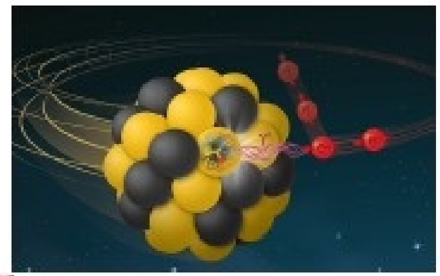
Particle and Nuclear Astrophysics (PNA)

Jim Kneller
NC State University

Conveners:
Kelly Chipps (ORNL),
Wei Jia Ong (LLNL),
Rebecca Surman (Notre Dame)

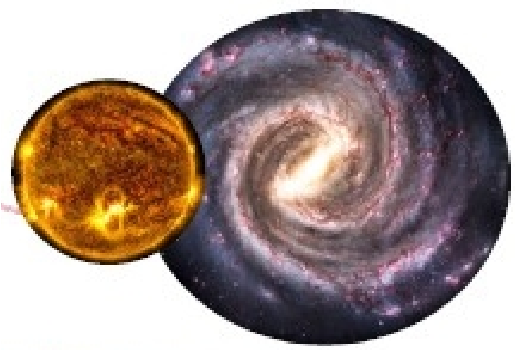
- In the PNA sessions we heard a mix of talks that really emphasized the theme of intersections.

Observation



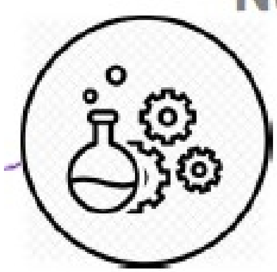
Nuclear Theory

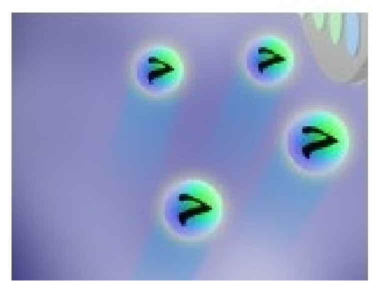
Machine Learning



Stellar, Solar, and Galactic Modeling

Nuclear Physics Experiment





Neutrino Physics

Constraining the 15O (α, γ)19Ne reaction rate in Type I X-ray bursts using GADGET II TPC *Ruchi Mahajan*

Old Madison 15:30 - 15:52

Nuclear Astrophysics With High Intensity Beams At LENA II *Caleb Marshall*

Old Madison 15:52 - 16:14

Nuclear Astrophysics Research with the MUSIC Detector at ATLAS and FRIB *Eilens Lopez Saavedra*

Old Madison 16:14 - 16:36

Efforts to incorporate neutrino oscillation in merger simulations *Somdutta Ghosh*

Old Madison 16:36 - 16:58

Detecting Solar Neutrinos and Fermionic Dark Matter with ^{136}Xe in nEXO *Glenn Richardson*

Old Madison 15:30 - 15:48

Supernova Detection with IceCube and the IceCube Upgrade *Segev BenZvi*

Old Madison 16:06 - 16:24

Direct Nuclear Parameter Estimation From Gravitational Waves *Brendan Reed*

Old Madison 16:24 - 16:42

Neutron Star Equation of State Measurements from Binary Mergers *Rossella Gamba*

Old Madison 16:42 - 17:00

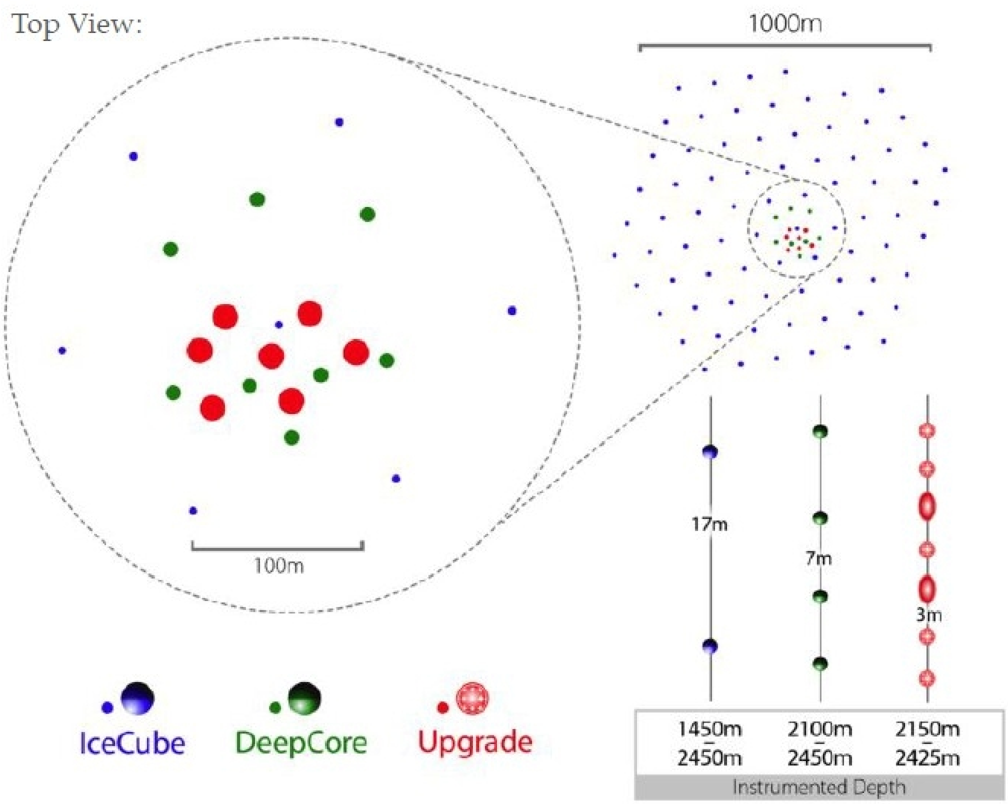
Prospects for detecting gamma rays from r-process producing Magneto-Rotational Supernovae	*Zhenghai Liu*	
Old Madison	19:00 - 19:18	
Ultra-High-Energy Cosmic Ray: Current Picture and Future Outlook.	*Eric Mayotte*	
Old Madison	19:18 - 19:36	
Status of the Radar Echo Telescope	*steven prohira*	
Old Madison	19:36 - 19:54	

Neutrino Self-Interaction in Core-Collapse Supernovae	*Anna Suliga*
Multicultural Greek	14:00 - 14:18
Local-equilibrium theory of neutrino oscillations in supernovae and mergers	*Luke Johns*
Multicultural Greek	14:18 - 14:36
Quantum Closures and Riemann Solvers for Neutrino Moment Transport	*Dr Jim Kneller*
Multicultural Greek	14:36 - 14:54
Towards Many-Body Models of Neutrino Flavor Instability	*Sherwood Richers*
Multicultural Greek	14:54 - 15:12
Predicting the outcome of neutrino flavor instabilities	*Julien Froustey*
Multicultural Greek	15:12 - 15:30

Supernova Detection with IceCube and the IceCube Upgrade — *Segev BenZvi*

Old Madison — 16:06 - 16:24

IceCube Upgrade



Upgrade: 7 new "infill" strings in the center of the 86-string detector.

Smaller string-string spacing provides:

- Improved systematic calibration of ice optical properties
- Improved angular/energy resolution
- Precision measurements of ν_{atm} oscillations

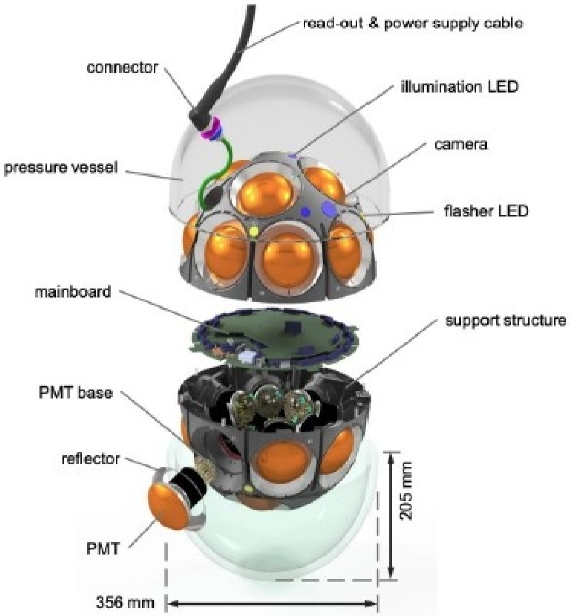
Installation: 2025/2026 polar season.

Currently IceCube cannot extract much info about supernovae given source uncertainty

New Optical Sensors: D-Egg and mDOM

New modules with 4π coverage to improve effective volume & event resolution. Included are LED flashers and cameras for improved ice calibration.

Credit: Abbasi+, JINST 18:P04014, 2023
PMTs: Hamamatsu R5912-100 8″ HQE

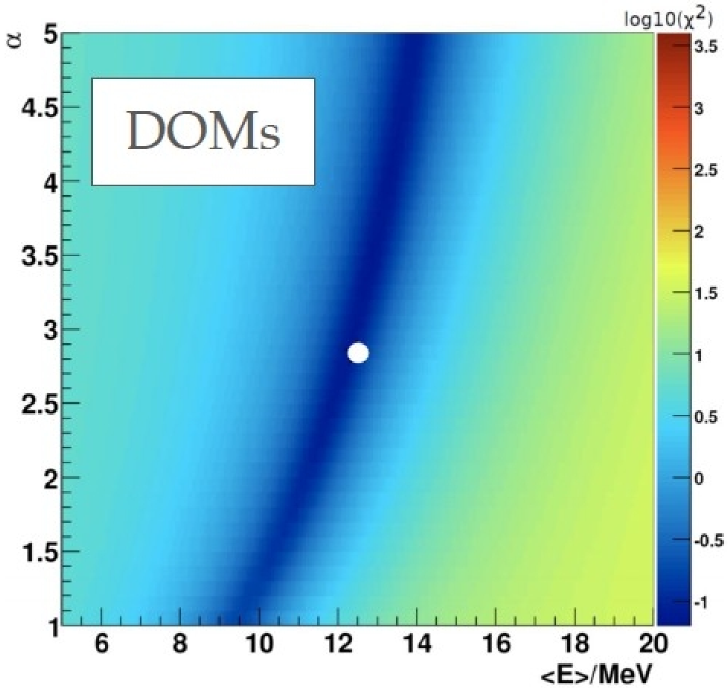


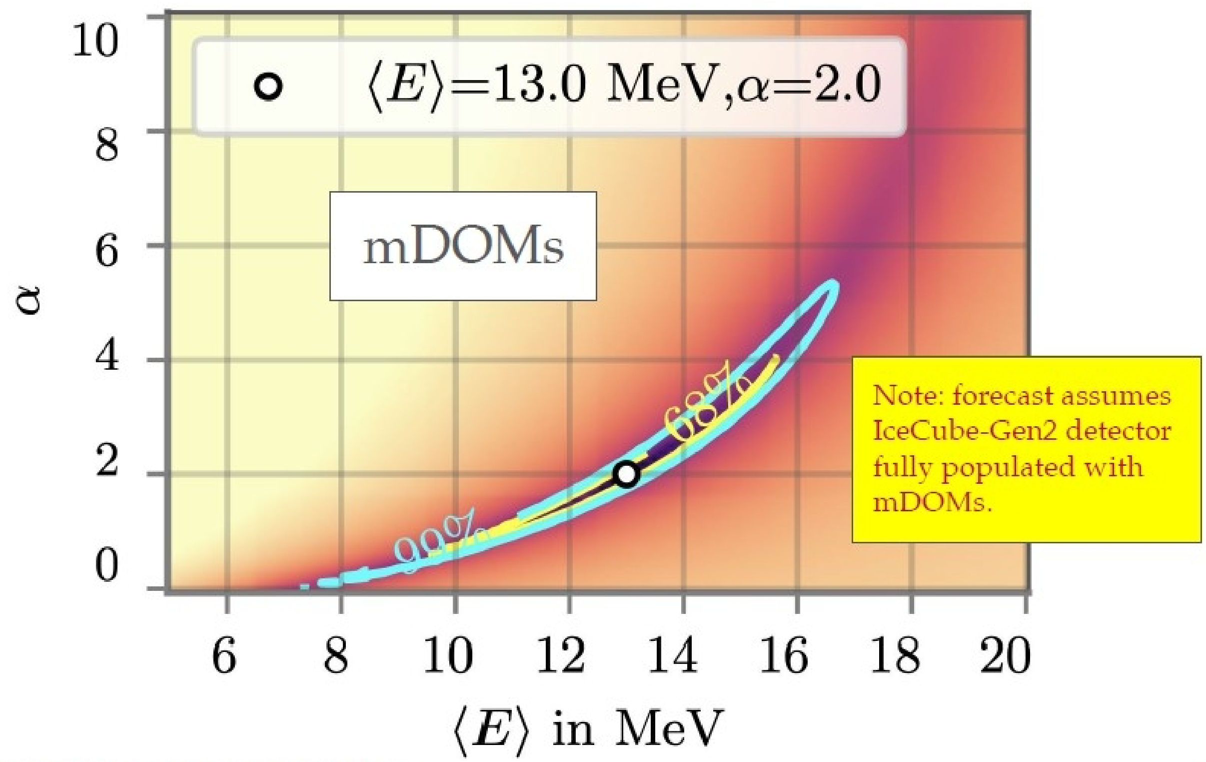
Credit: Anderson+, PoS(ICRC 2021)

New DOM design increases rate of coincident hits.

mDOMs and Supernova ν's

Constraints on CCSN neutrino spectrum using a χ^2 scan over $\langle E_\nu \rangle$ and α:





Credit: F. Sprenger, 2019

New DOM design allows extraction of neutrino mean energy and 'pinch parameter' allowing identification of mass hierarchy.

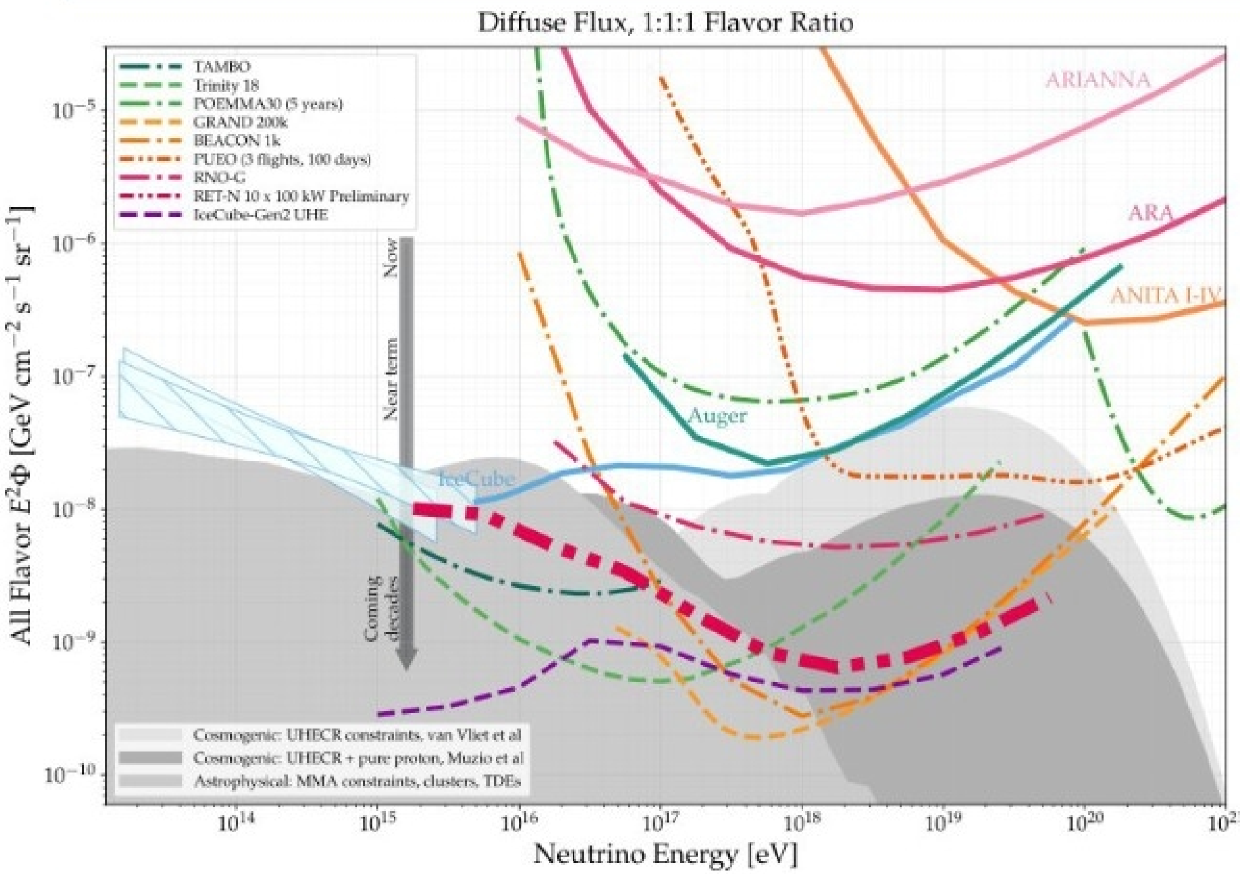
radar detection of neutrinos

(Simple) Big Picture Concept:

Bounce radio waves off of the ionization deposit left in the wake of a neutrino-induced cascade.

This is an old idea. It doesn't work in air, but it does work in ice

RET sensitivity in context



Adapted from UHE neutrinos Snowmass paper arXiv:2203.08096, highlighting RET curve.

RET **10 stations,** 10 years, thick red dashed curve (highlighted for emphasis)

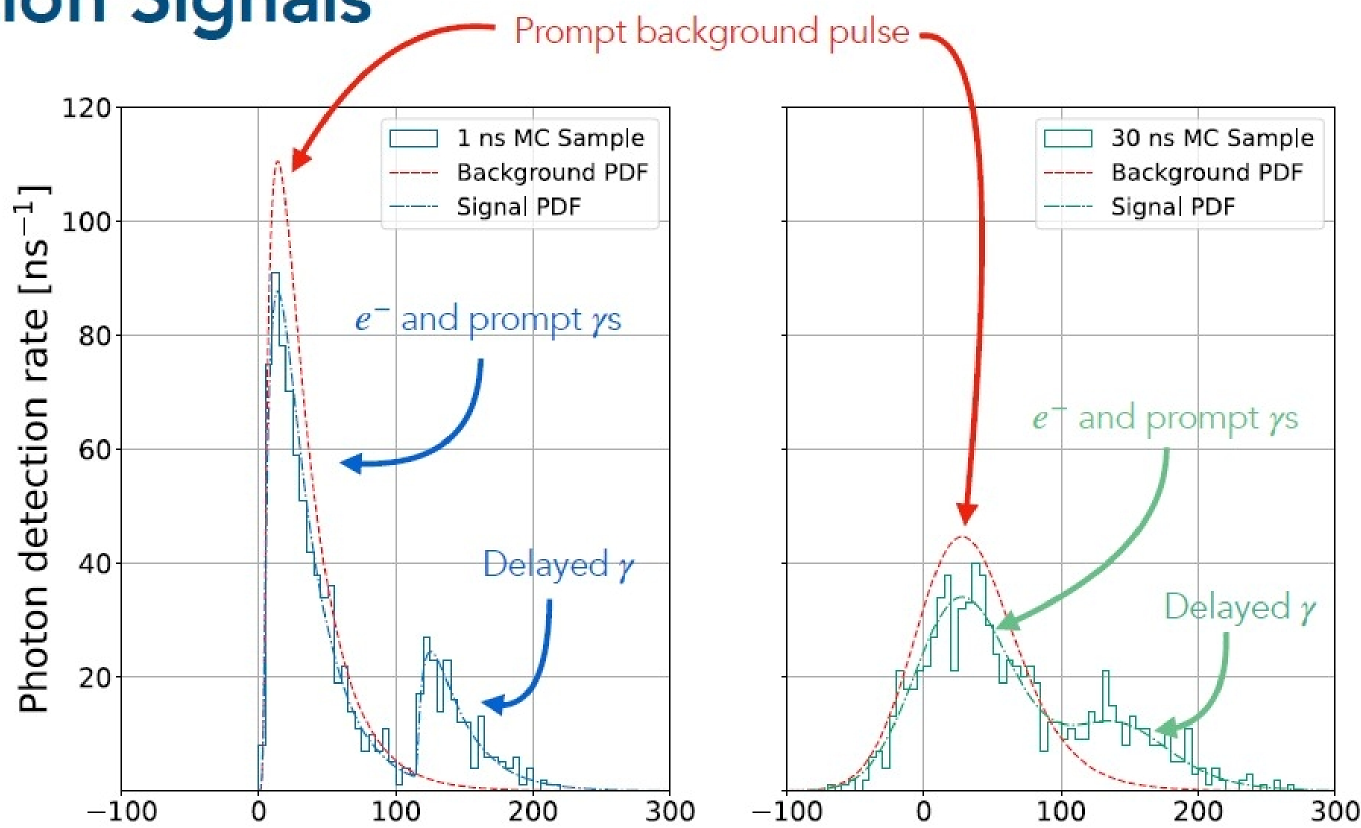
To my knowledge, we require the fewest number of stations of any ground-based radio method.

Also shown: Many experiments with different sensitivities

RET has demonstrated the idea works by detecting a cosmic ray shower in ice triggered by surface panels

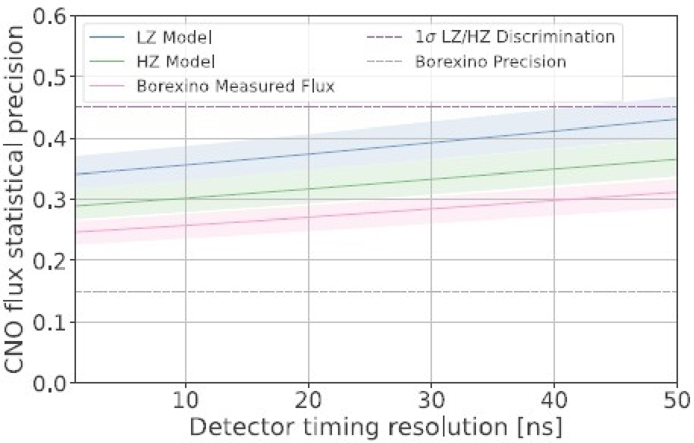
Simulated Scintillation Signals

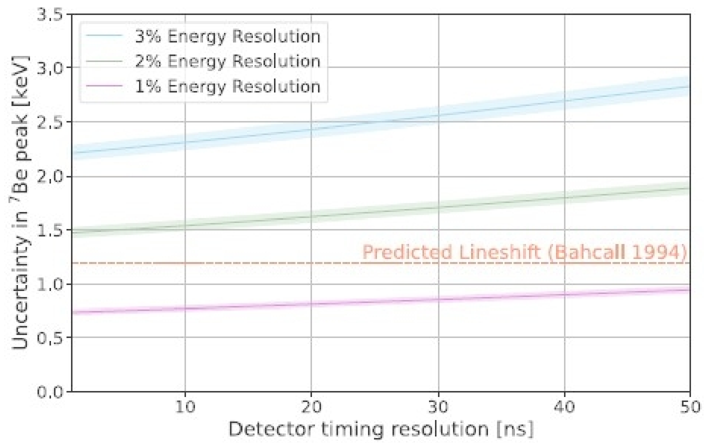
- Pulse shapes driven by
  - LXe scintillation time
  - ^{136}Cs de-excitation time
  - Photon travel time
  - Timing resolution of readout
- Delayed de-excitation can be tagged in scintillation channel

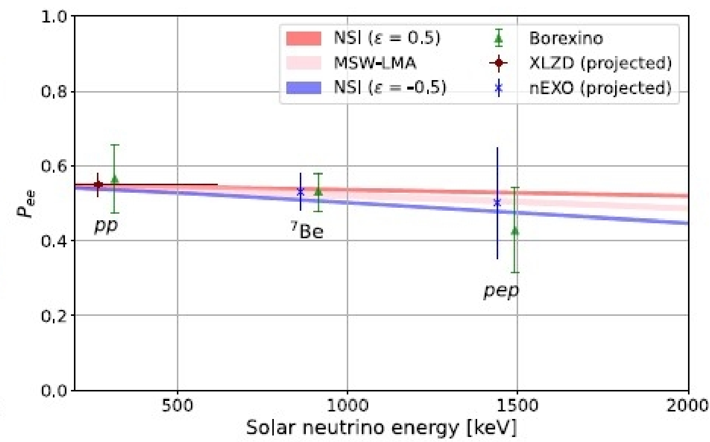


Isomeric states in Cs could create time-delayed coincident signals in nEXO. Tagging the interaction reduces backgrounds to 0.5 events per 10 years

Scientific Reach







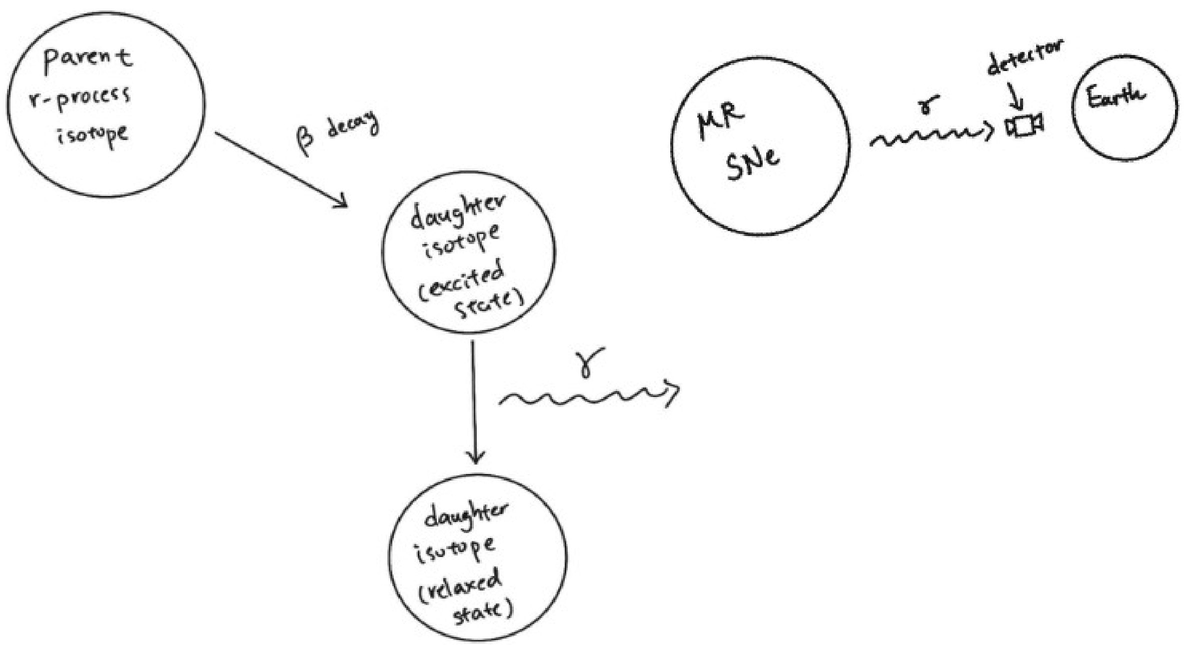
- **Solar Metallicity**: Can achieve up to 25% statistical precision of CNO flux
  - Comparable to current leading result
- **Solar Core Temperature**: Sensitive to ~ 1 keV shift in ^{7}Be energy
  - Order of magnitude improvement over current measurement
- **Non-Standard Interactions**: Set limits on NSI effects with $10 - 30\,\%$ resolution
  - Comparable to current leading results

Solar core temperature can be measured to ~1 keV accuracy using shift of Be-7 line energy

Prospects for detecting gamma rays from r-process producing Magneto-Rotational Supernovae *Zhenghai Liu*

Old Madison 19:00 - 19:18

Beta decay related gamma signal from the r-process as a direct probe

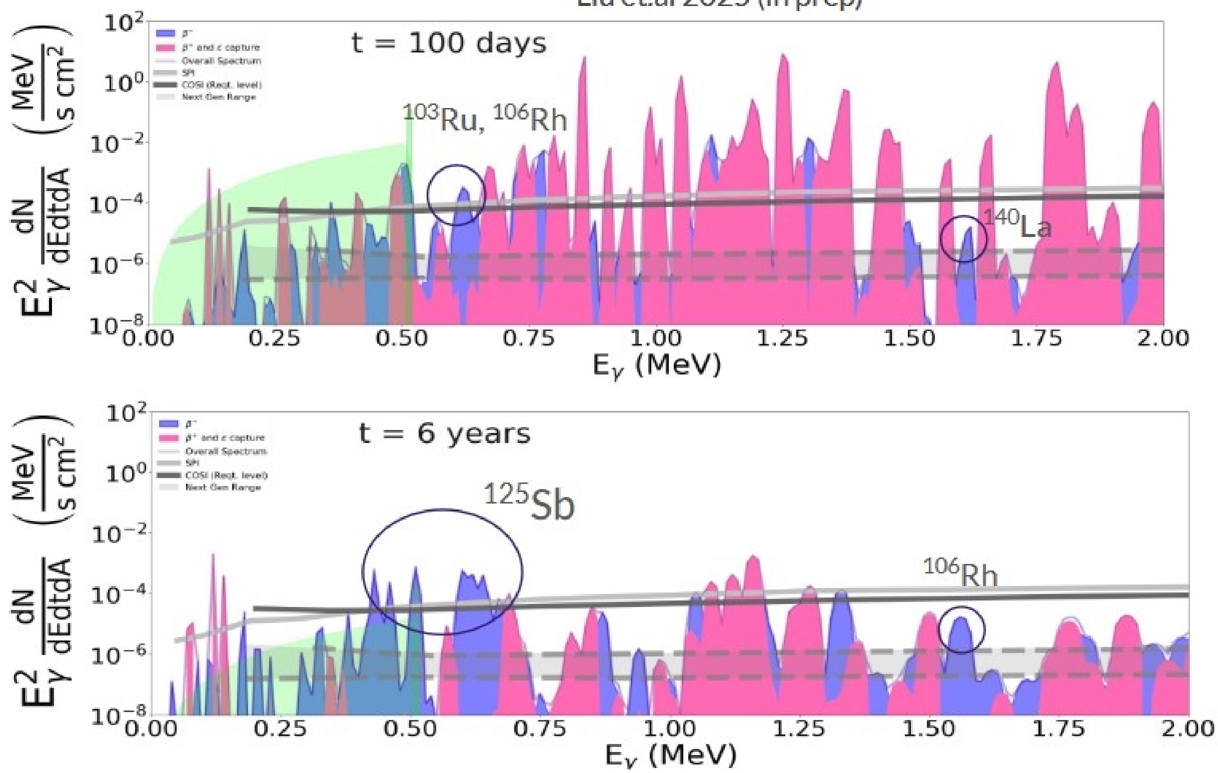


- The beta decay daughters of the freshly synthesized r-process isotopes will sometimes **gamma-decay** and release a **photon**.
- This gamma radiation is a **direct probe of nucleosynthesis**.
- **With proper instruments, we might be able to observe these gamma signals**

Magneto-Rotational SN are rare type of core-collapse SN where r-process elements may be made.

Time evolution

Liu et.al 2025 (in prep)



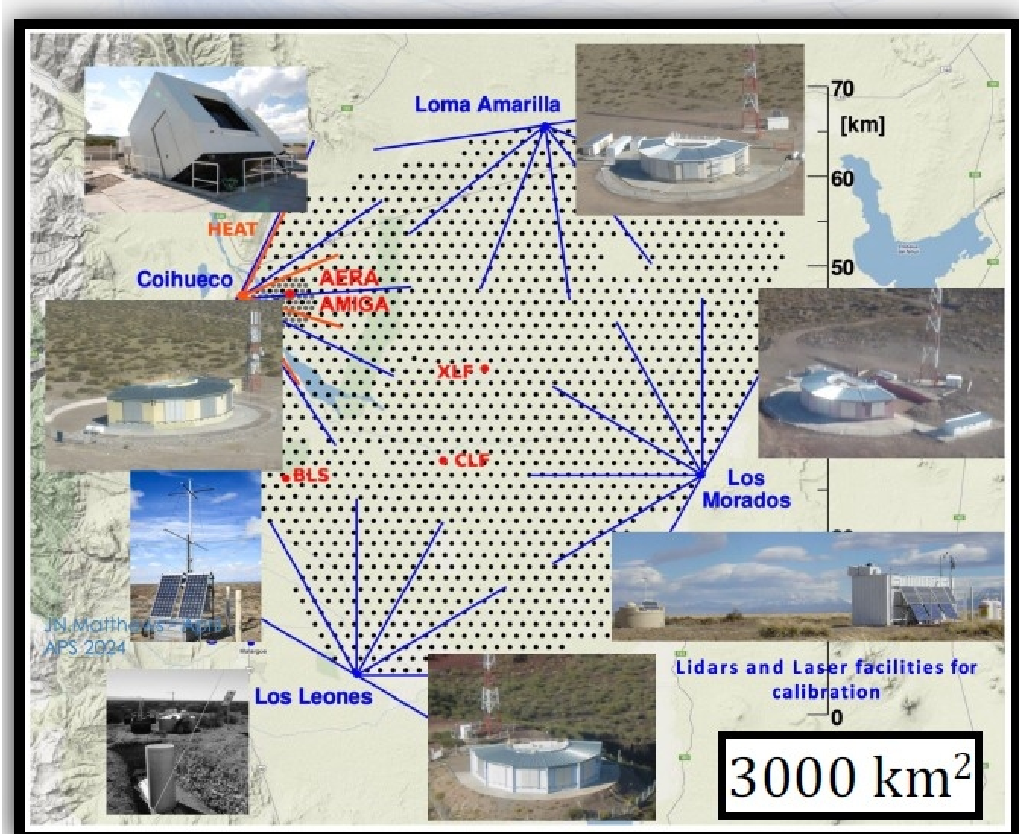
The same can be generalized for other times as well.

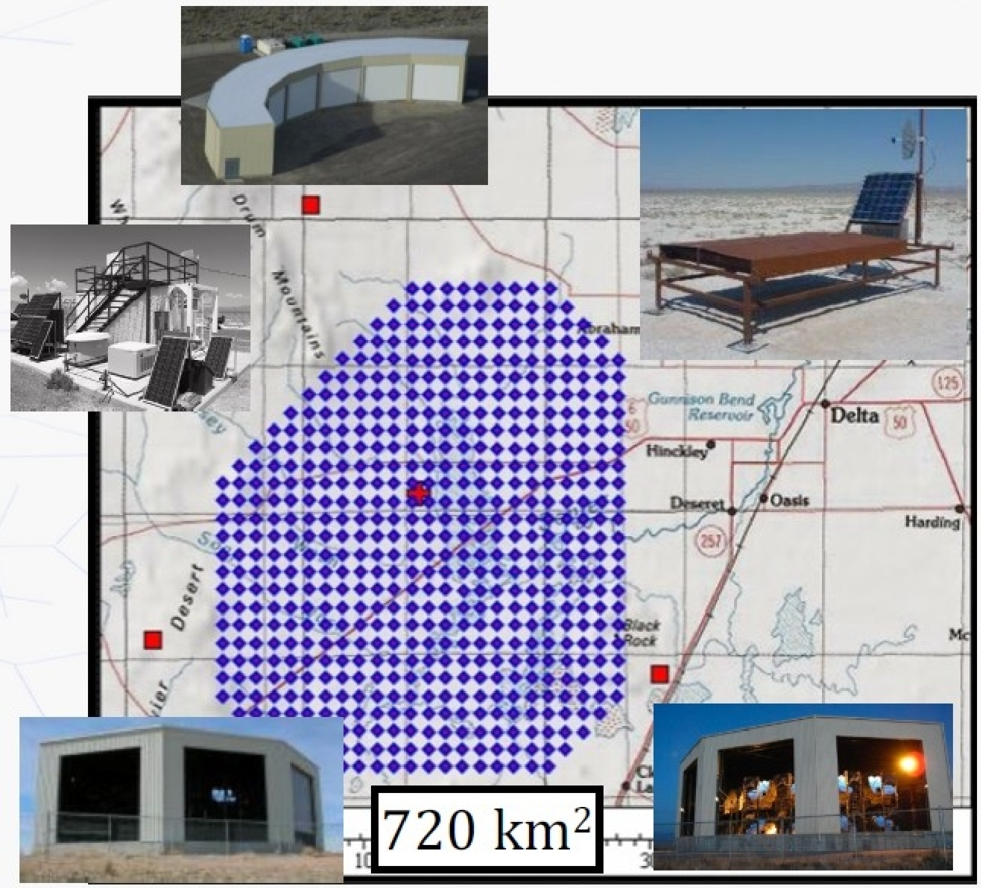
We identify **near second peak/weak r-process isotopes such as ^{103}Ru, ^{106}Rh, ^{125}Sb to be particularly interesting and could have a high possibility of being detected by instruments.**

Gamma ray spectrum contains other radioactive nuclei e.g. Ni-56
Nevertheless, some r-process lines are visible.
Observation would be direct evidence of r-process synthesis

The Pierre Auger Observatory

The Telescope Array Project





Pierre Auger and Telescope Array have been operating for many years and now have very refined data.

Talk Summary: The UHECR Picture

Spectrum:

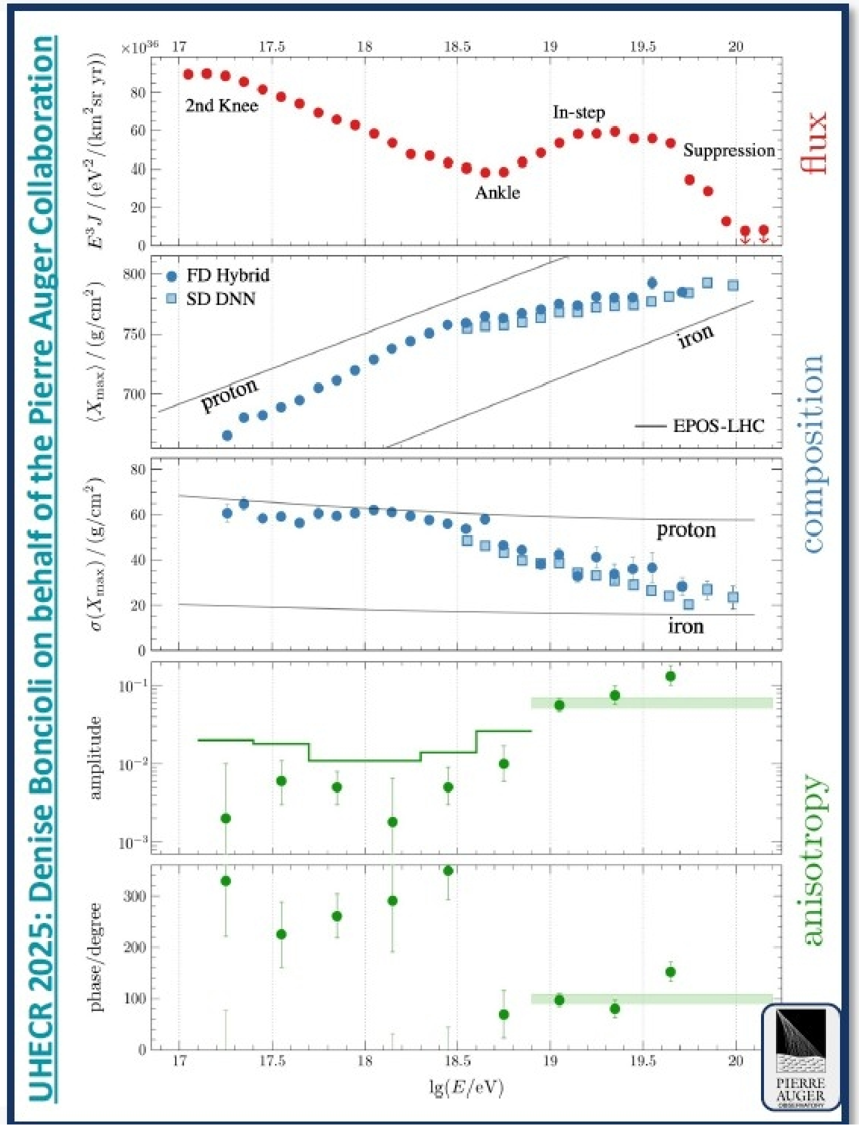
Before: Broken power law Knee, Ankle, maybe Cutoff
Now: New and old features resolved at high precision
With Upgrades: Full sky united with small differences
Far Future guess: Hints of new structure post-cutoff

Composition:

Before: Uncertain, very high all proton expectation
Now: Composition is mixed and gets heavier with energy
→ Emerging fine-structured energy evolution
With Upgrades: Clear mass and charge ordering structures
Far Future guess: Fine detail mass group spectra

Anisotropy:

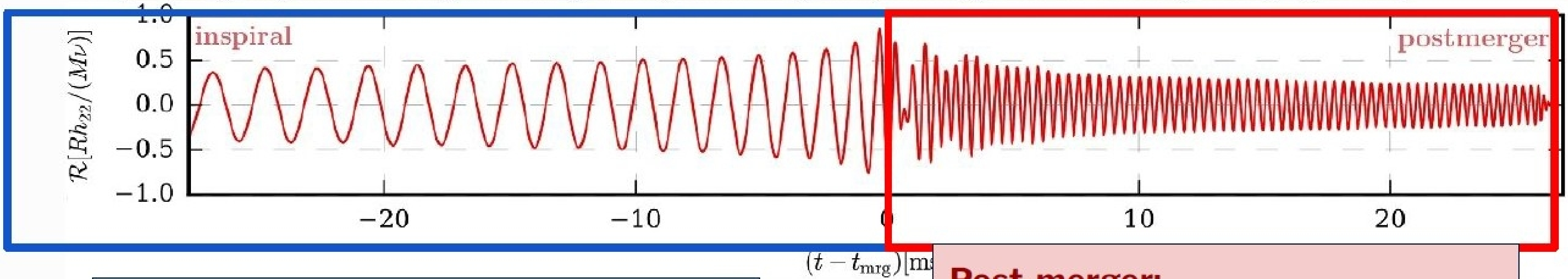
Before: Isotropic at all energies
Now: Not isotropic! Dipoles clear, source hints emerging
With Upgrades: 5 sigma source class correlations
Significant anisotropy in composition
Far Future guess: Clear targets for MM follow-up

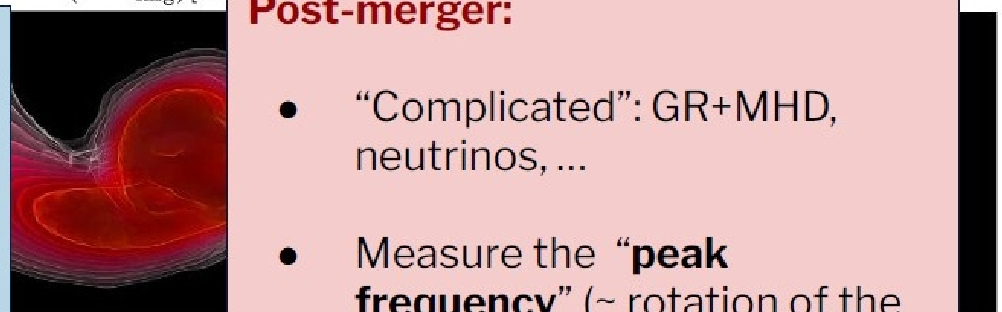


Mergers: GWs

[Dietrich+2021]

From: Interpreting binary neutron star mergers: describing the binary neutron star dynamics, modelling gravitational waveforms, and analyzing detections





Inspiral:

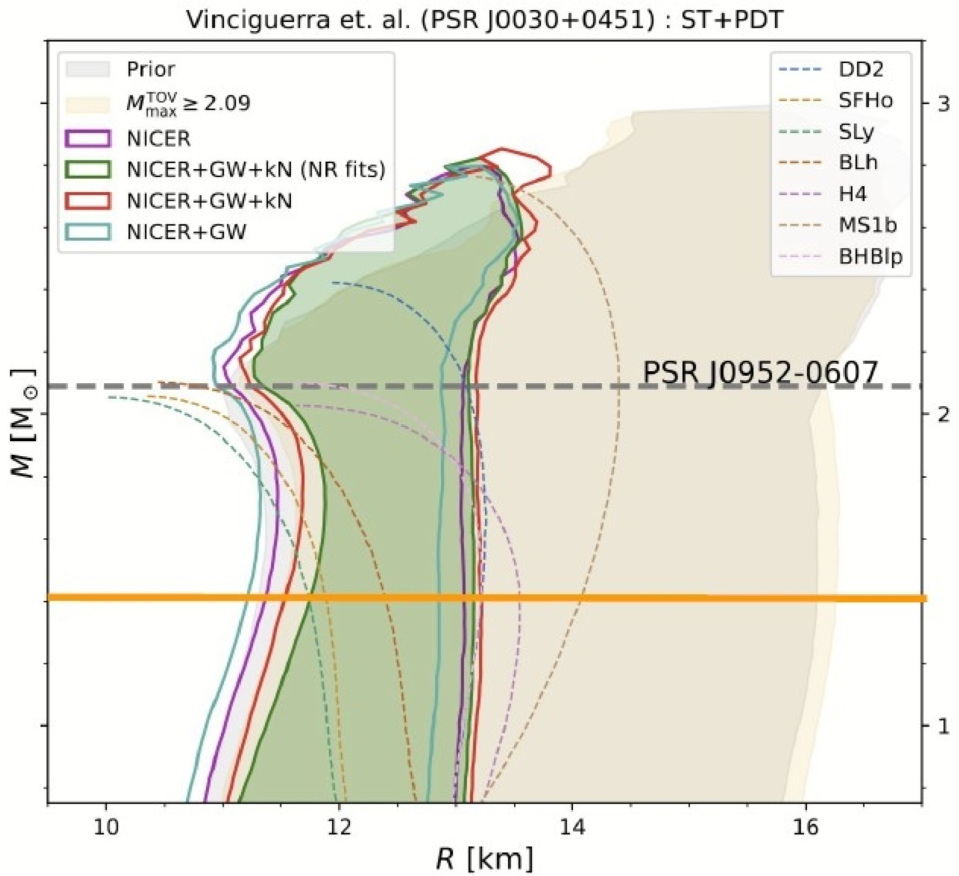
- "Simple" : until contact it's GR
- Good measurements of the **masses** of the NSs m_i
- **Adiabatic tidal parameters** Λ_i (instantaneous response between tidal field and quadrupole of stars)

Post-merger:

- "Complicated": GR+MHD, neutrinos, ...
- Measure the "**peak frequency**" (~ rotation of the remnant), related to **central density of maximum TOV mass** $\rho_{\rm max}^{\rm TOV}$ [Breschi+19]
- weak

Extracting info from post-merger signal is model dependent.

Results: GW170817 + AT2017gfo



[Breschi,Gamba+24]

- Real data!
- GWs give upper limits
- KN gives lower limits

→ Complimentary! (for this event)

$$R_{1.4M_\odot} = 12.30^{+0.81}_{-0.56}\ \text{km}$$

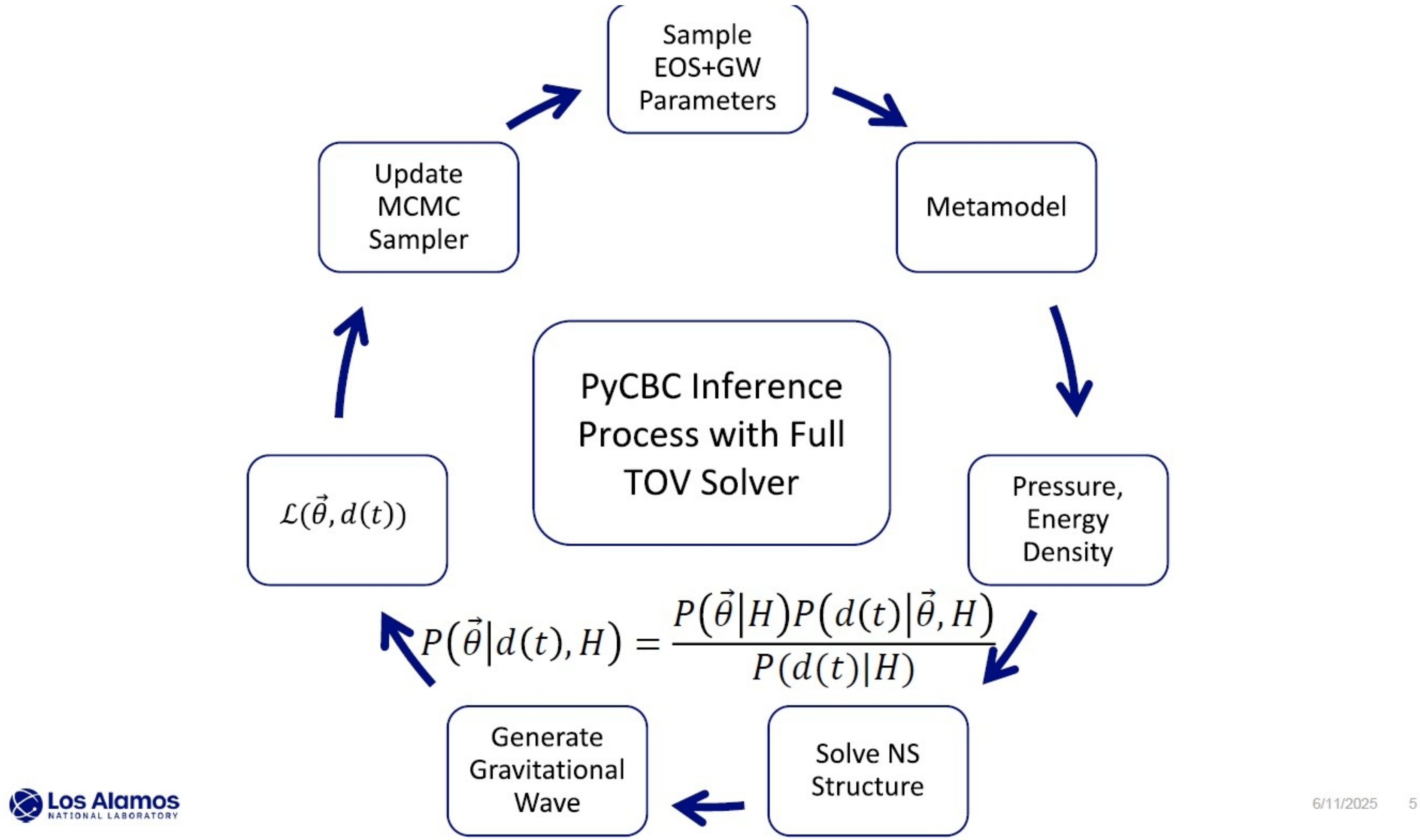
Notes:

- no post-merger GWs
- Other works give similar Constraints [Kohen+24]

In the future, if we measure post-merger GWs, we may be able to constrain the maximum TOV mass to ~5%

Direct Nuclear Parameter Estimation From Gravitational Waves *Brendan Reed*

Old Madison 16:24 - 16:42



Extracting parameters from GW signals using MCMC is a time consuming process.

The bottleneck is the computation of the NS structure.

Emulator Reliability

GW Parameters		
Parameter	Emulator	Full Solver
$\mathcal{M}_c^{\rm src}$	$1.186714^{+0.000066}_{-0.000057}$	$1.186714^{+0.000066}_{-0.000058}$
q	$1.16^{+0.19}_{-0.12}$	$1.16^{+0.19}_{-0.12}$
Δt_c	$0.00716^{+0.00039}_{-0.00121}$	$0.00715^{+0.00039}_{-0.00119}$
ι	$2.566^{+0.055}_{-0.052}$	$2.566^{+0.054}_{-0.051}$
χ_{1z}	$0.010^{+0.026}_{-0.031}$	$0.012^{+0.025}_{-0.032}$
χ_{2z}	$0.005^{+0.030}_{-0.032}$	$0.003^{+0.032}_{-0.033}$

Preliminary

Deformability Solver	#CPU Hours
5-Parameter Emulator	45
5-Parameter Full Solver	2900
10-Parameter Emulator	50

An emulator works 60 times faster and gives results which are almost as good.

Lepton number violating neutrino self-interactions

Motivation - to be taken with a grain of salt:

- lepton number conservation - accidental symetry
- potential cosmological hints

  Barenboim et al. (2019), Song, Gonzalez-Garcia, Salvado (2018), ..
- strong impact on core-collapse supernova

  Kolb et al. (1982), Fuller et al. (1988), Farzan et al. (2018), **AMS**, Tamborra (2020), ...

New Interaction Lagrangian

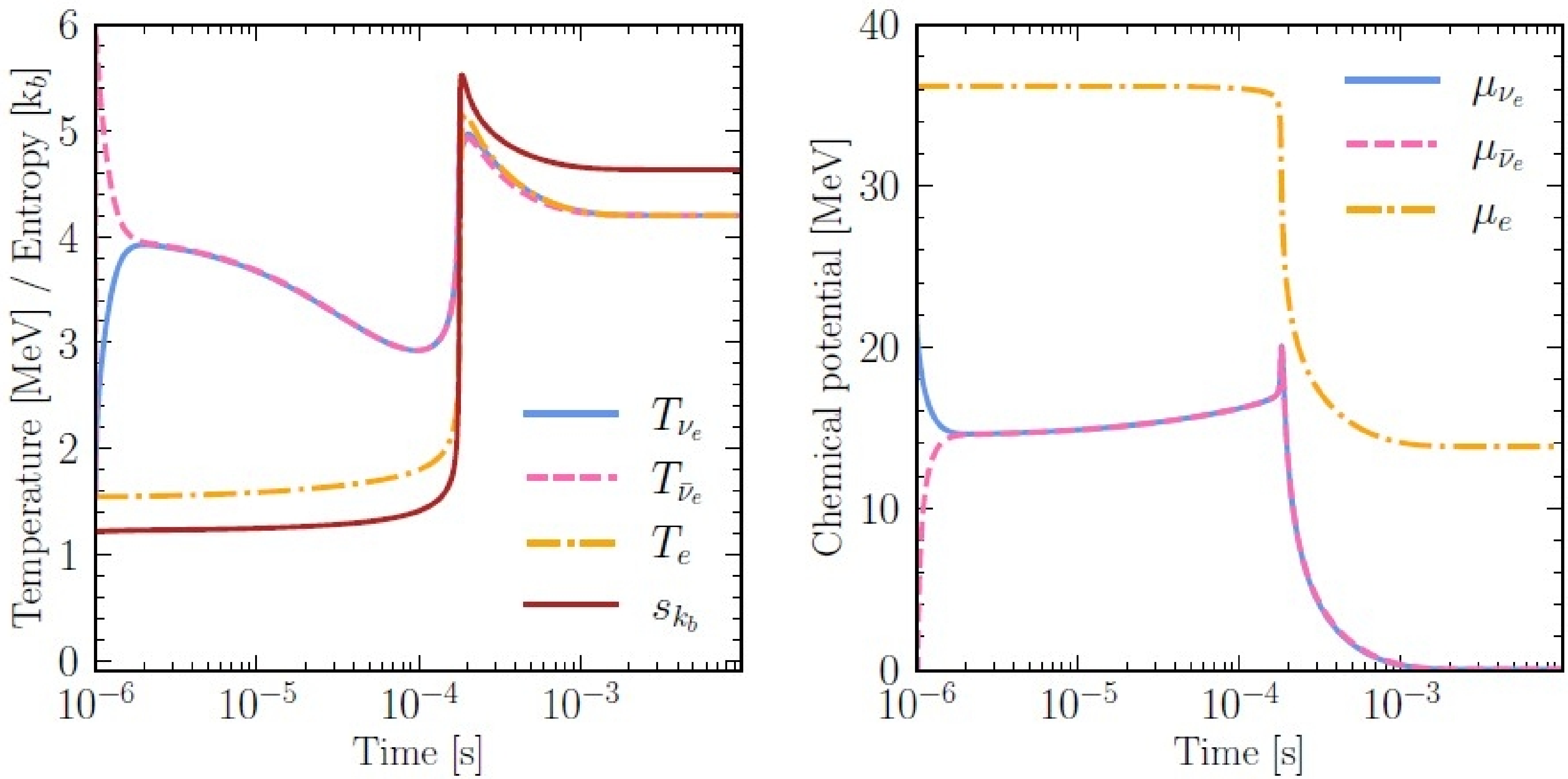
$$\mathcal{L}^{\phi} = g_{\phi,\alpha\beta}\, \phi\, \overline{\nu_{L,\alpha}}\, \nu^{c}_{L,\beta}$$

Probability of the New Interaction

$$\sigma_{\nu\mathrm{SI}} \approx \frac{G^2_{\nu\mathrm{SI}}}{8\pi} E^1_\nu E^2_\nu (1 - \cos\theta)$$

Supernovae are fantastic labs for neutrino physics.
e.g. new ‘stronger than weak’ neutrino interactions

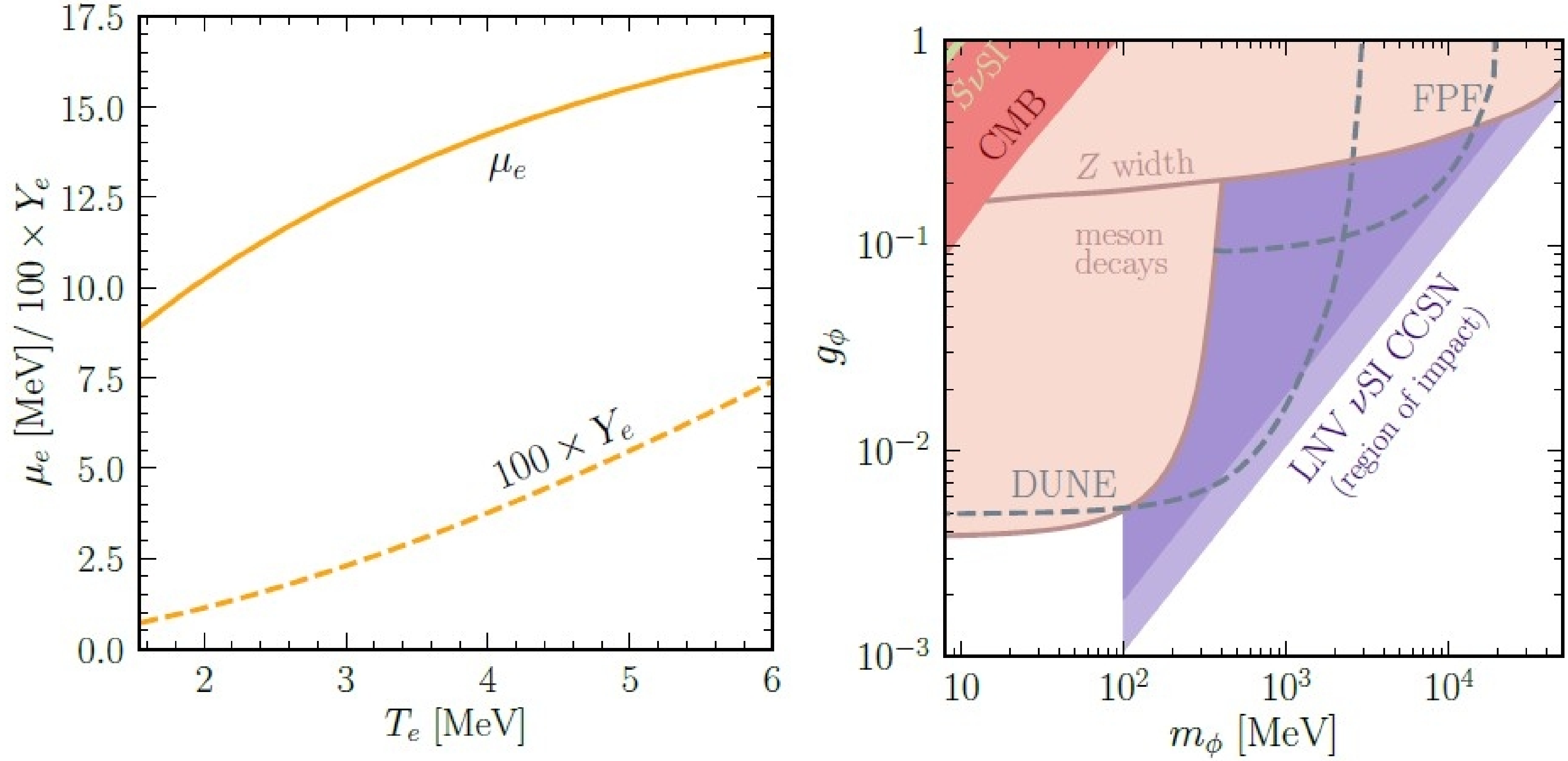
Evolution of Thermodynamical Quantities



- new interactions quickly equilbrate ν_e and $\bar{\nu}_e$ seas
- enhanced ν_e and e^- captures heat up the matter
- similar results for all flavors equilibration

The new interactions result in a different chemical and thermal equilibrium

New β-equilibrium with LNV νSI

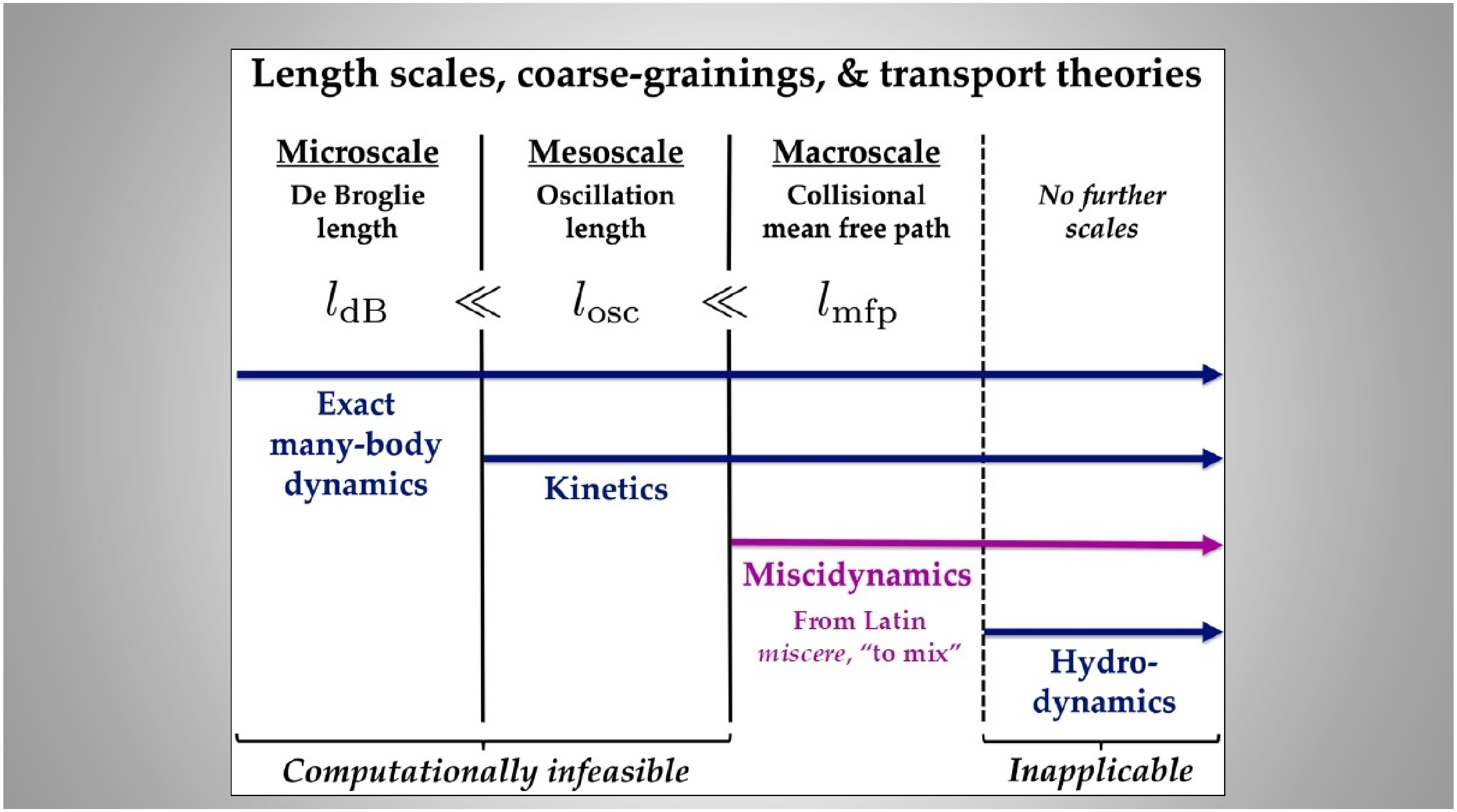


- regardless of the final T_e the new equilibrium has a very low Y_e
  $\mu_e = \delta m_{np} - T_e \ln\left(\frac{Y_e}{1-Y_e}\right)$, with $Y_e = \frac{1}{\pi^2 \rho} \int_0^\infty dp_e\, p_e^2\, f_e(E_e, T_e, \mu_e)$
- complementarity with future accelerator-based experiments

In order to properly assess impact of LNV νSI, we need to undertake full simulations

Local-equilibrium theory of neutrino oscillations in supernovae and mergers *Luke Johns*

Multicultural Greek 14:18 - 14:36



Adding neutrino oscillations to SN simulations will be **HARD**. Miscidynamics is the idea to assume neutrino flavor oscillations reach an equilibrium that is easier to follow computationally.

Miscidynamic equation in the local equilibrium frame:

Flavor polarization vector → $\mathbf{P}^{\mathrm{eq}}$

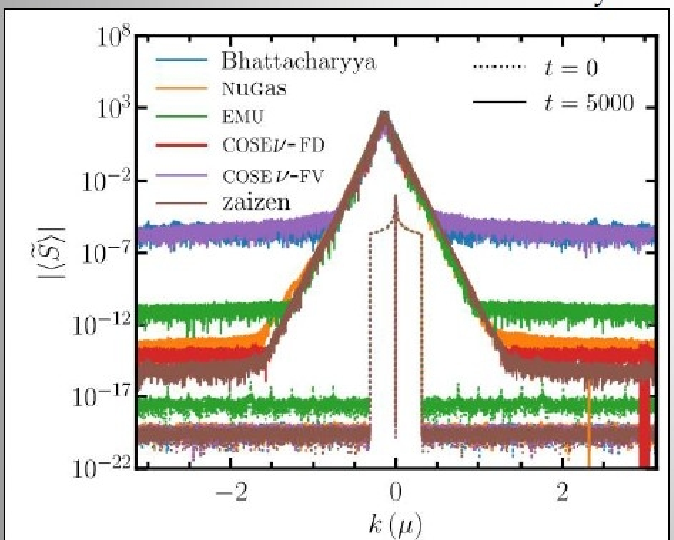
Collisional depolarization rate → Γ

$$(\partial_t + \hat{\mathbf{p}} \cdot \partial_{\mathbf{r}})\mathbf{P}^{\mathrm{eq}} = -(\gamma + \Gamma)\mathbf{P}^{\mathrm{eq}}$$

Turbulent flavor-wave viscosity → γ

(compare *turbulent eddy viscosity* in a fluid)

Flavor-wave turbulence after instability

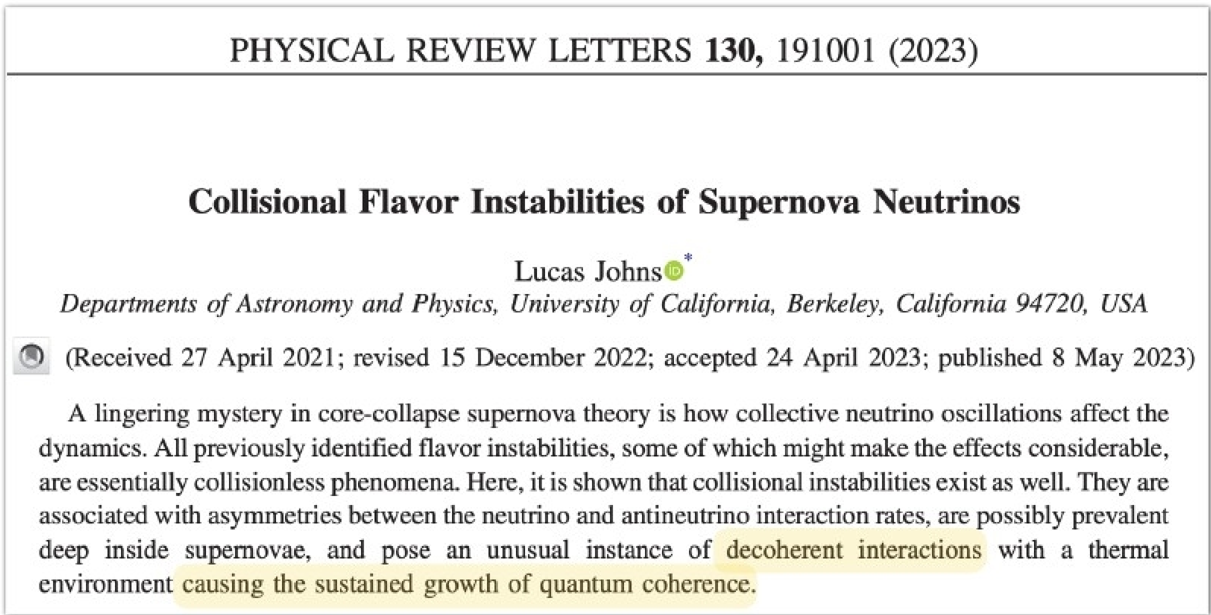


Richers et al., PRD (2020)

The flavor equilibrium follows a simple equation. The collisional rate is known, the flavor-wave viscosity is not.

Context

- Collisions are generally expected to **destroy** flavor coherence.
- In some regimes, a discrepancy between the neutrino and antineutrino reaction rates can actually **amplify** coherence *through the non-linear self-interaction term.*


PHYSICAL REVIEW LETTERS **130,** 191001 (2023)

Collisional Flavor Instabilities of Supernova Neutrinos

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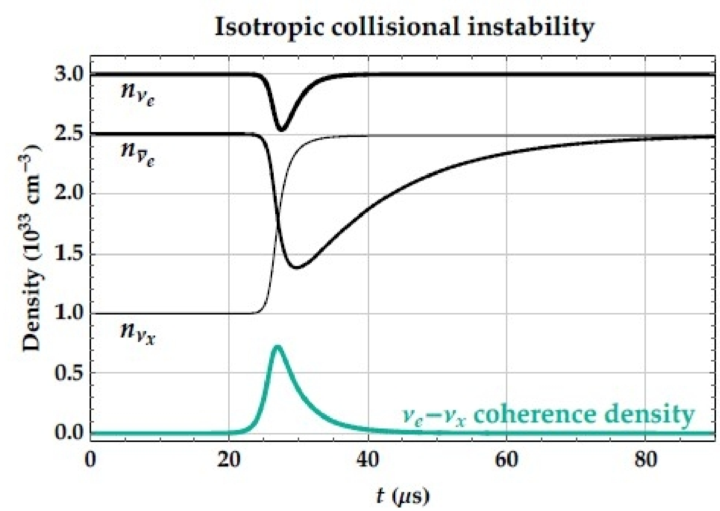
(Received 27 April 2021; revised 15 December 2022; accepted 24 April 2023; published 8 May 2023)

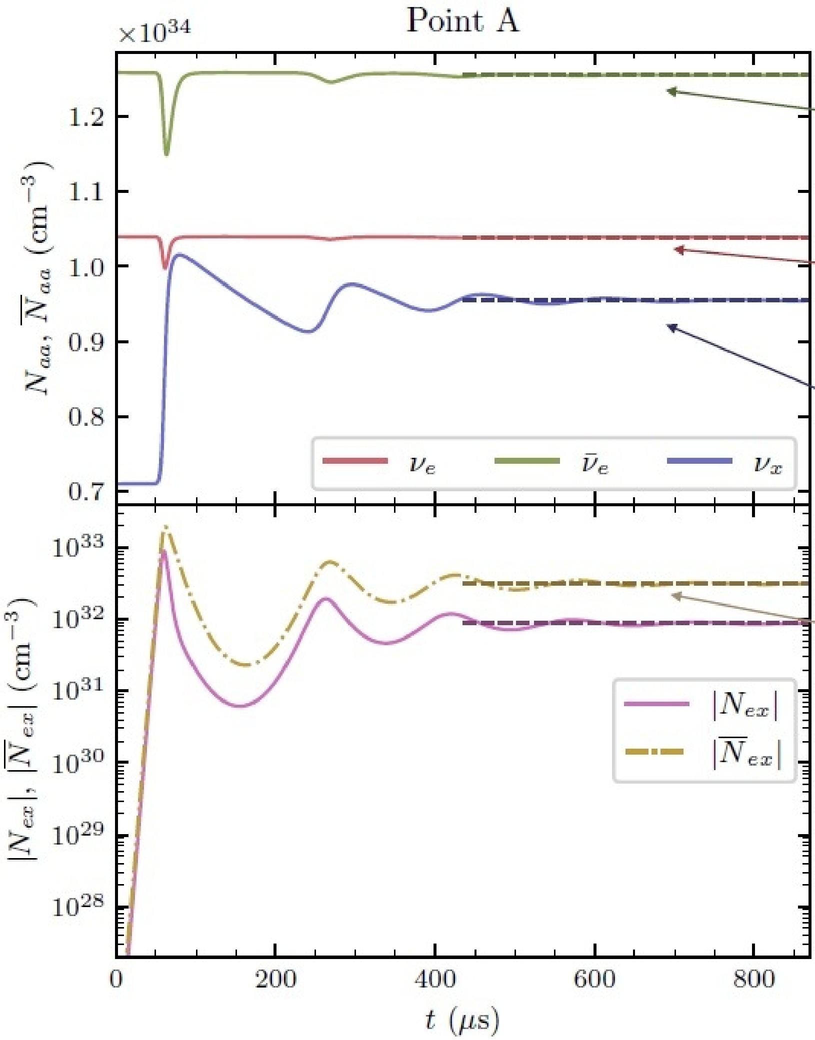
A lingering mystery in core-collapse supernova theory is how collective neutrino oscillations affect the dynamics. All previously identified flavor instabilities, some of which might make the effects considerable, are essentially collisionless phenomena. Here, it is shown that collisional instabilities exist as well. They are associated with asymmetries between the neutrino and antineutrino interaction rates, are possibly prevalent deep inside supernovae, and pose an unusual instance of decoherent interactions with a thermal environment causing the sustained growth of quantum coherence.



Surprisingly collisions can actually cause flavor change.

Asymptotic state and flavor coherence

JF, [2505.16961]



$$\bar{\kappa}_e \left[\overline{N}^{(\infty)}_{ee} - \overline{N}^{(\mathrm{cl})}_{ee}\right] = \kappa_e \left[N^{(\infty)}_{ee} - N^{(\mathrm{cl})}_{ee}\right]$$

$$N^{(\infty)}_{ee} - N^{(\mathrm{cl})}_{ee} = \frac{1}{\kappa_e} \frac{\bar{\Gamma}[\overline{N}^{(\mathrm{cl})}_{ee} - N^{(\mathrm{cl})}_{xx}] - \Gamma[N^{(\mathrm{cl})}_{ee} - N^{(\mathrm{cl})}_{xx}]}{\Gamma\left(\frac{1}{\kappa_e} + \frac{1}{\kappa_x}\right) - \bar{\Gamma}\left(\frac{1}{\bar{\kappa}_e} + \frac{1}{\kappa_x}\right)}$$

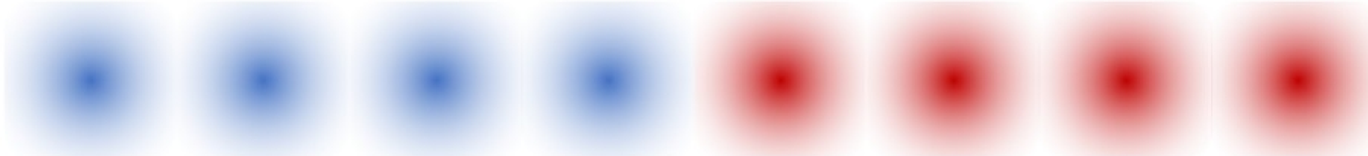
$$\kappa_x \left[N^{(\infty)}_{xx} - N^{(\mathrm{cl})}_{xx}\right] = -\kappa_e \left[N^{(\infty)}_{ee} - N^{(\mathrm{cl})}_{ee}\right]$$

$$|N_{ex}|^{(\infty)} = \sqrt{-\frac{\kappa_e}{\kappa_e + \kappa_x}[N^{(\infty)}_{ee} - N^{(\mathrm{cl})}_{ee}][N^{(\infty)}_{ee} - N^{(\infty)}_{xx}]}$$

When collisions and flavor transformation occur together, a new kind of quantum equilibrium is reached, different from flavor equilibrium and collisional equilibrium.

Hybrid Many-Body Simulation

$$\frac{\partial \psi}{\partial t} = -iH[X(t)]\psi$$

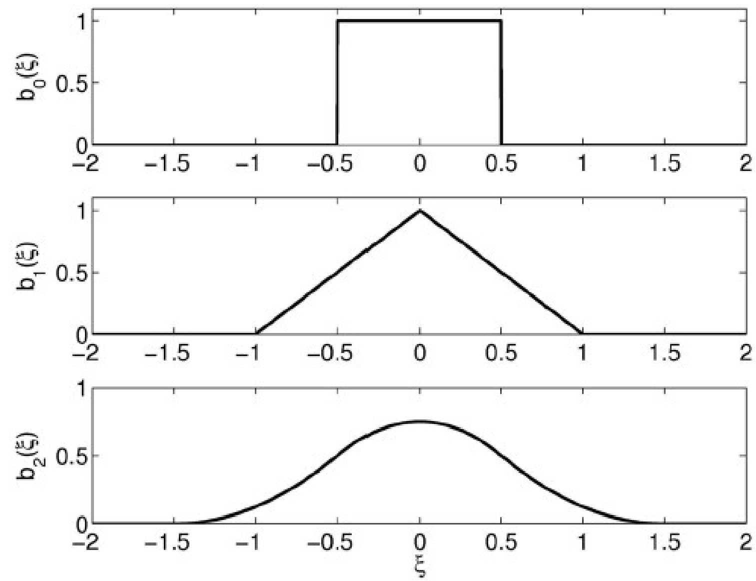


Forward-scattering term

$$H[X(t)] = \frac{\sqrt{2}G_F}{2} \sum_{i<j} \frac{N_i + N_j}{w^3} \boxed{\vec{\sigma}_i \cdot \vec{\sigma}_j} \boxed{J_{ij}} \boxed{S(\xi_{ij})}$$

Angular Factor

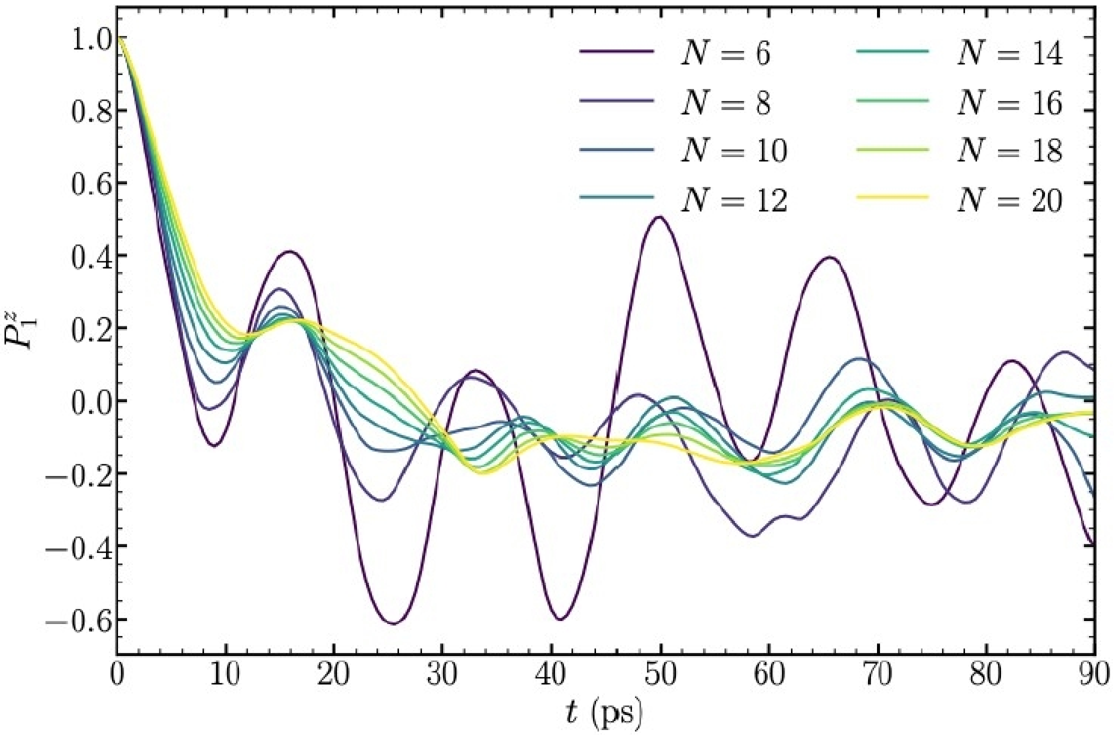
$$J_{ij} = (1 - \hat{p}_i \cdot \hat{p}_j)$$

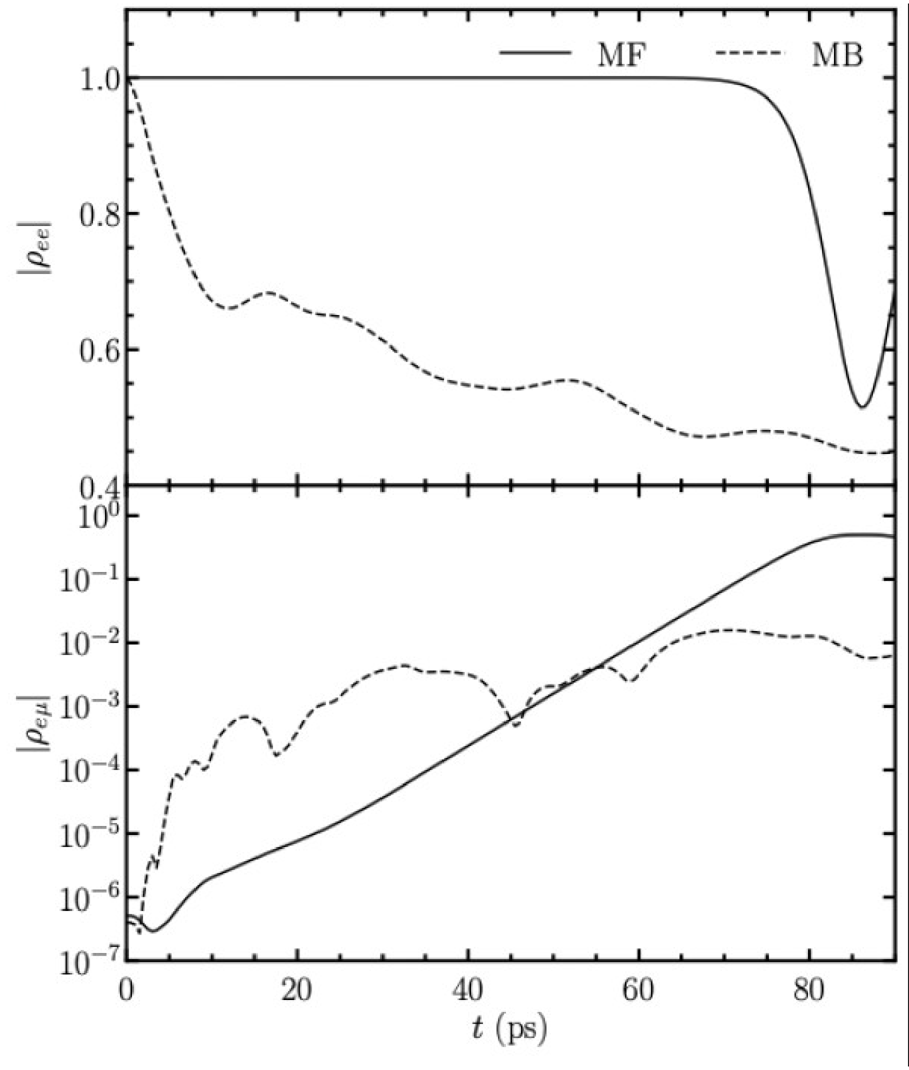


$$\xi_{ij} = (x_i - x_j)/w$$

An important open question is how well mean-field calculations of flavor transformation compare with results from many-body.

Is flavor instability a lie?





Many-body neutrino plasma model seems to predict fast many-body effects but results are limited by system size and use of approximate Hamiltonian.

Summary

- There's a lot of exciting things going on at the intersection of nuclear / particle physics and astrophysics:
  - new experiments measuring properties of nuclei far from stability
  - new ways to observe the Universe with greater precision
  - new ideas / approaches to extract information from observations
  - new theory ideas of how what is going on and how to model astrophysical systems