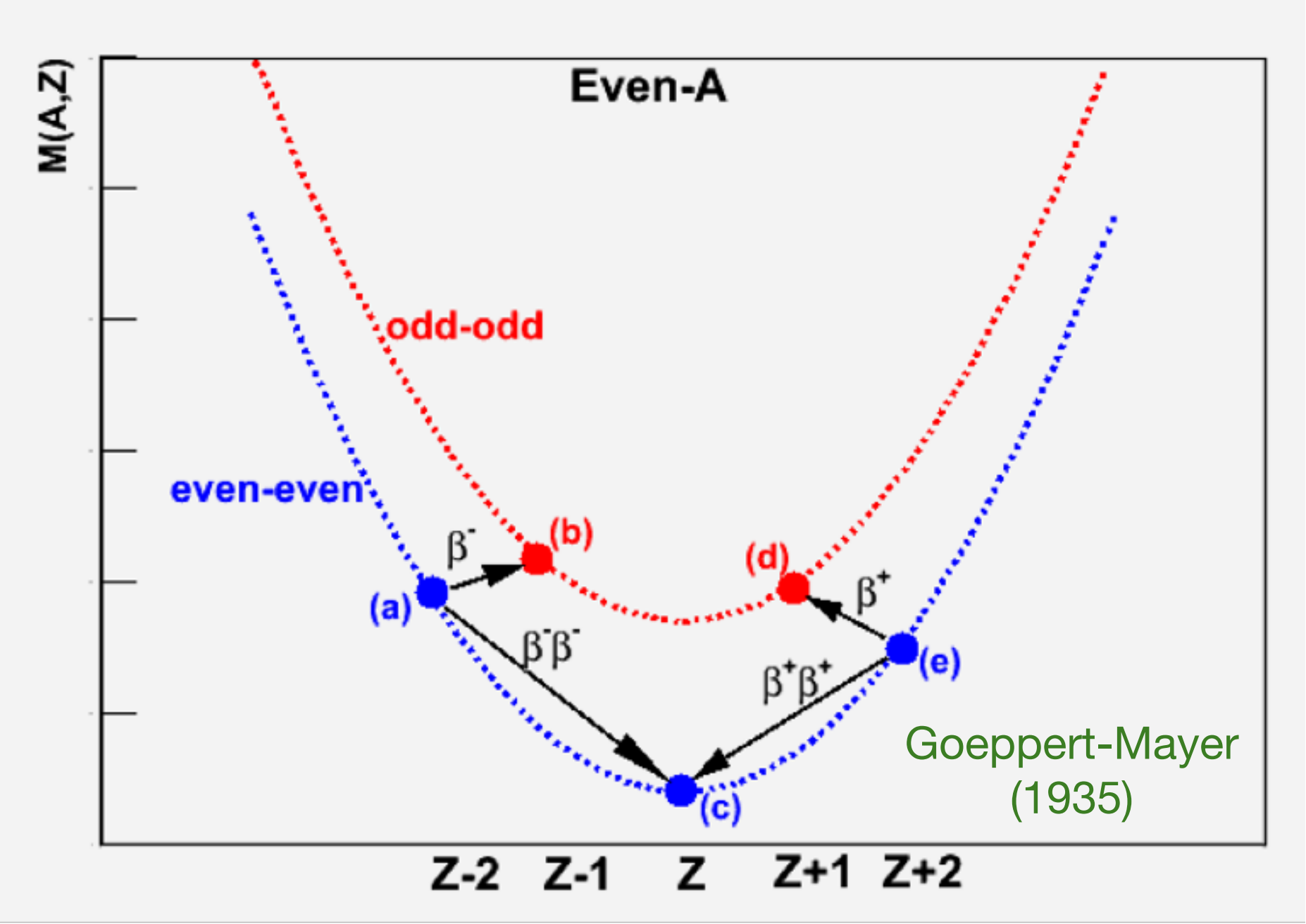
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What if there is no positive signal in $0\nu\beta\beta$ experiments?

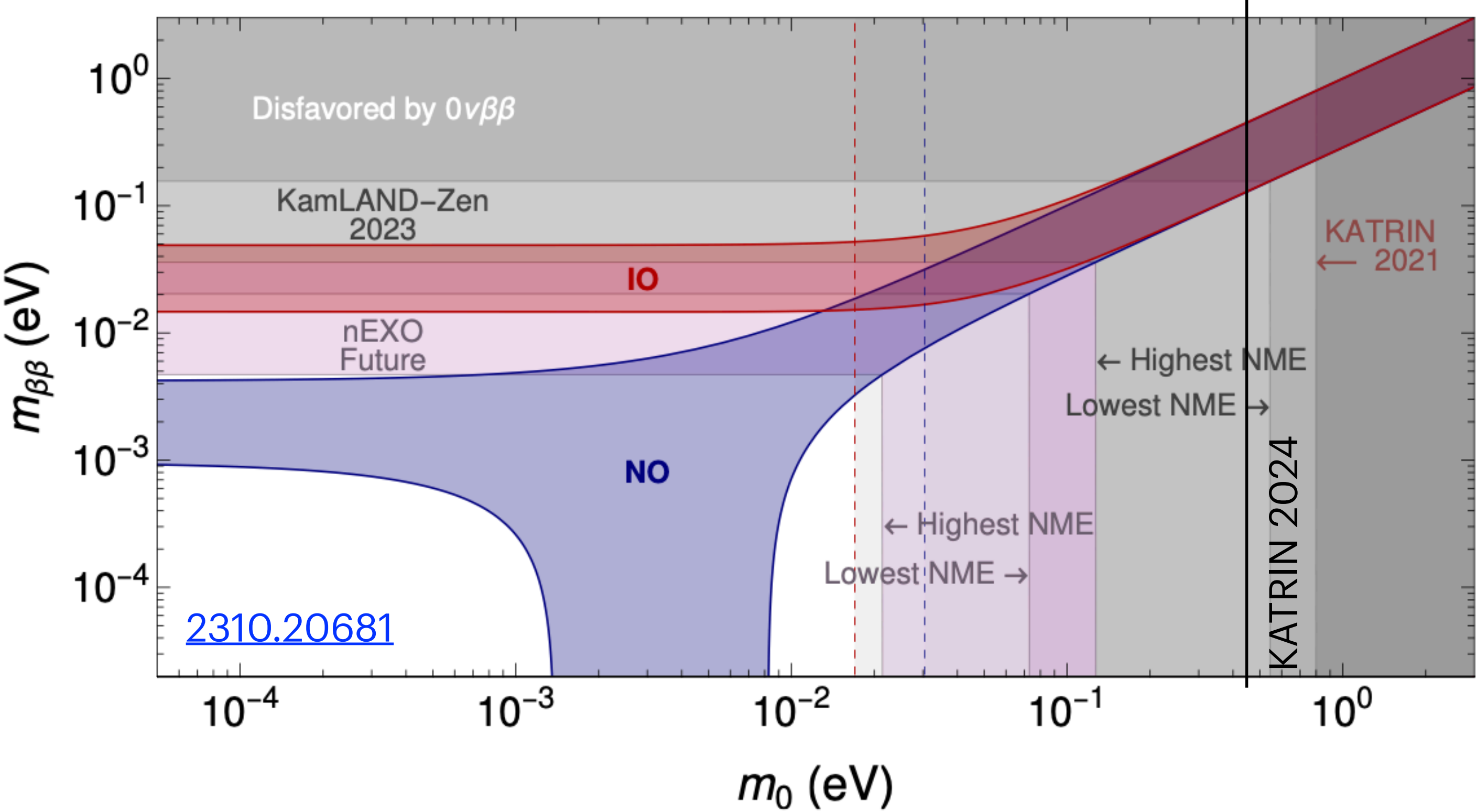
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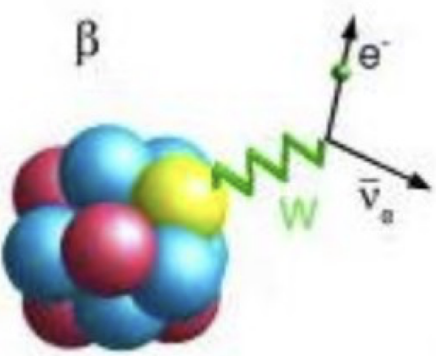
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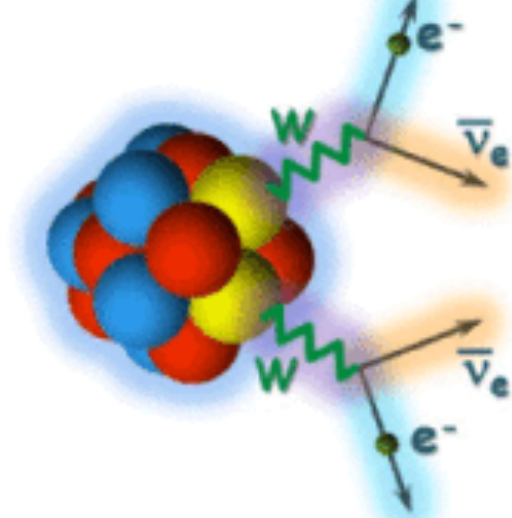
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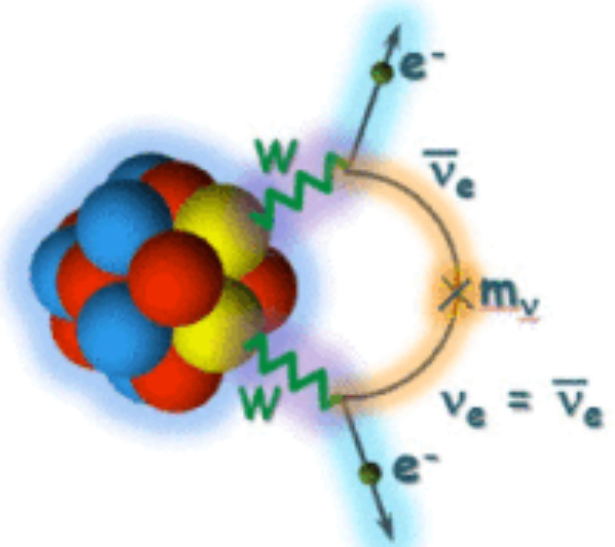
LNV searches at high-energy colliders is an alternative.



[Double beta decay]



Double beta decay
which emits anti-neutrinos



Neutrinoless
double beta decay



What if Neutrinos are Quasi-Dirac?

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}$$

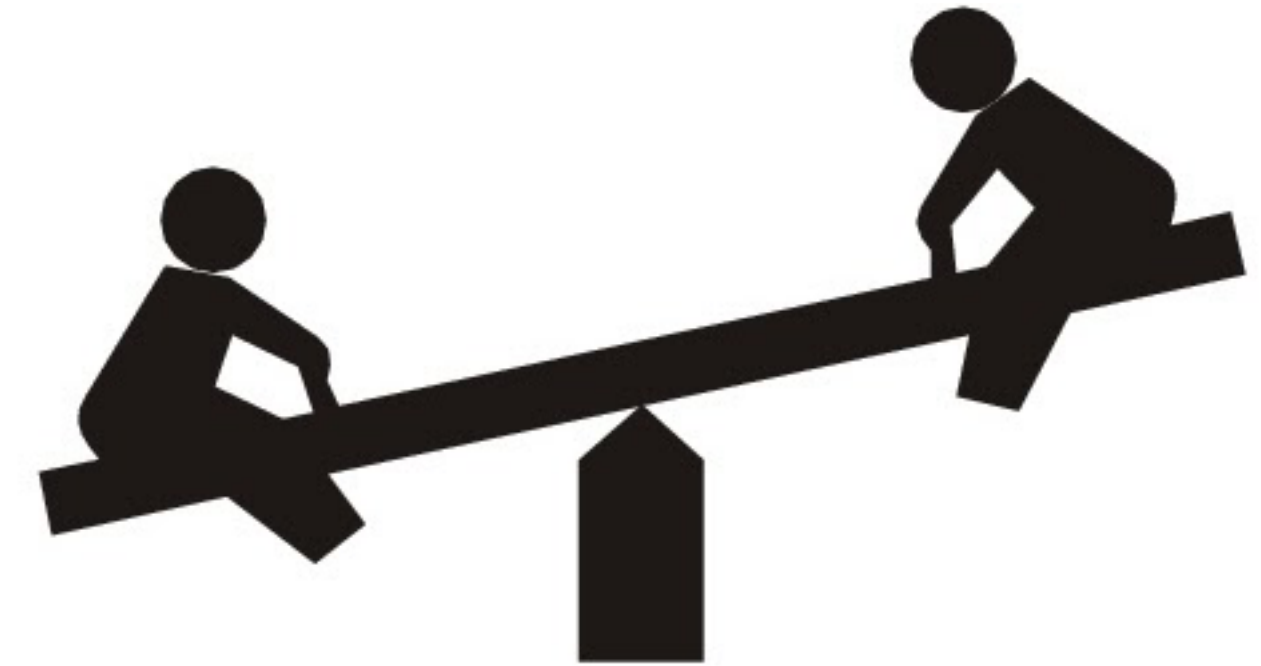
- If $m_R = 0$, lepton number is preserved and neutrinos are **Dirac**.
- If $m_R \neq 0$, lepton number is broken and neutrinos are **Majorana**.
- Typically, $||m_R|| \gg ||m_D||$ — **seesaw mechanism**. Minkowski (PLB '77); Mohapatra, Senjanovic (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79
- But $||m_R|| \ll ||m_D||$ is also a logical possibility — **Quasi-Dirac**. Wolfenstein (NPB '81); Petcov (PLB '82); Valle, Singer (PRD '83)
- Any model of Dirac neutrinos with Planck-suppressed operators would predict quasi-Dirac neutrinos.
- In fact, Dirac neutrinos are preferred by the **Swampland conjecture** in string theory.

Ooguri, Vafa, [1610.01533](#); Ibanez, Martin-Lozana, Valenzuela, [1706.05392](#);
Gonzalo, Ibanez, Valenzuela, [2109.10961](#); Casas, Ibanez, Marchesano, [2406.14609](#)



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Ooguri, Vafa, [1610.01533](#); Ibanez, Martin-Lozana, Valenzuela, [1706.05392](#);
Gonzalo, Ibanez, Valenzuela, [2109.10961](#); Casas, Ibanez, Marchesano, [2406.14609](#)

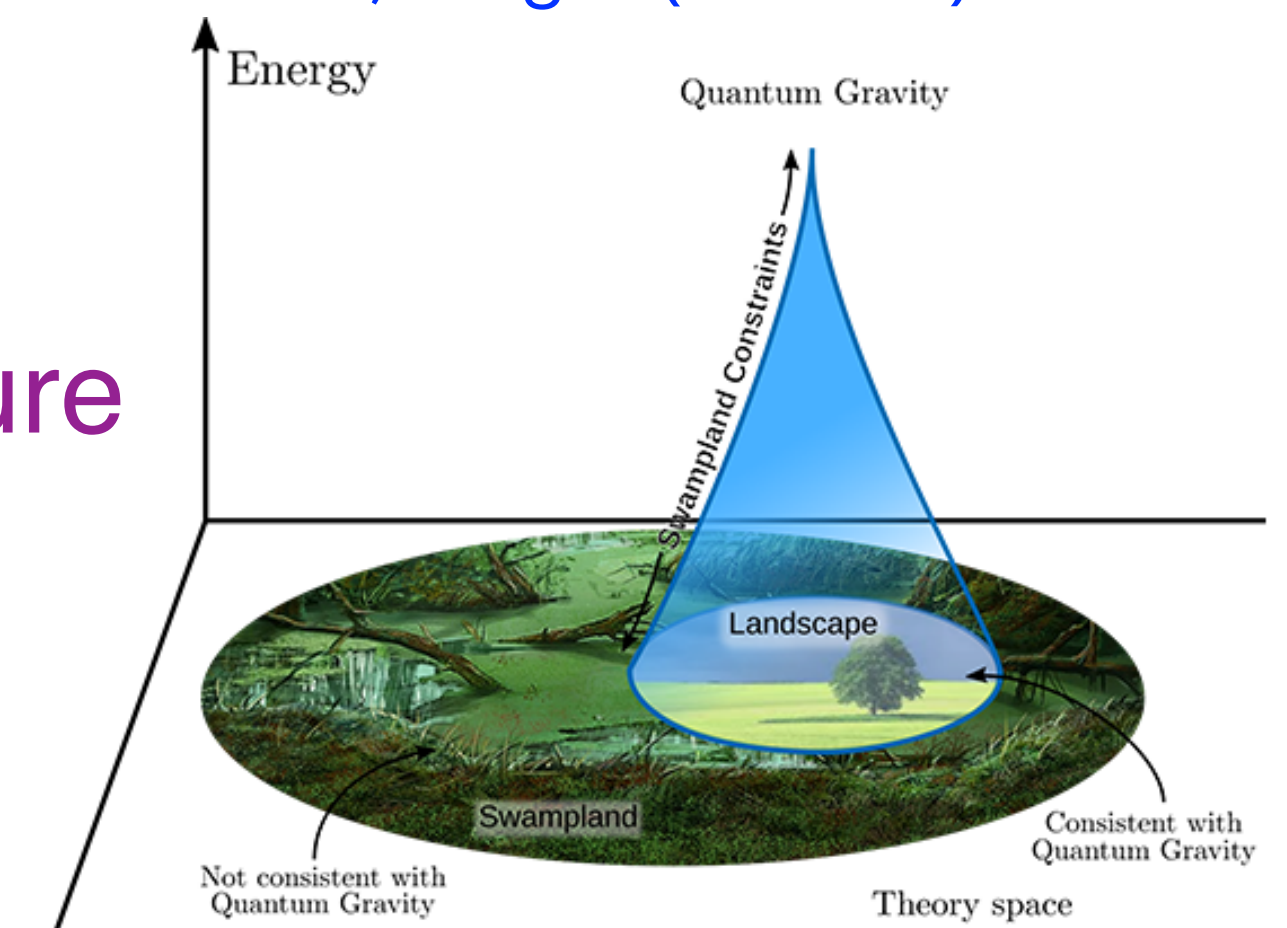
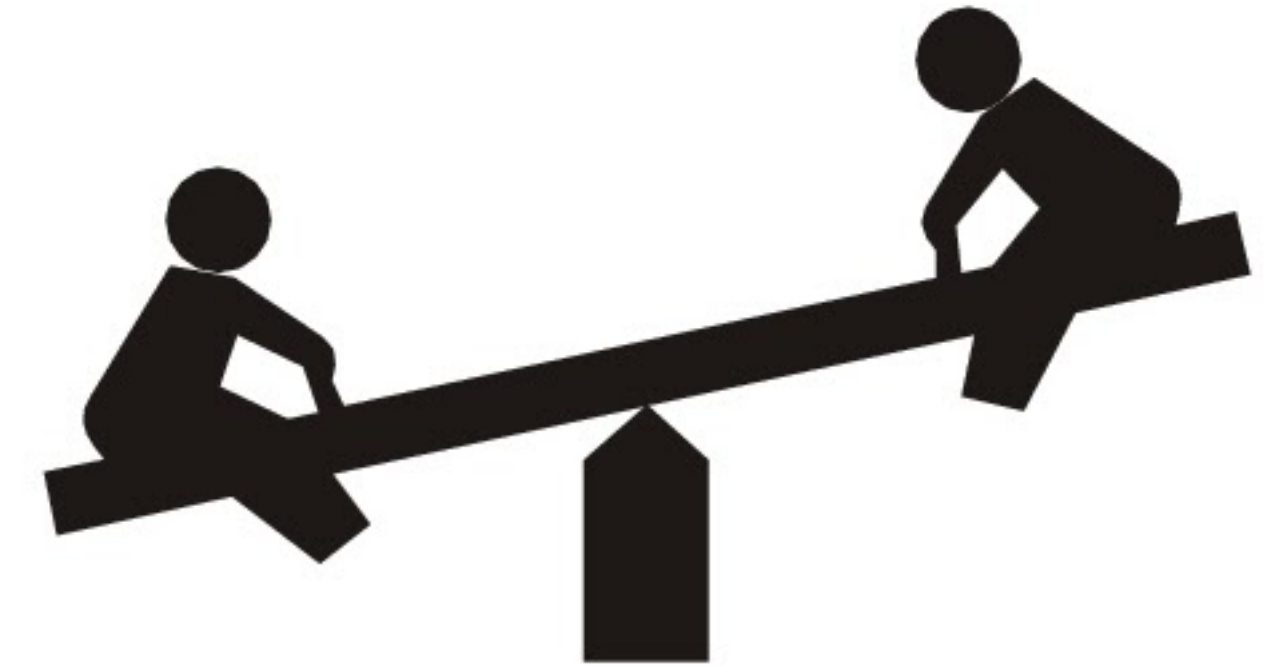


What if Neutrinos are Quasi-Dirac?

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}$$

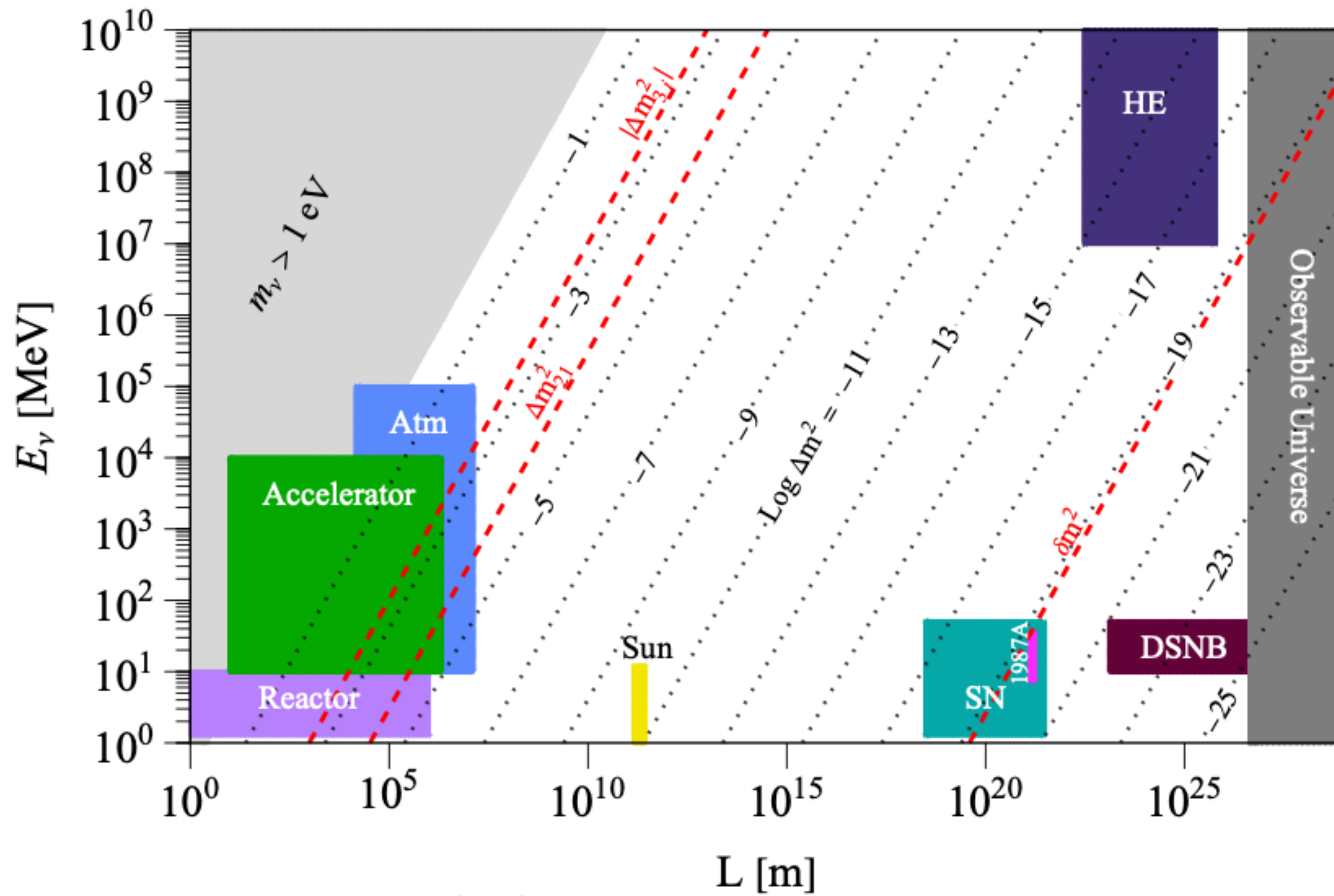
- If $m_R = 0$, lepton number is preserved and neutrinos are **Dirac**.
- If $m_R \neq 0$, lepton number is broken and neutrinos are **Majorana**.
- Typically, $||m_R|| \gg ||m_D||$ — **seesaw mechanism**. Minkowski (PLB '77); Mohapatra, Senjanovic (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79
- But $||m_R|| \ll ||m_D||$ is also a logical possibility — **Quasi-Dirac**. Wolfenstein (NPB '81); Petcov (PLB '82); Valle, Singer (PRD '83)
- Any model of Dirac neutrinos with Planck-suppressed operators would predict quasi-Dirac neutrinos.
- In fact, Dirac neutrinos are preferred by the **Swampland conjecture** in string theory.

Ooguri, Vafa, [1610.01533](#); Ibanez, Martin-Lozana, Valenzuela, [1706.05392](#);
Gonzalo, Ibanez, Valenzuela, [2109.10961](#); Casas, Ibanez, Marchesano, [2406.14609](#)





QDino Oscillations with Astrophysical Baselines

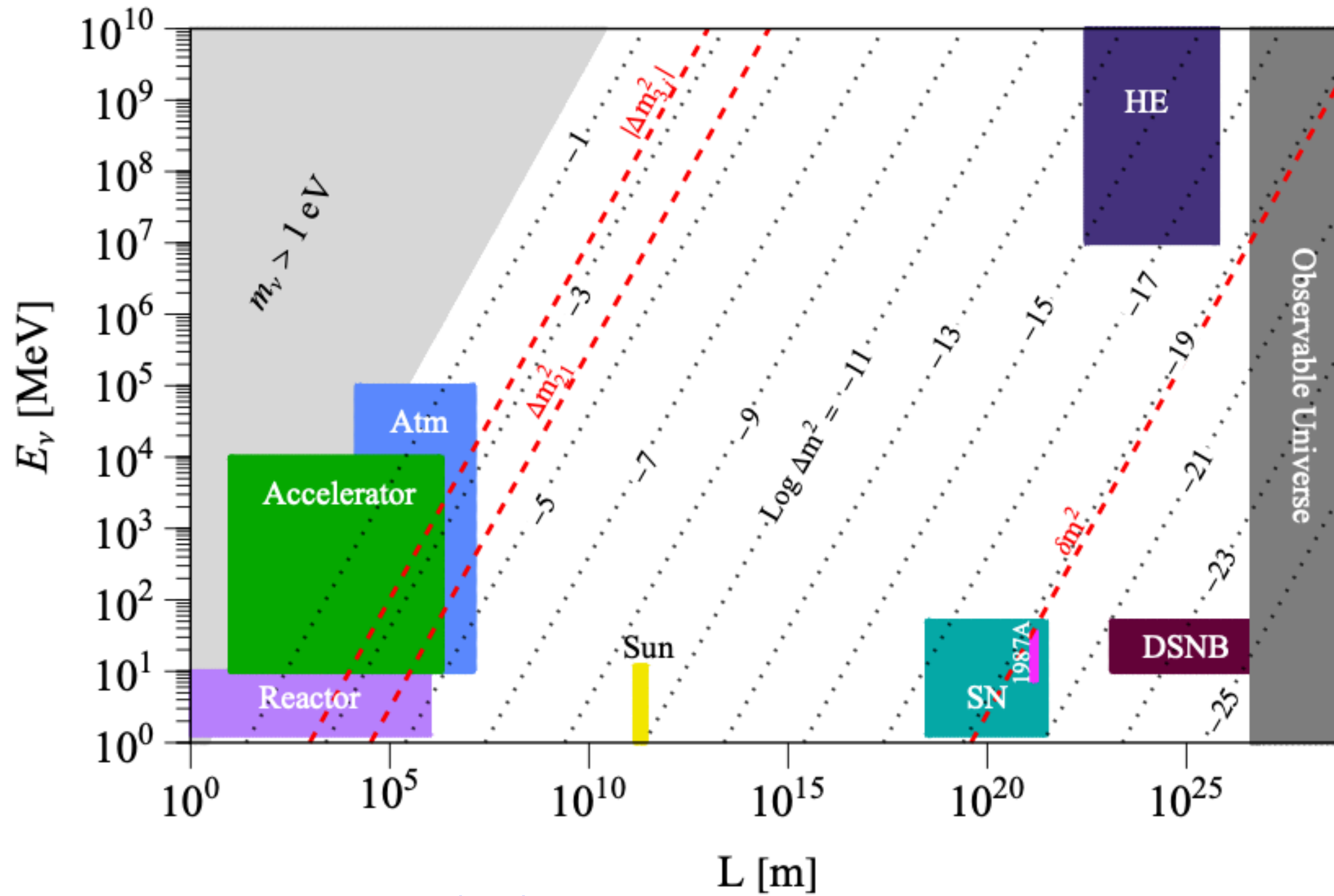


Beacom, Bell, Hooper, Learned, Pakvasa, Weiler, [0307151](#);
Martinez-Soler, Perez-Gonzalez, Sen, [2105.12736](#)



QDino Oscillations with Astrophysical Baselines

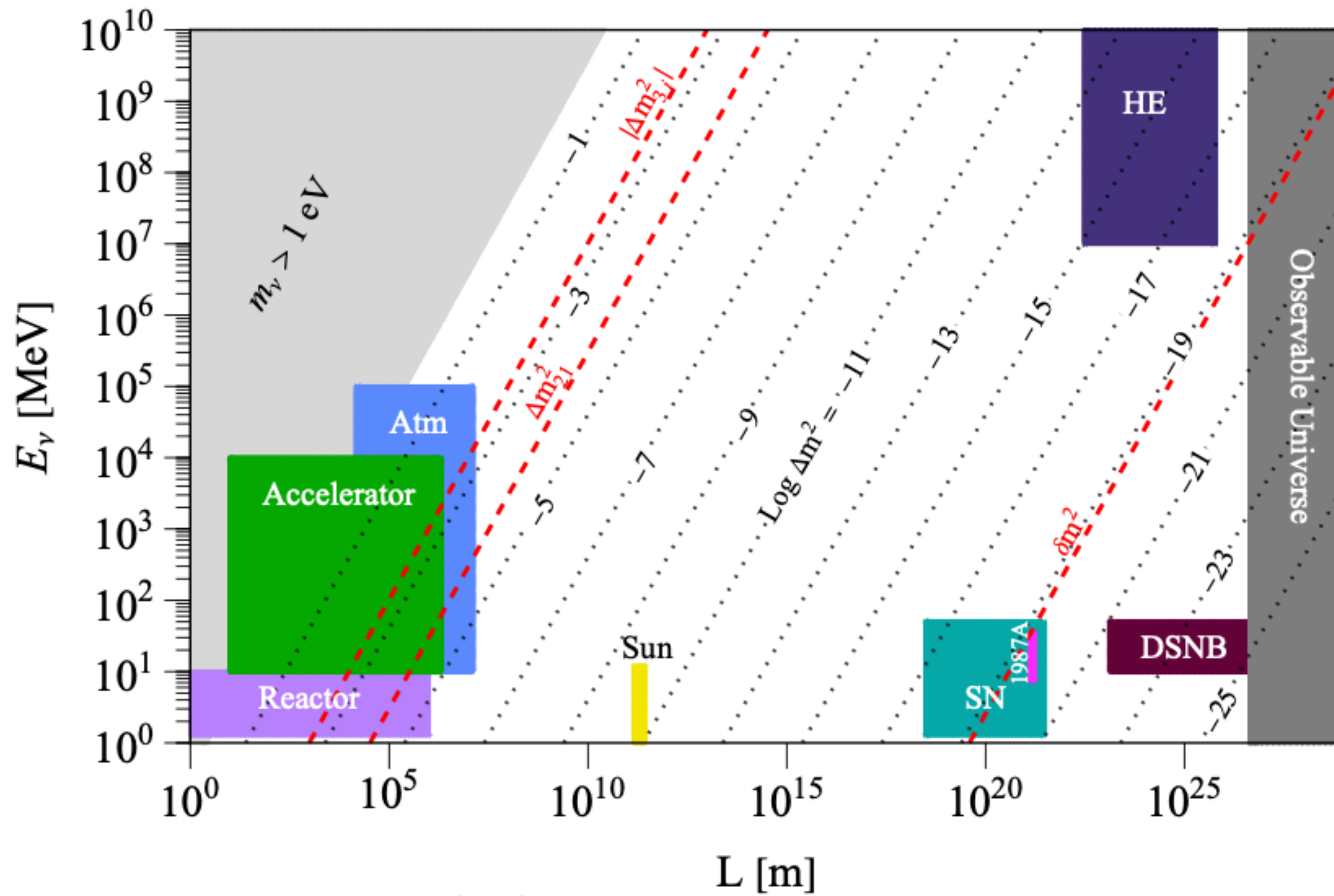
Solar Data: [Ansarifard, Farzan, 2211.09105](#)



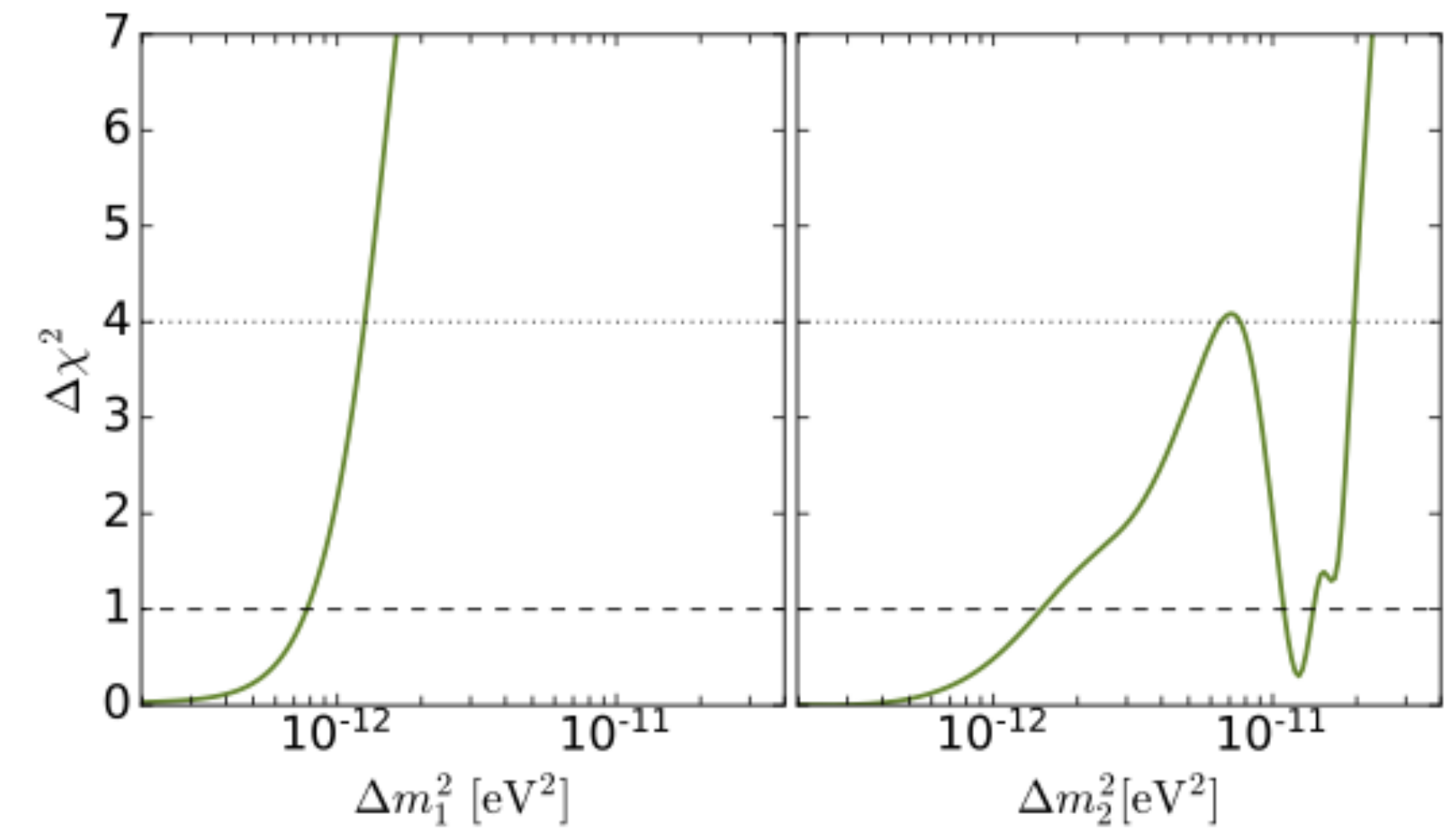
Beacom, Bell, Hooper, Learned, Pakvasa, Weiler, [0307151](#);
Martinez-Soler, Perez-Gonzalez, Sen, [2105.12736](#)



QDino Oscillations with Astrophysical Baselines



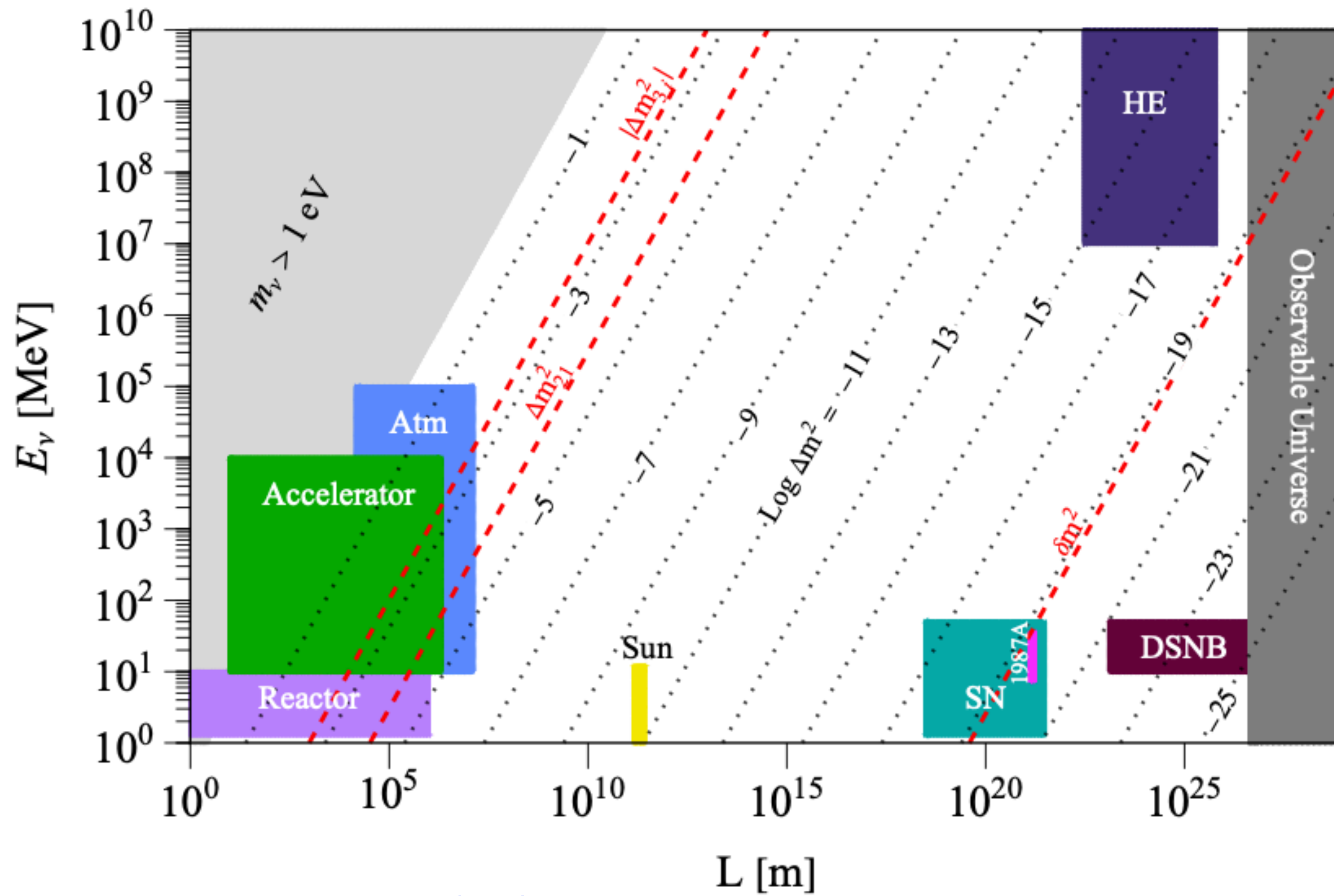
Solar Data: [Ansarifard, Farzan, 2211.09105](#)



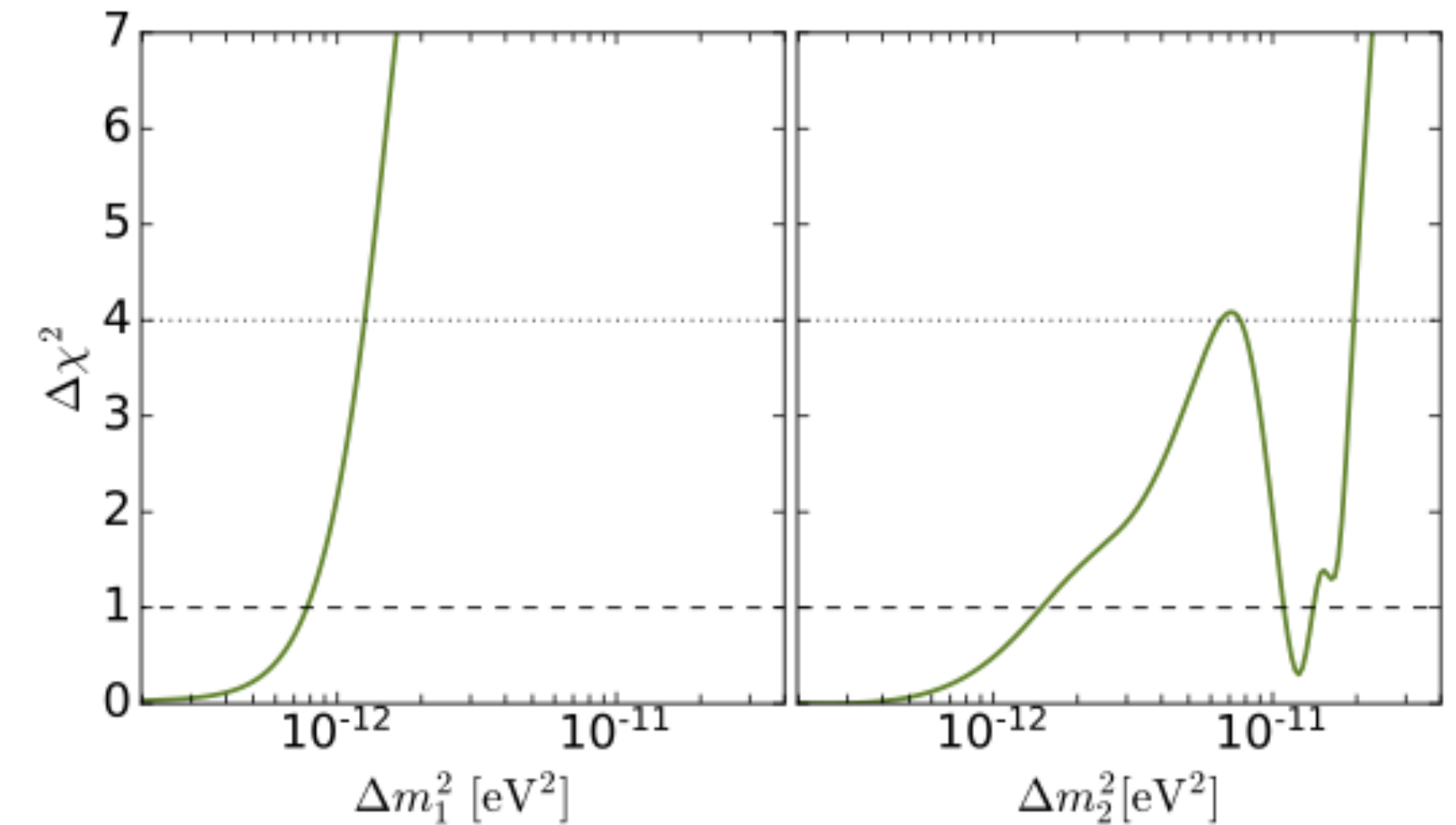
Beacom, Bell, Hooper, Learned, Pakvasa, Weiler, [0307151](#);
Martinez-Soler, Perez-Gonzalez, Sen, [2105.12736](#)



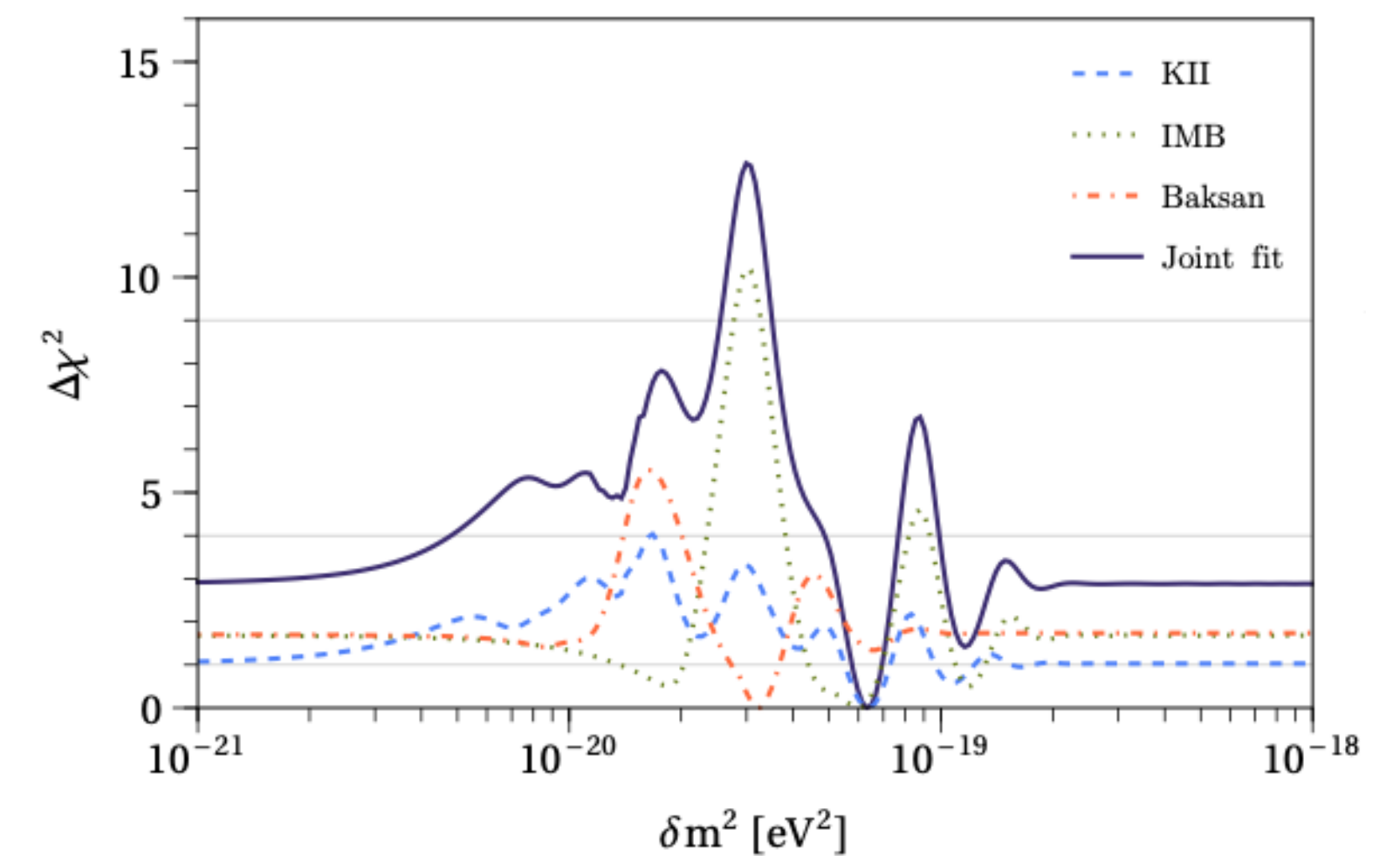
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Solar Data: [Ansarifard, Farzan, 2211.09105](#)



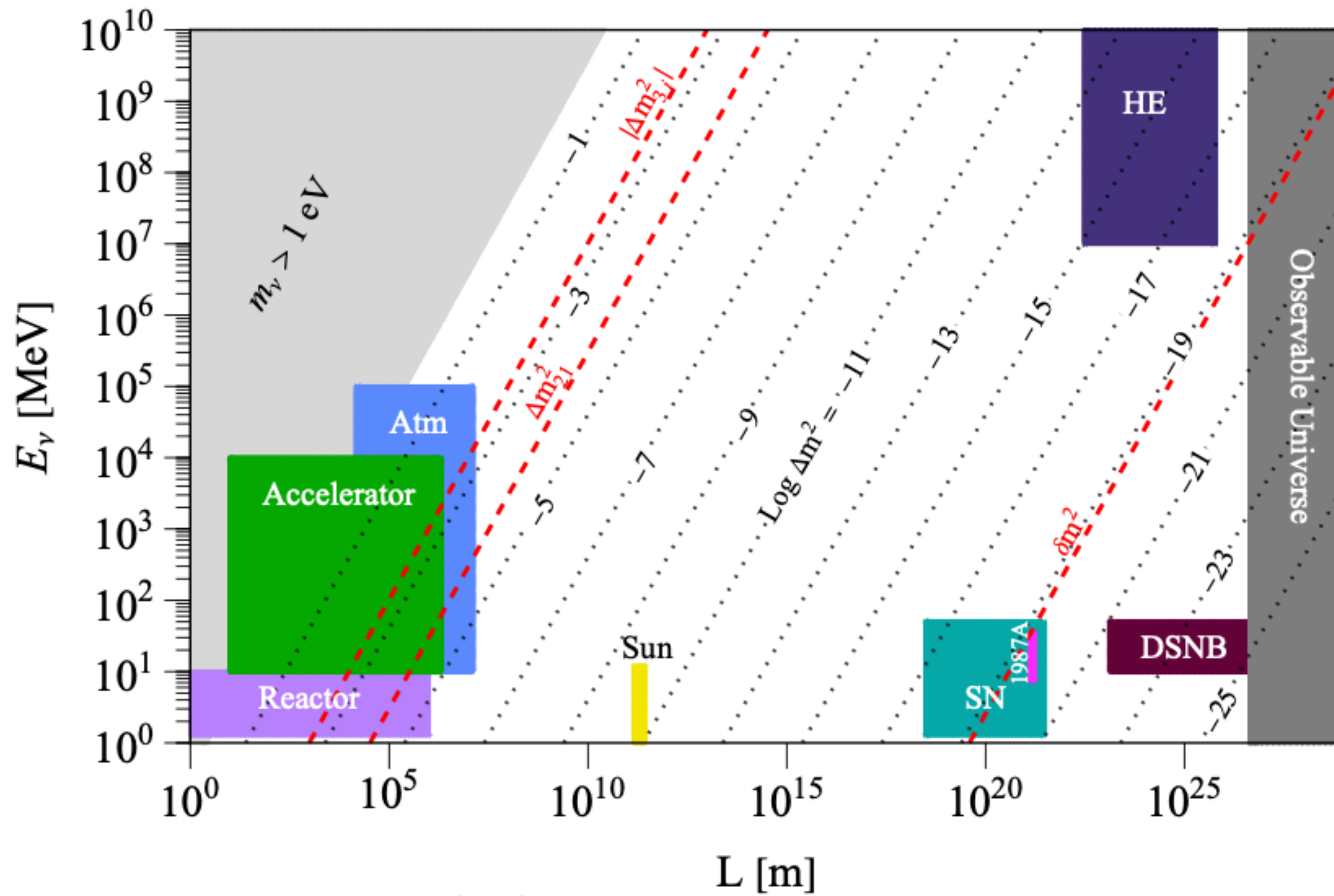
SN 1987 A



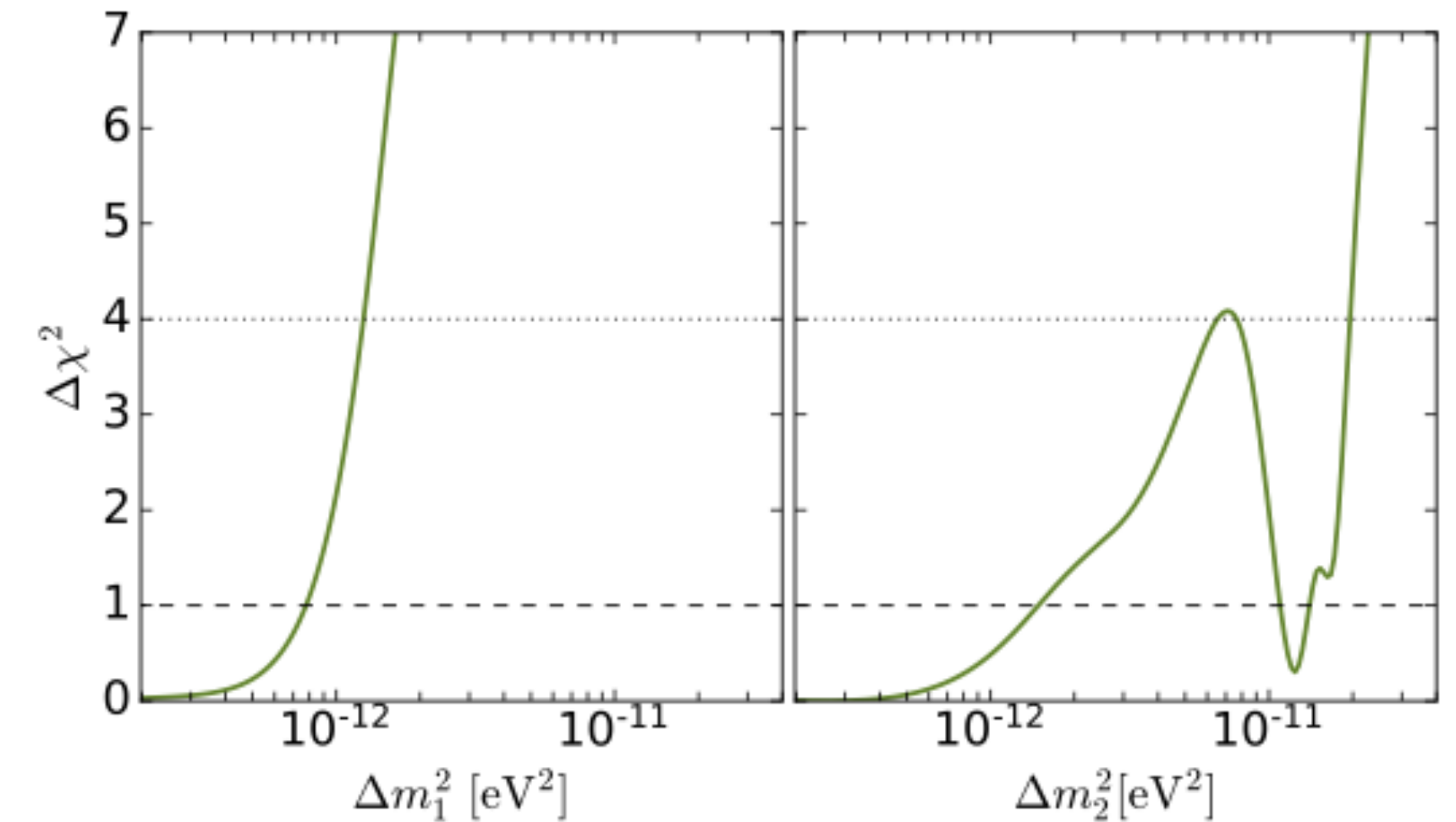
[Beacom, Bell, Hooper, Learned, Pakvasa, Weiler, 0307151](#);
[Martinez-Soler, Perez-Gonzalez, Sen, 2105.12736](#)



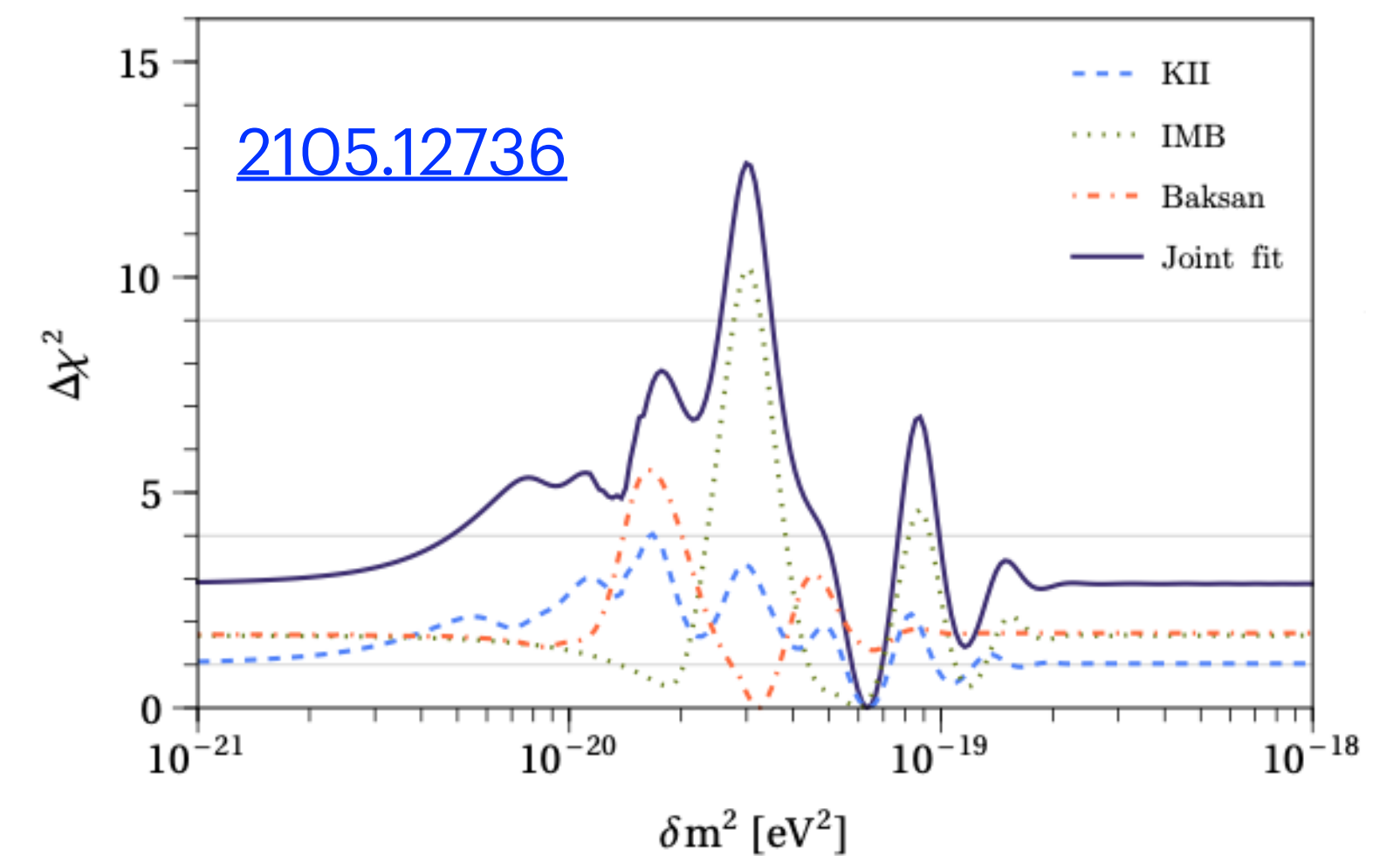
QDino Oscillations with Astrophysical Baselines



Solar Data: [Ansarifard, Farzan, 2211.09105](#)

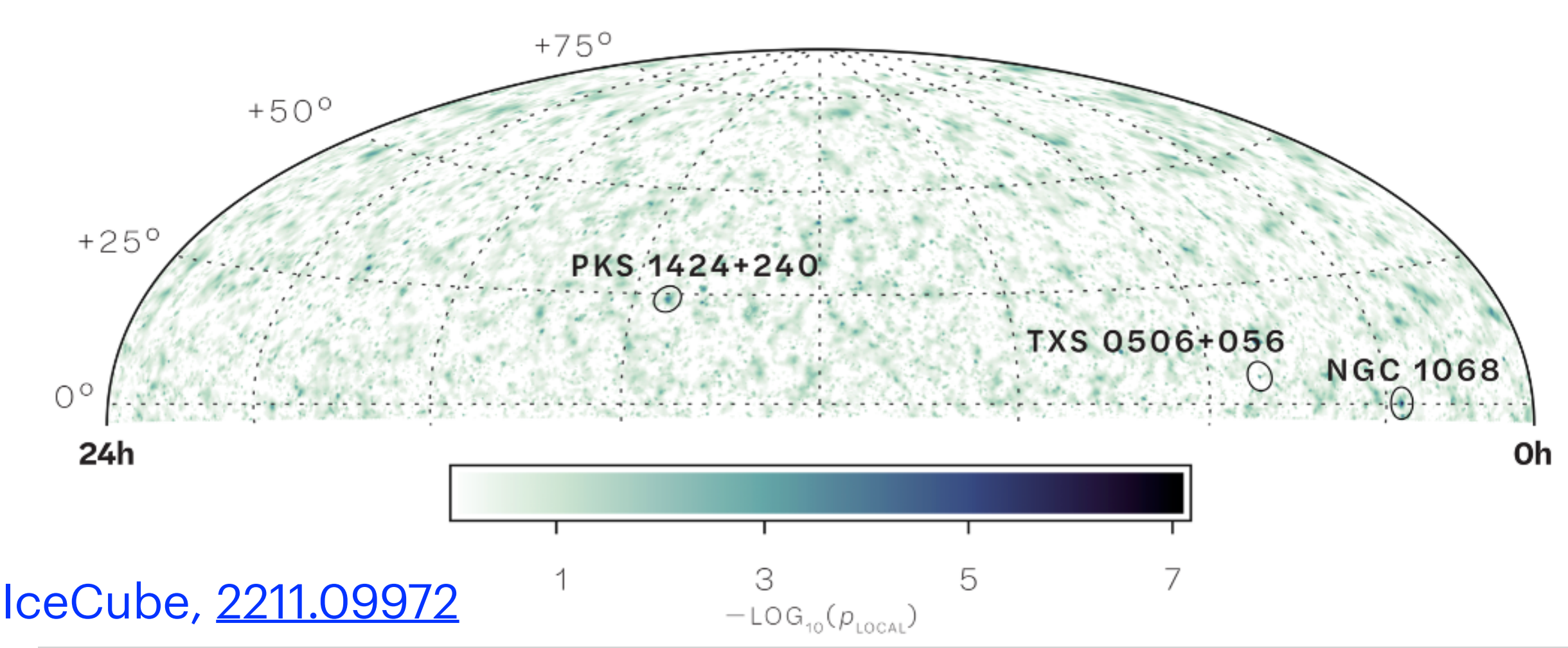


SN 1987 A



[Beacom, Bell, Hooper, Learned, Pakvasa, Weiler, 0307151](#);
[Martinez-Soler, Perez-Gonzalez, Sen, 2105.12736](#)

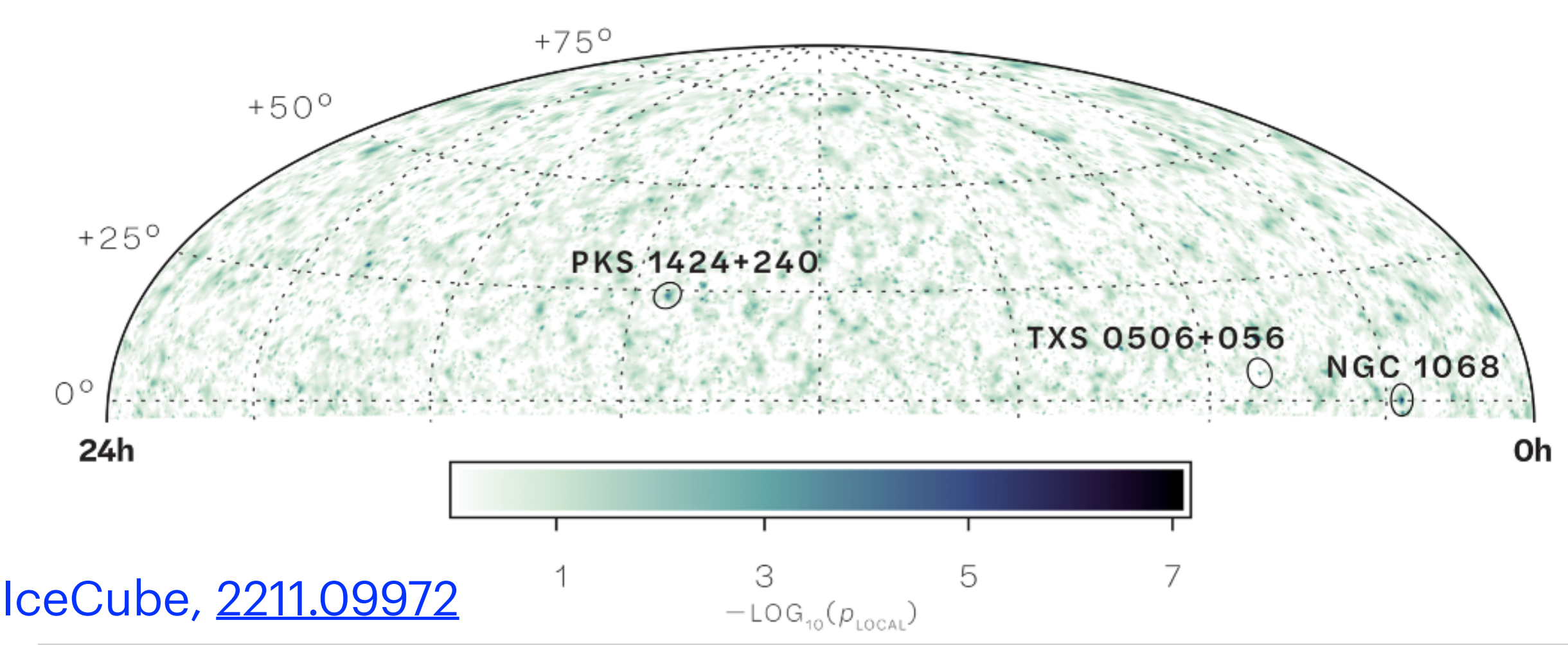
QDino Search using HEN Point Sources



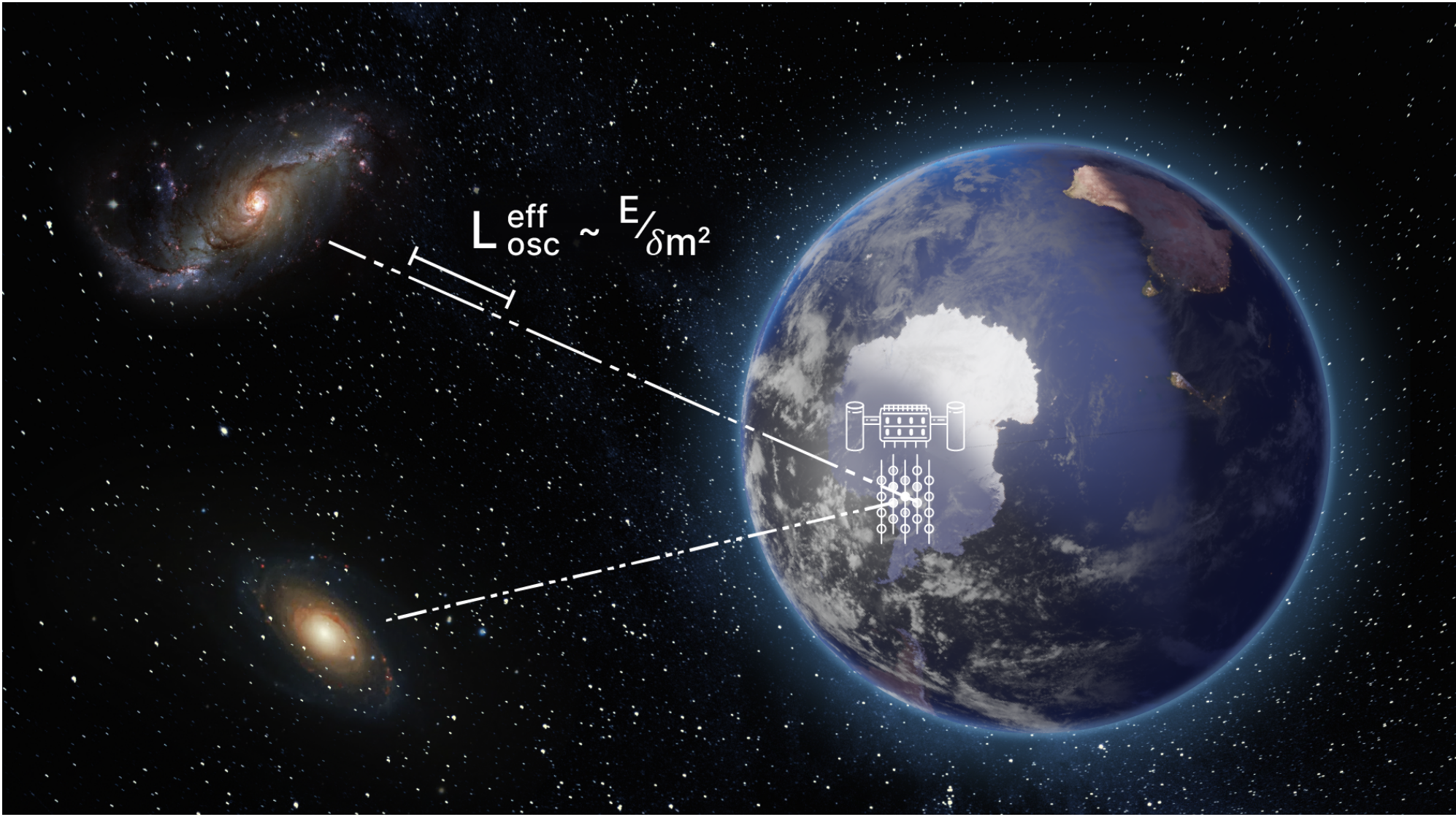
Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\text{local}}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5



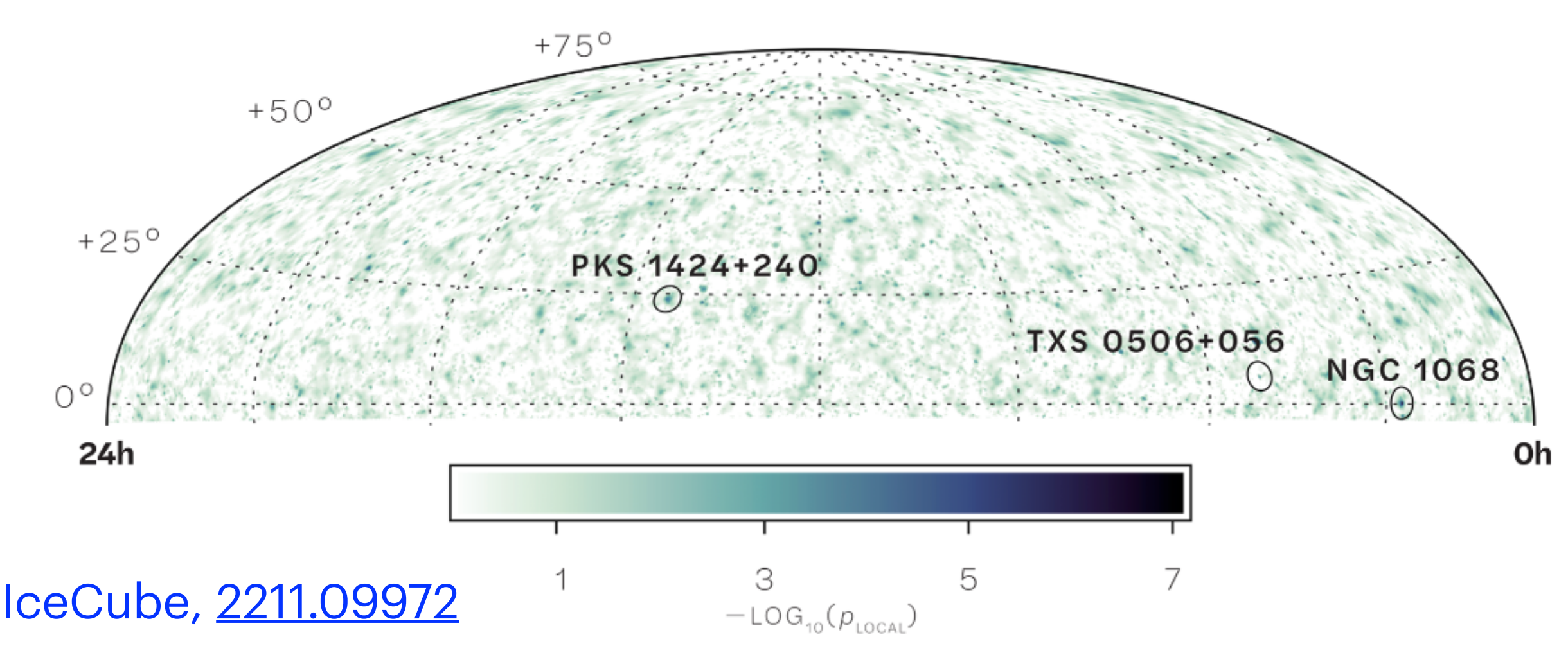
QDino Search using HEN Point Sources



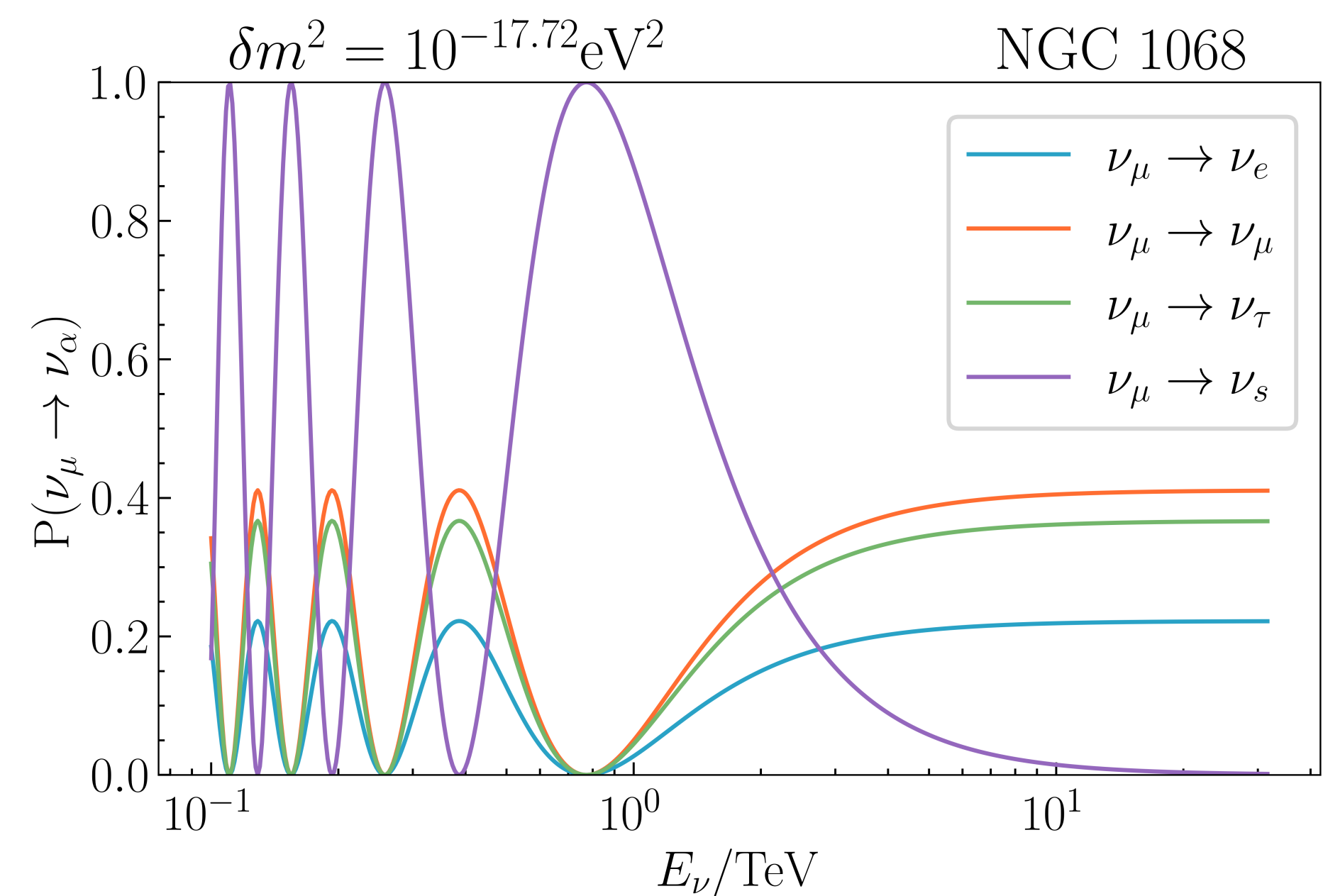
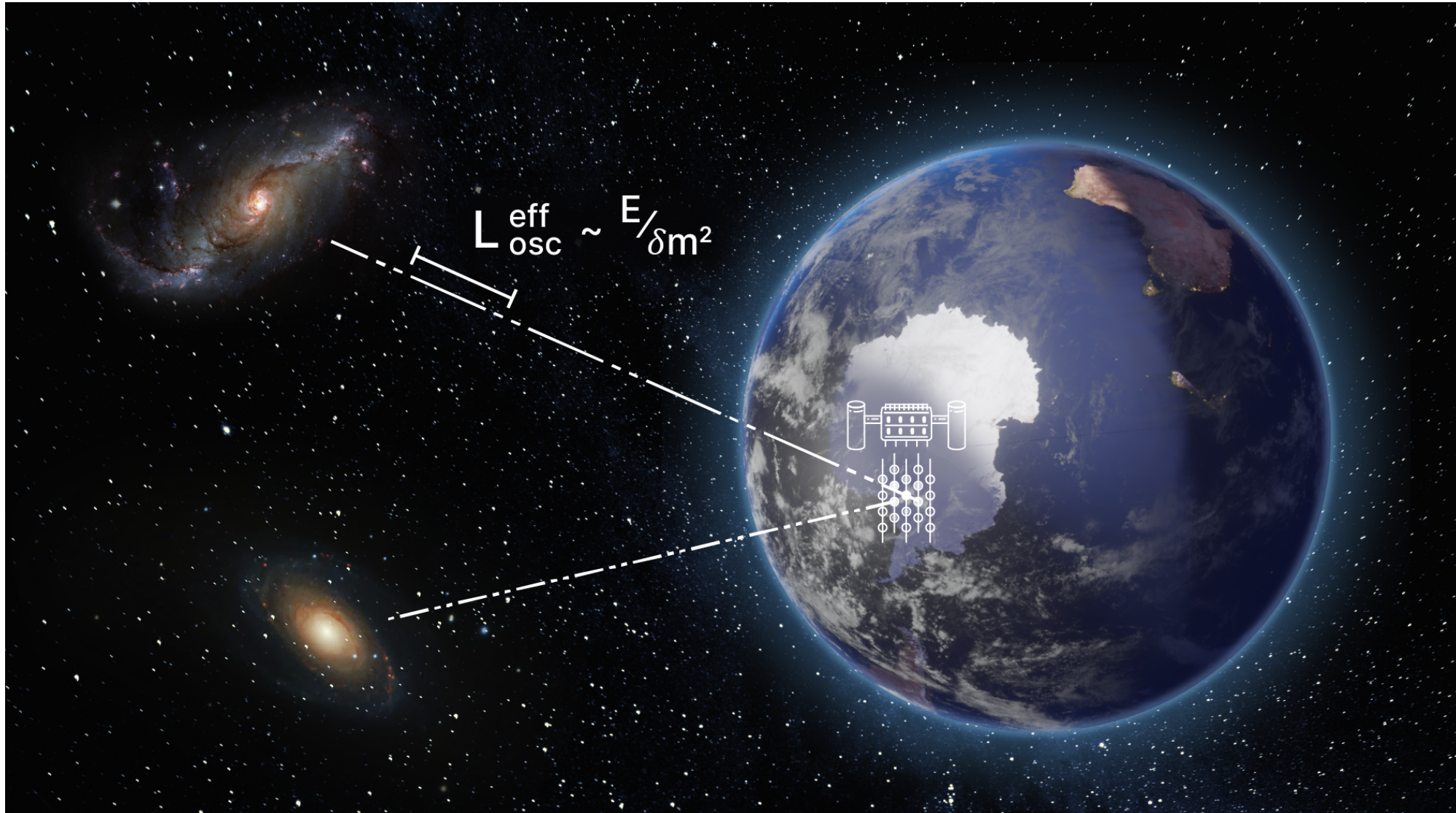
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QDino Search using HEN Point Sources

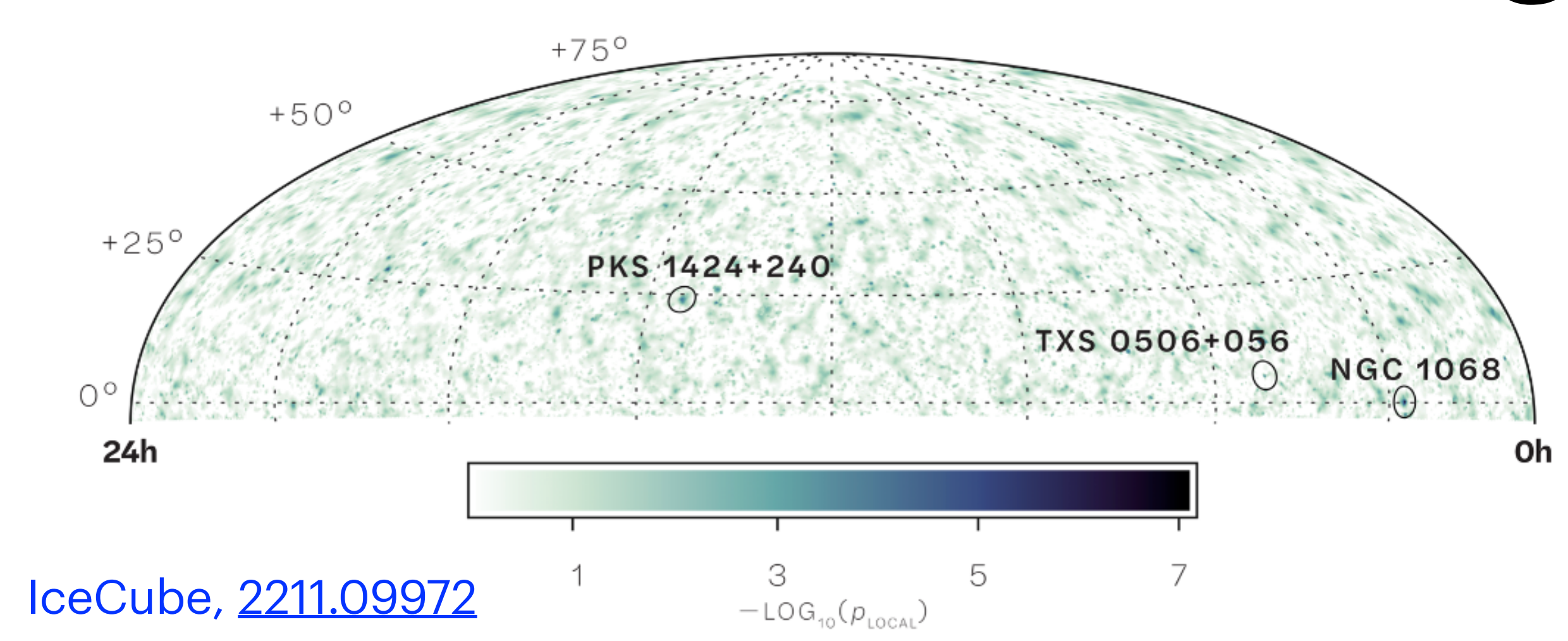


Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\text{local}}$	$\Phi_{90\%}$
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Carlioni, Martinez-Soler, Arguelles, Babu, BD, [2212.00737](#)

QDino Search using HEN Point Sources

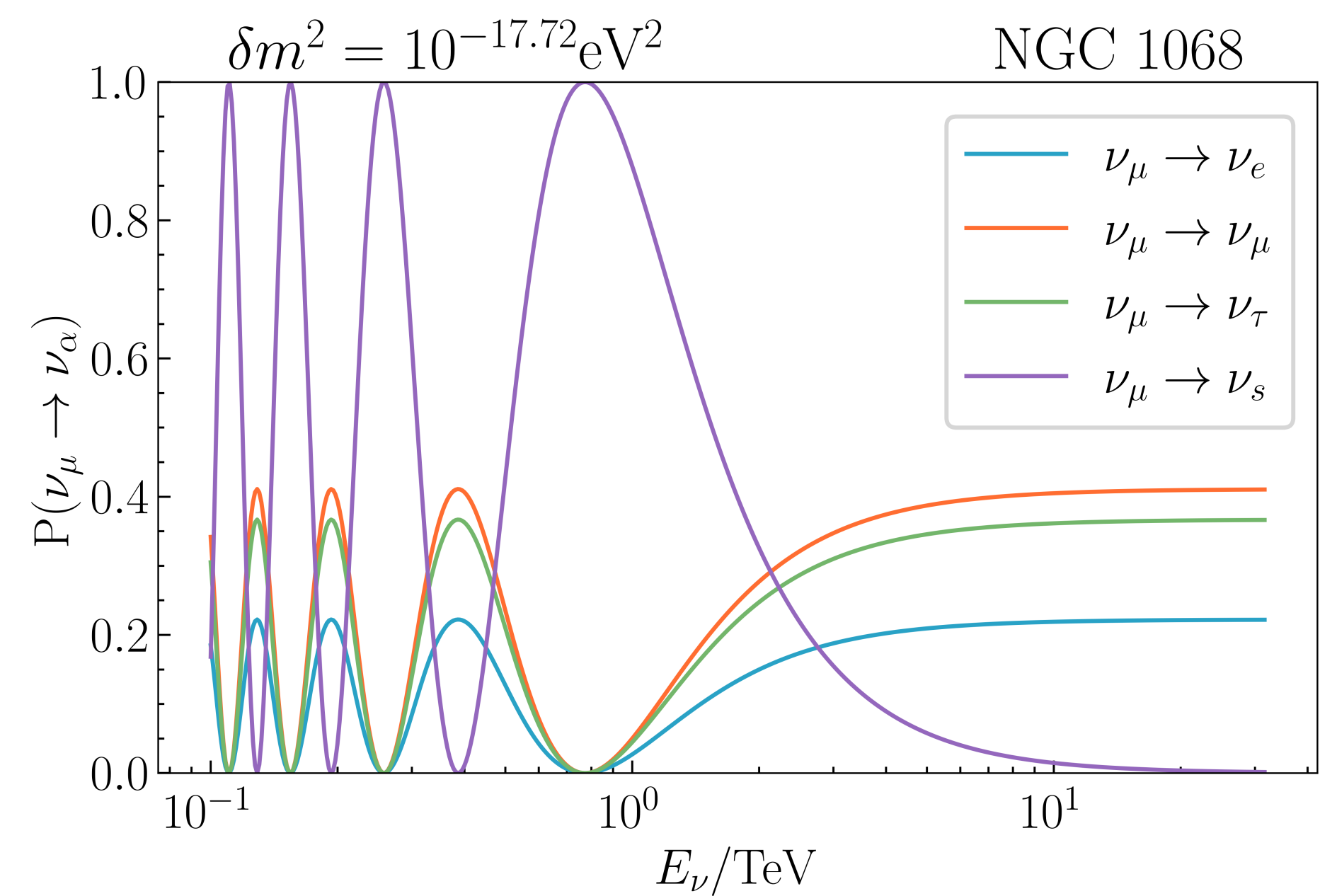
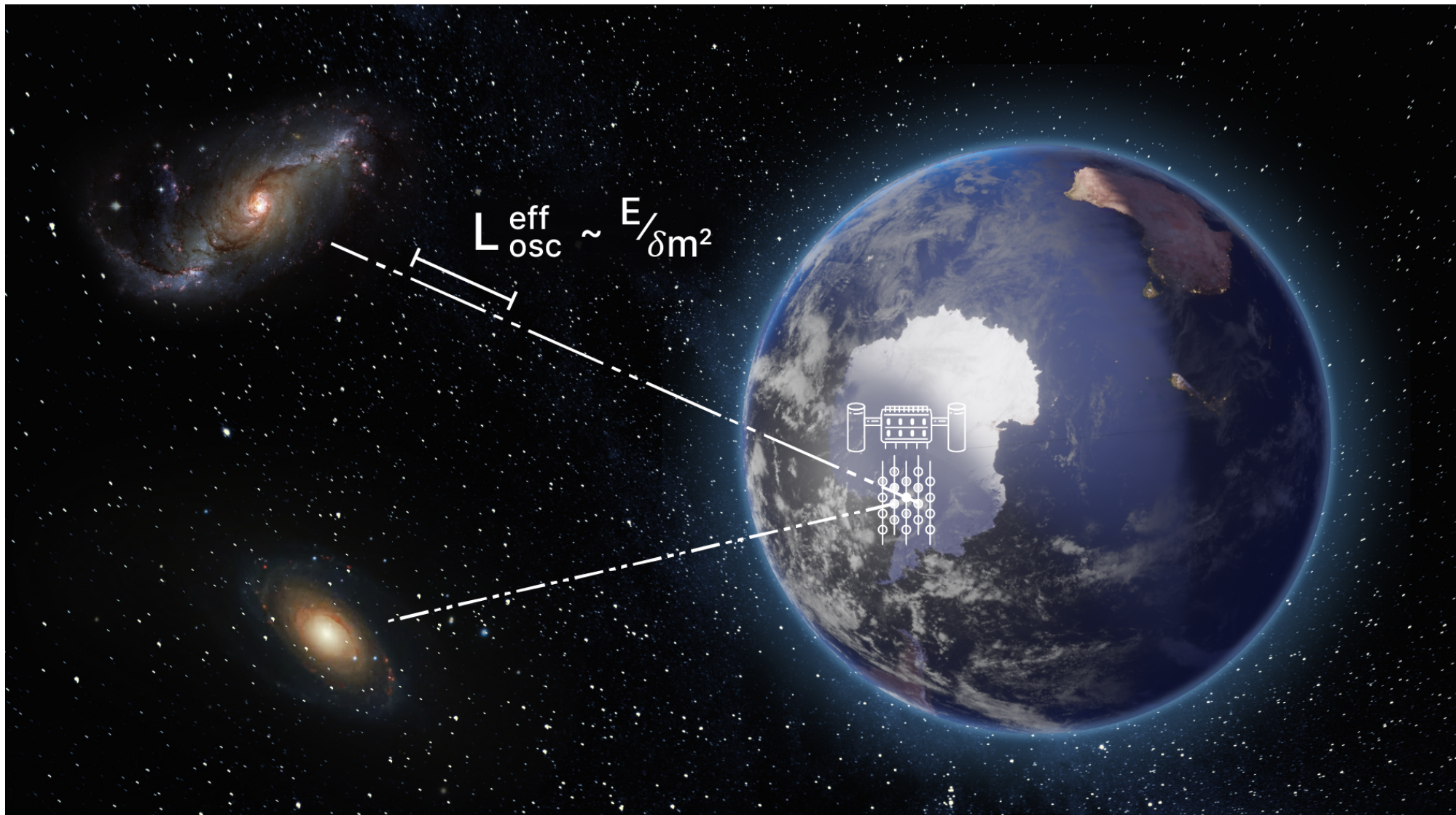


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TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5

$$P_{\alpha\beta} = \frac{1}{2} \sum_{j=1}^3 |U_{\beta j}|^2 |U_{\alpha j}|^2 \left[1 + \cos \left(\frac{\delta m_j^2 L_{\text{eff}}}{2E_\nu} \right) \right],$$

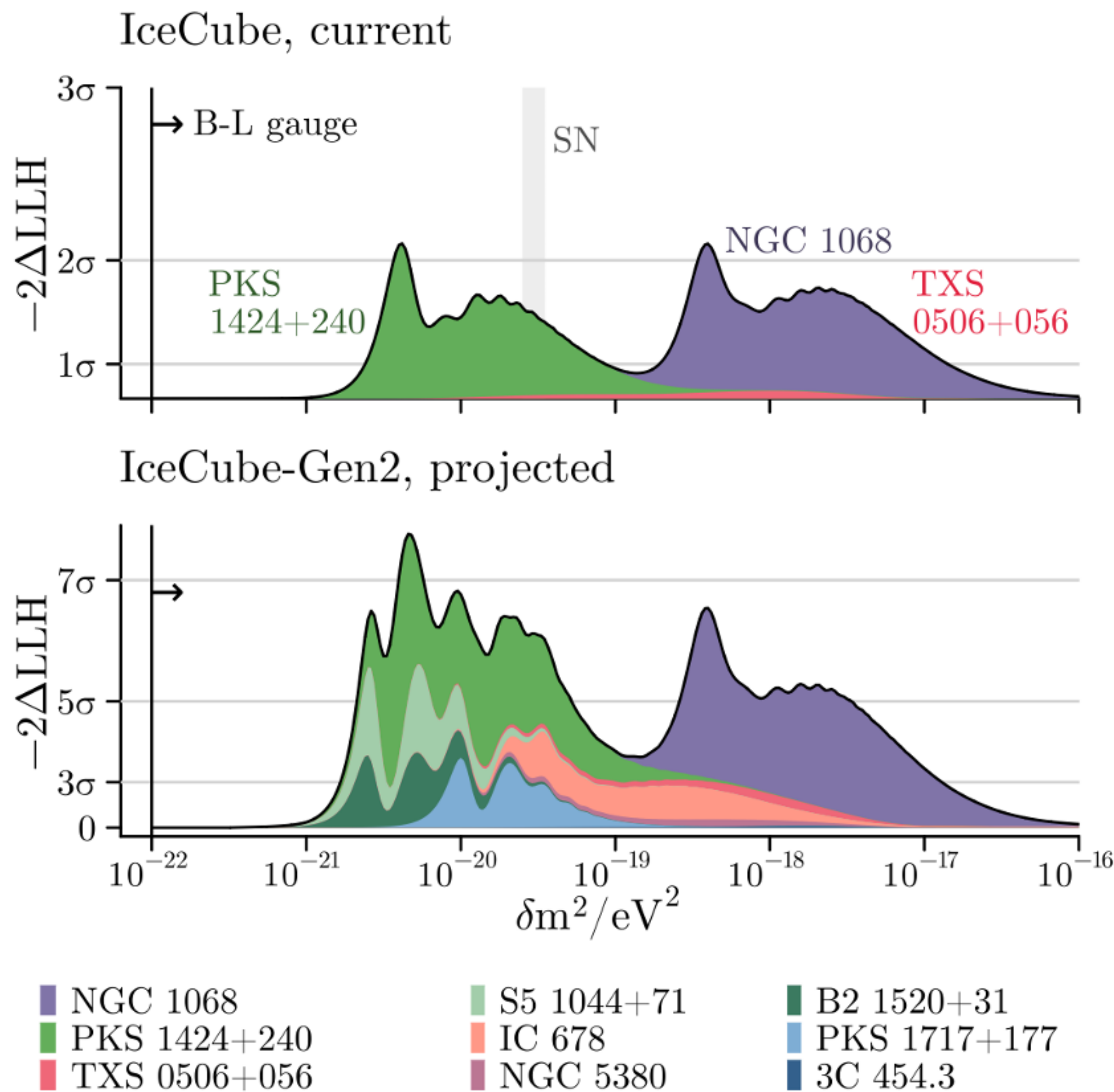
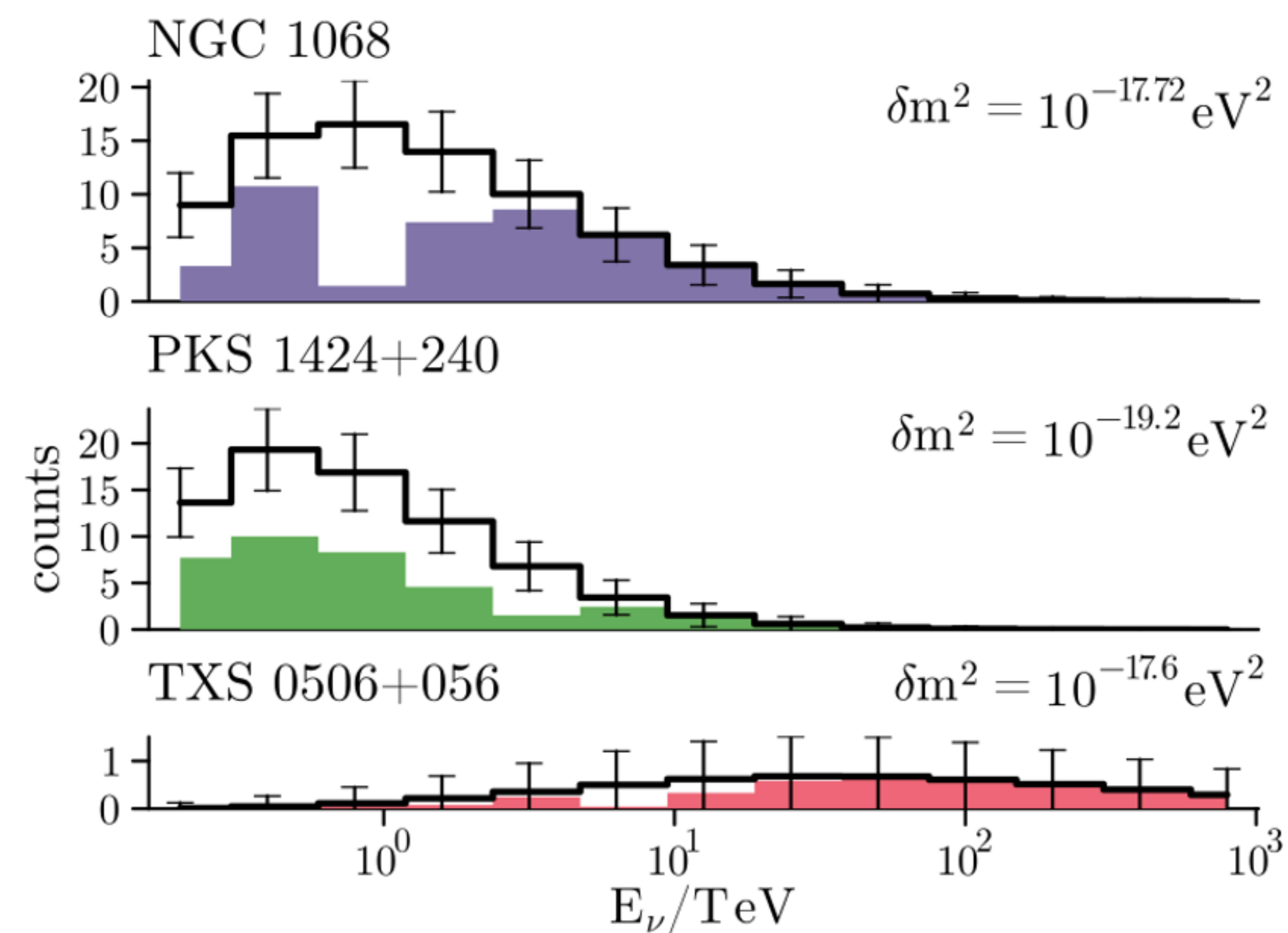
with $L_{\text{eff}} = \int \frac{dz}{H(z)(1+z)^2}$ and $H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + (1 - \Omega_m - \Omega_\Lambda)(1+z)^2}$.

Carloni, Martinez-Soler, Arguelles, Babu, BD, [2212.00737](#)



Constraining QDinos from IceCube Point-Source Data

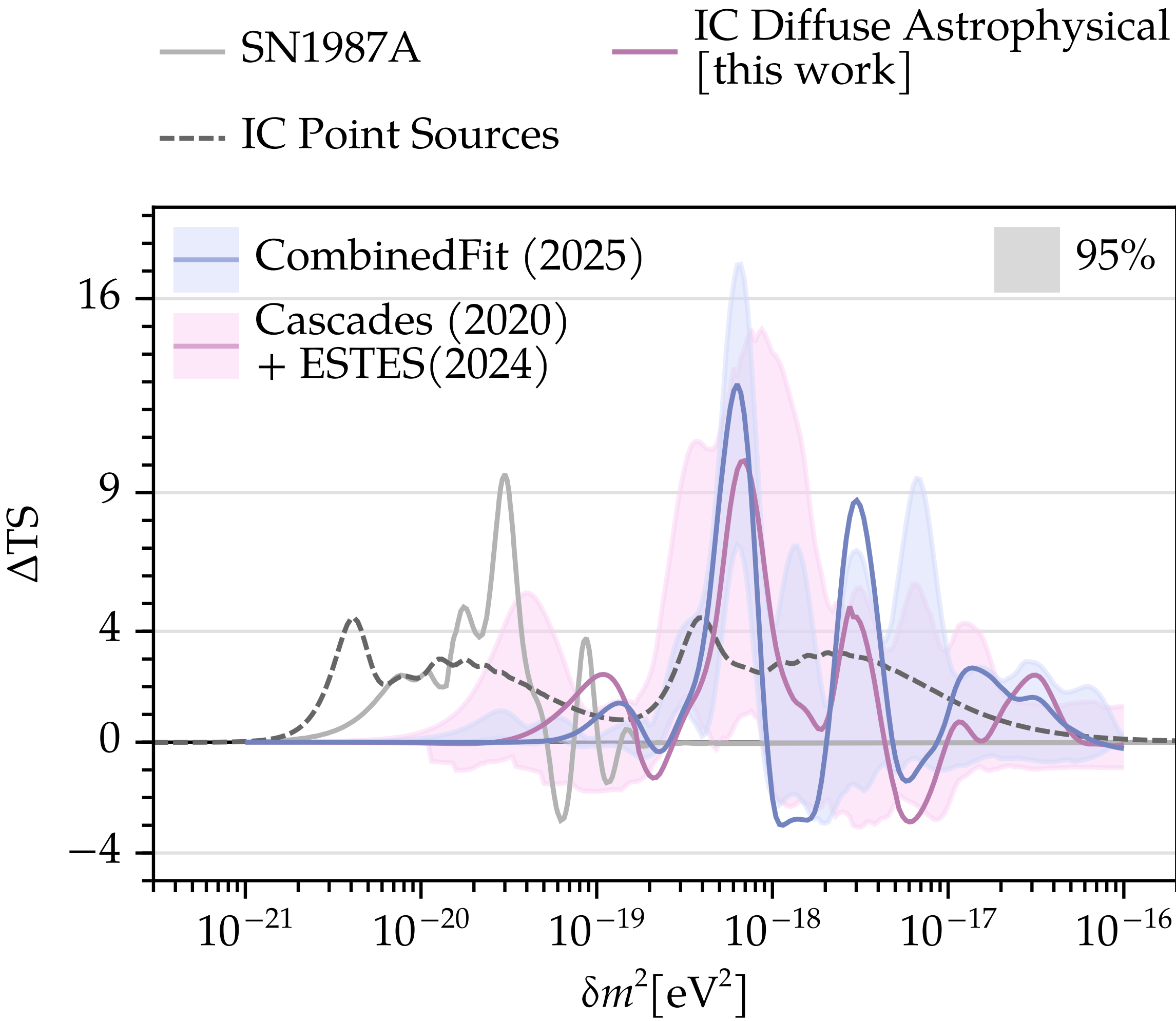
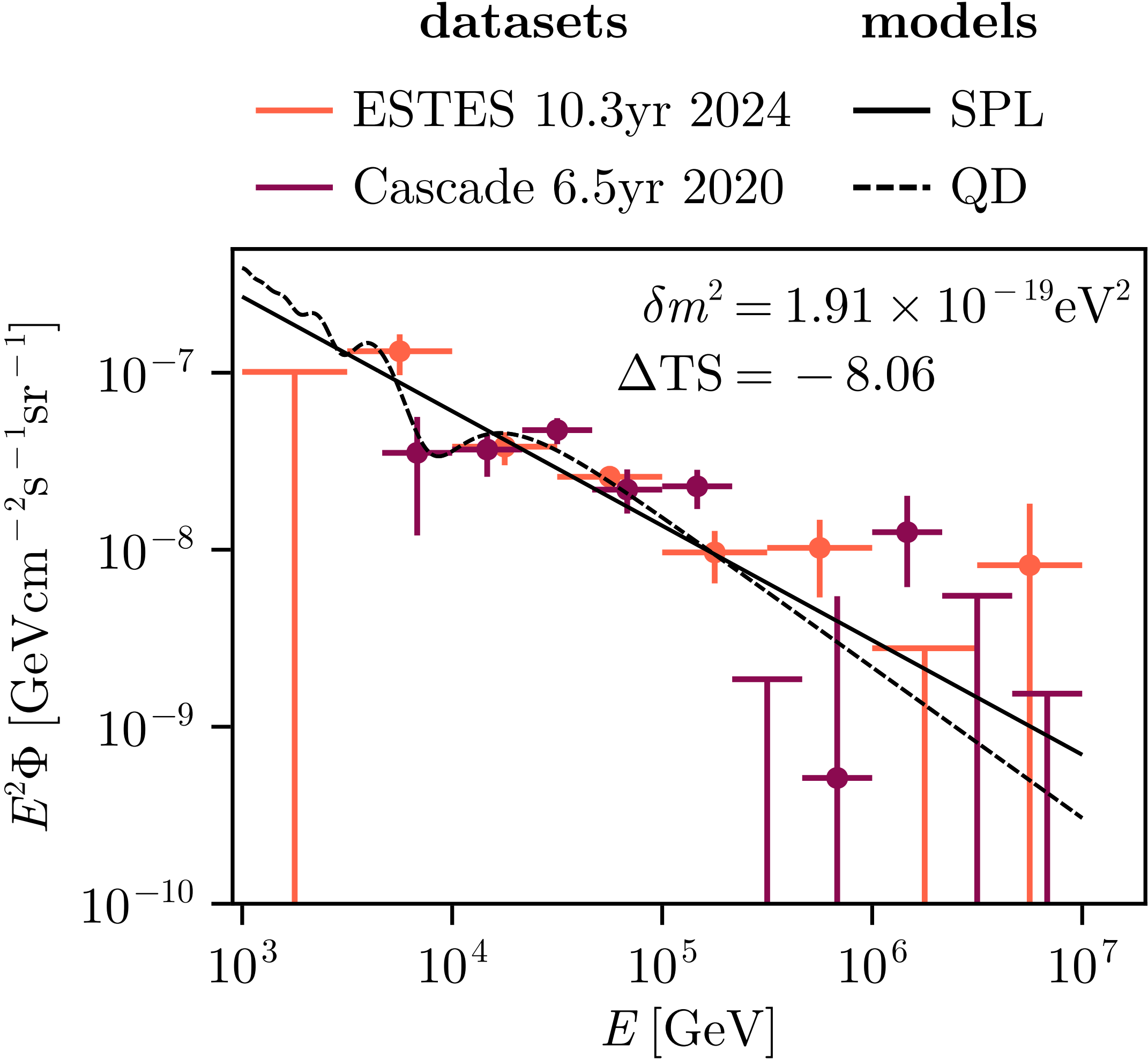
Source	Source Type	$-\log_{10} p_{\text{local}}$	$\hat{n}_s$	$\hat{\gamma}$	z
NGC 1068	SBG/AGN	7.0 (5.2σ)	79	3.2	0.0038 (16 Mpc)
PKS 1424+240	BLL	4.0 (3.7σ)	77	3.5	0.6047 (2.6 Gpc)
TXS 0506+056	BLL/FSRQ	3.6 (3.5σ)	5	2.0	0.3365 (1.4 Gpc)



Carlioni, Martinez-Soler, Arguelles, Babu, BD, [2212.00737](#)



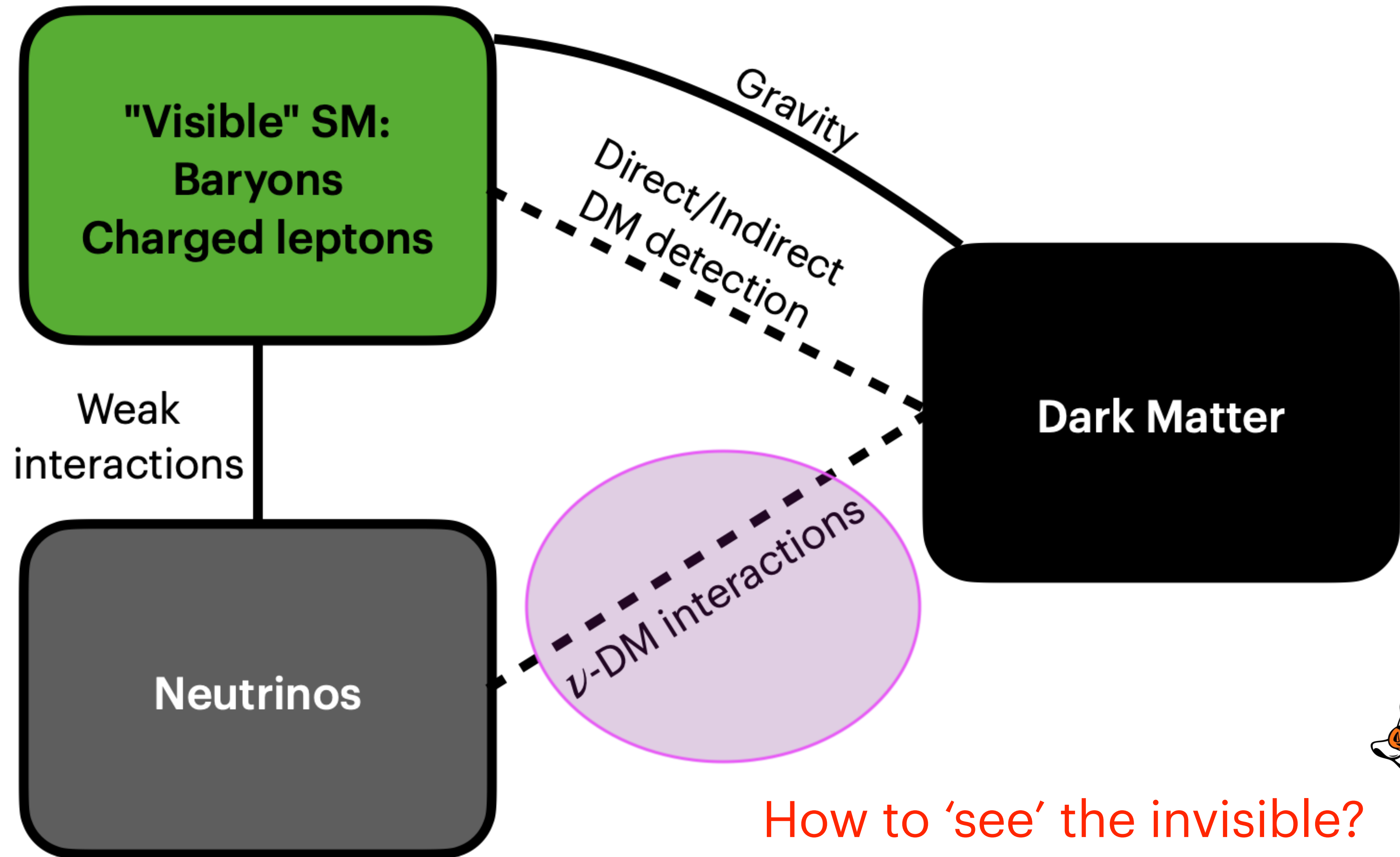
New QDino Constraints from IceCube Diffuse Data



Carlioni, Porto, Arguelles, BD, Jana, [2503.19960 v2](#)

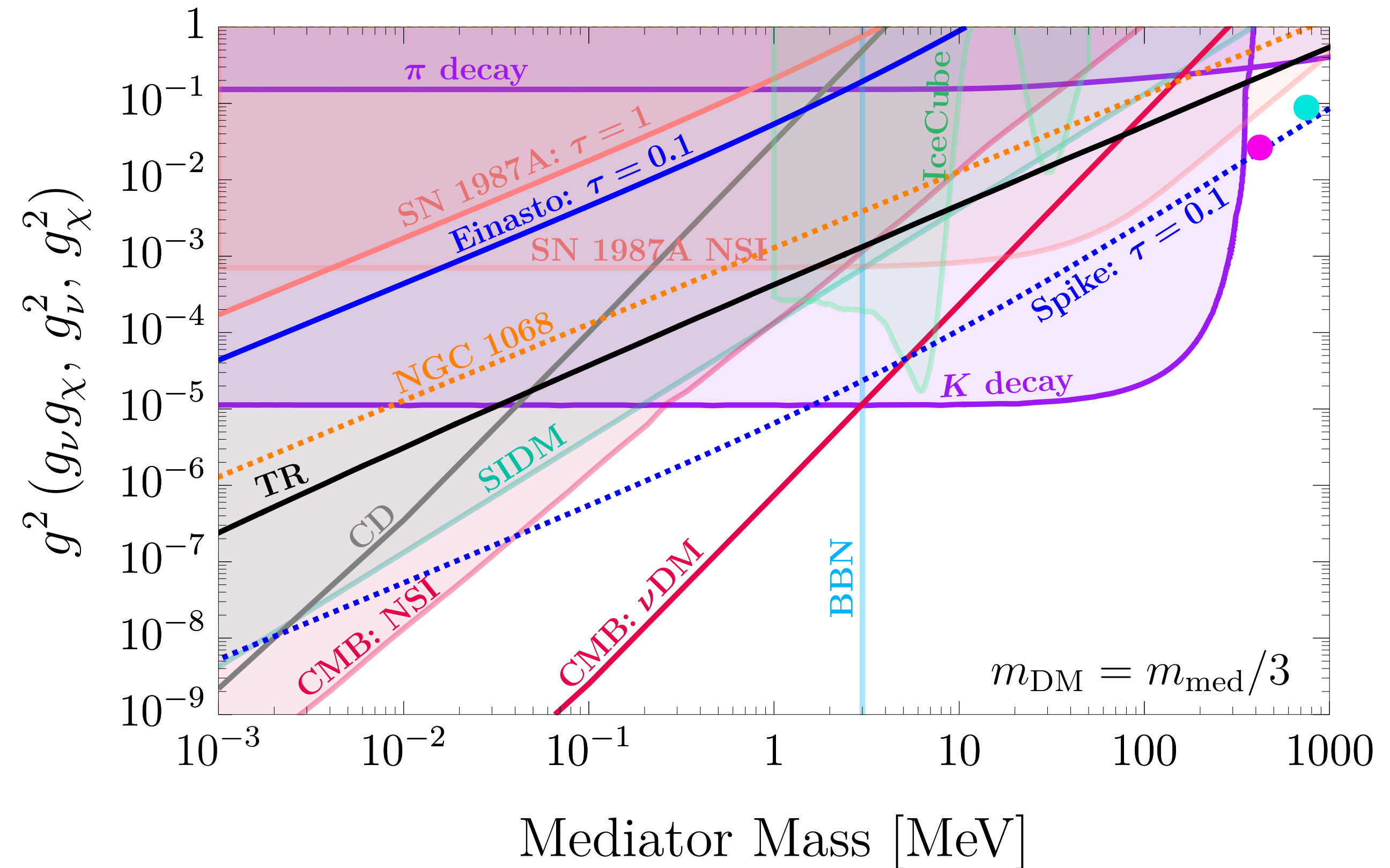
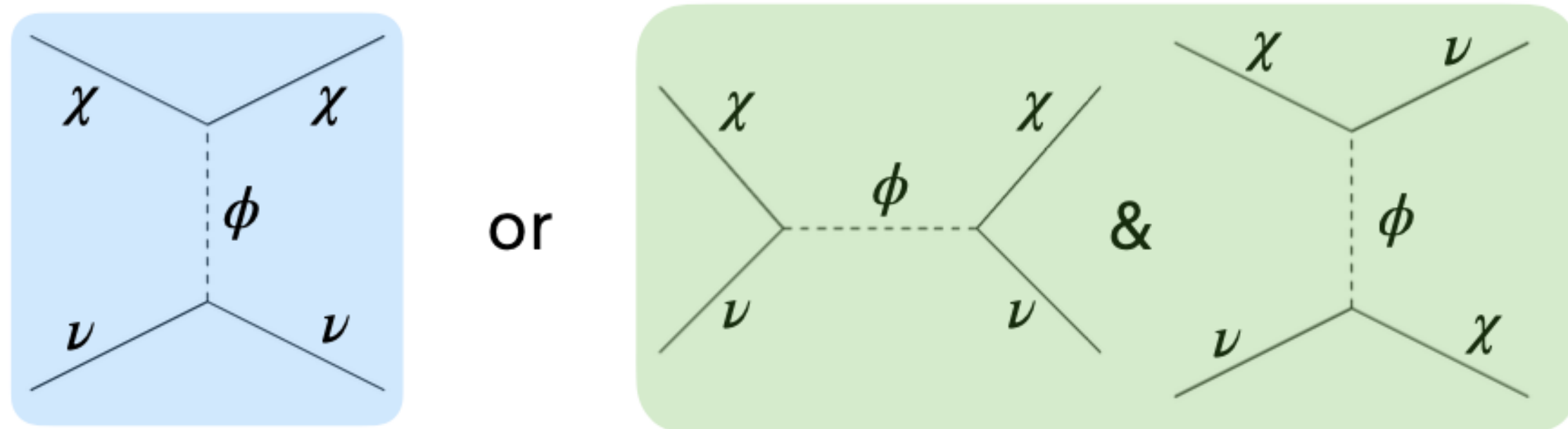


Dark Side of Neutrinos



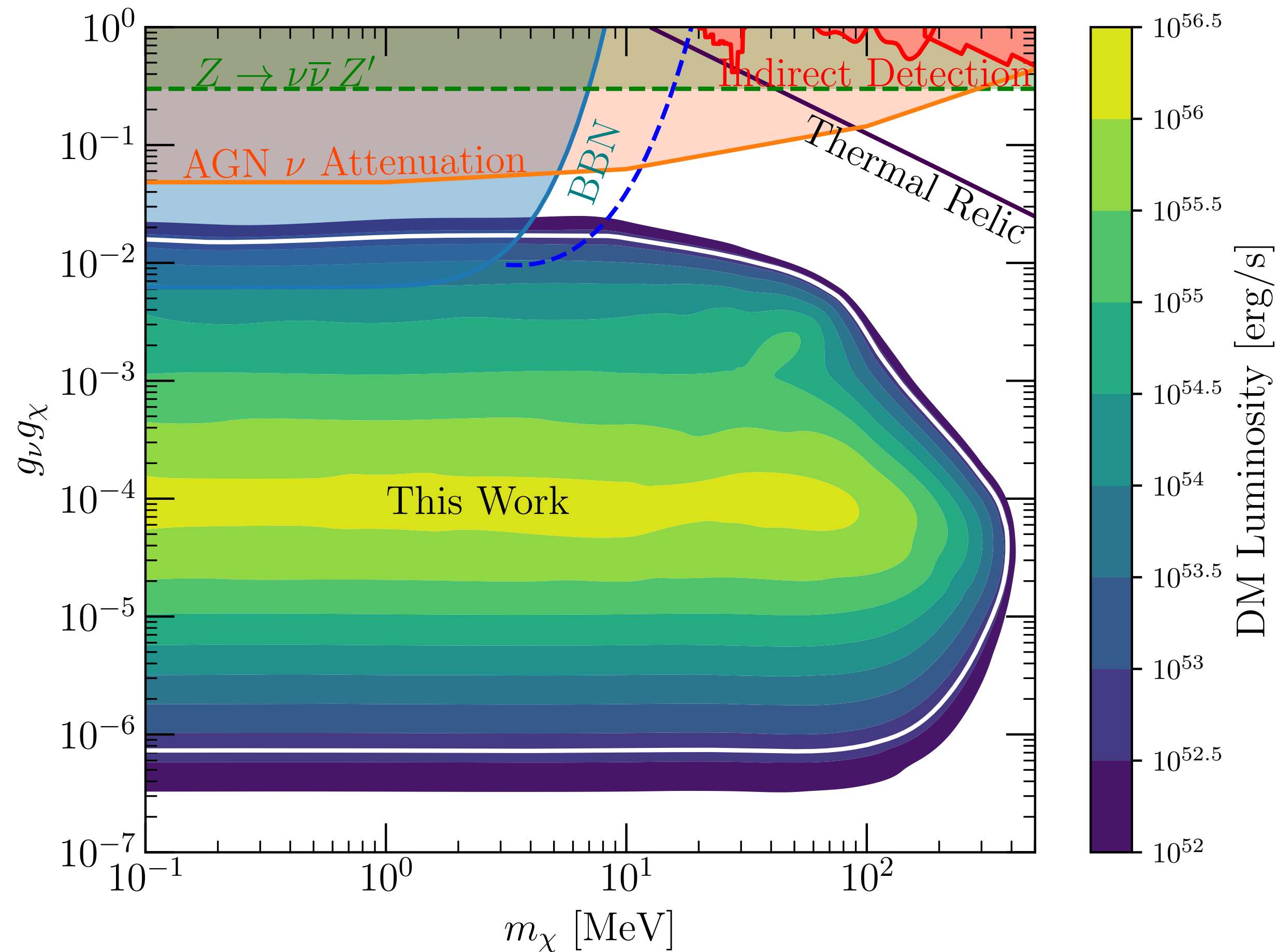
Constraints on Neutrino-DM Interactions

- Mostly applicable for ‘light’ dark sector.
- 3 types of constraints:
 - **Cosmological:** BBN, CMB, Collisional Damping, Neutrino free-streaming, Relic Density*
 - **Astrophysical:** Stellar, Supernova, High-energy neutrinos, Self-interacting DM
 - **Laboratory:** Decays of mesons, muon, tau, W, Z; (double) beta decay.
- Adopt a simplified model framework.

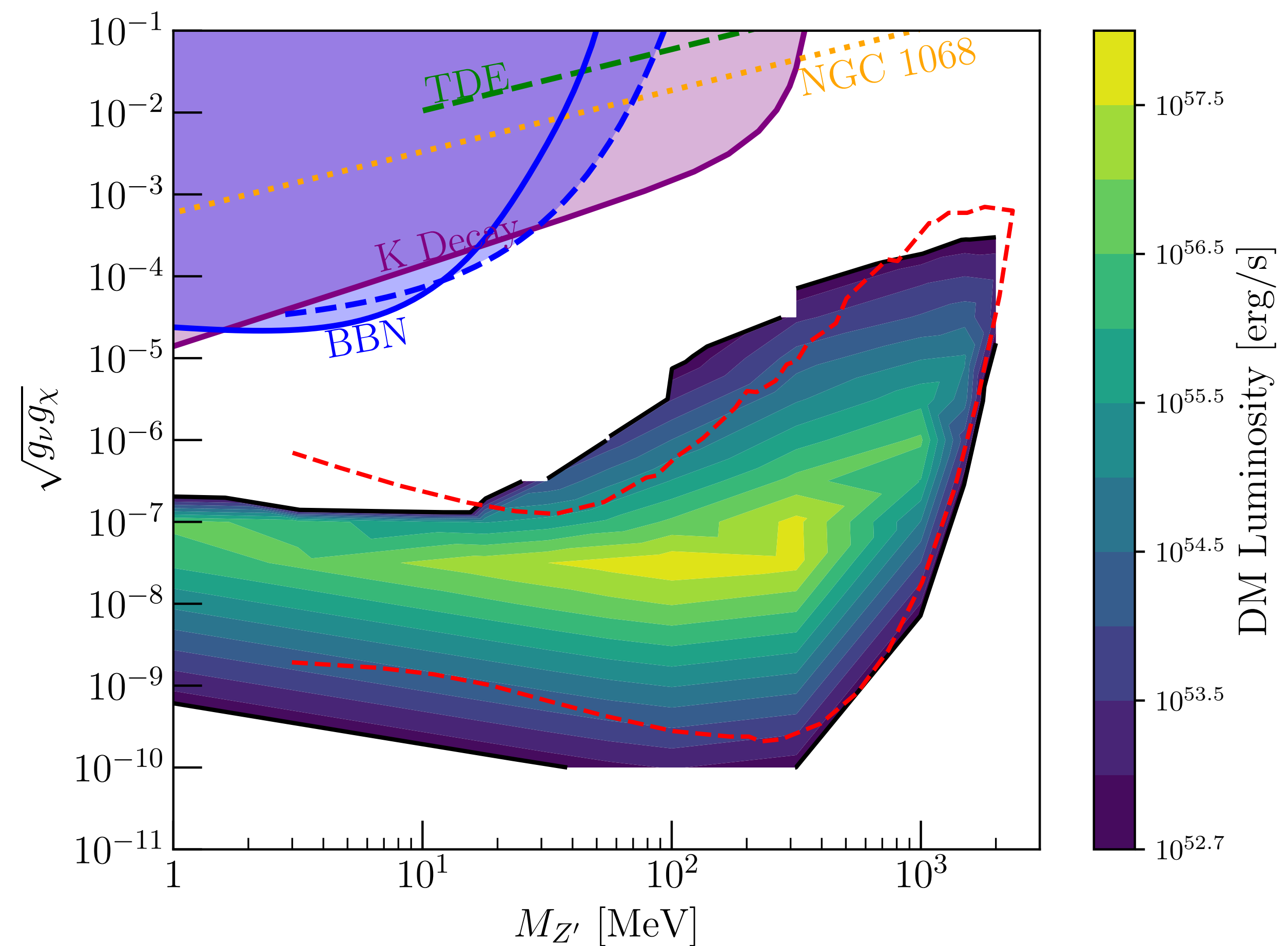


BD, Kim, Sathyan, Sinha, Zhang, [2507.01000](#)

SN1987A Limits on Neutrino-DM Interactions



Heavy mediator limit



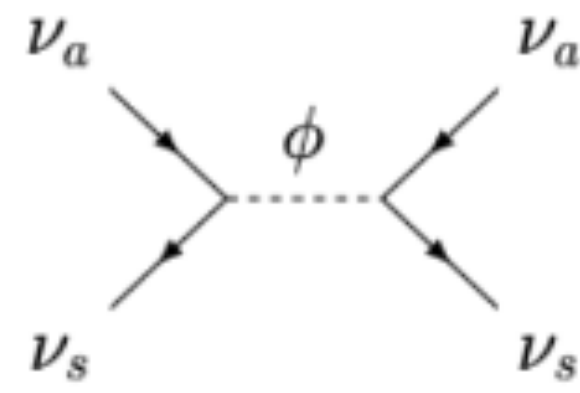
Assuming $m_\chi = m_{Z'}/3$

Cappiello, BD, Patwardhan, [2503.09691](#);

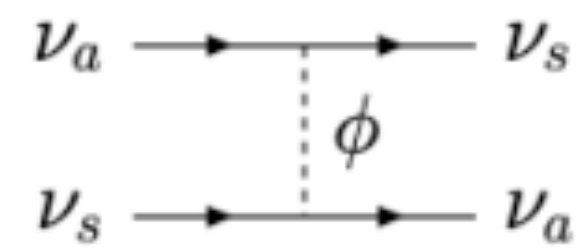
See also Manzari, Camalich, Spinner, Ziegler, [2307.03143](#) and A. Suliga's talk for other supernova constraints

DM Production in the Early Universe using Neutrino-DM NSI

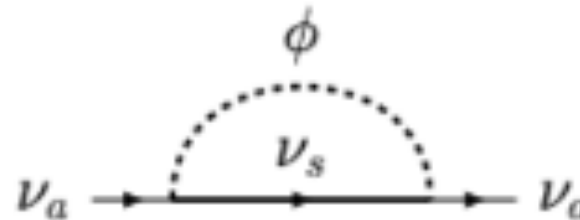
$$-\mathcal{L} \supset y_{as} \bar{\nu}_a \nu_s \phi + \text{h.c.}$$



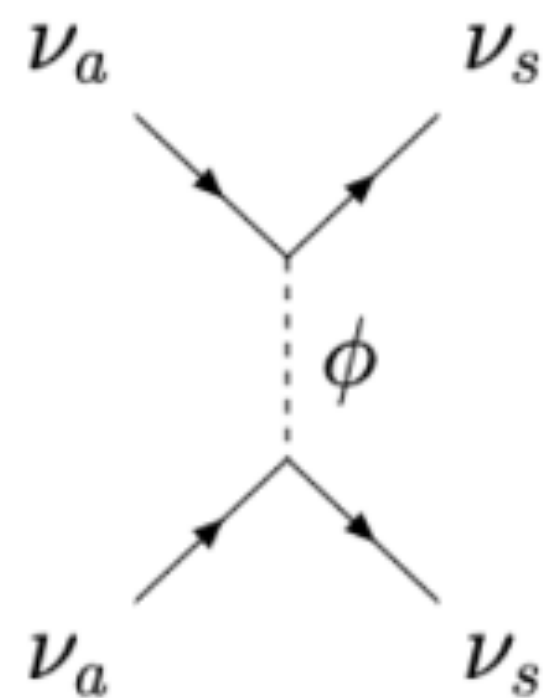
(a)



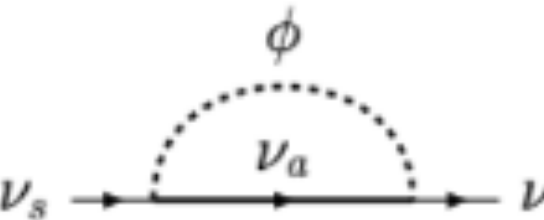
(b)



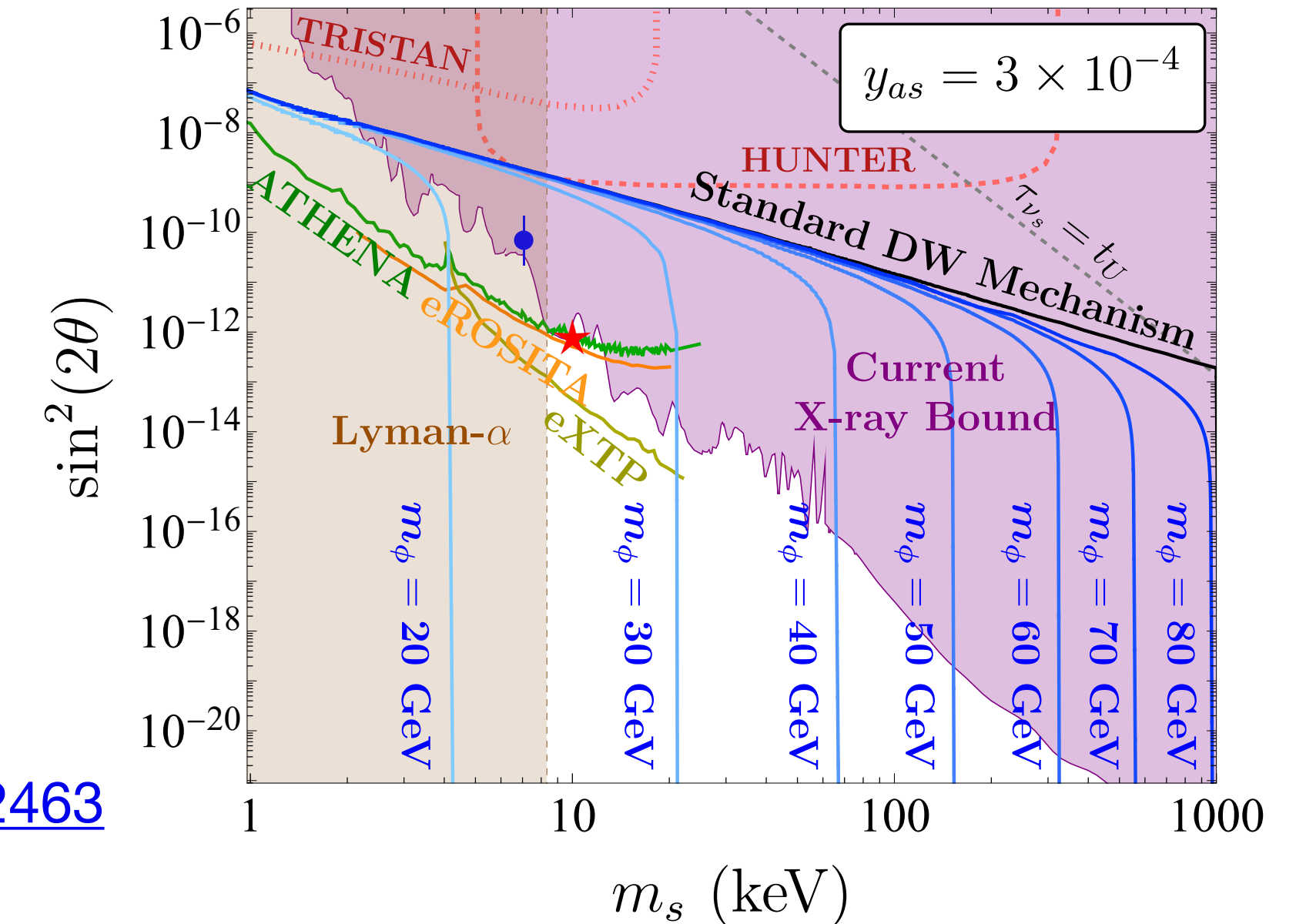
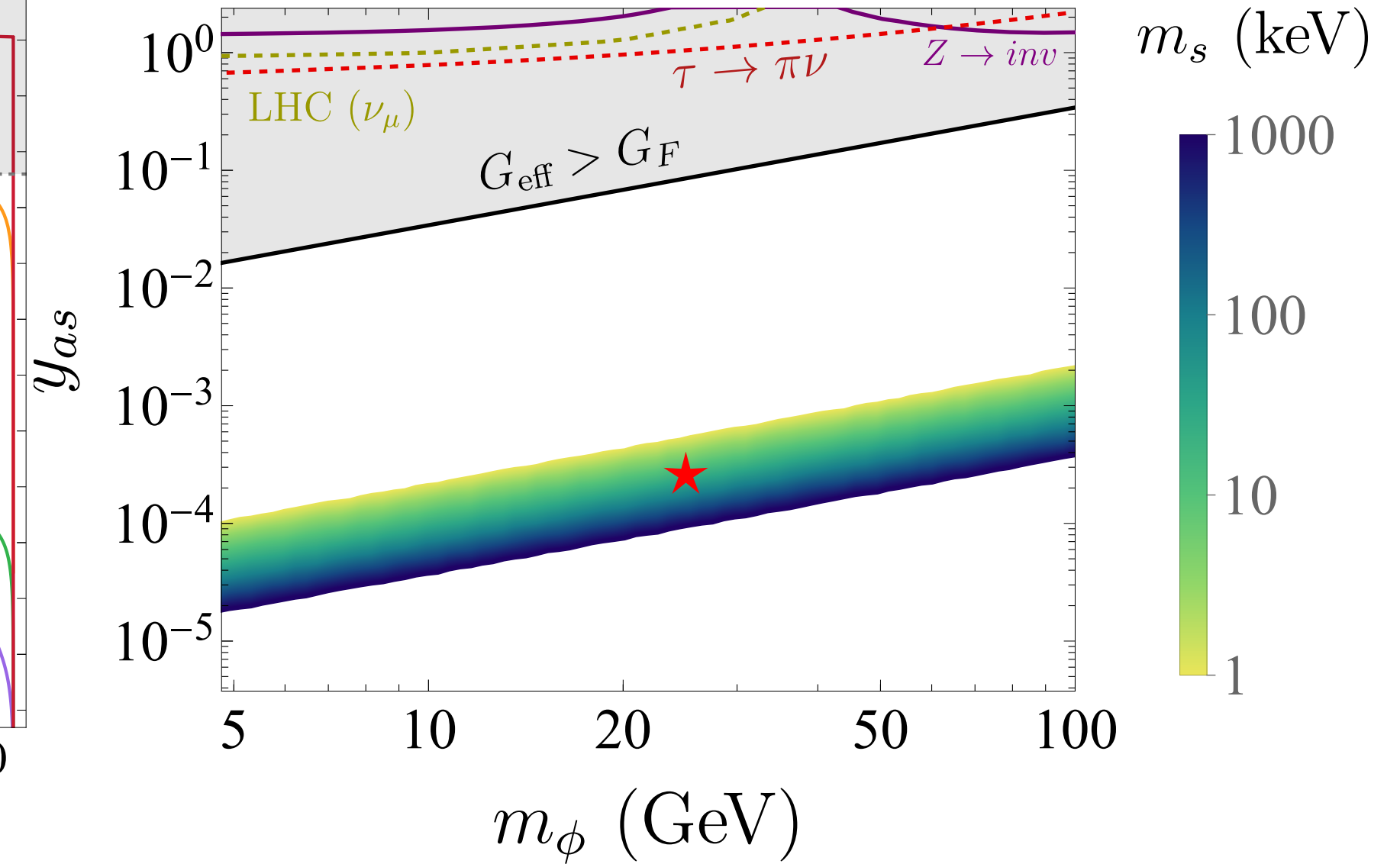
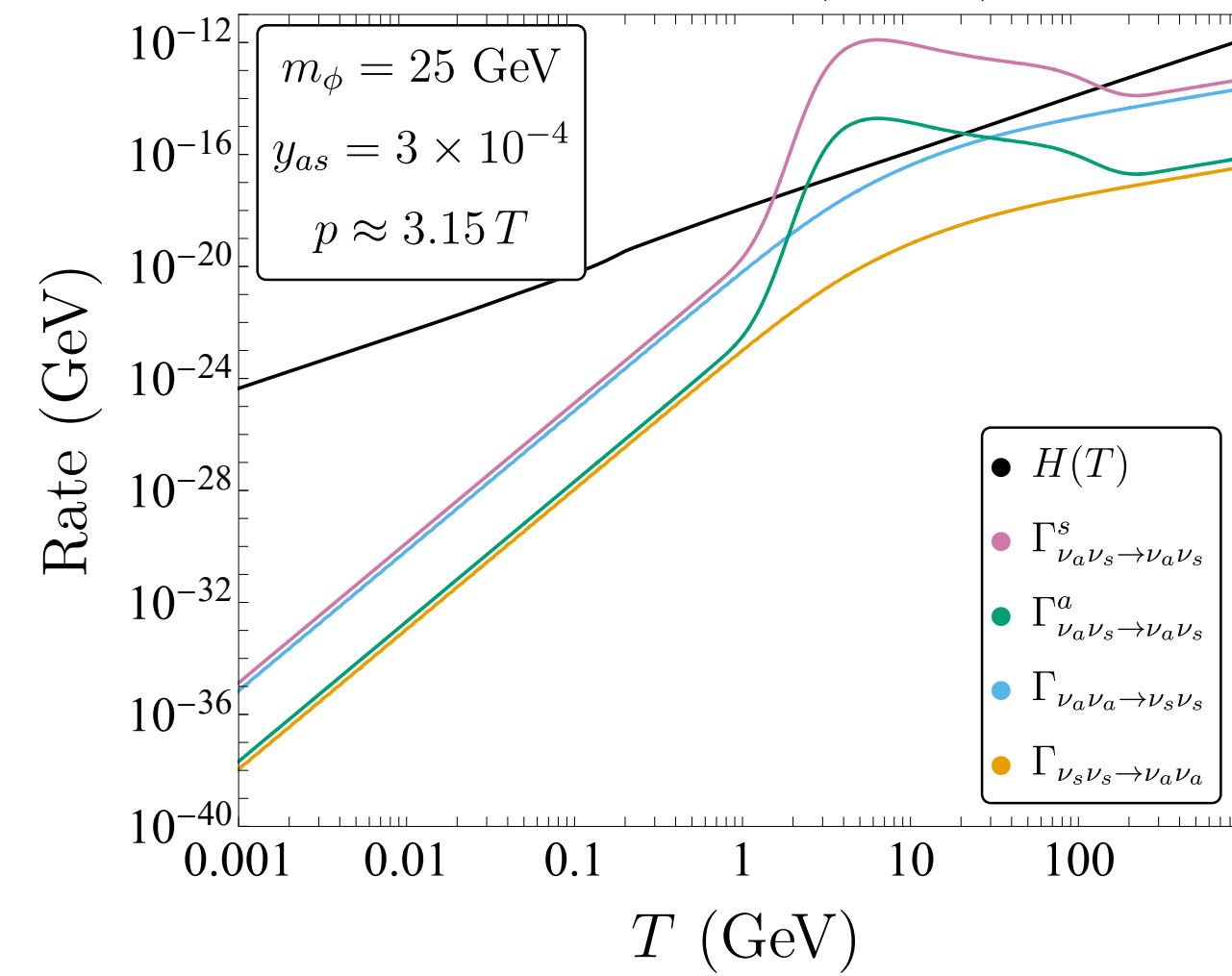
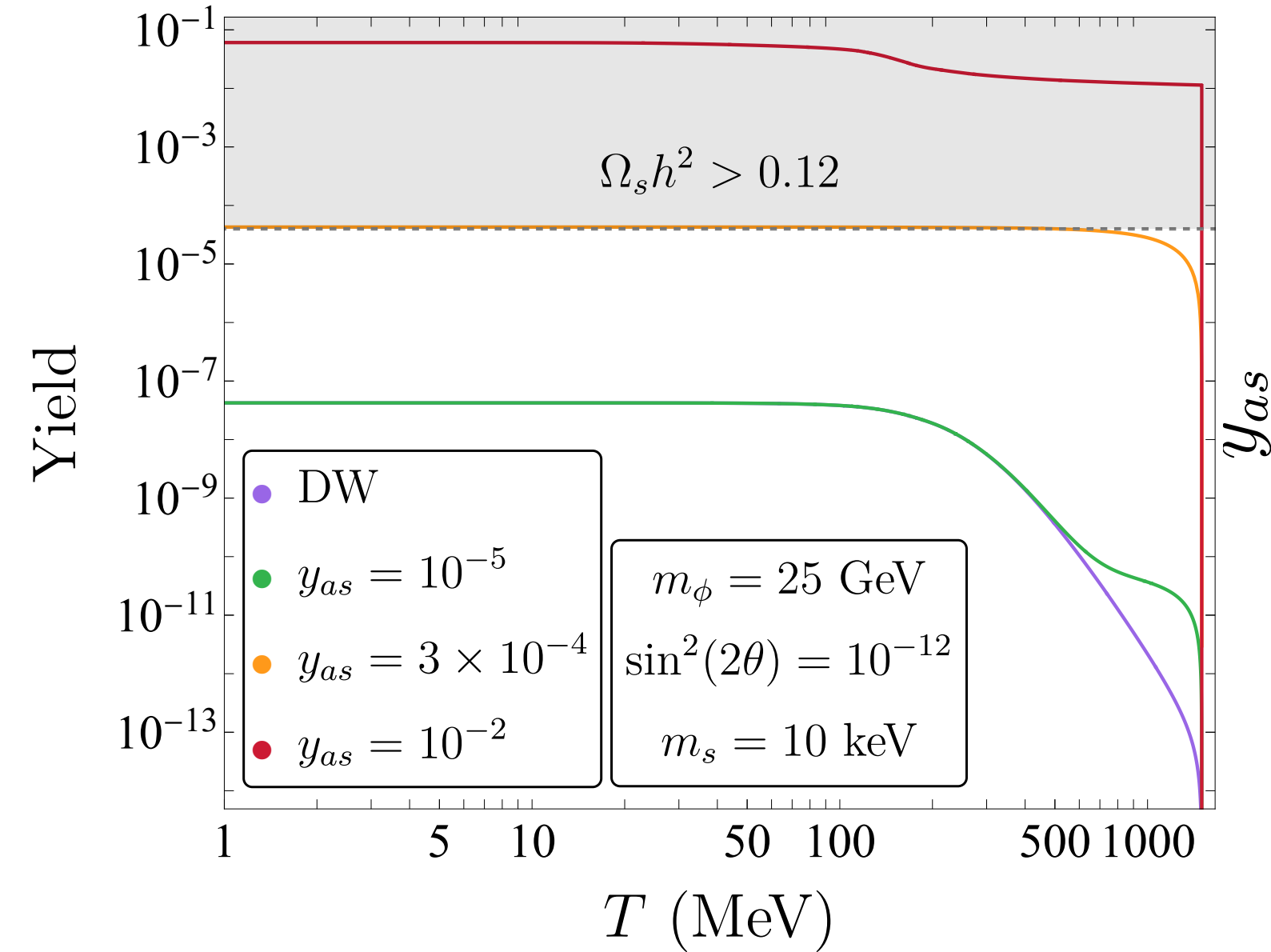
(d)



(c)



(e)



BD, Dutta, Goswami, Tang, Ramachandran, [2505.22463](#)

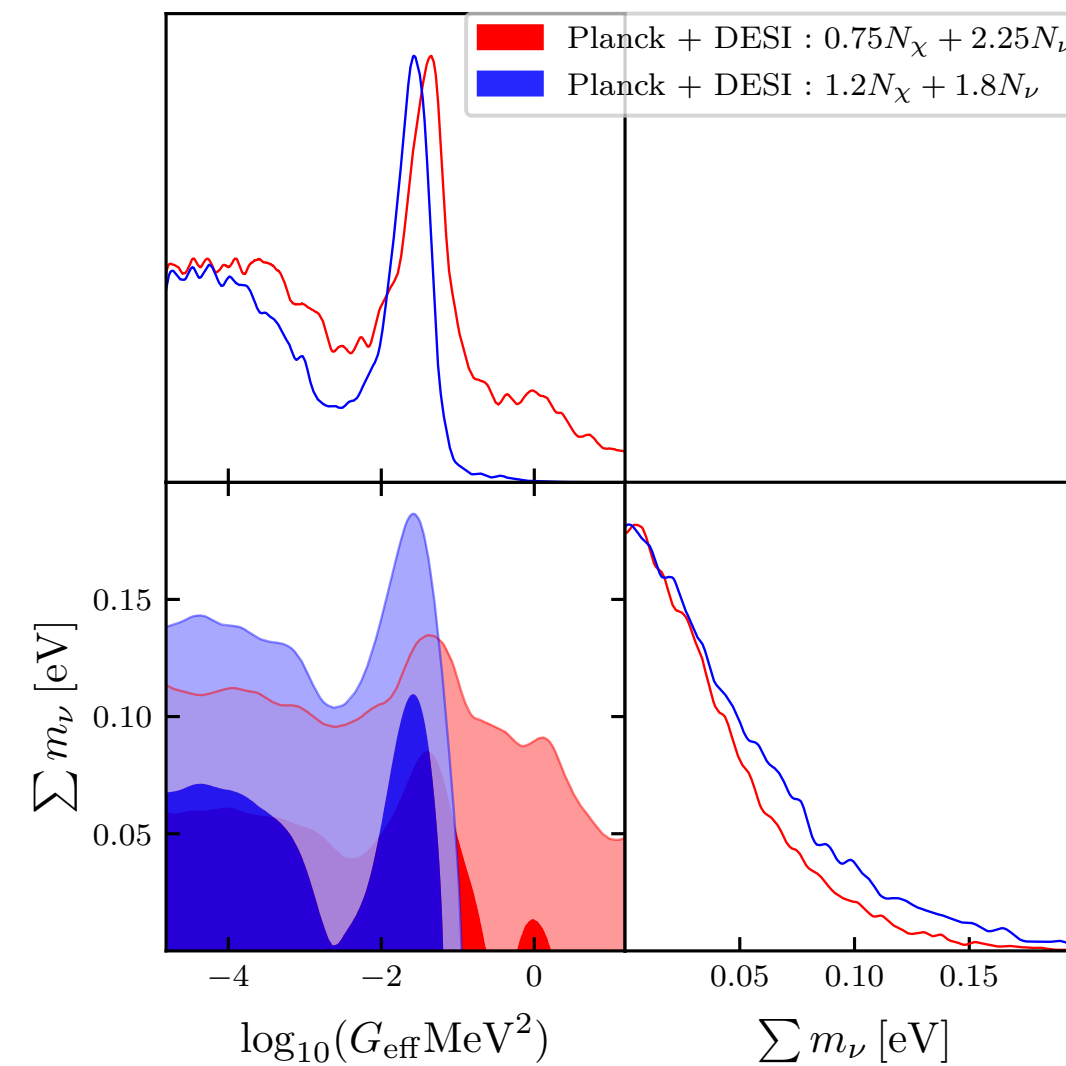
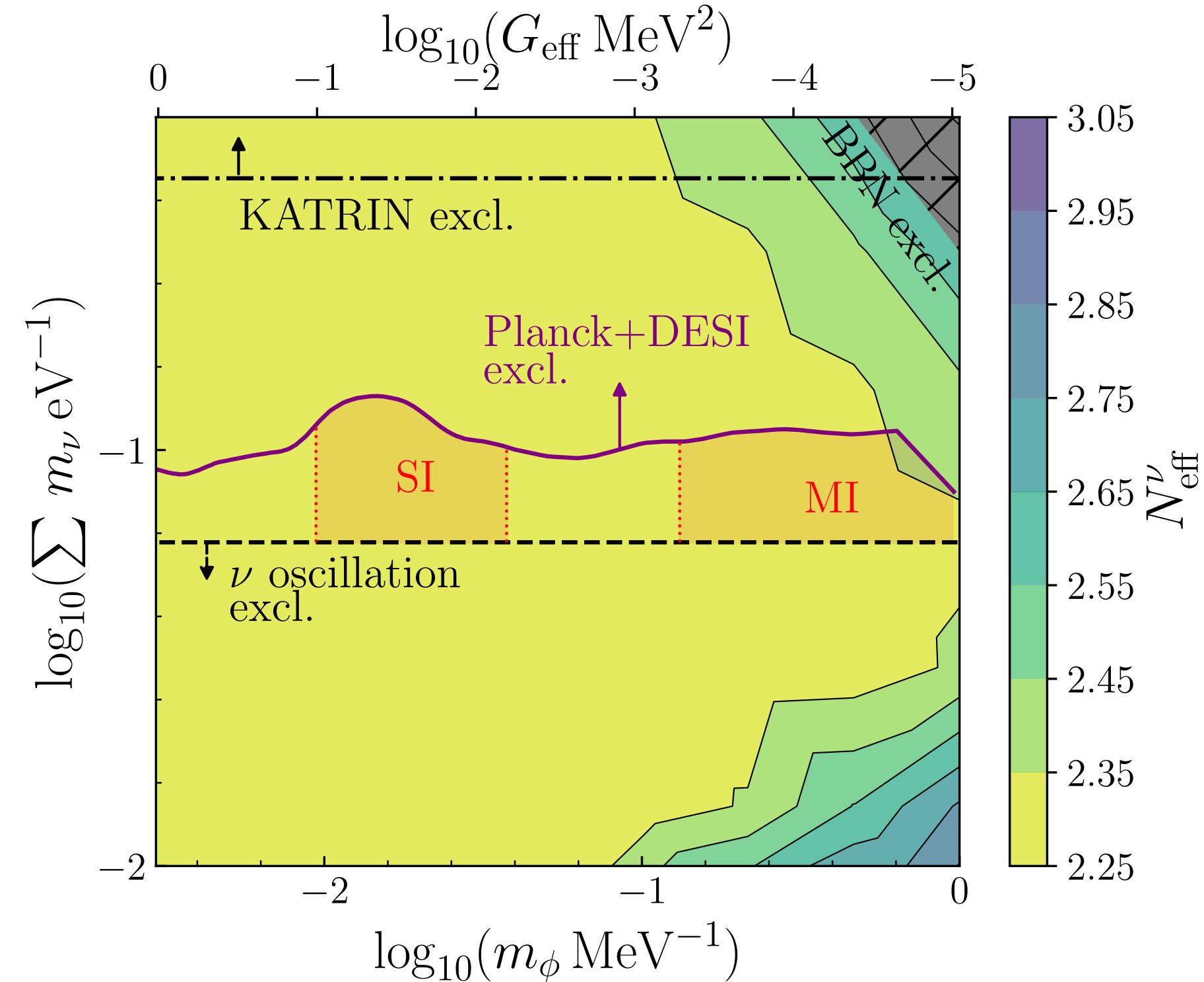
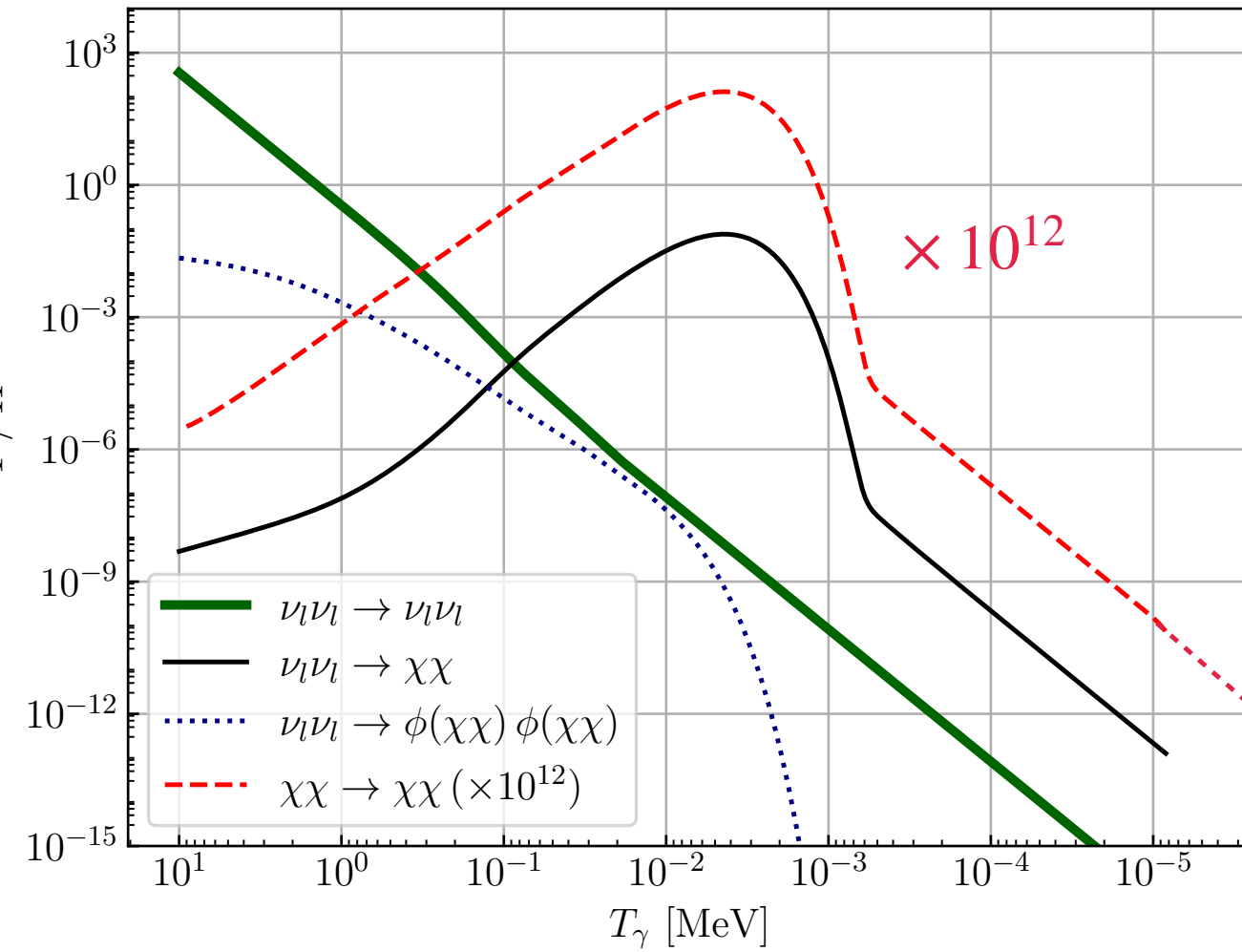
Dark Radiation Can Mimick (Flavor-Specific) Neutrino Self-Interaction

$$\mathcal{L}_{\text{eff}} = G_{\text{eff}}(\bar{\nu}\nu)(\bar{\nu}\nu)$$

$$G_{\text{eff}} = \begin{cases} (4.7^{+0.4}_{-0.6} \text{ MeV})^{-2} & (\text{SI}\nu) \\ (89^{+171}_{-61} \text{ MeV})^{-2} & (\text{MI}\nu) \end{cases}$$

Kreisch, Cyr-Racine, Dore, [1902.00534](#)

$$\Delta\mathcal{L} = \left(y^{\alpha i} L_{\alpha} N_i^c H - \frac{1}{2} M_N^{ii} N_i^c N_i^c + h.c. \right) - \frac{1}{2} \lambda_{\phi N} \phi N^c N^c - \frac{1}{2} \lambda_{\phi \chi} \phi \chi^2$$



Das, BD, Gao, Ghosh, Kim, [2506.08085](#)

Blinov, Kelly, Krnjaic, McDermott, [1905.02727](#)

Conclusions

- Neutrino oscillation is the first (and so far only) *laboratory* evidence of BSM physics.
- Next-generation neutrino experiments are poised to resolve the remaining issues in the **3-neutrino oscillation paradigm**.
- Still leave **many open questions** answered in neutrino physics.
- Cast a broad net covering **multiple experimental frontiers**.
- Possible connection to other puzzles, like **dark matter and leptogenesis**.

