Muons in supernovae:
implications for the axion-muon coupling

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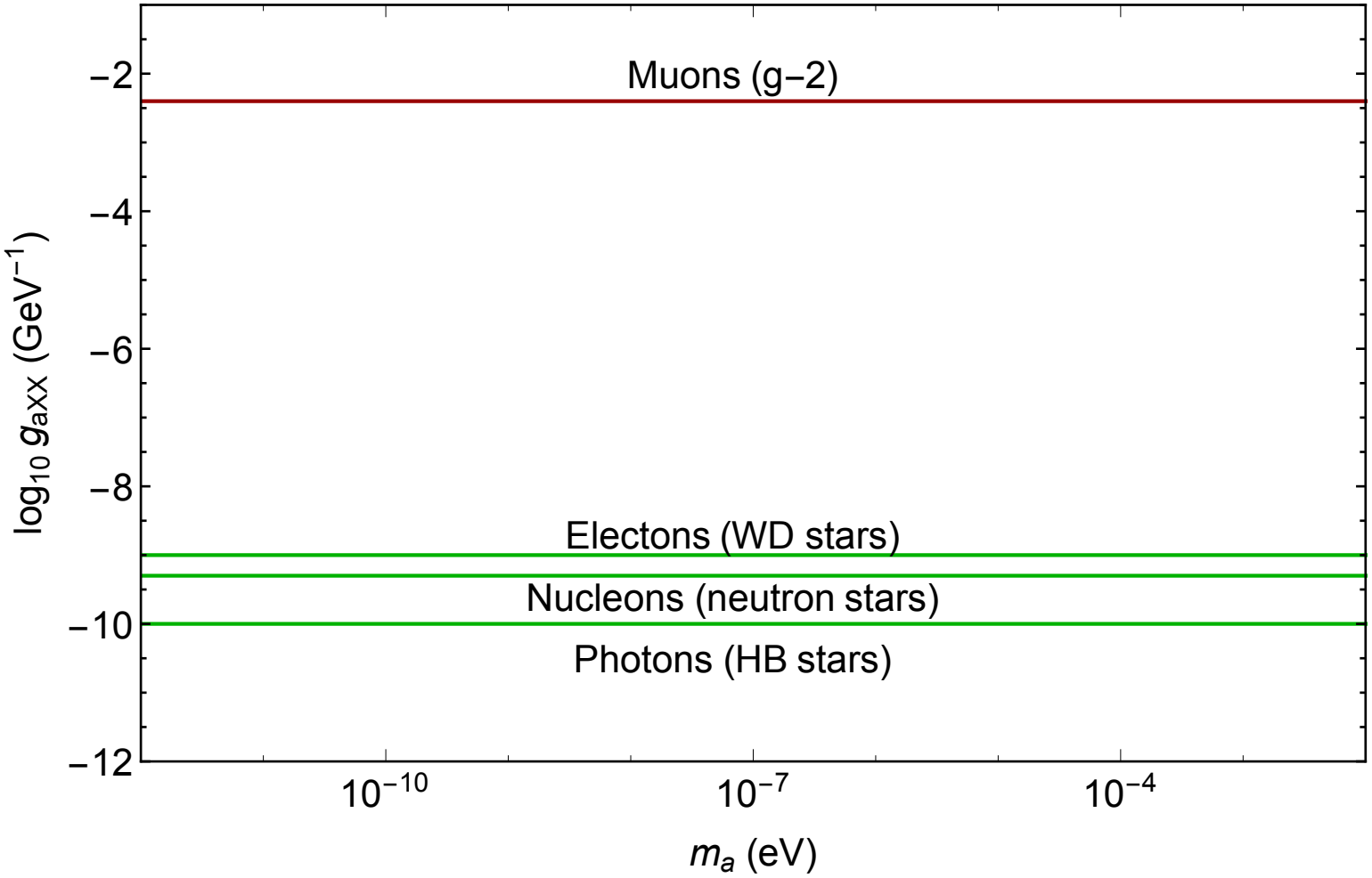
Motivation: stellar cooling limits

- **Axions:** hypothetical light pseudoscalar degrees of freedom
- Most axion couplings are constrained by stellar cooling
  - $L \supset g_{aff}(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$
  - $L \supset \frac{g_{a\gamma\gamma}}{4} a\, F\tilde{F}$
- What about muons?



Why hasn’t this been done?

Role of muons in SN only recently appreciated

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\+ Muon abundance *also* depends on temperature

Difficult to place robust bound

→ **But new results make this possible!**

Outline

- **Part I:** Observations of SN neutrinos constrain new physics.

- **Part II:** Supernovae are sensitive to new muonic couplings.

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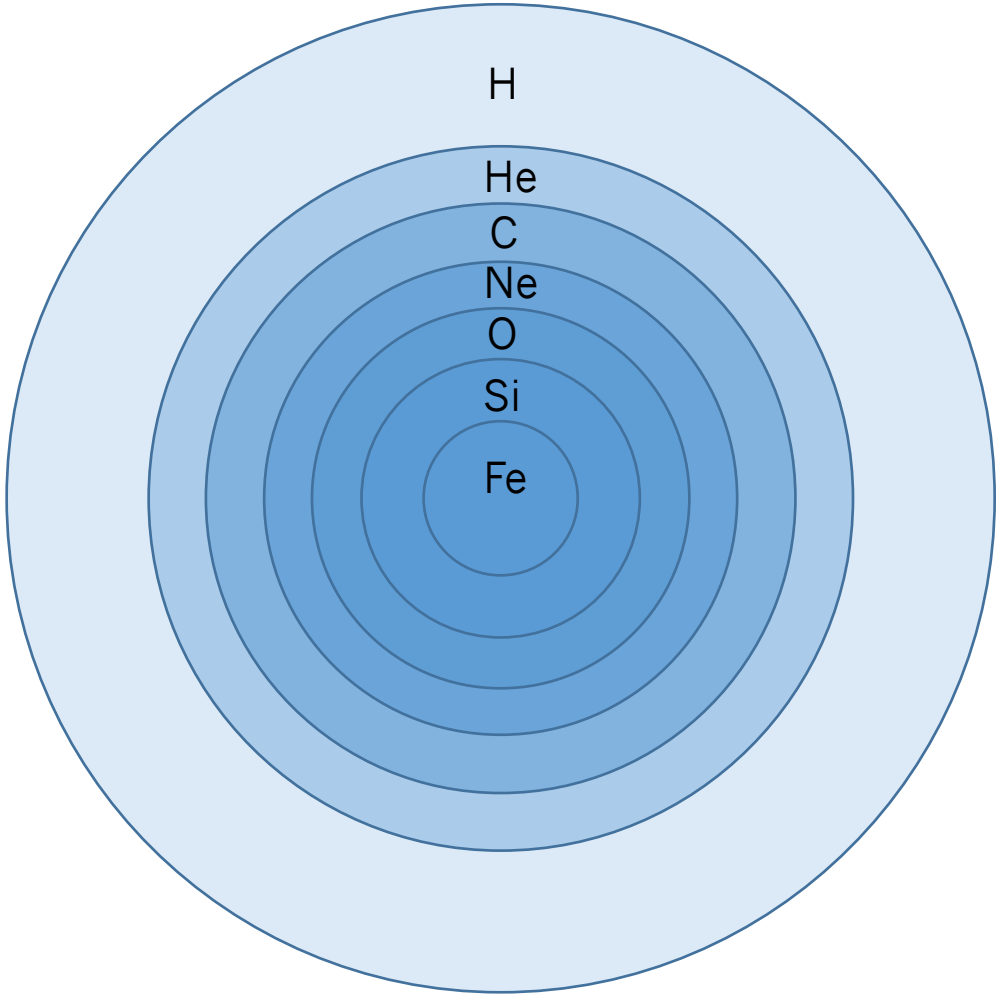
What is a supernova?

- Massive stars form layers of heavy elements via fusion

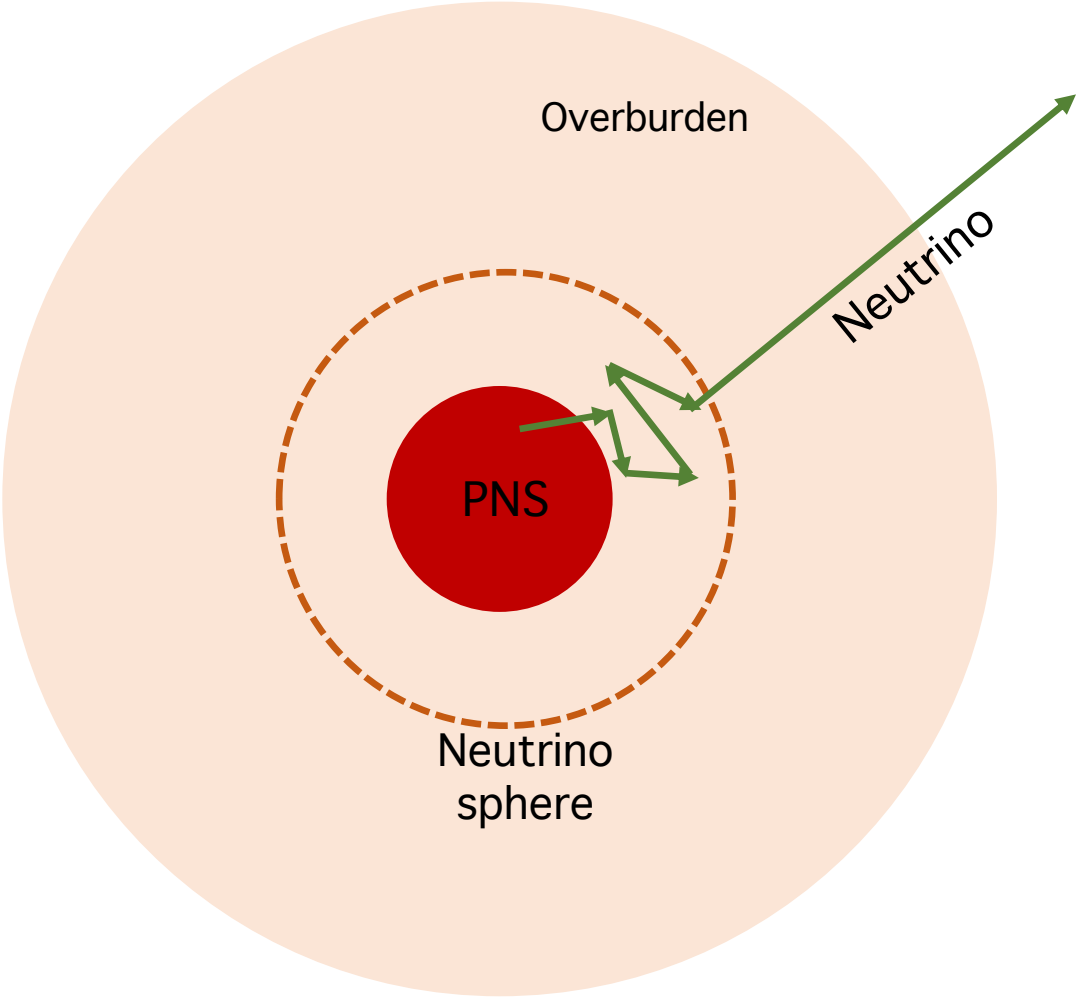
- Collapse of iron core leads to explosion (**>10^{53} erg**)



Supernovae

- PNS: *protoneutron star*
  - r ~ 10 km
  - T ~ 40 MeV
  - Nuclear density

- Neutrinos emitted from 'neutrino sphere,' cooling PNS in ~10 seconds



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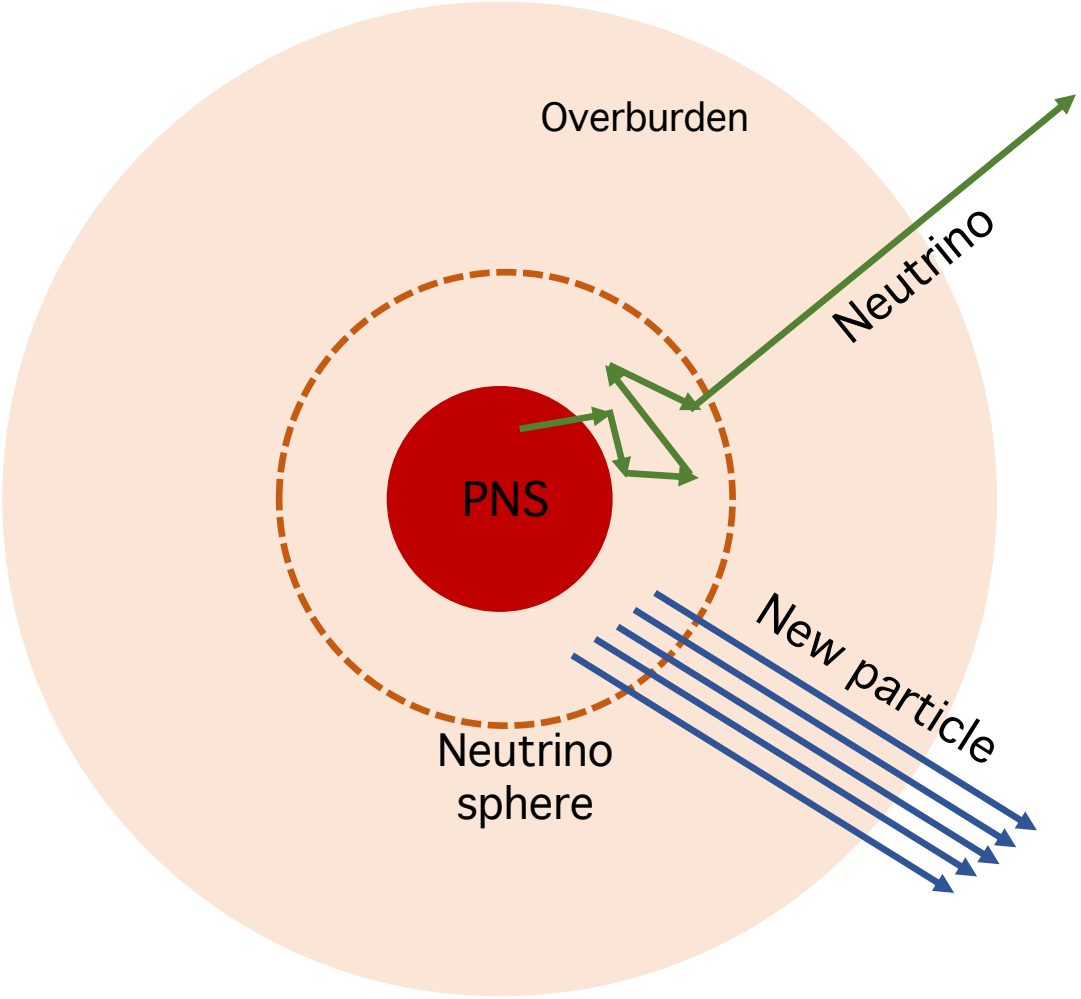
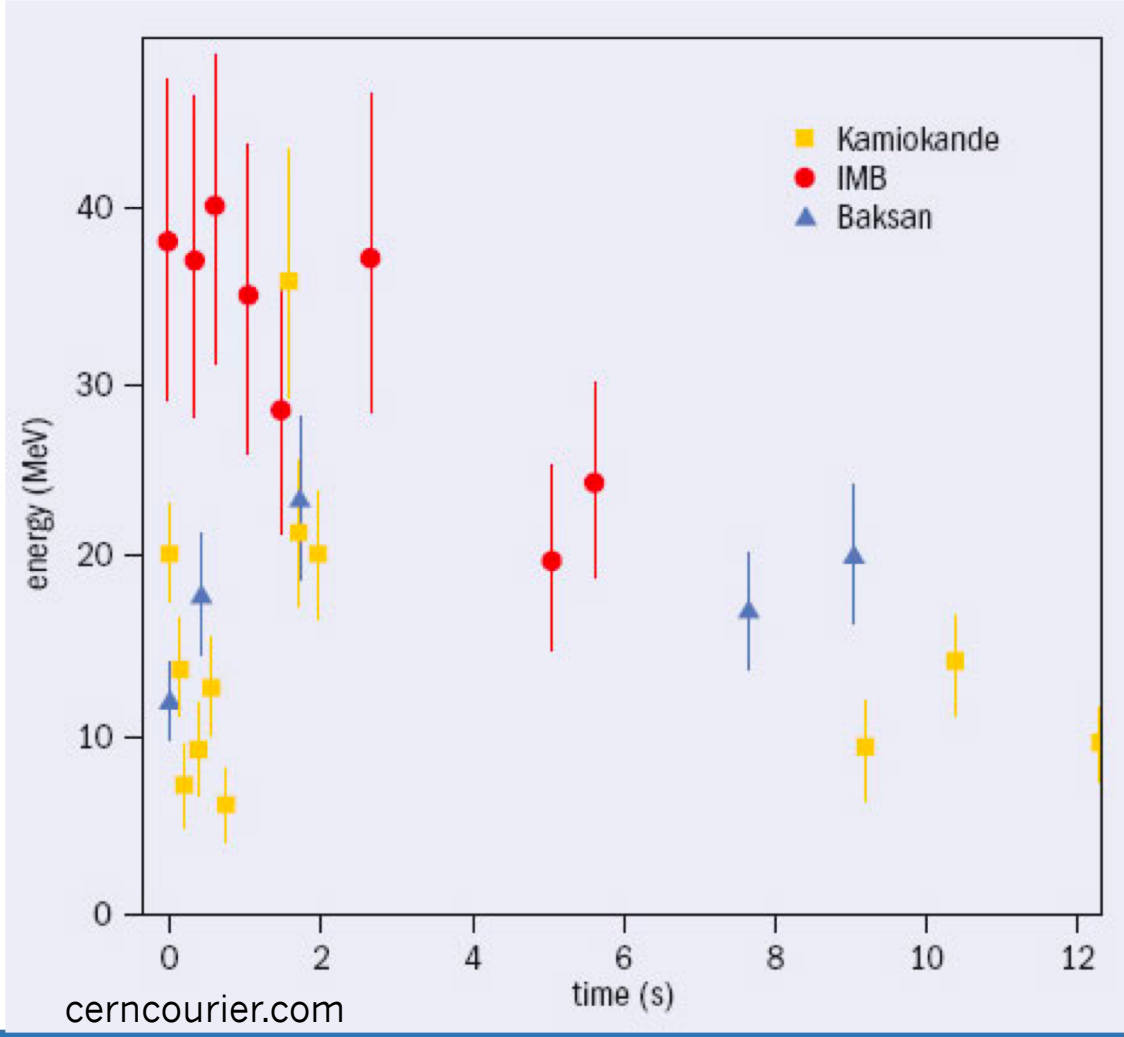
- **Cooling constraint:** new particle cannot transfer more energy than neutrinos



SN1987A

- Blue supergiant in Large Magellanic Cloud
- Neutrinos arrived over ~10 seconds (cooling timescale)
- Recent observations suggest cooling neutron star (Cigan et al., Oct. 2019; Page et al., May 2020)



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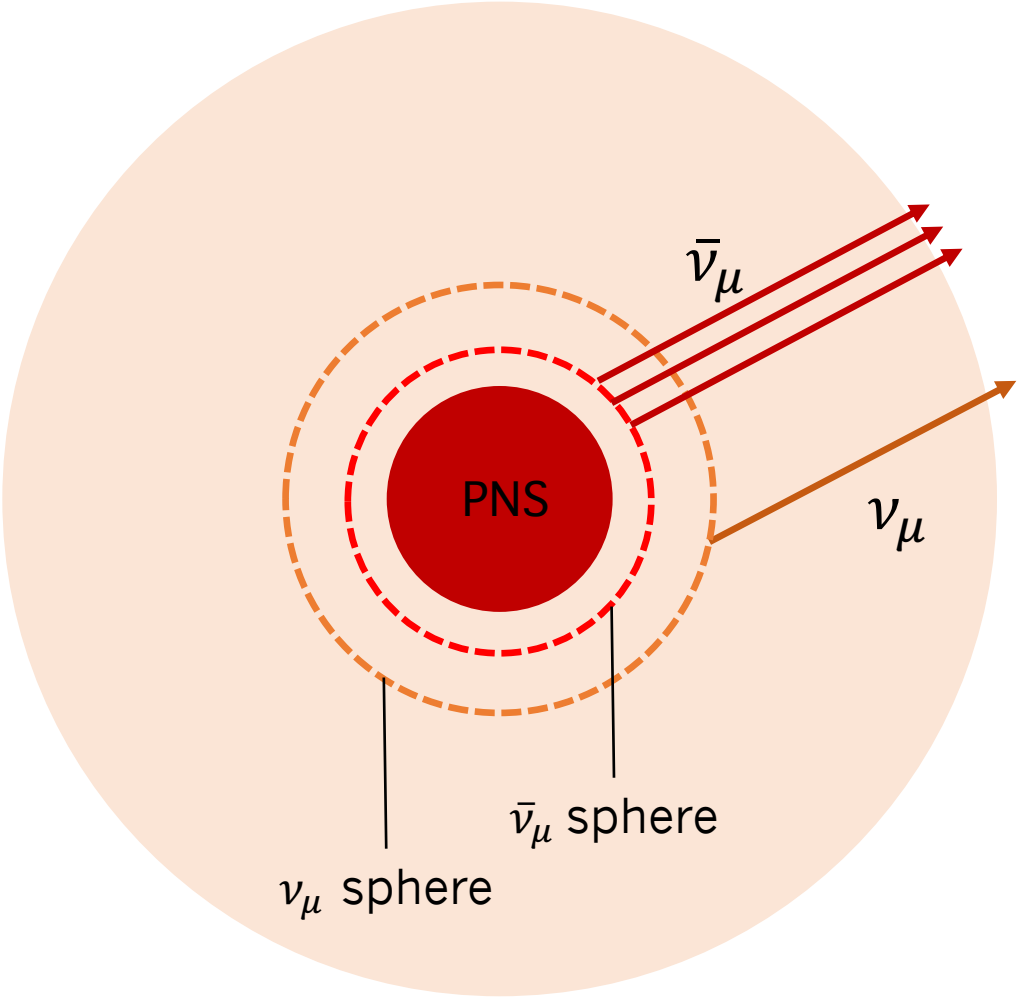
There are muons in supernovae! (June 2017)

- Boltzmann suppression small
  - $\gamma\,\gamma \rightarrow \mu^{+}\mu^{-}$, etc.
- Electron degeneracy above muon mass
  - $e^{-} \rightarrow \mu^{-}\,\nu_{e}\,\bar{\nu}_{\mu}$
- 'Muonization': $\bar{\nu}_{\mu}$ escape more easily than ν_{μ}



Muons help supernovae explode

Electron energy converted to muon rest mass

↓

Softer equation of state

↓

Higher temperature

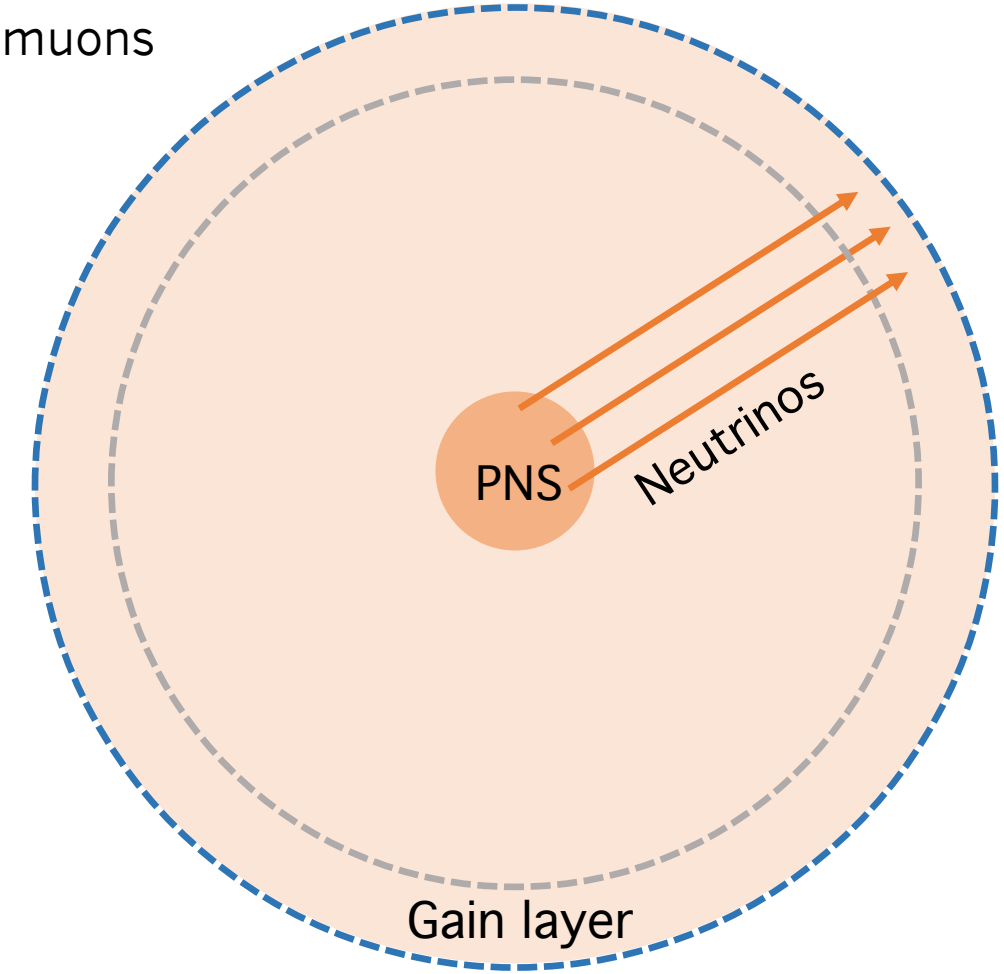
↓

Higher neutrino energy

↓

More efficient heating of gain layer

Without muons



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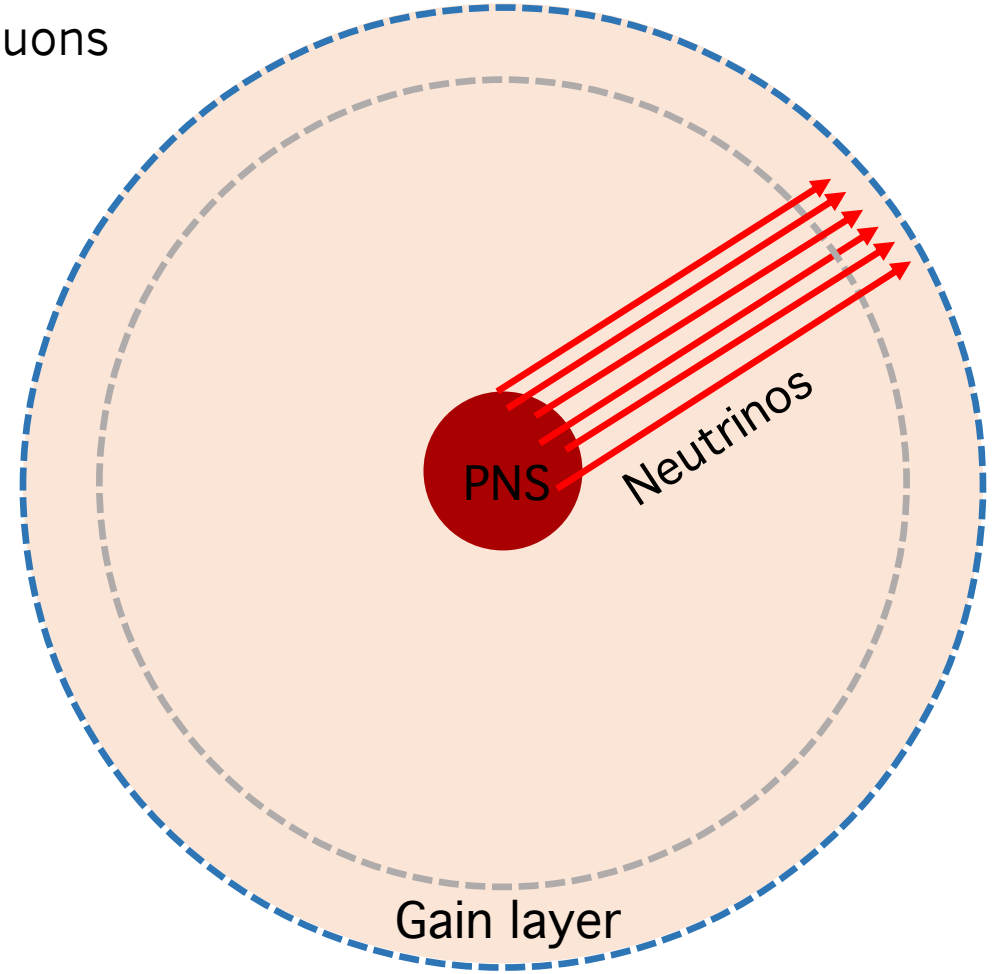
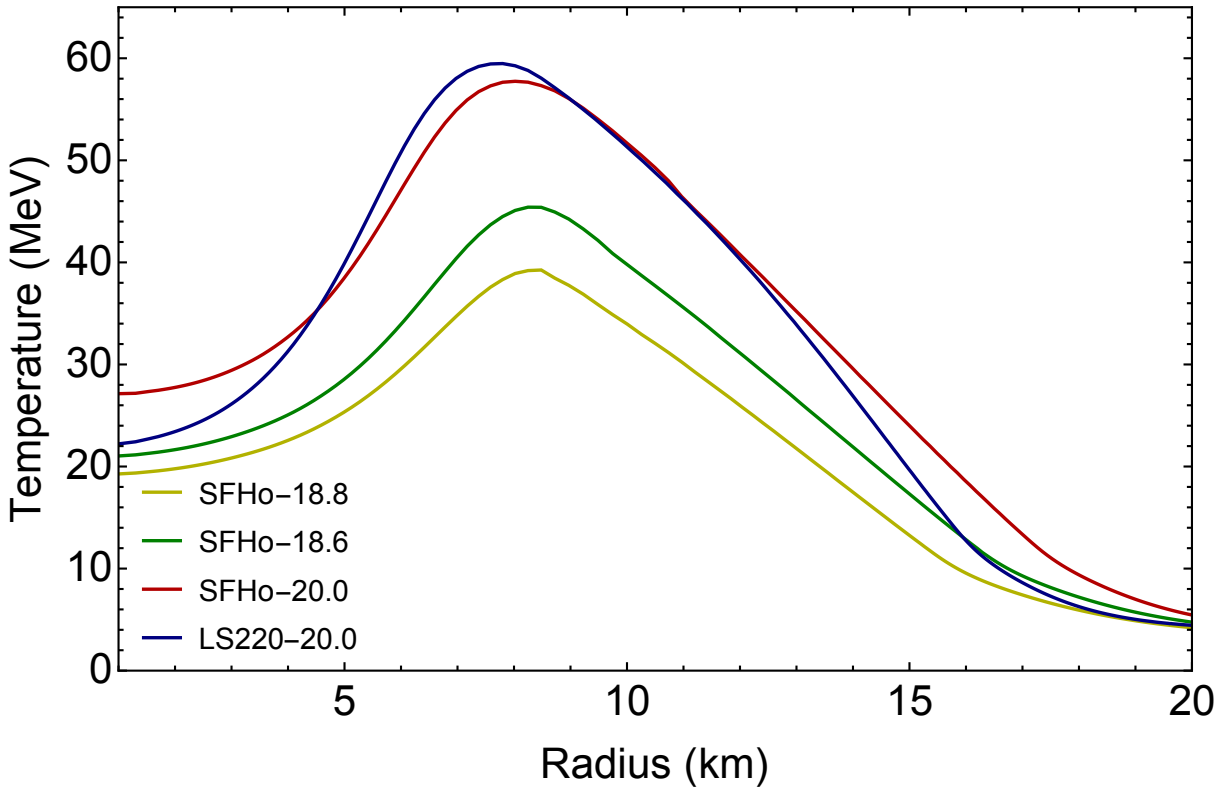


Simulations

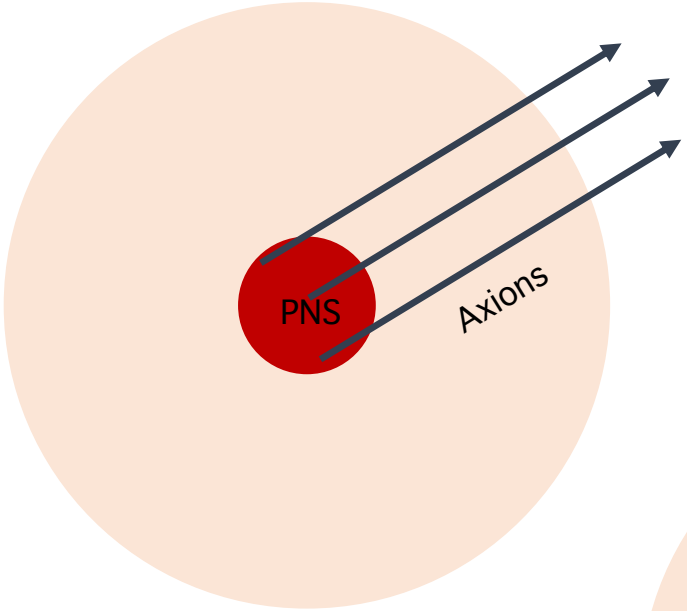
- Full simulations with multiple NS masses
  - GR corrections
  - Six-species neutrino transport
  - Full set of neutrino interactions
  - PNS convection
  - Seven weeks on supercomputer…
- First library of profiles with muons included
- Available to anyone!



Model name	Equation of state	Progenitor mass ($M_\odot$)	NS bary. mass ($M_\odot$)	NS grav. mass ($M_\odot$)
SFHo-18.8	SFHo [47]	18.8 [48]	1.351	1.241
SFHo-18.6	SFHo [47]	18.6 [49]	1.553	1.406
SFHo-20.0	SFHo [47]	20.0 [50]	1.947	1.712
LS220-20.0	LS220 [51]	20.0 [50]	1.926	1.707

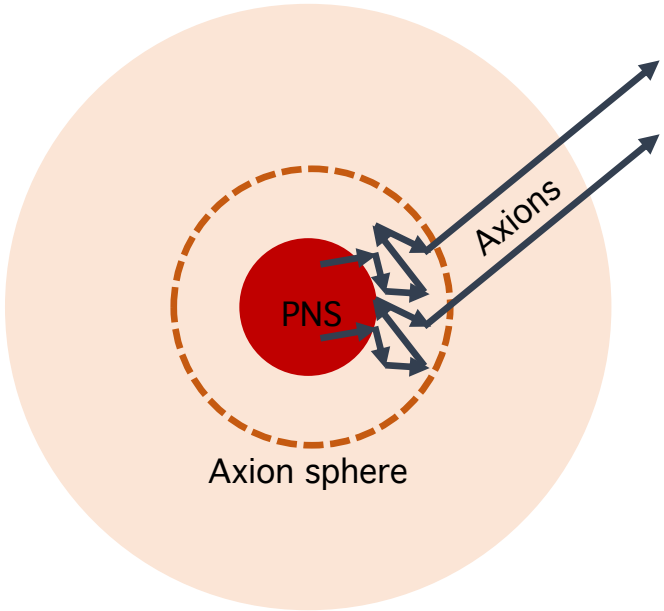
Axion cooling

- Produced by Compton scattering and bremsstrahlung
- *Free-streaming regime:* axions escape PNS without interacting
- *Trapping regime:* rapid reabsorption/reemission out to ‘axion sphere’



Free-streaming

Trapping

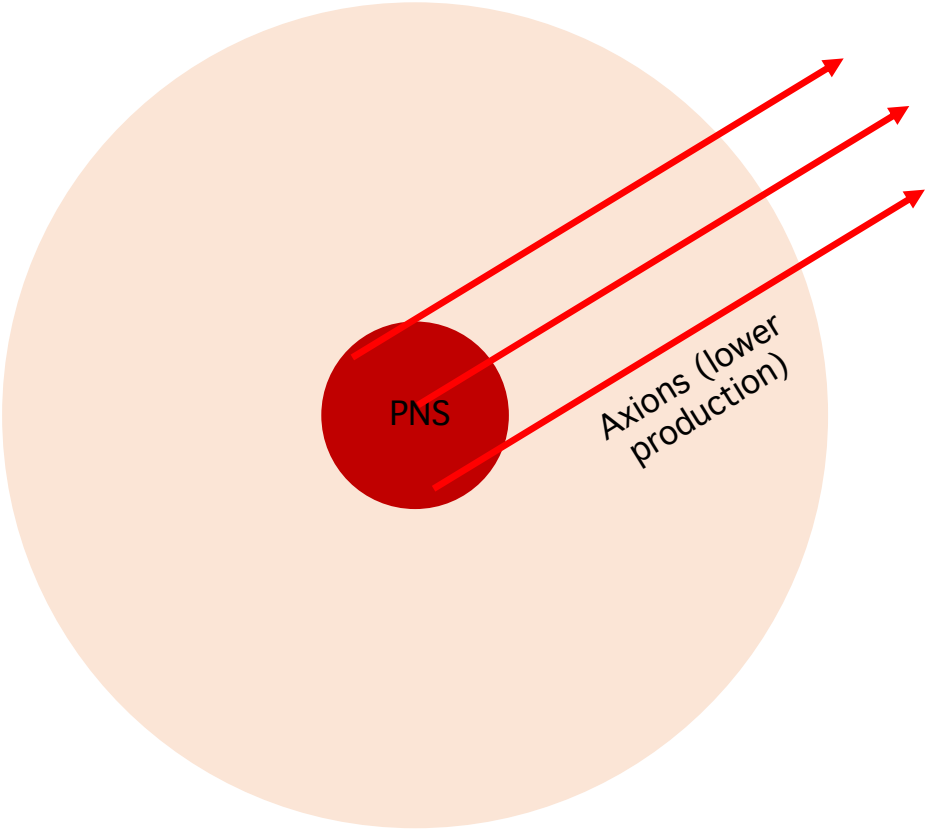


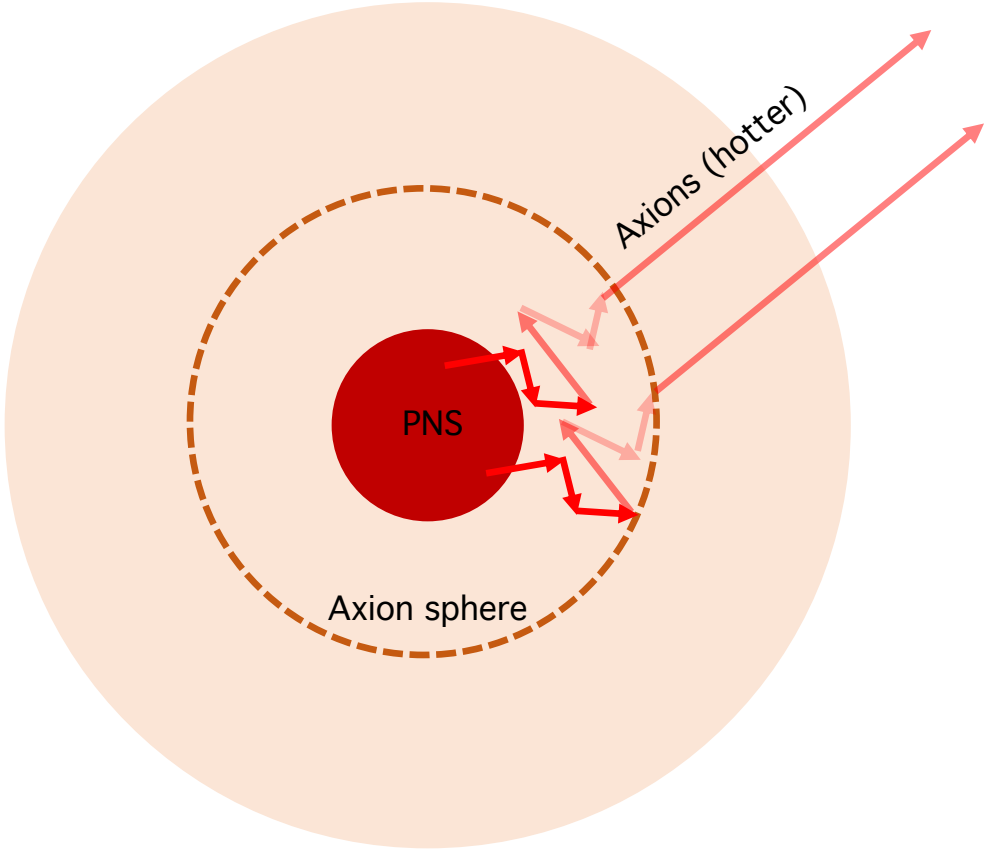
Different regimes

Free-streaming

Weaker coupling

Trapping



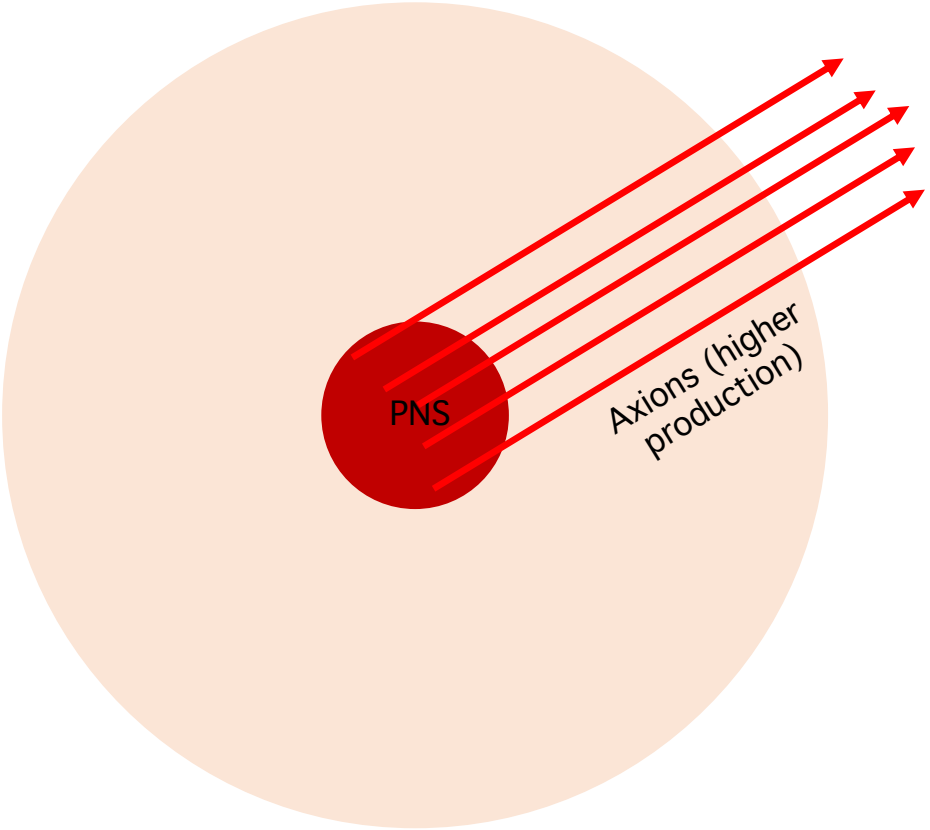


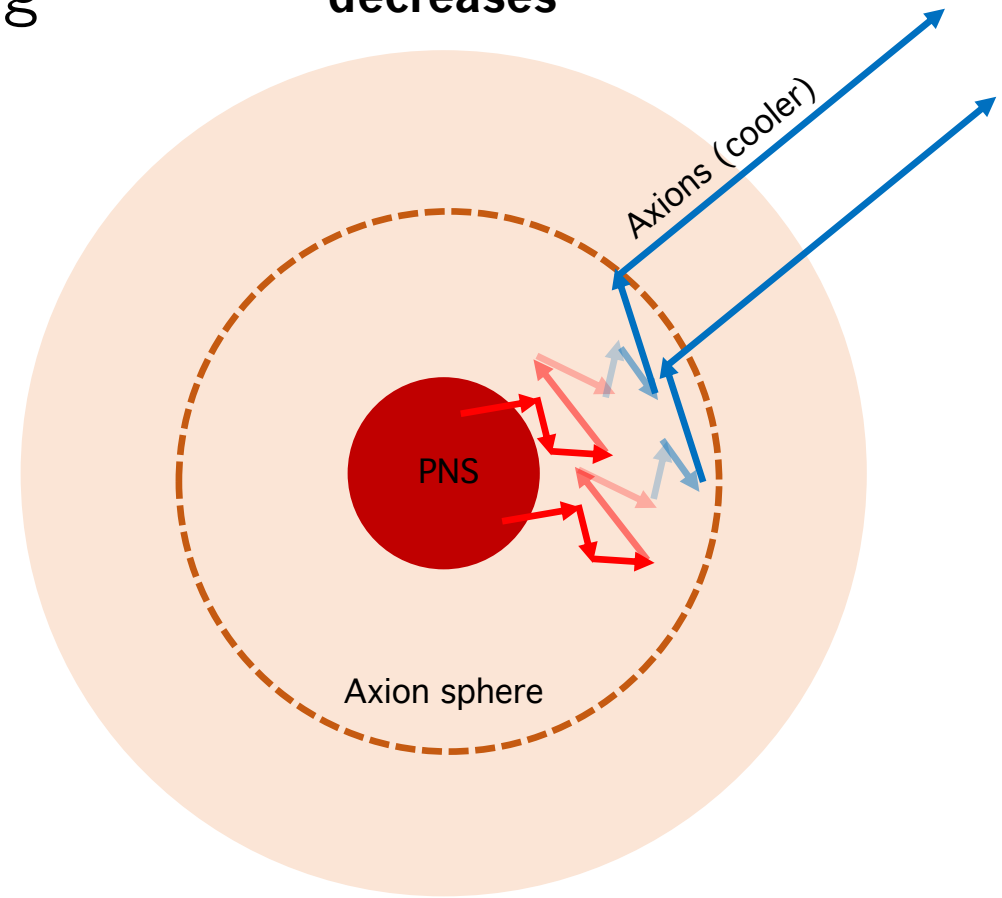
Different regimes

Free-streaming luminosity **increases**

Stronger coupling

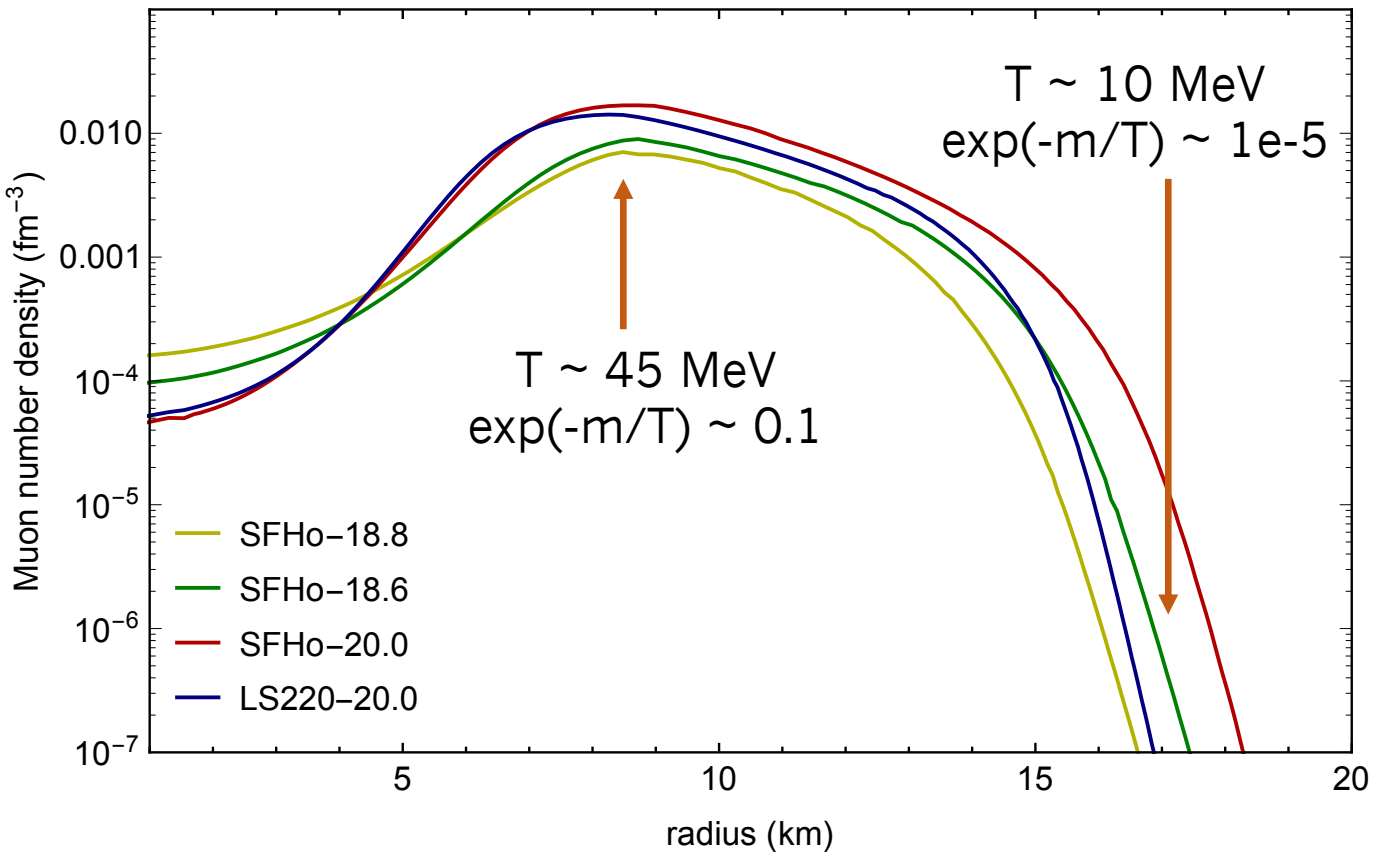
Trapping luminosity **decreases**





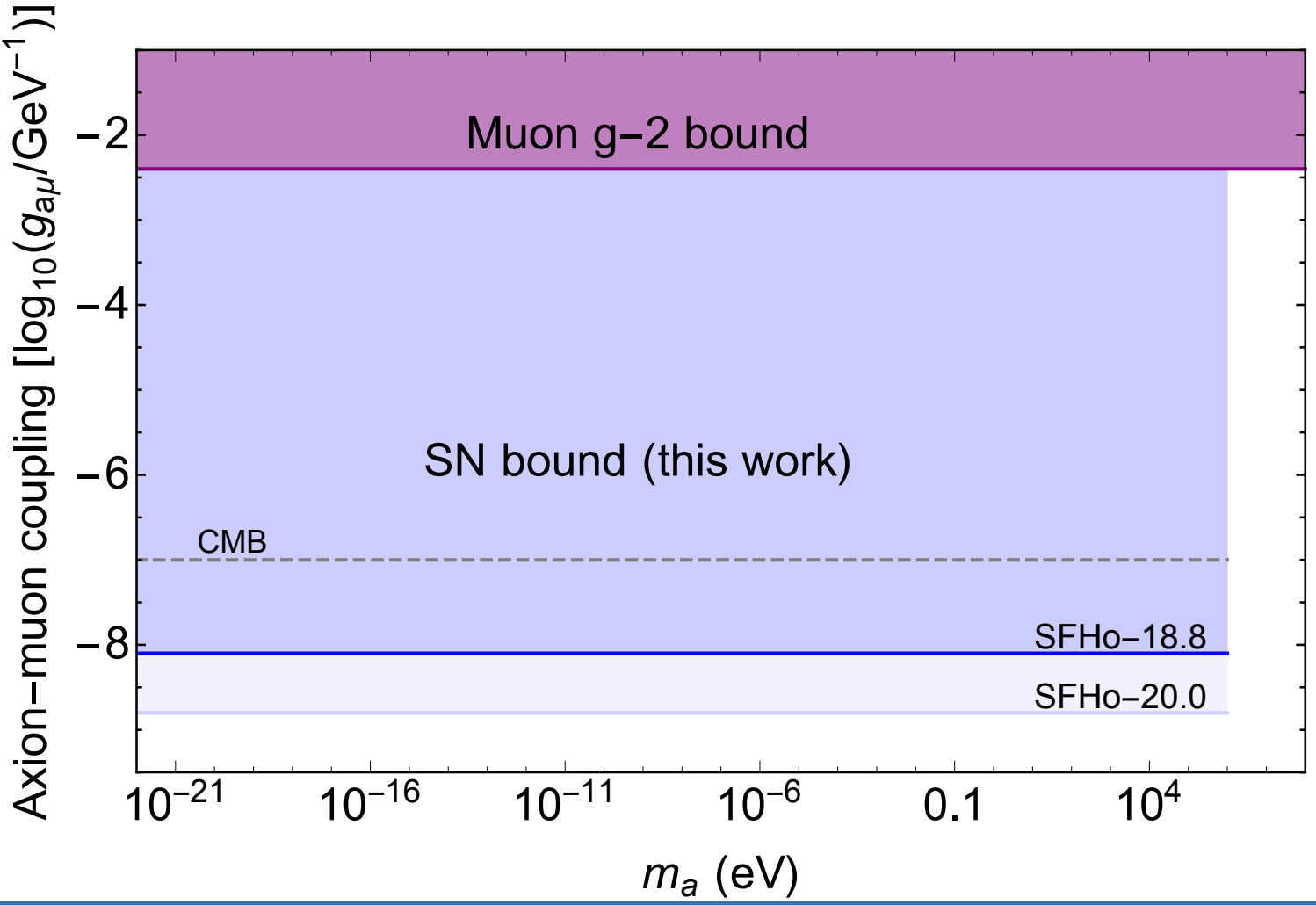
Axion sphere

- Muon abundance falls rapidly with temperature
- Axion sphere approaches ~18 km
- Trapping extends to high couplings
- Intermediate region excluded



Results

- Profile uncertainty well-controlled
- Just one example of new muon physics!



Takeaways

- **Part I:** Observations of SN neutrinos constrain new physics.

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Thank you for your attention!

Future work

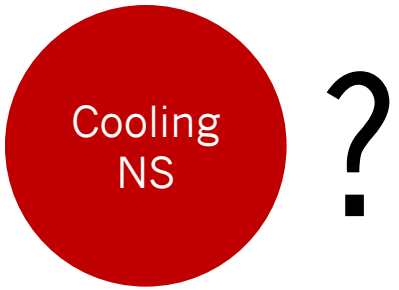
- Full dynamical simulations with axions included
- Signatures in intermediate regime?

H.-T. Janka

G. G. Raffelt

Lingering questions

- Compact remnant?
- Alternate mechanisms?



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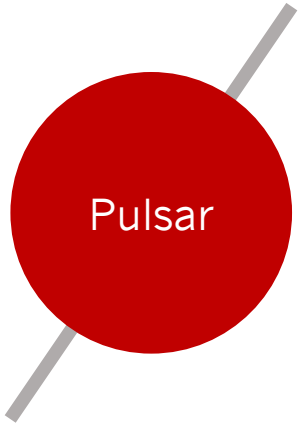

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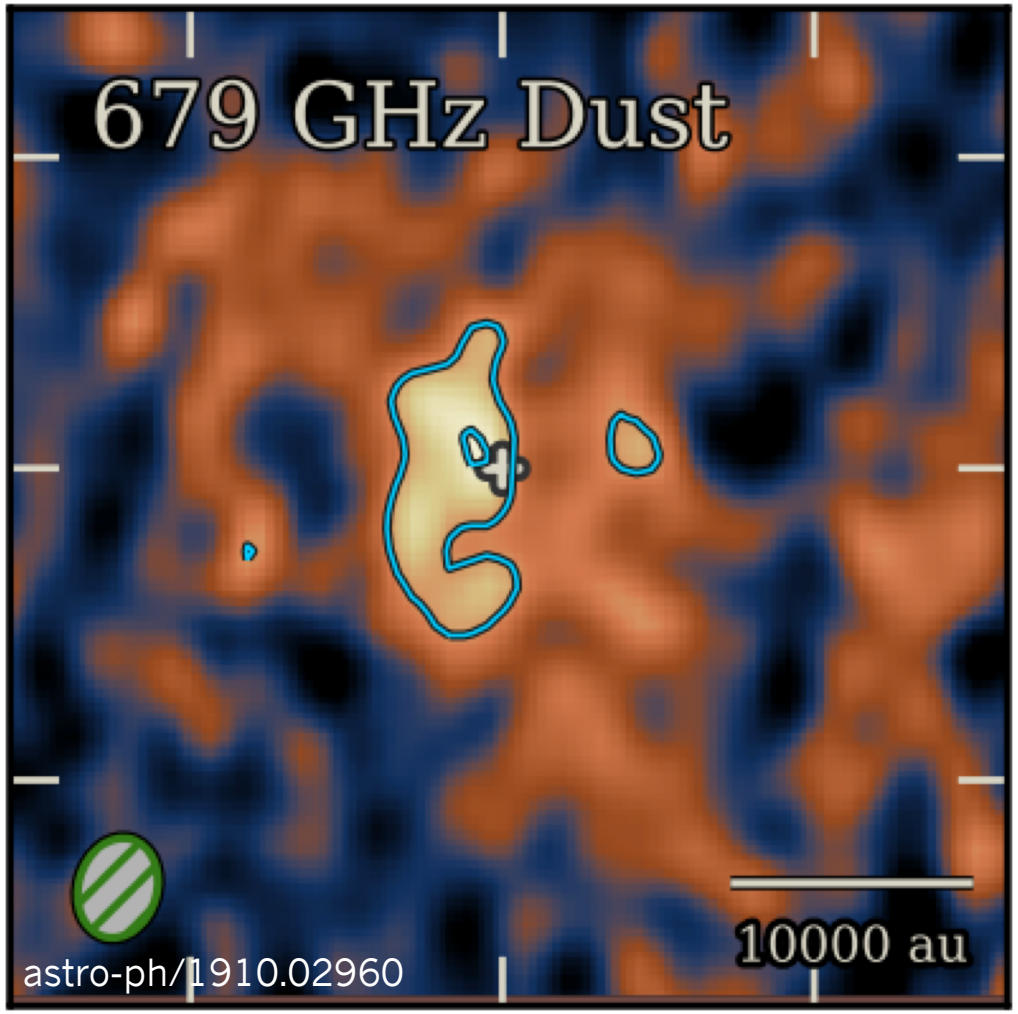
Evidence for neutron star

- ALMA observes “blob” of hot dust moving opposite to heavy elements (Cigan et al., Oct. 2019)
- Temperature consistent with NS cooling curve (Page et al., May 2020)
- Other explanations highly disfavored
  - Radioactivity too diffuse
  - Disjoint source too high energy



astro-ph/1910.02960

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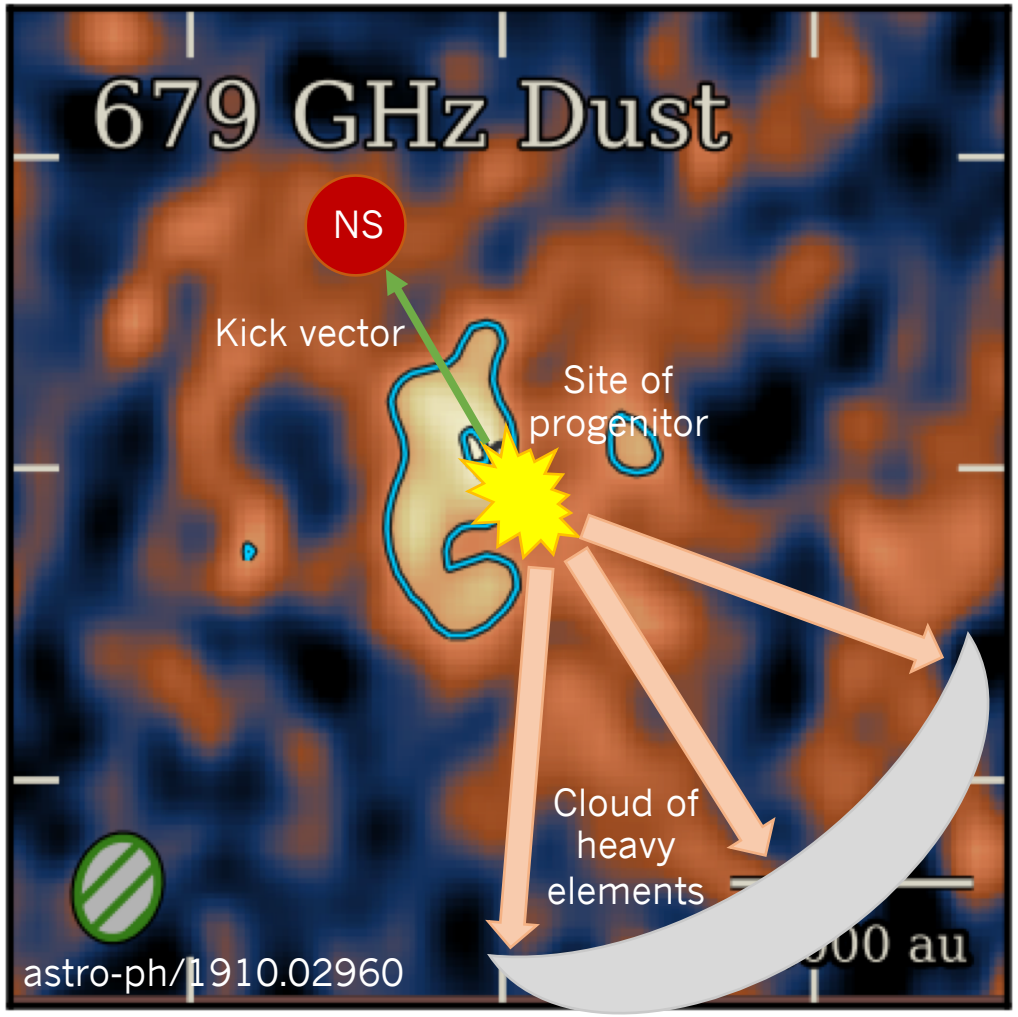

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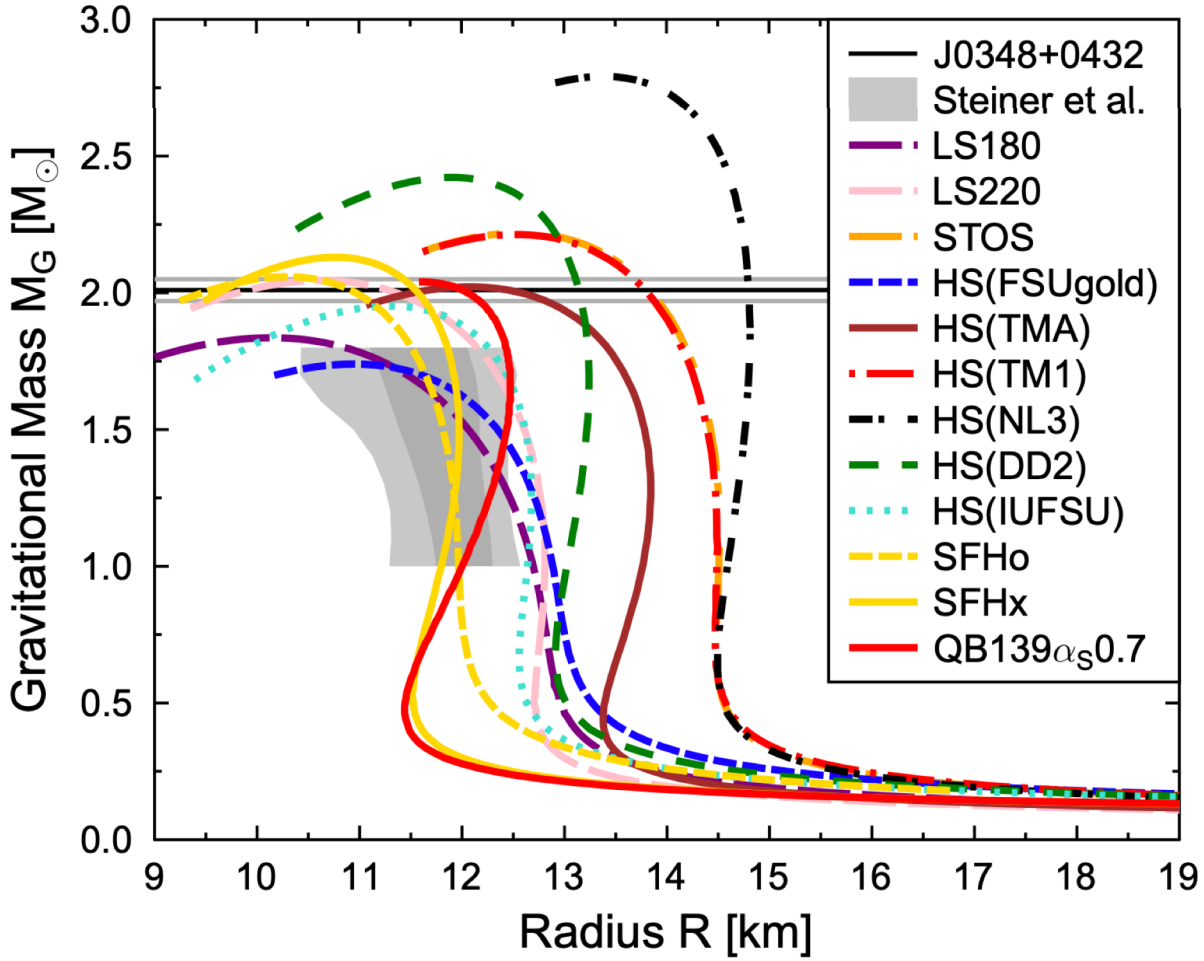
Takeaway 1:
Alternate mechanisms in increasing conflict with observations

New insights on neutron stars

- Improving constraints on equation of state (EoS)
  - X-ray bursts (Steiner et al. 2010, 2013)
  - Controlled EFT (Tews et al. 2018)
  - GW170817 (Capano et al. 2019)
  - High-mass radio pulsar (Cromartie et al. 2019)
  - NICER (Riley et al. 2019)

- EoS determines peak temperature in PNS



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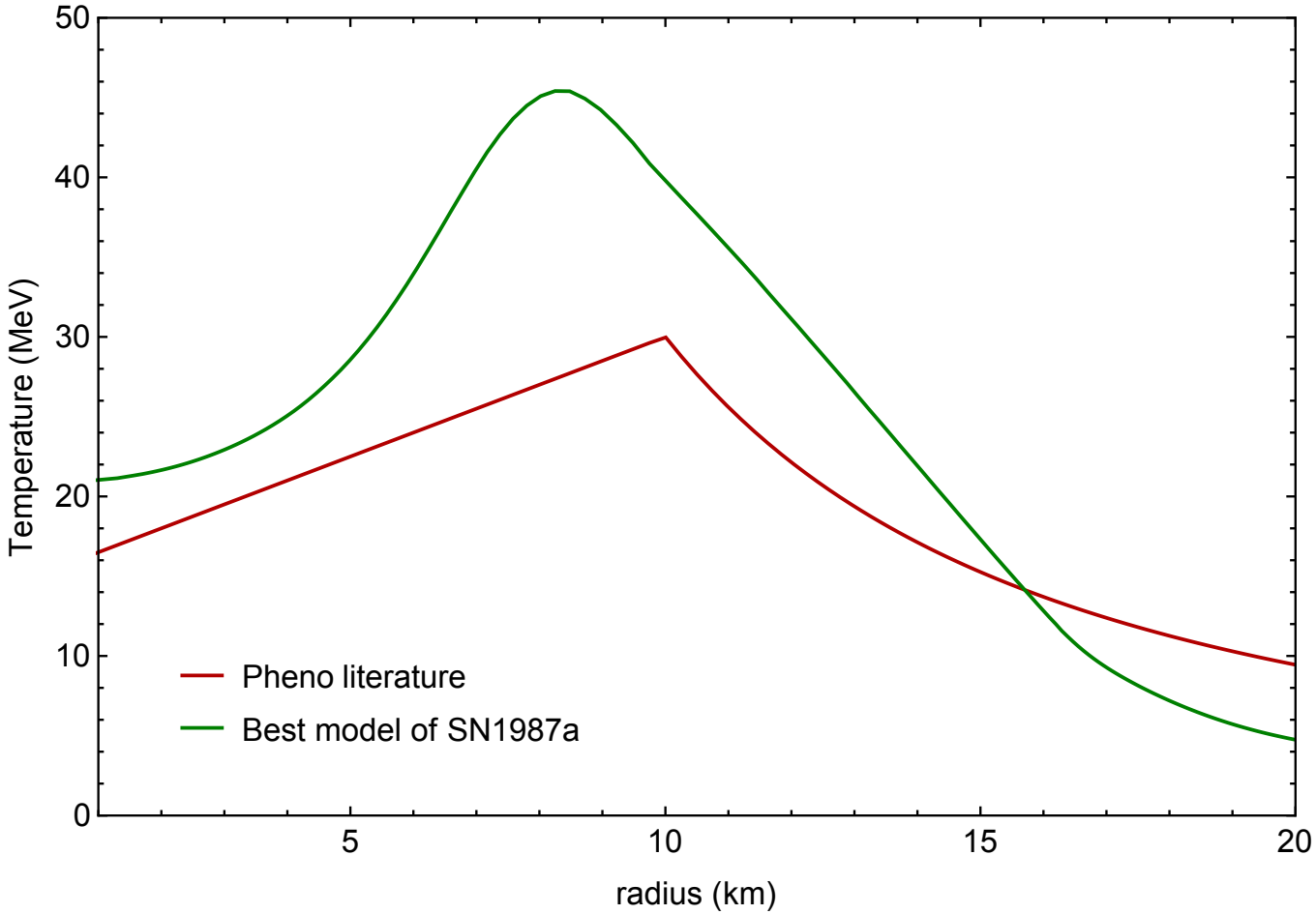
- What does this mean for BSM phenomenology?



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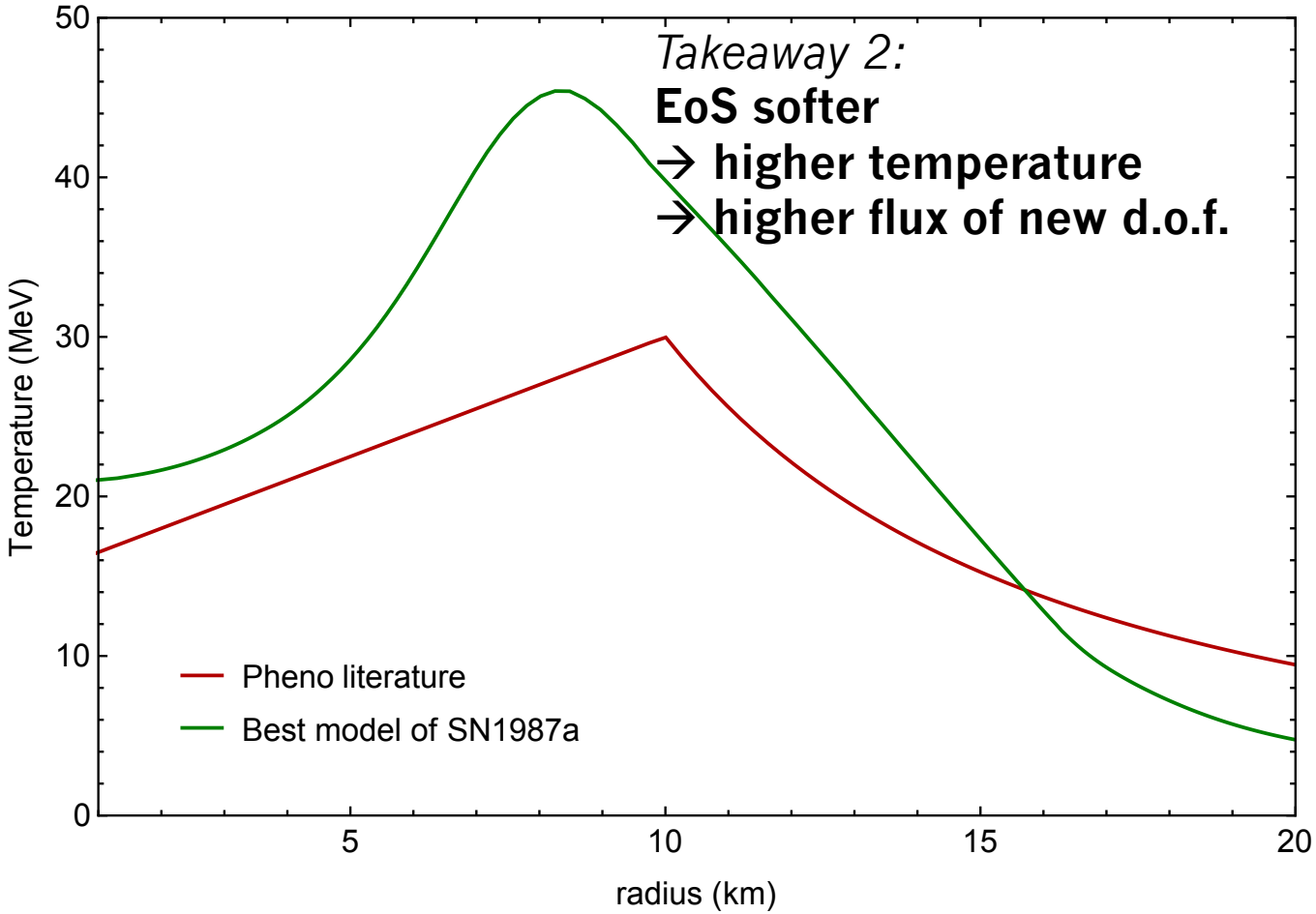
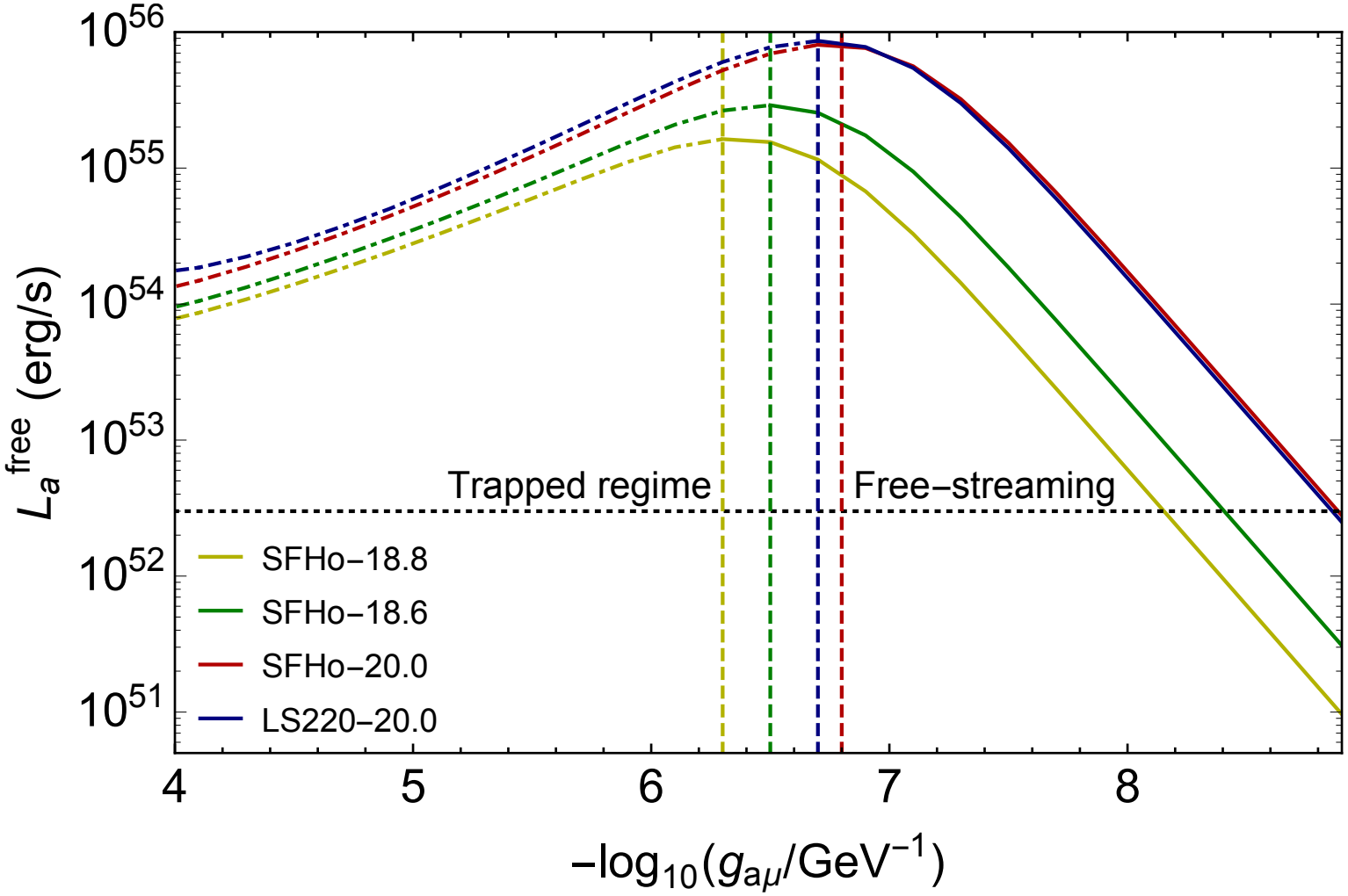


Luminosity

- $L_a > 3\times10^{52}$ erg/s excluded
- Transition between regions occurs smoothly
- Axion sphere approaches ~18 km in trapped regime



CITE Mechanism

- CCSN simulations consistent with:
  - Progenitor mass and radius
  - Supernova light curve
  - Observed neutrino spectrum
  - Observed amounts and distributions of ejected heavy elements
  - Observed asymmetric kick
  - Observed explosion energy
  - And now, inferred NS mass, temperature, and location

https://arxiv.org/pdf/2004.06078.pdf

- CITE consistent with:
  - Progenitor mass and radius
  - Observed neutrino spectrum
- CITE marginally consistent with:
  - Observed explosion energy

https://arxiv.org/pdf/1601.03422.pdf

ALMA Observation

- Could be thermal emission from surface or synchrotron from pulsar
- Heavy elements receding with right kick
- Compact object coming towards us

In summary, we suggest that the dust blob seen in the ALMA Cycle 2 Band 9 images could be due to dust heated by the compact object and potentially an emergence of a pulsar wind nebula based on the following arguments: (i) we expect a compact source to be present; (ii) we see one and only one blob which is difficult to reconcile with the expected geometry of ^{44}Ti; (iii) this scenario would produce a temperature increase at the location of the blob as proposed in this work; and (iv) the position of the dust blob is within the predicted SN kick, though towards the high end. However we caution that we only have one frequency band and as such, the nature of the dust peak is not clear: this argument is only valid if the blob is thermally or non-thermally heated emission from dust. Alternative possibilities, such as the direct detection of the compact object spectrum cannot be ruled out in this work.

https://arxiv.org/pdf/1910.02960.pdf

NS 1987A from SN 1987A

- Models show remnant of mass ~1.22-1.5 M_{sol}
- Lower than most pulsars, certainly lower than black holes
- Pulsar spin and magnetic field would also have to be “finely-tuned” over 4 orders of magnitude
- If blob disjoint from source, could be pulsar wind heating
- But observation of total luminosity would enforce pulsar to be weak and nearby
- Thermal just gives correct luminosity out of the box

https://arxiv.org/pdf/2004.06078.pdf

NS 1987A from SN 1987A

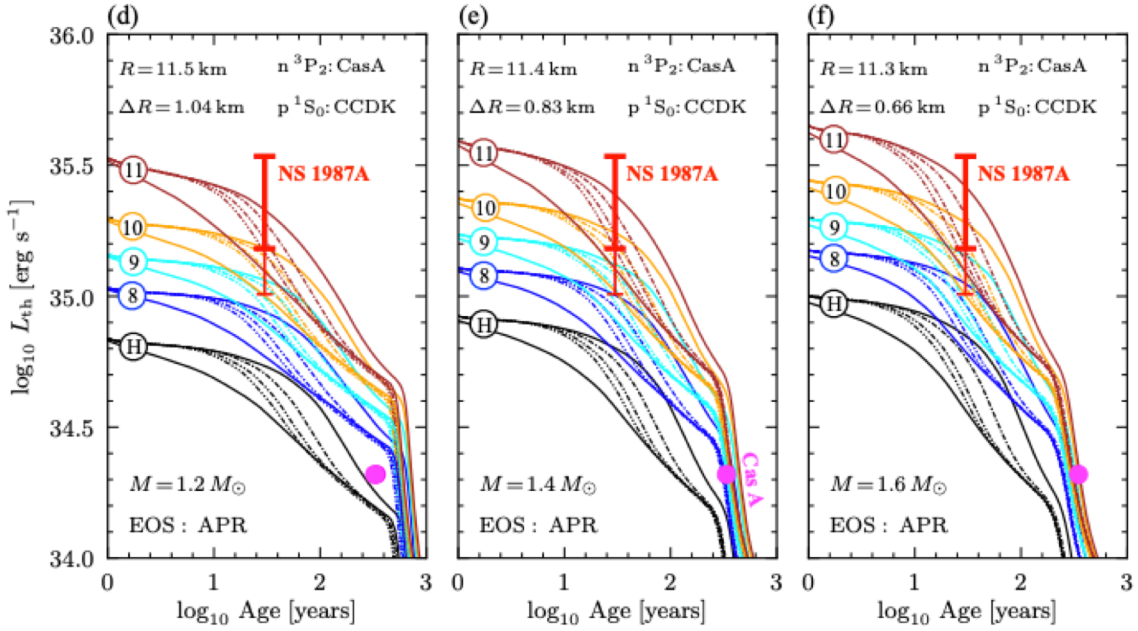
Table 1. Scenario Summary [Required power range taken from Fig. 2.]

Scenario/source	Expected power range	Advantages	Disadvantages
^{44}Ti heating	$L_{\rm Ti} \lesssim 13 L_\odot$ with radioactive heating to 22 K.	^{44}Ti is observed in the remnant of SN 1987A.	The required blob mass is too large; the blob is also optically thin to γ-rays.
compact object: neutron star or black hole		Blob's location offset from progenitor's and matches the kick velocity predictions from asymmetrical distributions of ^{56}Co and ^{44}Ti. This kick speed agrees with the known pulsar distribution.	
neutron star		SN 1987A simulations imply $1.22\,M_\odot \leq M \leq 1.62\,M_\odot$. The SN 1987A ν signal implies $0.98\,M_\odot \leq M \leq 1.81\,M_\odot$. Both imply $M < M_{\rm max}$.	
thermal emission	$5.8\,L_\odot - 72\,L_\odot$	$L_{\rm th} > 26\,L_\odot$ needs little fine-tuning. Evolution consistent with Cas A. Possible light-element envelope is compatible with surrounding dust and CO, SiO molecules; survival of this envelope supported by theory. Decent chance SNRs have CCOs.	$L_{\rm th}$ is likely insufficient unless the neutron star is inside the blob.
pulsar spindown	$3{\cdot}10^{-3}\,L_\odot - 3{\cdot}10^{5}\,L_\odot$	The pulsar does not have to be embedded in the blob. $W > 26\,L_\odot$ is possible.	$W < 138\,L_\odot$ from SNR observations, so the pulsar must be close to the blob. W and pulsar location require fine-tuning. B_p/P^2 also requires fine-tuning.
accretion	$\lesssim 3.4{\cdot}10^{5}(M/M_\odot)\,L_\odot$	$L_{\rm acc} > 26\,L_\odot$ is possible.	$L_{\rm acc}$ requires fine-tuning.
black hole			SN 1987A progenitors have small core masses; also, SN 1987A's observed explosion energy was high, implying a small fallback mass. Both strongly suggest $M < M_{\rm max}$.
accretion	$\lesssim 3.4{\cdot}10^{5}(M/M_\odot)\,L_\odot$	$L_{\rm acc} > 26\,L_\odot$ is possible.	$L_{\rm acc}$ requires fine-tuning.

https://arxiv.org/pdf/2004.06078.pdf

How will ultimately know?

- Periodic variations in luminosity → pulsar
- Cooling evolution consistent with thermal emission → CCO
- Irregular variations → accretion source
- NuSTAR measurement of decay line → ^{44}Ti
- Further observation narrows error bars



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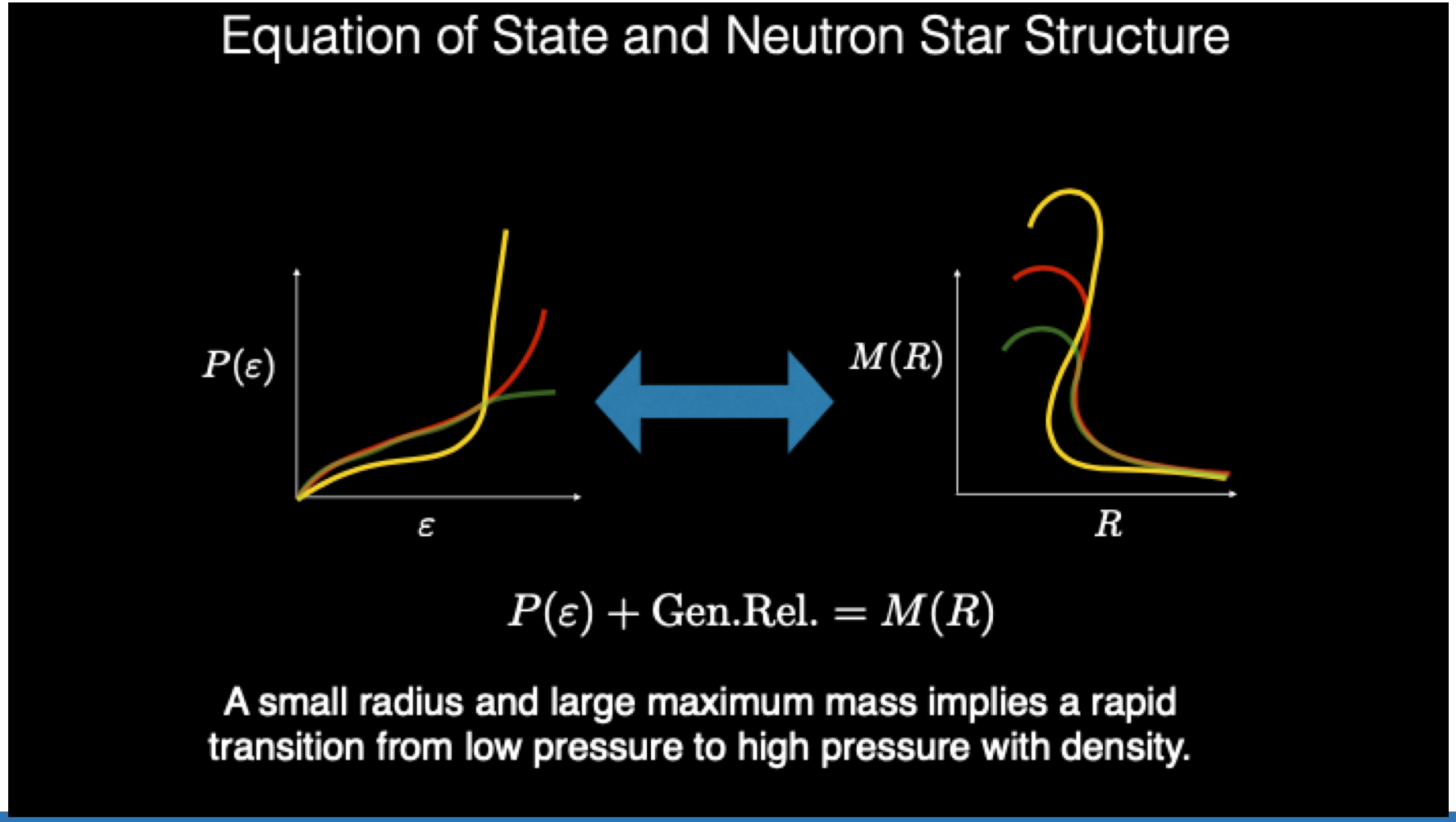
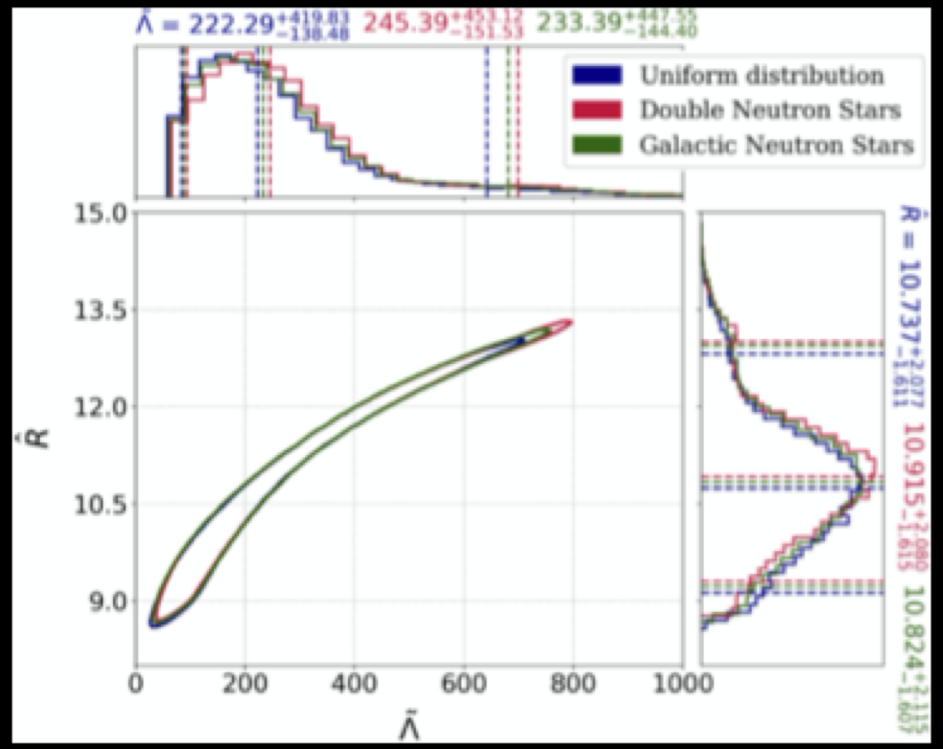
New EoS Measurements



New EoS Measurements

Neutron Stars are Small



Tidal deformations (not) observed in GW170817 implies a small NS radius:

R < 13 km

Requiring a maximum mass greater than 2 M_{sun} **implies:**

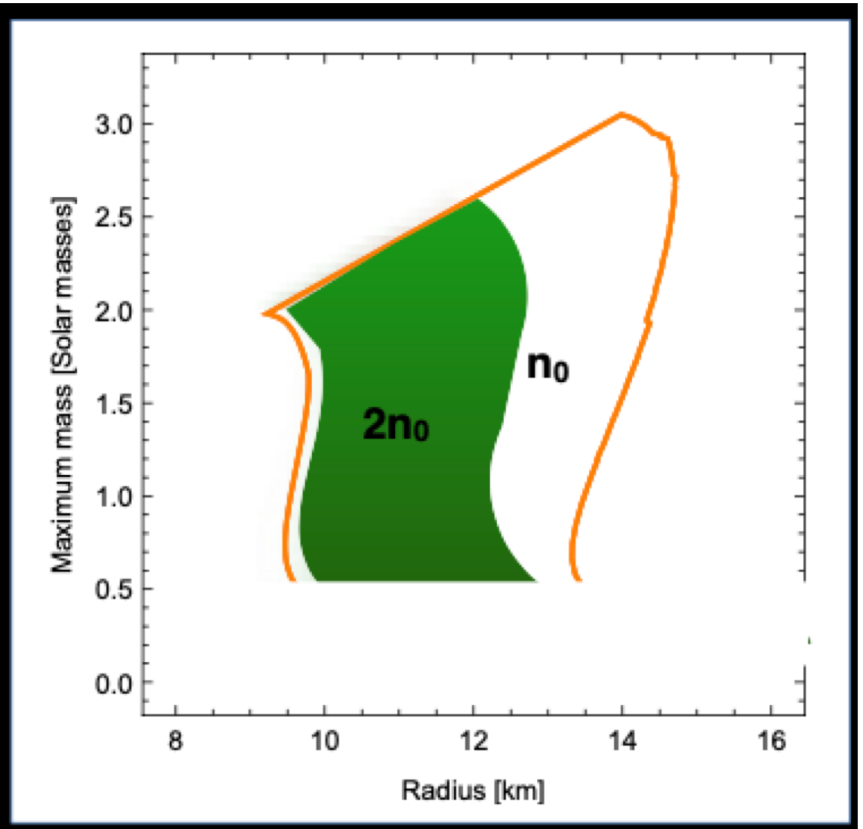
R > 9 km

De et al. PRL (2018)
See also LIGO and Virgo Scientific Collaboration arXiV:1805.11581v1

New EoS Measurements

Dense matter EOS and NS structure

Neutron matter calculations and a general parameterization of the sound speed at higher density, constrained by 2 solar mass NS and $c_s < c$, constrain NS structure.



Tews, Gandolfi, Carlson, Reddy (2018), Tews, Margueron, Reddy (2018)
Hebeler, Schwenk, Lattimer and Pethick (2010,2013) and Carlson, Gandolfi, Reddy (2012)

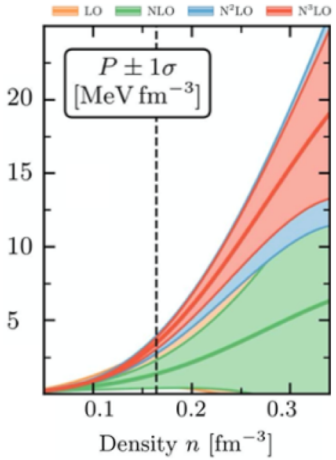
Equation of State of Neutron Matter

Quantum many-body calculations of neutron matter using EFT potentials appear to converge up to twice nuclear saturation density.

There remain some open questions about how to regulate the theory and best practicers to estimate errors.

	Tews et al. (QMC, N²LO)	Drischler et al. (MBPT)
$P(n_{sat})$	2.1 ± 0.7 MeV/fm^3	3.4 ± 0.7 MeV/fm^3
$P(2n_{sat})$	13 ± 7 MeV/fm^3	17 ± 4.5 MeV/fm^3

Hebeler and Schwenk 2009, Gandolfi, Carlson, Reddy 2010, Tews, Kruger, Hebeler, Schwenk (2013), Holt Kaiser, Weise (2013), Hagen et al. (2013), Roggero, Mukherjee, Pederiva (2014), Wlazlowski, Holt, Moroz, Bulgac, Roche (2014), Tews et al. (2018) Drischler, Furnstahl, Melendez, Phillips, (2020),



Drischler, Furnstahl, Melendez, Phillips (2020)

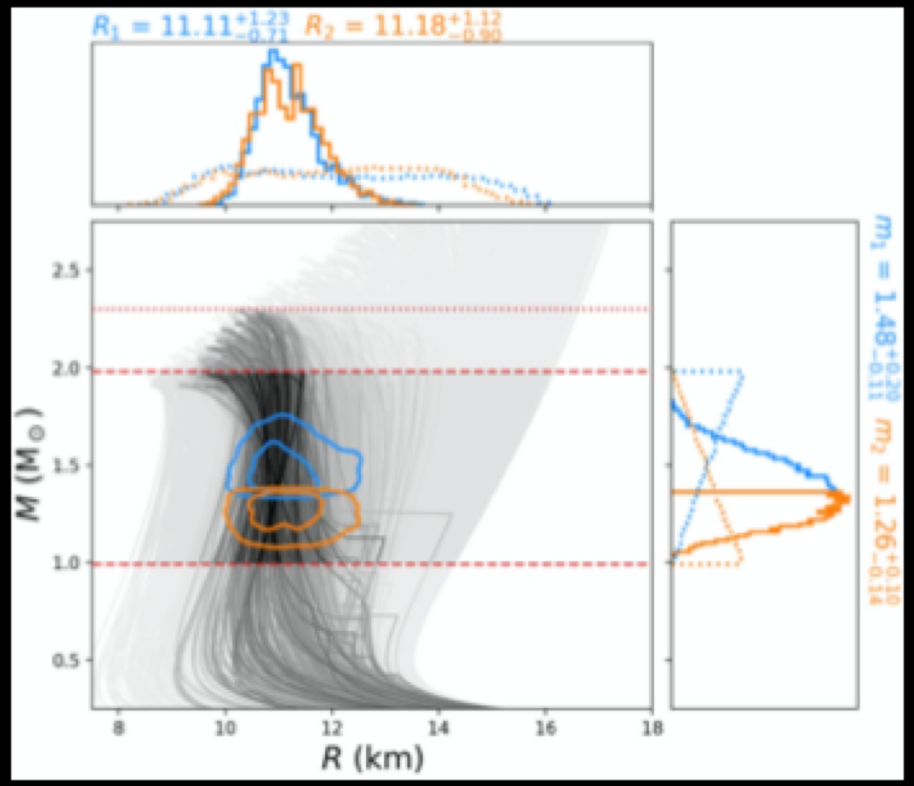
New EoS Measurements

Tighter Constraints: Combining Nuclear Physics and GW170817

Nuclear physics input correlates the neutron stars in the binary and provides an informed prior for GW data analysis. Helps extract stringent constraints on the NS radius:

$$R_{1.4} = 11.2 \; {}^{+1.2}_{-0.8} \; \text{km}$$

Lower bound is set by EM observations that disfavor the prompt collapse to a black-hole.



New EoS Measurements

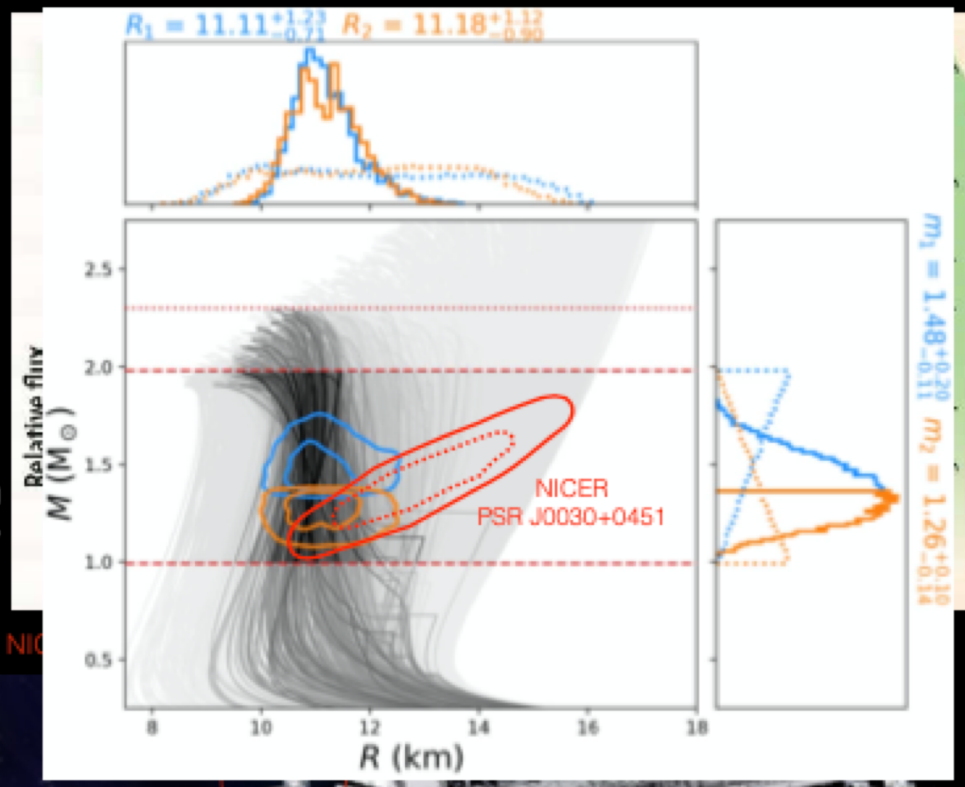
NICER: Radii from Hot Spots

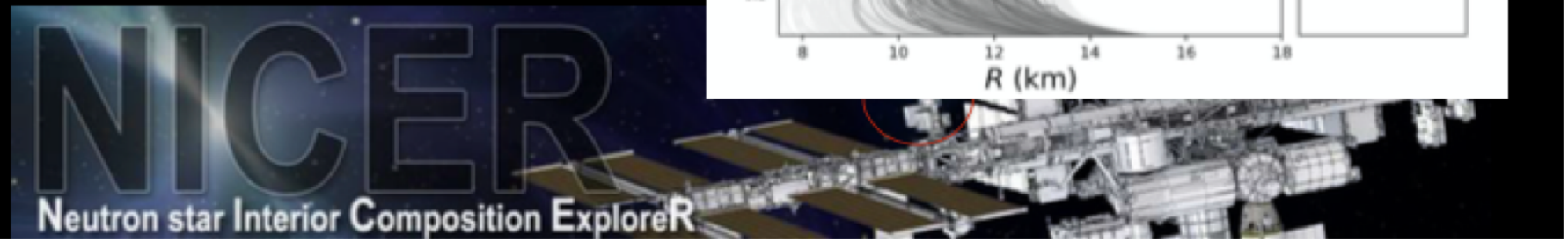
Emission from rotating neuron stars with hot spots is sensitive to the space-time geometry.

X-ray pulse profiles contain information about the source compactness.

NASA's NICER mission has acquired data from a couple of neutron stars. Data analyzed from one source is compatible with GW170817 but favors larger radii with larger errors.

Riley et al. (2019), Miller et al. (2019)





Muonization

- $\bar{\nu}_\mu$ escape more easily than ν_μ
- Weak magnetism effects: 15%

C. Weak Magnetism

The full weak vector current J_μ has Dirac (c_v) and Pauli or tensor (F_2) contributions,

$$J_\mu = c_v \gamma_\mu + F_2 \frac{i\sigma_{\mu\nu} q^\nu}{2M} \tag{10}$$

where $q_\mu = k_\mu - k'_\mu$ is the momentum transfered to the nucleon. The weak current J_μ is related by CVC (conserved vector current) to the electromagnetic current. Therefore the large anomalous magnetic moments of the proton and neutron give rise to a large F_2. The couplings c_v and F_2 are collected in table I.

The cross section to the first order in e is,

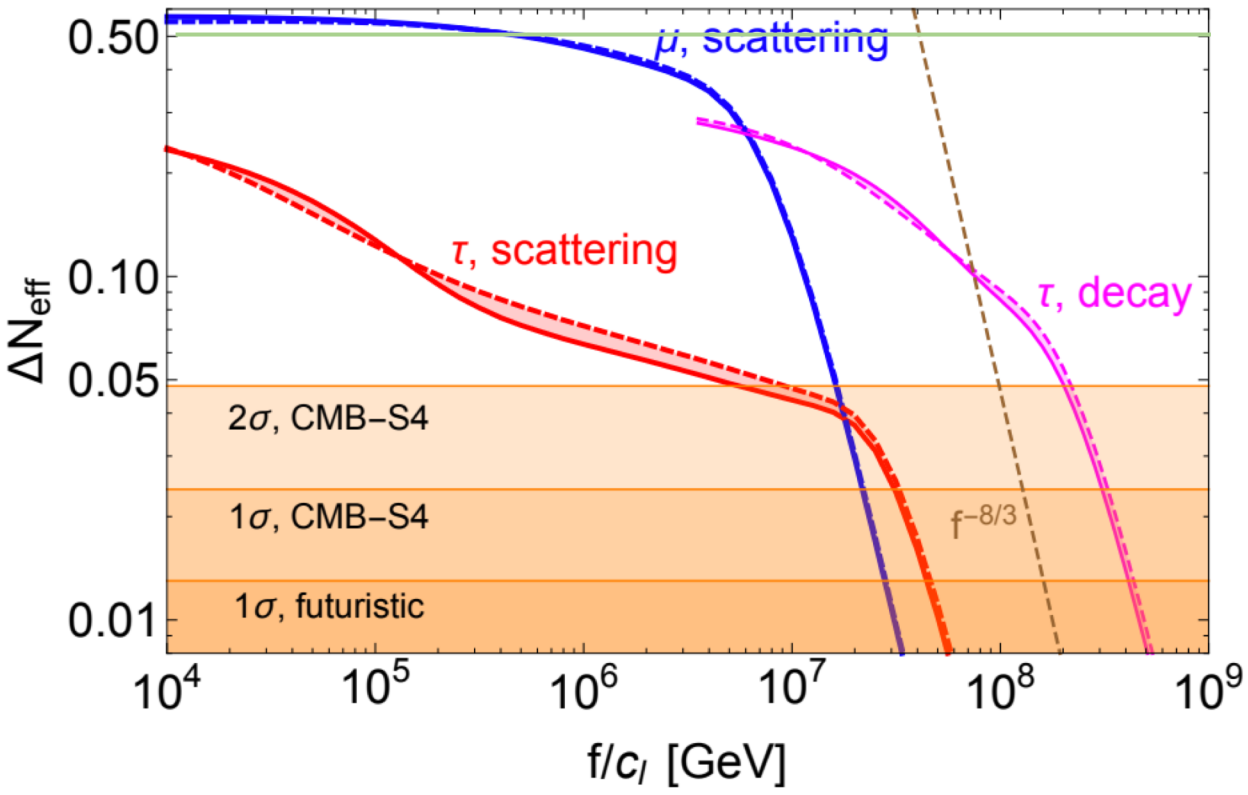
$$\frac{d\sigma}{d\Omega} \approx \frac{d\sigma_0}{d\Omega} \left[1 + \left(\pm \frac{4c_a(c_v + F_2)}{c_v^2(1+x) + c_a^2(3-x)} - 3 \right) e(1-x) \right], \tag{11}$$

with plus sign for ν and minus sign for $\bar{\nu}$. Weak magnetism increases ν and decreases $\bar{\nu}$, while recoil decreases both ν and $\bar{\nu}$ cross sections. Therefore weak magnetism and recoil corrections approximately cancel for ν but add for $\bar{\nu}$. Note, Burrows et al. [20], see also for example [21], include weak magnetism for the charged currents but neglect it for neutral currents. Equation (11) is a good approximation for ν. However it can become negative for large $\bar{\nu}$ energies. To cure this problem we include corrections to all orders in e.

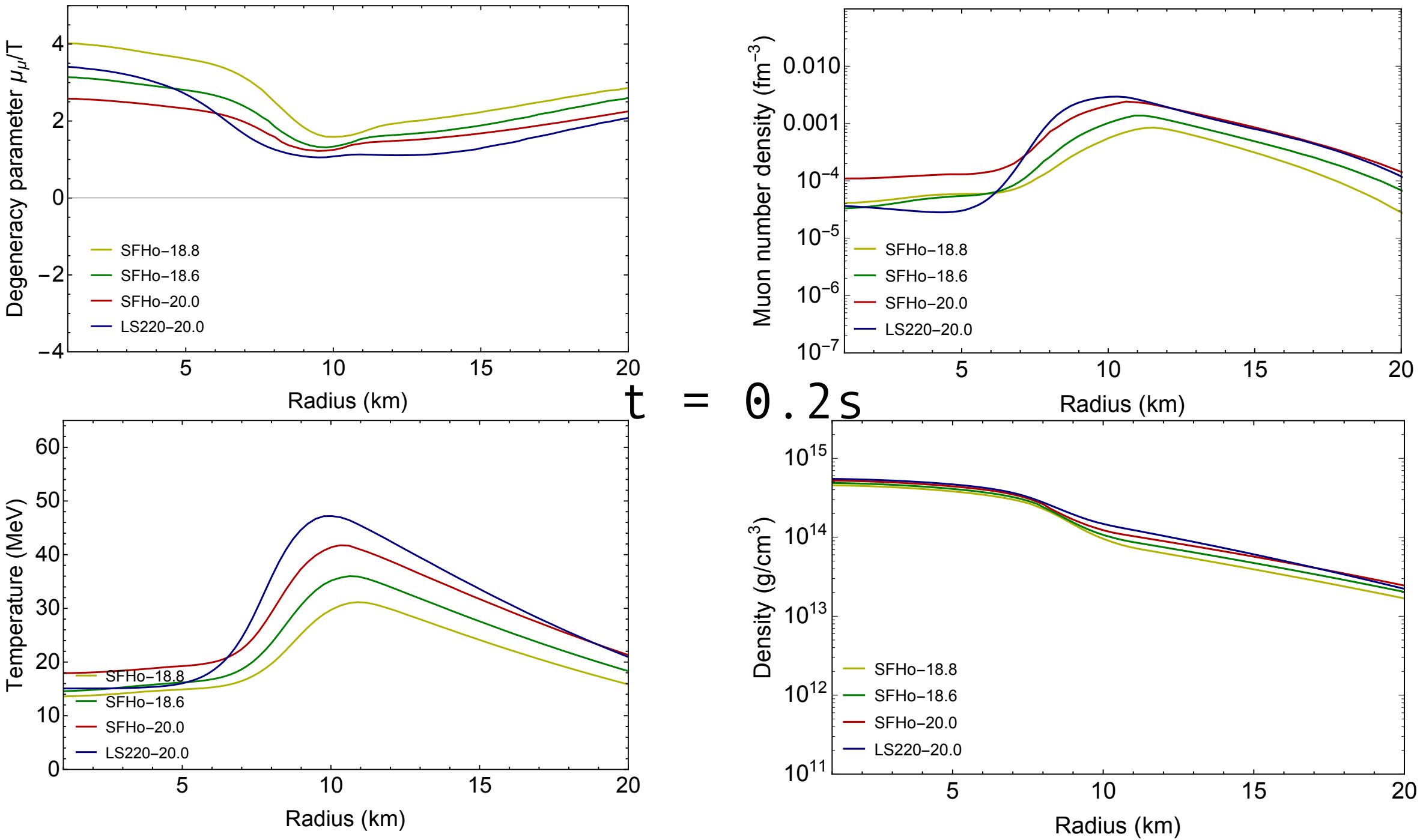
https://arxiv.org/pdf/astro-ph/0109209.pdf

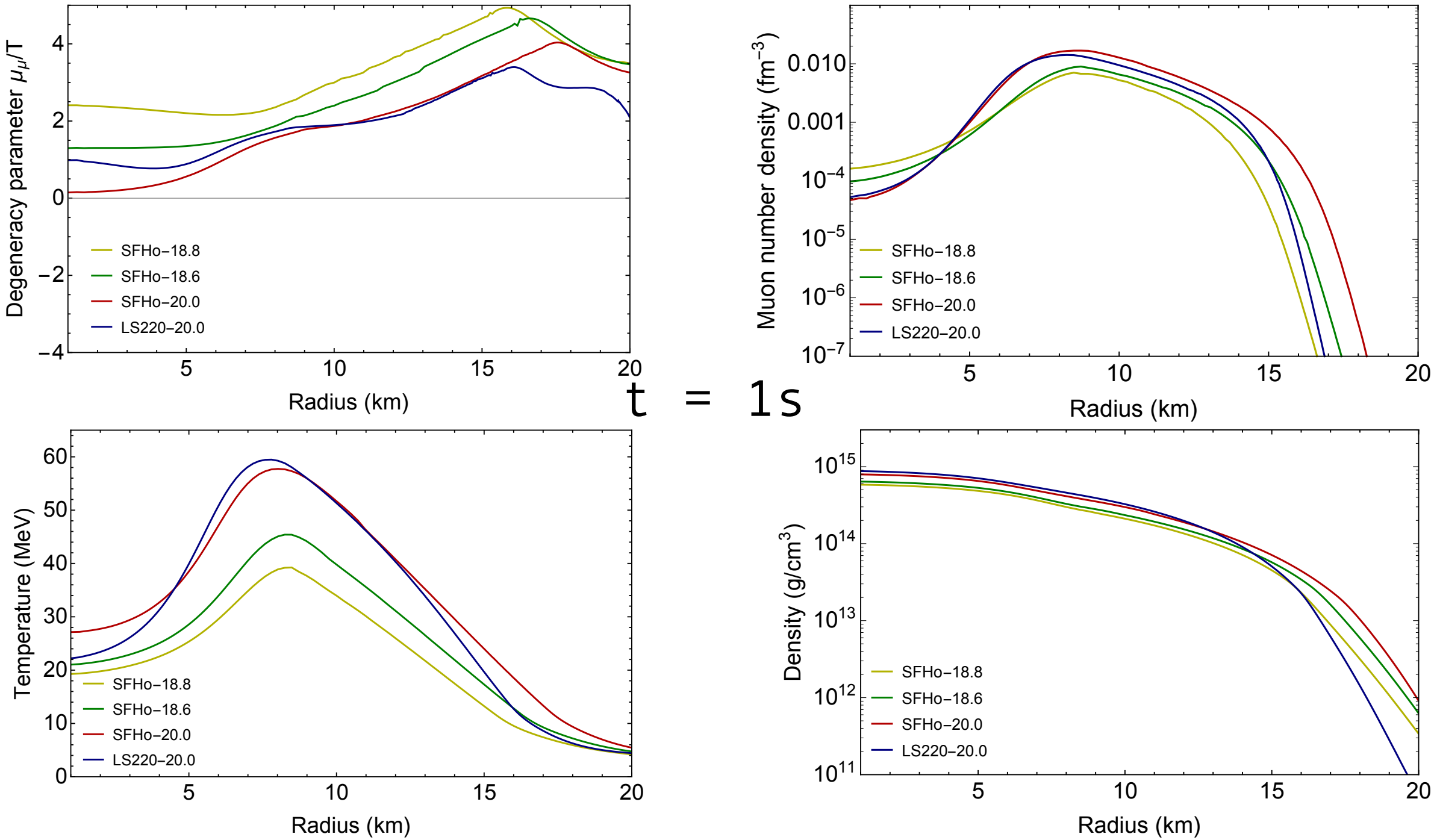
CMB bounds

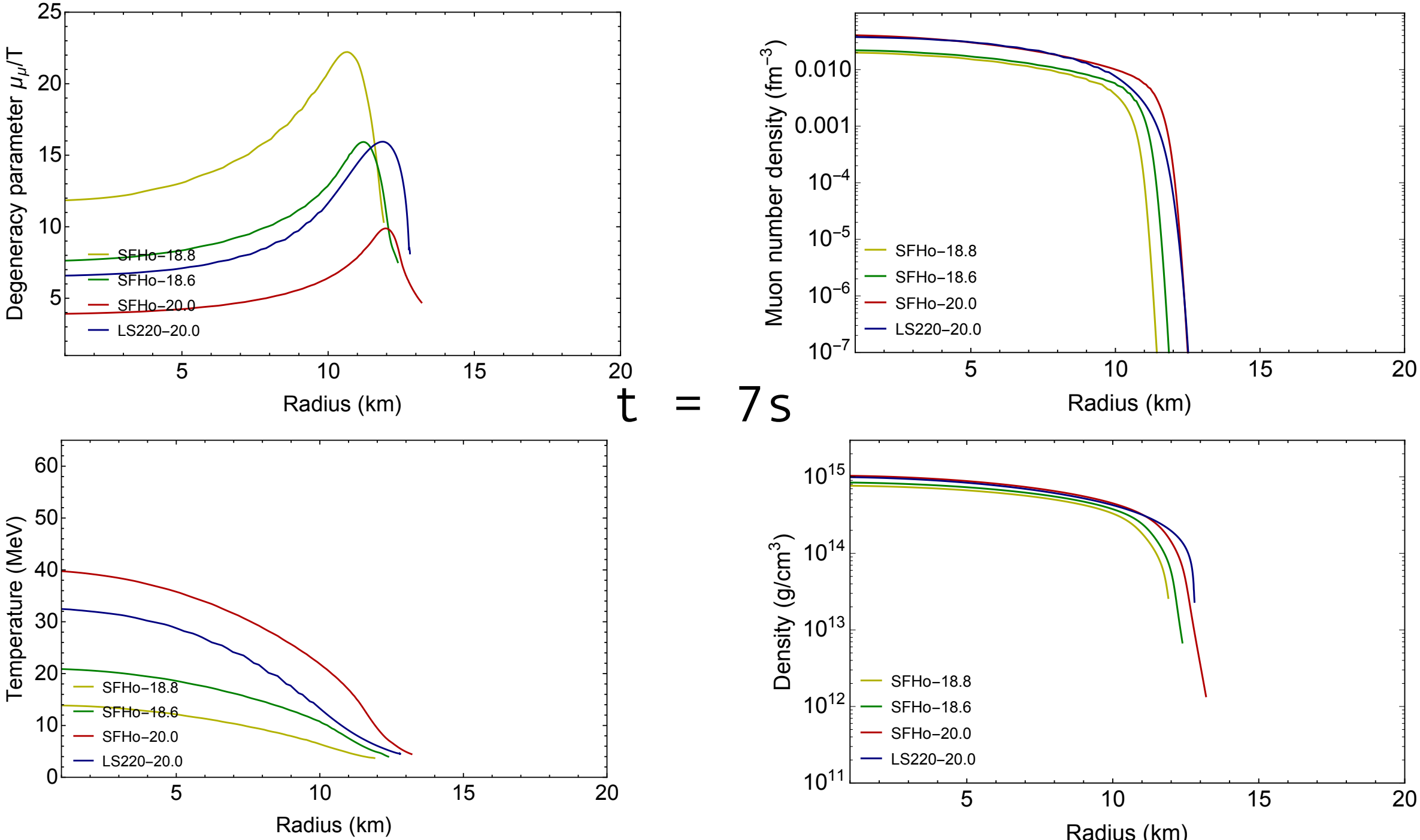
- Muons could produce axions in the early universe and change N_{eff}
- However, the change is highly dependent on the uncertainty on N_{eff}
- Difficult to place constraint now, rough estimate is 1e-7 GeV^{-1}
- N.B. a reheating temperature below the muon mass would also eliminate this contribution



https://arxiv.org/pdf/1808.07430.pdf


Degeneracy parameter μ_μ/T
Radius (km)
SFHo−18.8
SFHo−18.6
SFHo−20.0
LS220−20.0
Muon number density (fm^{-3})
Radius (km)
t = 0.2s
Temperature (MeV)
Radius (km)
Density (g/cm^3)
Radius (km)


Degeneracy parameter μ_μ/T
Radius (km)
SFHo−18.8
SFHo−18.6
SFHo−20.0
LS220−20.0
Muon number density (fm^{-3})
Radius (km)
t = 1s
Temperature (MeV)
Radius (km)
Density (g/cm^3)
Radius (km)


Degeneracy parameter μ_μ/T
Radius (km)
SFHo−18.8
SFHo−18.6
SFHo−20.0
LS220−20.0
Muon number density (fm^{-3})
Radius (km)
t = 7s
Temperature (MeV)
Radius (km)
Density (g/cm^3)
Radius (km)