Continuum-Mediated Self-Interacting Neutrinos

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Light Dark World 25, Madrid

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Based on 2501.02049 with K. J. Kelly & M. Rai & Y. Zhang;

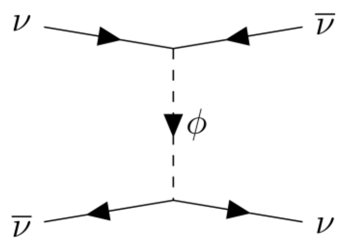
Outline

- Overview of Known Aspects of Neutrino Self-Interactions
- Neutrino Self-Interactions and Cosmological Observables
- Unparticle Physics
- Continuum-Mediated Scenarios for Strong Neutrino Self-Interactions

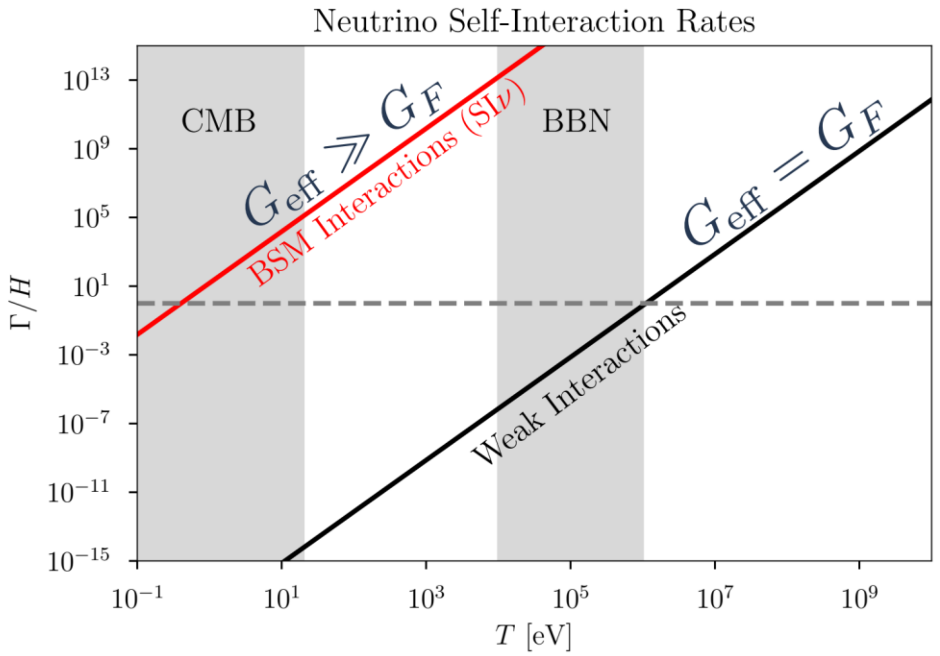
Motivations

- What if new neutrinophilic mediator exist?

- Neutrino mass generation: Models with a symmetry breaking mechanism in the neutrino sector (e.g. light pseudoscalar majoron) Chikashige et al ‘81



$$G_{\rm eff} \equiv \frac{g_\phi^2}{m_\phi^2} = (10{\rm MeV})^{-2}\left(\frac{g_\phi}{10^{-1}}\right)^2\left(\frac{\rm MeV}{m_\phi}\right)^2$$



- Address anomalies: e.g. Hubble tension

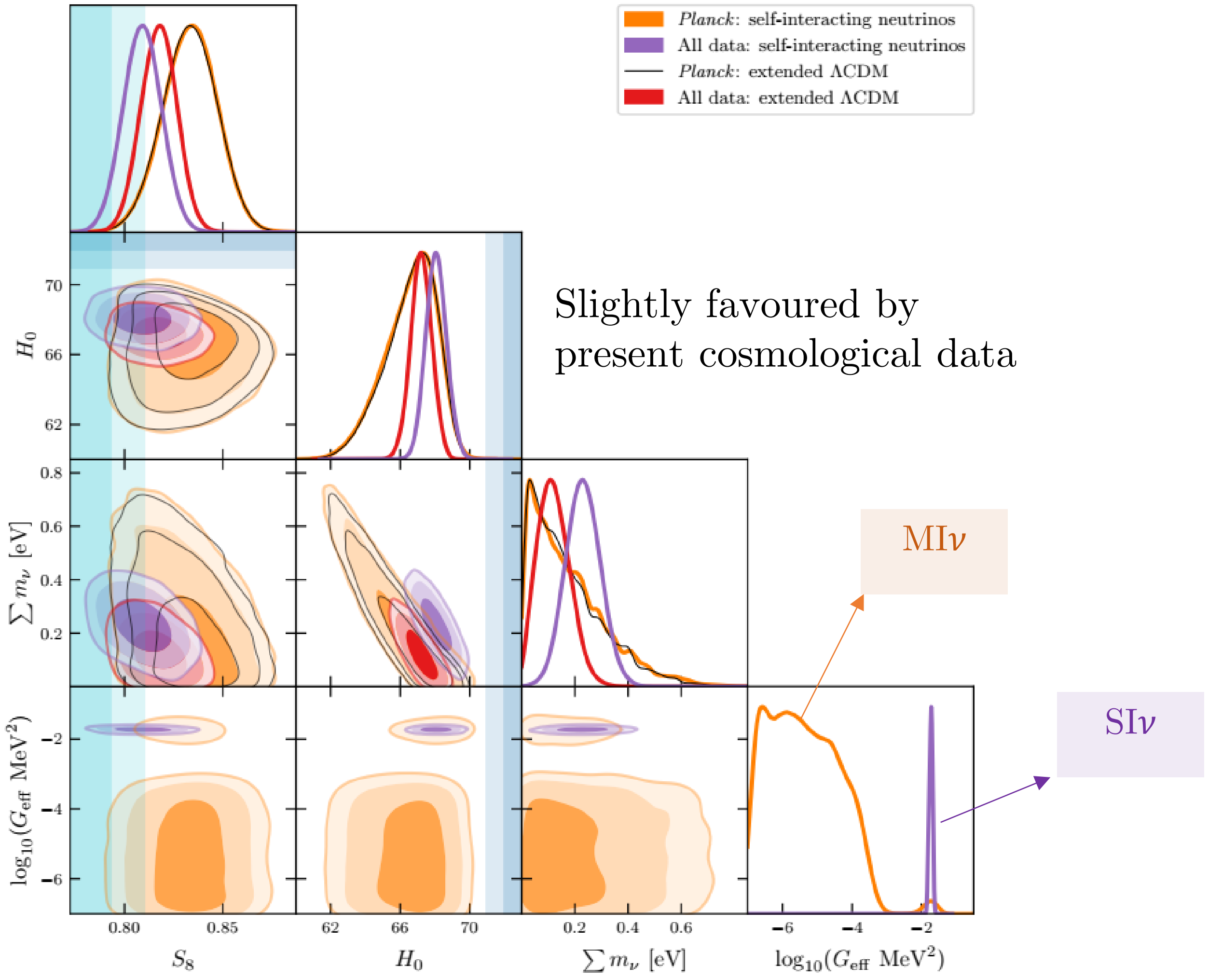
Cosmology

- Explore with the cosmological simulations the impact of νSI on CMB inference of H_0

  Kreisch et al [1902.00534]

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

- Requires larger Σm_ν



Slightly favoured by present cosmological data

He, An, Ivanov, Gluscevic [2309.03956]

Constraints

- The new particle, depending on its mass, can be produced in neutrino-related processes

Dev, Kim, Sathyan, et al. [2407.12738]

$$\mathscr{L} \supset \frac{\lambda_{\alpha\beta}}{2}\nu_\alpha\nu_\beta\phi$$

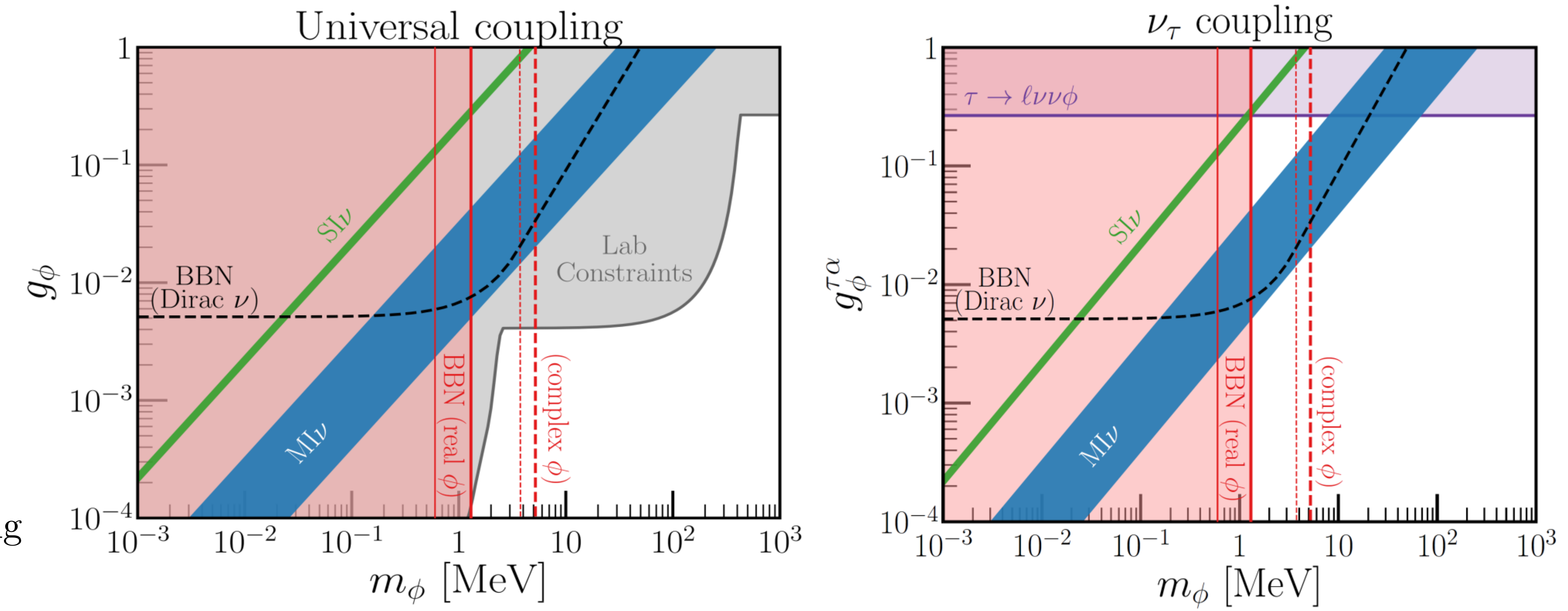
$\mathfrak{m}^\pm \to \ell^\pm_\alpha \nu_\beta \phi$

$Z \to \nu_\alpha\nu_\beta\phi$

$h \to \nu_\alpha\nu_\beta\phi$

$\phi\beta\beta$

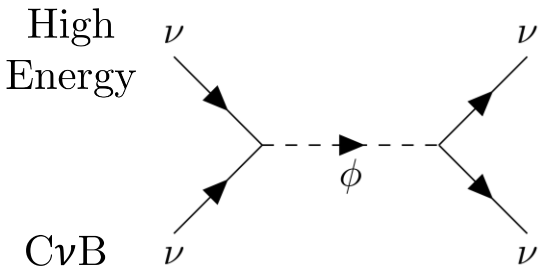
SIν and MIν with flavour-universal coupling is tightly constrained!



Blinov, Kelly, Krnjaic, McDermott [1905.02727]

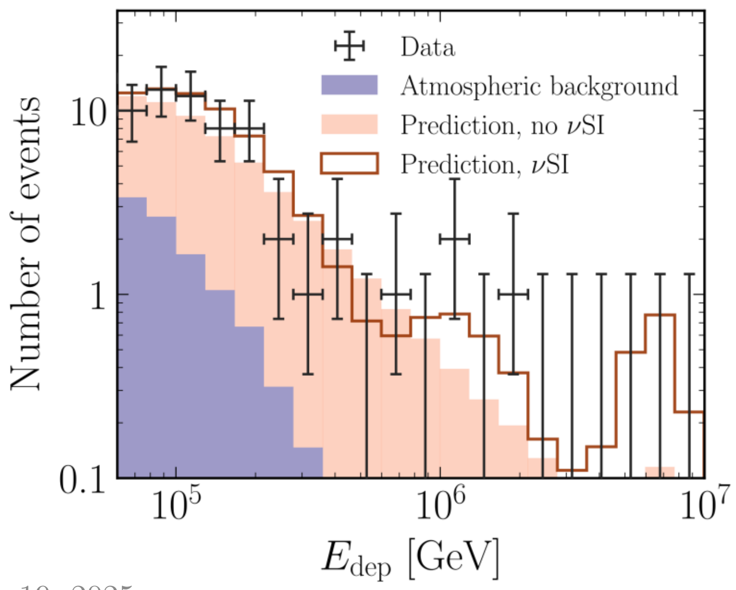
Absorption of HE Neutrinos

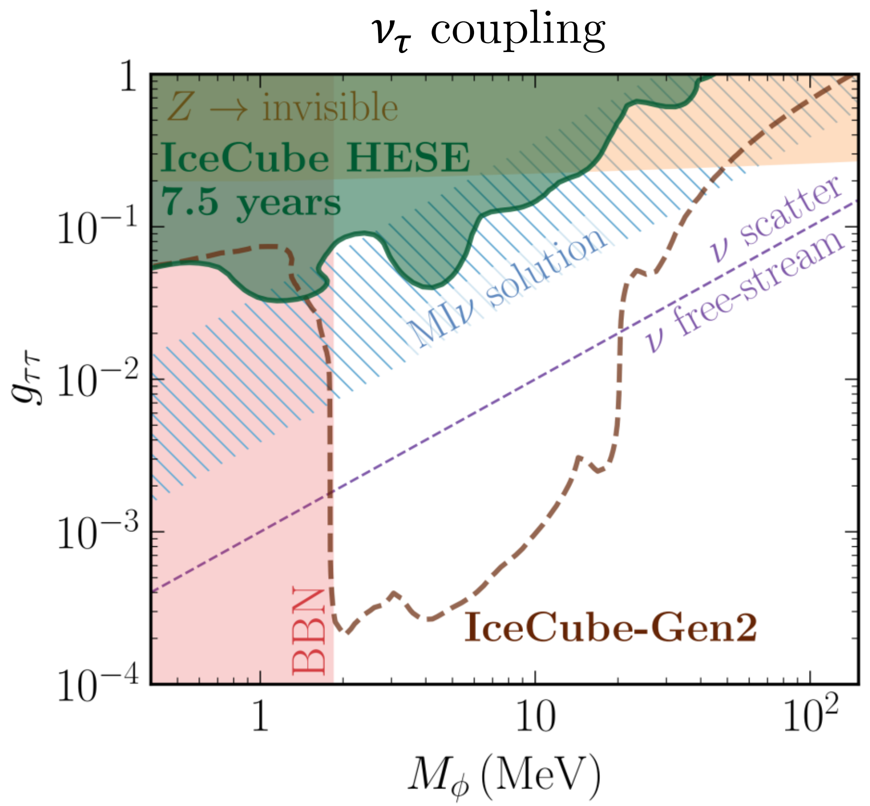
- Resonant absorption of the UHE cosmogenic neutrino and one from the CνB. e.g. see Ng, Beacom [1404.2288]



$$m_\phi^2 \sim s = 2m_\nu E_\nu$$

- Dips and bumps signature in the cosmic neutrino spectrum

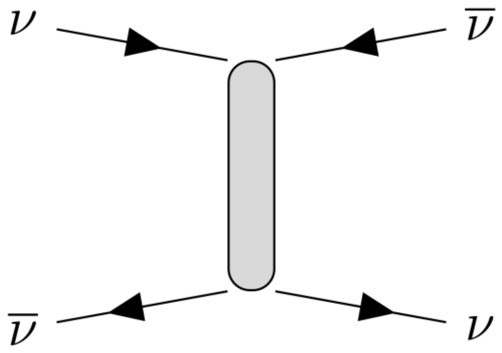




Esteban, Pandey, Brdar, Beacom [2107.13568]

Continuum Mediation

Neutrino self interaction through the exchange of a mediator with a
<u>continuous spectral density function</u>



$$\mathcal{L}_{\text{int}} = \frac{\lambda}{2\Lambda^{d_u - 1}} \overline{\nu_\tau^c} P_L \nu_\tau \mathcal{U} + \text{h.c.}$$

- Unparticle (conformal theory) is a low energy realization of a theory which has an IR fixed point

Georgi [0703260]

$$iD_F^{\mathcal{U}}(p^2) = \langle 0|\mathcal{O}_{\mathcal{U}}(p)\mathcal{O}_{\mathcal{U}}(-p)|0\rangle = \int_0^\infty \frac{d\mu^2}{2\pi} \frac{i\rho(\mu^2)}{p^2 - \mu^2 + i\epsilon}$$

$$\rho\left(\mu^2\right) \to (2\pi)\delta\left(\mu^2 - M^2\right)$$

Particle

Unparticle phase space

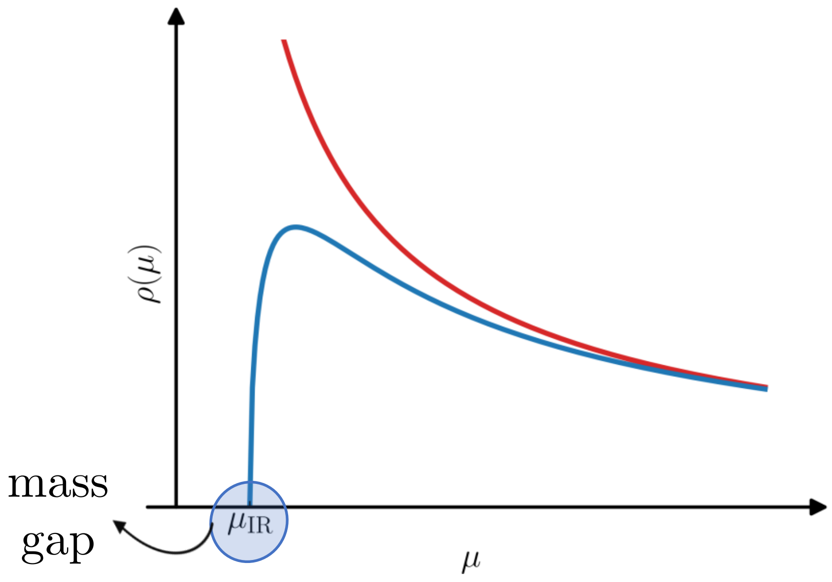
- Continuous spectral density as a result of *scale invariance*

Unitarity implies $1 < d_{\mathcal{U}} < 2$

$$\rho\left(p^2\right) = \int d^4x e^{ipx} \langle 0|\mathcal{O}_{\mathcal{U}}(x)\mathcal{O}_{\mathcal{U}}(0)|0\rangle \xrightarrow{\text{scale invariance}} \rho(p^2) \propto \left(p^2\right)^{d_{\mathcal{U}}-2}$$

- A purely conformal hidden sector does not have a definite mass

- Gapped continuum: *conformal symmetry breaking*
  e.g. such continuum naturally arises in warped 5D holographic models



Chaffey, Fichet, Tanedo [2102.05674]

Csáki, Perelstein et al [2105.07035]

νSI with Gapped Continuum

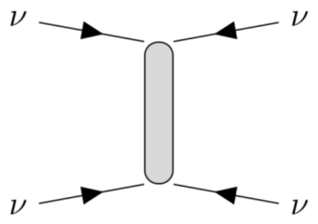
- Practical model of a gapped unparticle $\{\lambda,\ \Lambda,\ \mu_{\rm IR},\ d_u\}$

  Fox, Rajaraman, Shirman [0705.3092]

$$\rho(\mu^2) = A_{d_u}\left(\mu^2 - \mu_{\rm IR}^2\right)^{d_u-2}\Theta(\mu^2 - \mu_{\rm IR}^2)$$

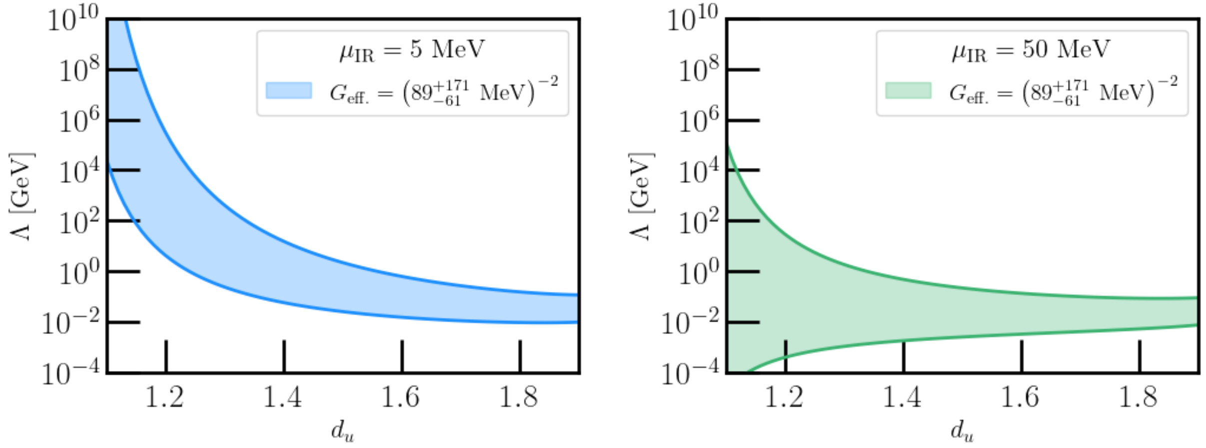
$$iD_F^{\mathcal{U}}(p^2) \simeq \frac{iB_{d_u}}{(p^2 - \mu_{\rm IR}^2)^{2-d_u} - i\,{\rm Im}\,\Sigma(p^2)}$$

- The dominant contribution of the neutrino self-interaction strength $(q^2 \ll \mu^2)$ coming from unparticle states close to the mass gap



$$G_{\rm eff.} = \frac{|B_{d_u}\lambda^2|}{\mu_{\rm IR}^2}\left(\frac{\mu_{\rm IR}}{\Lambda}\right)^{2d_u-2}$$

- Compare to $\quad d_u \to 1 \quad G_{\rm eff.} \to \dfrac{|\lambda^2|}{\mu_{\rm IR}^2}$

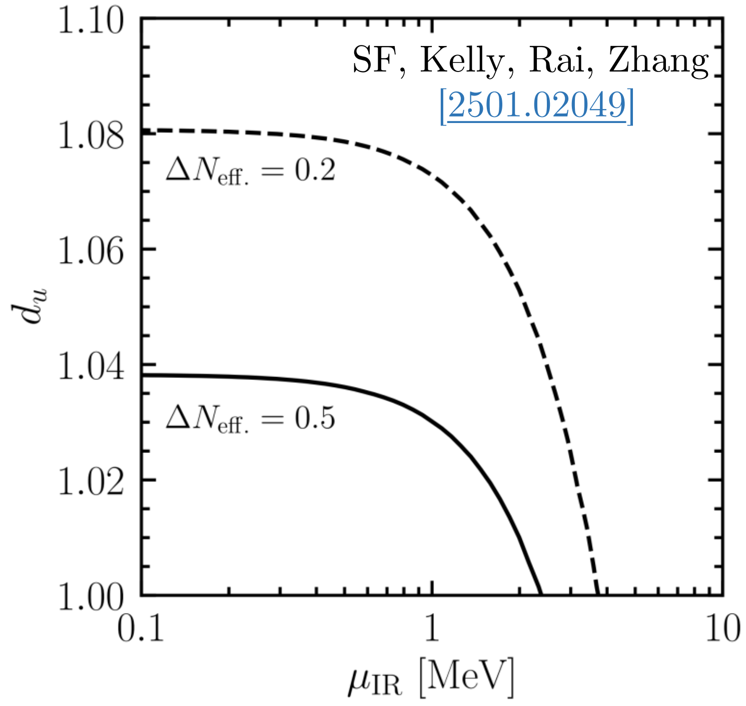


MIν band

Lifting BBN/CMB Constraint

- Thermal equilibrium in the early universe, leading to a contribution to ΔNeff

$$\varrho_u(T) = \frac{\int_{\mu^2_{\rm IR}}^{\mu^2_{\rm UV}} \frac{d\mu^2}{2\pi}\, \rho_{\mathcal{U}}(\mu^2)\, g \int \frac{d^3\vec{p}}{(2\pi)^3} \frac{E_{\vec{p}}}{\exp(E_{\vec{p}}/T)-1}}{\int_{\mu^2_{\rm IR}}^{\mu^2_{\rm UV}} \frac{d\mu^2}{2\pi}\, \rho_{\mathcal{U}}(\mu^2)}$$



- Only states with masses $\mu_{\rm IR} < \mu \lesssim T$ contribute to ΔNeff

- Heavier modes $(T \ll \mu)$ are Boltzmann suppressed

- Extra suppression factor compared to the particle case

$$\Delta N_{\rm eff} \propto \left(\frac{T_{\rm BBN}}{\Lambda}\right)^{2d_u-2} \qquad \mu_{\rm IR} \ll T_{\rm BBN}$$

Lifting Astrophysical Constraint

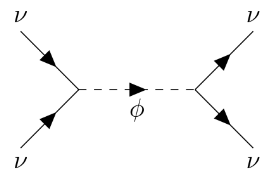
- Solve the UHE neutrino transport equation

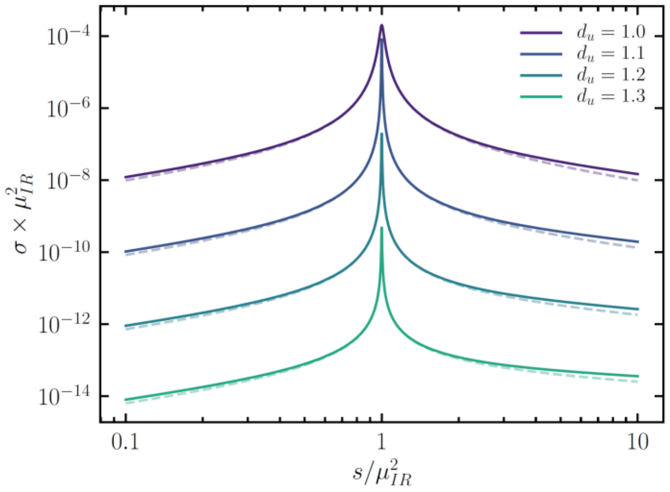
$$\frac{\partial^2\Phi(t,E_\nu)}{\partial t\partial E_\nu} = \frac{\partial}{\partial E_\nu}\left[H(t)E_\nu\frac{\partial\Phi(t,E_\nu)}{\partial E_\nu}\right] + \text{source} + \text{absorption} + \text{regeneration}$$

Source Term

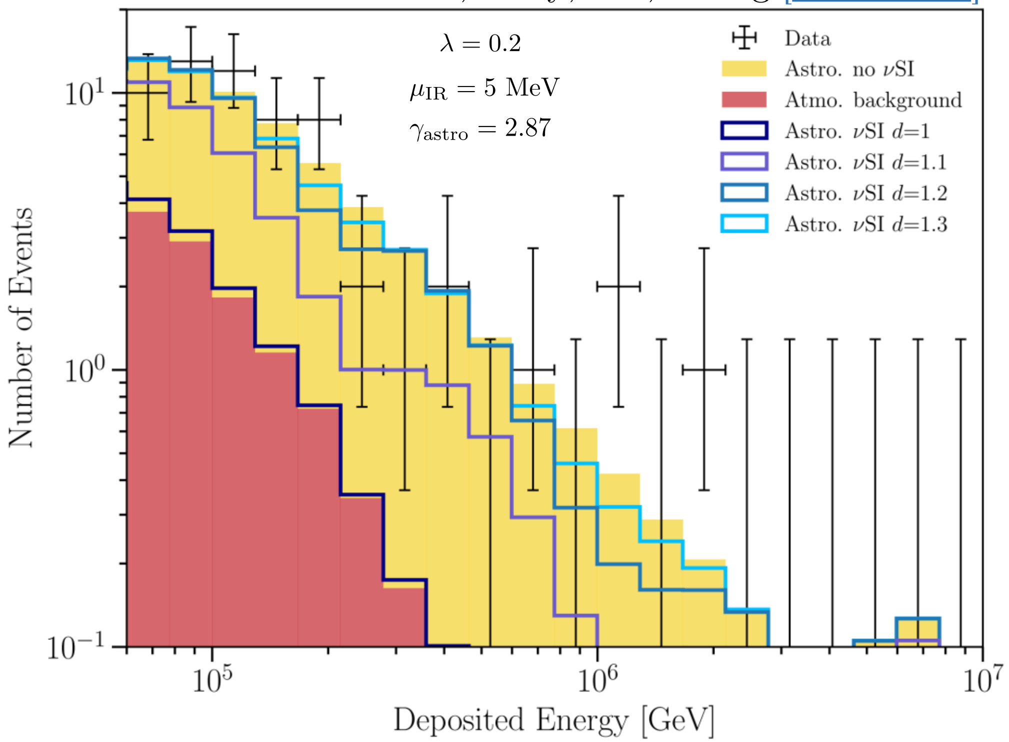
$$\frac{d\Phi_{\text{astro.}}}{dE_\nu} \propto \left(\frac{E_\nu}{100\,\text{TeV}}\right)^{-\gamma}$$

- The effect is dramatically suppressed for unparticles ($d_u > 1$), reducing the UHE–CνB neutrino cross section, thus, weakening IceCube limits.





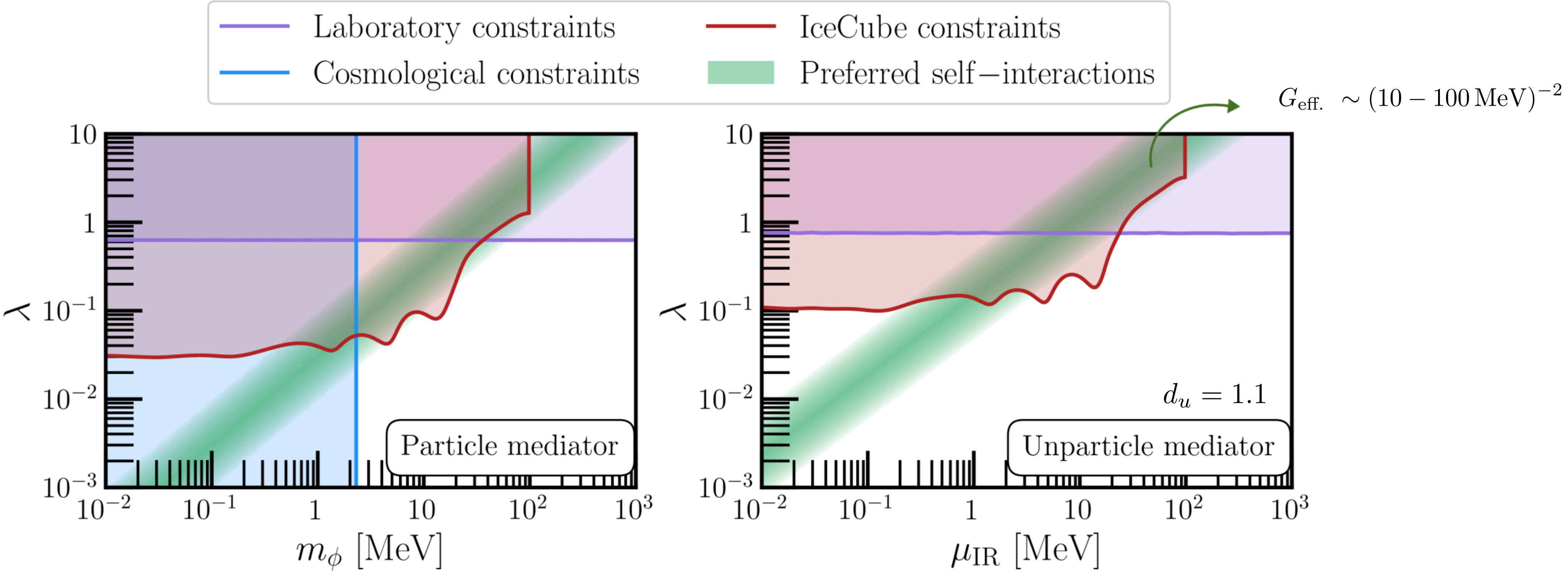
SF, Kelly, Rai, Zhang [2501.02049]



IceCube HESE 7.5-year data release

Lifting Constraints

- A light unparticle mediator (with sub-MeV mass gap) enables strong neutrino self-interactions relevant for late-time cosmology.



SF, Kelly, Rai, Zhang [2501.02049]

Conclusion

- Sizable neutrino self-interactions can address the tension in Hubble constant measurements.
- Neutrino self-interactions mediated by a light neutrinophilic scalar has already been tightly constrained by complementary terrestrial, astrophysical, and cosmological probes.
- A gapped unparticle mediator can open significant regions of parameter space for strong neutrino self-interactions relevant to cosmology
- BBN allows for a sub-MeV mass gap holds generically for dark sectors made of unparticle states
- With enough data, it is possible that IceCube-Gen2 could distinguish between positive signals involving particle mediators versus unparticle ones

Thank you!

UV Completion

- Theory of Neutrinophilic Mediator similar to the Weinberg operator

Neutrino Self-Interactions:
A White Paper [2203.01955]

$$\mathscr{L} \supset \frac{(L_\alpha H)\,(L_\beta H)\,\phi}{\Lambda_{\alpha\beta}^2} \longrightarrow \frac{\lambda_{\alpha\beta}}{2}\nu_\alpha\nu_\beta\phi \qquad \left(\lambda_{\alpha\beta} \equiv \frac{\nu^2}{\Lambda_{\alpha\beta}^2}\right)$$

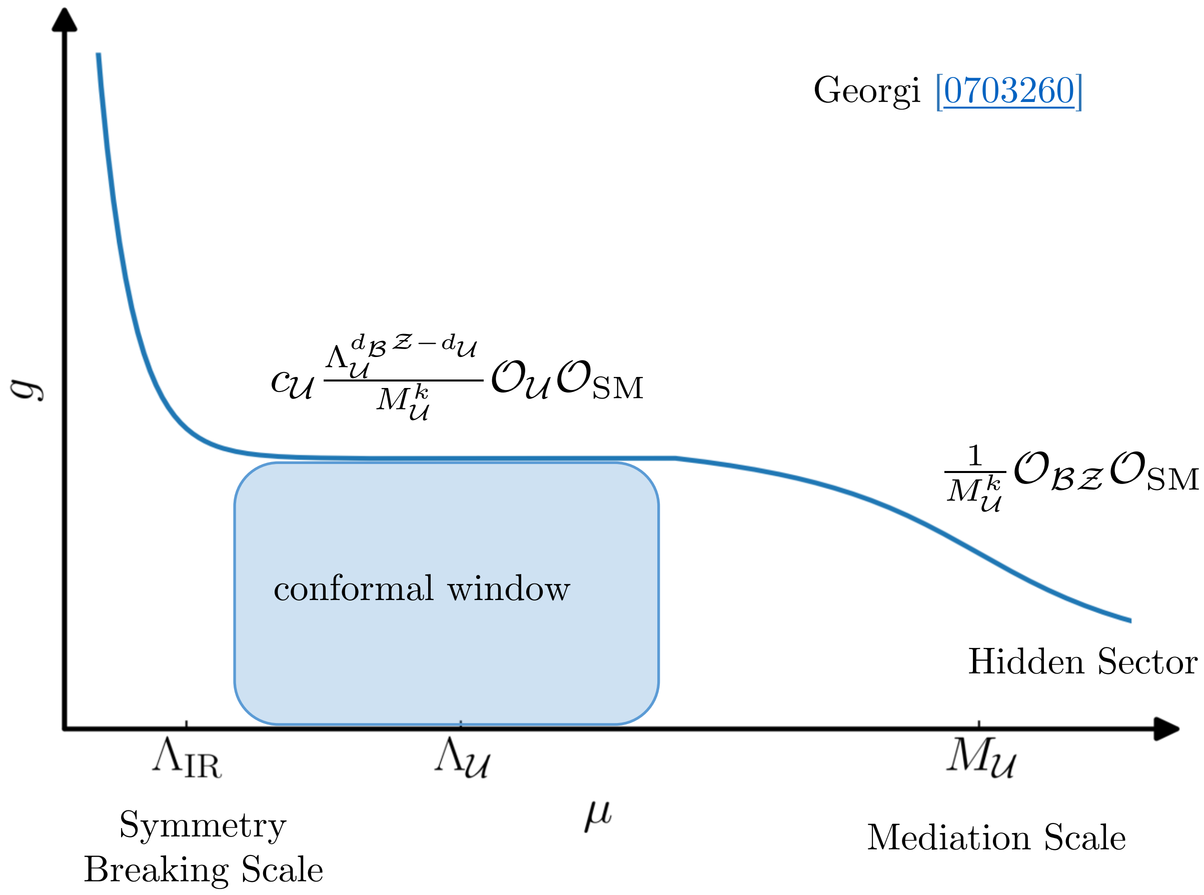
Conformal Hidden Sector

- Banks-Zaks theory: SU(3) for a range of NF, the theory flows to a perturbative infrared stable fixed point.

- Unparticle physics is realized at low energy in the conformal window at transmutation scale $\Lambda_{\mathcal{U}}$

- Conformal symmetry breaking below Λ_{IR} through a renormalizable operator (e.g. $\mathcal{U}^2 H^\dagger H$)

- The IR cutoff scale introduces a mass gap - realizes a confinement in the hidden sector.



Unparticle propagator

- Due to *scale invariance*, an unparticle operator with scaling dimension d_u exhibits a continuous spectral density

Unitarity implies $1 < d_{\mathcal{U}} < 2$

$$\rho\left(p^2\right) = \int d^4x e^{ipx} \langle 0|\mathcal{O}_{\mathcal{U}}(x)\mathcal{O}_{\mathcal{U}}(0)|0\rangle$$

$$\rho(\mu^2) = A_{d_u}\left(\mu^2\right)^{d_u-2}\Theta(\mu^2)$$

$$A_{d_u} = \frac{16\pi^{5/2}}{(2\pi)^{2d_u}}\frac{\Gamma\left(d_u+\frac{1}{2}\right)}{\Gamma\left(d_u-1\right)\Gamma\left(2d_u\right)}$$

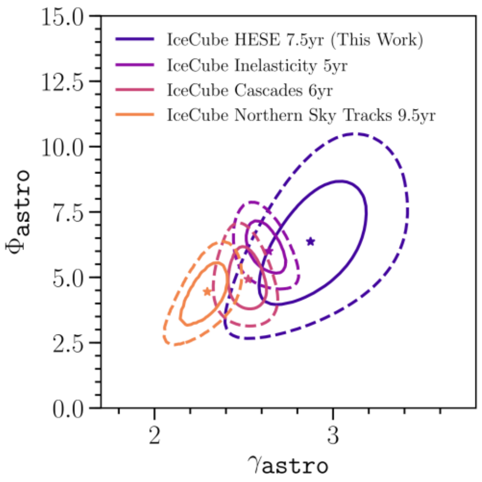
- The propagator: $iD_F^{\mathcal{U}}(p^2) = \langle 0|\mathcal{O}_{\mathcal{U}}(p)\mathcal{O}_{\mathcal{U}}(-p)|0\rangle = \int_0^\infty \frac{d\mu^2}{2\pi}\frac{i\rho(\mu^2)}{p^2-\mu^2+i\epsilon}$

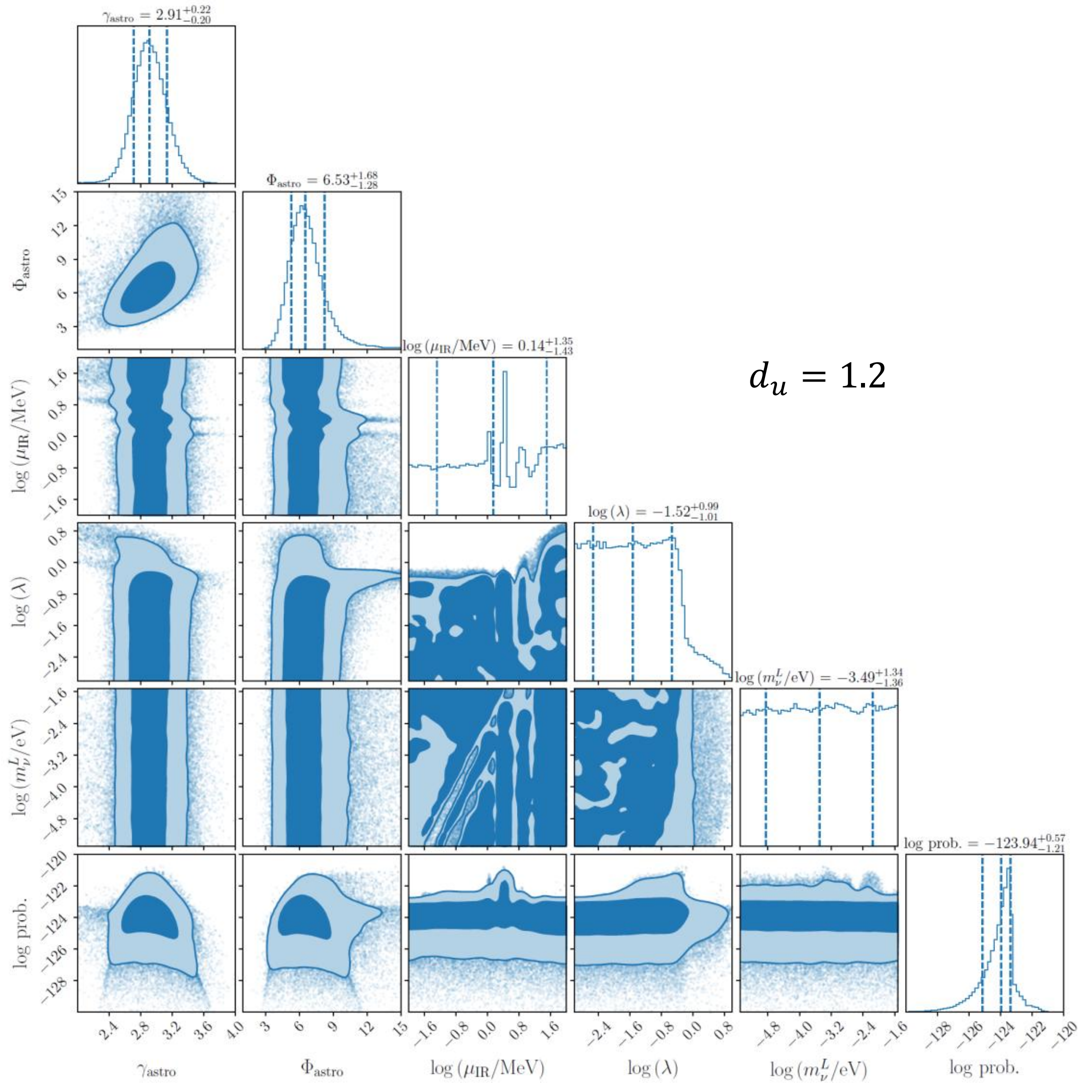
IceCube Constraint: Posterior Distributions

- We scan over λ, μIR, mν, Φastro and γastro and compare the predicted neutrino spectrum by the unparticle mediator model with the IceCube 7.5-year data.

- Use [nuSIprop] code to solve the UHE neutrino transport equation

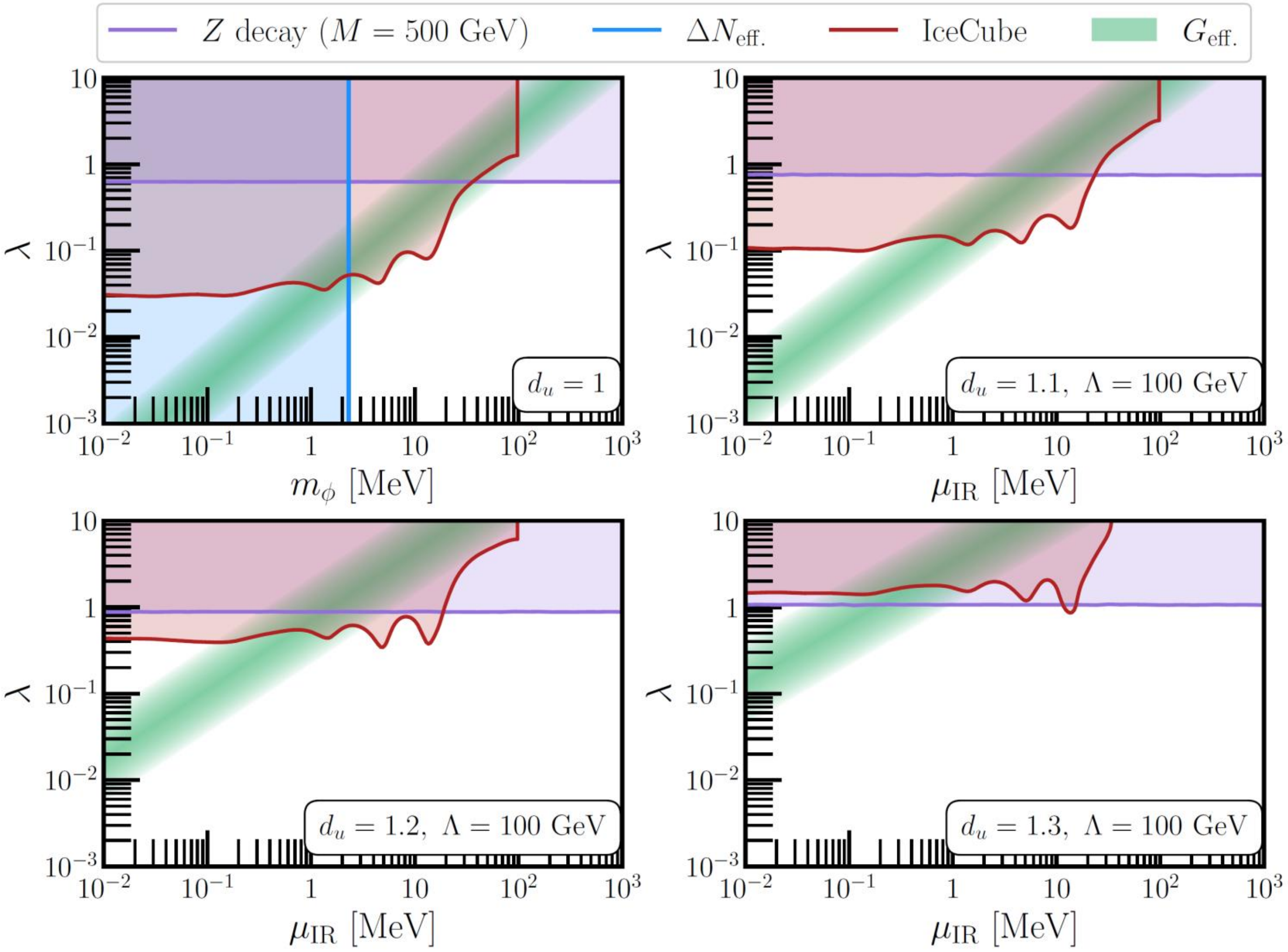
IceCube HESE
7.5 year data release
[2011.03545]





$d_u = 1.2$

Lifting Constraints



SF, Kelly, Rai, Zhang [2501.02049]