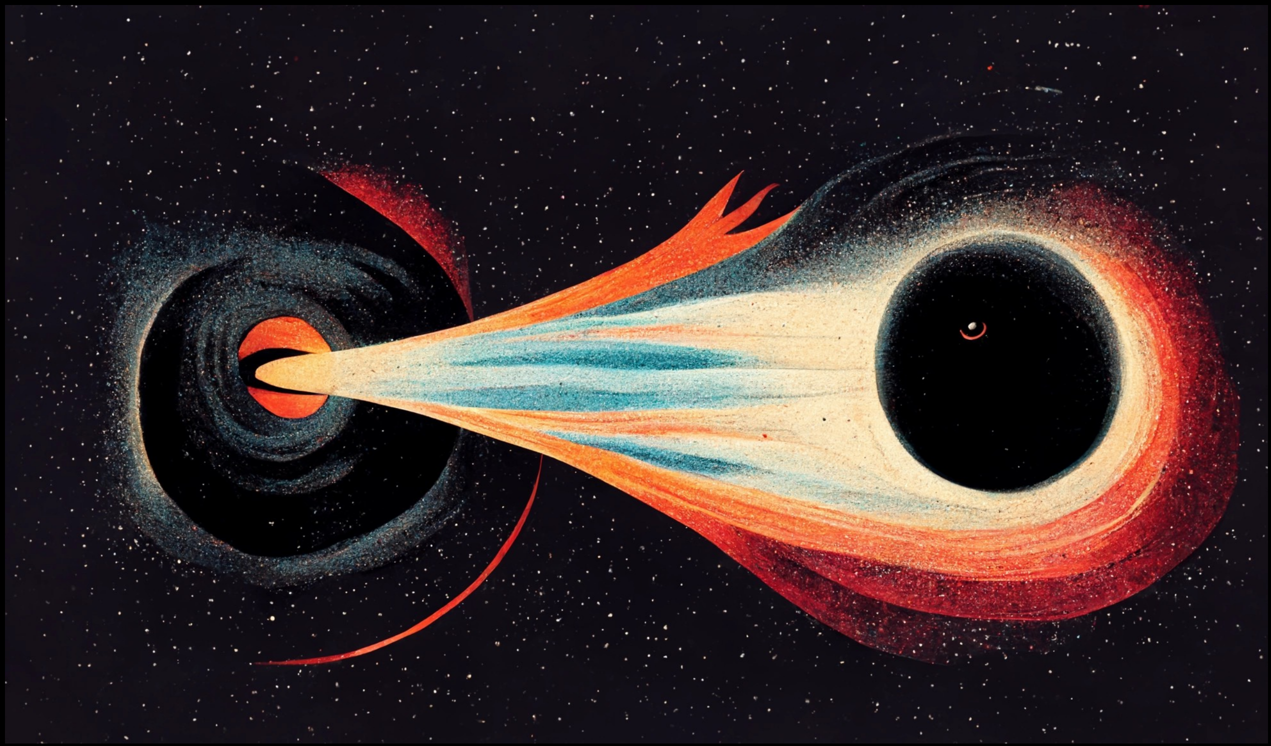
Testing Neutrino Secret Interactions with Supernovae

John Beacom
CCAPP, The Ohio State University

In collaboration with

Po-Wen Chang, Ivan Esteban,
Todd Thompson, Chris Hirata

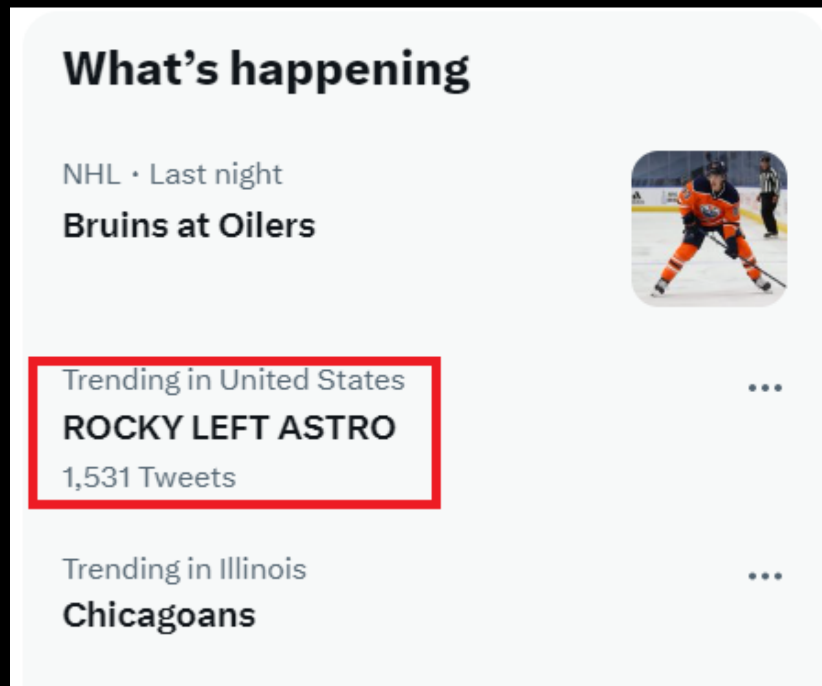
arXiv:2206.12426



CCAPP THE OHIO STATE UNIVERSITY

RockyFest, Chicago, March 2023

Why I’m here


What’s happening
NHL · Last night
Bruins at Oilers
Trending in United States
ROCKY LEFT ASTRO
1,531 Tweets
Trending in Illinois
Chicagoans


symmetry
dimensions of particle physics
topics
07/01/06
John Beacom:
Family business
A fact of life
won't get to
papers–they
are. In a glob

Neutrinos are special particles

In the *laboratory:*

- Their lack of strong and EM interactions makes neutrinos *exquisitely sensitive to new forces*

In *cosmology:*

- Their high cosmic abundance makes neutrinos *exquisitely sensitive to the conditions of the early universe*

In *astronomy:*

- Their penetrating power makes neutrinos *exquisitely sensitive to the physics in the dense interiors of sources*

But do they have secrets?

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) × SU(2) × U(1) model.

Outline

Where to test νSI?

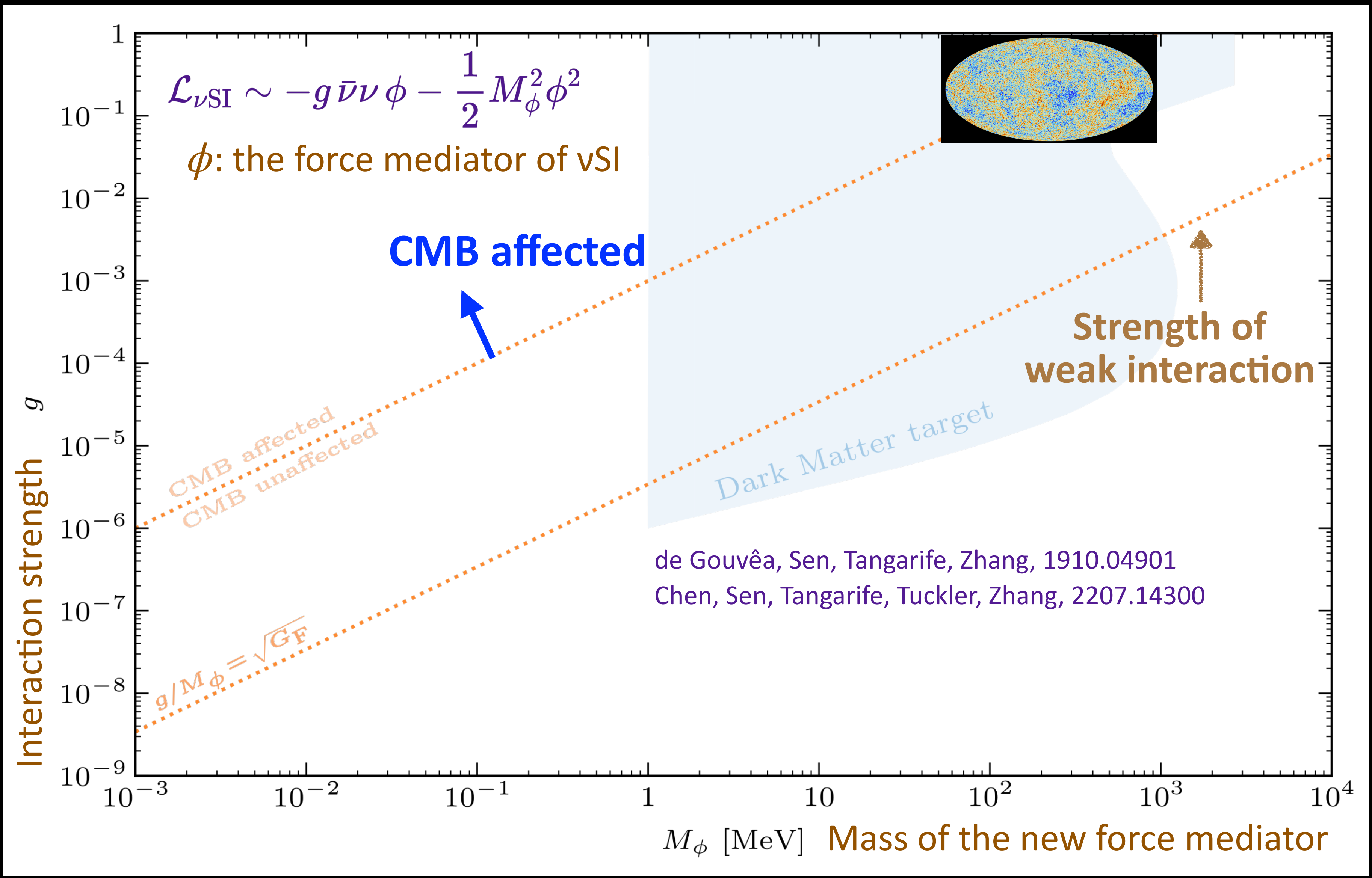
Testing νSI with supernovae: prior work

Testing νSI with supernovae: our work

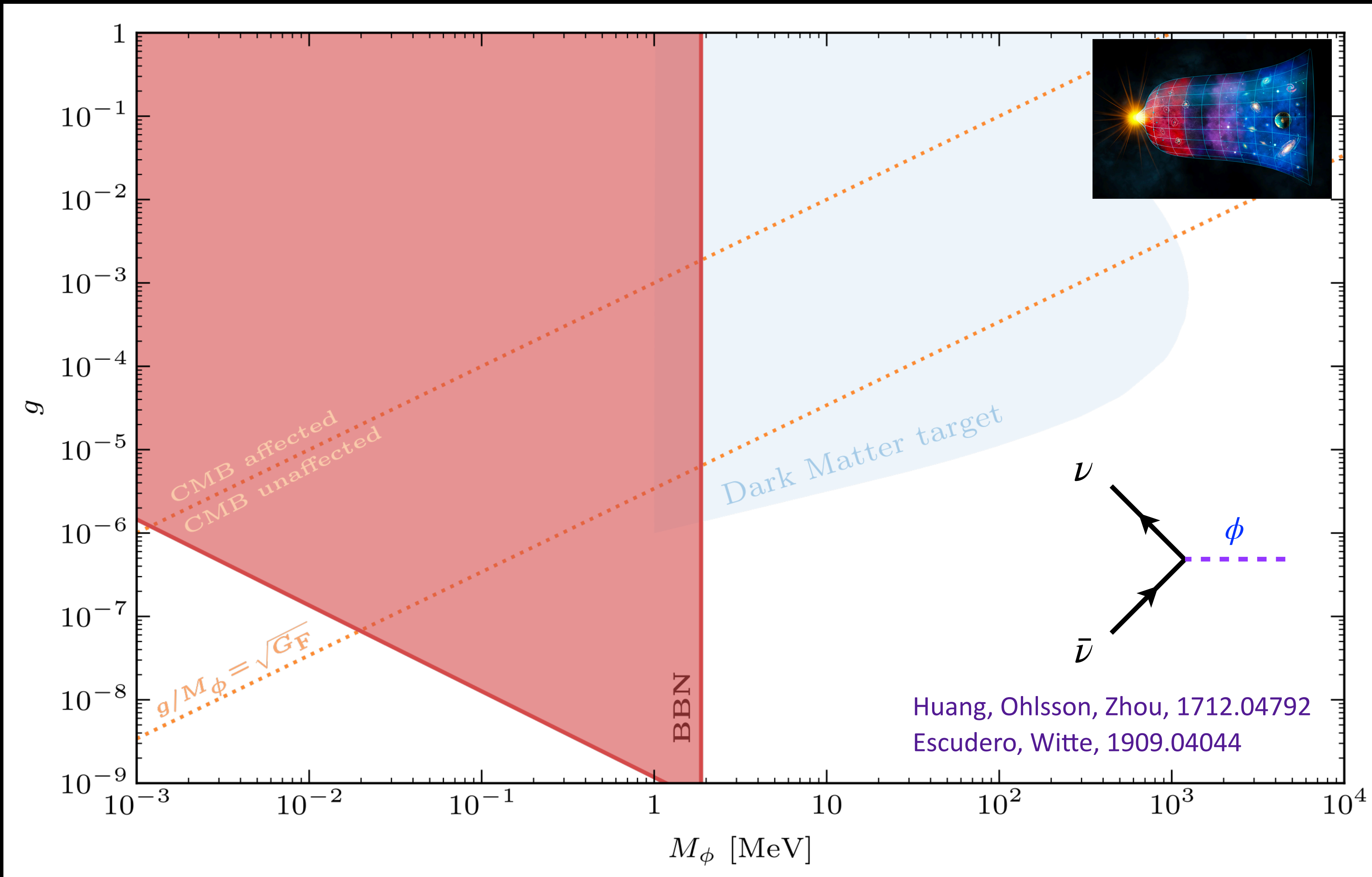
Concluding perspectives

Where to test νSI?

Where to test νSI?



Where to test νSI?



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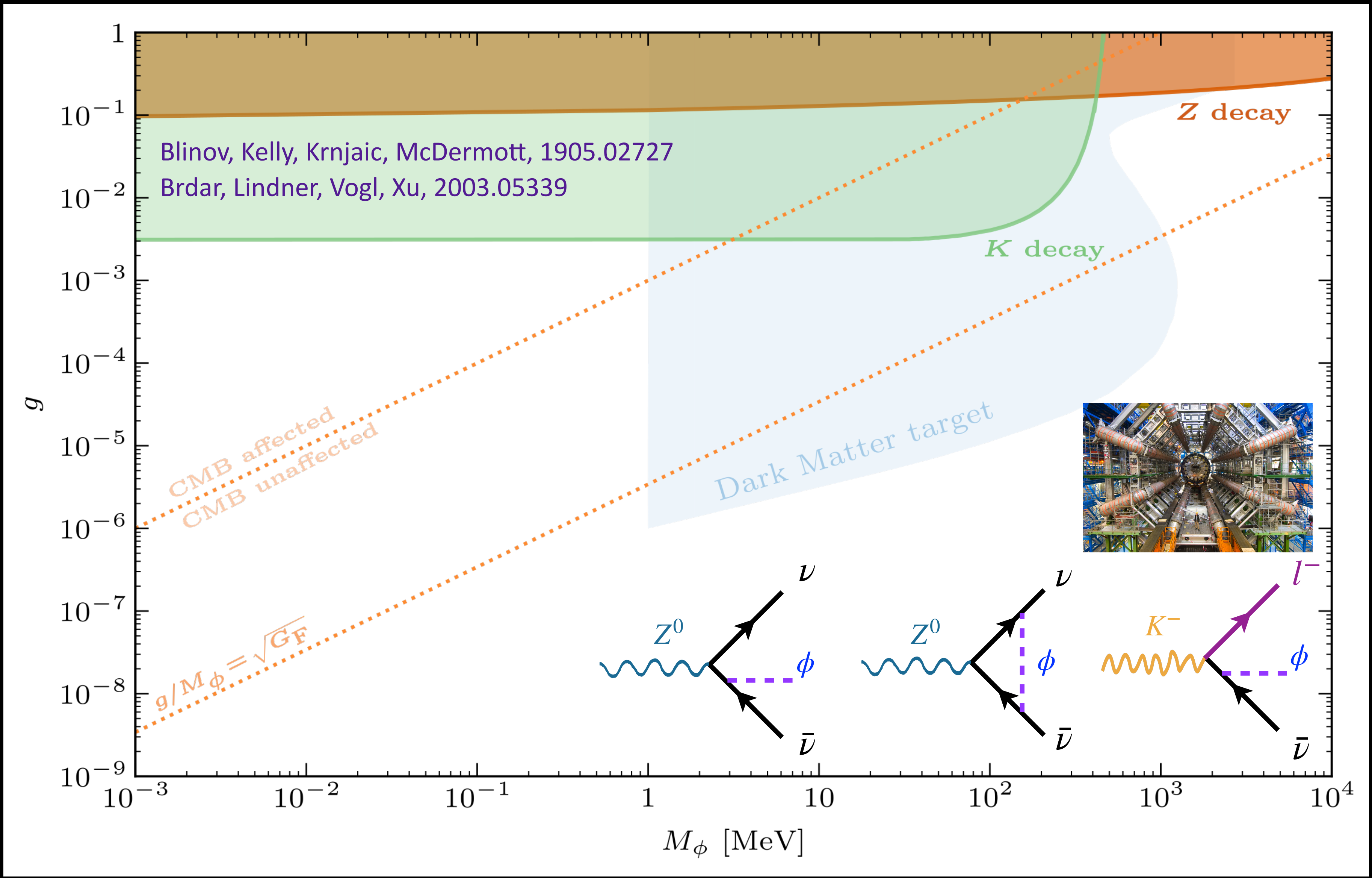

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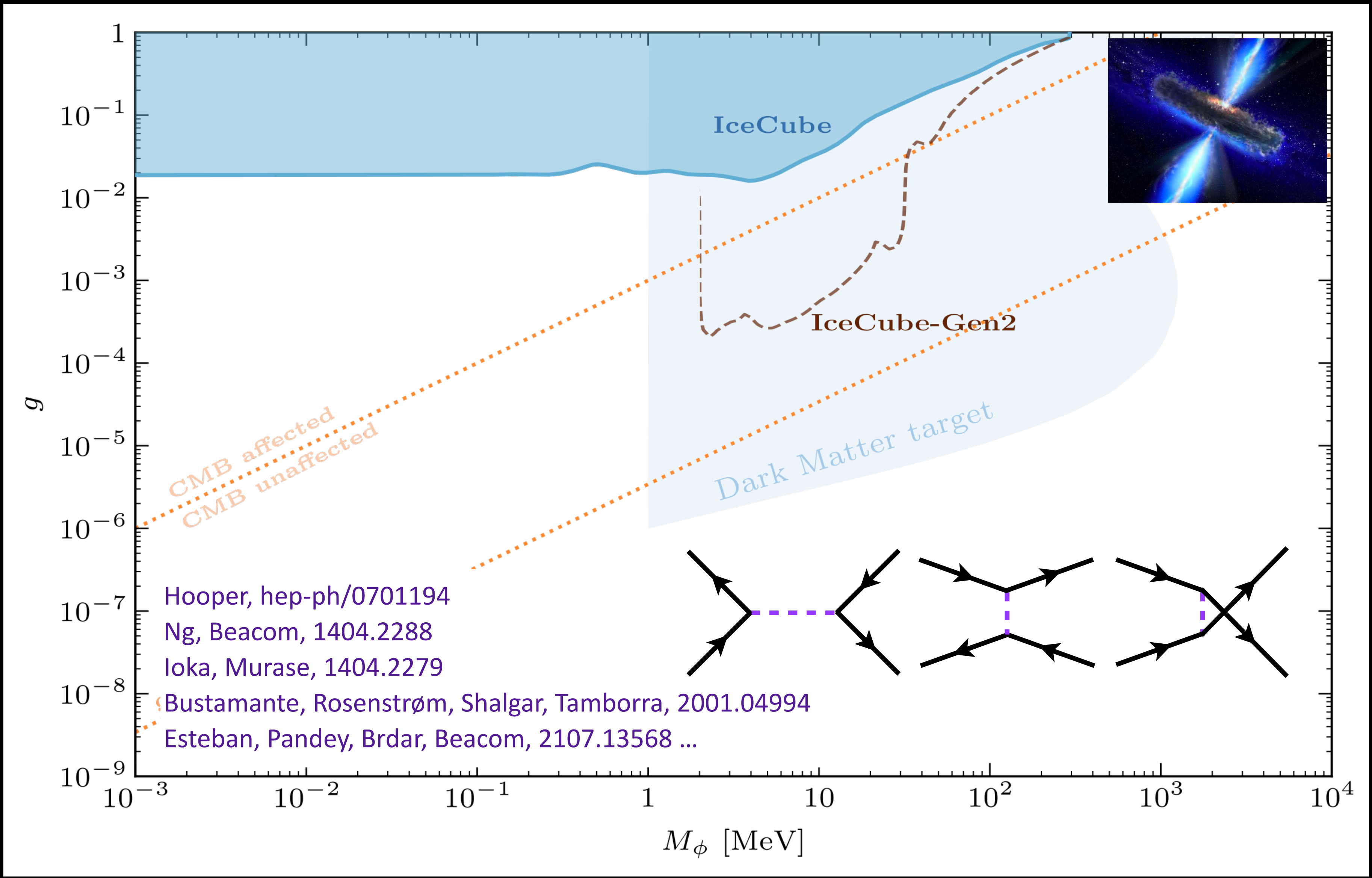


Testing νSI with supernovae: prior work

Core-collapse supernovae

Final fate of a massive star

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

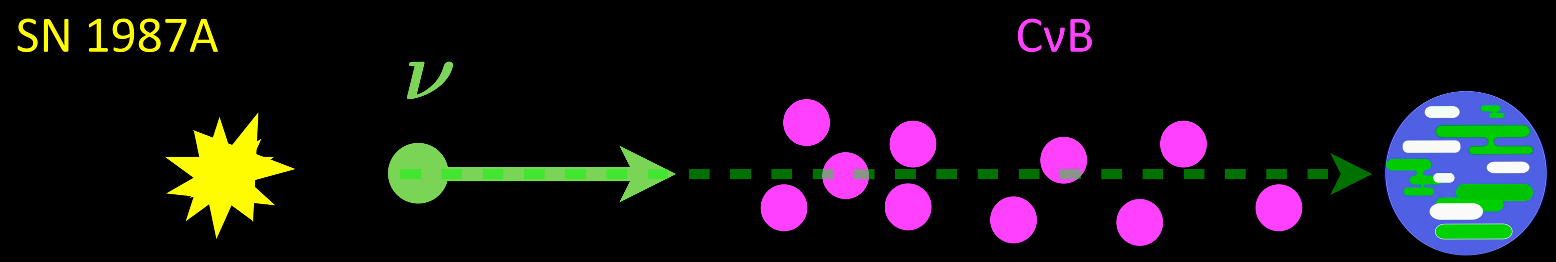
Core-collapse supernovae are **efficient neutrino factories**

Tremendous amount of gravitational energy

99%	**neutrinos**
	+
1%	kinetic energy of ejecta
	+
0.01%	photons

Core-collapse supernovae

Propagation of SN 1987A neutrinos



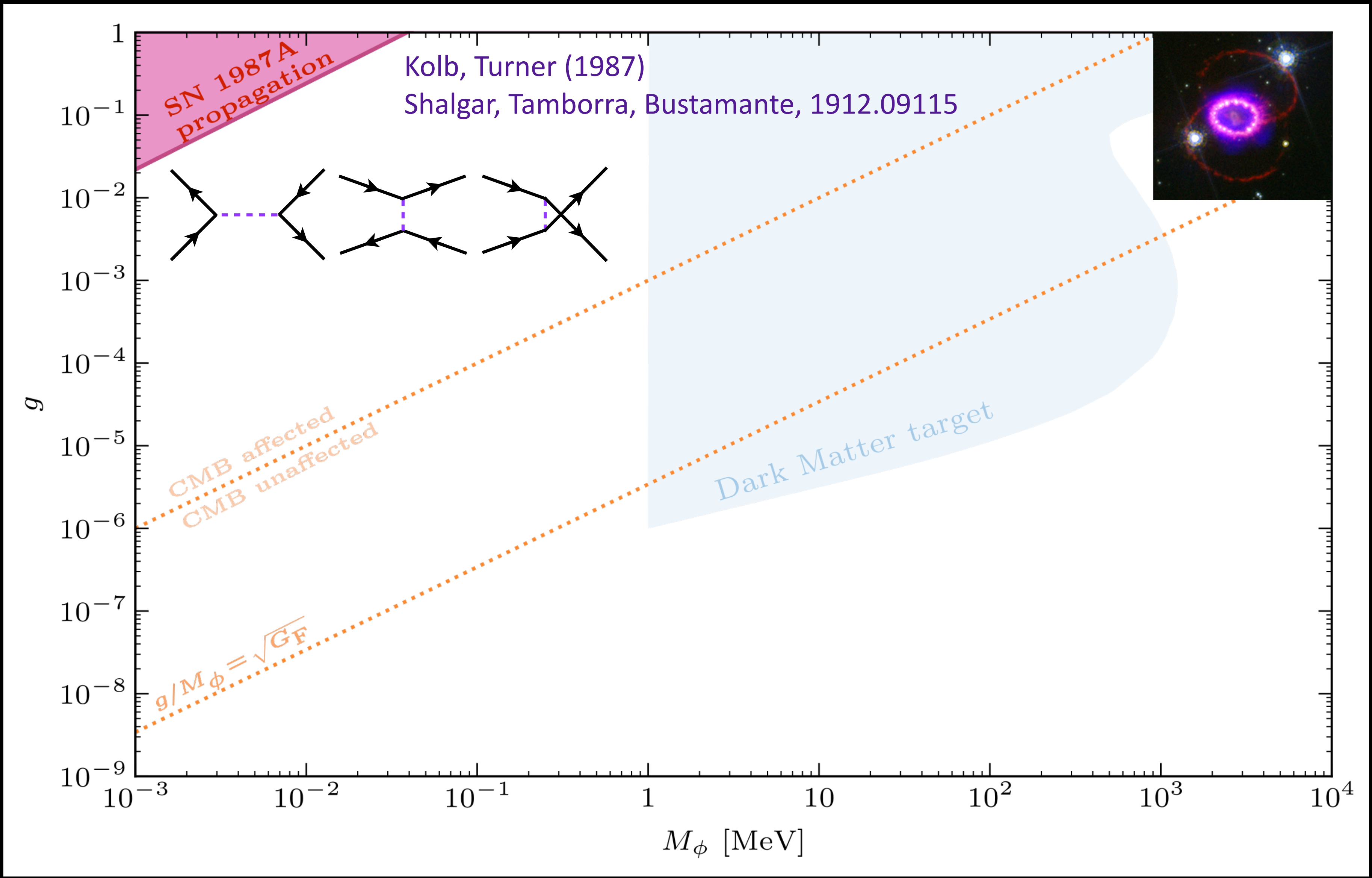
$$\nu + \nu \to \nu + \nu$$

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

Kolb, Turner (1987)

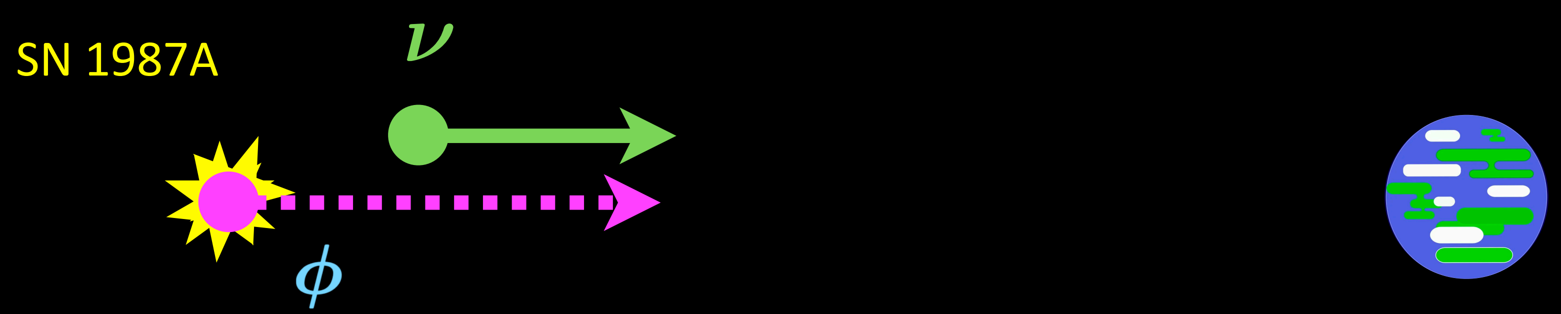
Shalgar, Tamborra, Bustamante, 1912.09115

Core-collapse supernovae



Core-collapse supernovae

Cooling of SN 1987A

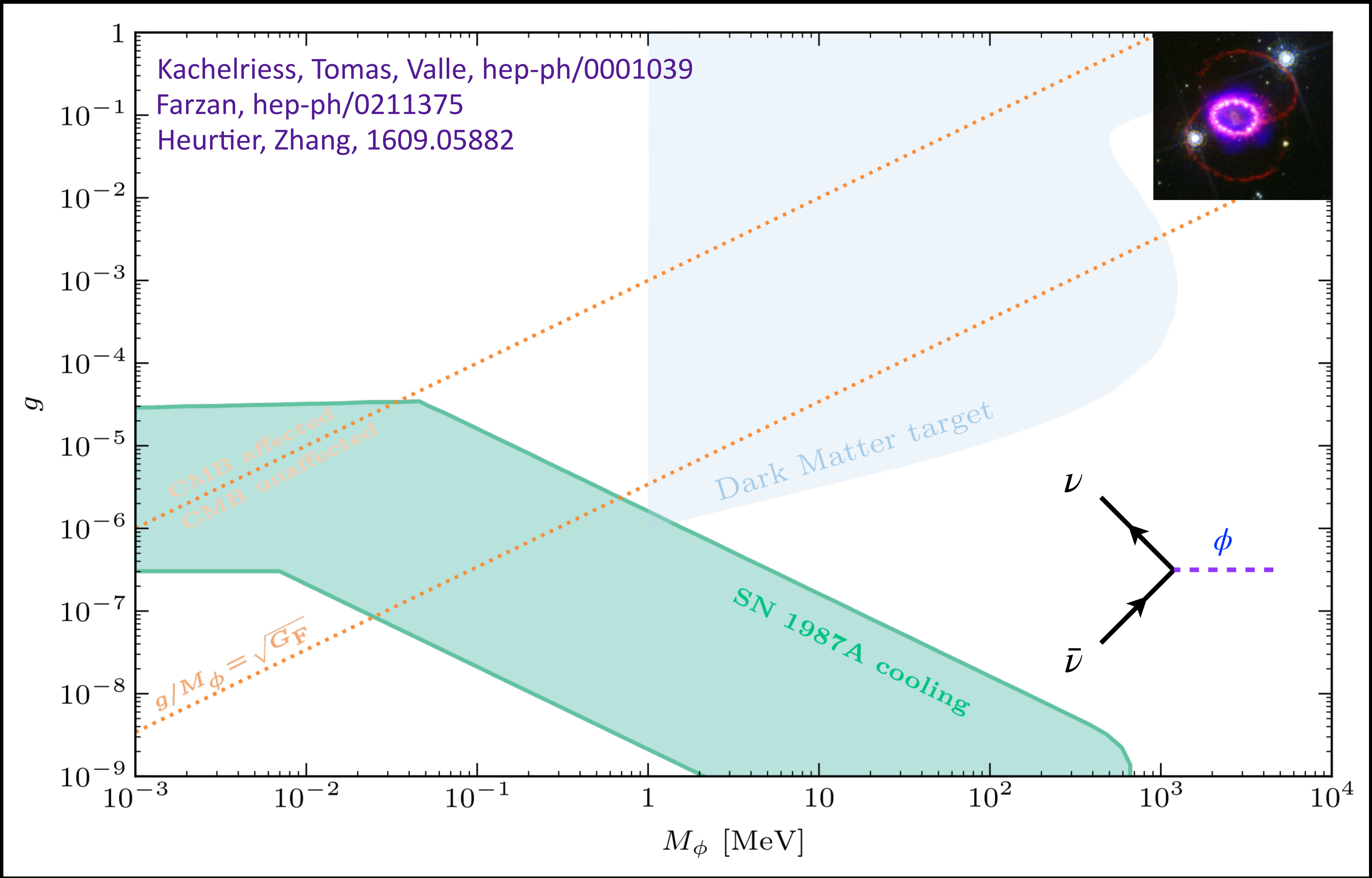


$$\nu + \nu \rightarrow \phi$$

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

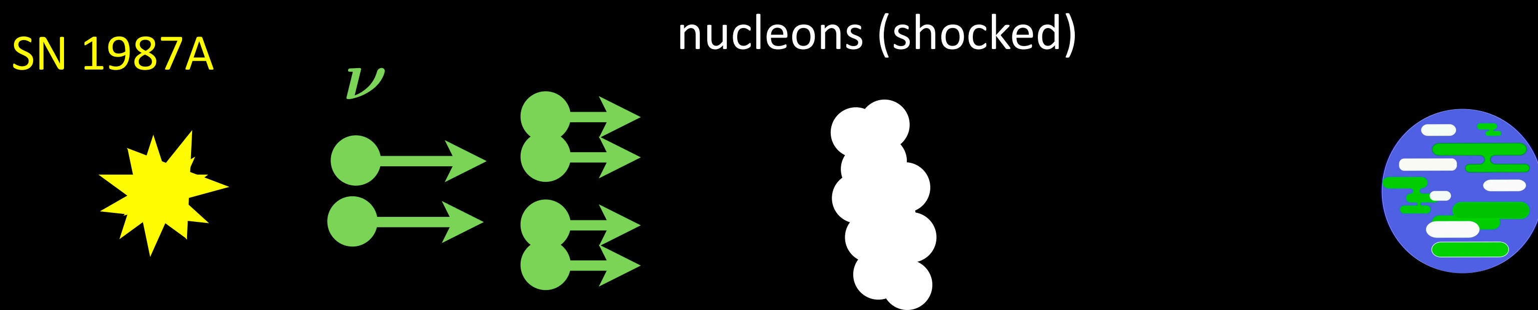
Kachelriess, Tomas, Valle, hep-ph/0001039
Farzan, hep-ph/0211375
Heurtier, Zhang, 1609.05882

Core-collapse supernovae



Core-collapse supernovae

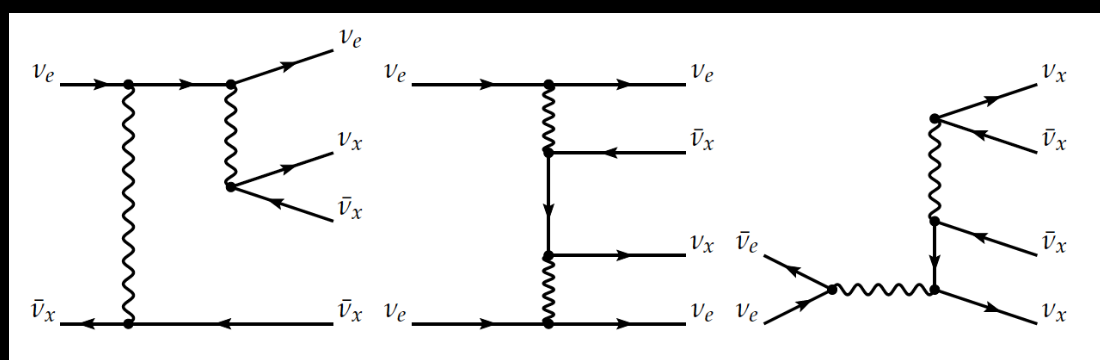
Shock of SN 1987A



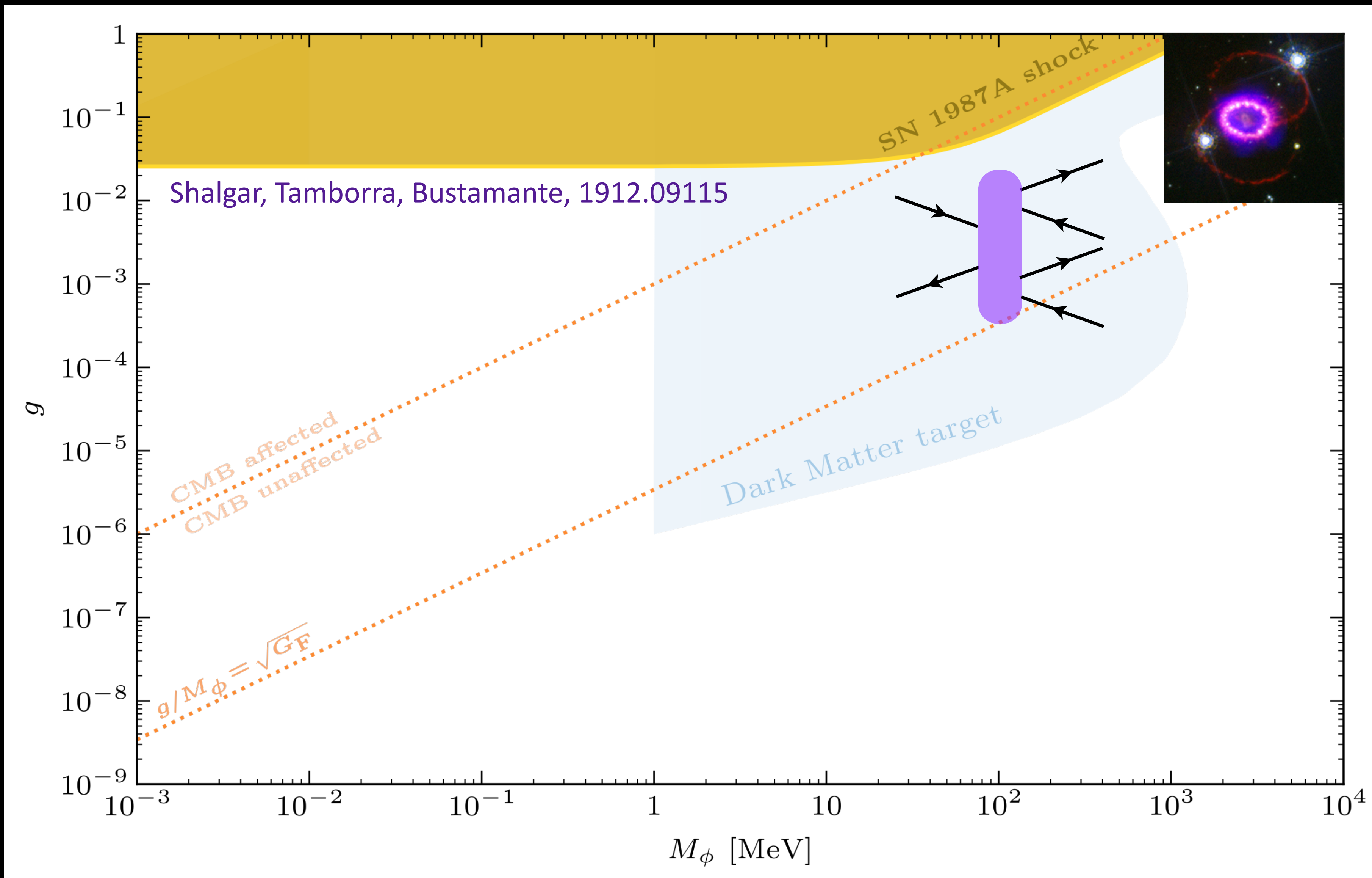
$$\nu + \nu \rightarrow \nu + \nu + \nu + \nu$$

Strong νSI: 2ν→4ν processes **fail** to produce a neutrino-driven shock

Shalgar, Tamborra, Bustamante, 1912.09115



Core-collapse supernovae



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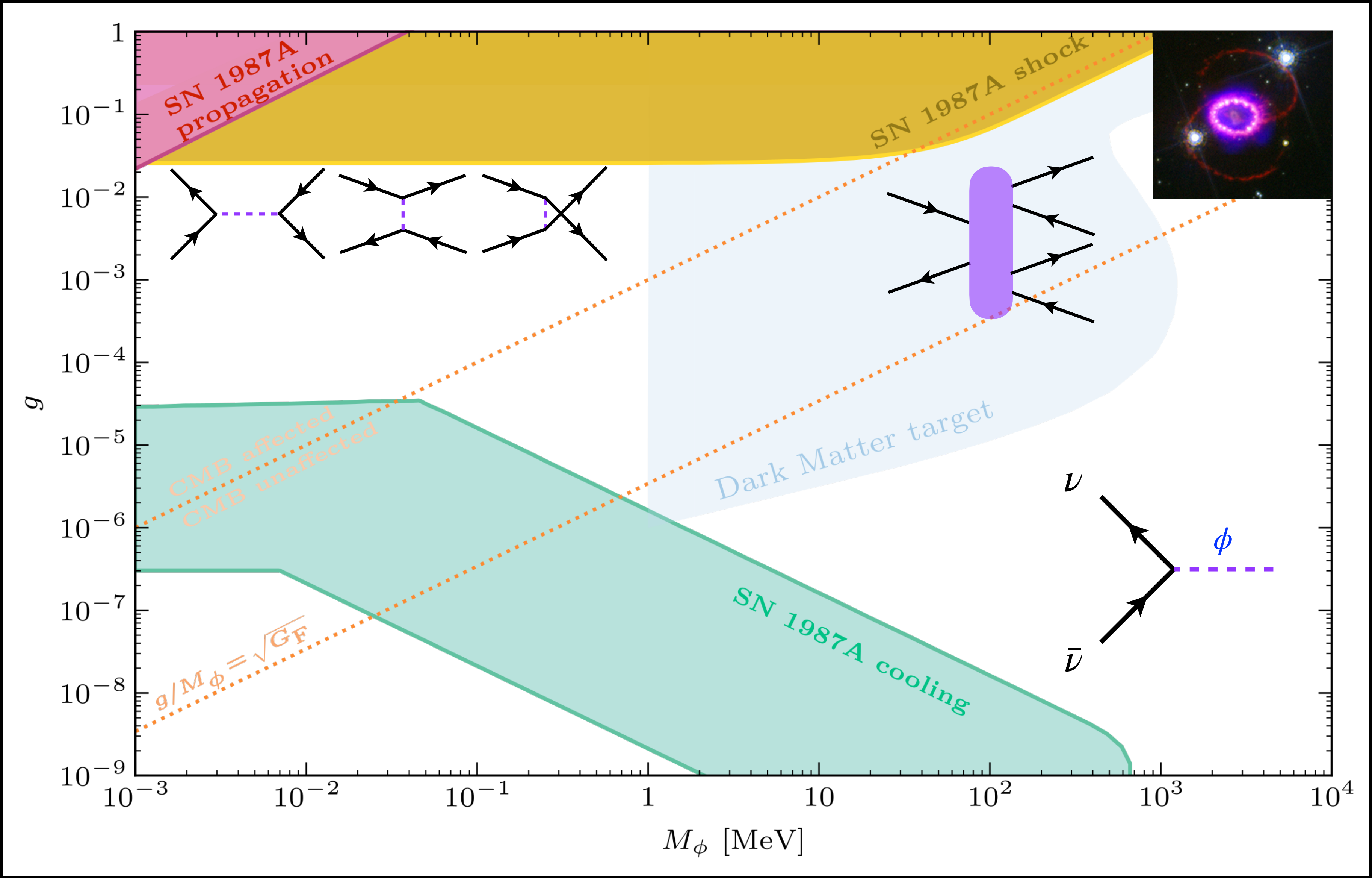

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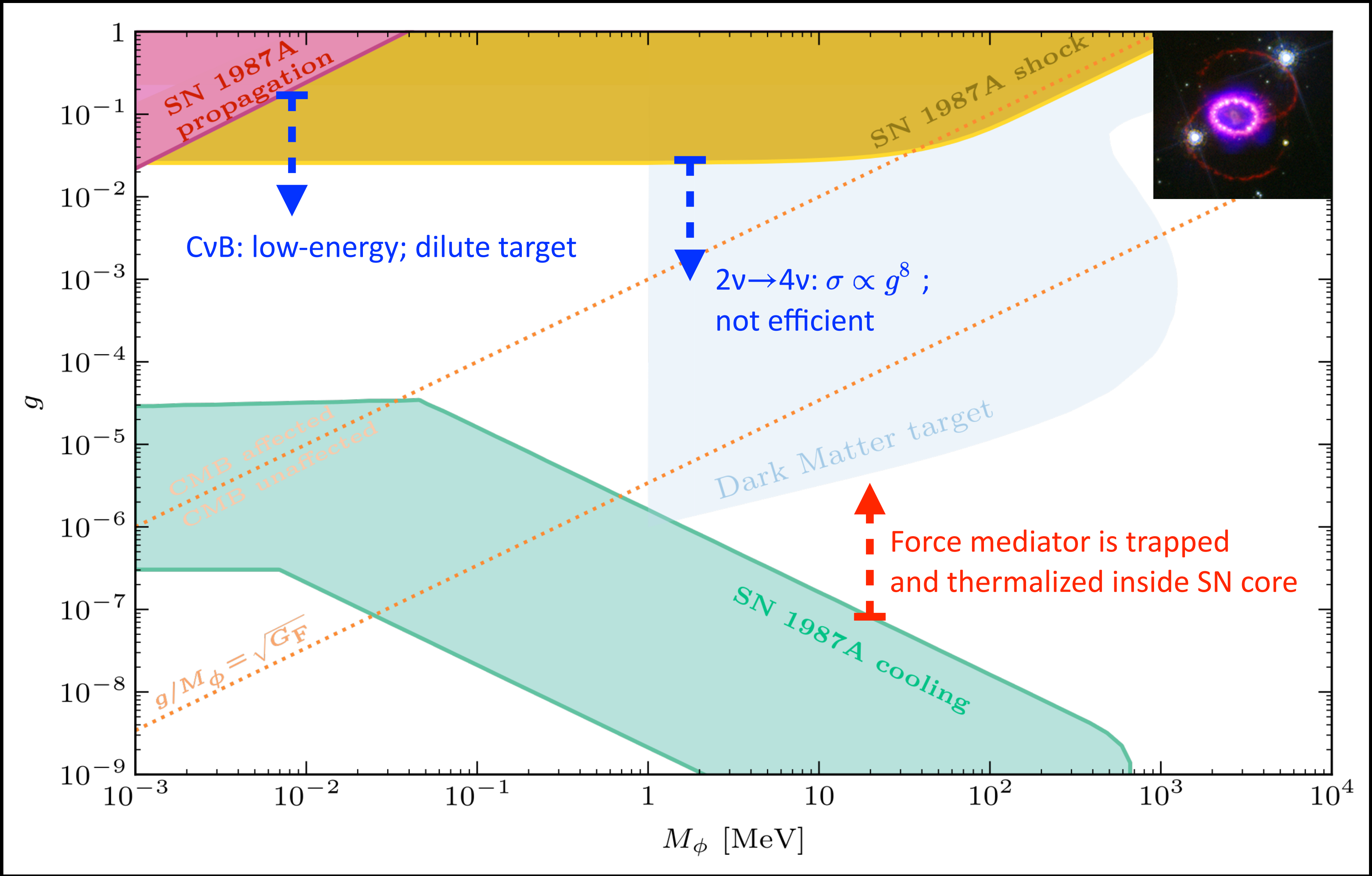
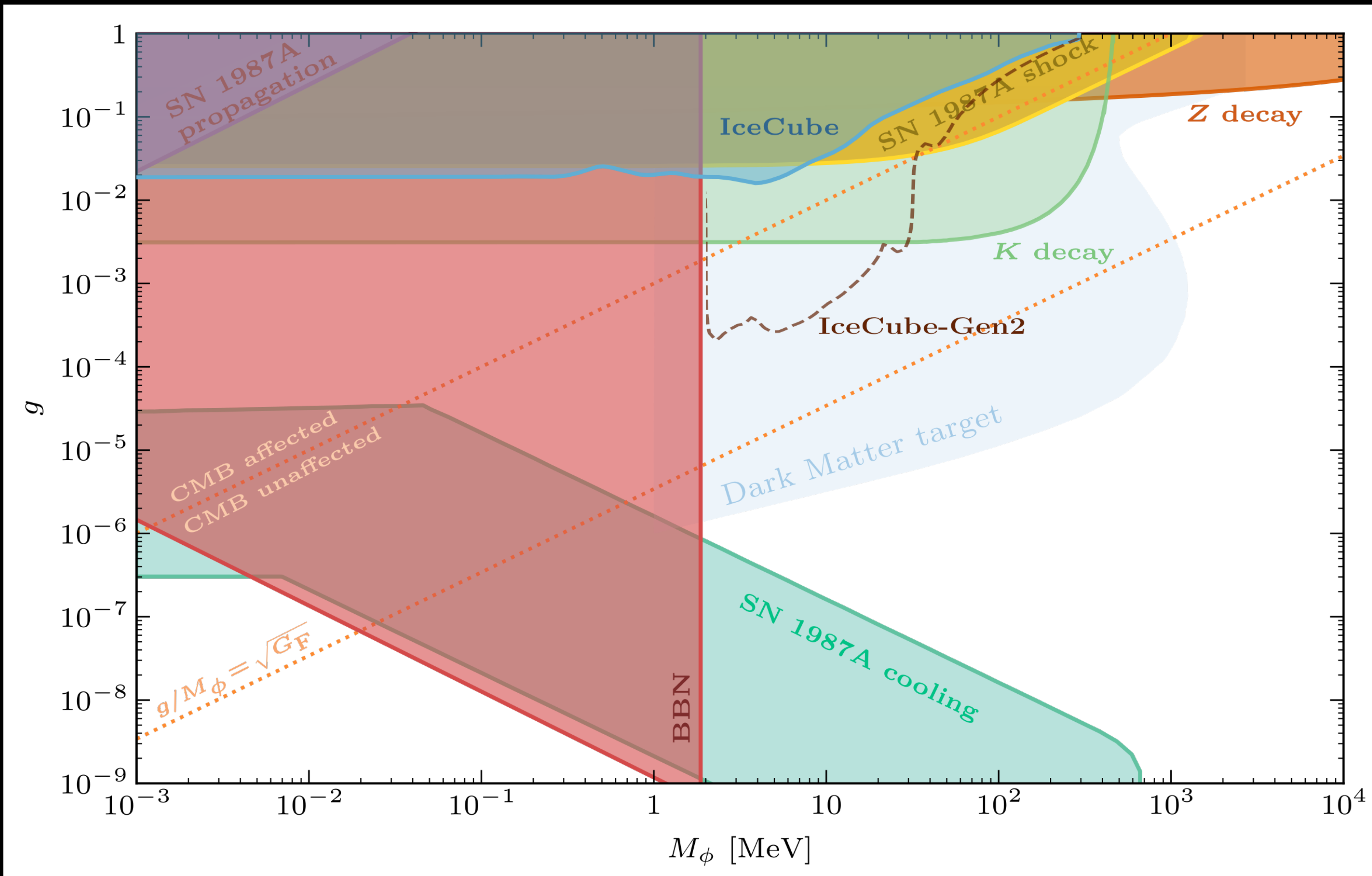


Core-collapse supernovae



Core-collapse supernovae

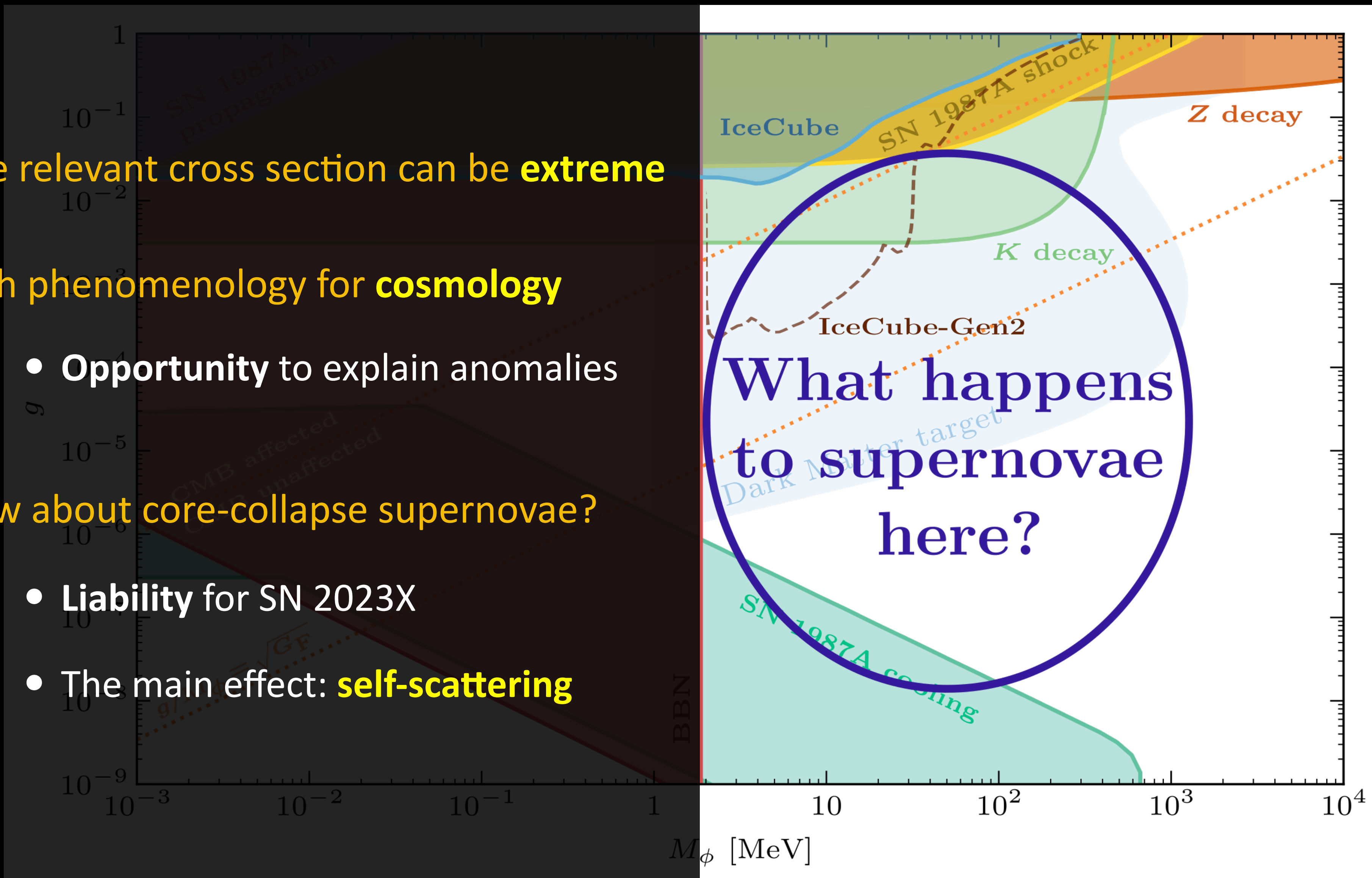
The relevant cross section can be **extreme**

Rich phenomenology for **cosmology**

- **Opportunity** to explain anomalies

How about core-collapse supernovae?

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



Testing νSI with supernovae: our work

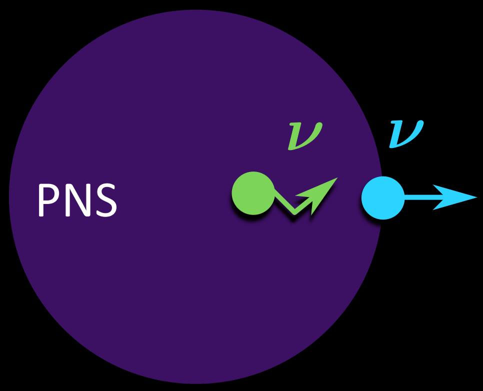
Based on **2206.12426**

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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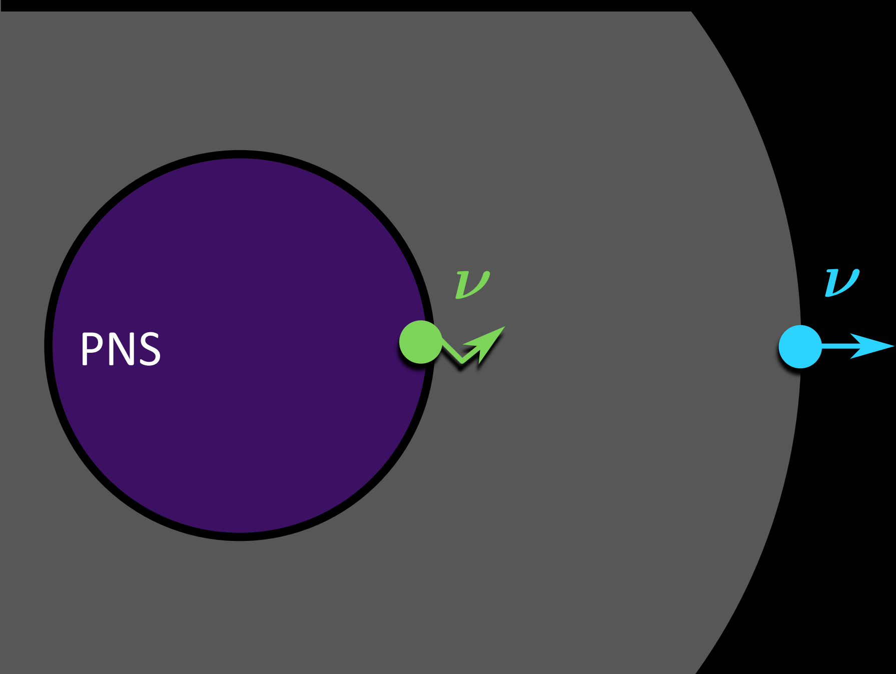


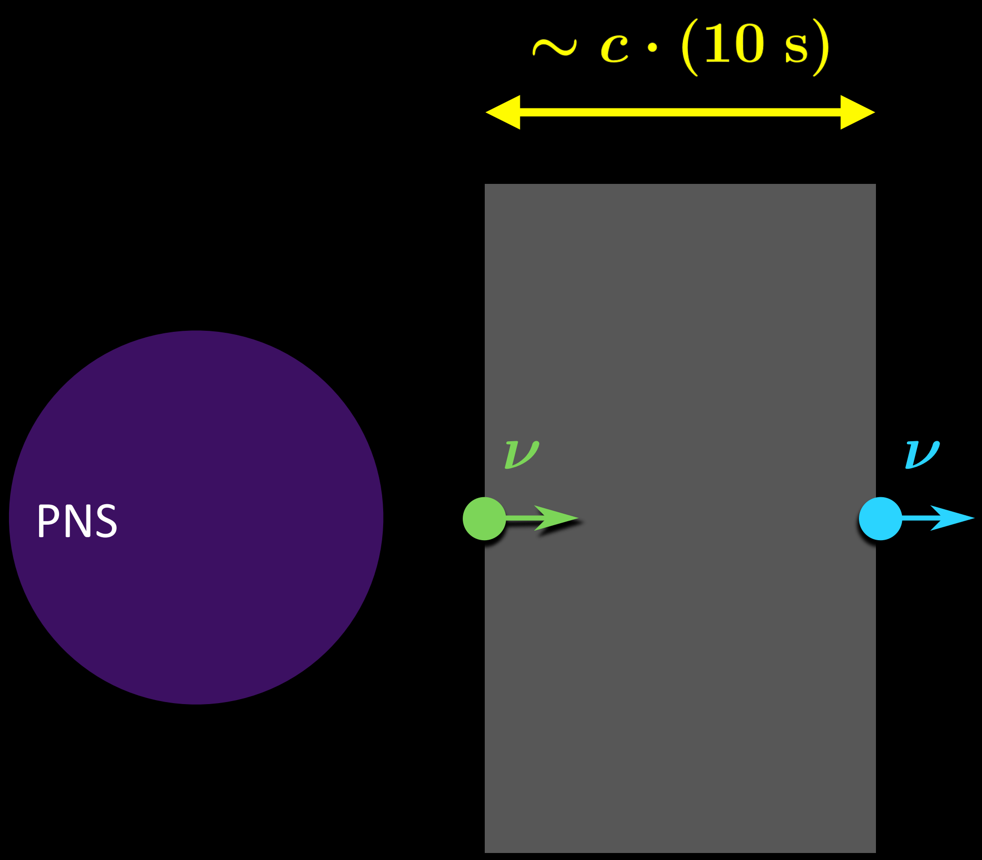
Order-of-magnitude:

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

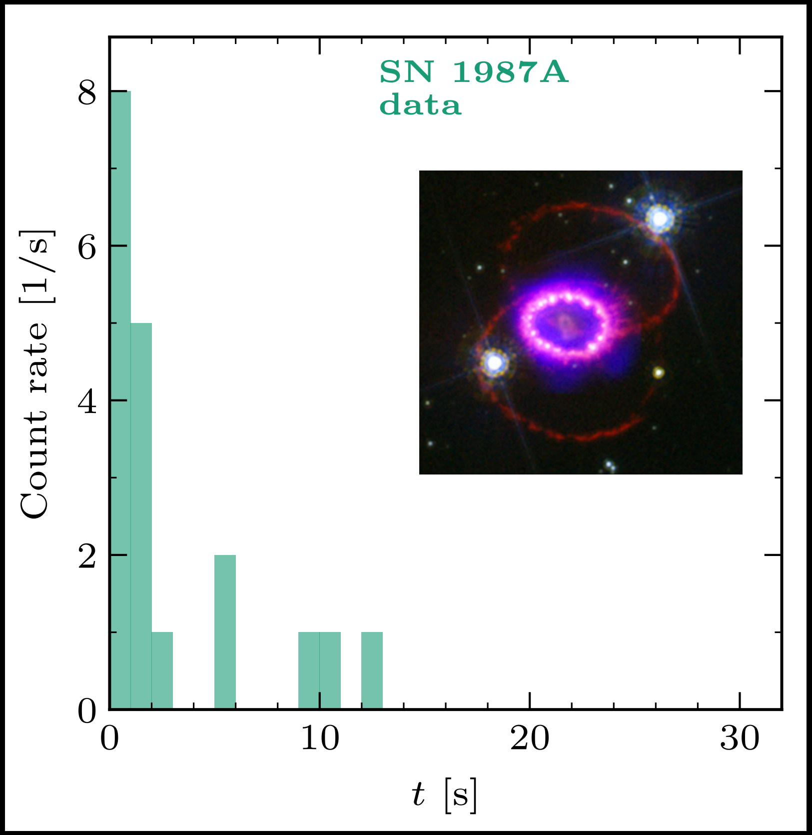
Strong probes of self-scattering

Supernova neutrino emission: no νSI

Extended shell of free-streaming neutrinos



Confirmed by **SN 1987A**



Strong probes of self-scattering

What if strong νSI exist?

Can νSI can affect the observed duration of the supernova neutrino pulse?

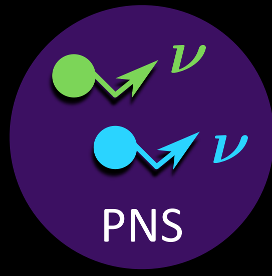
- Manohar (1987): **Yes!**
- Dicus, Nussinov, Pal, Teplitz (1989): ***No!***

We show that both papers are at best incomplete

Strong probes of self-scattering

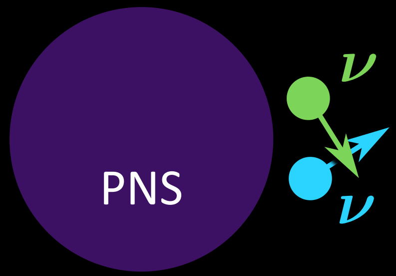
What if strong νSI exist?

Inside the PNS:



- Complicated effects with 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 self-scattering

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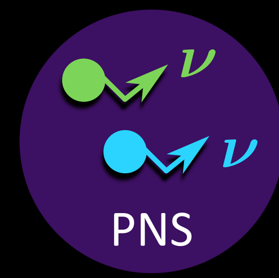

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Focus of our work 2206.12426

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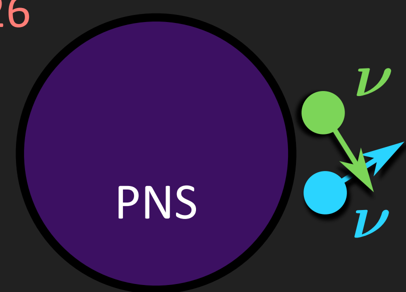

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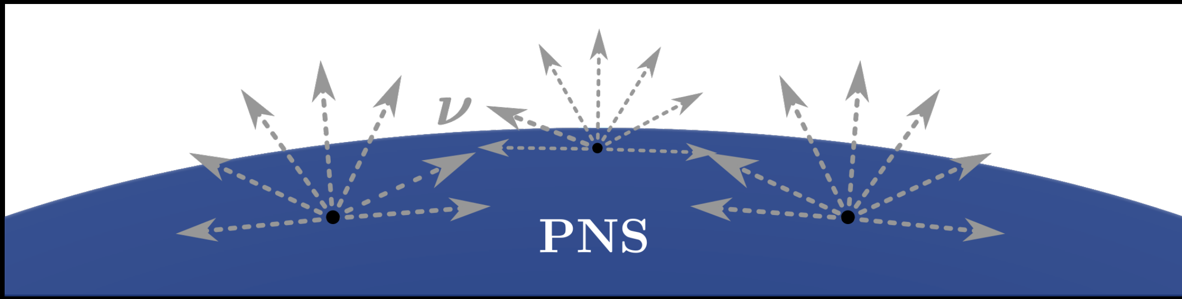
Strong probes of self-scattering

If strong νSI exist

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



Strong probes of self-scattering

If strong νSI exist

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

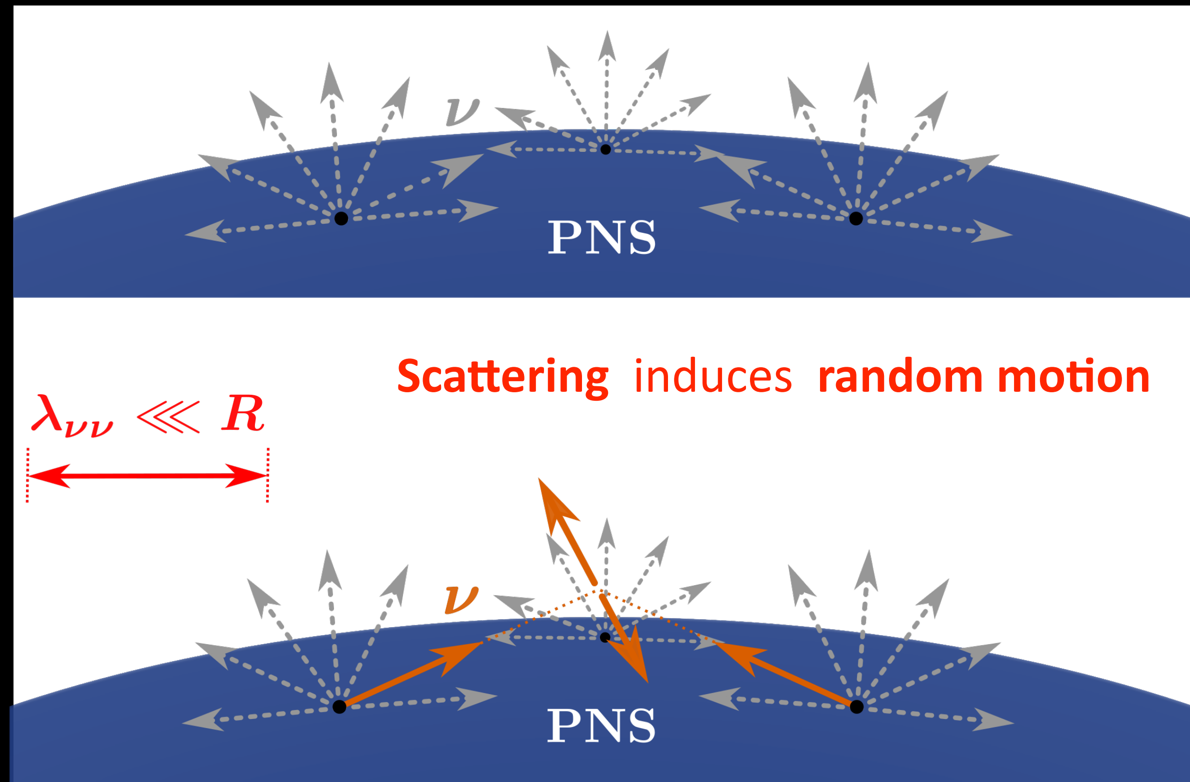
↓

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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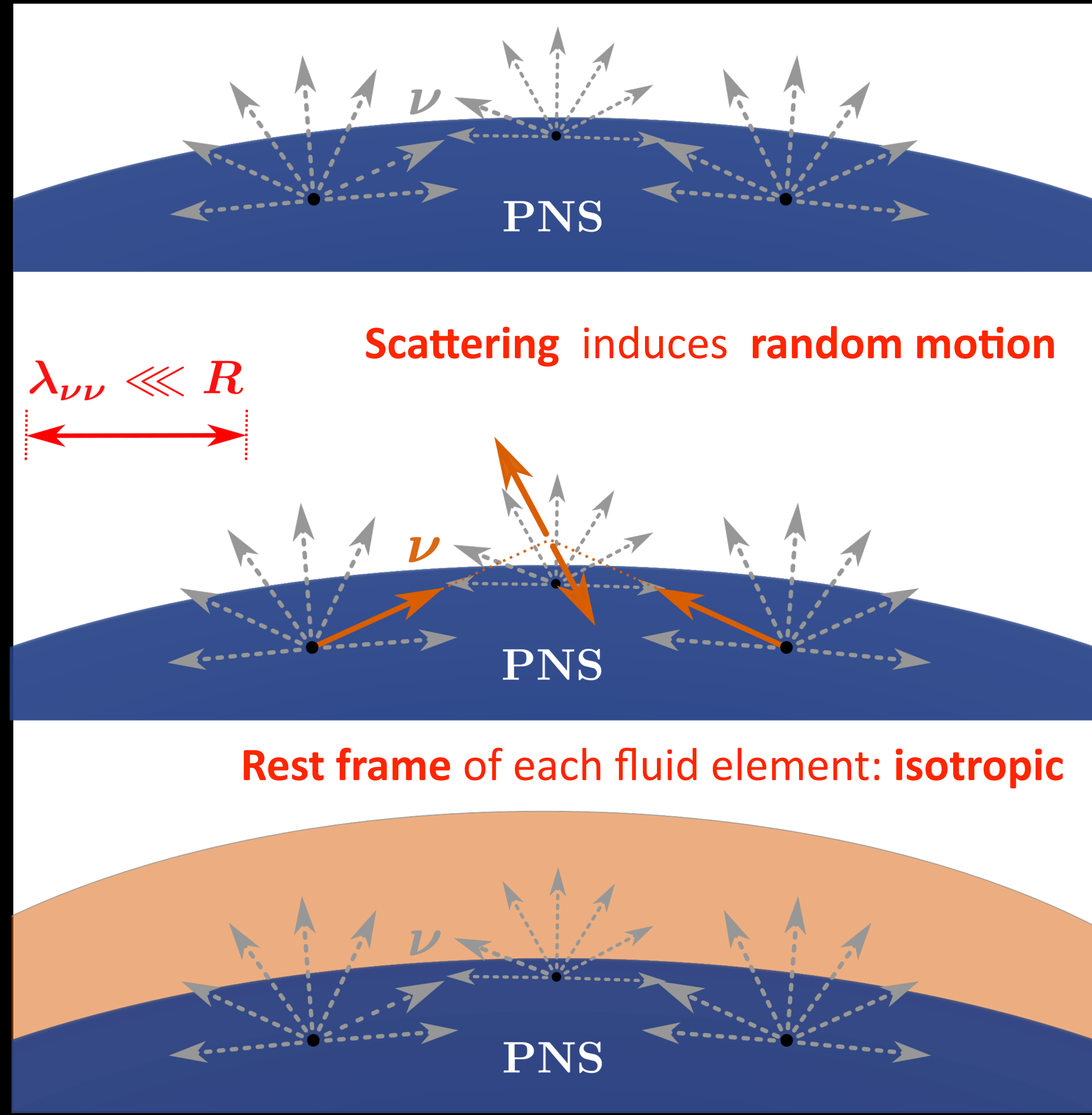
↓

Hydrodynamic limit: **relativistic fluid**



Strong probes of 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 self-scattering

Relativistic hydrodynamics

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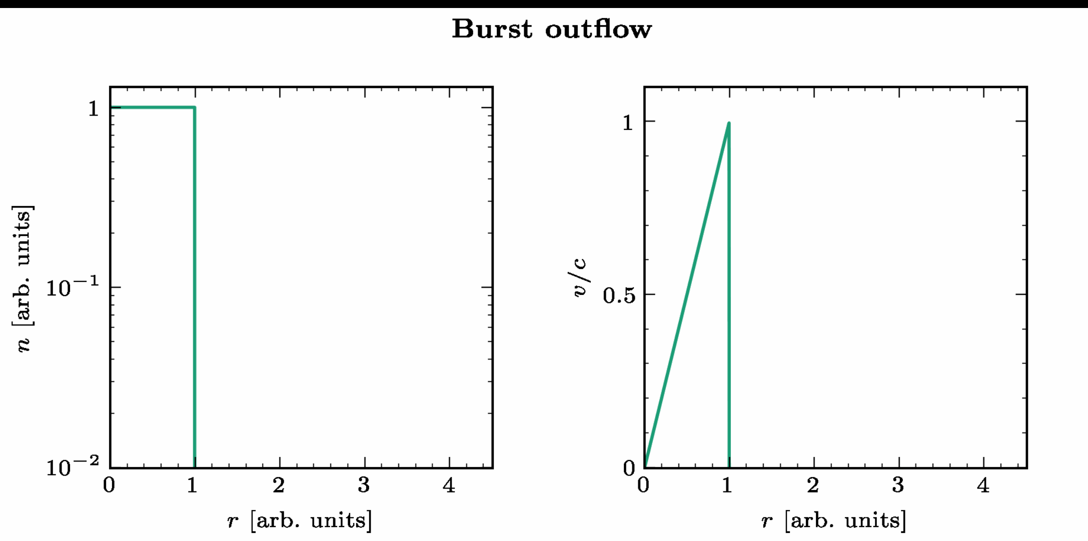
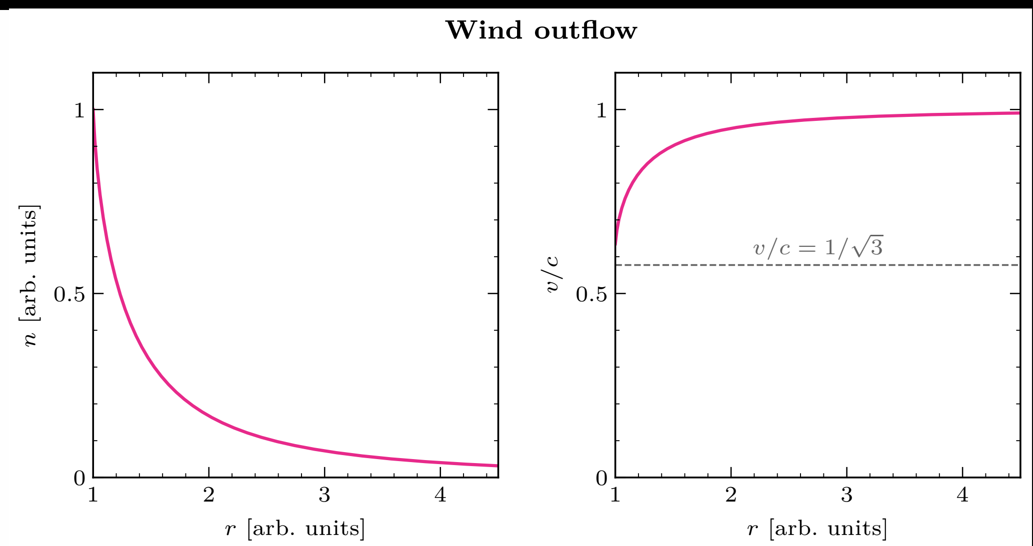


2) **Steady-state wind**



Strong probes of self-scattering

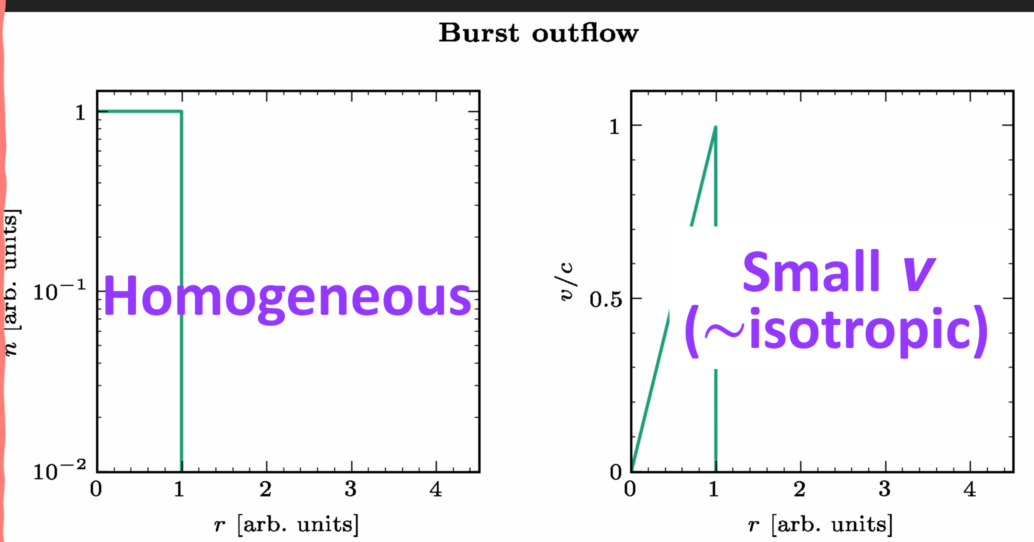
Relativistic hydrodynamics

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

Interesting phenomenology should exist for both cases!

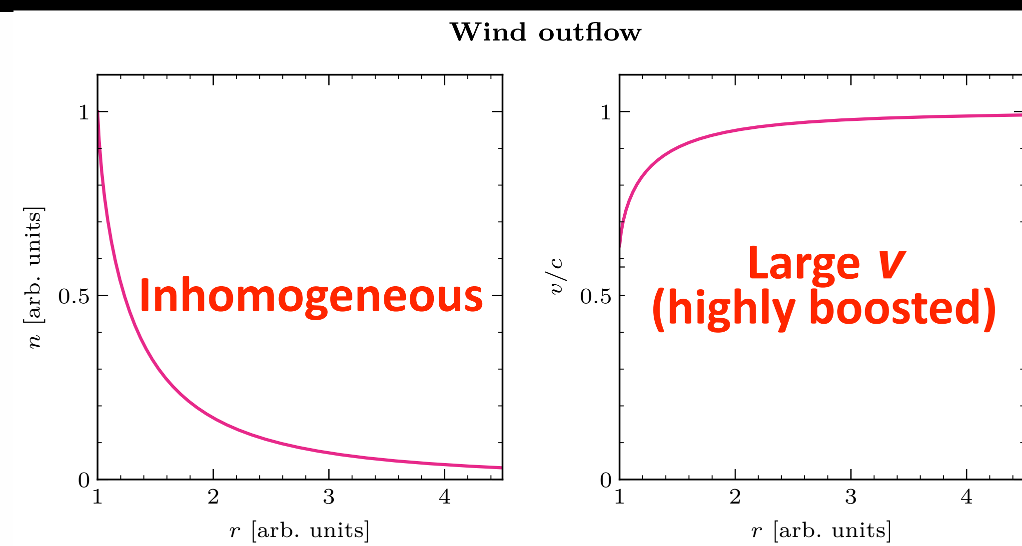
Our work

1) **Transient burst**



Future work

2) **Steady-state wind**



Strong probes of self-scattering

Burst outflow: robust observable with interesting phenomenology

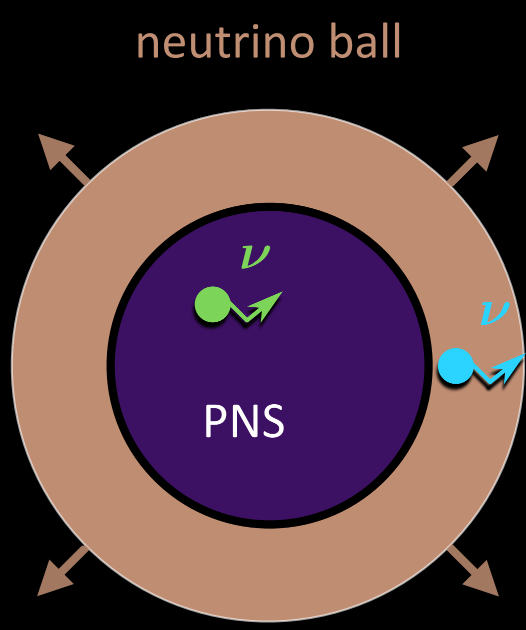
We find that if the burst is realized,
strong νSI will ***extend*** the **observed duration of supernova neutrinos**.

Key ideas: random motion in all directions & neutrino decoupling

Strong probes of self-scattering

Burst outflow: robust observable with interesting phenomenology

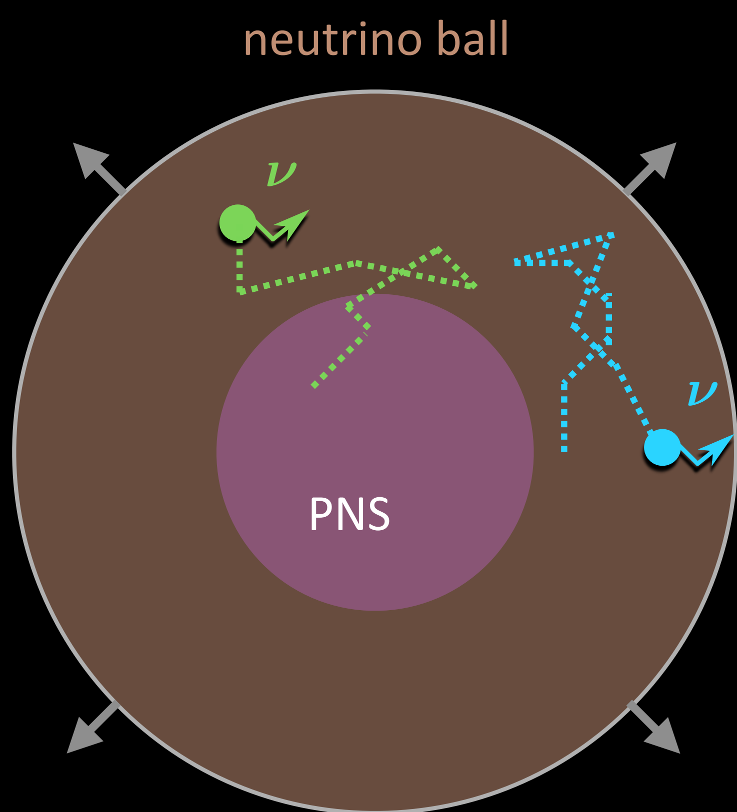
The fluid is a tightly coupled, expanding ***neutrino ball***.



Strong probes of self-scattering

Burst outflow: robust observable with interesting phenomenology

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

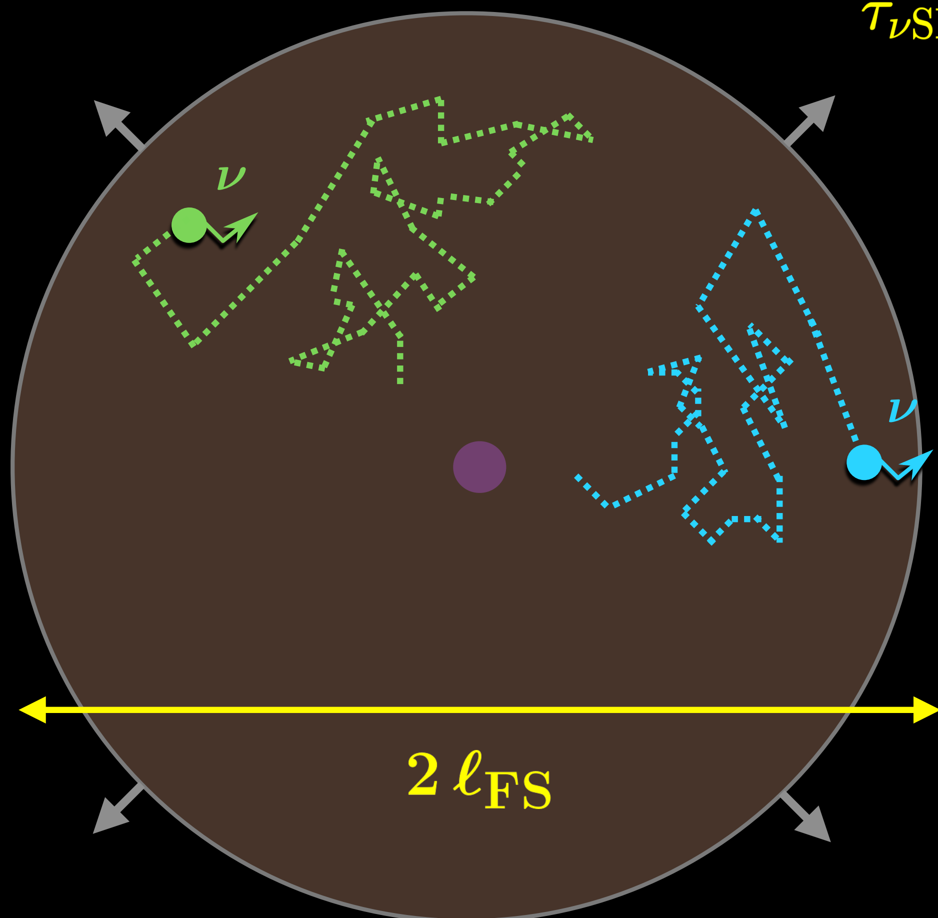


Strong probes of self-scattering

Burst outflow: robust observable with interesting phenomenology

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

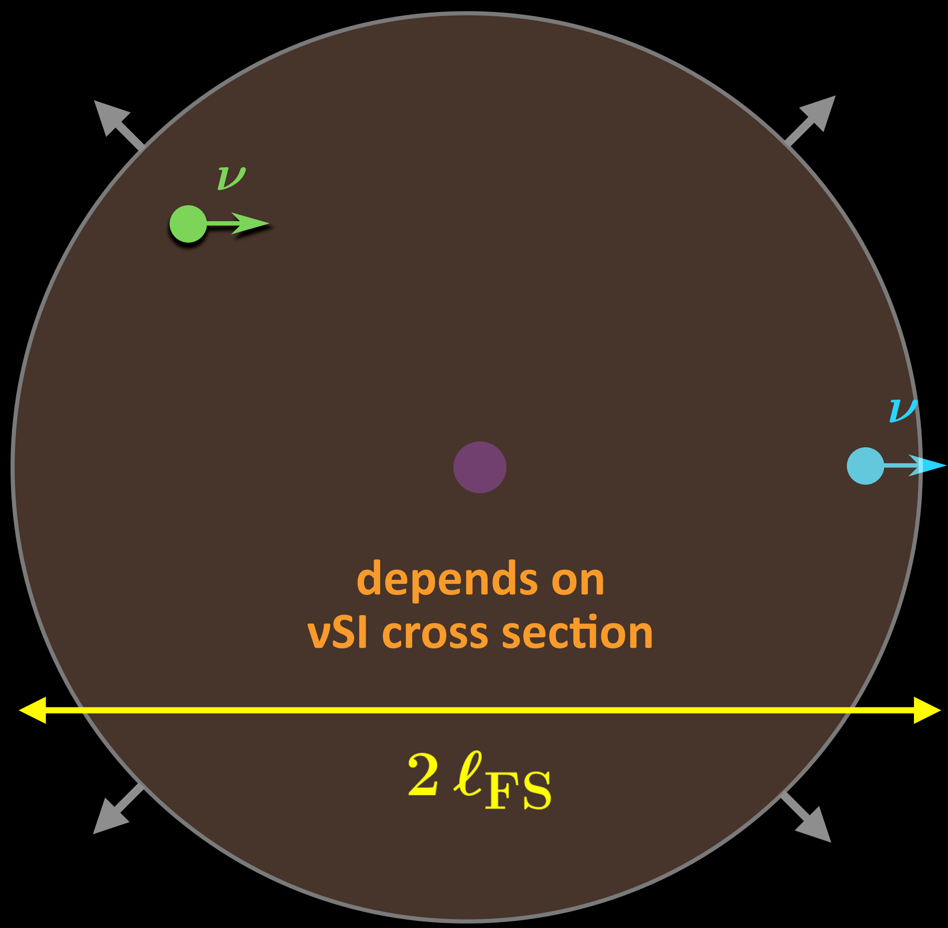
$$\tau_{\nu \mathrm{SI}} \sim n_\nu \, \sigma_{\nu \mathrm{SI}} \, \ell_{\mathrm{FS}} \lesssim \mathcal{O}(1)$$



Strong probes of self-scattering

Burst outflow: robust observable with interesting phenomenology

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

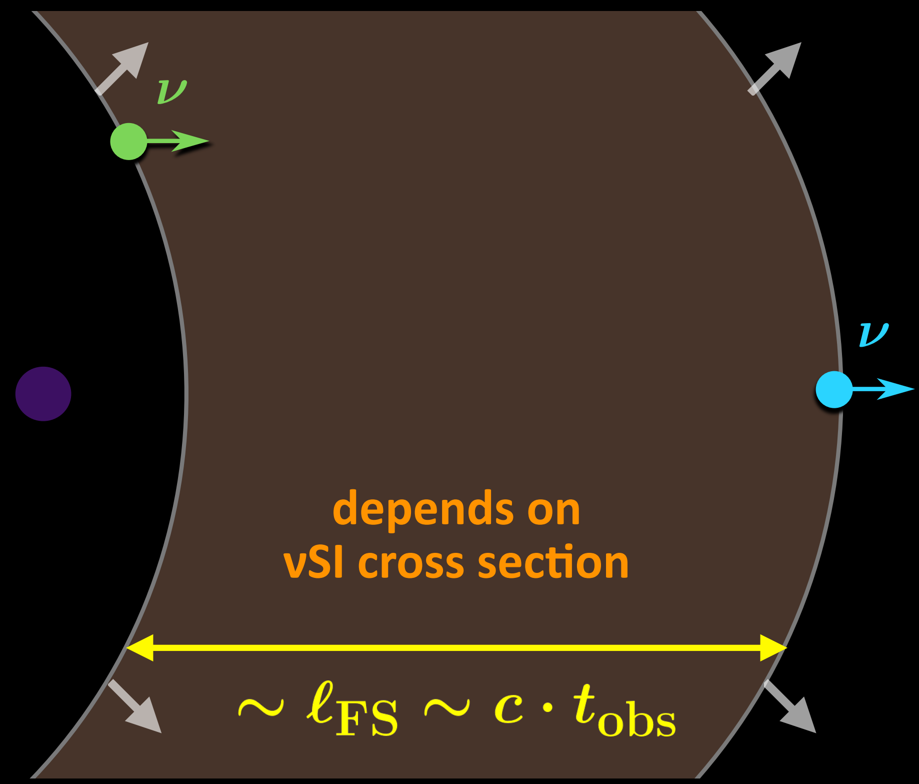


Strong probes of self-scattering

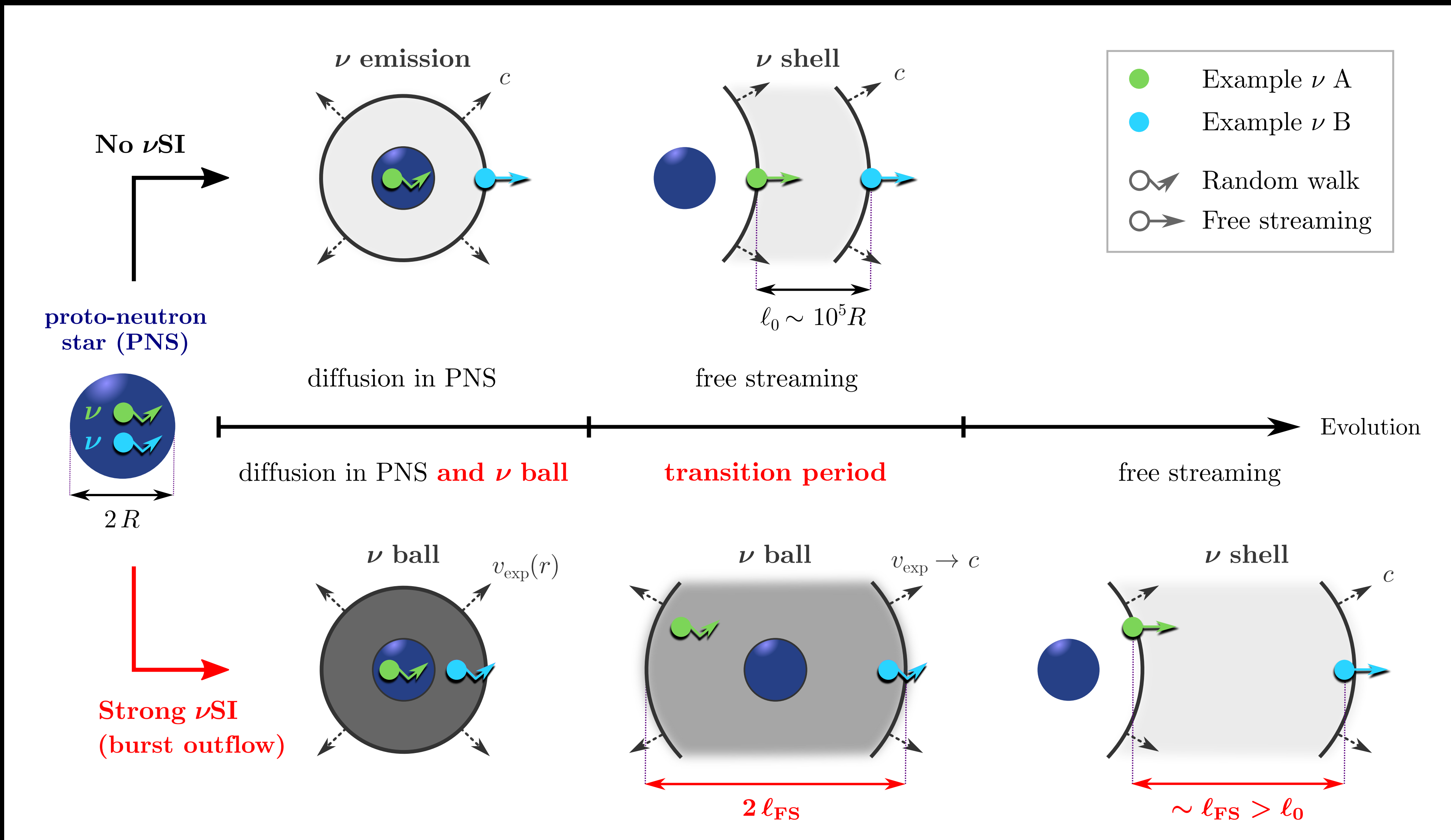
Burst outflow: robust observable with interesting phenomenology

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

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

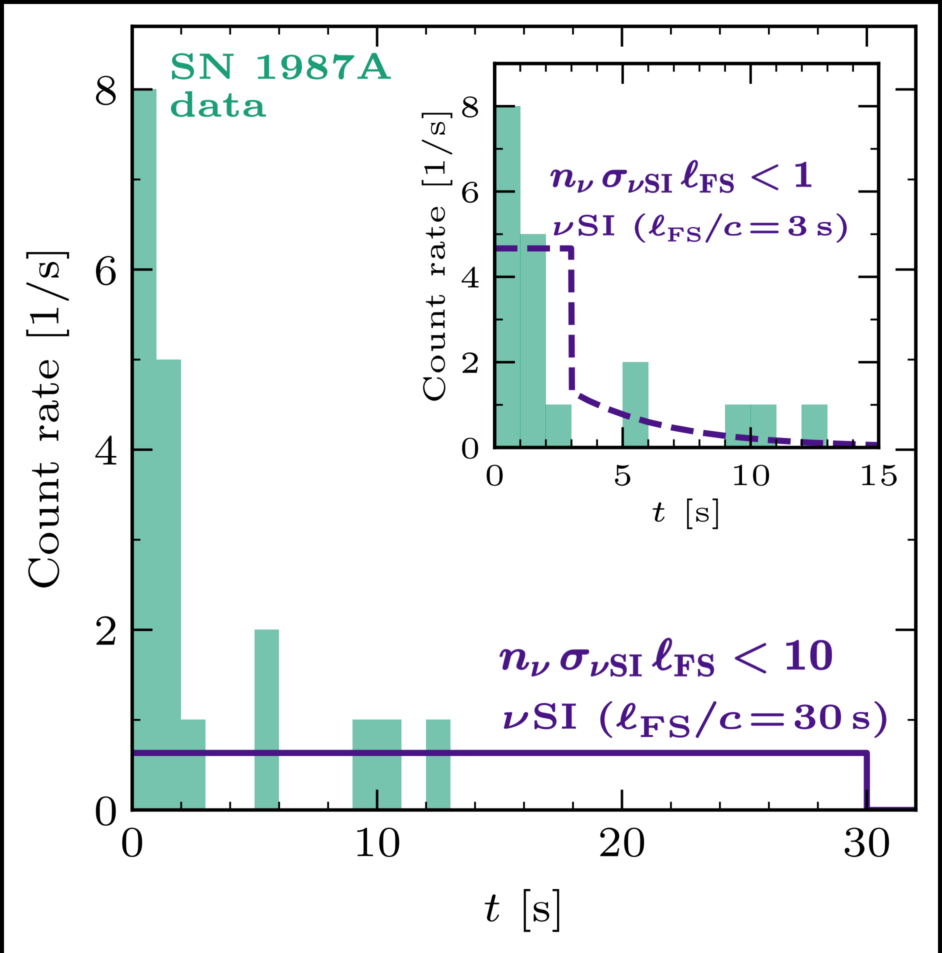


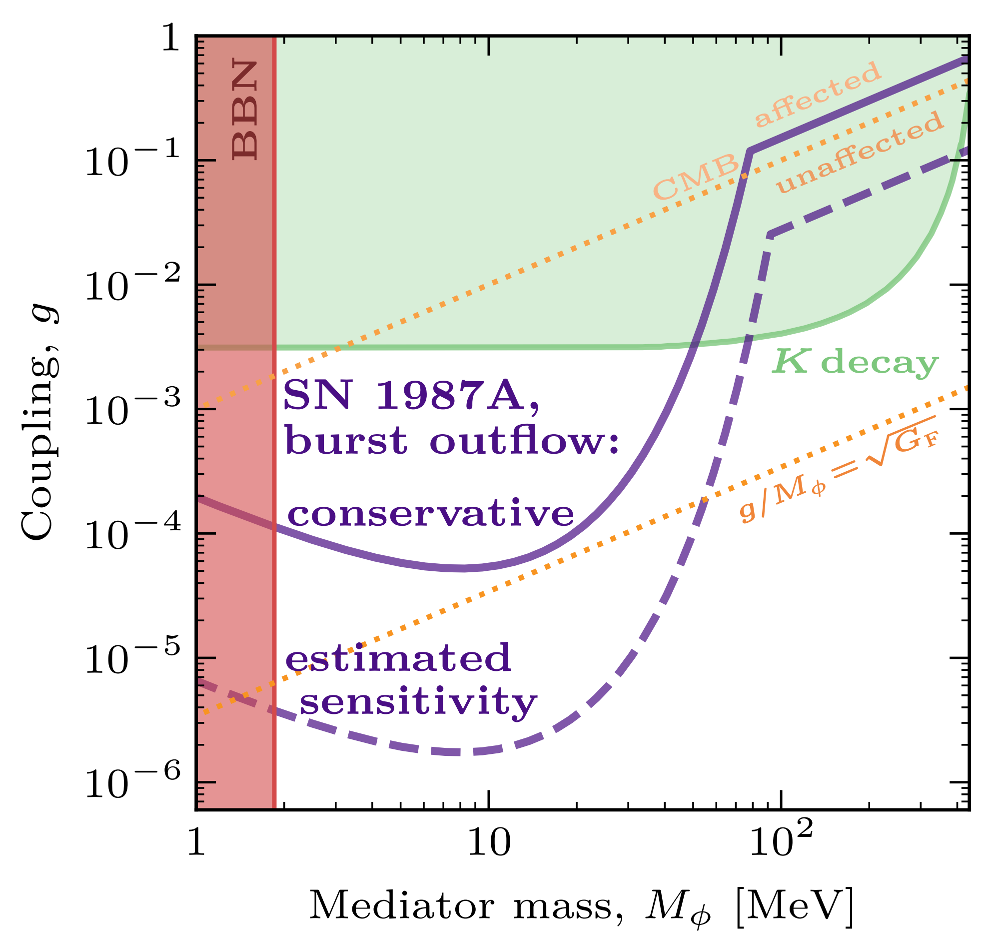
Strong probes of self-scattering



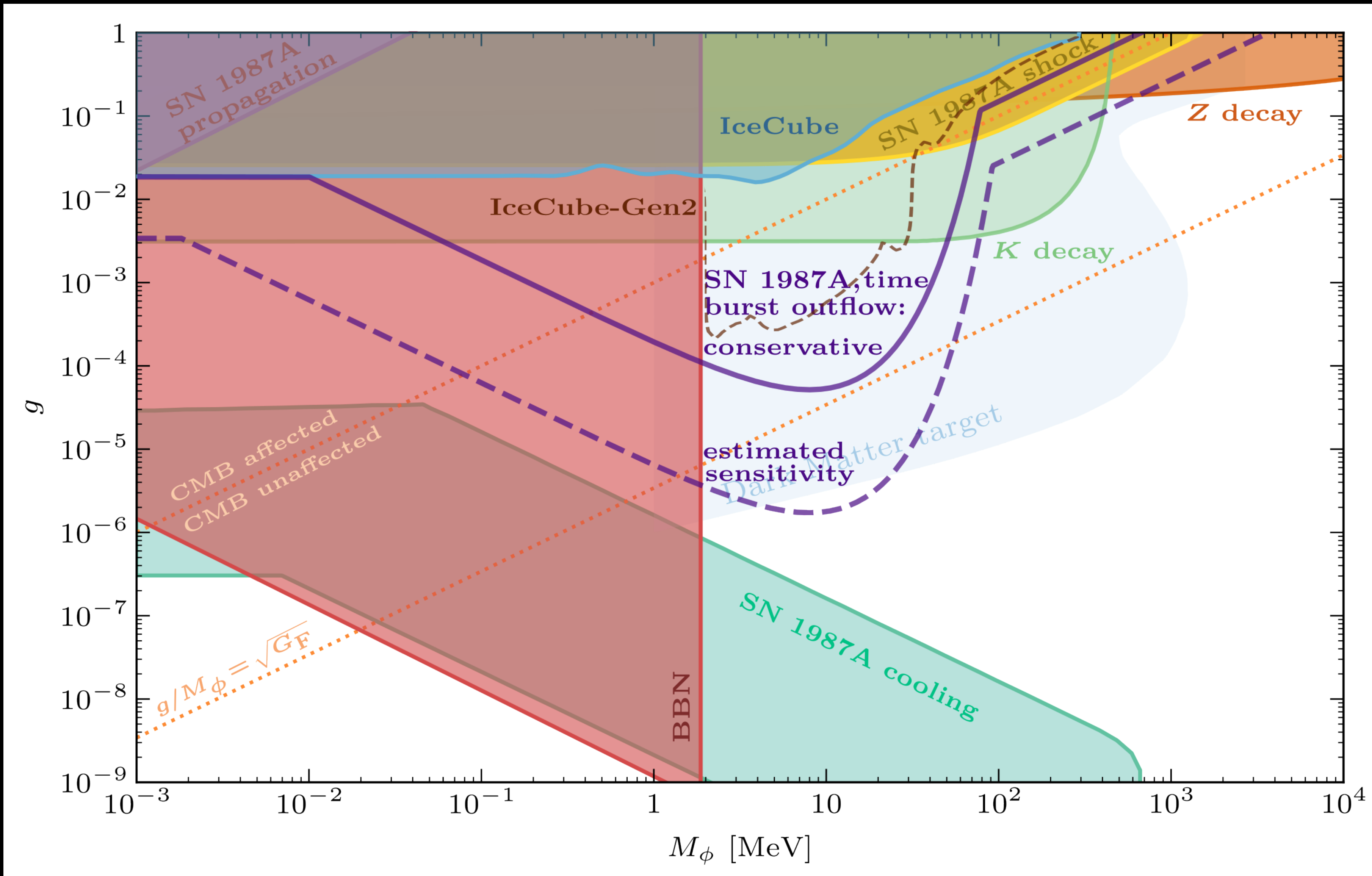
Potential sensitivity from SN 1987A

Phenomenology of the **burst outflow**





Potential sensitivity from SN 1987A



Concluding perspectives

Summary of results

- Understanding neutrinos relies upon connecting laboratory, cosmology, and astronomy data.

- Strong neutrino secret interactions remain allowed and could affect all three.

- Even 36 years after SN 1987A, we are still not sure how νSI affect the dense neutrinos in supernovae.

- Our work provides a roadmap, identifying two possible cases for the behavior of the expanding neutrino fluid: a burst or a steady-state wind.

- In the burst case, we obtain strong new limits on νSI. In the wind case, we are optimistic about identifying other new observables. Lots of work in progress.

Thank you to Rocky

Examples of opportunities Rocky and the group gave me:

- New directions to my research
- Resources and freedom to grow my own initiatives
- The platform to take larger roles

Examples of what Rocky specifically taught:

- How to be a complete scientist
- How to be a leader and mentor
- How to make it all fun

Thank you to Rocky

What's happening

NHL · Last night

Bruins at Oilers

Trending in United States

ROCKY WINS ASTRO

1,531 Tweets

Trending in Illinois

Chicagoans Rejoice