Towards Powerful Probe of Neutrino Self-Interactions in Supernovae

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Do neutrinos interact with each other?

In Standard Model, neutrinos are

The feeblest particles

Hard to detect

Great mystery

Encode secret information

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

Encode secret information

Laboratory probes remain weak

The allowed νSI cross sections can be *larger* than weak interactions by *10+ 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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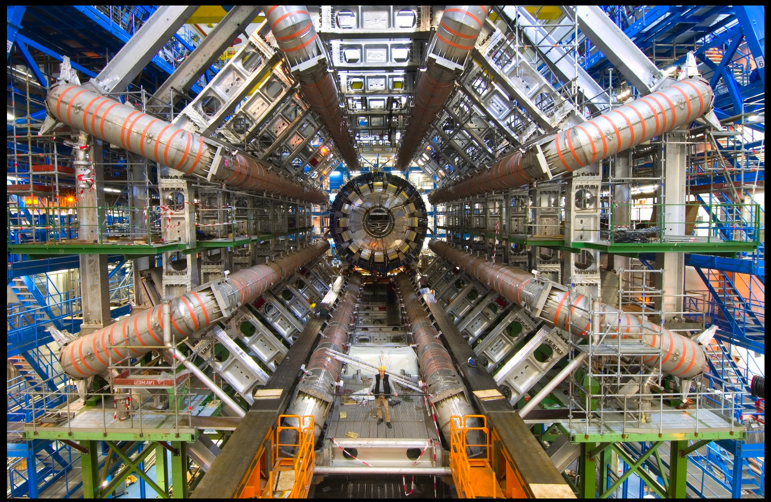
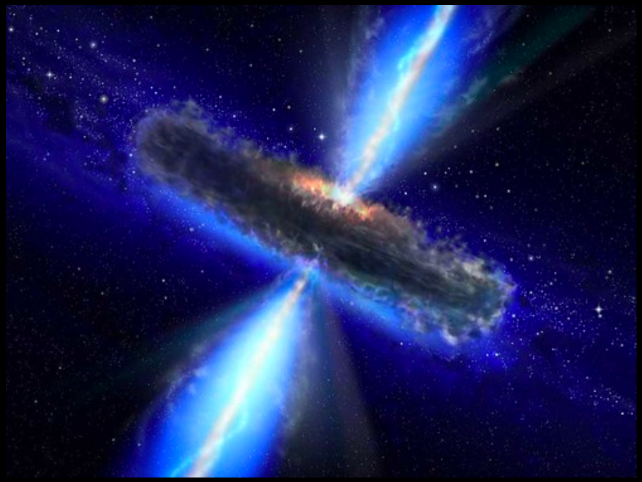
Will νSI spoil our knowledge in the heaven?

Where to find vSI?

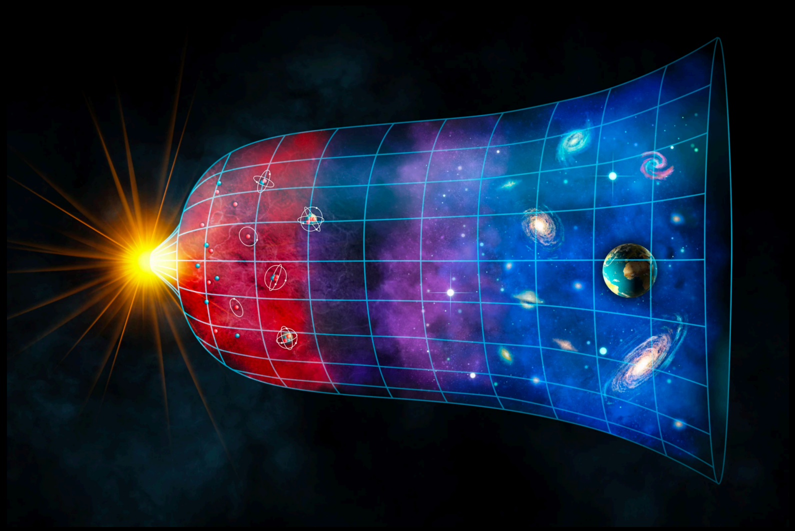
Where to find νSI?



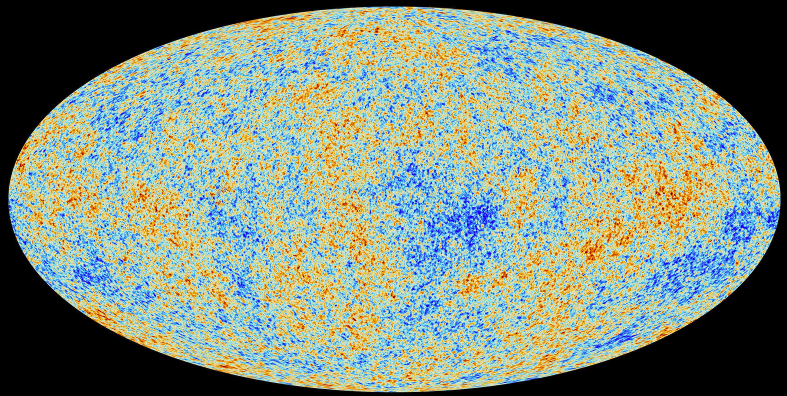
terrestrial experiments



high energy astrophysical neutrinos

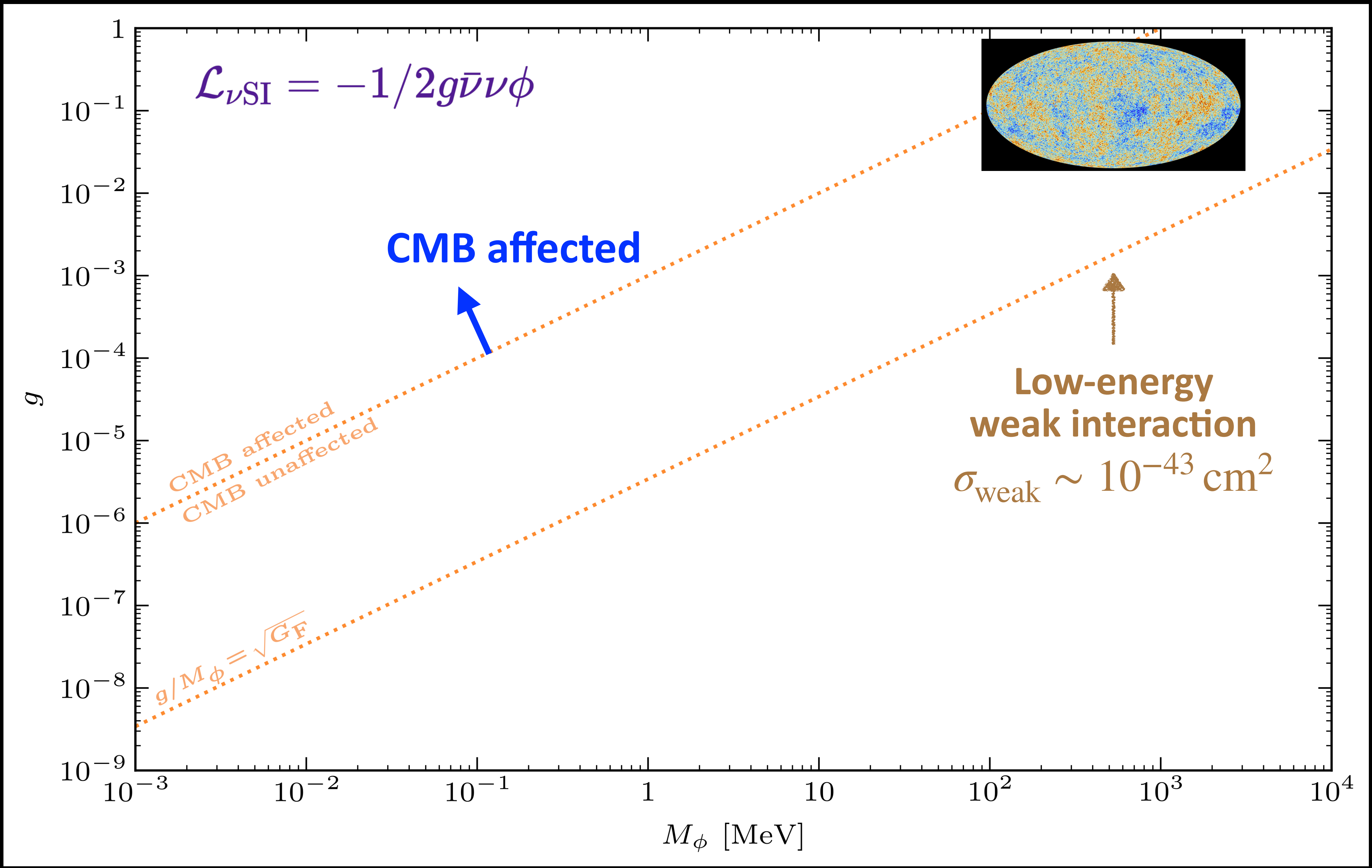


big bang nucleosynthesis



cosmic microwave background

Where to find νSI?



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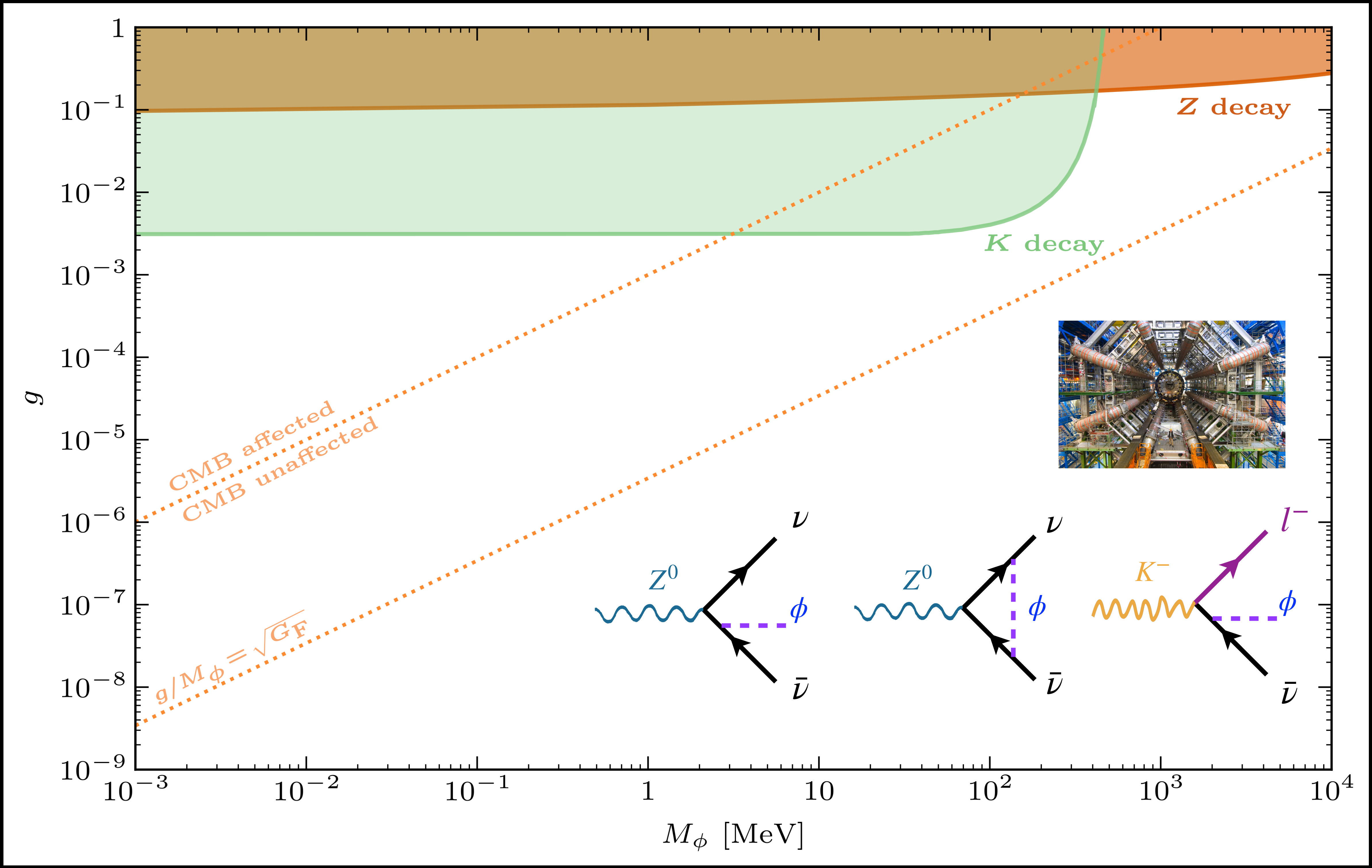

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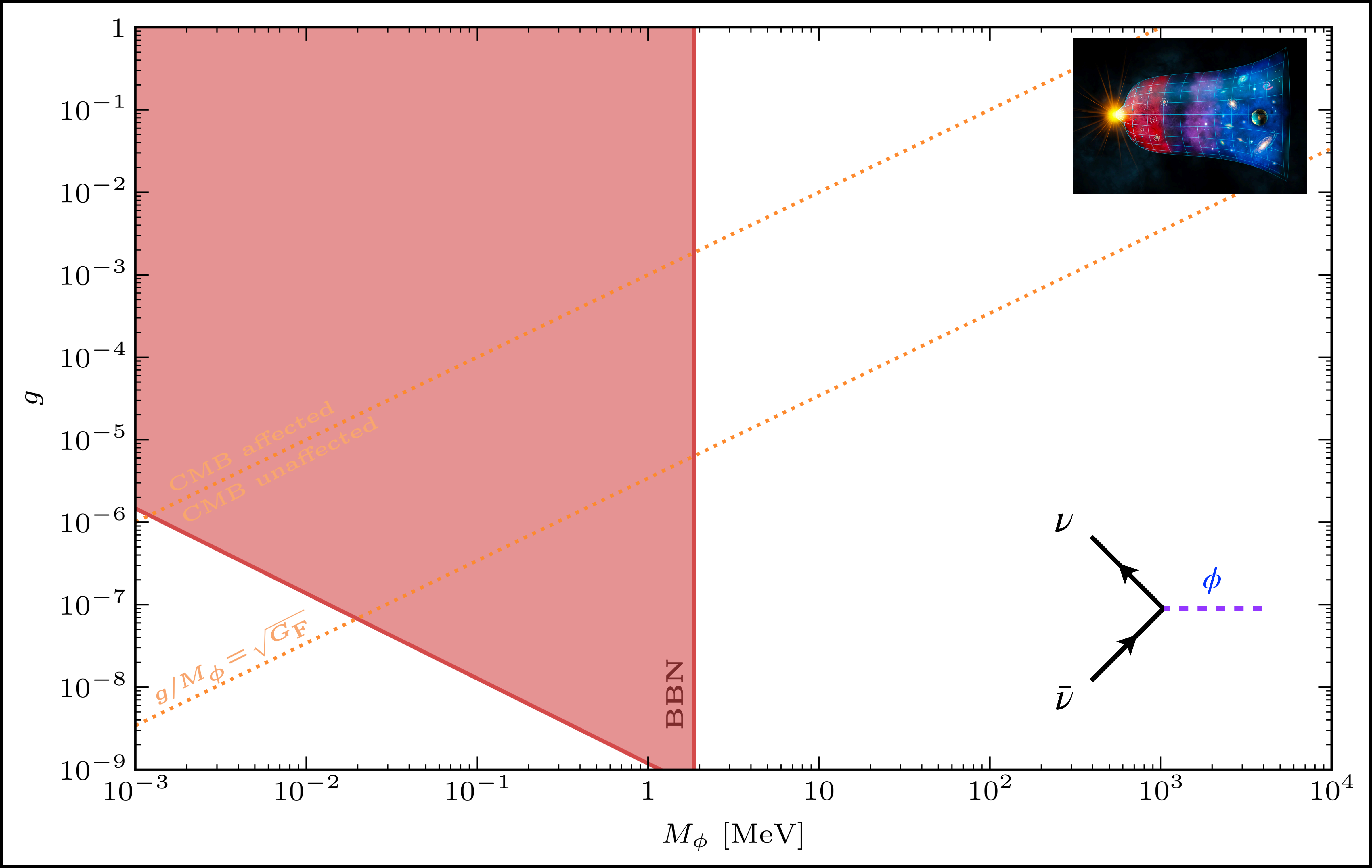

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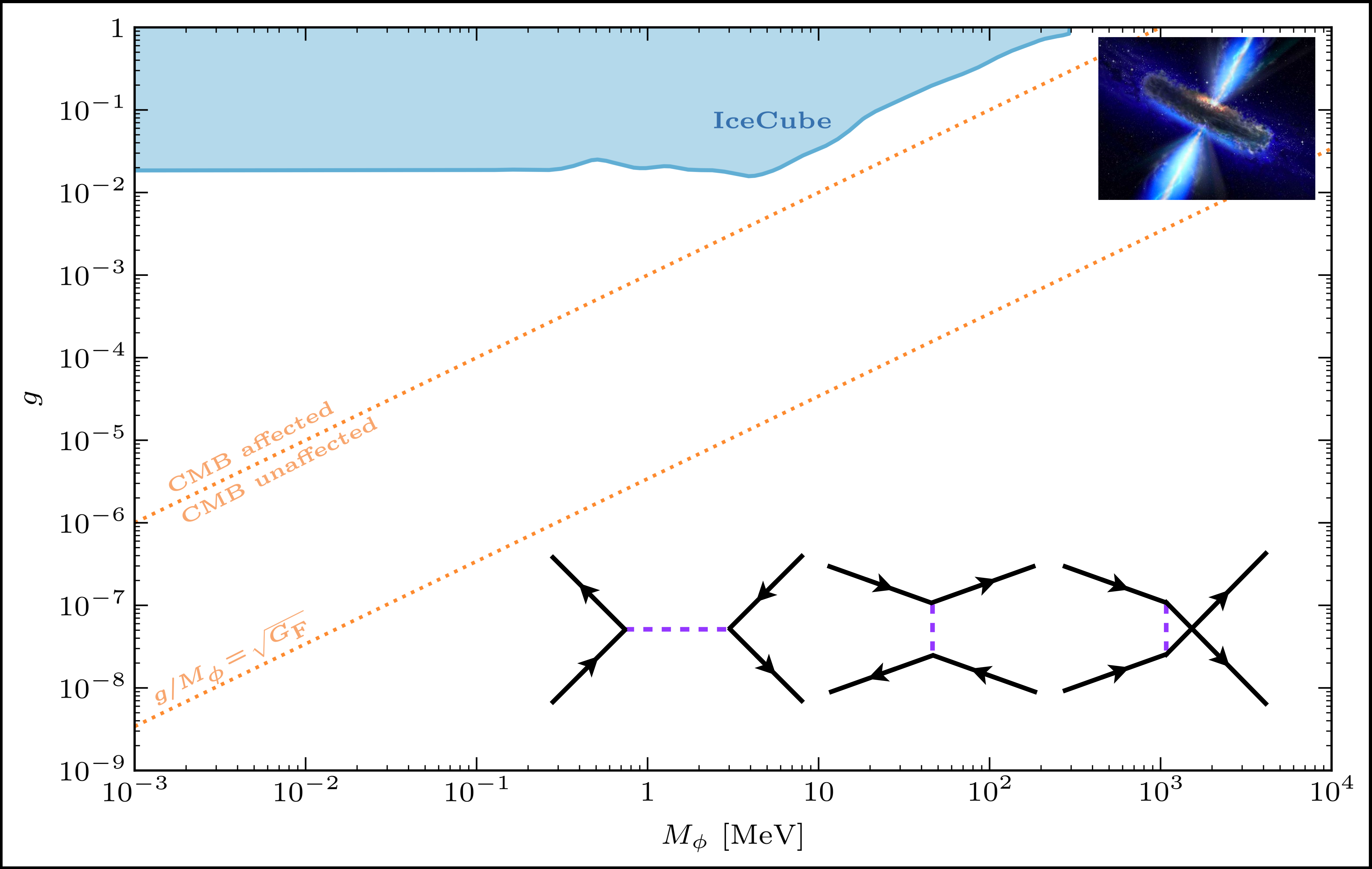

Core-collapse supernovae

Core-collapse supernovae

Final fate of the massive stars

Form a dense **proto-neutron star (PNS)**

Tremendous amount of gravitational energy

$$\sim 3 \times 10^{53} \text{ ergs}$$

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

Core-collapse supernovae

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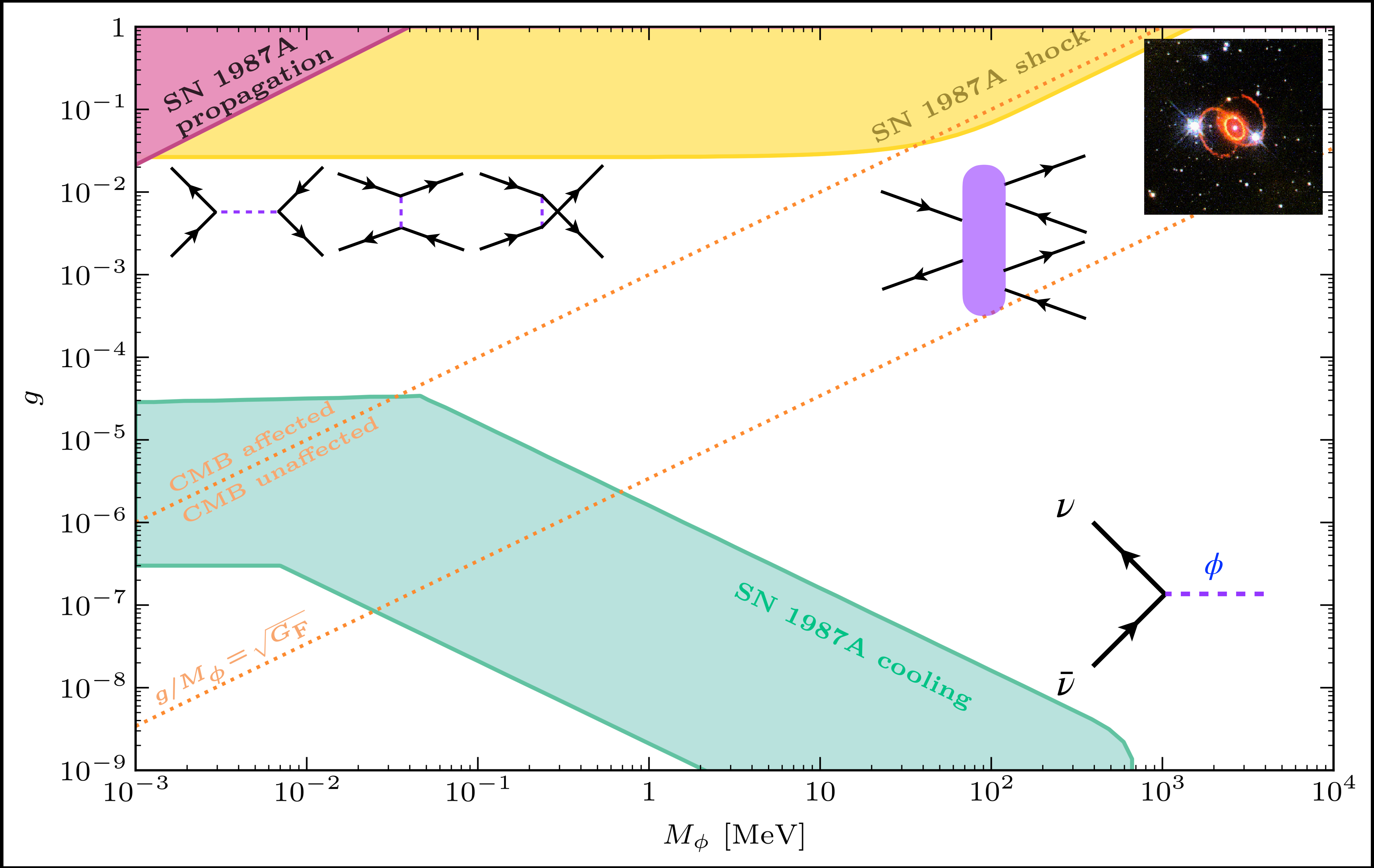
$$\sim 3 \times 10^{53} \text{ ergs}$$

10 MeV neutrinos

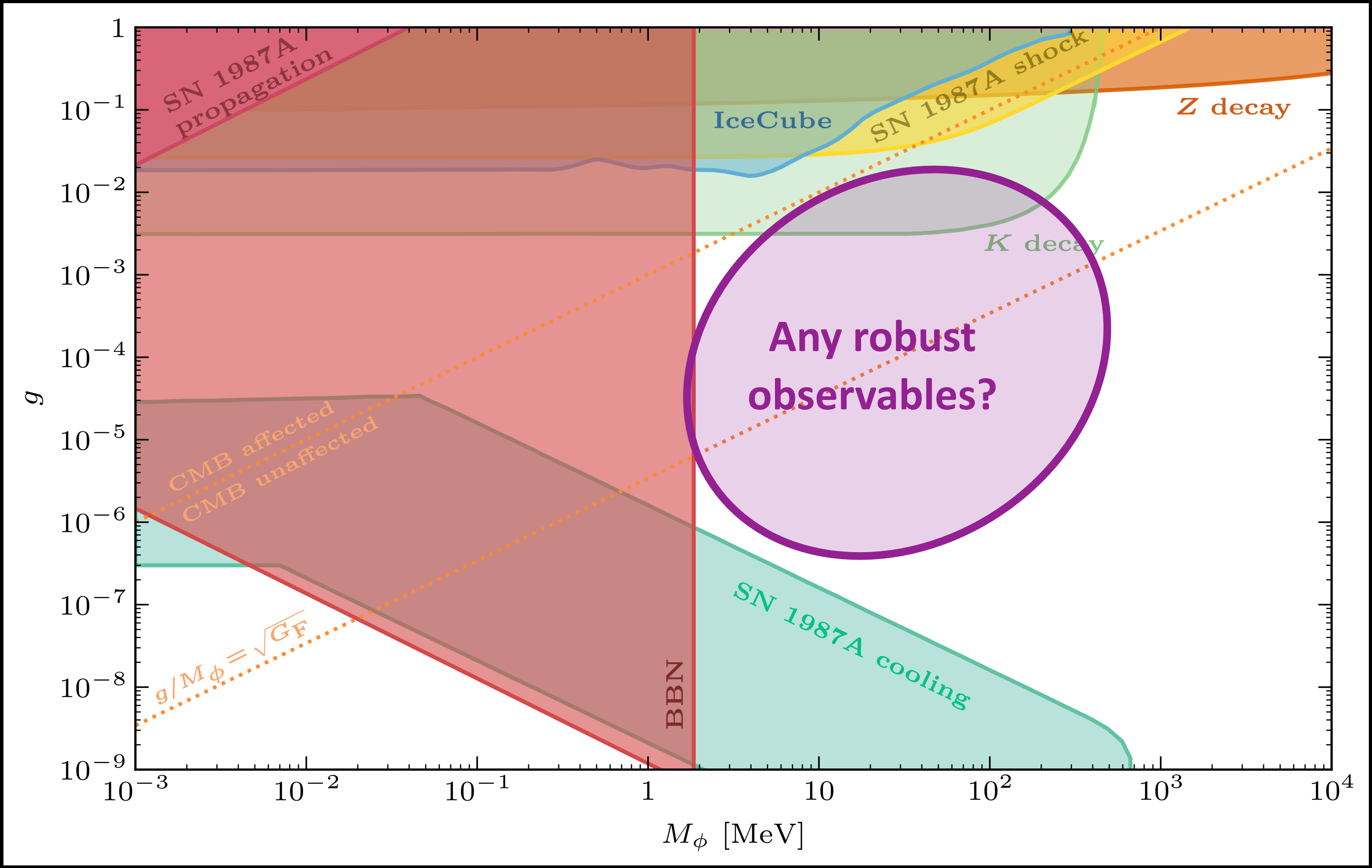
Extremely dense neutrino environment

$$n_\nu \gtrsim 10^{36} \text{ cm}^{-3}$$

Core-collapse supernovae



Core-collapse supernovae



Observed neutrino pulse duration

Observed neutrino pulse duration

We find that νSI could significantly **extend**
the duration of neutrino signal from supernovae

To begin with…

A system of neutrinos with strong self-interactions = a perfect fluid

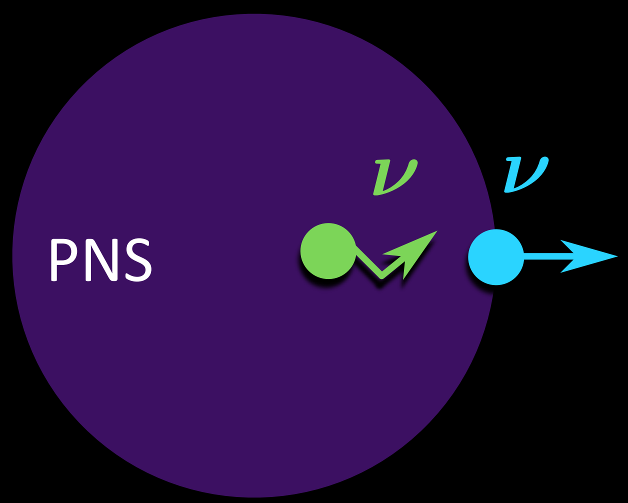
From relativistic hydrodynamics, the outflow can either be a ***"transient burst"*** or ***"steady wind"***, depending on whether neutrino fluid has relaxed to a steady state

We focus on the burst outflow

Observed neutrino pulse duration

Standard scenario: no strong νSI

Neutrinos diffuse inside the PNS
and eventually free stream to us



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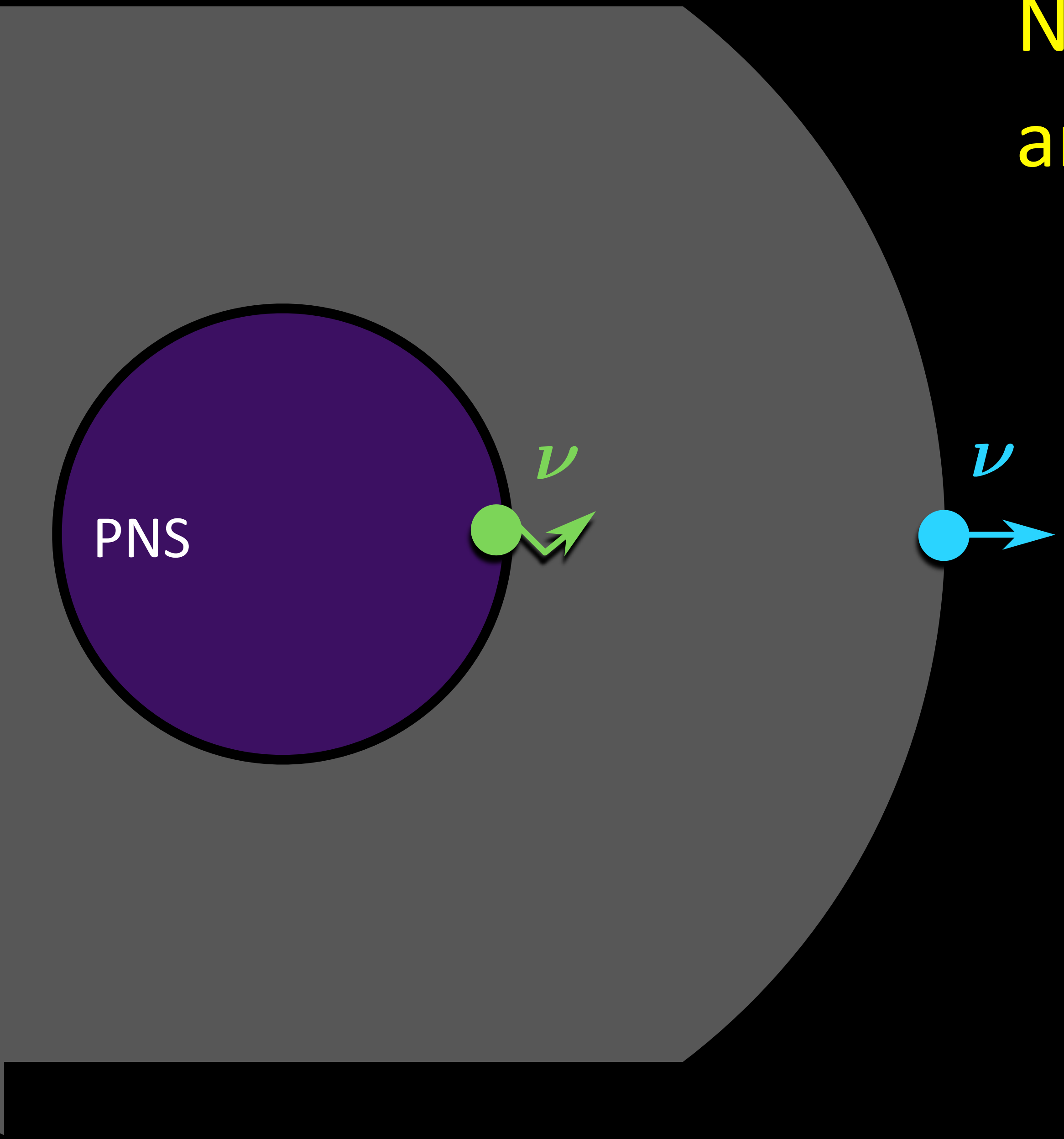

Observed neutrino pulse duration

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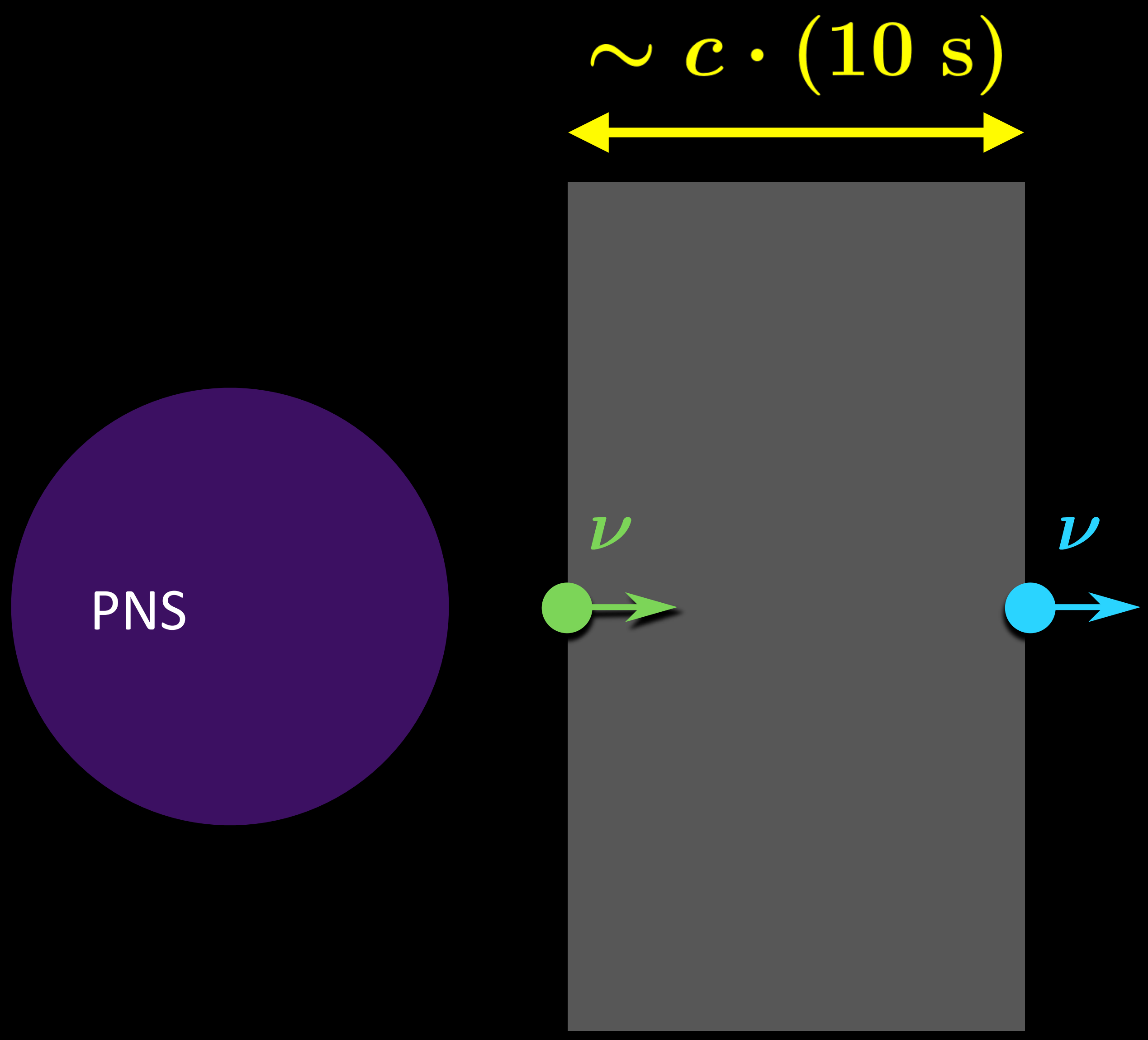
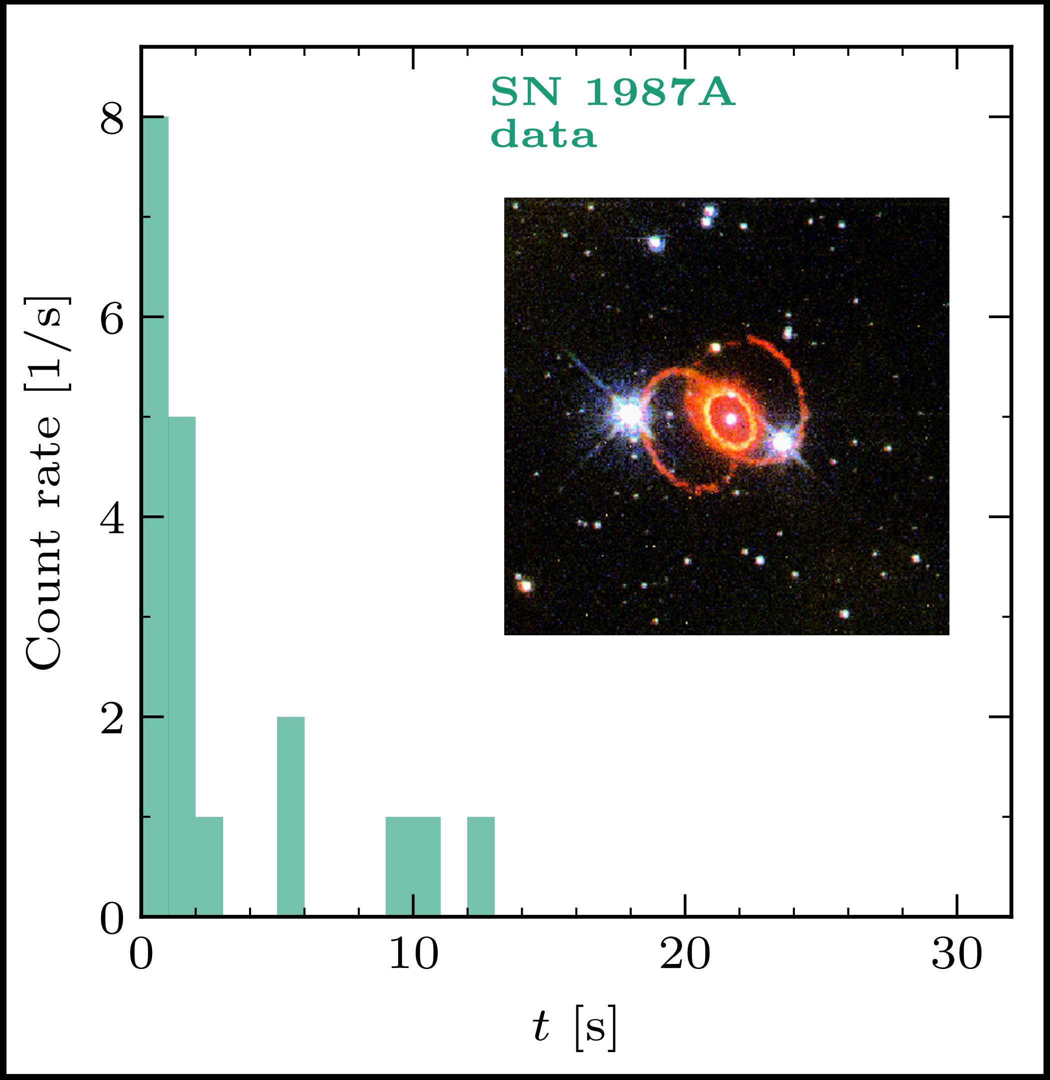
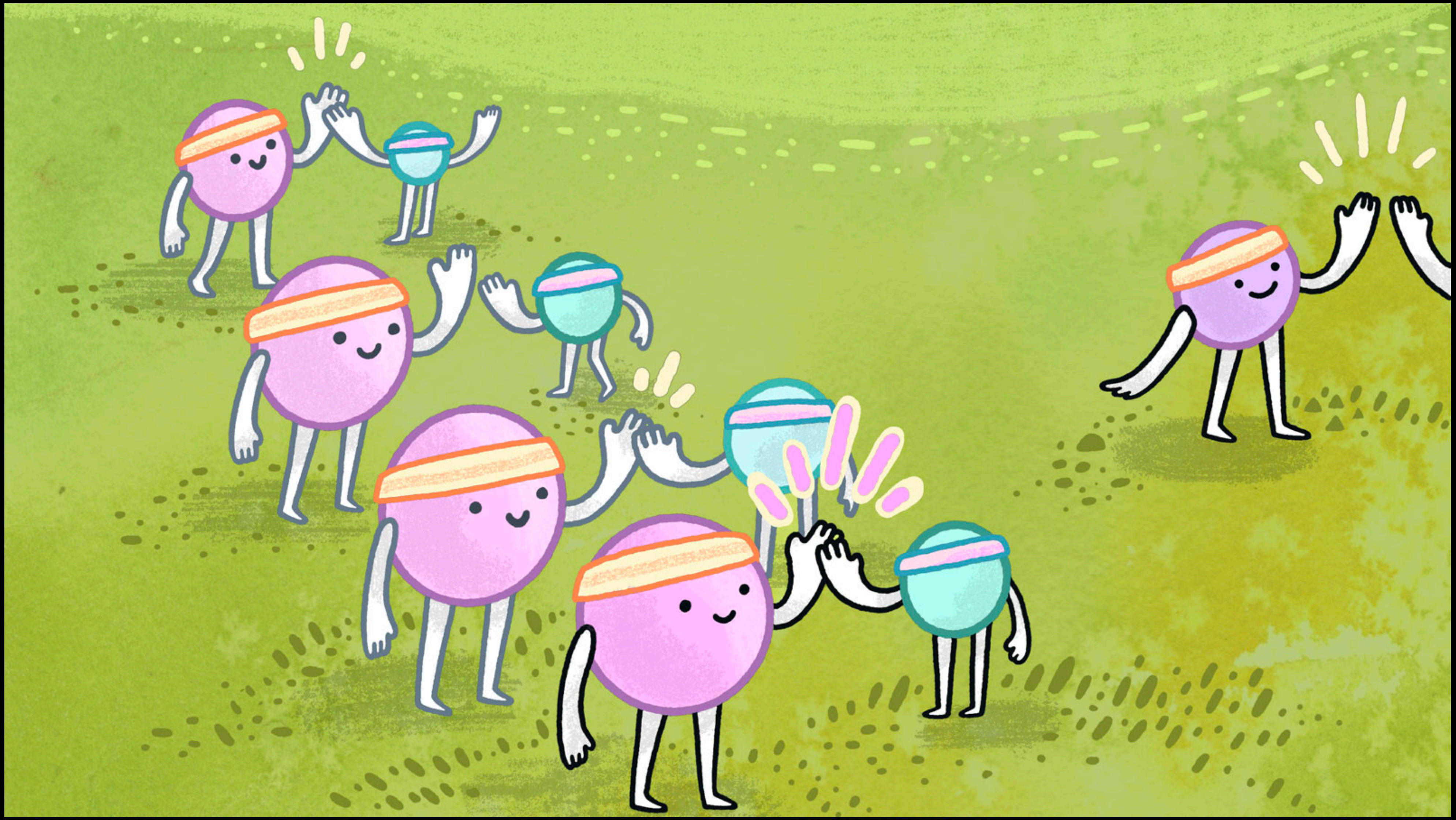


Confirmed by **SN 1987A**



Observed neutrino pulse duration

What if strong νSI exist?



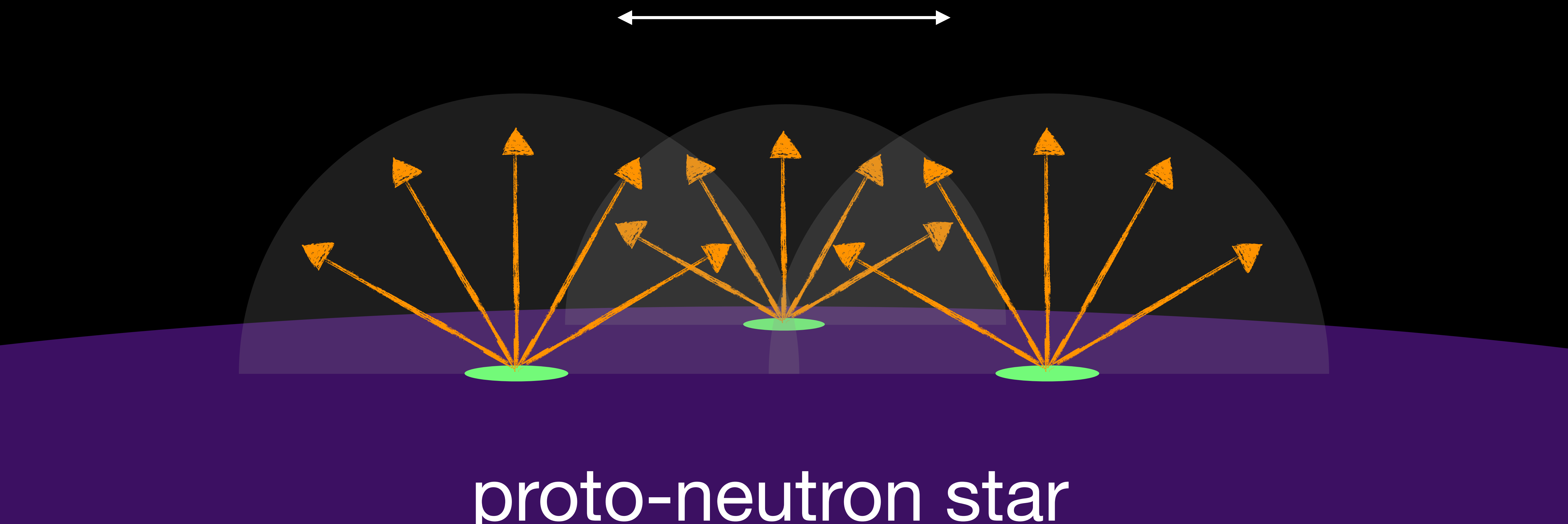
Observed neutrino pulse duration

What if strong νSI exist?

νSI will induce extremely frequent **ν-ν scattering**

Neutrinos will remain **tightly coupled even *outside* the PNS**

$$\lambda_{\nu\nu} \lll R_{\rm PNS}$$

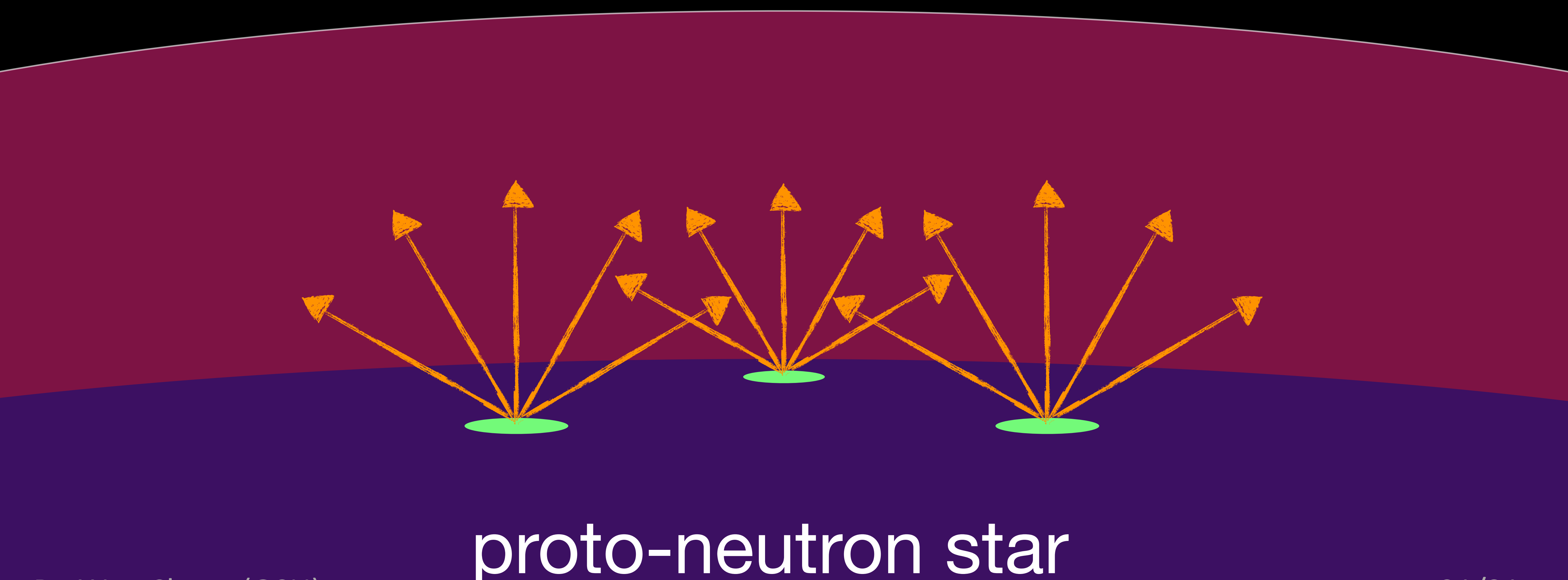


Observed neutrino pulse duration

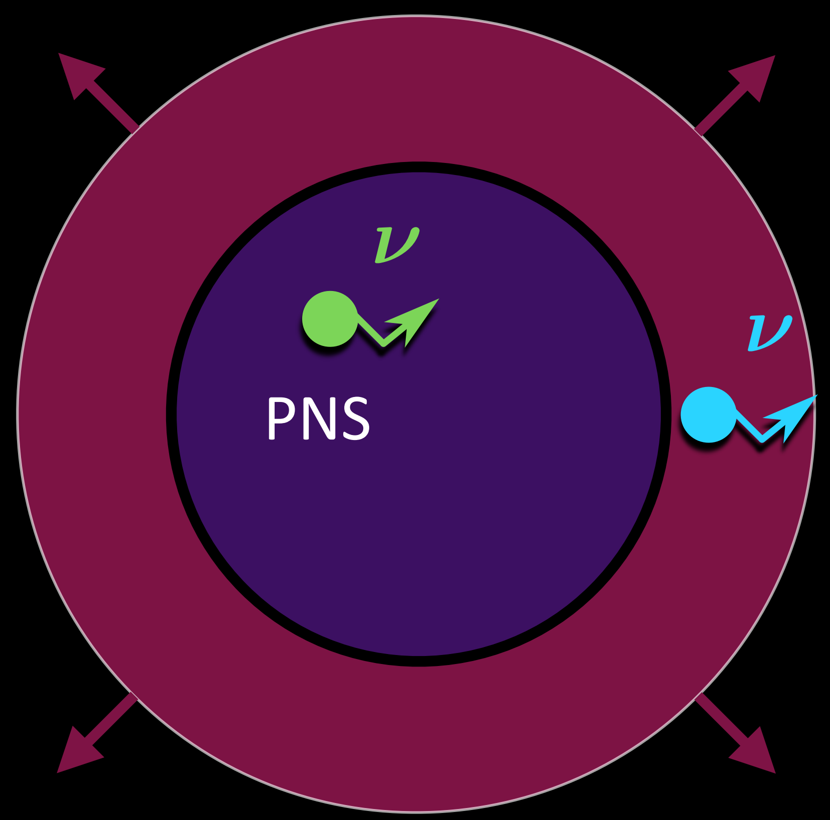
What if strong νSI exist?

νSI will induce extremely frequent **ν-ν scattering**

Neutrinos behave like a **relativistic fluid**



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



In the ***burst-outflow*** scenario,

the neutrino ball keeps expanding and diluting

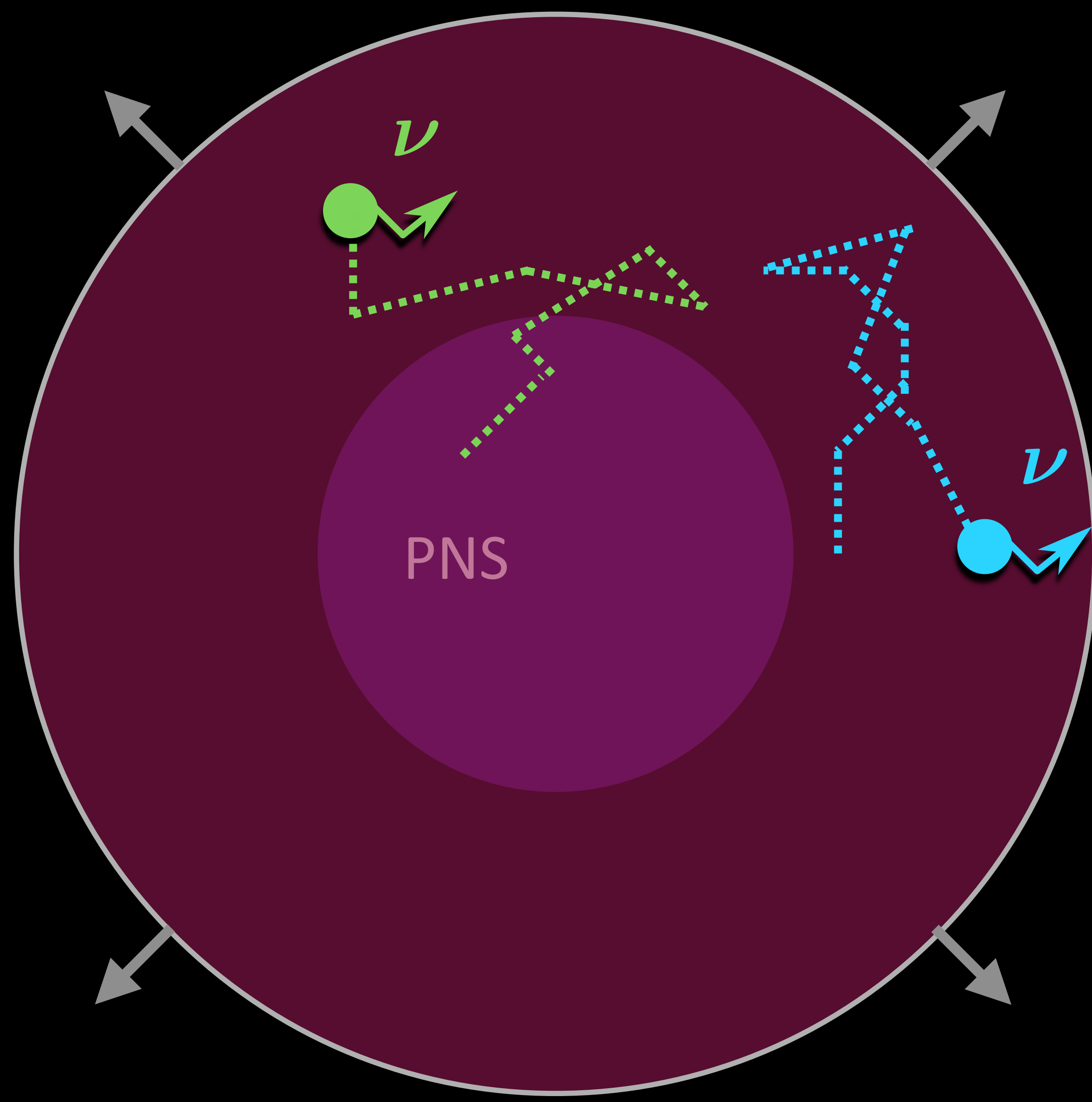
Most neutrinos inside the ball keep scattering with each other, leading to a random walk

burst outflow:

$n_\nu \sim \text{uniform}$

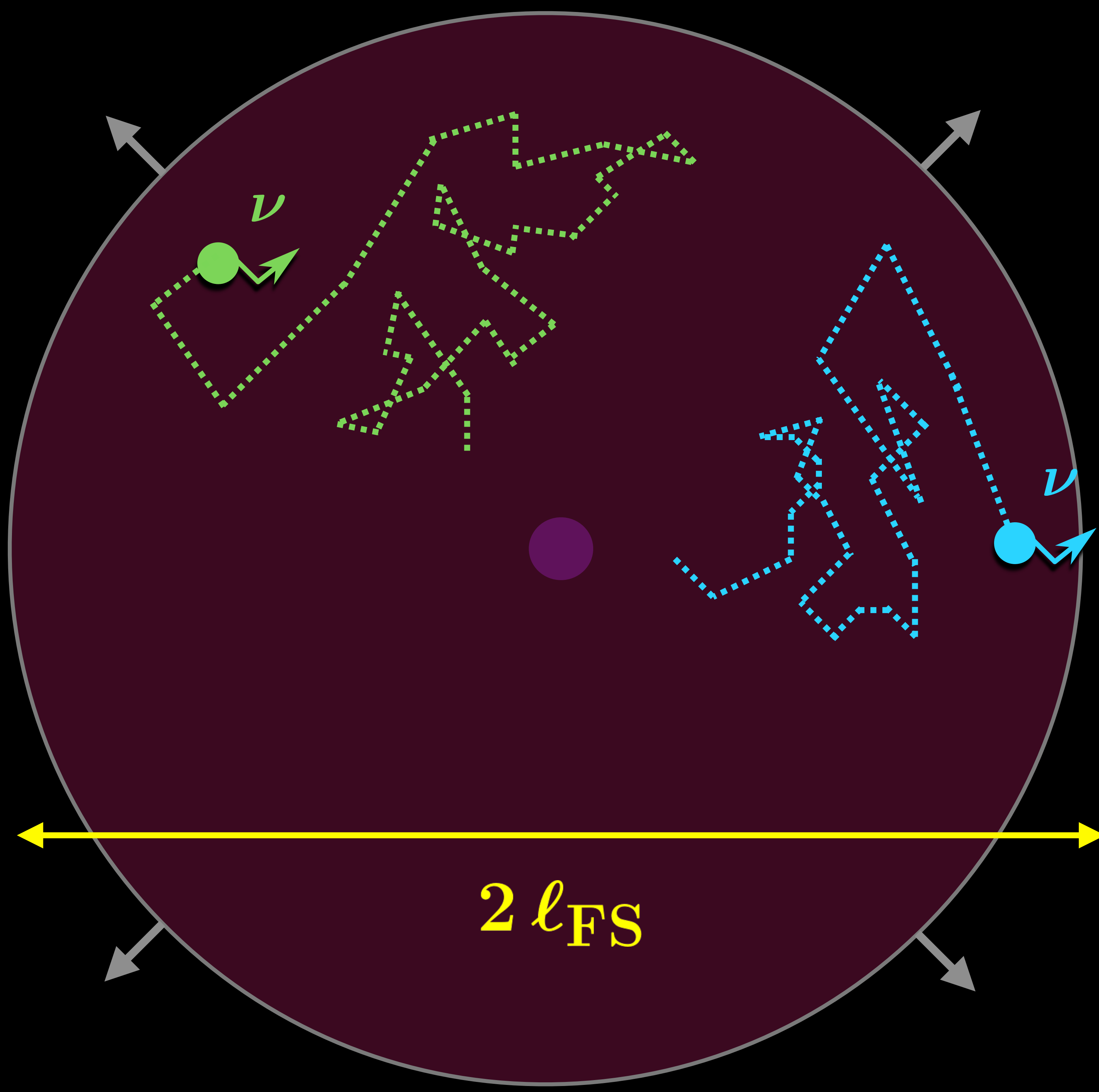
$\bar{v}(r) \sim (3/4)c$

$n_\nu \downarrow \;\; \Rightarrow \;\; \tau_{\nu\text{SI}} \downarrow$

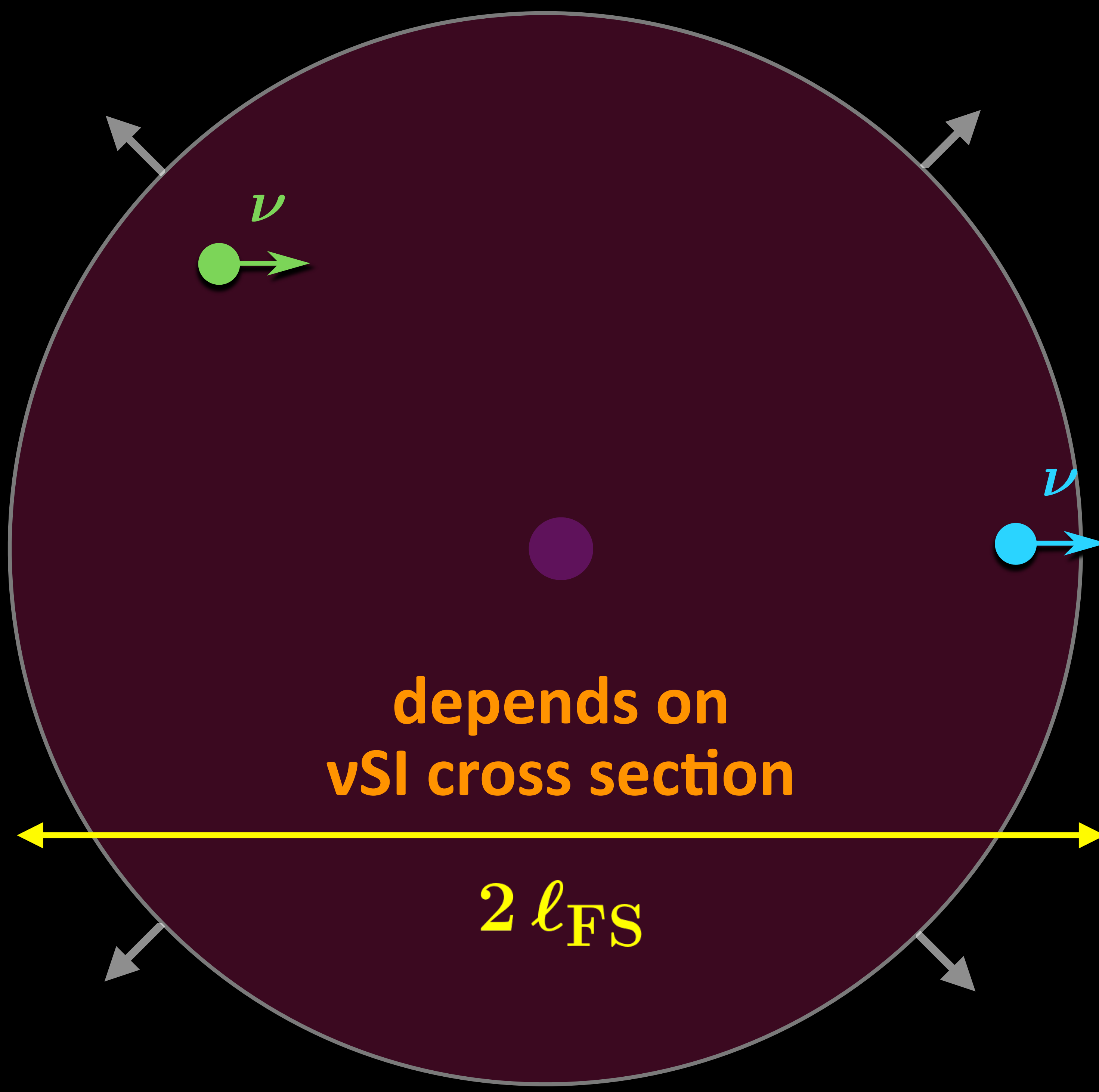


At some point, the interaction rate becomes too low

Neutrinos ***decouple*** from each other

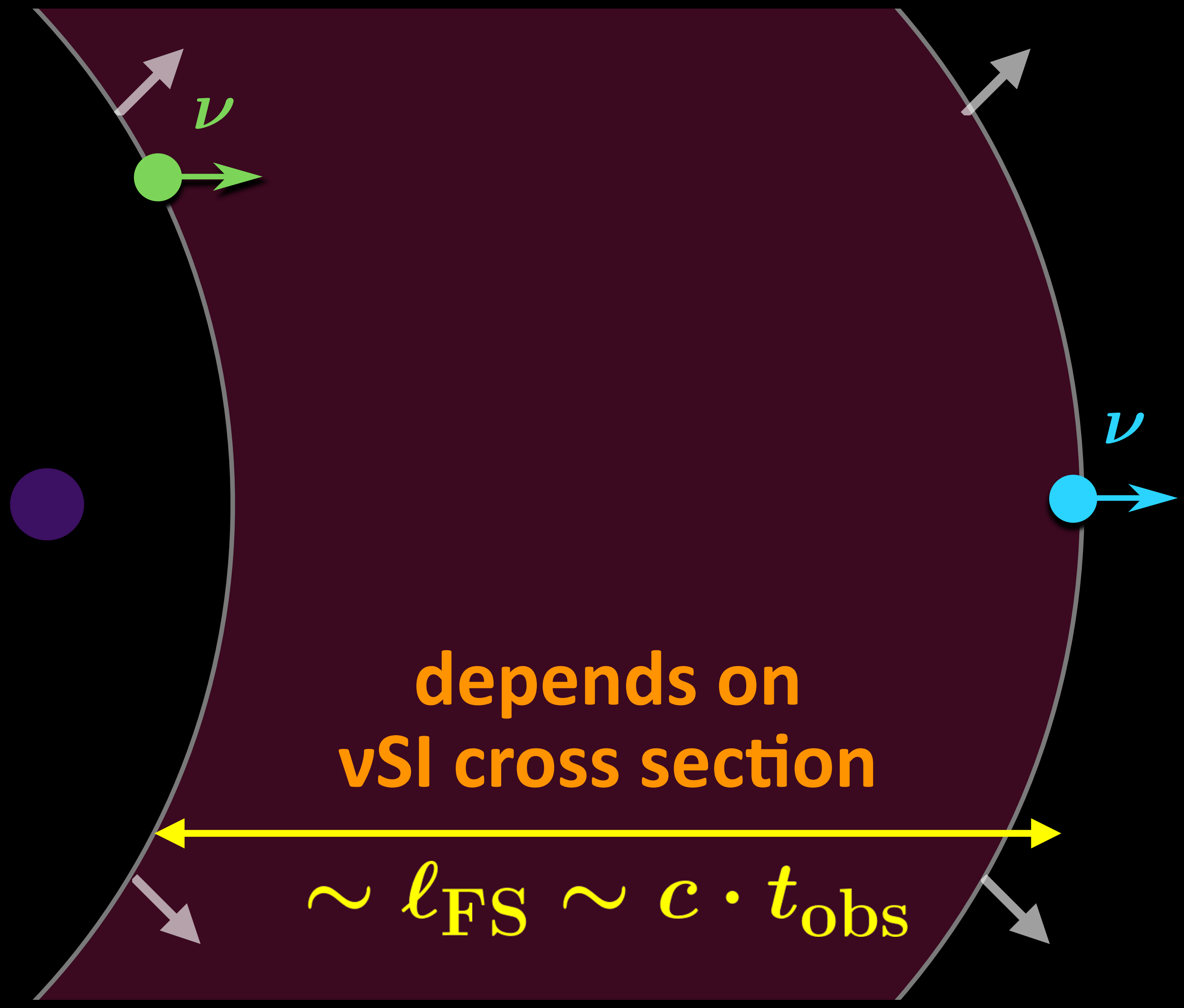


The directions of neutrino motion "*freeze*" after the last scattering



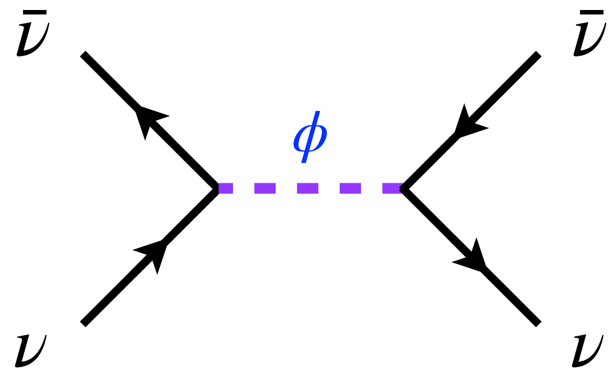
The ball eventually becomes a ***free-streaming neutrino shell***

The thickness of the shell sets
The observed duration neutrino signal

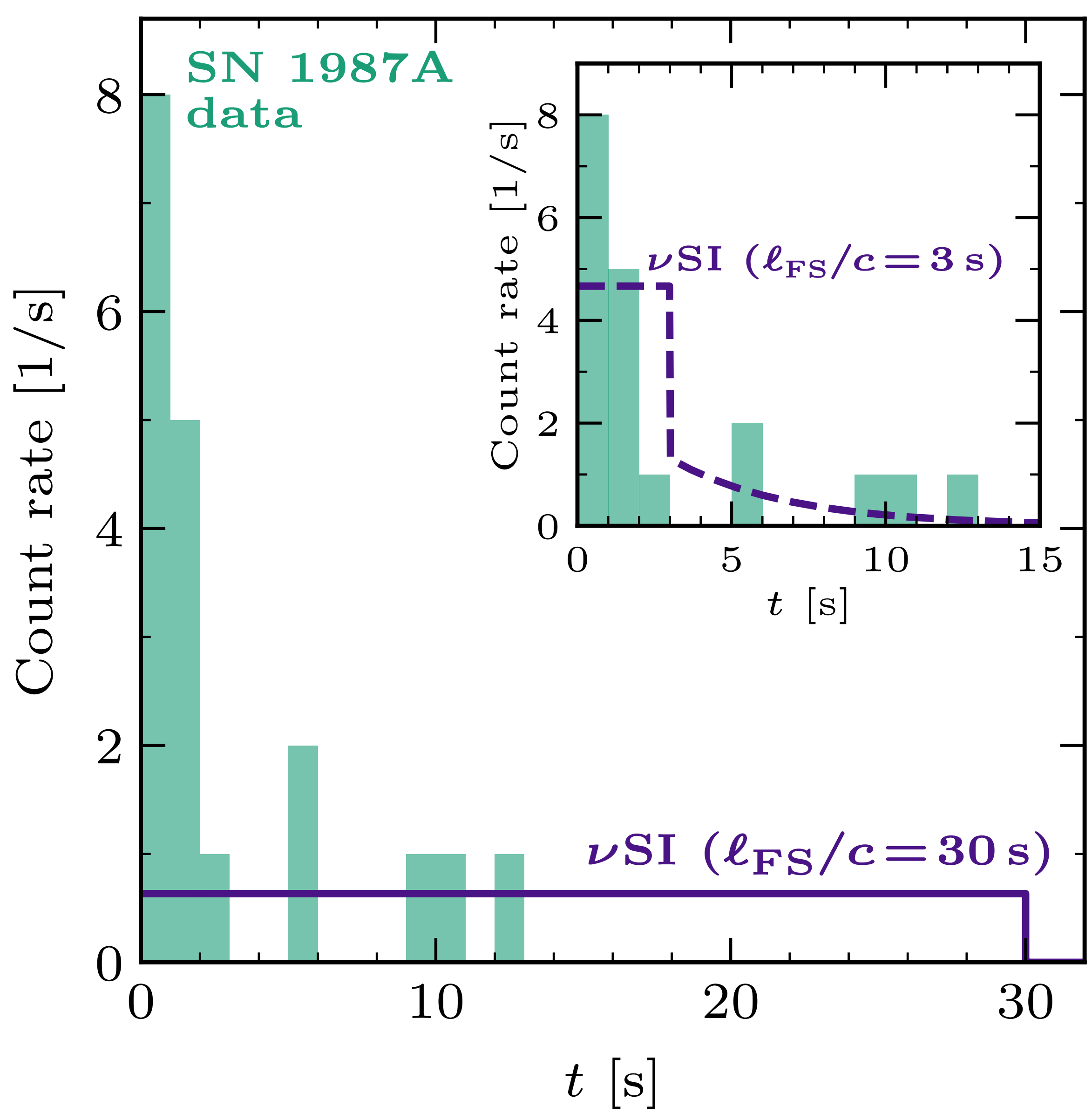


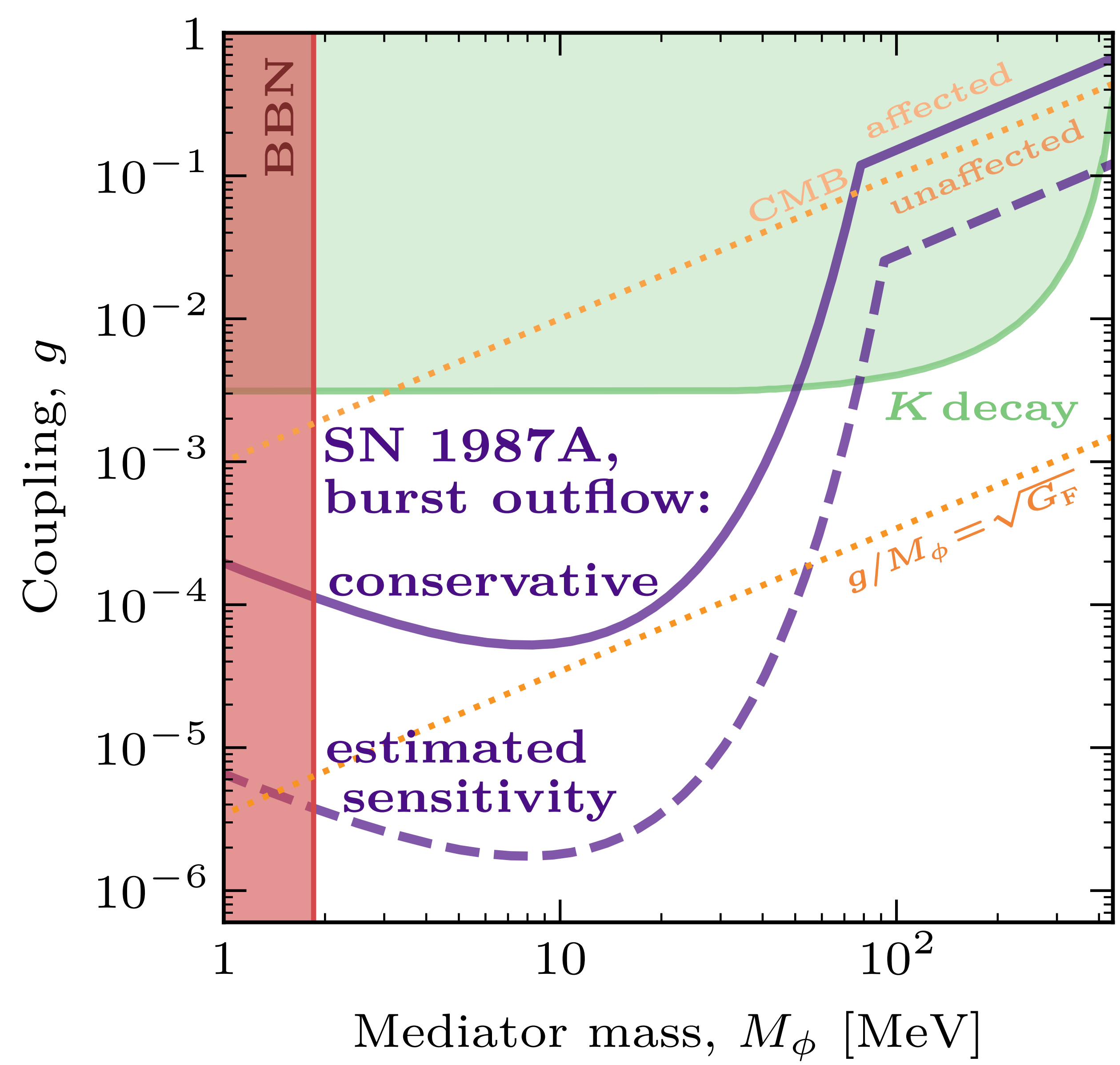
Potential constraints from SN 1987A

Breit-Wigner cross section (resonance: $s \sim M_\phi^2$)



$$\sigma_{\nu\nu} = \frac{g^4}{16\pi} \frac{s}{(s - M_\phi^2)^2 + M_\phi^2 \Gamma^2}$$





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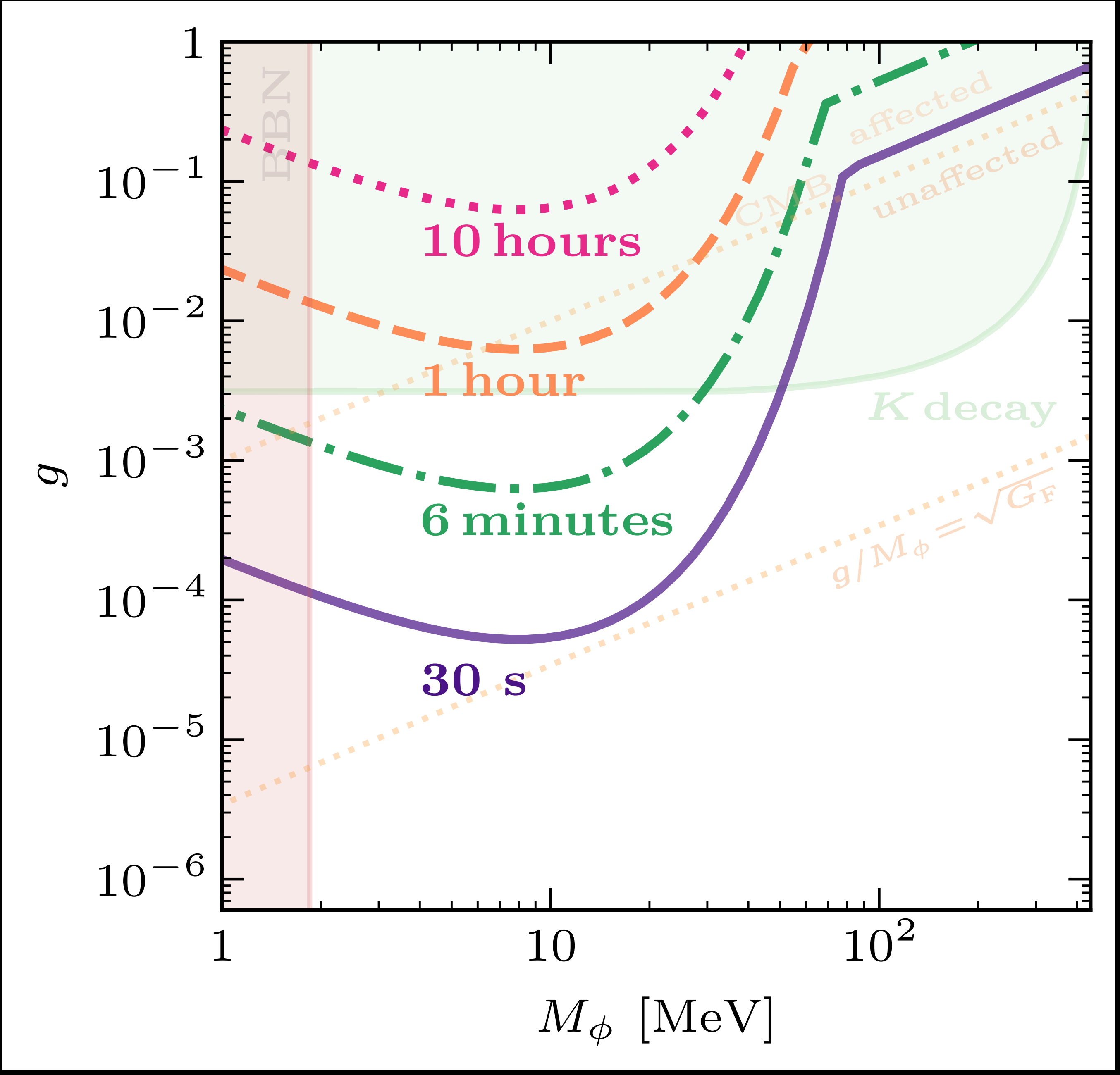
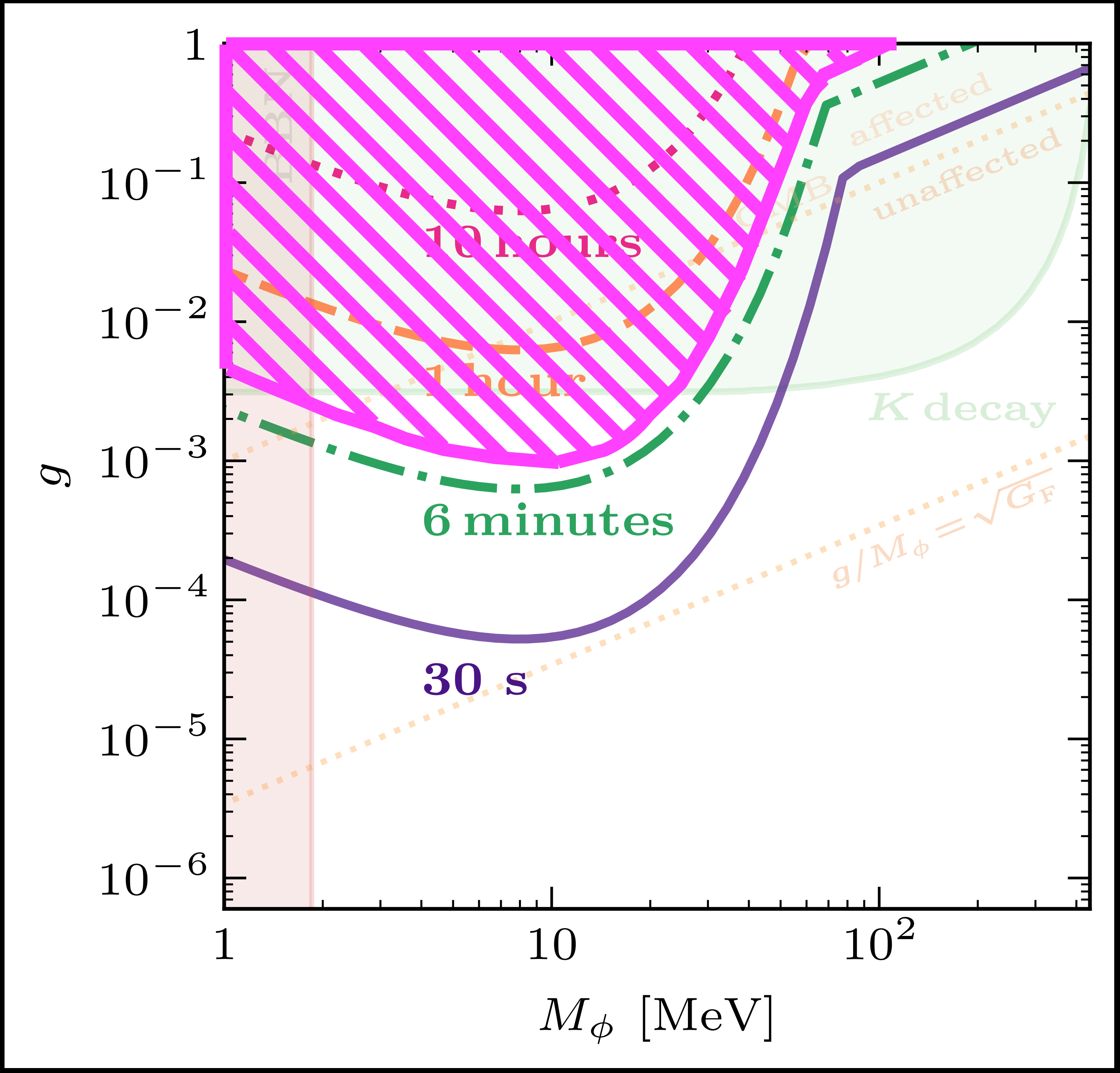
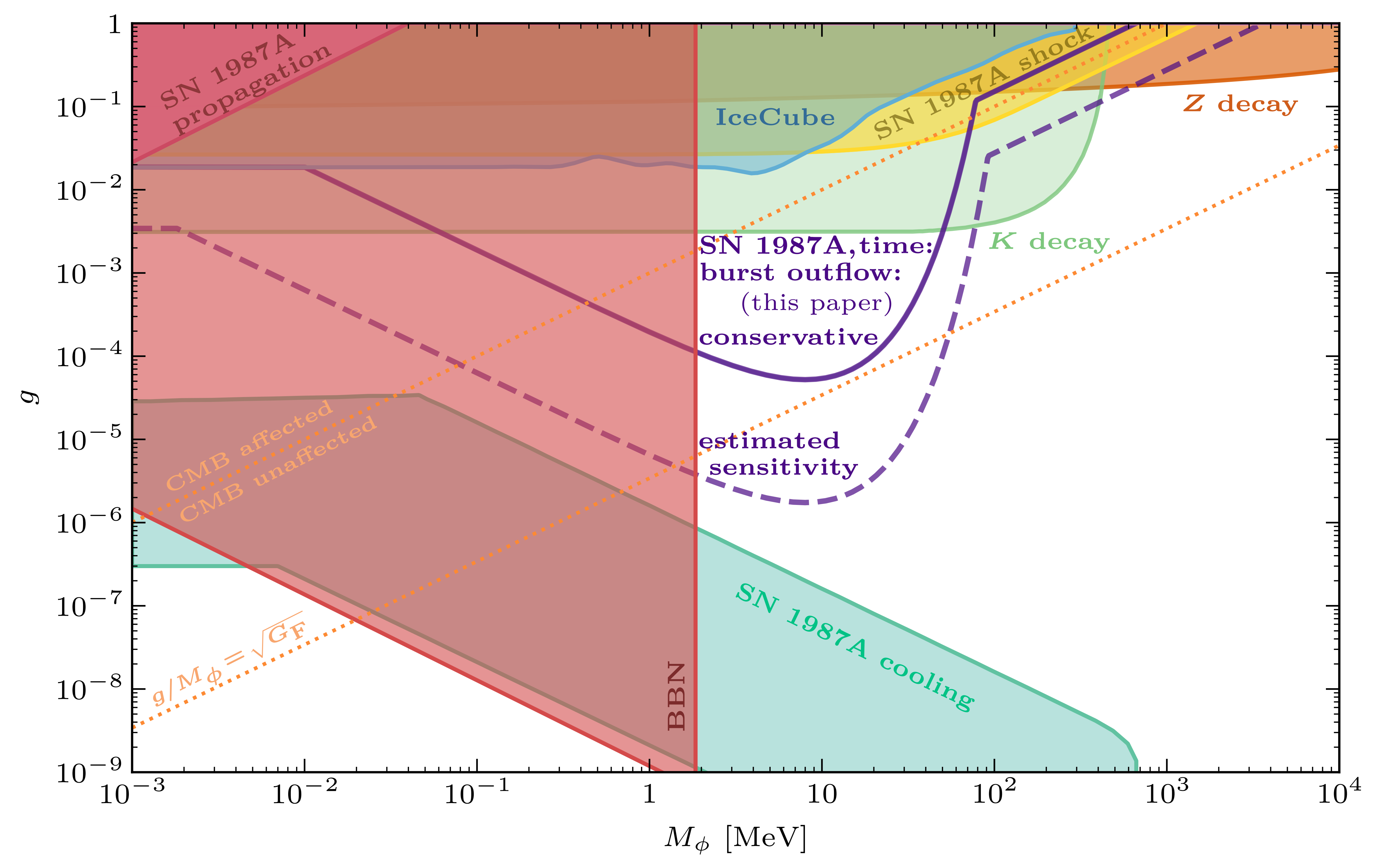


Potential constraints from SN 1987A

SN 1987A would have never been discovered
(burst outflow)



Potential constraints from SN 1987A



Conclusions

The effects of νSI may be biasing our deductions about astrophysics

For 35 years since SN 1987A, we are not sure how νSI affect the dense neutrinos in supernovae. We lack a robust observable.

Strong νSI: relativistic hydrodynamic outflow of neutrinos

Fork in the road

?

This work

Transient burst

The neutrino signal duration is a powerful, model-independent probe of νSI.

Steady wind

Observables?

Thank you!

arXiv: 2206.12426

Backup material

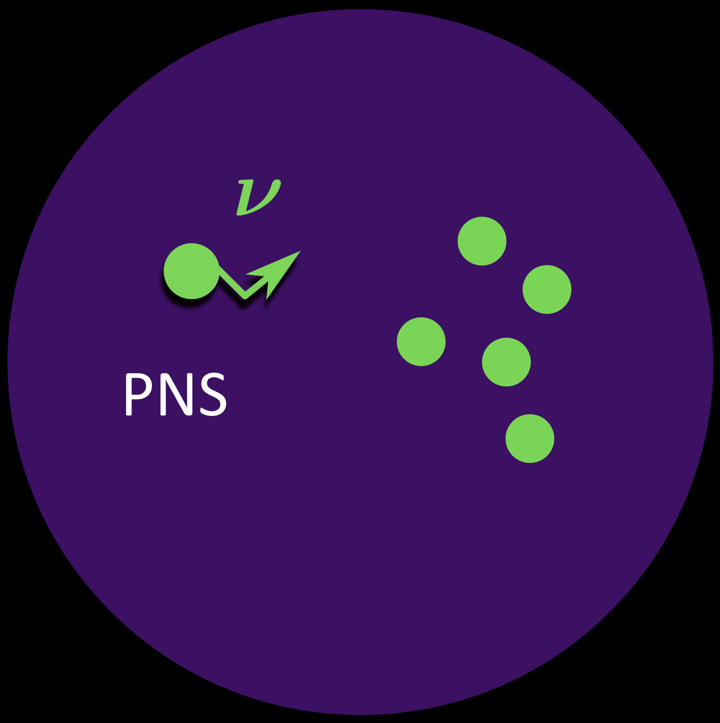
Relevant prior works

Manohar (1987)

"

...The anti-neutrino-anti-neutrino scattering cross section $\sigma_{\nu\nu}$ *causes the anti-neutrinos to collide with each other, and hinders their escape from the star...*

"



Relevant prior works

Dicus, Nussinov, Pal, Teplitz (1989)

"

...The hot [neutrino] gas will expand with nearly the velocity of light, *independent of* $\sigma_{\nu\nu}$. On a microscopic level if a neutrino is deflected away from its course another is deflected into the first neutrino's direction...

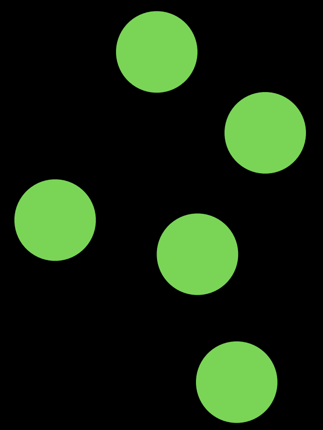
...*the neutrinos leave the supernova just as a pressurized gas leaves a container whose lid is suddenly removed.*

"

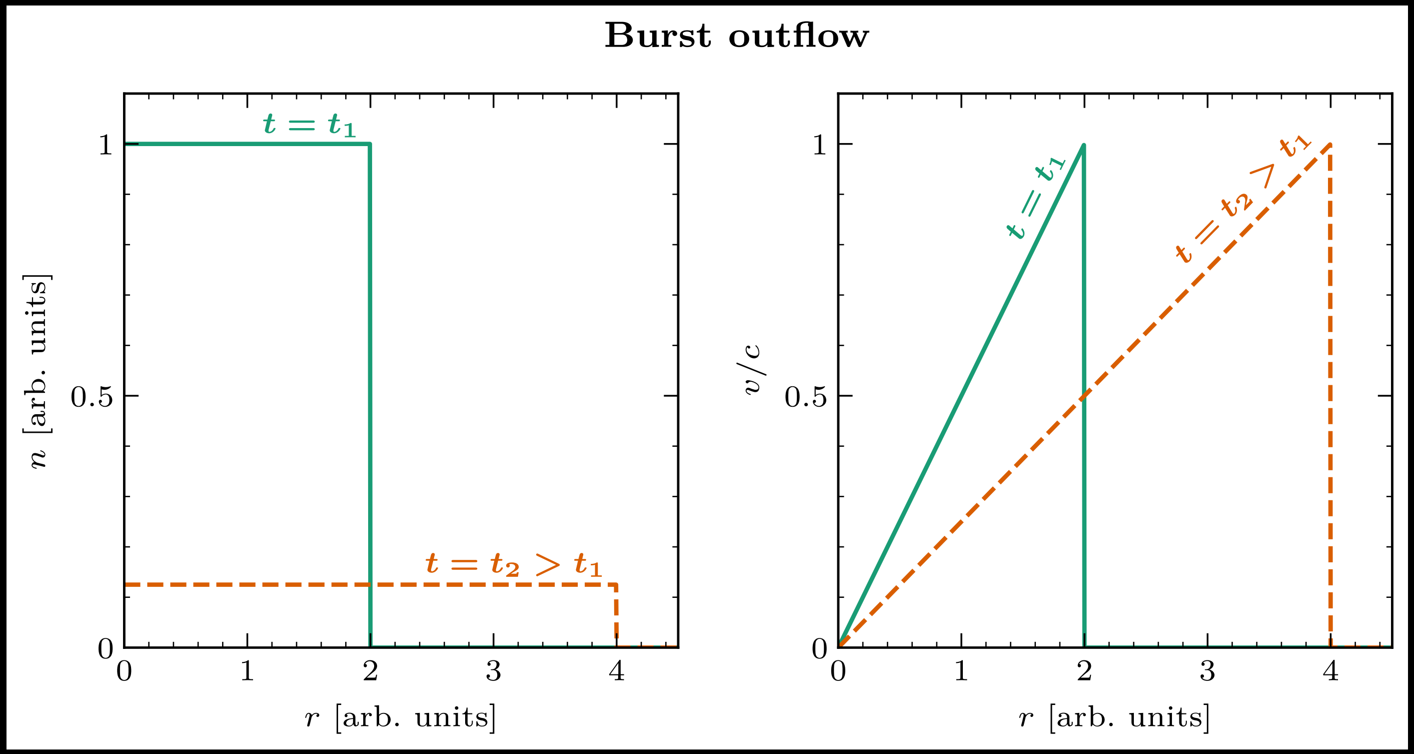
Relevant prior works

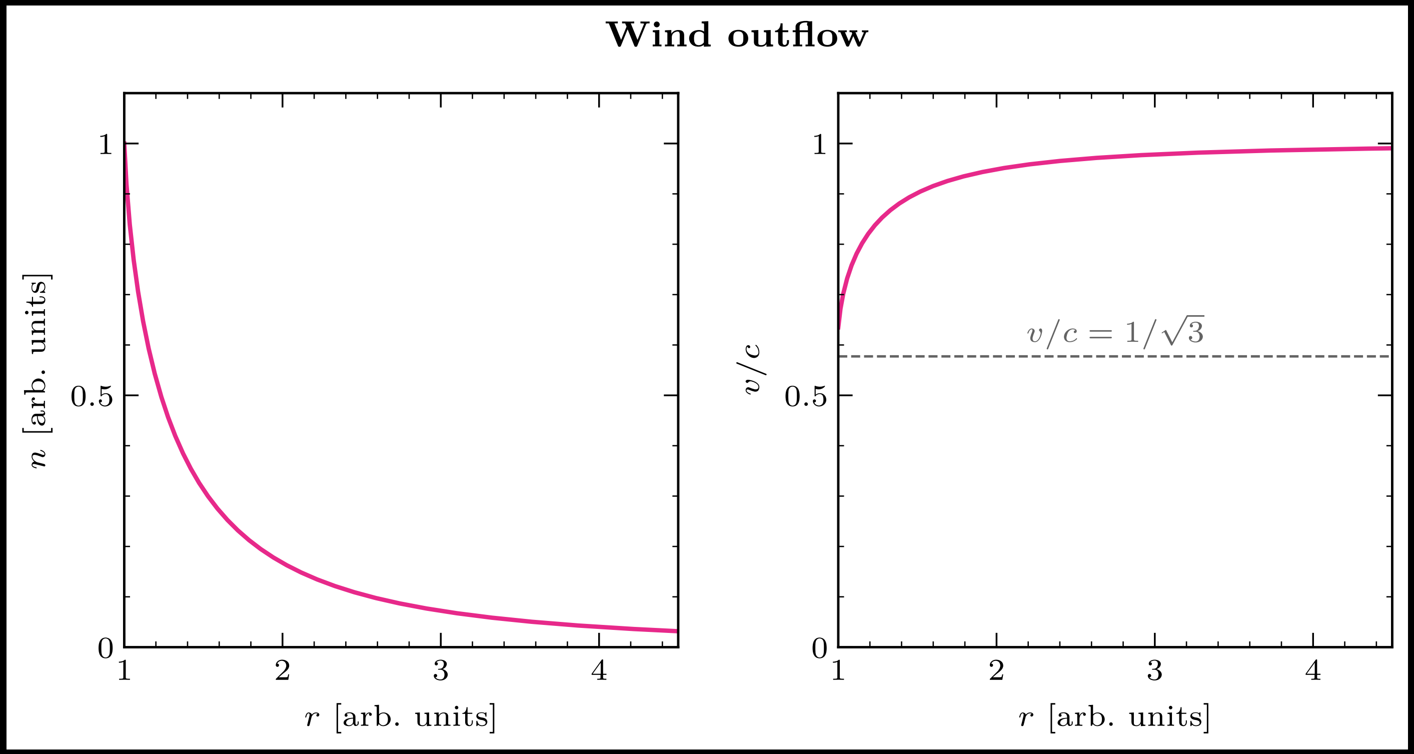
Dicus, Nussinov, Pal, Teplitz (1989)

Momentum conservation



Relativistic outflows





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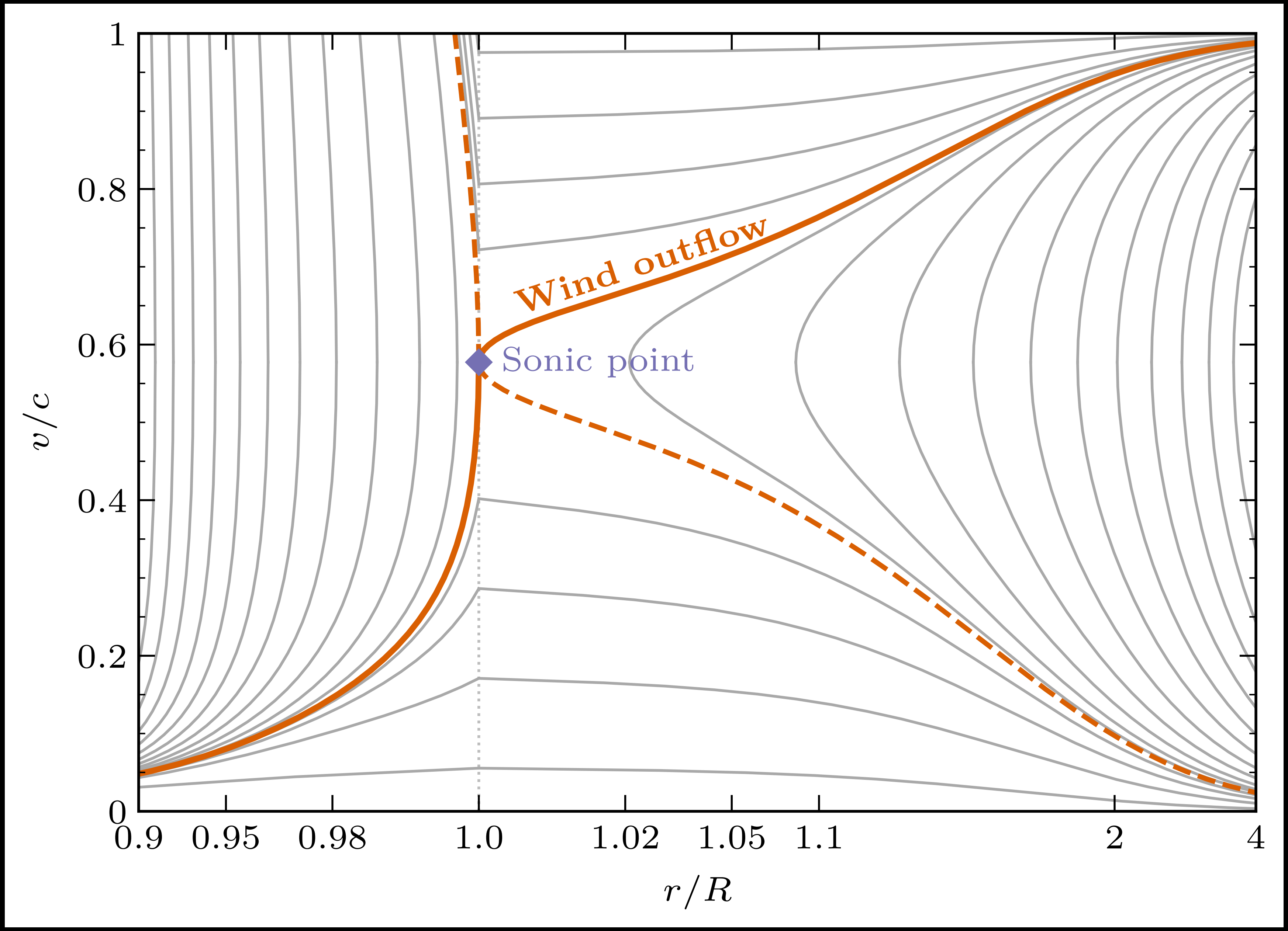
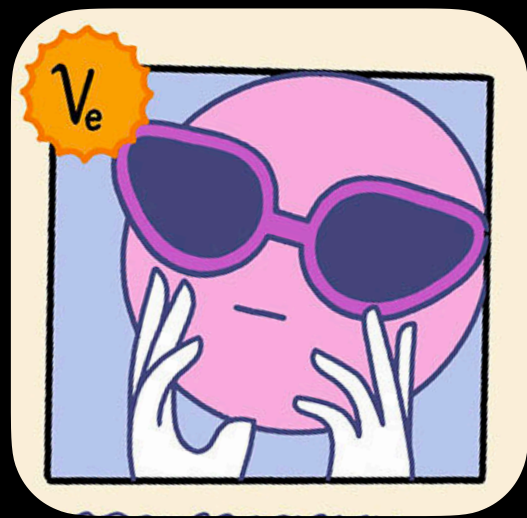
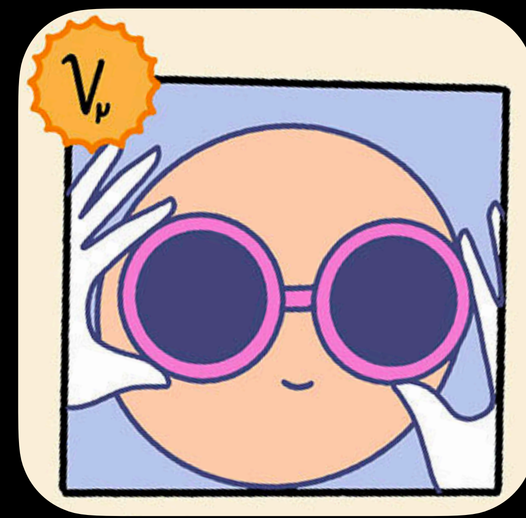
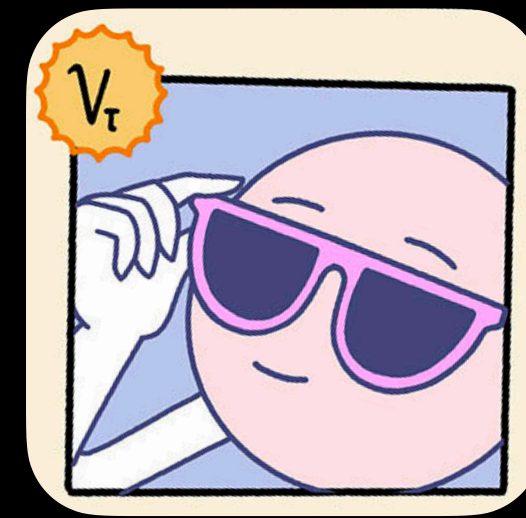
Relativistic outflows

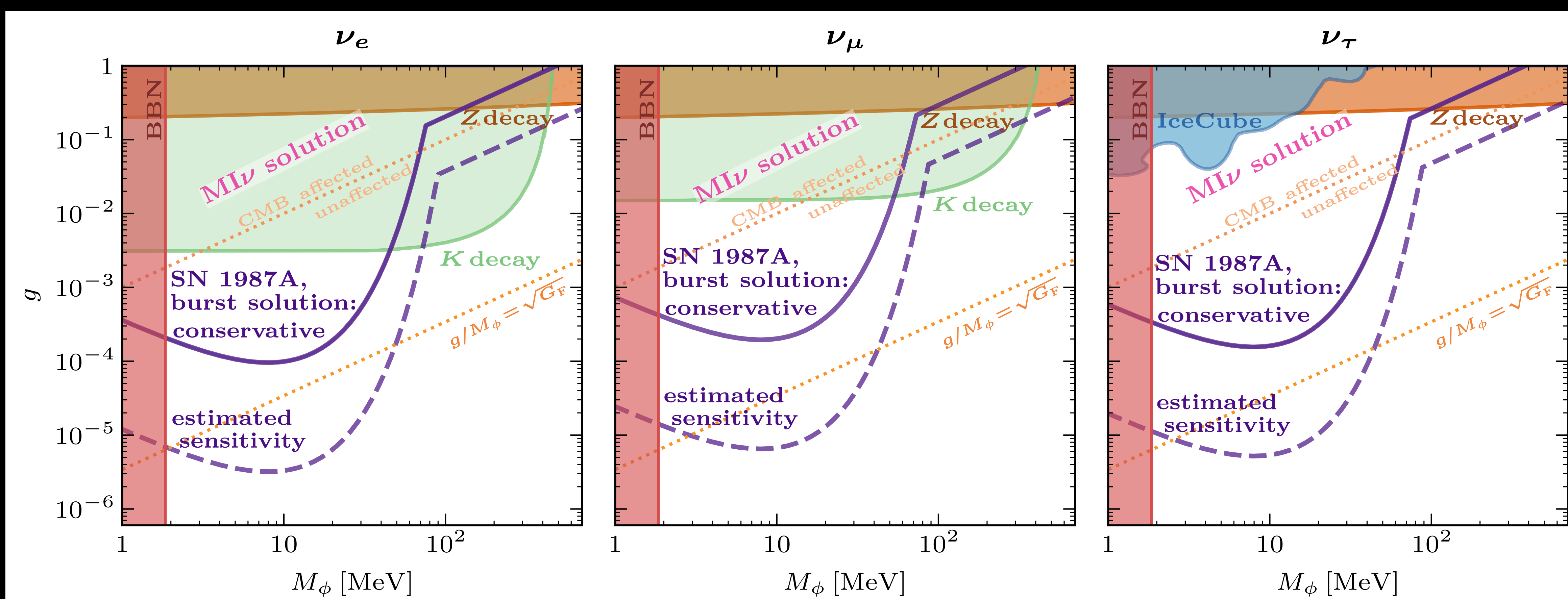


Single-flavor scenario









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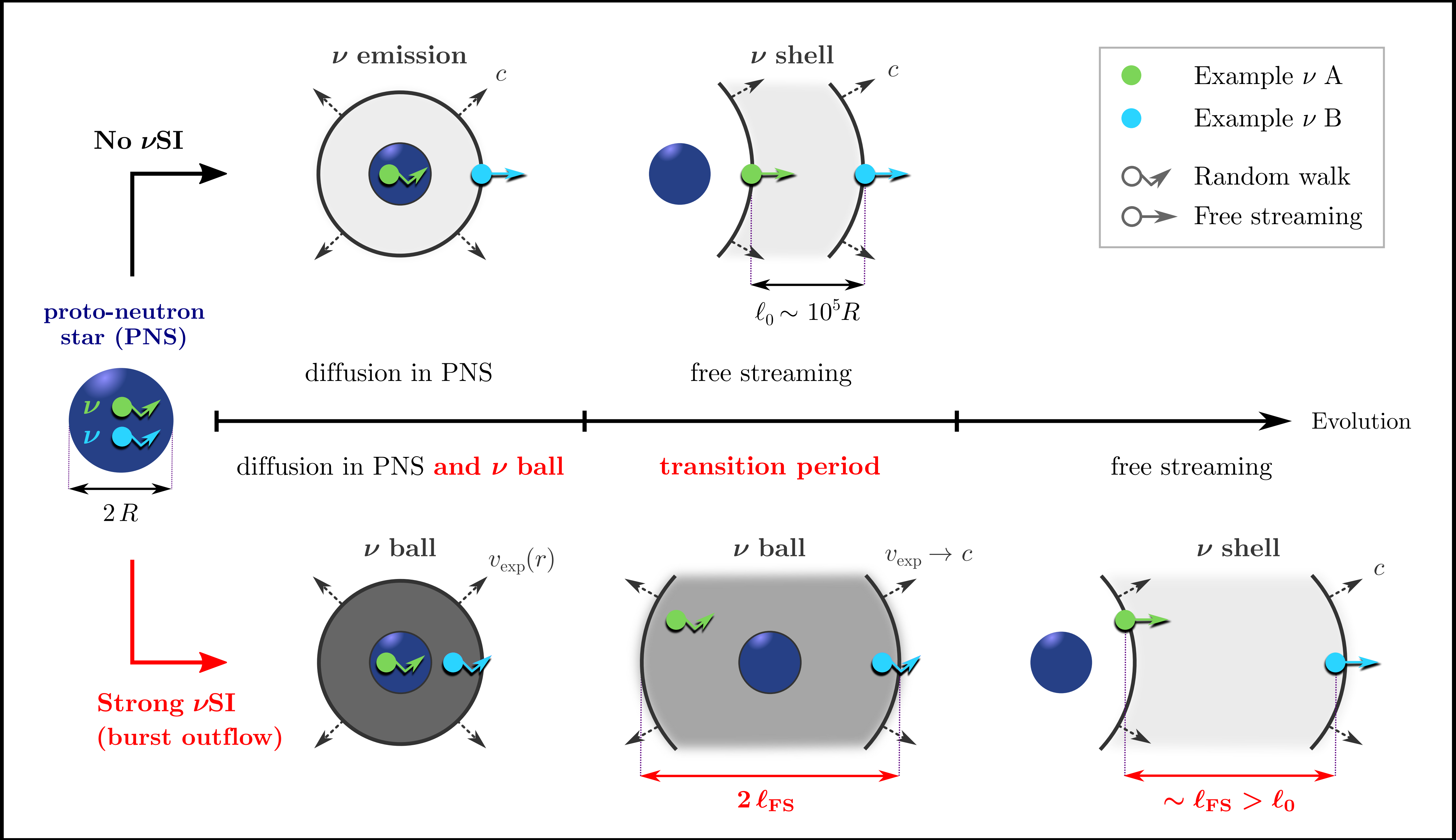
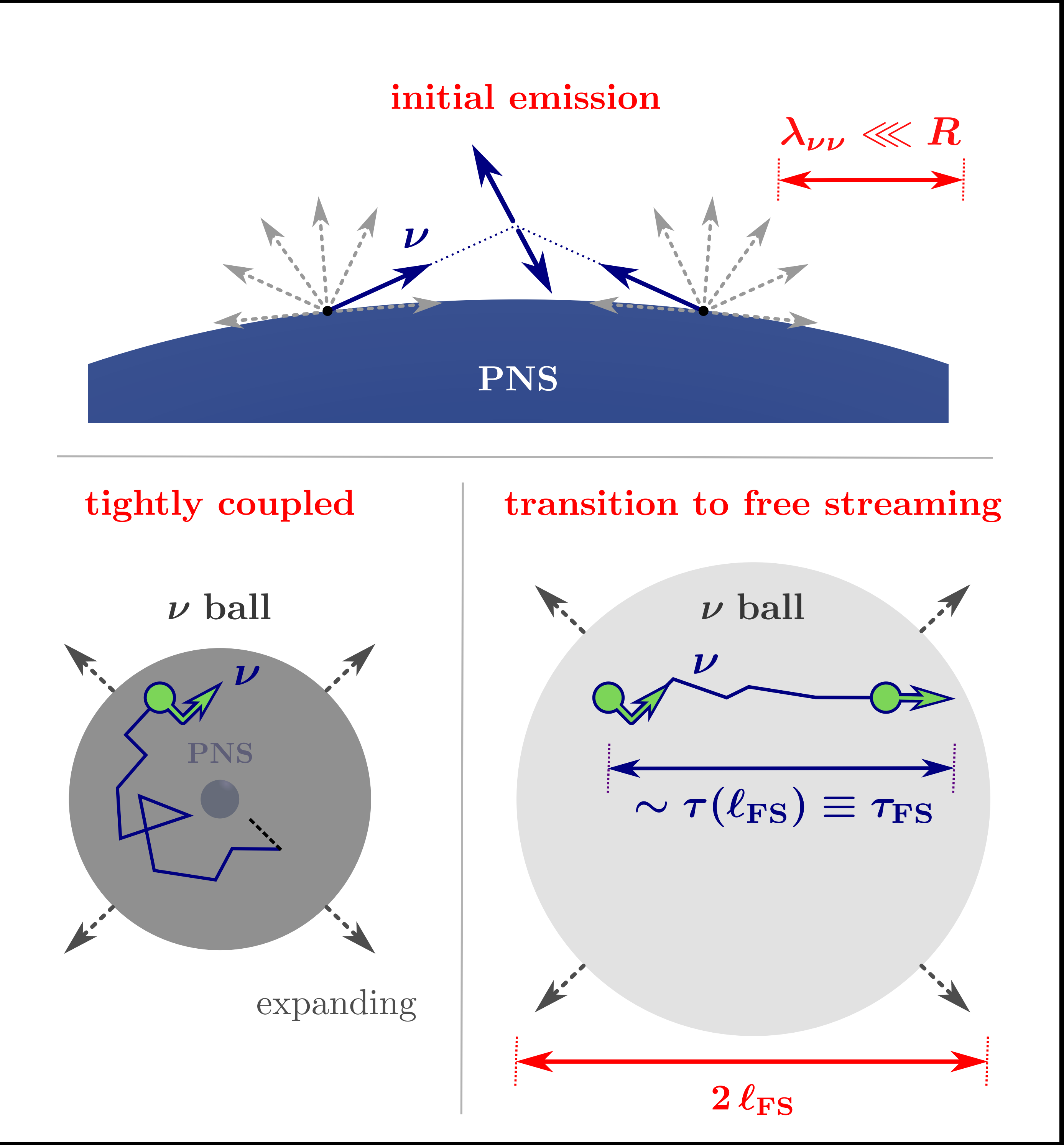
Macroscopic point of view

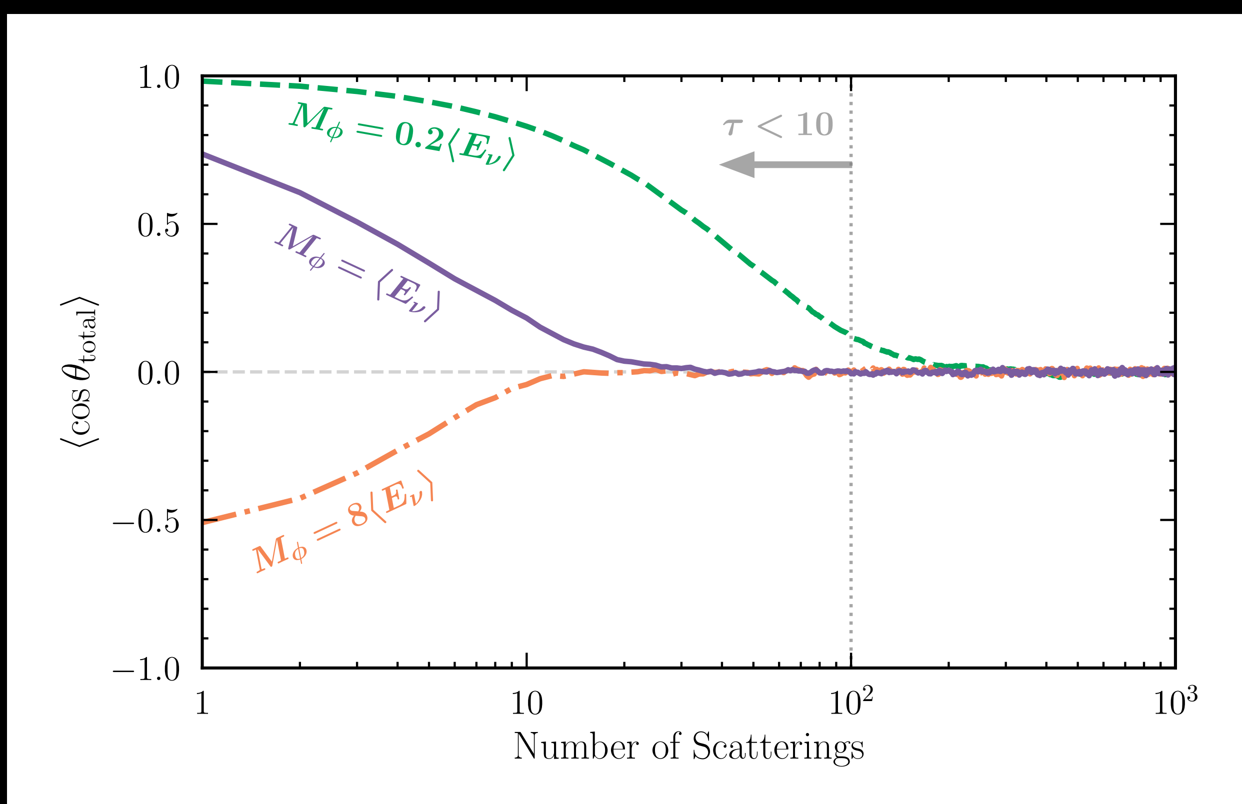


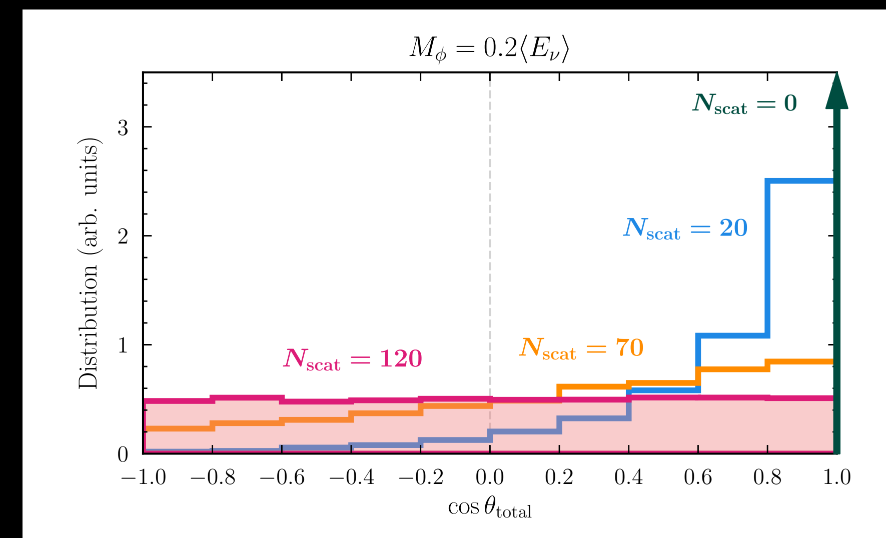
Microscopic point of view

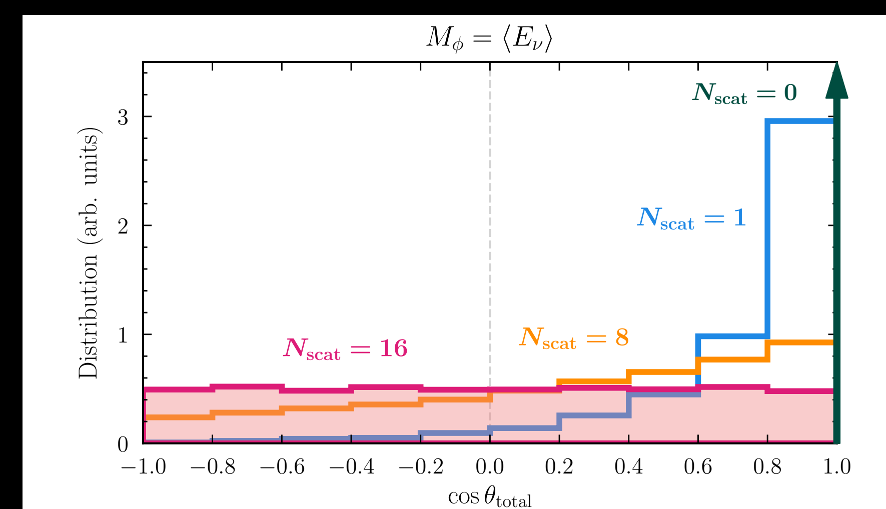


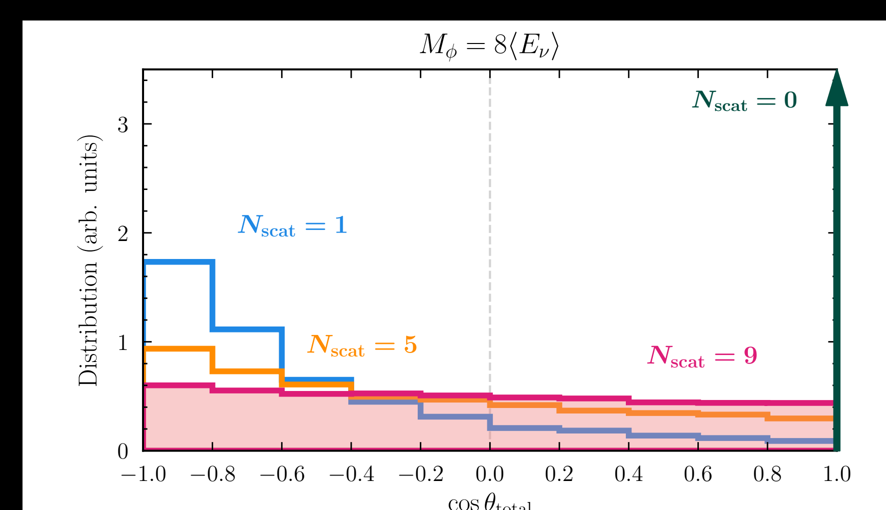
Microscopic point of view

How isotropy is *lost* by decreasing optical depth

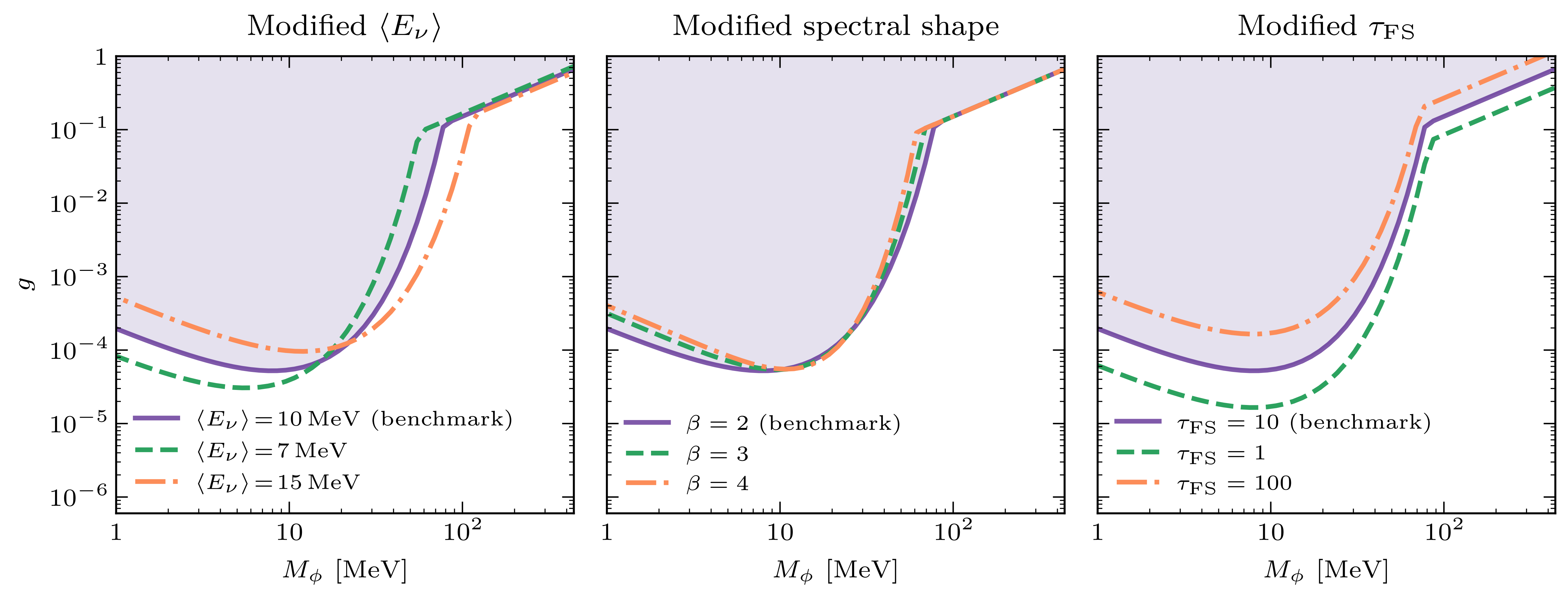








Robustness check



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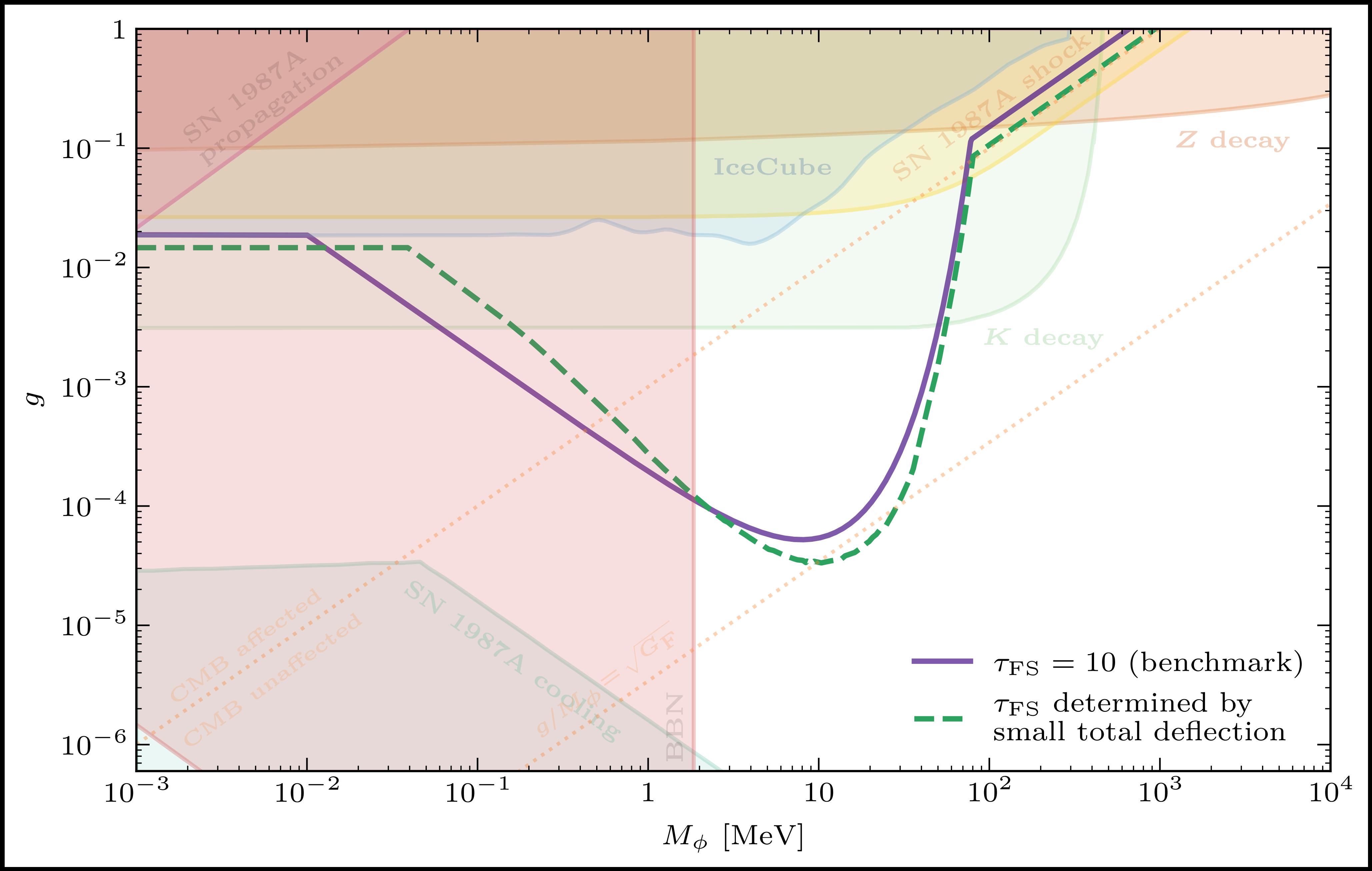

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