Workshop on Dark Universe

Uncovering secret neutrino interactions at ν_τ experiments

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arXiv:2311.14945 with Pouya Bakhti, Meshkat Rajaee

Why neutrino?

- Understanding the evolution and current feature of our Universe:

  BBN, CMB, Dark Matter, SN, AGN, ..

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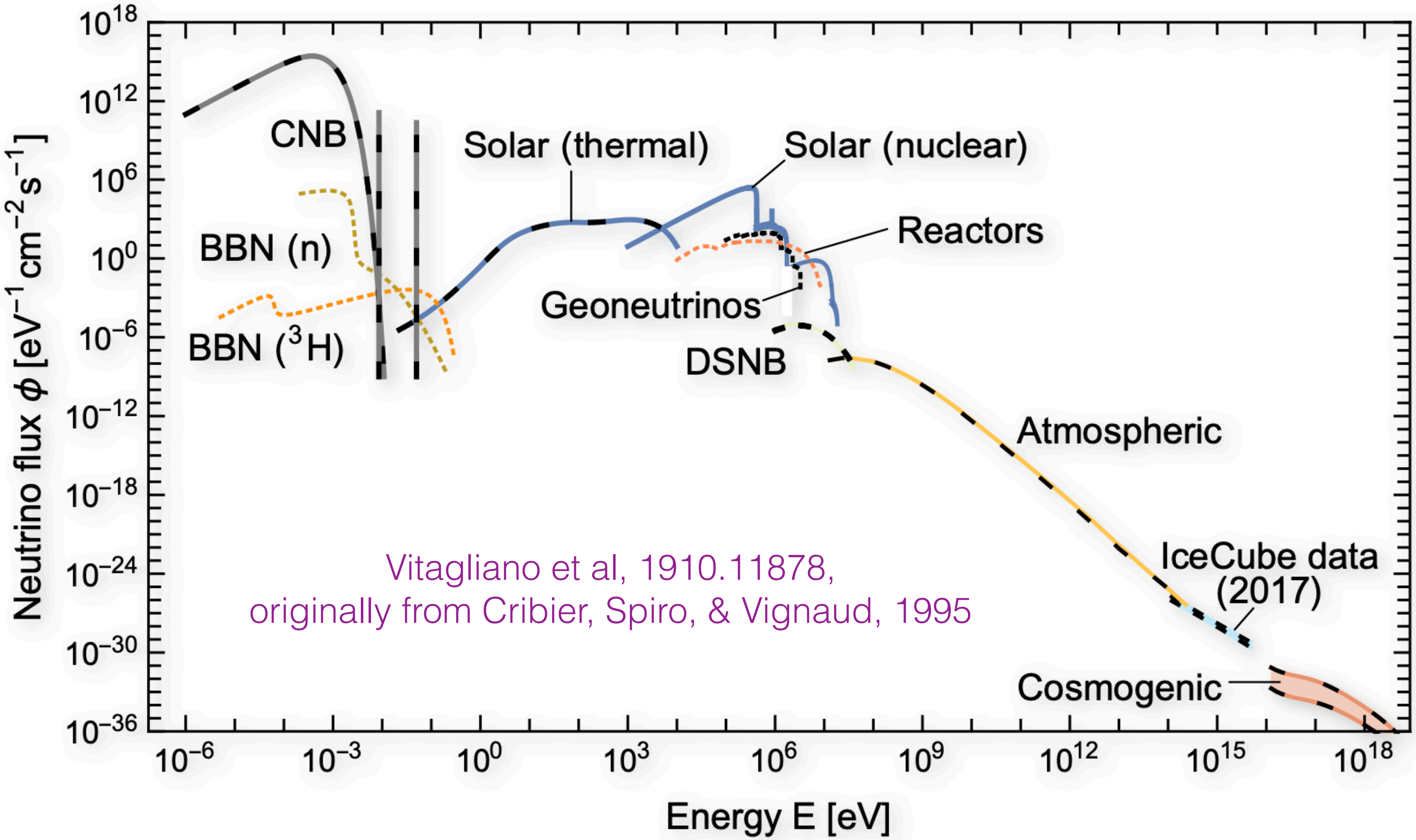
- A variety of current & future observations



New symmetry in the neutrino sector

Neutrino oscillation: clear evidence of BSM

→ *ν physics can provide guidelines for BSM*

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- Mass generation (not from Higgs mechanism)

  - L, B - L, GUT, … (along with EW breaking)
  - New particles from the symmetry or its breaking: mediator

    e.g., Majoron, SU(2) triplet, …

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- Extended gauge symmetry, e.g., by gauging anomaly free global symmetry such as B - L, L_α - L_β, …

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Focus: self interactions among active ν or + sterile ν

⇨ secret neutrino interaction (SNI)

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See also SNOWMASS WP 2022,
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Theoretical set-up

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⟶ Tau neutrino experiments (coming soon)

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Reference scenario (for concreteness): a sub-GeV Z' scenario

$$\mathcal{L} \supset \sum_{\alpha,\beta} g_{\alpha\beta} Z'_\mu \bar{\nu}_\alpha \gamma^\mu \nu_\beta$$

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  - Active neutrinos couple to Z' through the mixing with Ψ

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Phenomenological set-up: exclusive coupling

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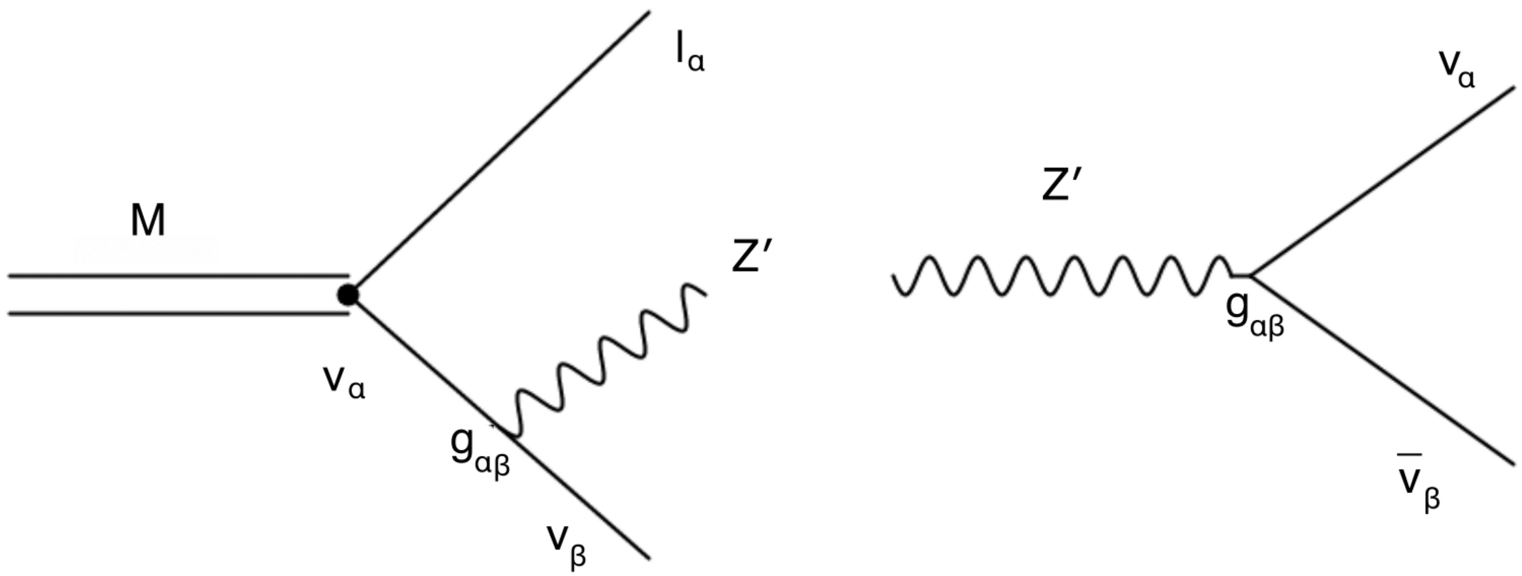
Kinematic process on our focus: 3-body meson decay



- Conventional 2-body decay of a pseudoscalar meson such as $\pi^\pm \to \mu^\pm \nu$: chiral suppression. m_ℓ^2/m_M^2

- 3-body decay: enhanced by the longitudinal mode of Z' $m_M^2/m_{Z'}^2$

Barger, Chiang, Keung, Marfatia, PRL 2012 Carson, Rislow, PRD 2012

Laha, Dasgupta, Beacom, PRD 2014 Bakhti, Farzan, PRD 2017

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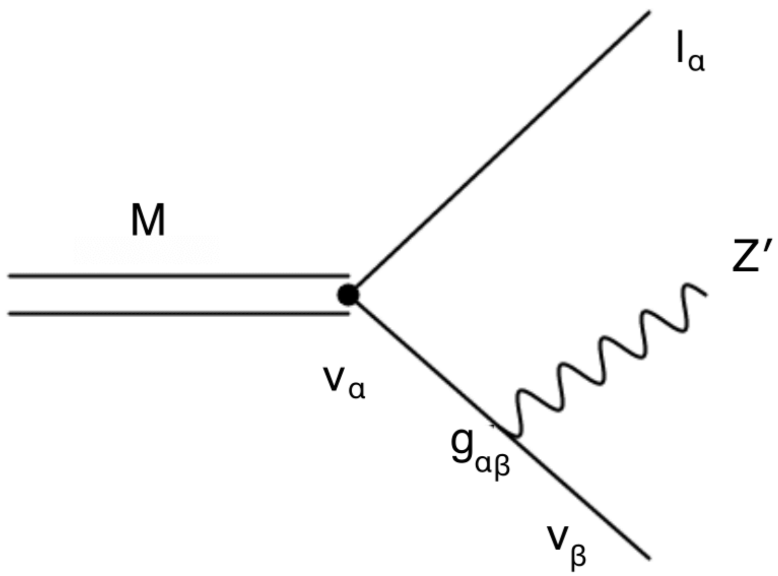

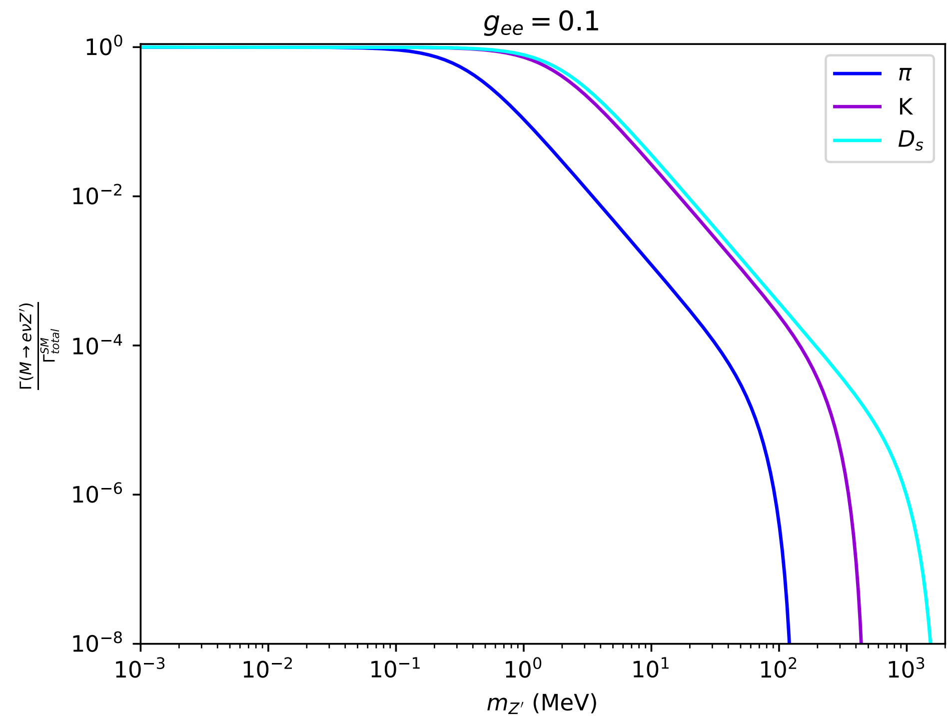

- Branching ratio of the 3-body decay can be dominant for light Z' despite the phase space suppression.
- Accordingly, very strong exp. bounds on g_{ee} : below ≲ 10^{-4}.

Reference experiments

- Observations of ν_τ challenging due to prompt and semi-visible decays of τ (identification and reconstruction) as well as high $E_{\rm th}$ > 3 GeV beyond the oscillation maxima & small σ.

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Now we are ready to directly detect enormous ν_τ events!!!

- Experiments in the future: FLArE100, FASERν2, AdvSND, SHiP

  also SND@LHC for comparison

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- DUNE far detector: atmospheric data

  unexpected downward-going ν_τ appearance

  (no oscillation $\nu_\mu \rightarrow \nu_\tau$ & small flux)

Reference experiments

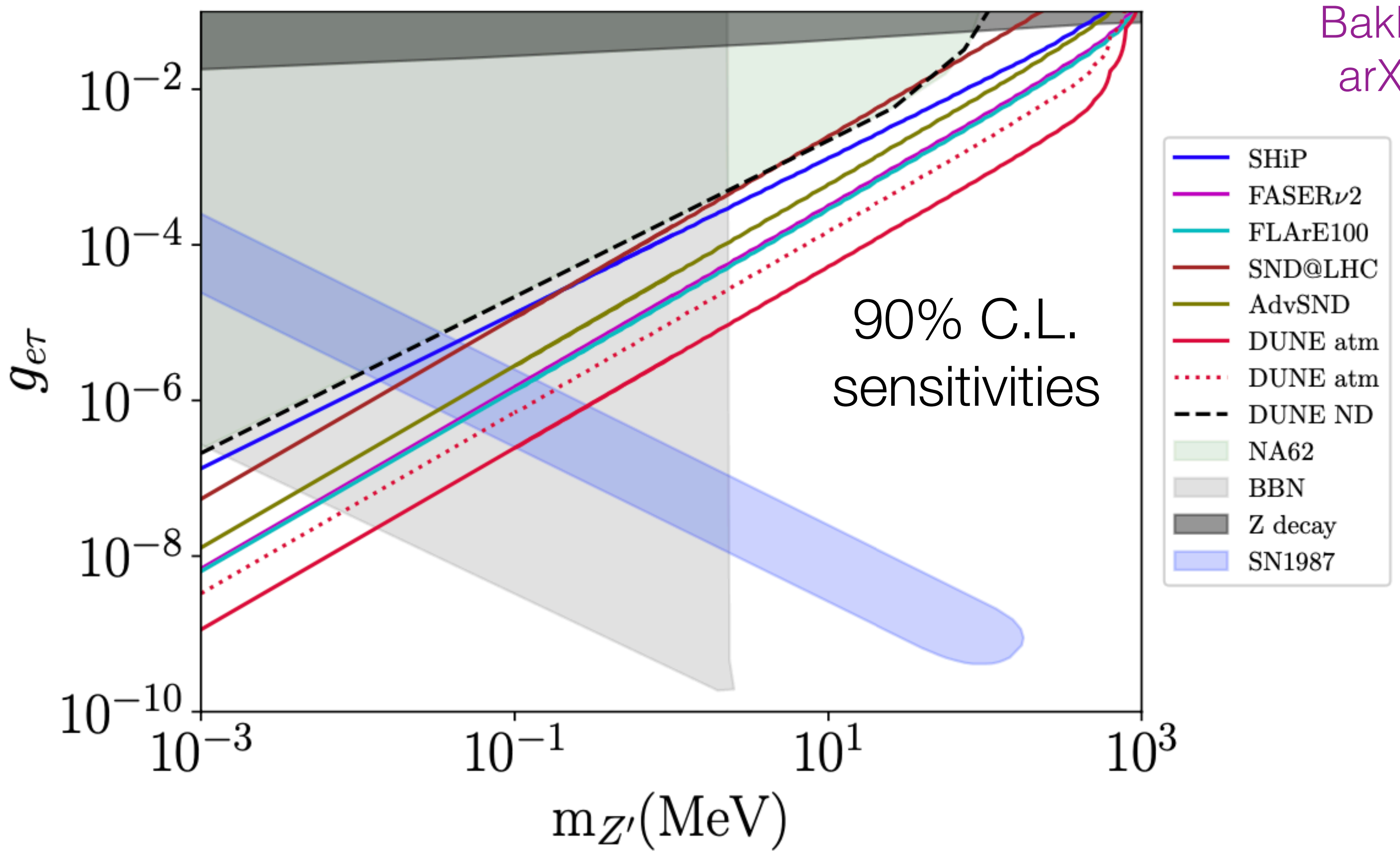
Detector		number of events		
Detector name	mass	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SND@LHC	800 kg	250	1000	11
FASERν2	20 tonnes	7.5×10^4	4×10^5	1.7×10^3
FLArE100	100 tonnes	2.5×10^4	1.38×10^5	1.3×10^4
SHiP	10 tonnes	3.4×10^4	2.35×10^5	1.2×10^4
DUNE	40 kilo-tonnes	1.6×10^4	2.4×10^4	150

TABLE I. Estimated numbers of standard model neutrino events assuming a final integrated luminosity of 150 fb^{-1} for SND@LHC, while 3000 fb^{-1} for FASERν2 and FLArE100. For SHiP, we assume 2×10^{20} POT in five years. We assume a data-taking period of 10 years for DUNE atmospheric neutrinos.

Experimental details: Kling, Nevay, PRD 2021 & FPF SNOWMASS 2203.05090

- FPF experiments: huge flux of ν_τ compared to SND@LHC (current)
- SHiP: larger ratio of ν_τ due to a hadron absorber (light mesons)
- DUNE: 150 upward-going ν_τ from the oscillation $\nu_\mu \to \nu_\tau$

Sensitivities for ν_τ SNI



Bakhti, Rajaee, **SS**,
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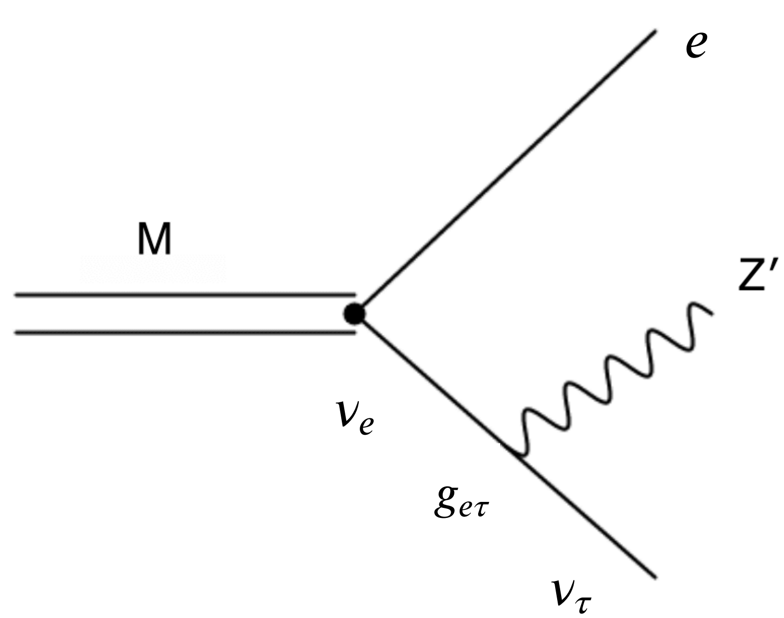

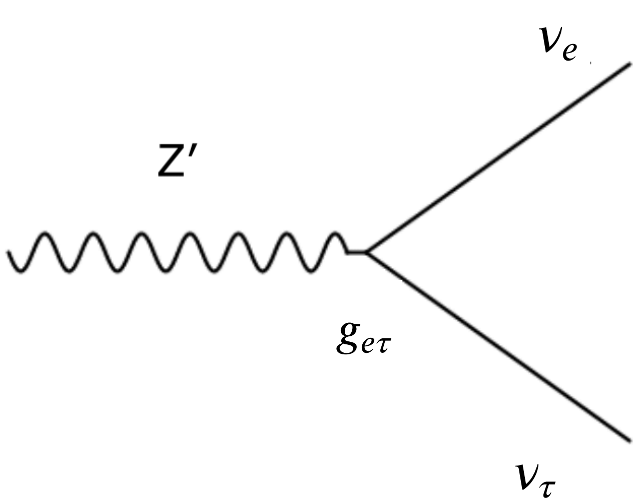

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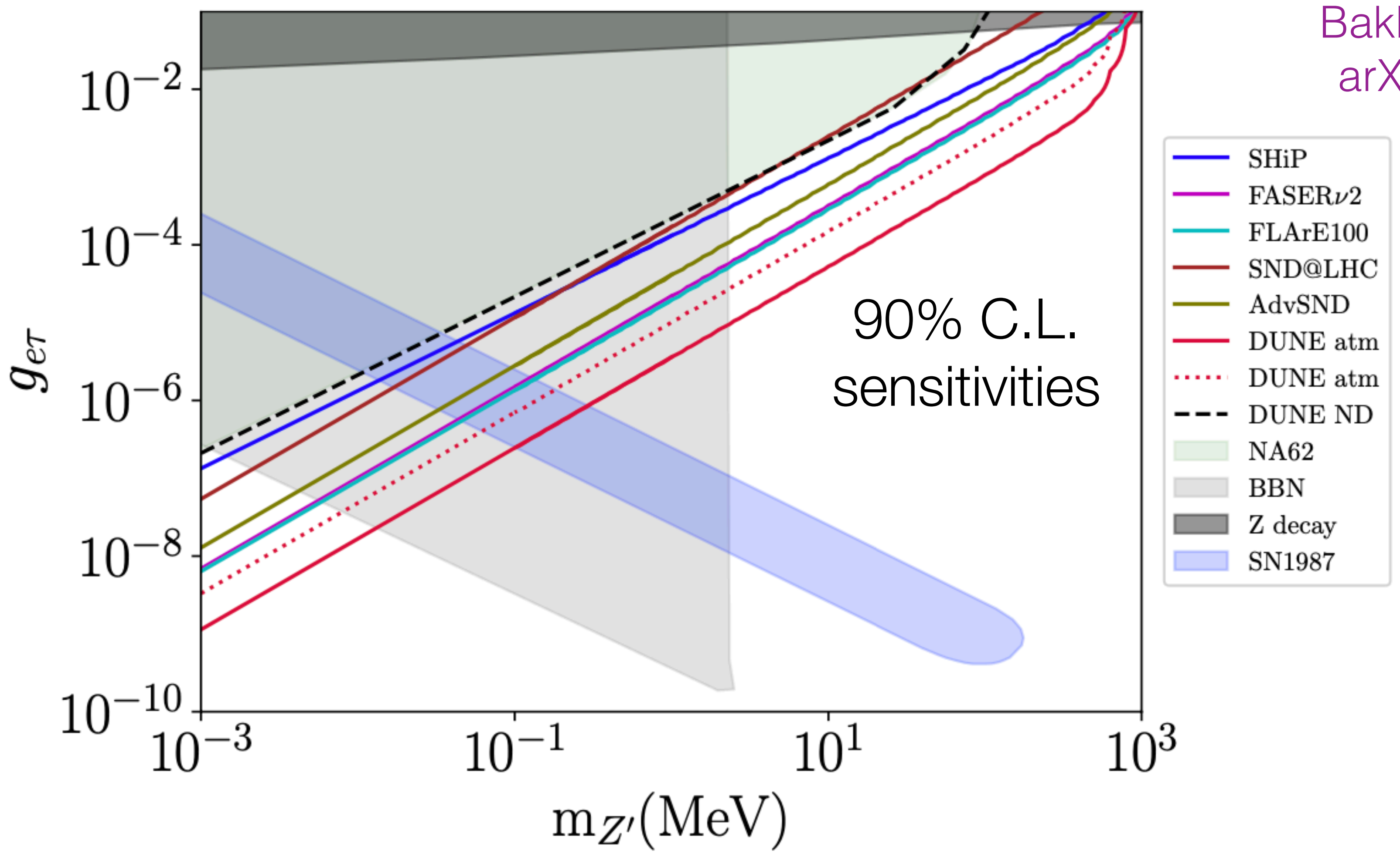

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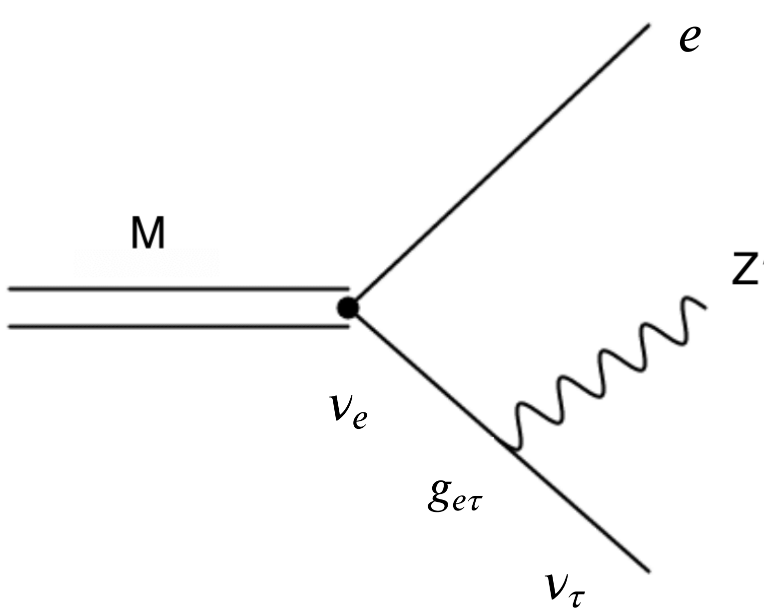

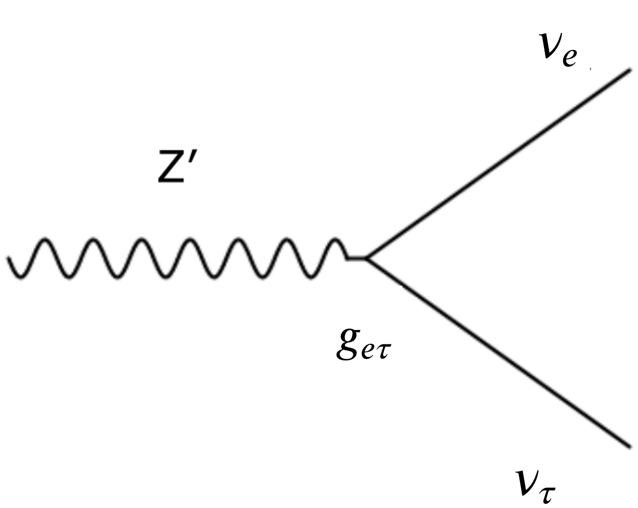

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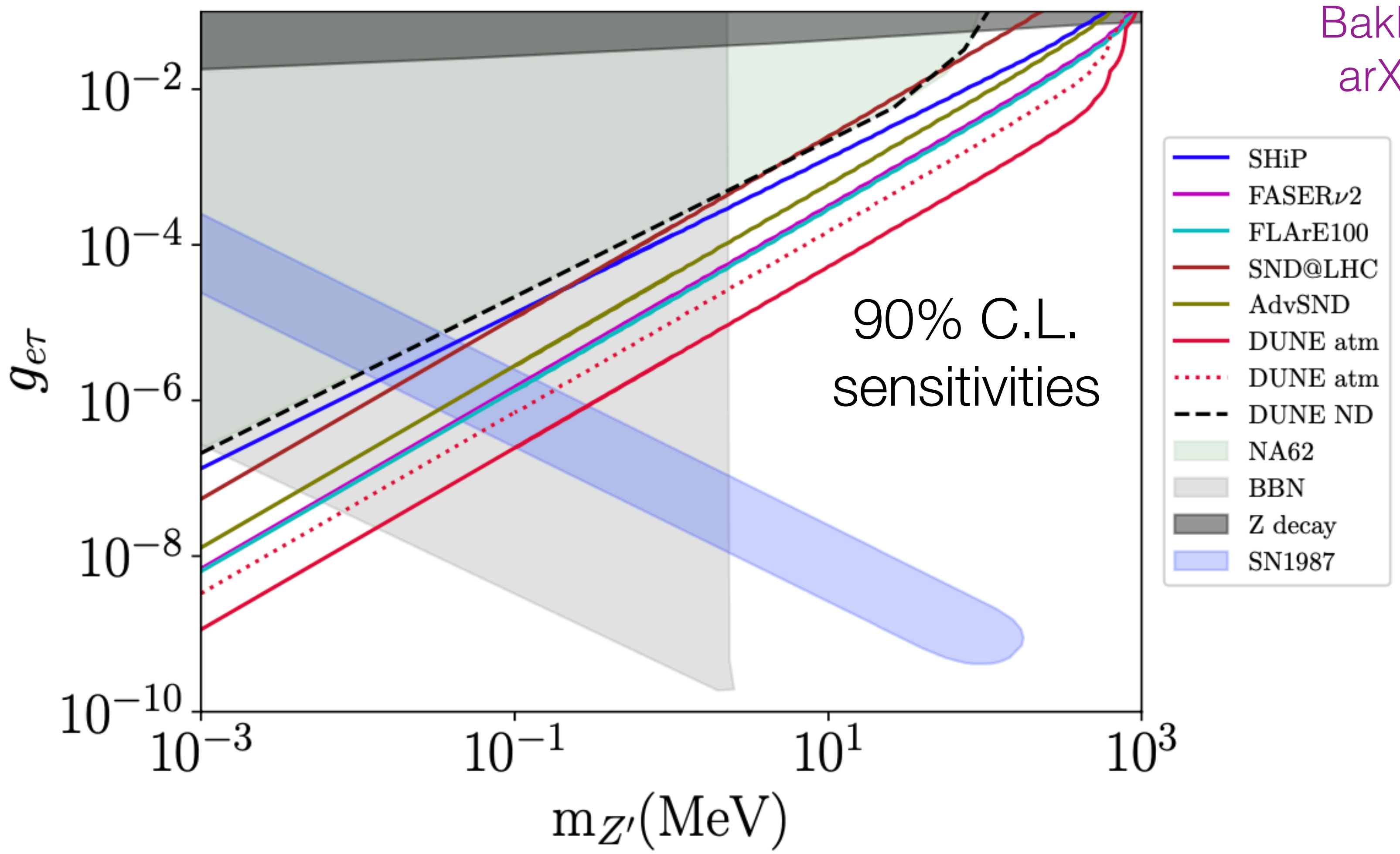

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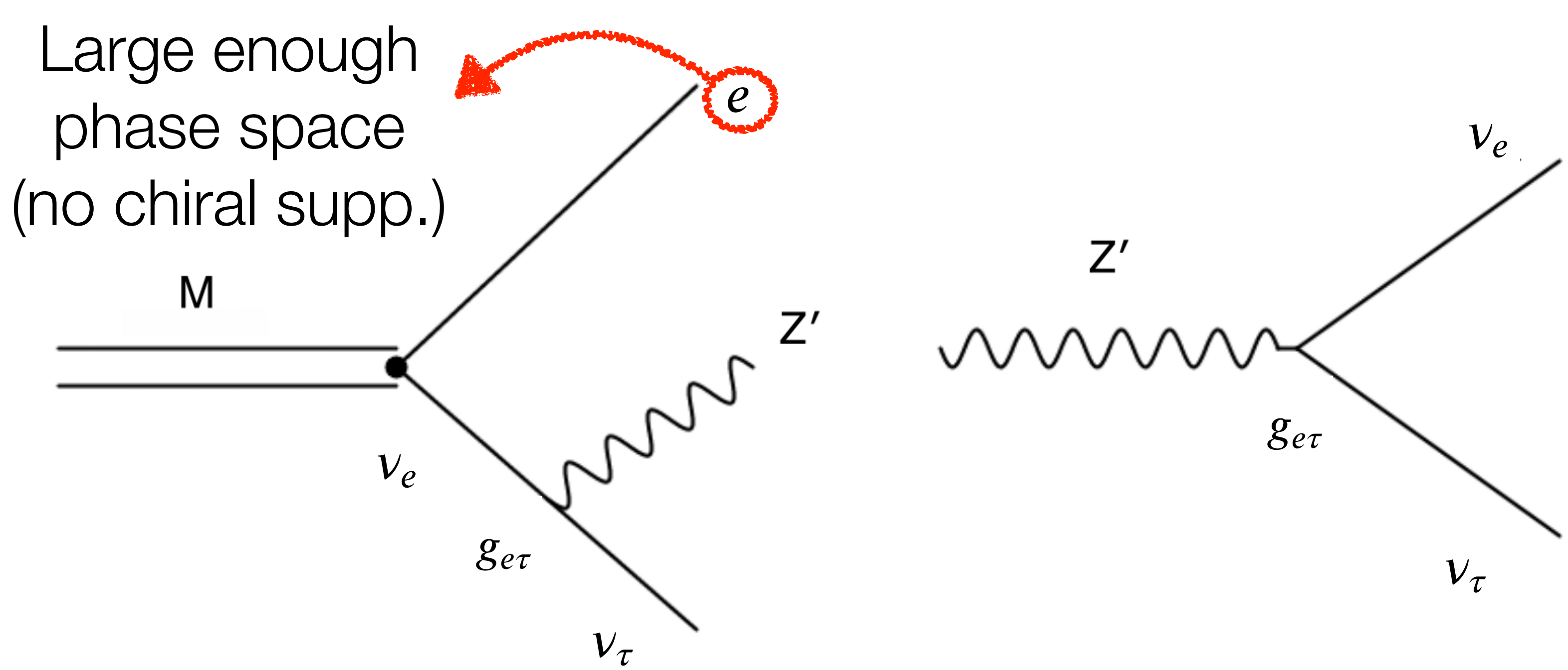

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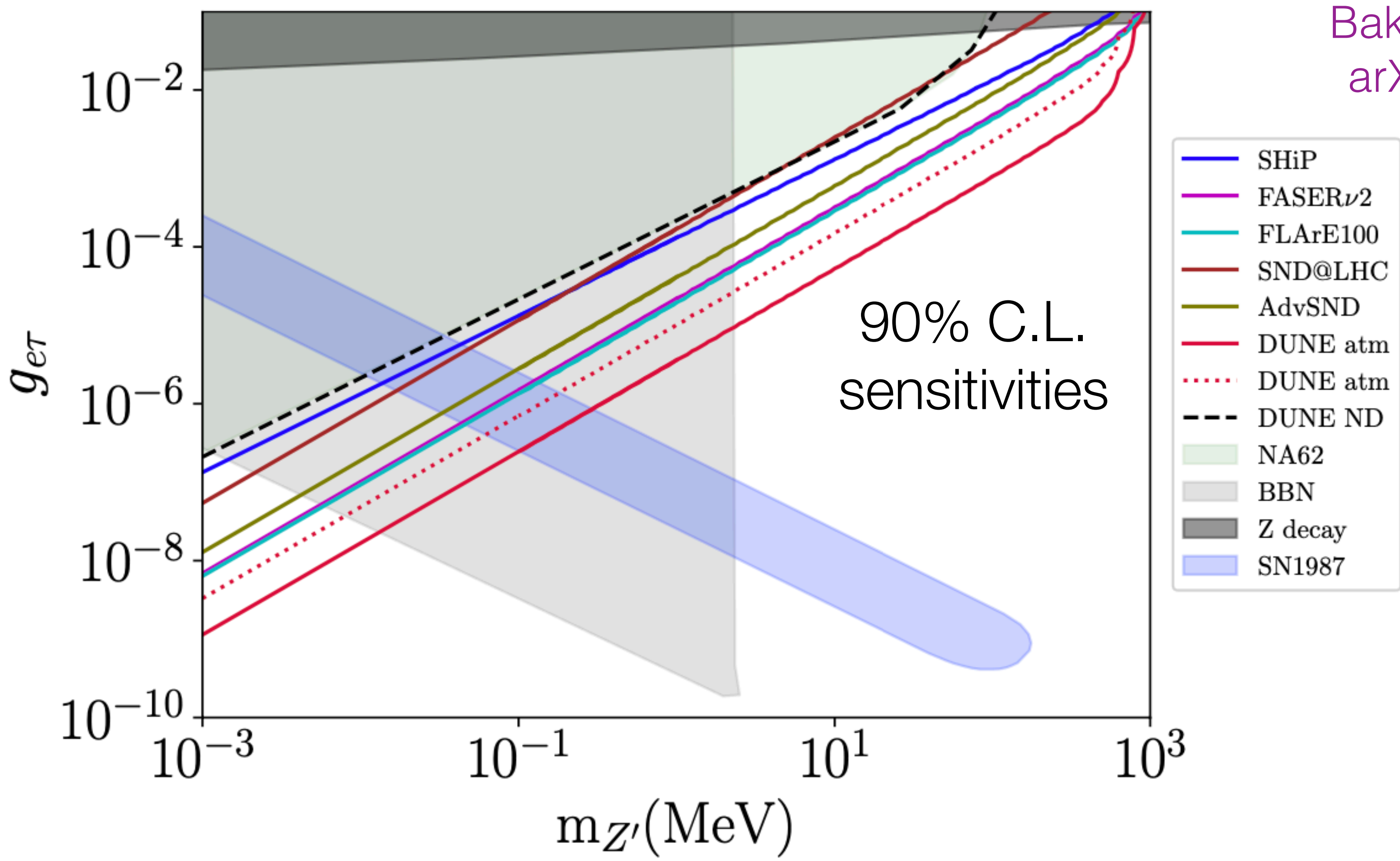

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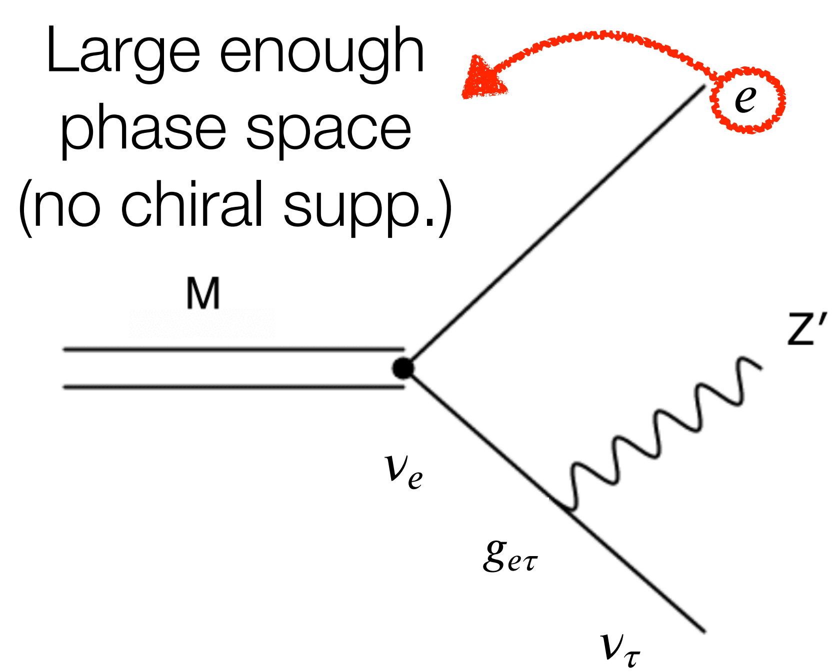
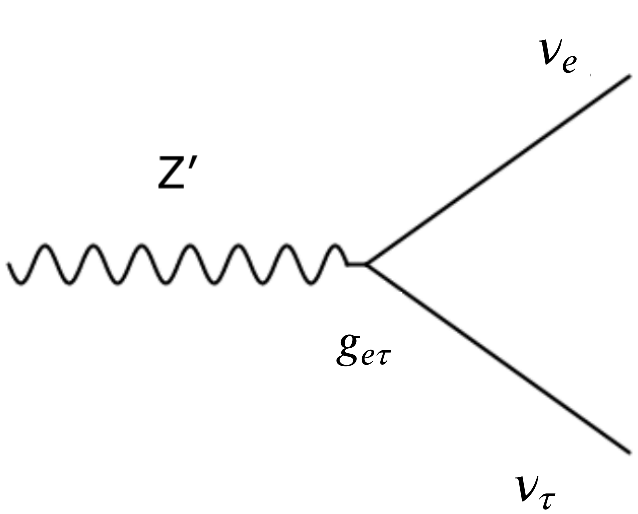
- $g_{e\tau}$ only: no other couplings to ν, $\ell^\pm$, B
- For $g_{\tau\tau}$, sensitivities are much weaker (BR: 10^{-4} smaller for 1 MeV) due to phase space suppression.





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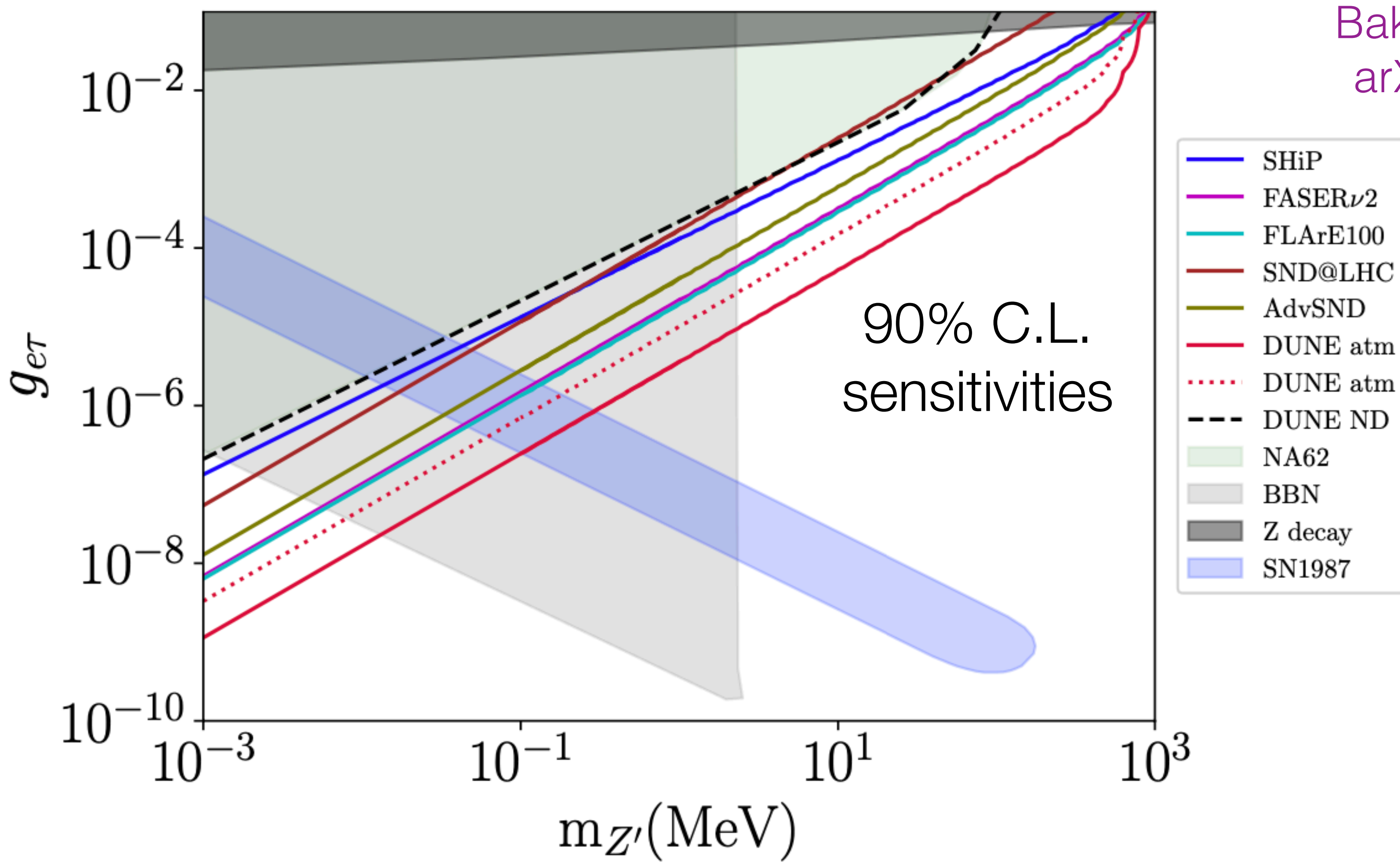

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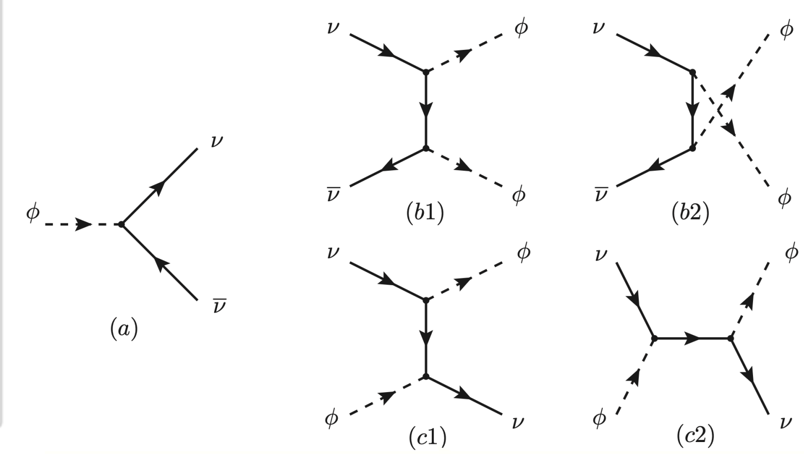

$$N_{\rm eff} = \frac{\rho_r - \rho_\gamma}{\rho_\nu^{\rm SM}/3}$$

- BBN bound: $\Delta N_{\rm eff} \lesssim 1$ when in thermal equilibrium at $T \sim$ 1MeV,

  primordial abundances of light elements for ν_e (similar)

Huang, Ohlsson,
Zhou, PRD 2018

$$\nu\bar{\nu} \to Z' \qquad \nu\bar{\nu} \to Z'Z' \qquad \nu Z' \to \nu Z'$$

- Cosmological bounds are stronger than the scalar mediator due to d.o.f.

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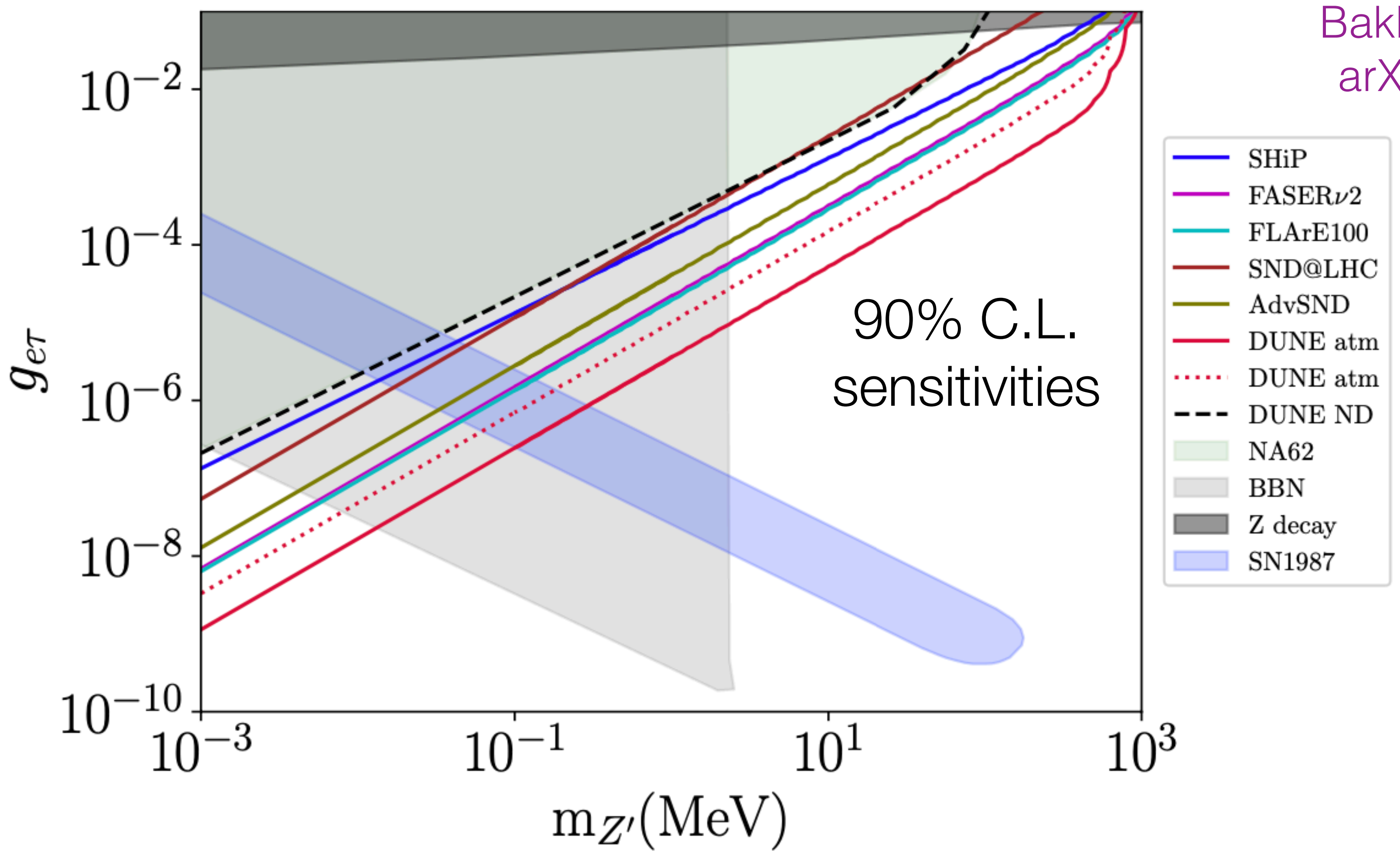

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- Core-collapse supernova: SN1987A energy loss rate in blue shaded region (flavor universal & diagonal case)

Brune, Pas, PRD 2019 Heurtier, Zhang, JCAP 2017

- More general case: dedicated study needed.

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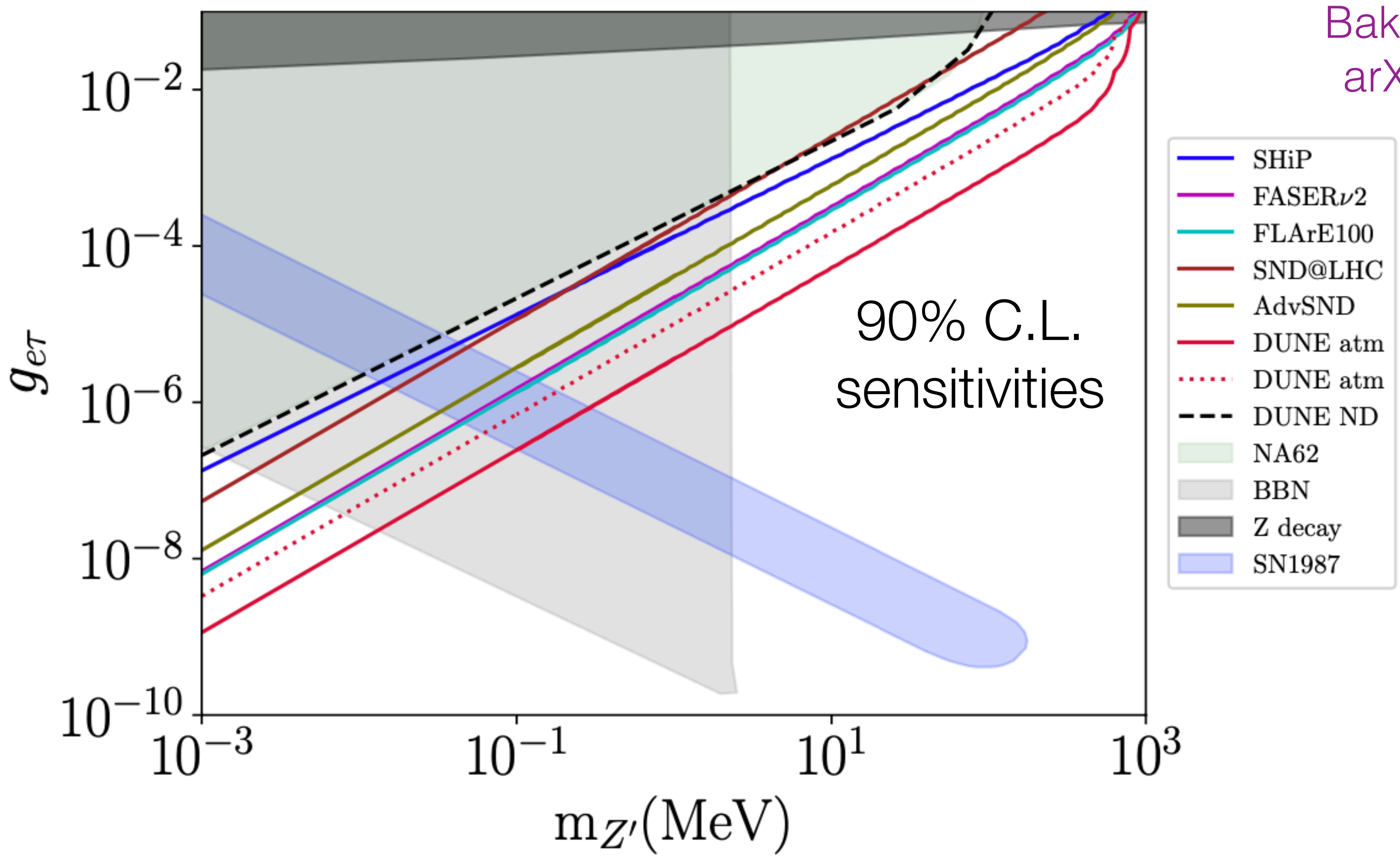

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- CMB bound?

- Phase shift of the power spectrum by late ν free streaming

  → much weaker than NA62 for the flavor-universal scenario $g_{ee}=g_{\mu\mu}=g_{\tau\tau}$

  Das, Gosh, JCAP 2021 Archidiacono, Hannestad, JCAP 2014

- $\Delta N_{\rm eff} \lesssim 0.3$ applies when $Z' \to \nu_e \nu_\tau$ in prior to the recombination epoch.

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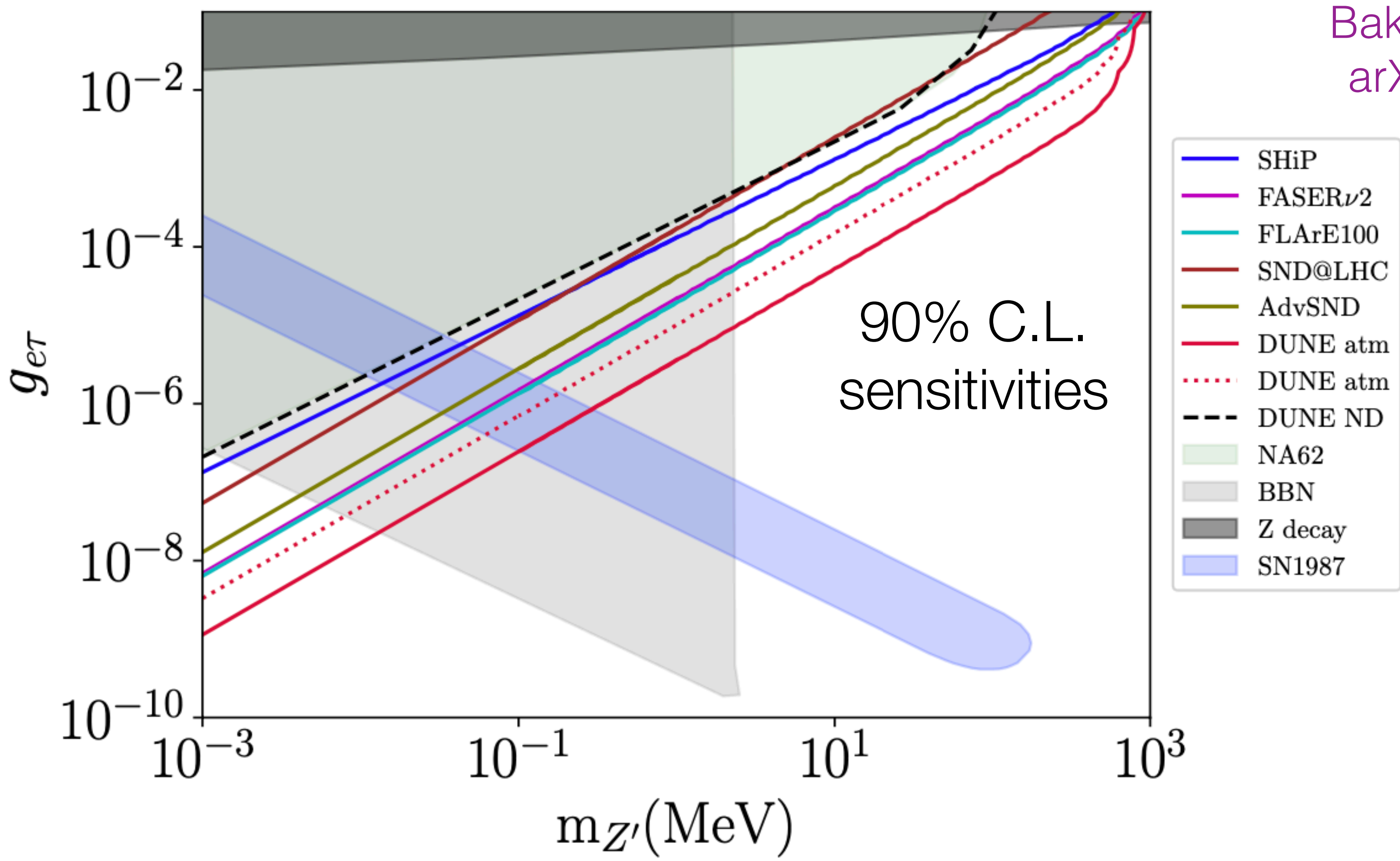

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  → Dedicated study with flavor non-universal and off-diagonal SNI

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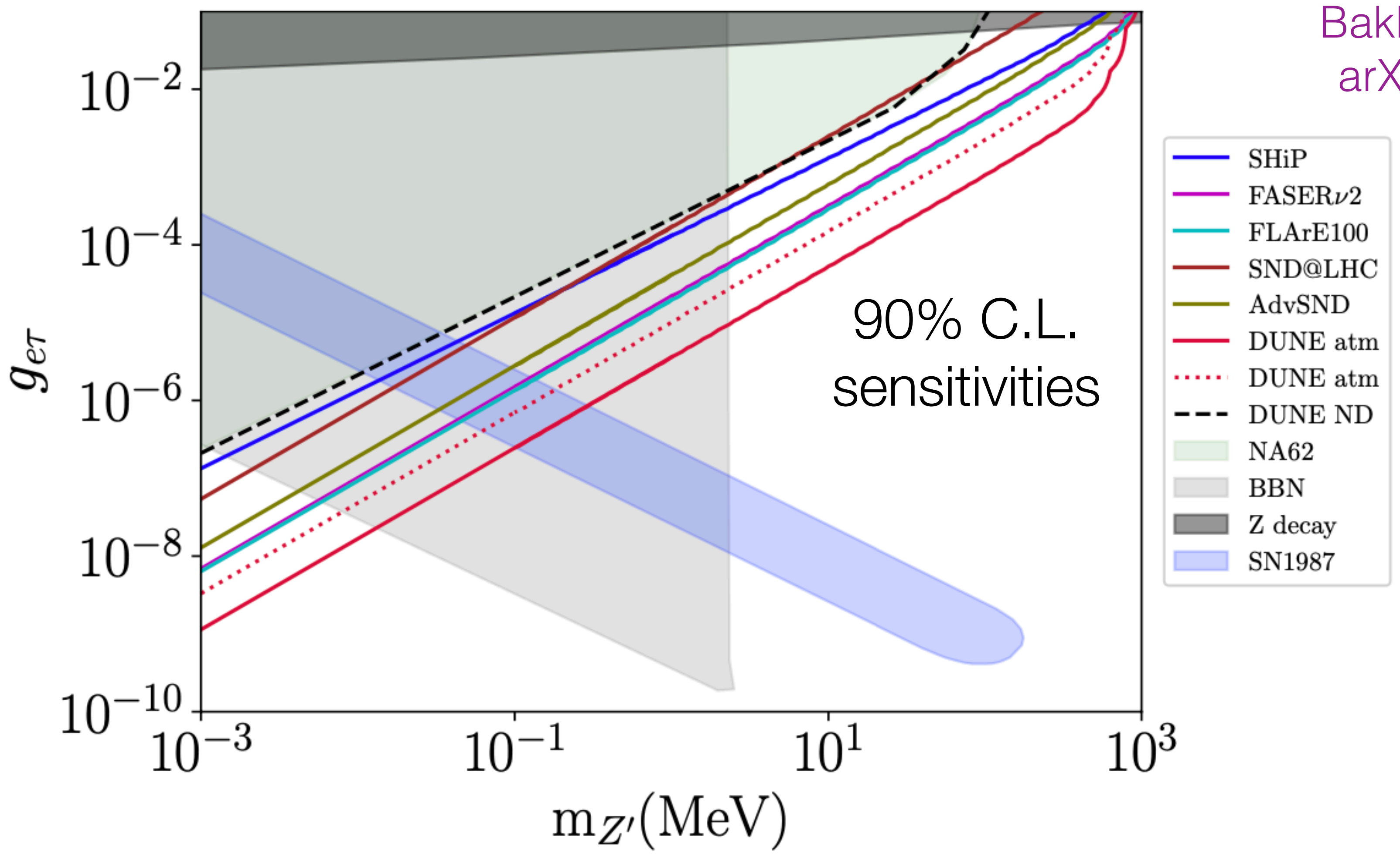

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- NA62 (green): $$R_K = \frac{\Gamma(K^+ \to e^+ \nu_e)}{\Gamma(K^+ \to \mu^+ \nu_\mu)}$$

Bakhti, Farzan, PRD 2017

- $Z \to \nu\nu Z'$ (dark gray)

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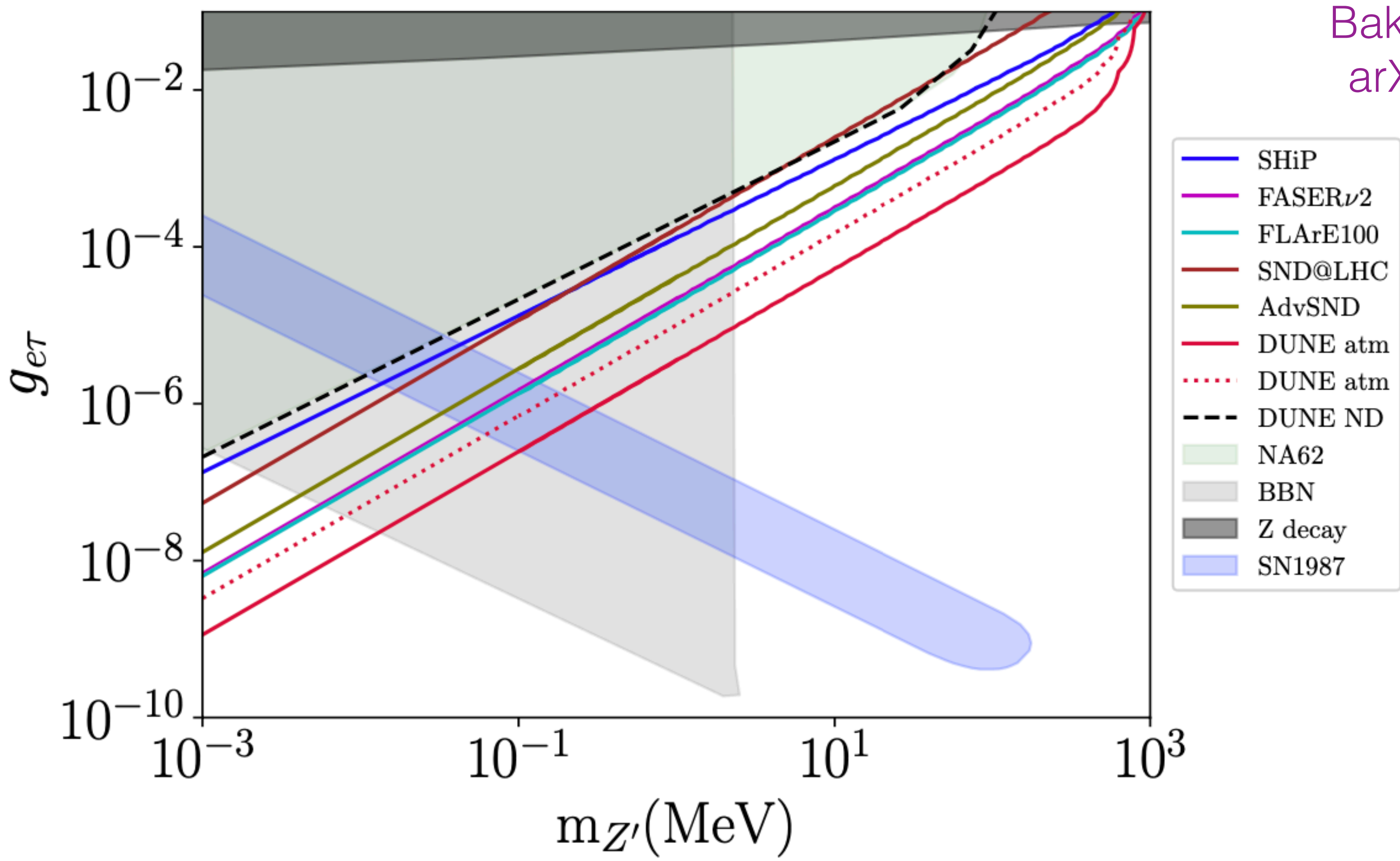

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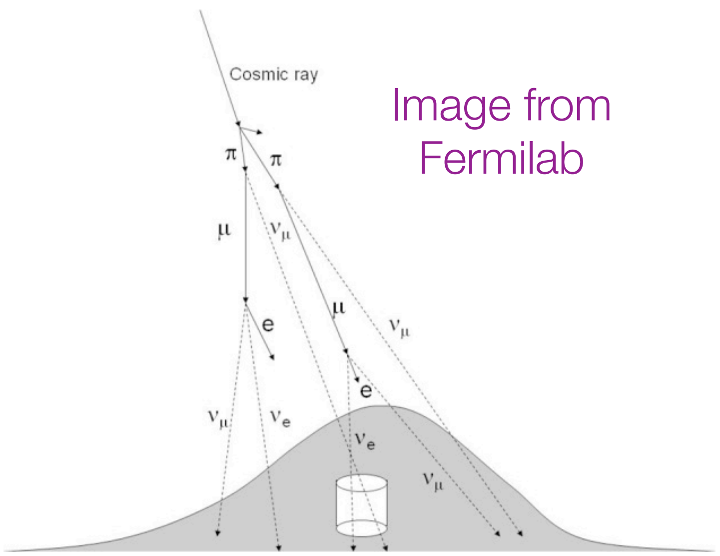

Image from Fermilab

- DUNE far detector (400 kt·yr) is most sensitive for $m_{Z'} \gtrsim 1$ MeV, $m_{Z'} \lesssim 60$ keV by observing the **downward-going ν_τ appearance**. (better than cosmo)
- Red solid: no background, red dotted: NC background (70 for 10 years).

Aurisano, NuTau2021 talk

- Assume 100% efficiency for the ν_τ reconstruction: dedicated study needed.

Machado, Schulz, Turner, PRD 2020

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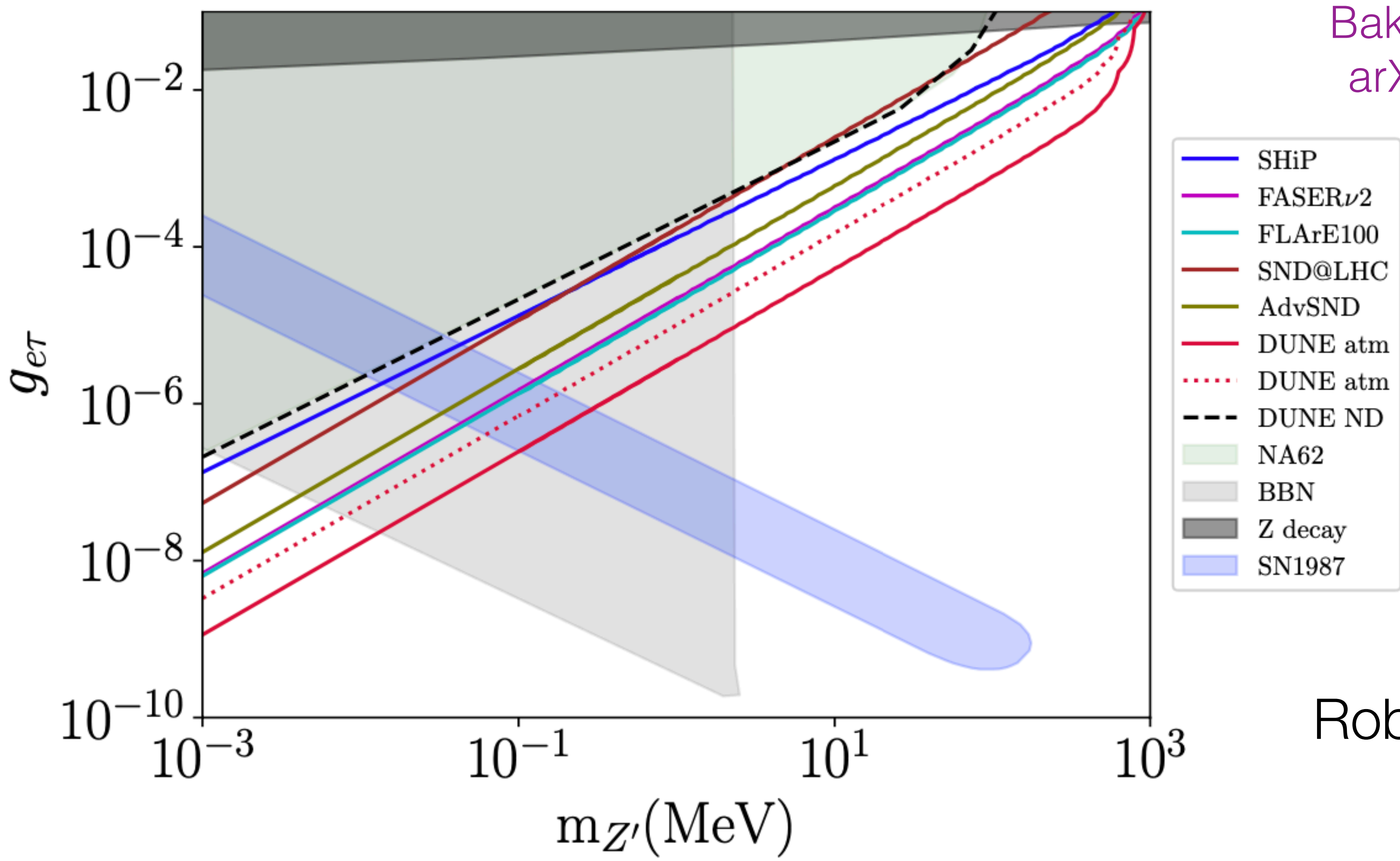

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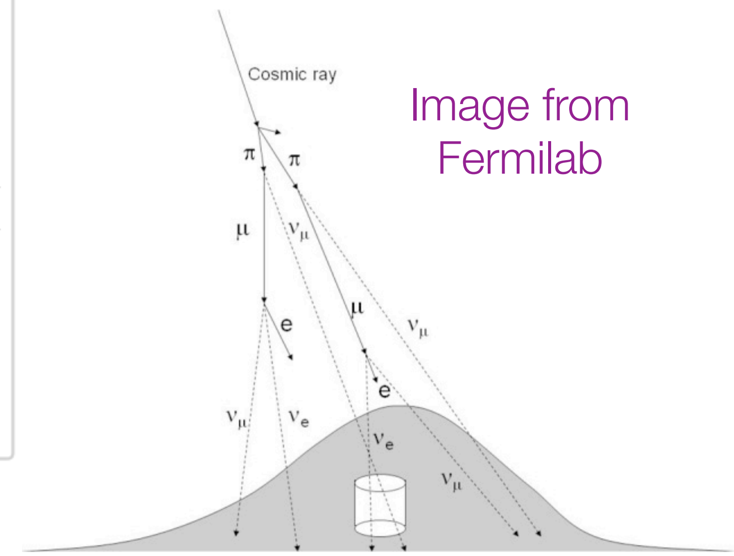

Image from Fermilab

Robust w.r.t. the shape of flux uncertainty.

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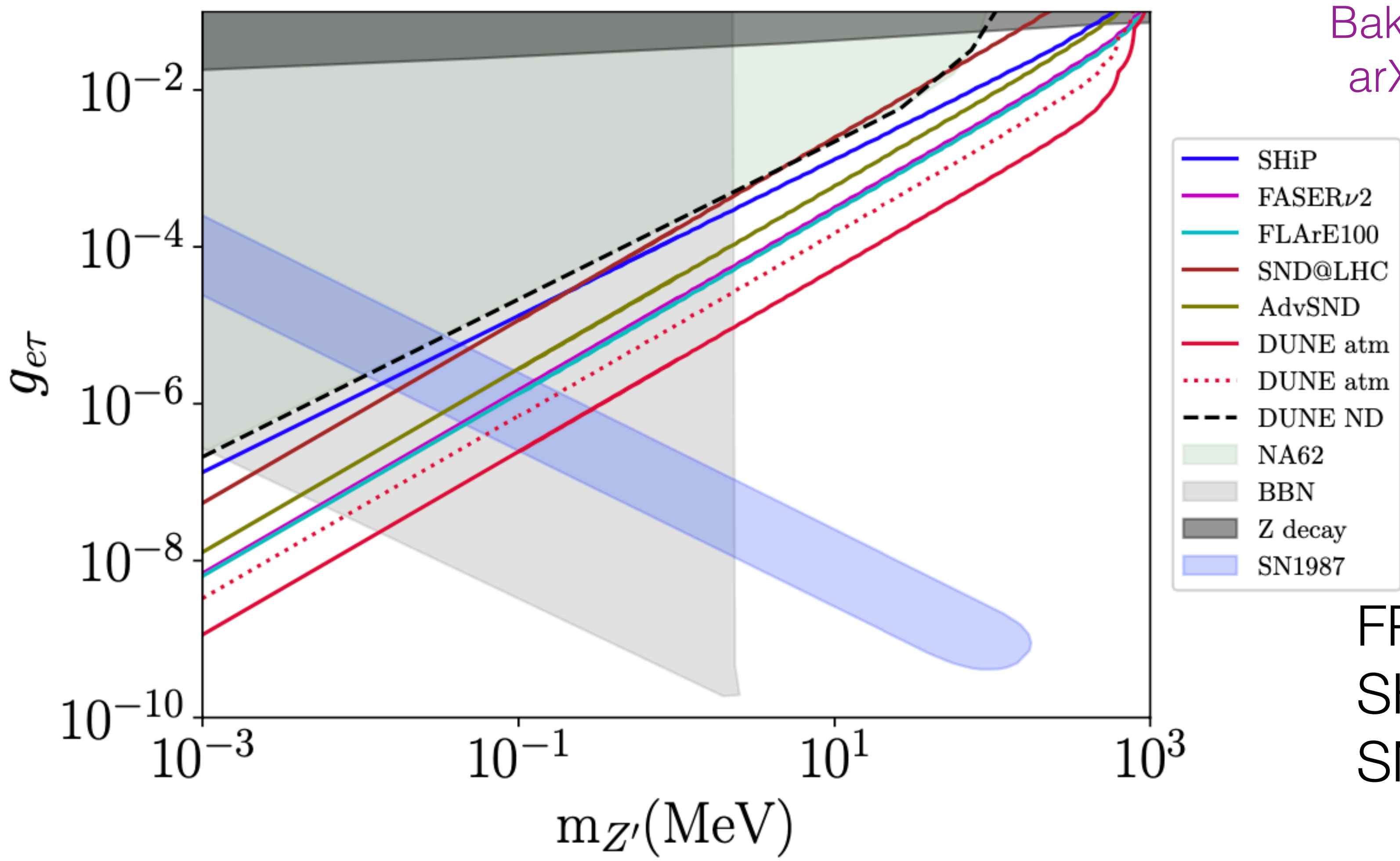

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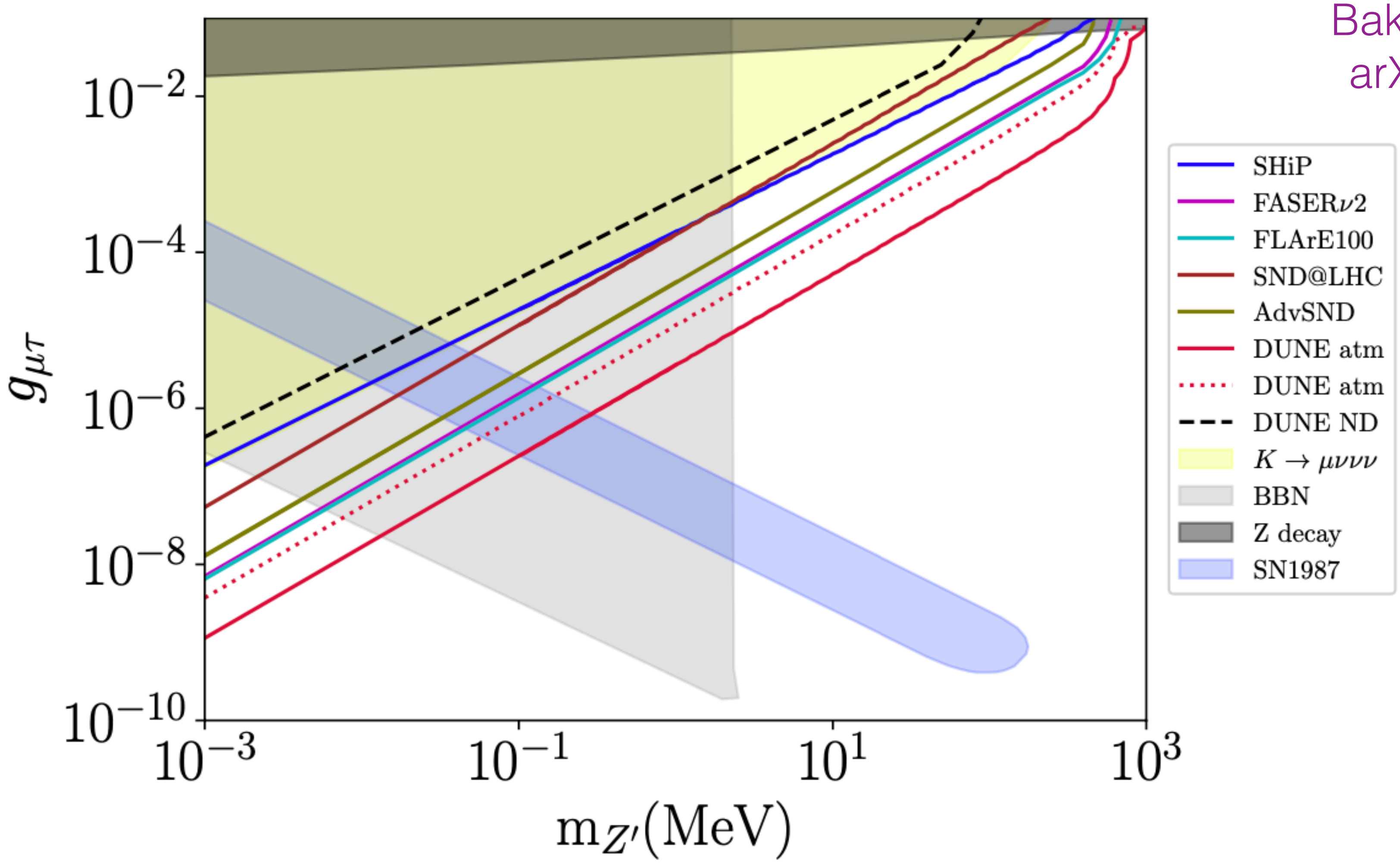
100% efficiency for ν_τ event reconstruction (ambitious)

FPF: 3 ab^{-1}
SHiP: 2×10^{20} POT (5 yrs)
SND@LHC: 150 fb^{-1}

- FLArE100 (cyan, 100 ton) and FASERν2 (purple, 20 ton) can be most sensitive among the accelerator based experiments. Our results depend on the flux uncertainties.

- SHiP becomes better as Z' gets heavier since its hadron absorber increases the relative flux of D_s meson providing large phase space.

Sensitivities for ν_τ SNI



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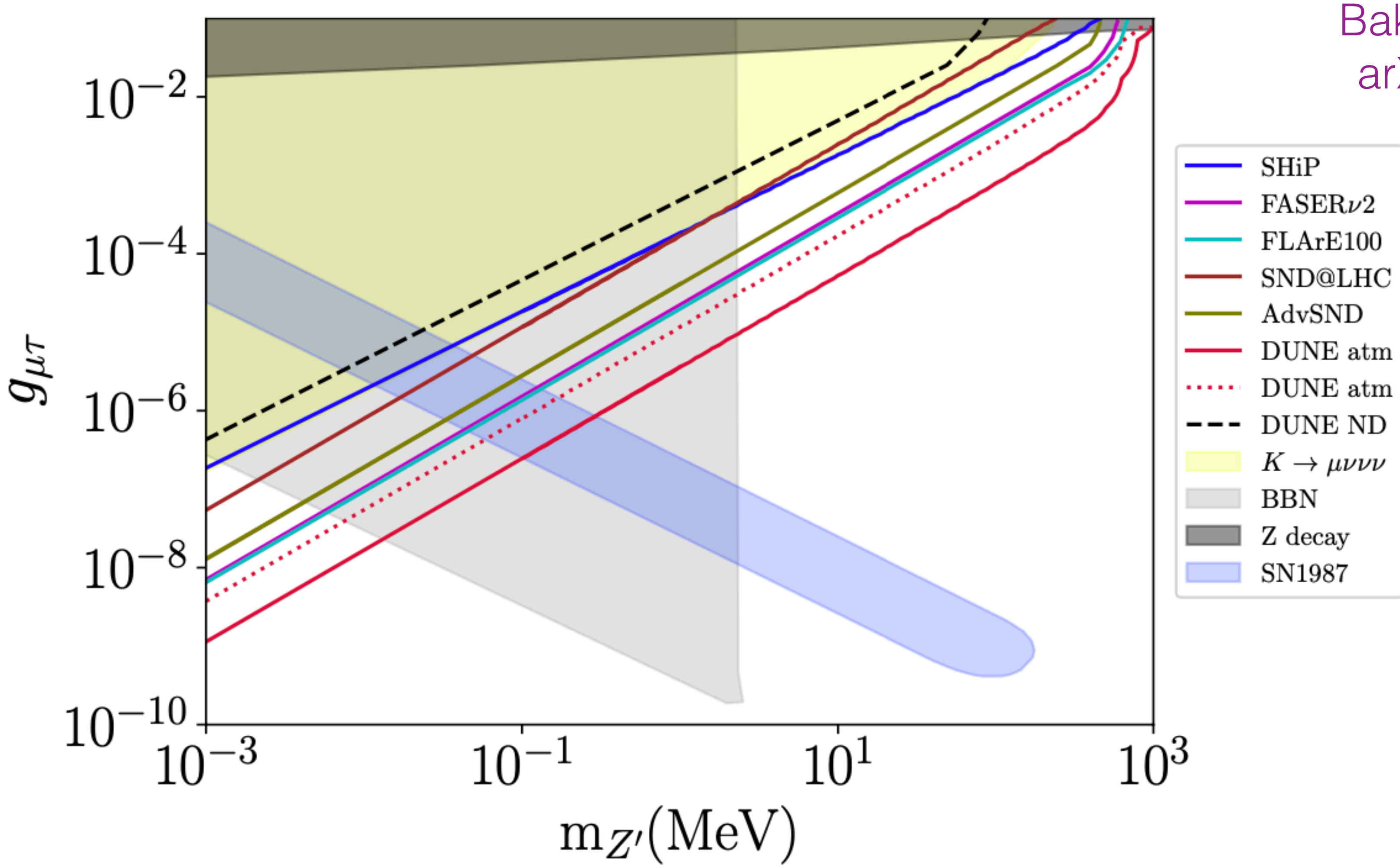
- DUNE far detector (400 kt·yr) is still most sensitive for $m_{Z'} \gtrsim 1$ MeV, $m_{Z'} \lesssim 60$ keV.

- We now apply the rare Kaon decay constraint at E949 (yellow).

$$\mathrm{BR}(K^+ \to \mu^+ \nu\nu\nu) < 2.4 \times 10^{-6}$$

Sensitivities for ν_τ SNI



Bakhti, Rajaee, **SS**,
arXiv:2311.14945

- Sensitivities are comparable or slightly weaker (SHiP) due to the phase space.

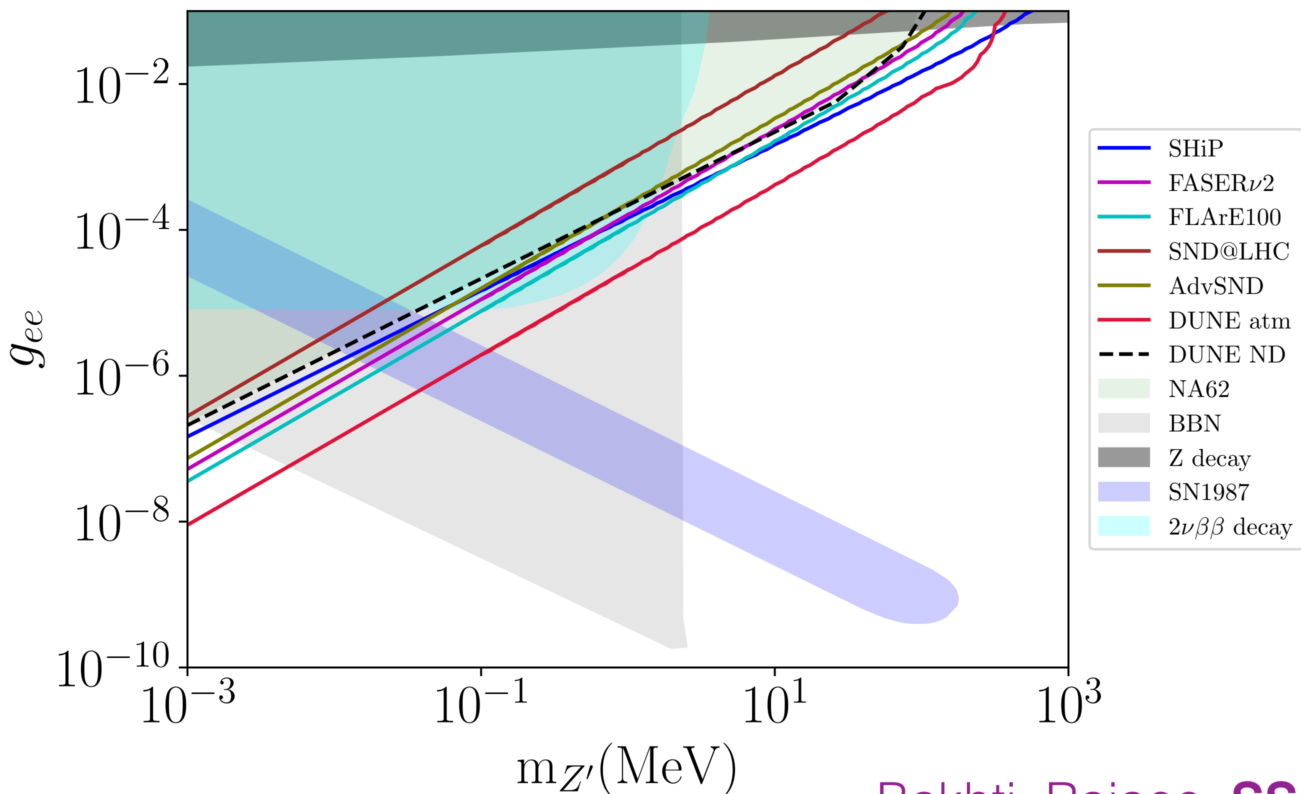
- DUNE far detector (400 kt·yr) is still most sensitive for $m_{Z'} \gtrsim$ 1 MeV, $m_{Z'} \lesssim$ 60 keV.

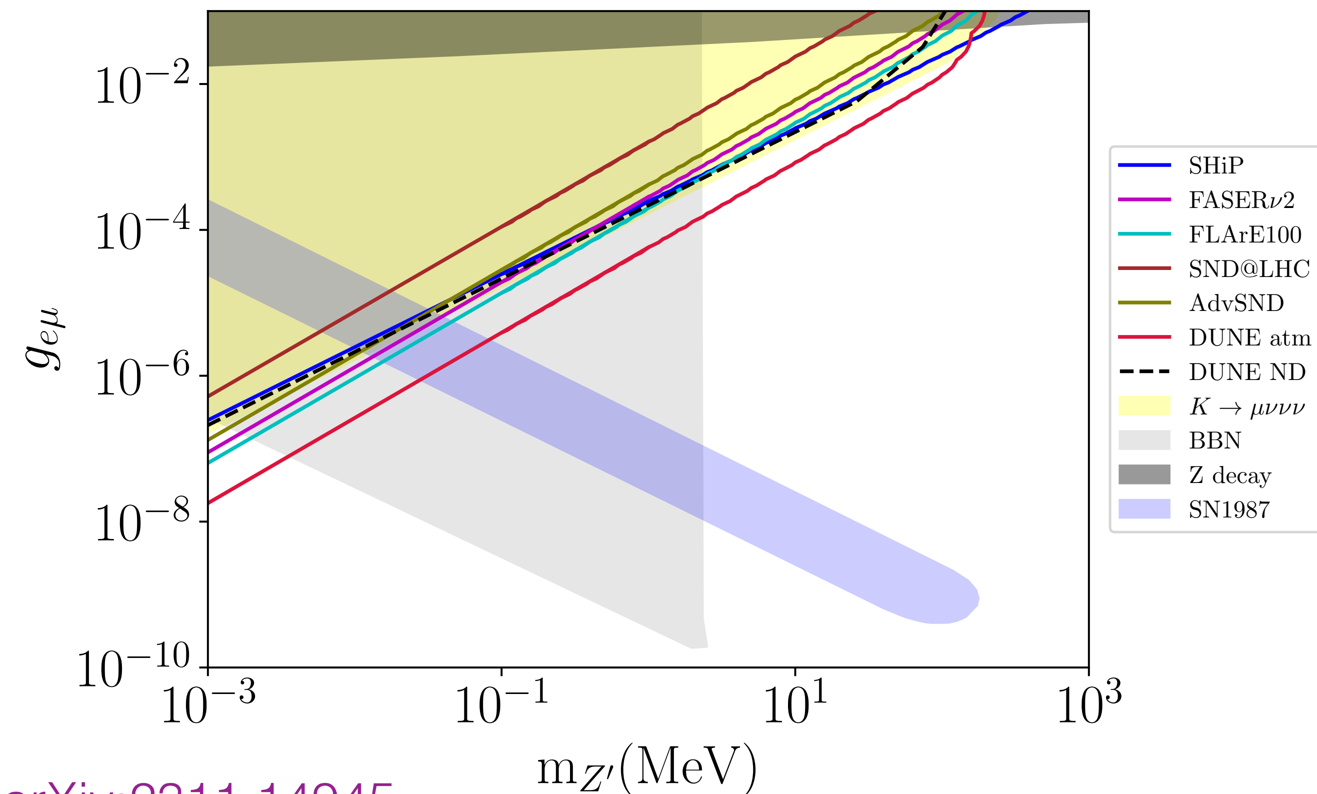
- We now apply the rare Kaon decay constraint at E949 (yellow).

$$\mathrm{BR}(K^+ \to \mu^+ \nu\nu\nu) < 2.4 \times 10^{-6}$$

Sensitivities for ν_τ SNI

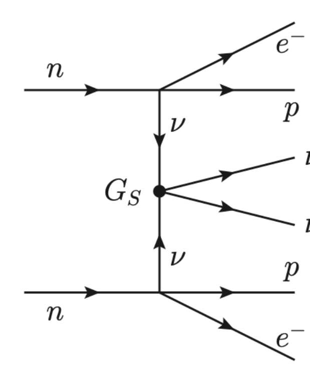
Comparison with the other flavor couplings





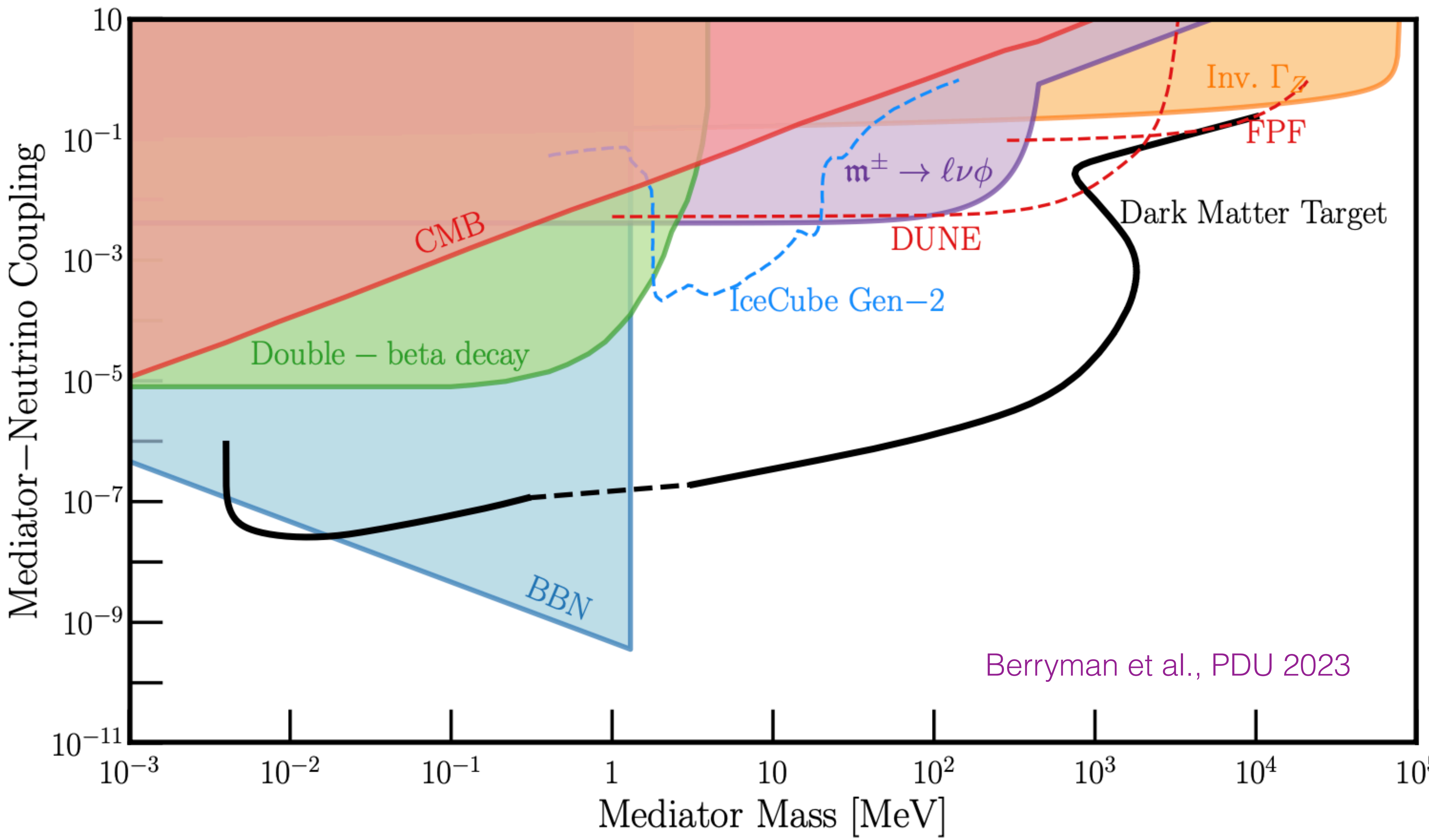
Bakhti, Rajaee, **SS**, arXiv:2311.14945

- DUNE far detector (400 kt·yr) is still most sensitive for $m_{Z'} \gtrsim$ 1 MeV, $m_{Z'} \lesssim$ 10 keV but at least about an order of magnitude weaker than $g_{e\tau}$, $g_{\mu\tau}$.
- $2\nu\beta\beta$ applies but weaker than the others.
- Shape of the (atmospheric) flux uncertainty can wash out the sensitivities.



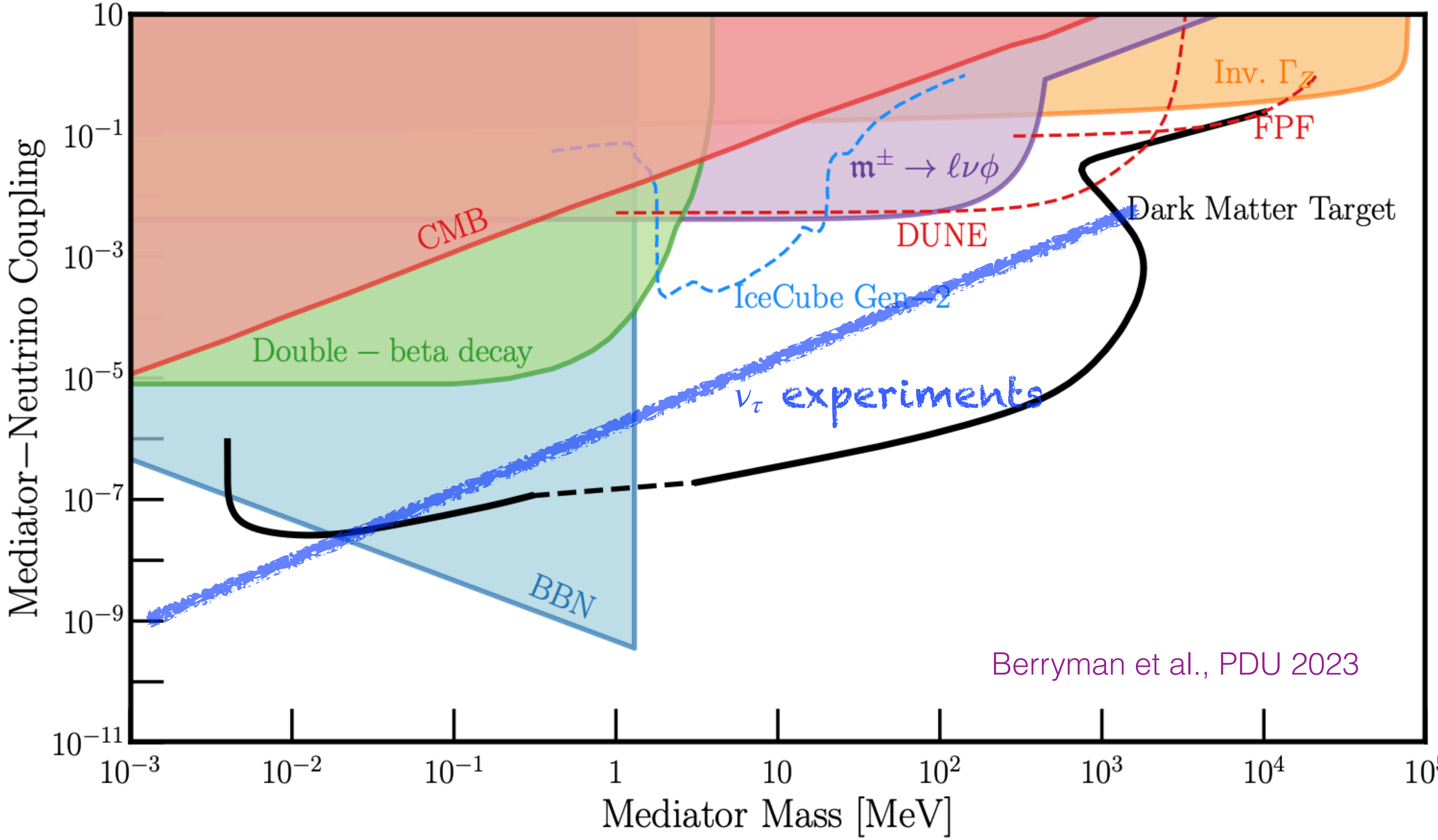
Deppisch, Graf, Rodejohann, Xu, PRD 2020

Sensitivities for ν_τ SNI



Universal coupling case

Sensitivities for ν_τ SNI



Universal coupling case

Conclusions

- Identification of secret (and non-standard) interactions of neutrino is a very important step forward BSM.

- Tau neutrino experiments play important roles in probing flavor non-universal (ν_τ-philic) SNI preferred by cosmo/astro/lab.: we use SND@LHC, AdvSND, SHiP, FLArE100, FASERν2, and DUNE

- Atmospheric data at DUNE far detector shows the best sensitivities due to the unexpected downward-going ν_τ appearance with small backgrounds: stronger than cosmo for $m_{Z'} \gtrsim 1$ MeV, $m_{Z'} \lesssim 60$ keV.

- Tau identification and reconstruction efficiency are important.

- Future: dedicated study of flavor non-universal & off-diagonal SNI in cosmo/astro, mediators with other spins, cLFV rare decays.