DEPARTMENT OF PHYSICS

A comprehensive analysis of supernova neutrino-dark matter interactions

Mitchell Conference

Deepak Sathyan

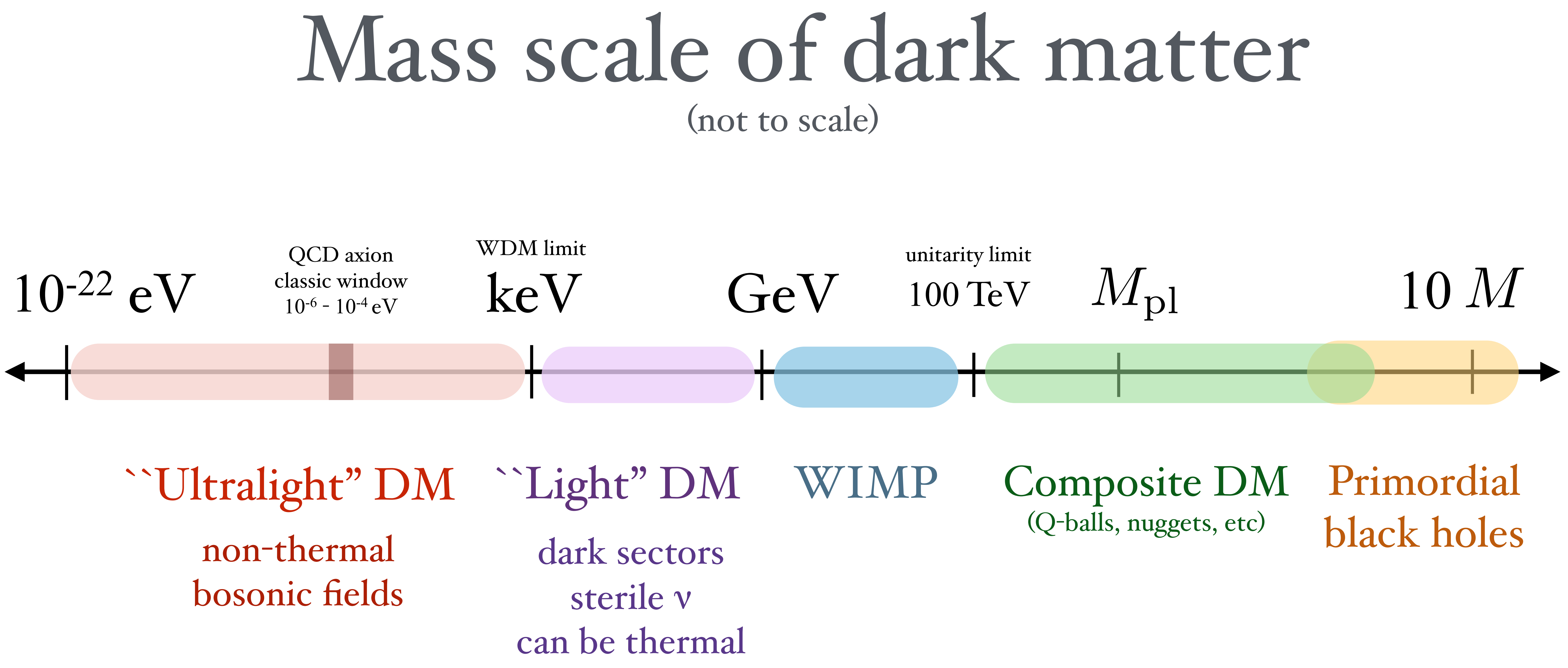
May 23, 2024

[2406:xxxx] by Bhupal Dev, Doojin Kim, DS, Kuver Sinha, and Yongchao Zhang

Two sectors of interest:

Dark Matter and Neutrinos

- What is the nature of dark matter and its interactions?
  - What is its mass?
  - What is its spin?
  - Does it have non-gravitational interactions?



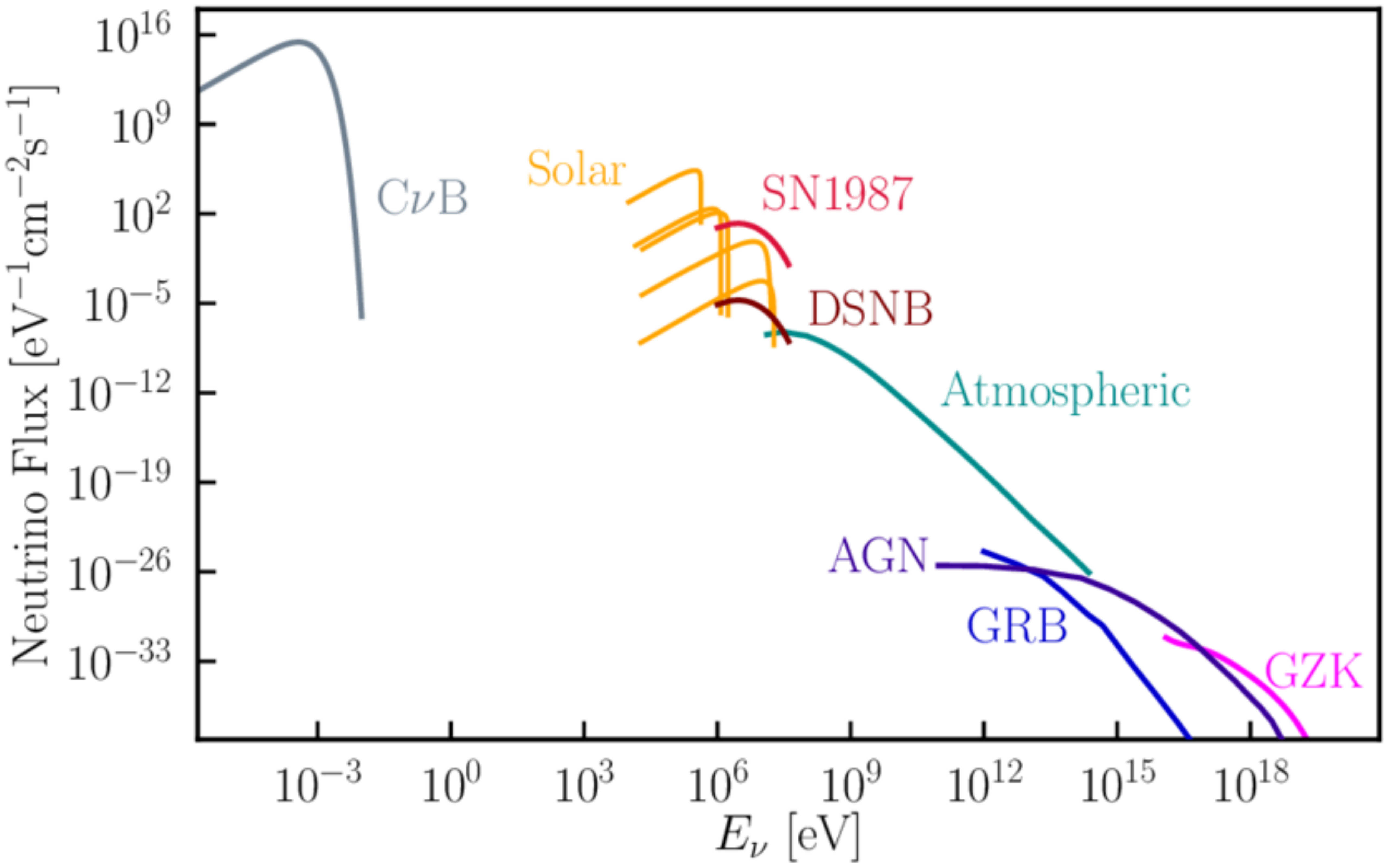
Tongyan Lin [1904.07915]

Two sectors of interest:

Dark Matter and Neutrinos

- Exploring neutrinos
  - Majorana vs Dirac?
  - Normal/Inverted ordering?
  - Any non-standard interactions?

- Observed neutrino energy scale can tell us about different kinds of physics

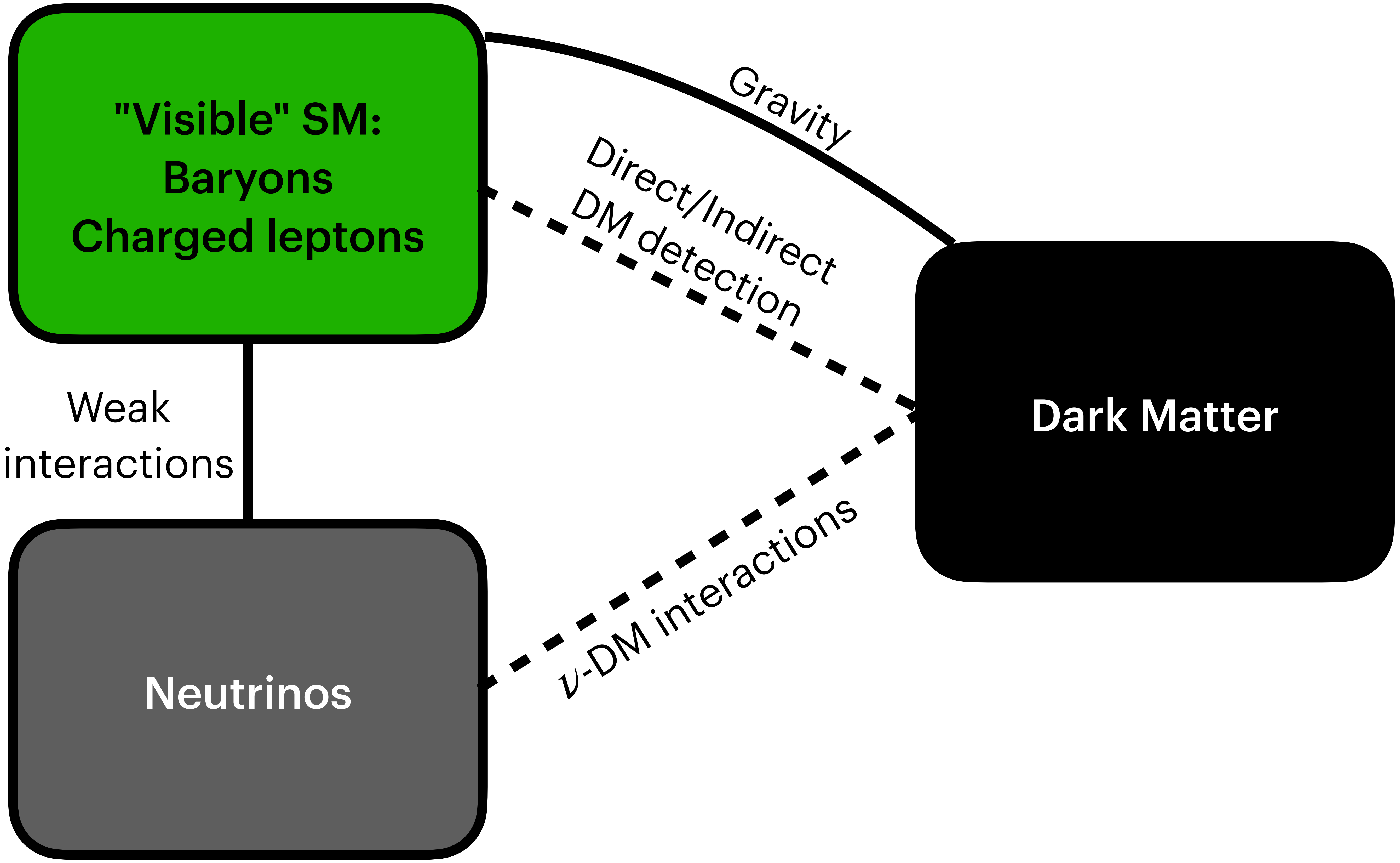


C. Argüelles, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A. Vincent
[DOI: 10.22323/1.395.0542]

Two sectors of interest:

Dark Matter and Neutrinos

- Can these two sectors interact, and can we be sensitive to it?



Observing ν-DM interactions

- How do we observe ν-DM interactions?

Opacity $\tau = \sigma \int \frac{\rho_\chi}{m_\chi} \mathrm{d}\ell$

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- Large τ obtained from:
  - large number density of DM
  - large distance for neutrinos to travel through DM

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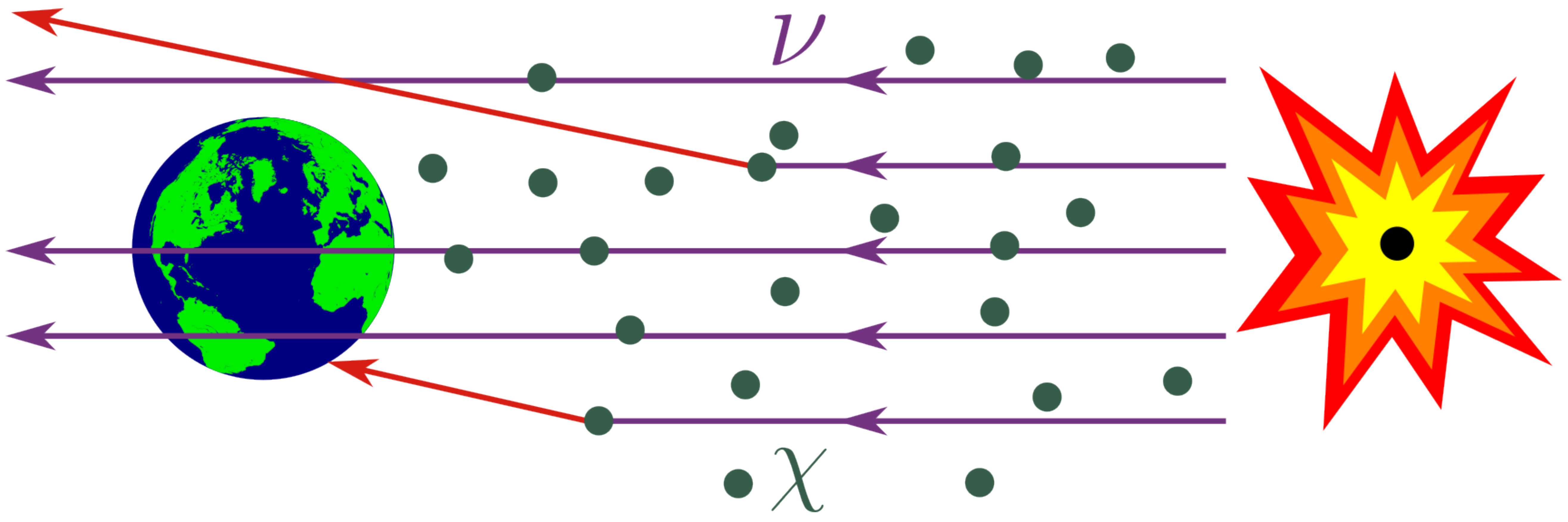


- Modified neutrino flux $\Phi/\Phi_0 \sim e^{-\tau}$
- Large τ obtained from:
    - large number density of DM
    - large distance for neutrinos to travel through DM
- Motivates considering astrophysical sources:
    - local supernova
    - diffuse supernova neutrino background
    - high energy astrophysical neutrinos

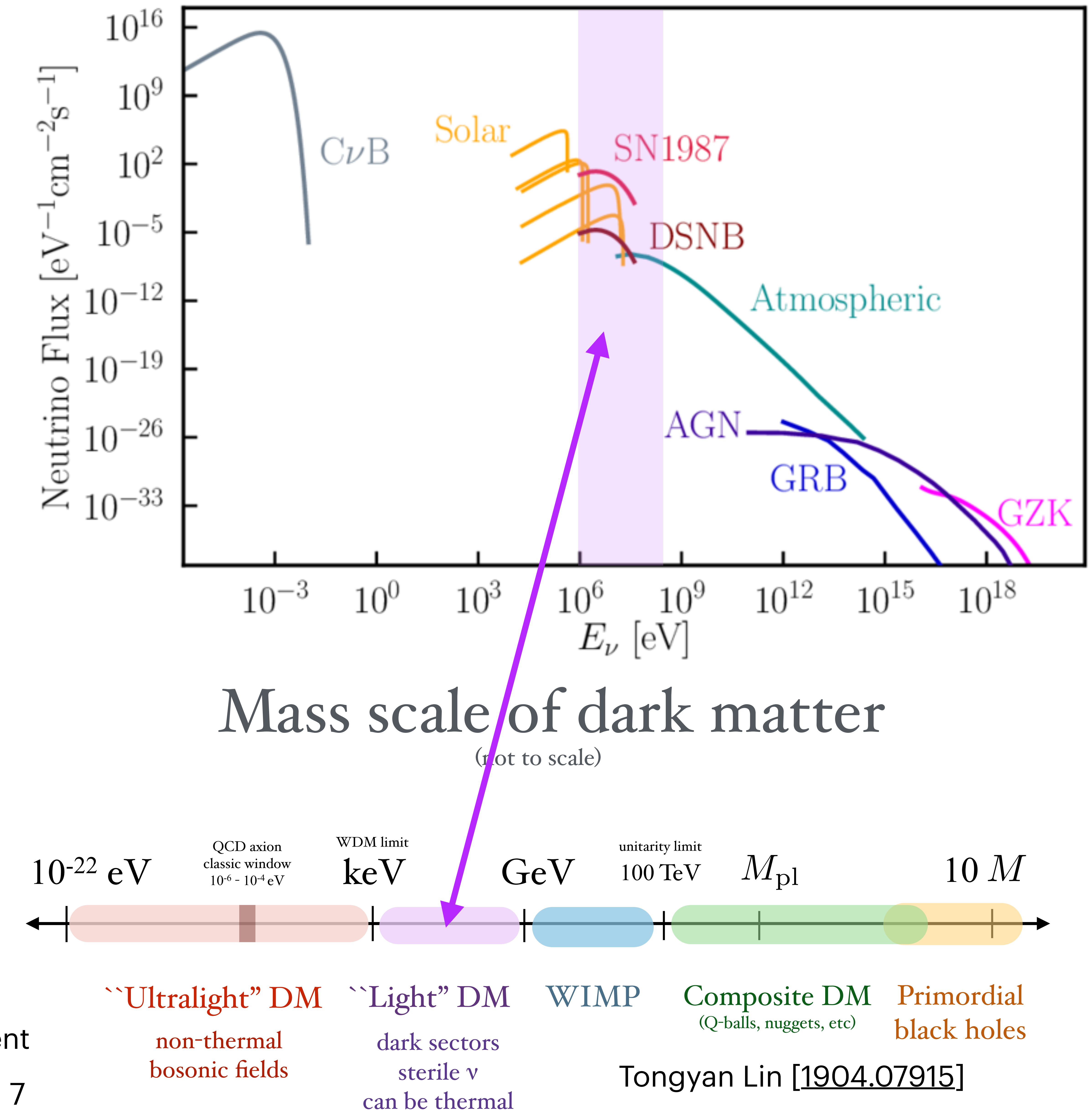
Observing ν-DM interactions

- Upcoming neutrino experiments sensitive to SN neutrino flux, dominantly at MeV range
  - Can they probe effects of SN neutrinos passing through galactic DM halo?
  - Such a signal prefers higher number density of DM: $m_\chi < 1\,\mathrm{GeV}$

Scales of ν-DM interactions

- DM mass ranges from keV - GeV
- neutrino energy scales ~ MeV

- How do we model such interactions?
  - Focus on light mediators < EW scale to maximize σ



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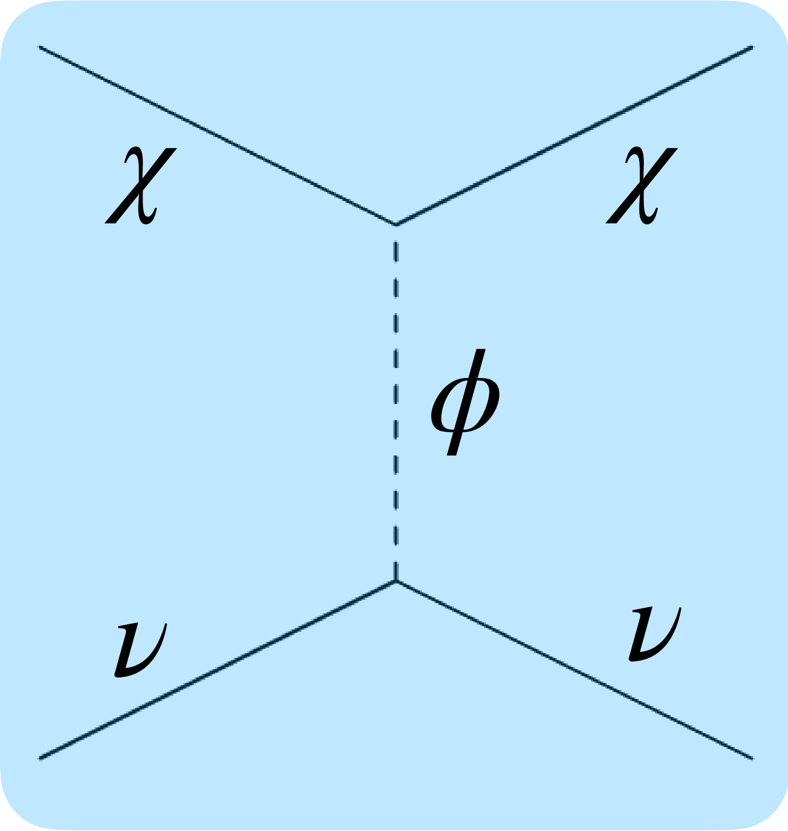
Modeling ν-DM interactions

- Categorize models into DM, mediator types
- Three mediator types:
  - Scalar mediator
  - Fermion mediator
  - Vector mediator



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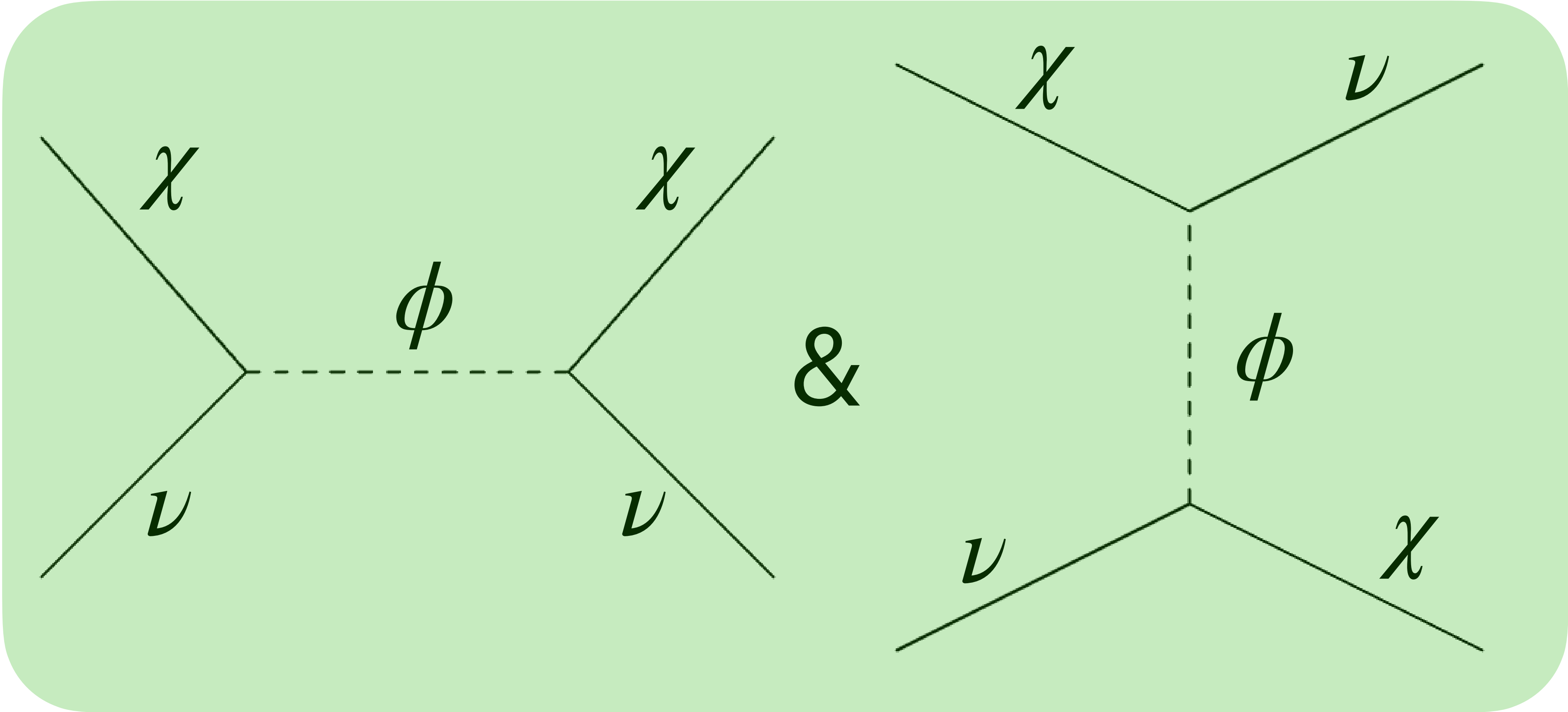


- Secondary categorization is t-channel or s&u-channel

- Consider different dark matter types as well: scalar, fermion, vector
  - Fermion DM restricts mass scale > keV

S. Tremaine, J.E. Gunn [DOI: 10.1103/PhysRevLett.42.407]

Modeling ν-DM interactions

- For each model, compute $\dfrac{d\sigma}{d\cos\theta}$ exactly
    - only assumption is non-relativistic DM in the initial state
- Comparing to results in the literature
    - found some inconsistencies with other results
- Scalar mediator cases:

scenario	Lagrangian	channels	amp. sq.	[54]	[32]
complex scalar †	(2.7)	t	(2.8)	–	✓
Dirac fermion	(2.9)	DM-ν: u	(2.10)	✓*	–
		DM-$\bar{\nu}$: s	(2.11)	–	–
Majorana fermion	(2.9)	s, u	(2.12)	✗	–
Dirac fermion †	(2.13)	t	(2.14)	–	✓
complex vector †	(2.15)	t	(2.16)	–	–

[32] C. Argüelles, A. Kheirandish, A. Vincent [1703.00451]
[54] A. Campo, C. Bœhm, S. Palomares-Ruiz, S. Pascoli [1711.05283]

Bounds on ν-DM interactions

- Three categories for bounds on these interactions:
  - Cosmological
  - Astrophysical
  - Lab

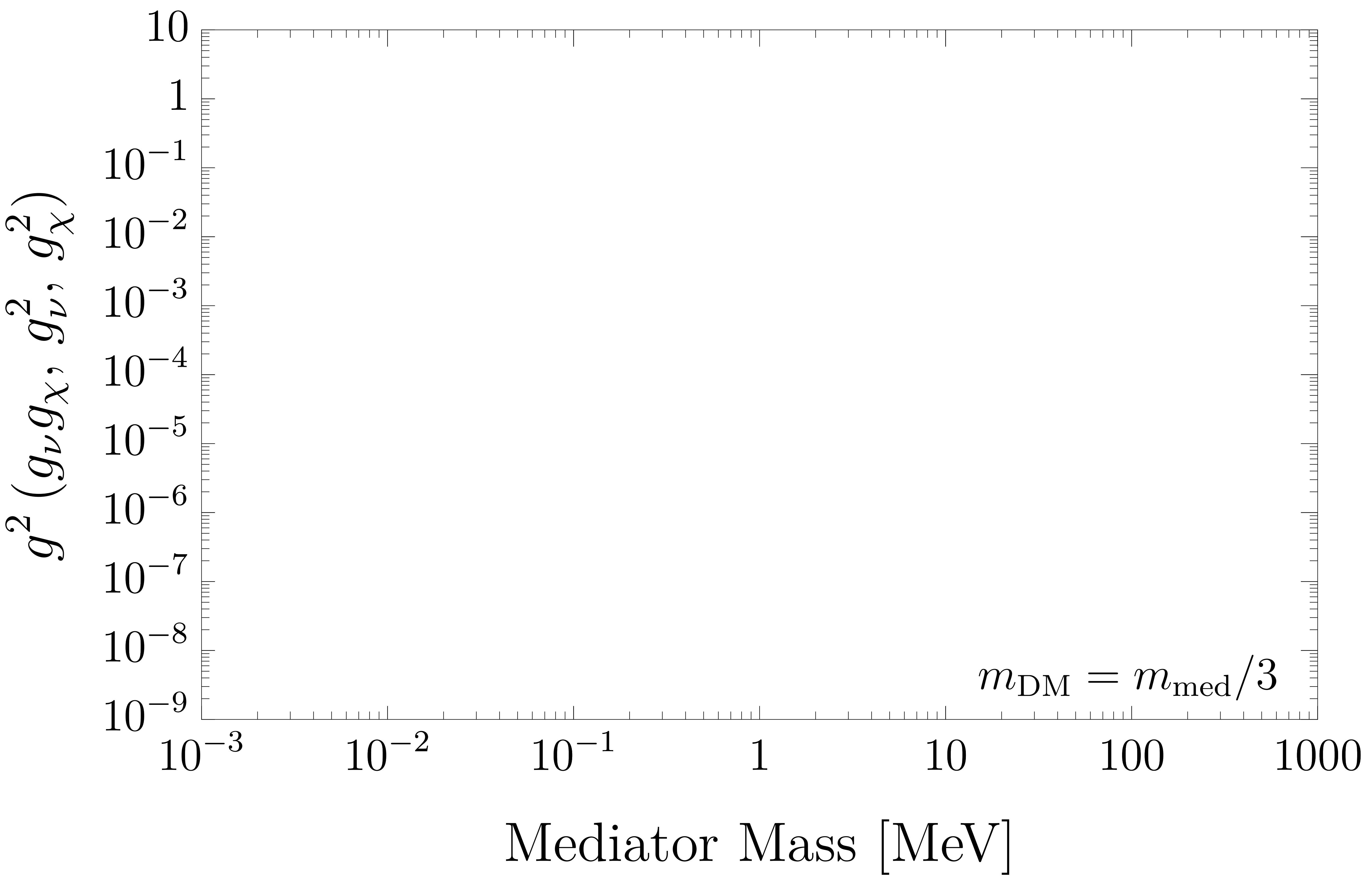
- Will carefully show each bound for one example model: Dirac fermion DM, scalar mediator:

$$\mathscr{L} = -\,\phi\bar{\nu}\left(g_{\nu\,s} + i g_{\nu\,p}\gamma_5\right)\nu - \phi\bar{\chi}\left(g_{\chi\,s} + i g_{\chi\,p}\gamma_5\right)\chi$$

Bound Plots for Example Models

Dirac Fermion DM, Scalar mediator

- Cosmological bounds:



Neutrino Self-Interactions: A White Paper [2203.01955]

A. Campo, C. Bœhm, S. Palomares-Ruiz, S. Pascoli [1711.05283]

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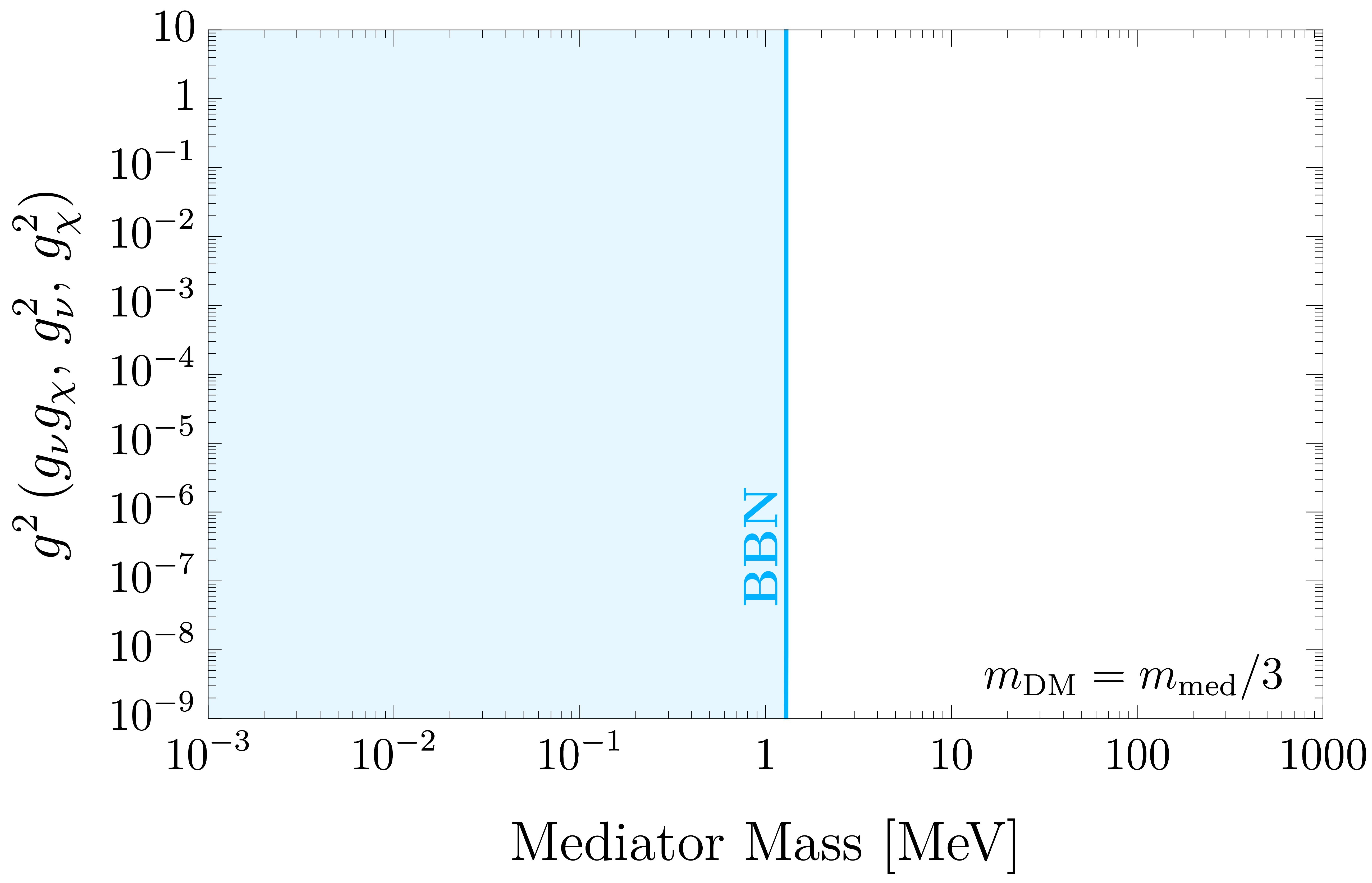
- Cosmological bounds:
  - BBN: neutrino NSI affects N_{eff}



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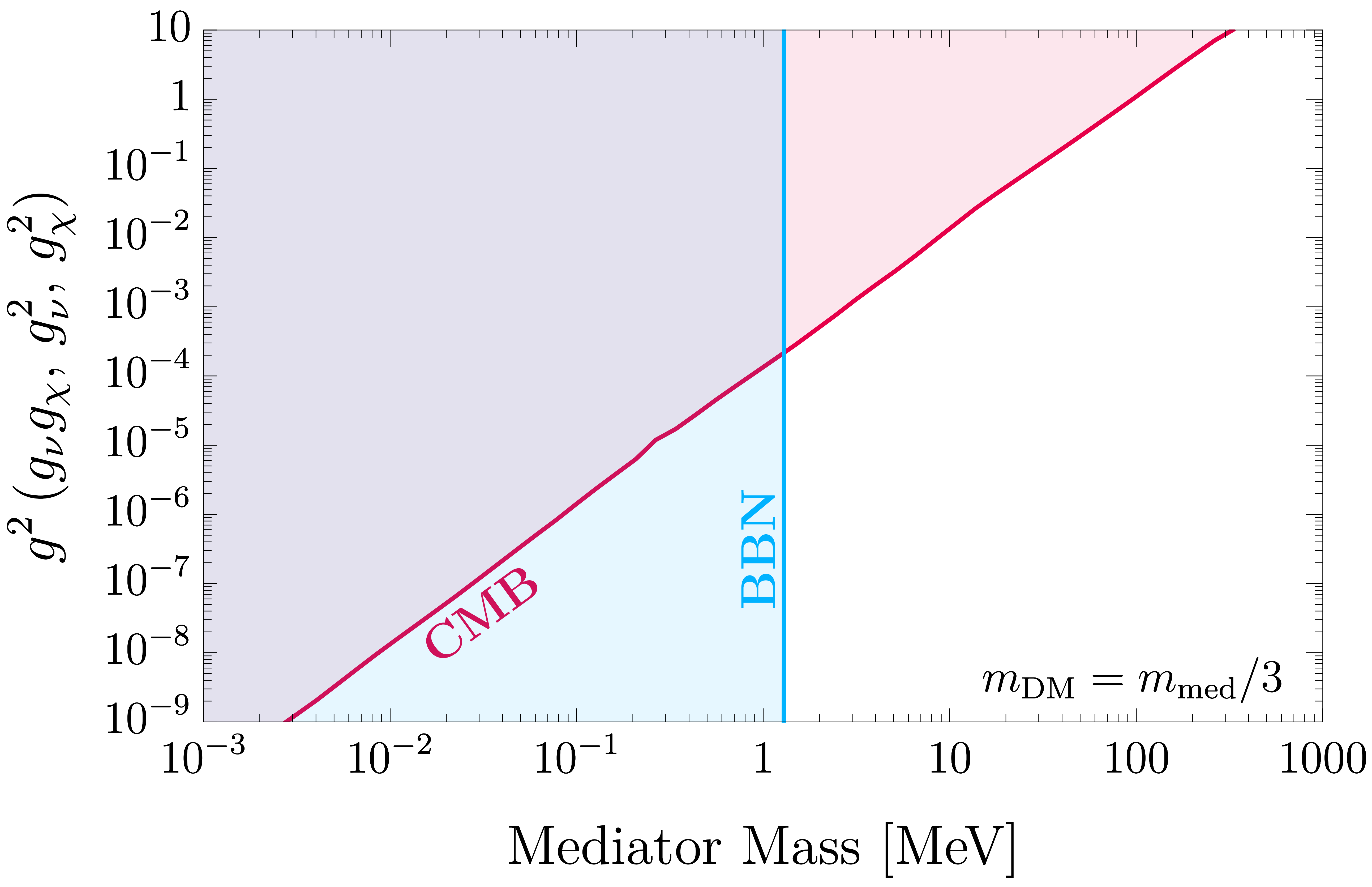

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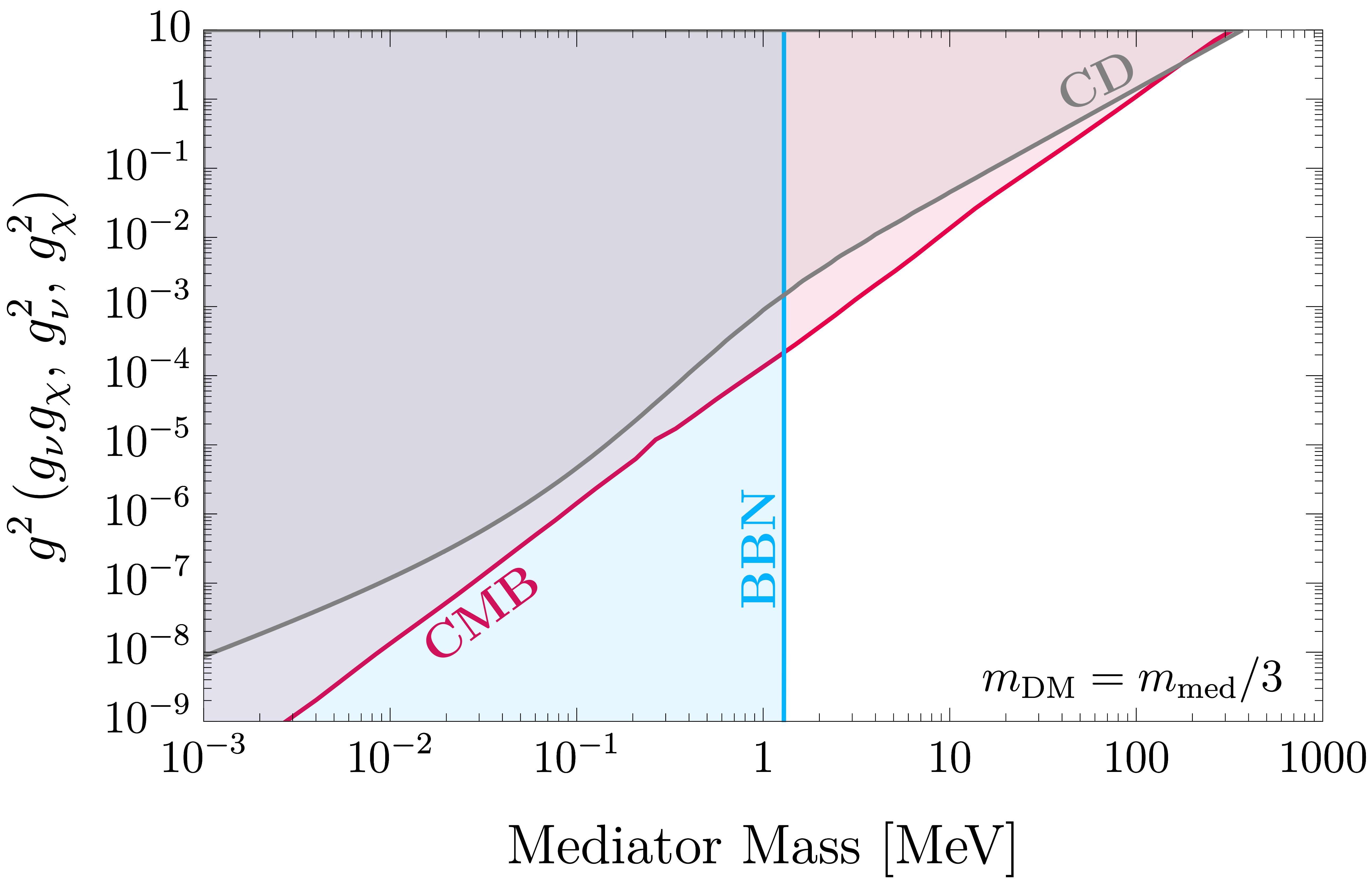
  - Collisional Damping: upper limit on ν-DM interactions from CMB and LSS



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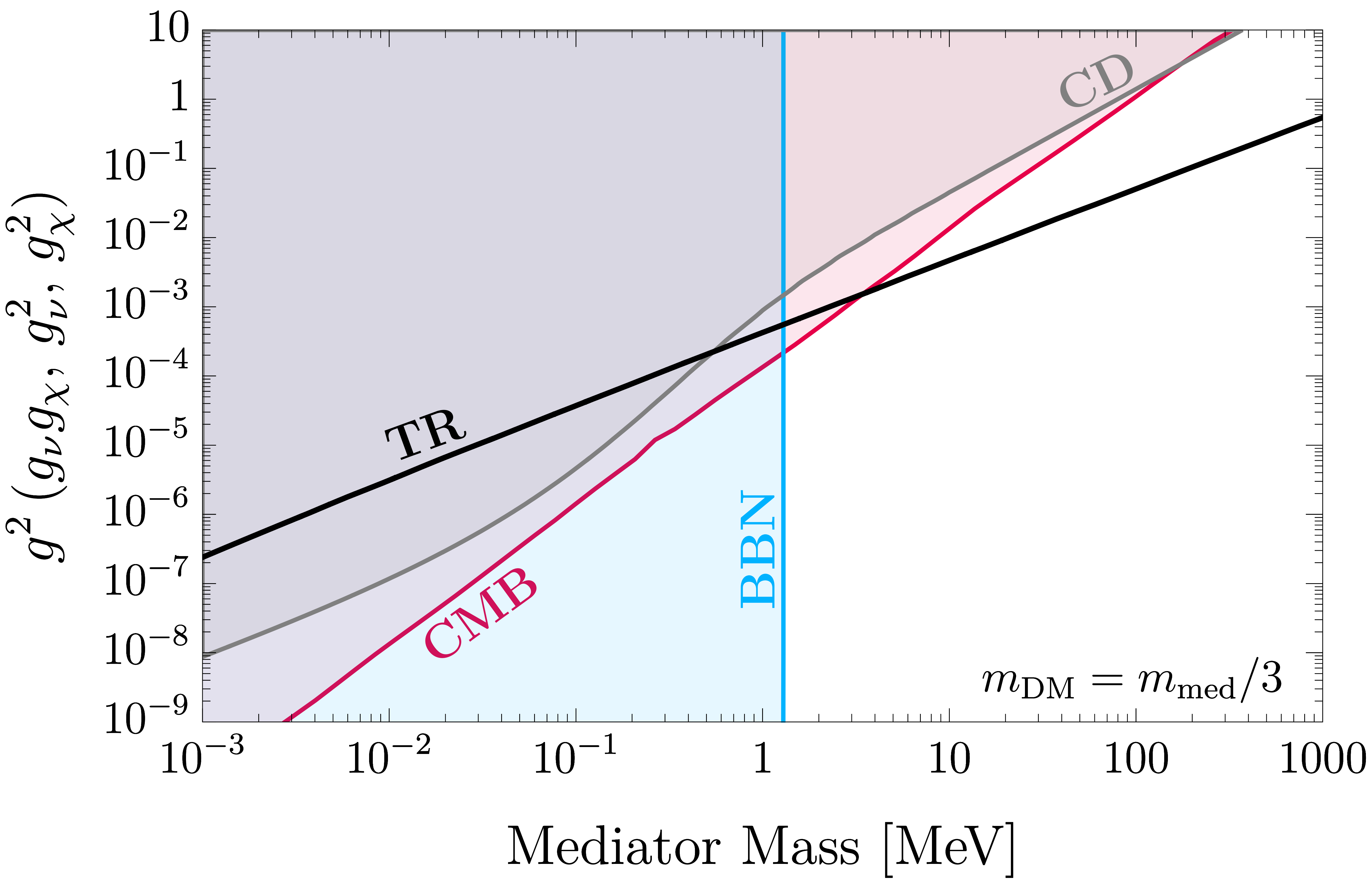
  - Collisional Damping: upper limit on ν-DM interactions from CMB and LSS
  - Thermal relic density: annihilation of DM into neutrinos needed to match relic abundance



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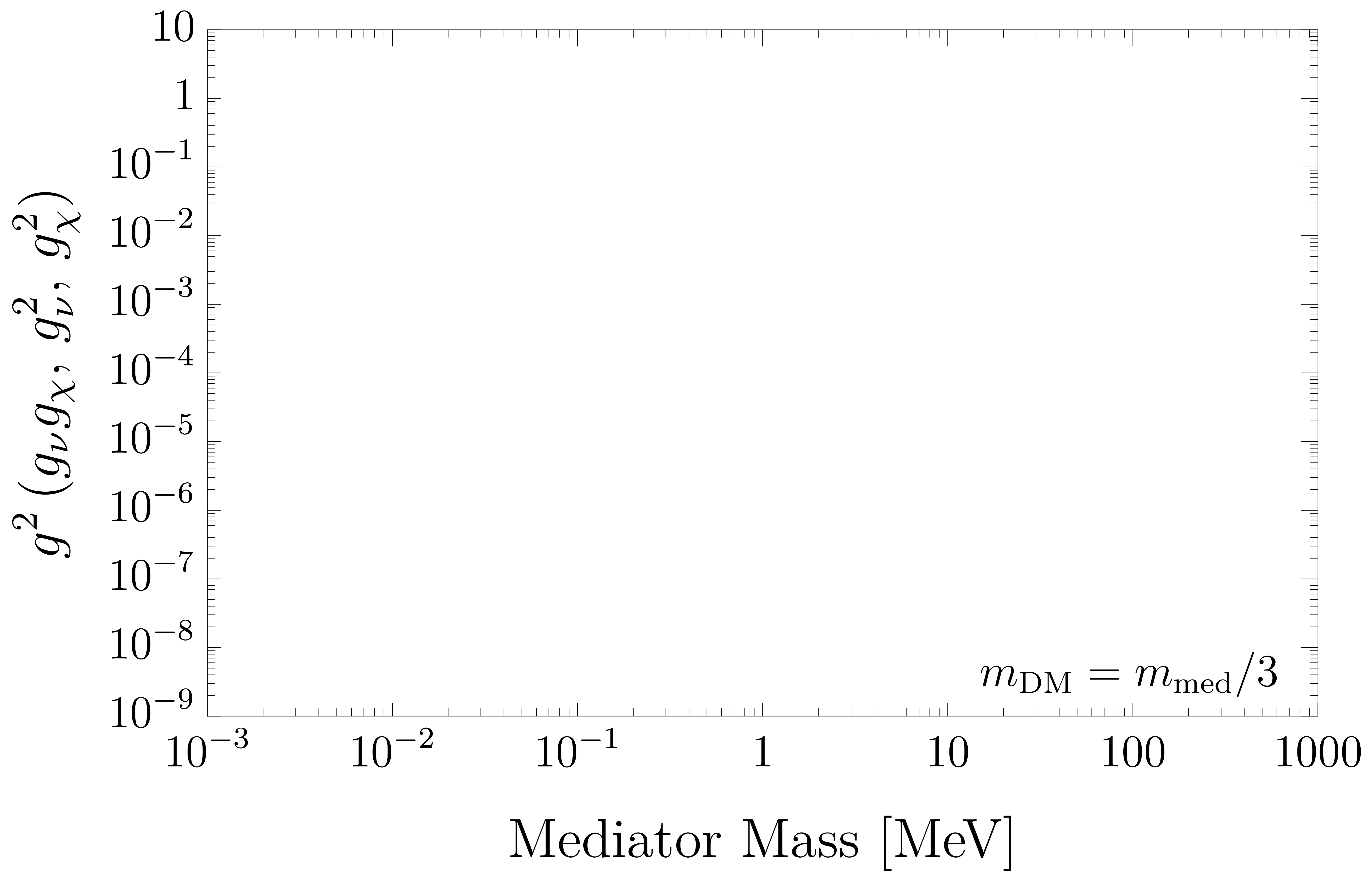
Bound Plots for Example Models

Dirac Fermion DM, Scalar mediator

- Astrophysical bounds:



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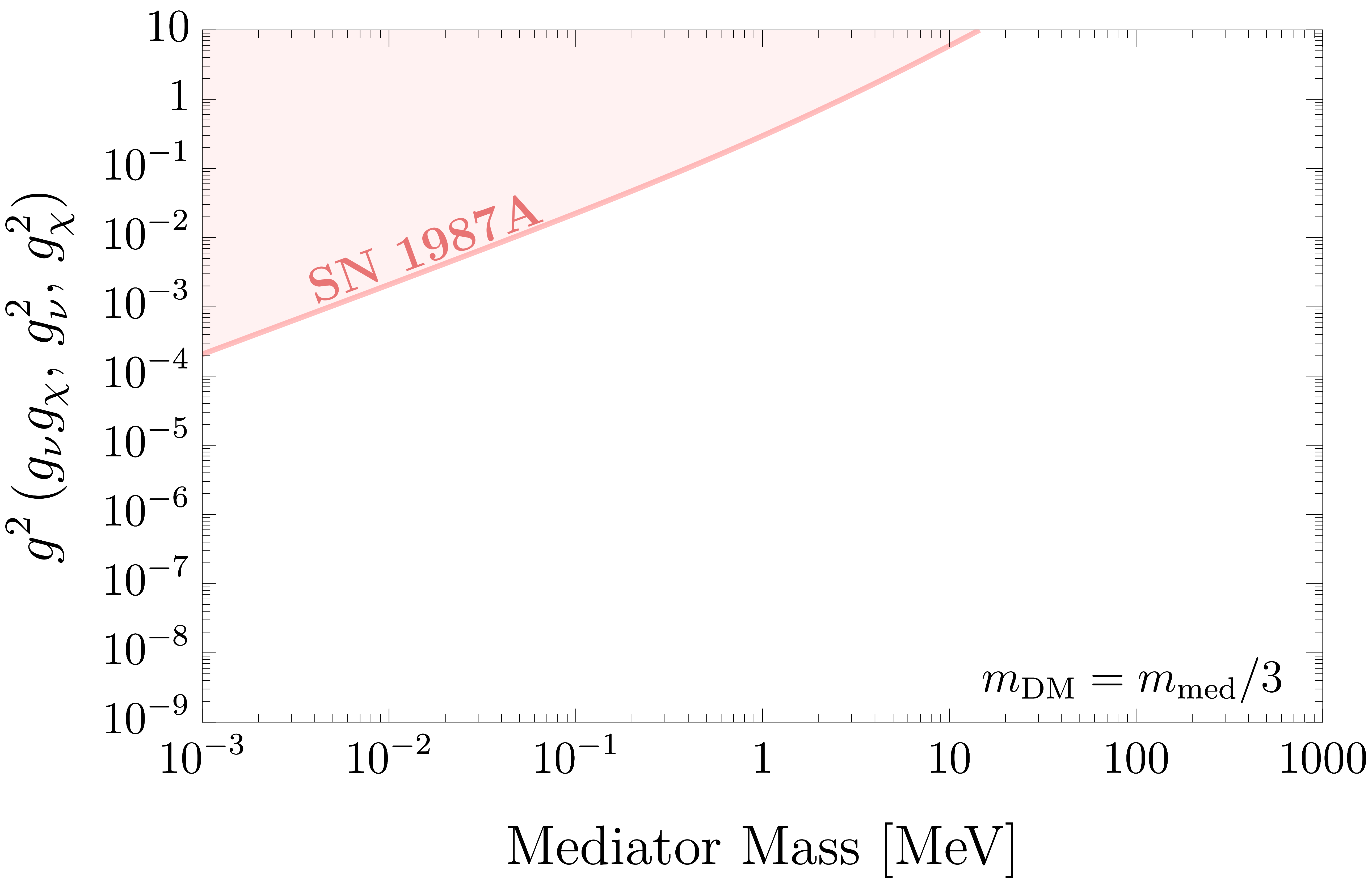
M. Markevitch et al. [astro-ph/0309303]
A. Robertson, R. Massey, V. Eke [1605.04307]

Bound Plots for Example Models

Dirac Fermion DM, Scalar mediator

- Astrophysical bounds:
  - SN 1987A
    - Updated calculation of integrated column density
    - $\mathcal{O}(1)$ opacity region excluded



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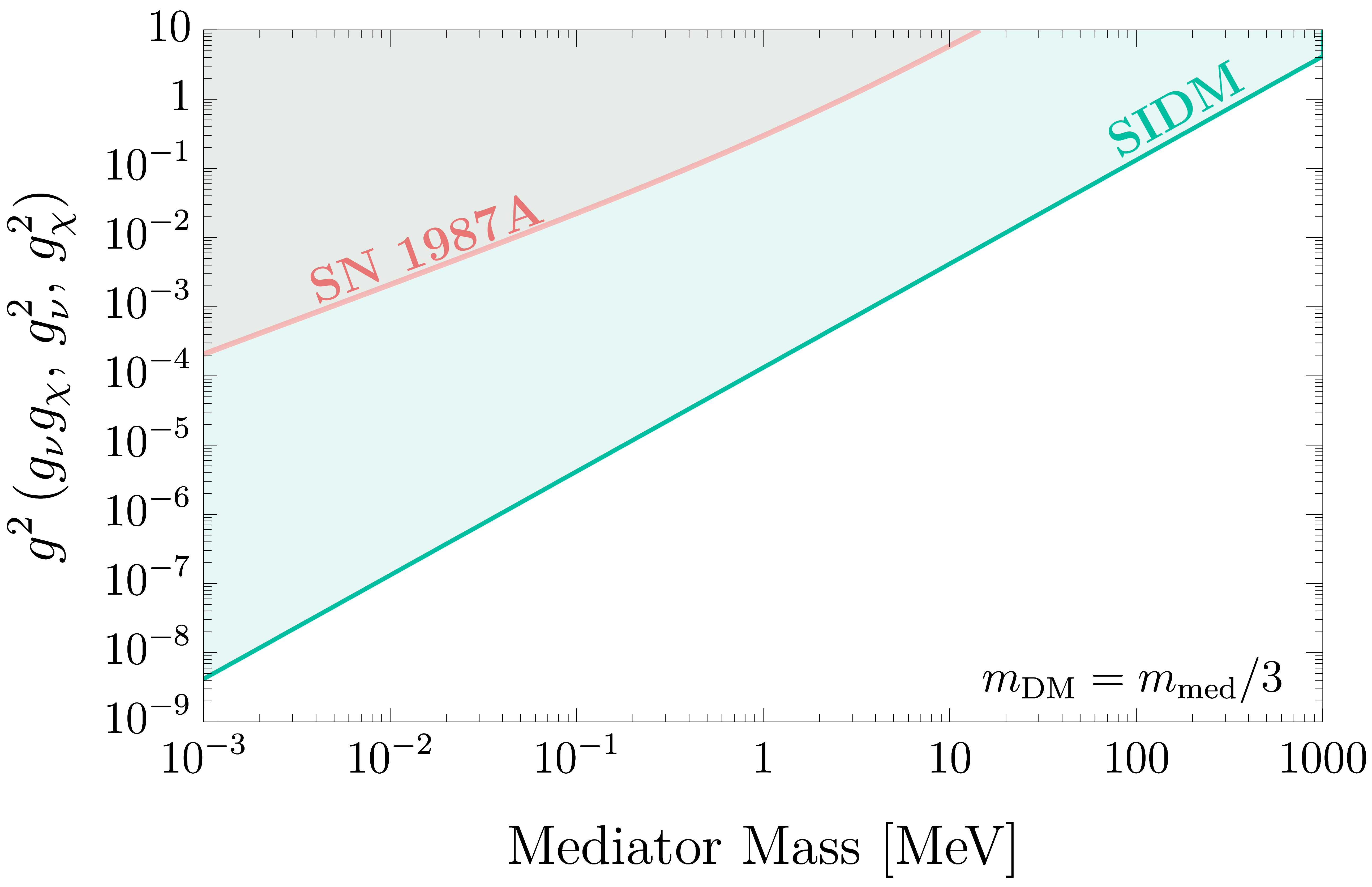
Bound Plots for Example Models

Dirac Fermion DM, Scalar mediator

- Astrophysical bounds:
  - SN 1987A
    - Updated calculation of integrated column density
    - $\mathcal{O}(1)$ opacity region excluded
  - Bullet Clustering (SIDM)
    - Only applies to t-channel models



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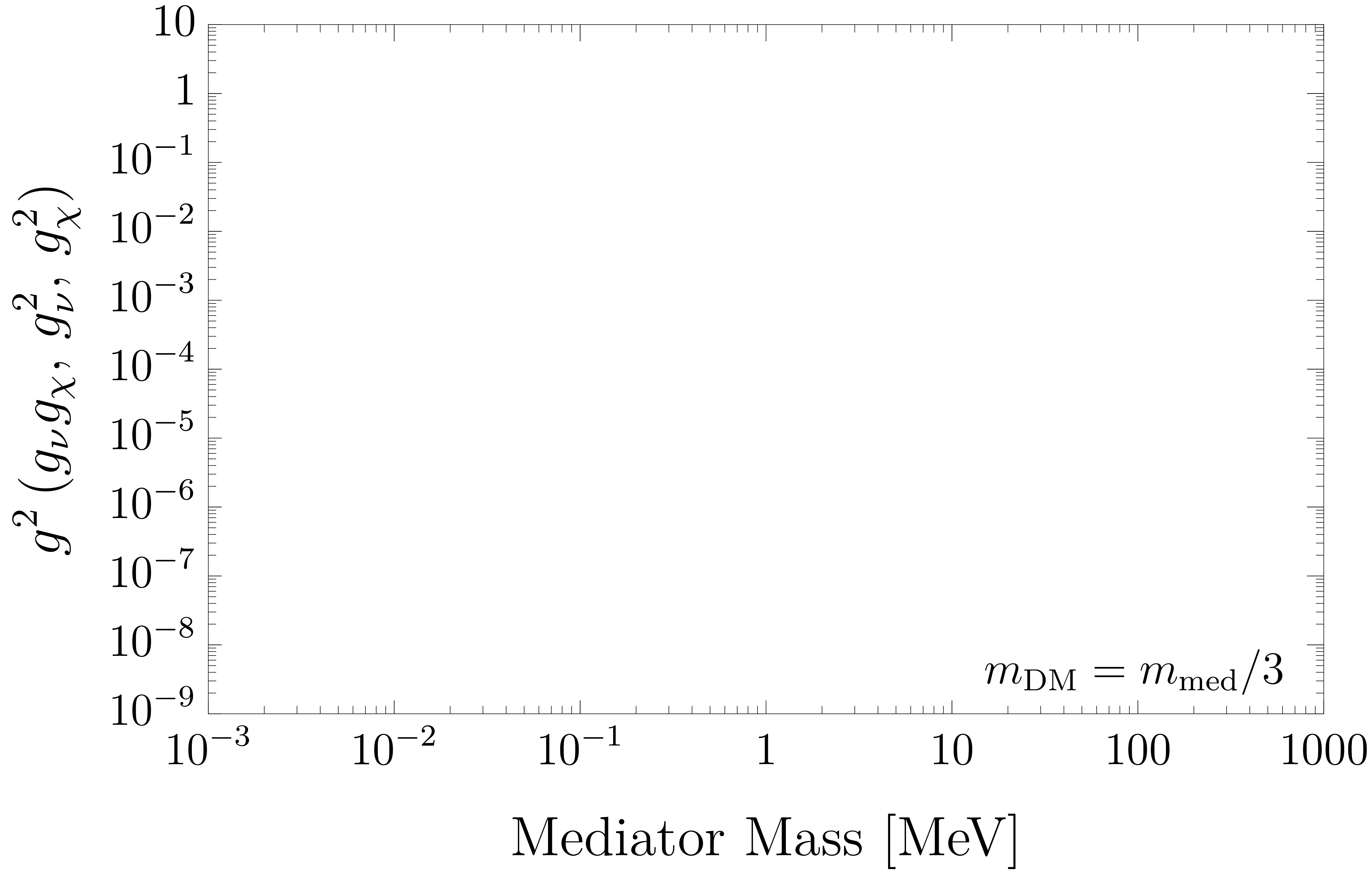
Bound Plots for Example Models

Dirac Fermion DM, Scalar mediator

- Lab bounds:



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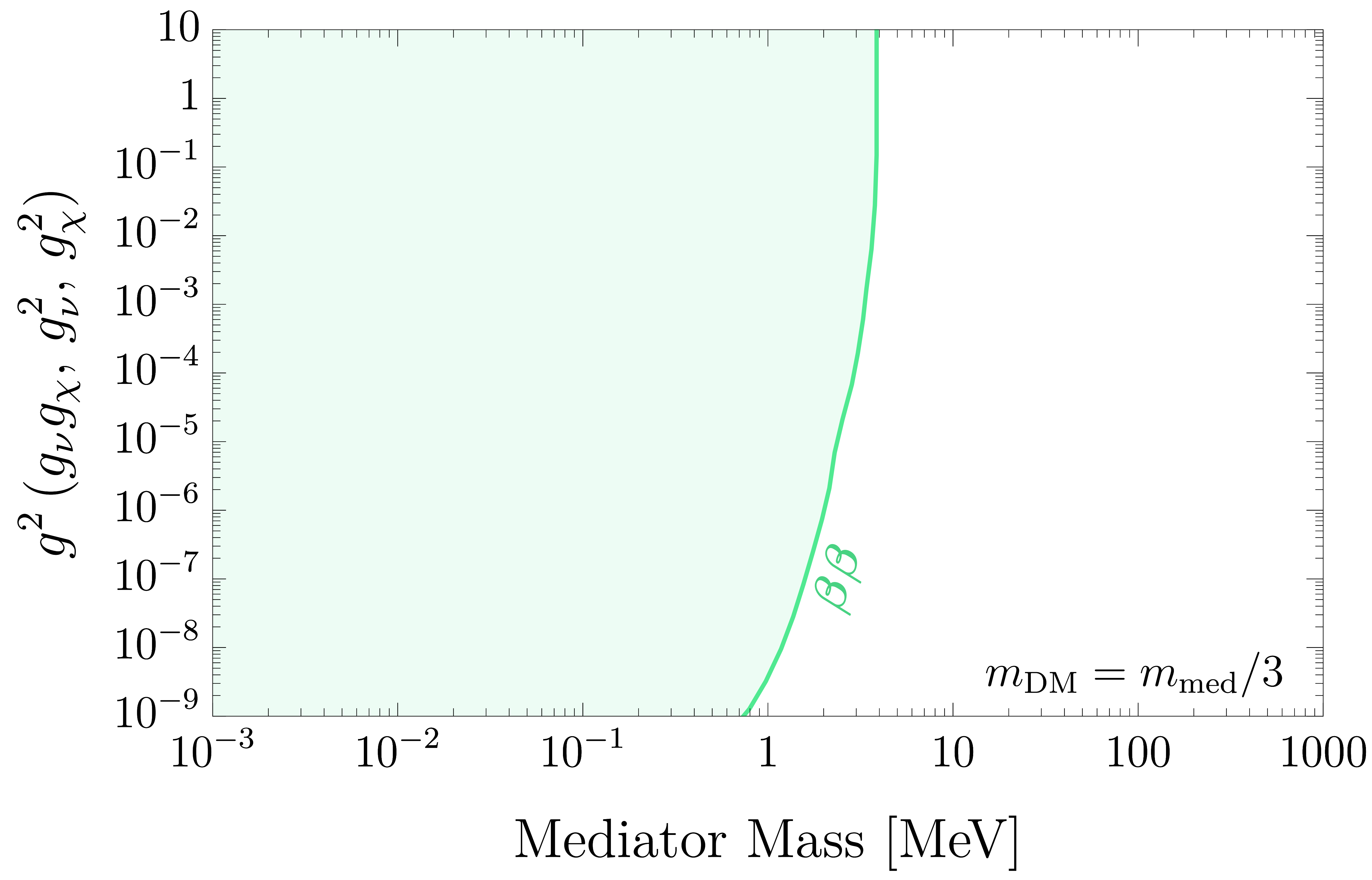
Bound Plots for Example Models

Dirac Fermion DM, Scalar mediator

- Lab bounds:
  - $\beta\beta$ decay: ν NSI effects can be seen in searches



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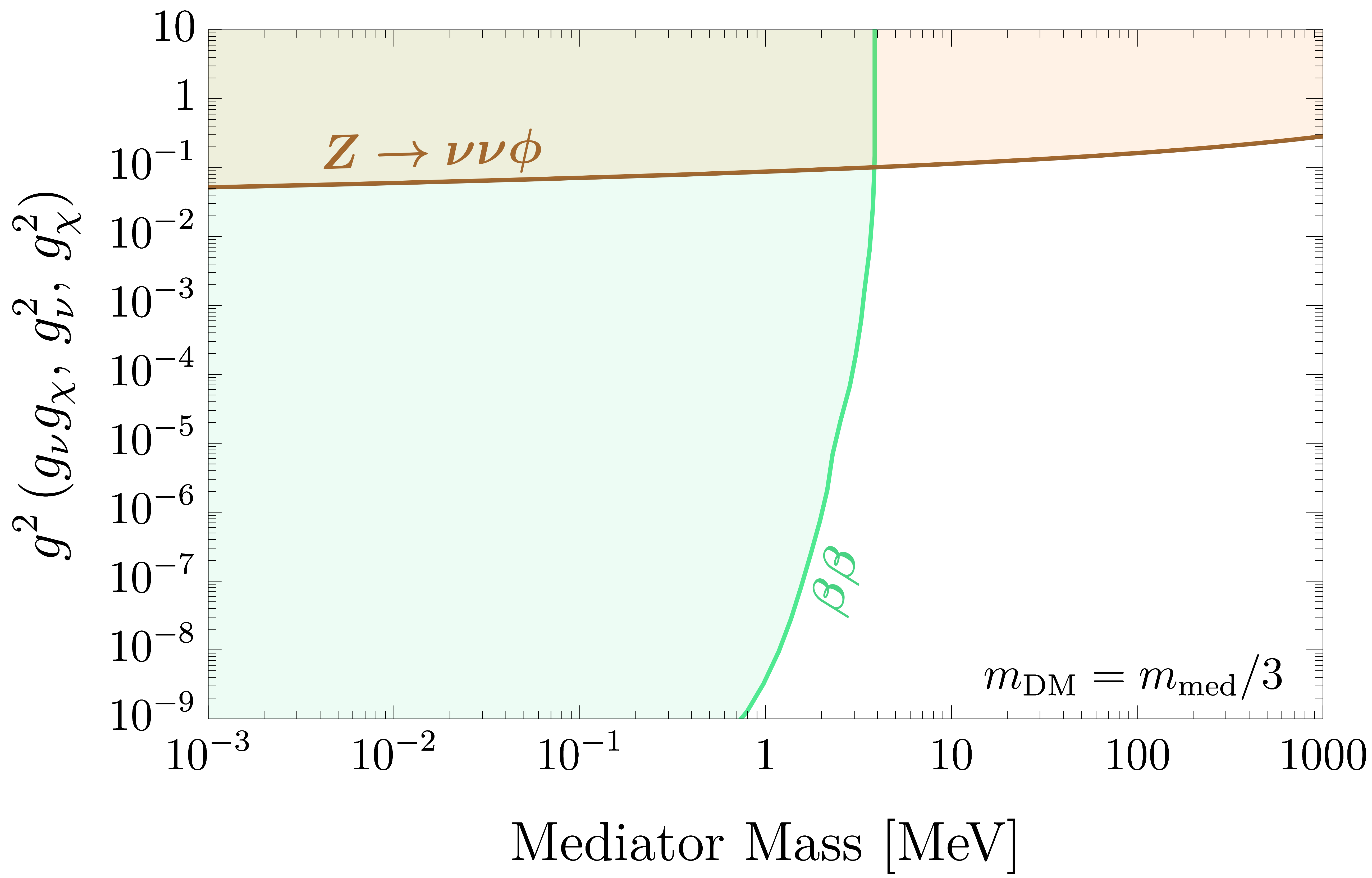
  - Invisible Z decays*



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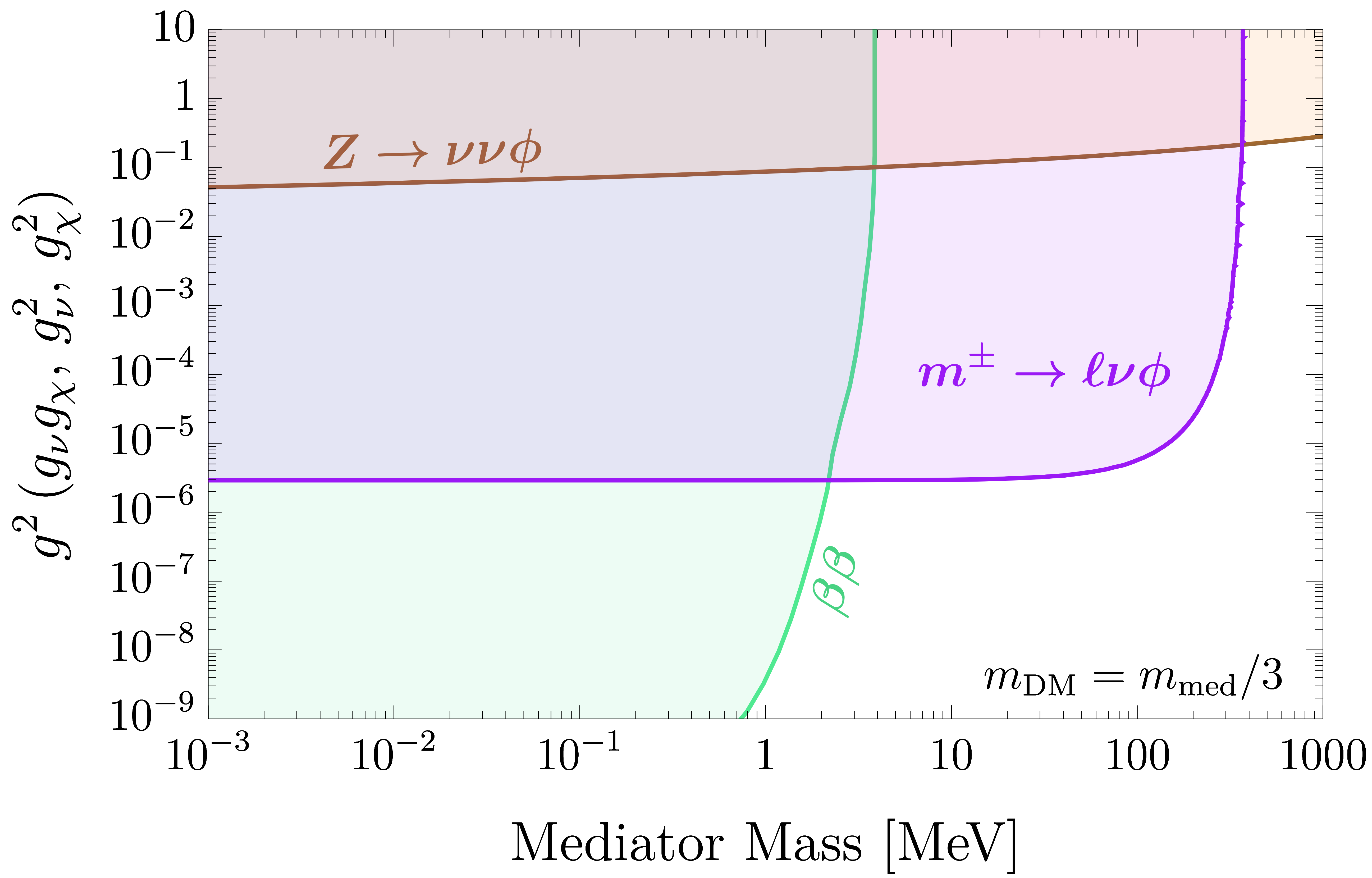
Bound Plots for Example Models

Dirac Fermion DM, Scalar mediator

- Lab bounds:
  - $\beta\beta$ decay: ν NSI effects can be seen in searches
  - Invisible Z decays*
  - Meson decays*



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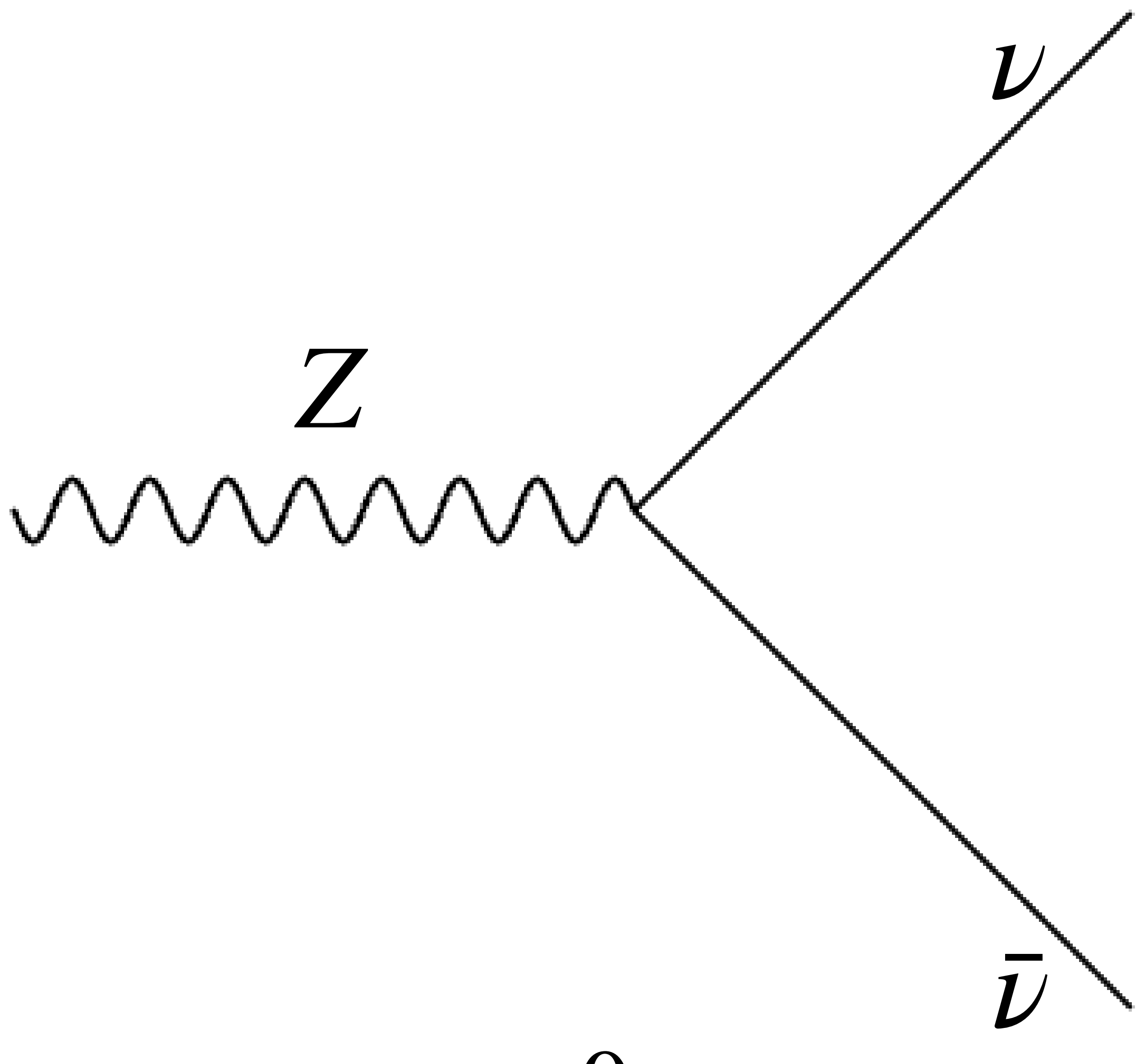
Bounds on ν-DM interactions

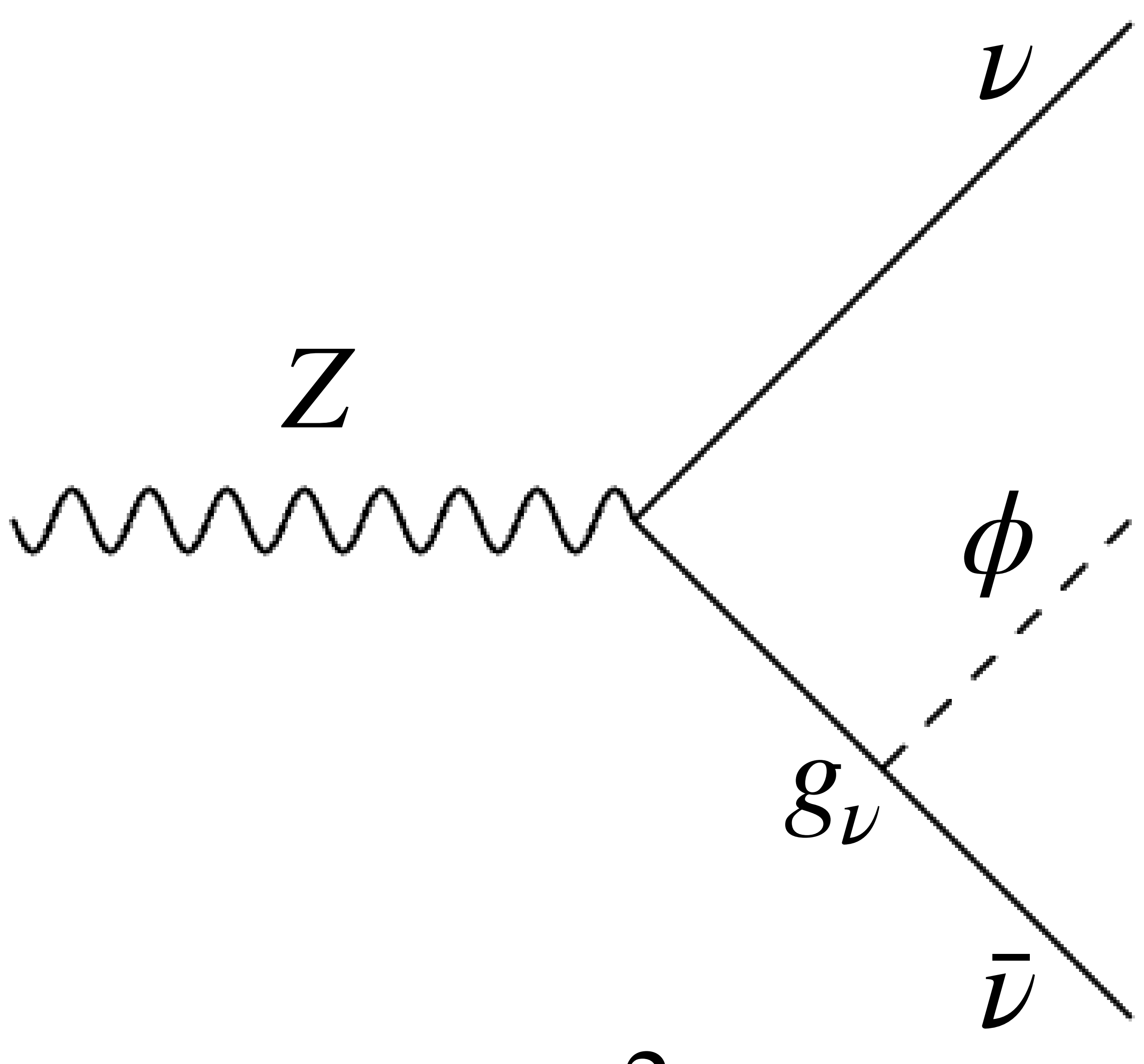
Updating bounds

- Current Z and Meson decay bounds computed at tree-level

$\Gamma_{Z\to\text{inv}} \sim \Big|$



$\Big|^2 + \Big|$



$\Big|^2$

IR divergence

$\mathcal{O}(g_\nu^0)$ $\qquad$ $\mathcal{O}(g_\nu^2)$

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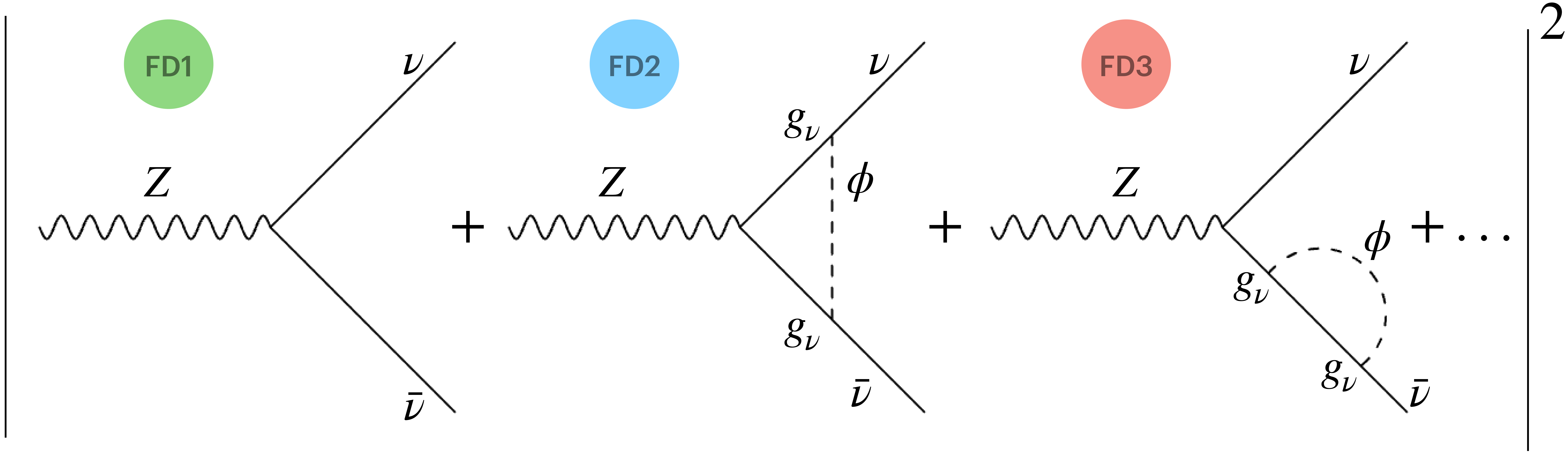
Bounds on ν-DM interactions

Updating bounds

- Current Z and Meson decay bounds computed at tree-level
- Adding one loop interference terms cancels the IR divergence

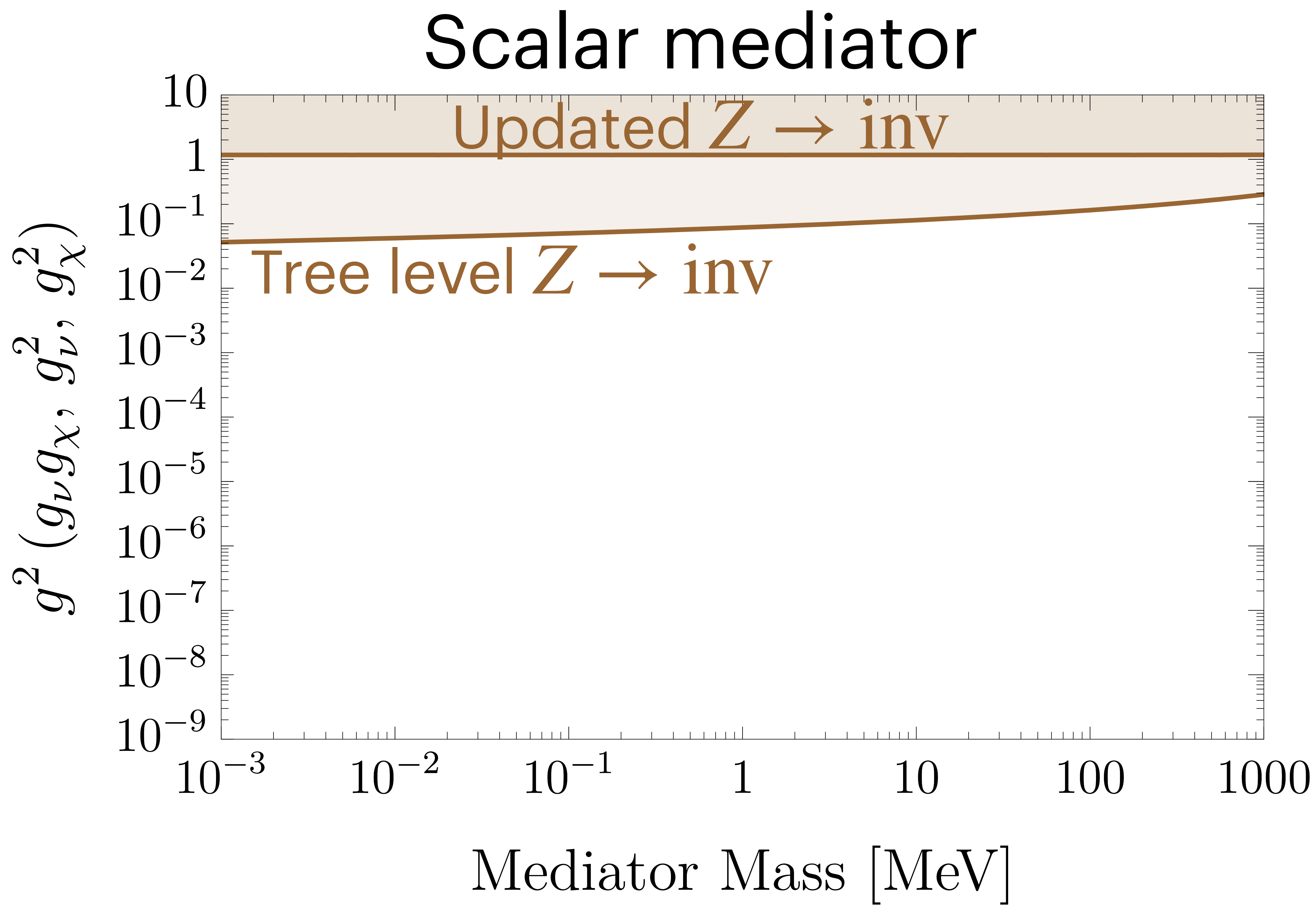


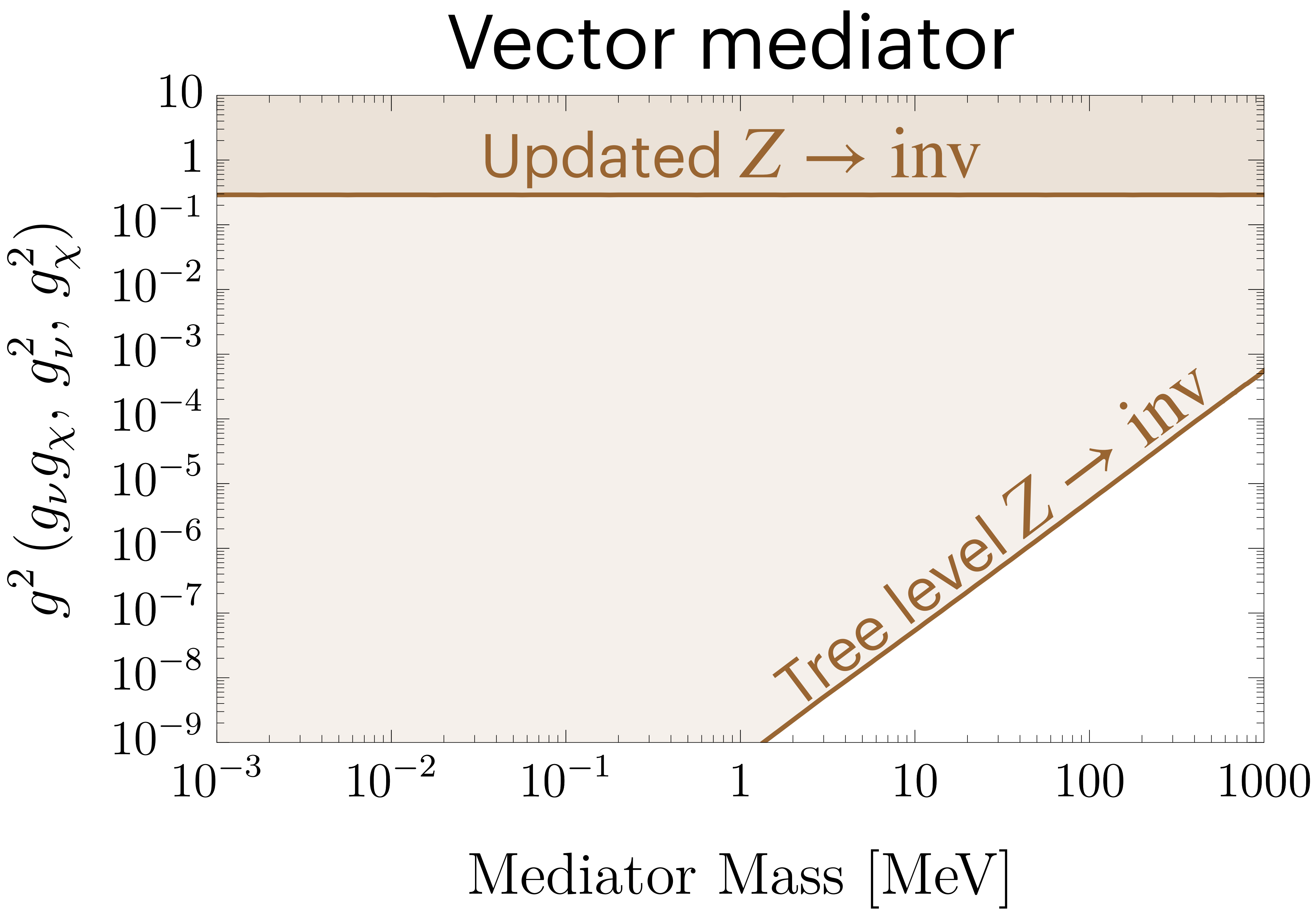
Interference terms FD1 FD2 and FD1 FD3 are $\mathcal{O}(g_\nu^2)$, like tree level $Z \to \nu\nu\phi$

Bounds on ν-DM interactions

Updating bounds

- Updated bound for scalar and vector mediators are relaxed for Z and meson decays



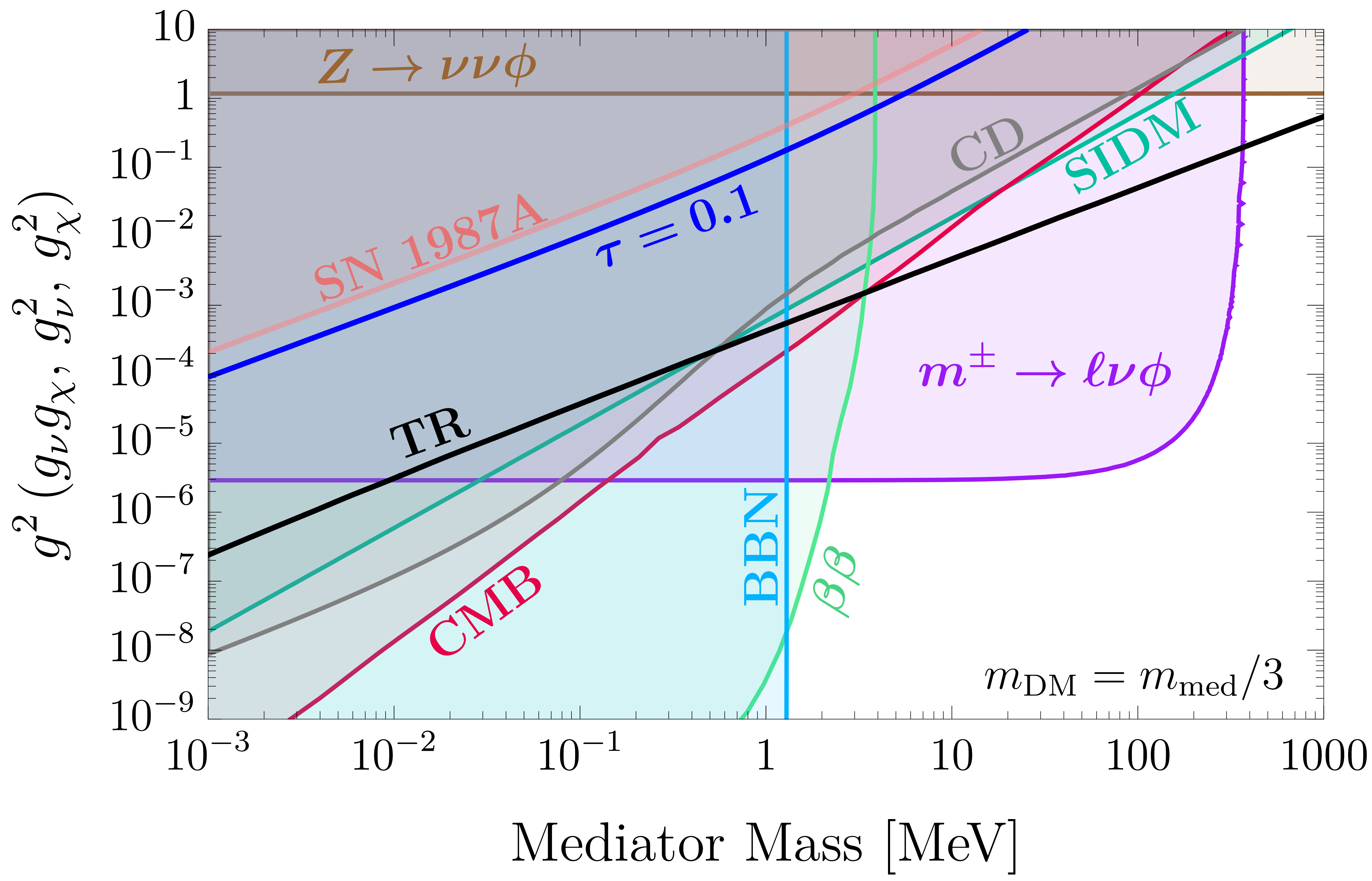


Bound Plots for Example Models

Dirac Fermion DM, Scalar Mediator

- Compiling all the bounds for this model:

- $\tau = 0.1$: Opacity of 10 MeV neutrinos for SN in Milky Way galaxy 10 kpc away
  - improves over 1987A bound
  - but already ruled out by many other constraints for $m_{\mathrm{DM}} = m_{\mathrm{med}}/3$



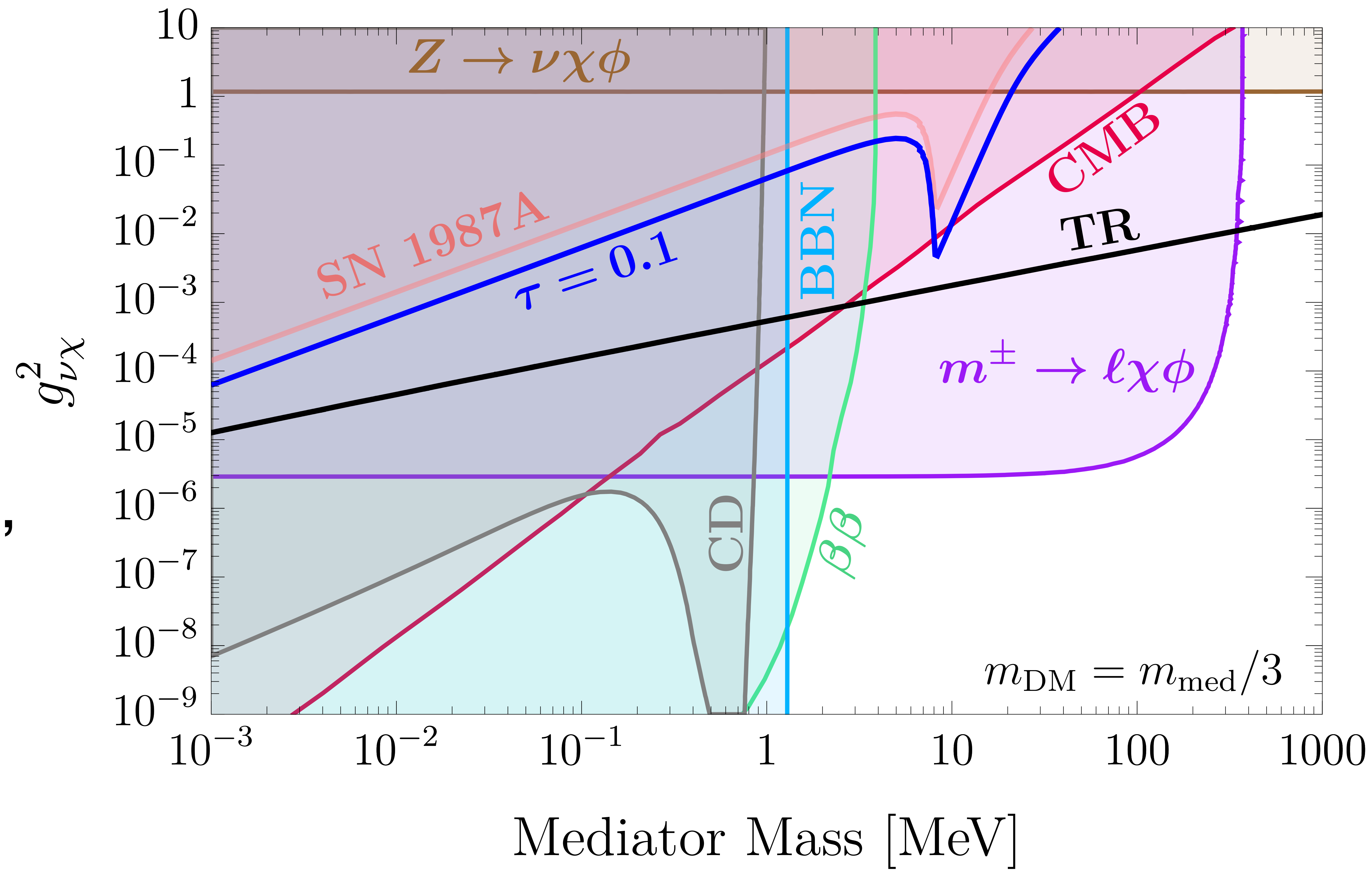
Bound Plots for Example Models

Scalar DM, Fermion mediator

- Now for a fermion mediator, where the process is s&u-channel:

$$\mathscr{L} = -\phi \overline{N}(g_s + i g_p \gamma_5) P_L \nu_L \ + \ \mathrm{H.c.}$$

- No tree level DM-self interactions, removing SIDM bounds
- Collisional damping bound interpolated for each model



Bound Plots for Example Models

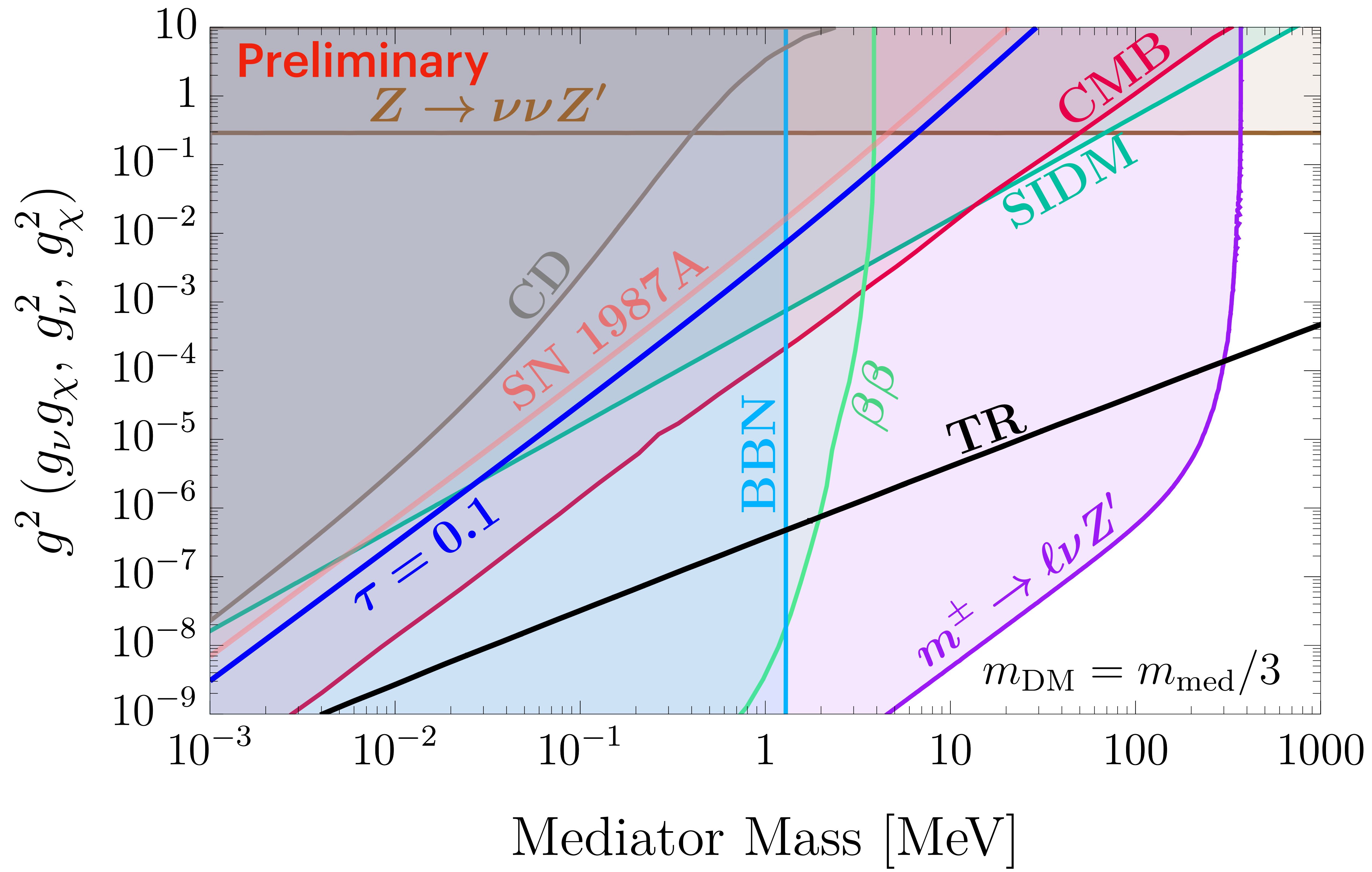
Vector DM, Vector mediator

- Lastly, a vector mediator scenario, with real vector DM:

$$\mathscr{L} = Z'_\mu \bar{\nu} \left(g_{\nu L} \gamma^\mu P_L + g_{\nu R} \gamma^\mu P_R \right) \nu + \left(\frac{1}{2} g_\chi \chi^\mu \left(\partial_\mu \chi^\nu \right) Z'_\nu + \mathrm{H.c.} \right)$$

- Parameter space heavily constrained

- Overall, no sensitivity in unexplored regions of parameter space with galactic SN for $m_{\rm DM} = m_{\rm med}/3$



Best case scenario for local SN

- What about best case scenario?
  Consider keV scale DM
- Is there any parameter space available to probe?
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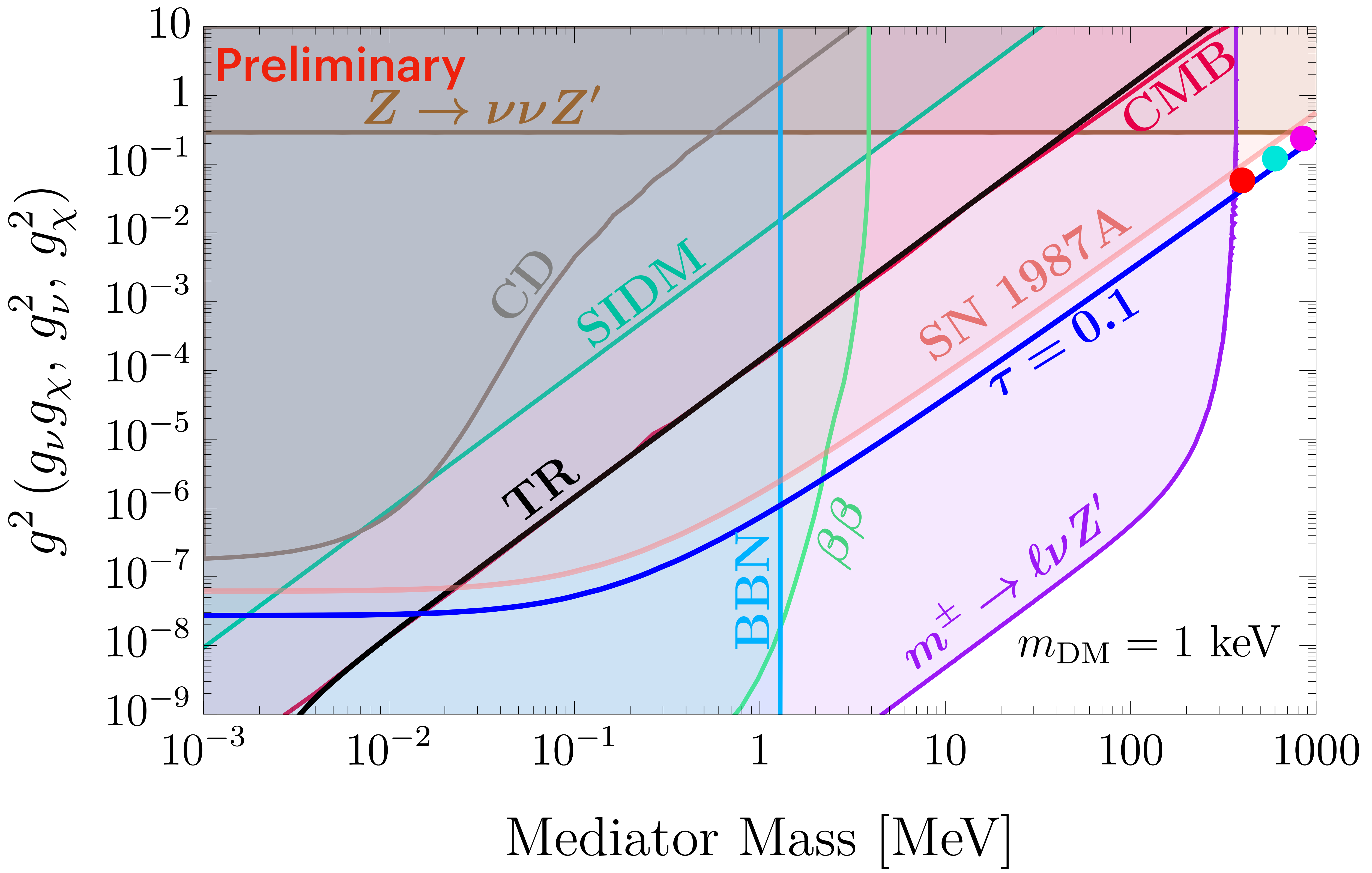

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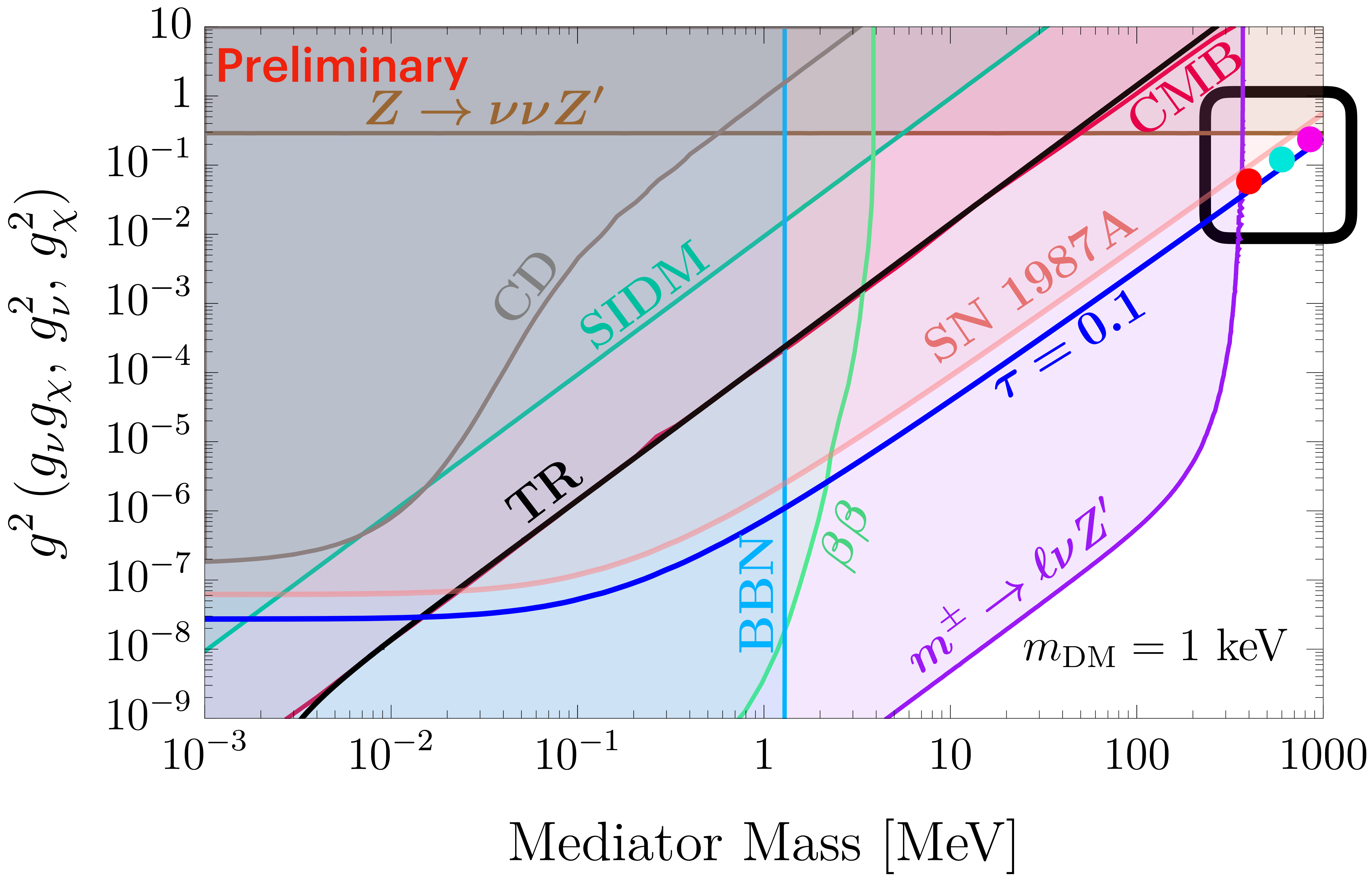

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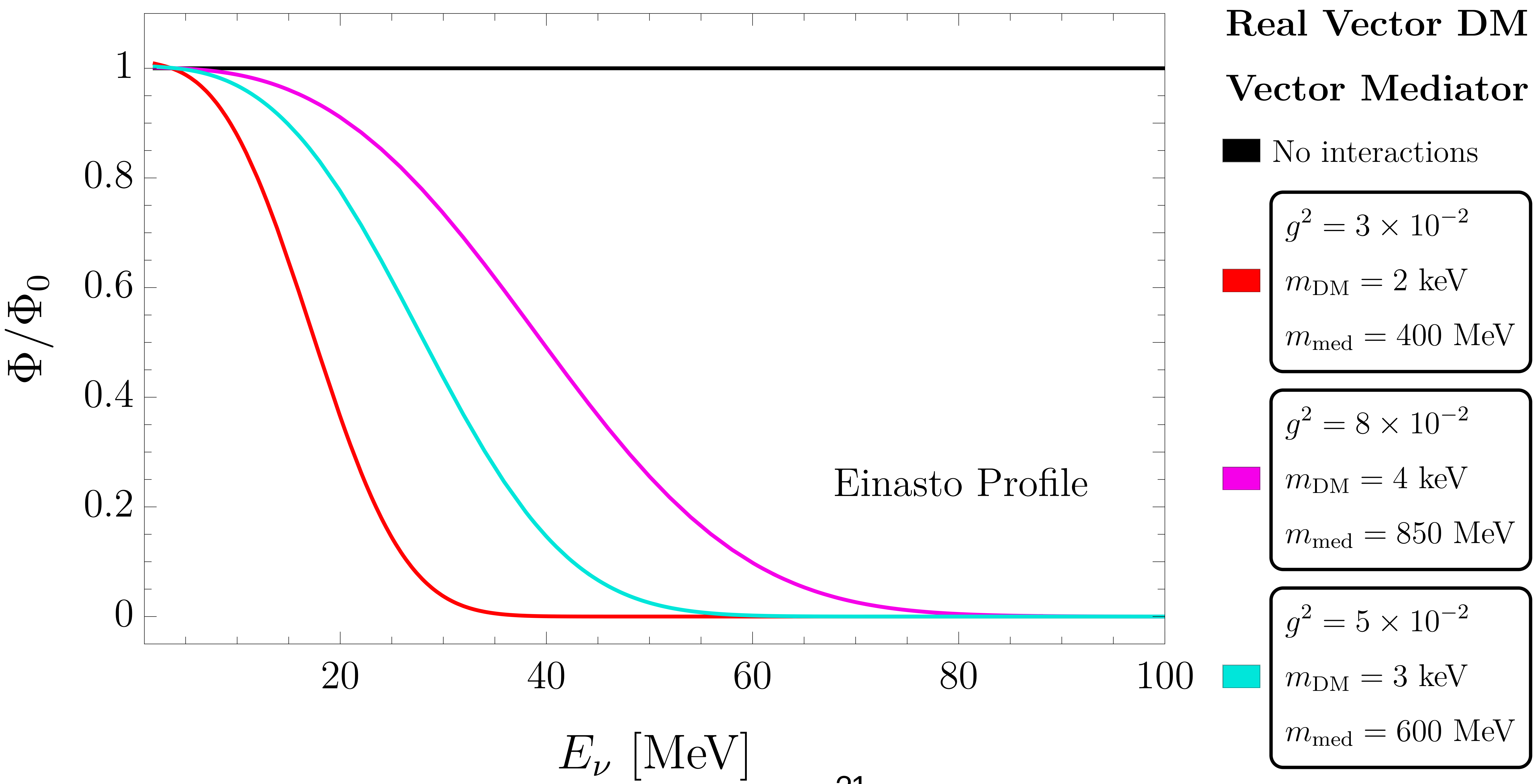

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  - Inverse Beta Decay at Hyper-K/JUNO

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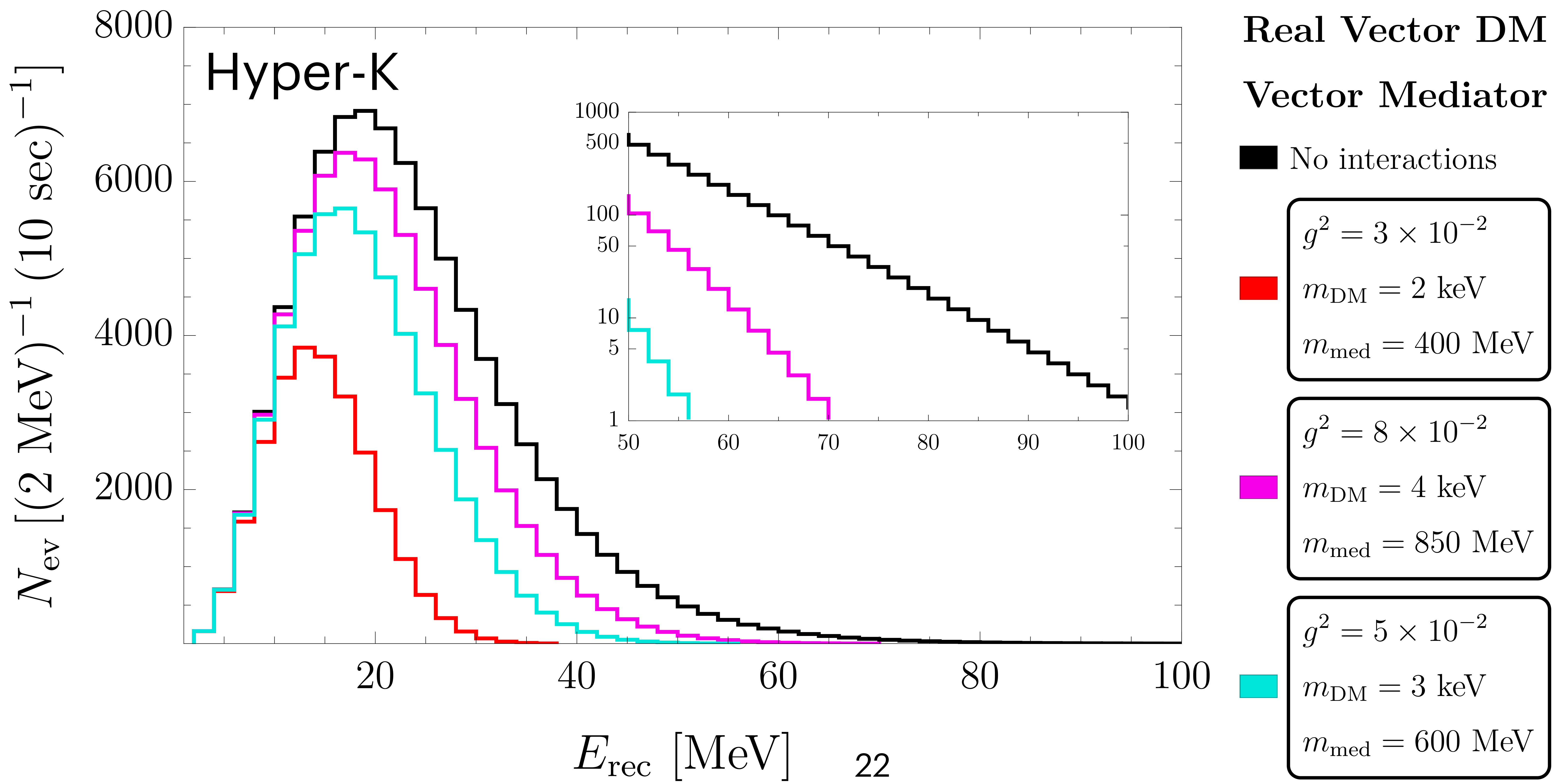


Summary and Outlook

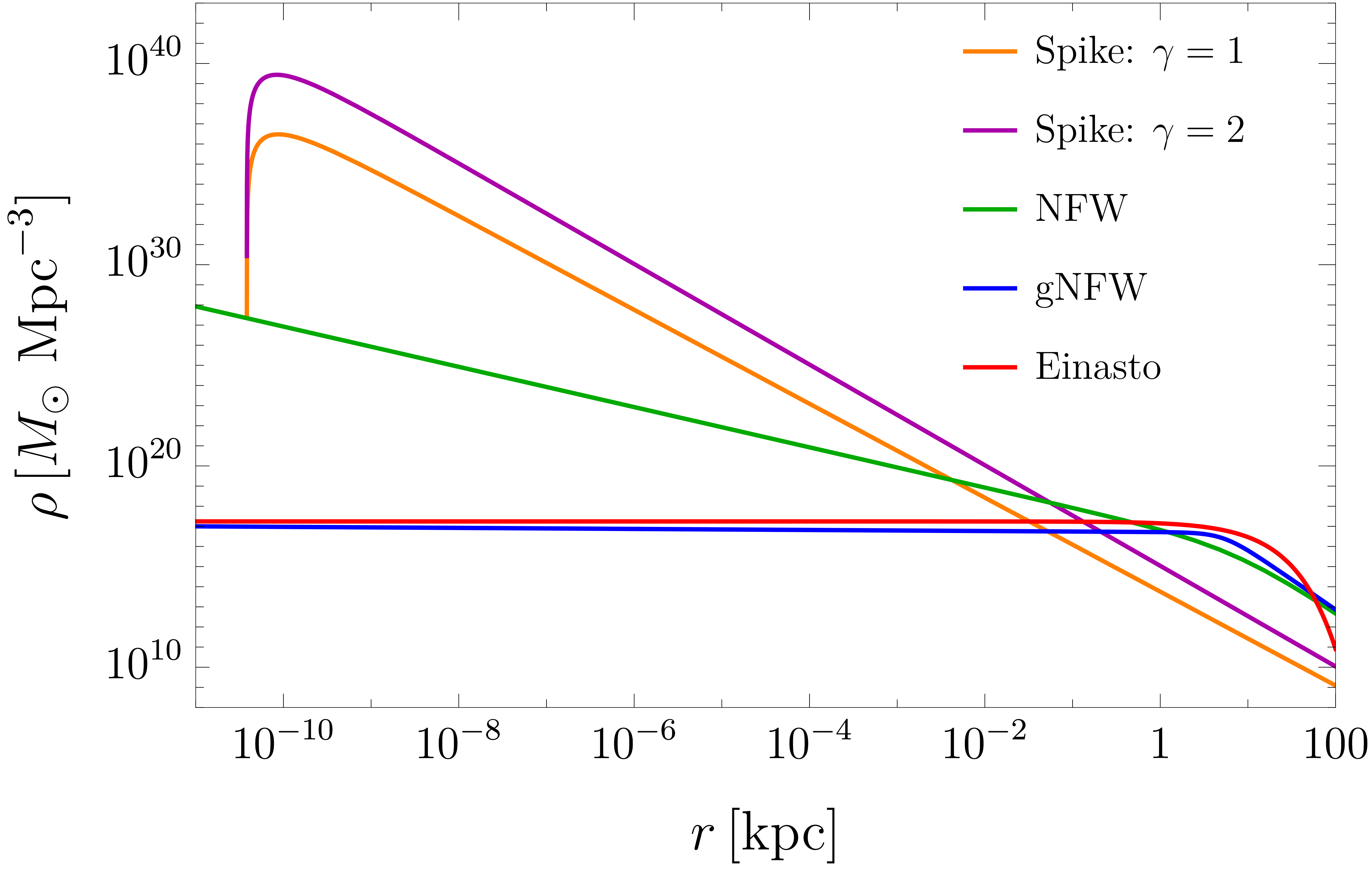
- Carried out a comprehensive analysis of models for general effective ν-DM interactions
  - Inconsistencies in comparisons to results in literature
- Many strong constraints from cosmology, astrophysics, and labs
  - Updated lab bounds, relaxing them for heavier mediators
- Even so, potential opportunities to probe neutrino interactions with light DM
- For each model, show the remaining parameter space, unexplored for $>$ MeV mediator masses
- Other scenarios:
  - axions/ALPs (large number density)
  - HEANs interacting with DM, measured at IceCube

Thank you!

Backup Slides

Comparison of DM Profiles

- Einasto, gNFW are cored
- Spike, NFW are cuspy



Event rate plot at DUNE