

Nano-Hz Gravitational Waves and Supernova Neutrinos

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Supernova 1987A • November 28, 2003
Hubble Space Telescope • ACS

NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)

STScI-PRC04-09a

Based on: H.D., P. Denton, and A. Suliga, 2510.23713

TaoFest, University of Pittsburgh, May 14-15, 2026

My $\$ 2 \times 10^{-2}$

- I met Tao many ($\sim 26?$) years ago
- Later, I was a postdoc in Madison (Dirac Fellow, 2004-2006)
- We, with Heather, wrote a paper there on invisible Higgs decays

Discovering an Invisibly Decaying Higgs at Hadron Colliders

Hooman Davoudiasl,^{1,*} Tao Han,^{1,2,†} and Heather E. Logan^{1,‡}

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²*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510*

- It has done fairly well over the years

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#5


Hooman Davoudiasl (Wisconsin U., Madison), Tao Han (Wisconsin U., Madison and Fermilab), Heather E. Logan (Wisconsin U., Madison) (Dec, 2004)

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
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 138 citations

- Tao's support has made a significant difference in the careers of a large group of physicists, including myself
- On a larger scale, his steady stewardship of the Phenomenology Symposia has been instrumental in providing a welcoming venue for researchers at all levels to gather, have productive scientific interactions, and feel that they are part of a community
- In my experience (space-time independent): Tao \Rightarrow good physics \oplus fun times

Leading Particle Physicist and Higgs Expert Coming to the University of Siegen



Professor Tao Han will be researching at the University of Siegen thanks to support from the Humboldt Foundation.

The University of Pittsburgh's Professor Tao Han, an elementary particle physicist, is a world-renowned expert in Higgs physics. He will conduct regular research visits to the University of Siegen as part of the Humboldt Research Award.

Professor Tao Han, an elementary particle physicist and Higgs expert, has received the Alexander von Humboldt Foundation Research Award. With the prize money of 60,000 euros, the American scientist can now conduct research at the University of Siegen for up to twelve months. His host will be Professor Wolfgang Kilian from the Siegen Research Group for Theoretical Particle Physics. It was Kilian who nominated Han for the research prize.

I am truly thrilled that we have succeeded in bringing Professor Han to the University of Siegen through the Humboldt Research Award. Professor Han is a distinguished expert in the field of particle physics; his name is naturally familiar to everyone in our field. For our early career researchers and students, this is a fantastic opportunity to work and learn under one of the luminaries in the field," Kilian noted.

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Evidence for Stochastic GWs

- Pulsar Timing Array (PTA) evidence for stochastic GWs, e.g. from NANOGrav
NANOGrav: North American Nanohertz Observatory for Gravitational Waves

- GWs in the nano-Hz frequency range

- Strengthens prior hints

- The signal can have an astrophysical origin

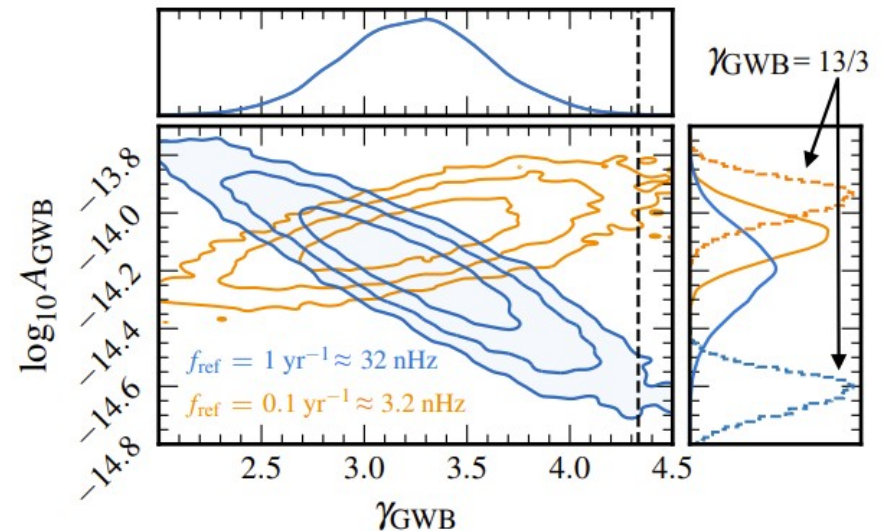
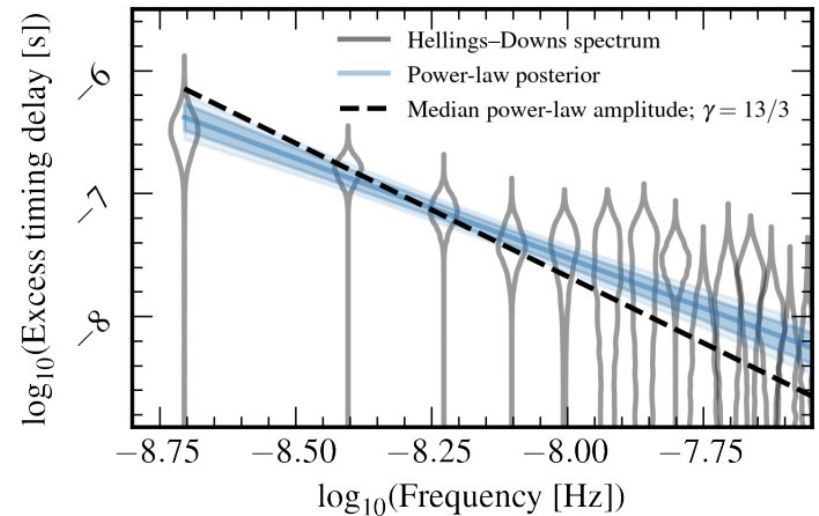
- Supermassive black holes (SMBHs)

- SMBH Mass range: $10^8 - 10^{10} M_{\odot}$

- Stochastic GWs from binary inspirals

- SMBHs: commonly found in galactic centers (expected to contribute to signal)

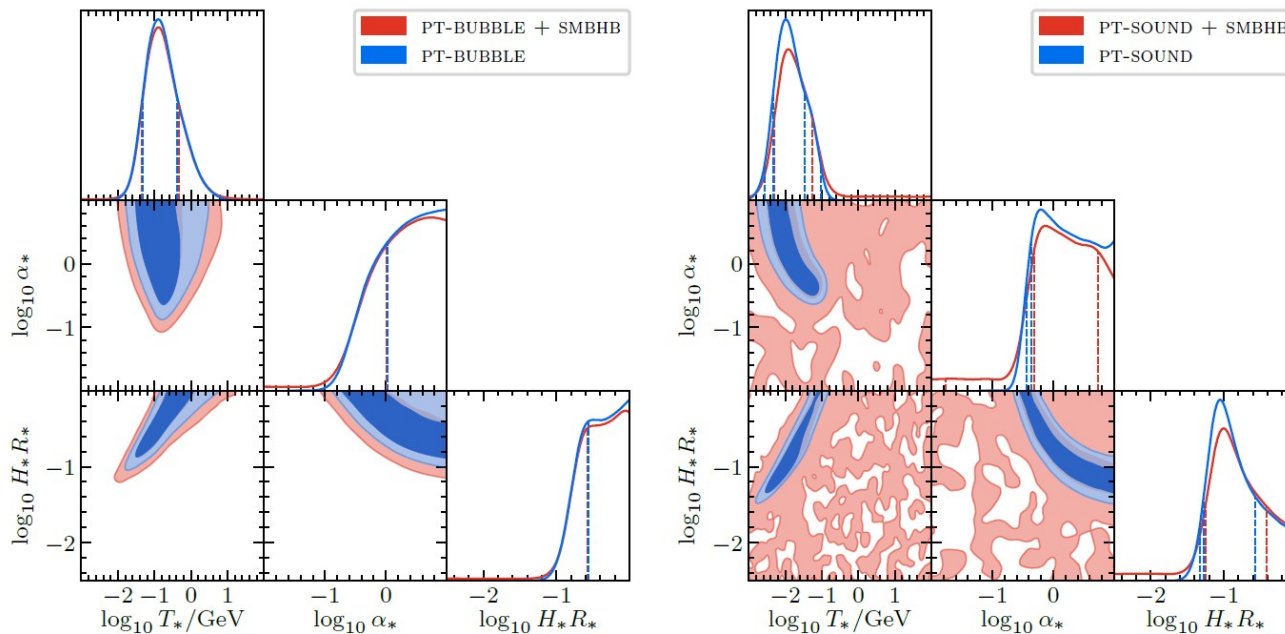
See also: 2009.04496 (NANOGrav),
2110.13184 (European PTA),
2107.12112, 2306.16215 (Parkes PTA),
2201.03980 (International PTA)
2306.16214 (European PTA & Indian PTA)
2306.16216 (Chinese PTA)



Figures from NANOGrav, 2306.16213

Hint of a Primordial Source

- The data could be showing signs of another contribution
 - Primordial first order phase transition (FOPT) a possibility
 - FOPT at $T_* \sim \mathcal{O}(10 - 1000)$ MeV
 - Parameters of FOPT depend on the assumed GW source
 - Bubble collisions: runaway behavior, weak coupling with plasma
 - Sound waves: strong coupling with plasma, conversion of kinetic energy



NANOGrav, 2306.16219 (darker 68%, lighter 95% Bayesian credible regions)

General Setup

- For $T_* \sim \mathcal{O}(10 - 100)$ MeV, expect associated physics at scales $\sim 10 - 100$ MeV
 - Such particles generally assumed feebly coupled to charged SM states
- We focus on new sector coupling mainly to neutrinos, thermalizing with SM
 - Less constrained than charged matter; provide a feasible path
- *Main observations:*
 - $T_* \sim 10$ -100 MeV near initial temperature of a core collapse supernova (CCSN)
 - Initial CCSN: thermalized new sector \rightarrow “hidden sphere”
 - Cooling CCSN: potentially detectable neutrino signals
 - Possible restoration of *false vacuum*
- Comparison with Cosmology
 - Early Universe: low baryon density, homogeneous plasma
 - CCSN: high baryon density, inhomogeneities
 - However, the CCSN relativistic neutrino “plasma” largely homogeneous

Underlying Interactions

- Let us adopt the coupling

$$\frac{\tilde{H}^* \bar{L} \phi \nu_R}{M} + \text{H.C.} \rightarrow y \phi \bar{\nu}_L \nu_R + \text{H.C.}$$

H, L : Higgs, lepton doublets; ν_R : right-handed SM singlet; $y \equiv \langle H \rangle / M$

- Dirac masses not feasible: excess BBN degrees of freedom
 - Naturally led to $m_R \neq 0$

$$\Gamma(\nu_R \rightarrow \nu_L \phi, \bar{\nu}_L \phi) \sim \frac{y^2 m_R}{16\pi}$$
$$\Rightarrow m_\nu \sim \frac{y^2 \langle \phi \rangle^2}{m_R} \sim 0.1 \text{ eV}$$

- ν_R decay before BBN $\Rightarrow y \gtrsim 10^{-10}$, for $m_R \gtrsim 10 \text{ MeV}$ (decay to on-shell ϕ)

Aside:

- We have assumed that $\langle H \rangle \bar{\nu}_L \nu_R$ is suppressed
- Could be due to $Z_2(\nu_R) = Z_2(\phi) = -1$ (broken softly by ϕ^3 term in the potential)

Benchmark Parameters

- At energies below m_R , ϕ - ν interaction: $\xi_\nu \phi \bar{\nu}_L^c \nu_L$
- $\langle \phi \rangle \sim 30 \text{ MeV} \Rightarrow \xi_\nu \sim m_\nu / \langle \phi \rangle \sim 10^{-9}$
- For these ξ_ν values, ϕ emission leads to excessive CCSN cooling
E.g., Fiorillo, Raffelt, Vitagliano, 2022
- For $m_R \lesssim 100 \text{ MeV}$, $\nu_L \phi \rightarrow \nu_R$ followed by $\nu_R \rightarrow \phi \nu_L$ allowed in CCSN
- The above leads to $3 \times 10^{-5} \lesssim y \lesssim 10^{-4}$ ($m_\nu \sim 0.1 \text{ eV}$)
 - ϕ would not free-stream out of the core*
- ν_R is a Majorana fermion \Rightarrow Lepton Number Violation (LNV)
- LNV time scale $\ll \mathcal{O}(\text{ns})$, fast compared to weak interaction's $\gtrsim \mathcal{O}(\text{ns})$
- We will adopt

$\langle \phi \rangle$	m_ϕ	y	m_R
30 MeV	10 MeV	10^{-4}	100 MeV

* (i) $m_R \gtrsim 10 \text{ MeV}$ (allow decay into ϕ): $y \gtrsim 3 \times 10^{-5}$, (ii) meson decay, Z width for $m_R \lesssim 100 \text{ MeV}$:
 $y \lesssim 4 \times 10^{-3}$ ($m_\nu \sim 0.1 \text{ eV}$ requires $y \sim 10^{-4}$)

Supernova Dynamics

- Formation of a *Hidden Sphere*, composed of ϕ and ν_R
 - Analogy with the neutrino-sphere; expect the spheres approximately overlap, same temperature
 - For $m_R \sim 100$ MeV, the ν_R population is Boltzmann-suppressed, ignored henceforth
- ϕ emission from the hidden sphere, followed by $\phi \rightarrow \nu\bar{\nu}$ outside (true vacuum)
 - $c\tau_\phi \gtrsim 100 - 1000$ km (decays outside ν -sphere)
 - The emitted ν s will inherit the Bose-Einstein distribution of ϕ s H.D., Huber, 2005
 - These neutrinos carry about 1/2 the energy of those emitted from the core
 - New flux potentially distinguishable from the standard pinched Fermi-Dirac ν s
- Possible restoration of false vacuum $\langle\phi\rangle \rightarrow 0$
 - Return to true vacuum, followed by condensate decay $\phi \rightarrow \nu\nu$ (with $E_\nu \approx m_\phi/2$)
 - Likely within the neutrino sphere: mono-chromatic ν s get thermalized, wash out signal

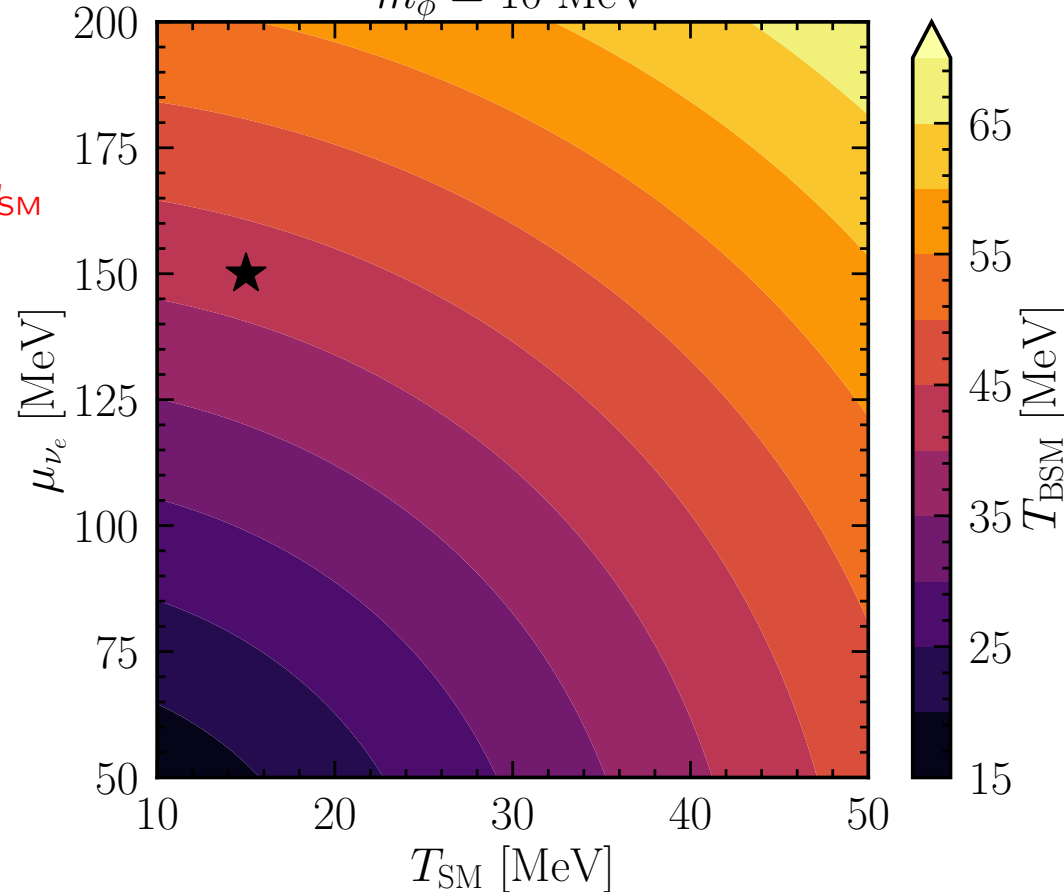
Rapid LNV Effects in CCSNe

- Rapid LNV mediated by ϕ drives neutrino chemical potentials to zero
 - Consistent with Suliga *et al.*, 2410.01080:
 - Fast LNV effect on β -equilibrium during CCSN infall
- Electron fraction of the core will decrease as a consequence
 - Follows from enhanced electron capture:
 - Reduced neutrino chemical potential (less ν_e blocking)
 - Entropy release increasing proton fraction
- This raises the core temperature, well beyond $\sim 10\%$ variation seen in simulations

See, e.g., O'Connor et al., 2018
- Potentially observable in neutrinos detected from a future Galactic CCSN
- We do not expect the above to disrupt successful CCSN explosion
 - Similar to conditions with LNV via $\nu_e + N \rightarrow \bar{\nu}_e + N$ [Rampp, Buras, Janka, Raffelt, 2002](#)

$m_\phi = 10 \text{ MeV}$

$T_{\text{BSM}} \sim (2.5 - 3) \times T_{\text{SM}}$



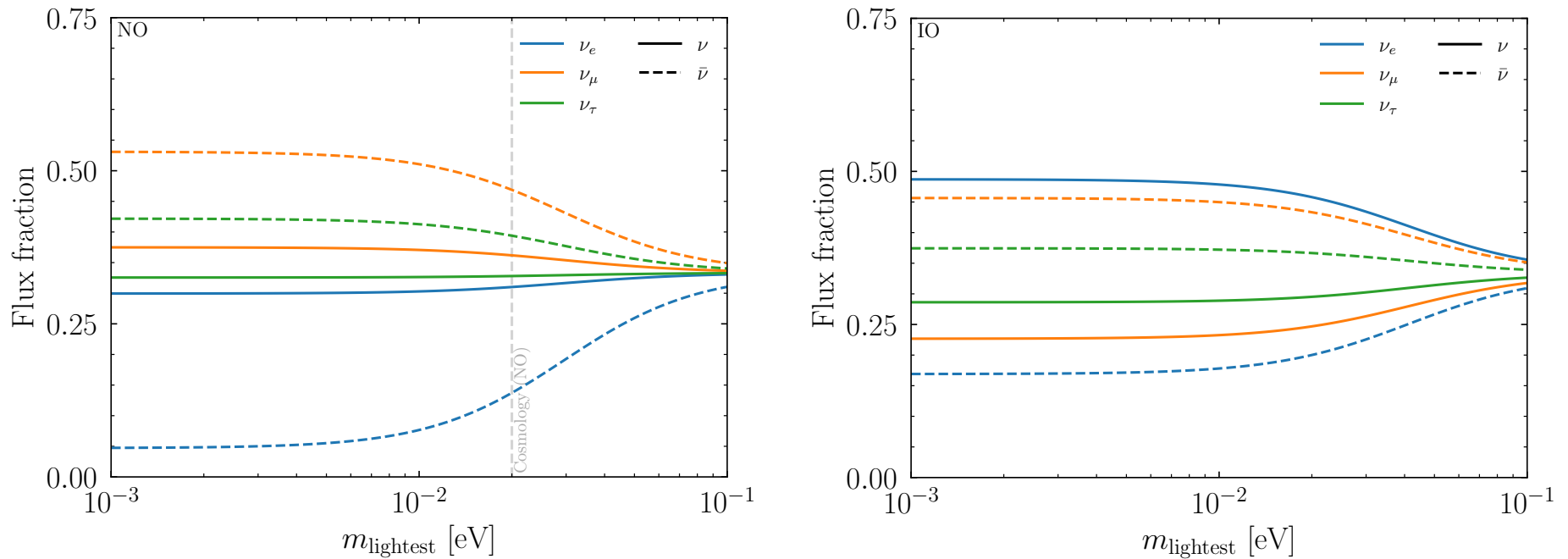
From 2510.23713

★: conditions just after the core bounce in SM CCSN

See, e.g., Raffelt, Janka, Fiorillo, 2509.16306

- T_{BSM} : six ν flavors, two ν_R s at $m_R = 100 \text{ MeV}$, and ϕ equilibration
- The SM CCSN temperature is T_{SM} , μ_{ν_e} is the chemical potential of ν_e
- T_{BSM} will be reduced if ϕ transitions to false vacuum (stored potential energy)

Neutrino Flux from ϕ Decays



From 2510.23713

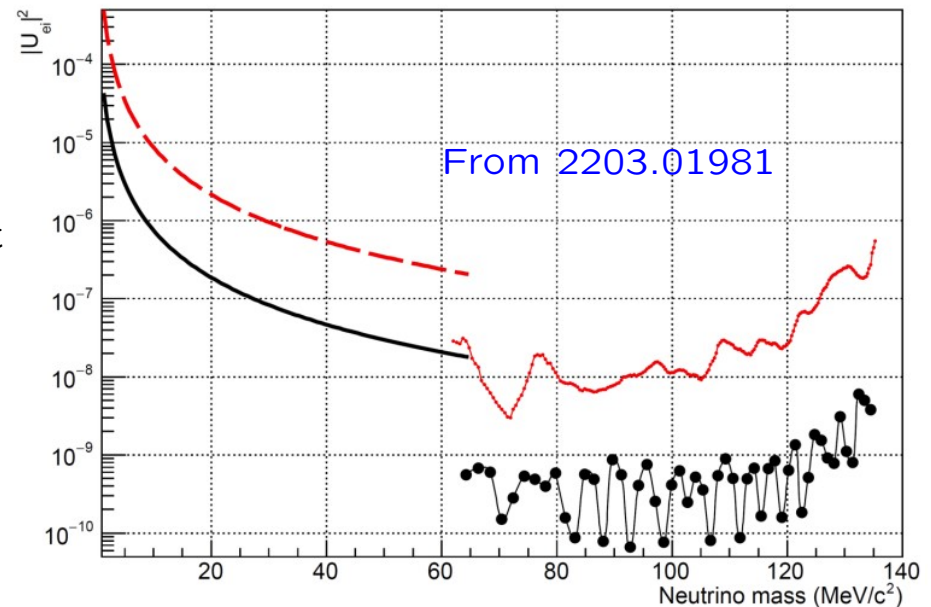
- Neutrino flux $\propto m_i^2$, where m_i is the mass of eigenstate ν_i
- The flux of flavor ν_α is given by $\Phi_{\nu_\alpha} \propto m_i^2 P_{i\alpha}$ ($P_{i\alpha}$: transition probability)
- Left panel normal ordering (NO); cosmological constraint (Planck, 2018) in gray
- Right panel inverted ordering (IO); nominally disfavored by cosmology
- Unique signal: total $\nu/\bar{\nu}$ ratio is 1
- In NO (IO) $\bar{\nu}$ (ν) flavor ratio outside allowed region for any standard production

Capanema, Porto, Saez, 2024

Other Possible Effects

- Right-handed neutrino mixing $(y\langle\phi\rangle/m_R)^2 \sim 10^{-9}$
 - Currently allowed by constraints from, *e.g.* $\pi^+ \rightarrow e^+\nu$ [PIENU Collaboration, 2018](#)
 - Can be well-tested by future PIONEER experiment

- Constraints on $|U_{ei}|^2$, 90% CL
- PIENU (red), PIONEER projection (black)
- $m_R < 65$ MeV: branching ratio measurement
- $m_R > 65$ MeV: peak search

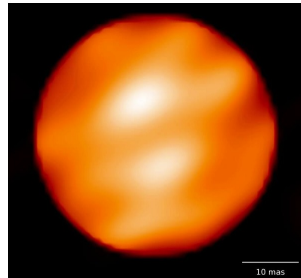


- Effects on CCSN nucleosynthesis
 - Similar ν_e and $\bar{\nu}_e$ fluxes after ϕ equilibration
 - Neutron rich ejecta (lower e fraction)
- Potential effect on diffuse supernova neutrino background
- FOPT at $T_* \sim \mathcal{O}(10 \text{ MeV})$ could lead to primordial black holes of mass $\gtrsim 30M_\odot$
 - Depends on the details of the FOPT [FOPT from modified QCD: H.D., 1902.07805](#)
 - May correspond to a slight excess at $\sim 35M_\odot$ seen by LIGO-VIRGO-KAGRA

[LIGO-VIRGO-KAGRA, GWTC-4.0, 2025](#)

Concluding Remarks

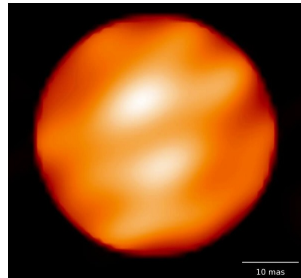
- Recent evidence for stochastic GWs may be due to a FOPT at $T \lesssim \mathcal{O}(100 \text{ MeV})$
- We adopted this view, based on the NANOGrav analysis
- Energetics: significant overlap with initial seconds of a CCSN
- We invoked a simple scalar ϕ model of the FOPT
- Primordial thermalization via ϕ - ν interactions, other channels largely disfavored
- This naturally leads to $m_\nu \neq 0$ via a low mass seesaw from $\langle \phi \rangle \neq 0$
- LNV in CCSN can lead to significant departures from standard picture
- FOPT dynamics in a Galactic CCSN may yield observable neutrino signals



Credit: Observatoire de Paris/Xavier Hauboys et al

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Wishing Tao many more years of good physics and fun times!