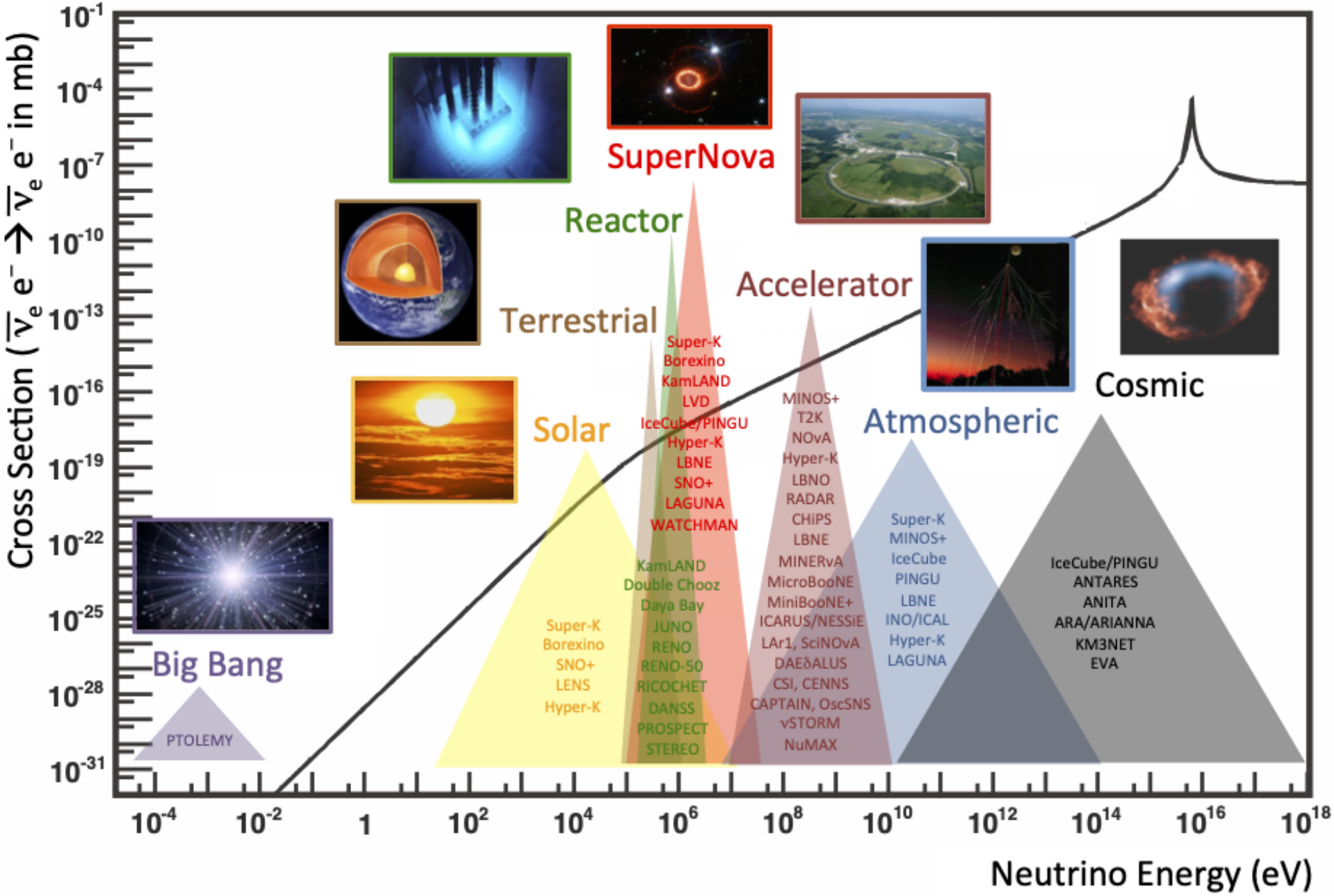
Probing Neutrino Mass Models at Neutrino Telescopes

Bhupal Dev
(bdev@wustl.edu)

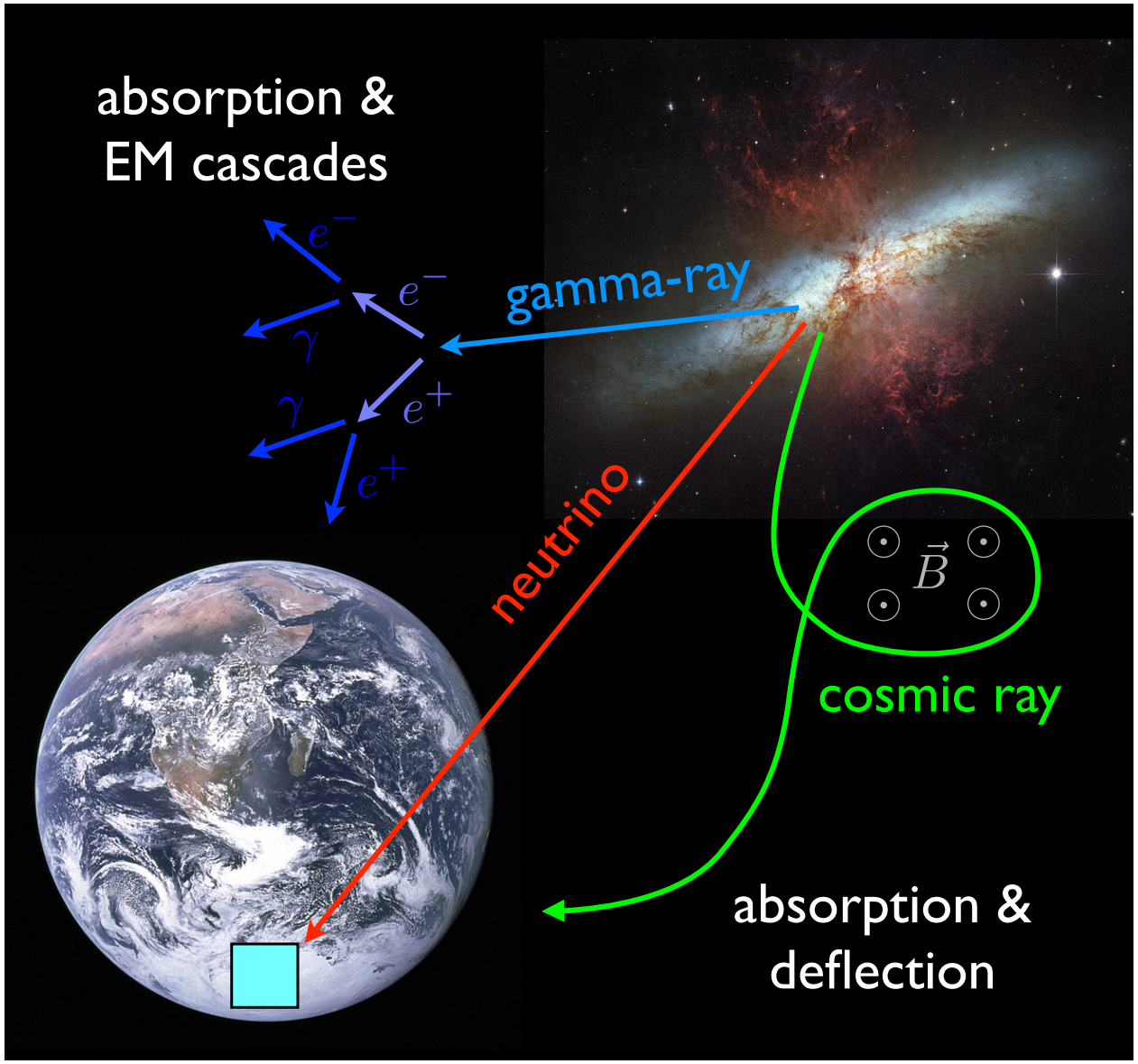
Washington University in St. Louis

Friends across 20 orders of magnitude

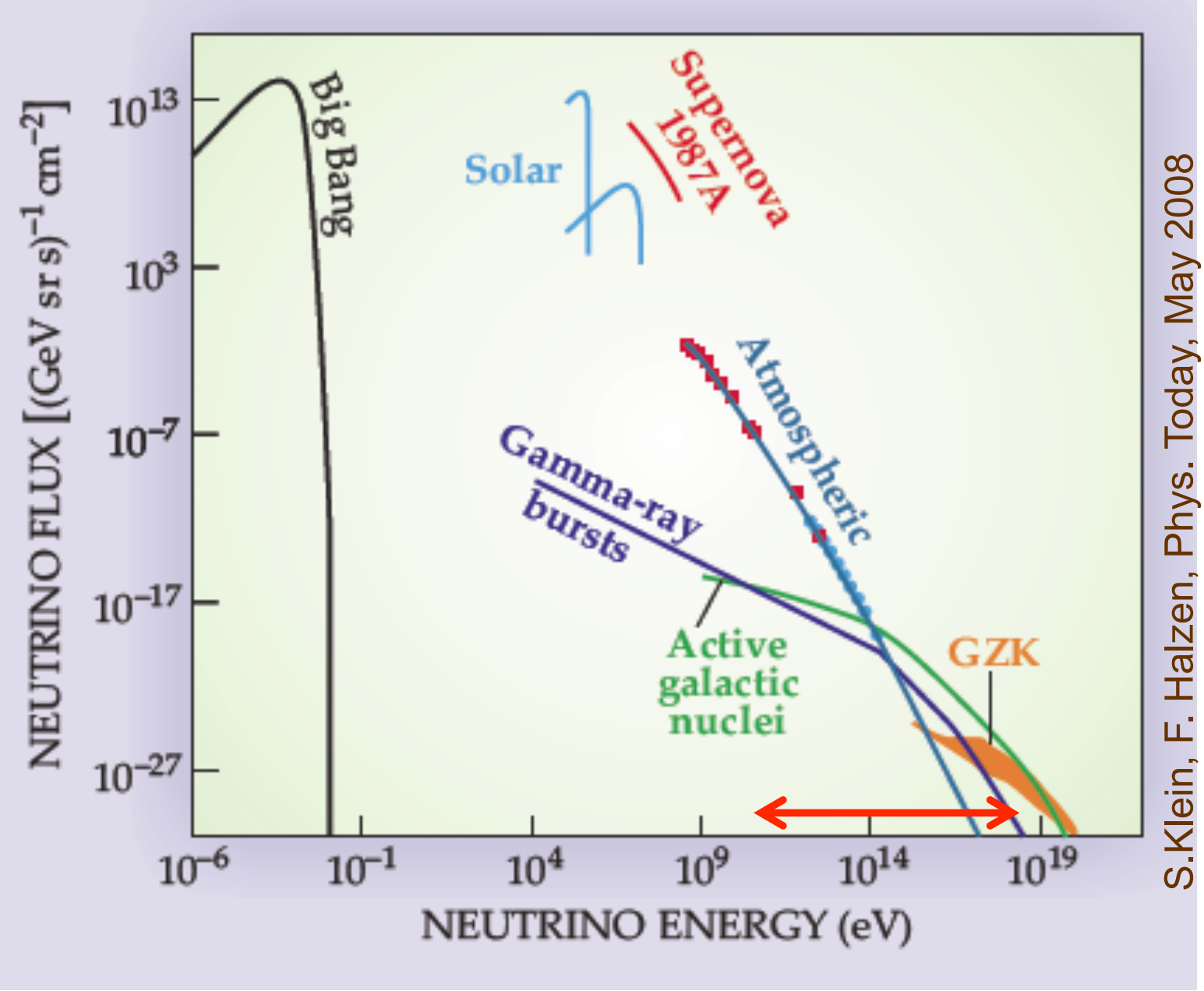


J. L. Hewett *et al*, 1401.6077 (Snowmass Report)

Ultra High-energy (UHE) Neutrinos: Astrophysical Messengers

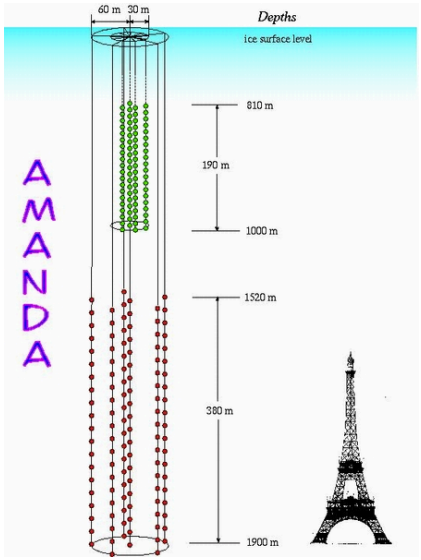


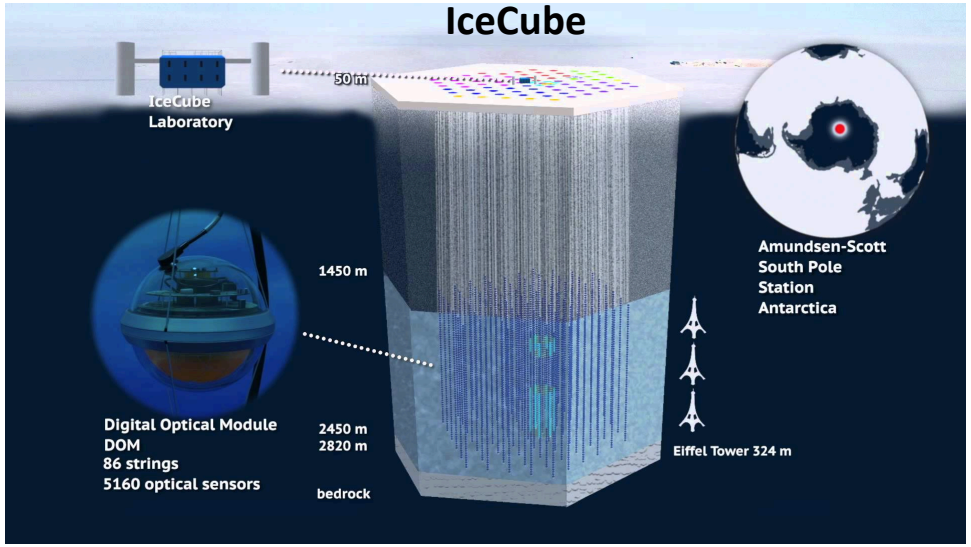
But the Flux is Small

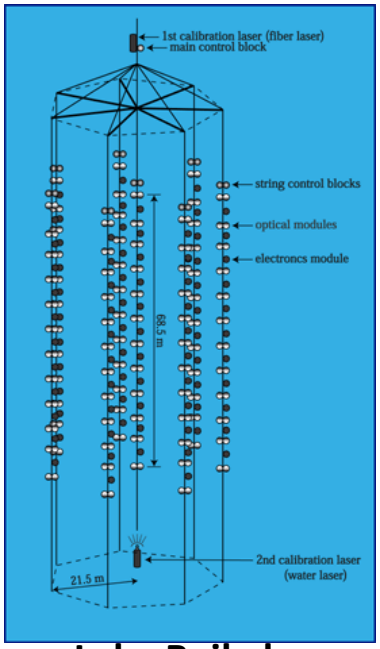


S.Klein, F. Halzen, Phys. Today, May 2008

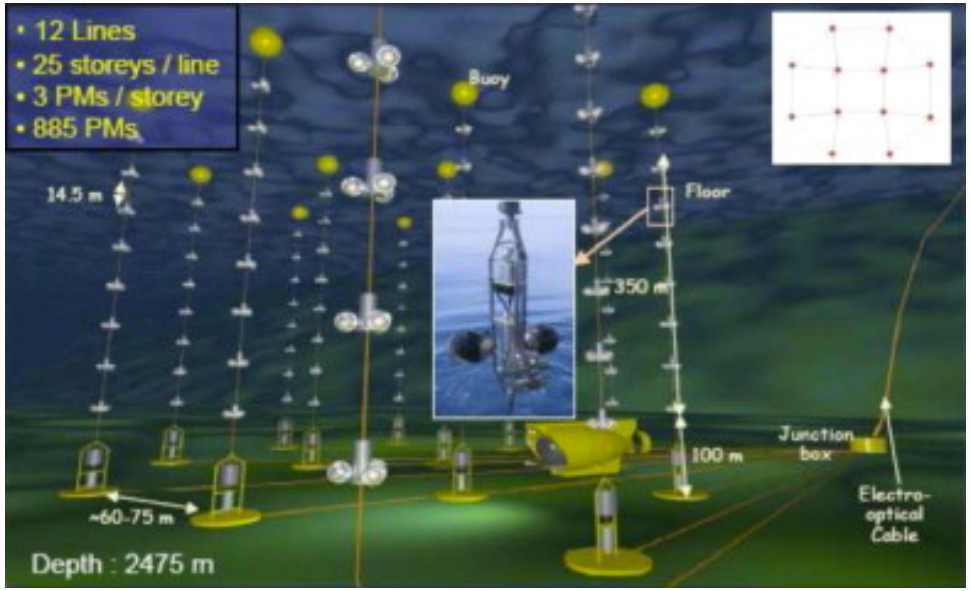
Need *Very* Large Detectors







Lake Baikal

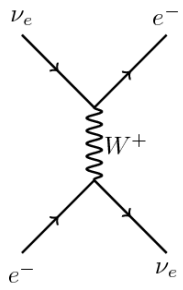


ANTARES

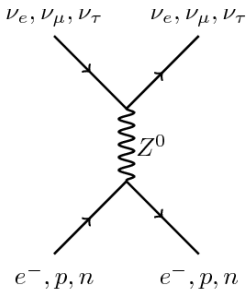
Neutrino Detection at IceCube

$$\nu_\ell + N \quad \rightarrow \quad \begin{cases} \ell + X & \text{(CC)} \\ \nu_\ell + X & \text{(NC)} \end{cases}$$

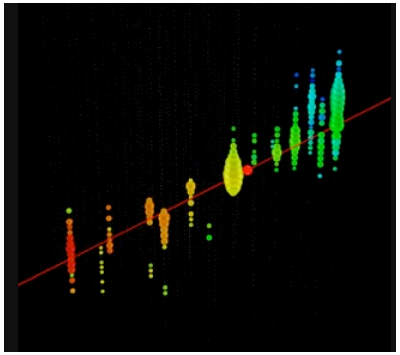
Events: Shower vs. Track; Contained vs. Throughgoing



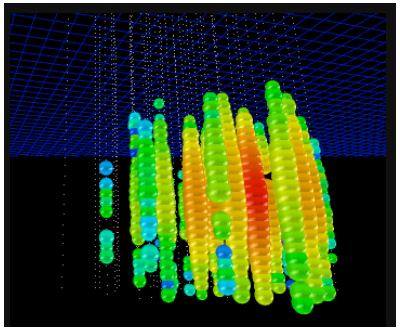
Charged-current



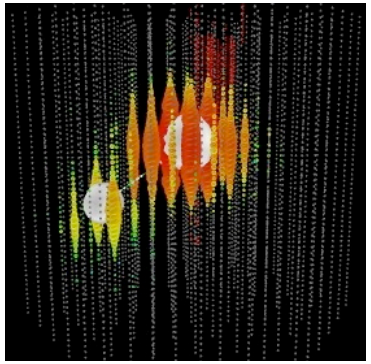
Neutral-current



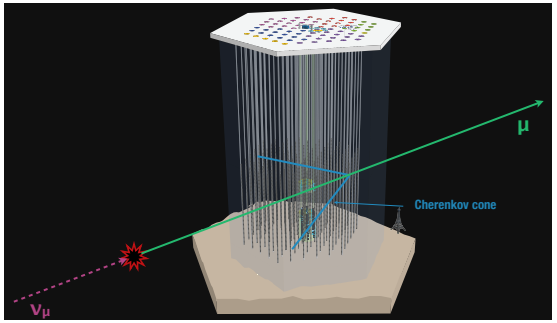
CC Muon (track)



CC EM/NC all (shower)



CC tau 'double bang'



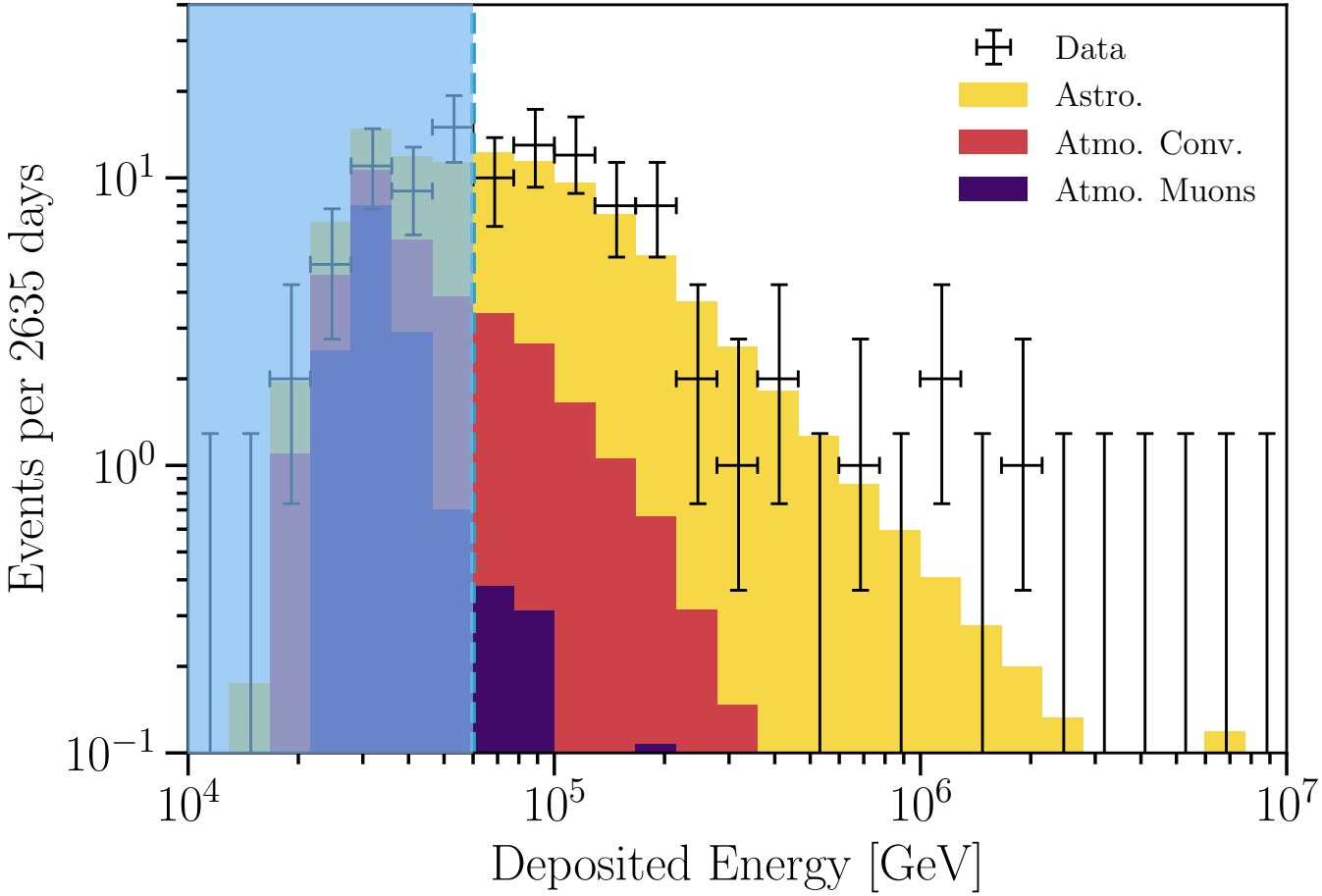
Throughgoing muon (track only)

High Energy Starting Events (HESE)

[IceCube Collaboration, PRL '13; Science '13; PRL '14]

[Picture courtesy: C. Kopper]

7.5-year HESE Dataset

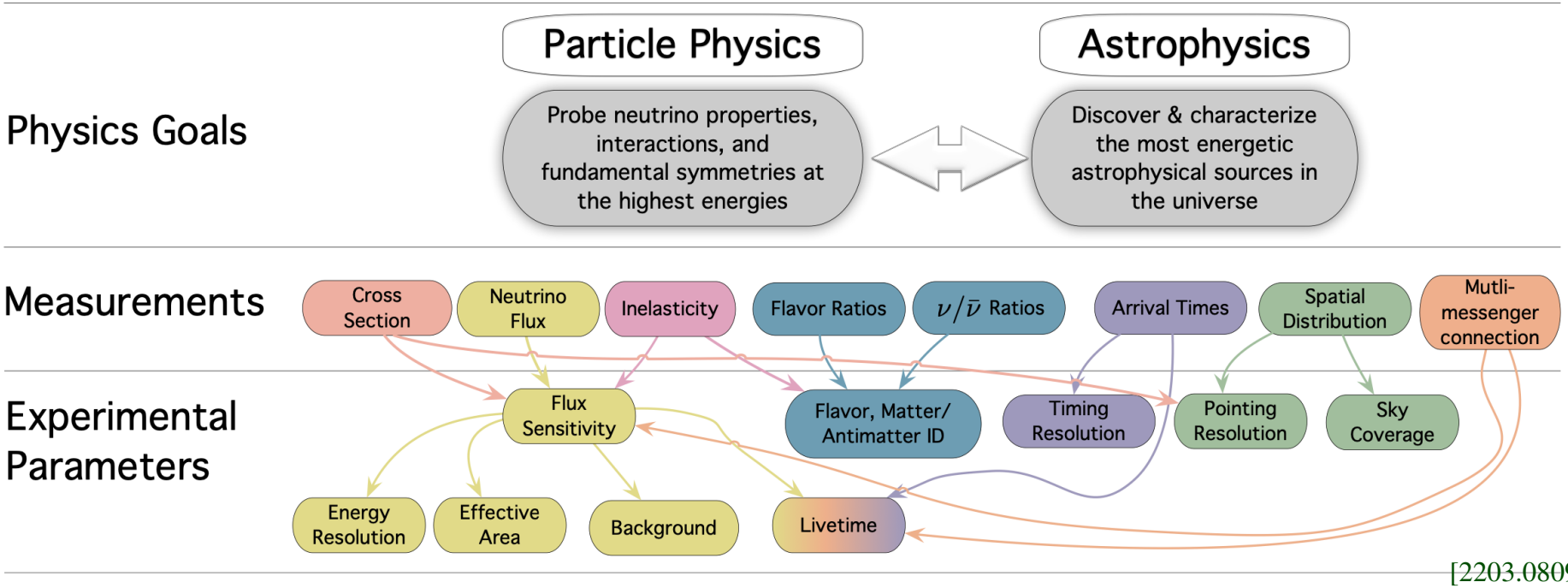


$$\frac{d\Phi_\nu}{dE} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\ \text{TeV}}\right)^{-\gamma_{\text{astro}}} \cdot 10^{-18}\ \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

with $\Phi_{\text{astro}} = 6.37^{+1.46}_{-1.62}$ and $\gamma_{\text{astro}} = 2.87^{+0.20}_{-0.19}$.

[IceCube Collaboration, Phys. Rev. D **104** (2021) 022002 [arXiv:2011.03545 [astro-ph.HE]]

A New Era of Neutrino (Astro)physics



[2203.08096]

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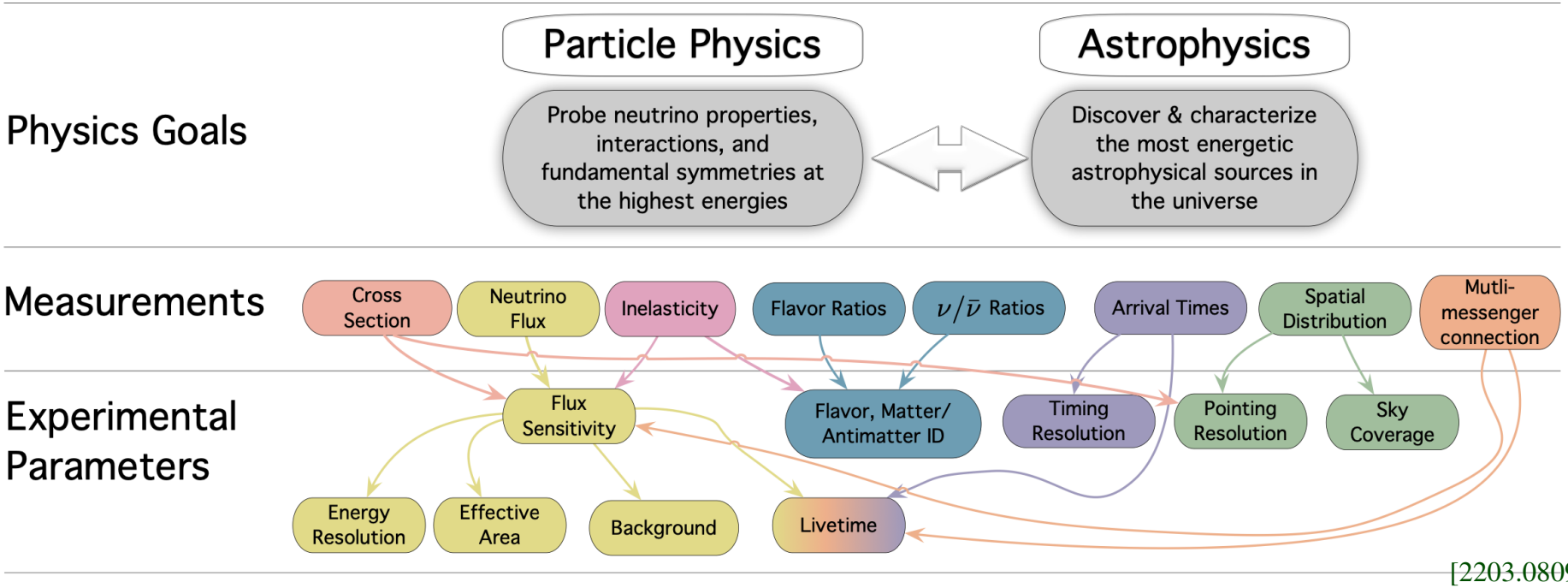
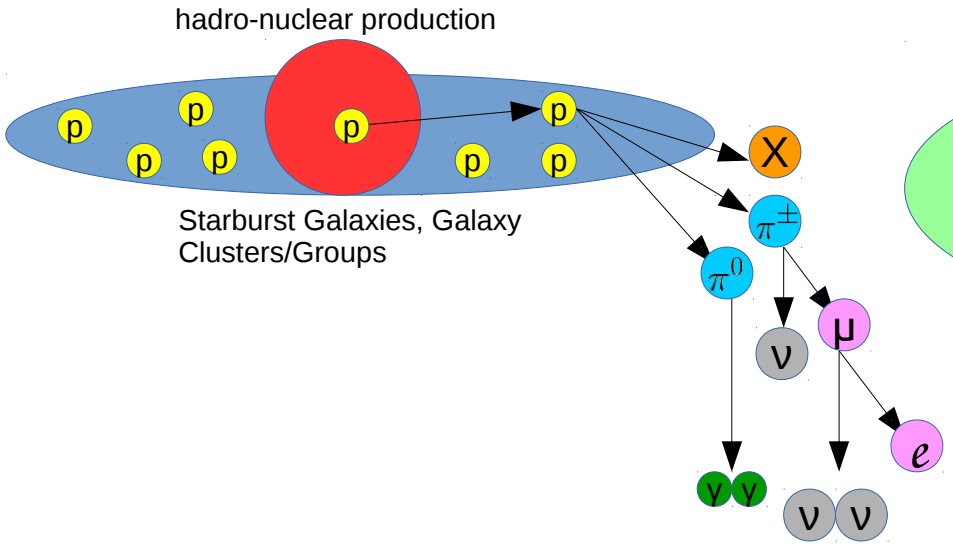


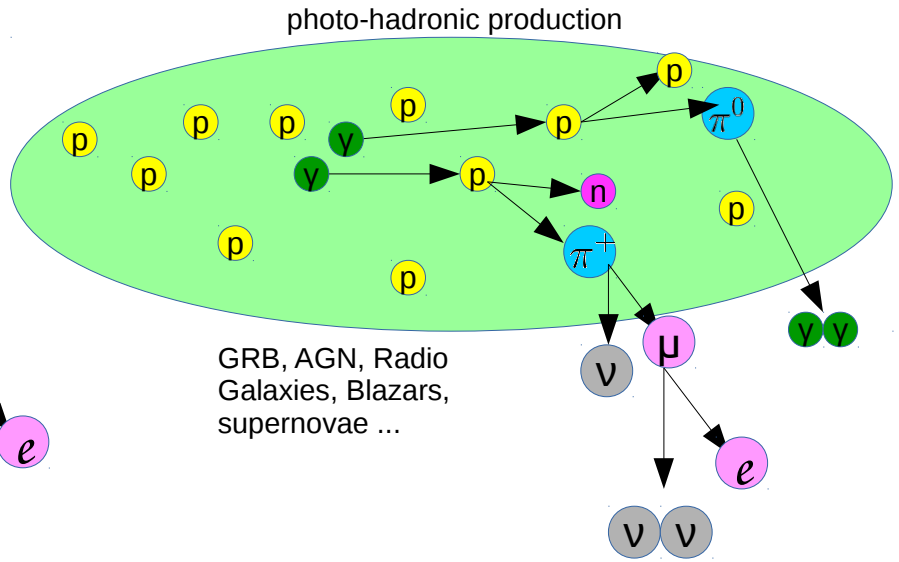
[2203.08096]

Three main aspects:

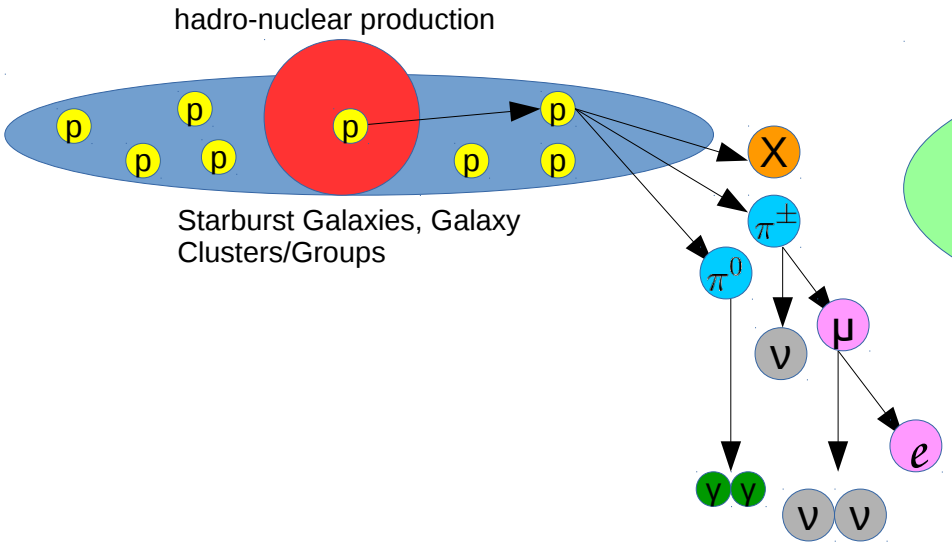
- Source: flux and initial flavor composition
- Propagation: final flavor composition on Earth
- Detection: showers and tracks, upgoing and downgoing events, features in the spectrum

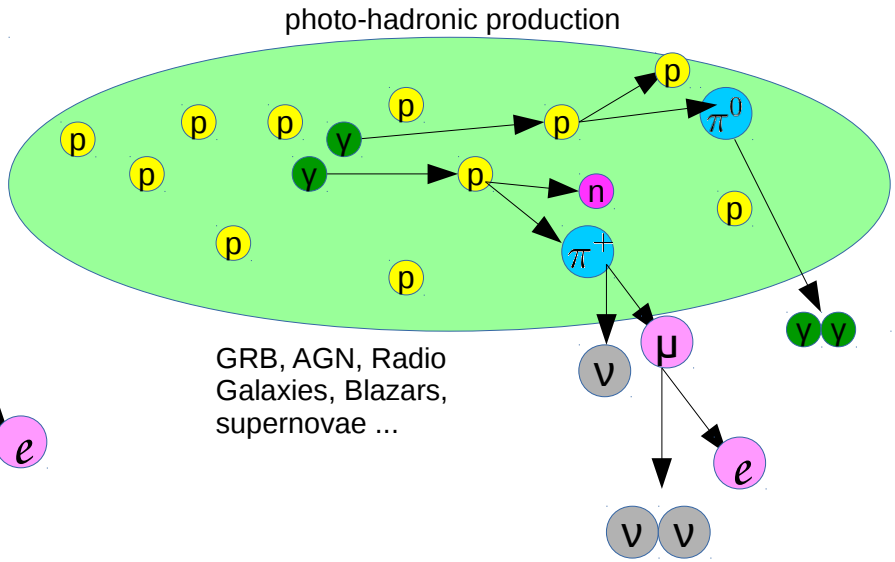
Potential Sources





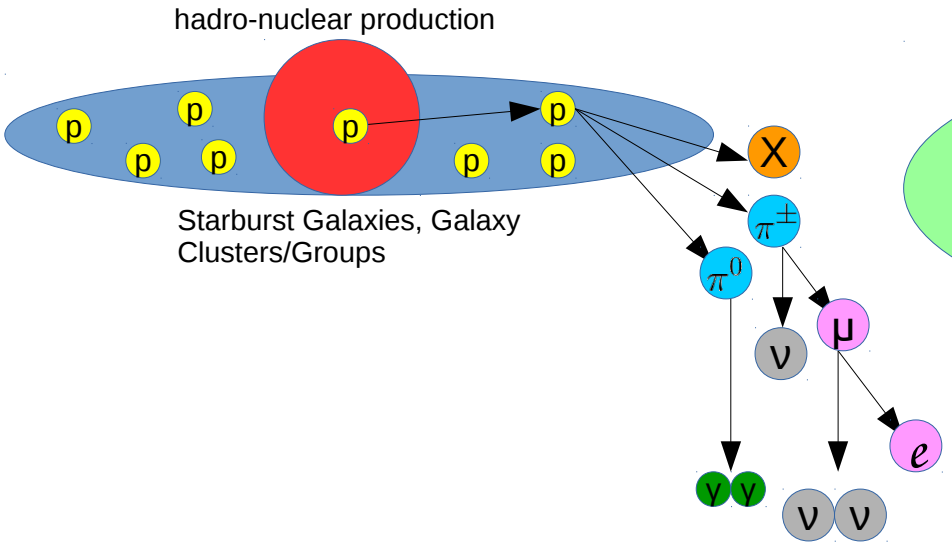
Potential Sources

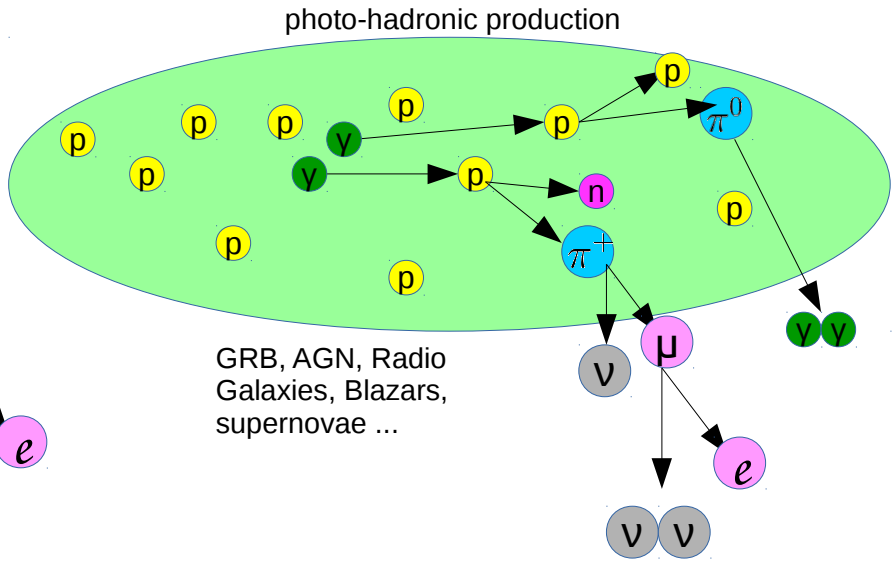




	Prompt				Delayed		
Event class	γ	ν	n	gw	x	IR/O/UV	Radio
High-luminosity GRBs (HL-GRB)	✔	✔		✔	✔	✔	✔
Low-luminosity GRBs (LL-GRBs)	✔	✔		✔	✔	✔	✔
Short-hard GRBs (SHBs)	✔	✔		✔	✔	✔	✔
Choked jet SN		✔		✔	✔	✔	✔
Core-collapse SN		✔	✔		✔	✔	
Blazars	✔	✔			✔	✔	✔
Primordial black holes (PBHs)	✔	✔	✔				
Other exotica	✔	✔	✔	✔			

Potential Sources





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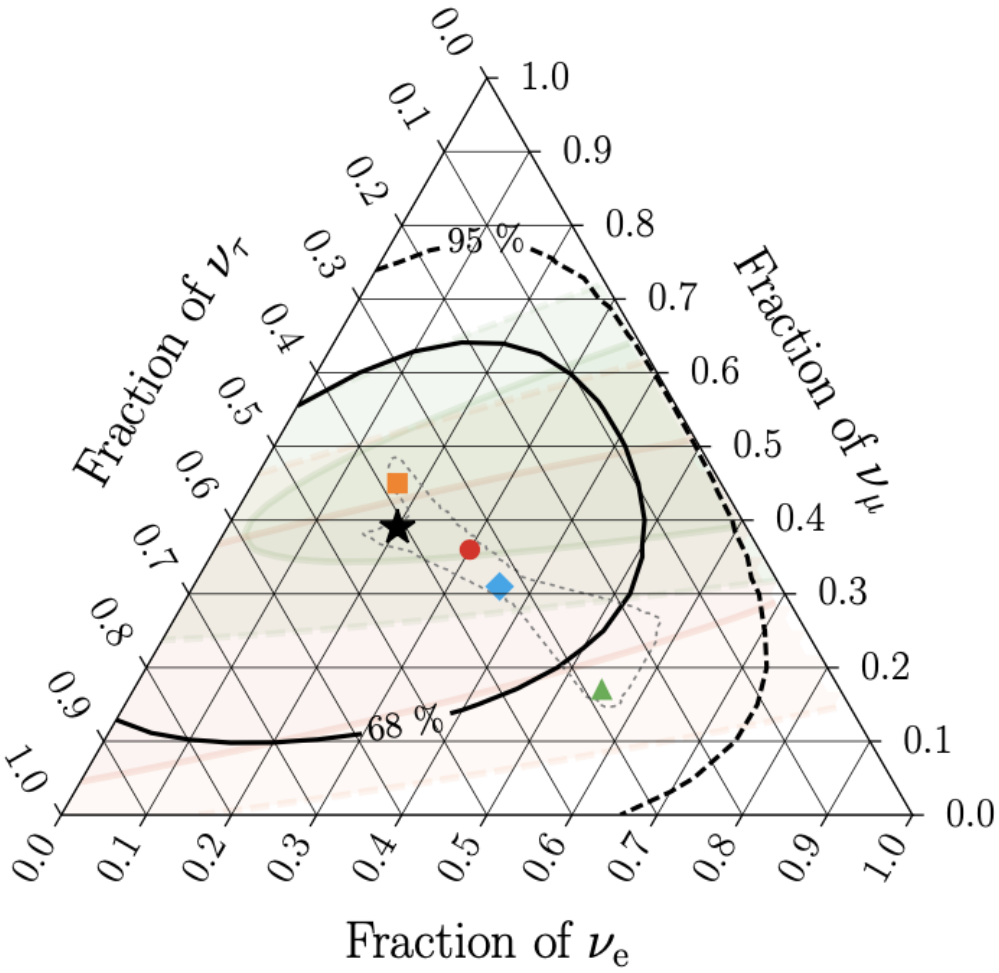
Short-hard GRBs (SHBs)	✔	✔		✔	✔	✔	✔
Choked jet SN		✔		✔	✔	✔	✔
Core-collapse SN		✔	✔		✔	✔	
Blazars	✔	✔			✔	✔	✔
Primordial black holes (PBHs)	✔	✔	✔				
Other exotica	✔	✔	✔	✔			

Flavor Composition



HESE with ternary topology ID
Best fit: 0.20 : 0.39 : 0.42
Global Fit (IceCube, APJ 2015)
Inelasticity (IceCube, PRD 2019)
3ν-mixing 3σ allowed region

$\nu_e : \nu_\mu : \nu_\tau$ at source $\rightarrow$ on Earth:
0:1:0 $\rightarrow$ 0.17 : 0.45 : 0.37
1:2:0 $\rightarrow$ 0.30 : 0.36 : 0.34
1:0:0 $\rightarrow$ 0.55 : 0.17 : 0.28
1:1:0 $\rightarrow$ 0.36 : 0.31 : 0.33

2011.03561

A New Probe of BSM Physics

- Improved precision on the astrophysical neutrino flux measurement is expected.
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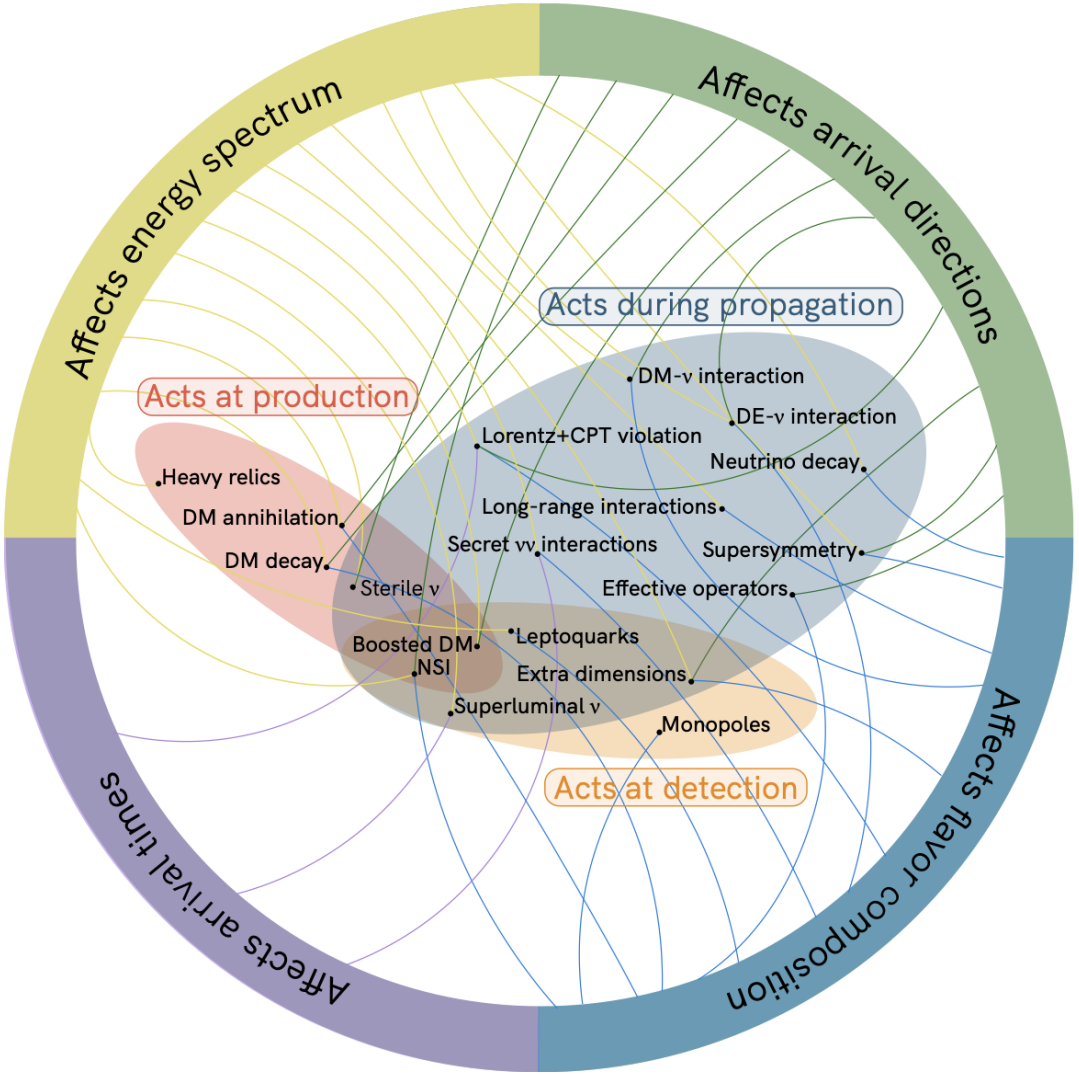

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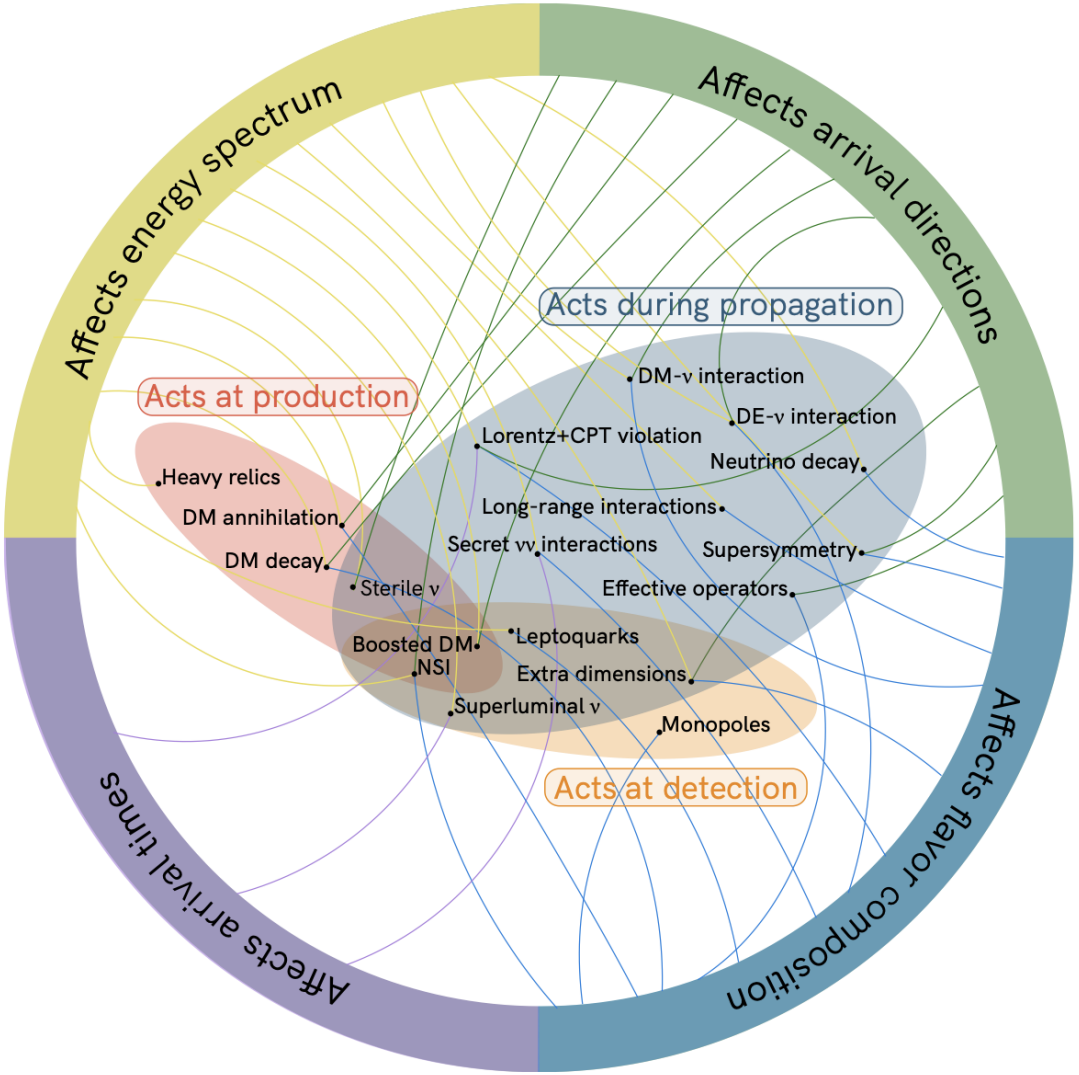
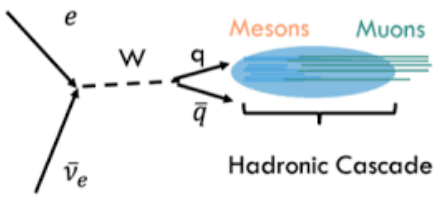


[2203.08096]

This talk: Probing Neutrino Mass Models using UHE Neutrino Resonance

SM Resonances



[Glashow (Phys. Rev. '60)]

Glashow resonance

$$E_\nu = \frac{m_W^2}{2m_e} = 6.3 \text{ PeV}$$

Recently observed by IceCube

[Nature **591**, 220 (2021)]

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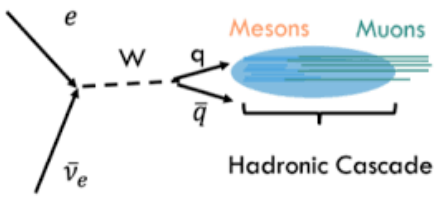

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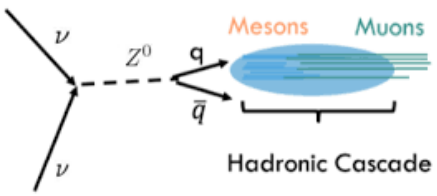

[Weiler (PRL '82)]

Z-burst

$$E_\nu = \frac{m_Z^2}{2m_\nu} > 10^{14} \text{ GeV}$$

Beyond GZK cutoff

Unlikely to be seen

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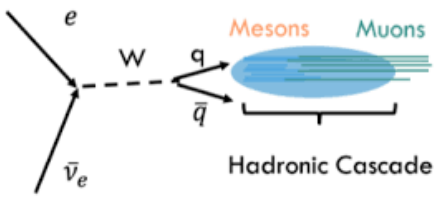

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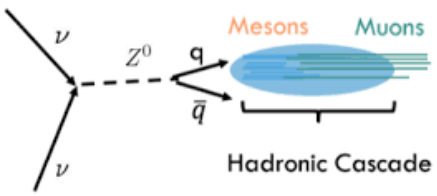

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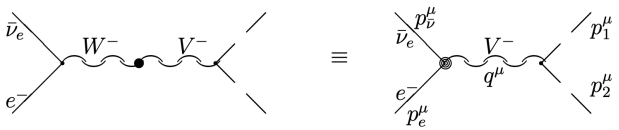

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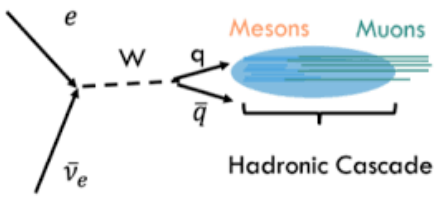

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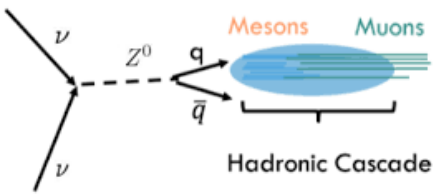

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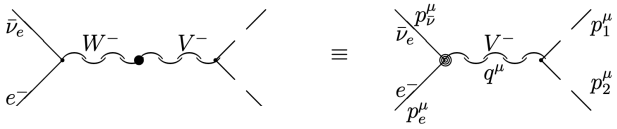

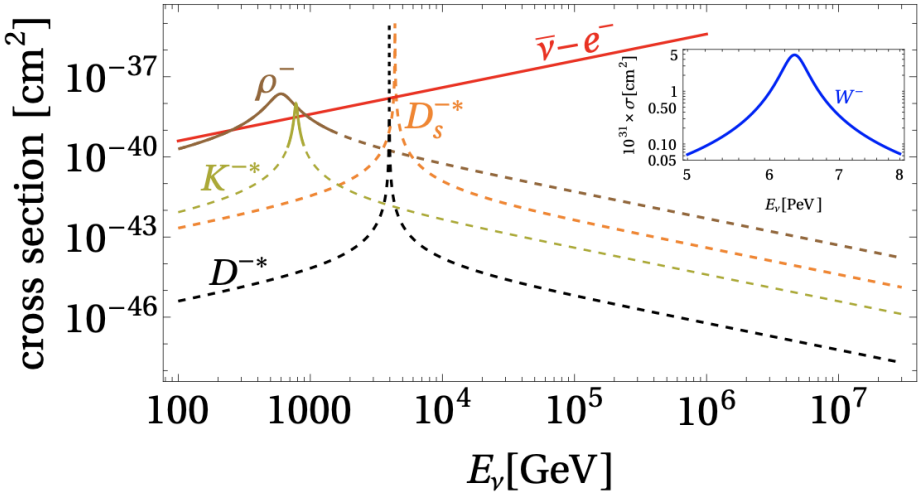

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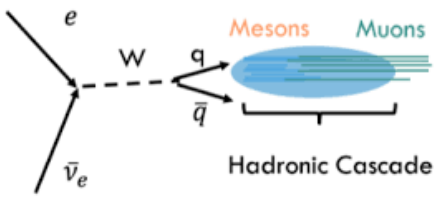

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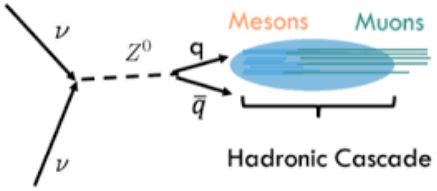

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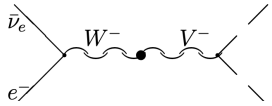

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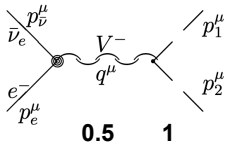
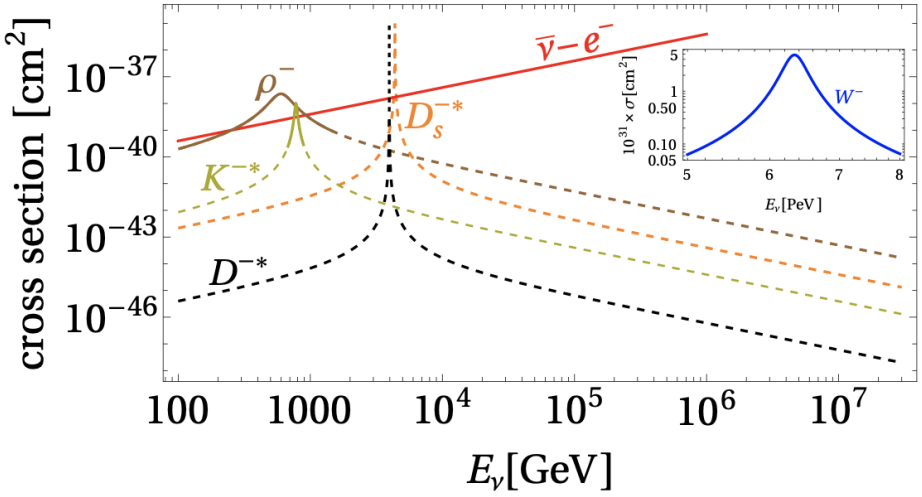
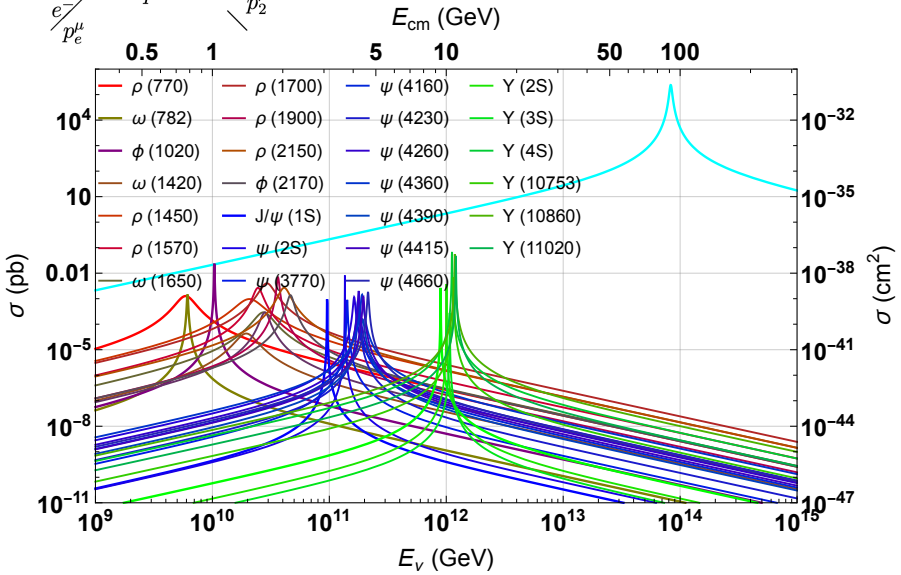


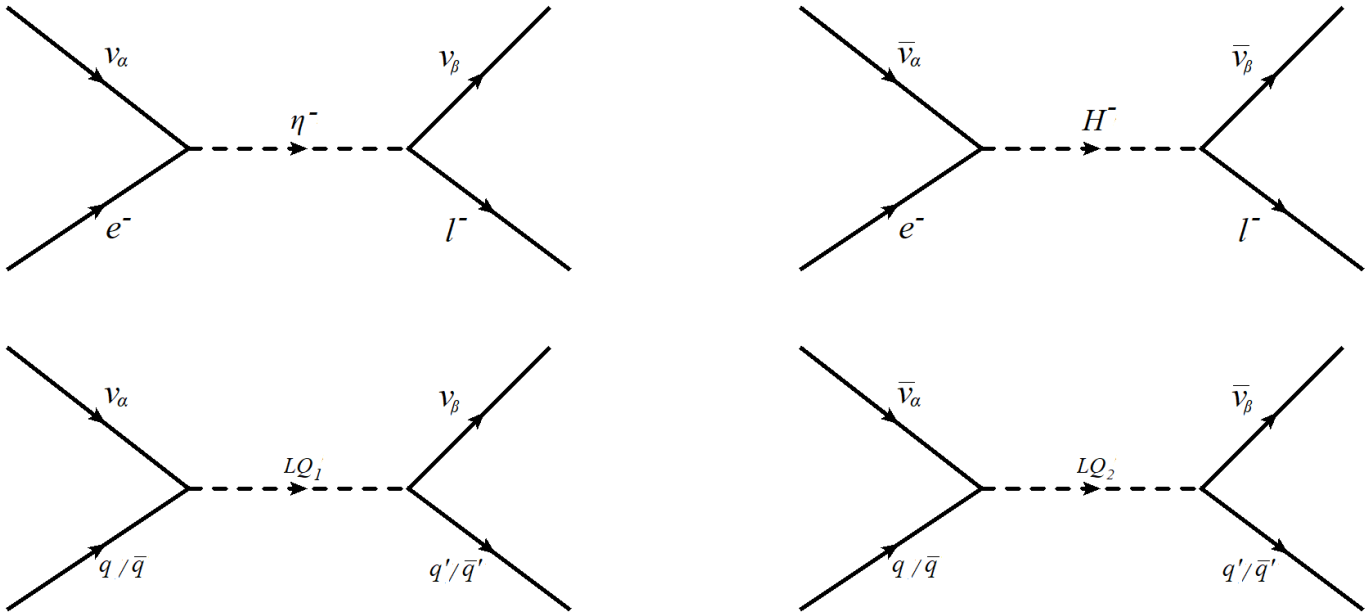




Rate is small [Paschos, Lalakulich, hep-ph/0206273; BD, Soni, 2112.01424; Brdar, de Gouvea, Machado, Plestid, 2112.03283]

New Resonances in Neutrino Mass Models

Particle Content	Lagrangian term
$\eta^+(\mathbf{1},\mathbf{1},1)$ or $h^+(\mathbf{1},\mathbf{1},1)$	$f_{\alpha\beta} L_\alpha L_\beta\, \eta^+$ or $f_{\alpha\beta} L_\alpha L_\beta\, h^+$
$H\left(\mathbf{1},\mathbf{2},\frac{1}{2}\right) = \left(H^+, H^0\right)$	$Y_{\alpha\beta} L_\alpha \ell^c_\beta \widetilde{H}$
$S_1\left(\bar{\mathbf{3}},\mathbf{1},\frac{1}{3}\right)$	$\lambda_{\alpha\beta} L_\alpha Q_\beta S_1$
$S_3\left(\bar{\mathbf{3}},\mathbf{3},\frac{1}{3}\right) = \left(\rho^{4/3}, \rho^{1/3}, \rho^{-2/3}\right)$	$\lambda'_{\alpha\beta} L_\alpha Q_\beta S_3$
$R_2\left(\mathbf{3},\mathbf{2},\frac{7}{6}\right) = \left(\delta^{5/3}, \delta^{2/3}\right)$	$\lambda''_{\alpha\beta} L_\alpha u^c_\beta R_2$
$\widetilde{R}_2\left(\mathbf{3},\mathbf{2},\frac{1}{6}\right) = \left(\omega^{2/3}, \omega^{-1/3}\right)$	$\lambda'''_{\alpha\beta} L_\alpha d^c_\beta \widetilde{R}_2$



An Example: Zee Model

[Zee (PLB '80)]

- Scalar sector: $\eta^+(\mathbf{1},\mathbf{1},1)$ and $\Phi_{1,2}\left(\mathbf{1},\mathbf{2},\frac{1}{2}\right) = \left(\phi^+_{1,2},\phi^0_{1,2}\right)$.
- Leads to the Yukawa Lagrangian and potential term

$$
\begin{aligned}
-\mathcal{L}_Y &\supset f_{\alpha\beta} L^i_\alpha L^j_\beta \epsilon_{ij}\eta^+ + (y_1)_{\alpha\beta}\widetilde{\Phi}^i_1 L^j_\alpha \ell^c_\beta \epsilon_{ij} + (y_2)_{\alpha\beta}\widetilde{\Phi}^i_2 L^j_\alpha \ell^c_\beta \epsilon_{ij} + \text{H.c.}\,. \\
V &\supset \mu \Phi^i_1 \Phi^j_2 \epsilon_{ij}\eta^- + \text{H.c.}\,.
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$$

An Example: Zee Model

[Zee (PLB '80)]

- Scalar sector: $\eta^+(\mathbf{1},\mathbf{1},1)$ and $\Phi_{1,2}\left(\mathbf{1},\mathbf{2},\frac{1}{2}\right) = \left(\phi^+_{1,2},\phi^0_{1,2}\right)$.
- Leads to the Yukawa Lagrangian and potential term

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- Higgs basis: $$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} c_\beta & e^{-i\xi}s_\beta \\ -e^{i\xi}s_\beta & c_\beta \end{pmatrix}\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}.$$

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + H^0_1 + iG^0) \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+_2 \\ \frac{1}{\sqrt{2}}(H^0_2 + iA) \end{pmatrix}.$$

- Charged scalars: $$\begin{aligned} h^+ &= \cos\varphi\,\eta^+ + \sin\varphi\, H^+_2\,, \\ H^+ &= -\sin\varphi\,\eta^+ + \cos\varphi\, H^+_2\,, \end{aligned}$$

with $\sin 2\varphi = \frac{-\sqrt{2}\,v\mu}{m^2_{H^+} - m^2_{h^+}}$.

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- Similarly, in the CP-even neutral sector:

$$\begin{aligned} h &= \cos(\alpha-\beta)\, H^0_1 + \sin(\alpha-\beta)\, H^0_2\,, \\ H &= -\sin(\alpha-\beta)\, H^0_1 + \cos(\alpha-\beta)\, H^0_2\,. \end{aligned}$$

  where $\sin 2(\alpha-\beta) = \frac{2\lambda_6 v^2}{m^2_H - m^2_h}$. Work in alignment limit.

Radiative Neutrino Mass

- Rewrite the Yukawa Lagrangian in Higgs basis:

$$-\mathcal{L}_Y \supset f_{\alpha\beta} L^i_\alpha L^j_\beta \epsilon_{ij} \eta^+ + \widetilde{Y}_{\alpha\beta} \widetilde{H}^i_1 L^j_\alpha \ell^c_\beta \epsilon_{ij} + Y_{\alpha\beta} \widetilde{H}^i_2 L^j_\alpha \ell^c_\beta \epsilon_{ij} + \text{H.c.}\,.$$

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- Lepton number violation is obtained by the cubic term

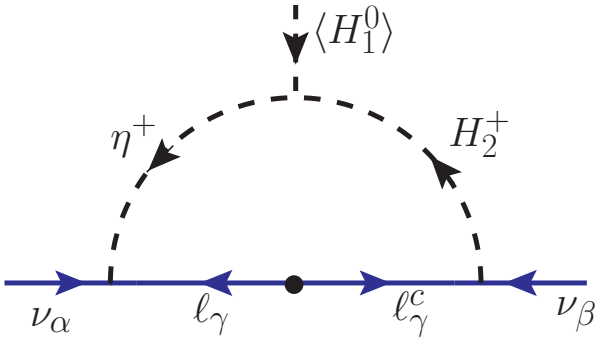
$$V \supset \mu\, H^i_1\, H^j_2 \epsilon_{ij}\, \eta^- + \text{H.c.}$$

- Open up the $\Delta L = 2$ effective $d = 7$ operator $\mathcal{O}_2 = L^i L^j L^k e^c H^l \epsilon_{ij} \epsilon_{kl}$ to generates neutrino mass at one-loop: [Zee (PLB '80)]

$$M_\nu = \kappa \left(f M_\ell Y + Y^T M_\ell f^T \right),$$

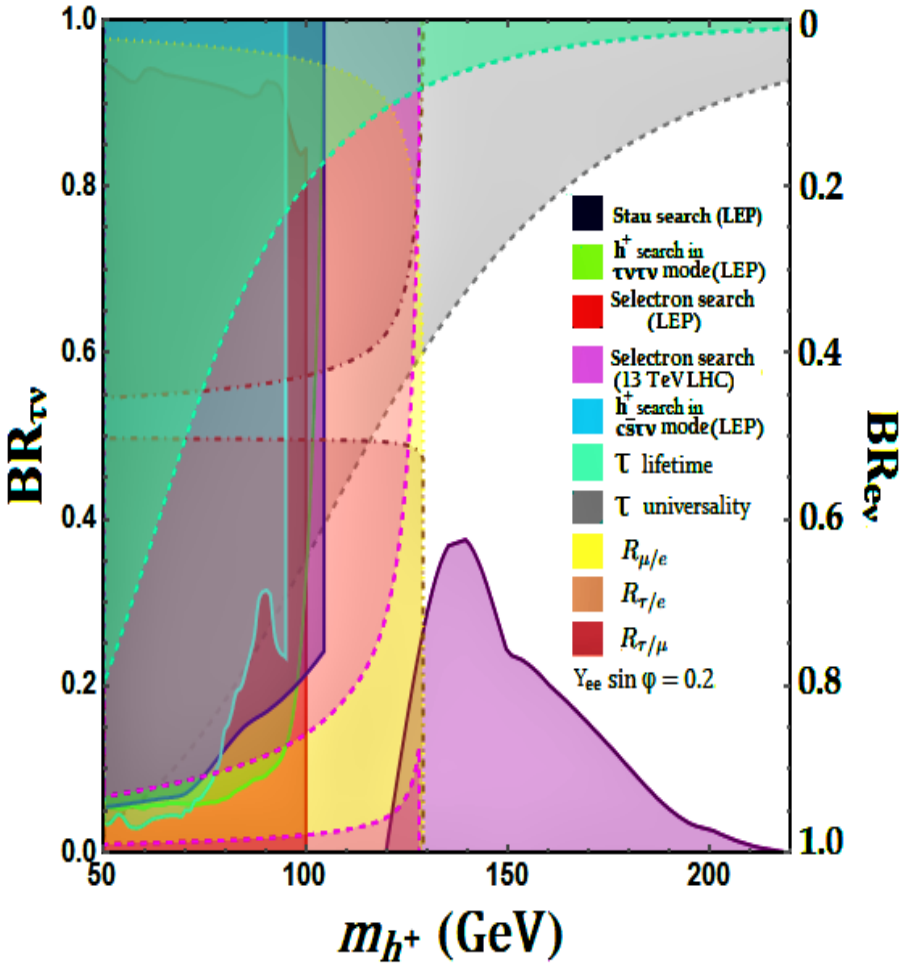
where

$$\kappa = \frac{1}{16\pi^2} \sin 2\varphi \log \left(\frac{m^2_{h^+}}{m^2_{H^+}} \right)\,.$$



How Light Can the Charged Higgs be?

[Babu, BD, Jana, Thapa, 1907.09498 (JHEP '20)]



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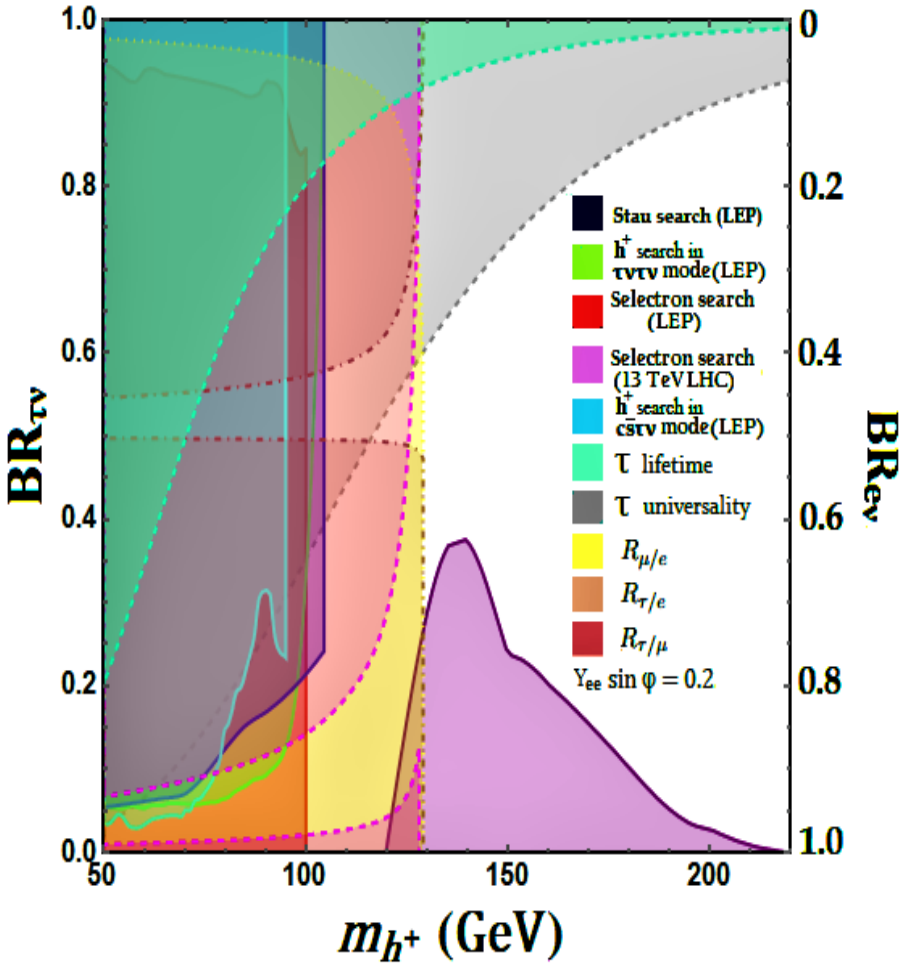
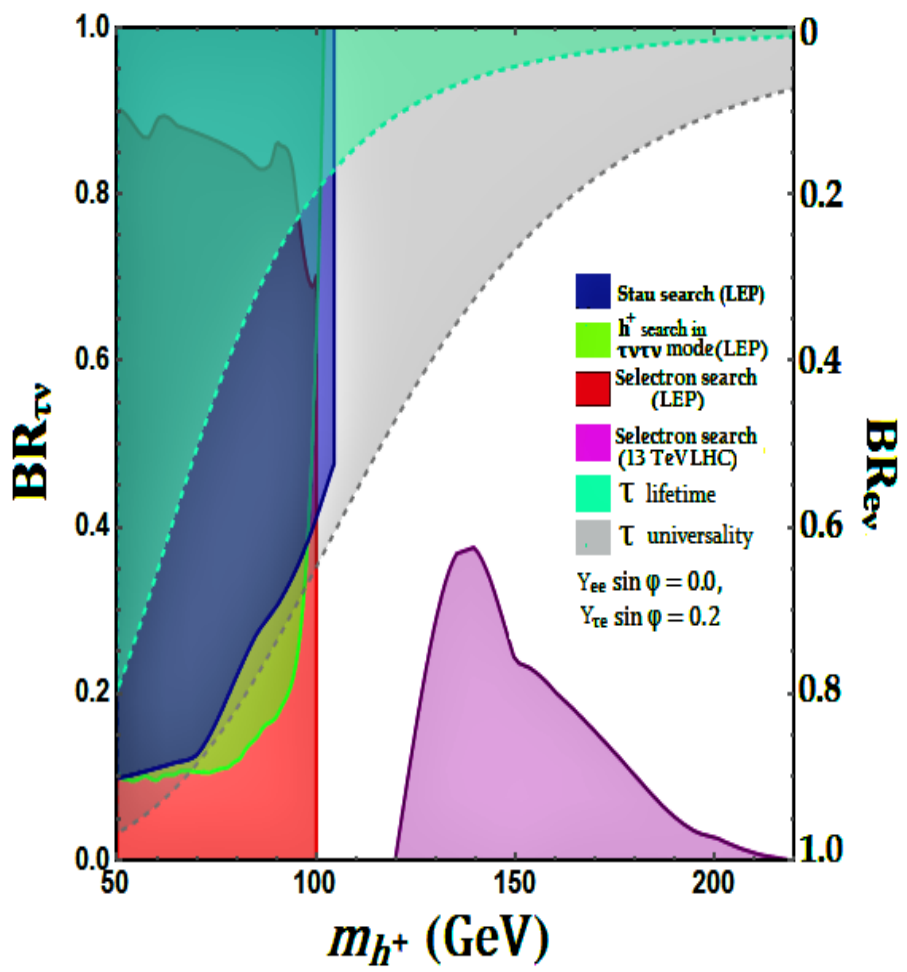
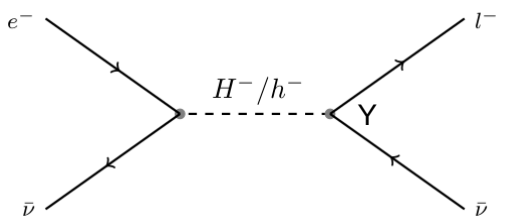




Can be as light as 100 GeV.

‘Zee-burst’: New Resonance at IceCube



$$E_\nu = \frac{m^2_{h^-/H^-}}{2m_e} \gtrsim 10 \text{ PeV (observable at IceCube)}$$

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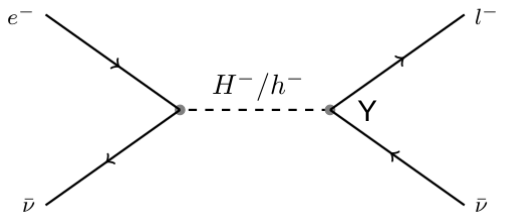

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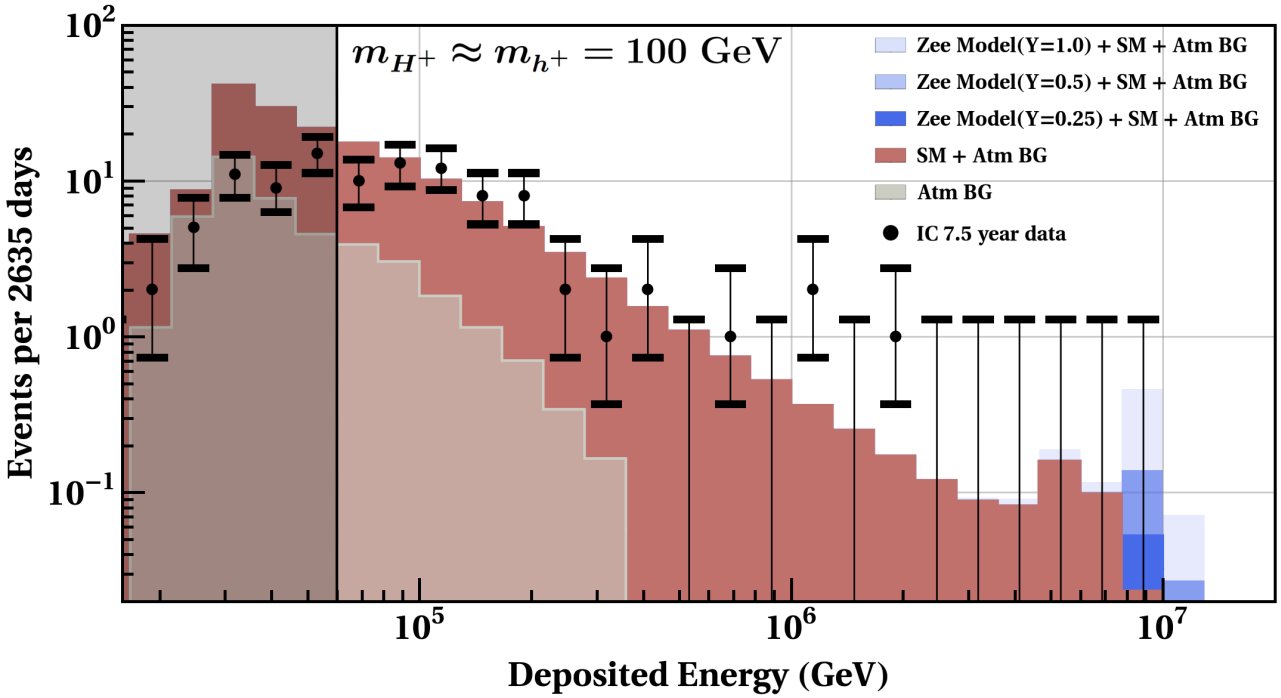
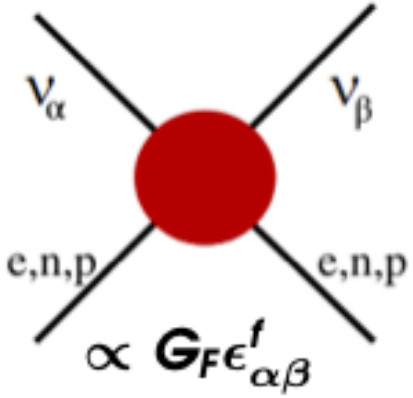


[Babu, BD, Jana, Sui, 1908.02779 (PRL ’20)]

Neutrino Non-Standard Interactions

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\varepsilon^{fX}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_X f)$$

[Wolfenstein (PRD '78)]



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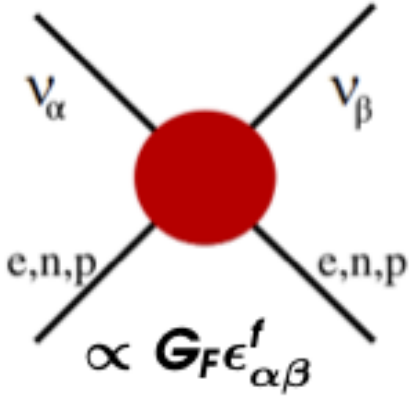
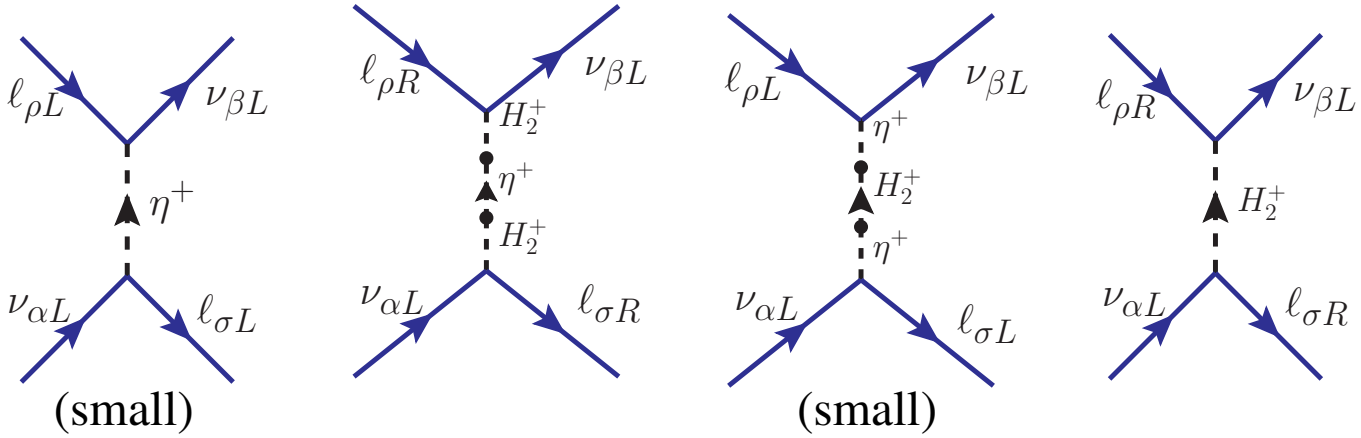
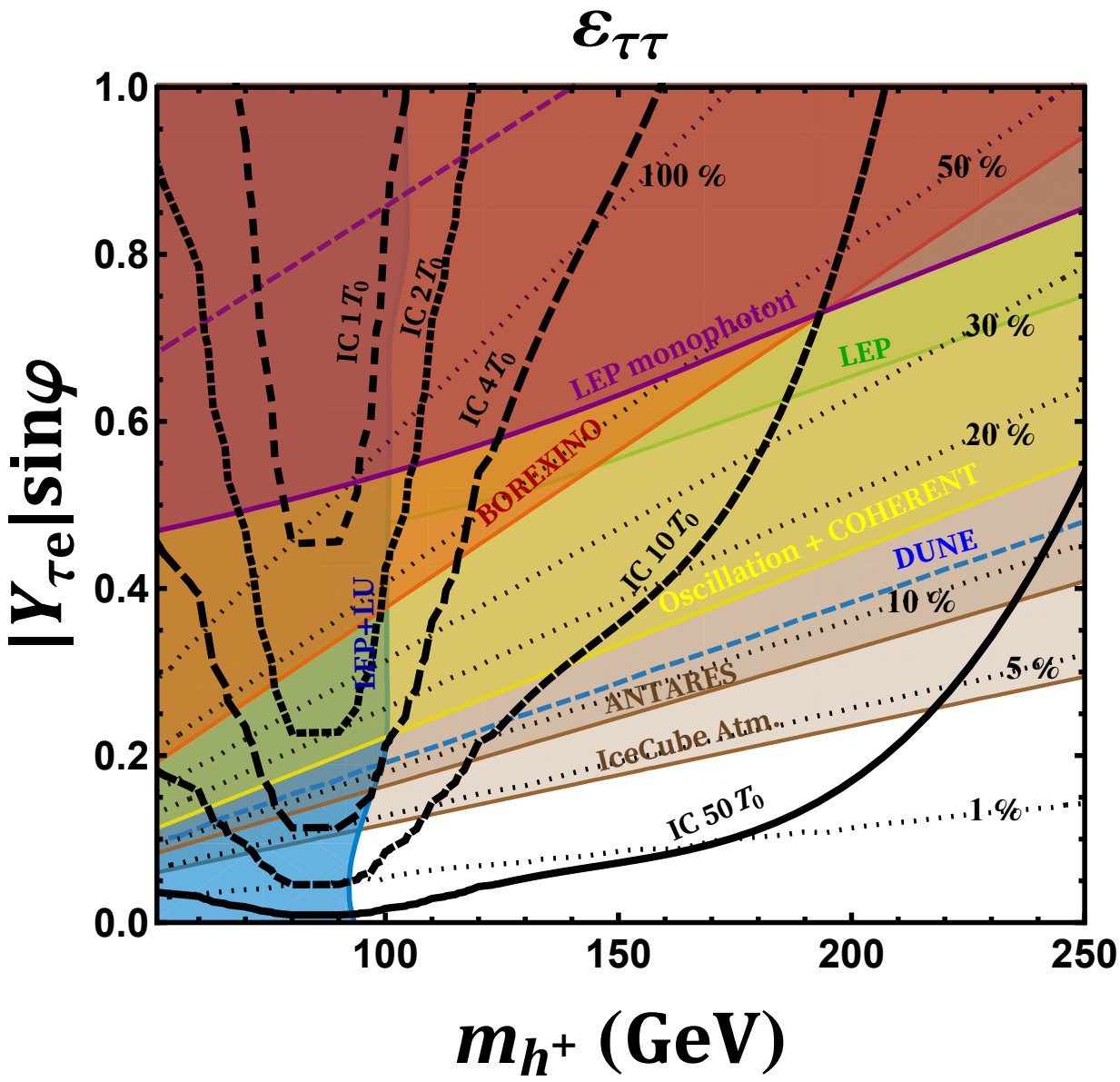




$$\boxed{\varepsilon_{\alpha\beta} \equiv \varepsilon^{(h^+)}_{\alpha\beta} + \varepsilon^{(H^+)}_{\alpha\beta} = \frac{1}{4\sqrt{2}G_F}Y_{\alpha e}Y^\star_{\beta e}\left(\frac{\sin^2\varphi}{m^2_{h^+}} + \frac{\cos^2\varphi}{m^2_{H^+}}\right).}$$

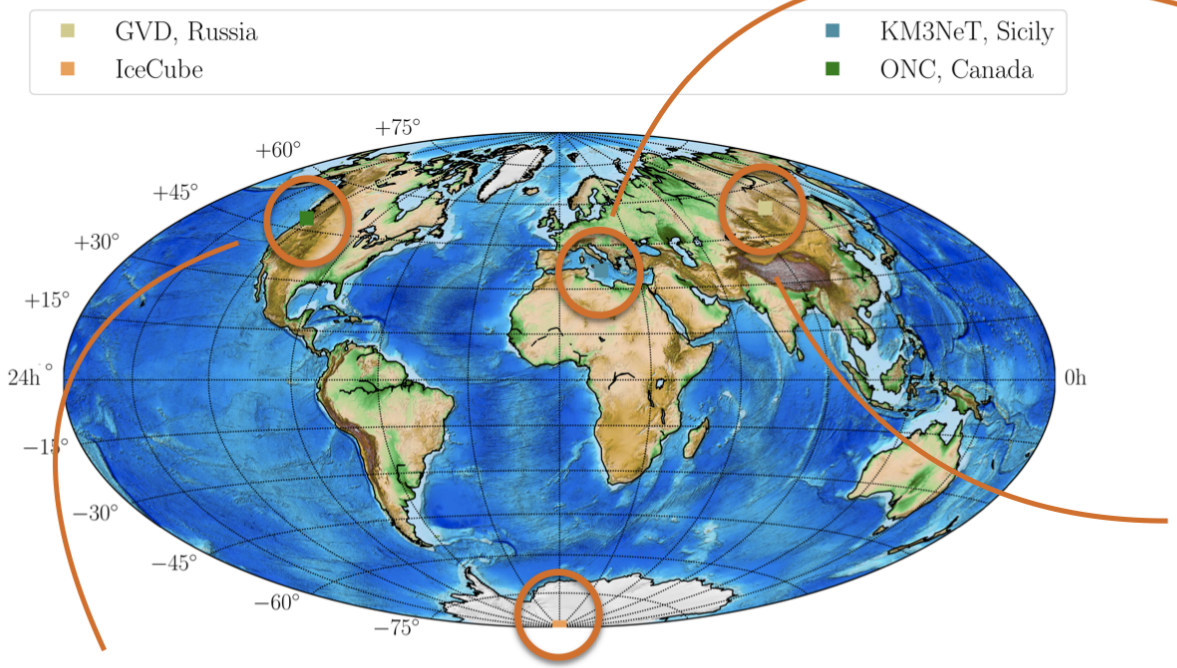
A New Probe of NSI



[Babu, BD, Jana, Sui, 1908.02779 (PRL '20); Babu, BD, Jana, arXiv:2202.06975]

May not have to wait 75 years!

PLEνM : A planetary neutrino telescope



KM3NeT

E>10GeV

under construction

BAIKAL-GVD

E>50TeV

under construction

OCEAN NETWORKS CANADA

E>50TeV

under construction

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

E>10GeV

measuring data for more than 10years

12

[slide from M. Huber]

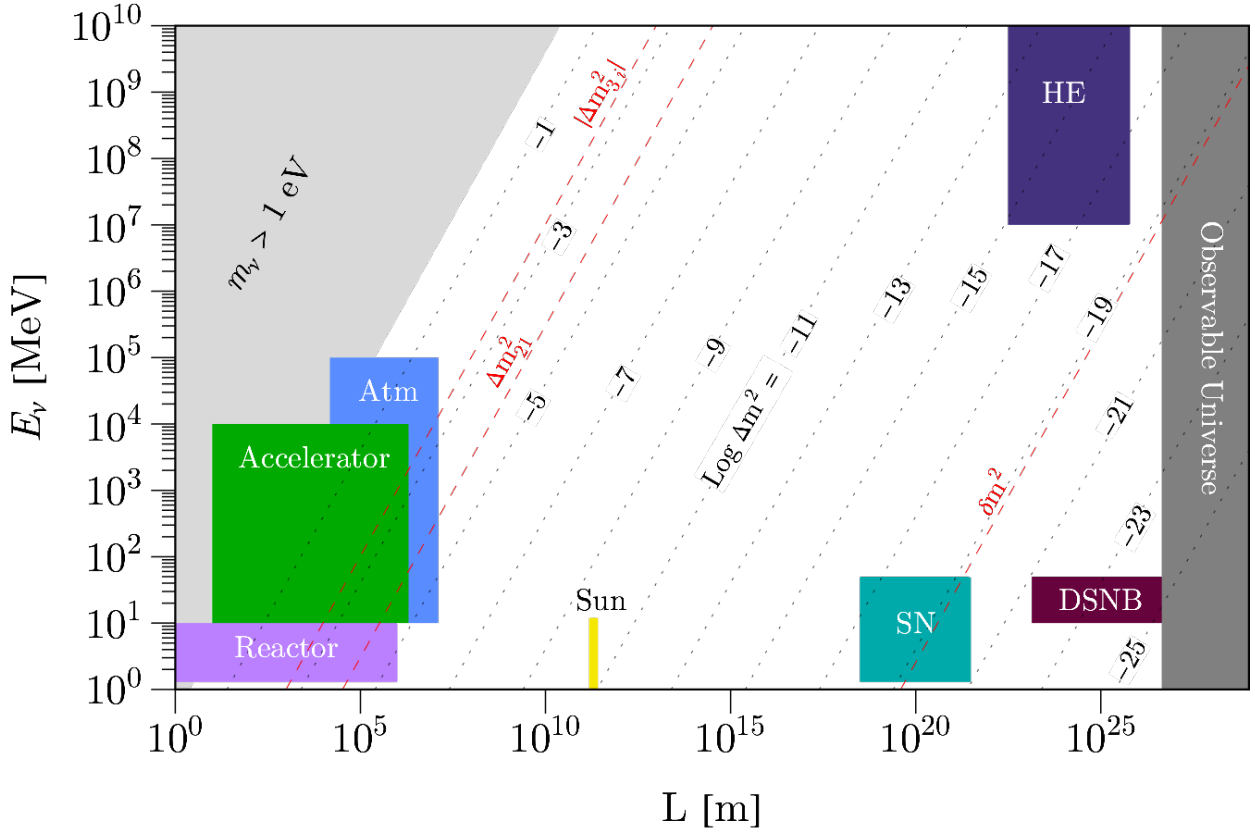
Pseudo-Dirac Neutrinos

[Wolfenstein (NPB '81); Petcov (PLB '82); Kobayashi, Lim (PRD '01)]

Consider a maximally mixed superposition of active and sterile states:

$$\nu_{\beta L} = \frac{U_{\beta k}}{\sqrt{2}}(\nu_{ks} + i\nu_{ka})$$

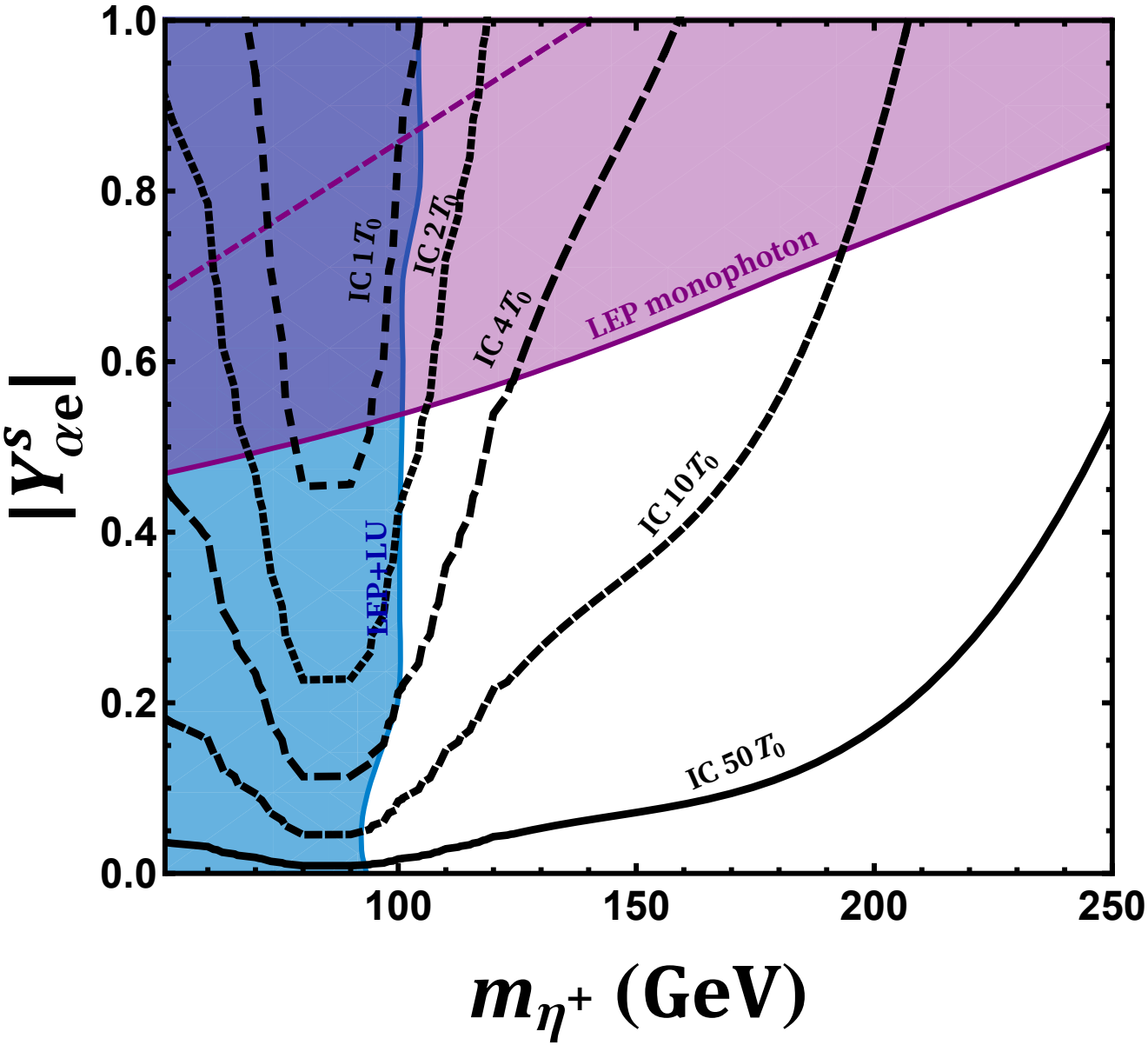
with $m^2_{ks,ka} = m^2_k \pm \delta m^2_k/2$ (with $k = 1, 2, 3$).



[Keranen, Maalampi, Myyrylainen, Riittinen (PLB '03); Beacom, Bell, Hooper, Learned, Pakvasa, Weiler (PRL '04); Martinez-Soler, Perez-Gonzalez, Sen, 2105.12736]

Pseudo-Dirac Neutrino-Induced Resonance at IceCube

$$\mathcal{L} \supset Y^s_{\alpha\beta}\overline{\nu^c_{s\alpha}}\eta^+\ell_{\beta R} + \text{H.c.}$$



Conclusion

- Detection of UHE neutrinos has ushered in a new era of Neutrino Astrophysics.
- Also provides a new opportunity window for BSM physics searches.
- Radiative neutrino mass models with (relatively) light mediators can give rise to distinct resonance features.
- Color-neutral mediators are accessible to IceCube and/or future neutrino telescopes (IceCube Gen-2, KM3NeT, P-ONE) .
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Thank You.