N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries PHYSICS FRONTIER CENTER

N3AS Seminar, Dec 20th, 2022

Towards Powerful Probes of Neutrino Self-Interactions in Supernovae

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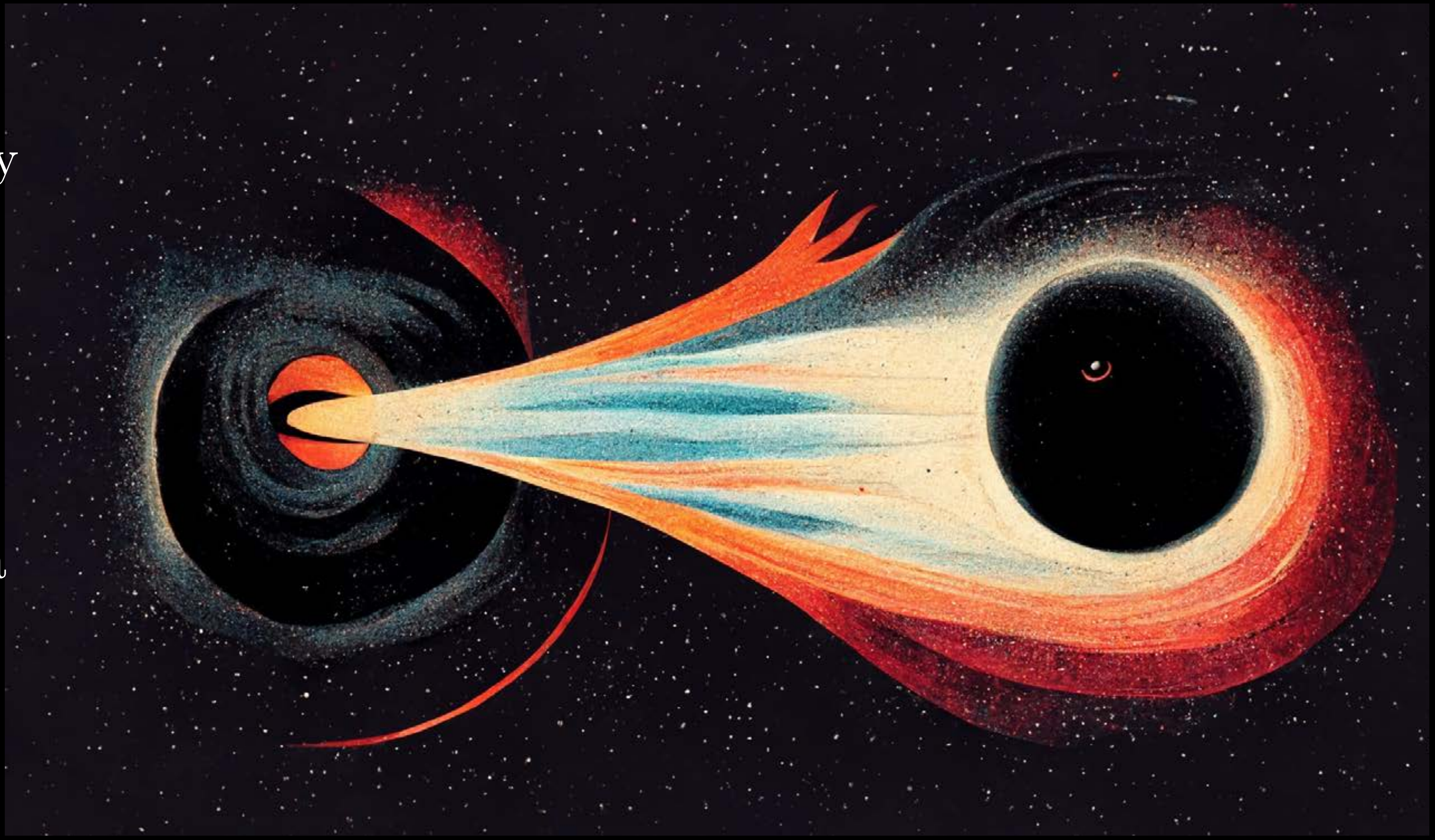
CCAPP, The Ohio State University



In collaboration with

Ivan Esteban, John Beacom,
Todd Thompson, Chris Hirata

Based on arXiv: 2206.12426

CCAPP The Ohio State University

Outline

Do neutrinos interact with each other?

Where to find νSI?

Core-collapse supernovae

Strong probes of the self-scattering

Potential sensitivity from SN 1987A

Conclusions

Do neutrinos interact with each other?

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In Standard Model, neutrinos are

The feeblest particles

Hard to detect

Great mystery

Interesting phenomenology

Encode secret information beyond Standard Model

Do neutrinos interact with each other?

Enhanced *neutrino self-interactions* (νSI)

Kolb, Turner (1987)

> Although the interactions of neutrinos with "matter" (electrons, protons, neutrons, nuclei, etc.) are weak, *it is possible that neutrinos have "stronger than weak" interactions with other unknown particles (e.g., Majorons), or with themselves...*

> *...By secret interactions, we mean interactions not shared by charged particles, i.e., interactions beyond those in the* $SU(3) \times SU(2) \times U(1)$ *model.*

Do neutrinos interact with each other?

Enhanced *neutrino self-interactions* (νSI)

The feeblest particles

Hard to detect

Great mystery

Interesting phenomenology

Laboratory probes remain weak

The allowed νSI cross sections can be *larger* than weak interactions by *20 order of magnitudes*

Do neutrinos interact with each other?

Enhanced *neutrino self-interactions* (νSI)

The most abundant particles

Rich physics

Impact astronomy
and cosmology

Induce diverse effects

Cosmological anomalies

Laboratory anomalies

Neutrino mass origin

Dark matter origin

For a comprehensive review,
see Berryman et al., 2203.01955

Do neutrinos interact with each other?

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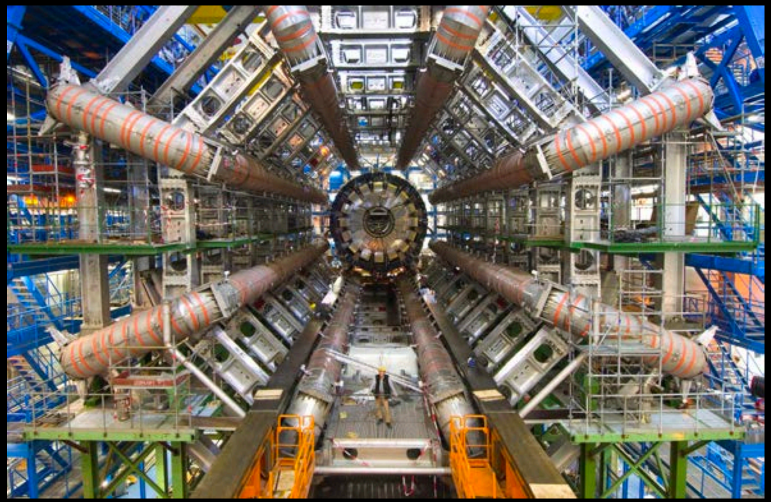
Dark matter origin

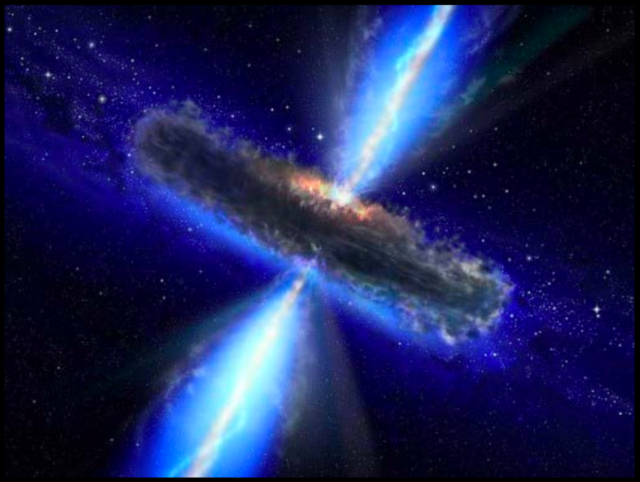
Will νSI spoil our knowledge in the cosmos?

Where to find vSI?

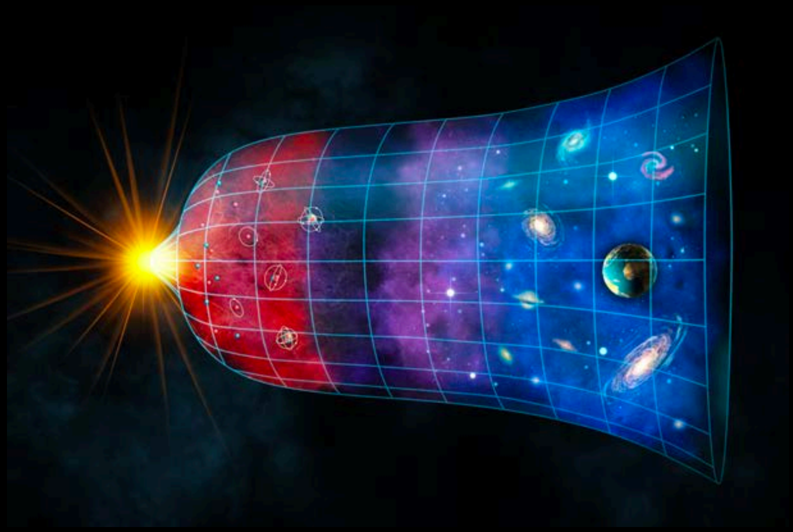
Where to find νSI?



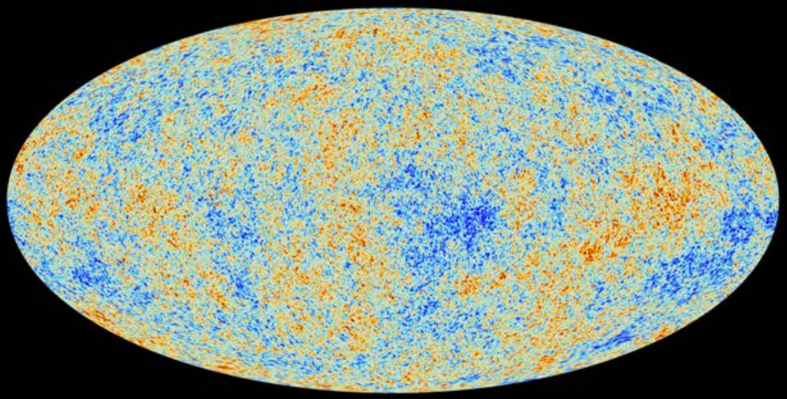
terrestrial experiments



high energy astrophysical neutrinos

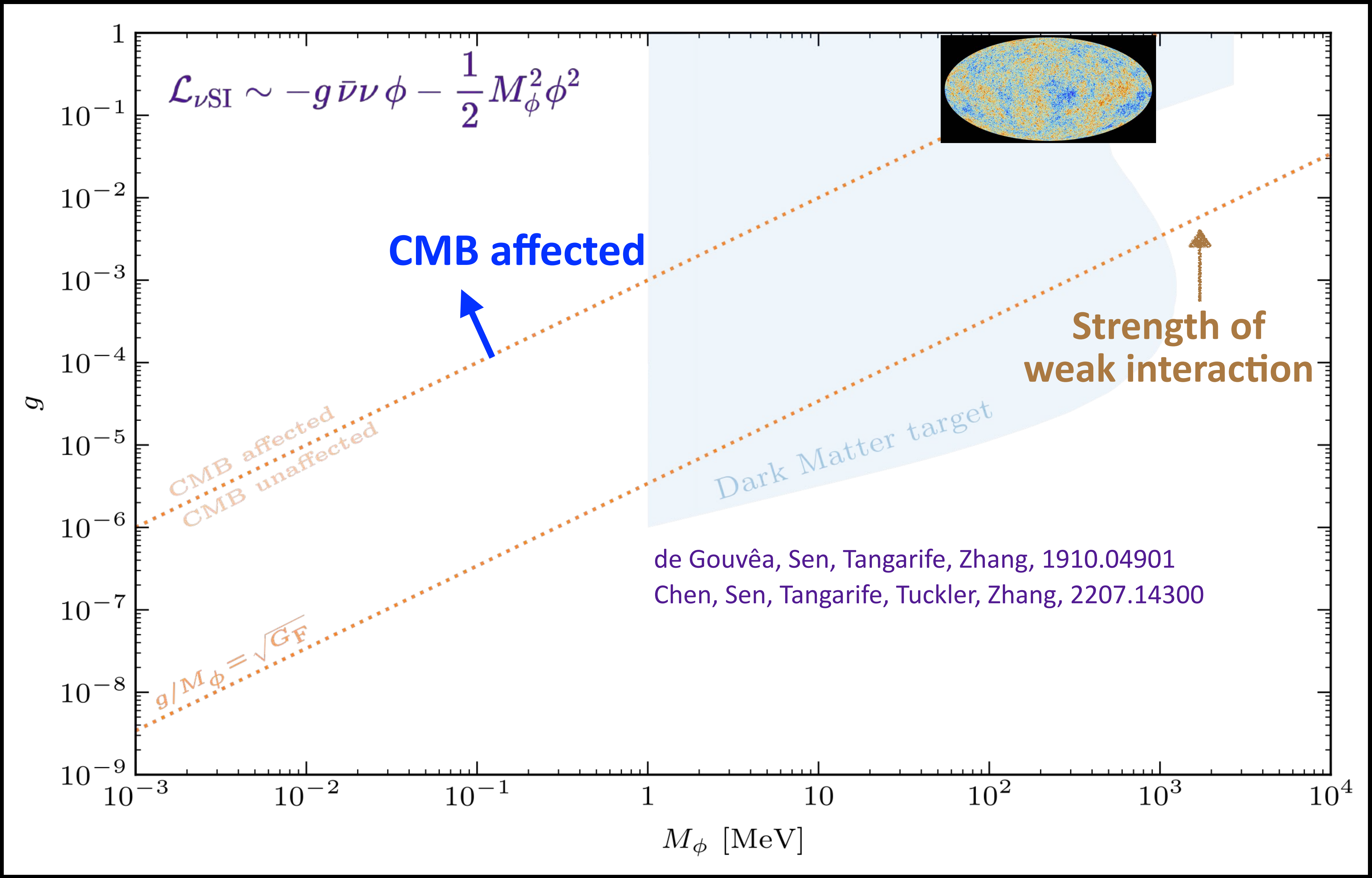


big bang nucleosynthesis



cosmic microwave background

Where to find νSI?



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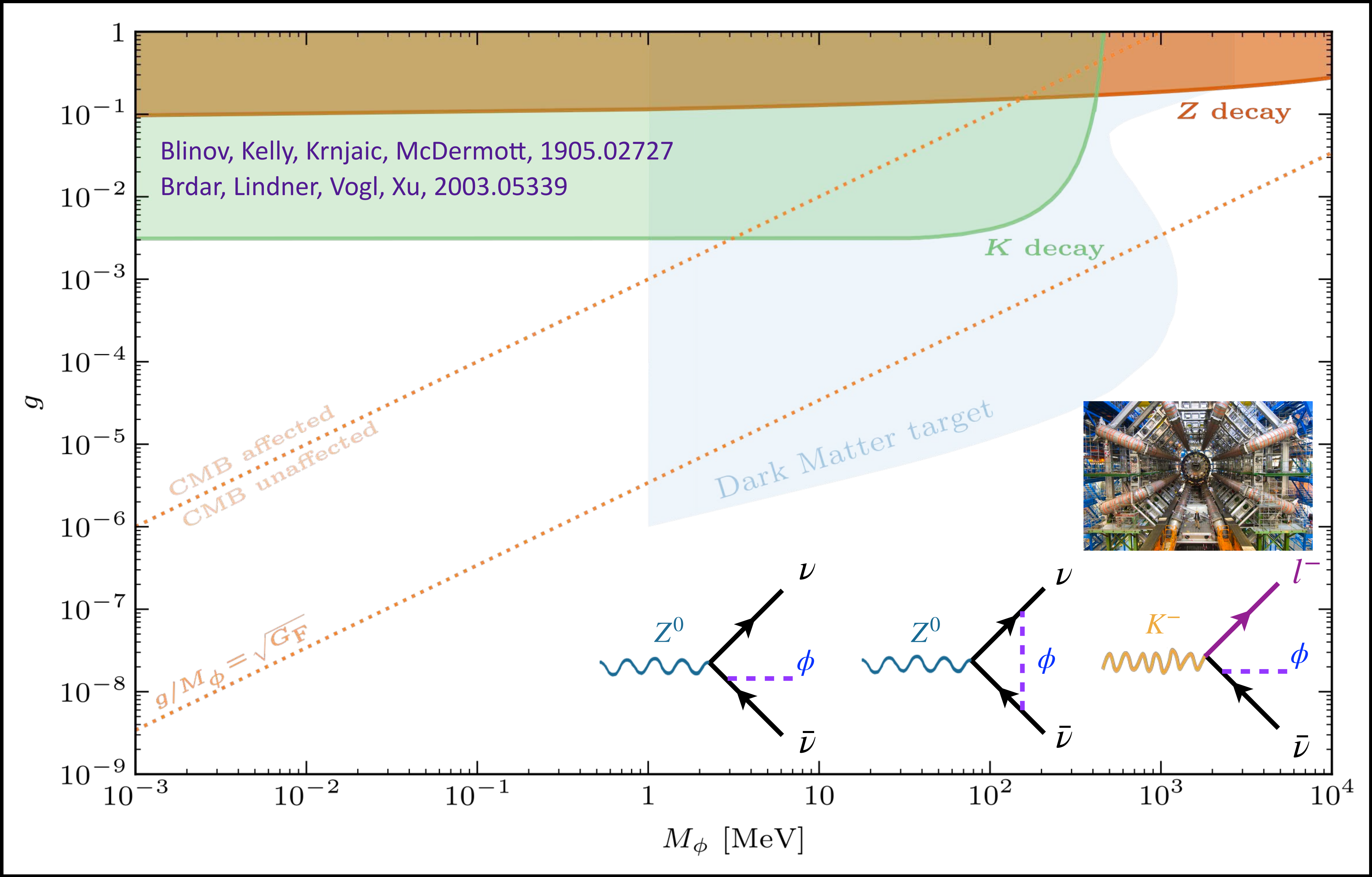

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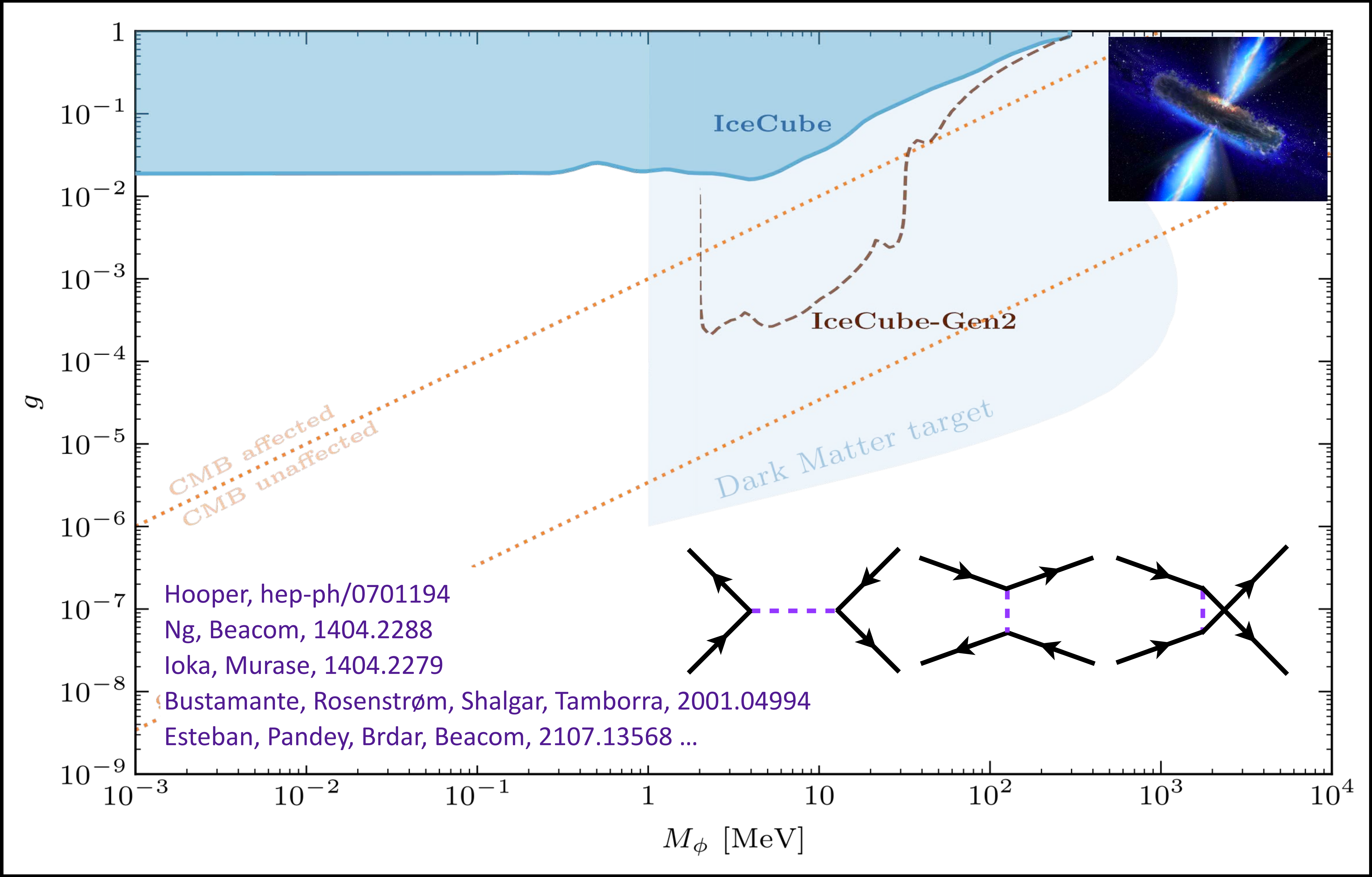

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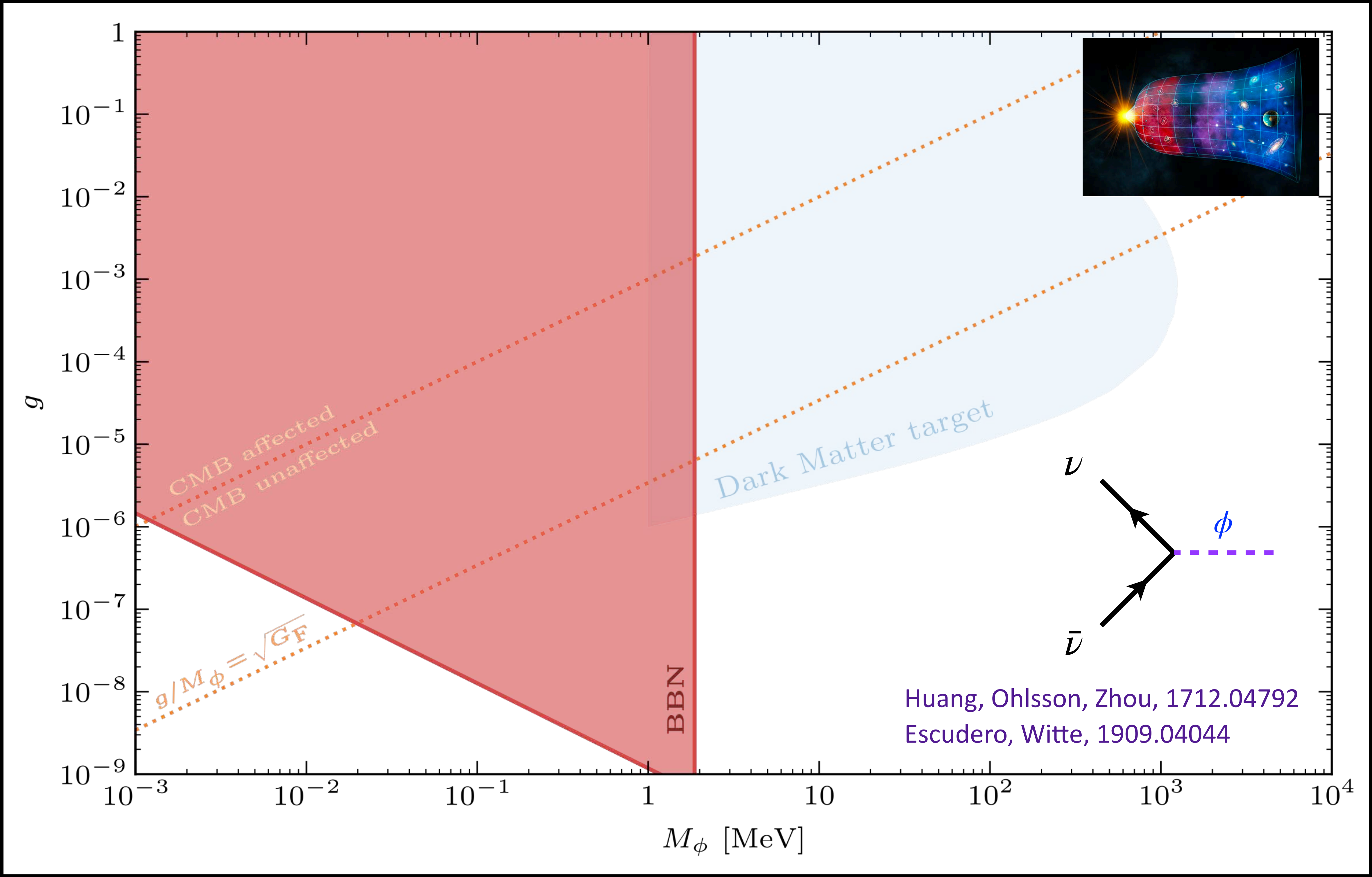

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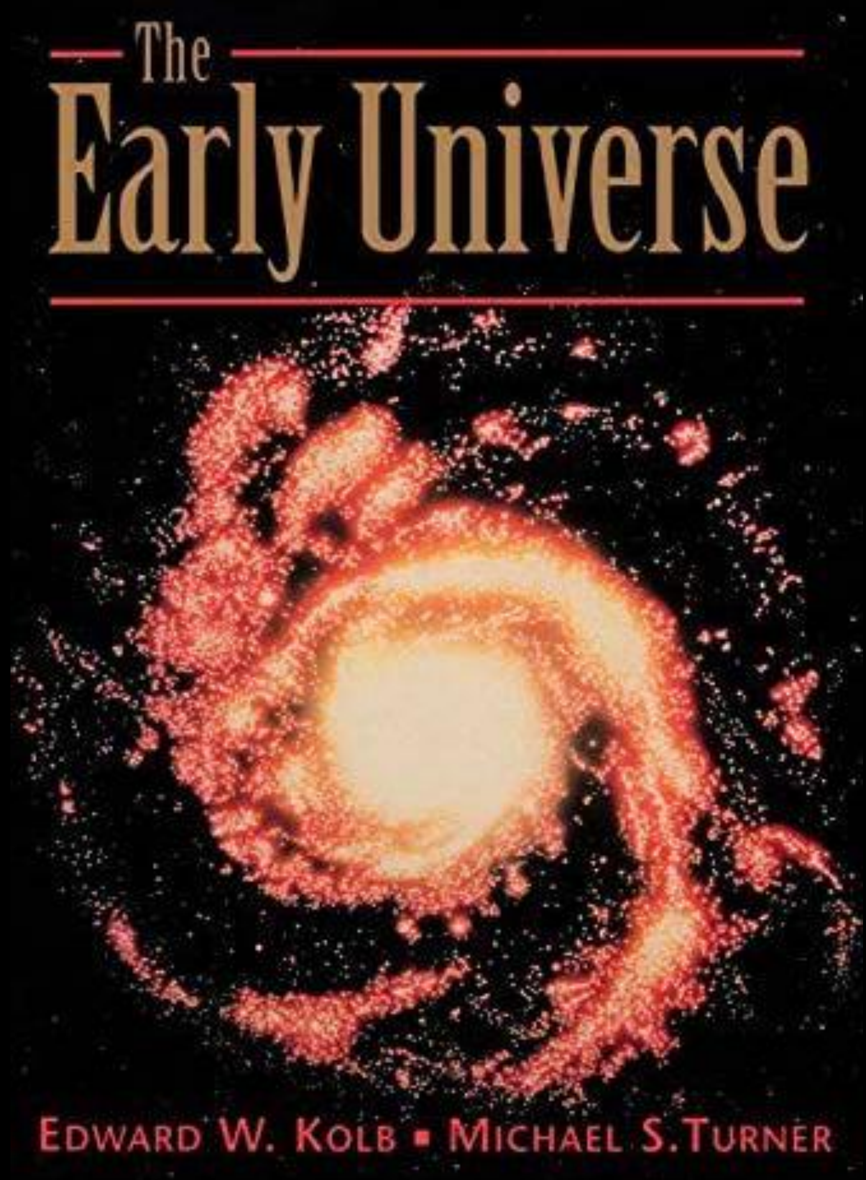


The sensitivity of cosmological and astrophysical probes of νSI
are both benefited from the **high neutrino number density** in the early Universe

Core-collapse supernovae

Core-collapse supernovae

Final fate of a massive star

The collapsed core becomes a dense **proto-neutron star (PNS)**

Core-collapse supernovae are **efficient neutrino factories**

Tremendous amount of gravitational energy

99% **neutrinos**

+

1% kinetic energy of ejecta

+

0.01% photons

Core-collapse supernovae

Supernovae should offer ideal probes of νSI!!

- Extremely ***dense*** neutrino environment

$$\langle E_\nu \rangle \sim 10 - 100\,\mathrm{MeV} \qquad N_\nu \sim E_{\rm total}/\langle E_\nu \rangle \sim 10^{58}$$

$$n_\nu \sim 10^{33} - 10^{38}\,\mathrm{cm}^{-3}$$

A bottle of water with this density would weigh 1000 Empire State Buildings

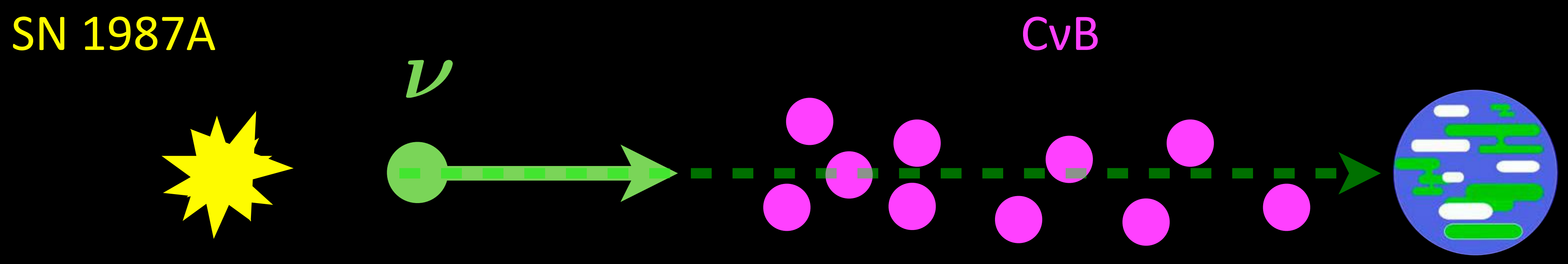
- Observational evidence from SN 1987A
- Robust against astrophysical uncertainties

Key questions:

- Does SN 1987A tell us anything about νSI?
- How do νSI affect core-collapse supernovae?

Core-collapse supernovae

Propagation of SN 1987A neutrinos



$$\nu + \nu \to \nu + \nu$$

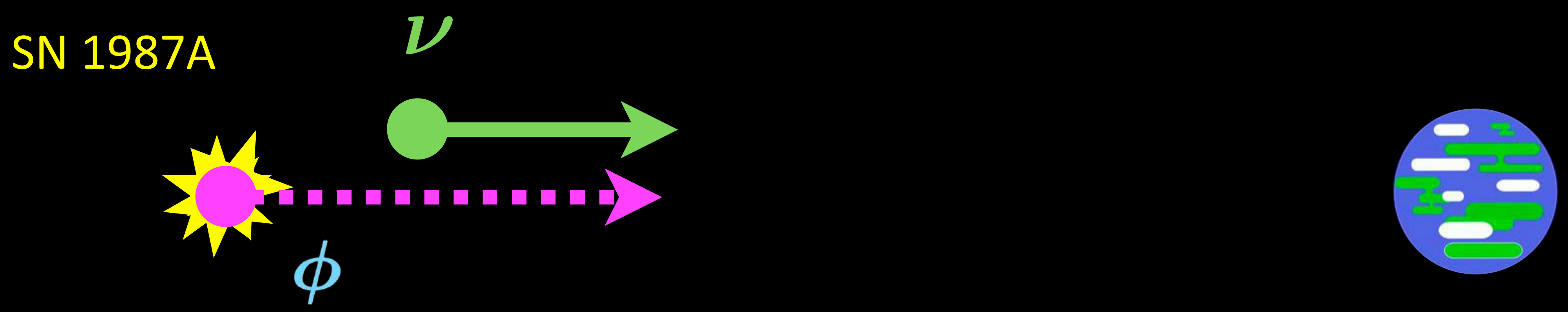
Strong νSI: supernova neutrinos will **get attenuated** en route to Earth

Kolb, Turner (1987)

Shalgar, Tamborra, Bustamante, 1912.09115

Core-collapse supernovae

Cooling of SN 1987A



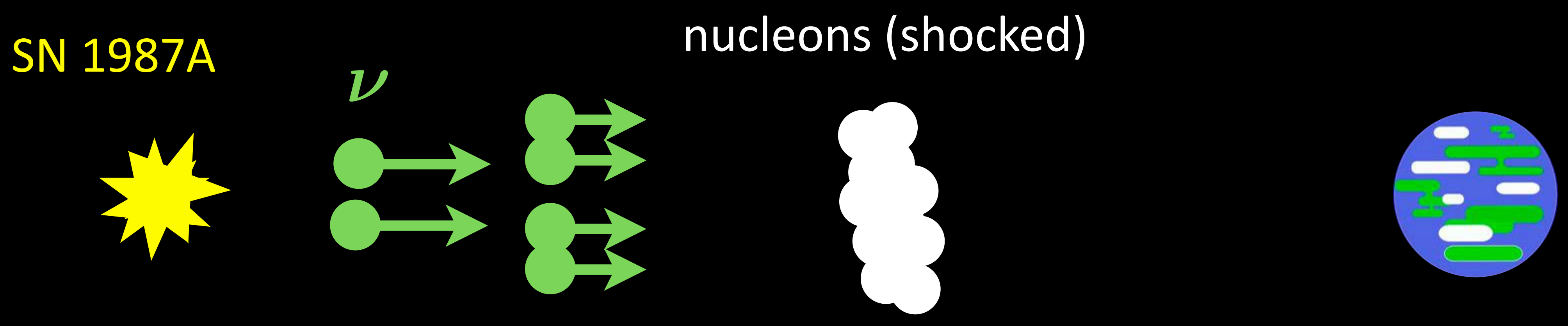
$$\nu + \nu \to \phi$$

νSI: force mediator can lead to **extra cooling** of supernovae

Kachelriess, Tomas, Valle, hep-ph/0001039
Farzan, hep-ph/0211375
Heurtier, Zhang, 1609.05882

Core-collapse supernovae

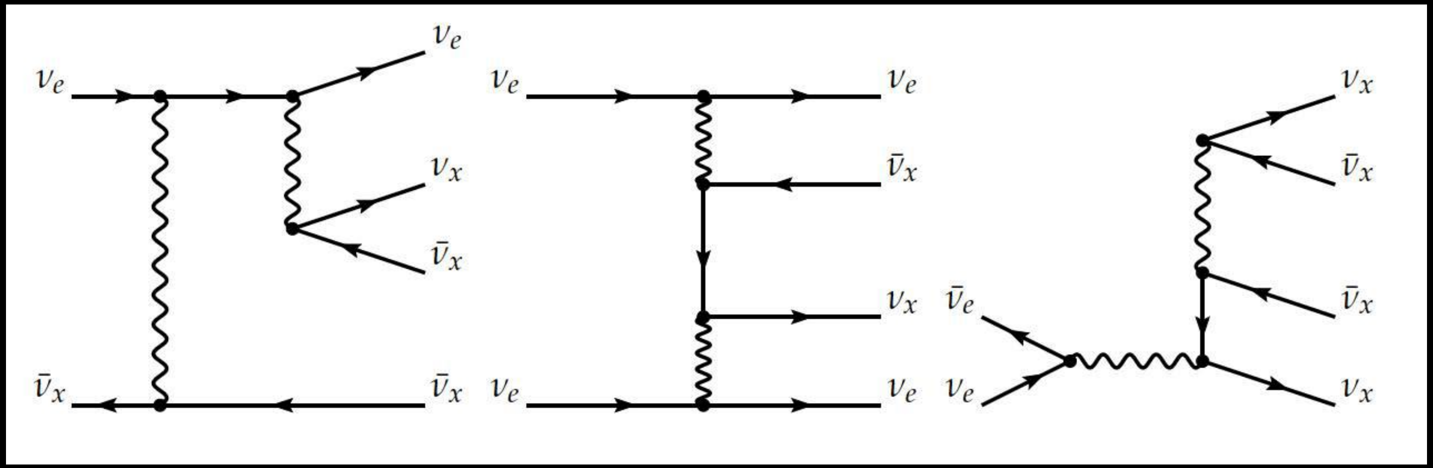
Shock of SN 1987A



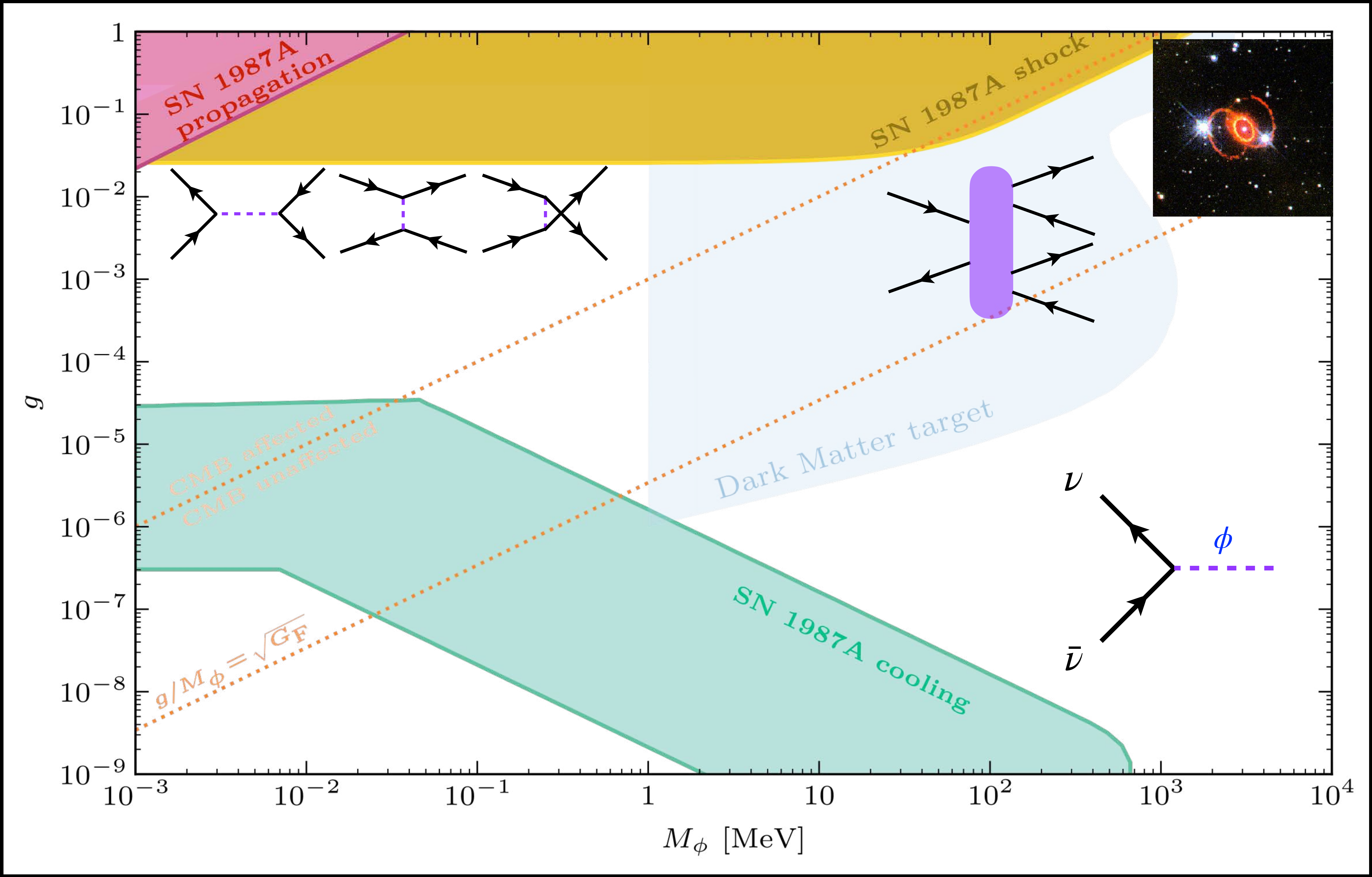
$$\nu + \nu \rightarrow \nu + \nu + \nu + \nu$$

Strong νSI: 2ν→4ν processes **fail** the neutrino-driven shock

Shalgar, Tamborra, Bustamante, 1912.09115



Core-collapse supernovae



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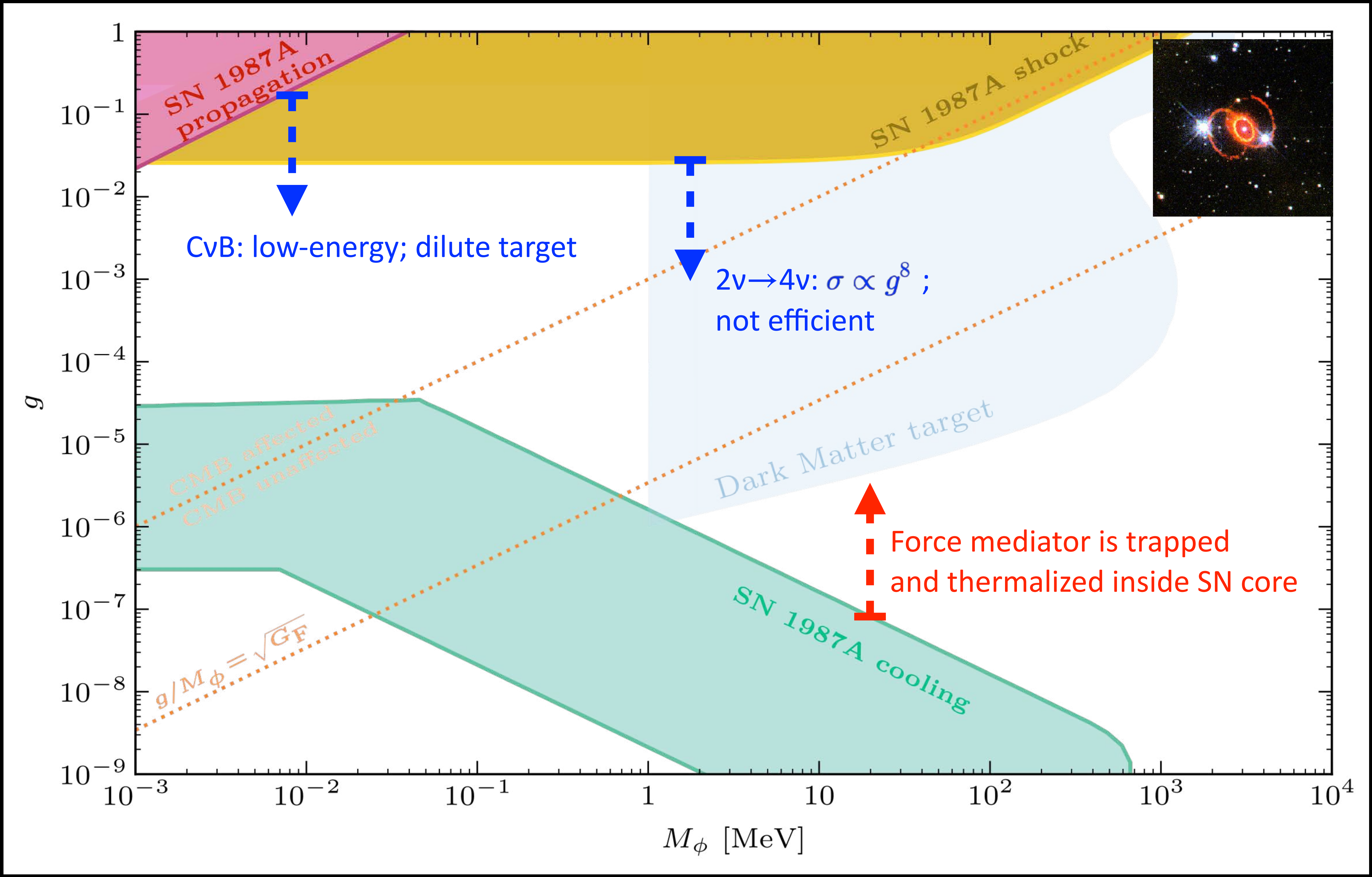
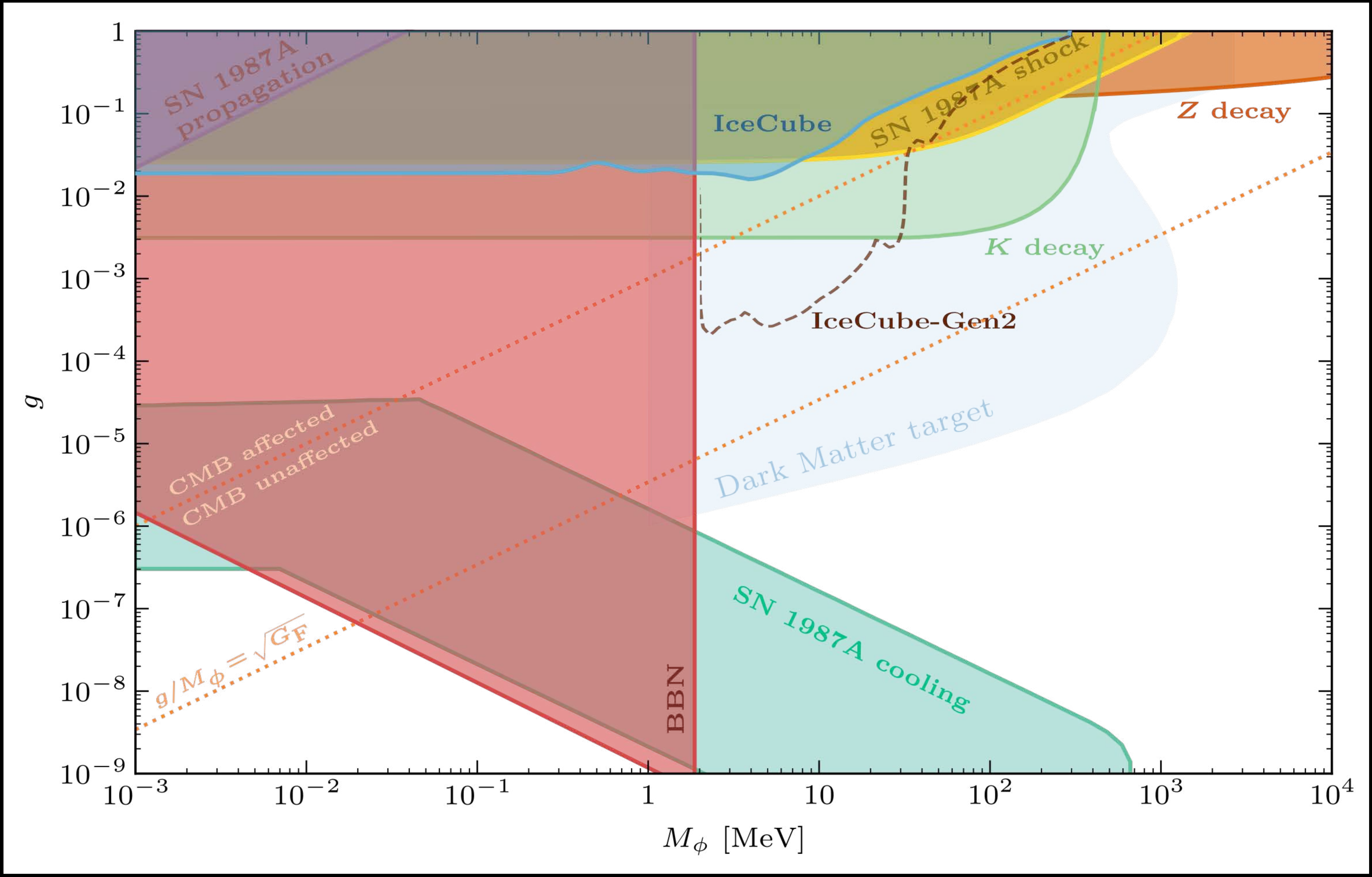
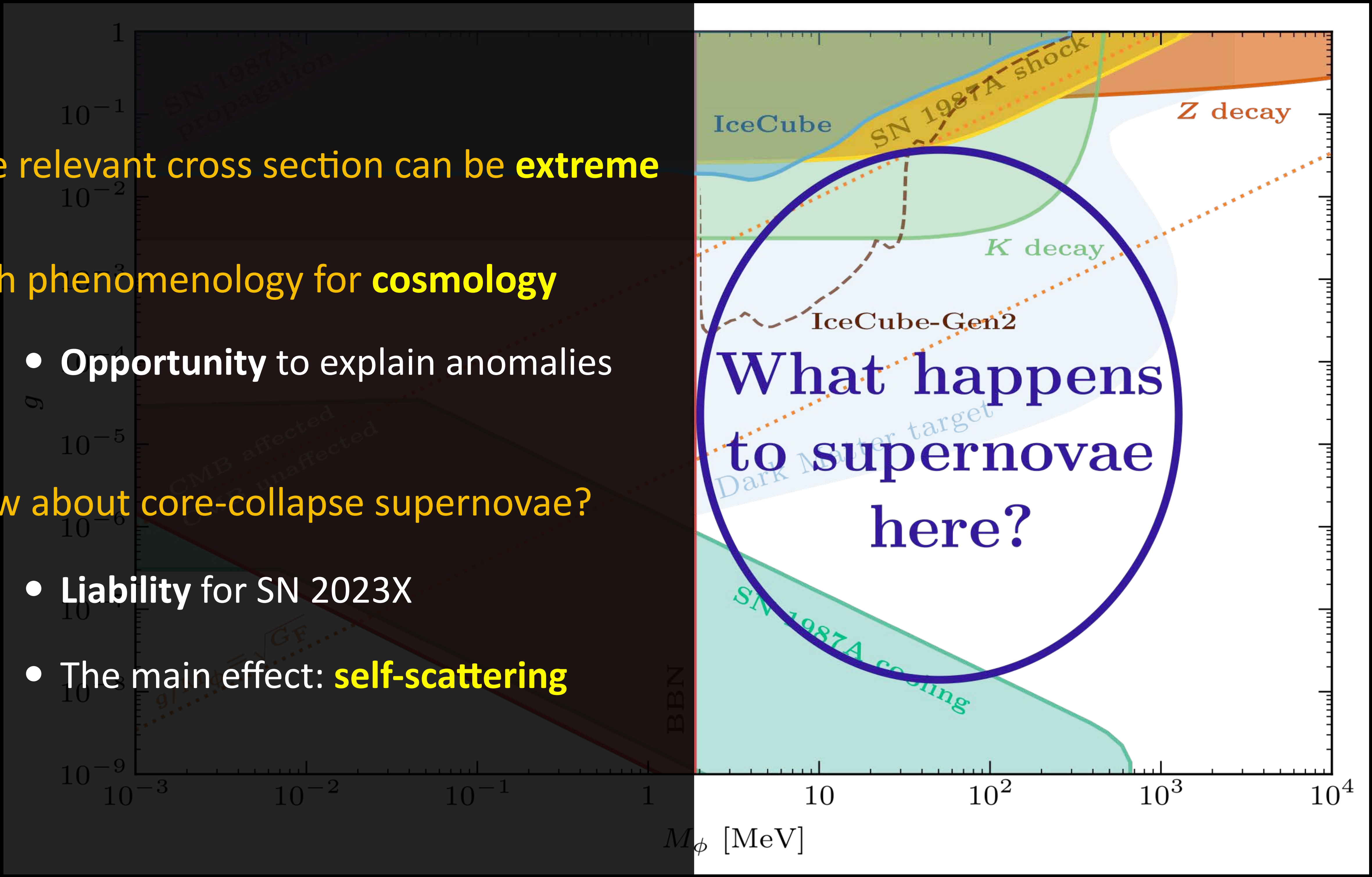


Core-collapse supernovae



Core-collapse supernovae



The relevant cross section can be **extreme**

Rich phenomenology for **cosmology**

- **Opportunity** to explain anomalies

How about core-collapse supernovae?

- **Liability** for SN 2023X
- The main effect: **self-scattering**

Strong probes of the self-scattering

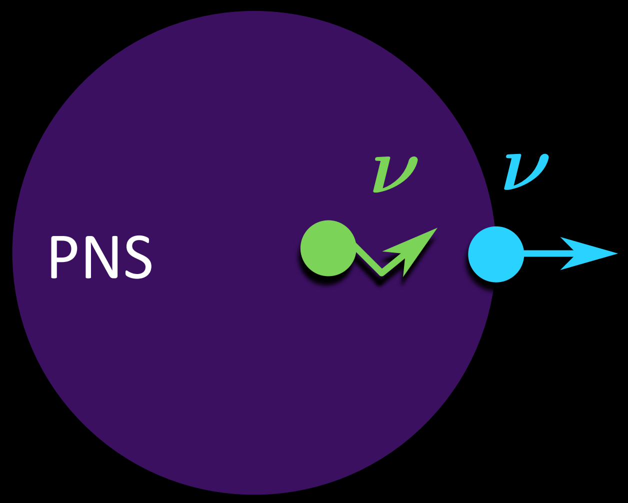
Based on **2206.12426**

Strong probes of the self-scattering

Supernova neutrino emission: no νSI

Inside the proto-neutron star (PNS): neutrinos **diffuse** through baryons

Outside the PNS: neutrinos **free stream** to us



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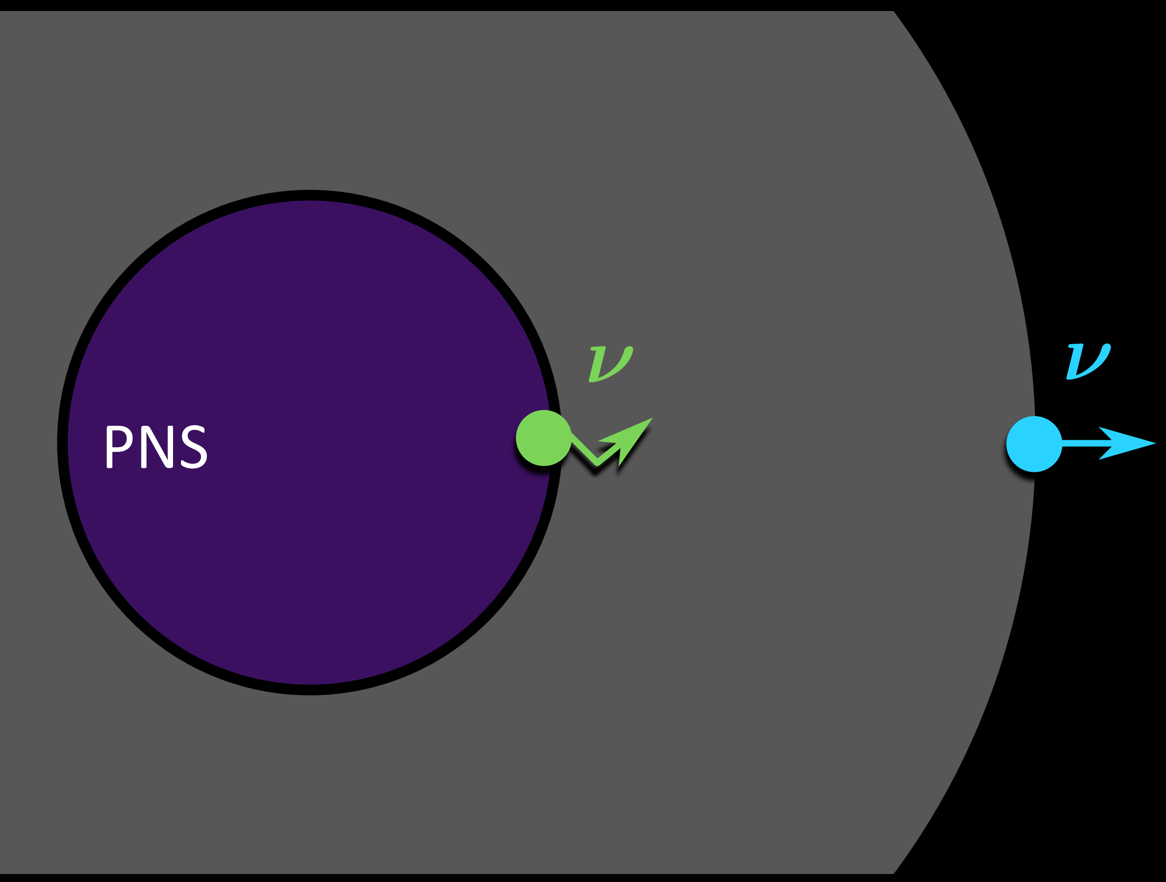


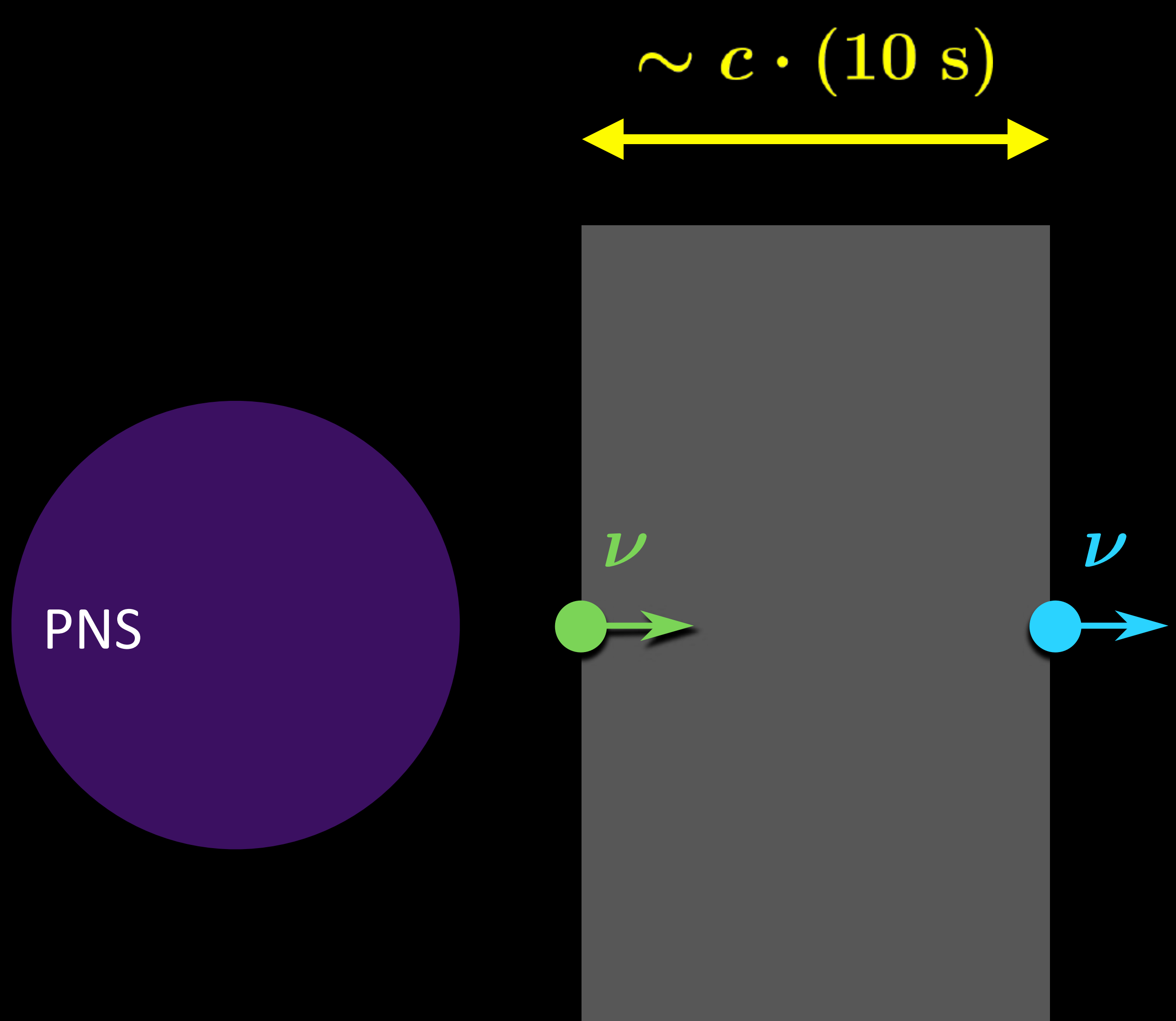
Order-of-magnitude challenge:

$$t_{\rm diff} \sim 3R^2/(c\lambda_{\nu N}) \sim 10\,{\rm s}$$

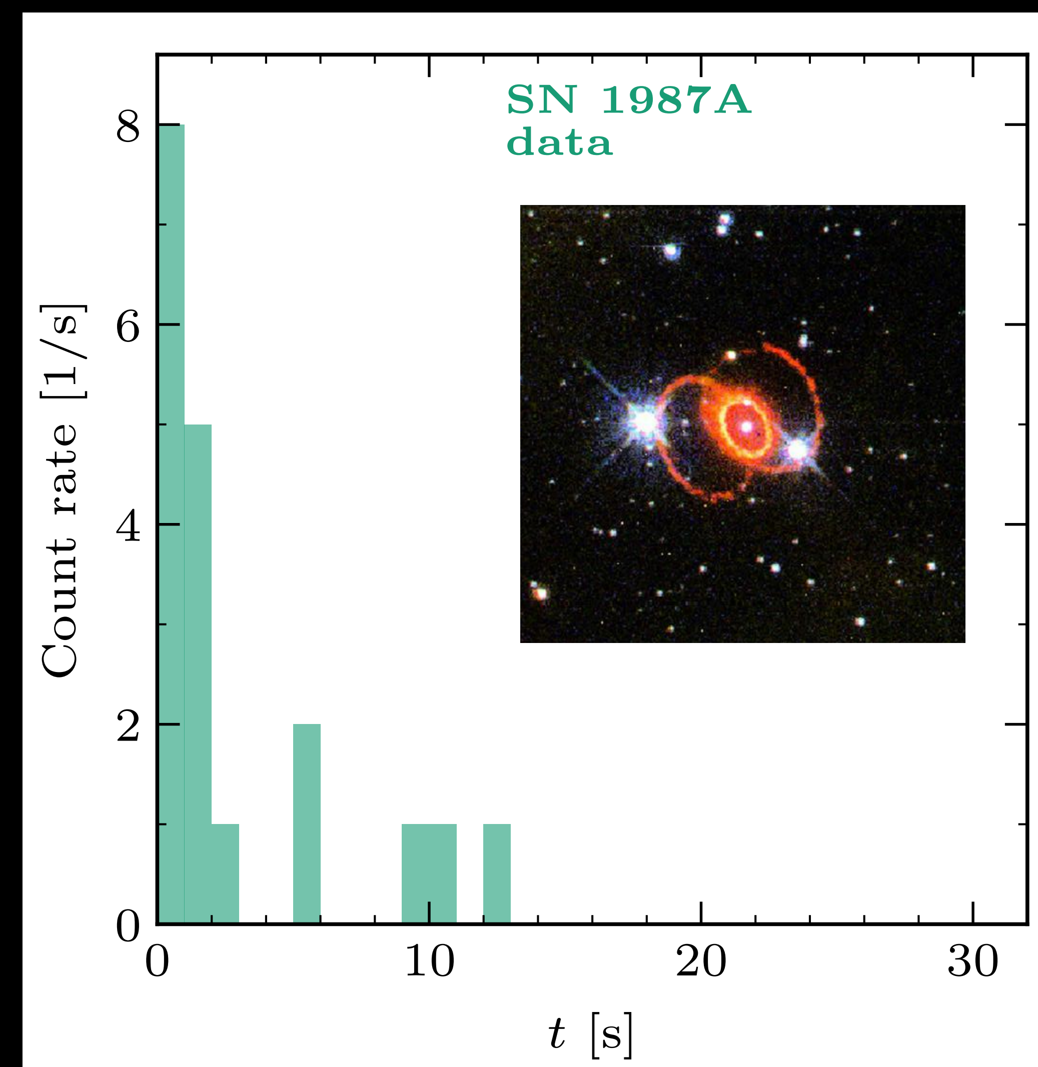
Strong probes of the self-scattering

Supernova neutrino emission: no νSI

Extended shell of free-streaming neutrinos



Confirmed by **SN 1987A**



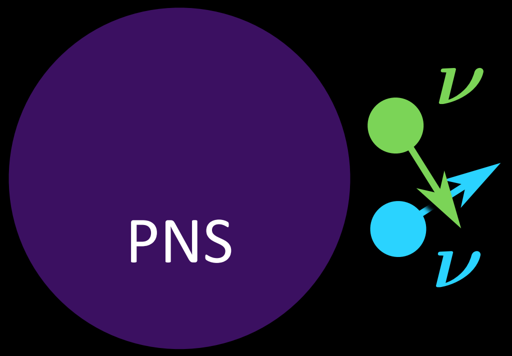
Strong probes of the self-scattering

What if strong νSI exist?

Inside the PNS:

- Complicated effects from baryons?
- Degenerate neutrinos?
- SN + neutrino transport simulation with νSI

Outside the PNS:



- Baryon effects are largely reduced
- Neutrinos (almost) only talk with each other
- **The problem is just relativistic hydrodynamics!**
- **A system of neutrinos with strong self-scattering = a perfect fluid**

Strong probes of the self-scattering

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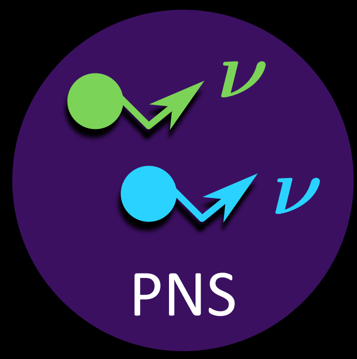

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Focus of our work 2206.12426

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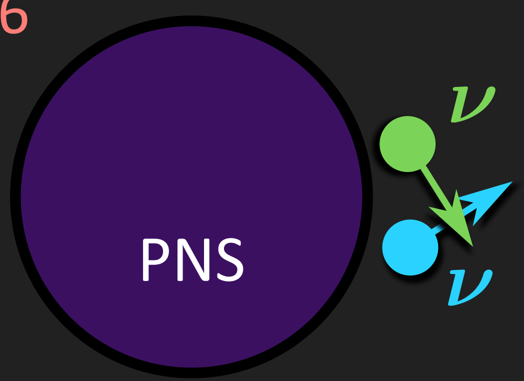

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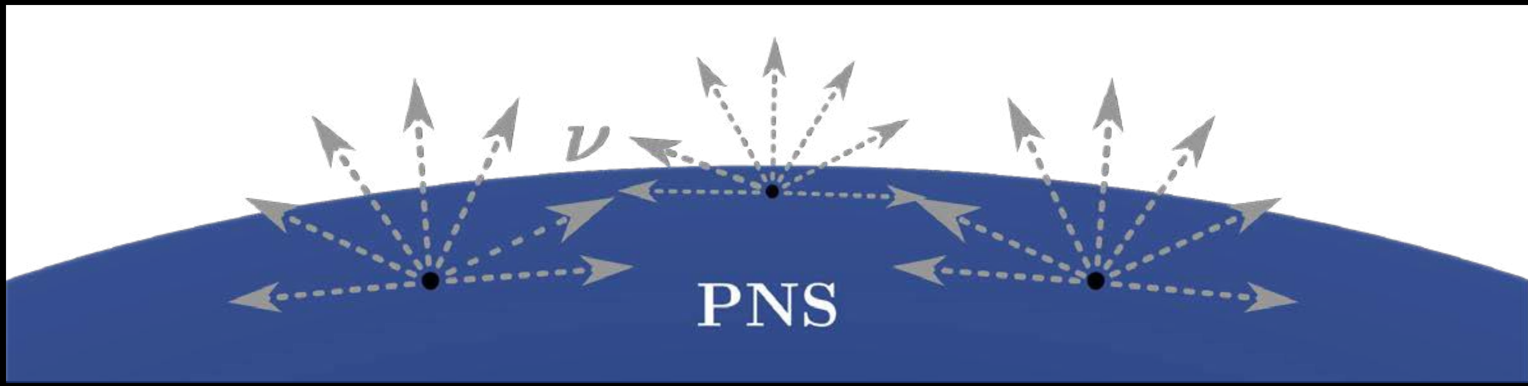
Strong probes of the self-scattering

If strong νSI exist

Extremely frequent **ν-ν scattering** persist outside the PNS



Strong probes of the self-scattering

If strong νSI exist

Extremely frequent **ν-ν scattering** persist outside the PNS

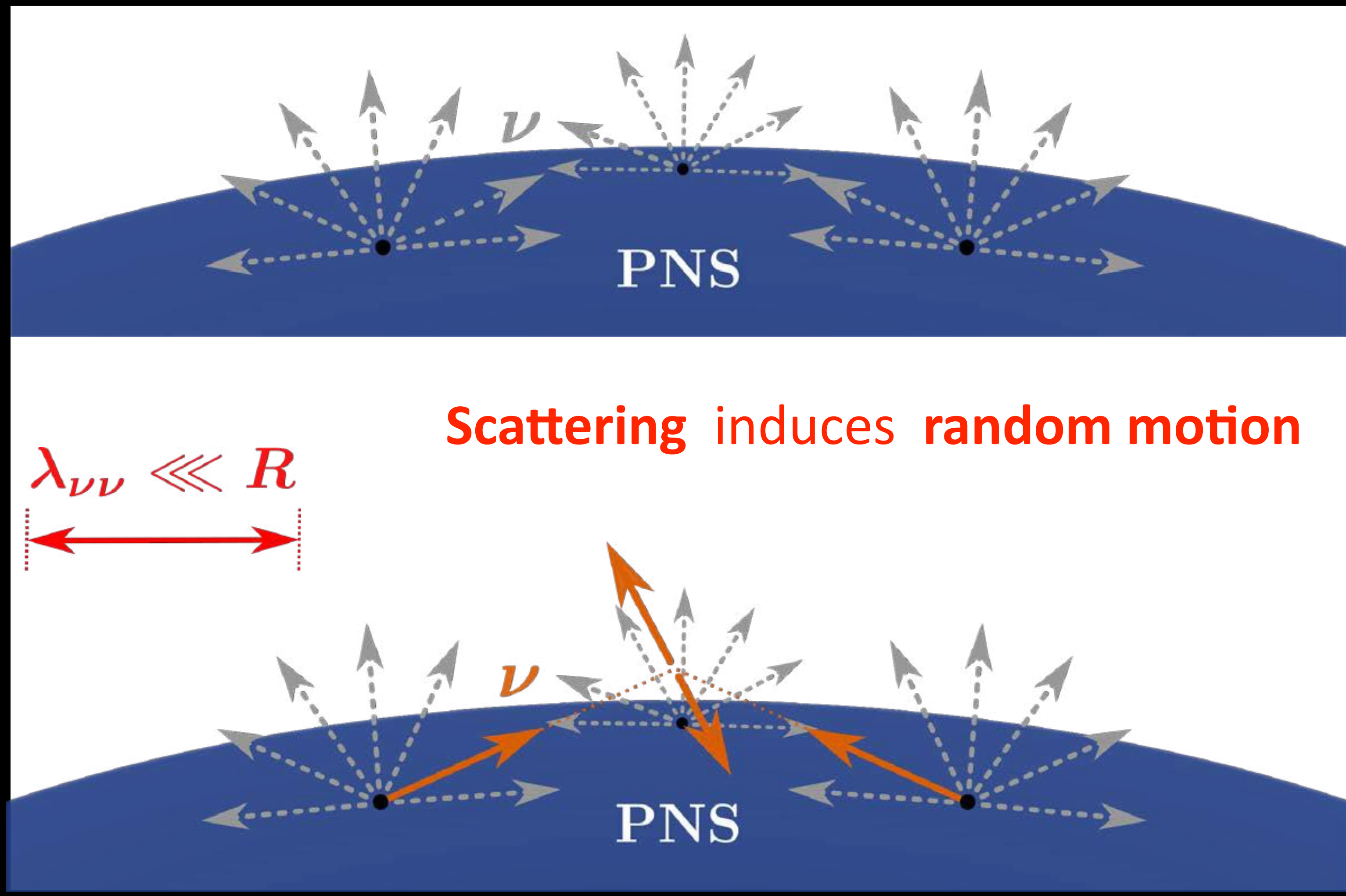
↓

Mean free path:

$$n_\nu \sim 10^{33}\,\mathrm{cm}^{-3},\;\; \sigma_{\nu\mathrm{SI}} \sim g^2/M_\phi^2$$

$$g \sim 10^{-4},\;\; M_\phi \sim 10\,\mathrm{MeV}$$

$$\boldsymbol{\lambda_{\nu\nu} \sim (n_\nu \sigma_{\nu\mathrm{SI}})^{-1} \sim 0.1\,\mathrm{mm}}$$



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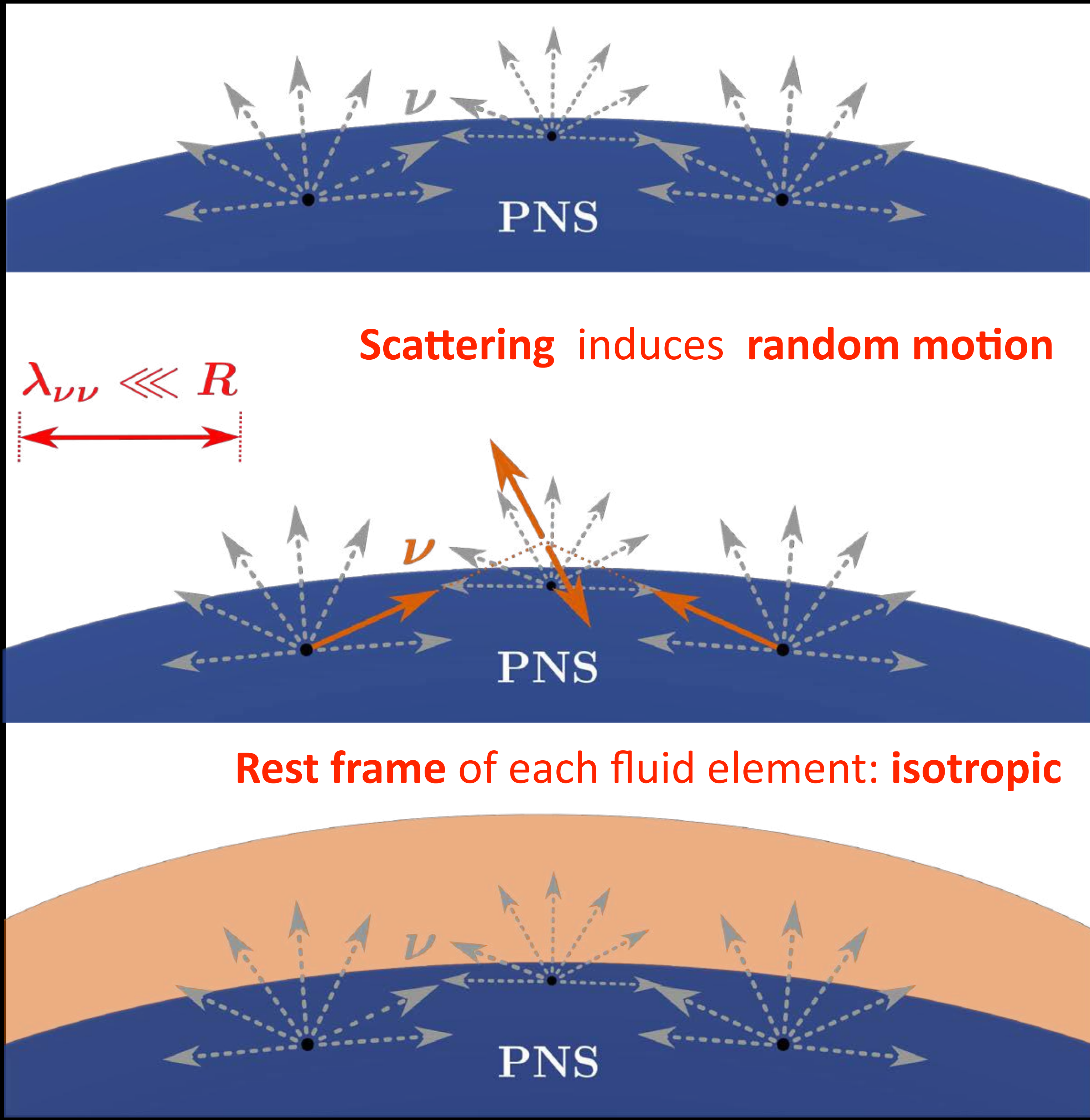
↓

Hydrodynamic limit: **relativistic fluid**



Strong probes of the self-scattering

Relativistic hydrodynamics

Comoving frame of perfect fluid: $\widetilde{T}^{\alpha\beta} = \mathrm{diag}(\tilde{\rho}, \widetilde{P}, \widetilde{P}, \widetilde{P})$ $\widetilde{P} = \tilde{\rho}/3$

- Energy-momentum conservation $\nabla_\alpha T^{\alpha\beta} = 0$
- Number conservation $\nabla_\alpha(\tilde{n}\, U^\alpha) = 0$

1) **Transient burst**

2) **Steady-state wind**

Strong probes of the self-scattering

Relativistic hydrodynamics

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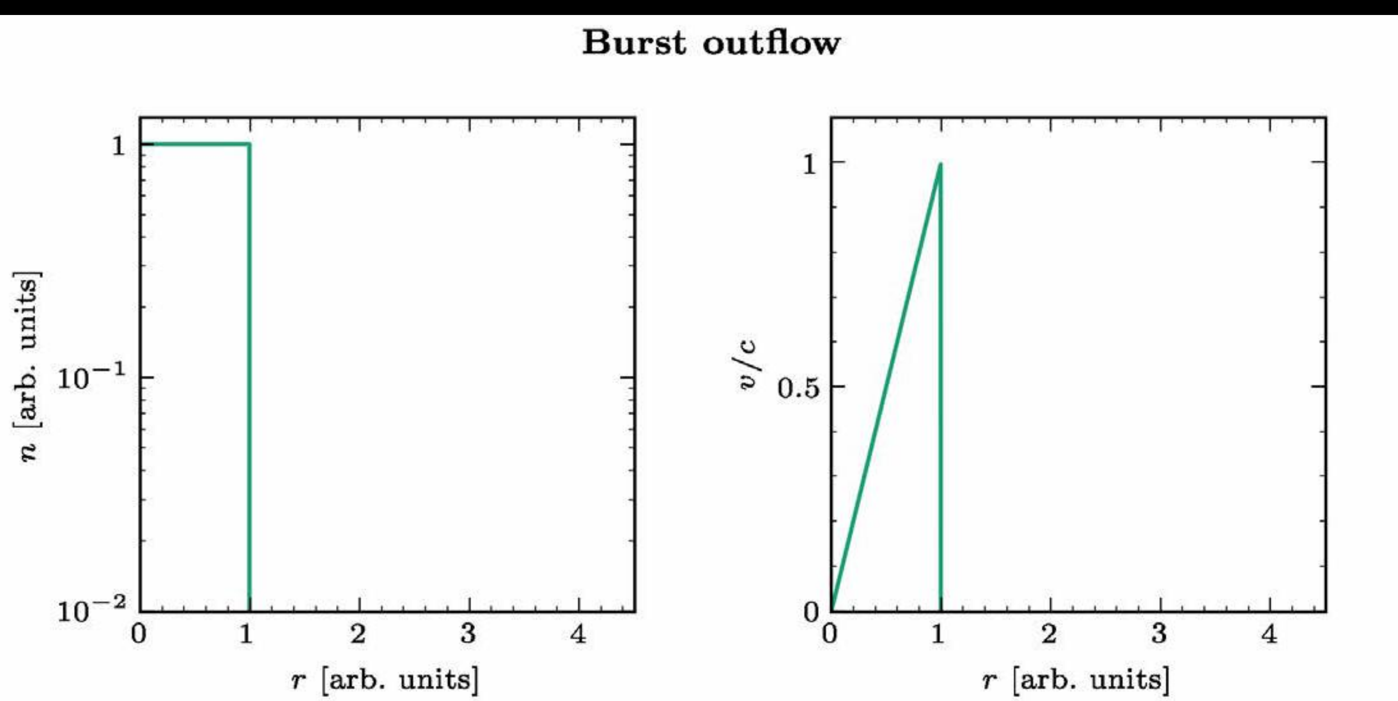
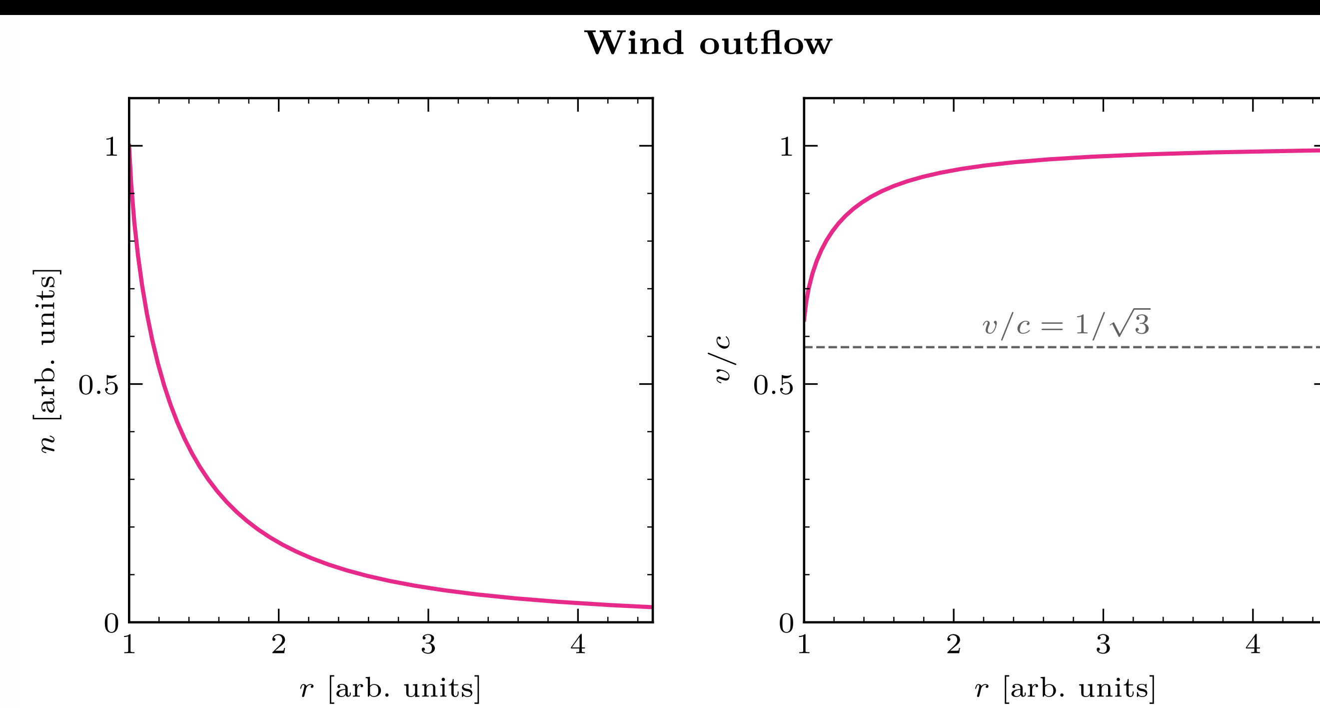




Strong probes of the self-scattering

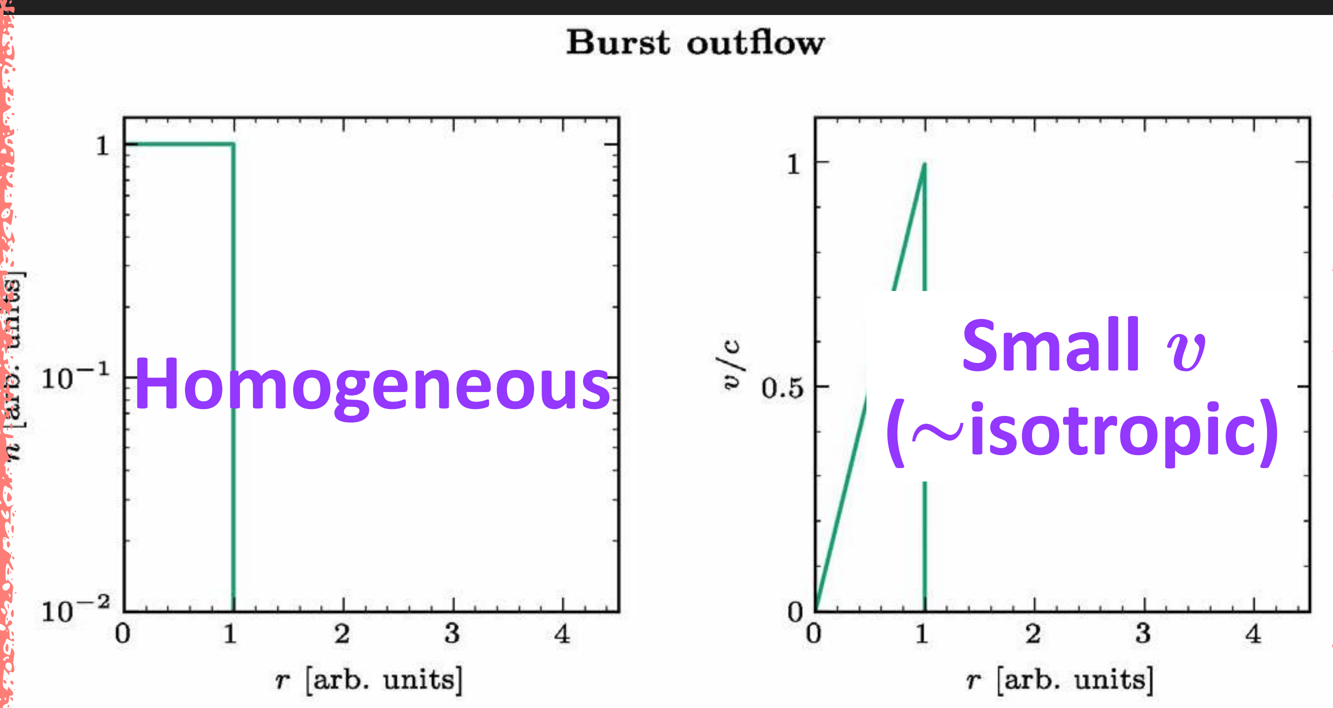
Relativistic hydrodynamics

Complicated supernova dynamics involving νSI: unclear which type of outflow is obtained

Interesting phenomenology should exist for both cases!

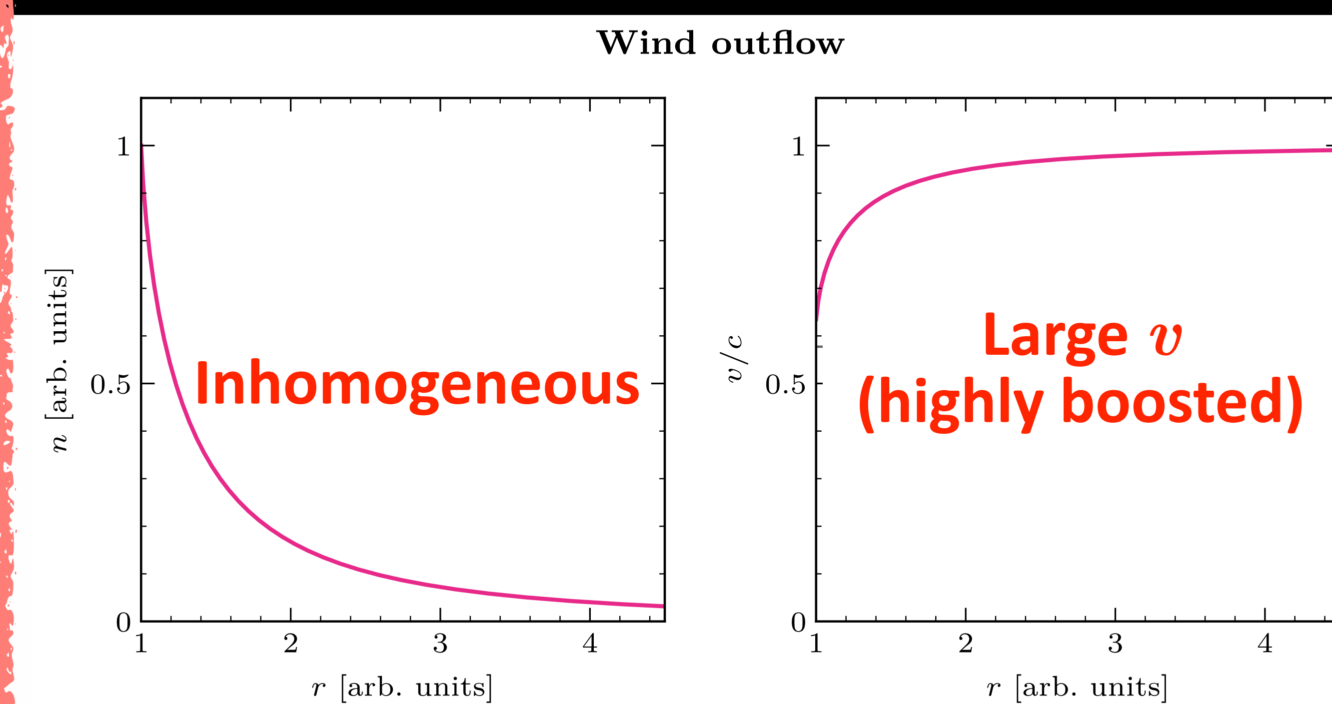
Our work

1) **Transient burst**



Future work

2) **Steady-state wind**



Strong probes of the self-scattering

Burst outflow: robust observable with interesting phenomenology

We find that if the burst is realized,
strong νSI will ***extend*** the **observed duration of supernova neutrinos**.

Key ideas: **random motion in all directions** & **neutrino decoupling**

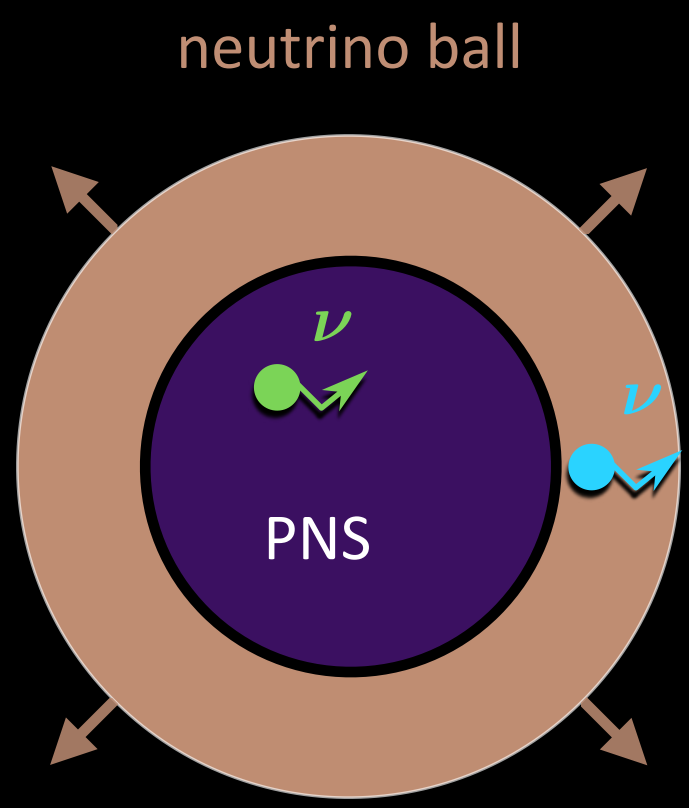
Early debate regarding to whether to not νSI can affect the observed duration of supernova neutrino:

- Manohar (1987)
- Dicus, Nussinov, Pal, Teplitz (1989)

Strong probes of the self-scattering

Burst outflow: robust observable with interesting phenomenology

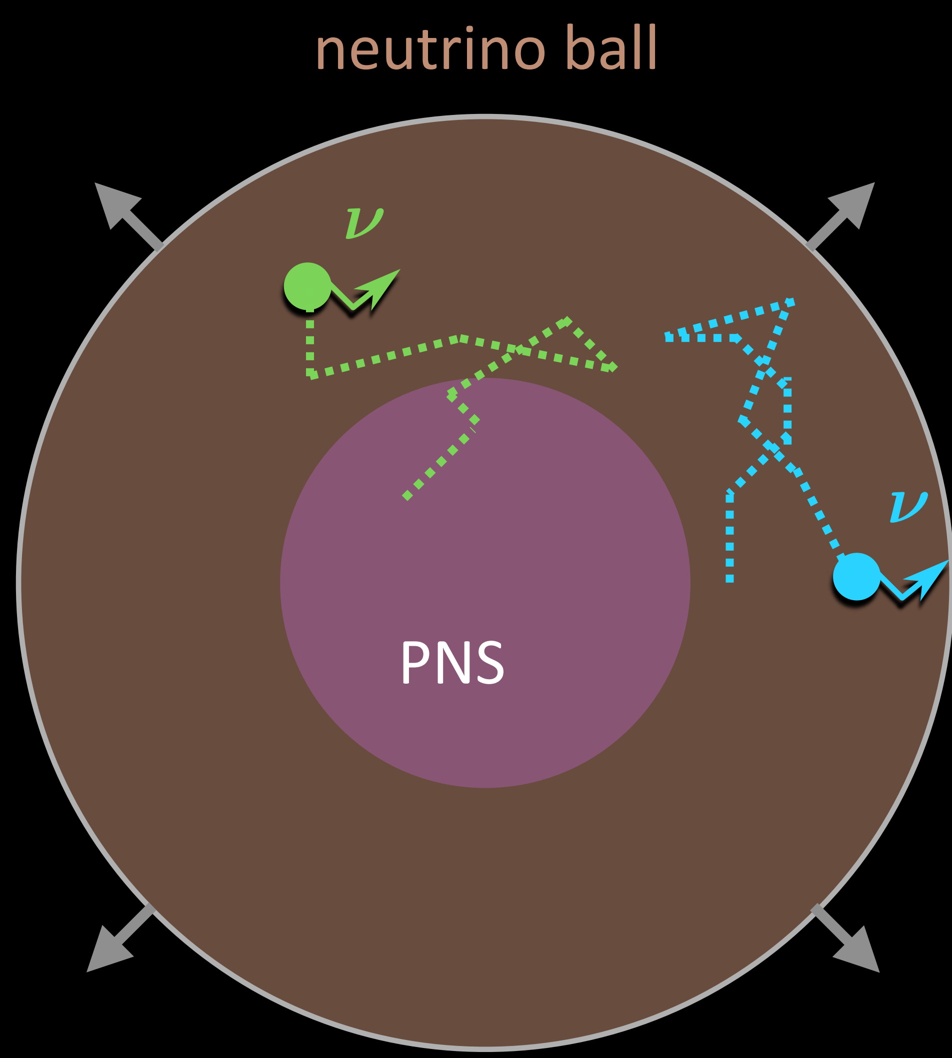
The fluid is a tightly coupled, expanding ***neutrino ball***.



Strong probes of the self-scattering

Burst outflow: robust observable with interesting phenomenology

The homogeneous neutrino ball keeps expanding and diluting. $n_\nu \downarrow \;\Rightarrow\; \tau_{\nu \mathrm{SI}} \downarrow$

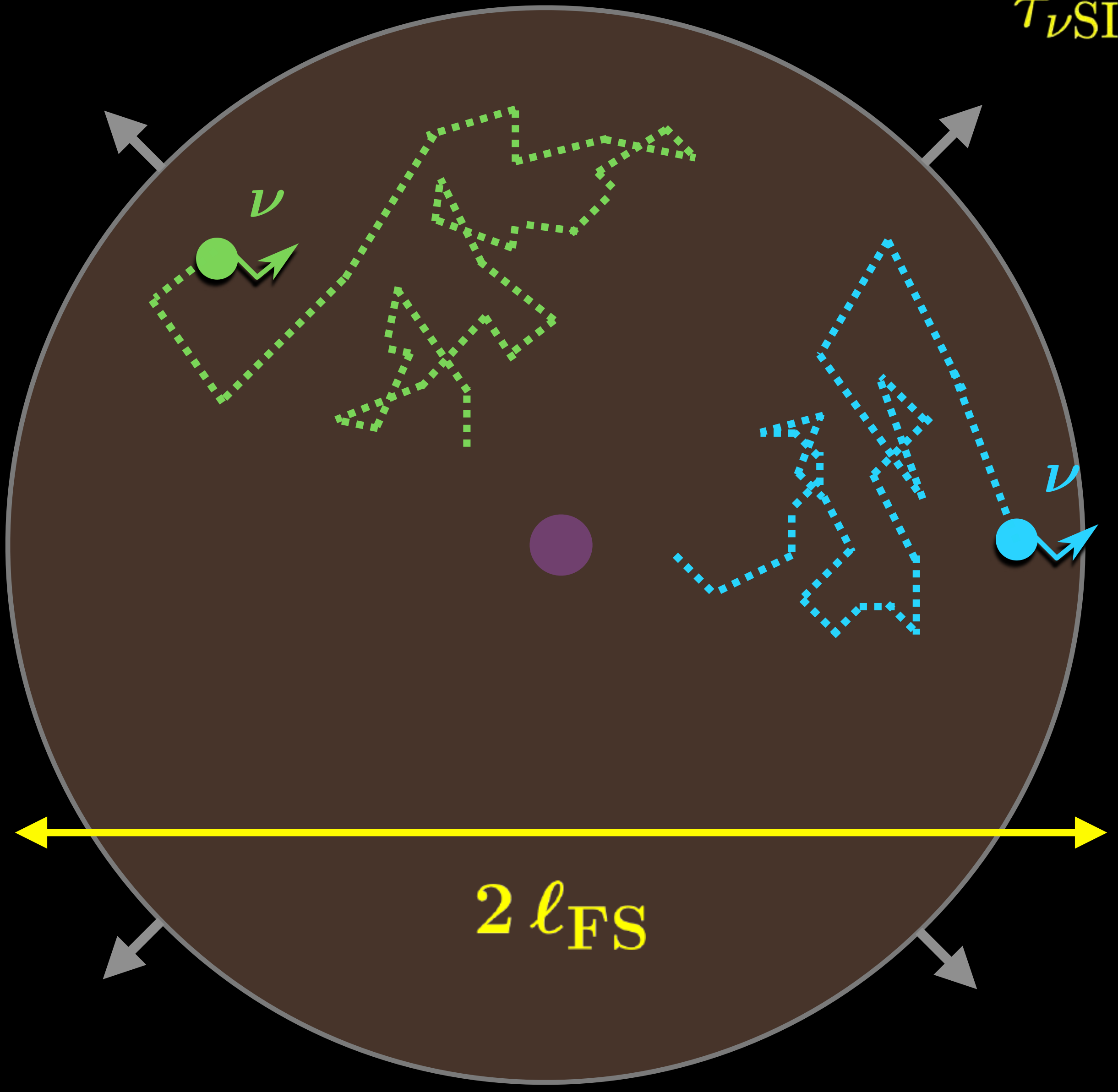


Strong probes of the self-scattering

Burst outflow: robust observable with interesting phenomenology

At some point, the interaction rate becomes too small. Neutrinos ***decouple*** from each other.

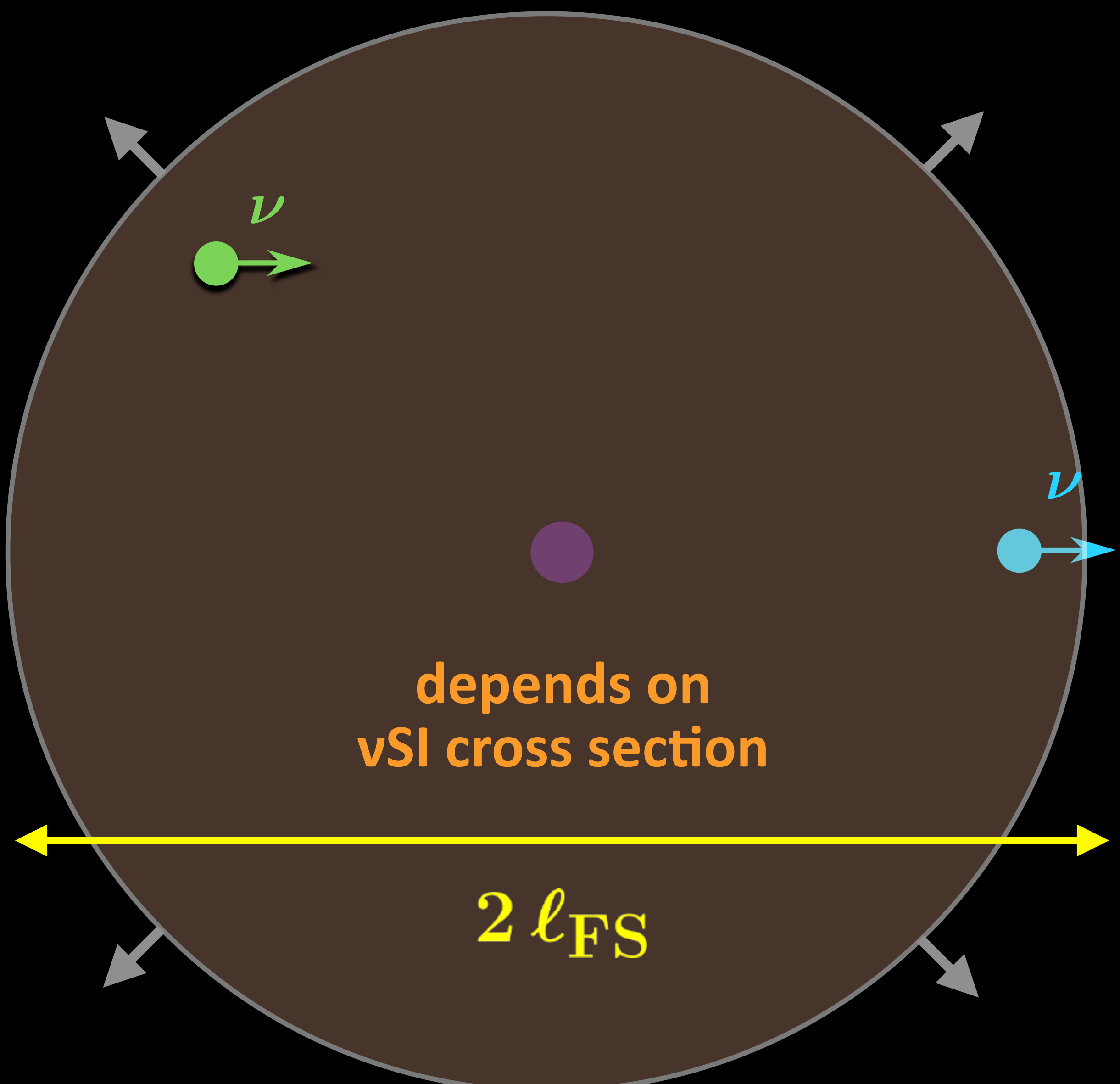
$$\tau_{\nu SI} \sim n_\nu \, \sigma_{\nu SI} \, \ell_{FS} \lesssim \mathcal{O}(1)$$



Strong probes of the self-scattering

Burst outflow: robust observable with interesting phenomenology

The directions of neutrino motion "***freeze***" after the last scattering.

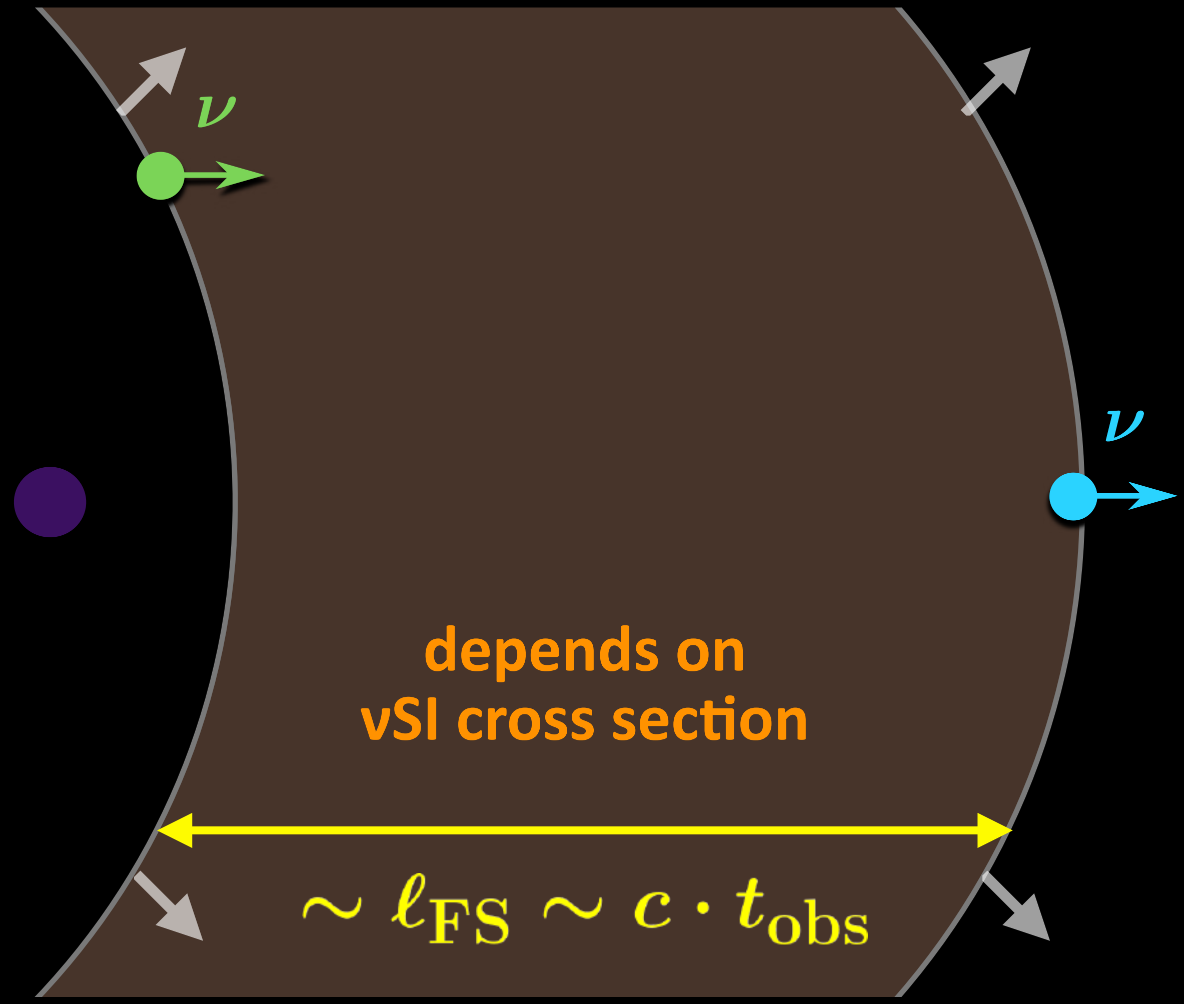


Strong probes of the self-scattering

Burst outflow: robust observable with interesting phenomenology

The ball eventually becomes a ***free-streaming neutrino shell***

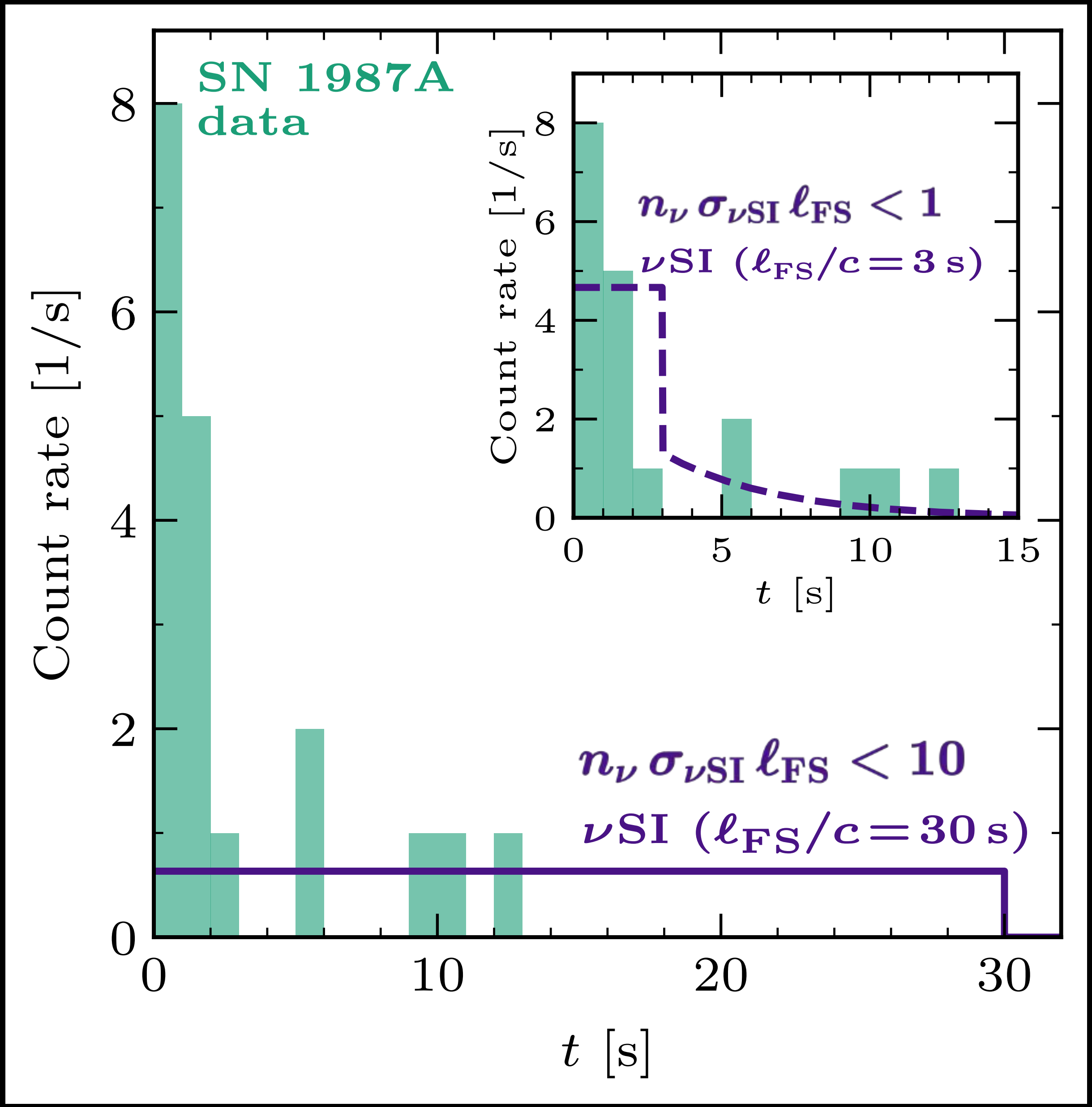
The thickness of the shell $\sim$ observed duration of supernova neutrino signals

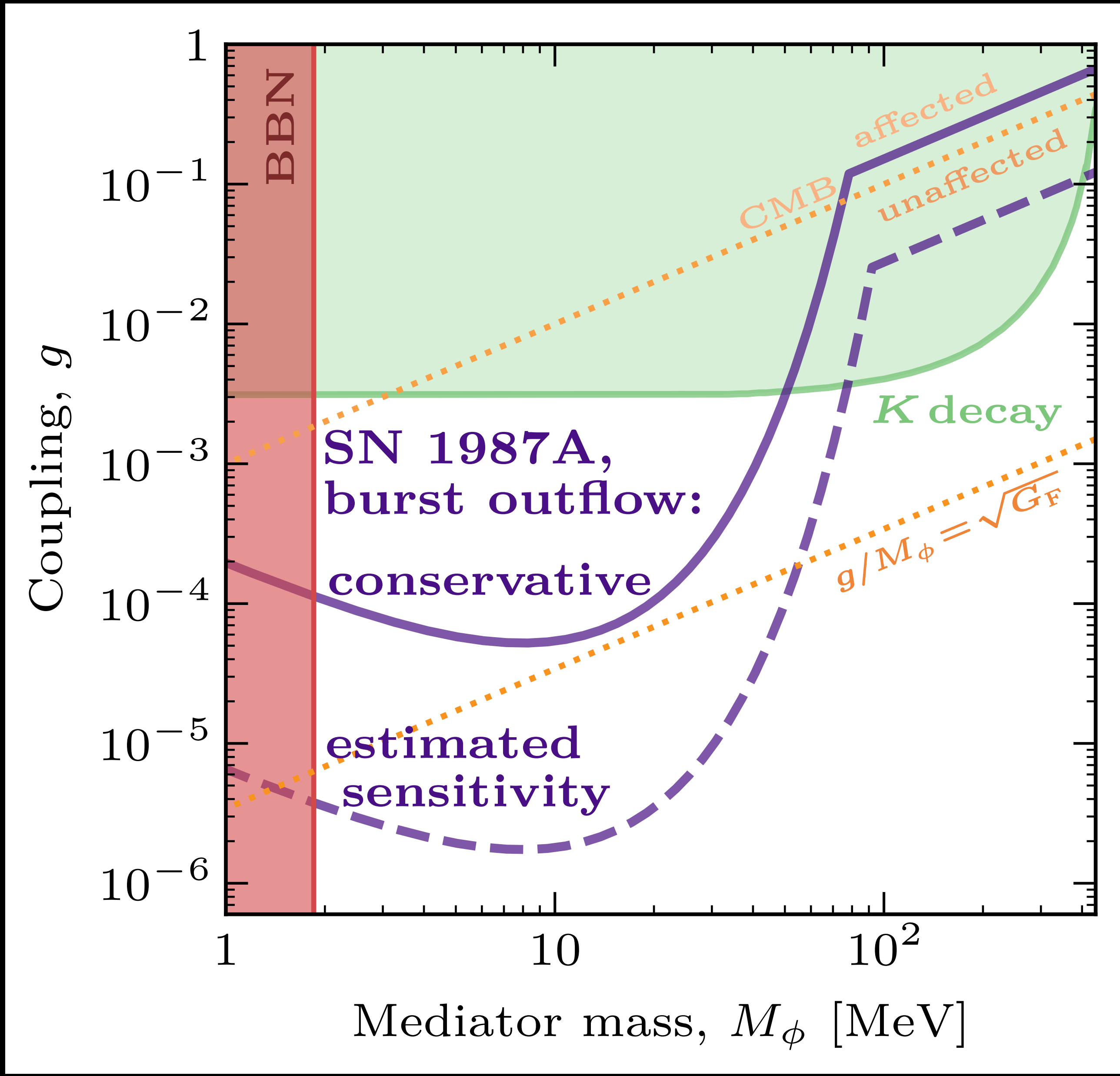


Potential sensitivity from SN 1987A

Potential sensitivity from SN 1987A

Phenomenology of the **burst outflow**





Potential sensitivity from SN 1987A

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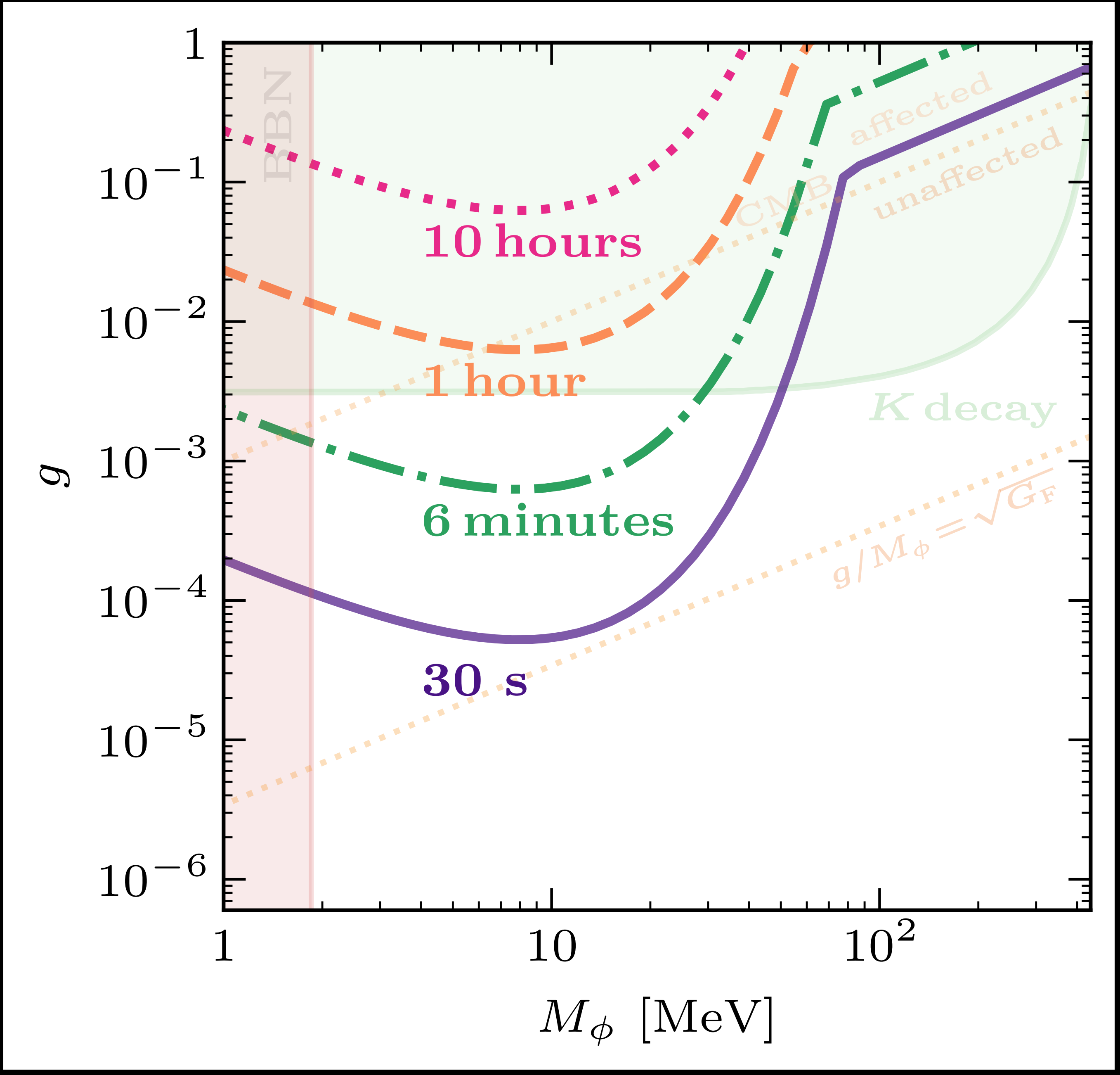
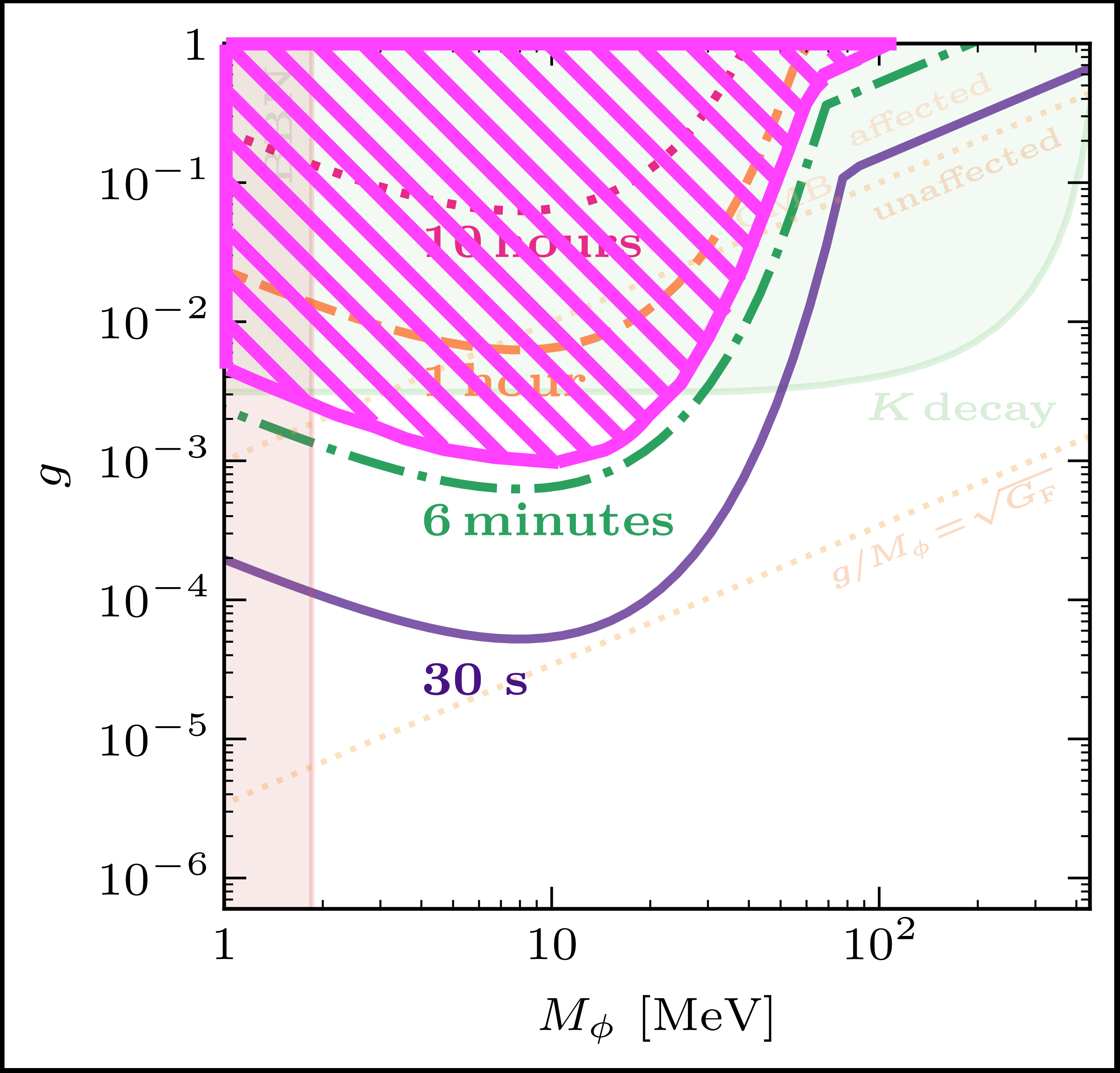


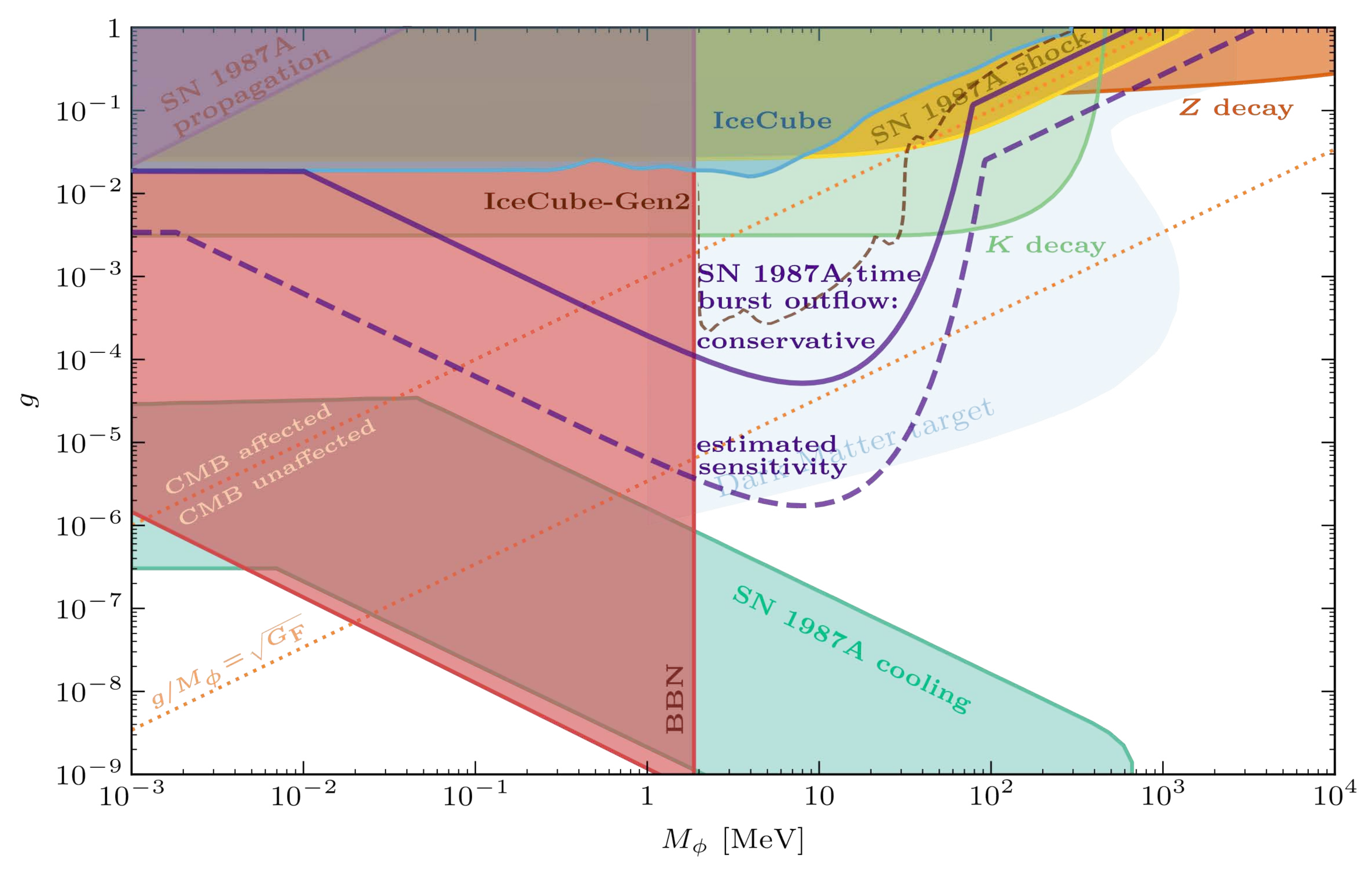
Potential sensitivity from SN 1987A

Phenomenology of the **burst outflow**

SN 1987A neutrinos would "disappear"



Potential sensitivity from SN 1987A



Conclusions

- νSI: rich phenomenology across the laboratory, cosmology, and astrophysics.
- Understanding the effects of νSI is crucial in interpreting the data of dense neutrino environments (e.g., the early Universe, core-collapse supernovae) and developing powerful constraints.
- For 35 years since SN 1987A, we are not sure how νSI affect the dense neutrinos in supernovae. **We have lacked a roadmap and robust observable.**

Our work: New roadmap towards fully exploiting supernova to test νSI.
We find that potential observable does exist!
(SN 1987A might already tell us something…)

- How about the νSI effects inside the PNS?
  How about the steady-state wind?
  Which outflow case is realized by nature?
  Does burst/wind regime appear in different phase of supernova neutrino emission?
  …

Really exciting area with lots of promising directions

Thank you!

Our paper: 2206.12426