DPF-PHENO 2024

Uncovering secret neutrino interactions 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*

New symmetry in the neutrino sector

Neutrino oscillation: clear evidence of BSM

→ ν physics can provide guidelines for BSM

New symmetries? New particles?

New symmetry in the neutrino sector

Neutrino oscillation: clear evidence of BSM

→ ν physics can provide guidelines for BSM

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

New symmetry in the neutrino sector

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

⇨ secret neutrino interaction (SNI)

New symmetry in the neutrino sector

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

⇨ secret neutrino interaction (SNI)

- Neutrino oscillation anomalies: LSND, MiniBooNE

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

New symmetry in the neutrino sector

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

⇨ secret neutrino interaction (SNI)

- Neutrino oscillation anomalies: LSND, MiniBooNE

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

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

Rothstein, Babu, Seckel, NPB 1993

De Gouvea, Sen, Tangarife, Zhang, PRL 2020

New symmetry in the neutrino sector

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

⇨ secret neutrino interaction (SNI)

- Neutrino oscillation anomalies: LSND, MiniBooNE

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

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

Rothstein, Babu, Seckel, NPB 1993

De Gouvea, Sen, Tangarife, Zhang, PRL 2020

- Cosmological issues: small scale problems (strongly constrained)

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

H_0 tension

Escudero et al., JHEP 2019 Brinckmann, Chang, LoVerde, PRD 2021 Lyu, Stamou, Wang, PRD 2021

New symmetry in the neutrino sector

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

⇨ secret neutrino interaction (SNI)

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

- Neutrino oscillation anomalies: LSND, MiniBooNE

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

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

Rothstein, Babu, Seckel, NPB 1993

De Gouvea, Sen, Tangarife, Zhang, PRL 2020

- Cosmological issues: small scale problems (strongly constrained)

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

H_0 tension

Escudero et al., JHEP 2019   Brinckmann, Chang, LoVerde, PRD 2021   Lyu, Stamou, Wang, PRD 2021

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

Deppisch, Graf, Rodejohann, Xu, PRD 2020

Berryman et al., PDU 2023

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

Deppisch, Graf, Rodejohann, Xu, PRD 2020

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

Neutrino 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 CC-σ.

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

- 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

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, …

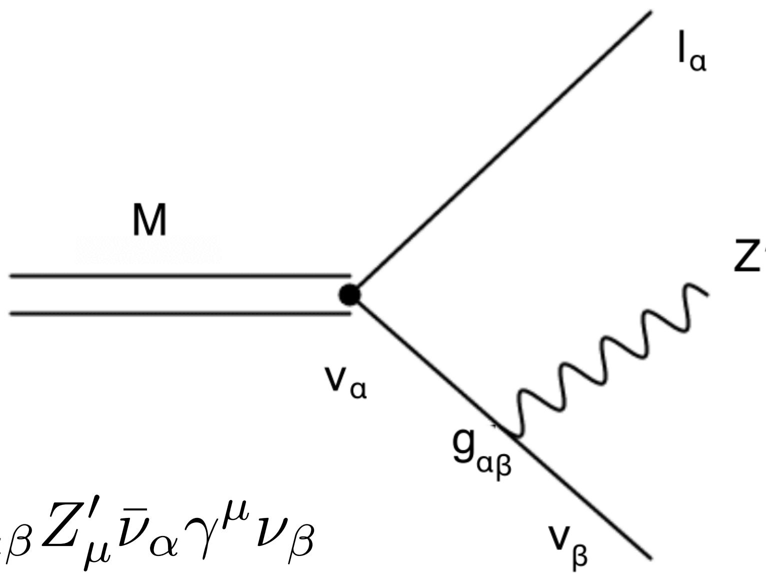
  - Upward-going ν_τ events: Directly confirm atmospheric ν oscillation, & probe New Physics involved there

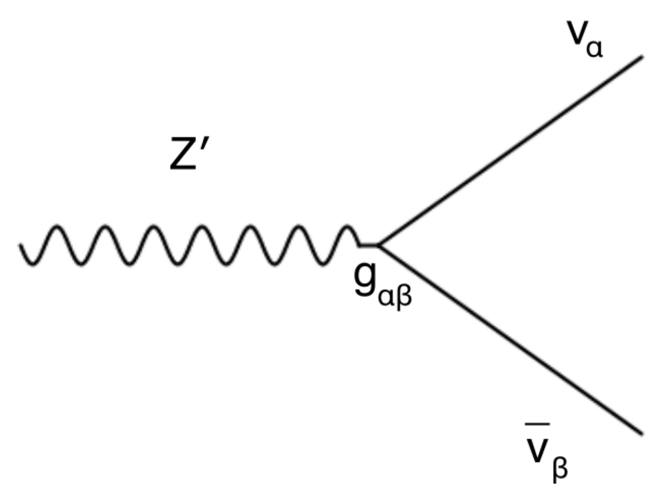
  - Downward-going ν_τ events: Not from oscillation, ⇒ Anomalous ν_τ appearance

Extremely sensitive to New Physics

Theoretical set-up

Kinematic process: 3-body meson decay





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

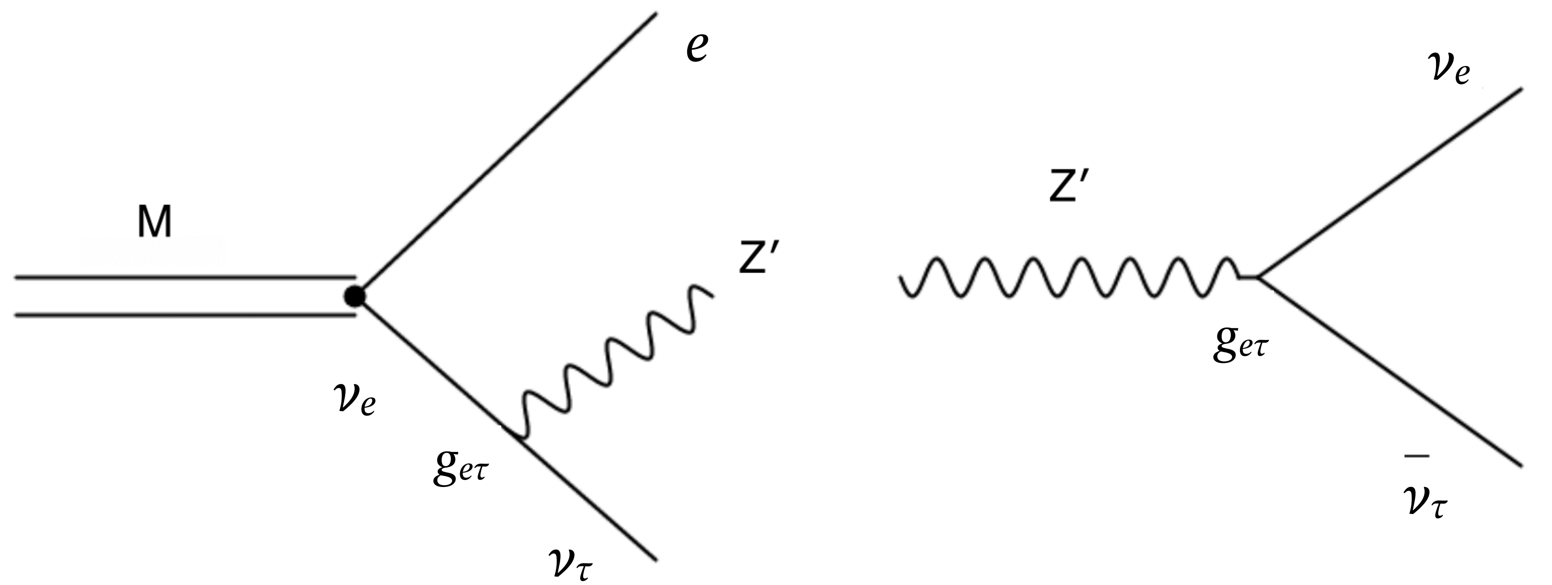
- Conventional 2-body decay of a pseudoscalar meson such as $\pi^\pm \to \mu^\pm \nu$: chiral suppression. m_ℓ^2/m_M^2

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

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

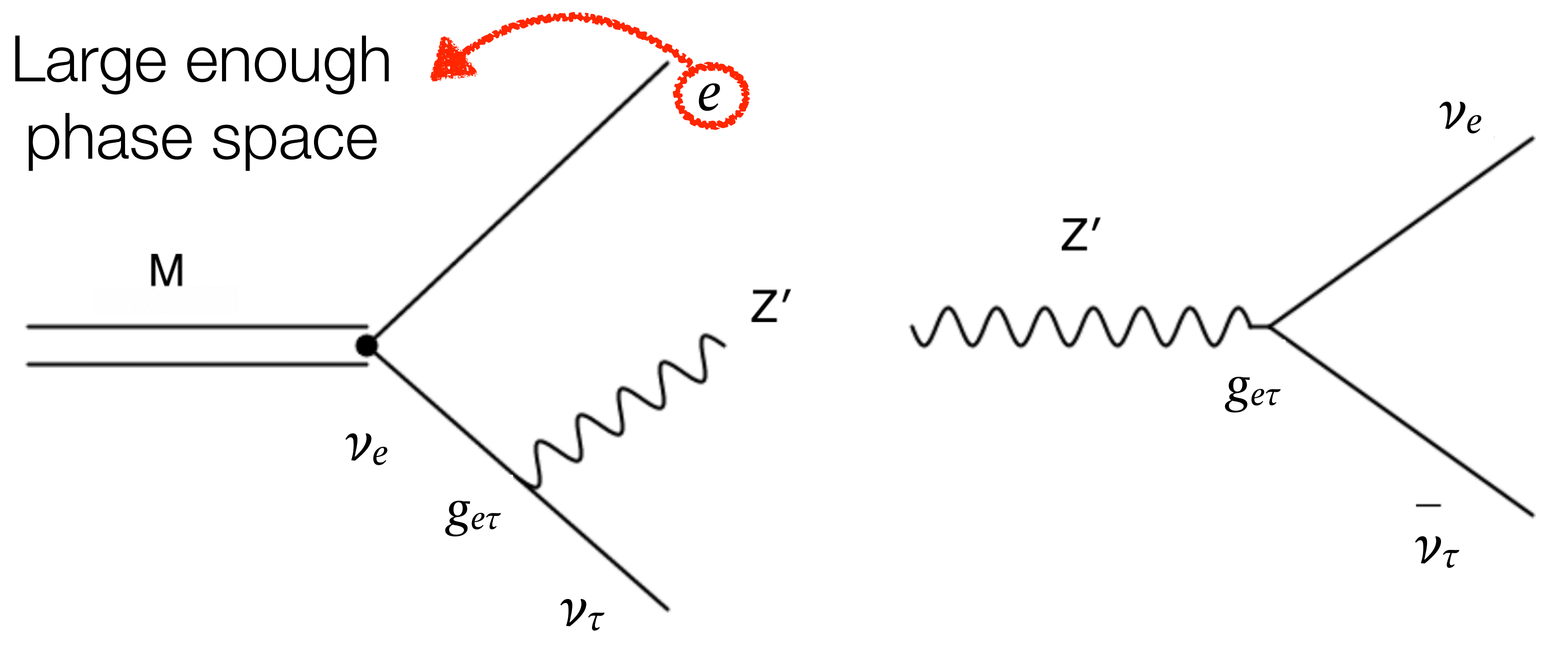
Laha, Dasgupta, Beacom, PRD 2014 　 Bakhti, Farzan, PRD 2017

Sensitivities for ν_τ SNI



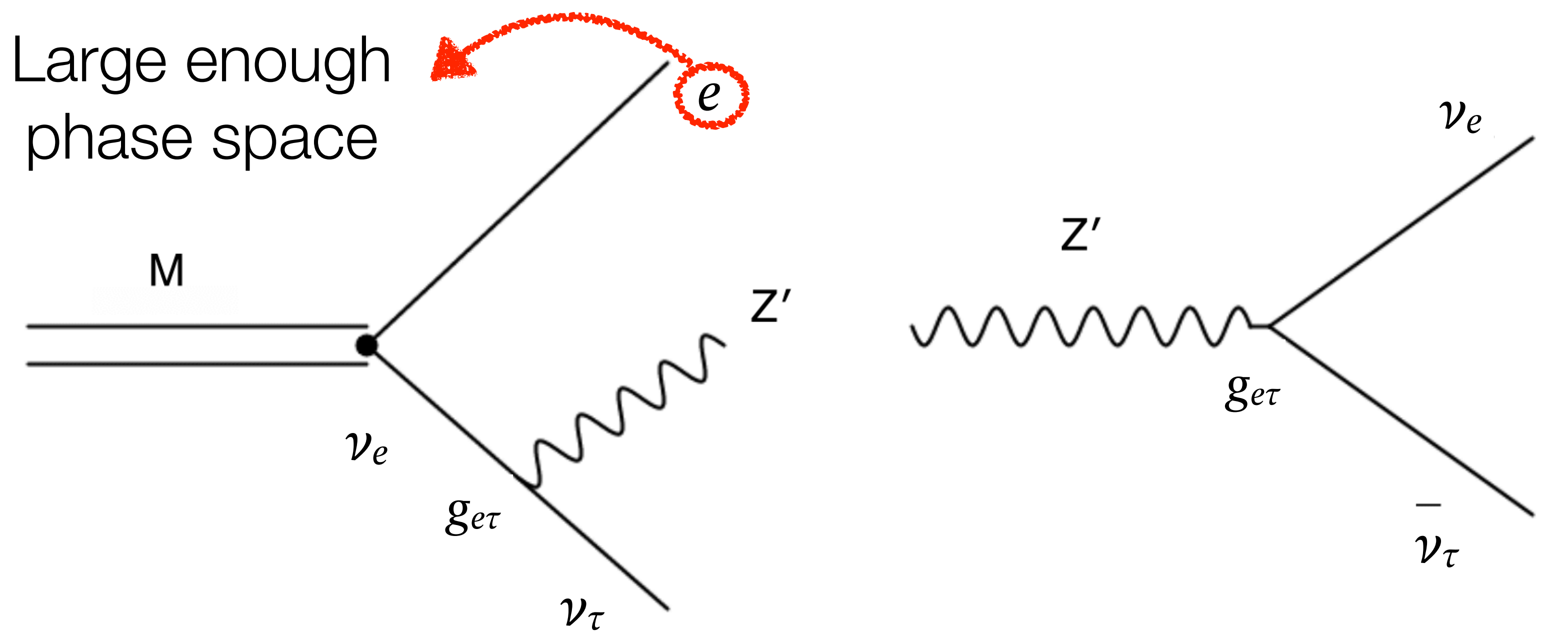
- $g_{e\tau}$ only: no other couplings to ν, $\ell^\pm$, B

Sensitivities for ν_τ SNI



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

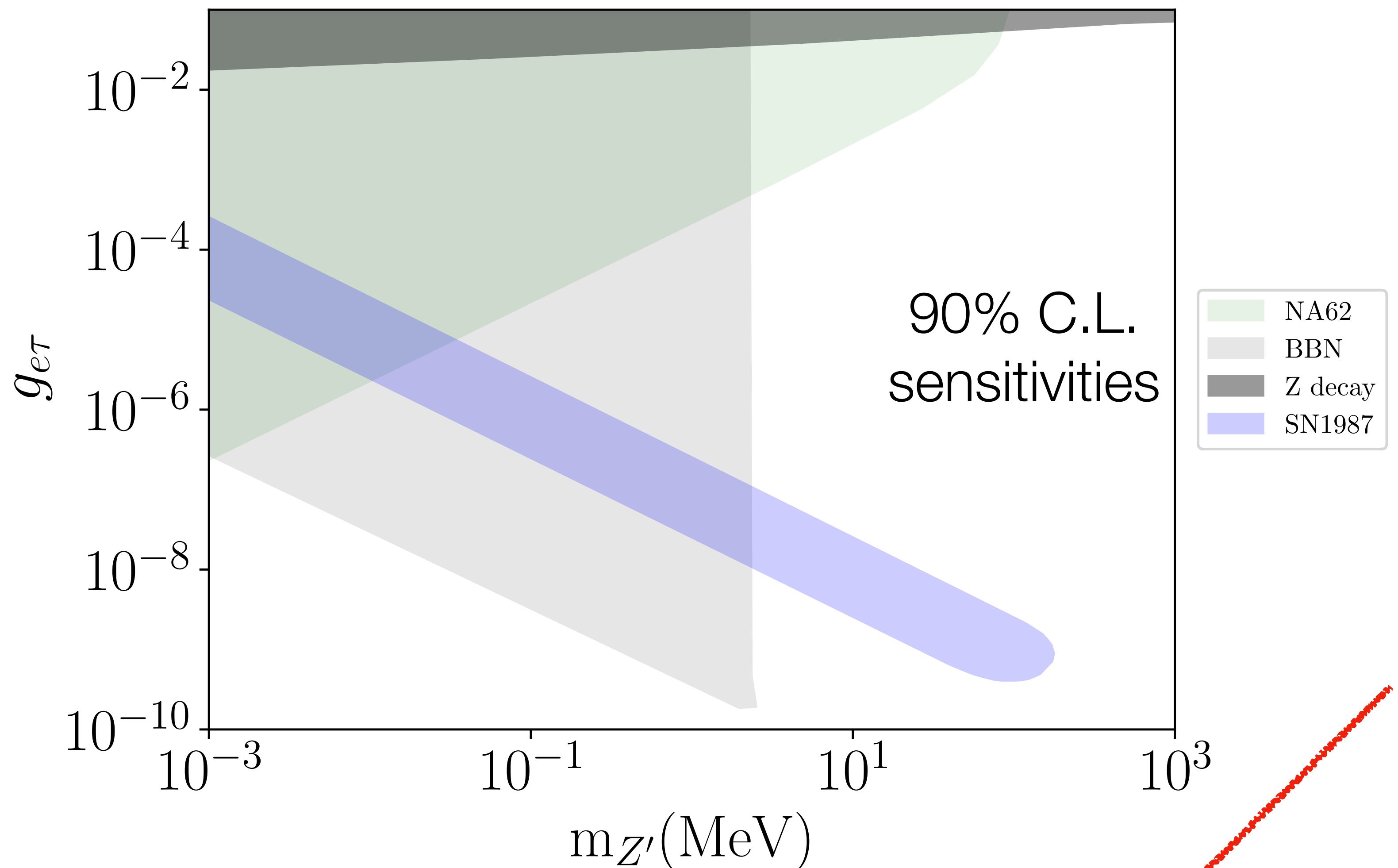
Sensitivities for ν_τ SNI



- $g_{e\tau}$ 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



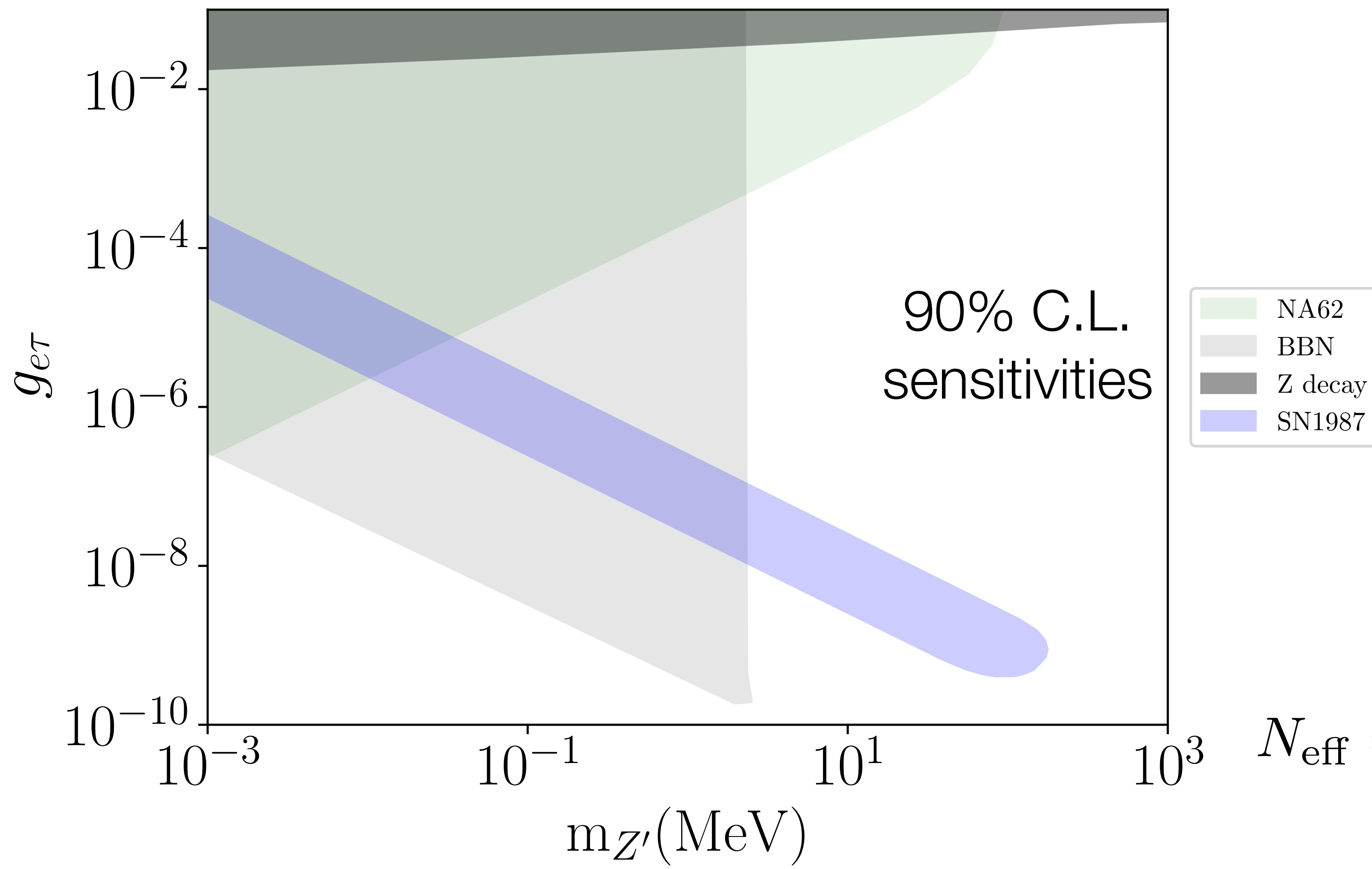
$K^+ \to e^+ Z' \nu_\tau$

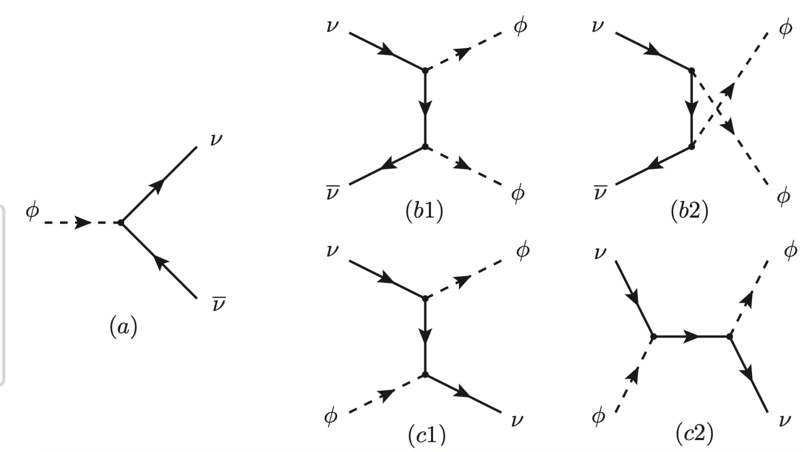
- NA62 (green): $$R_K = \frac{\Gamma(K^+ \to e^+ \nu_e)}{\Gamma(K^+ \to \mu^+ \nu_\mu)}$$

Bakhti, Farzan, PRD 2017

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

Sensitivities for ν_τ SNI





$$N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\rm rad}-\rho_\gamma}{\rho_\gamma}\right)$$

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

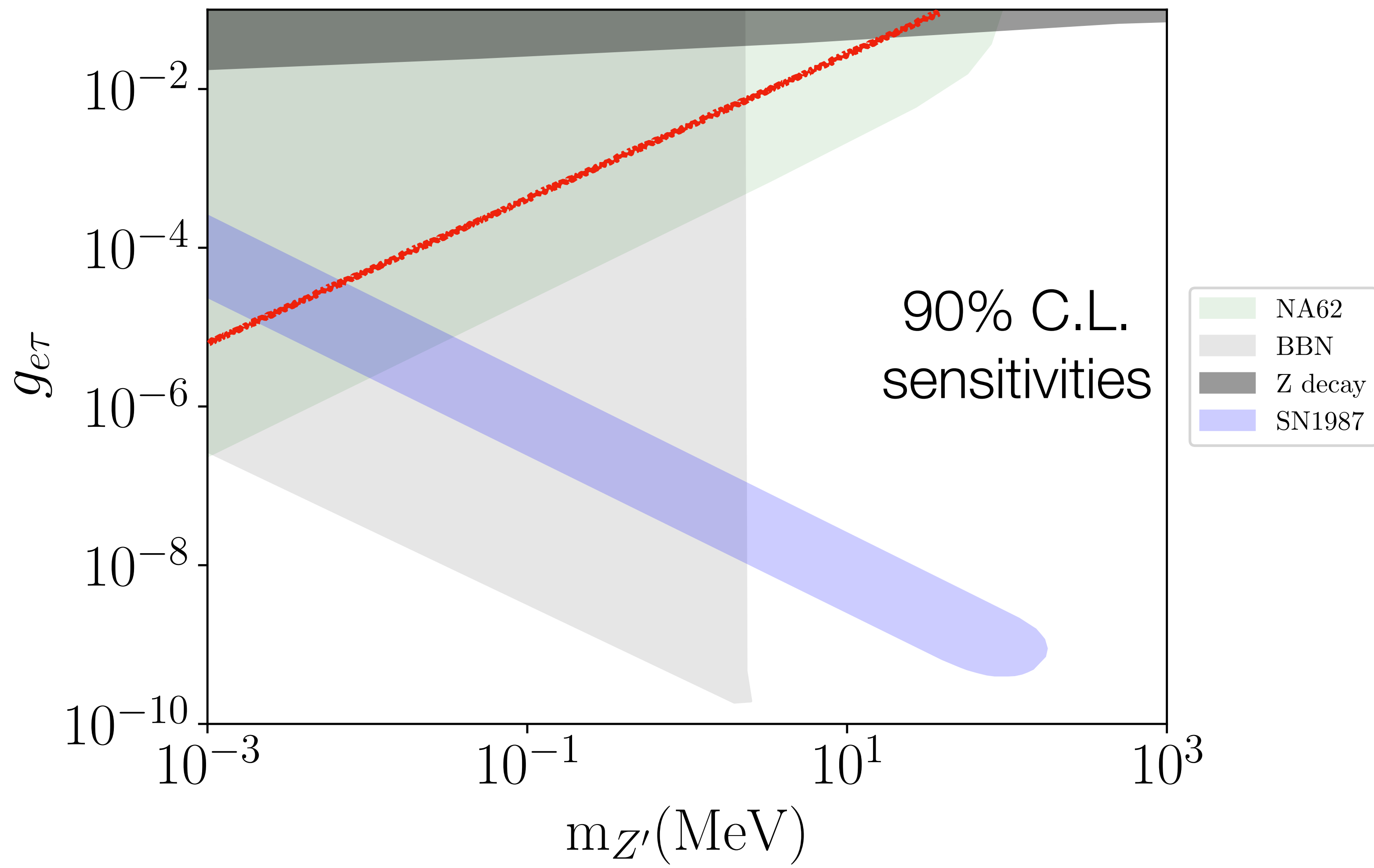
  primordial abundances of light elements for ν_e (similar)

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



CMB bound?

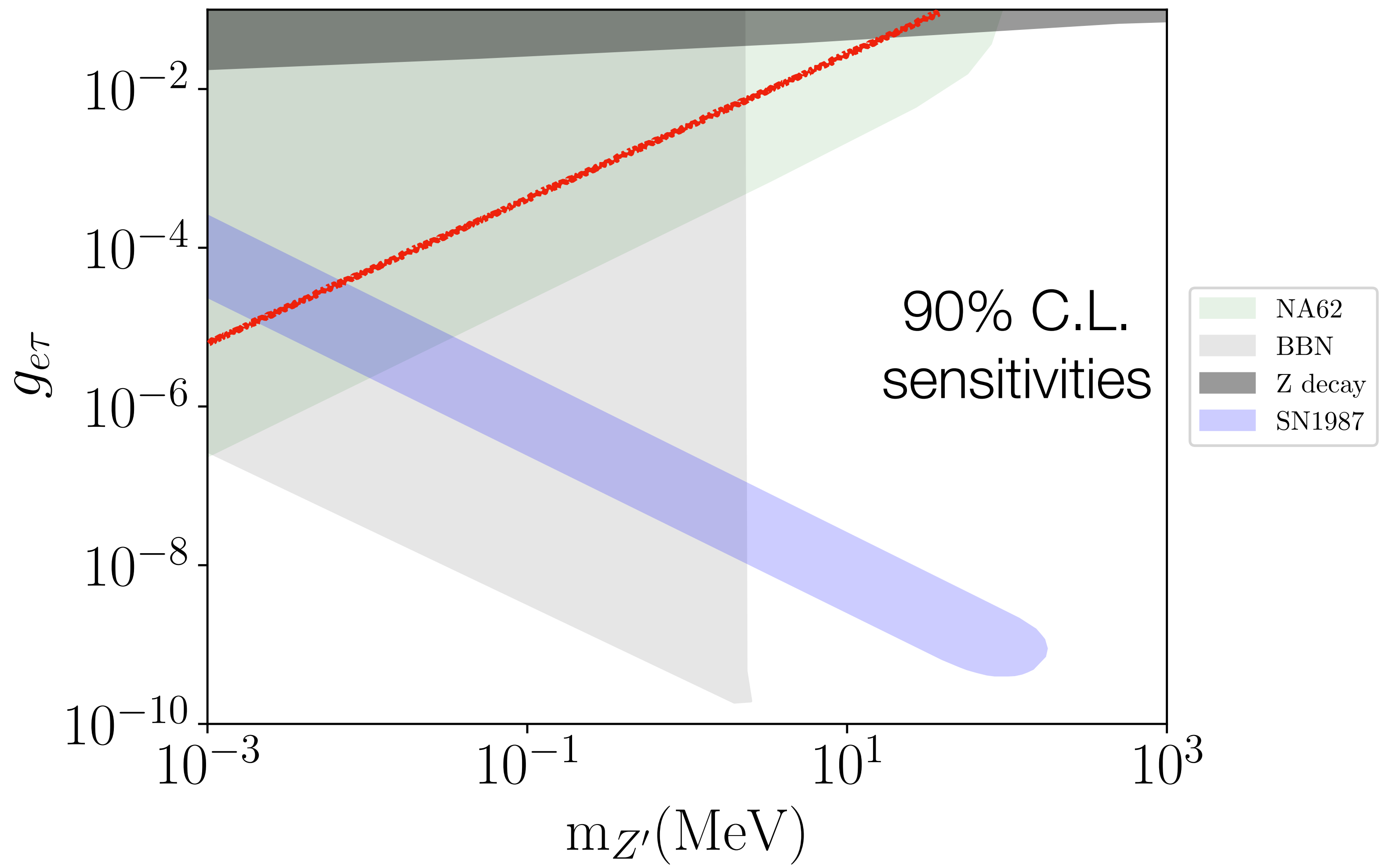
- Phase shift of the power spectrum by late ν free streaming

  → 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.

Sensitivities for ν_τ SNI



CMB bound?

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

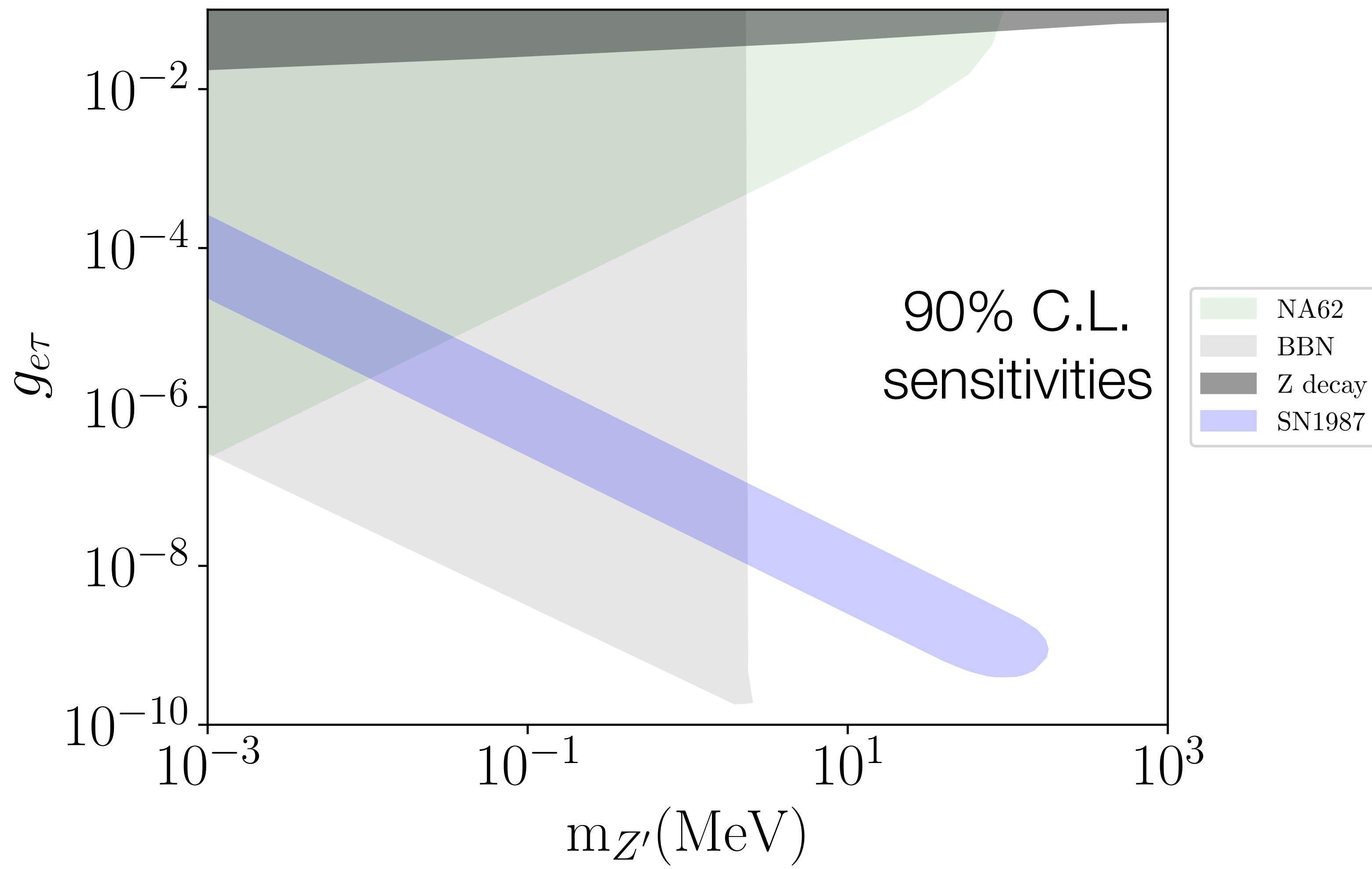
  → much weaker than NA62 for the flavor-universal scenario $g_{ee}=g_{\mu\mu}=g_{\tau\tau}$

  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.

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

Sensitivities for ν_τ SNI

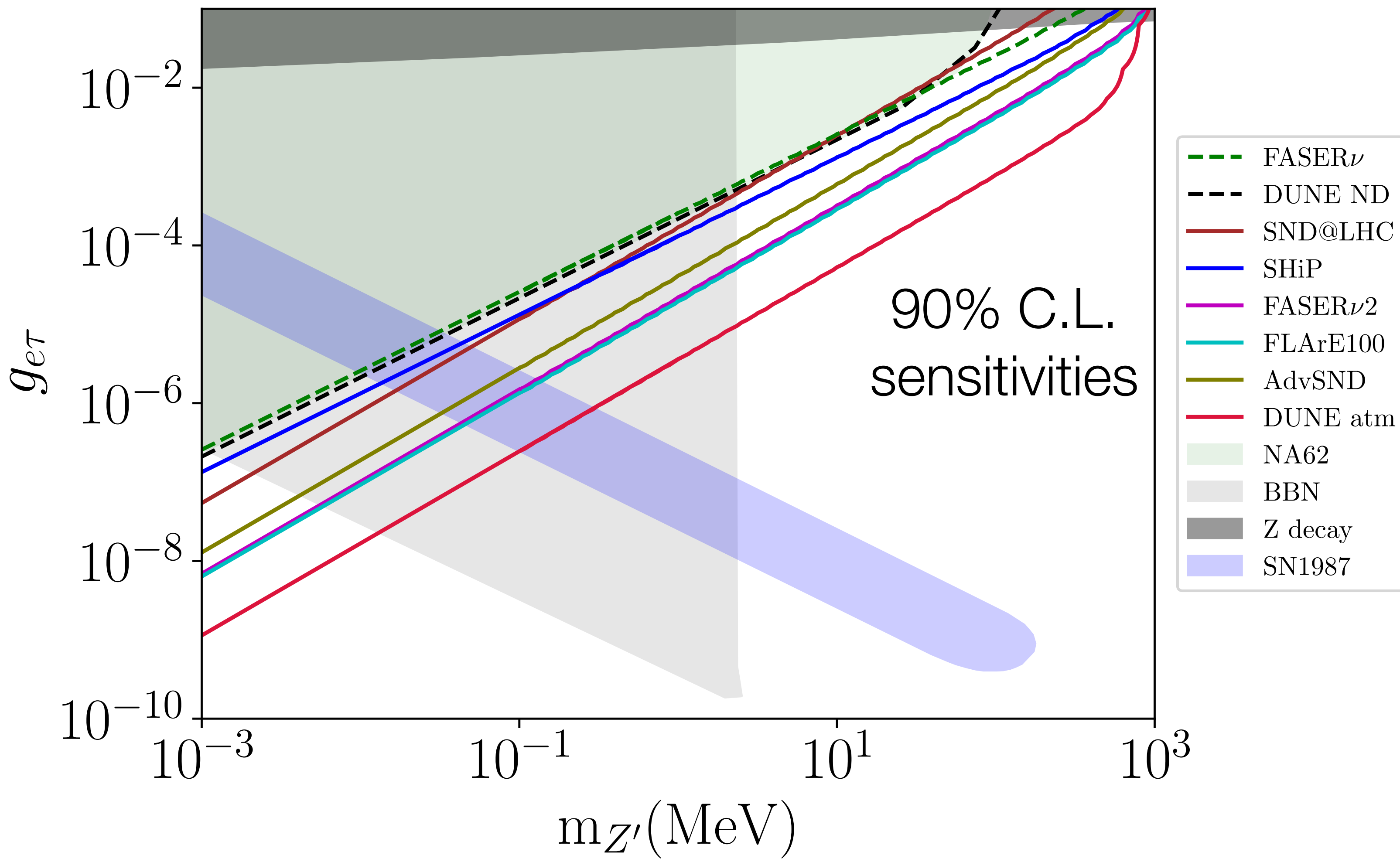


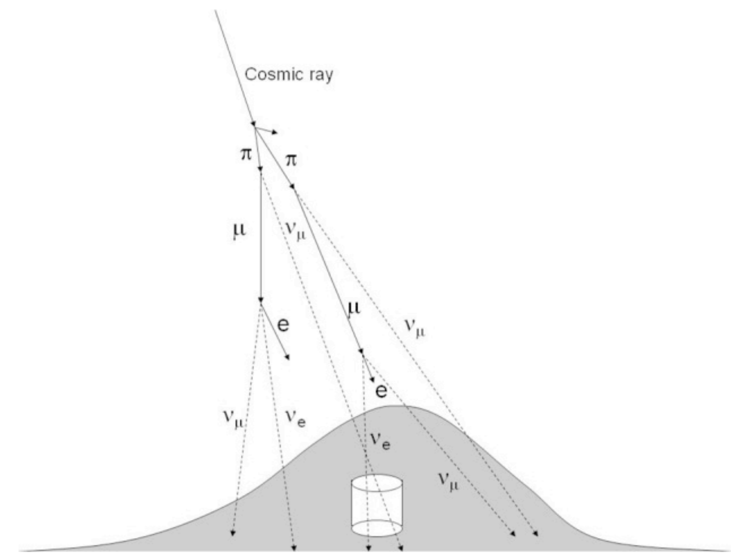
- Core-collapse supernova: SN1987A energy loss rate in blue shaded region (flavor universal & diagonal case)

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

- More general case: dedicated study needed.

Sensitivities for ν_τ SNI



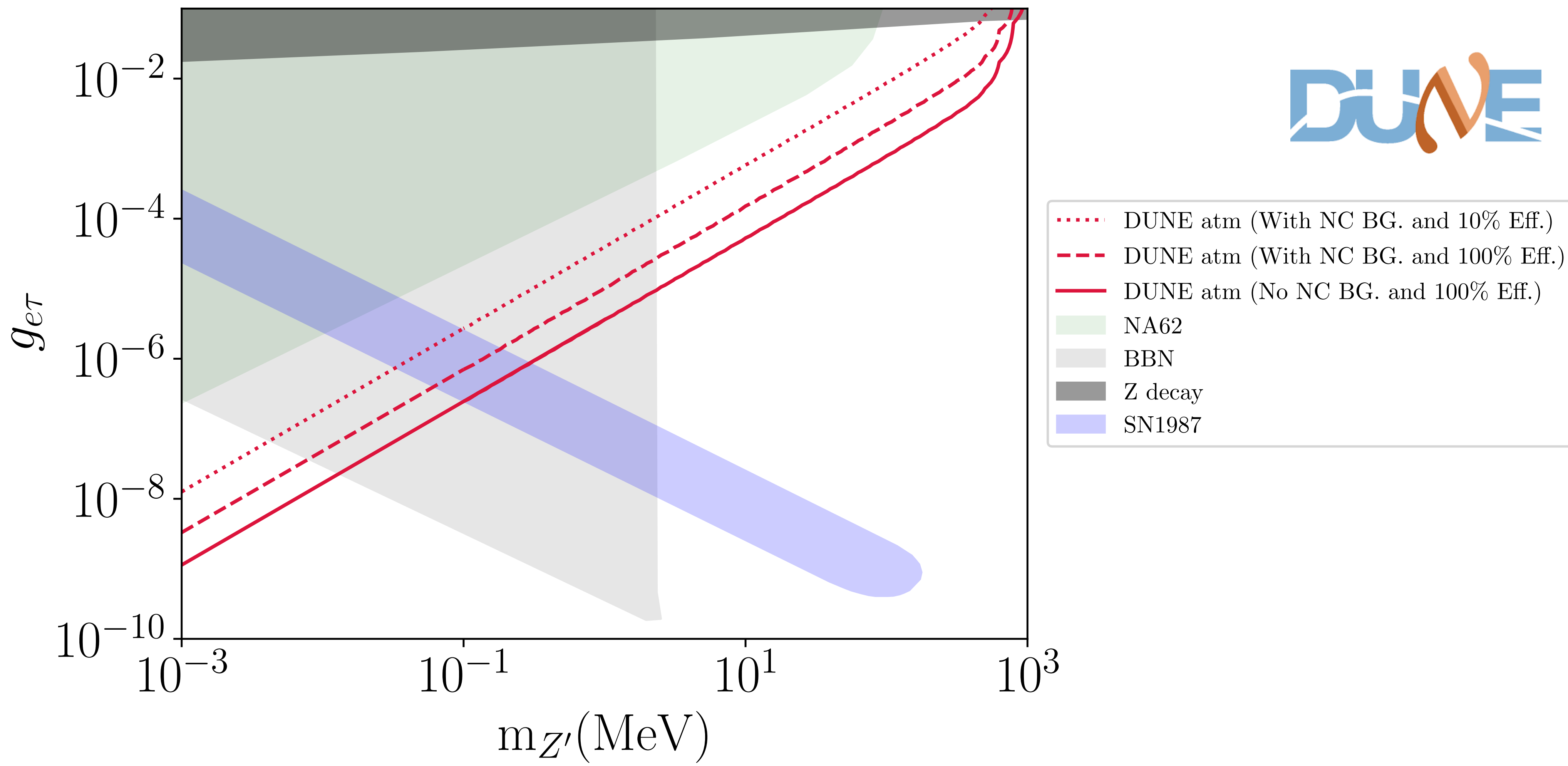


Robust w.r.t. the shape of flux uncertainty.

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

Machado, Schulz, Turner, PRD 2020

Sensitivities for ν_τ SNI

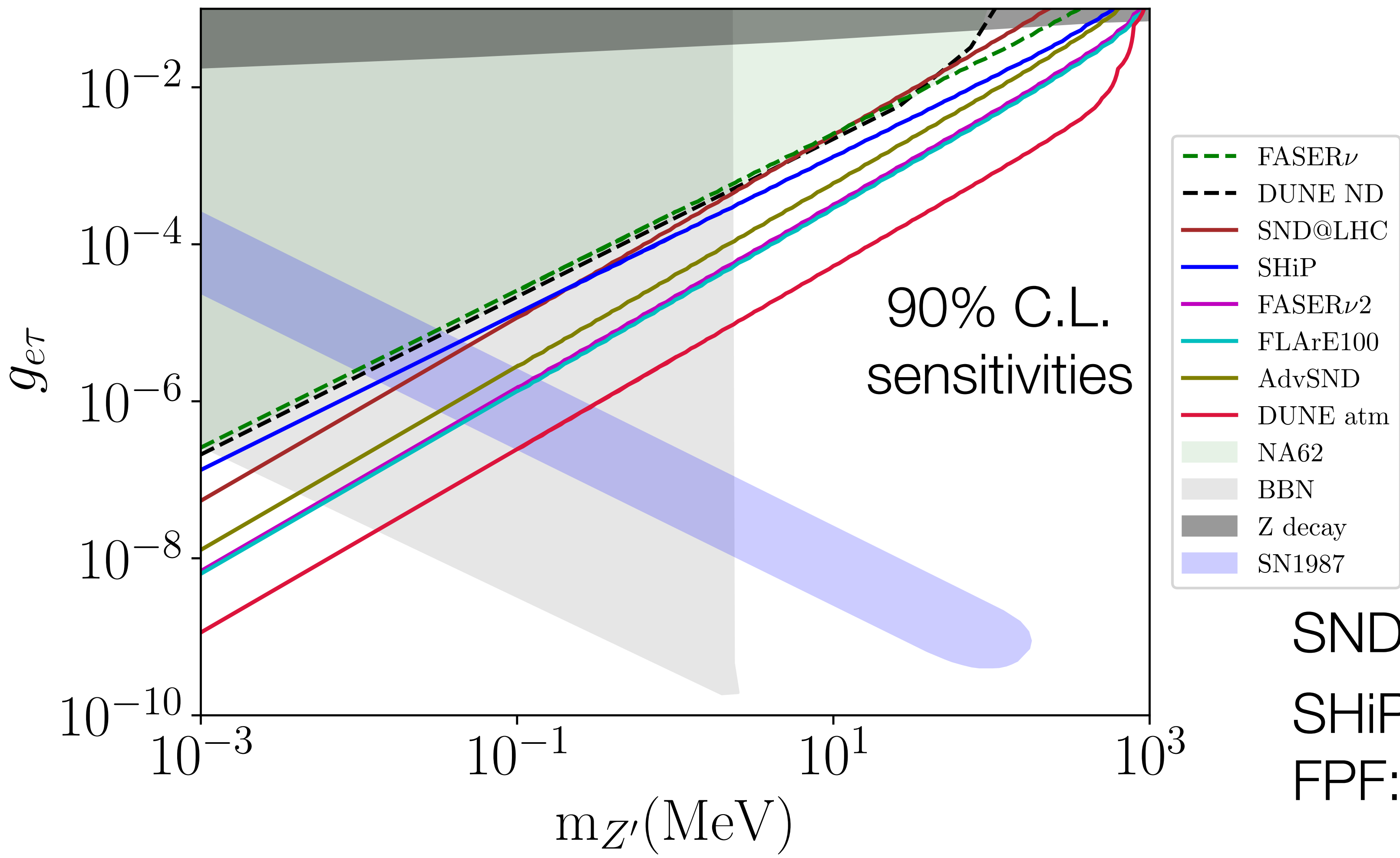


- Increasing detection efficiencies and subtracting background is important.

- Solid: No background with 100% efficiency
  Dashed: Neutral Current background (70 for 10 years)
  Dotted: Neutral Current background & 10% efficiency

Aurisano, NuTau2021 talk

Sensitivities for ν_τ SNI



100% efficiency for ν_τ event reconstruction (ambitious)

SND@LHC/FASERν: 150 fb^{-1}

SHiP: 2×10^{20} POT (5 yrs)

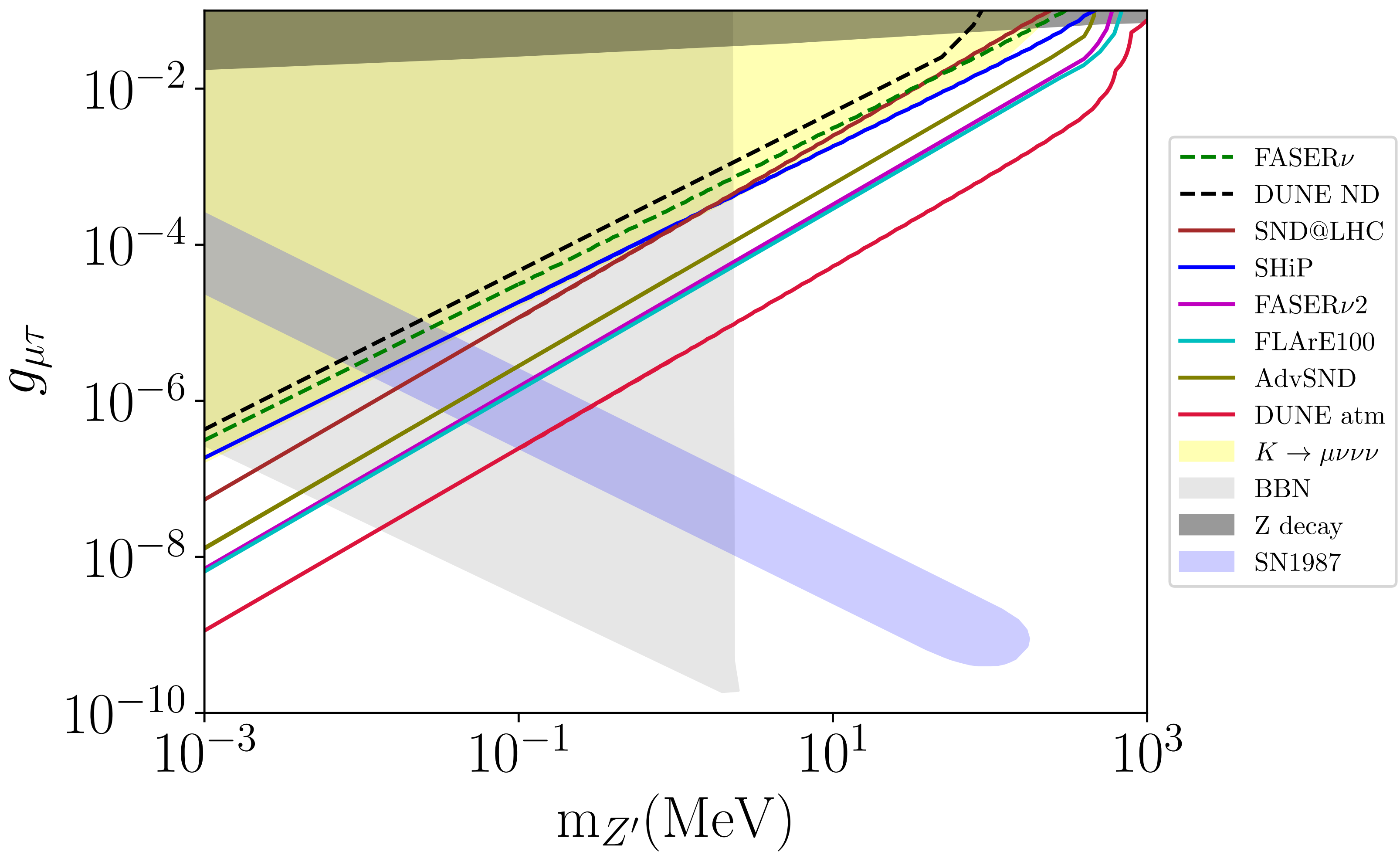
FPF: 3 ab^{-1}

- FLArE100 (cyan, 100 ton) and FASERν2 (purple, 20 ton) can be most sensitive among the accelerator based experiments. 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

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



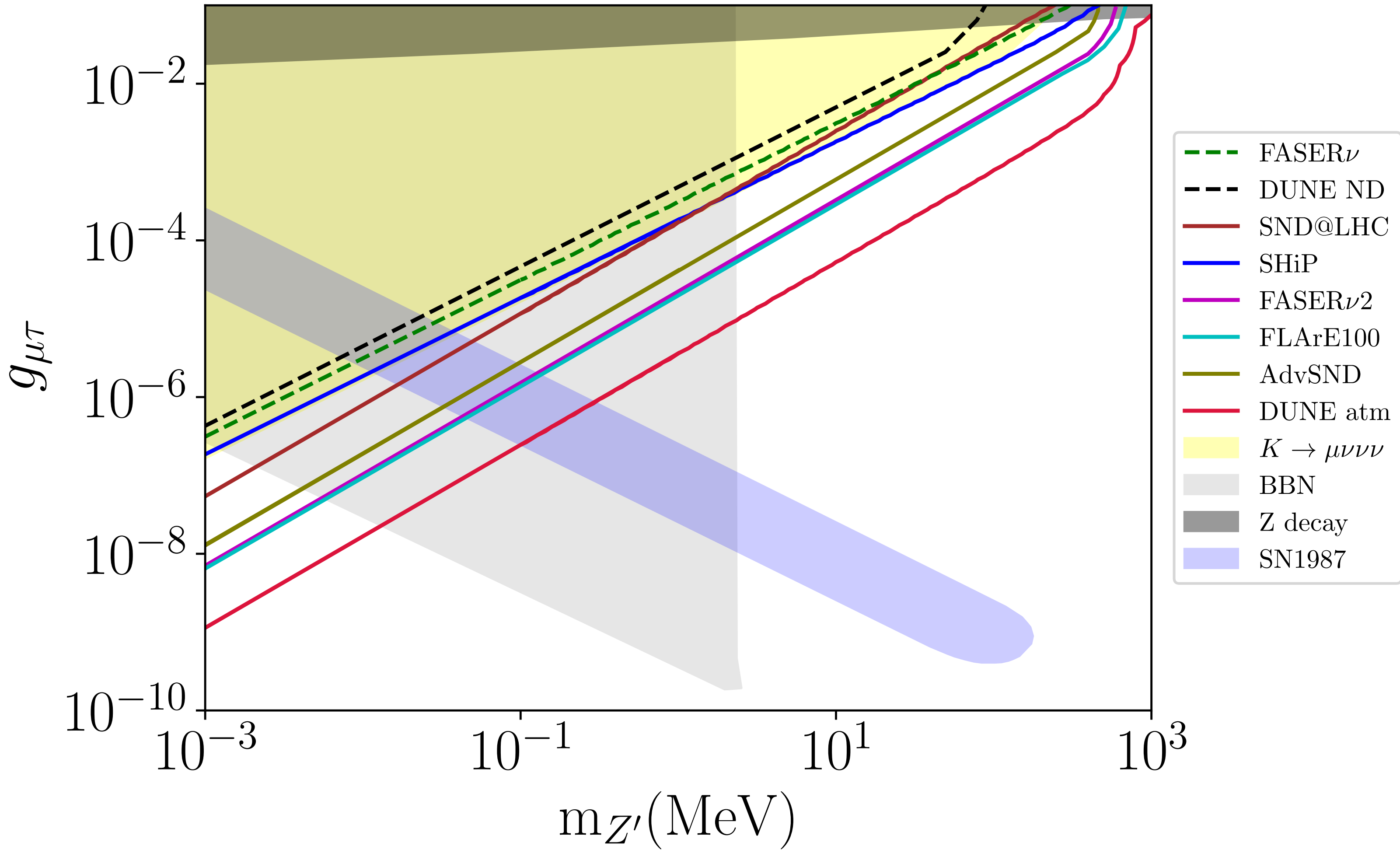
- DUNE far detector (400 kt·yr) is still most sensitive for $m_{Z'} \gtrsim 1$ MeV, $m_{Z'} \lesssim 60$ keV.

- 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



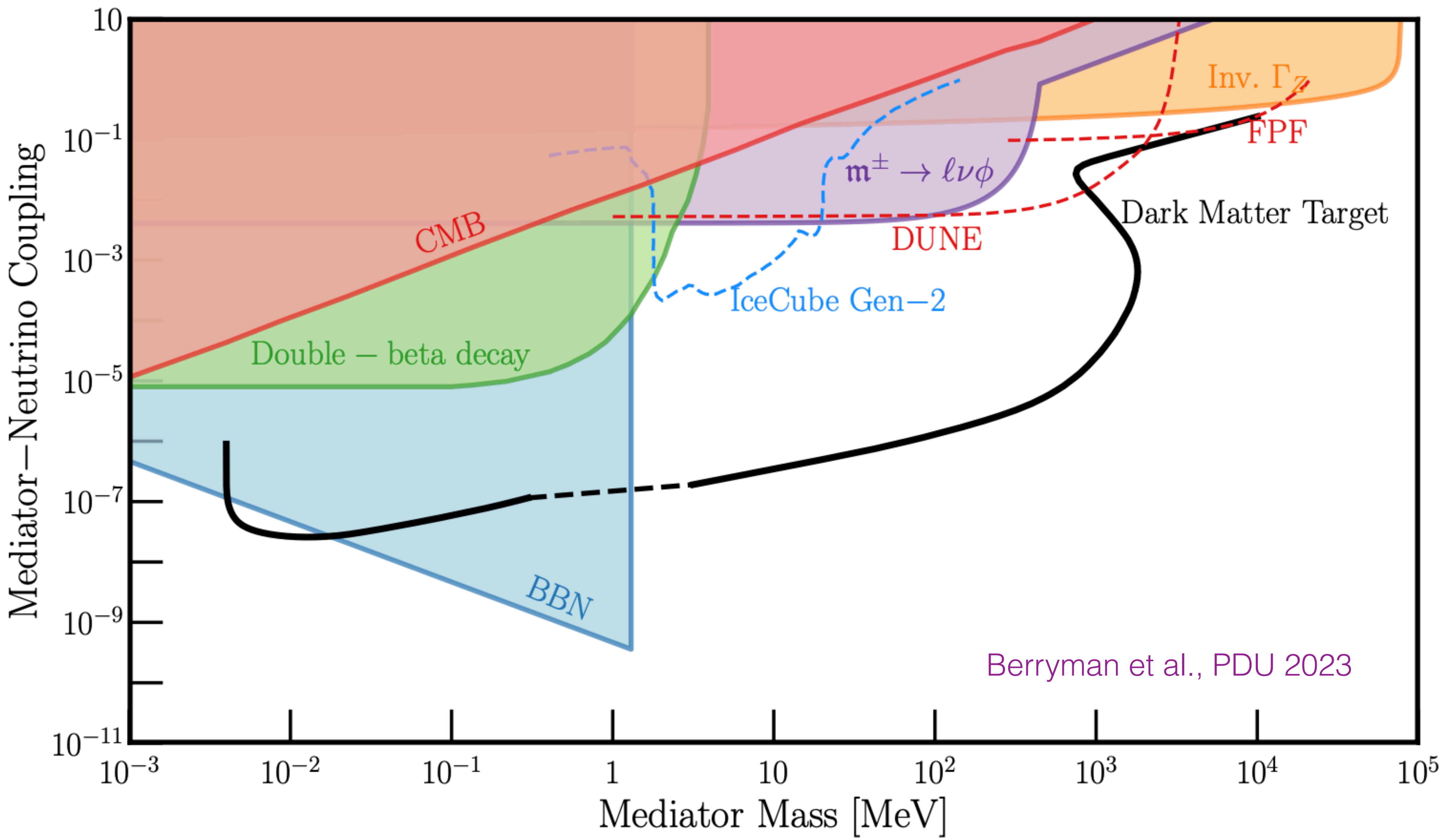
- Sensitivities are comparable or slightly weaker (SHiP) due to the phase space.

- 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).

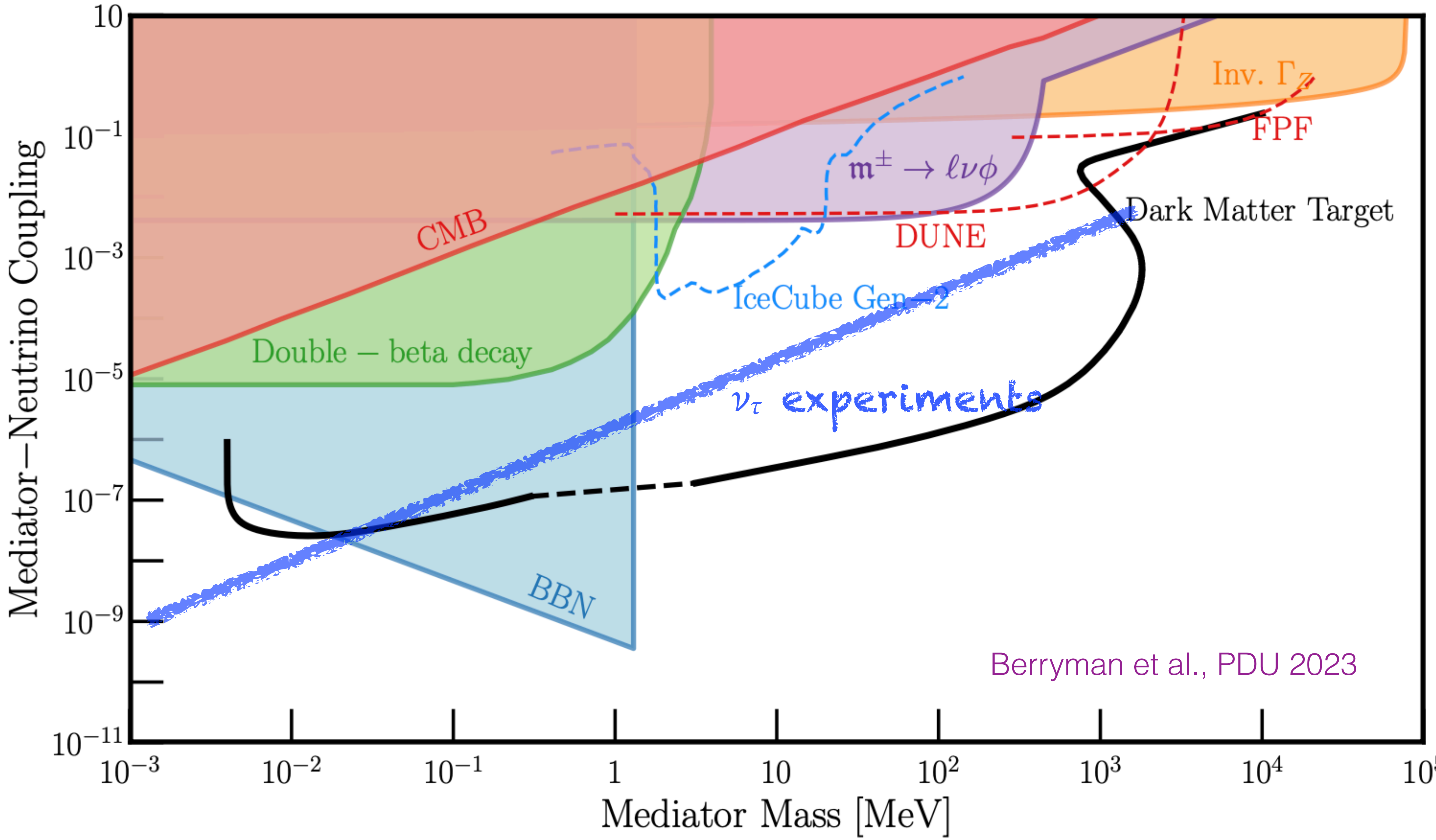
$$\mathrm{BR}(K^+ \to \mu^+\nu\nu\nu) < 2.4 \times 10^{-6}$$

Sensitivities for ν_τ SNI



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.

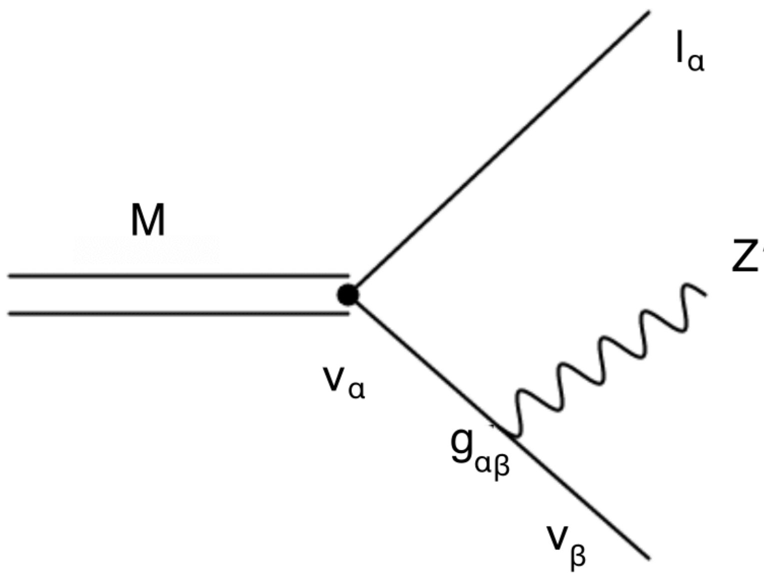
- For example, we can probe flavor non-universal (ν_τ-philic) SNI preferred by cosmo/astro/lab.: we use SND@LHC, FASERν, AdvSND, SHiP, FLArE100, FASERν2, and DUNE

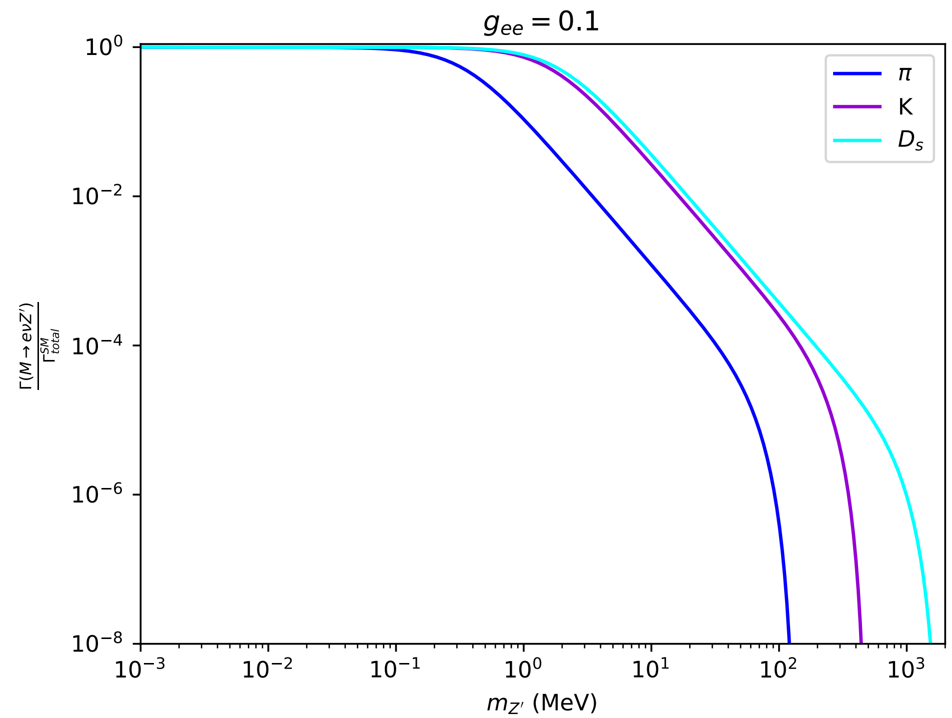
- Atmospheric data at DUNE far detector shows the best sensitivities due to the unexpected downward-going ν_τ appearance with small backgrounds: stronger than cosmo for $m_{Z'} \gtrsim 1$ MeV, $m_{Z'} \lesssim 60$ keV.

- Tau identification and reconstruction efficiency are important.

Backup

Kinematic process on our focus: 3-body meson decay





- 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 $\lesssim 10^{-4}$.

Backup

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	40 kilo-tonnes	1.6×10^4	2.4×10^4	150

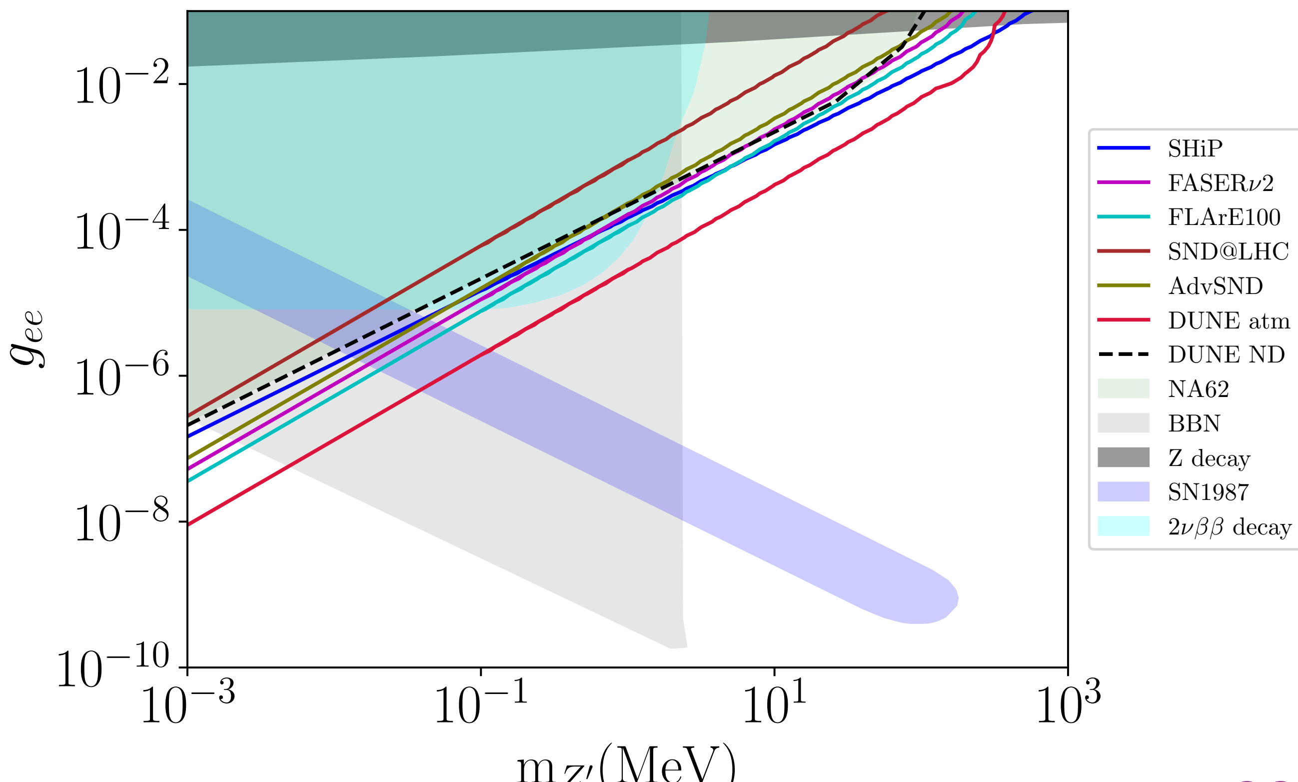
TABLE I. Estimated numbers of standard model neutrino events assuming a final integrated luminosity of 150 fb^{-1} for FASERν and SND@LHC, while 3000 fb^{-1} for FASERν2 and FLArE100. For SHiP, we assume 2×10^{20} POT in five years. We assume a data-taking period of 10 years for DUNE atmospheric neutrinos.

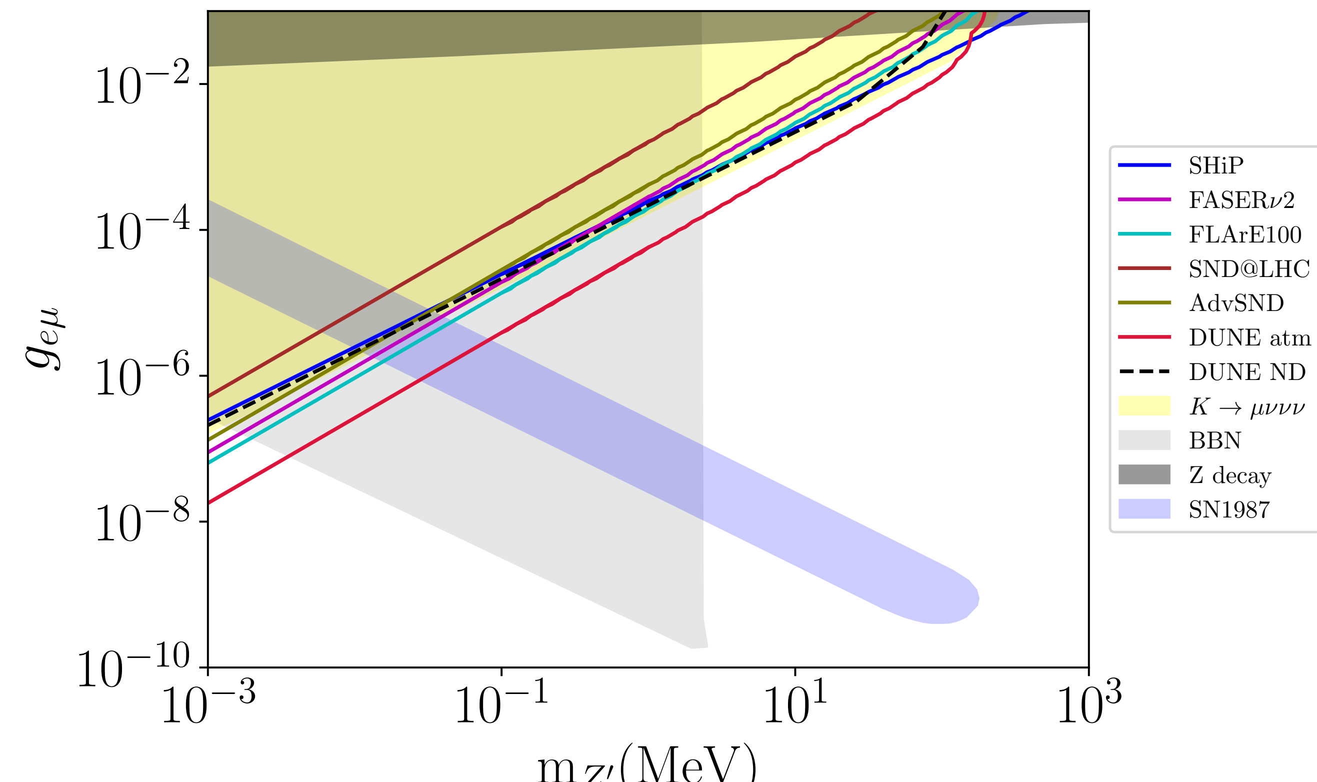
Experimental details: Kling, Nevay, PRD 2021 & FPF SNOWMASS 2203.05090

- 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 $\nu_\mu \rightarrow \nu_\tau$

Backup

Comparison with the other flavor couplings



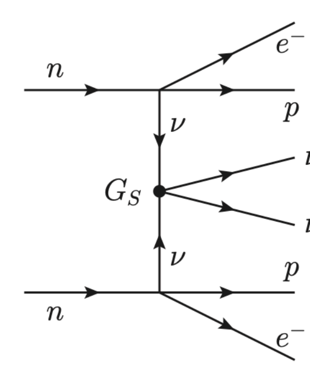


Bakhti, Rajaee, **SS**, arXiv:2311.14945

- 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