DEPARTMENT OF PHYSICS

TEXAS A&M UNIVERSITY
Physics & Astronomy

A comprehensive analysis of supernova neutrino-dark matter interactions

NuFact 2024

Deepak Sathyan

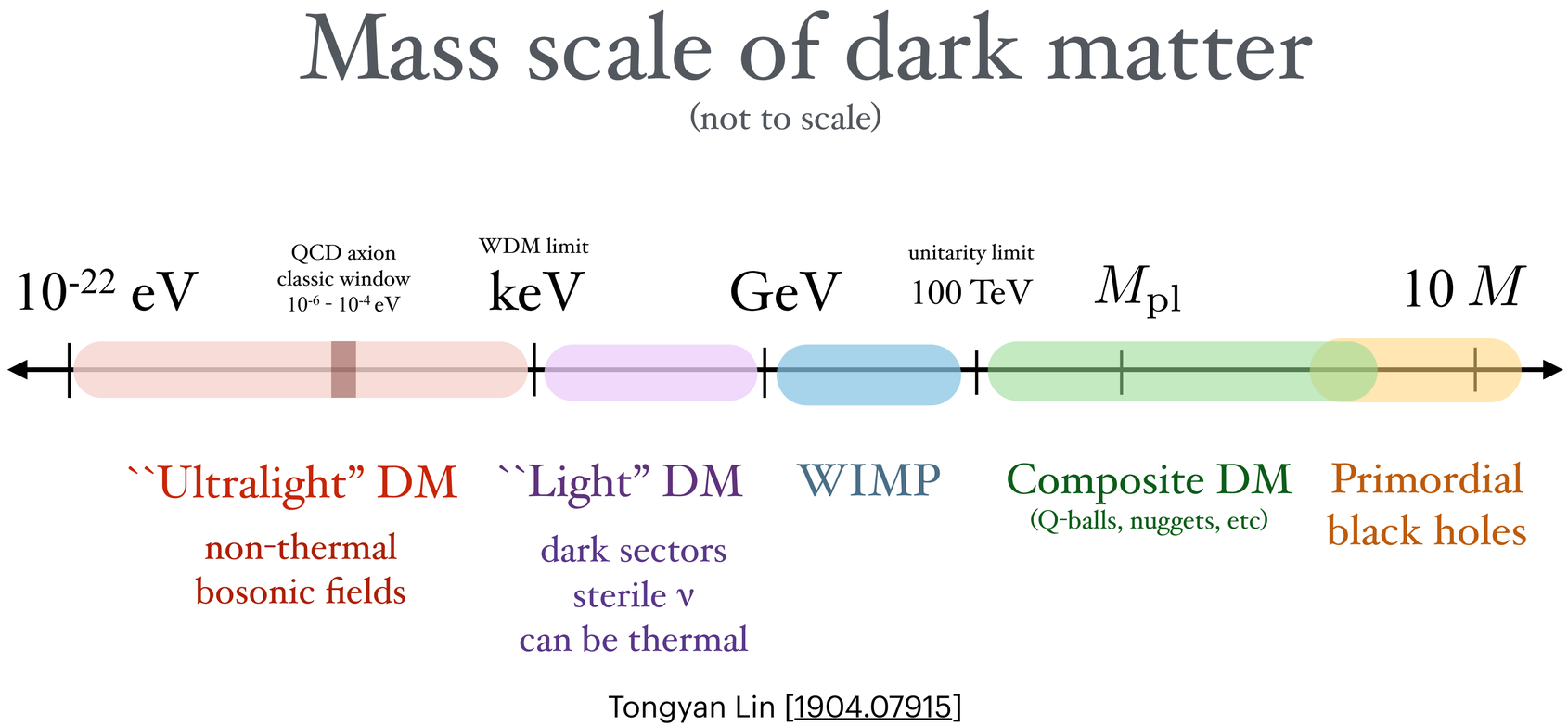
September 17, 2024

[2407.12738, 2409: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?



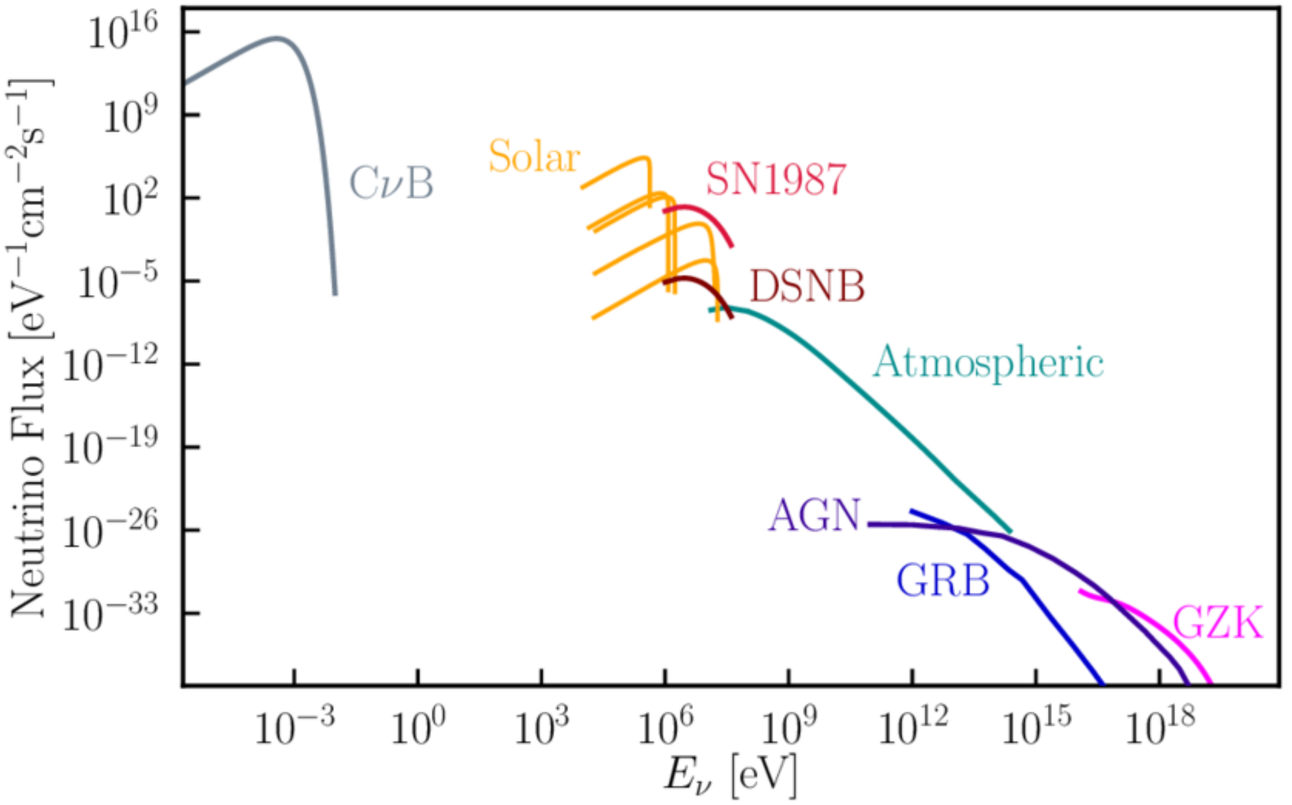
Tongyan Lin [1904.07915]

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]

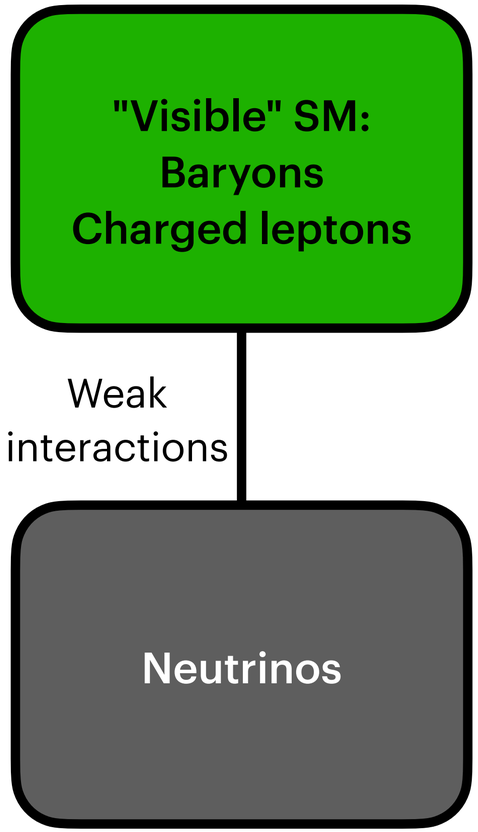
Two sectors of interest:

Dark Matter and Neutrinos

"Visible" SM:
Baryons
Charged leptons

Two sectors of interest:

Dark Matter and Neutrinos



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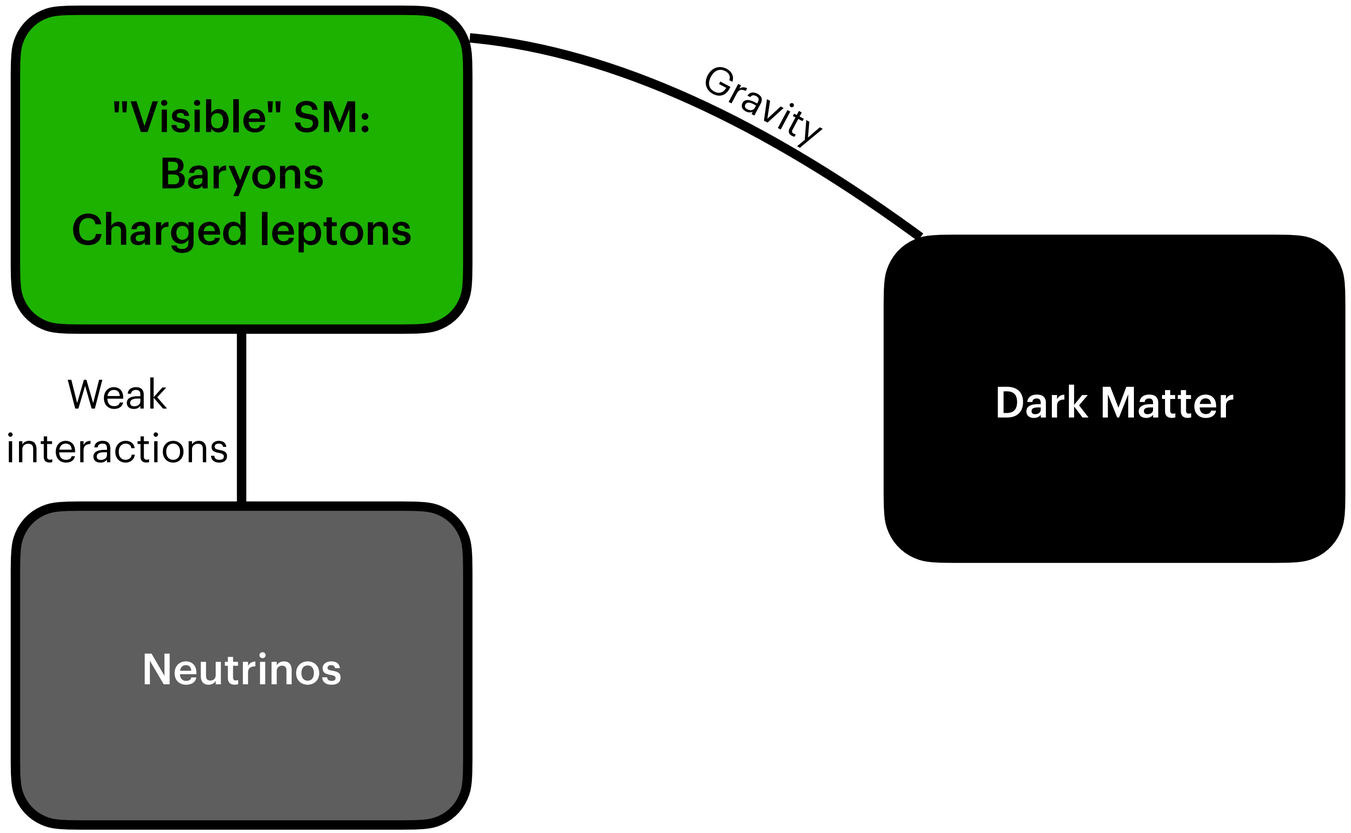

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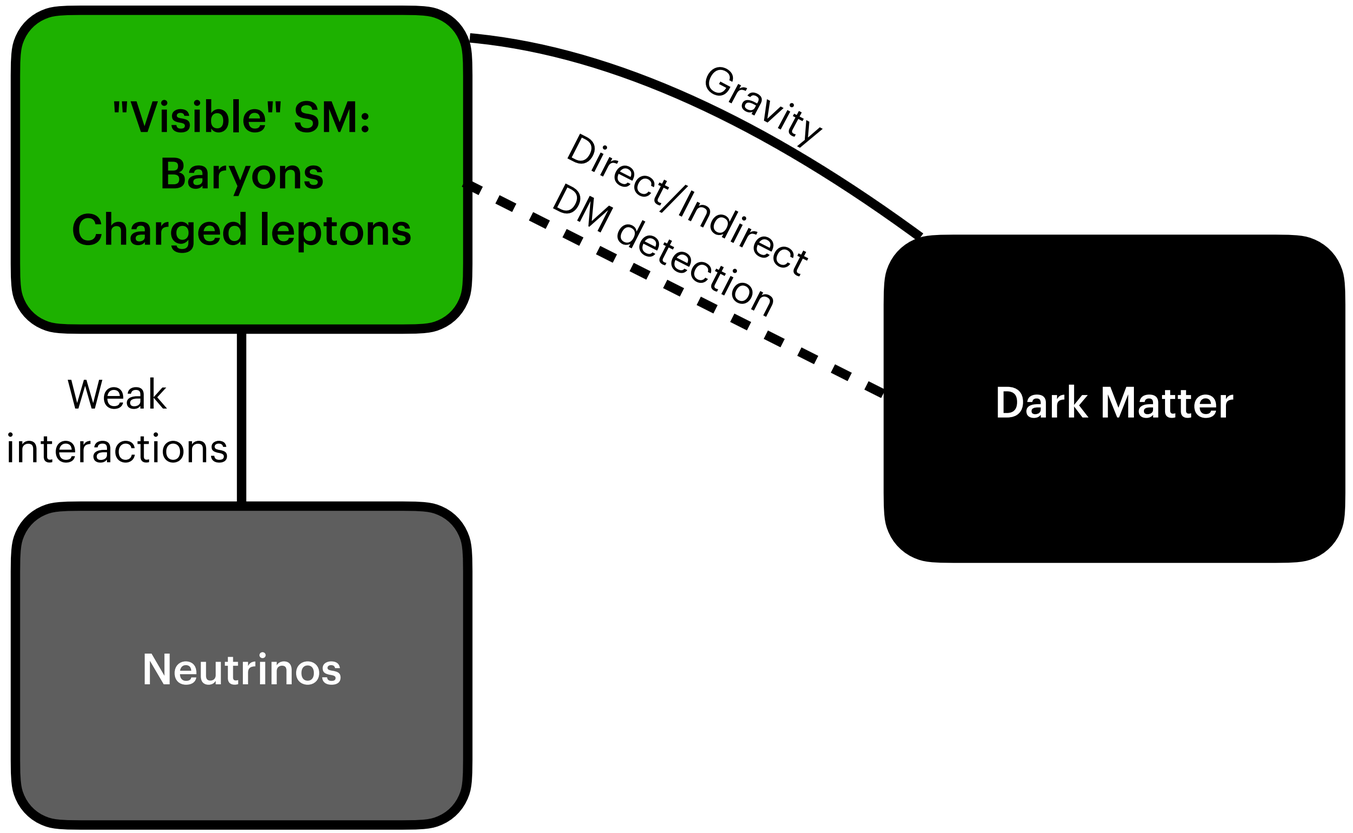
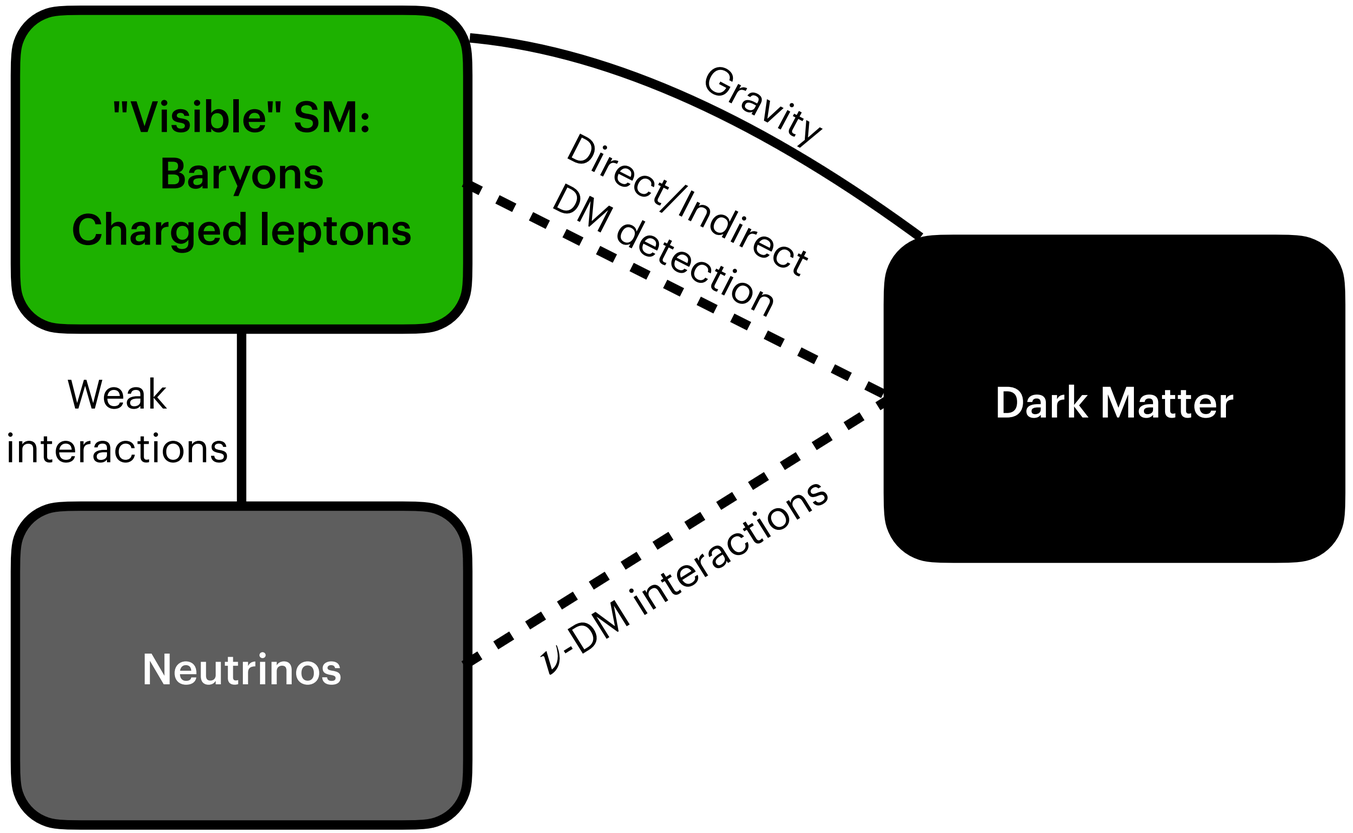


Two sectors of interest:

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?

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

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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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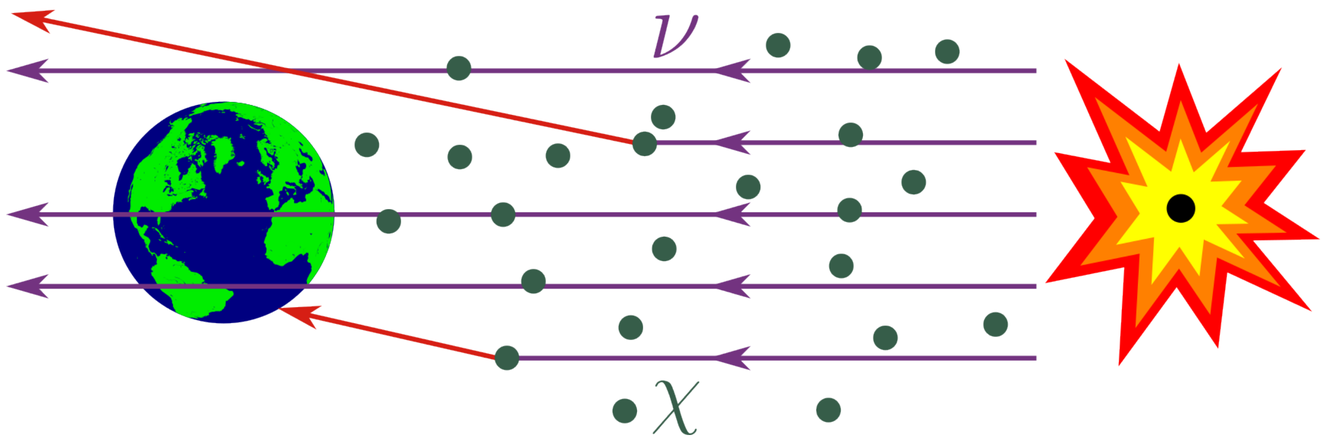
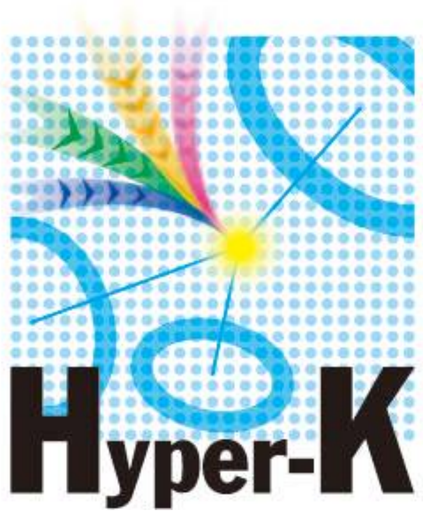


- Modified neutrino flux $\Phi/\Phi_0 \sim e^{-\tau}$
- Large τ obtained from:
  - large number density of DM
  - large distance for neutrinos to travel through DM
- Motivates considering astrophysical sources:
  - local supernova
  - diffuse supernova neutrino background
  - high energy astrophysical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

Observing ν-DM interactions

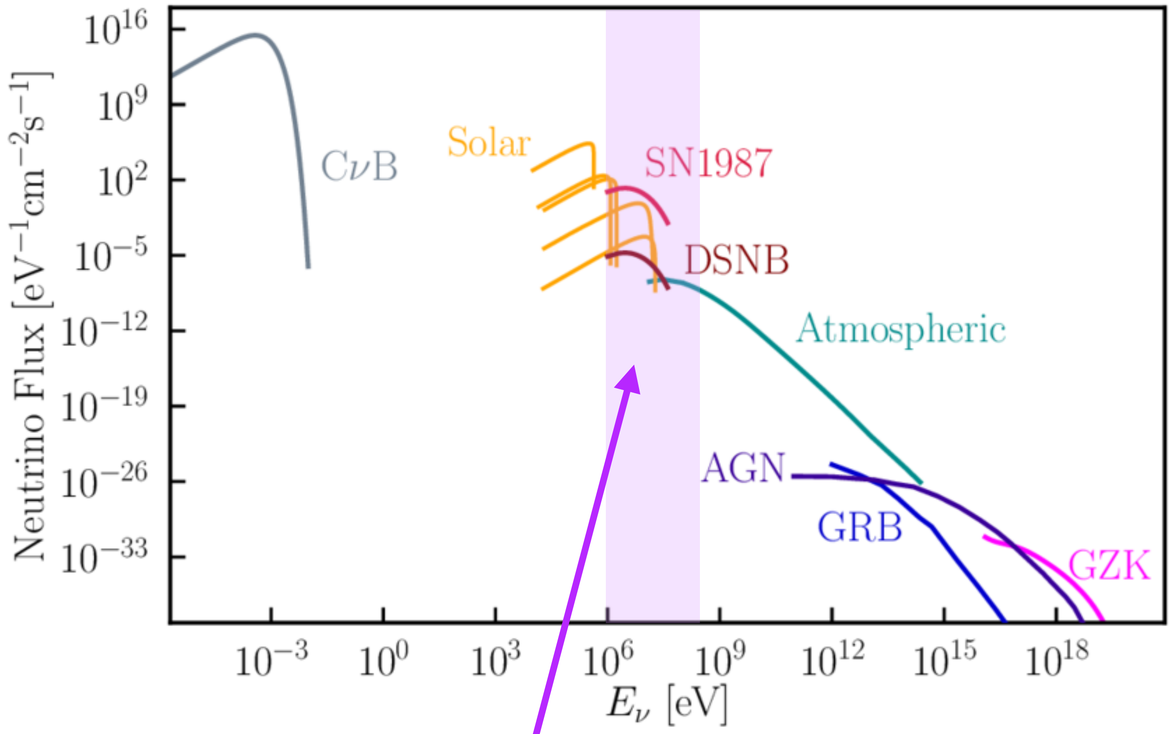
- Upcoming neutrino experiments sensitive to SN neutrino flux, dominantly at MeV range
  - Can they probe effects of SN neutrinos passing through galactic DM halo?
  - Such a signal prefers higher number density of DM:
    $m_\chi < 1\,\mathrm{GeV}$

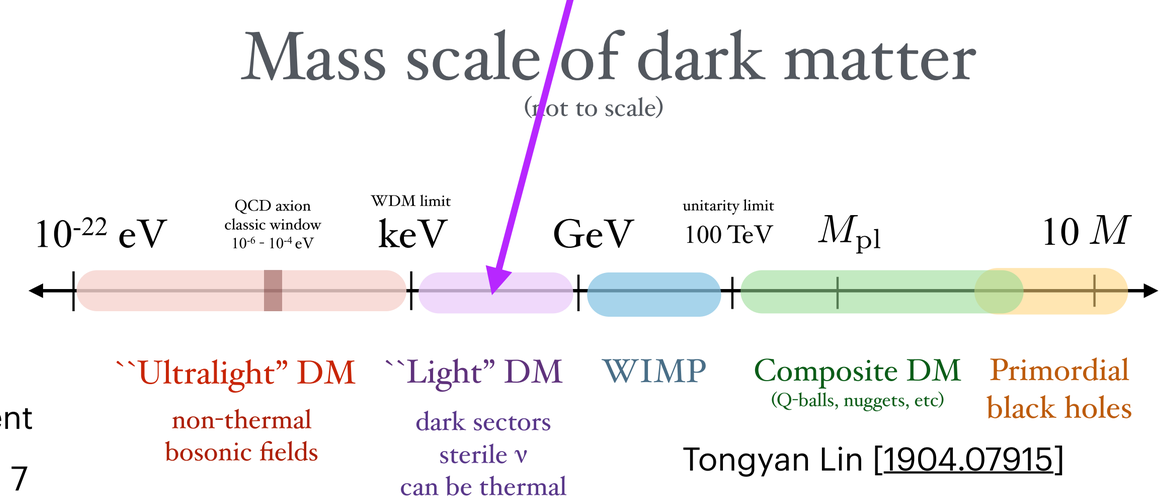


Scales of ν-DM interactions

- 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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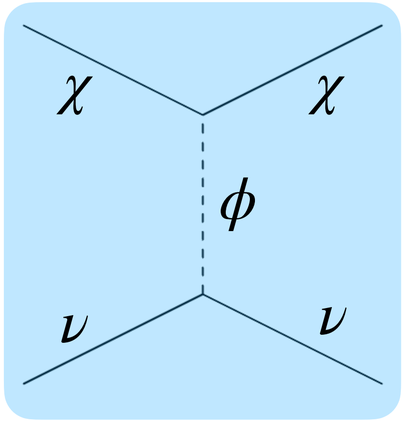
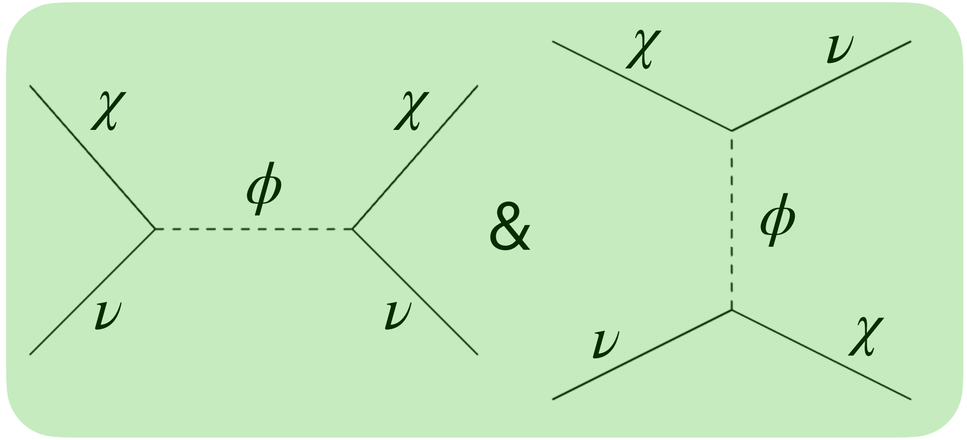
Modeling ν-DM interactions

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



or



- 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 $\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}$ 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

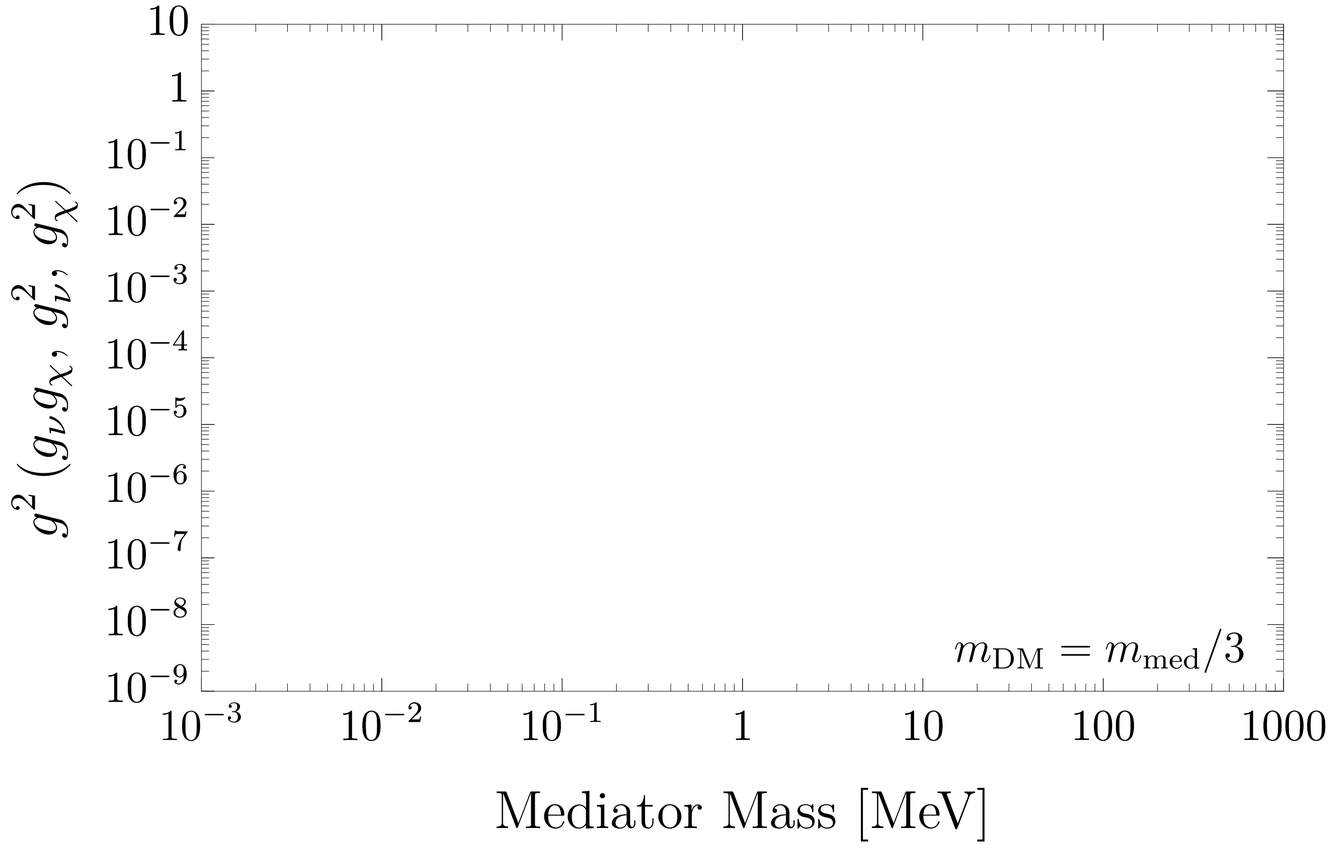
- Will carefully show each bound for one example model: Dirac fermion DM, scalar mediator:

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

Bound Plots for Example Model

Dirac Fermion DM, Scalar mediator

- Cosmological bounds:



Neutrino Self-Interactions: A White Paper [2203.01955]

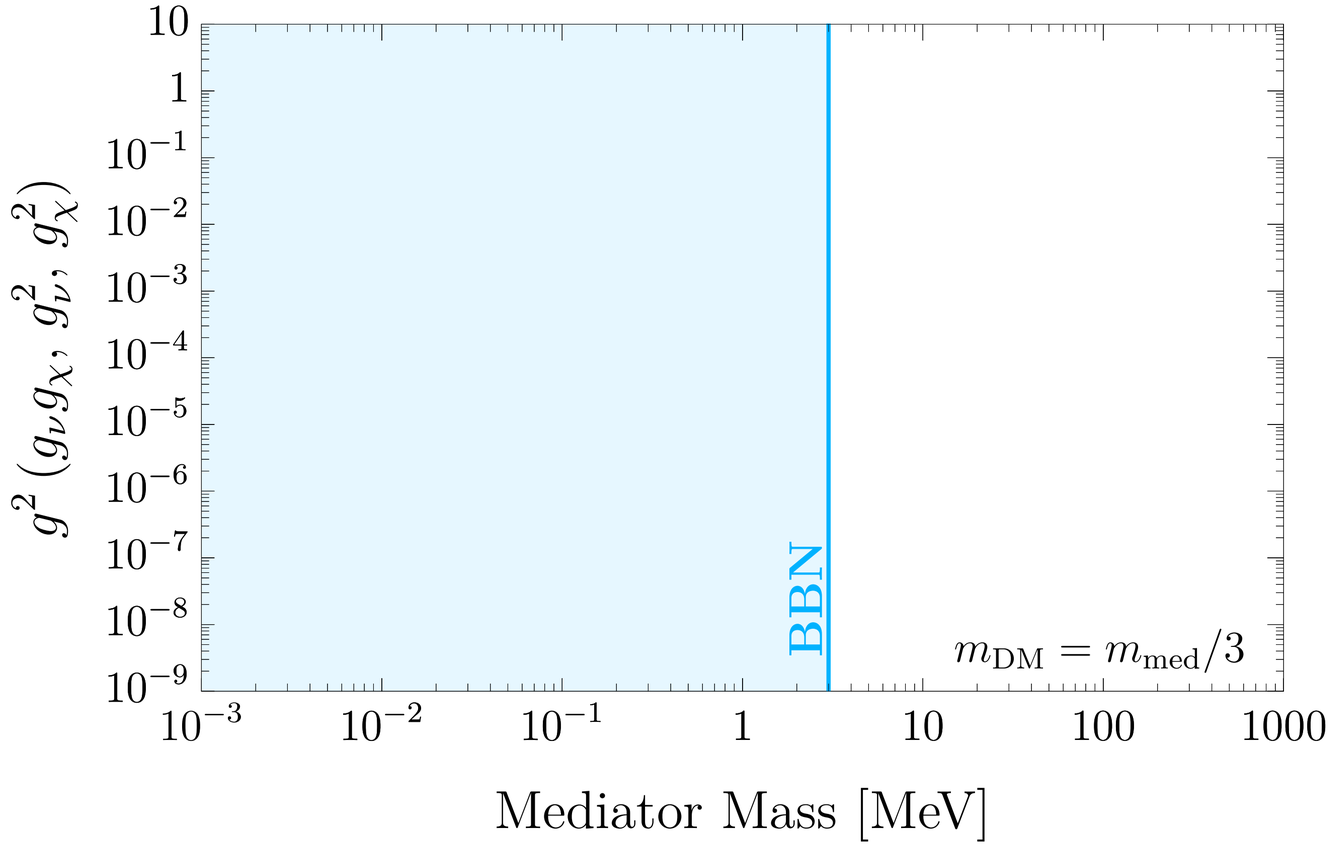
A. Campo, C. Bœhm, S. Palomares-Ruiz, S. Pascoli [1711.05283]

G. Steigman, B. Dasgupta, J. Beacom [1204.3622]

Bound Plots for Example Model

Dirac Fermion DM, Scalar mediator

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



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Dirac Fermion DM, Scalar mediator

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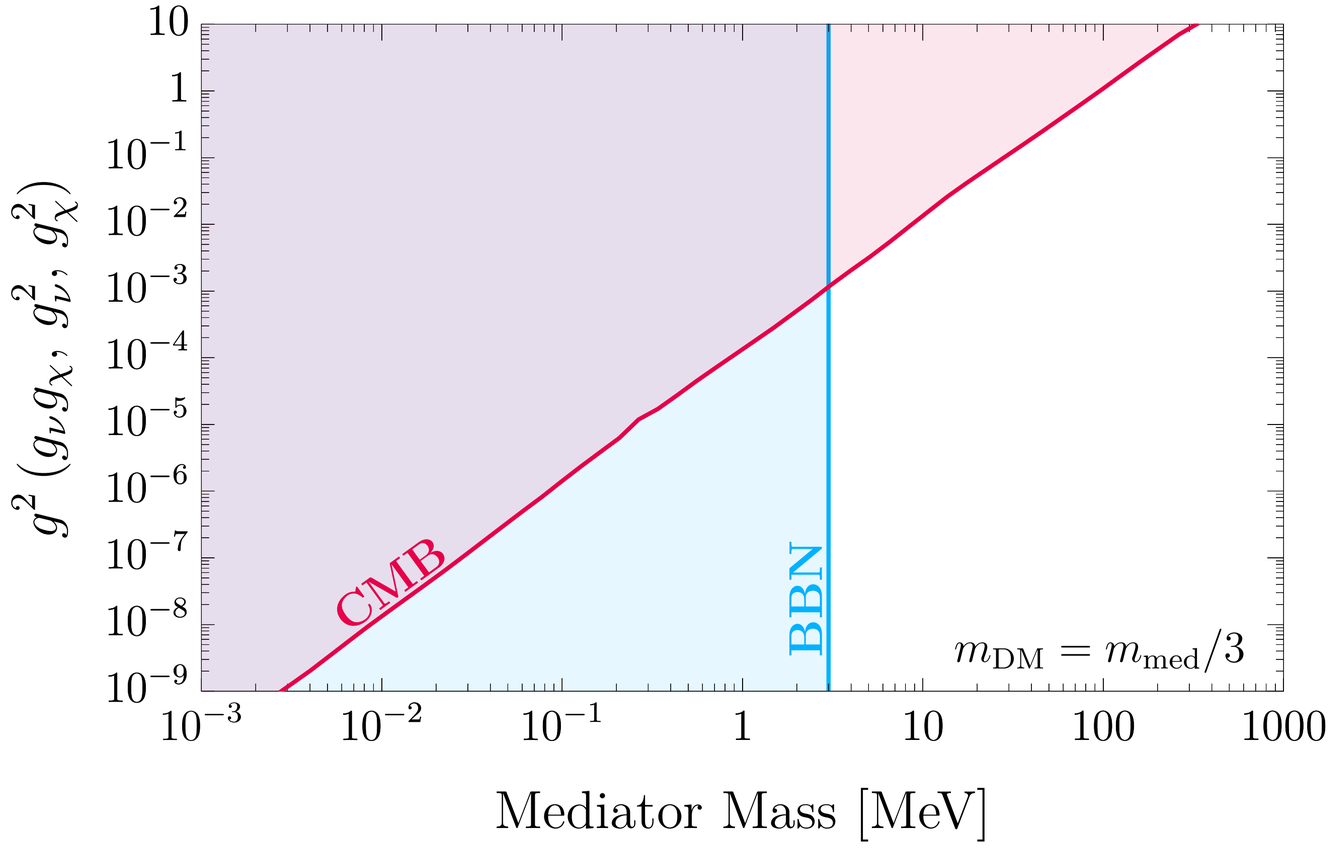
  - CMB: neutrino NSI affects phase shift and amplitude in matter power spectrum



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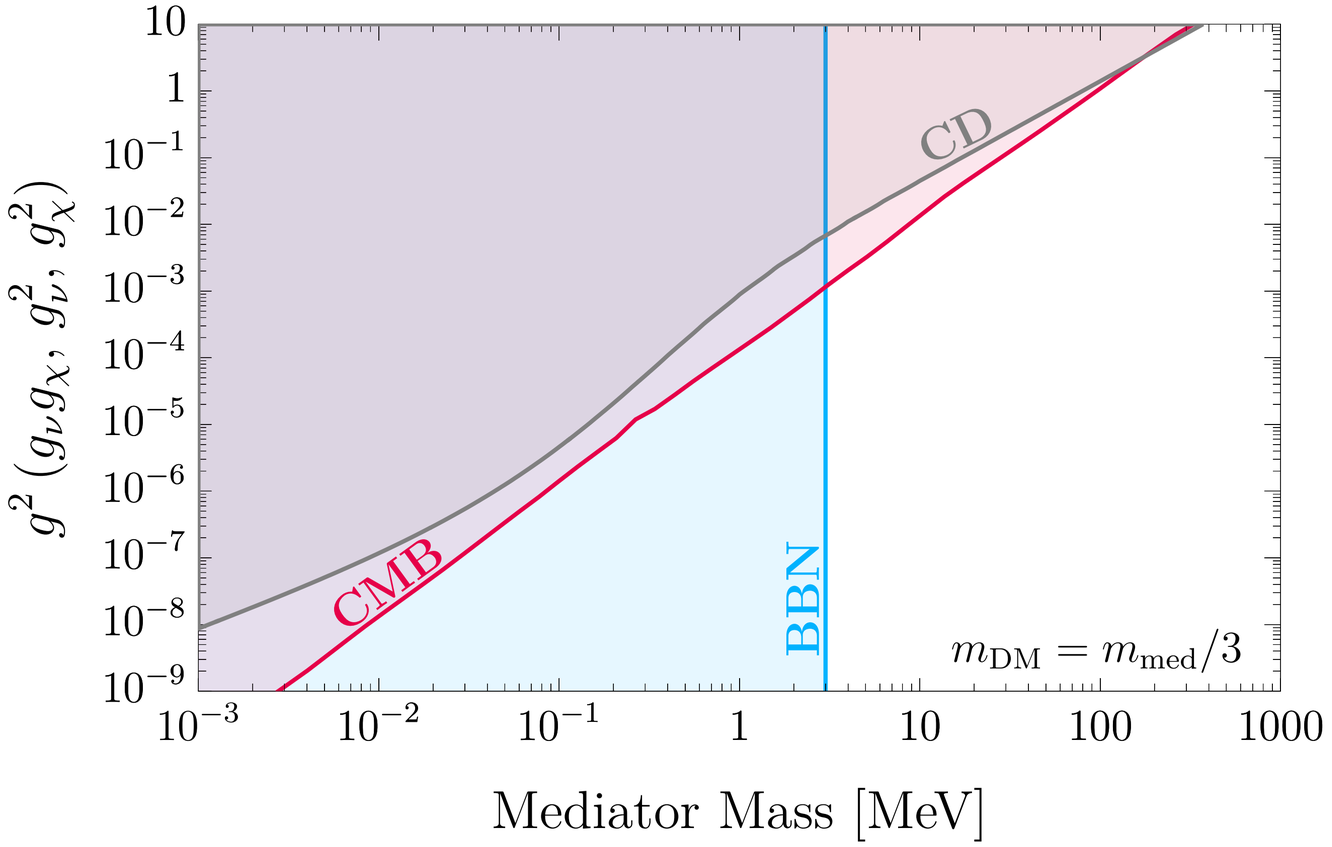
  - Collisional Damping: upper limit on ν-DM interactions from CMB and LSS



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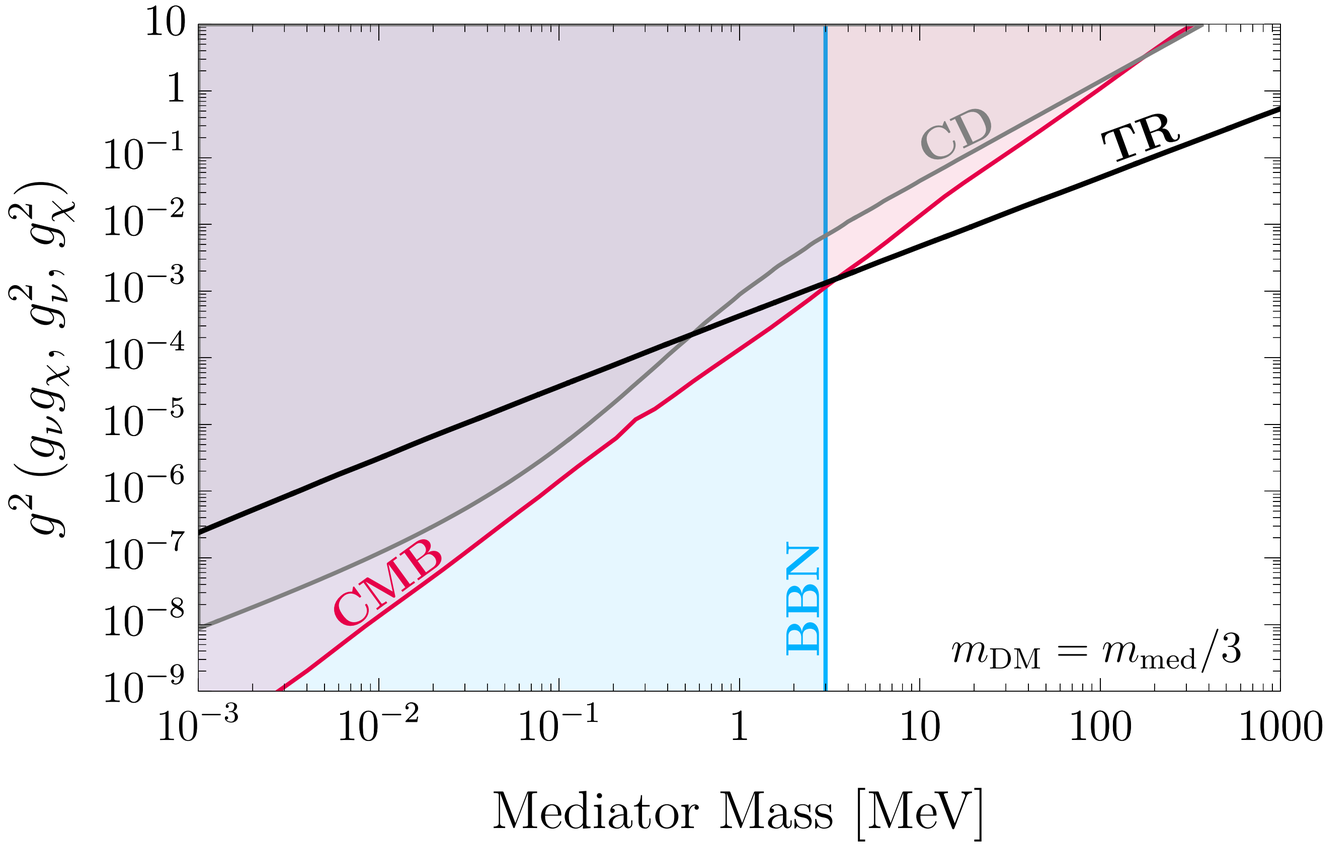
  - CMB: neutrino NSI affects phase shift and amplitude in matter power spectrum
  - Collisional Damping: upper limit on ν-DM interactions from CMB and LSS
  - Thermal relic density: annihilation rate of DM into neutrinos needed to match relic abundance



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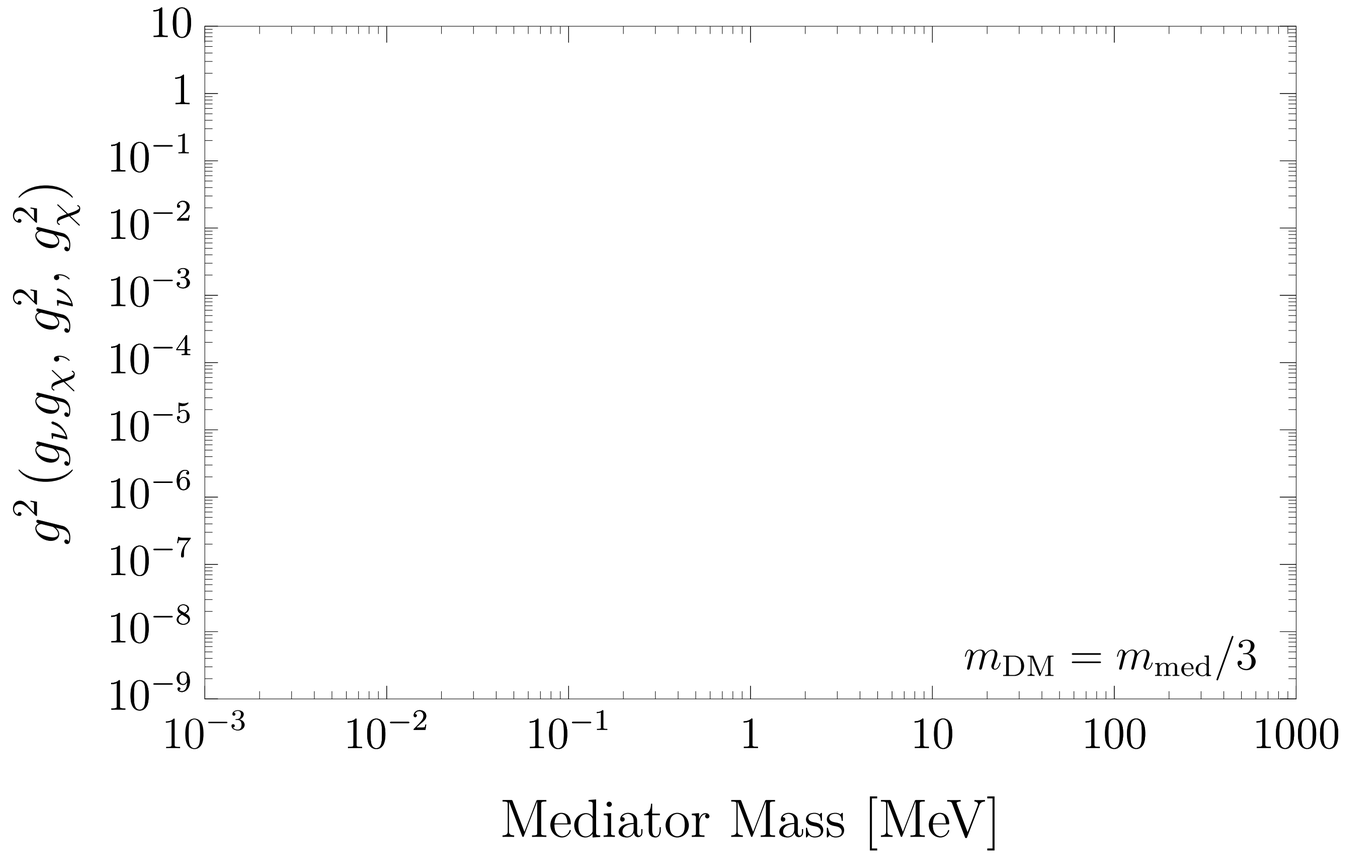
Summary Plot for Example Model

Dirac Fermion DM, Scalar mediator

- Astrophysical bounds:



G. Mangano, A. Melchiorri, P. Serra, A. Cooray, M. Kamionkowski [astro-ph/0606190]

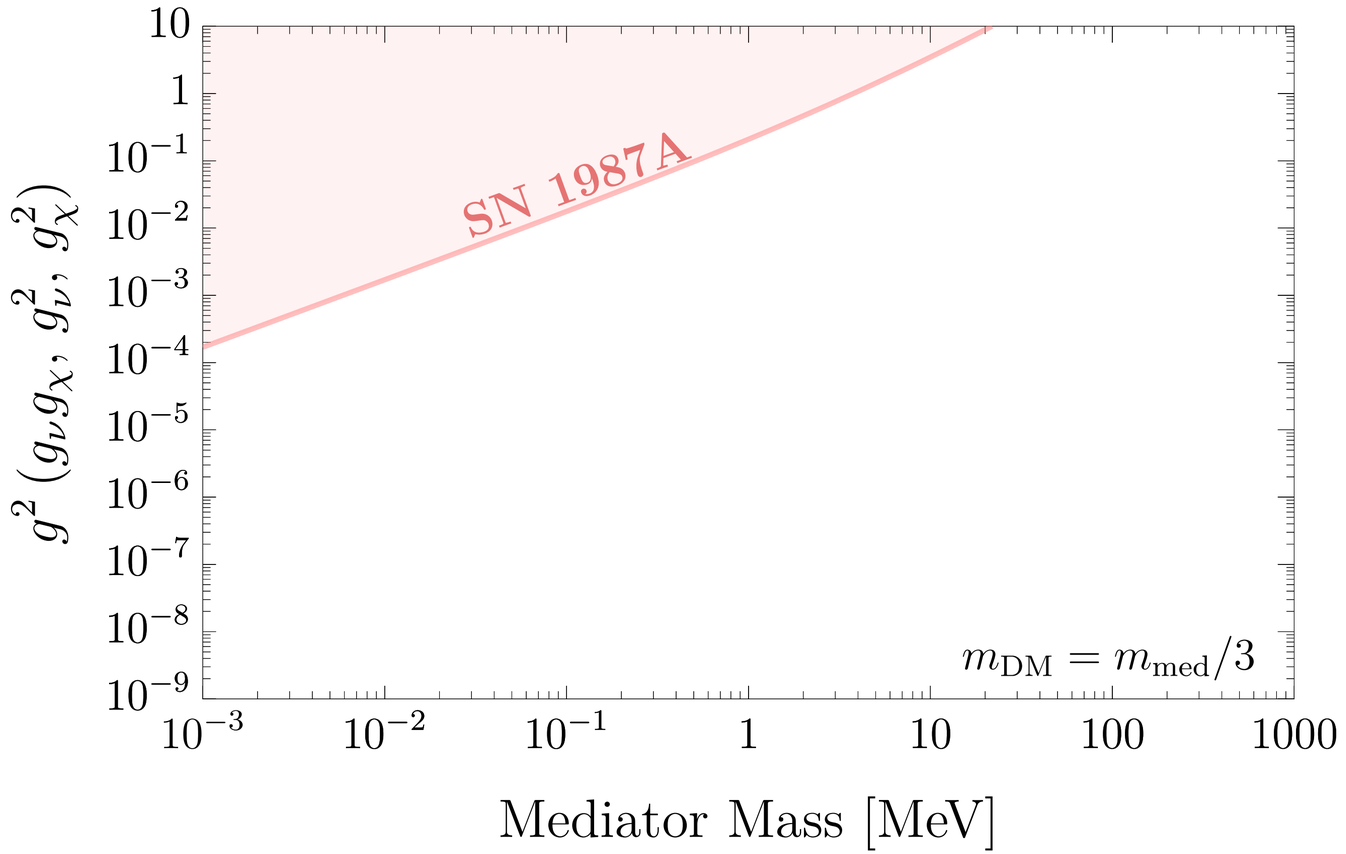
M. Markevitch et al. [astro-ph/0309303]

A. Robertson, R. Massey, V. Eke [1605.04307]

Summary Plot for Example Model

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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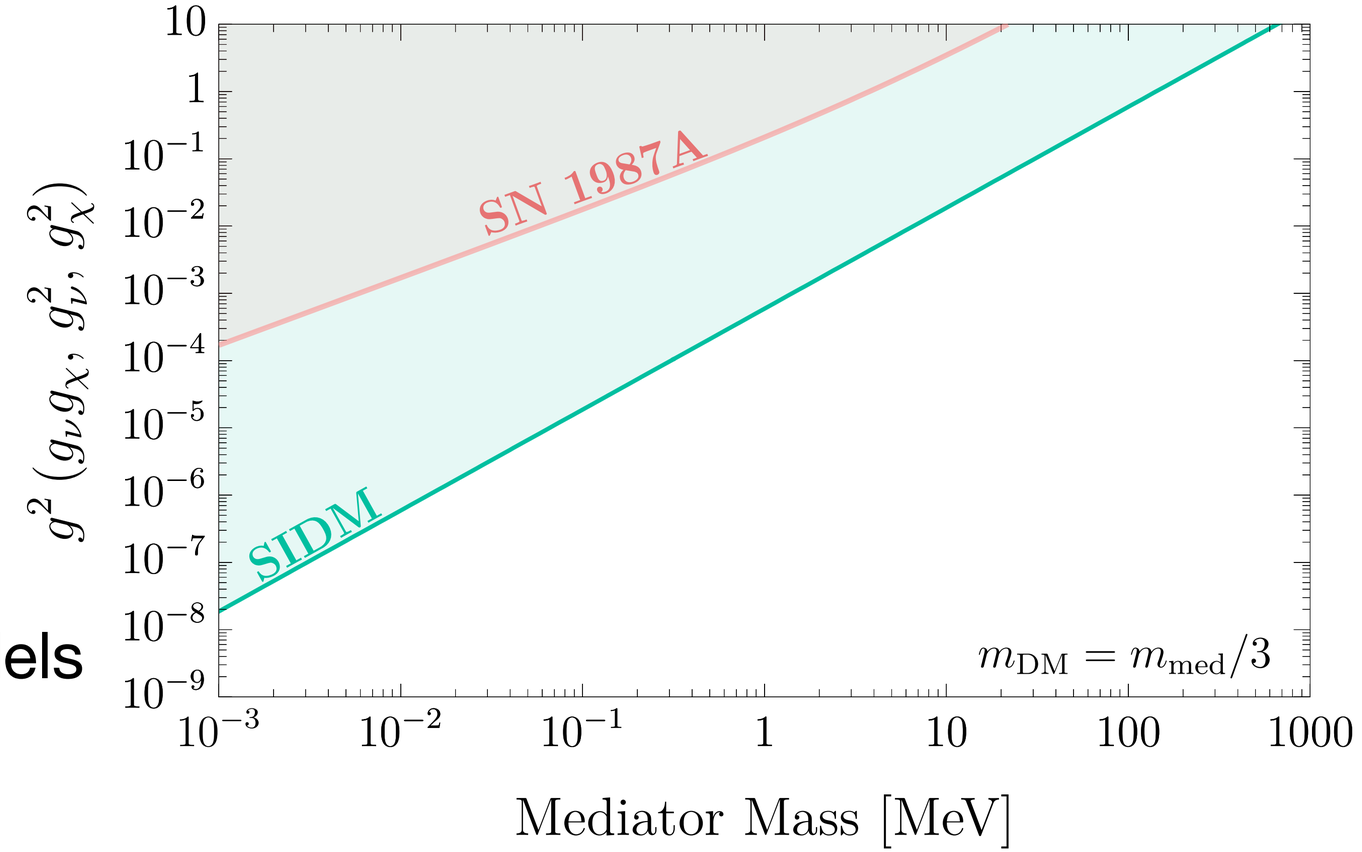
Summary Plot for Example Model

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 with $\chi\bar{\chi}\phi$ coupling



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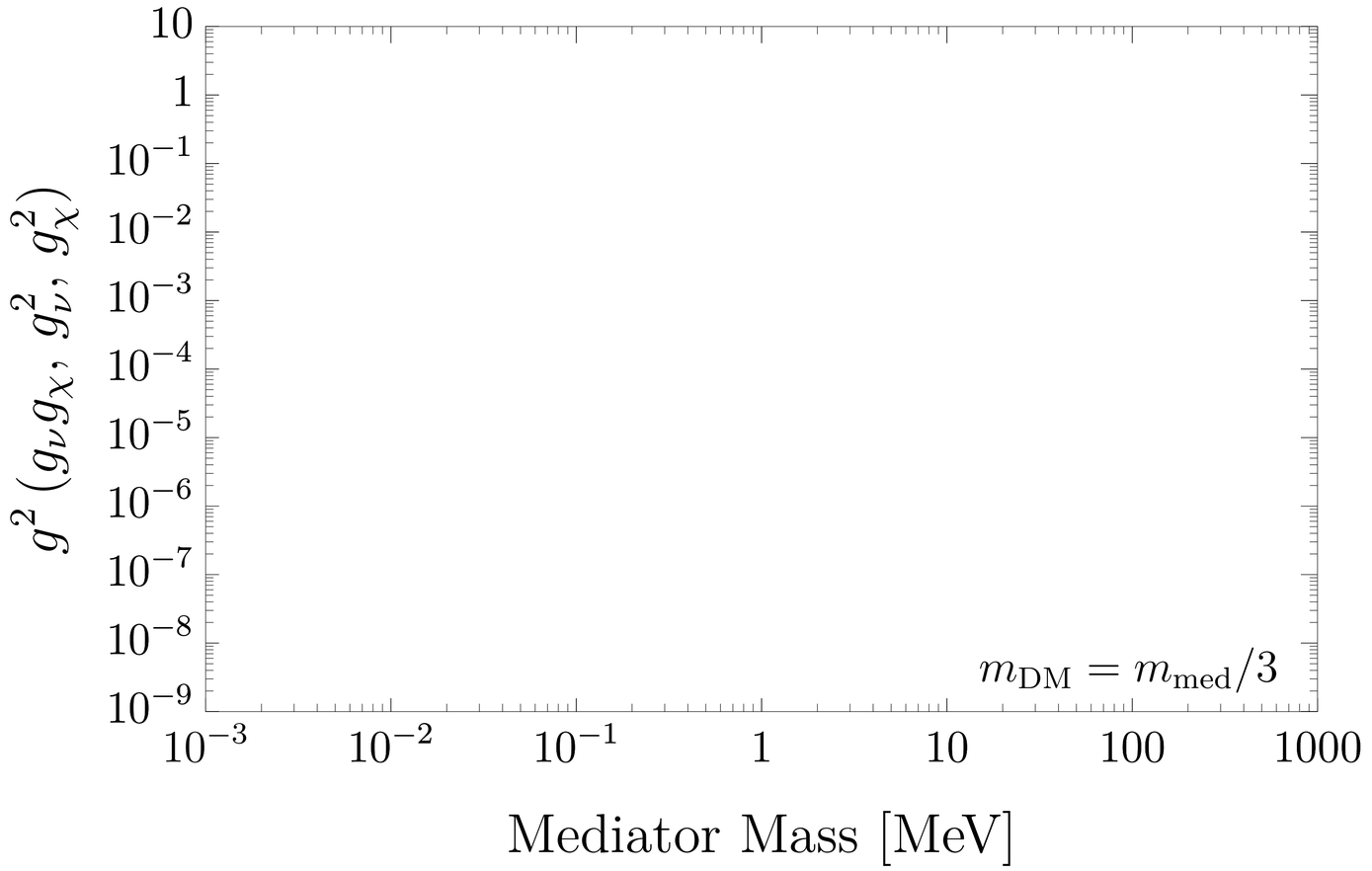

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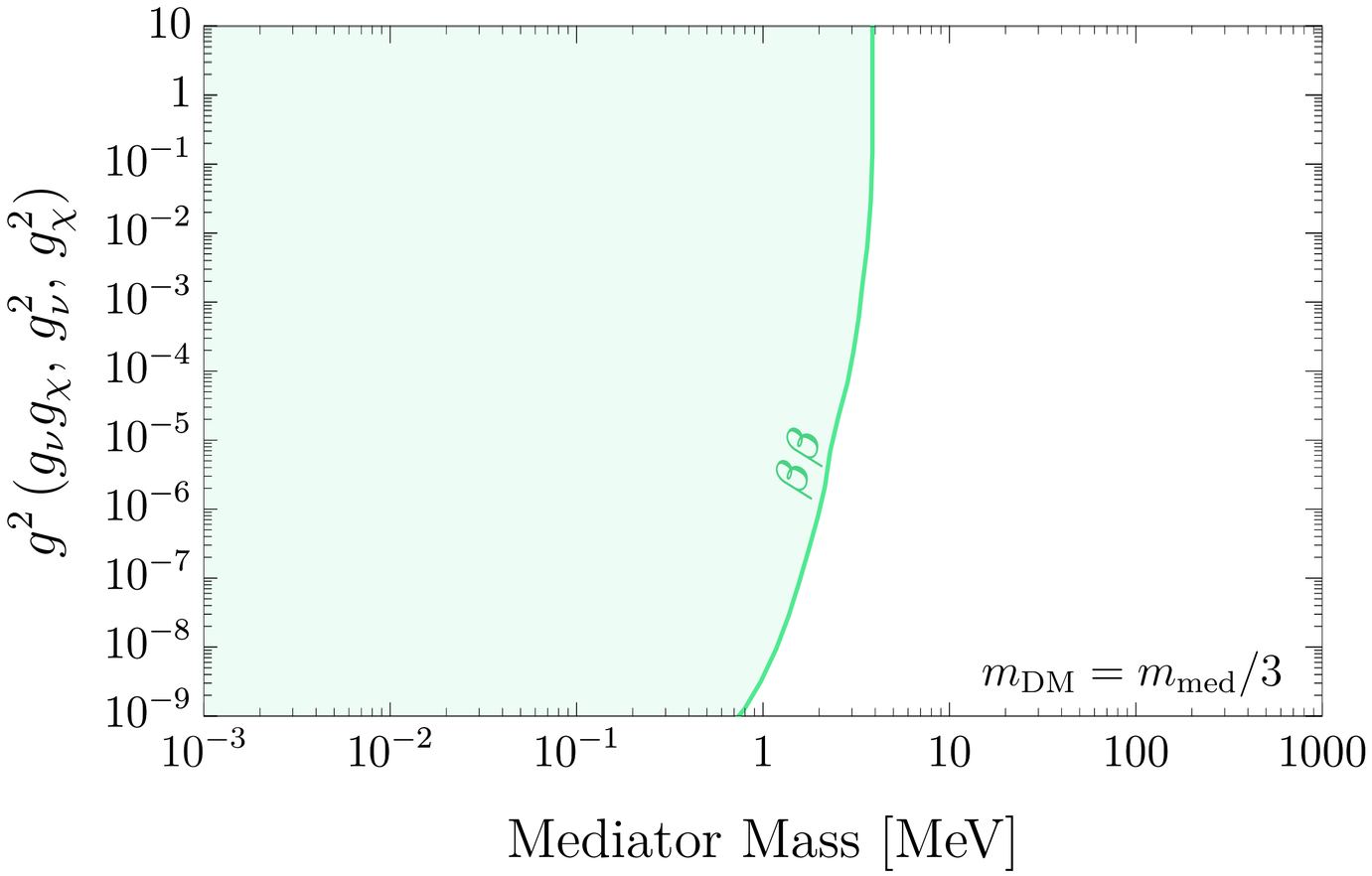
- Lab bounds:
  - $\beta\beta$ decay: ν NSI effects can be seen in searches



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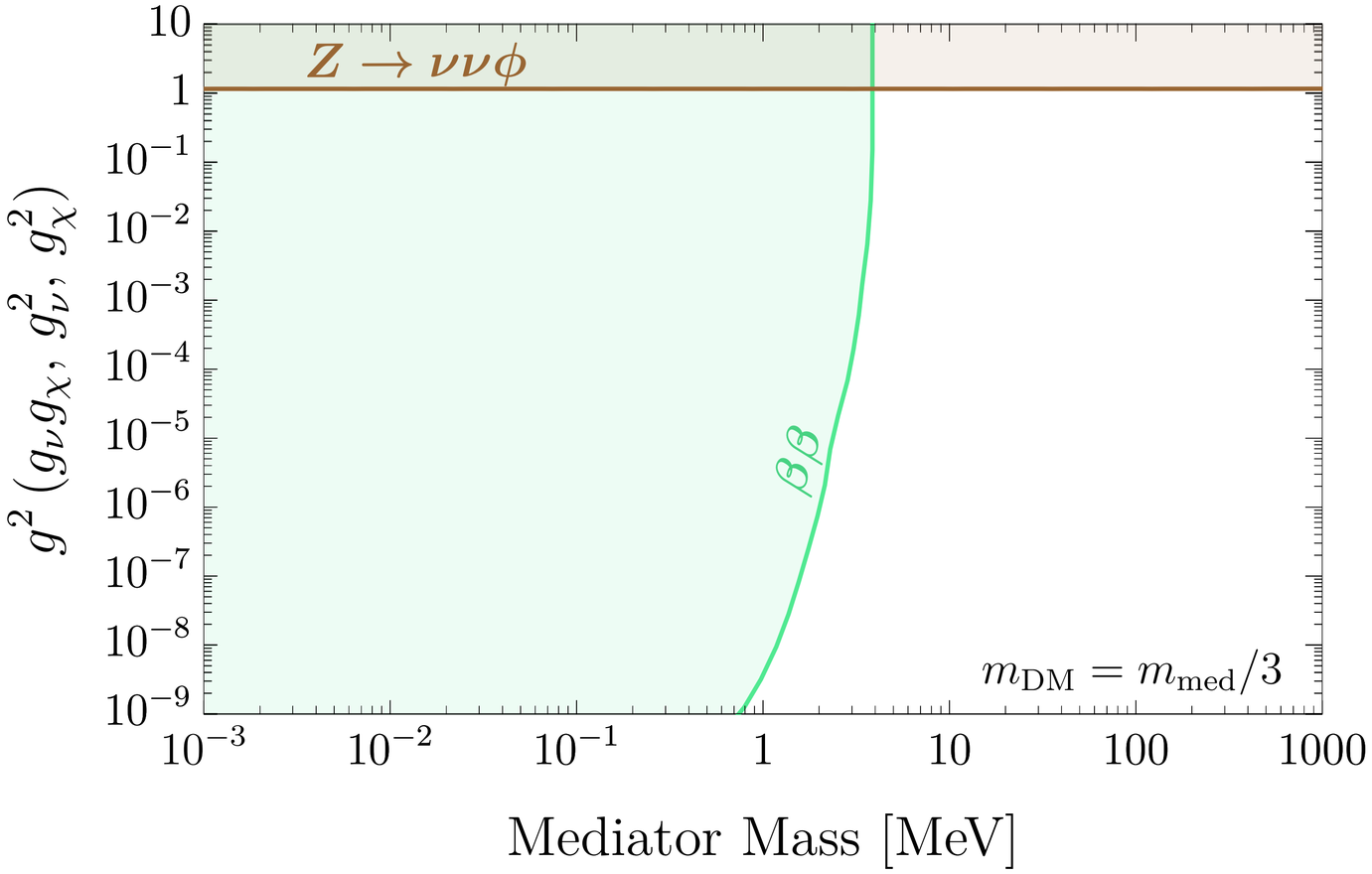
  - Invisible Z decays*



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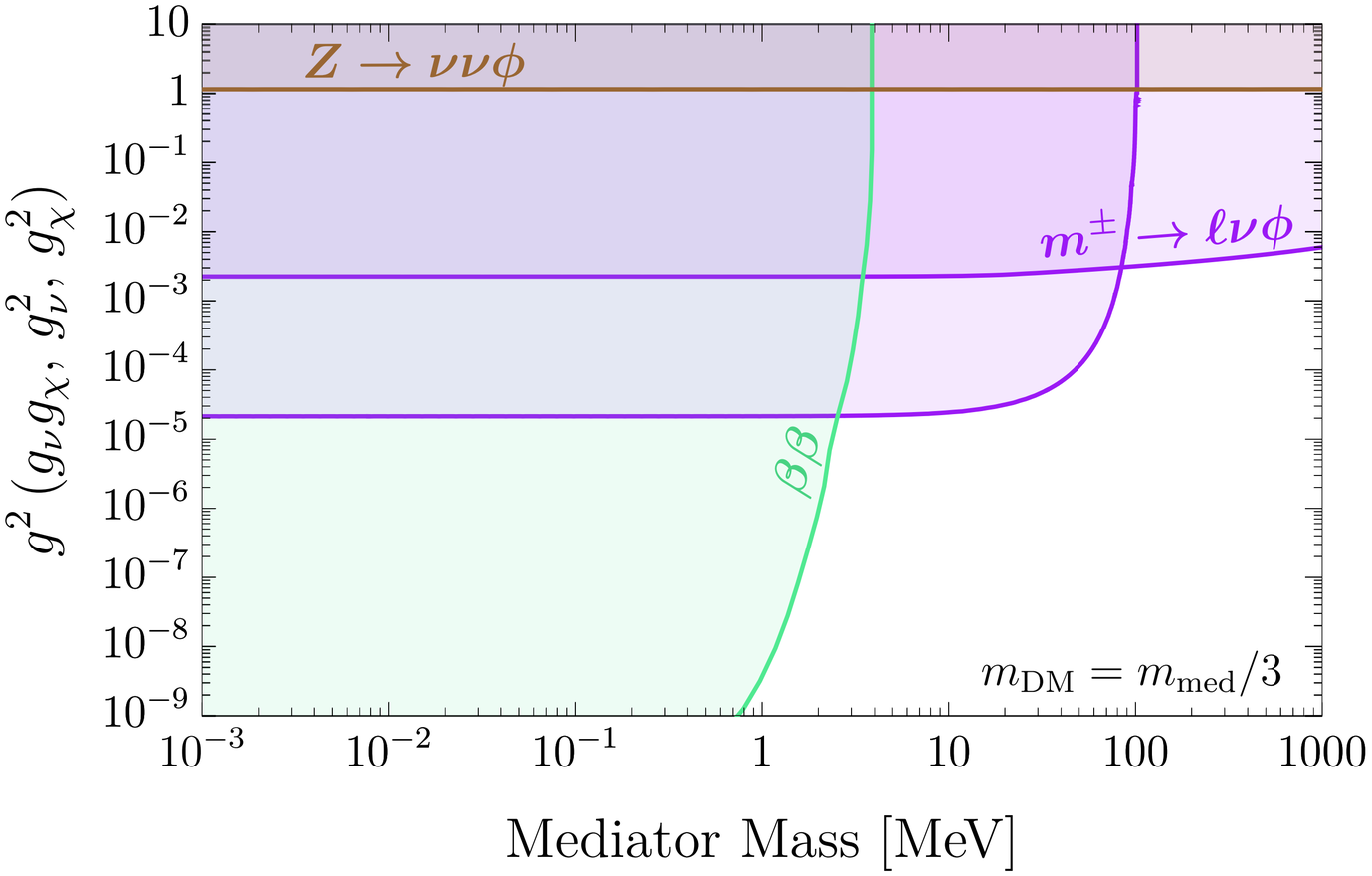
  - Invisible Z decays*
  - Meson decays*



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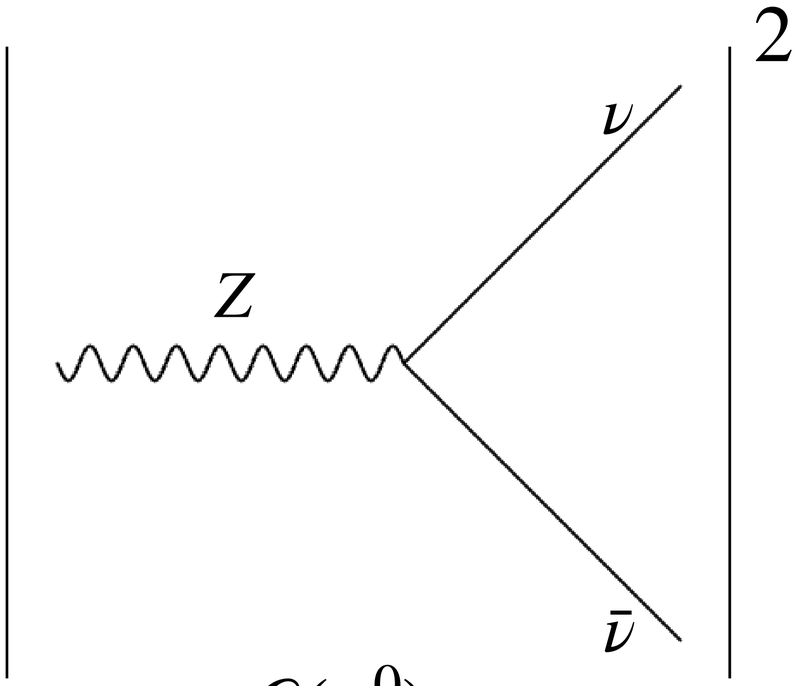
Updating Bounds on ν-DM interactions

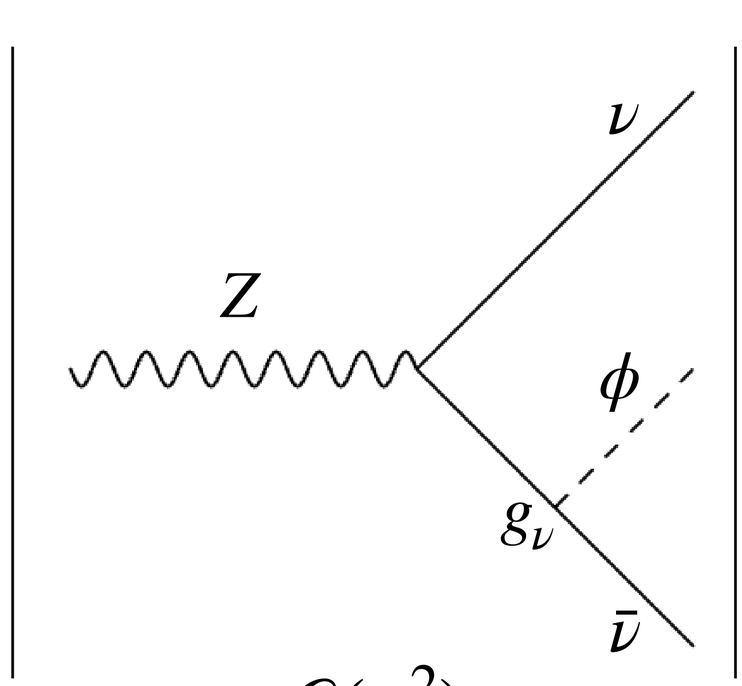
- Current Z and Meson decay bounds computed at tree-level

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



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

$+$



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

IR divergence

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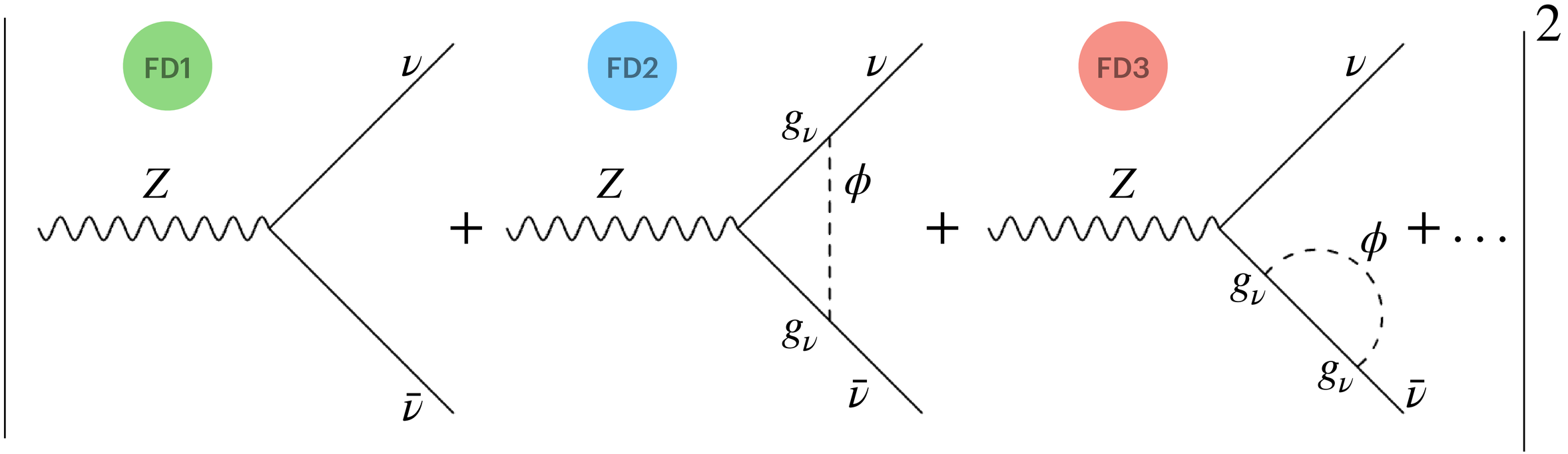
Updating Bounds on ν-DM interactions

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

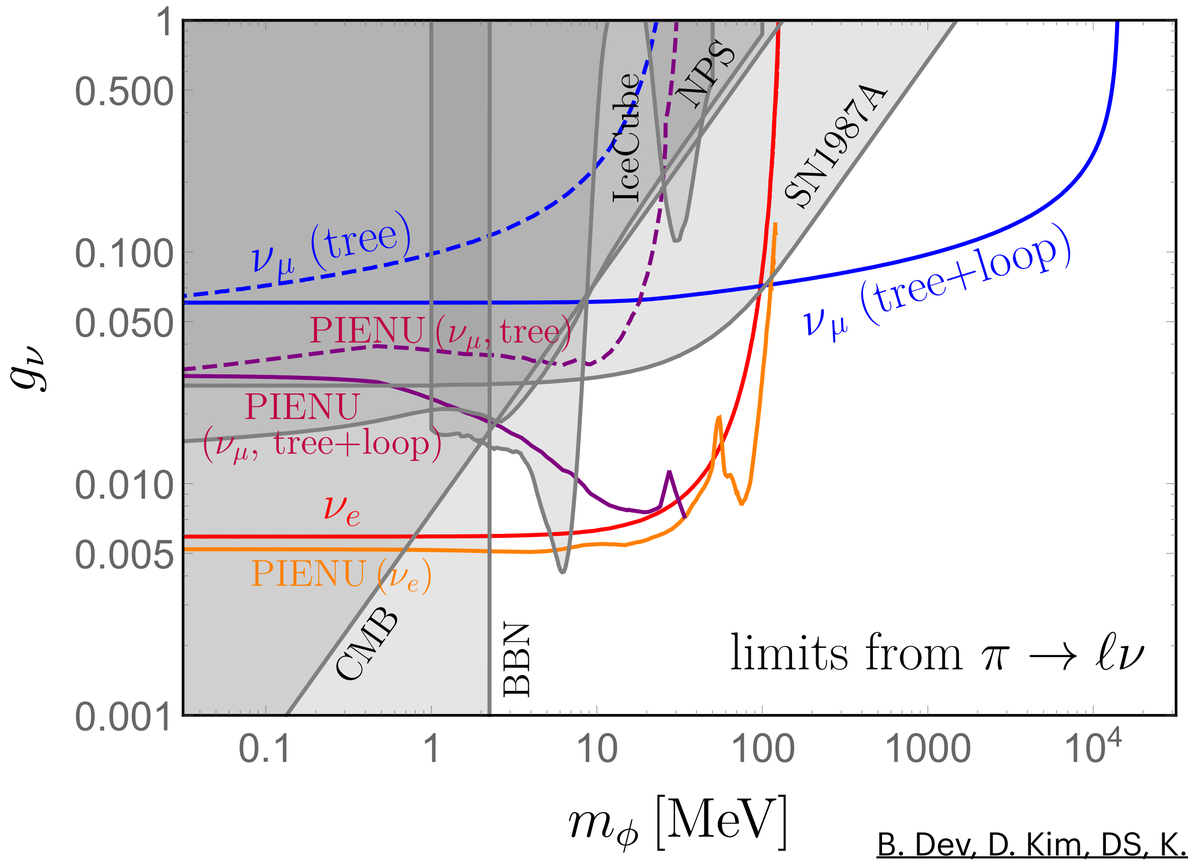


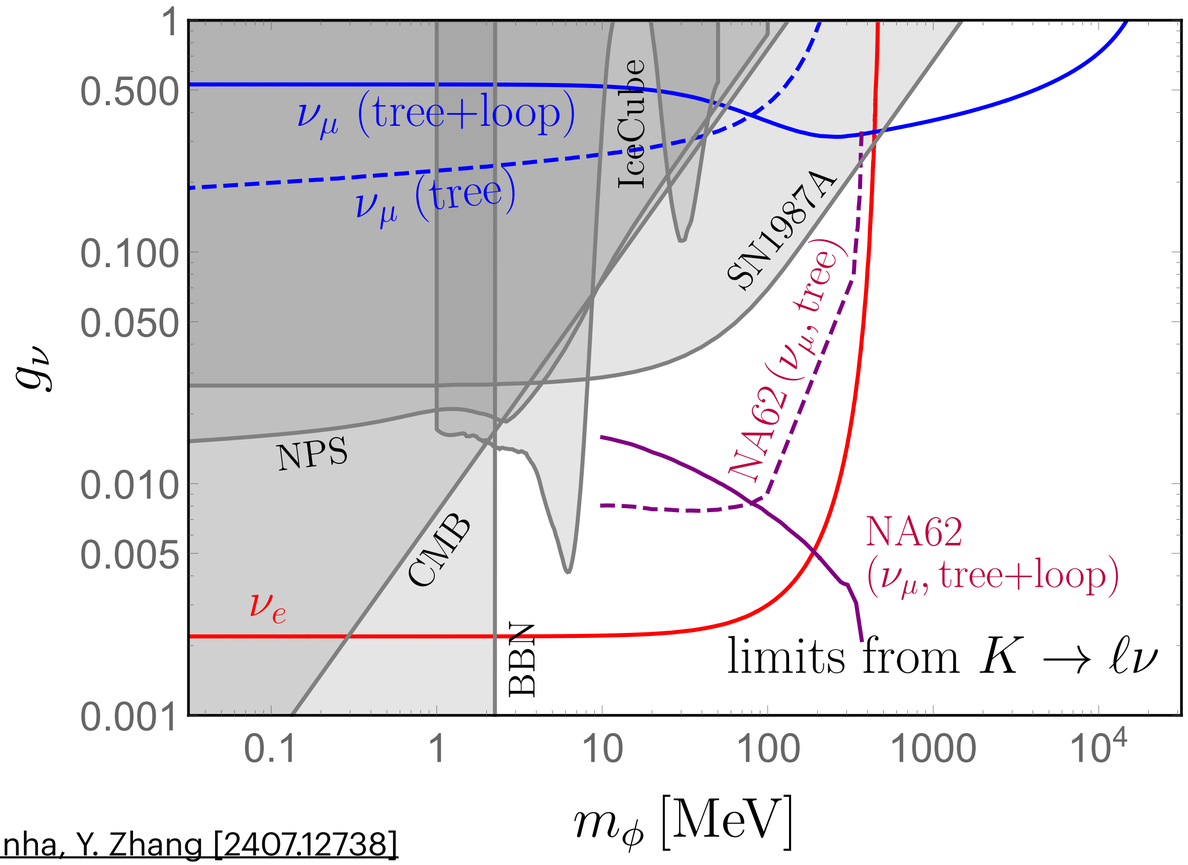
Interference terms FD1 FD2 and FD1 FD3 are $\mathcal{O}(g_\nu^2)$, like tree level $Z \to \nu\nu\phi$

Updating Bounds on ν-DM interactions

Meson decays

- Updated bound for scalar mediators of π, K decays



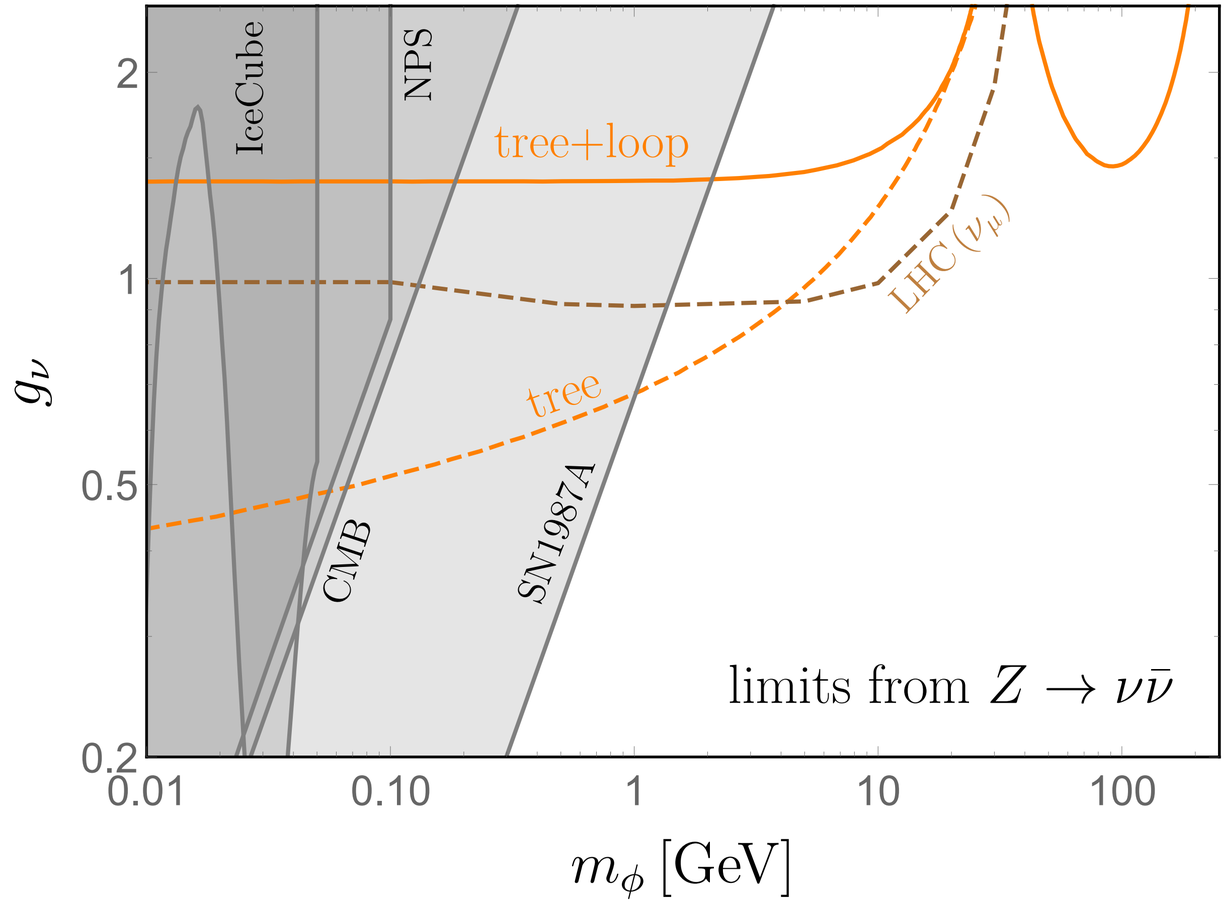


B. Dev, D. Kim, DS, K. Sinha, Y. Zhang [2407.12738]

Updating Bounds on ν-DM interactions

Z decays

- Updated bound for scalar mediators of Z decays



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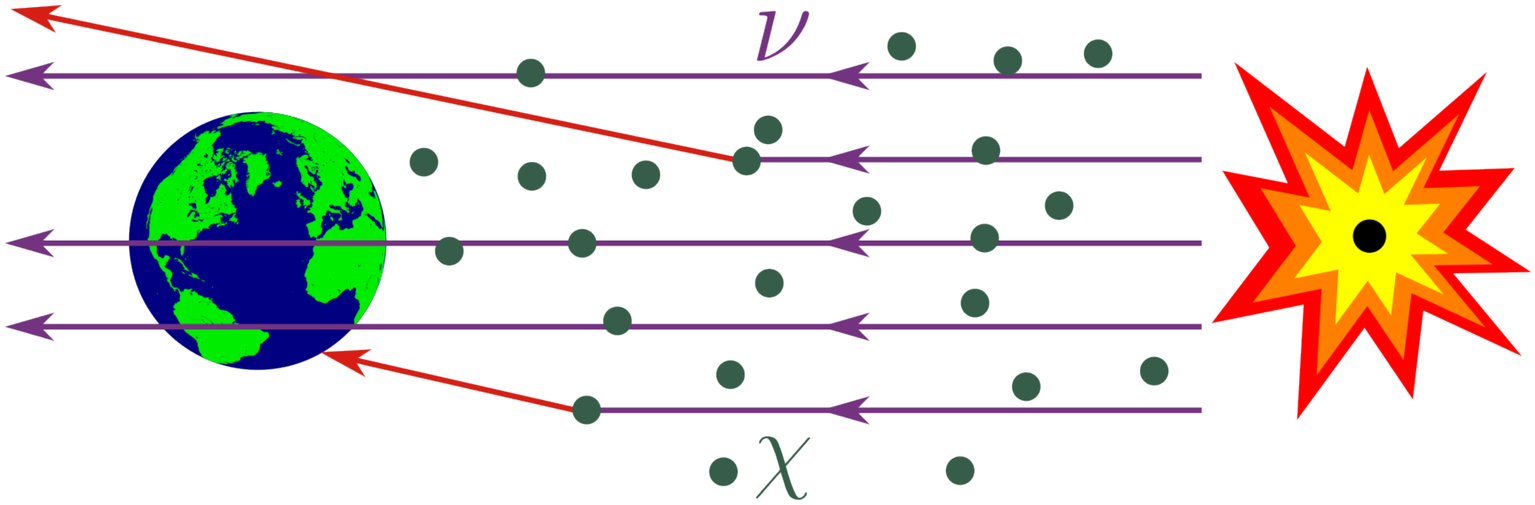
Sensitivity from Galactic SN

- Neutrinos move through DM medium, interactions cause change in flux



- Modeled by cascade equation:

$$\frac{\mathrm{d}\varphi(E,\eta)}{\mathrm{d}\eta} = -\,\sigma(E)\,\varphi(E,\eta) + \int_E^\infty \mathrm{d}\tilde{E}\,\frac{\mathrm{d}\sigma(\tilde{E},E)}{\mathrm{d}E}\,\varphi(\tilde{E},\eta)$$

A. McMullen, A. Vincent, and C. Argüelles, A. Schneider [2107.11491]

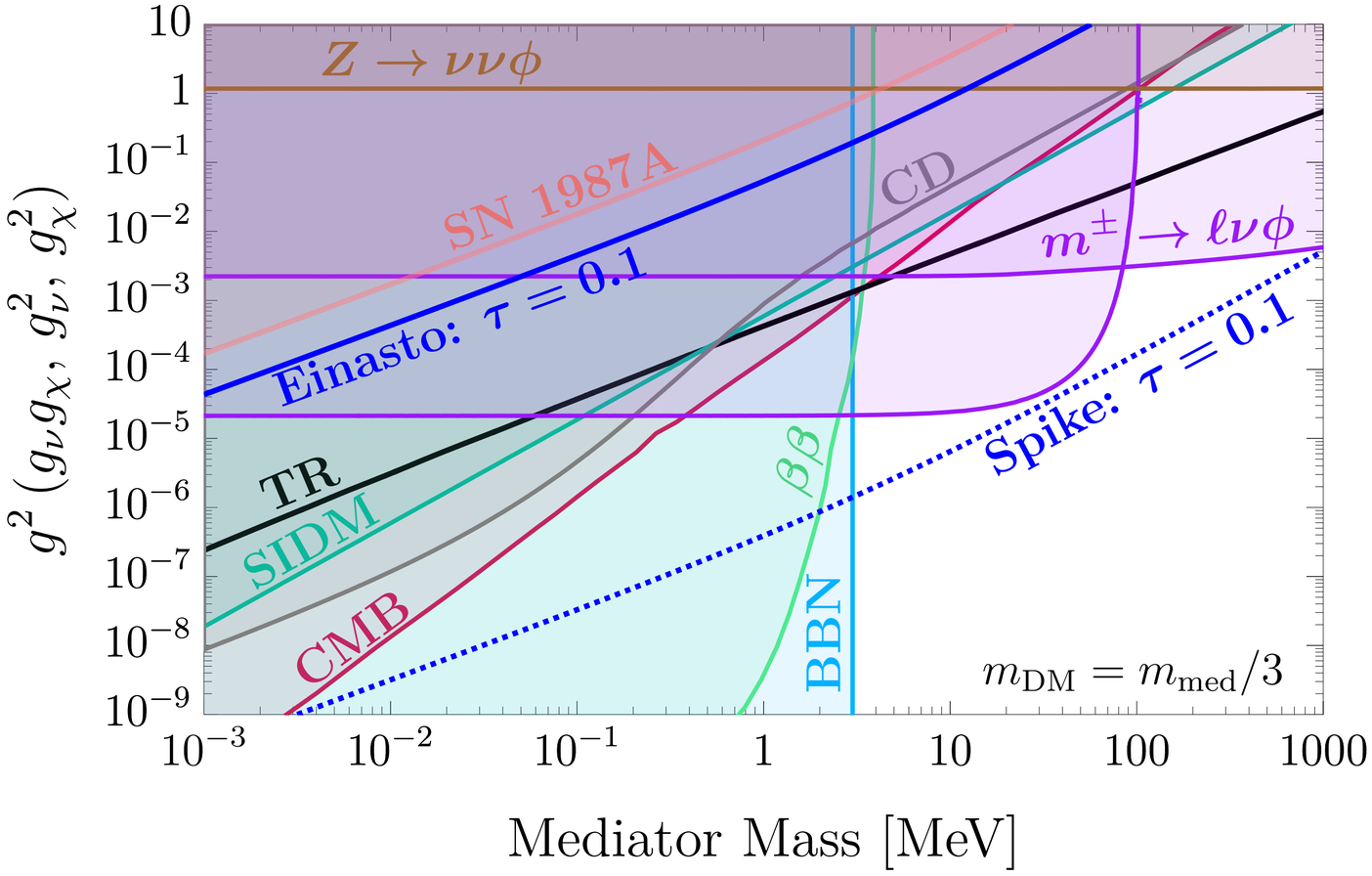
- Compute survival rate φ/φ_0 as a function of neutrino energy

Summary Plot for Example Model

Dirac Fermion DM, Scalar Mediator

- Compiling all the constraints for this model:

- Einasto $\tau = 0.1$: Opacity of 25 MeV neutrinos for SN in Milky Way galaxy 10 kpc away
  - on other side of galactic center
  - greater potential sensitivity over SN 1987A
  - already ruled out by many other constraints for $m_{\rm DM} = m_{\rm med}/3$



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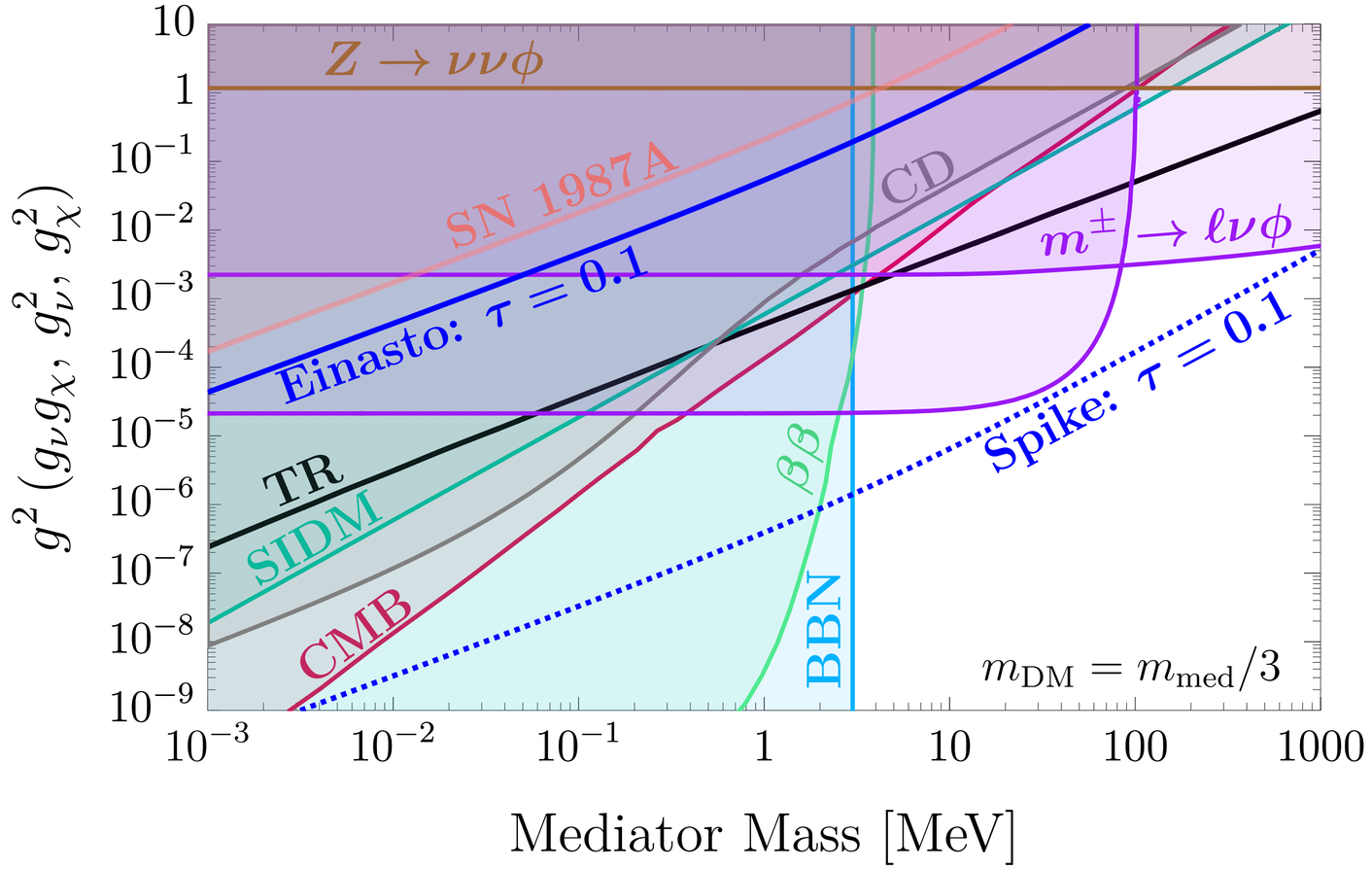
Dirac Fermion DM, Scalar Mediator

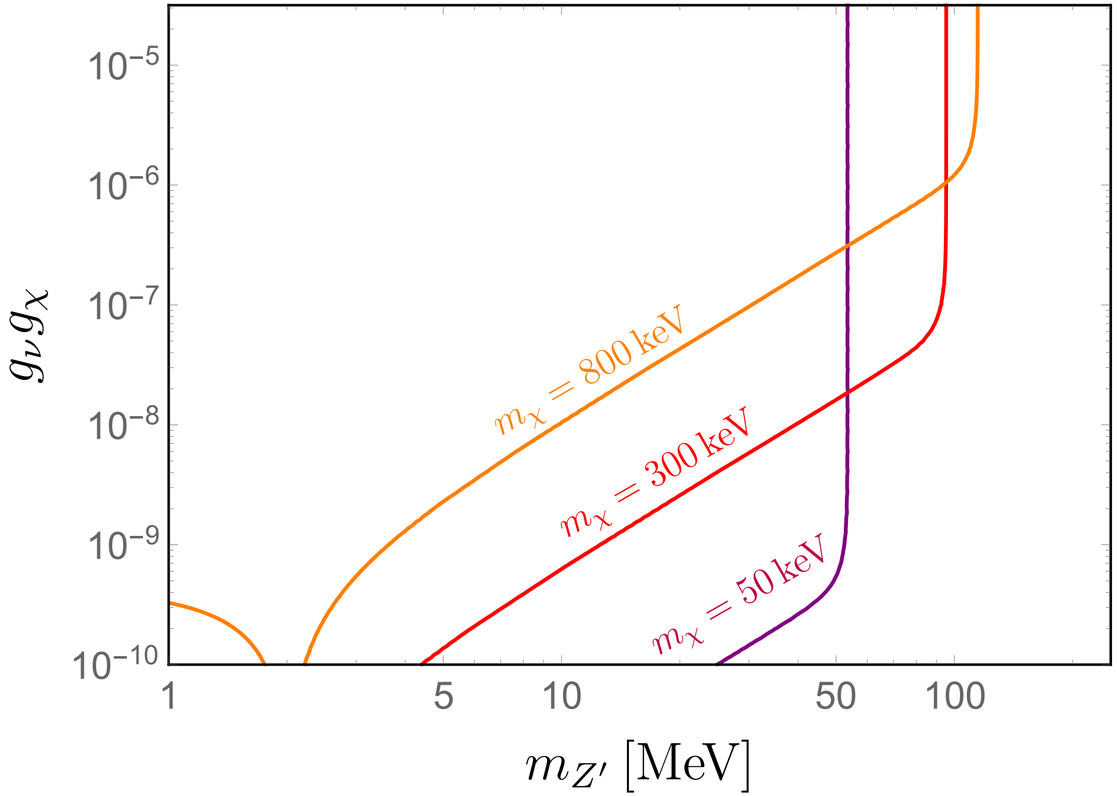
- Compiling all the constraints for this model:

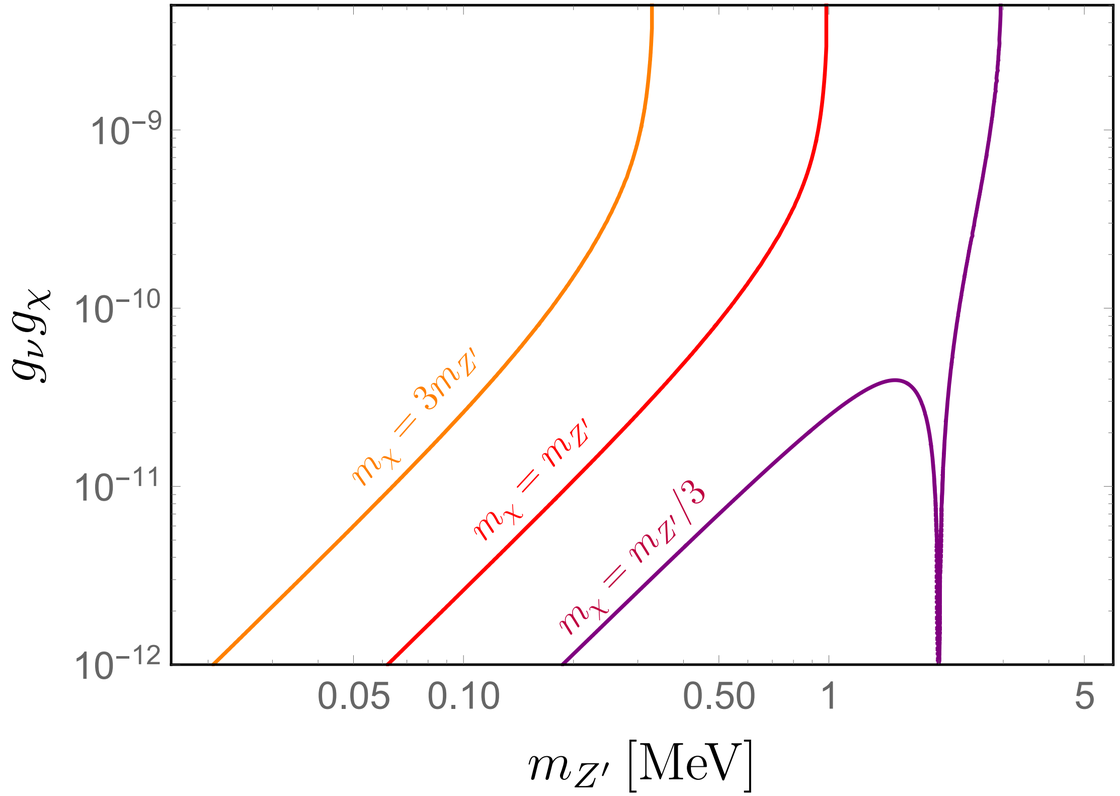
- Spike $\tau = 0.1$: Opacity of 25 MeV neutrinos for SN in Milky Way galaxy 10 kpc away
  - SN on other side of spike radius
  - Optimistic best case scenario for this probe



What about light DM?

- Sub-MeV mediators are ruled out by BBN constraints, but what about sub-MeV DM with > MeV mediators?

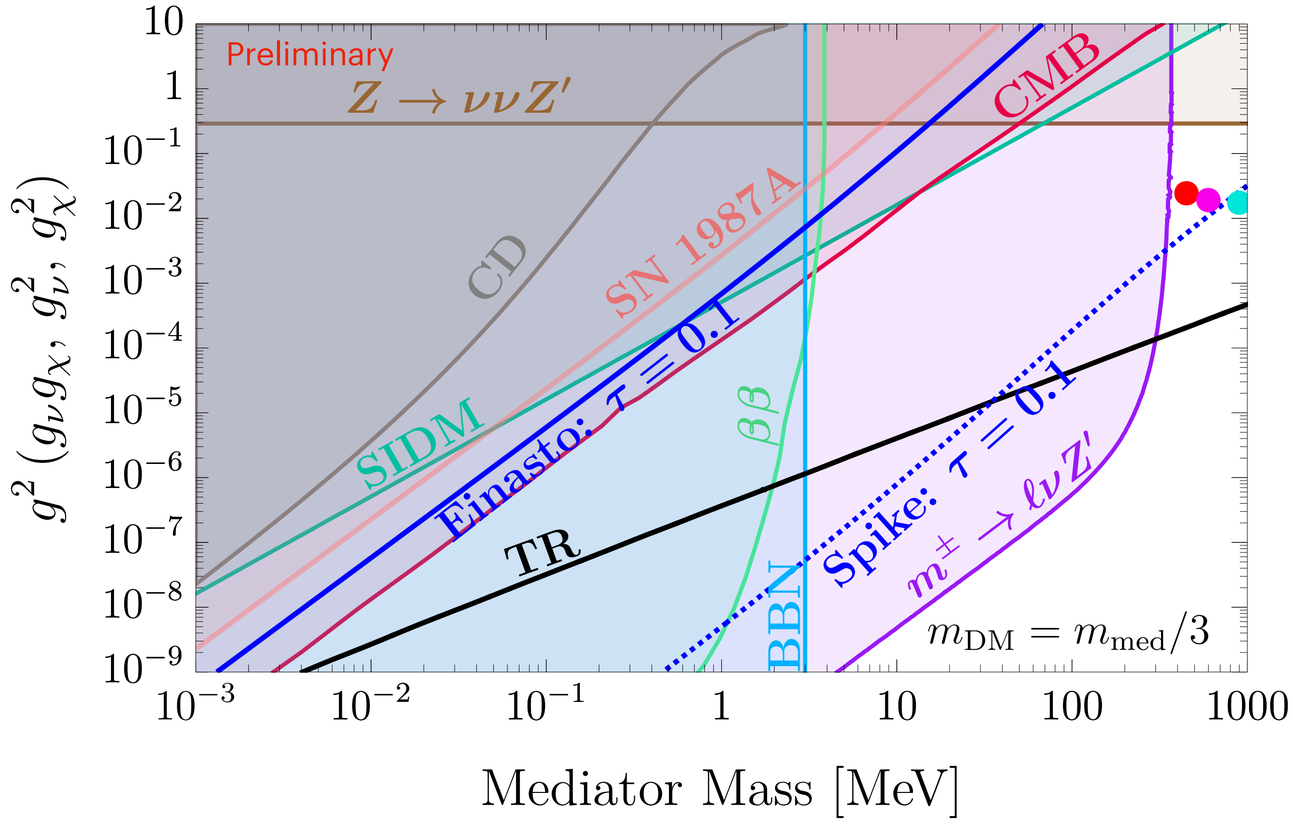




Event rate plots for Local SN

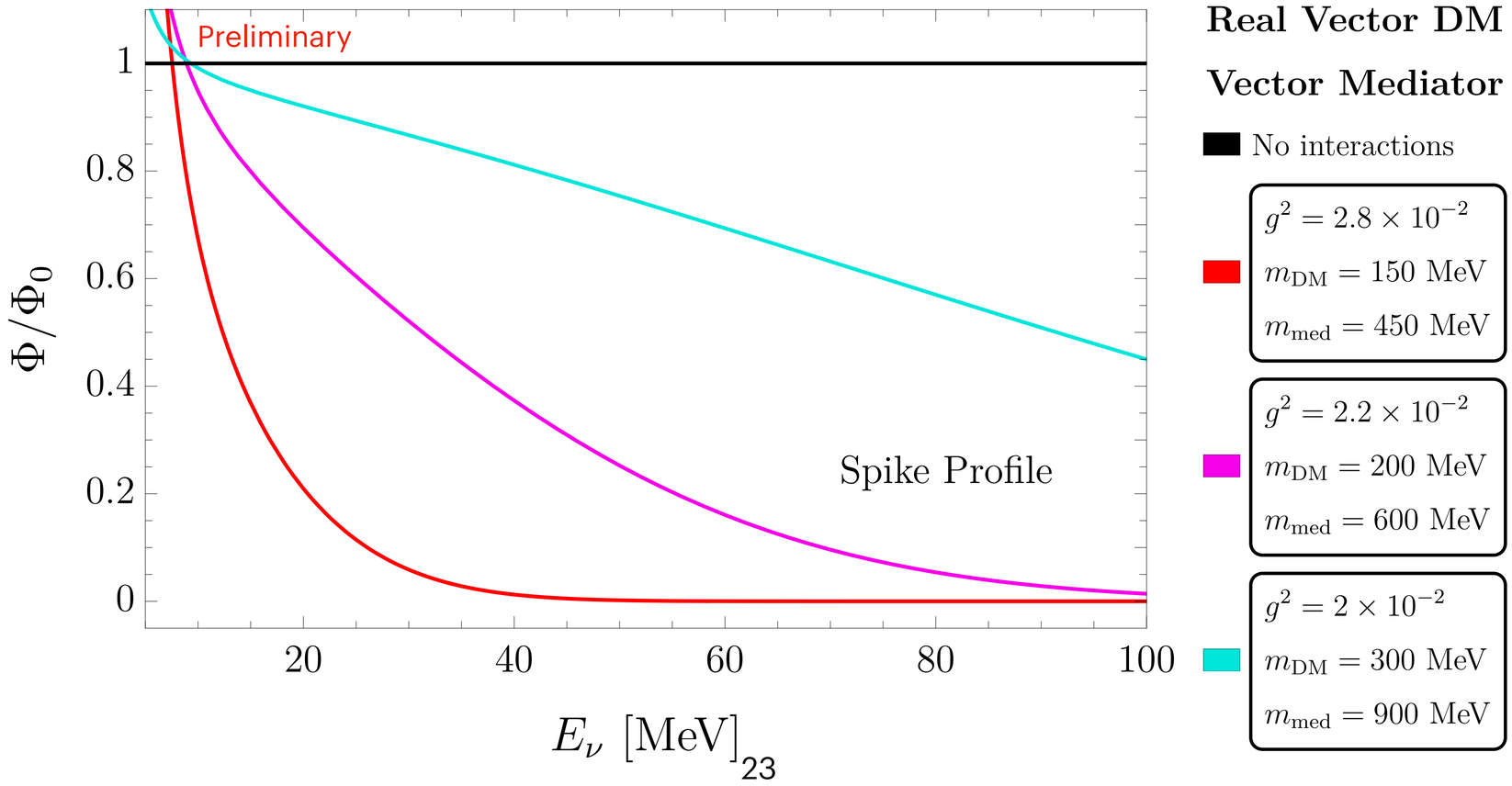
Vector DM, Vector Mediator

- Vector DM, vector mediator model:
  - Consider these benchmark points in the available parameter space
  - What would Hyper-K, JUNO, and DUNE see?



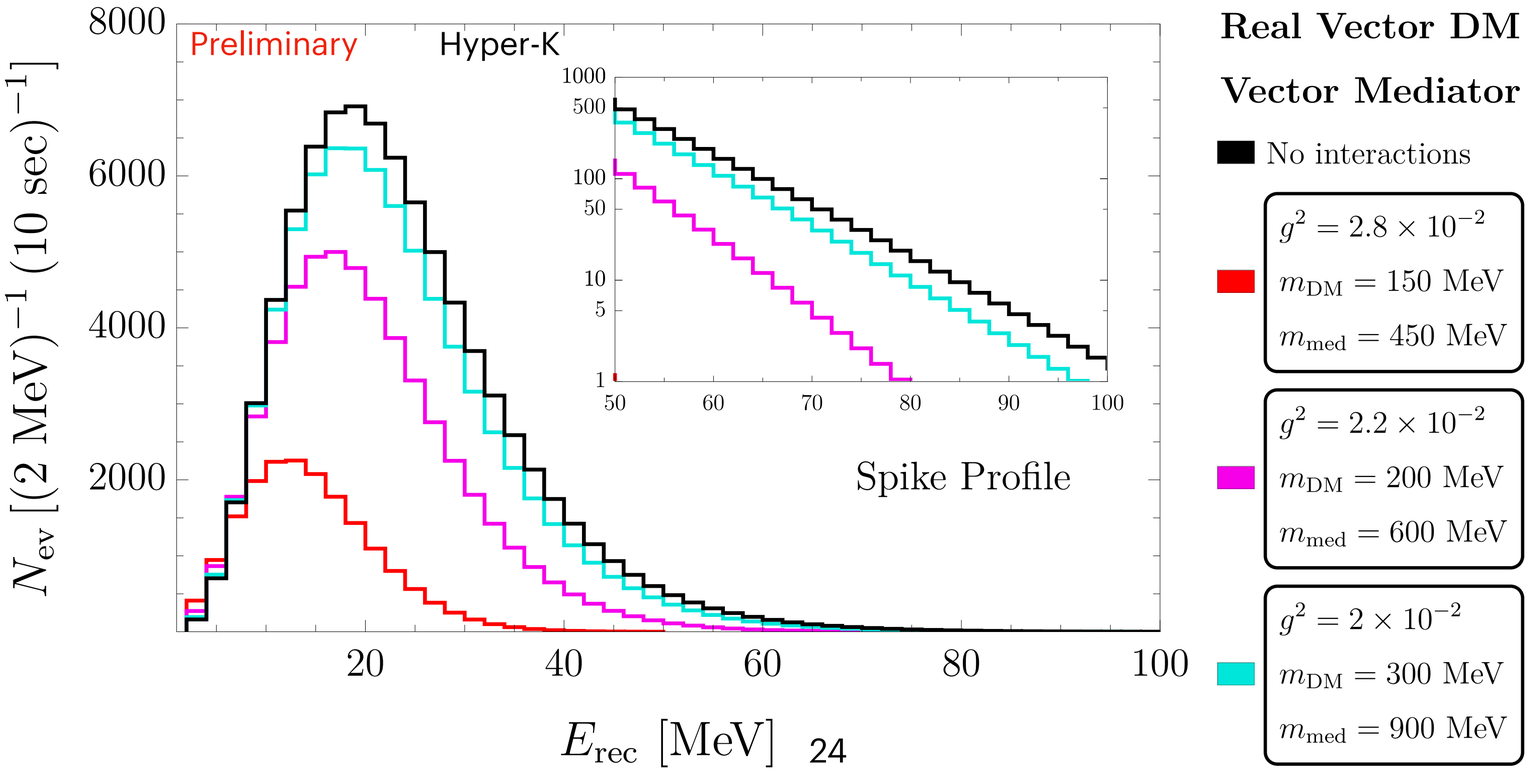
Light DM Scenario for local SN

- How would the measured neutrino flux at DUNE, Hyper-K, JUNO change?
- Model neutrino flux Φ_0 as a function of energy
- Use cascade equation to calculate attenuated flux Φ



Light DM Scenario for local SN

- How would the measured neutrino flux at DUNE, Hyper-K, JUNO change?
- Apply survival rate to observed neutrino flux
  - Inverse Beta Decay at Hyper-K/JUNO
  - Charged Current interaction with Argon at DUNE



Summary and Outlook

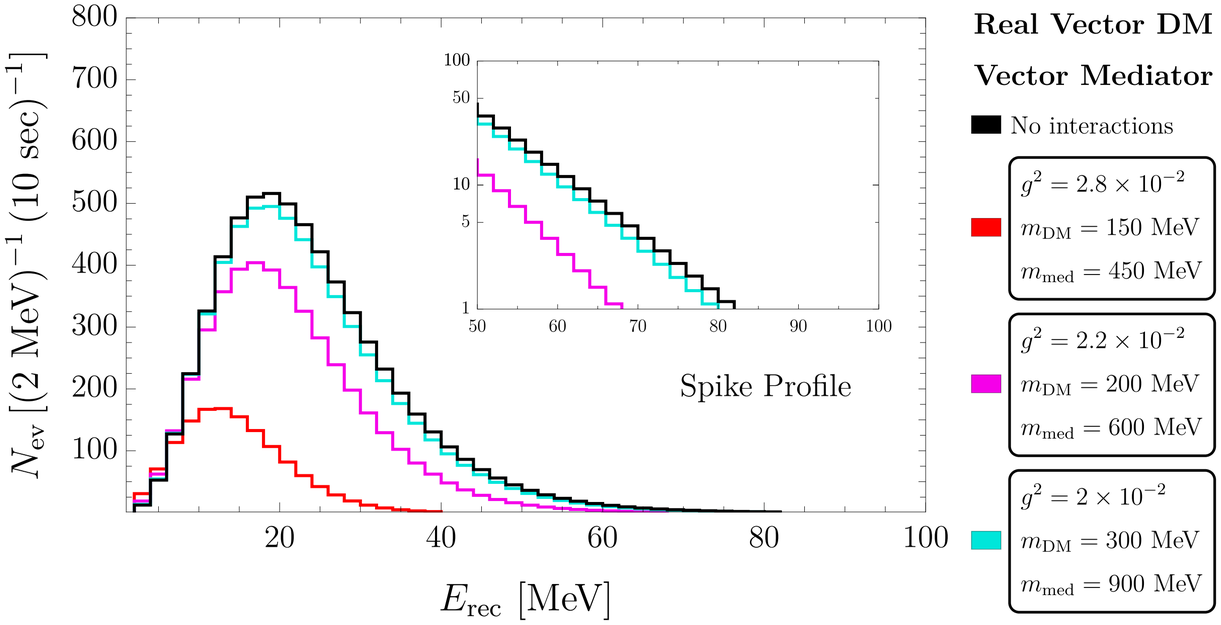
- Carried out a comprehensive analysis of models for general effective ν-DM interactions
- Many strong constraints from cosmology, astrophysics, and labs
  - Updated lab bounds, important for > 1 MeV mediators!
- Even so, potential opportunities to probe neutrino interactions
- For each model, show the remaining parameter space, mostly unexplored for > MeV mediator masses
- Other scenarios:
  - axions/ALPs (large number density)
  - HEANs interacting with DM, measured at IceCube

Thank you!

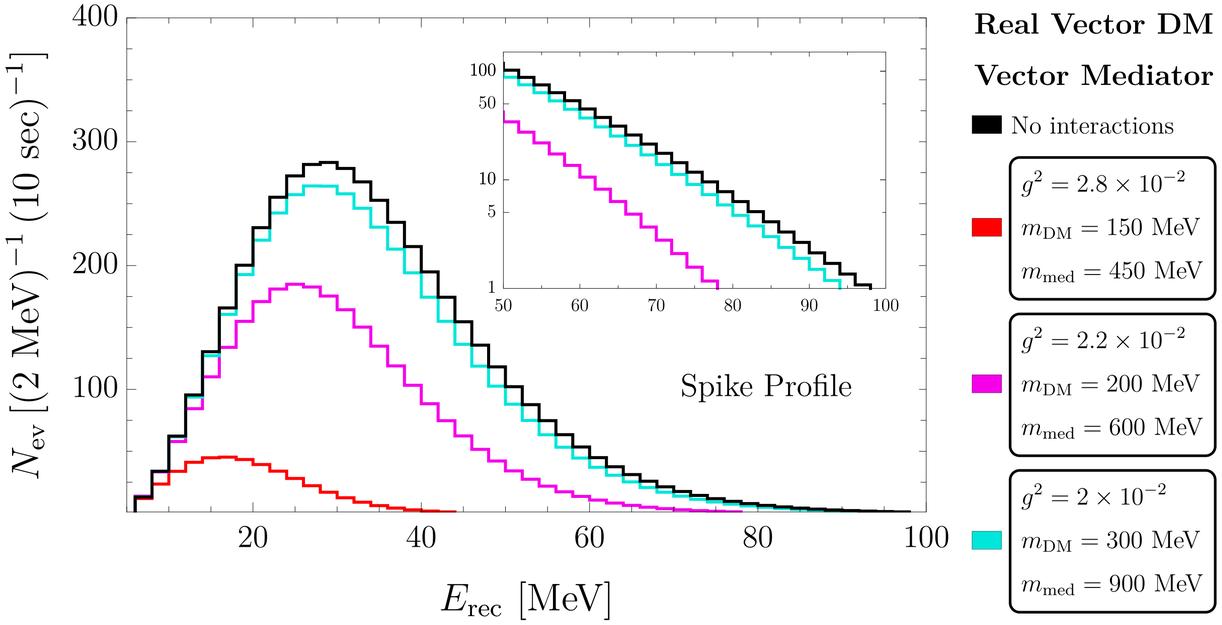
Backup Slides

Event rate plots at DUNE, JUNO

JUNO

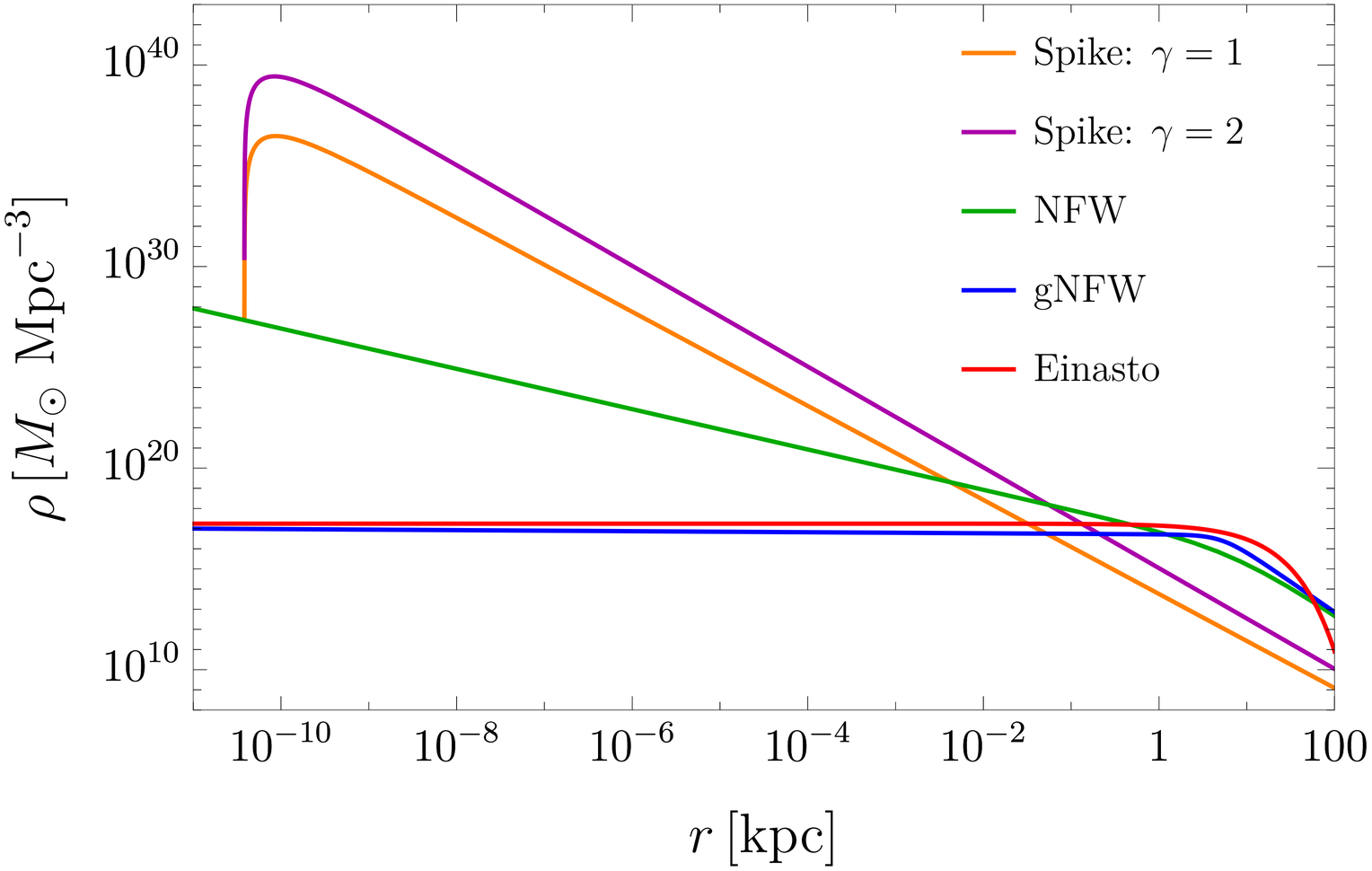


DUNE

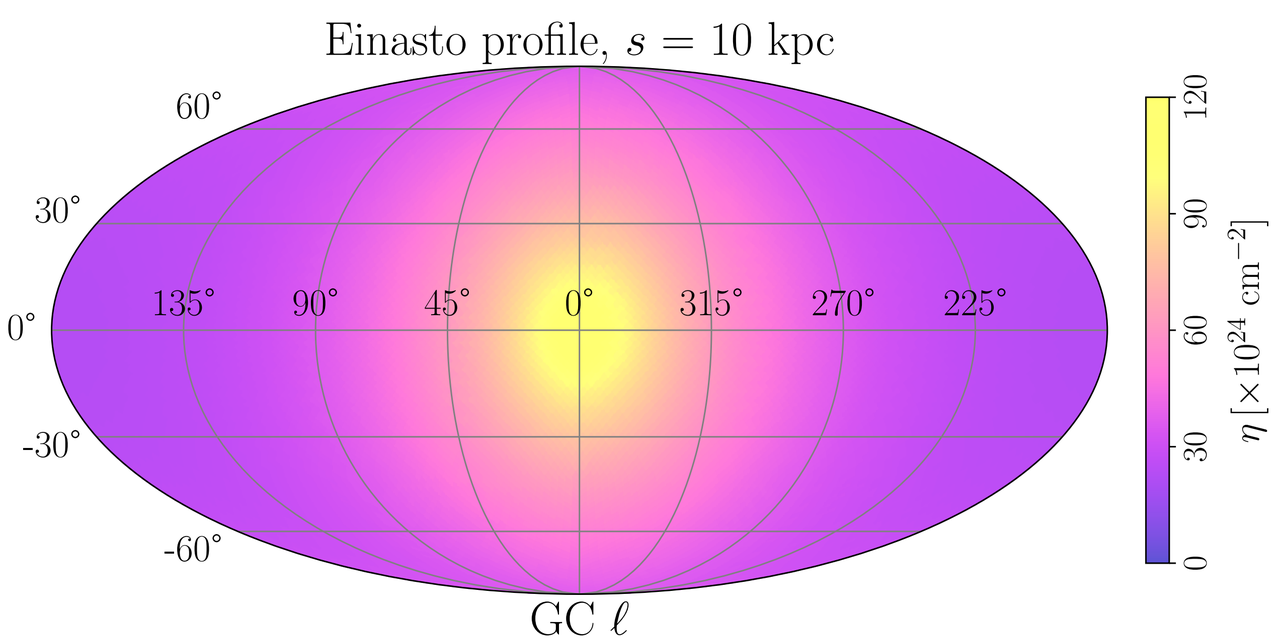


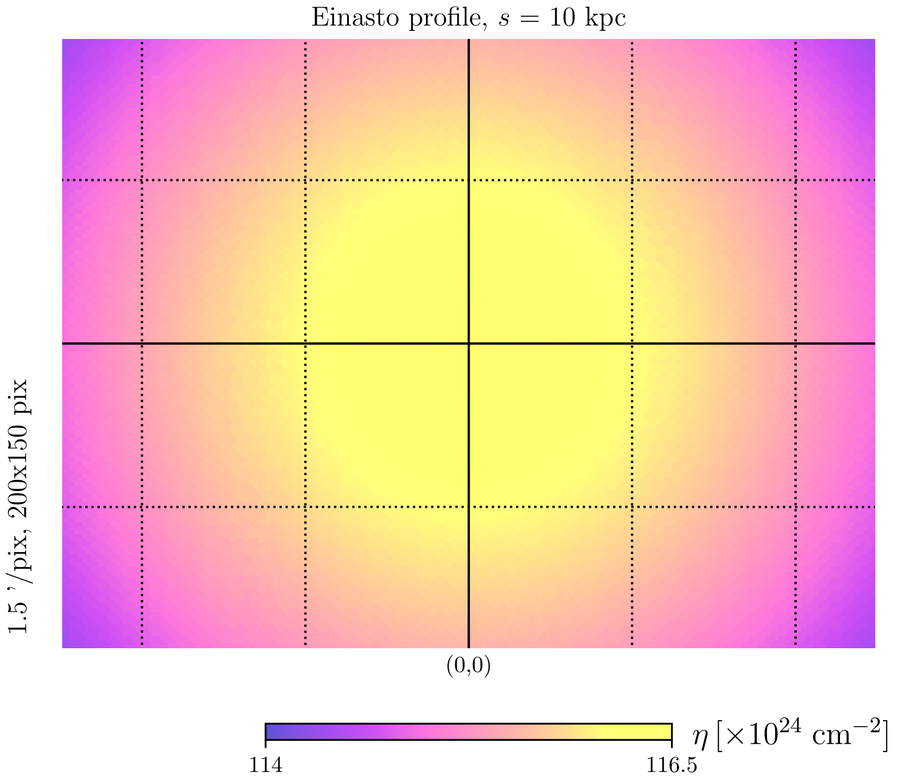
Comparison of DM Profiles

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



Einasto Profile Skymaps





Spike Profile Skymaps