Mitchell conference 2024

New opportunities at ν_τ experiments

Seodong Shin (신서동)

전북대학교
JEONBUK NATIONAL UNIVERSITY

arXiv:2311.14945 (accepted in PRD) with Pouya Bakhti, Meshkat Rajaee

New symmetry in the neutrino sector

Neutrino oscillation: clear evidence of BSM

→ ν physics can provide guidelines for BSM

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New symmetries? New particles?

- These can be identified by probing new interactions of ν inducing

- Unexpected appearance of (charged) SM particles
- Missing energy in accelerators
- Appearance/disappearance of SM ν in neutrino experiments

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Focus: self interactions among active ν (or + sterile ν)

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Asadi et al., PRD 2018   Smirnov, Valera, JHEP 2021

Dentler, Esteban, Kopp, Machado, PRD 2019

Abdallash, Gandhi, Roy, JHEP 2022   Dutta et al., PRL 2022

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- Dark matter interacting with active ν: Majoron DM, sterile ν DM

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Talk by Yue

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- Cosmological issues: small scale problems (strongly constrained)

Aarssen, Bringman, Pfrommer, PRL 2012 Ahlgren, Ohlsson, Zhou, PRL 2013

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See also SNOWMASS WP 2022,
Berryman et al., PDU 2023

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New symmetry in the neutrino sector

- Flavor-universal SNIs are strongly constrained by cosmological/ astrophysical observations: CMB, BAO, BBN, ..

Brinckmann, Chang, LoVerde, PRD 2021 Das, Ghosh, JCAP 2021

Huang, Ohlsson, Zhou, PRD 2018 Kolb, Turner, PRD 1987

- Laboratory experiments provide strong constraints on SNI with ν_e, ν_μ

Burgess, Cline, PLB 1993 Lessa, Peres, PRD 2007 Bauer, Foldenauer, Jäckel, JHEP 2018

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Berryman et al., PDU 2023

Probe flavor non-universal & general SNI with ν_τ , $g_{\tau\alpha}$?

→ Tau neutrino experiments

Neutrino experiments

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

- ν oscillations so far: either ν_μ / ν_e disappearance or ν_e appearance

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- DONuT (9 events), OPERA (10 events), IceCube (7 high E events)
  Statistically from $\nu_\mu \to \nu_\tau$: SK (291), IceCube (1804 CC + 556 NC)

Neutrino experiments

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

- Accelerator based experiments: SND@LHC & FASERν (current)

  FLArE100, FASERν2, AdvSND, SHiP, DUNE ND (future)

- Atmospheric experiments: IceCube, DUNE FD, …

  - Upward-going ν_τ events: Directly confirm atmospheric ν oscillation, & probe New Physics involved there

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  - Upward-going ν_τ events: Directly confirm atmospheric ν oscillation, & probe New Physics involved there

  - Downward-going ν_τ events: Not from oscillation,

    $\Rightarrow$ **Anomalous downward-going ν_τ appearance**

Extremely sensitive to New Physics

See also Dev, Dutta, Han, Kim, PLB 2024 for short-baseline experiments

Theoretical set-up

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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- A theoretical cook-up suppressing the $\ell^\pm$ interactions possible.

  - SM singlet but U(1)$'$ charged vectorlike fermion Ψ:
    → mixing with active neutrinos (through a sterile heavy singlet N)

Farzan, Heeck, PRD 2016 Farzan, Tortolla, Front. Physics 2018

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

$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i} \nu_i \longrightarrow g_{\alpha\beta} = g_\Psi U^*_{\alpha 4} U_{\beta 4}$$

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    no tree level & loops through very heavy fields

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Phenomenological set-up: exclusive coupling

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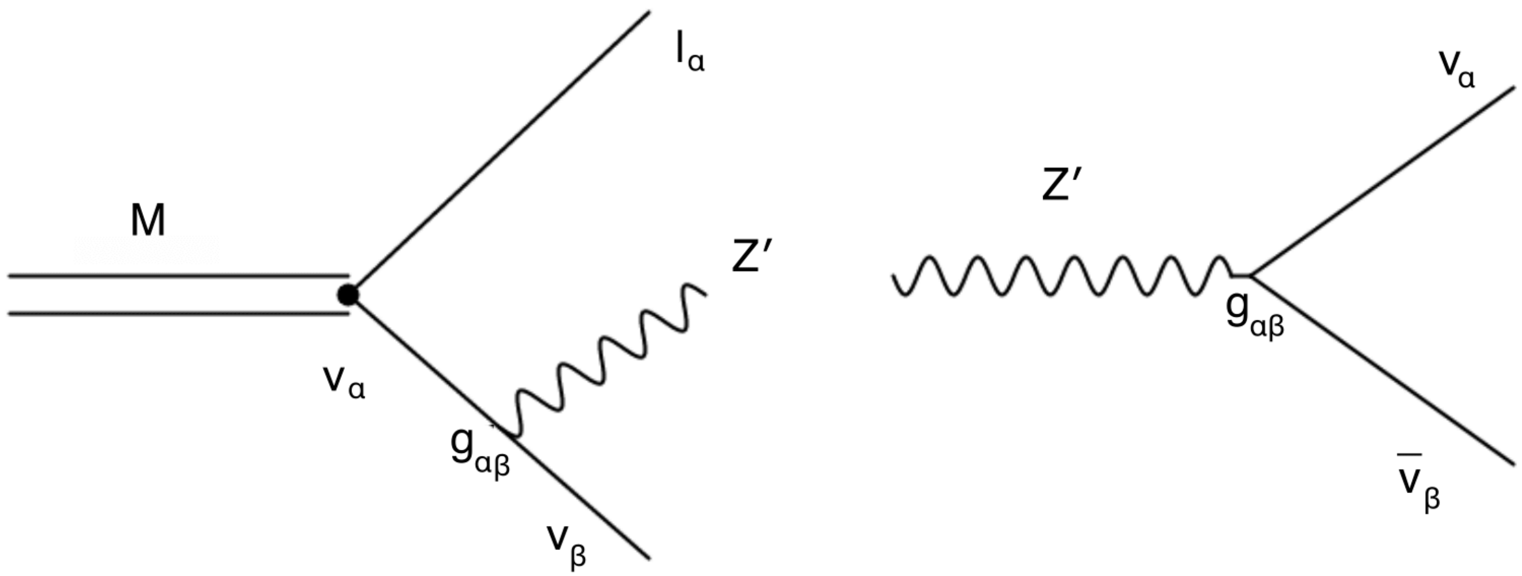
Theoretical set-up

Kinematic process: 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

See also Dutta et al., PRL 2022

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

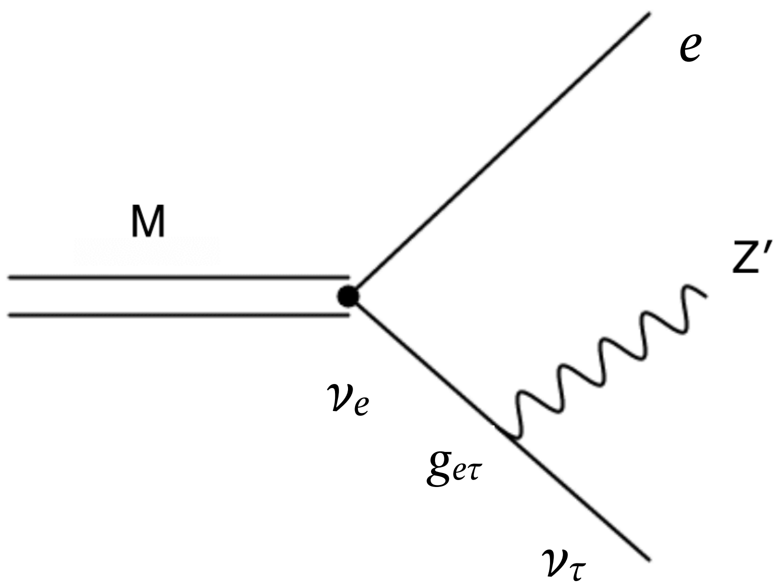
Barger, Chiang, Keung, Marfatia, PRL 2012

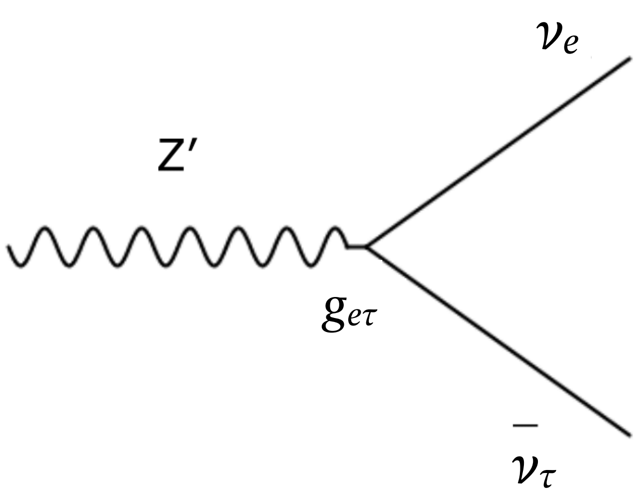
Carson, Rislow, PRD 2012

Laha, Dasgupta, Beacom, PRD 2014

Bakhti, Farzan, PRD 2017

Sensitivities for ν_τ SNI





- Single coupling $g_{e\tau}$ only: no other couplings to ν, $\ell^{\pm}$, B

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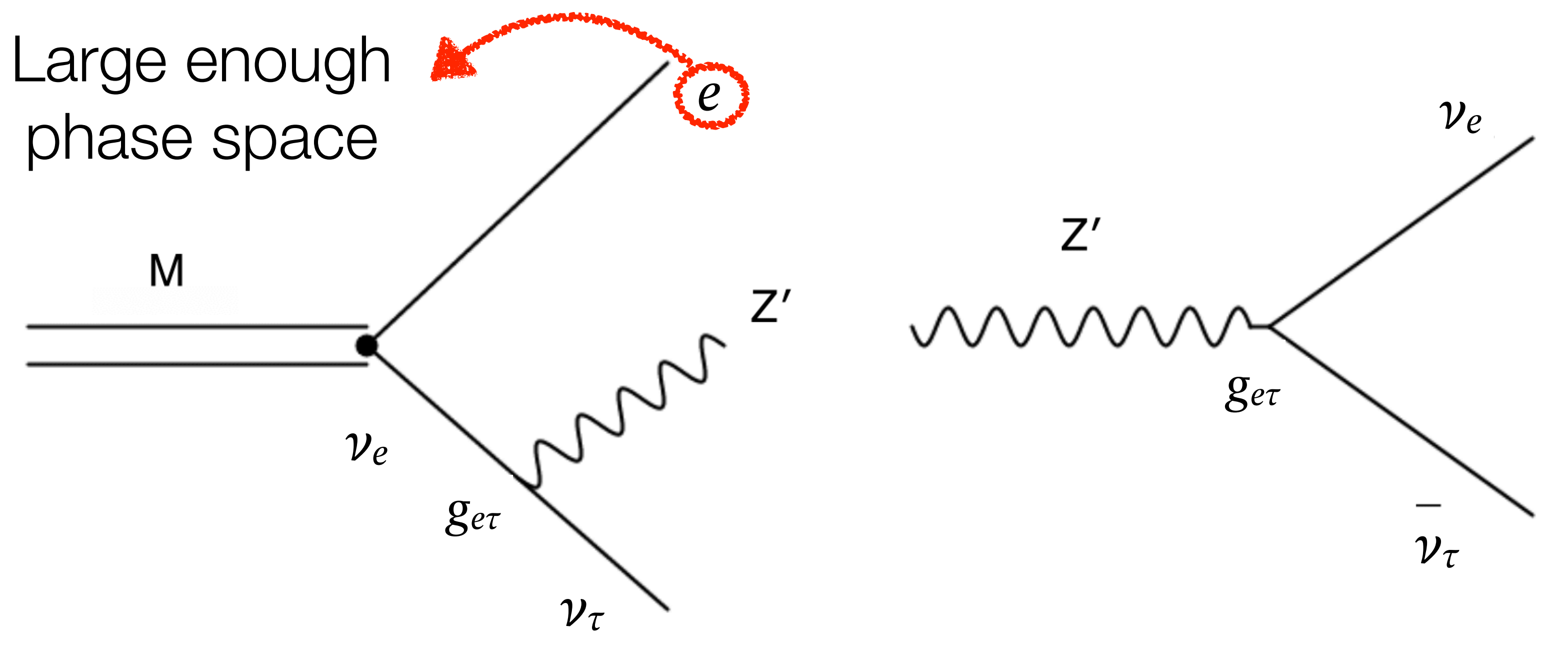

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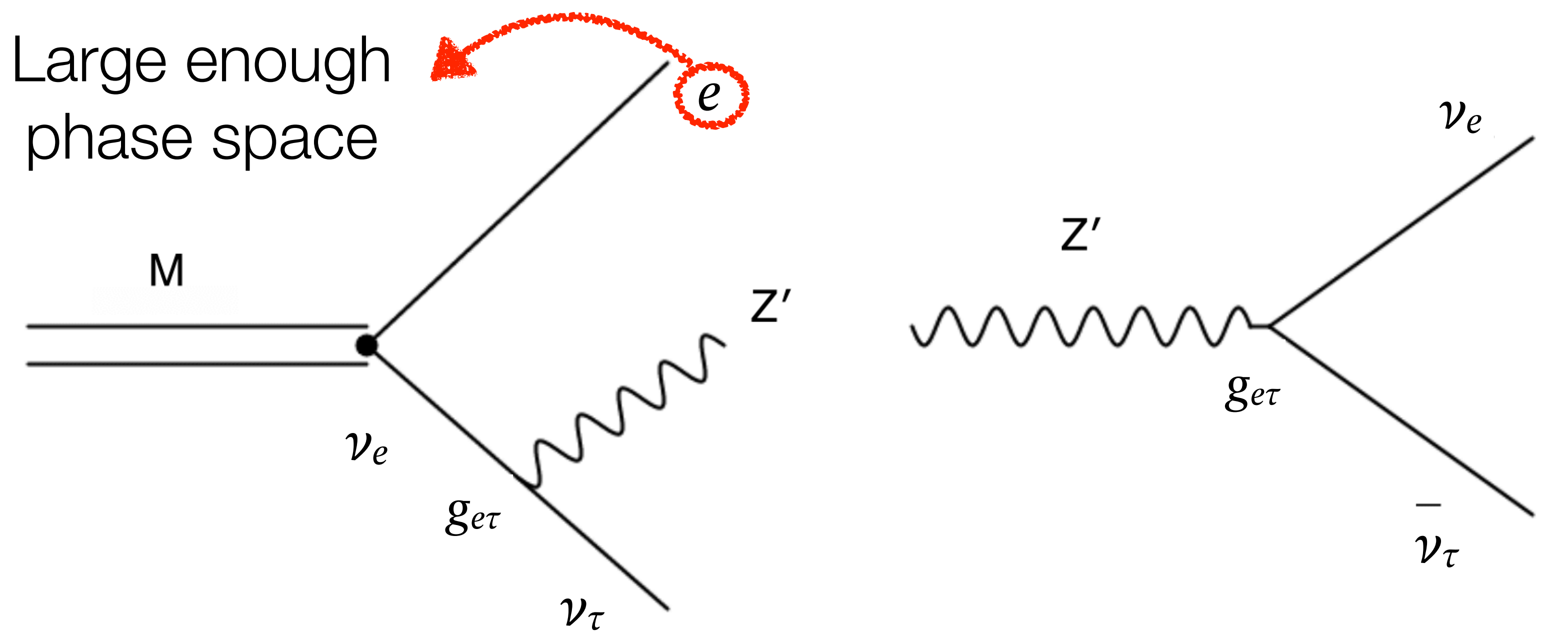
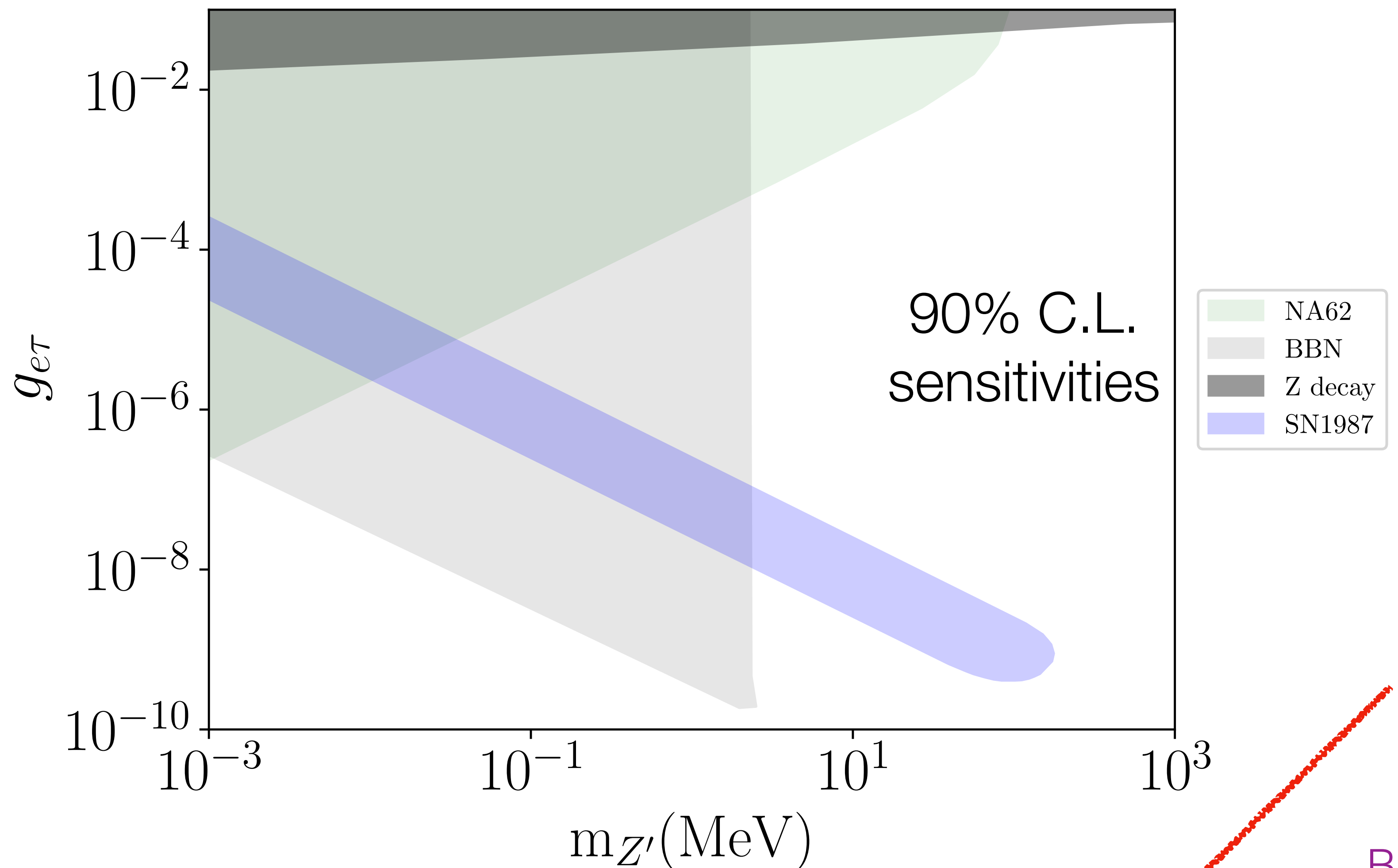


- Single coupling $g_{e\tau}$ only: no other couplings to ν, $\ell^\pm$, B
- For $g_{\tau\tau}$, sensitivities are much weaker (BR: 10^{-4} smaller for 1 MeV) due to phase space suppression.

Sensitivities for ν_τ SNI: lab. bounds



$K^+ \to e^+ Z' \nu_\tau$

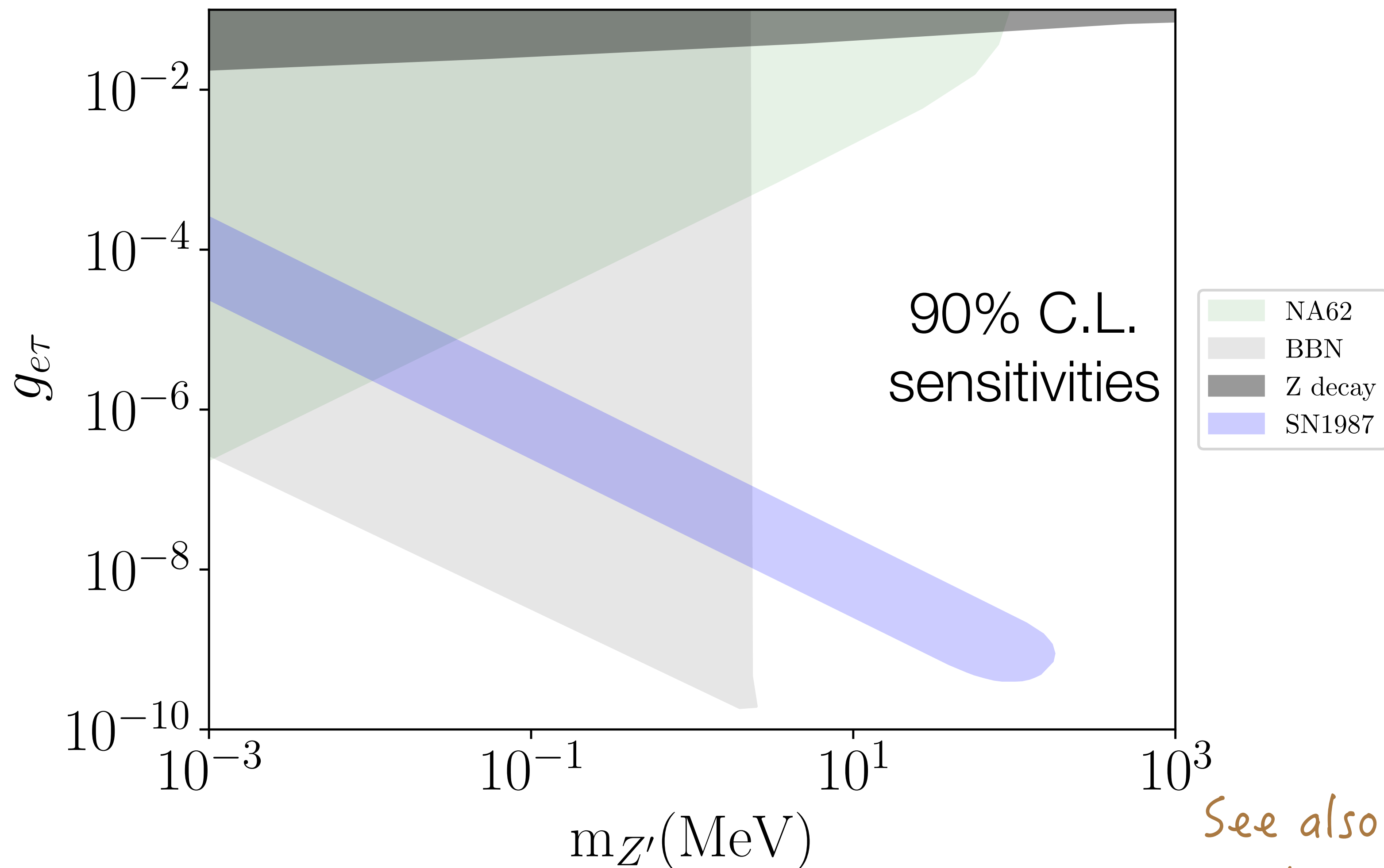
Bakhti, Farzan, PRD 2017

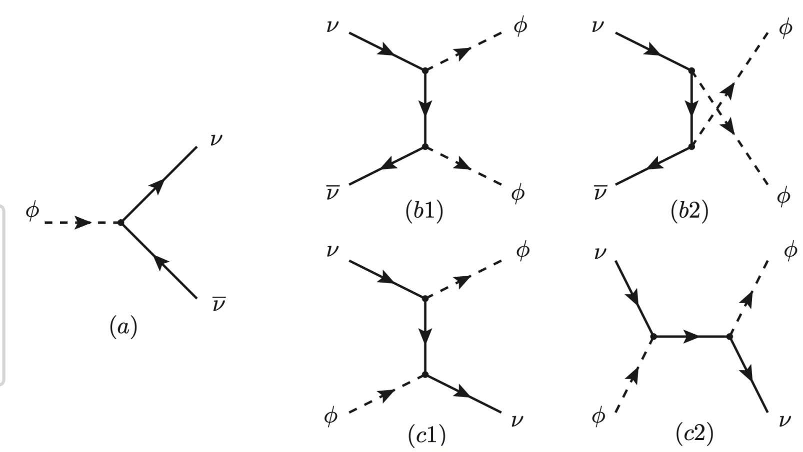
- NA62 (green): $R_K = \dfrac{\Gamma(K^+ \to e^+\nu_e)}{\Gamma(K^+ \to \mu^+\nu_\mu)} \longrightarrow (2.488 \pm 0.010) \times 10^{-5}$

$$R_K^{\mathrm{SM}} = (2.477 \pm 0.001) \times 10^{-5}$$

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

Sensitivities for ν_τ SNI: cosmo bounds





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

See also talk by Kimberly

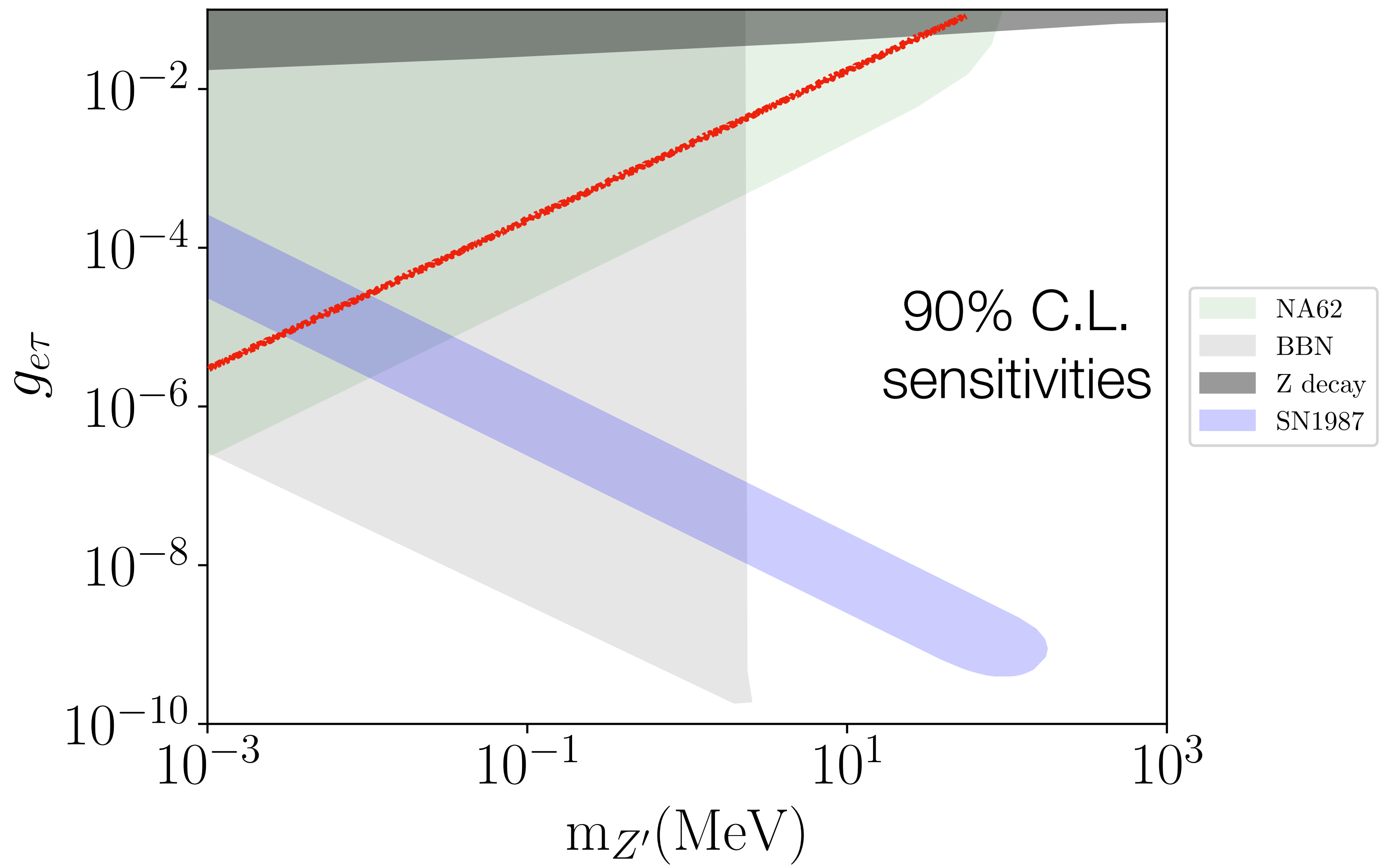
- BBN bound: $\Delta N_{\rm eff} \lesssim 1$ when in thermal equilibrium at $T \sim$ 1MeV, primordial abundances of light elements for ν_e (similar)

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.

Sensitivities for ν_τ SNI: cosmo bounds



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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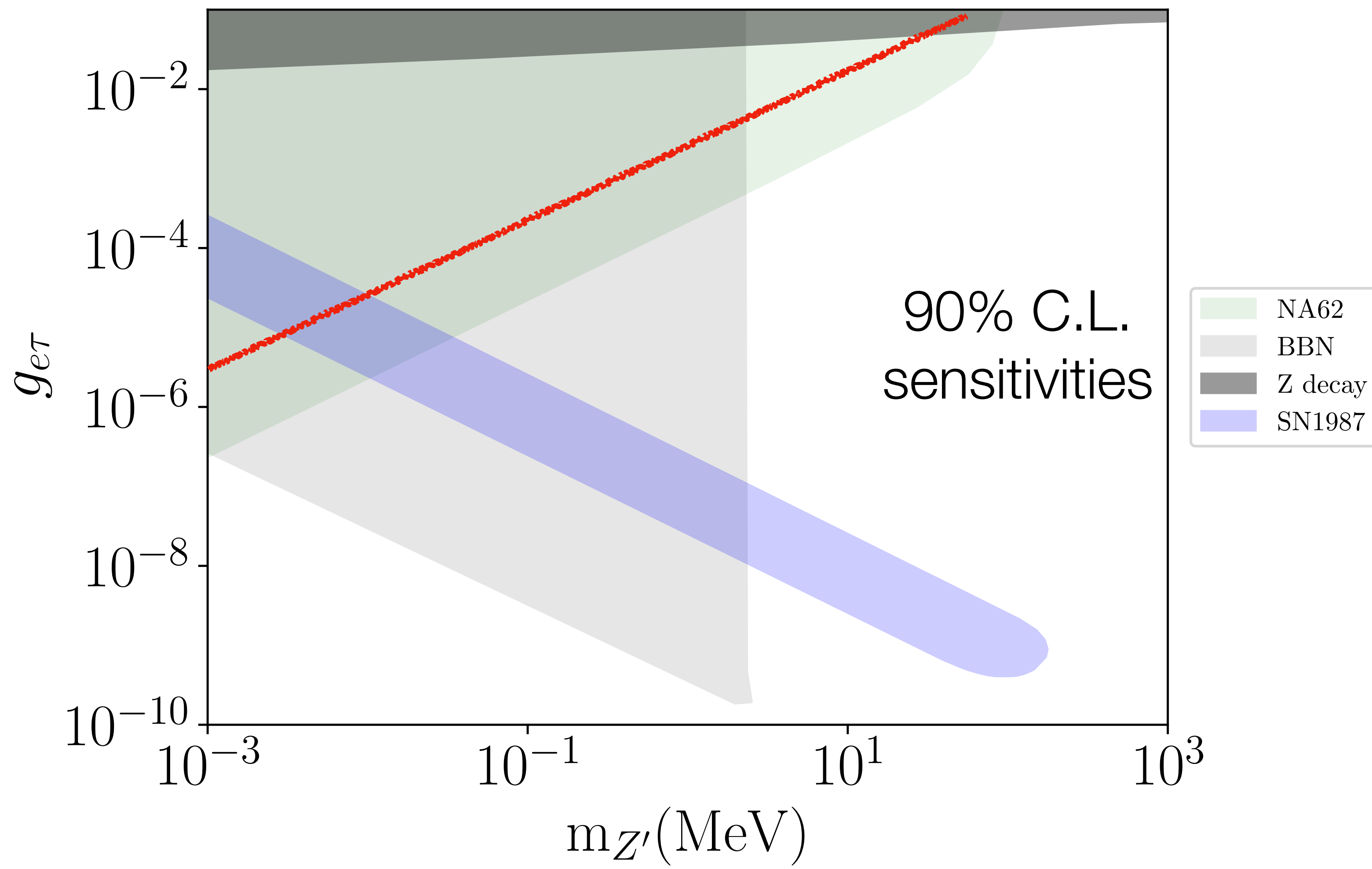

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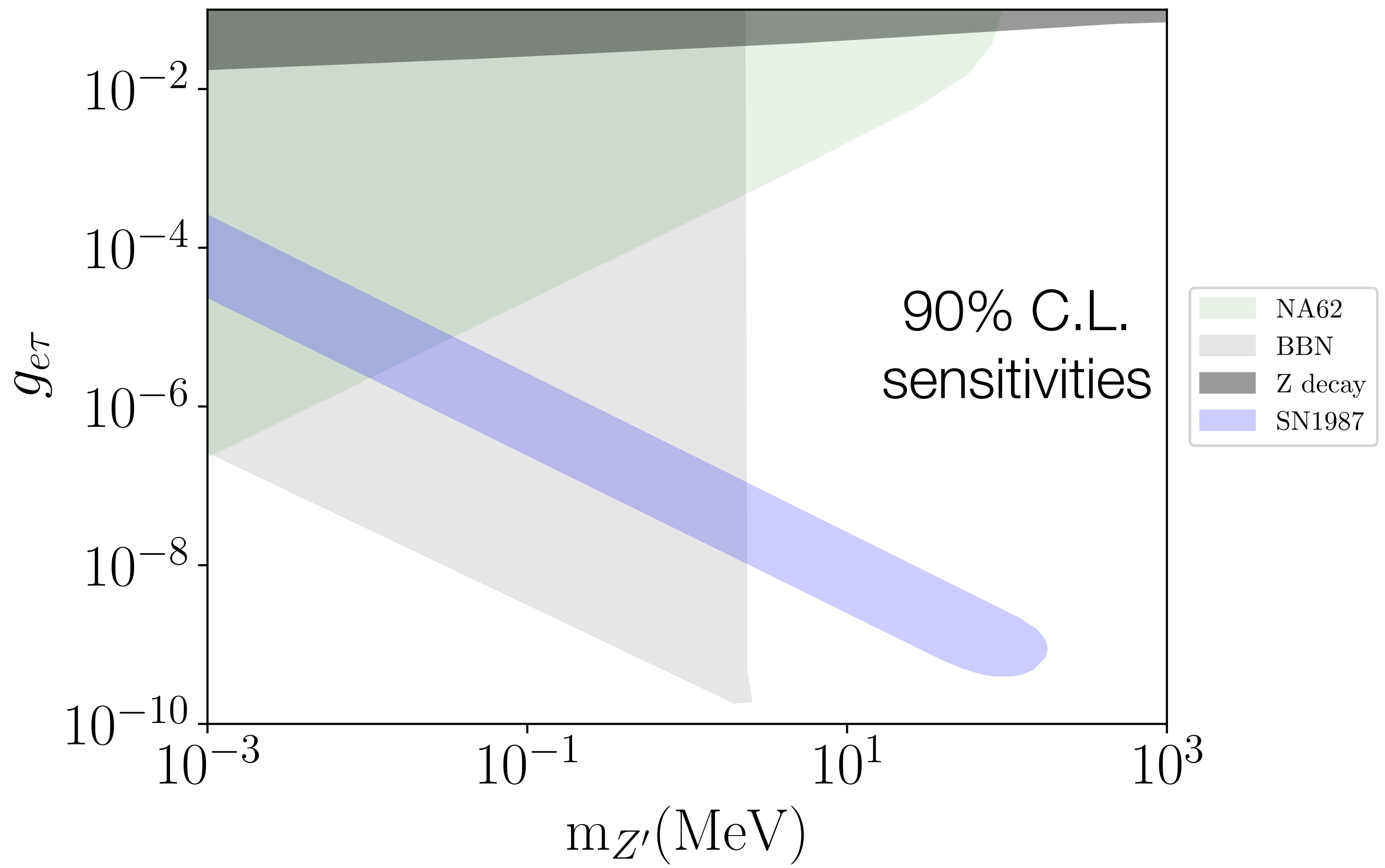
  ⟶ Dedicated study with flavor non-universal and off-diagonal SNI needed.

Sensitivities for ν_τ SNI: astro bounds

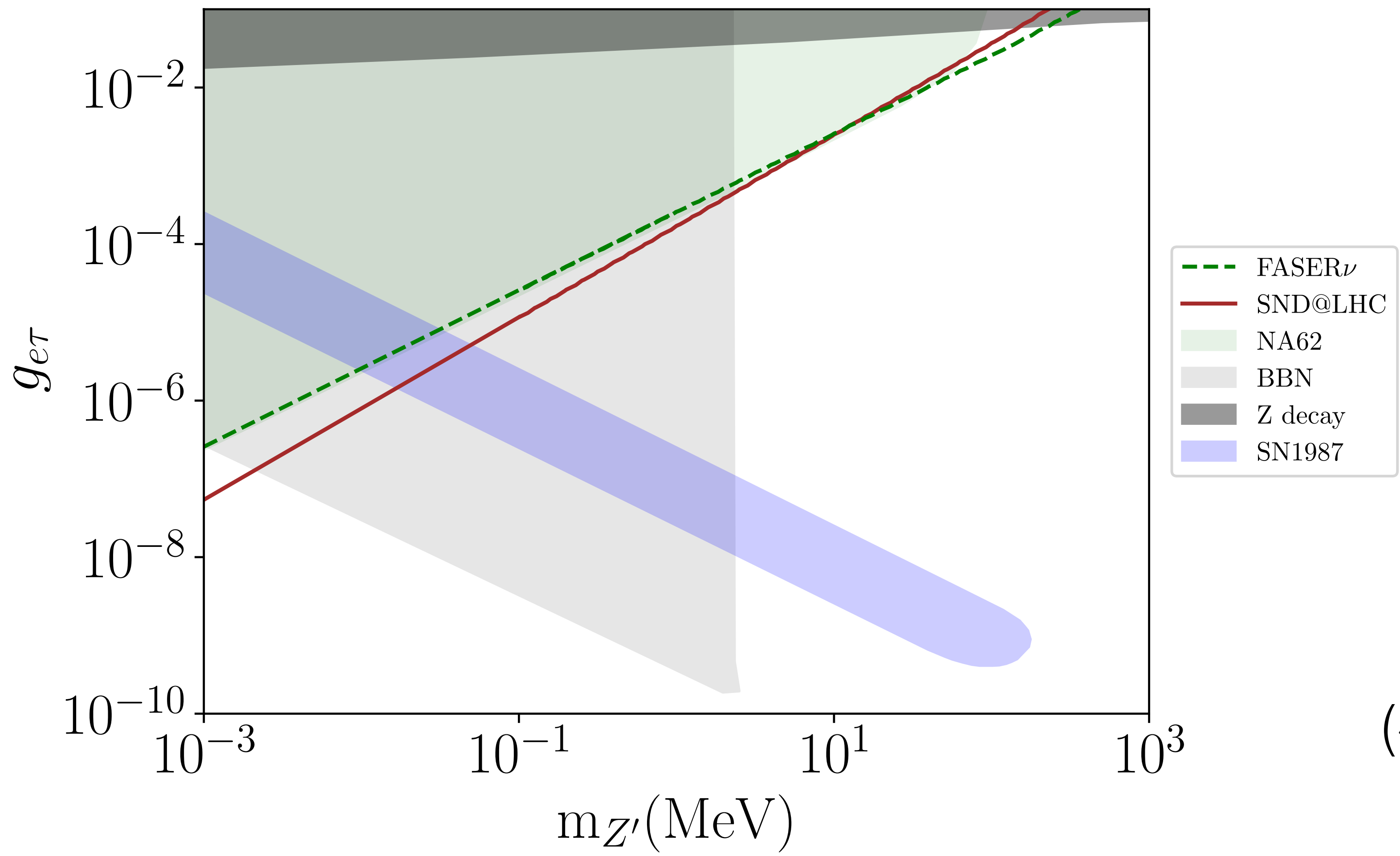


- Core-collapse supernova: SN1987A energy loss rate in blue shaded region (flavor universal & diagonal case)

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

- More general case: dedicated study needed.

Sensitivities for ν_τ SNI: SND & FASERν



SND@LHC/
FASERν: 150 fb^{-1}

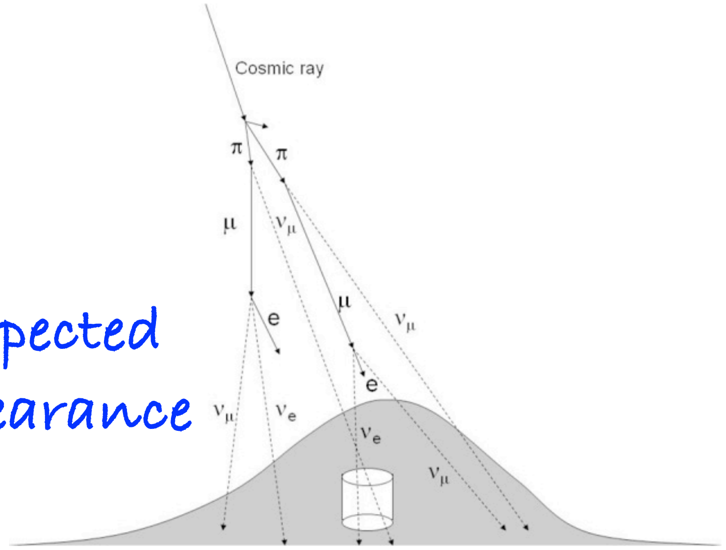
for Run 3 of the
LHC following
Kling, Nevay, PRD 2021

(~ 30 fb^{-1} as of Mar 2023)

- Both experiments can obtain the sensitivities beyond the current bounds for $m_{Z'}$ ~ 30 - 50 MeV or $m_{Z'} \lesssim$ 2 keV.

- Although slight smaller, SND@LHC can be more sensitive than FASERν due to its slight off-axis location.

Sensitivities for ν_τ SNI: DUNE FD

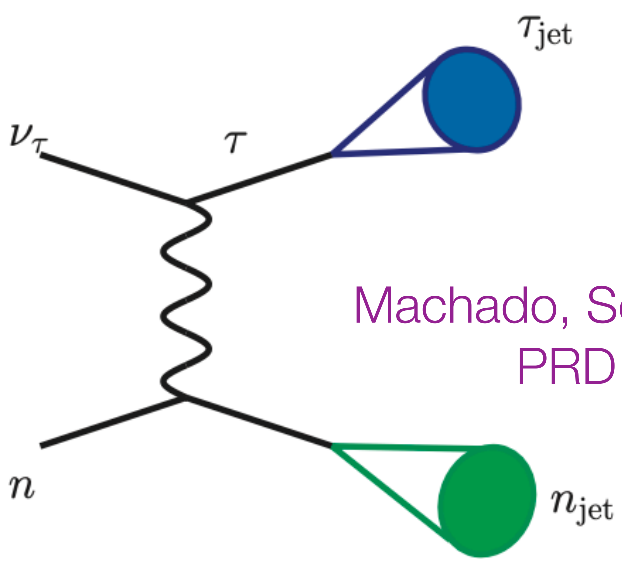


Unexpected
ν_τ appearance

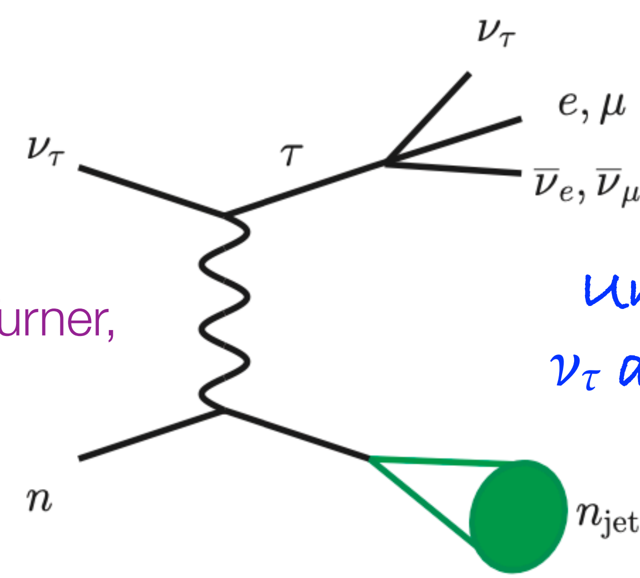
Sensitivities for ν_τ SNI: DUNE FD

Background?

- In ideal situations, no backgrounds.



Machado, Schulz, Turner,
PRD 2020



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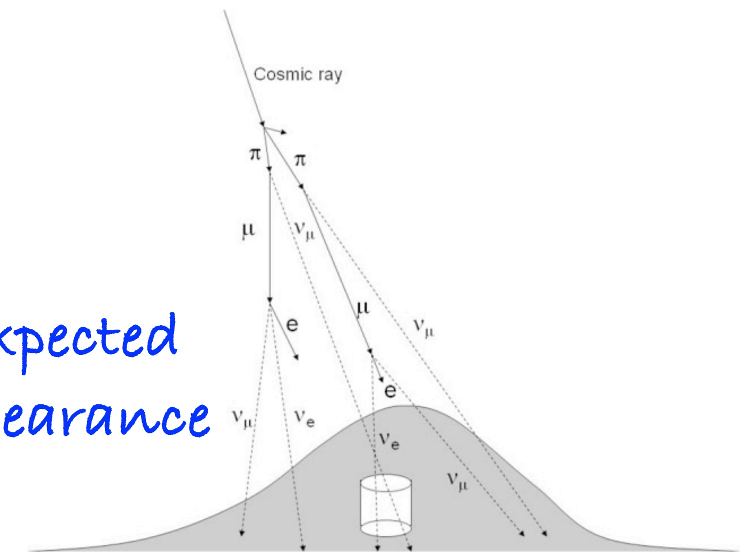

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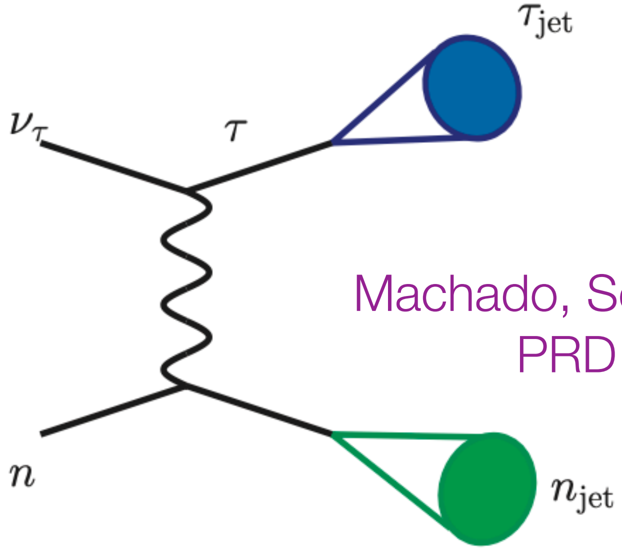
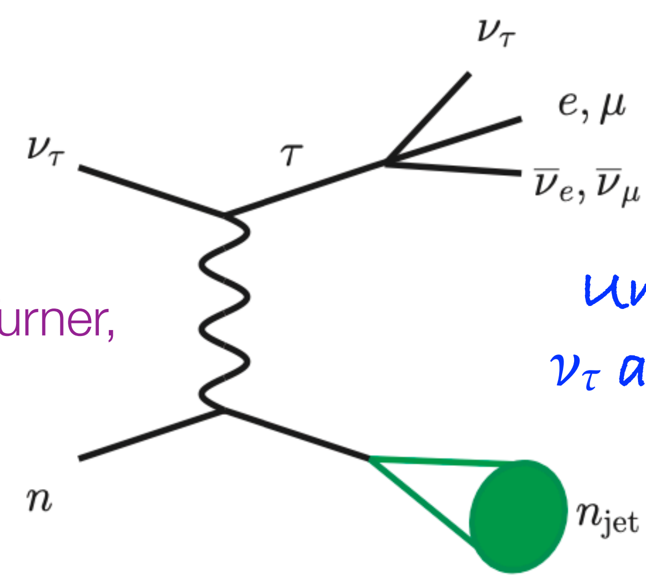


Machado, Schulz, Turner, PRD 2020



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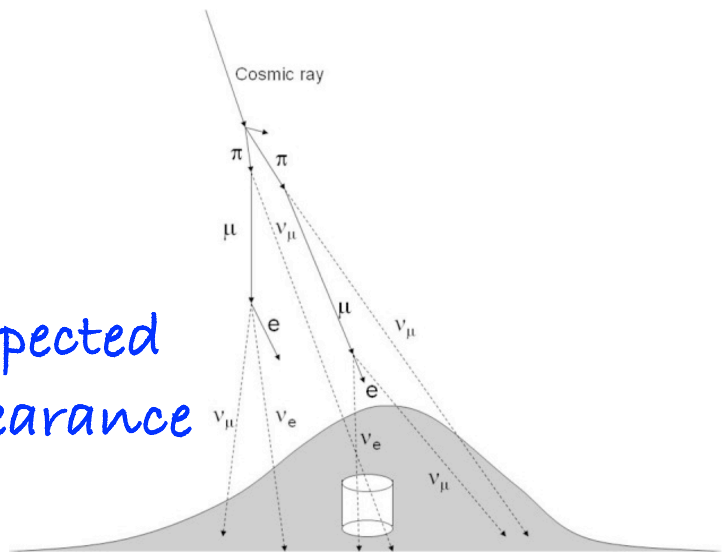
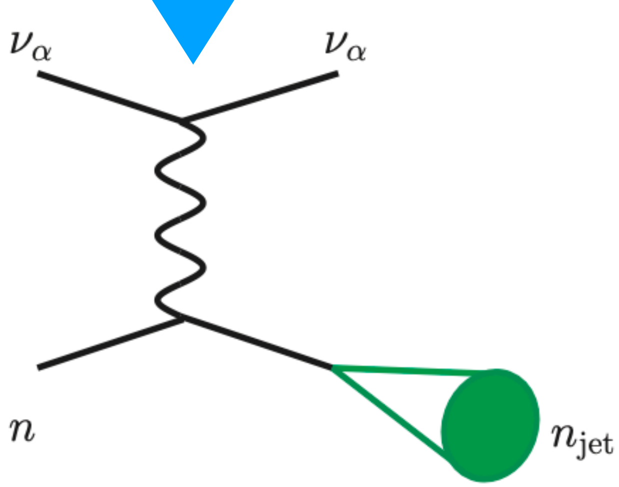
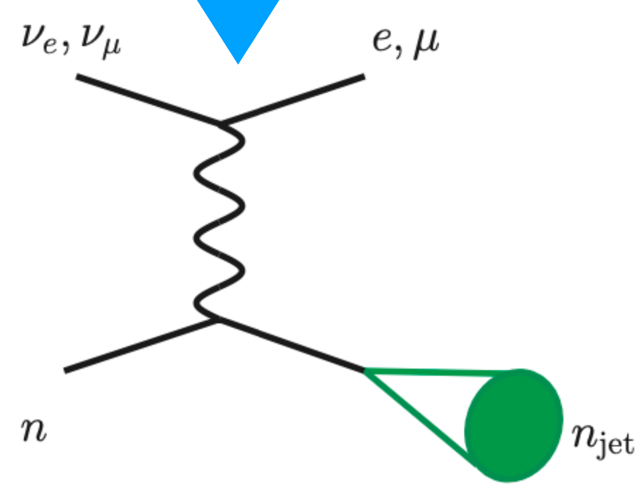


NC background?





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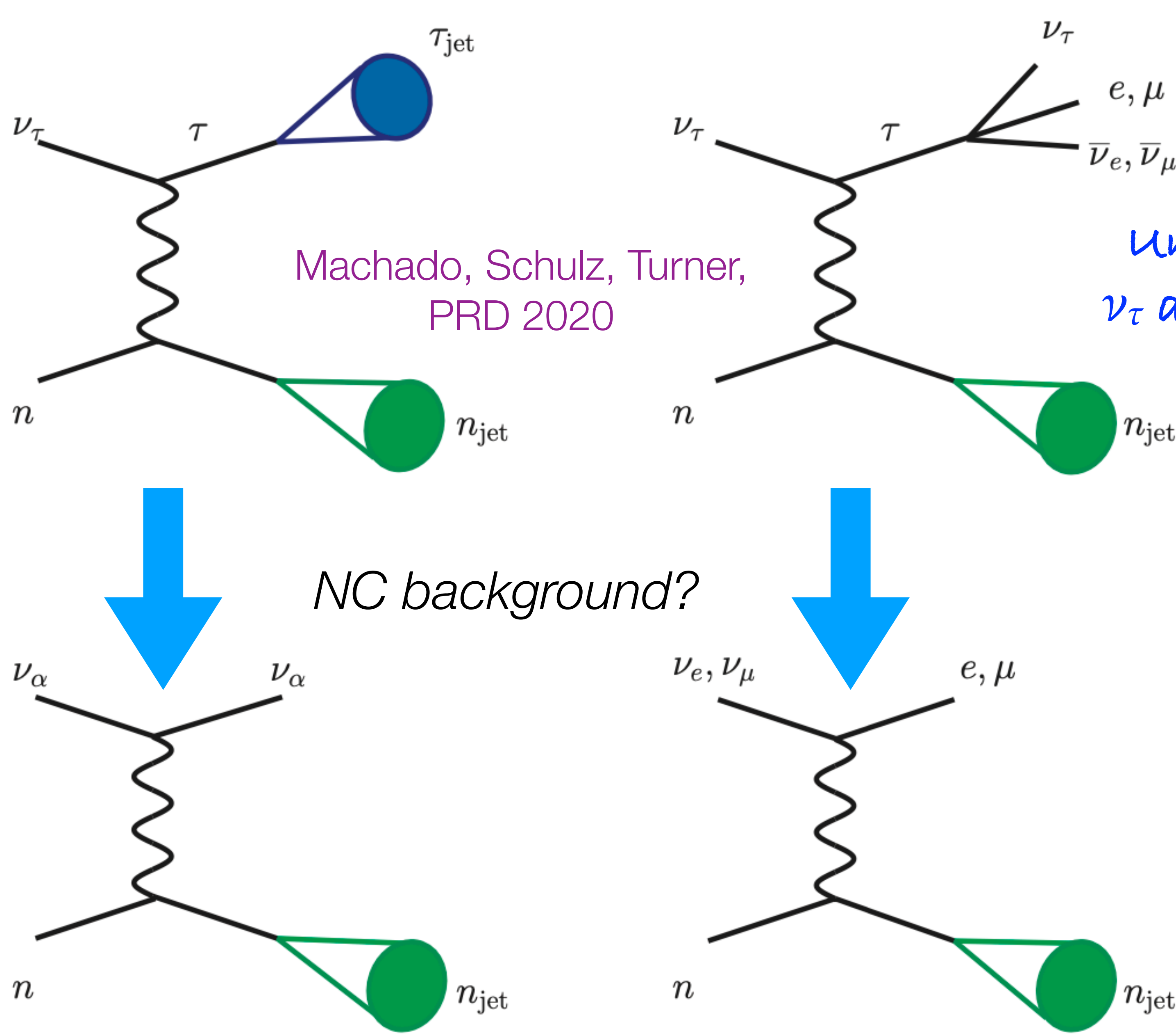

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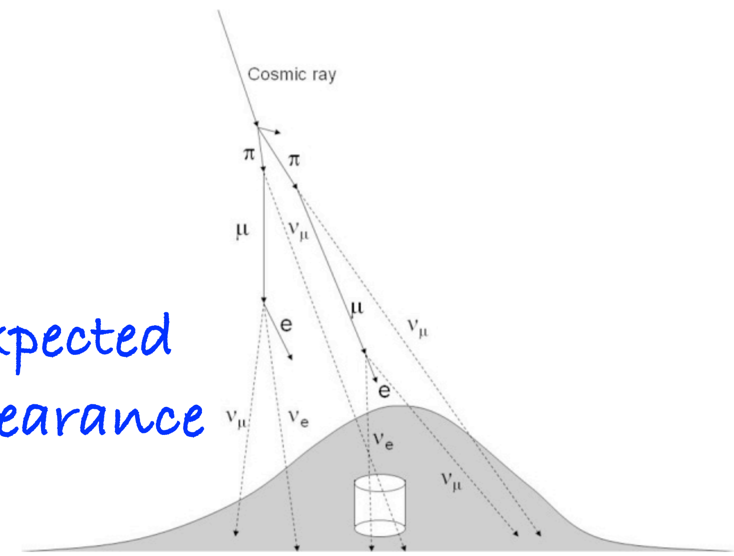

DUNE: expected to have excellent event topology reconstruction capabilities.

↓

Apply the methods in collider pheno, e.g., jet clustering, cuts, …

Sensitivities for ν_τ SNI: DUNE FD

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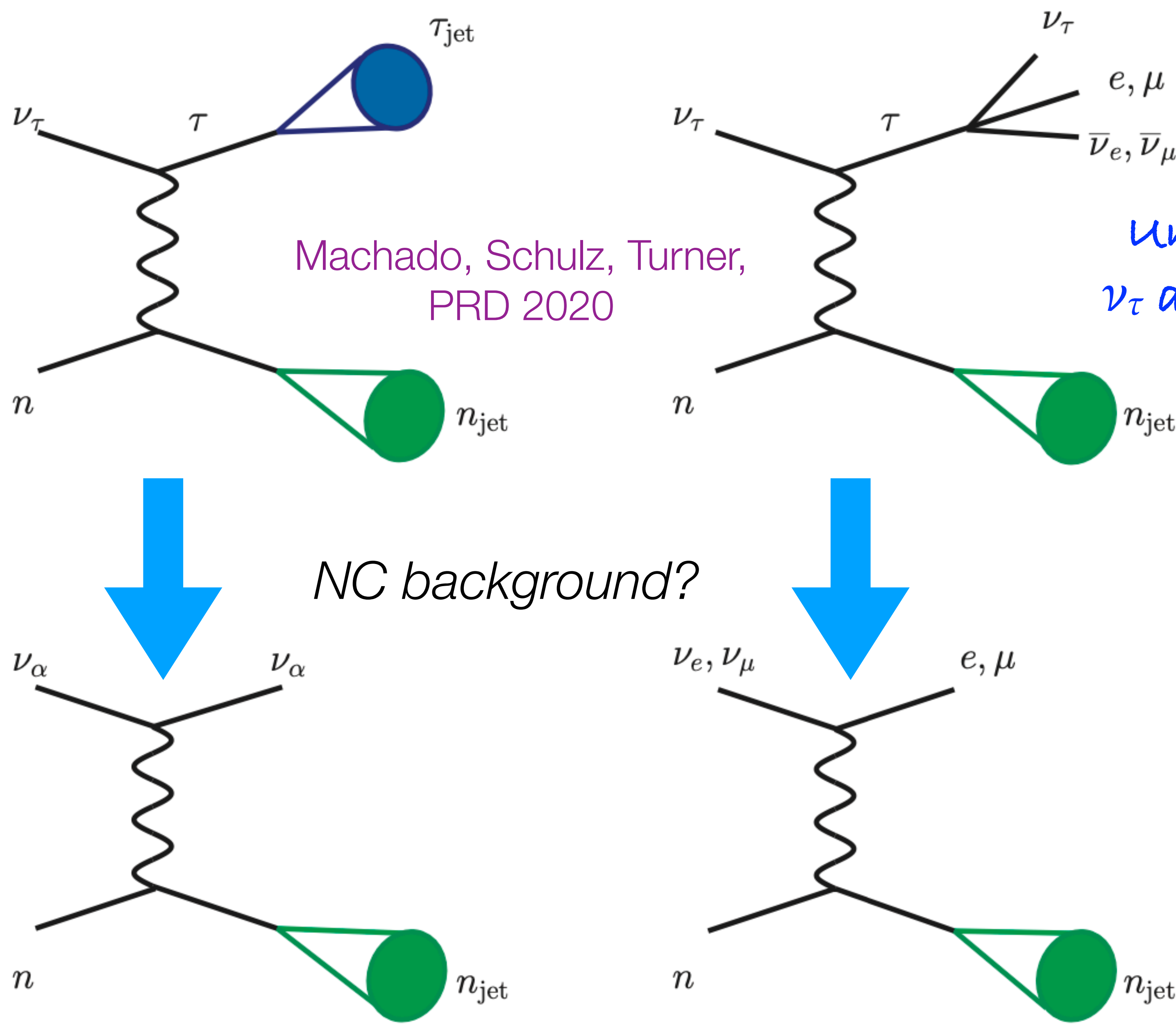
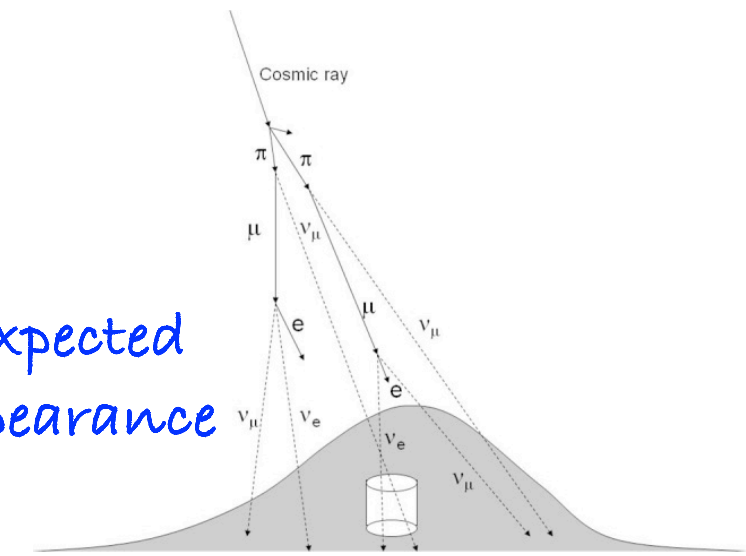


- Signal-to-background efficiencies increase!

unexpected
ν_τ appearance



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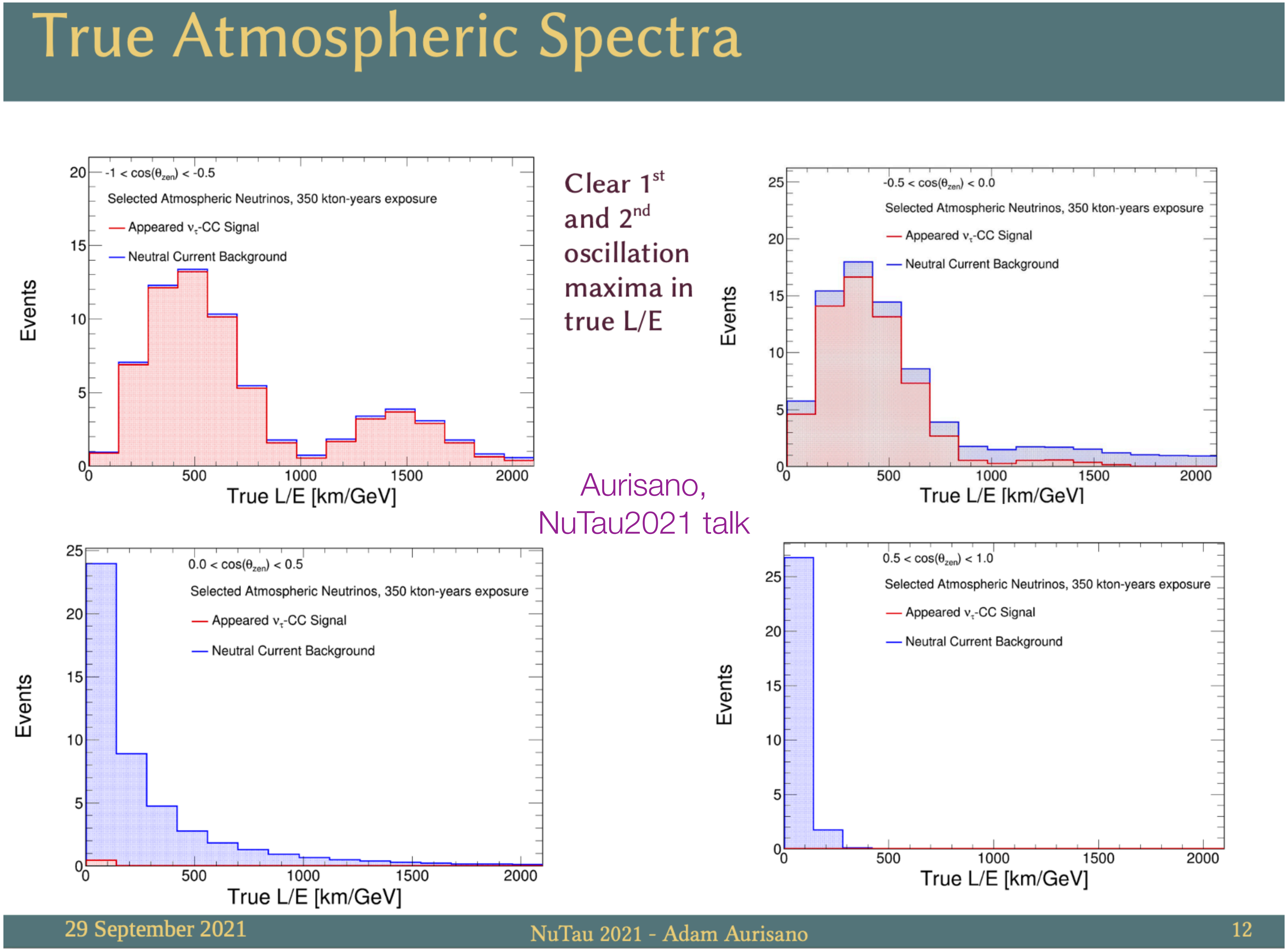
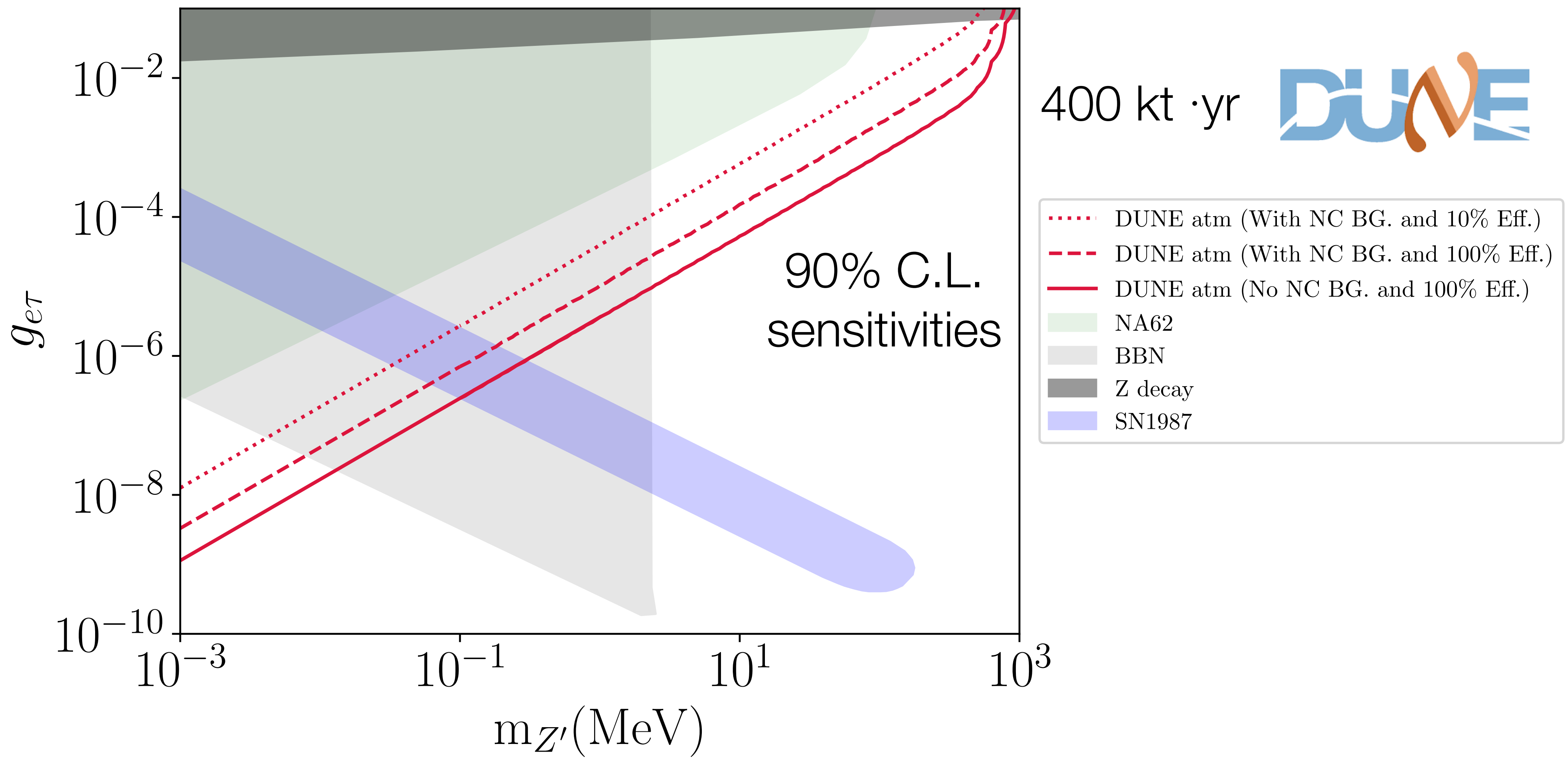


- NC background ~ 70 for 10 years: this may be still very optimistic.

Sensitivities for ν_τ SNI: DUNE FD



- Solid: No background with 100% identification and reconstruction efficiency
  Dashed: Neutral Current background (70 for 10 years)
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DUNE, arXiv:2002.03005 Machado, Schulz, Turner, PRD 2020

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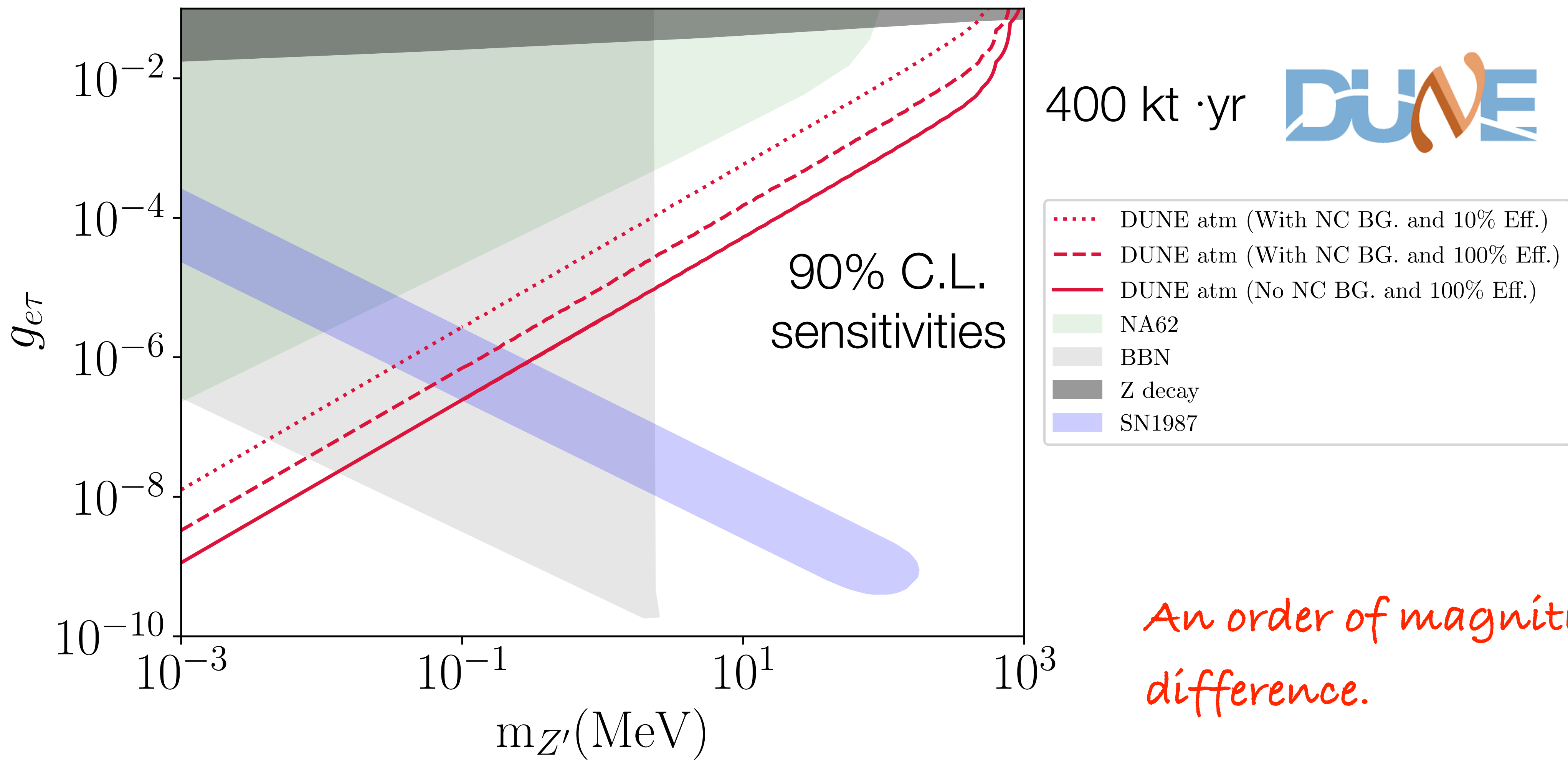

An order of magnitude difference.

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DUNE, arXiv:2002.03005 Machado, Schulz, Turner, PRD 2020

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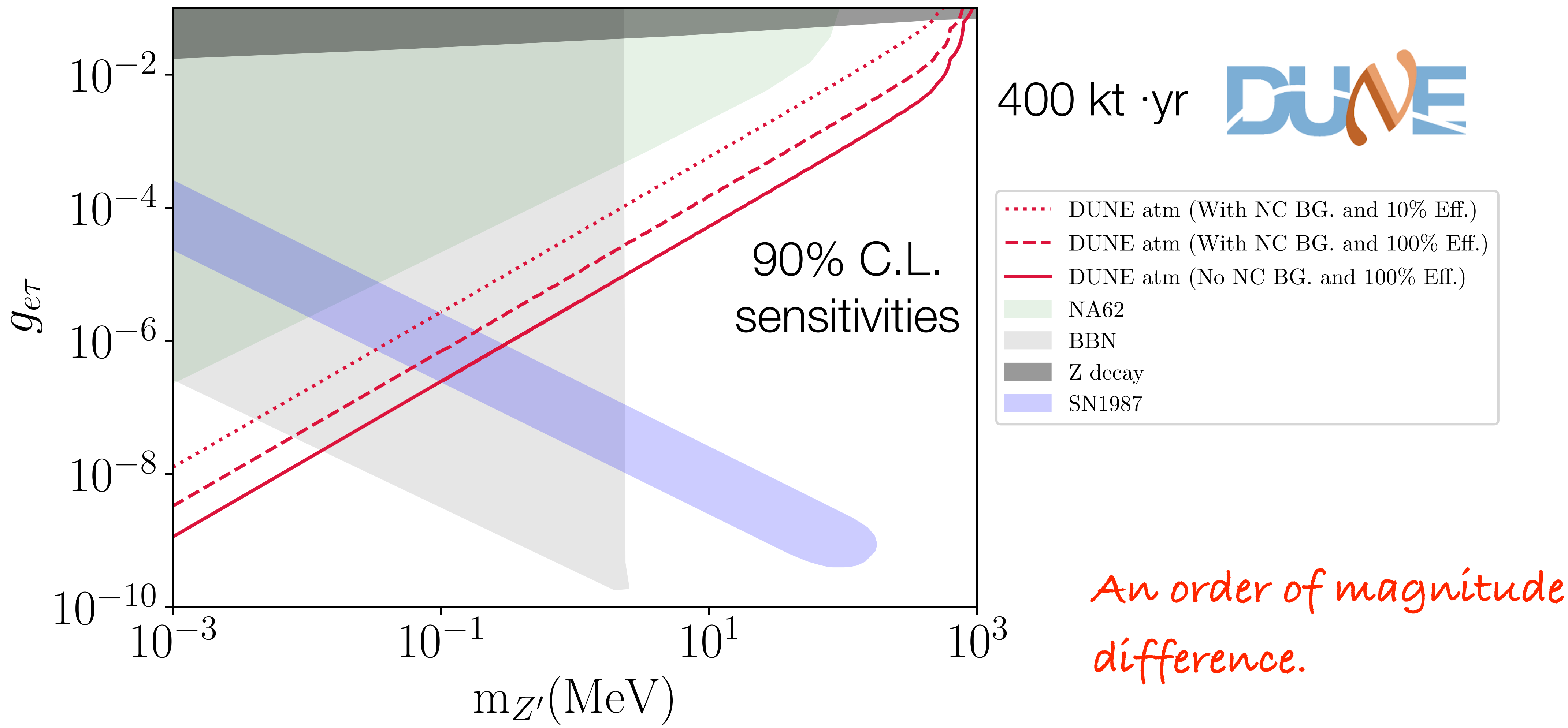

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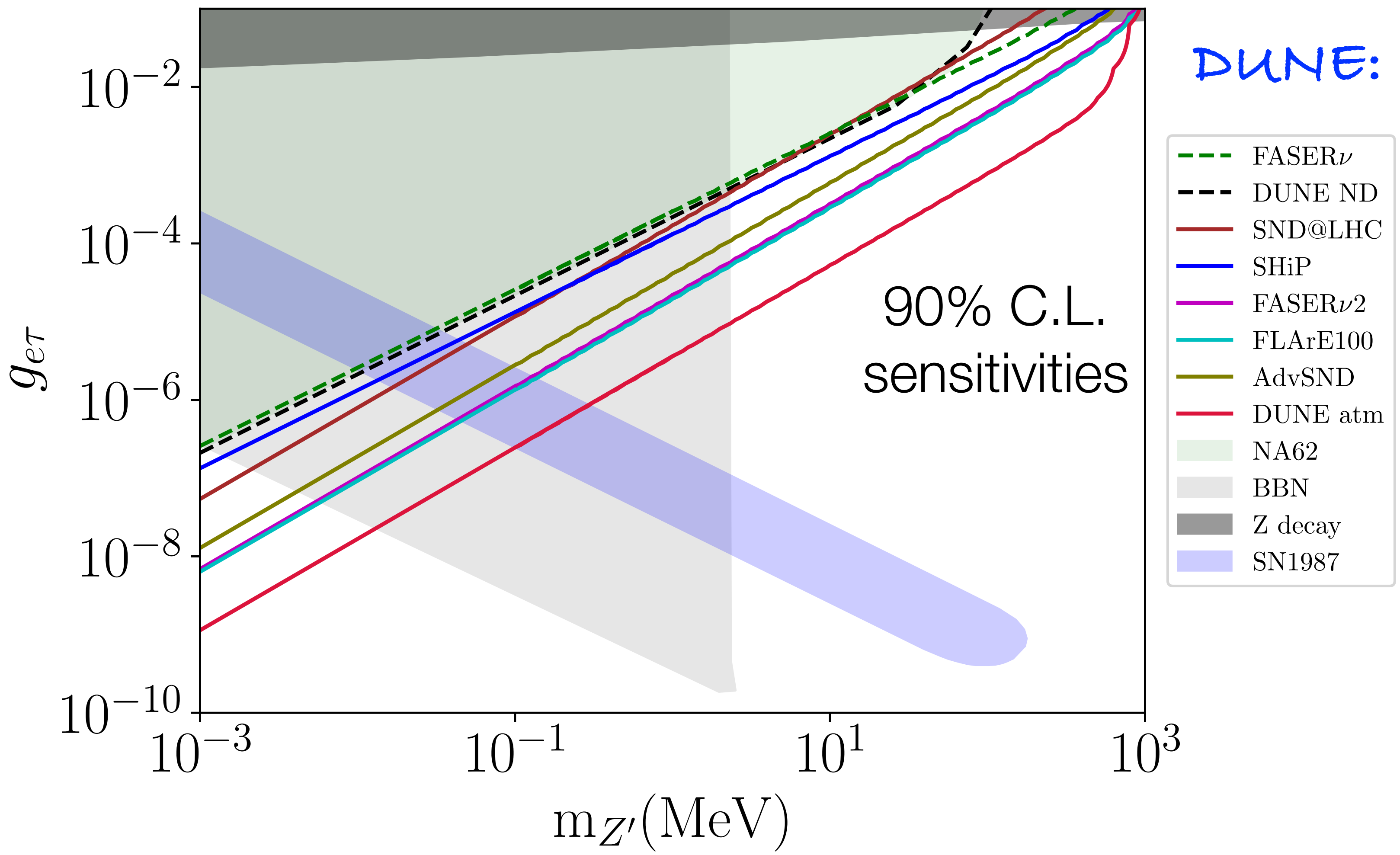
DUNE, arXiv:2002.03005 Machado, Schulz, Turner, PRD 2020

- 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)

Sensitivities for ν_τ SNI: FPF, SHiP



DUNE: most sensitive

SND@LHC/ FASERν: 150 fb^{-1}

SHiP: 2×10^{20} POT (5 yrs)

FPF: 3 ab^{-1}

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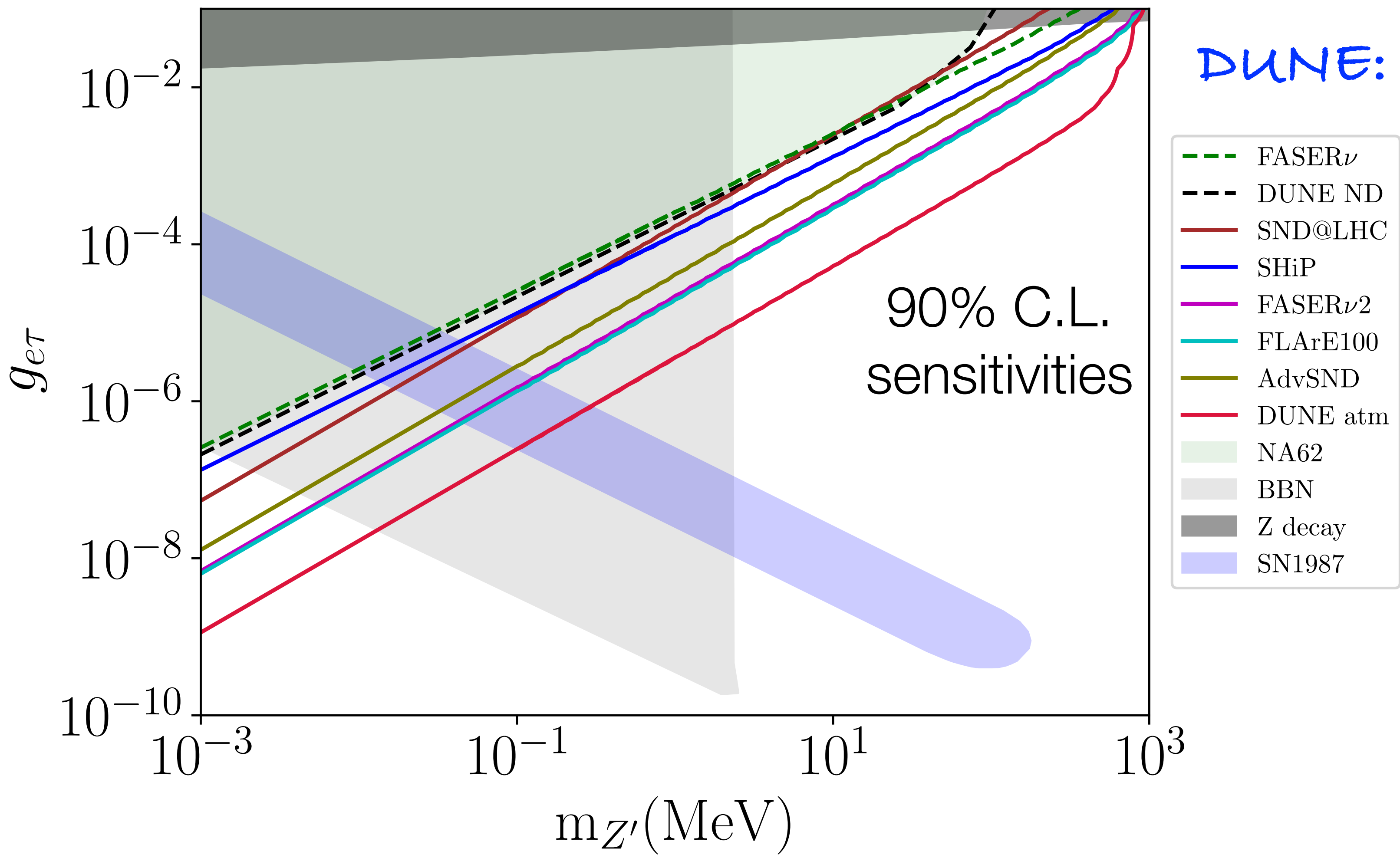

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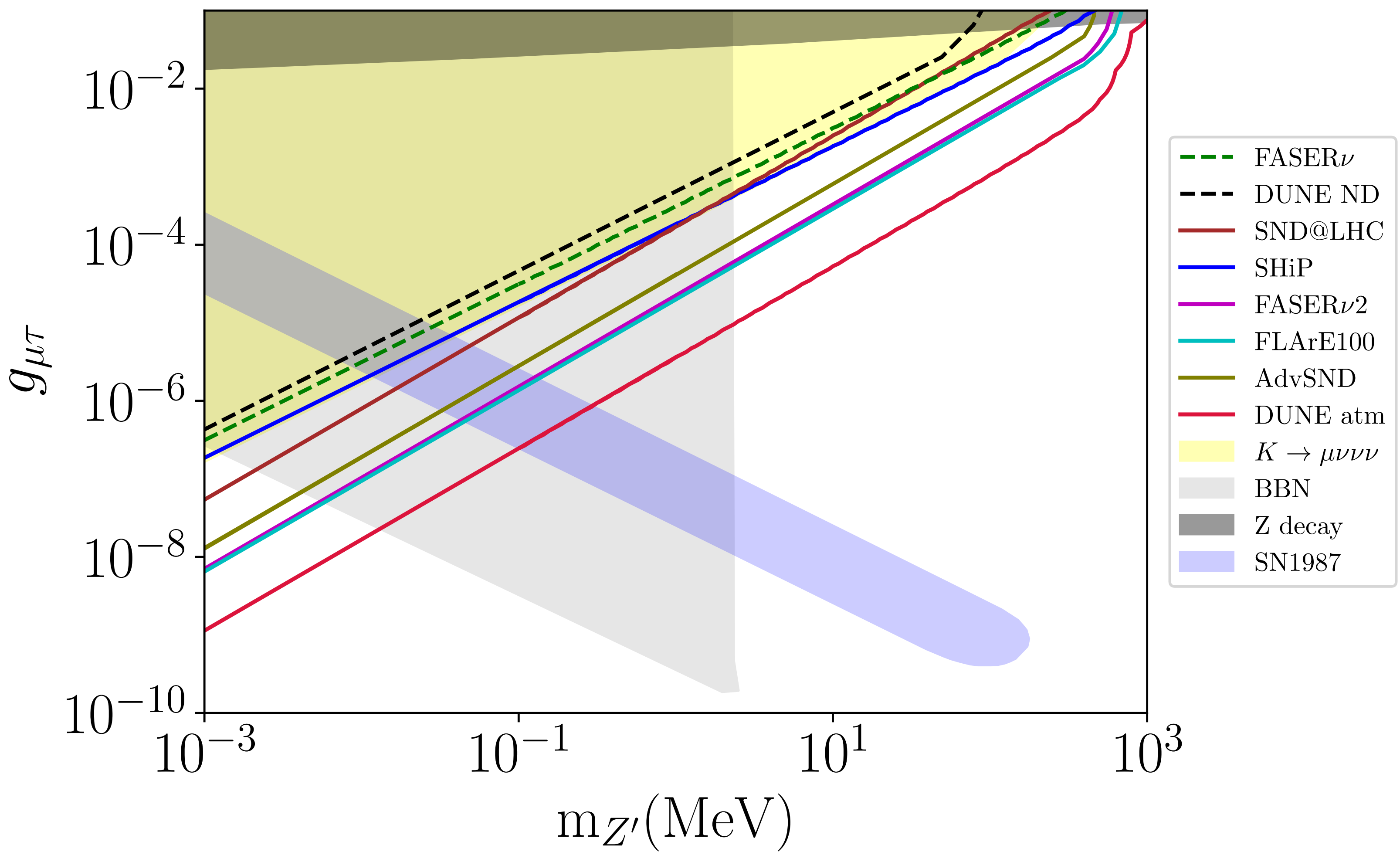
SHiP: 2×10^{20} POT (5 yrs)

FPF: 3 ab^{-1}

- FLArE100 (cyan, 100 ton) and FASERν2 (purple, 20 ton) can be most sensitive among the accelerator based experiments (comparable to the worse sensitivity at DUNE) but the 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



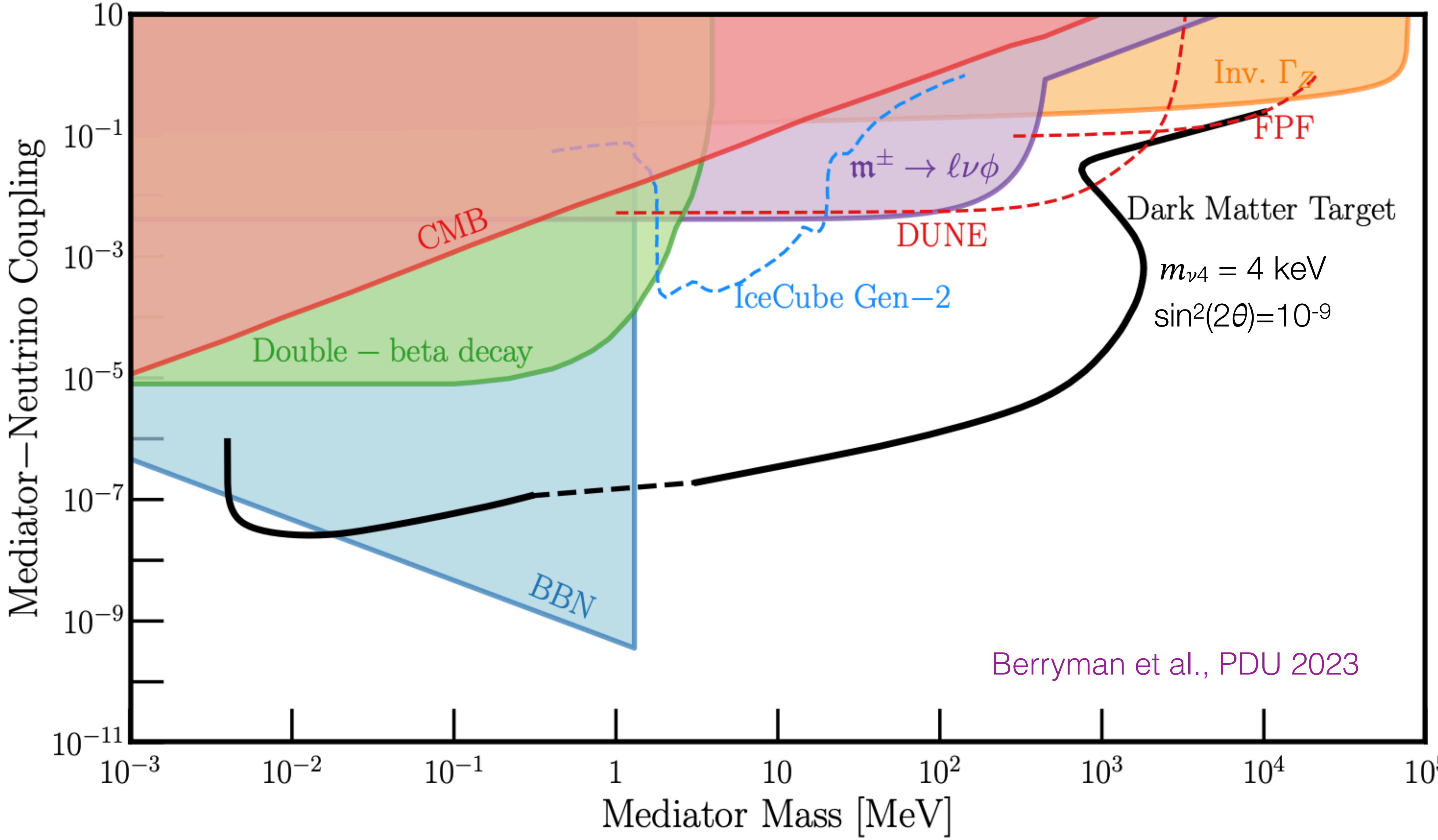
- Sensitivities are comparable or slightly weaker (SHiP) due to the phase space.

- 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).

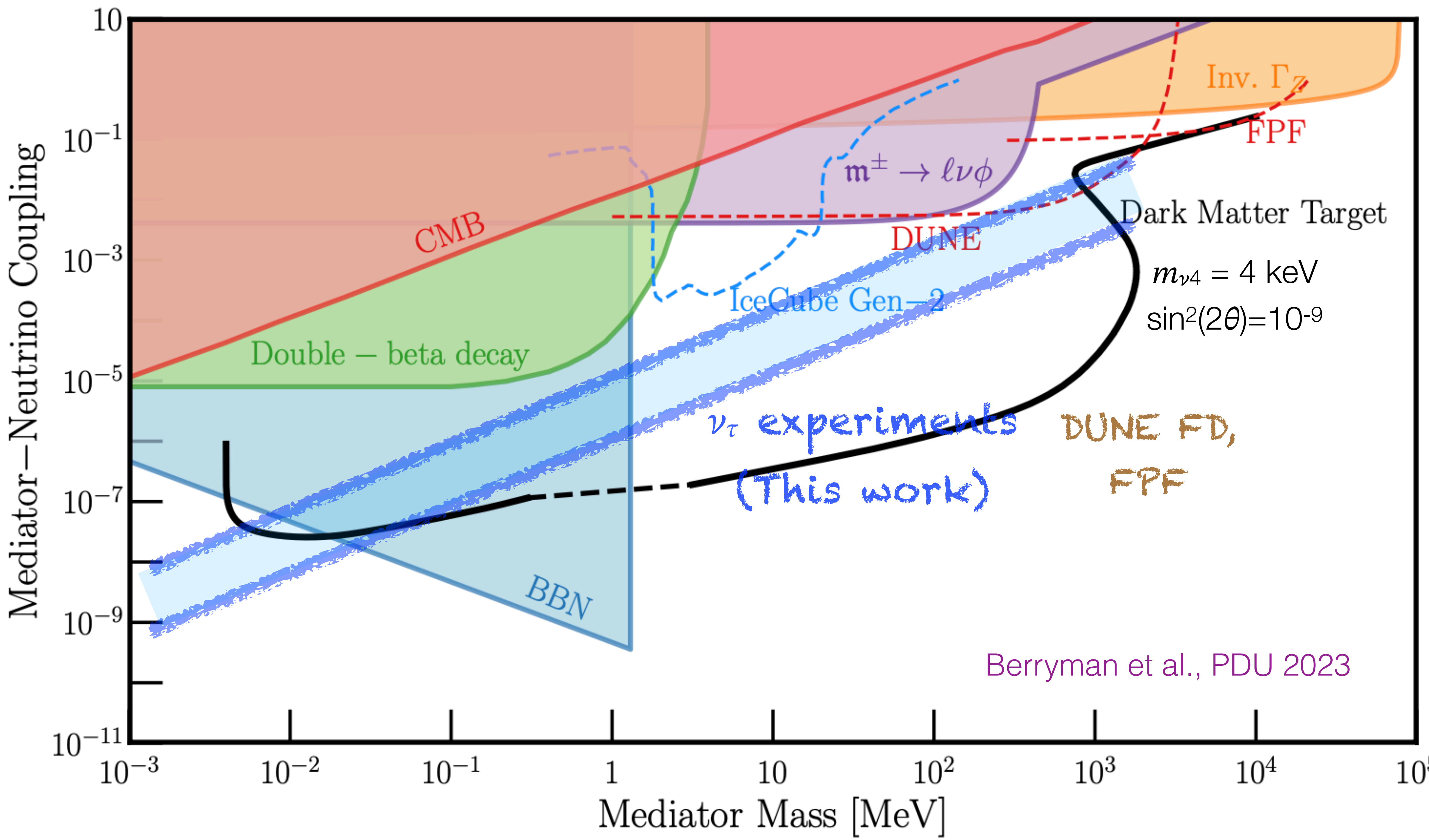
$$\mathrm{BR}(K^+ \to \mu^+ \nu\nu\nu) < 2.4 \times 10^{-6}$$

Sensitivities for ν_τ SNI



Universal coupling case

Sensitivities for ν_τ SNI



Universal coupling case

Conclusions

- Upcoming (& ongoing) tau neutrino experiments can shed light on our steps toward New Physics BSM.

- We can probe flavor non-universal (ν_τ-philic) SNI preferred by cosmo/astro/lab.: we use SND@LHC, FASERν, 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.

Backup: Reference experiments

Detector		number of events		
Detector name	mass	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
FASERν	1.2 tonnes	1000	5000	20
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(upward-going)	40 kilo-tonnes	1.6×10^4	2.4×10^4	150

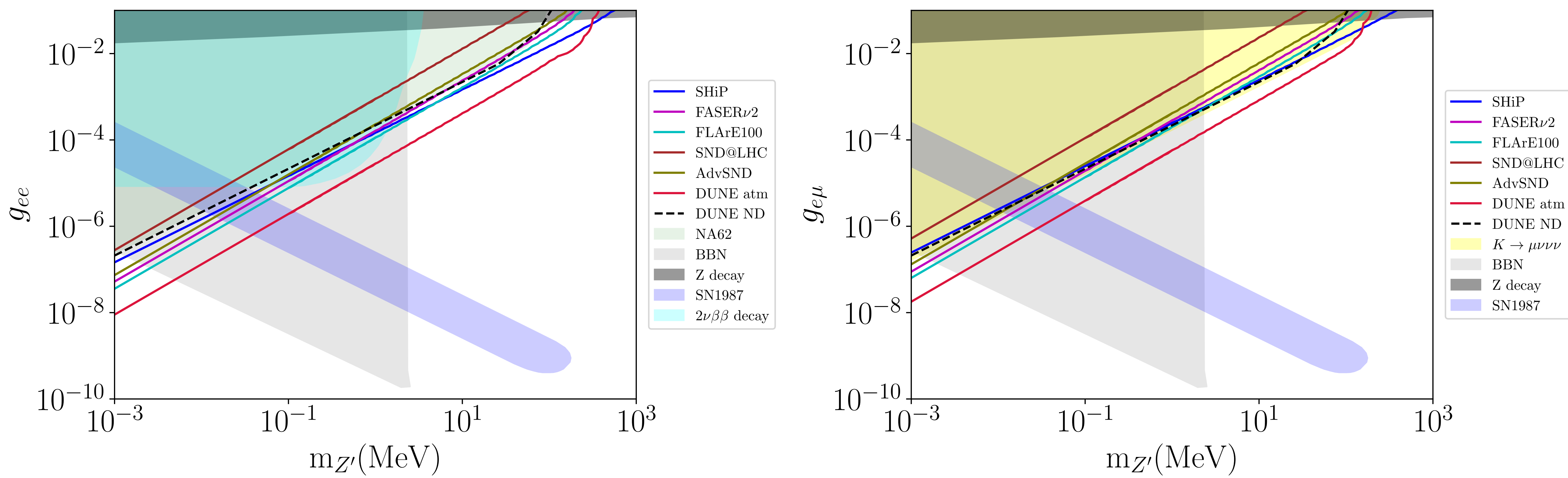
TABLE I. Estimated numbers of standard model neutrino events assuming a final integrated luminosity of 150 fb^{-1} for FASERν and SND@LHC, while 3000 fb^{-1} for FASERν2 and FLArE100. For SHiP, we assume 2×10^{20} POT in five years. We assume a data-taking period of 10 years for DUNE atmospheric neutrinos.

Experimental details: Kling, Nevay, PRD 2021, FPF SNOWMASS 2203.05090, Aurisano, talk in NuFact 2021

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

Backup:Sensitivities for ν_τ SNI

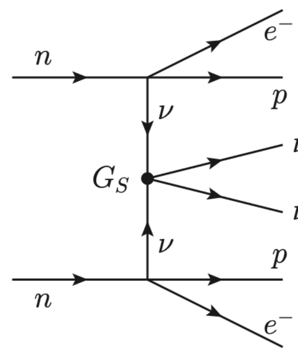
Comparison with the other flavor couplings



- 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