GGI Neutrino Focus Week

Uncovering Secret Neutrino Interactions at ν_τ experiments

Seodong Shin (신서동)

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

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New symmetry in the neutrino sector

Neutrino oscillation: clear evidence of BSM

→ *ν physics can provide guidelines for BSM*

New symmetries? New particles?

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Neutrino oscillation: clear evidence of BSM

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New symmetries? New particles?

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

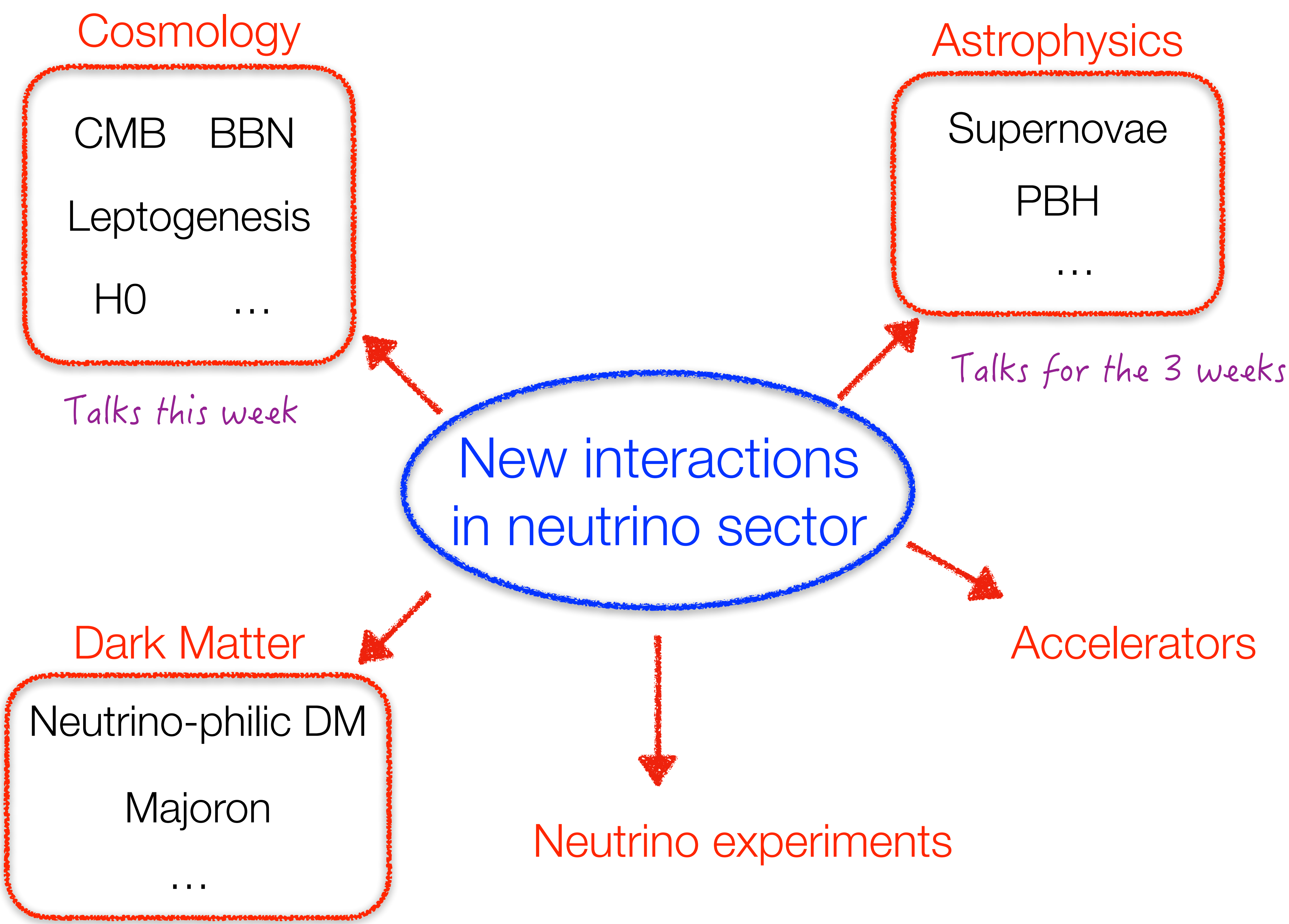
- Unexpected appearance of SM particles

Talk by G. Karagiorgi

- Appearance/disappearance of SM ν in neutrino experiments

- Missing energy in accelerators

New symmetry in the neutrino sector



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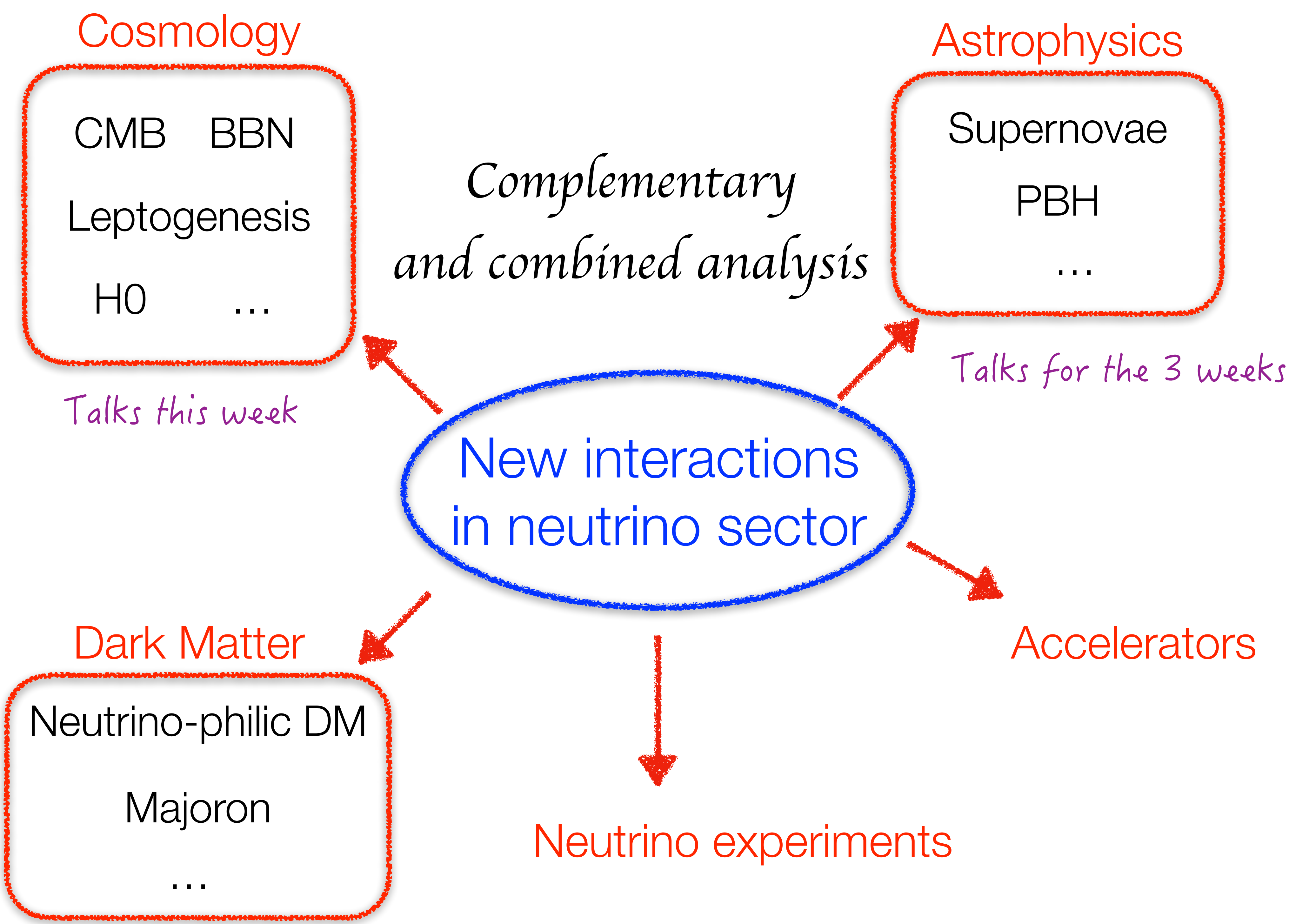

New symmetry in the neutrino sector

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

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

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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

Deppisch, Graf, Rodejohann, Xu, PRD 2020 Berryman et al., PDU 2023

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Berryman et al., PDU 2023

Probe flavor non-universal or off-diagonal 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 $\nu_\mu \rightarrow \nu_\tau$: 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)

Talk by Carlos

- Atmospheric experiments: IceCube, TAMBO, 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

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

Phenomenological set-up: exclusive coupling

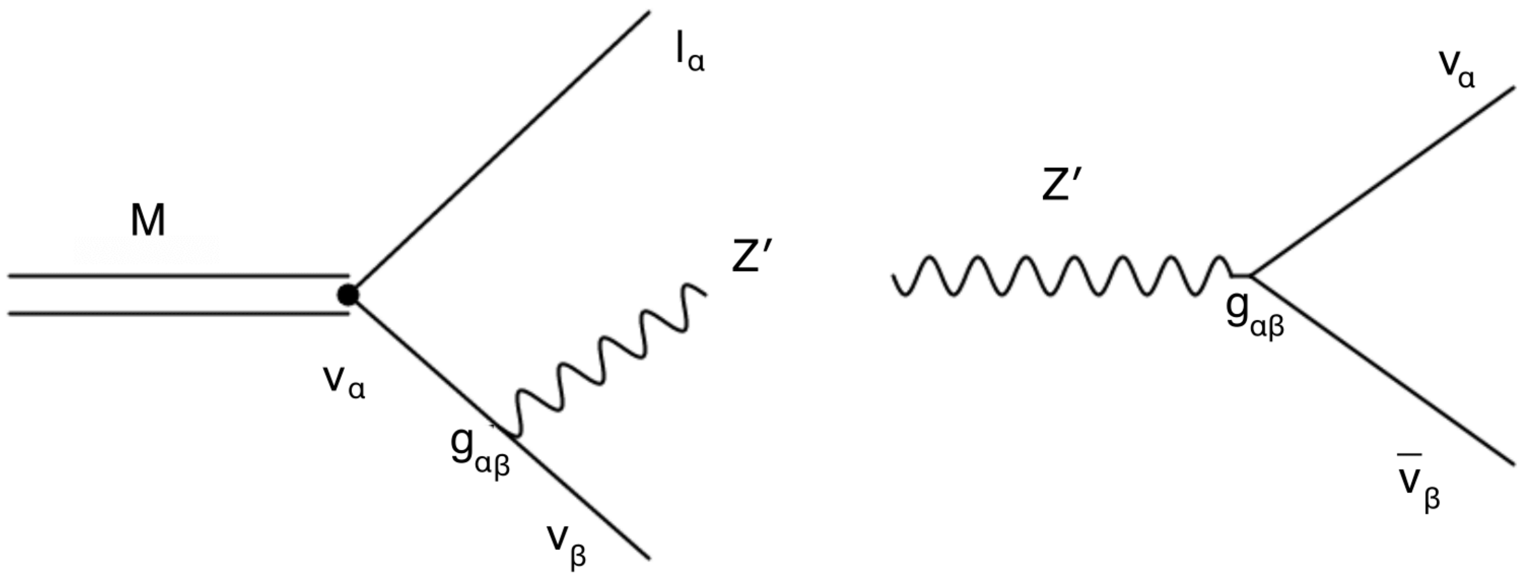
- A theoretical cook-up suppressing the $\ell^\pm$ interactions needed.

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

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

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

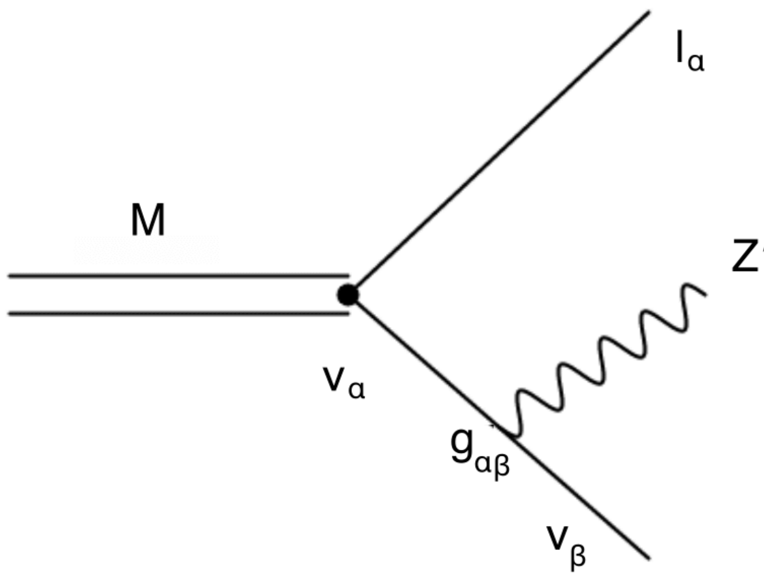
- 3-body decay: enhanced by the longitudinal mode of Z' $m_M^2/m_{Z'}^2$

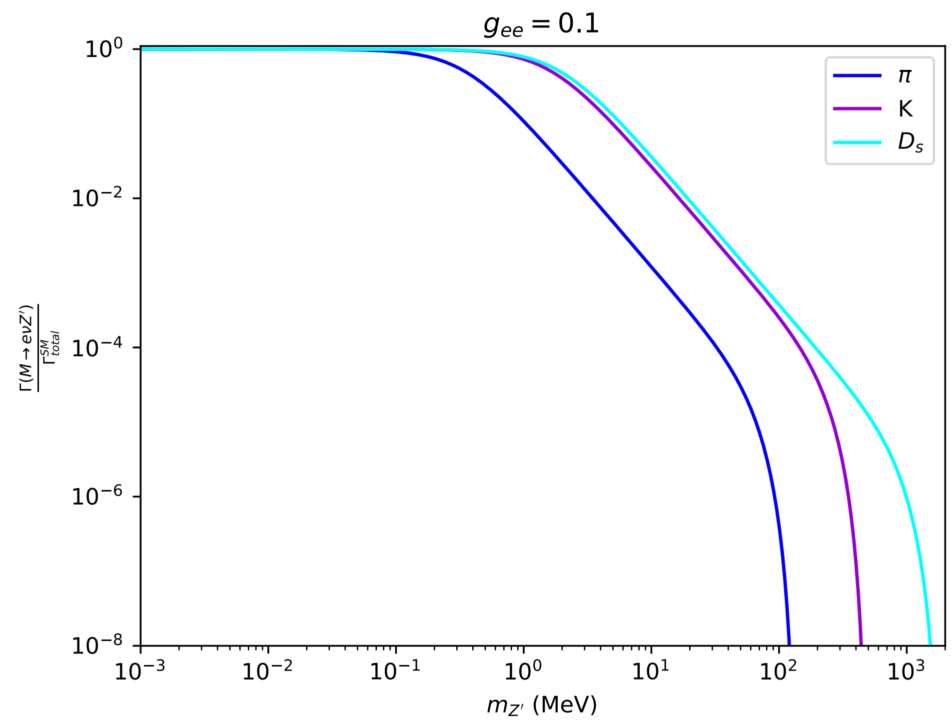
Barger, Chiang, Keung, Marfatia, PRL 2012 Carson, Rislow, PRD 2012

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

Theoretical set-up

Kinematic process on our focus: 3-body meson decay

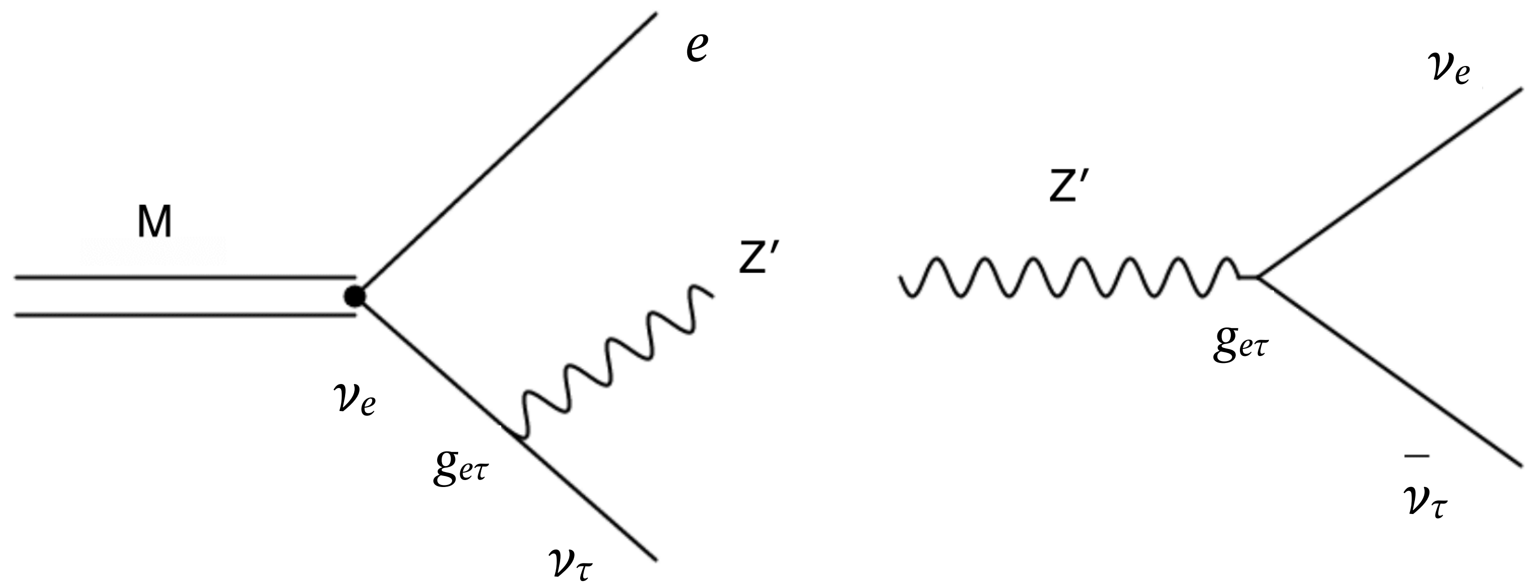




- Branching ratio of the 3-body decay can be dominant for light Z' despite the phase space suppression.

- Accordingly, very strong exp. bounds on g_{ee} : below ≲ 10^{-4}.

Sensitivities for ν_τ SNI



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

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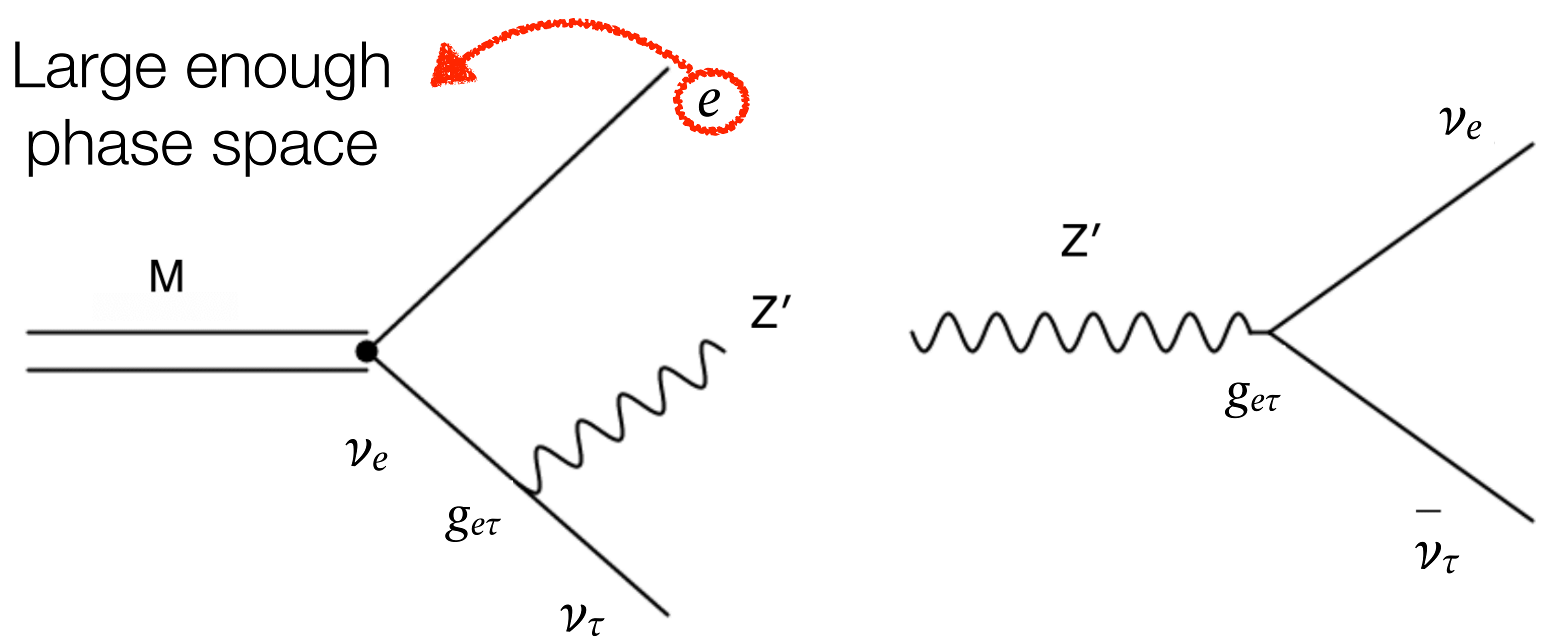

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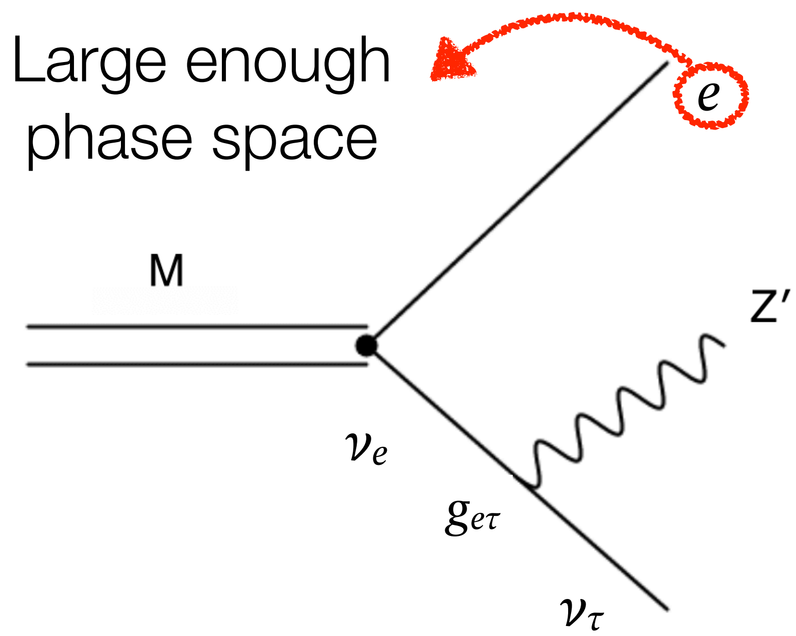
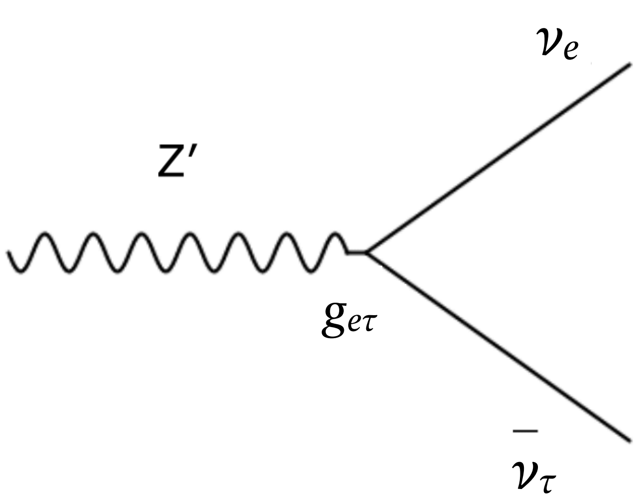
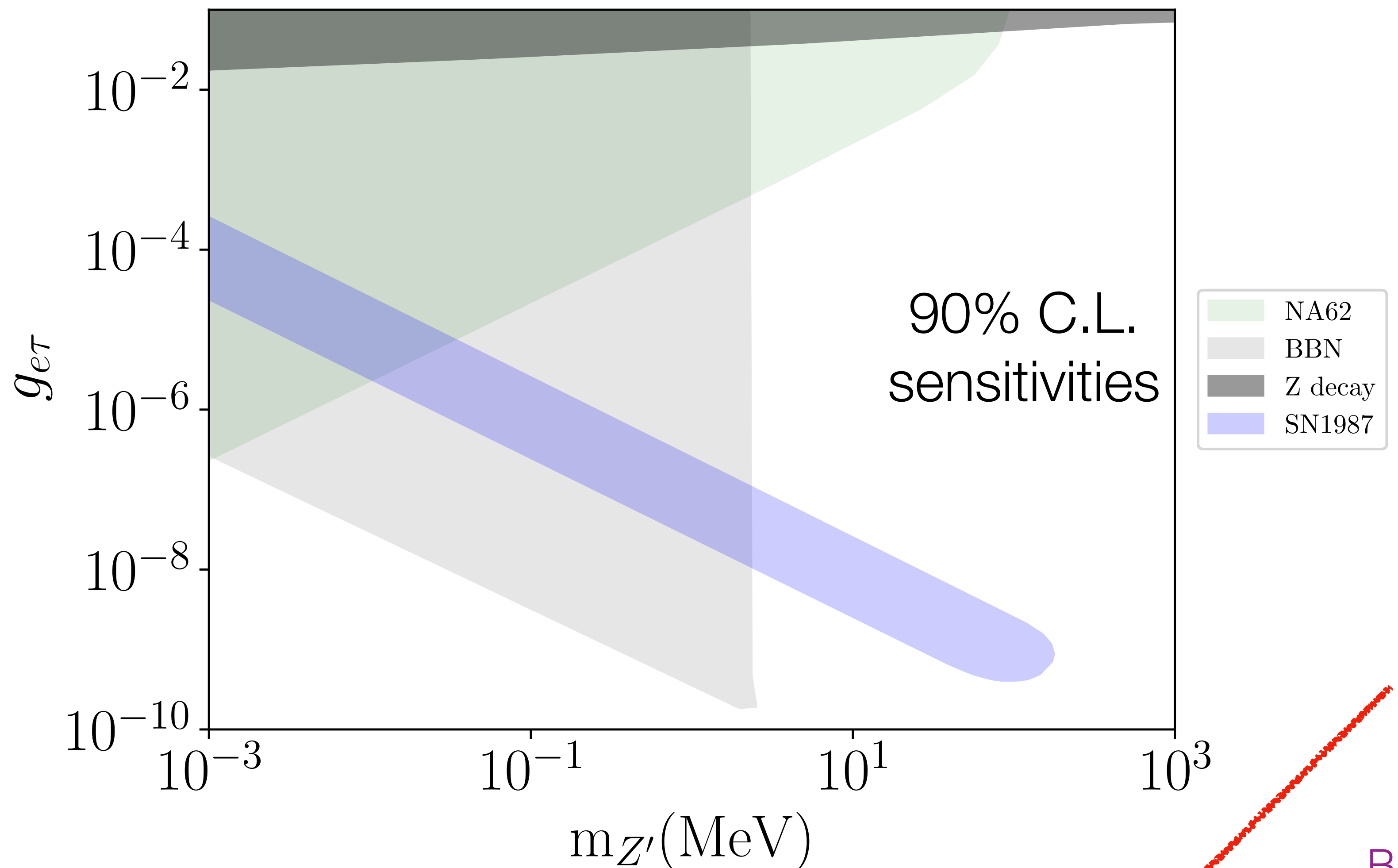




- $g_{e\tau}$ only: no other couplings to ν, $\ell^\pm$, B
- For $g_{\tau\tau}$, sensitivities are much weaker (BR: 10^{-4} smaller for 1 MeV) due to phase space suppression.

Sensitivities for ν_τ SNI: lab. bounds



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

Bakhti, Farzan, PRD 2017

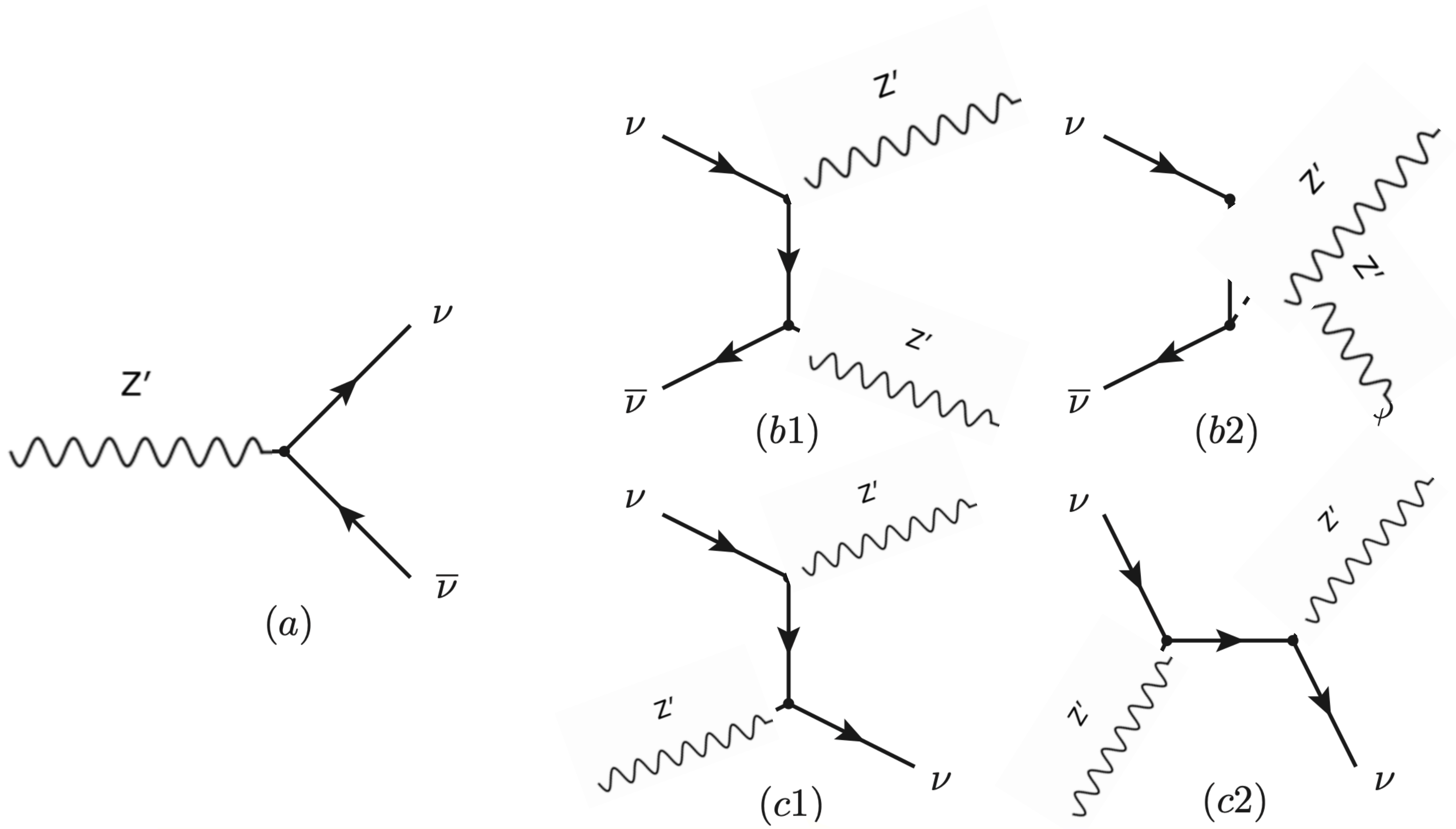
- NA62 (green): $R_K = \dfrac{\Gamma(K^+ \to e^+\nu_e)}{\Gamma(K^+ \to \mu^+\nu_\mu)}$ $(2.488 \pm 0.010) \times 10^{-5}$

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

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

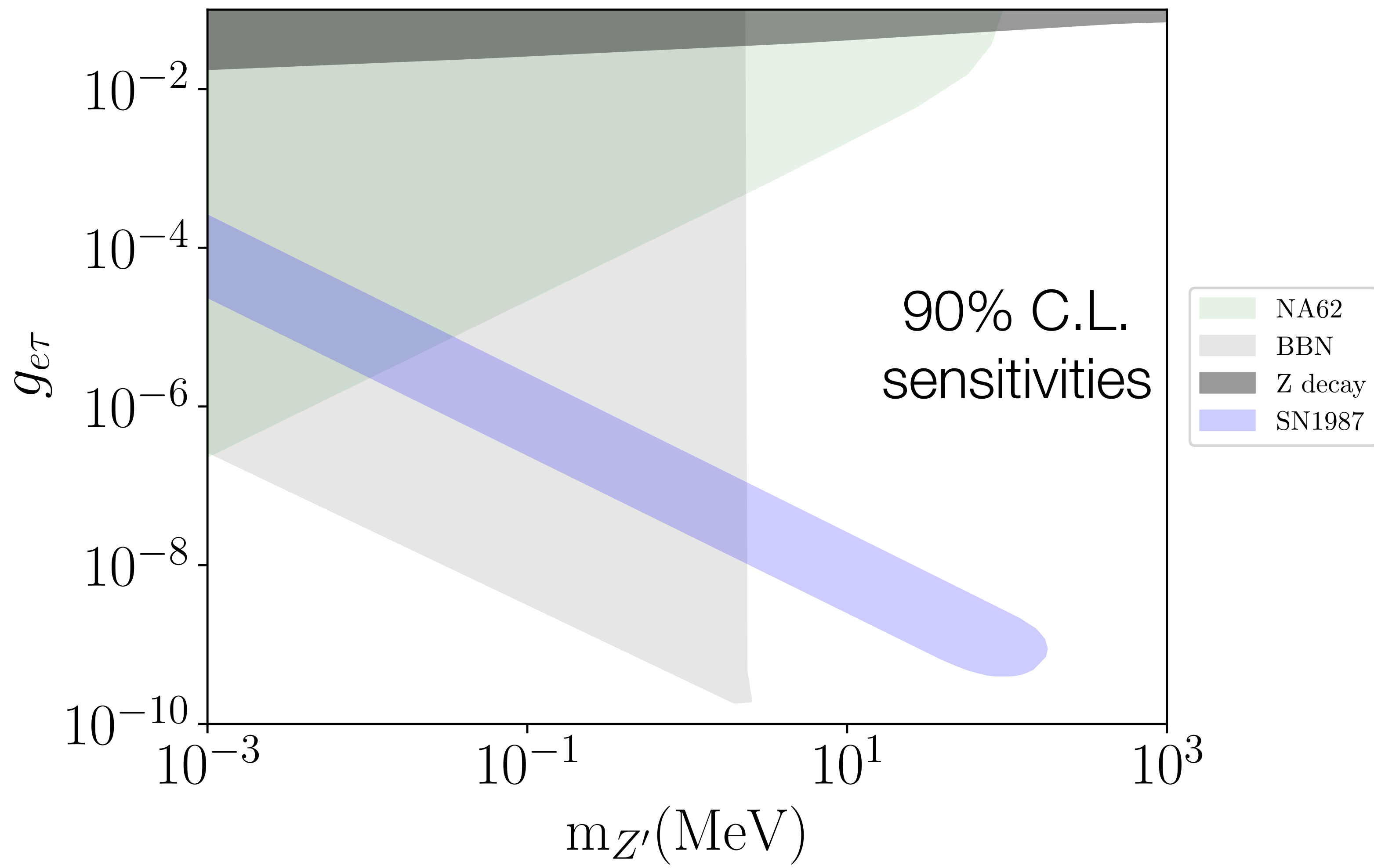
Sensitivities for ν_τ SNI: cosmo bounds

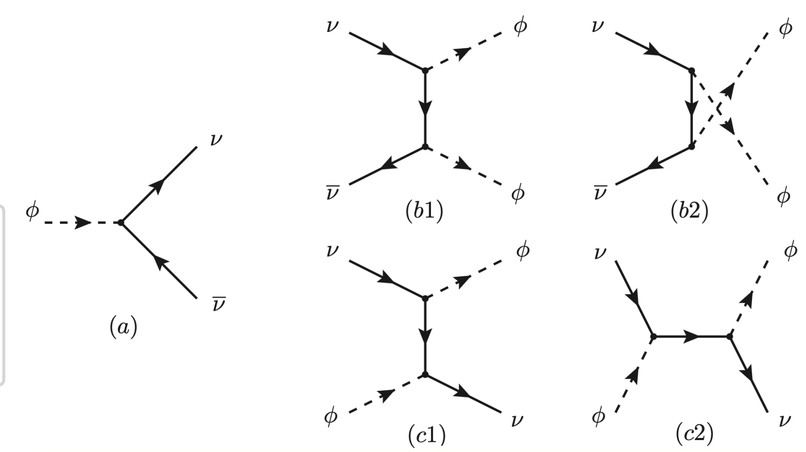
Main processes for thermal equilibrium or production of light mediators



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

Sensitivities for ν_τ SNI: cosmo bounds





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

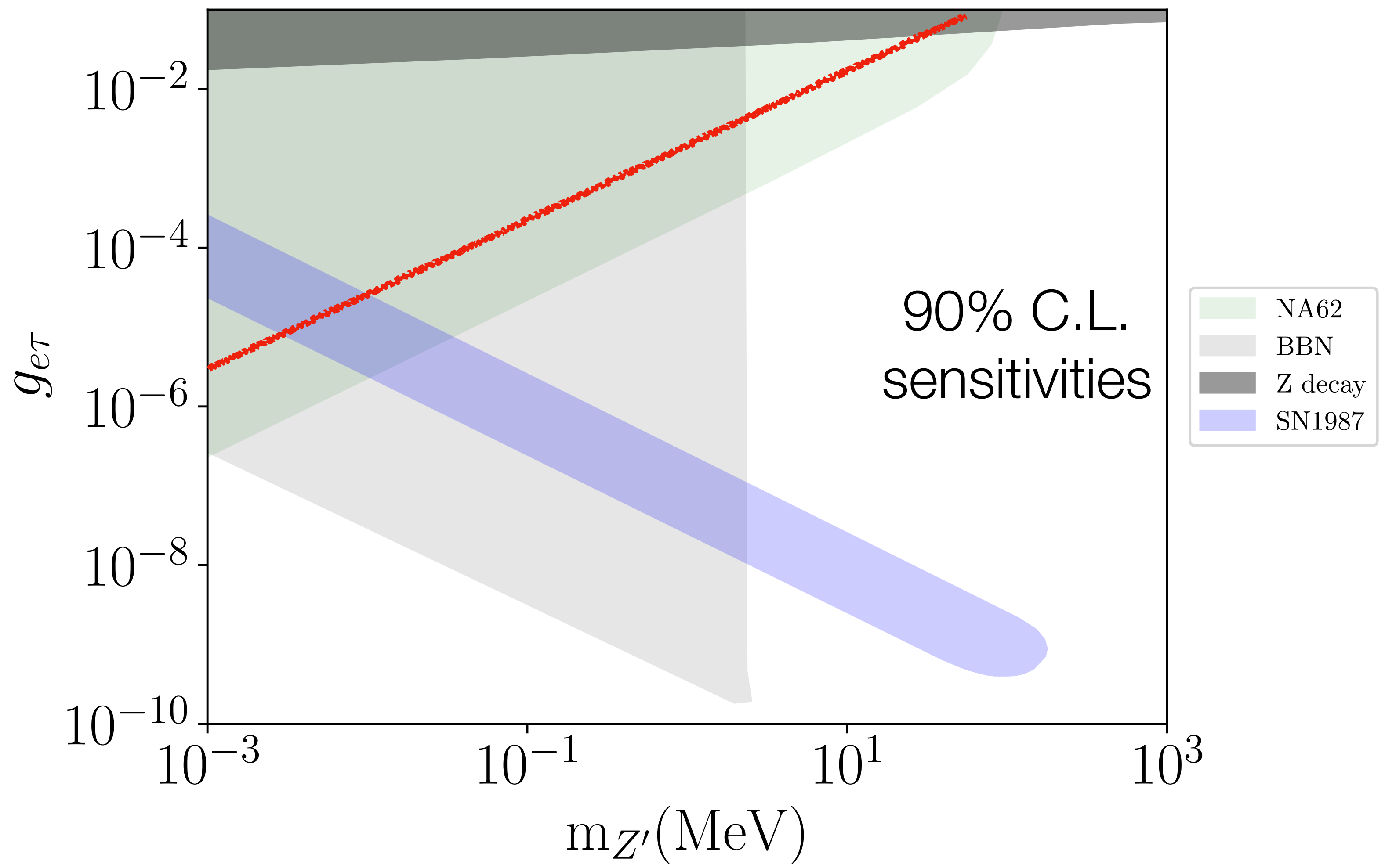
  primordial abundances of light elements for ν_e (similar)

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?

Talk by D. Camarena

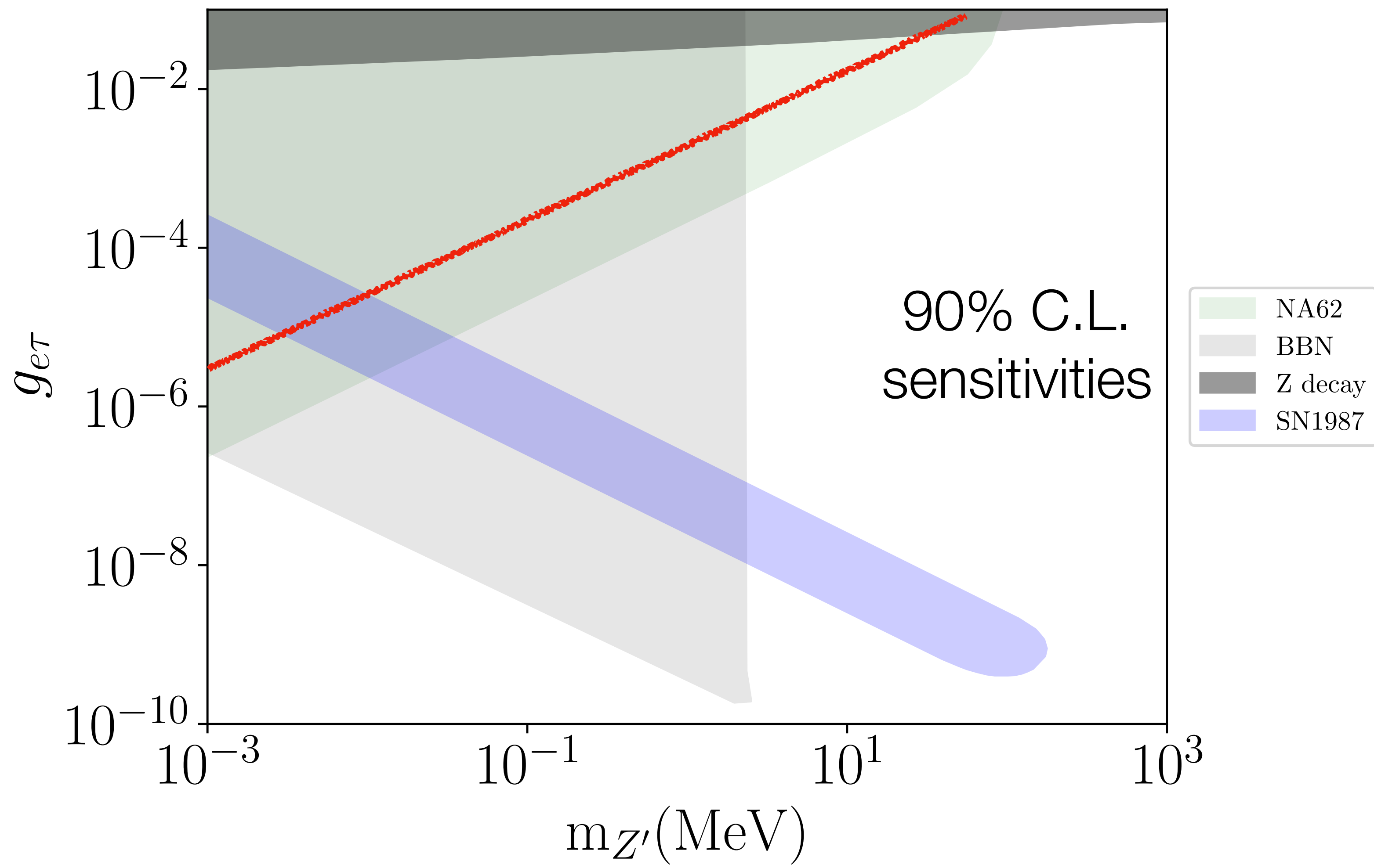
- Phase shift of the power spectrum by late ν free streaming

  → 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: cosmo bounds



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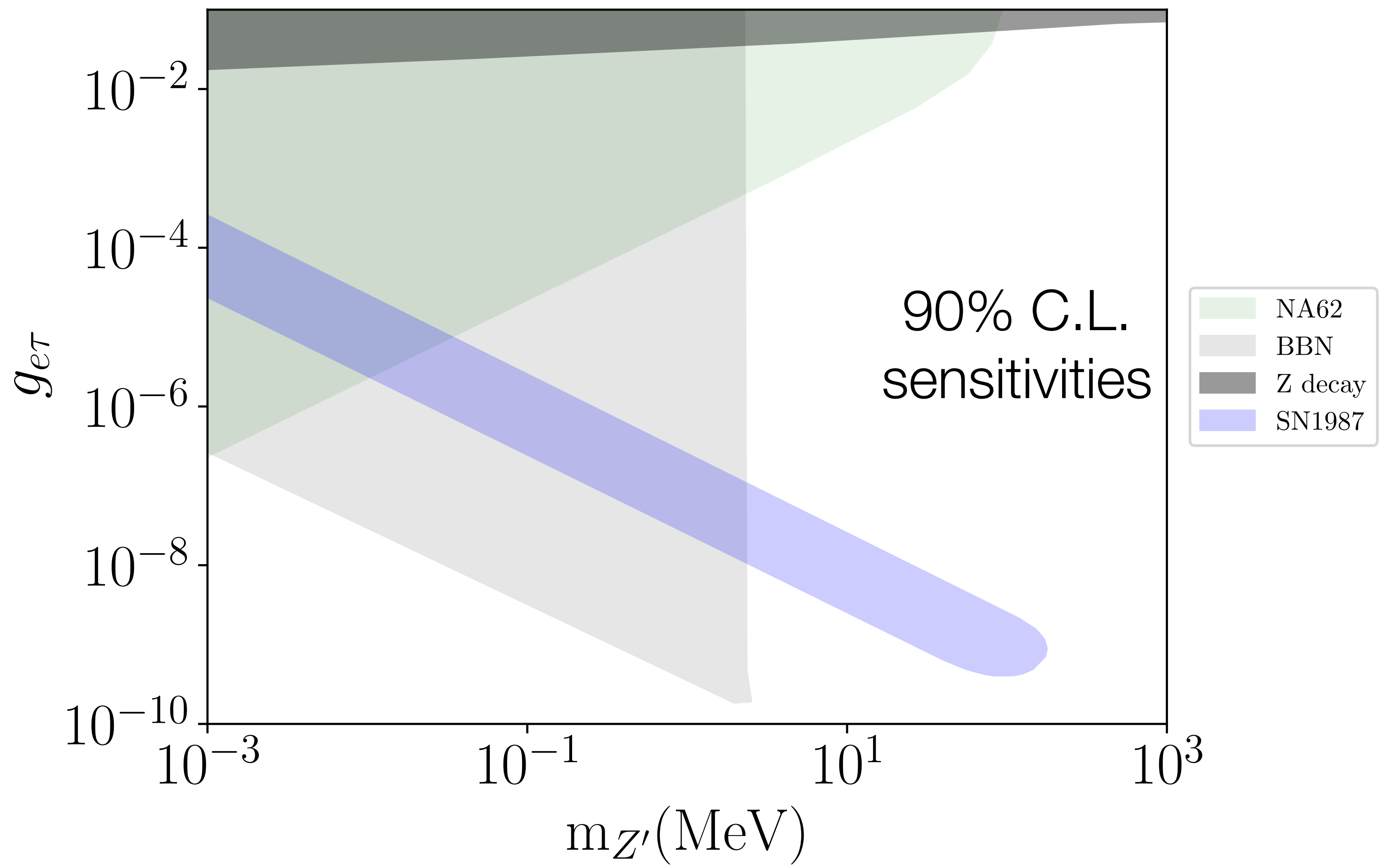
- $\Delta N_{\rm eff} \lesssim 0.3$ applies when $Z' \to \nu_e \nu_\tau$ in prior to the recombination epoch.

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

Sensitivities for ν_τ SNI: astro bounds



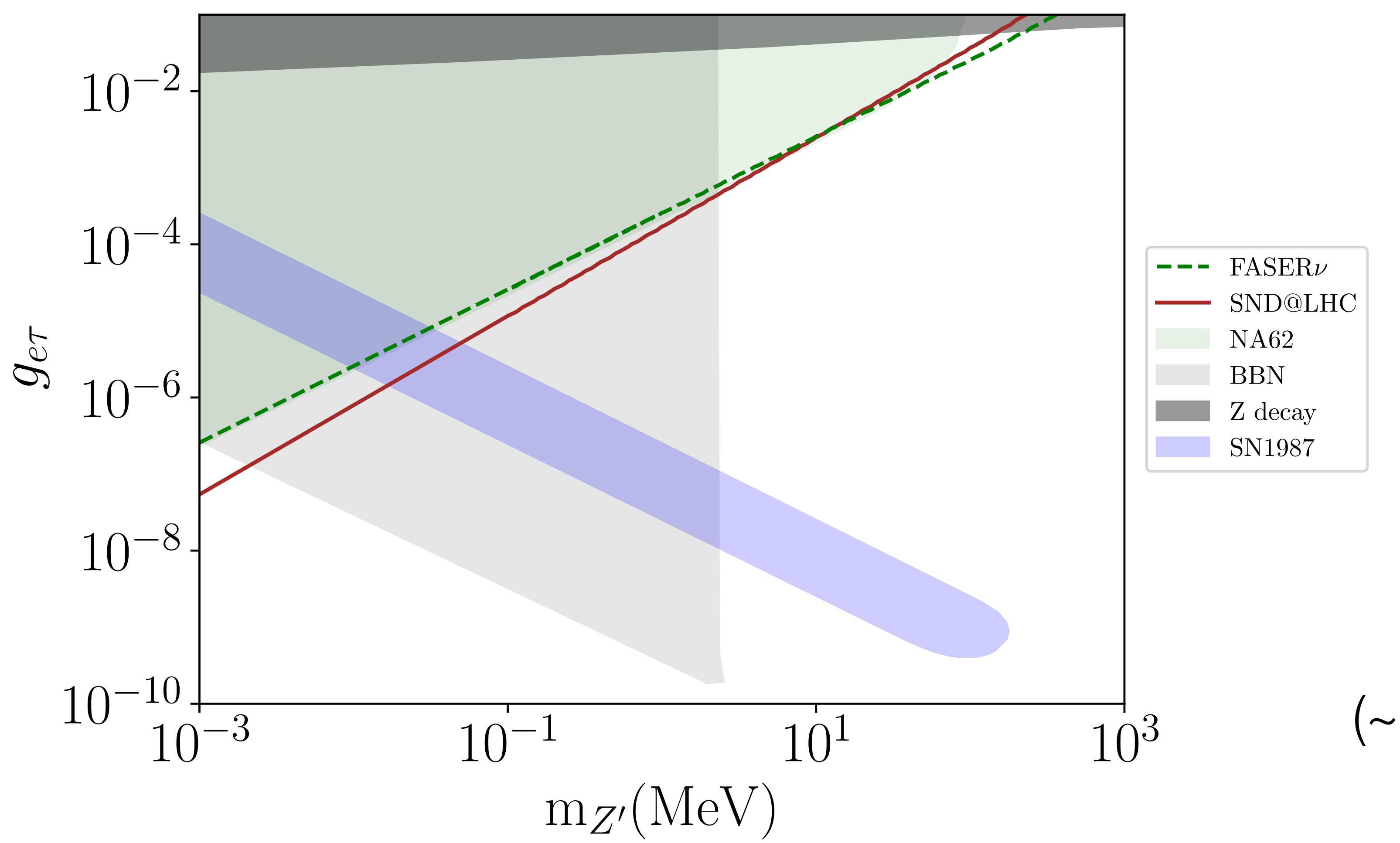
Talk by Y.Z. Qian

- 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

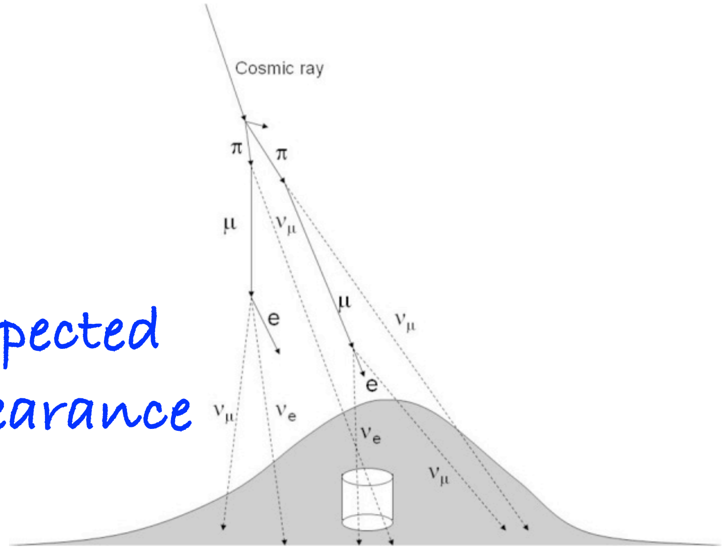
(~ 30 fb^{-1} as of Mar 2023)

- 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 (detailed analysis in progress).

Sensitivities for ν_τ SNI: DUNE FD

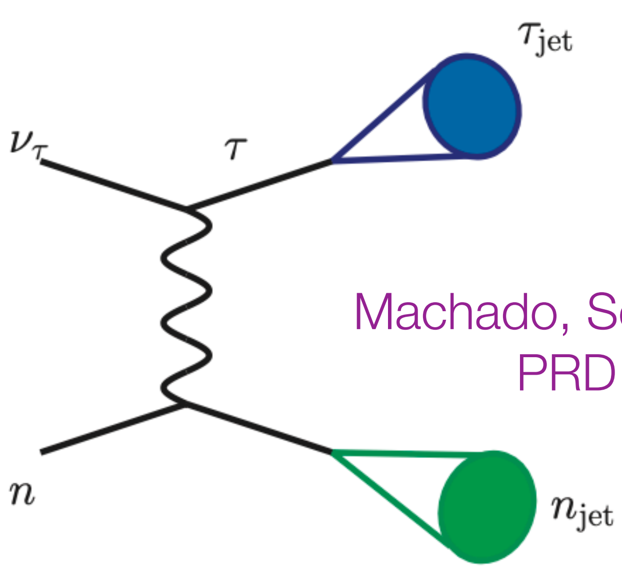
Unexpected
ν_τ appearance



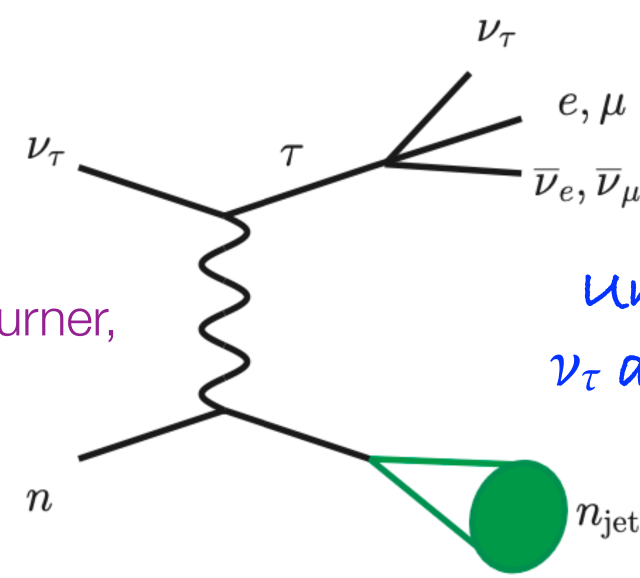
Sensitivities for ν_τ SNI: DUNE FD

Background?

- In ideal situations, no backgrounds.



Machado, Schulz, Turner,
PRD 2020



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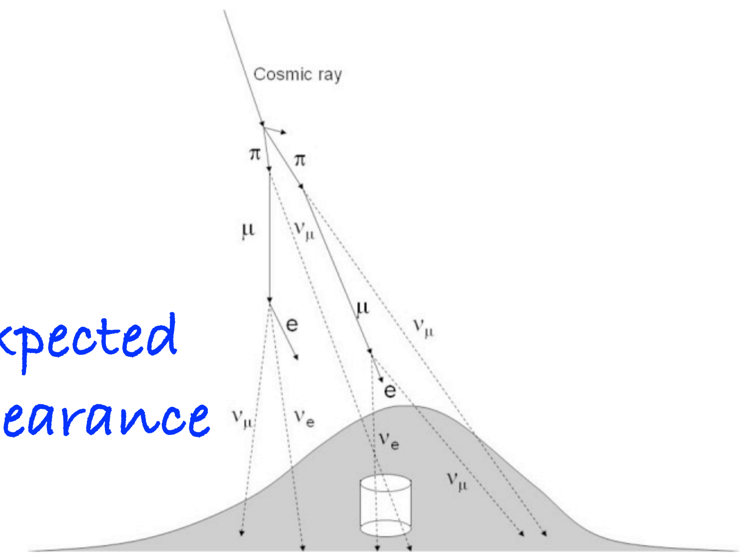

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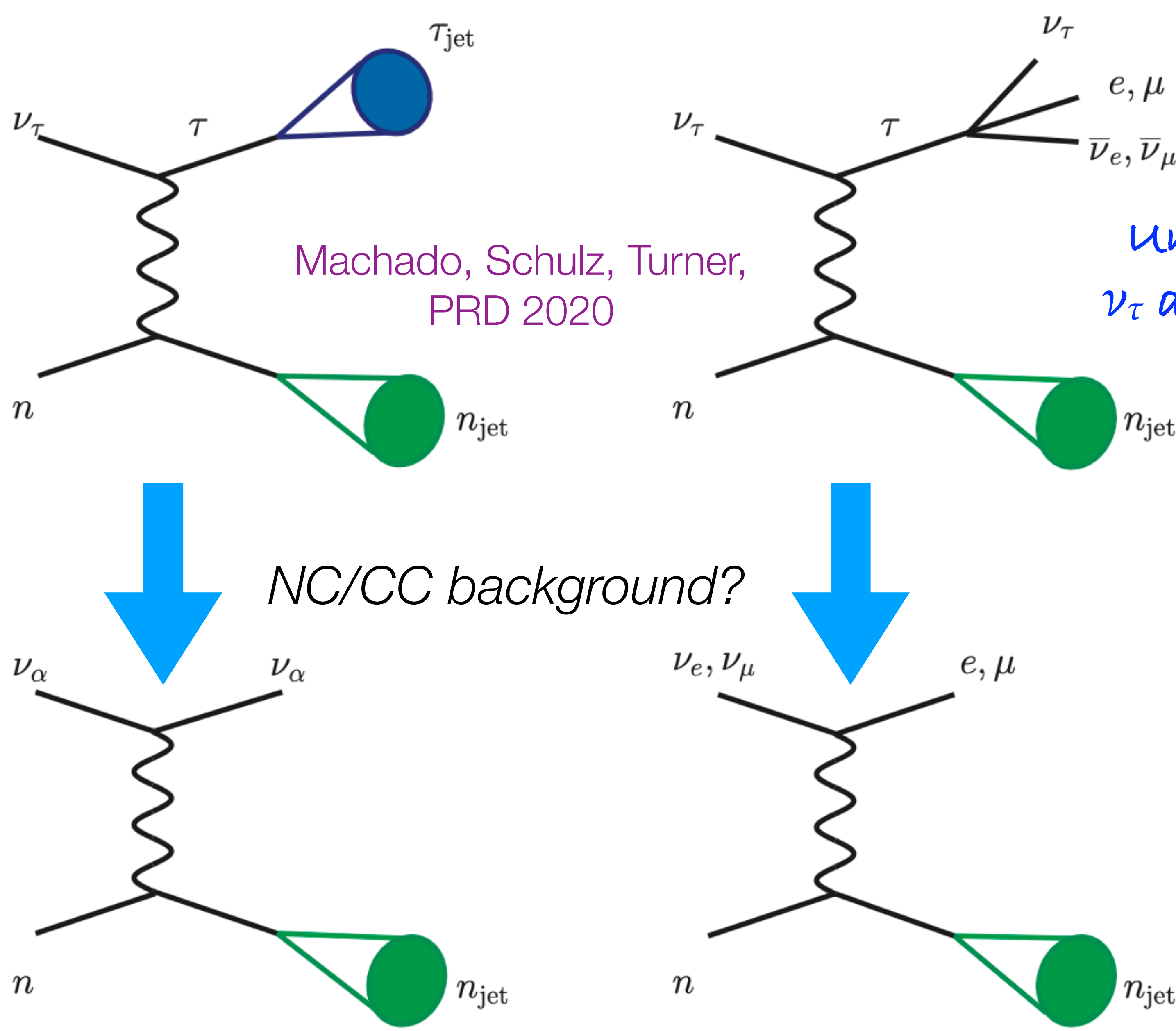

Machado, Schulz, Turner, PRD 2020

NC/CC background?

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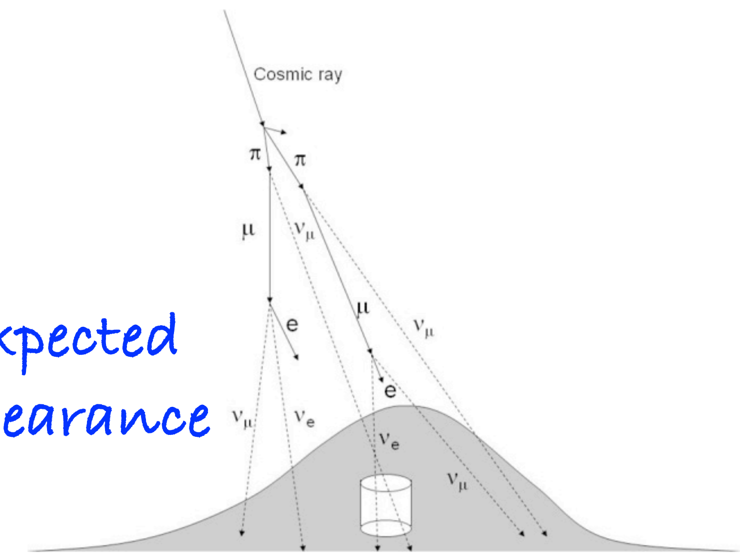

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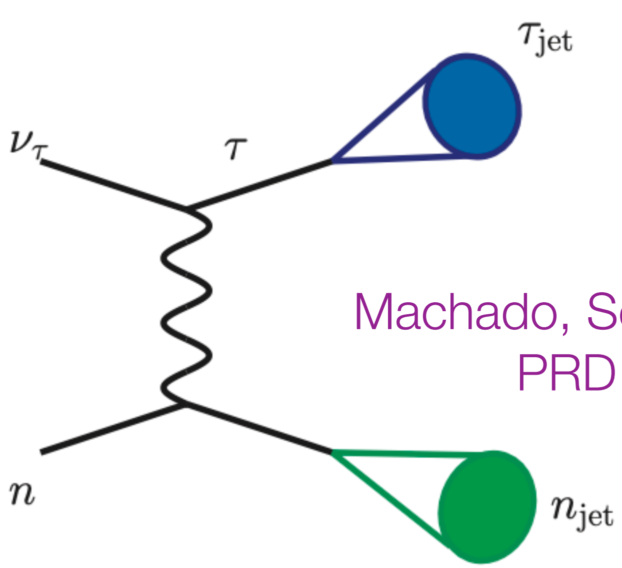

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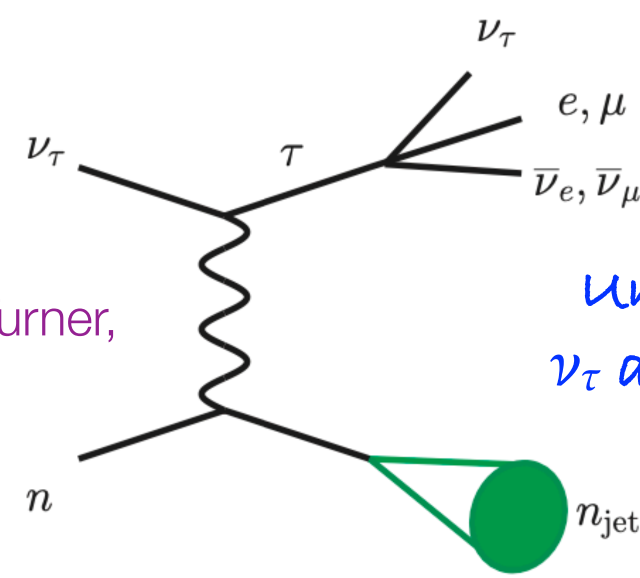

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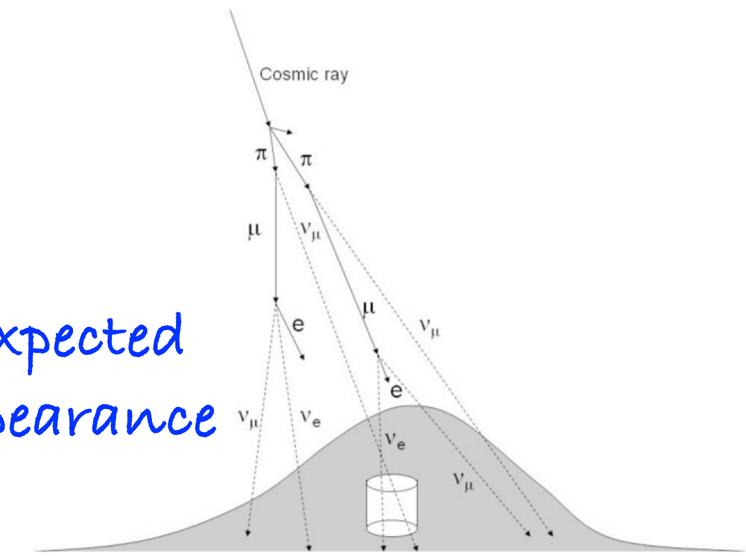

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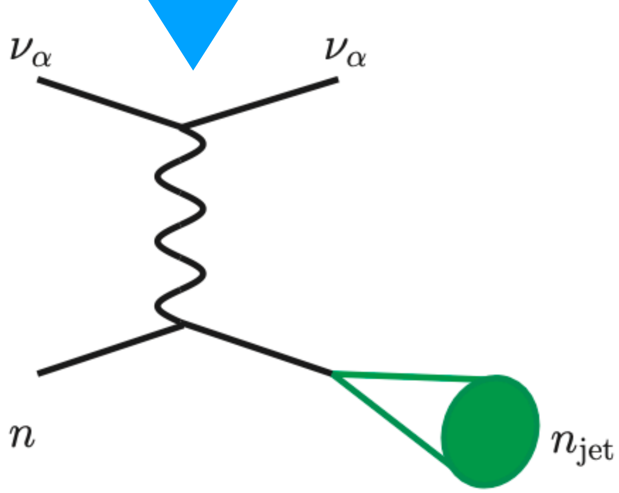

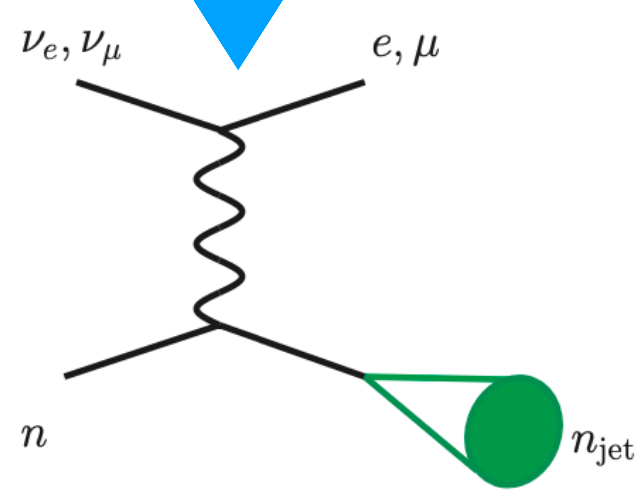

DUNE: expected to have excellent event topology reconstruction capabilities.

↓

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

Sensitivities for ν_τ SNI: DUNE FD

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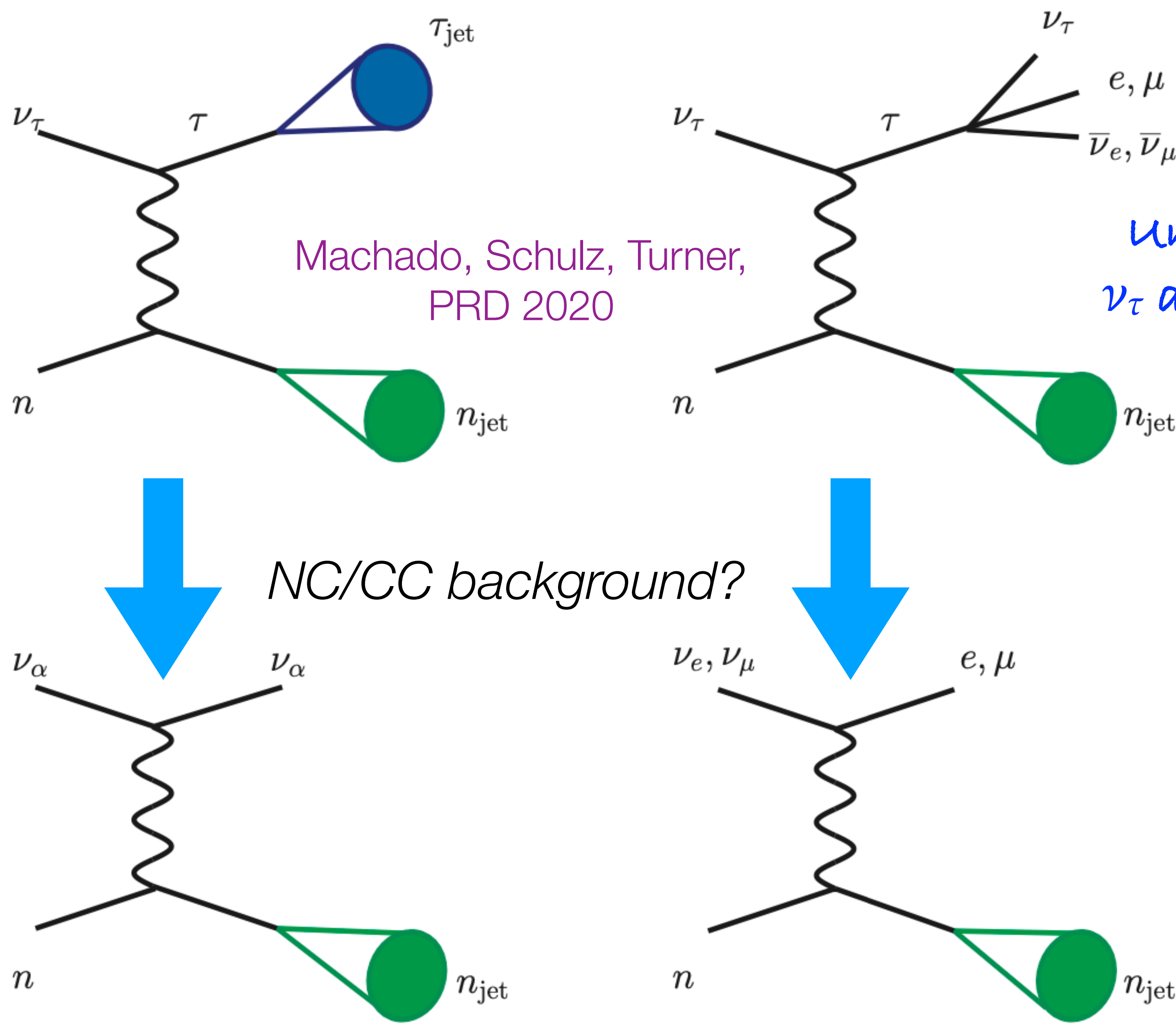

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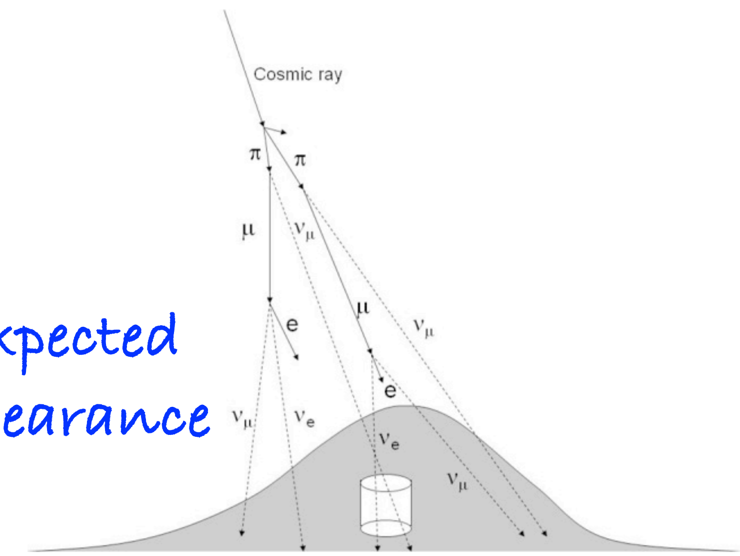

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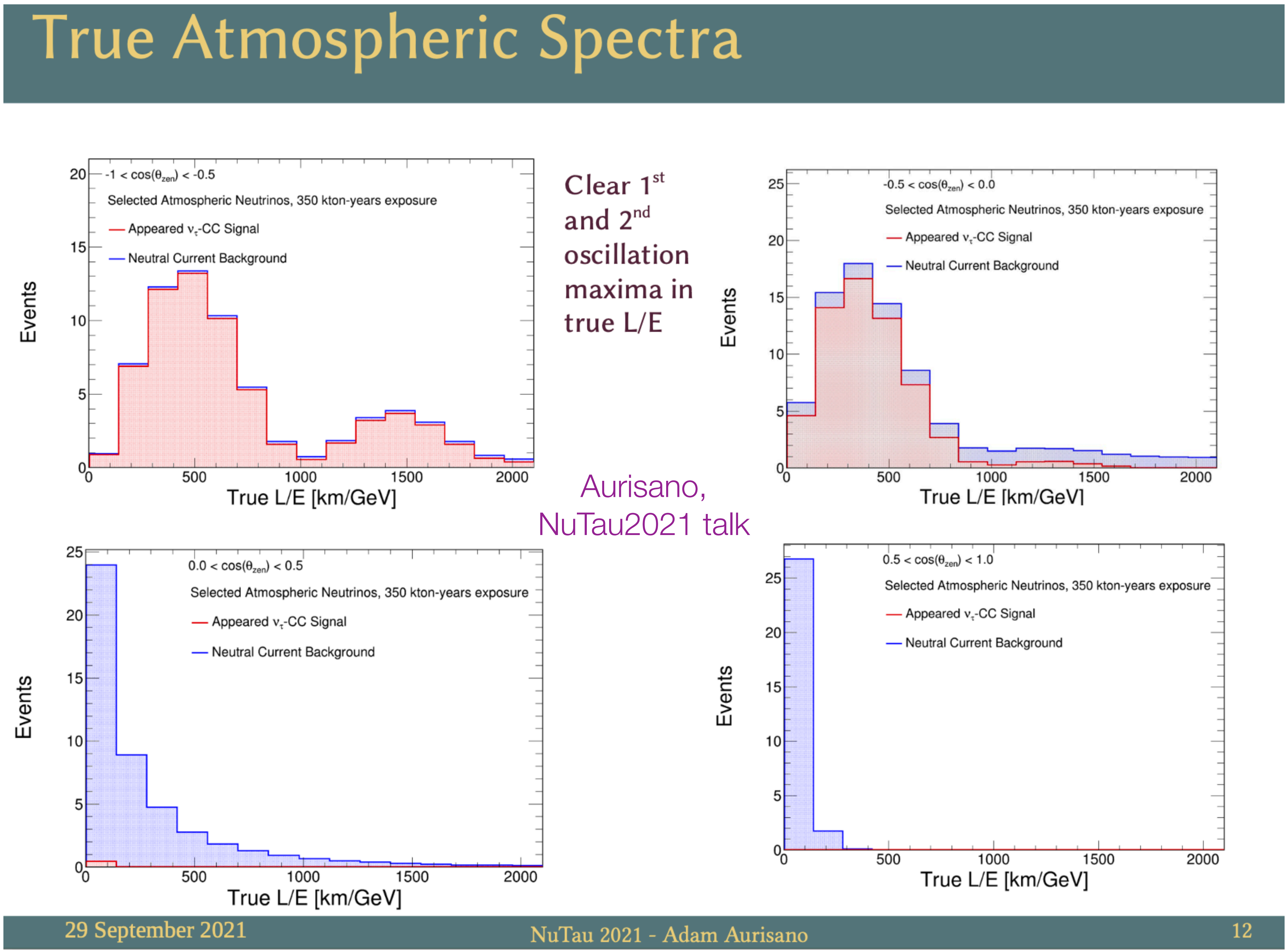
Apply the methods in collider pheno, e.g., jet clustering, cuts, …

- Signal-to-background efficiencies increase!

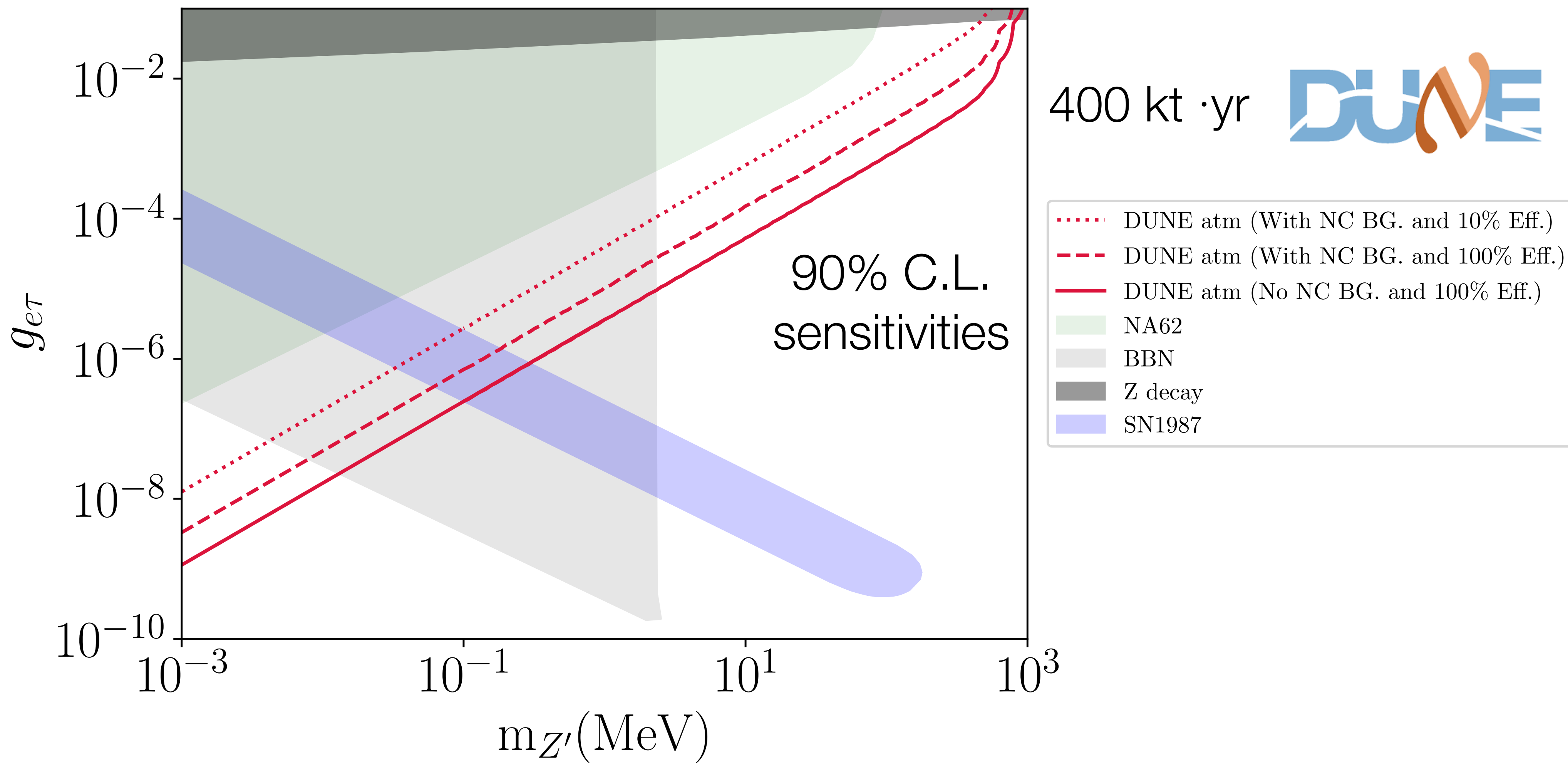
Sensitivities for ν_τ SNI: DUNE FD



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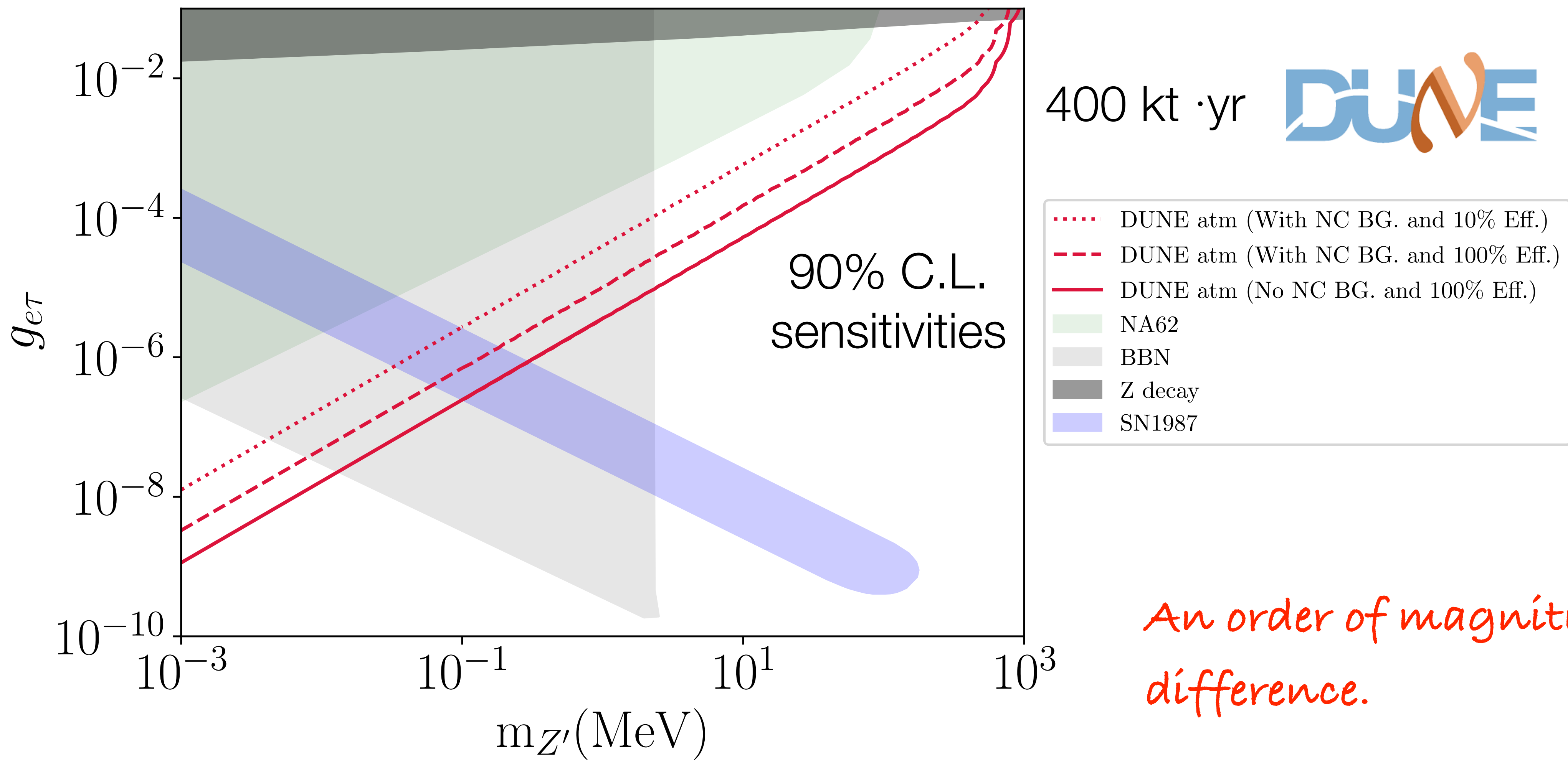
DUNE, arXiv:2002.03005 Machado, Schulz, Turner, PRD 2020

Sensitivities for ν_τ SNI: DUNE FD



An order of magnitude difference.

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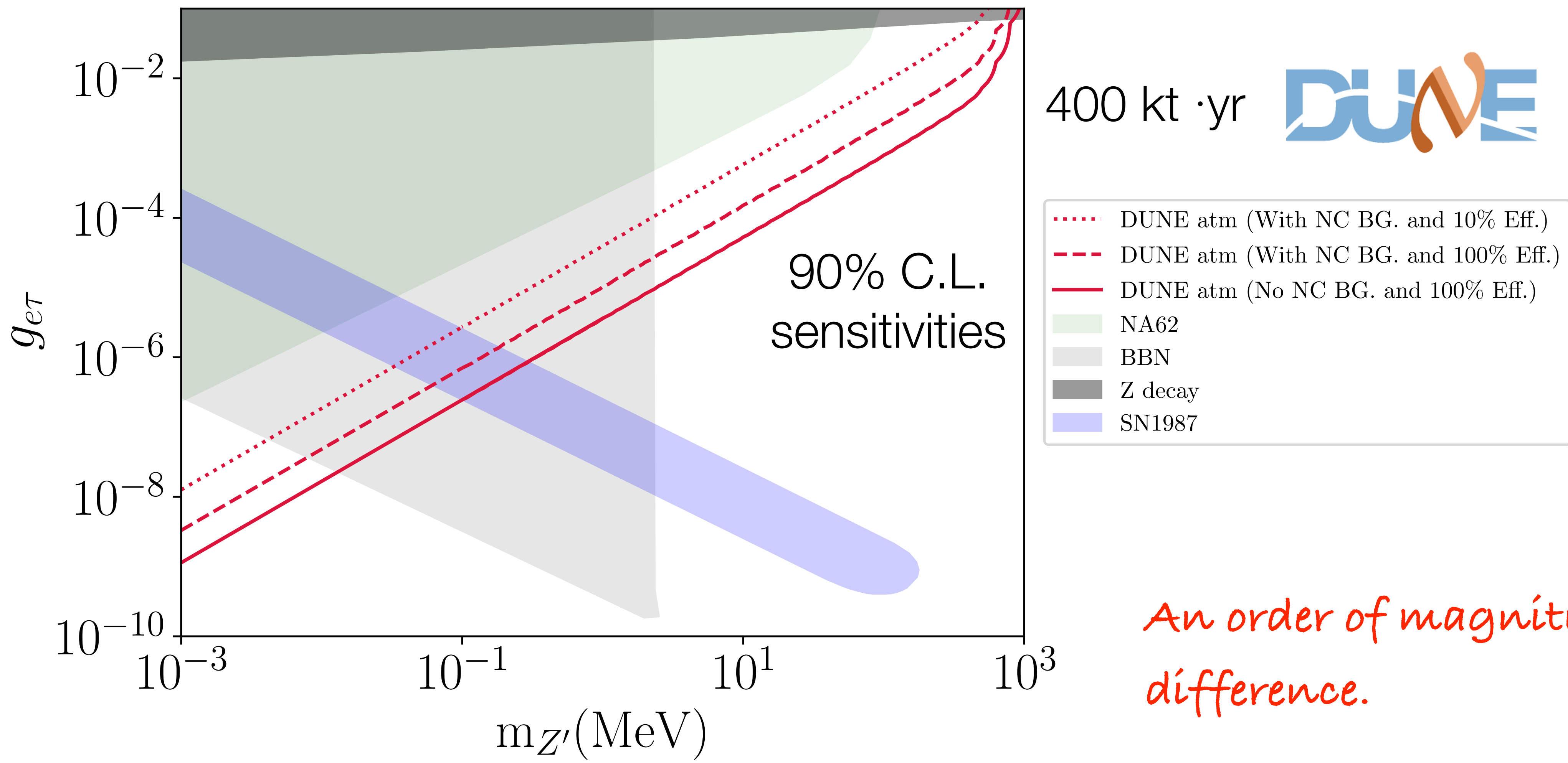

400 kt ·yr

DUNE

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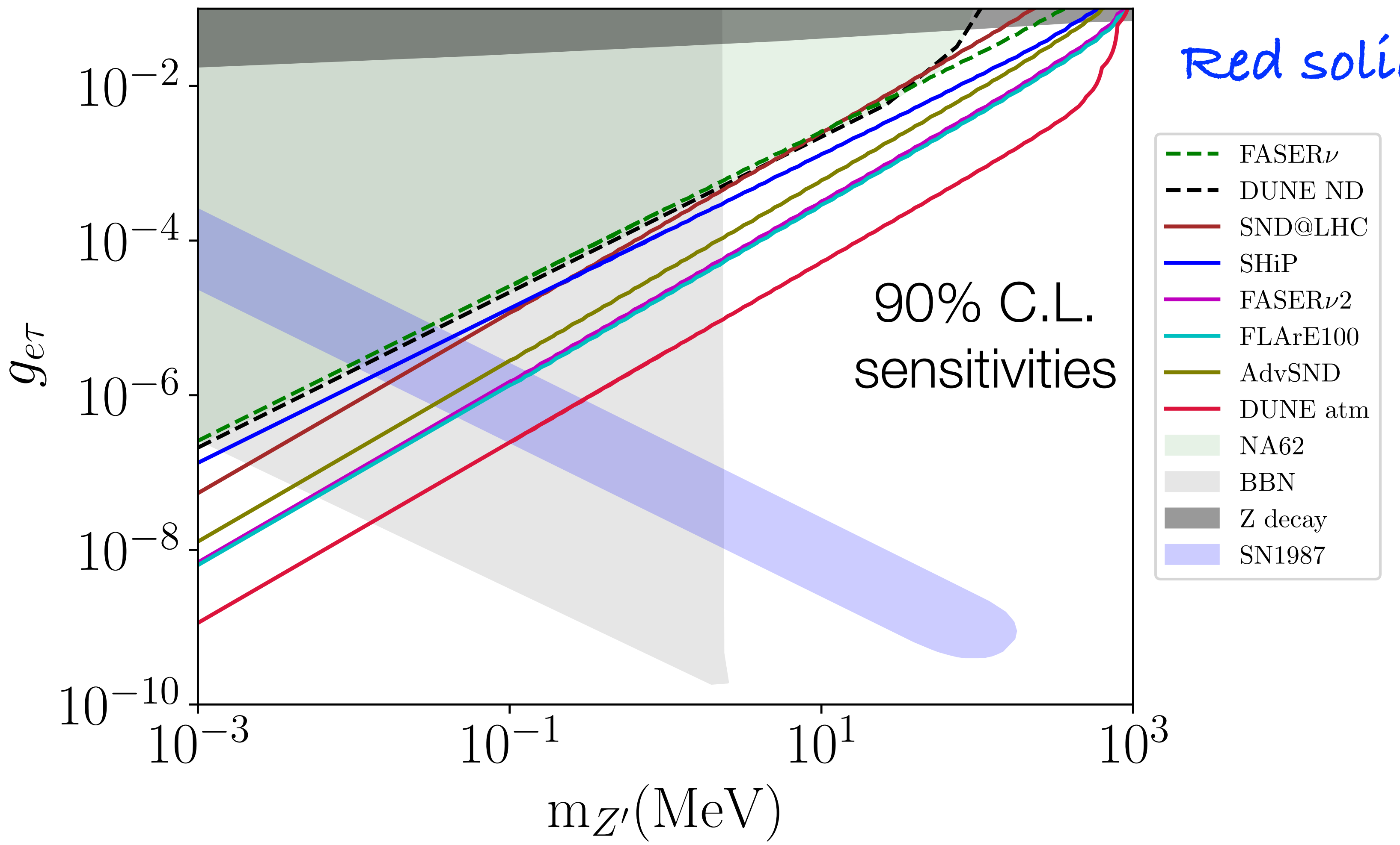
DUNE, arXiv:2002.03005 Machado, Schulz, Turner, PRD 2020

- 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



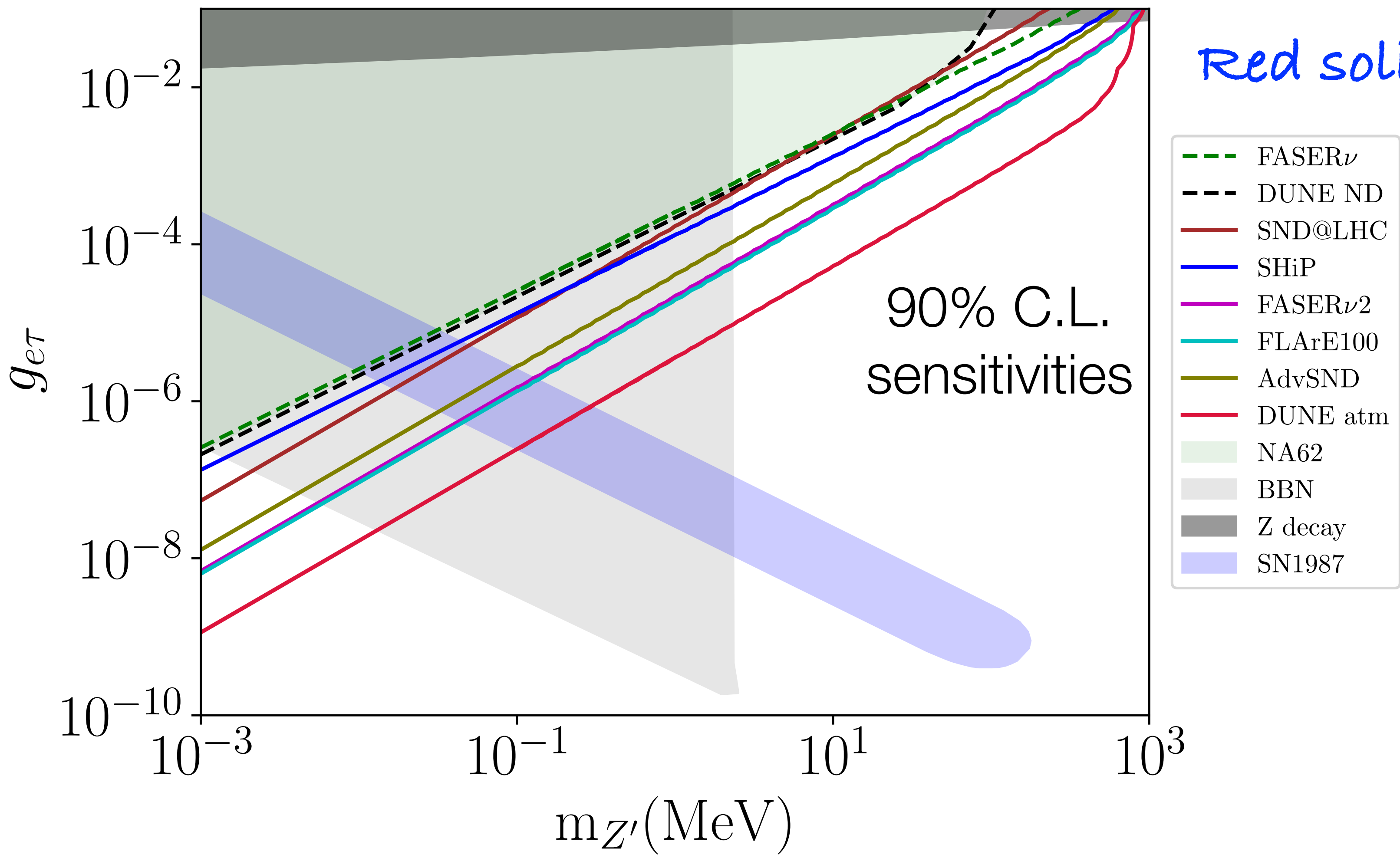
Red solid: DUNE best case

SND@LHC/ FASERν: 150 fb^{-1}

SHiP: 2×10^{20} POT (5 yrs)

FPF: 3 ab^{-1}

Sensitivities for ν_τ SNI: FPF, SHiP



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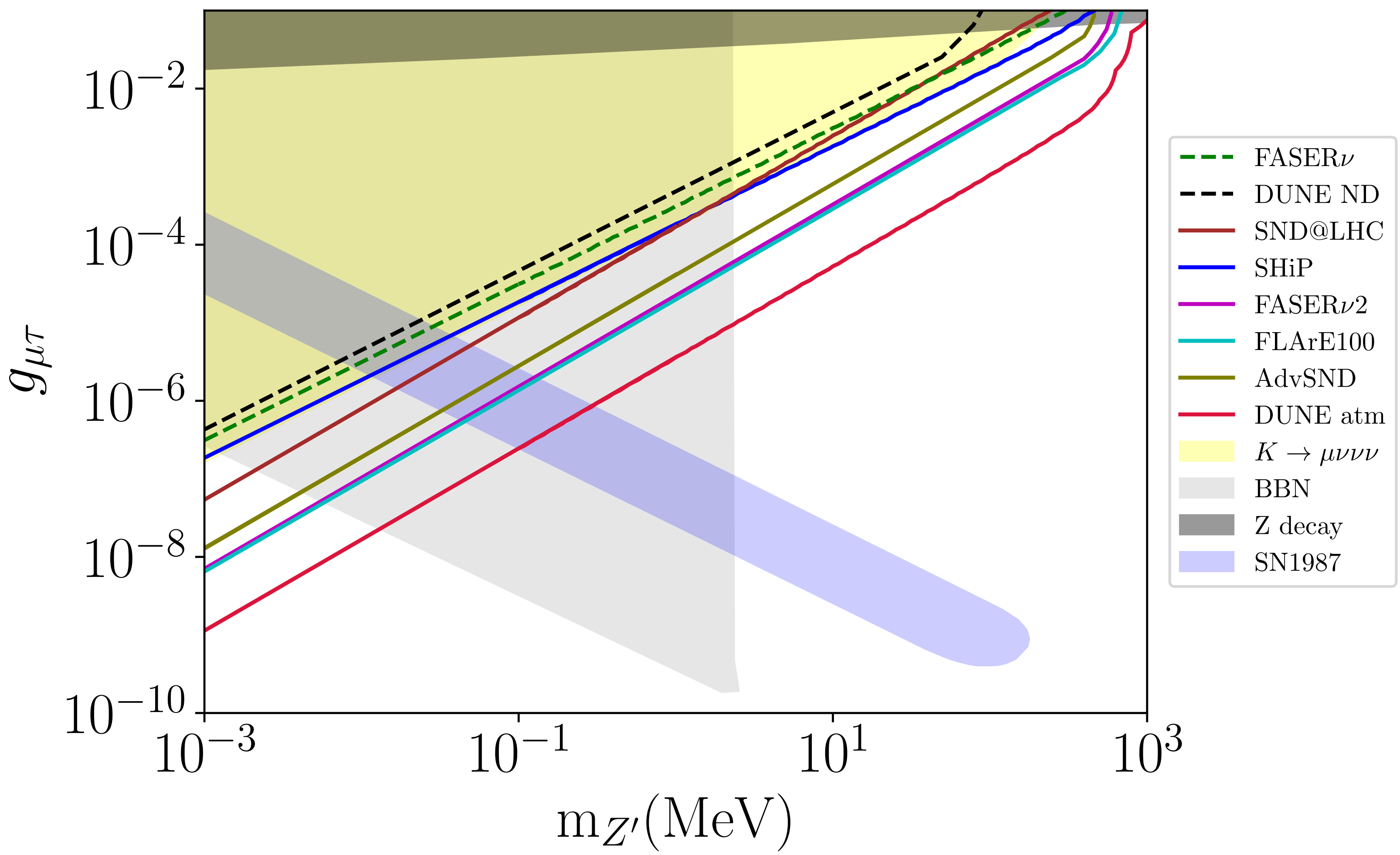
SHiP: 2×10^{20} POT (5 yrs)

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.

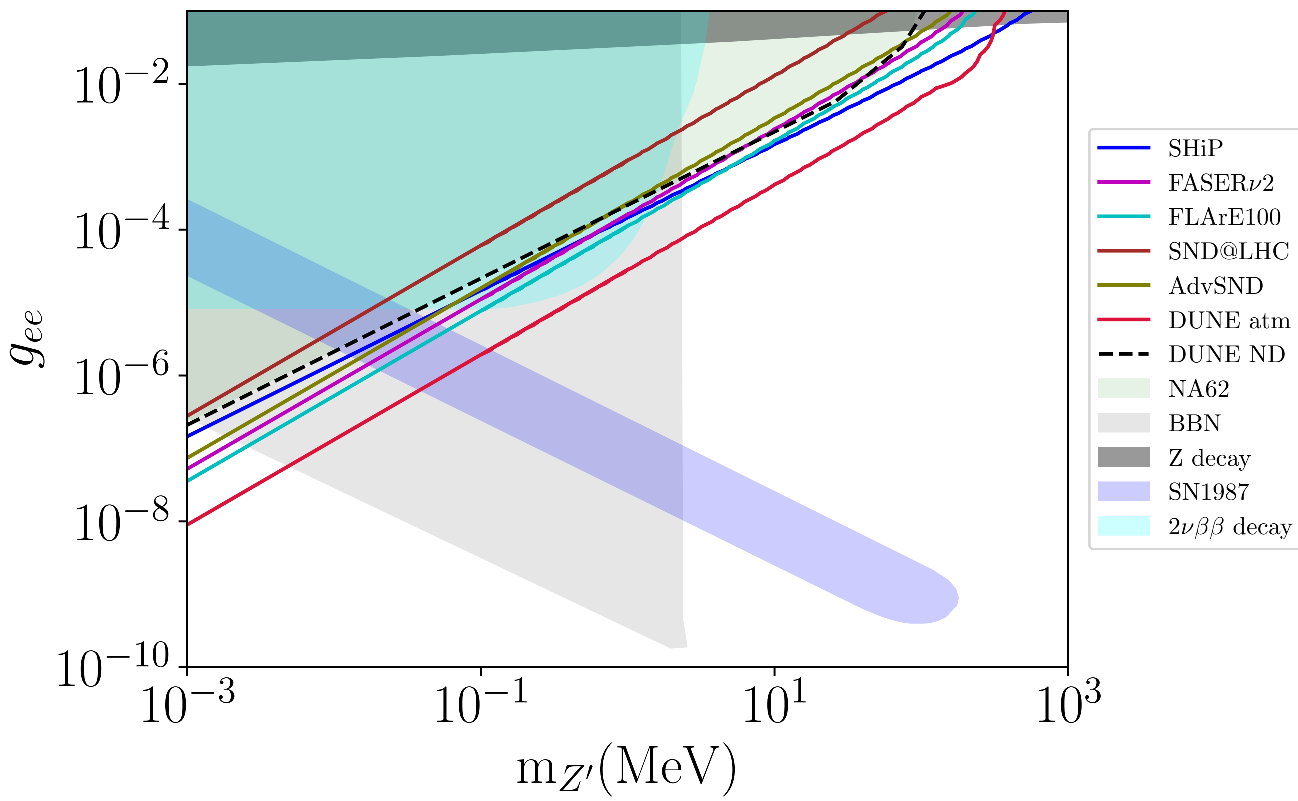
- DUNE far detector (400 kt·yr) is still most sensitive for $m_{Z'} \gtrsim 1$ MeV, $m_{Z'} \lesssim 60$ keV.

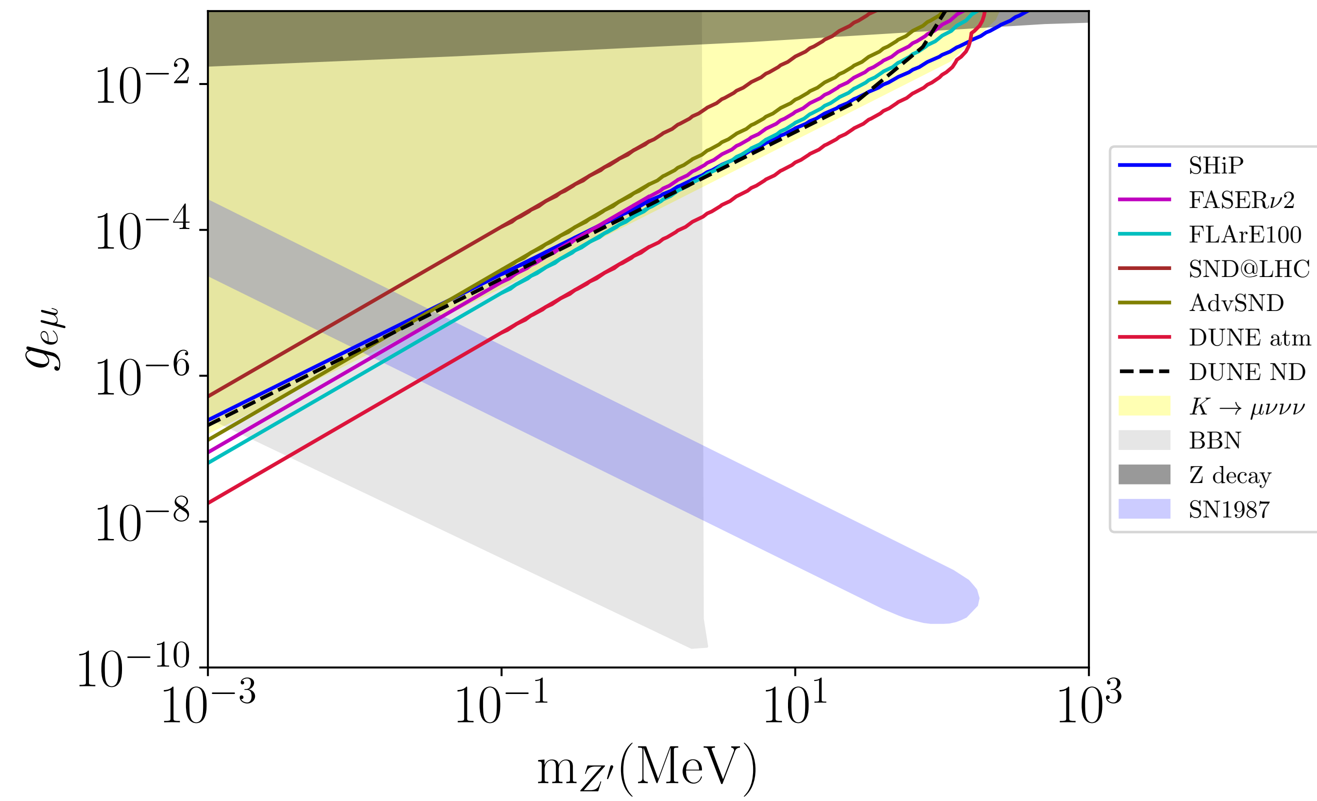
- We now apply the rare Kaon decay constraint at E949 (yellow).

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

Sensitivities for ν_τ SNI

Comparison with the other flavor couplings

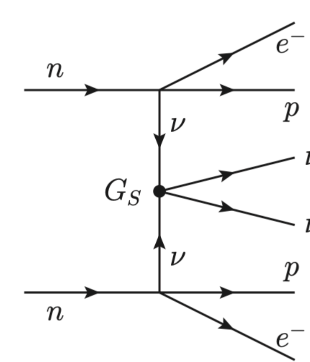




- DUNE far detector (400 kt·yr) is still most sensitive for $m_{Z'} \gtrsim 1$ MeV, $m_{Z'} \lesssim 10$ keV but at least about an order of magnitude weaker than $g_{e\tau}$, $g_{\mu\tau}$.

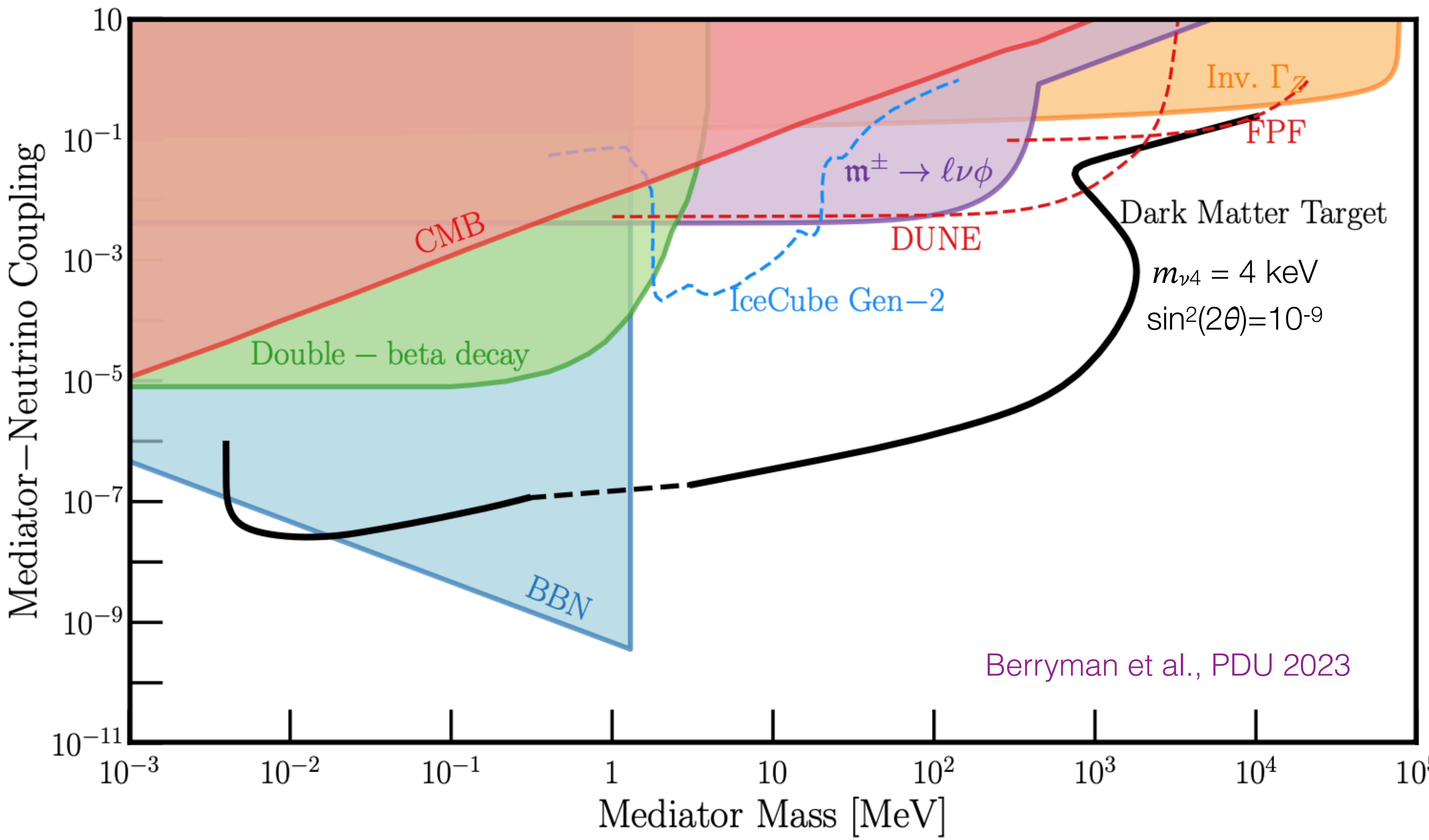
- $2\nu\beta\beta$ applies but weaker than the others.

- Shape of the (atmospheric) flux uncertainty can wash out the sensitivities.



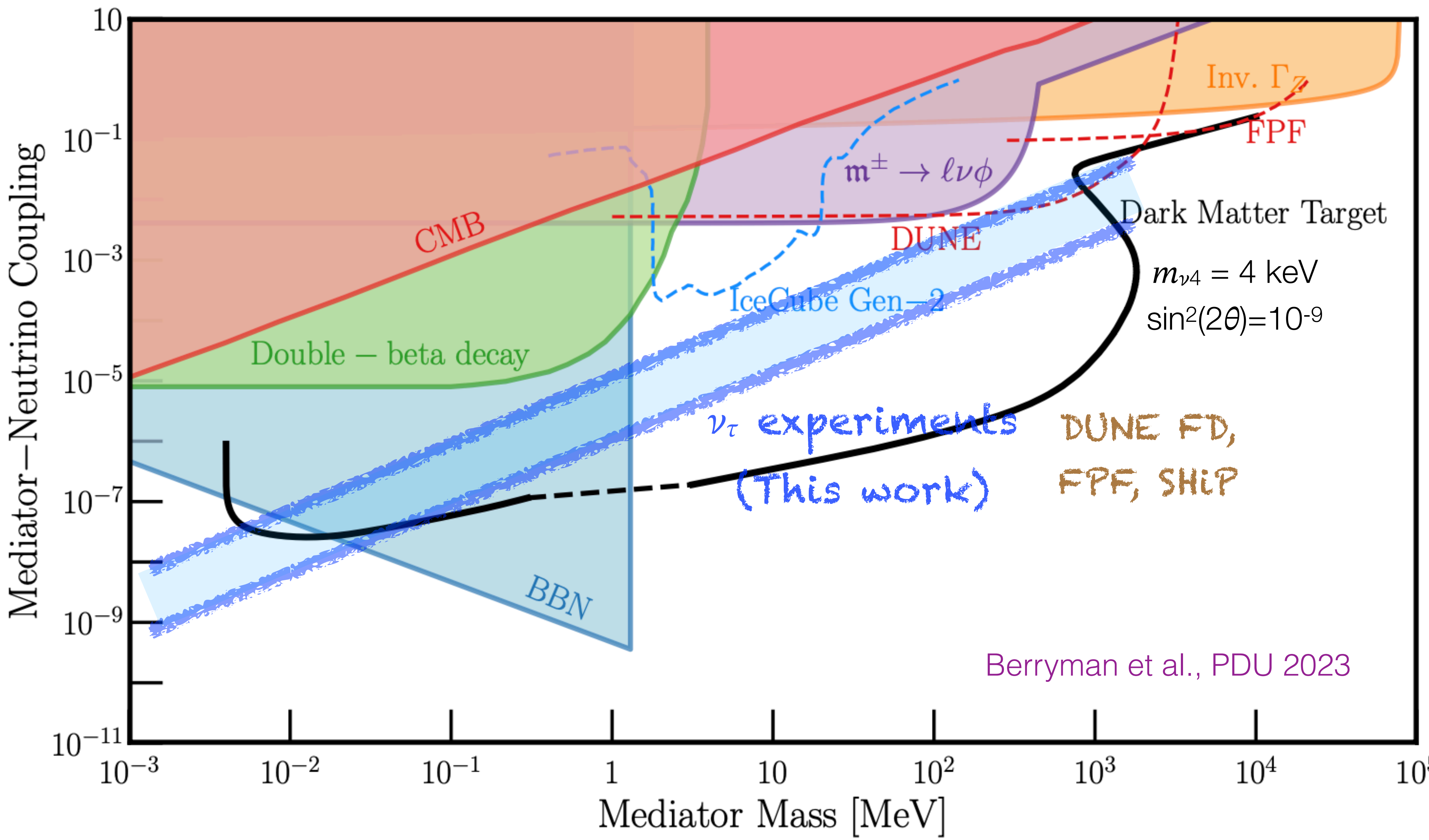
Deppisch, Graf, Rodejohann, Xu, PRD 2020

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 flavor non-universal or off-diagonal SNI in cosmo/astro, mediators with other spins, cLFV rare decays.