PPC 2024, Hyderabad, India

Uncovering ν_τ - philic Secret Interactions in DUNE

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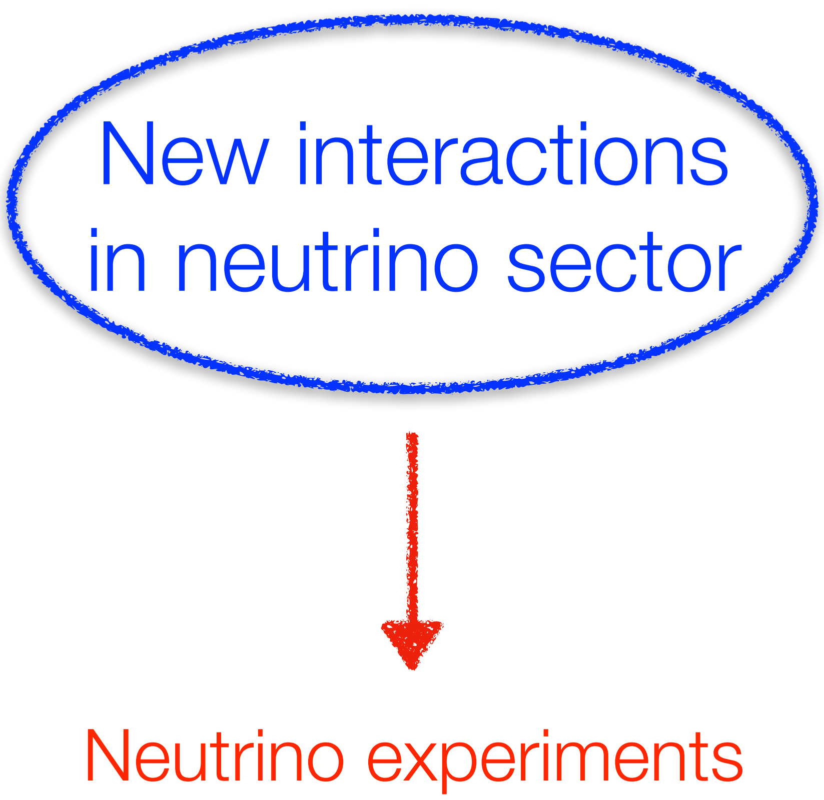
PRD 109, no. 9, 095043 (arXiv:2311.14945) with Pouya Bakhti, Meshkat Rajaee

New symmetry in the neutrino sector

Neutrino: a portal to New Physics BSM

- Neutrino oscillation itself is a crucial evidence of BSM.
- Not many things are known in the neutrino sector: mass, CPV, …
- Precise observation is experimentally challenging but a variety of program is on its way: new interactions/symmetries can be tested.

New symmetry in the neutrino sector



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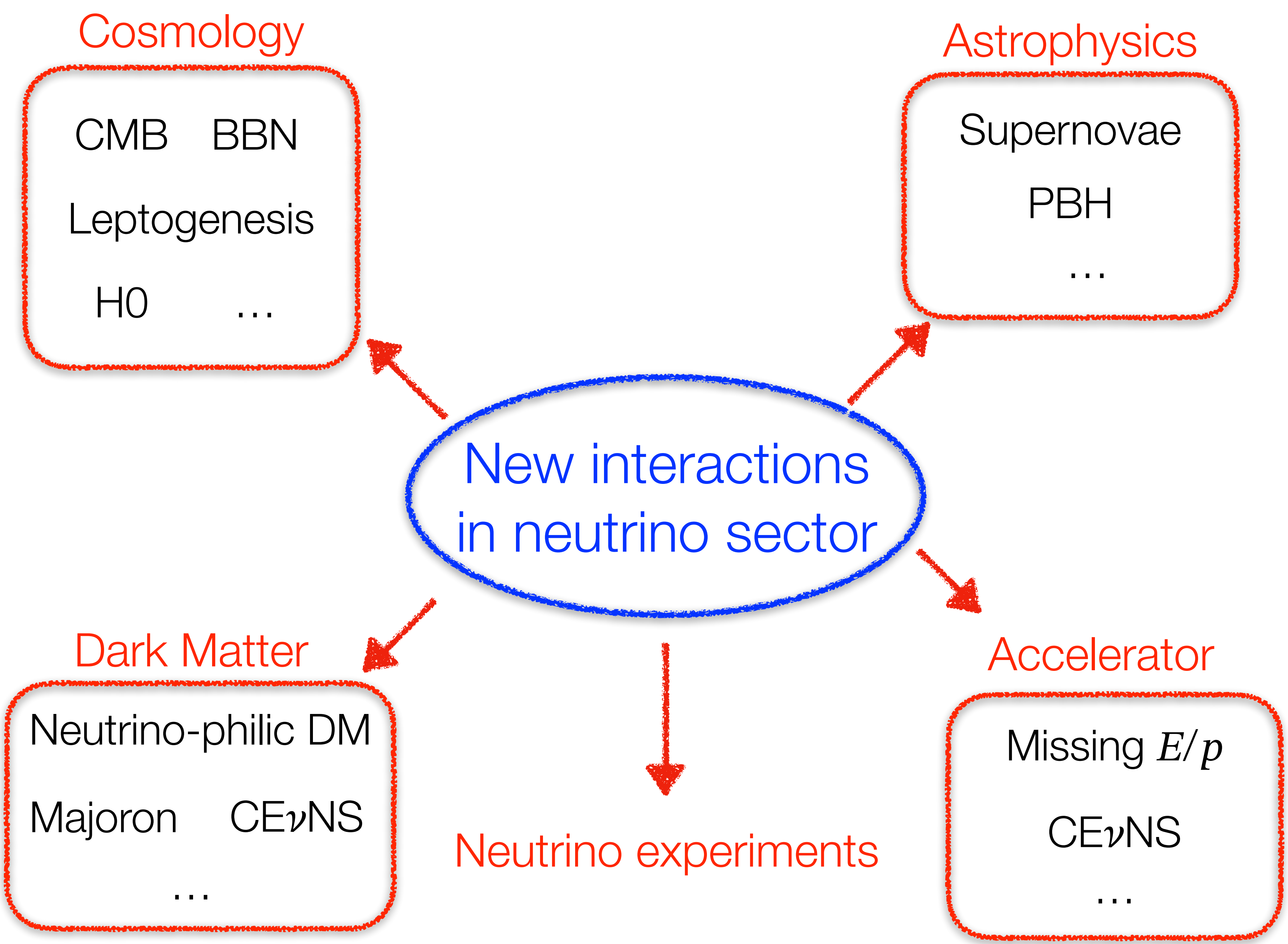

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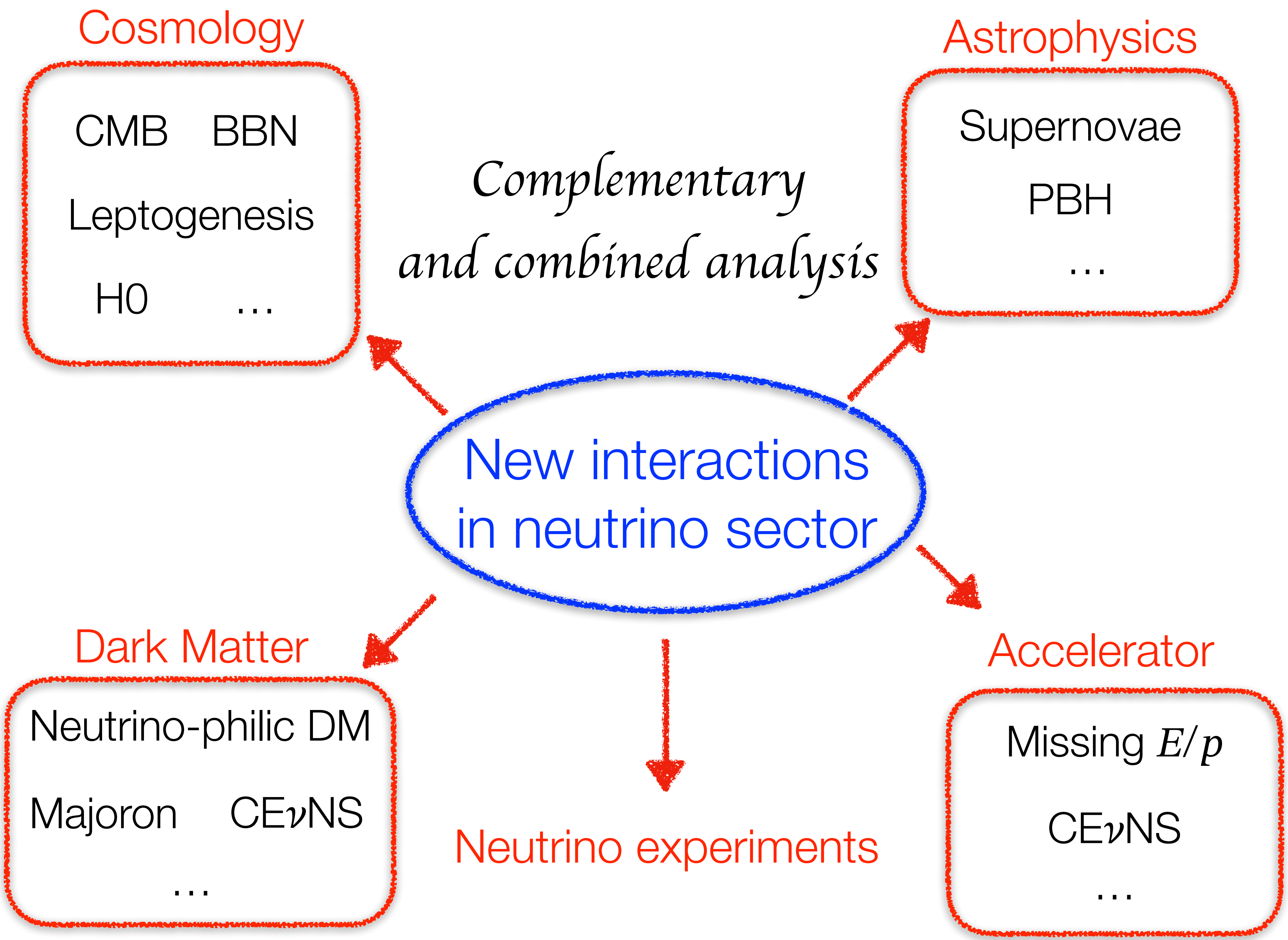

New symmetry in the neutrino sector

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

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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

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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, ..

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Probe flavor non-universal or off-diagonal SNI with ν_τ , $g_{\tau\alpha}$?

→ Tau neutrino experiments

Observations of ν_τ

Direct observation of ν_τ from $\nu_\tau N \to \tau X$ is challenging.

- Decay of τ is prompt and semi-visible making its identification and reconstruction hard.

- $E_{\text{th}} > 3$ GeV is high beyond the oscillation maxima.

- CC-σ is smaller than the values of other flavor neutrinos.

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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)

Observations of ν_τ

More data will be coming soon!

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

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

- Atmospheric experiments: IceCube, TAMBO, DUNE FD, …

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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

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

Phenomenological set-up: exclusive coupling

- A theoretical cook-up suppressing the $\ell^{\pm}$ interactions needed.

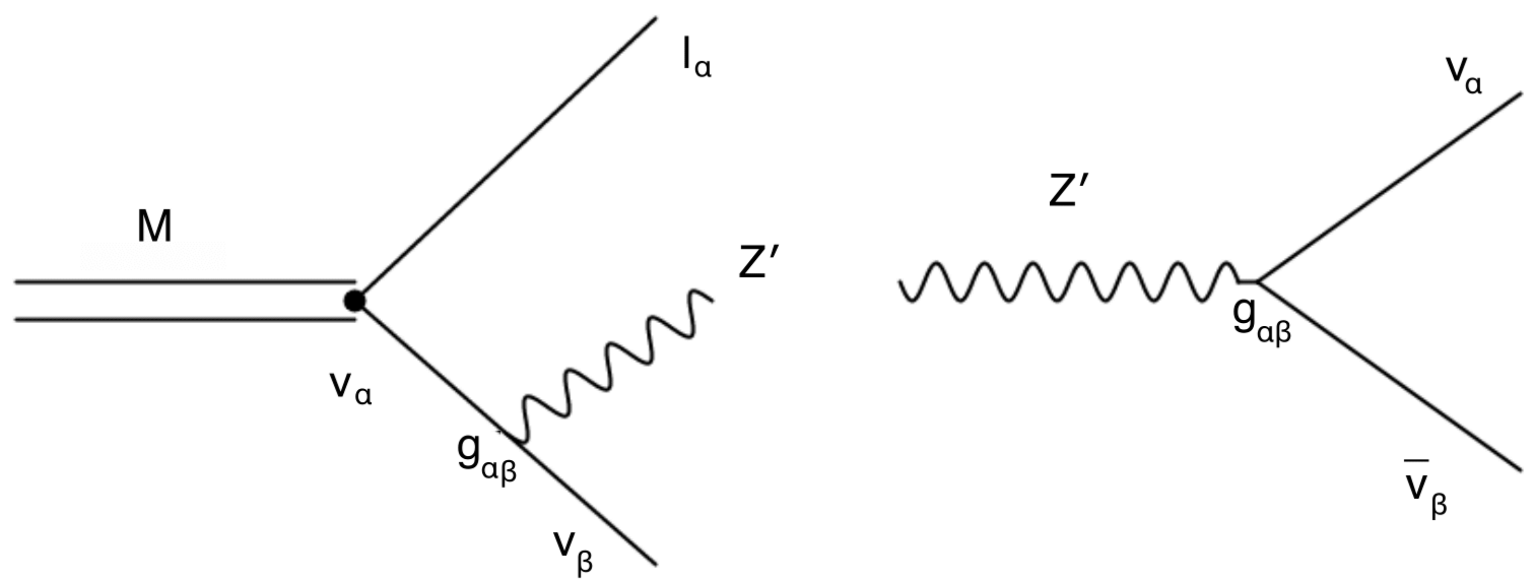
Farzan, Heeck, PRD 2016 Farzan, Tortolla, Front. Physics 2018

- Other spin mediator, e.g., Majoron, can be considered

Work in progress with Bakhti, Park, Rajaee

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

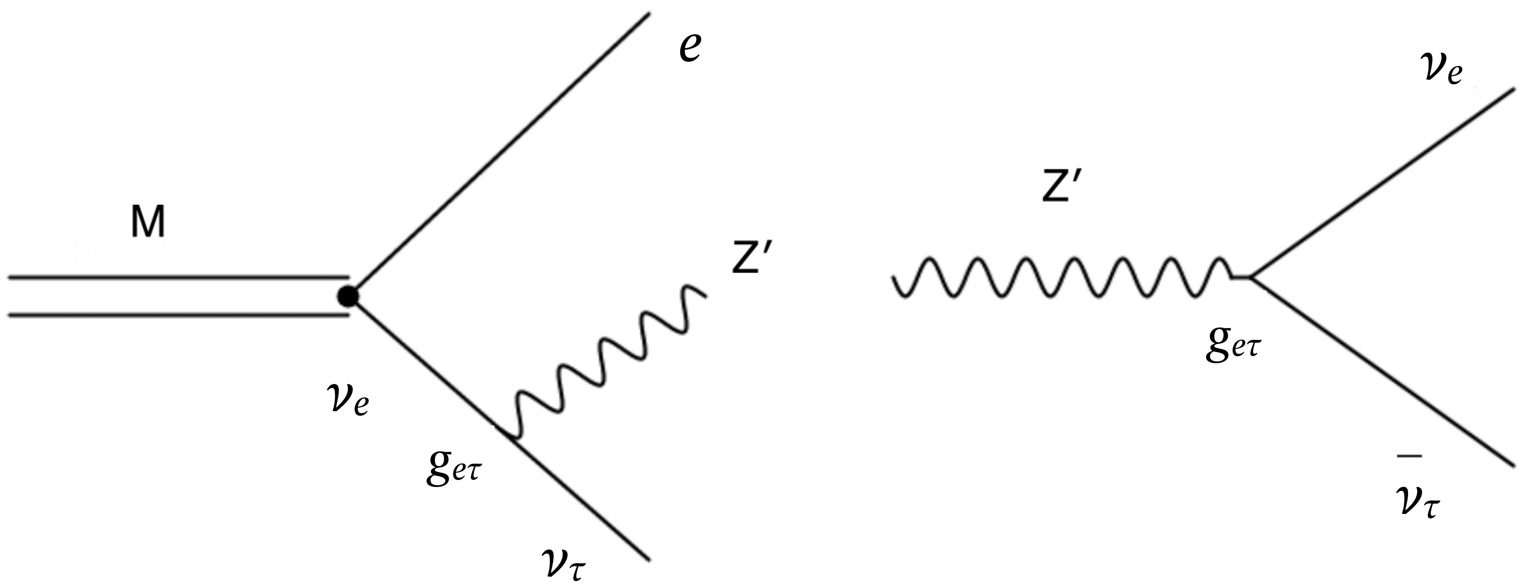
See also Dutta et al., PRL 2022

- 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



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

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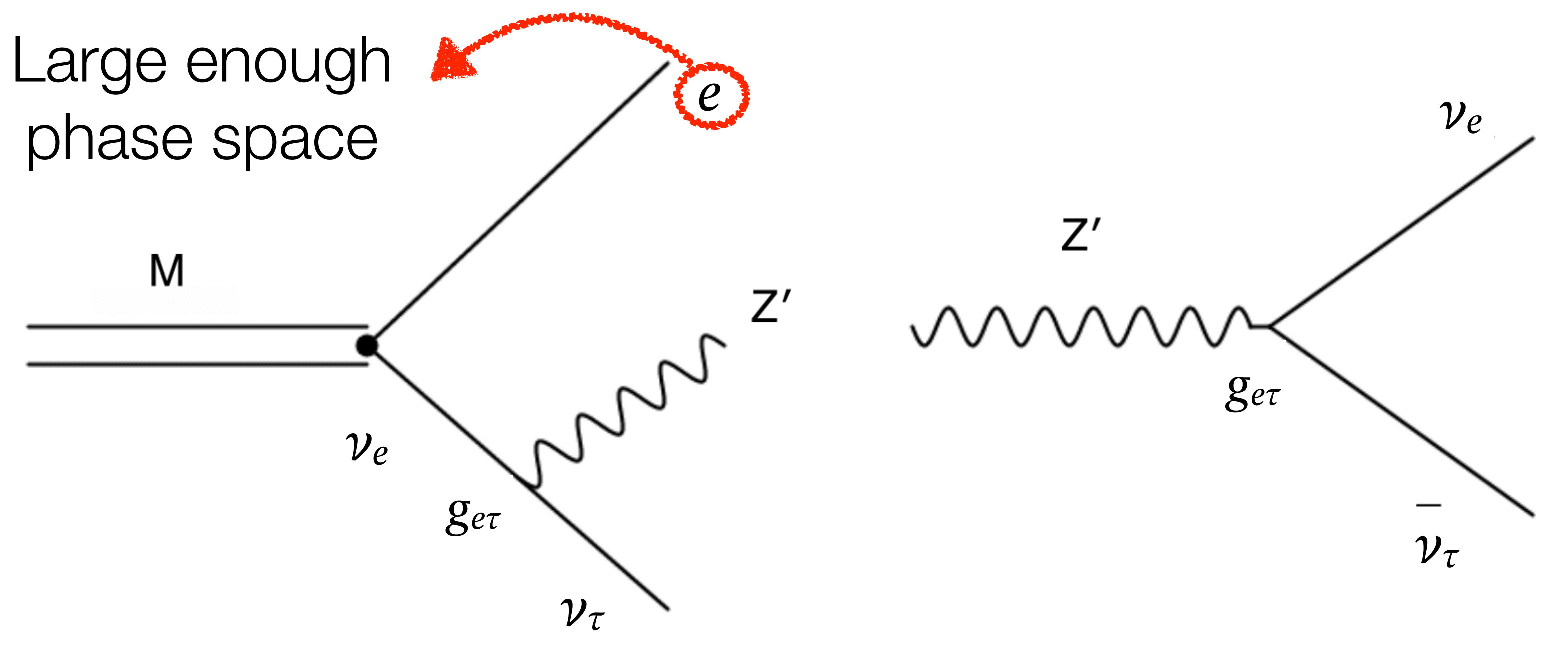

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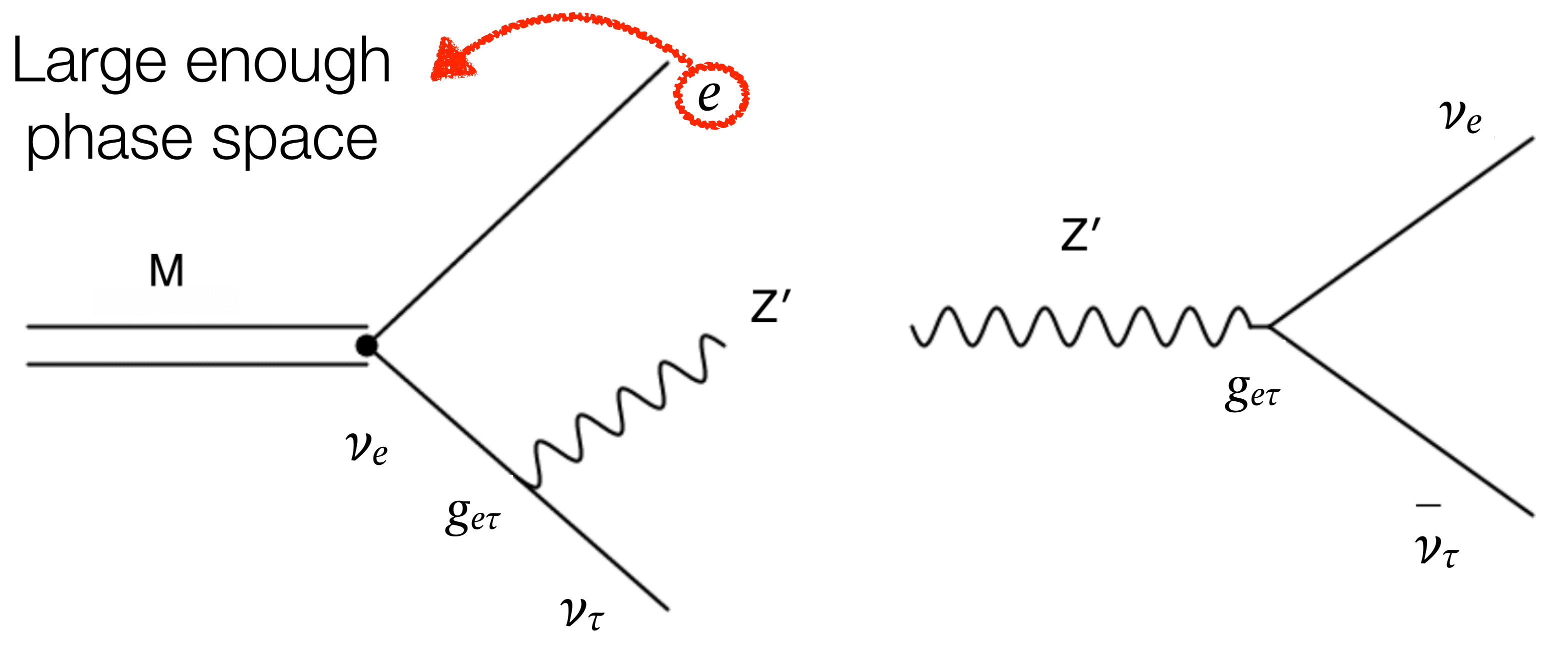

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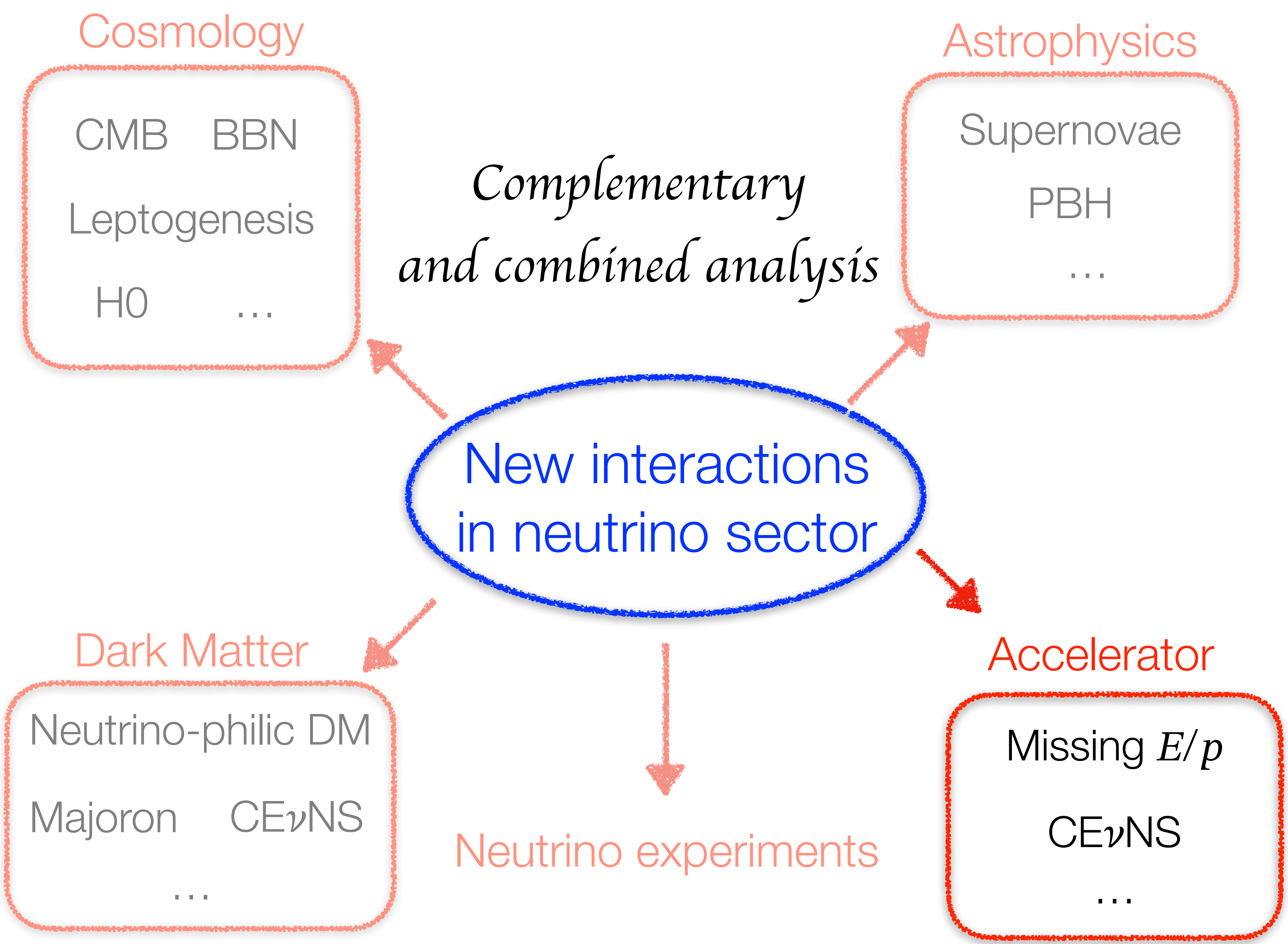
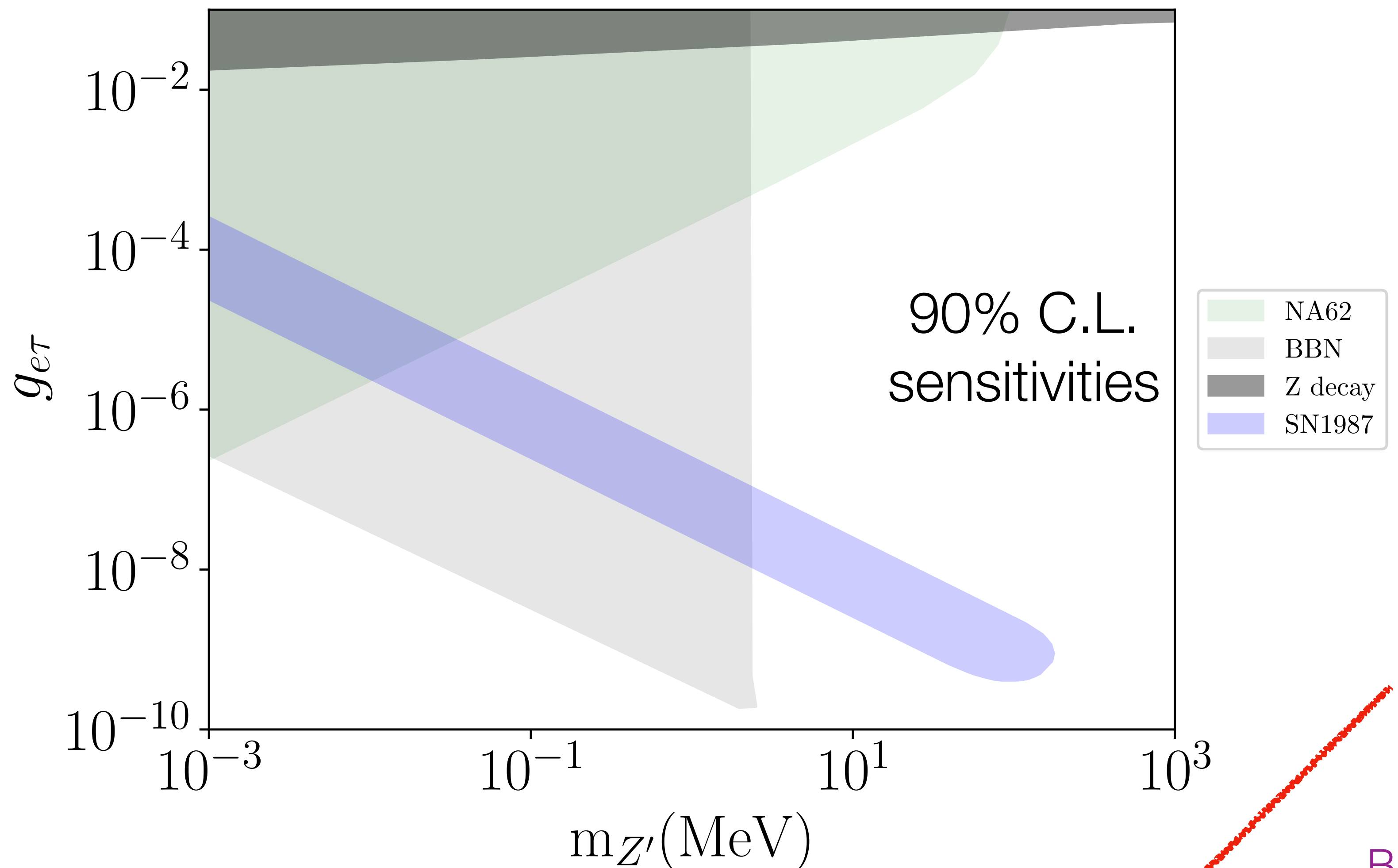
- For $g_{\tau\tau}$, sensitivities are much weaker (BR: 10^{-4} smaller for 1 MeV) due to phase space suppression.

Sensitivities for ν_τ SNI: accelerators



Constraints for ν_τ SNI: accelerators



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

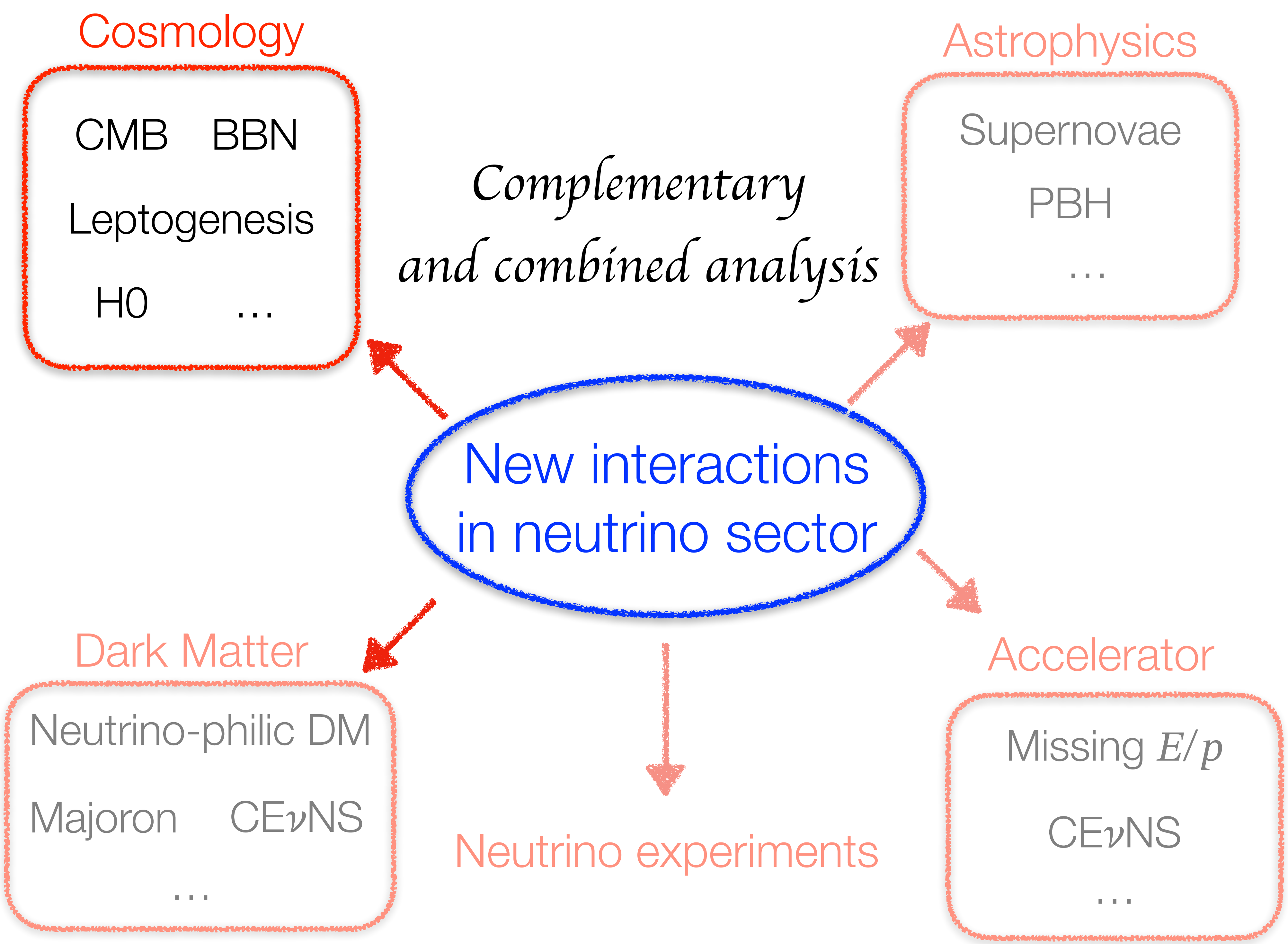
Bakhti, Farzan, PRD 2017

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

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

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

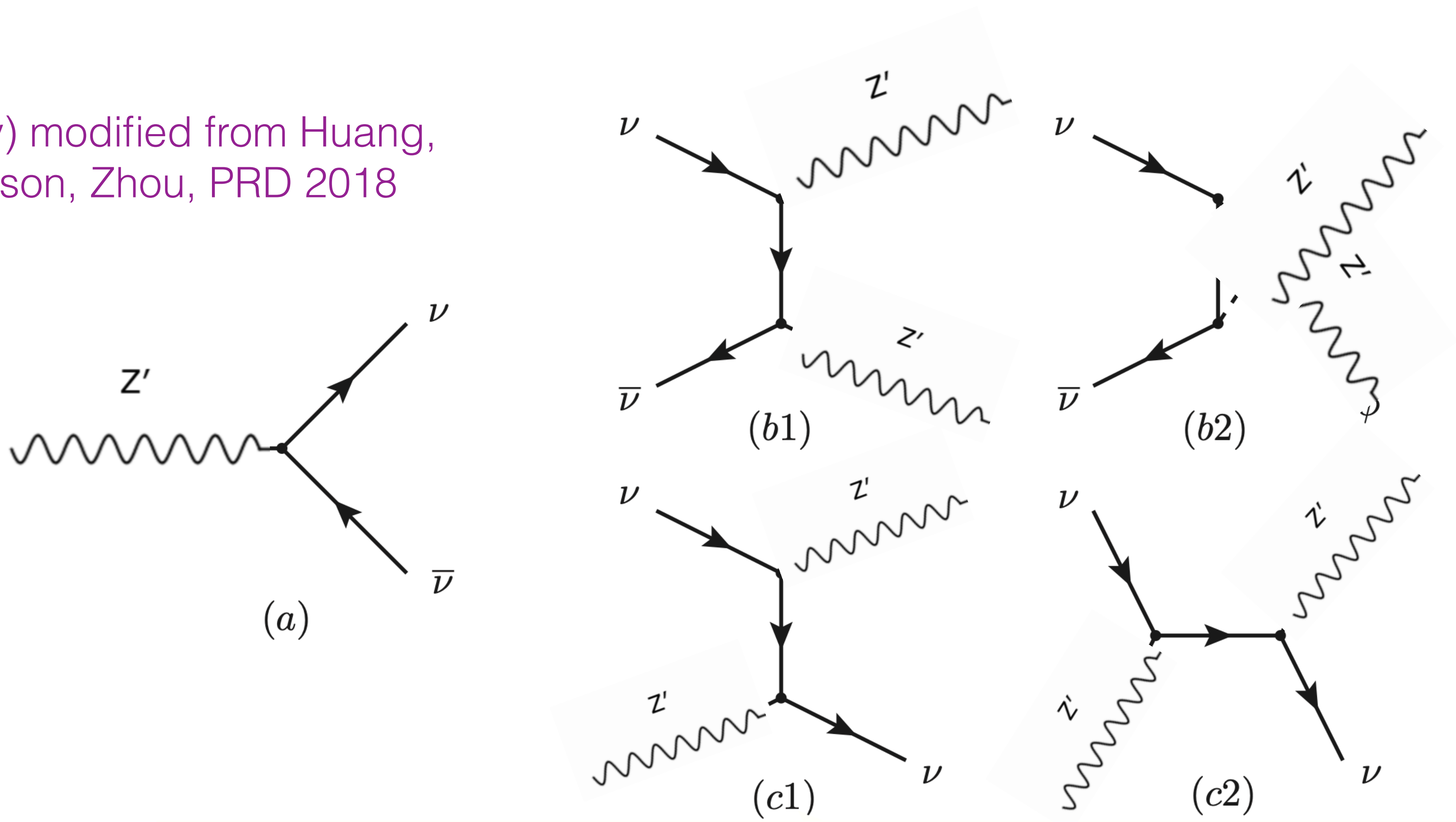
Constraints for ν_τ SNI: cosmology



Constraints for ν_τ SNI: cosmology

Main processes for thermal equilibrium & production of light mediators

(Poorly) modified from Huang, Ohlsson, Zhou, PRD 2018



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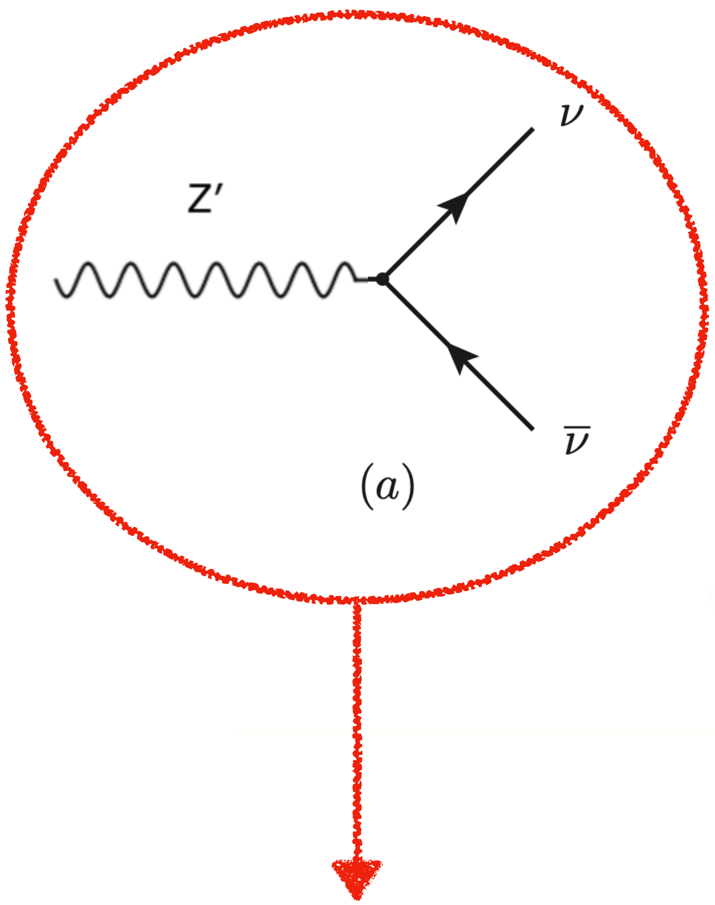

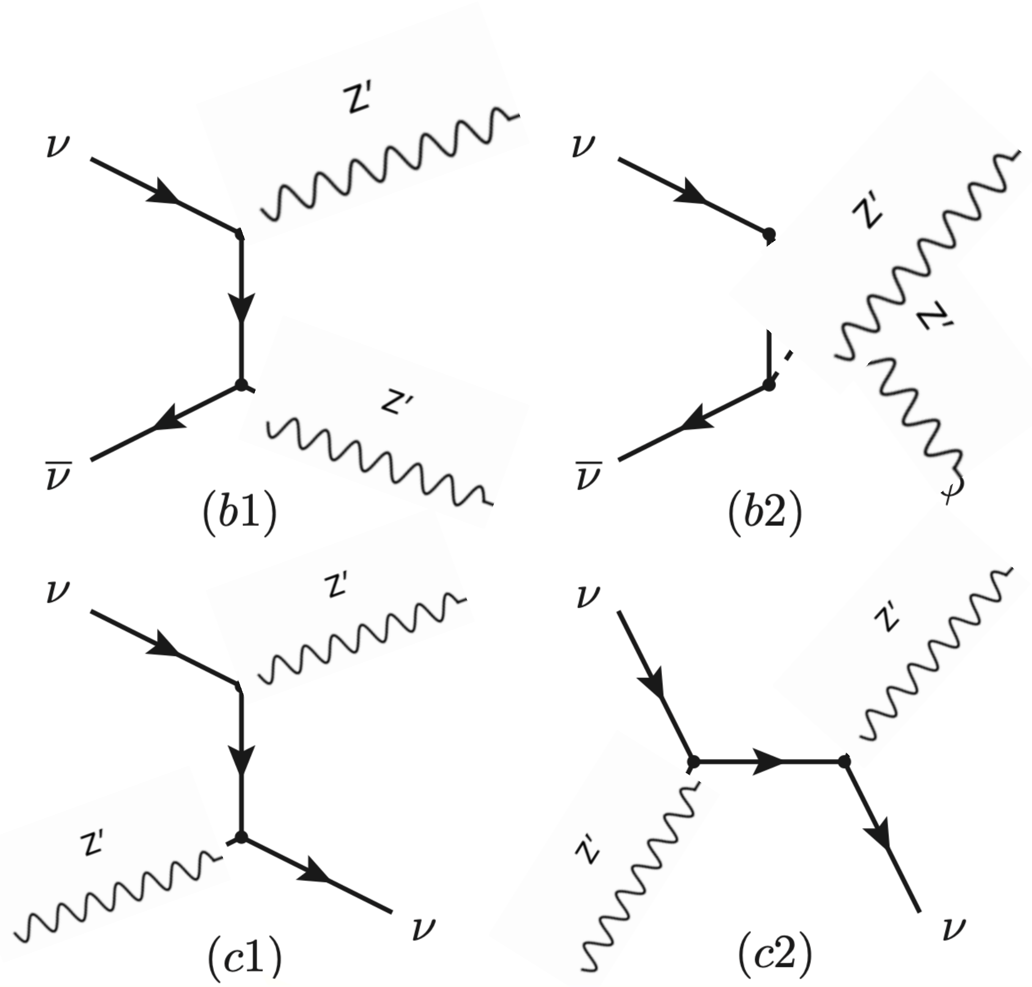

Efficient for heavy $M_{Z'} \gtrsim O$ (keV)

$$\Gamma(Z') \propto M_{Z'}^2$$

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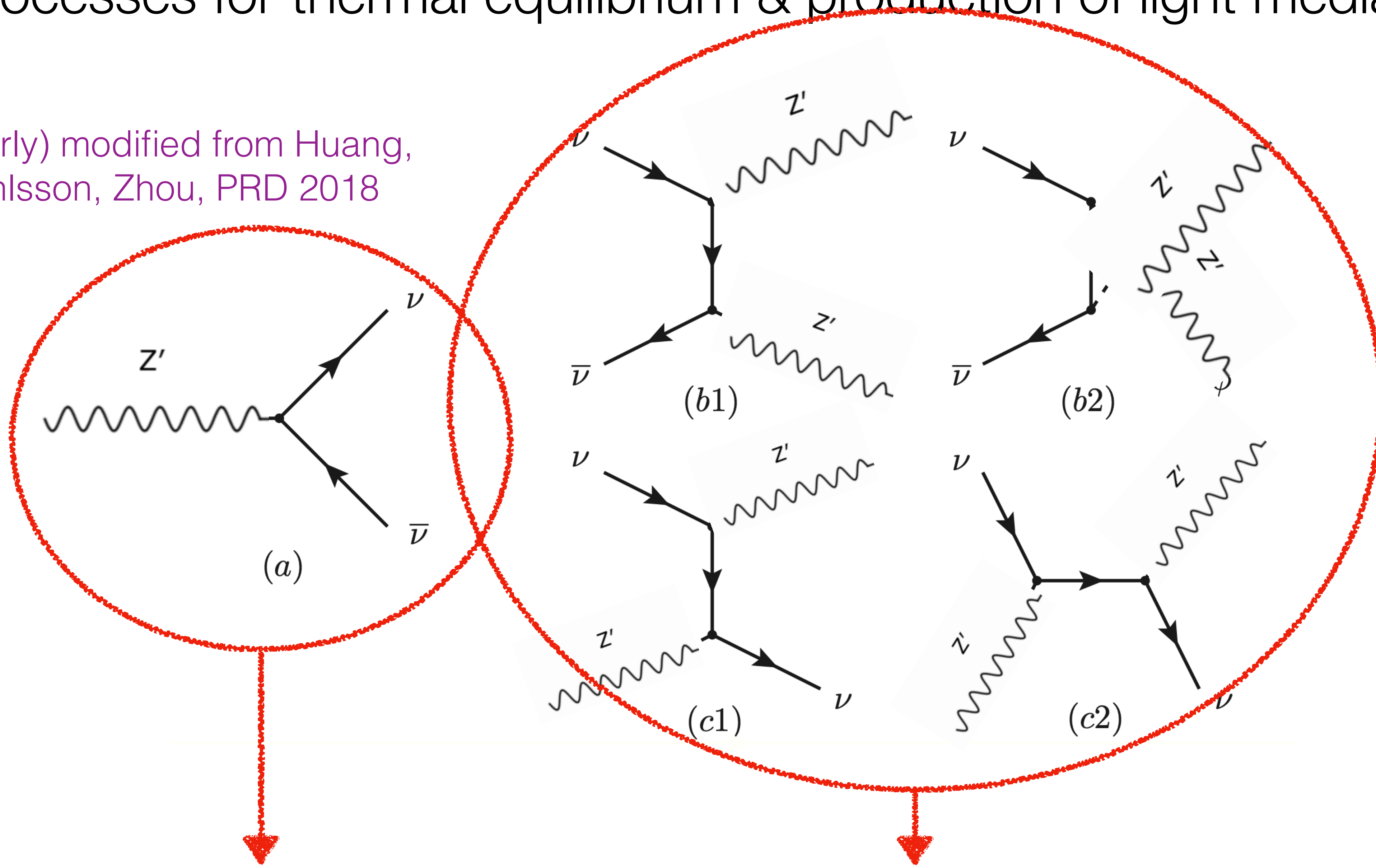

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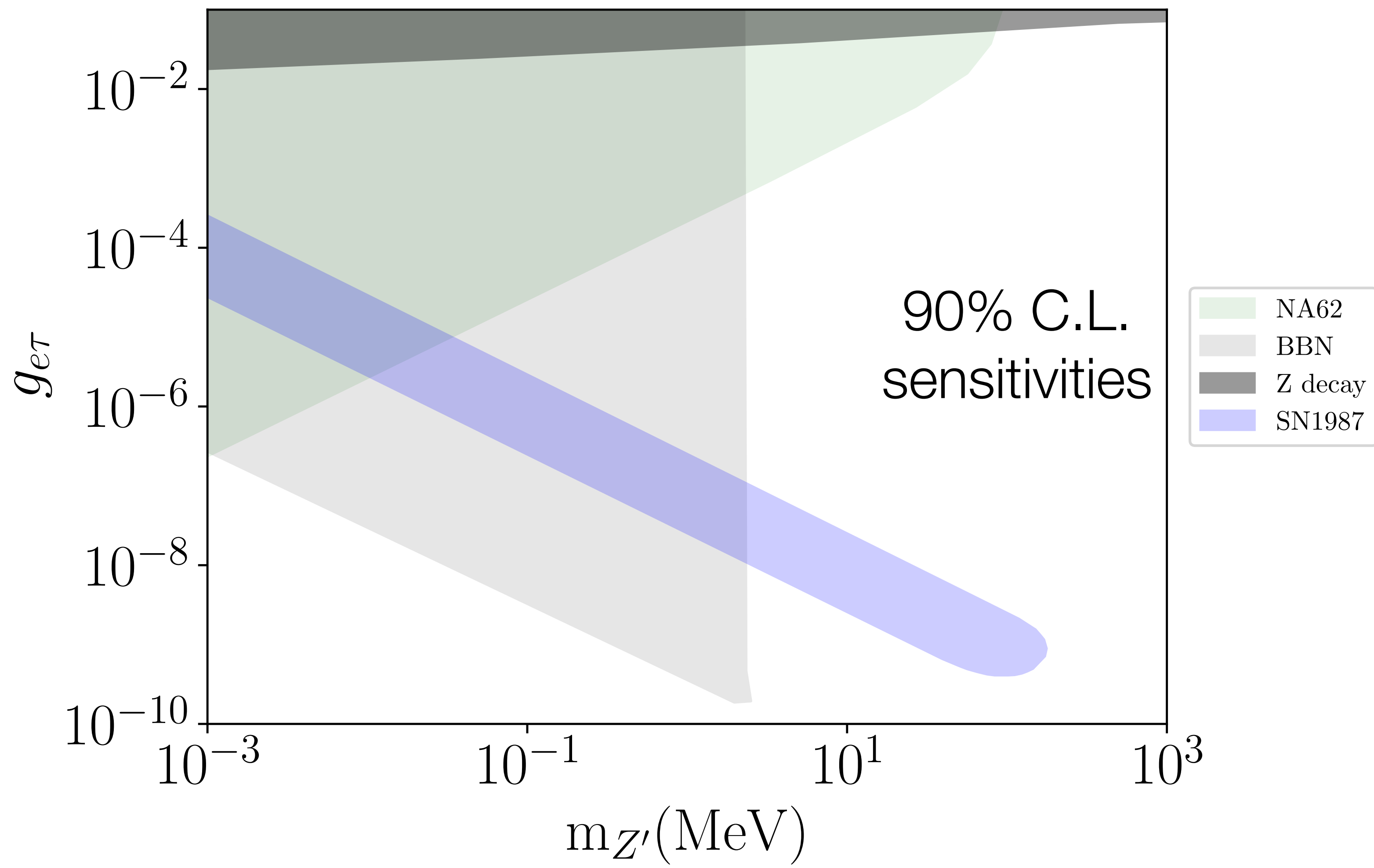
Efficient for light $M_{Z'} \lesssim O$ (keV)

$\Gamma(Z')$: $M_{Z'}$ dependence is sub-dominant for T ~ MeV

Constraints for ν_τ SNI: cosmology



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

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

Huang, Ohlsson, Zhou, PRD 2018

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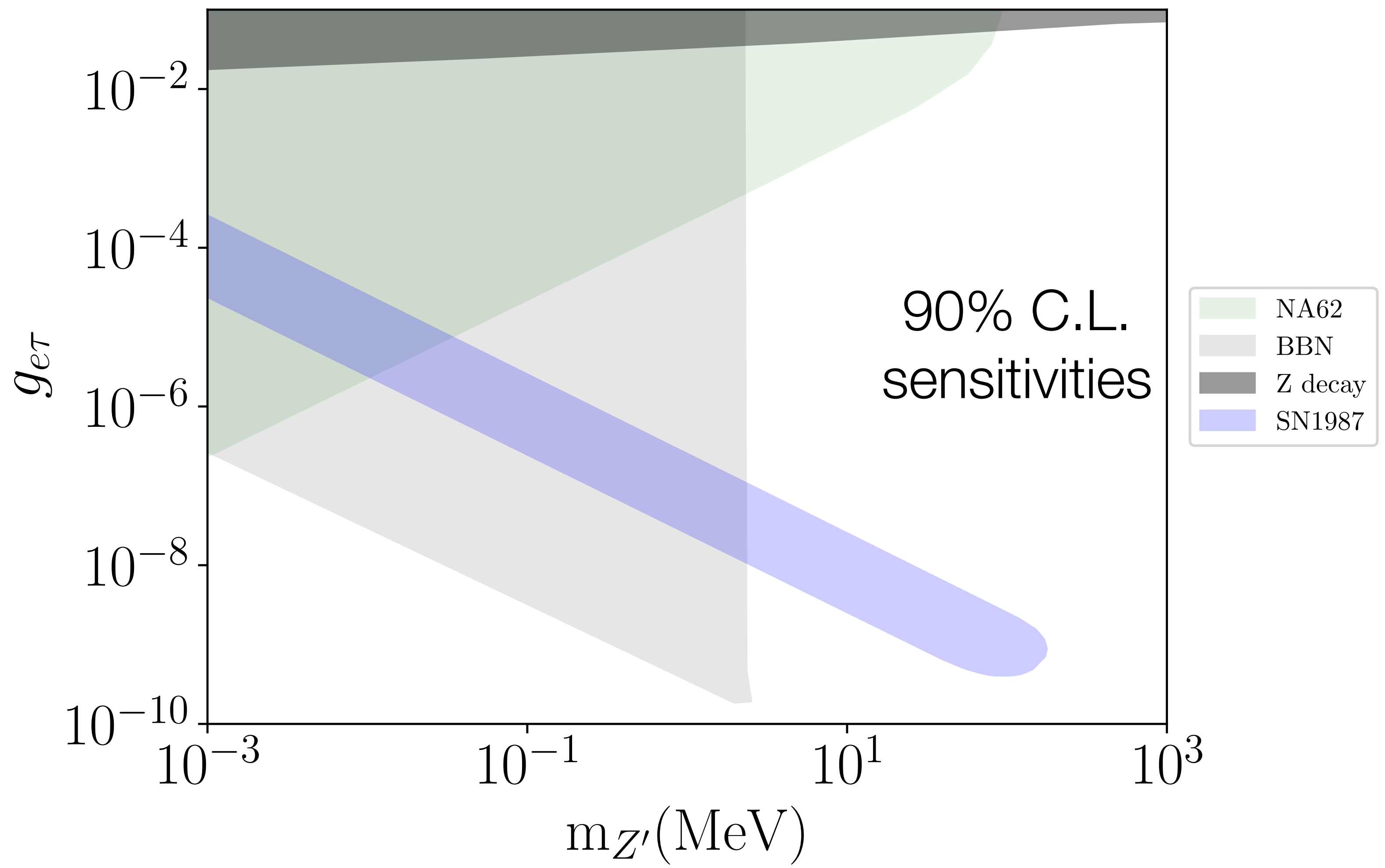

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Nominal bounds of the flavor universal & diagonal case applied.

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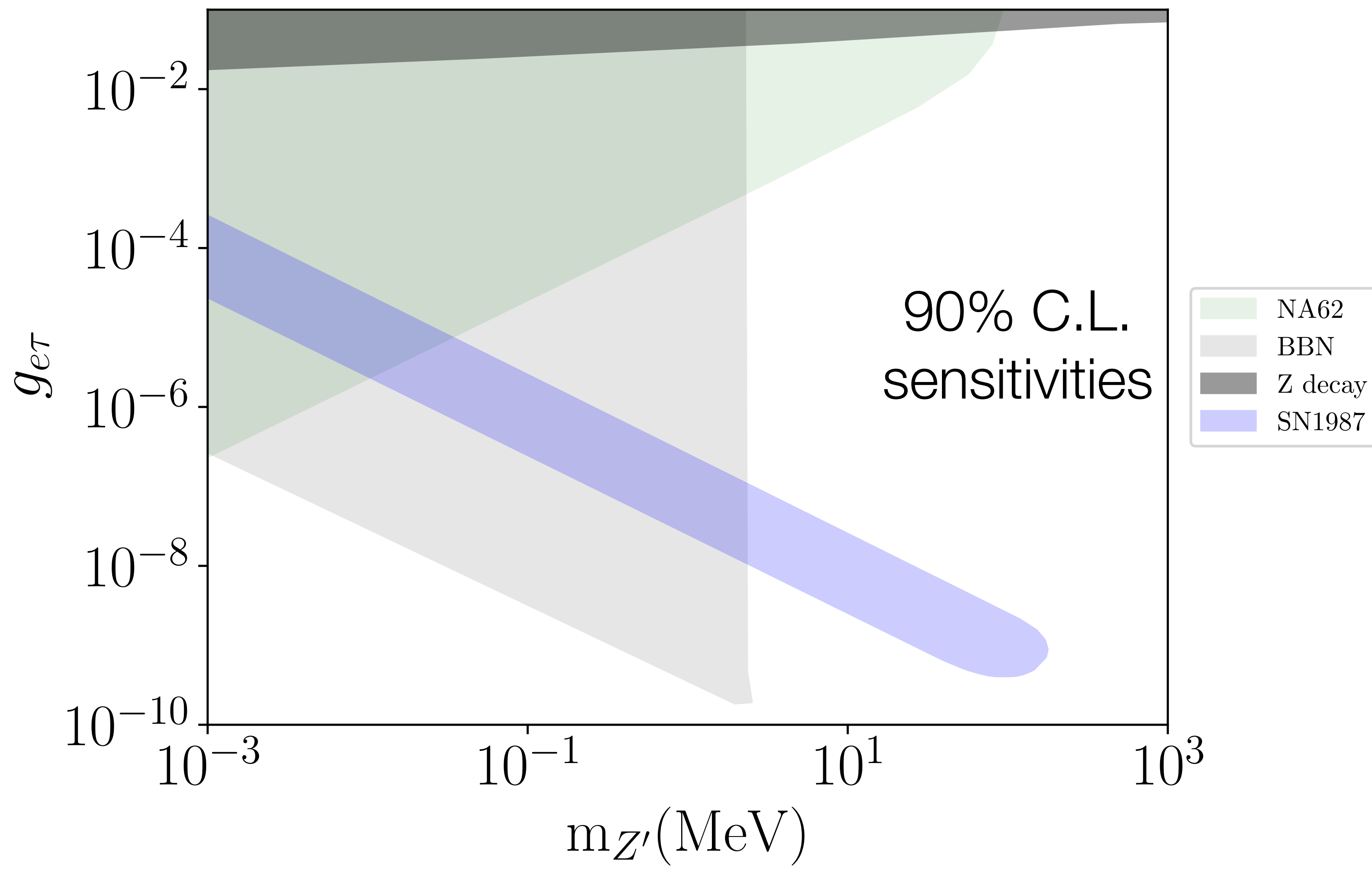

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- Cosmological bounds are stronger than the scalar mediator due to d.o.f.

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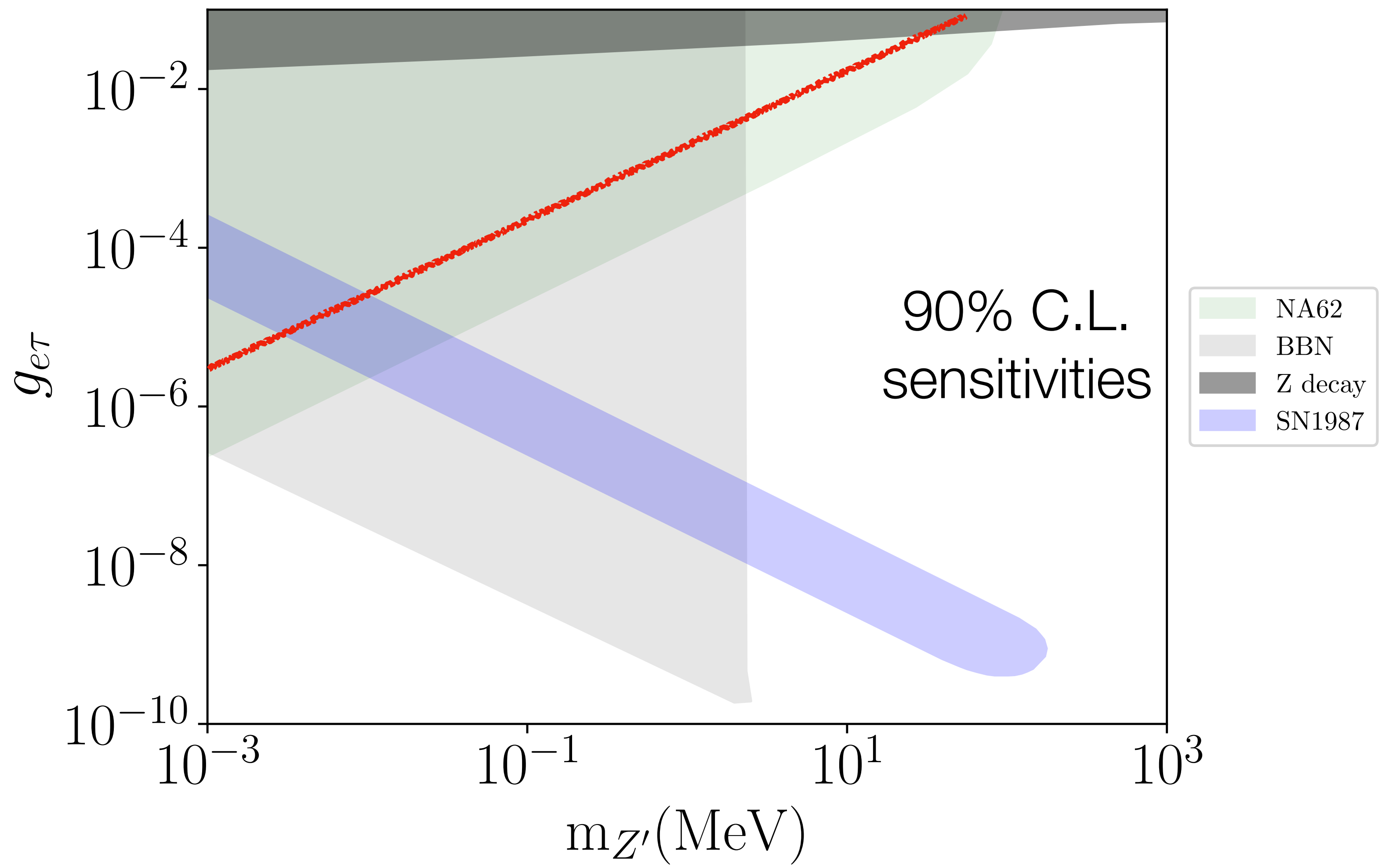

CMB bound?

- 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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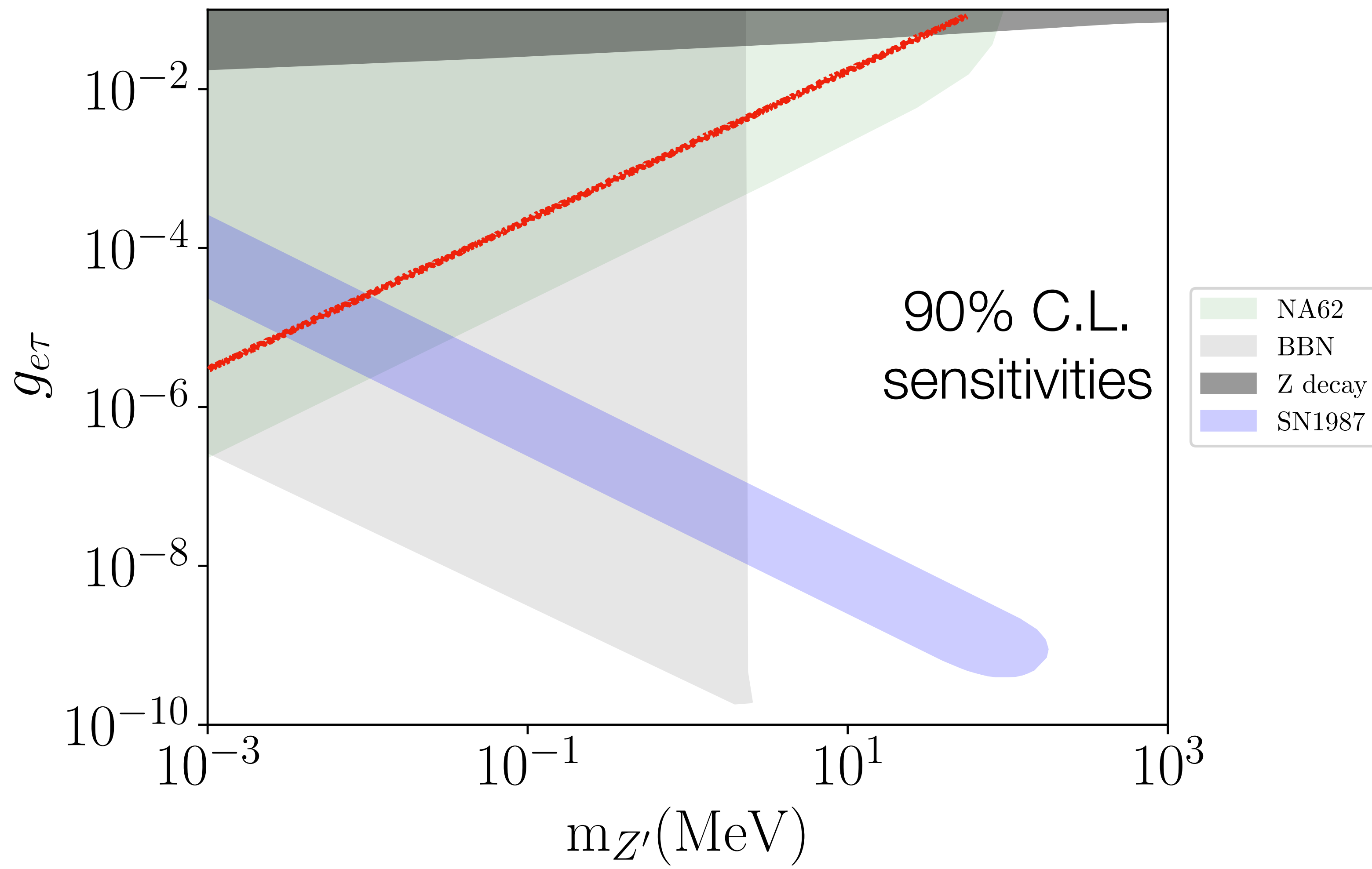

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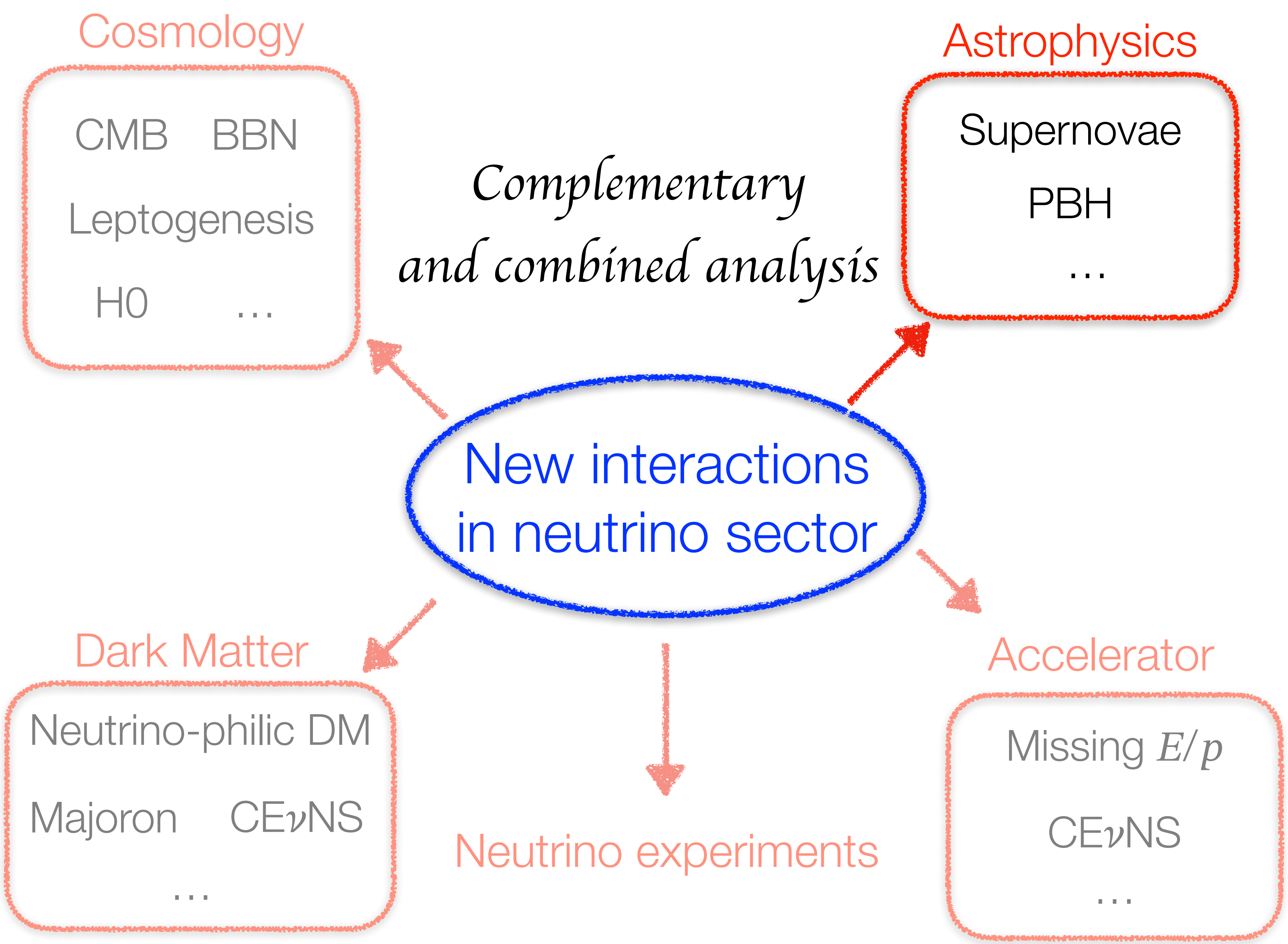
  ⟶ Dedicated study with flavor non-universal and off-diagonal SNI needed.

Constraints for ν_τ SNI: astrophysics



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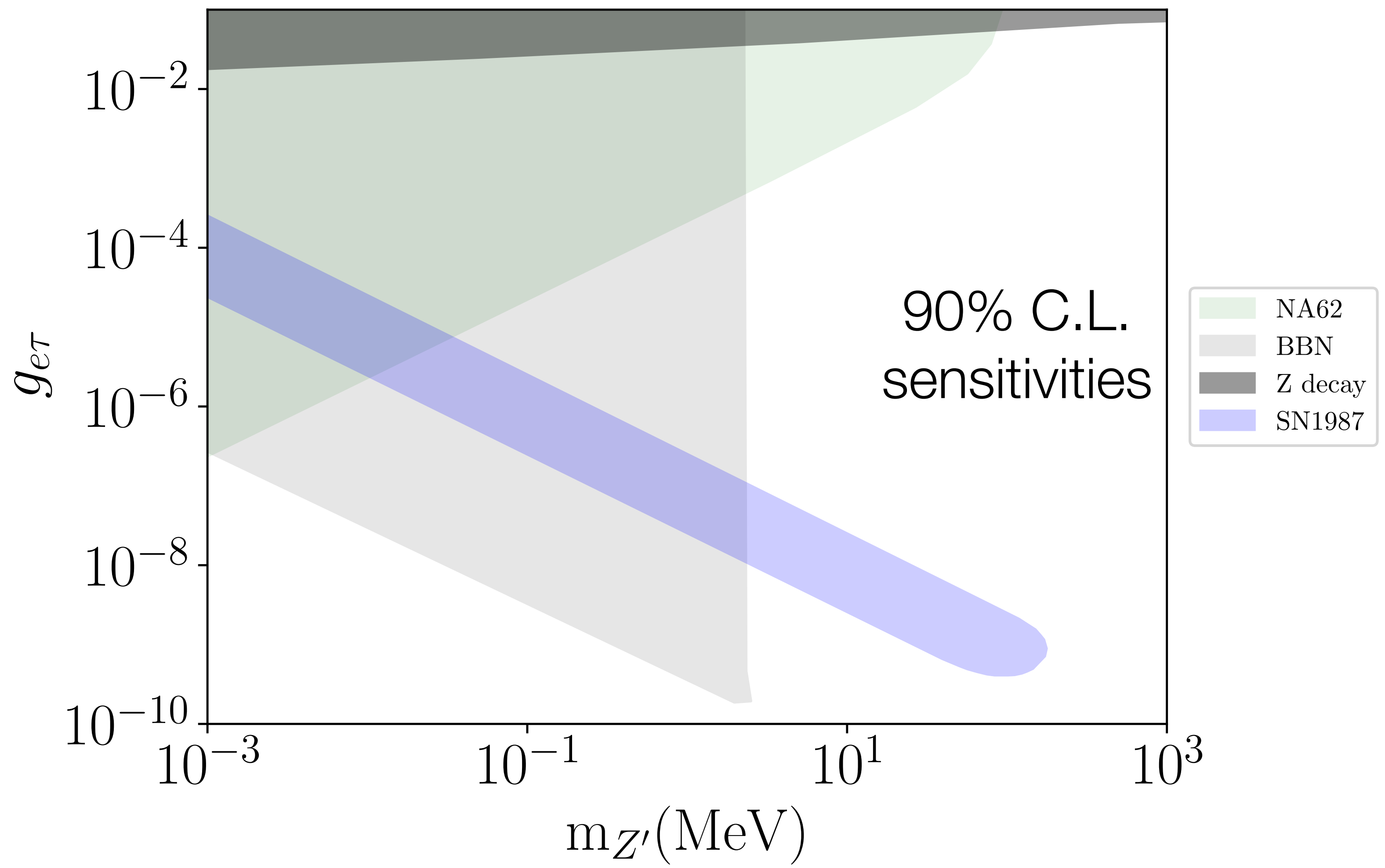
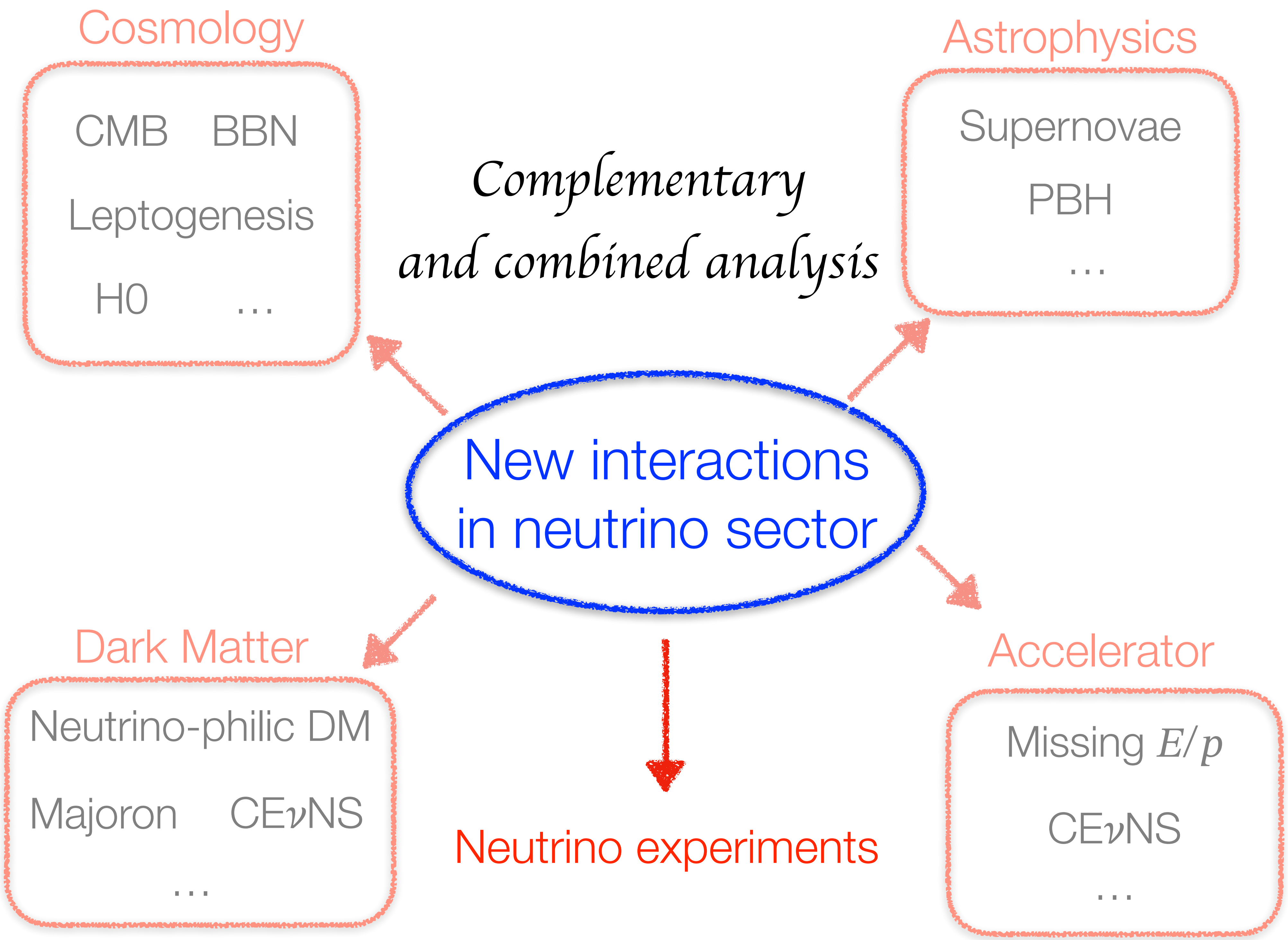


- Core-collapse supernova: SN1987A energy loss rate in blue shaded region (flavor universal & diagonal case)

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

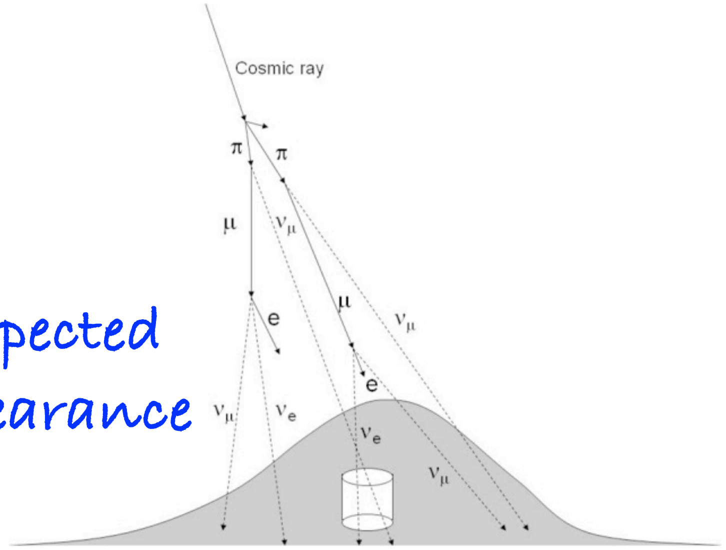
- More general case: dedicated study needed.

Sensitivities for ν_τ SNI: Future ν exp.



Sensitivities for ν_τ SNI: DUNE FD

Unexpected ν_τ appearance



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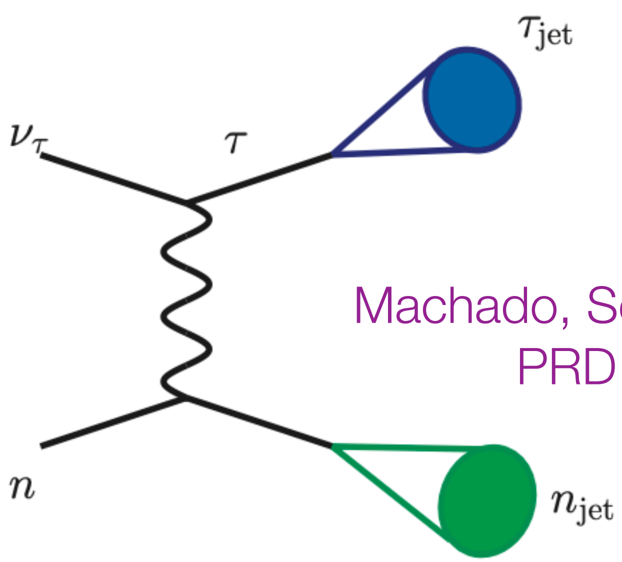
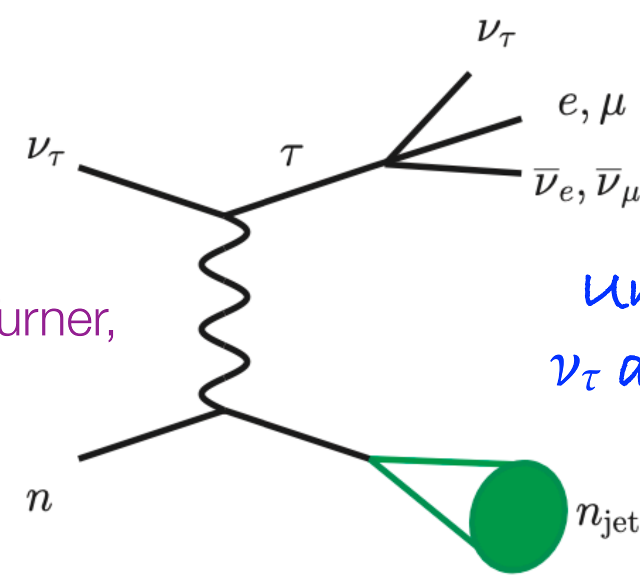


Machado, Schulz, Turner, PRD 2020



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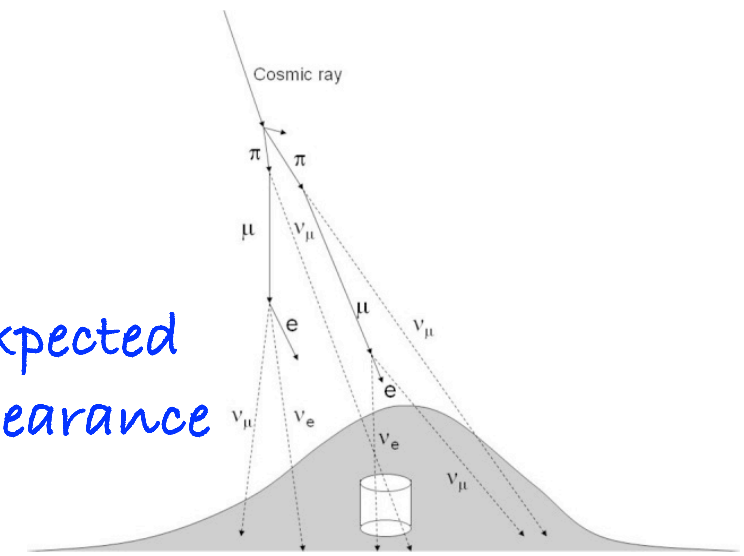

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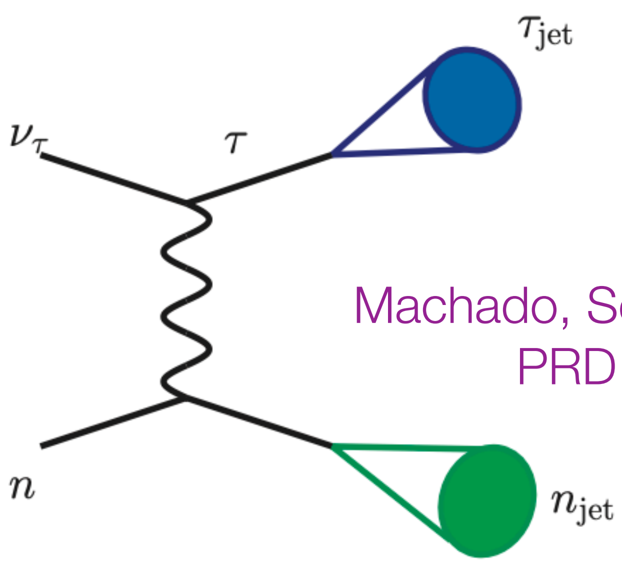

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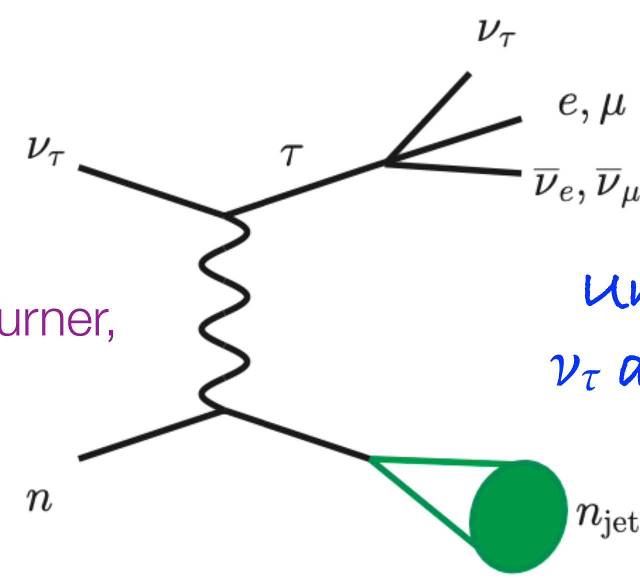

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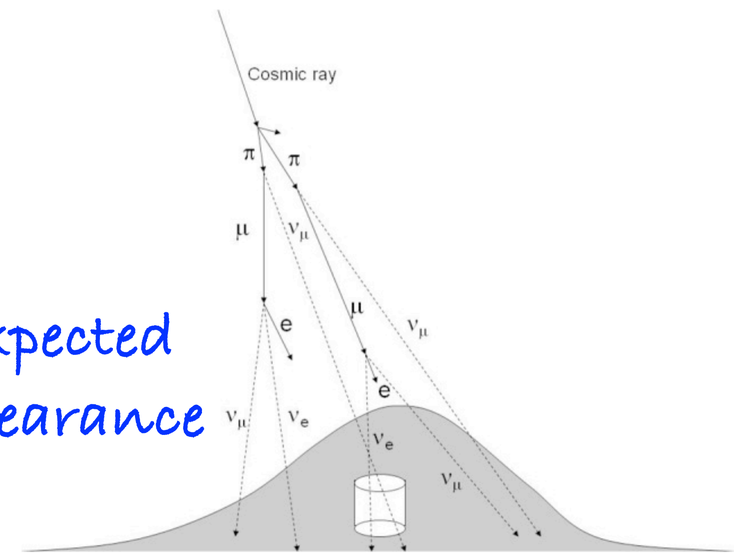

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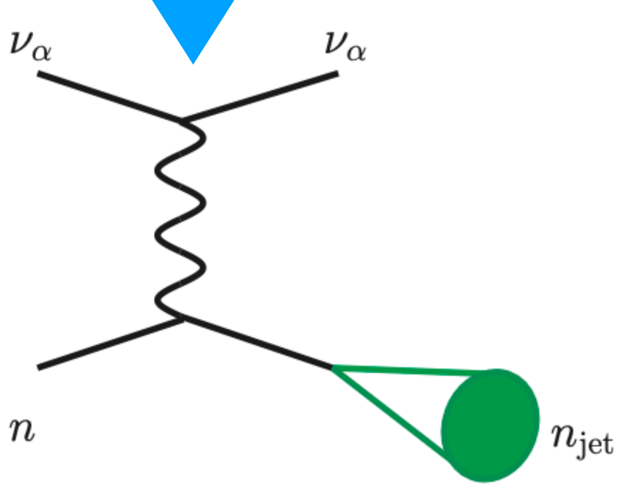

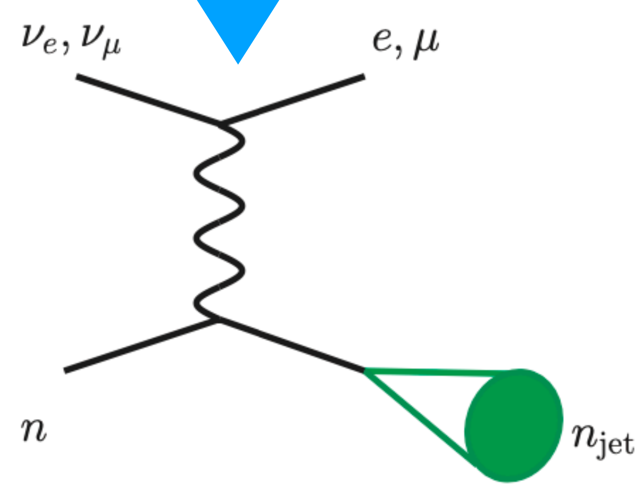

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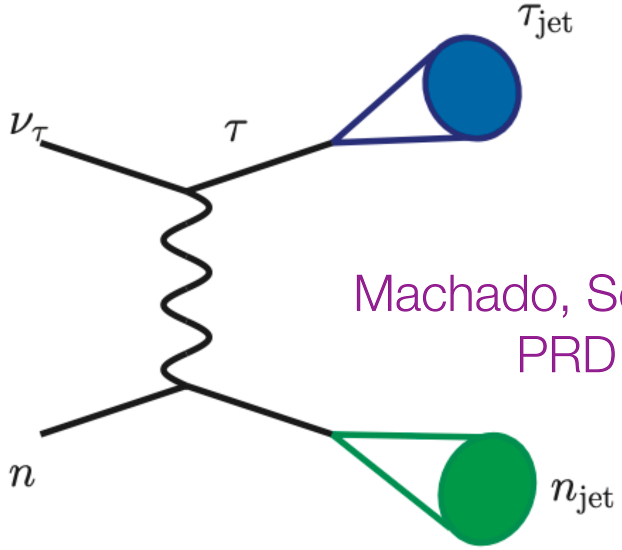

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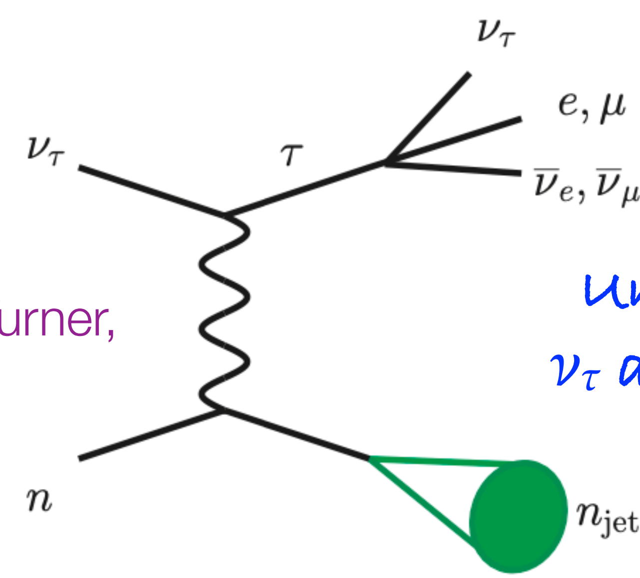

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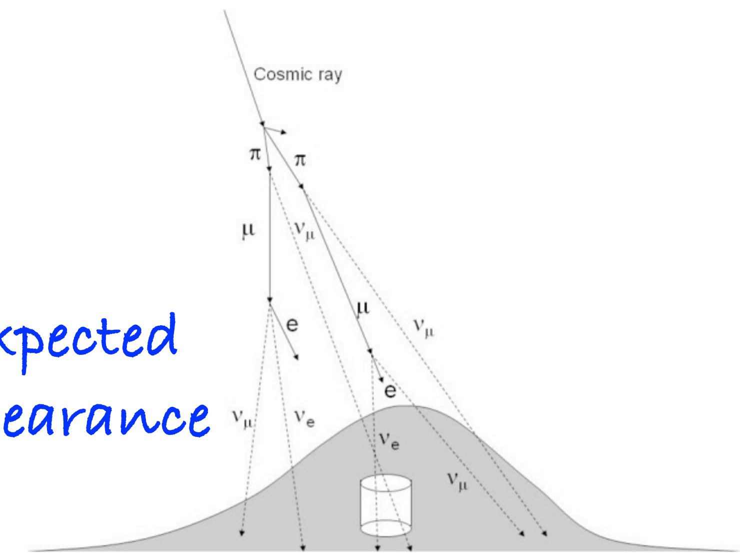

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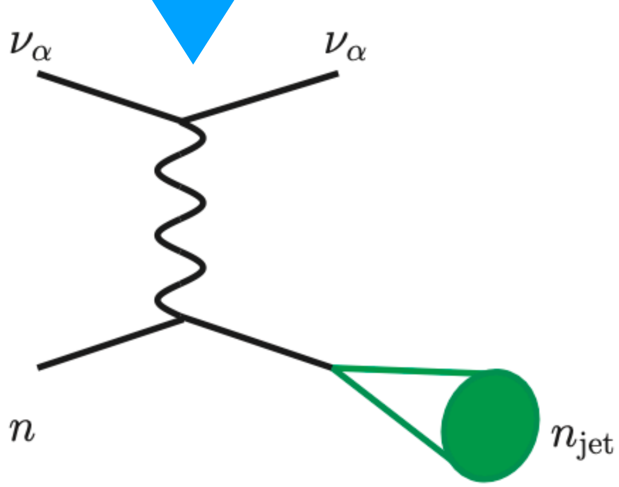

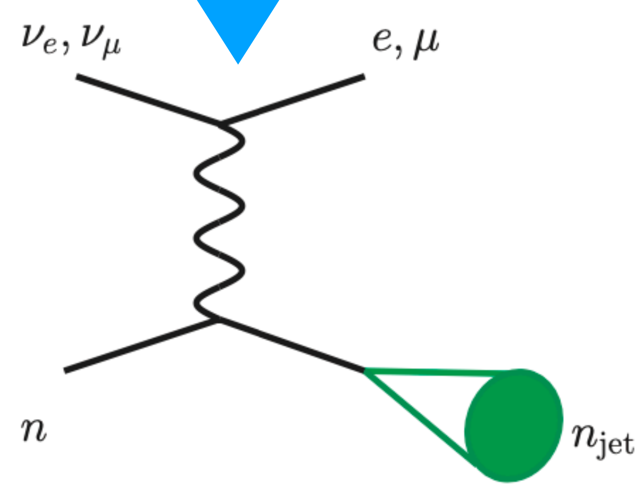

DUNE: expected to have excellent event topology reconstruction capabilities.

↓

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

Sensitivities for ν_τ SNI: DUNE FD

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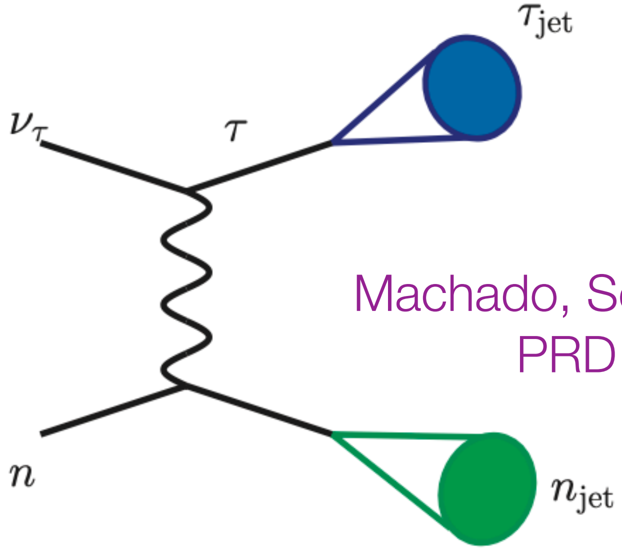

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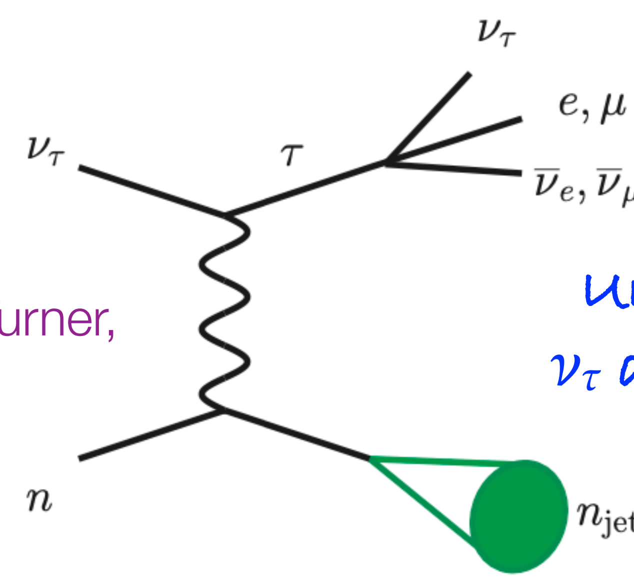

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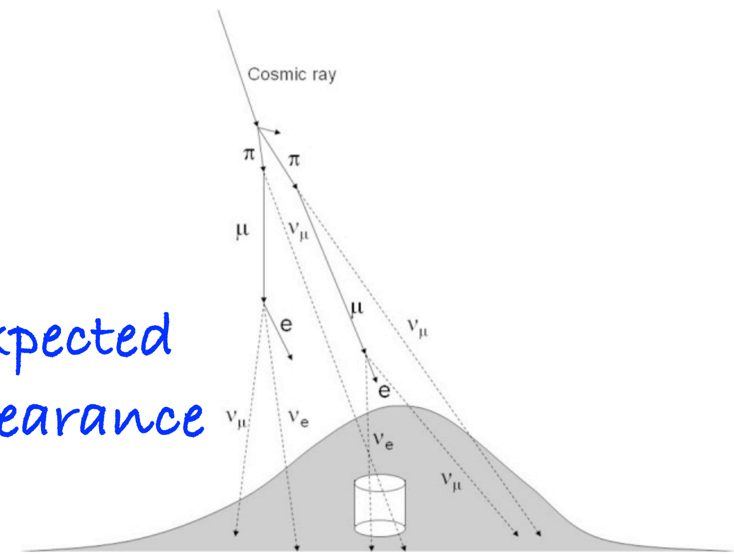

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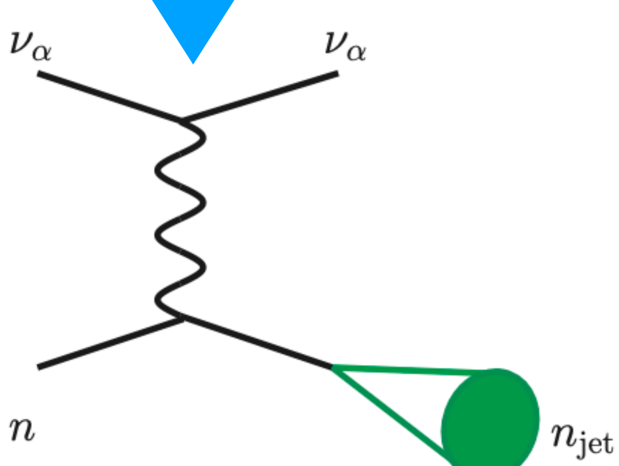

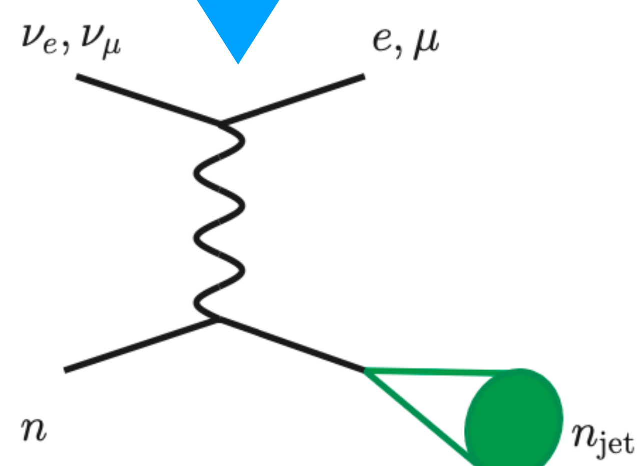

- Signal-to-background efficiencies increase!

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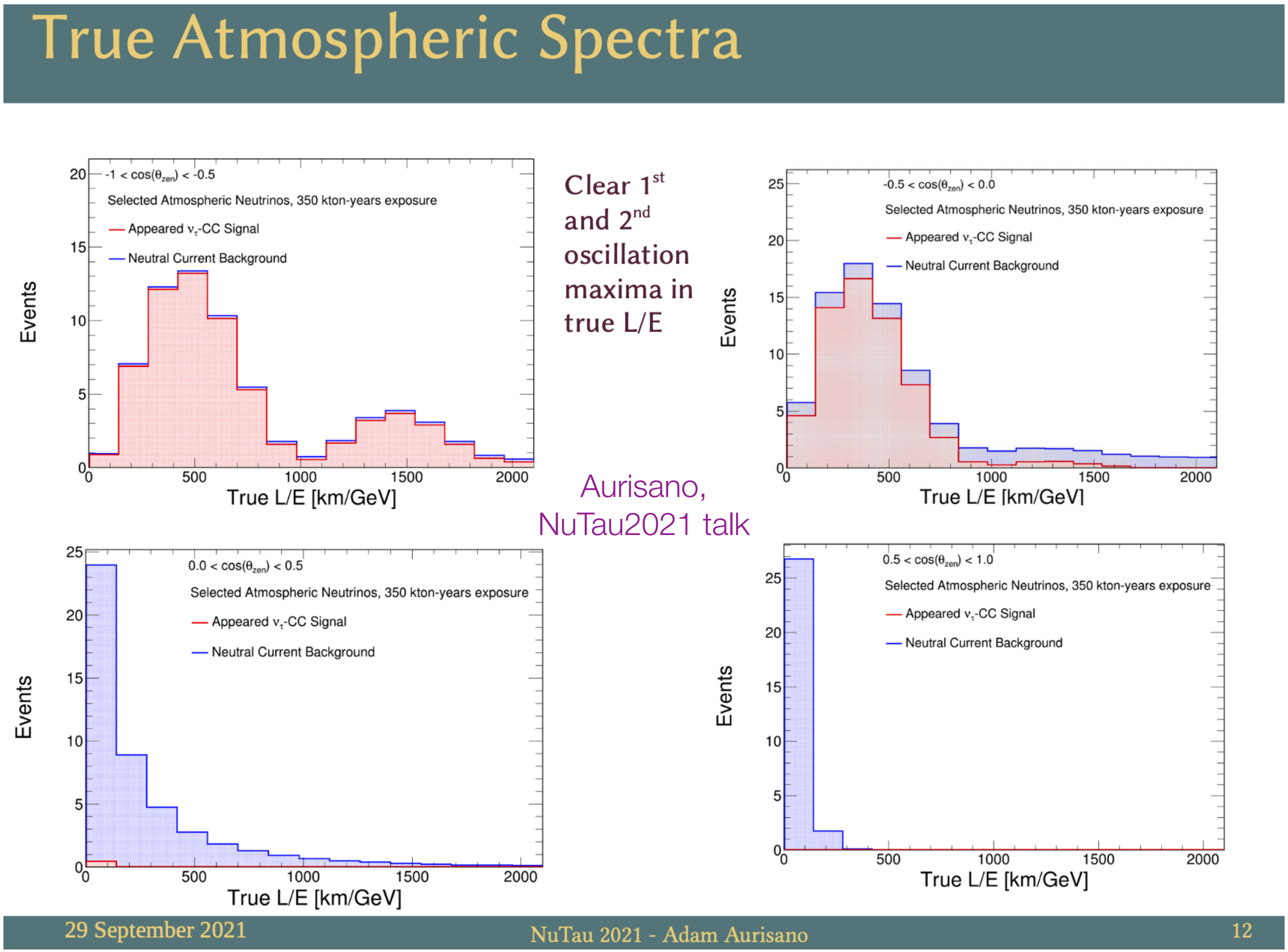
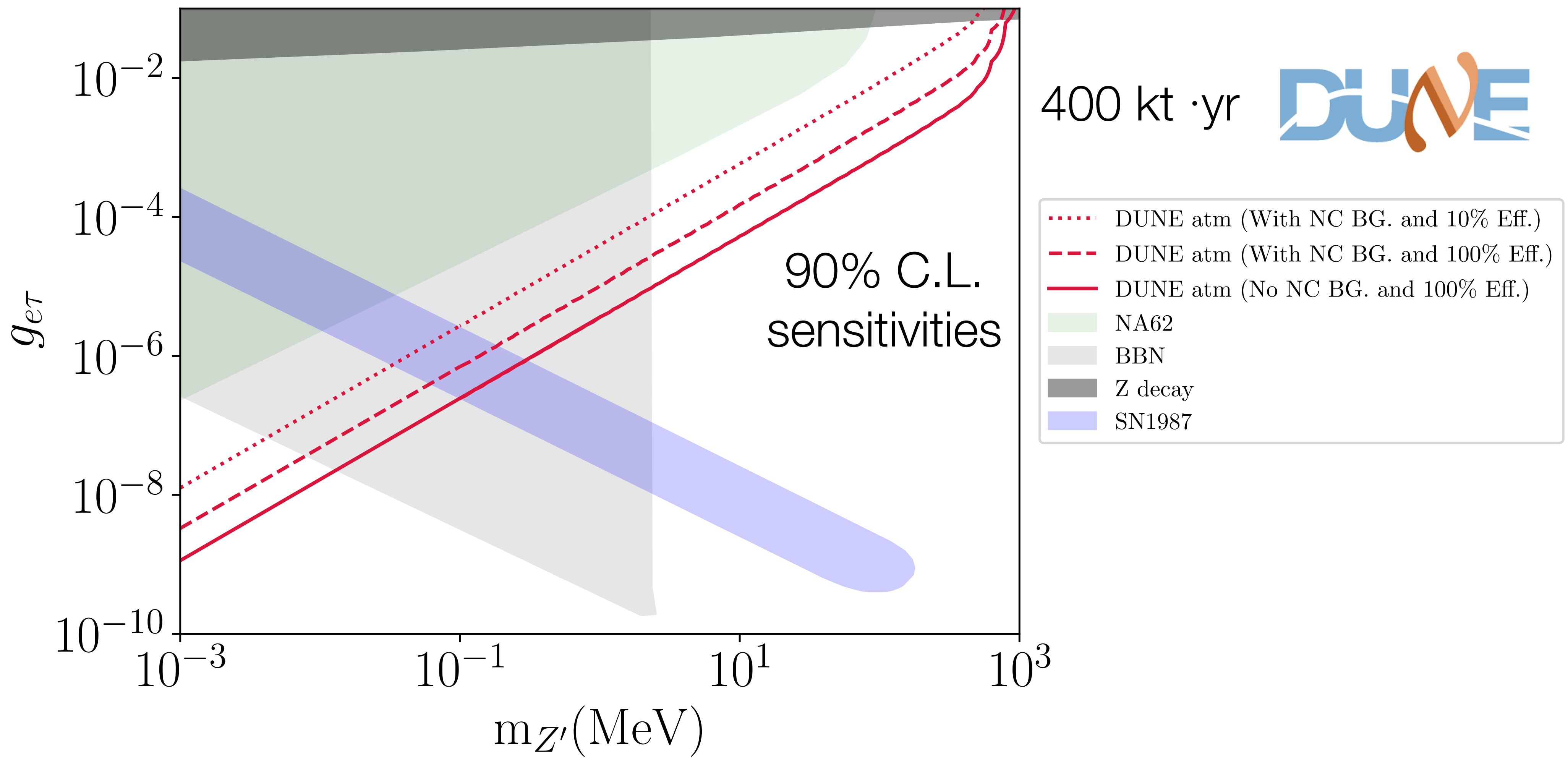
Sensitivities for ν_τ SNI: DUNE FD



Aurisano, NuTau2021 talk

- NC background ~ 70 for 10 years: this might be still 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)
  Dotted: Neutral Current background & 10% efficiency

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

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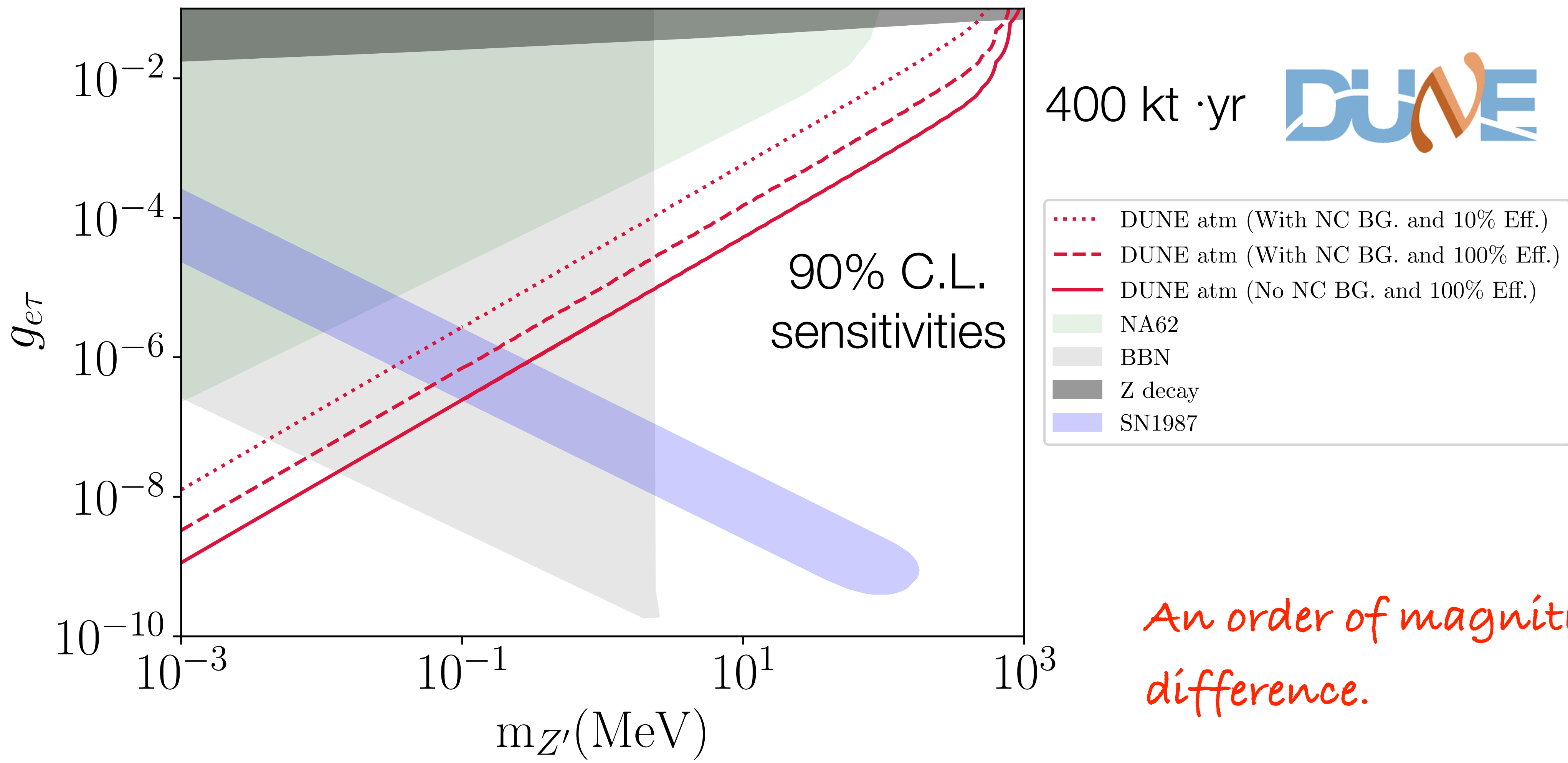

An order of magnitude difference.

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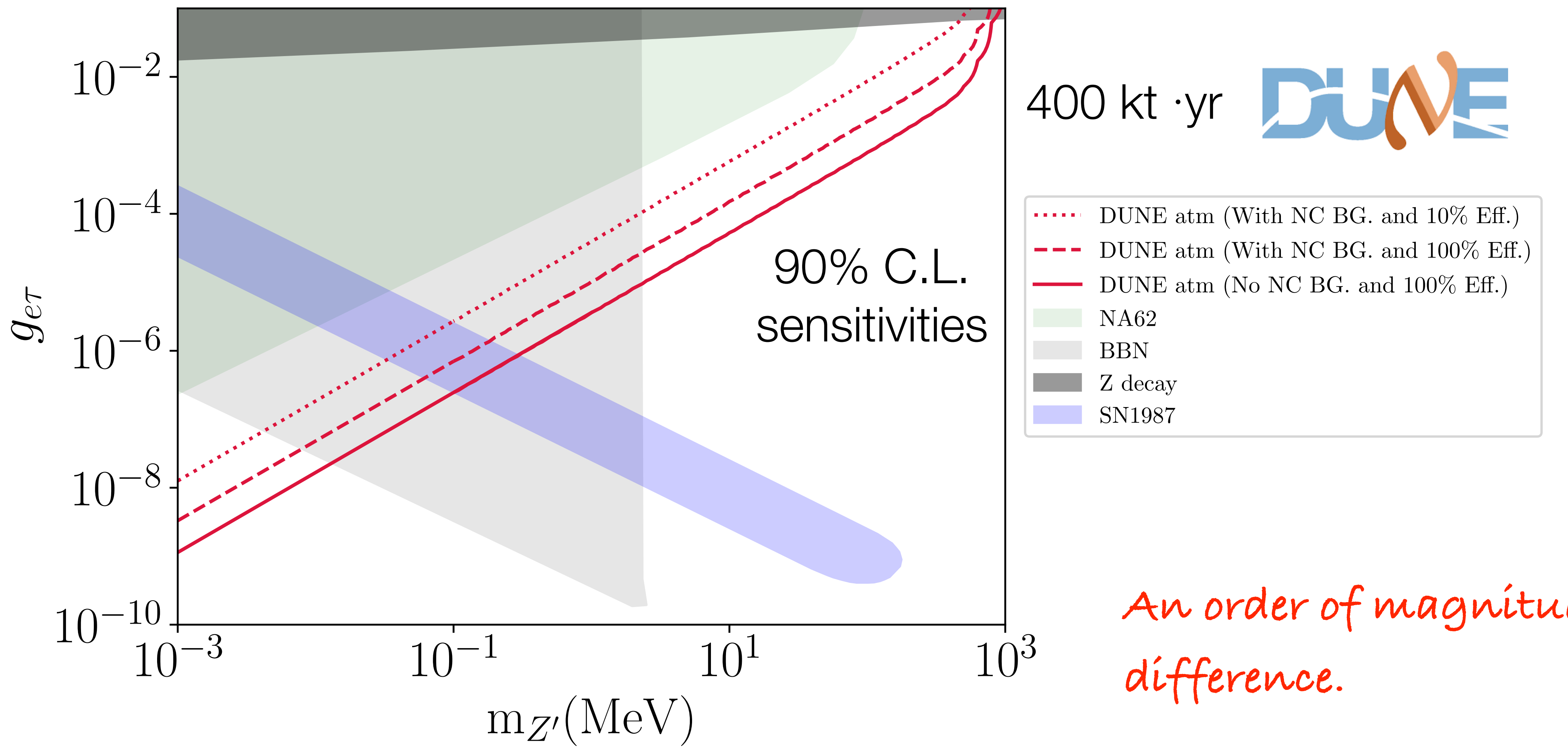

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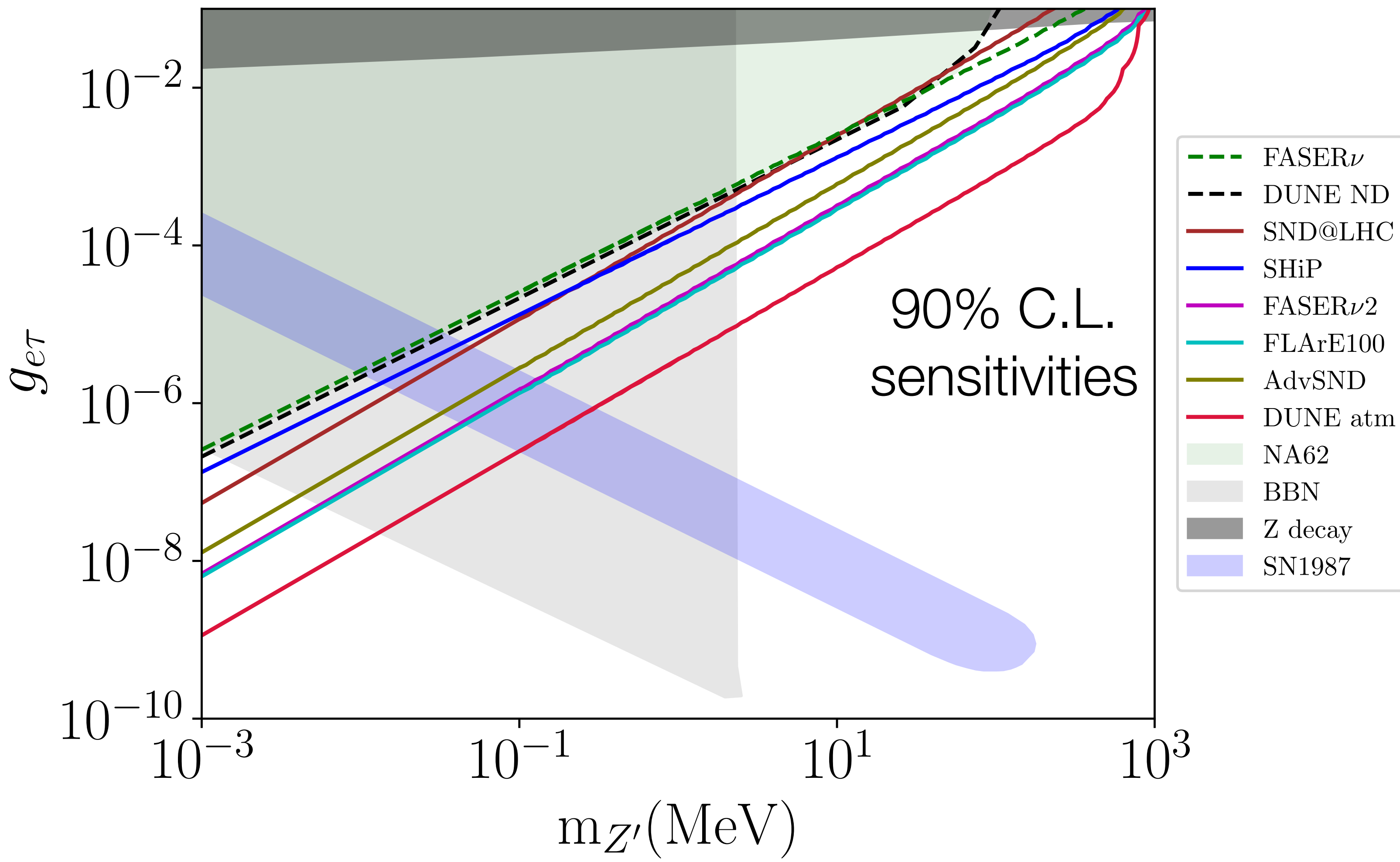
DUNE, arXiv:2002.03005 Machado, Schulz, Turner, PRD 2020

- 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



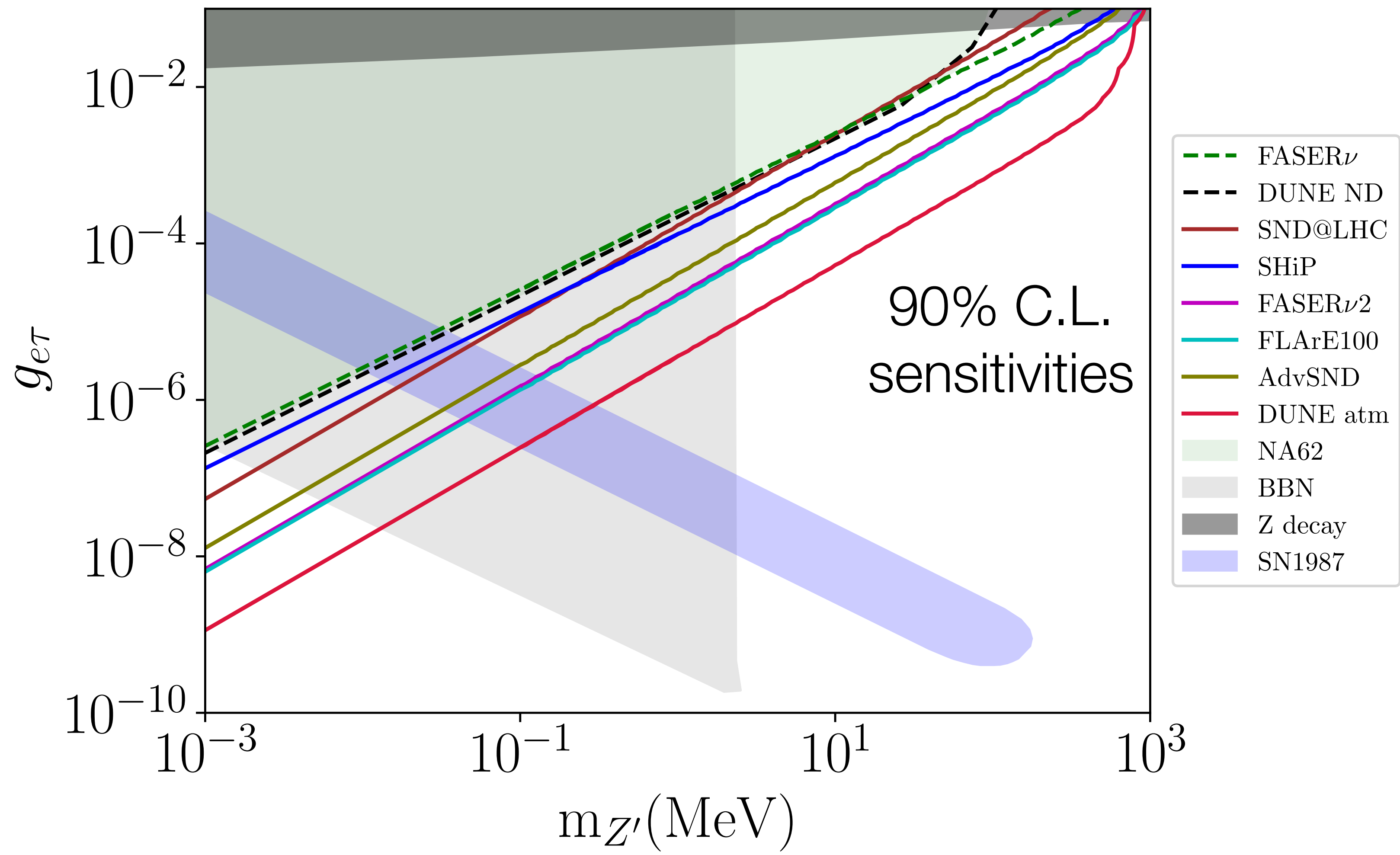
SND@LHC/ FASERν: 150 fb^{-1}

SHiP: 2×10^{20} POT (5 yrs)

FPF: 3 ab^{-1}

Red solid: DUNE best case

Sensitivities for ν_τ SNI: FPF, SHiP



SND@LHC/ FASERν: 150 fb^{-1}

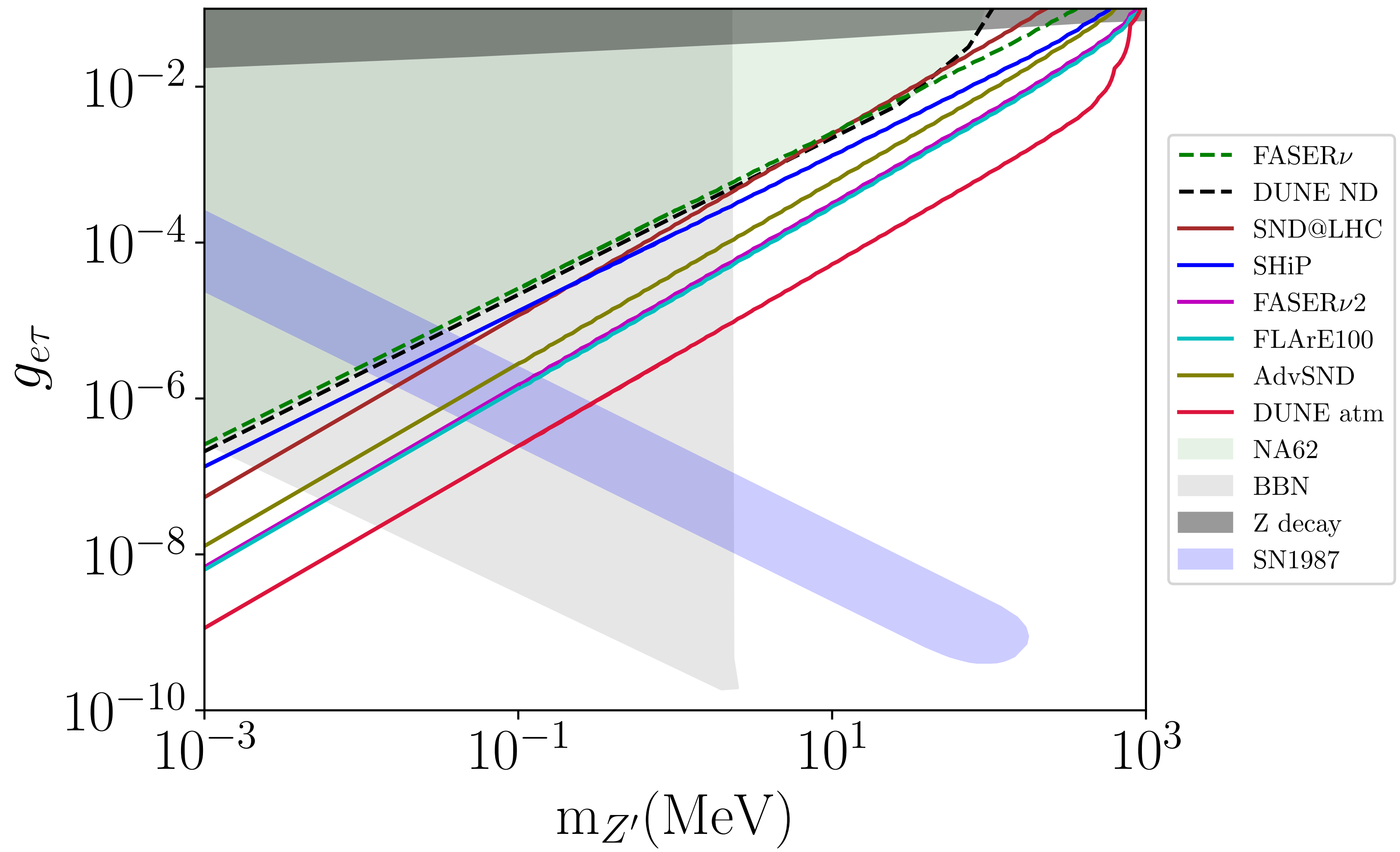
SHiP: 2×10^{20} POT (5 yrs)

FPF: 3 ab^{-1}

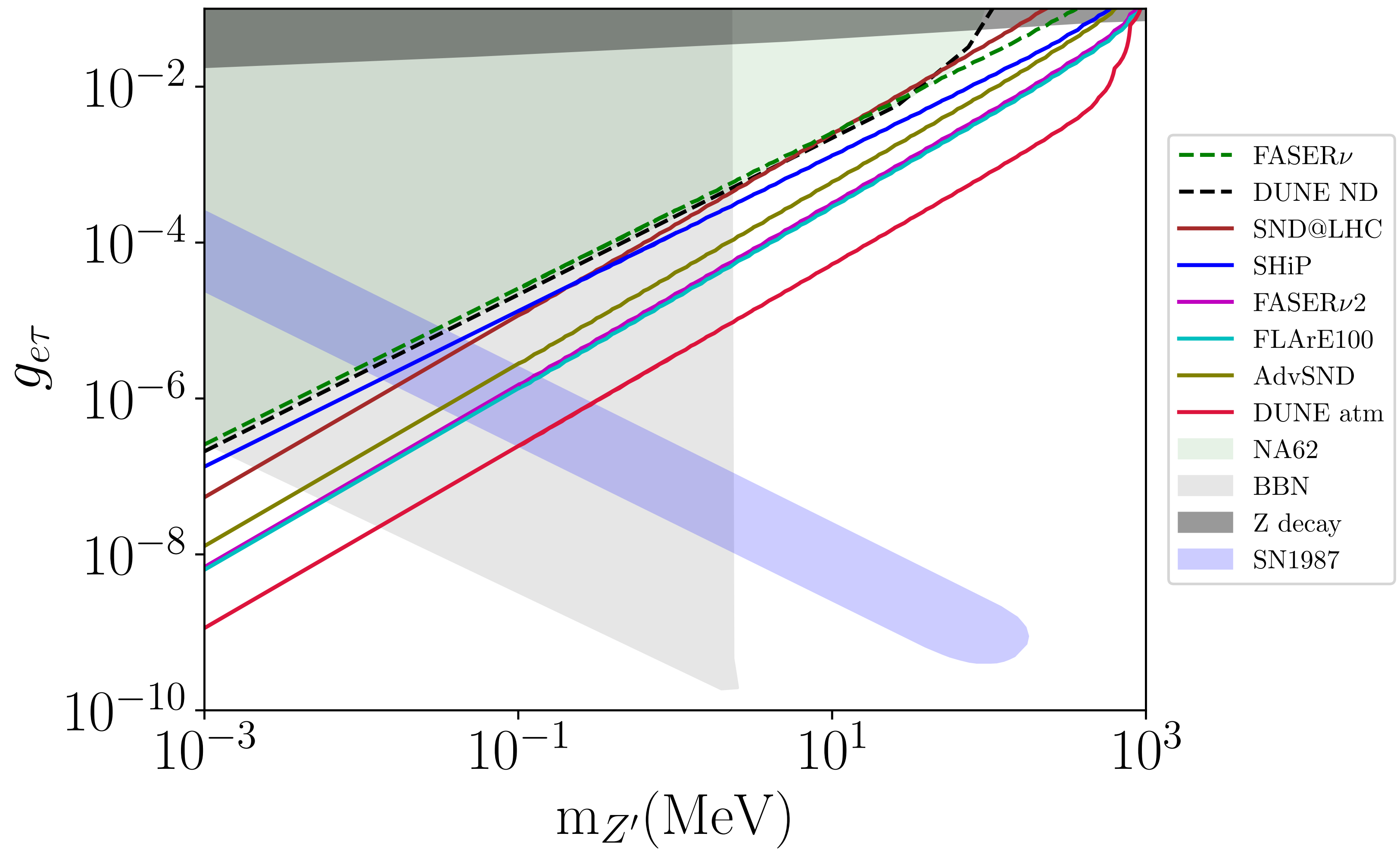
Red solid: DUNE best case

- FLArE100 (cyan, 100 ton) and FASERν2 (purple, 20 ton) can be comparable to the "realistic" sensitivity at DUNE but the flux uncertainties of the accelerator produced neutrinos can reduce their sensitivities.

IR divergent behavior?

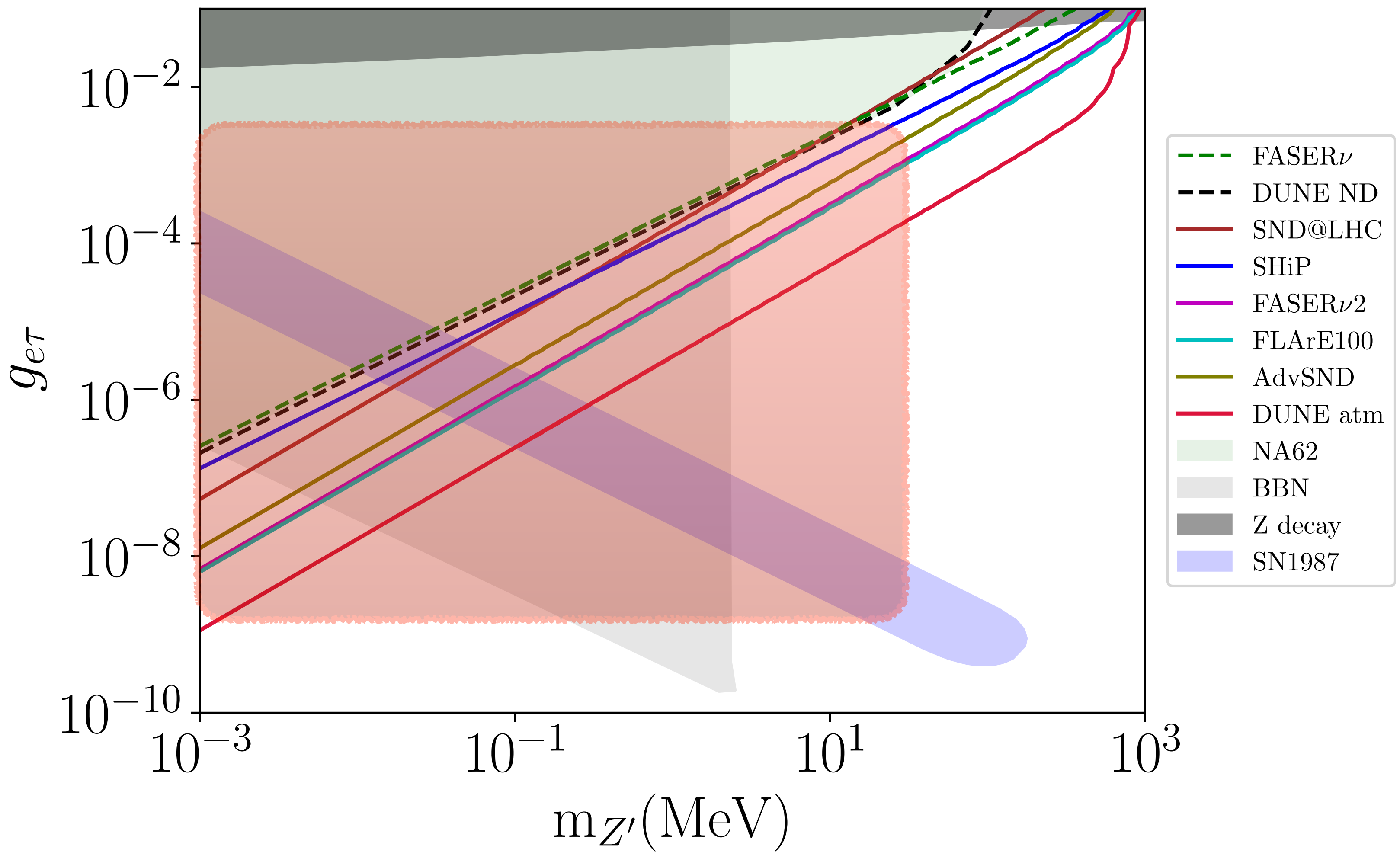


IR divergent behavior?



- Increase of the sensitivities should stop for some light $m_{Z'}$: future work

IR divergent behavior?

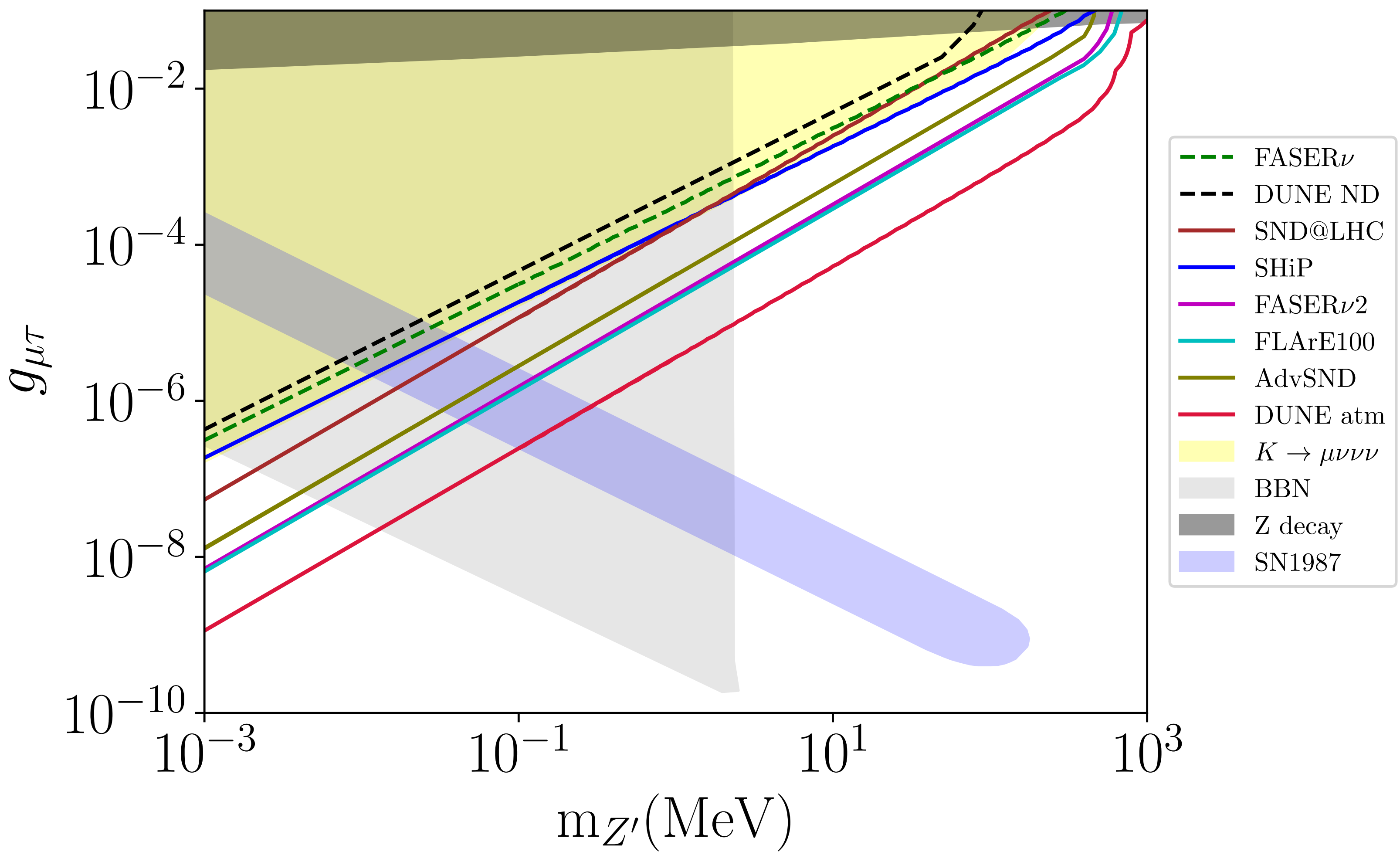


- Increase of the sensitivities should stop for some light $m_{Z'}$: future work

- Scalar mediator case study: IR divergence cancellation for $M_{Z'} \lesssim$ 100 MeV and hence sensitivities get pushed back

Dev, Kim, Sathyan, Sinha, Zhang, arXiv:2407.12738

Sensitivities for ν_τ SNI



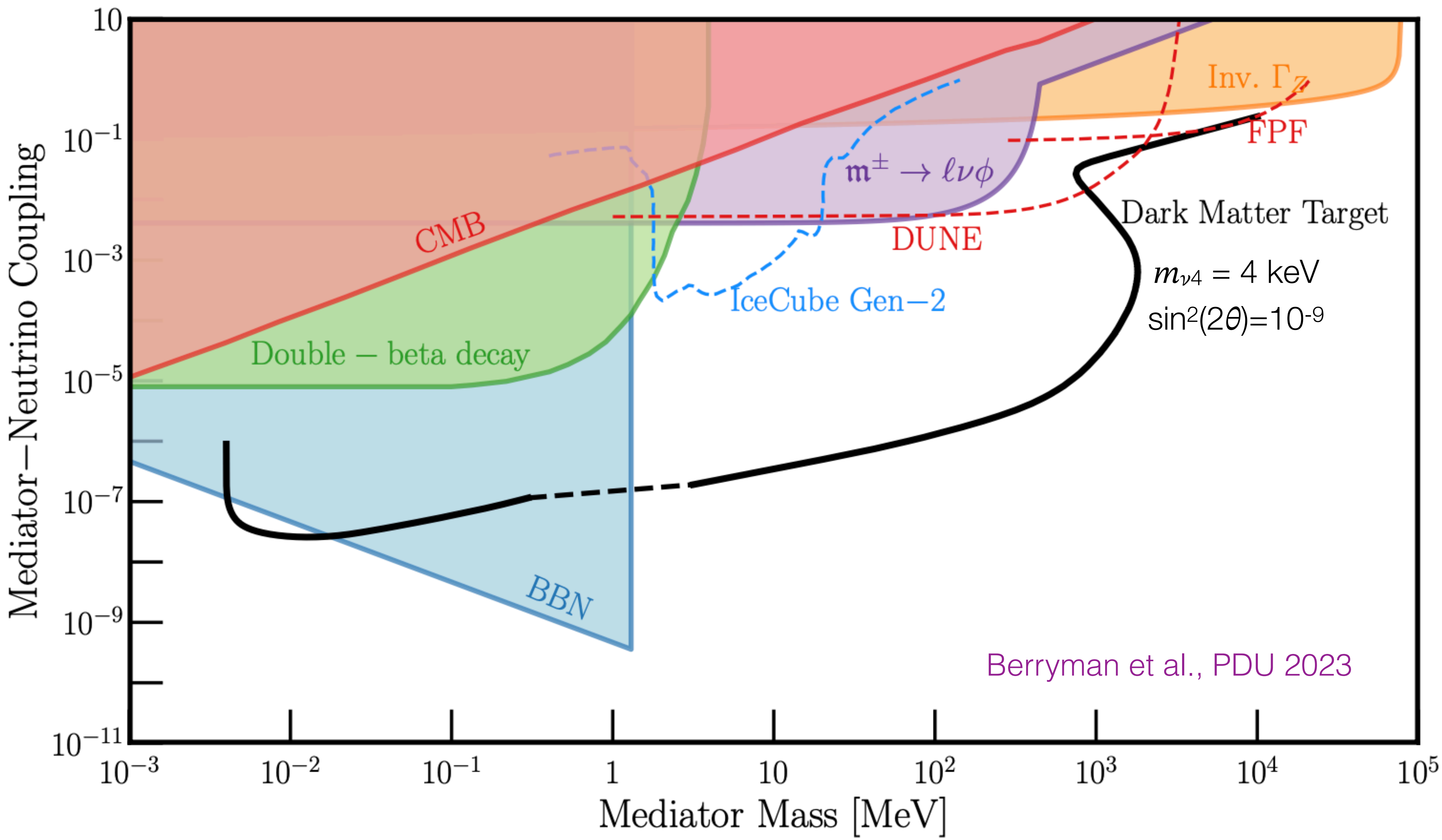
- Sensitivities are comparable or slightly weaker (SHiP) due to the phase space.

- 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).

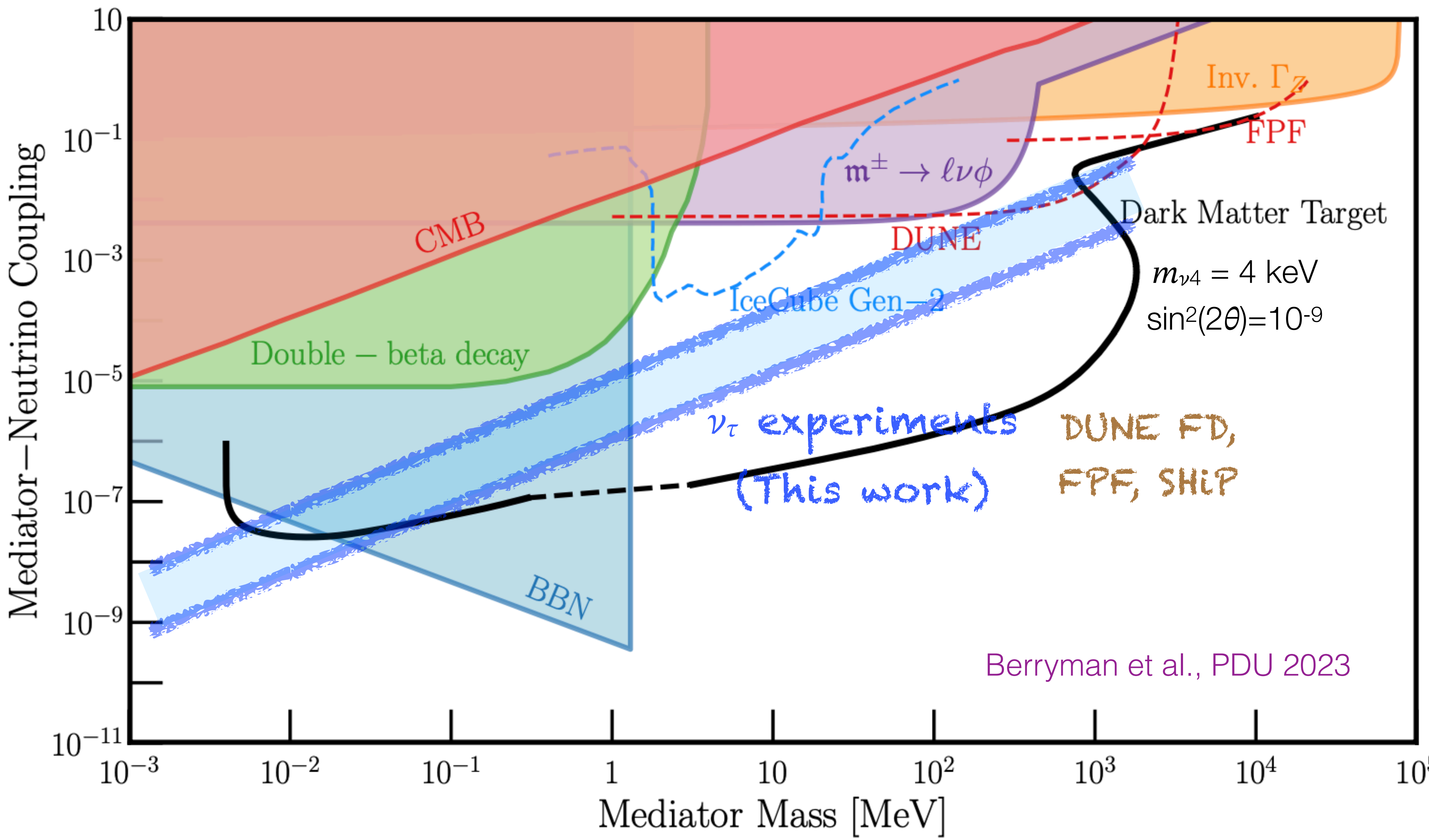
$$\mathrm{BR}(K^+ \to \mu^+\nu\nu\nu) < 2.4 \times 10^{-6}$$

Sensitivities for ν_τ SNI



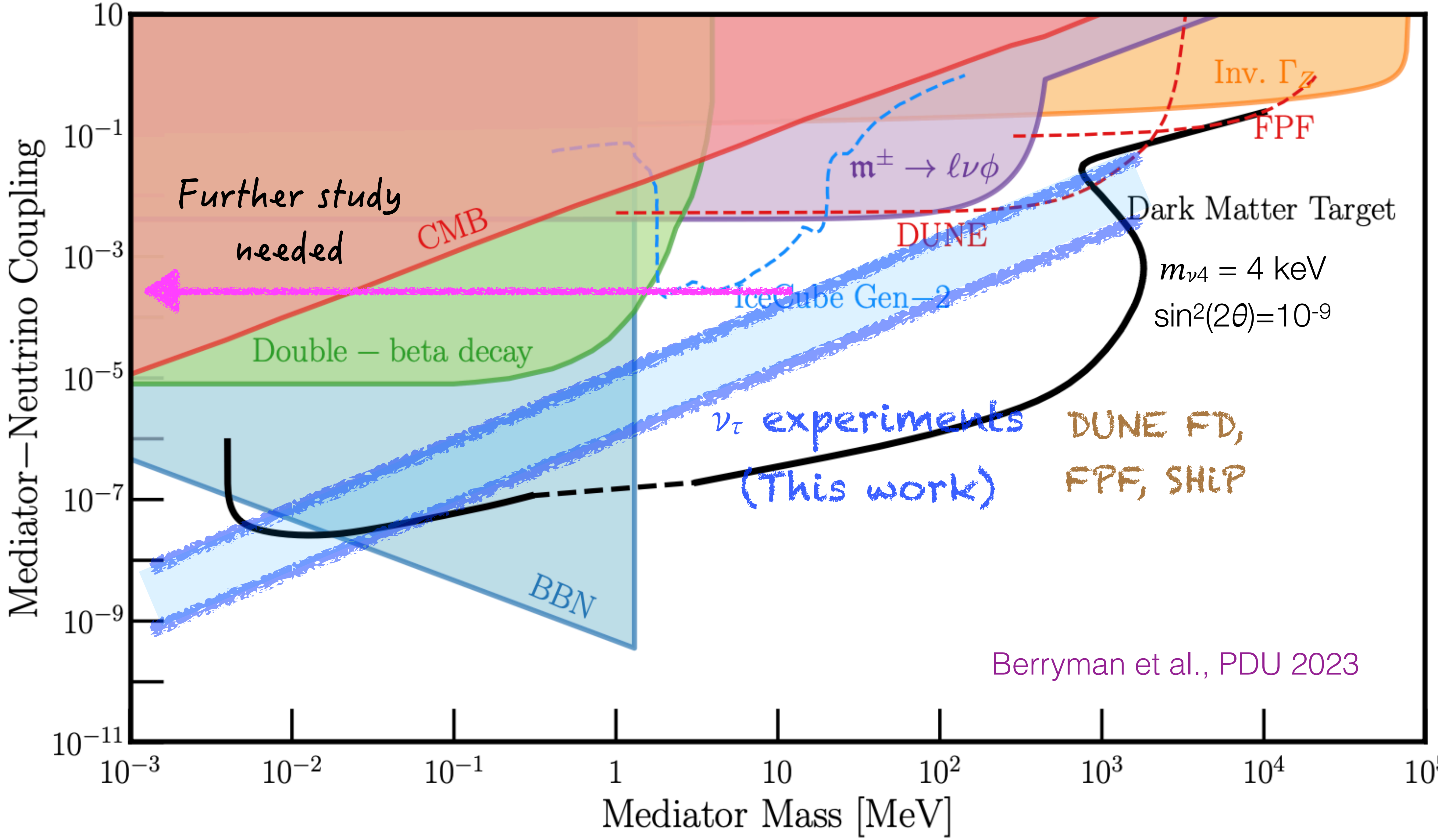
Universal and diagonal coupling & scalar mediator case

Sensitivities for ν_τ SNI



Universal and diagonal coupling & scalar mediator case

Sensitivities for ν_τ SNI



Universal and diagonal coupling & scalar mediator 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 flavored SNI in cosmo/astro, mediators with other spins, cLFV rare decays & calculations for light $m_{Z'}$