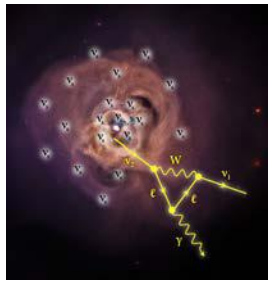
Neutrino Astrophysics II

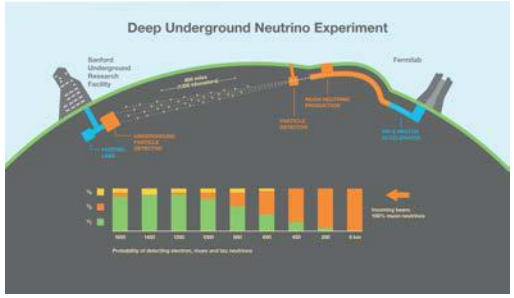
***Neutrino Physics, Entropy, Gravitation*: flavor, compact objects, nucleosynthesis**

CMB: e.g., Simons Observatory

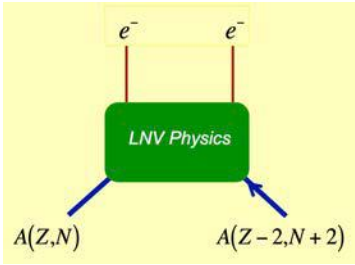
30m telescope/ NAOJ



X-Ray Astronomy
Image credit:
Science/Abazajian



Long Baseline Oscillation experiments, e.g.,
DUNE, https://www.dunescience.org/



Lepton Number Violation:
$0\nu\beta\beta$
Lepton degeneracy in compact objects

N3AS Summer School in Multi-Messenger Astrophysics
July 22 and 23, 2023

George M. Fuller
Department of Physics
University of California, San Diego

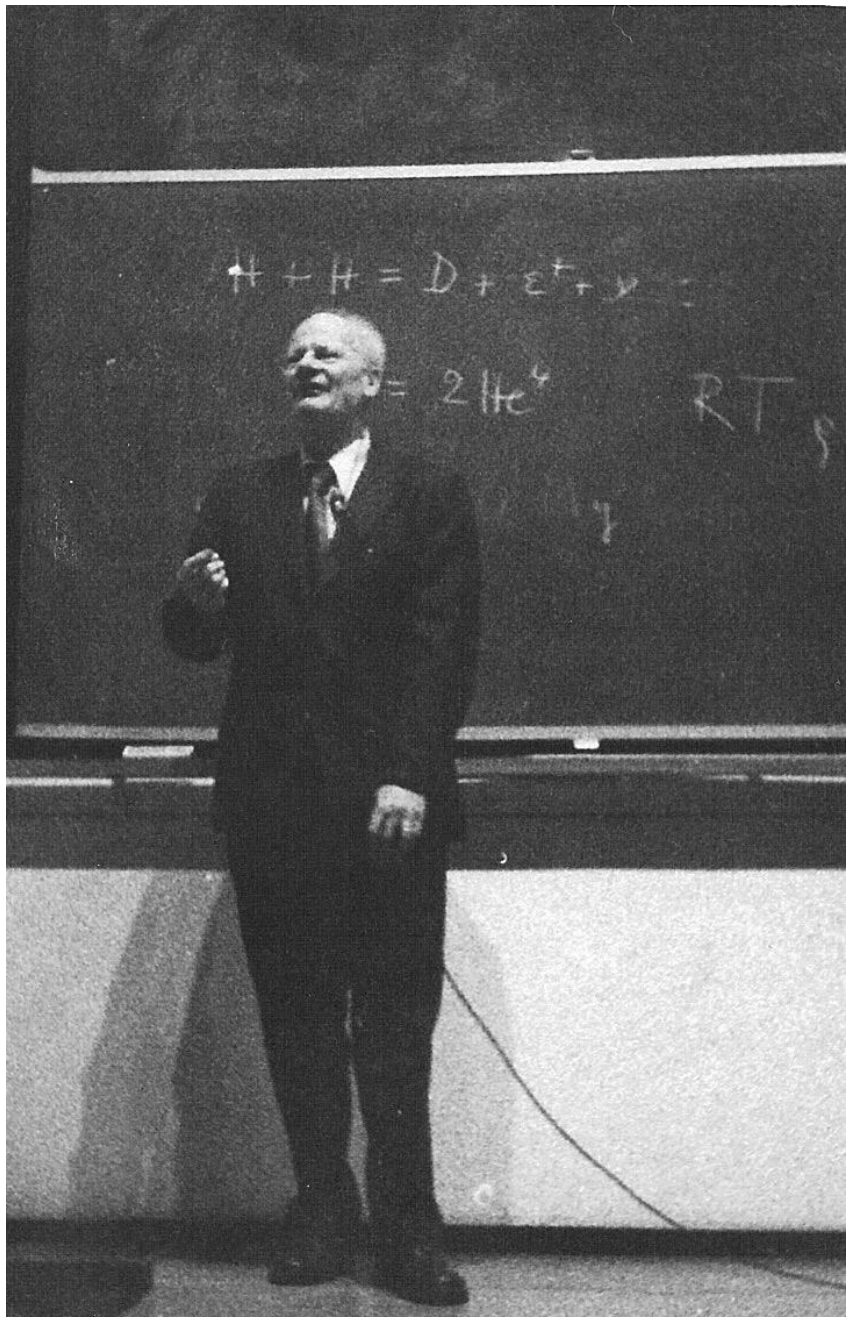
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

Finish BBN Discussion

The man who figured out how stars shine made many other fundamental contributions in particle, nuclear, and condensed matter physics, as well as astrophysics.

For example, Hans Bethe completely changed the way astrophysicists think about equation of state and nucleosynthesis with his 1979 insight on the role of entropy.

Bethe, Brown, Applegate, & Lattimer (1979)



Hans A. Bethe

1906 - 2005

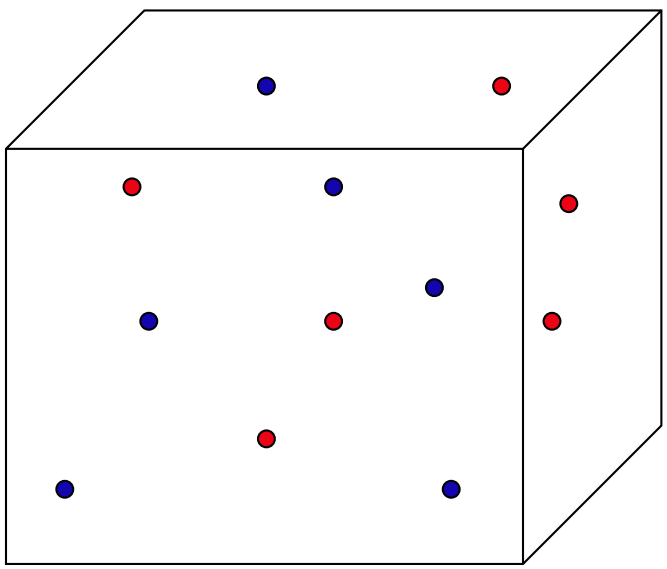
Boltzmann's tomb www-history.mcs.st-and.ac.uk

Entropy

$$S = k_{\mathrm{b}} \log \Gamma$$

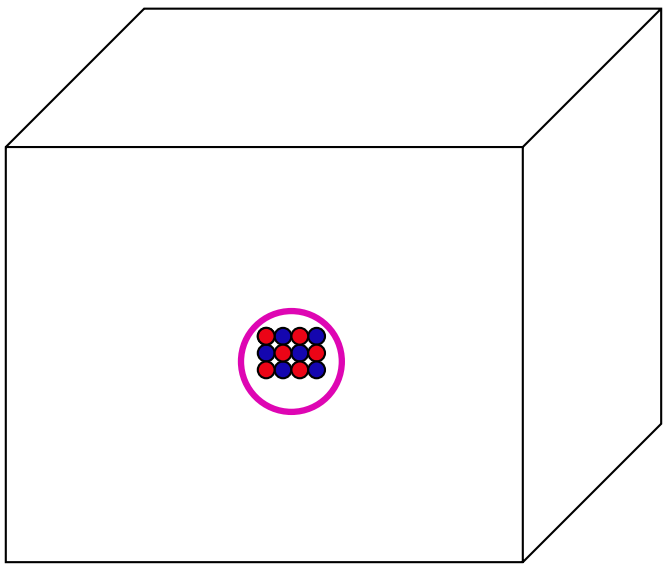
a measure of a system's disorder/order

High Entropy



12 free nucleons

Low Entropy



^{12}C nucleus

Freeze-Out from Nuclear Statistical Equilibrium (NSE)

In NSE the reactions which build up and tear down nuclei have equal rates, and these rates are large compared to the local expansion rate.

$$Z\,p + N\,n \longleftrightarrow A(Z,N) + \gamma$$

nuclear mass A is the sum of protons and neutrons A=Z+N

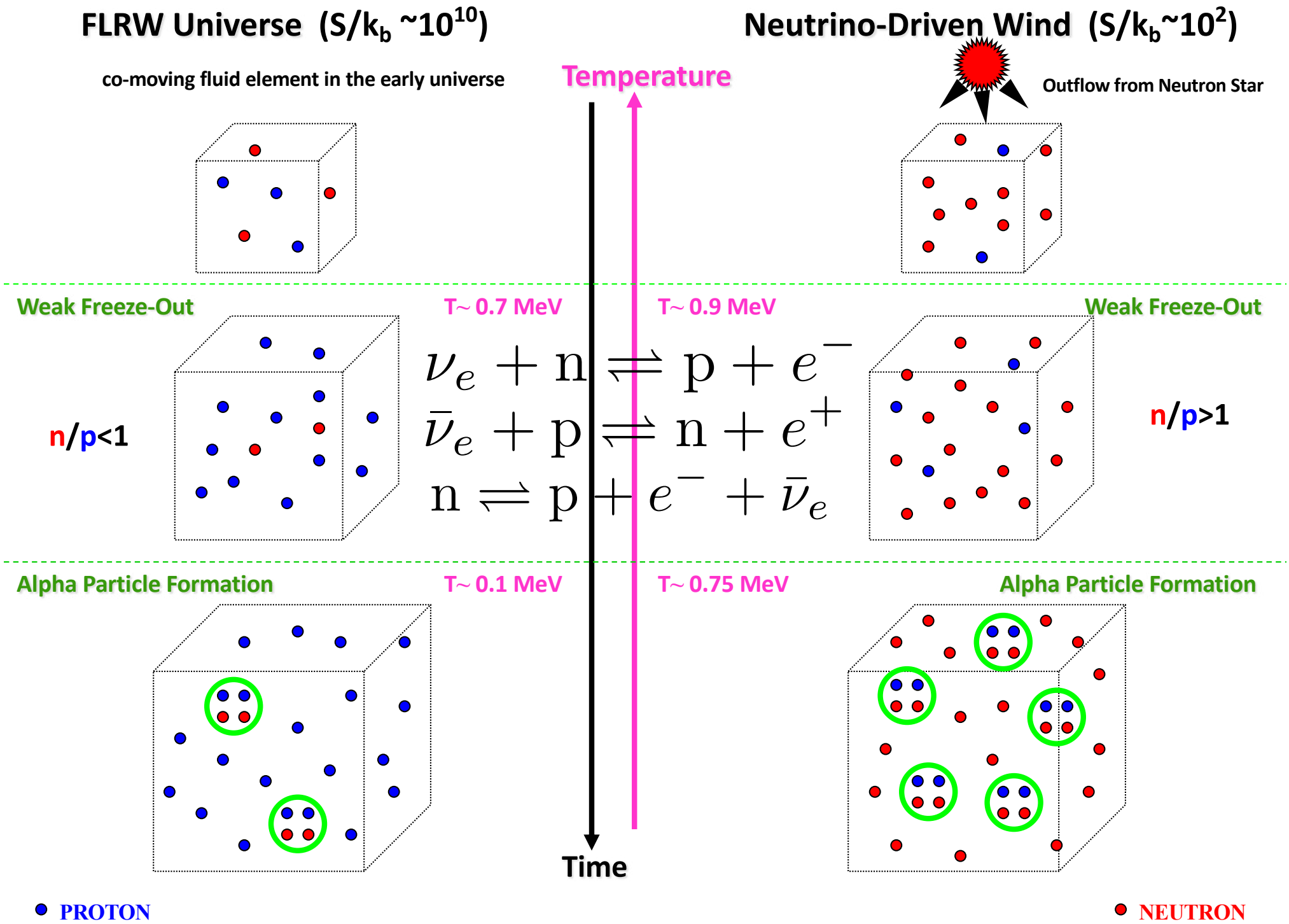
Saha Equation

$$Z\,\mu_p + N\,\mu_n = \mu_A + Q_A$$

Binding Energy of Nucleus A

Abundance (mass fraction X) of nucleus with mass number $A = Z + N$, is a fight between binding and disorder:

$$X(A,Z) \propto s^{1-A}\ \exp\left(\frac{\text{binding energy } Q_{\rm A}}{T}\right)$$


FLRW Universe (S/k_b ~10^10)
Neutrino-Driven Wind (S/k_b~10^2)
co-moving fluid element in the early universe
Temperature
Outflow from Neutron Star
Weak Freeze-Out
T~ 0.7 MeV
T~ 0.9 MeV
Weak Freeze-Out
n/p<1
n/p>1
$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$
$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$
$\mathrm{n} \rightleftharpoons \mathrm{p} + e^- + \bar{\nu}_e$
Alpha Particle Formation
T~ 0.1 MeV
T~ 0.75 MeV
Alpha Particle Formation
Time
PROTON
NEUTRON

STARS

and *Entropy & Neutrinos*

For a review of neutrino/weak interaction physics in stars see:
Fuller, Haxton, Grohs, in “Encyclopedia of. Cosmology”, Ellsevier 2023

Do we even know the fundamental physics necessary to understand the evolution of stars and compact objects?

History:

In the 20th Century there were, broadly, three key developments in understanding stellar interiors and evolution:

(1) quantum mechanics and, especially, the connection between spin and statistics;

(2) Nuclear and Particle Physics

laboratory explorations went hand-in-hand with astrophysical modeling, e.g., Kellogg Radiation Laboratory, Caltech

(3) Large scale numerical simulation/computers

Today:

We already know that the otherwise successful Standard Model *is inadequate*
(e.g., it cannot explain dark matter, dark energy, aspects of neutrino physics, etc.)

Are there "secret interactions" between neutrinos?

Are there new light particles that figure in the physics of stars?

Are there whole new "Dark Sectors" of particles?

The advent of Multi-Messenger Astrophysics,
especially gravitational wave astronomy, is already a game changer

A new regime with synergistic coupling between the lab and observation??

Beyond Standard Model Physics

– Neutrinos: NSIs; lepton number violation; sterile νs (range of masses/mixing)
– axion-like particles (ALPs), etc.
– dark sectors (e.g., dark photons, etc.)

Dark Matter/Dark Sectors

Revolution in ideas about dark matter !

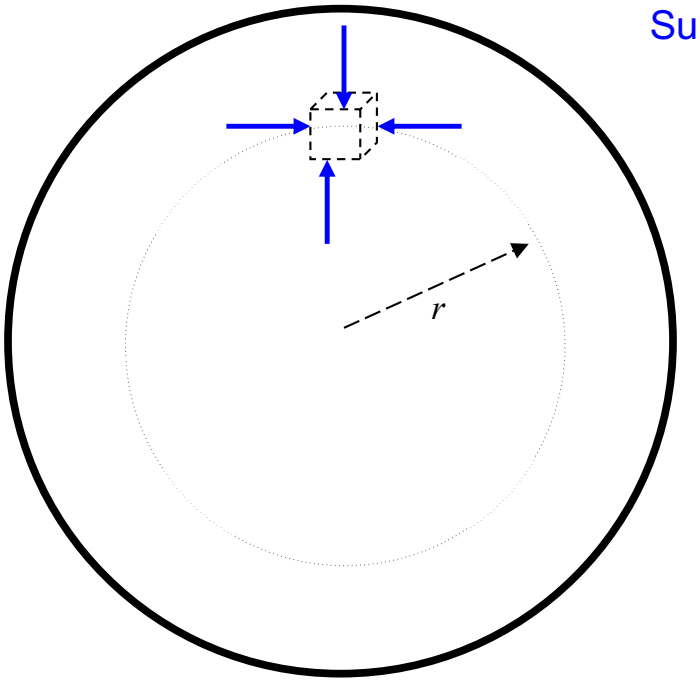
see the INT program (August 2022):
"*Dark Matter in Compact Objects, Stars, and Low Energy Experiments*"

– direct detection: light dark matter (detector physics)
– gravitational wave probes/other gravitational signatures
– nucleosynthesis constraints
– dark matter-induced neutron star implosion (nuclear EOS; heat transport)

. . . neutrinos are murder weapons
when it comes to massive stars!

Hydrostatic Equilibrium

Consider a fluid element in a star --- hydrostatic equilibrium obtains when all pressure forces on this fluid element balance gravitational forces



Sum of pressure forces on surface of fluid element

$$\oint \mathrm{P}\, d\mathbf{Surf} = \int \nabla \mathrm{P}\, d\mathrm{Vol}$$

Sum of gravitational forces on fluid element

$$\int \frac{\mathrm{G}M(r)\,\rho}{r^2} \cdot \left[\frac{-\mathbf{r}}{r}\right] d\mathrm{Vol}$$

Hydrostatic Equilibrium: equality of gravitational and pressure forces

$$\nabla \mathrm{P} = \frac{\mathrm{G}M(r)\,\rho}{r^2} \cdot \left[\frac{-\mathbf{r}}{r}\right]$$

Spherically symmetric star -- at radius r

$$\frac{d\mathrm{P}}{dr} = -\frac{\mathrm{G}M(r)\,\rho}{r^2}$$

Hydrostatic/Mechanical Equilibrium (*forces all balance*)
does not guarantee stability.

Nor does it guarantee thermal stability
(e.g., stability against convection requires a positive entropy gradient)

Nor does it guarantee chemical equilibrium
(e.g., *nuclear statistical equilibrium*)

The Adiabatic Index

$$\Gamma_1 \equiv \left.\frac{d\ln P}{d\ln \rho}\right|_S$$

This quantity gives a kind of "spring constant" of the material (matter and radiation) in the star.

It is a key determinant of stability

Maxwell-Boltzmann (non-relativistic) gas: $\Gamma_1 = 5/3$

Radiation (photons, relativistic particles, etc.): $\Gamma_1 = 4/3$

Stellar Stability with Newtonian Gravitation

The pressure-averaged value of the adiabatic index must satisfy

$$\langle \Gamma_1 \rangle \geq \frac{4}{3}$$

Stellar Stability in General Relativity

With nonlinear (self-coupled) gravitation stability now requires that the pressure-averaged value of the adiabatic index satisfy

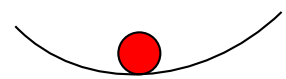
$$\langle \Gamma_1 \rangle \geq \frac{4}{3} + O\left(\frac{r_{\rm s}}{r}\right)$$

$$\left(\frac{r_{\rm s}}{r}\right) \sim 10^{-4} \left(\frac{M}{1.4\, M_\odot}\right) \cdot \left(\frac{10^9\ {\rm cm}}{\text{radius of star}}\right)$$

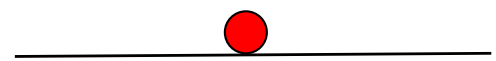
analogy: consider a ball rolling on a surface

Newtonian Gravitation+Maxwell-Boltzmann pressure: = *stable* (restoring forces)

$$\langle \Gamma_1 \rangle > 4/3$$

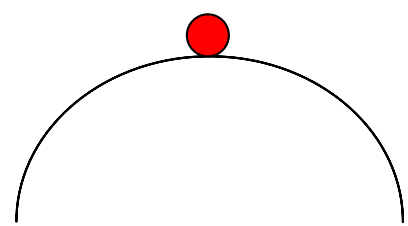


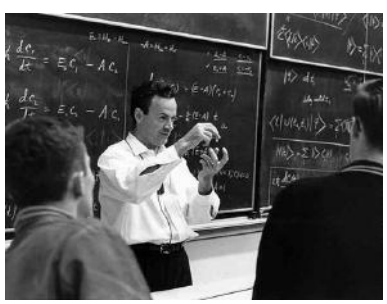
Newtonian Gravitation+radiation pressure:
Zero total (gravitational + thermal) energy = *neutrally stable* $\langle \Gamma_1 \rangle = 4/3$



General Relativity: nonlinear, so a little more "gravity" makes even more "gravity"
= *no restoring forces*;

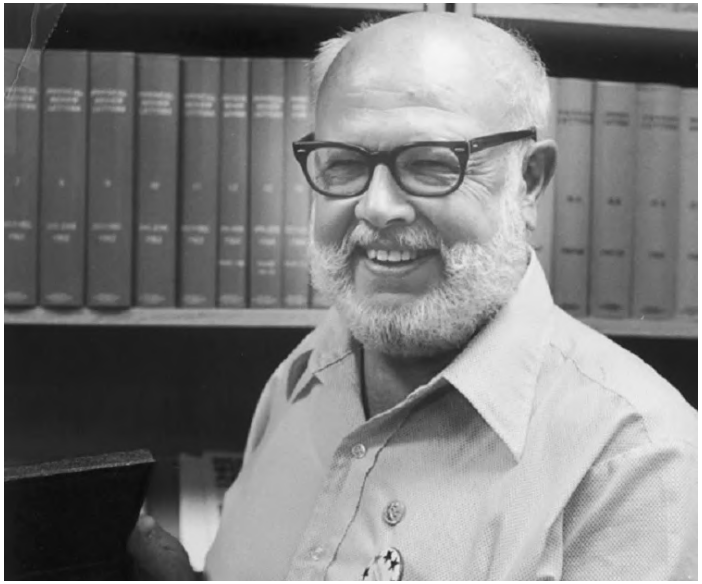
unstable whenever $\langle \Gamma_1 \rangle < 4/3 + \mathcal{O}(r_{\rm s}/r)$





This is the **Feynman-Chandrasekar** instability

whenever the pressure support for a star comes from particles moving near the speed of light
the star is "**trembling on the verge of instability**"*

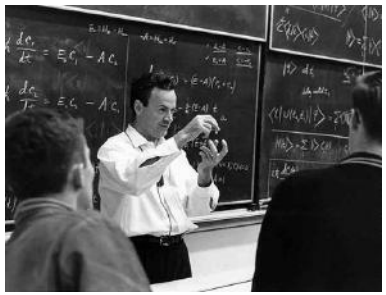


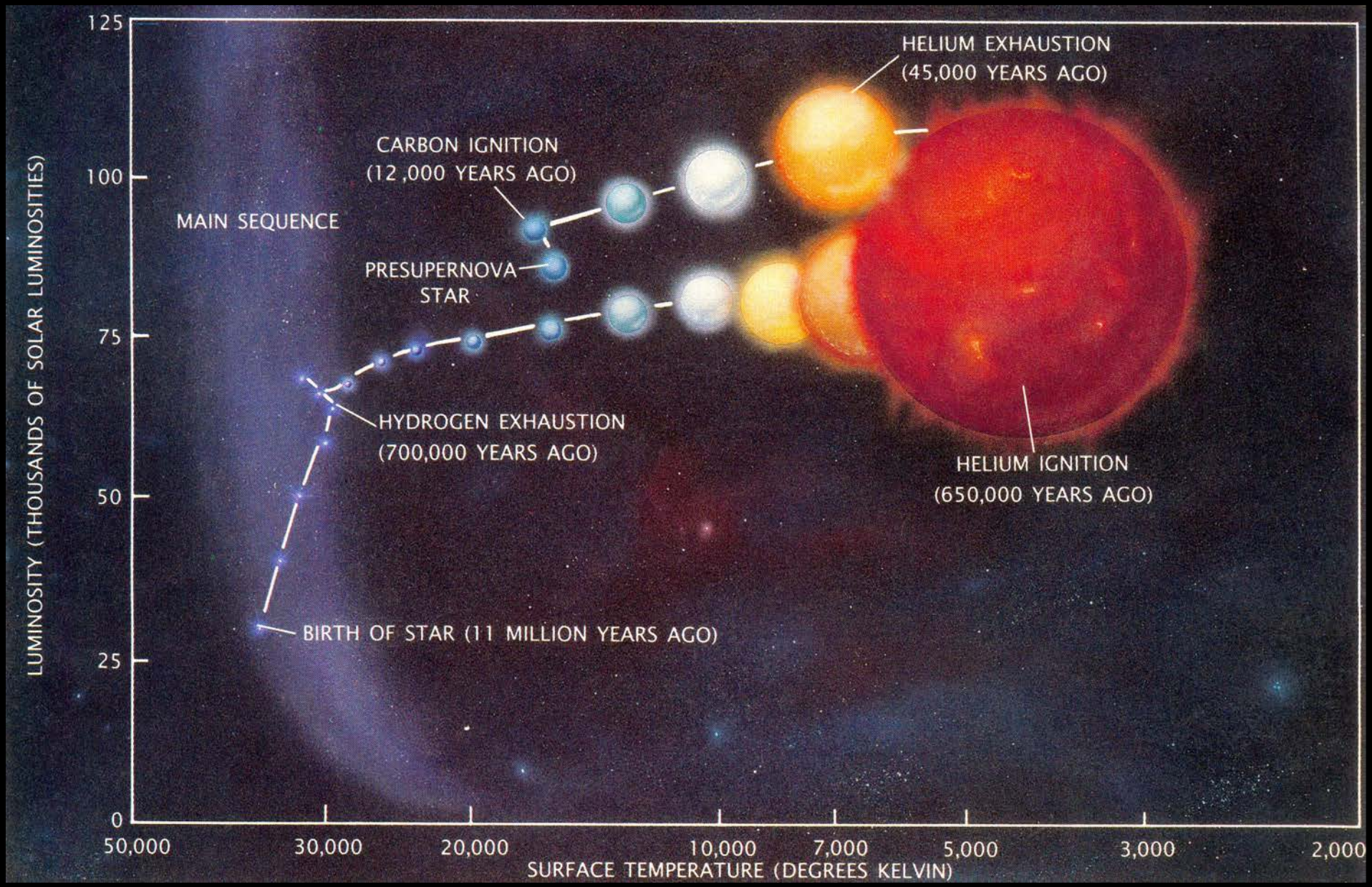
*

William A. Fowler

whenever the pressure support for the star is from particles moving near the speed of light the star is "**trembling on the verge of instability**"

MASS in $M_\odot$	**Main Seq. Entropy per baryon** s/k_B	**Collapse Entropy per baryon** s/k_B	**degenerate core mass** in $M_\odot$	**Instability Mechanism**	**Fraction of rest mass radiated as neutrinos**	**Neutrino Trapping / Thermal equilibrium**
10 to ~ 100	**~ 10**	**~ 1**	**~ 1.4**	**Electron capture / NSE Feynman-Chandrasekhar G.R. instab.**	**~ 10% of collapsing core mass**	**Yes**
~ 100 to ~ 10^4	**~ 100**	**~ 100**	**NONE**	**$e^\pm$ pair instability**	**~ 10% C/O burning core**	**Yes**
~ 10^4 to ~ 10^8	**~ 1000 no main seq.**	**~ 1000**	**NONE**	**Feynman-Chandrasekhar G.R. Instability**	**~ 3%**	**No**





Weaver & Woosley, *Sci Am*, 1987

Self-Gravitating Configurations (*stars, clusters, etc.*)

$\Rightarrow$ Sometimes these have negative heat capacity, $dQ/dT < 0$.
"When they cool off, they heat up" (Yogi Berra?)

Yogi Berra

"Baseball is 90 percent mental.
The other half is physical."

"When you come to a fork in the
road, take it"

Nuclear Burning Stages of a 25 M_{sun} Star

Burning Stage	Temperature	Density	Time Scale
Hydrogen	5 keV	5 g cm^{-3}	7 X 10^6 years
Helium	20 keV	700 g cm^{-3}	5 X 10^5 years
Carbon	80 keV	2 X 10^5 g cm^{-3}	600 years
Neon	150 keV	4 X 10^6 g cm^{-3}	1 year
Oxygen	200 keV	10^7 g cm^{-3}	6 months
Silicon	350 keV	3 X 10^7 g cm^{-3}	1 day
Core Collapse	700 keV at instability point $\mu_e \sim 10\,\mathrm{MeV}$ neutronization : $e^- + \mathrm{p} \rightarrow \mathrm{n} + \nu_e$	4 X 10^9 g cm^{-3}	~ seconds of order the free fall time
"Bounce"	~ 2 MeV	~10^{15} g cm^{-3}	~ milli-seconds
Neutron Star	< 70 MeV initial ~ keV "cold"	~10^{15} g cm^{-3}	initial cooling ~ 15-20 seconds ~ thousands of years

Massive Stars are Giant Refrigerators

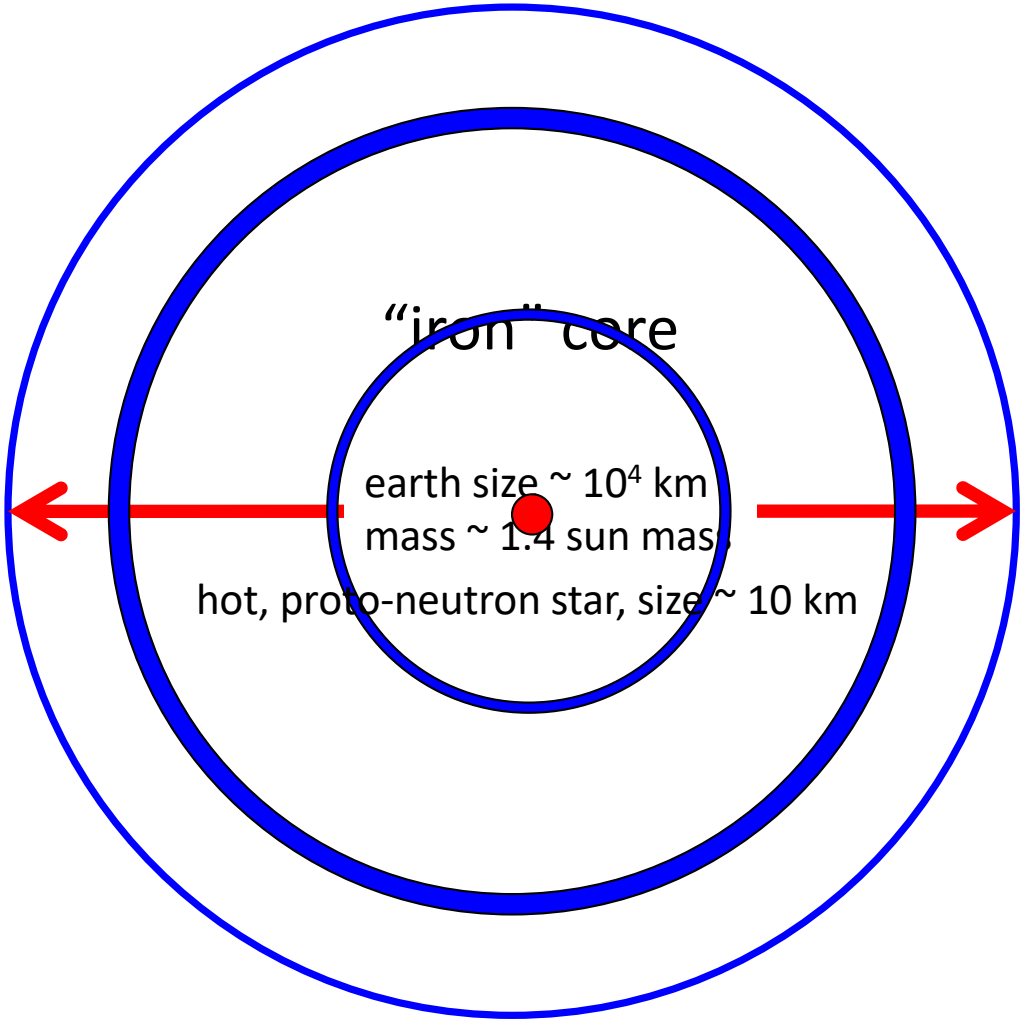
From core carbon/oxygen burning onward
the neutrino luminosity exceeds the photon luminosity.

Neutrinos carry energy/entropy away from the core!

Core goes from S/k_b~10 on the Main Sequence (hydrogen burning)
to a thermodynamically cold S/k_b ~1 at the onset of collapse!

e.g., the collapsing core of a supernova can be a
frozen (Coulomb) crystalline solid with a
temperature ~1 MeV!

. . . and in about one second . . .



Collapse (*in-fall*)

Low Entropy Collapse $S/k_{\rm b} \sim 1$

High electron Fermi energy $\mu_e \approx 11.1\,\mathrm{MeV}\,(\rho_{10}\,Y_e)^{1/3} \sim 40\,\mathrm{MeV}$

Temperature $T \approx 1\,\mathrm{MeV}$ to $\sim 2\,\mathrm{MeV} \Rightarrow$ Nuclear Statistical Equilibrium (NSE)

Mean nuclear mass is very large $\langle A \rangle \sim 100$; These large nuclei are in highly excited states $\langle E_x \rangle \approx a\,T^2 \approx ((A/8)\,\mathrm{MeV}^{-1})\,T^2 \sim 30\,\mathrm{MeV}$

Neutronization via electron capture: Raul Herrera, Calvin Johnson, GMF *Phys Rev* C **105**, 015801 (2022)

$e^- + A(Z,N) \to A(Z-1,N+1) + \nu_e \quad \Rightarrow \quad$ heats medium, increases entropy S

$e^- + p \to n + \nu_e \quad \Rightarrow \quad$ (initially)cools medium, decreases entropy S.
But very few free protons; free proton mass fraction is exponentially sensitive to temperature $X_p \approx e^{-\hat{\mu}/T}\,\mathrm{X_n}$

Neutrinos trapped by neutral current coherent scattering on heavy nuclei; thermalized by neutrino-electron scattering

$\Rightarrow$ Beta Equilibrium $e^- + \text{"}p\text{"} \rightleftharpoons \text{"}n\text{"} + \nu_e \;\Rightarrow\; \mu_e - \mu_{\nu_e} = \mu_n - \mu_p + \delta m_{np}$

Neutrinos Dominate the Energetics of Core Collapse Supernovae

Explosion
only ~1% of neutrino energy

Total optical + kinetic energy, 10^{51} ergs

Total energy released in Neutrinos, 10^{53} ergs

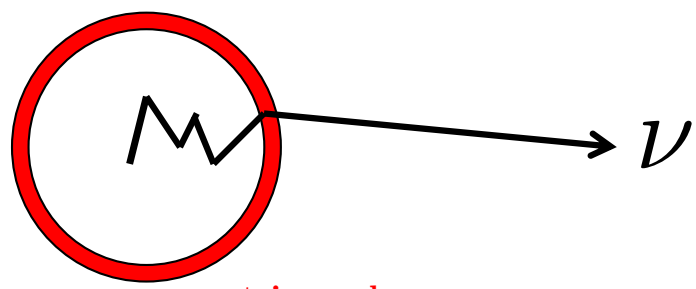
10% of star's rest mass!

$$E_{\rm grav} \approx \frac{3}{5}\,\frac{{\rm G}\,M_{\rm NS}^2}{R_{\rm NS}} \approx 3\times 10^{53}\,{\rm erg}\left[\frac{M_{\rm NS}}{1.4\,{\rm M}_\odot}\right]^2\left[\frac{10\,{\rm km}}{R_{\rm NS}}\right]$$

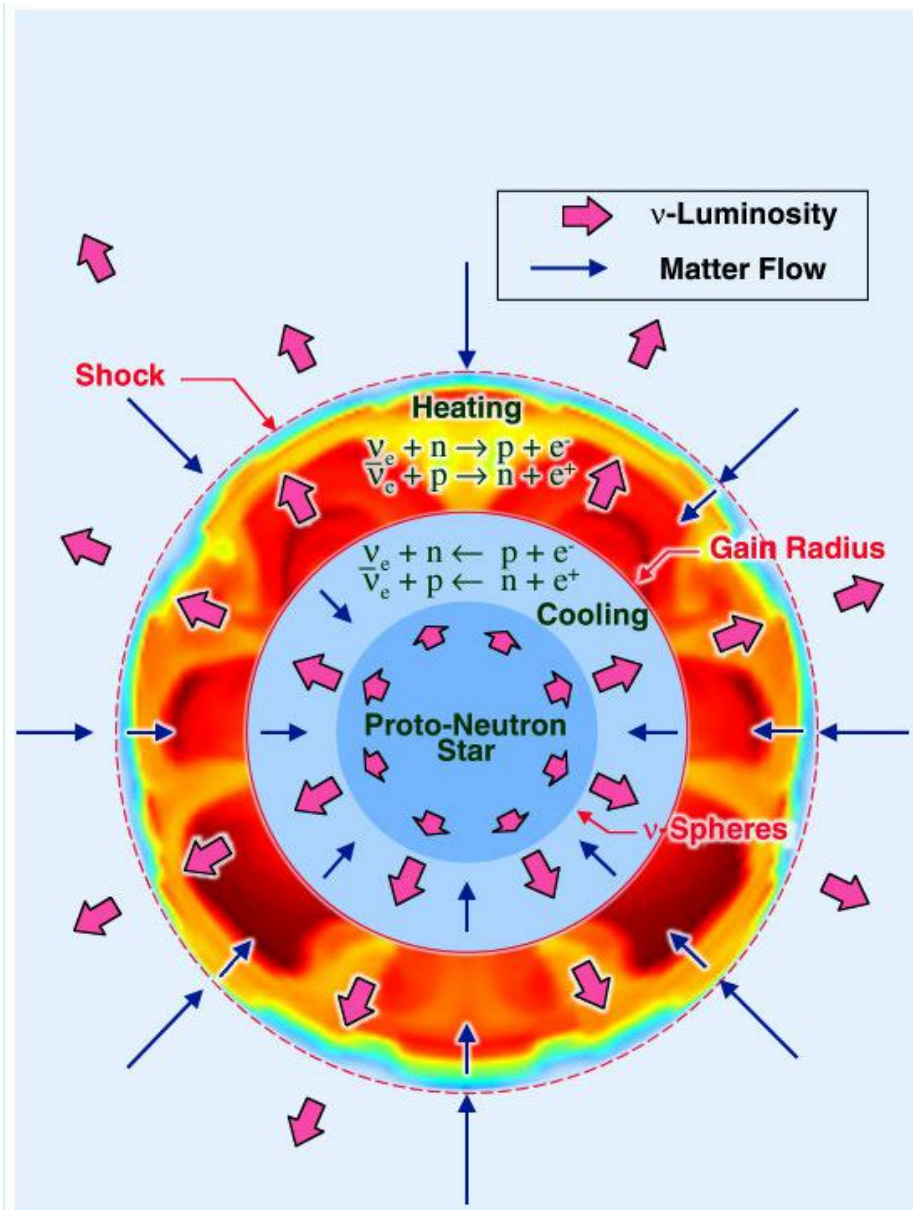
neutrino diffusion time $\tau \sim 2\,{\rm s}$ to $10\,{\rm s}$

typical luminosity (energy per second) for each of the 6 neutrino species:

$$L_\nu \approx \frac{1}{6}\cdot\frac{{\rm G}\,M_{\rm NS}^2}{R_{\rm NS}}\cdot\frac{1}{\tau} \approx 4\times 10^{51}\,{\rm ergs\ s^{-1}}$$



neutrino sphere
(*i.e.*, edge of neutron star)



Shock loses energy as it "photo-disintegrates" nuclei in the outer core – eventually "stalls"

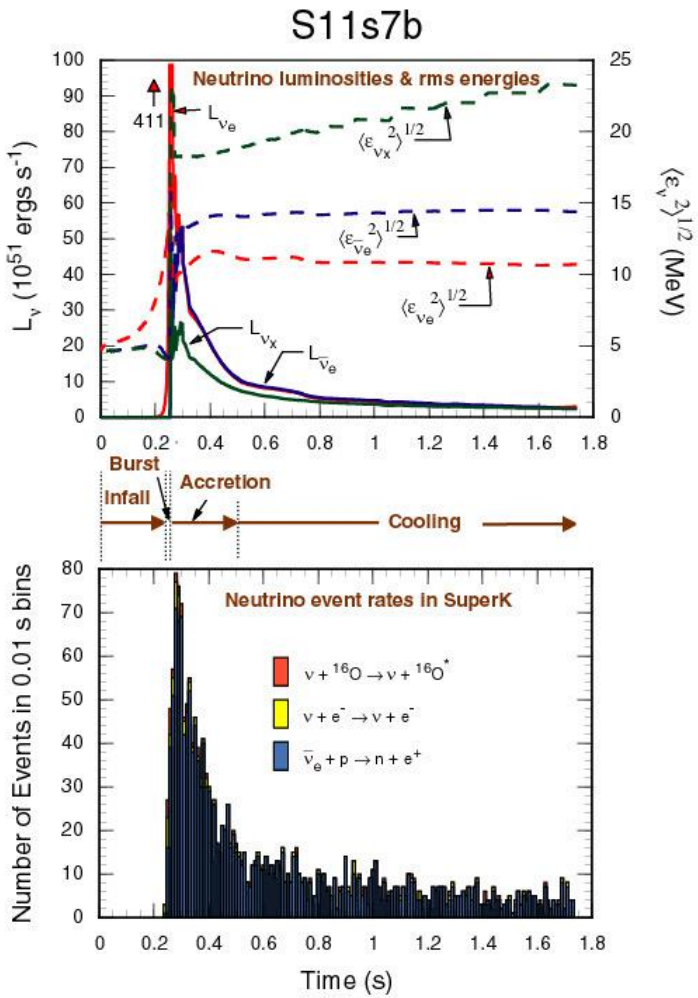
Just where it stalls is sensitive to Y_e at bounce; affects efficacy of neutrino re-heating

Shock stalls at $\sim 100\,\mathrm{km}$ at time post bounce $t_{\mathrm{pb}} \sim 100\,\mathrm{ms}$

Shock "re-energized" by neutrinos on timescales of $t_{\mathrm{pb}} < 0.5\,\mathrm{s}$

or not!

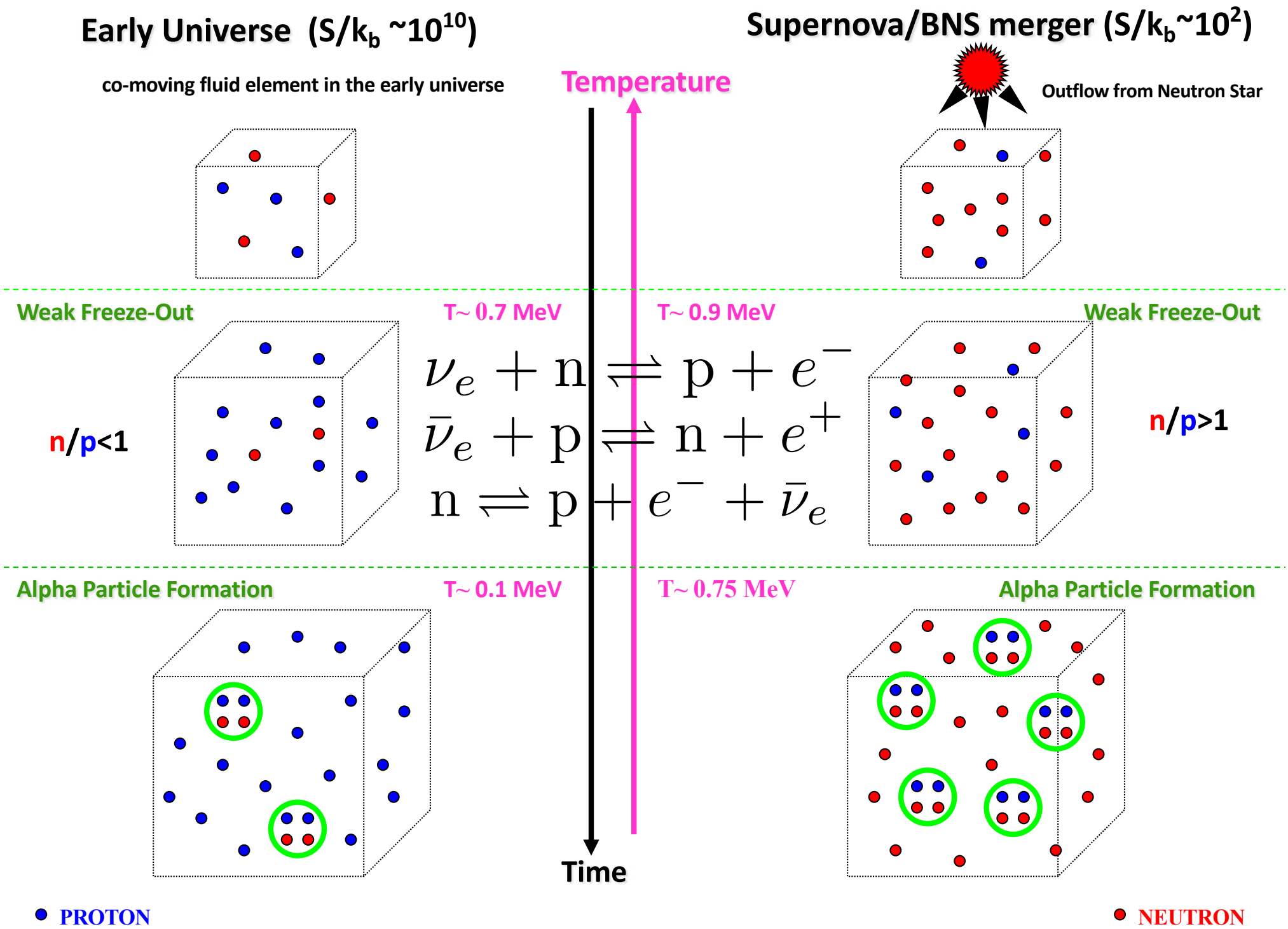
Neutrino Signal/Detectors



Bruen & Mezzacappa 2004

Detector	Type	Mass (kt)	Location	Events	Flavors	Status
Super-Kamiokande	H_2O	32	Japan	7000	$\bar{\nu}_e$	Running
LVD	$C_n H_{2n}$	1	Italy	300	$\bar{\nu}_e$	Running
KamLAND	$C_n H_{2n}$	1	Japan	300	$\bar{\nu}_e$	Running
Borexino	$C_n H_{2n}$	0.3	Italy	100	$\bar{\nu}_e$	Running
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Running
Baksan	$C_n H_{2n}$	0.33	Russia	50	$\bar{\nu}_e$	Running
MiniBooNE*	$C_n H_{2n}$	0.7	USA	200	$\bar{\nu}_e$	(Running)
HALO	Pb	0.08	Canada	30	ν_e, ν_x	Running
Daya Bay	$C_n H_{2n}$	0.33	China	100	$\bar{\nu}_e$	Running
NOνA*	$C_n H_{2n}$	15	USA	4000	$\bar{\nu}_e$	Turning on
SNO+	$C_n H_{2n}$	0.8	Canada	300	$\bar{\nu}_e$	Near future
MicroBooNE*	Ar	0.17	USA	17	ν_e	Near future
DUNE	Ar	34	USA	3000	ν_e	Proposed
Hyper-Kamiokande	H_2O	560	Japan	110000	$\bar{\nu}_e$	Proposed
JUNO	$C_n H_{2n}$	20	China	6000	$\bar{\nu}_e$	Proposed
RENO-50	$C_n H_{2n}$	18	Korea	5400	$\bar{\nu}_e$	Proposed
LENA	$C_n H_{2n}$	50	Europe	15000	$\bar{\nu}_e$	Proposed
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed

Mirizzi et al., Riv. Nuovo Cim. (2016)


Early Universe (S/k_b ~10^10)
Supernova/BNS merger (S/k_b~10^2)
co-moving fluid element in the early universe
Temperature
Outflow from Neutron Star
Weak Freeze-Out
T~ 0.7 MeV
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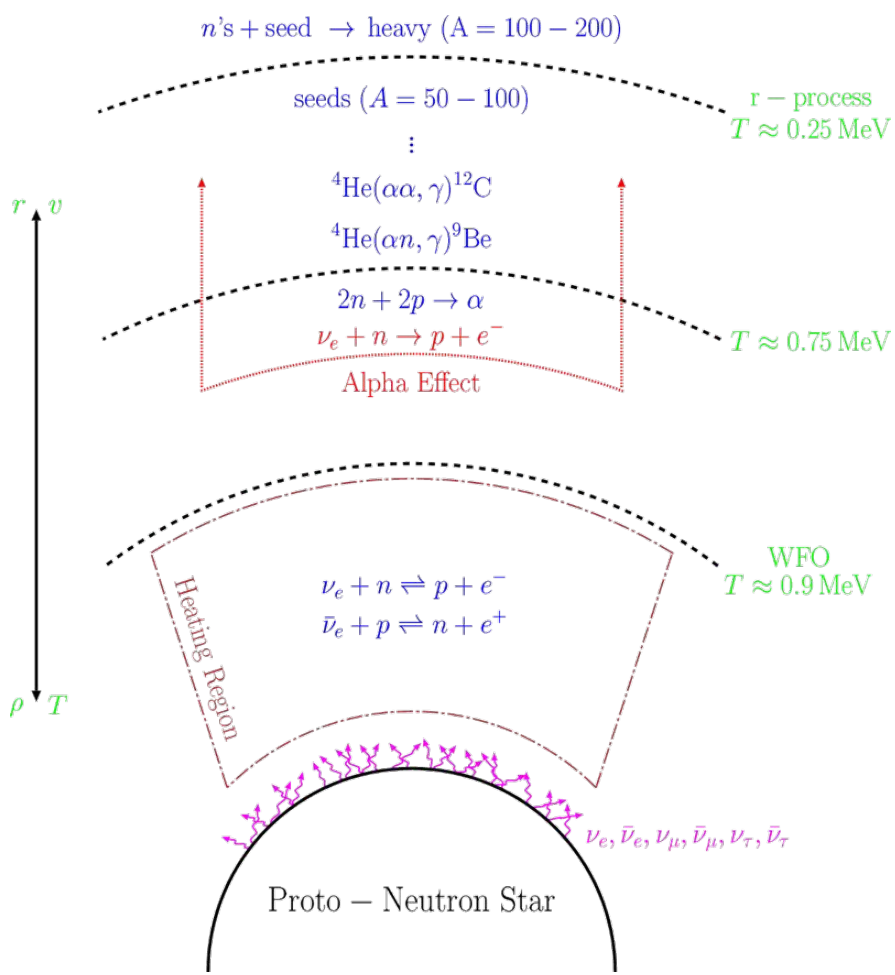
$\mathrm{n} \rightleftharpoons \mathrm{p} + e^- + \bar{\nu}_e$
Alpha Particle Formation
T~ 0.1 MeV
T~ 0.75 MeV
Alpha Particle Formation
Time
PROTON
NEUTRON

Post-Explosion, Neutrino-Driven "Wind", nucleosynthesis of the heavy elements



alpha-rich freeze-out $\Rightarrow$ sensitive to Y_e; ν-p process?

r-process key ingredient: neutron-to "seed" nucleus ratio

(1) **entropy** S - want this high

(2) Y_e - i.e., **the neutron-to-proton ratio** - want this high

(3) **expansion timescale** - want it short

Neutrinos

Takeaway from the experiments:

neutrino weak interaction (*flavor*) states
are not coincident with
the energy (*mass*) states

What this means is that neutrinos can change their flavors as they move through vacuum or a medium!

Calculating how neutrinos change flavors in medium is very difficult if the medium consists in part of other neutrinos!

a fiercely NONLINEAR quantum many-body problem

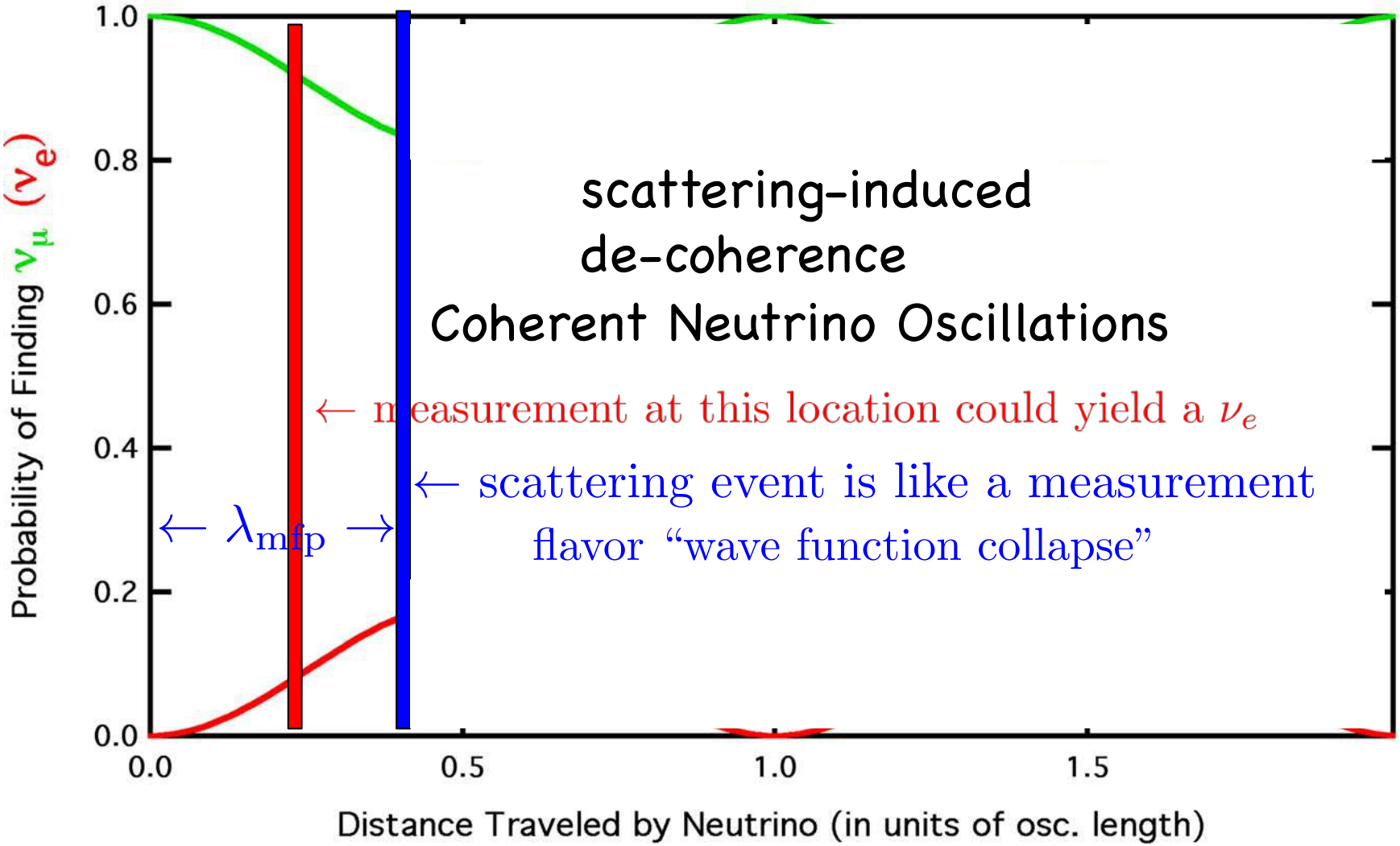
Standard Model

$$m_\nu \neq 0$$

Neutrino Flavor and/or Spin Transformation

Simple Example: two-by-two vacuum neutrino oscillations

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$



$$|\Psi(t=0)\rangle = |\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

$$|\Psi(t)\rangle = -\sin\theta\, e^{-iE_1 t}\,|\nu_1\rangle + \cos\theta\, e^{-iE_2 t}\,|\nu_2\rangle$$

in medium neutrino flavor/"spin" physics can be challenging!

A propagating neutrino state is, in general,
a coherent superposition of instantaneous "mass" states and,
if there are transverse potentials, a coherent superposition of
left-handed and right-handed ("spin") states

to begin with we will ignore "spin"

"mean field" neutrino and antineutrino evolution in time, momentum, flavor, and spin

Quantum Kinetic Equation (QKE) for flavor evolution along the trajectory of a neutrino with spacelike momentum components $\mathbf{p}$ at time t at location $\mathbf{r}$:

$$\underbrace{\left(\partial_t + \hat{\mathbf{p}} \cdot \partial_{\mathbf{r}}\right) \hat{\rho}}_{\text{advection}} = \underbrace{-i \left[\hat{H}, \hat{\rho}\right]}_{\text{coherent evolution}} + \underbrace{\hat{C}(\hat{\rho})}_{\text{collisions}} \tag{1}$$

The flavor density operator $\hat{\rho}\,(t, \mathbf{r}, \mathbf{p})$ and the collisional functional $\hat{C}(\hat{\rho})$ can be cast in the flavor basis as 3×3 matrices *when spin degrees of freedom are neglected*:

$$[\hat{\rho}]_{\text{flavor}} = \begin{pmatrix} \rho_{\nu_e \nu_e} & \rho_{\nu_e \nu_\mu} & \rho_{\nu_e \nu_\tau} \\ \rho_{\nu_\mu \nu_e} & \rho_{\nu_\mu \nu_\mu} & \rho_{\nu_\mu \nu_\tau} \\ \rho_{\nu_\tau \nu_e} & \rho_{\nu_\tau \nu_\mu} & \rho_{\nu_\tau \nu_\tau} \end{pmatrix} \quad \text{and} \quad \left[\hat{C}\right]_{\text{flavor}} = \begin{pmatrix} C_{\nu_e \nu_e} & C_{\nu_e \nu_\mu} & C_{\nu_e \nu_\tau} \\ C_{\nu_\mu \nu_e} & C_{\nu_\mu \nu_\mu} & C_{\nu_\mu \nu_\tau} \\ C_{\nu_\tau \nu_e} & C_{\nu_\tau \nu_\mu} & C_{\nu_\tau \nu_\tau} \end{pmatrix}$$

Similarly for antineutrinos.

These operators become 6×6 when *spin degrees of freedom are included* $\Rightarrow$ couples ν and $\bar{\nu}$ flavor evolution, even allowing $\nu \rightleftharpoons \bar{\nu}$ for Majorana neutrinos.

Classical: $\hat{H} = 0,\ \hat{C} \neq 0$

Classical (Boltzmann) evolution: $\hat{H} = 0$, the collisional operator is flavor diagonal, as is the density operator $\hat{\rho}$, the diagonal entries of which are the occupation probabilities f.

$$(\partial_t + \hat{\mathbf{p}} \cdot \partial_{\mathbf{r}})\, \hat{\rho} = -i \underbrace{\left[\hat{H}, \hat{\rho}\right]}_{0} + \hat{C}(\hat{\rho}) \tag{1}$$

$$(\partial_t + \hat{\mathbf{p}} \cdot \partial_{\mathbf{r}})\, \hat{\rho} = \hat{C}(\hat{\rho}) \tag{2}$$

Boltzmann neutrino transport

where now $[\hat{\rho}] \Rightarrow \begin{pmatrix} f_{\nu_e} & 0 & 0 \\ 0 & f_{\nu_\mu} & 0 \\ 0 & 0 & f_{\nu_\tau} \end{pmatrix}$ and $\left[\hat{C}\right] \Rightarrow \begin{pmatrix} C_{\nu_e} & 0 & 0 \\ 0 & C_{\nu_\mu} & 0 \\ 0 & 0 & C_{\nu_\tau} \end{pmatrix}$

Similarly for antineutrinos.

"Coherent": $\hat{H} \neq 0,\ \hat{C} = 0$

QKE becomes a nonlinear Schrödinger equation: $(\partial_t + \hat{\mathbf{p}} \cdot \partial_{\mathbf{r}})\, \hat{\rho} = -i \left[\hat{H}, \hat{\rho}\right]$

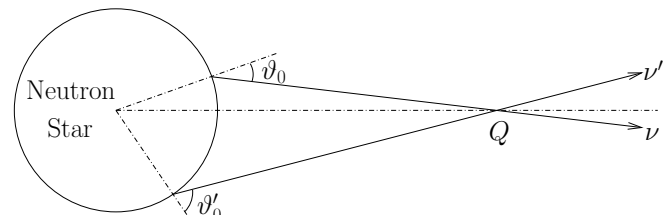
Neutrino & antineutrino *forward scattering* on targets carrying weak charge, plus vacuum oscillations, gives $\hat{H}$:

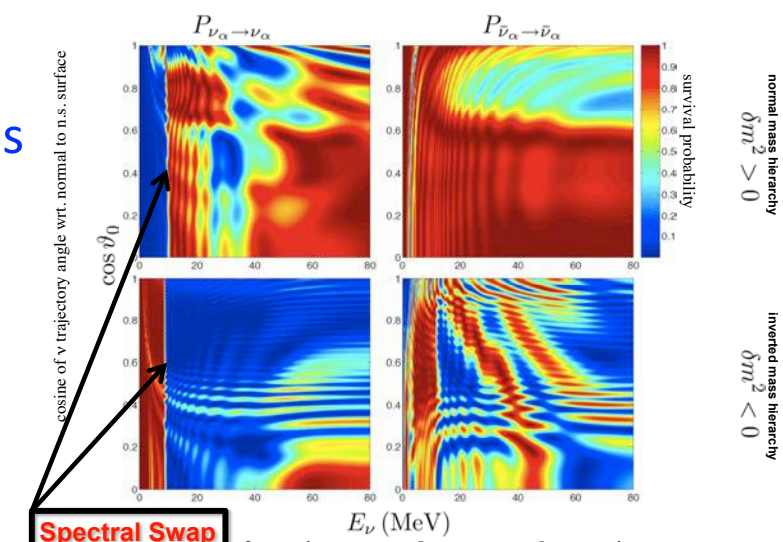
$$\hat{H} = \hat{H}_{\rm vac} + \hat{H}_{\nu\, e} + \hat{H}_{\nu\nu}$$

The neutrino-neutrino forward scattering potential $\hat{H}_{\nu\nu}$ causes **nonlinearity** and a nontrivial geometric dependence when the neutrino field is anisotropic:

$$\hat{H}_{\nu\nu} = \sqrt{2} G_{\rm F} \int (1 - \hat{\mathbf{p}} \cdot \hat{\mathbf{p}}')\, \left(\hat{\rho}_{\mathbf{p}'} - \hat{\bar{\rho}}_{\mathbf{p}'}\right) d^3\mathbf{p}'$$

Bulb Model: collective neutrino oscillations





Consequences of neutrino mass and quantum coherence in supernovae
H. Duan, G. M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **97**, 241101 (2006) astro-ph/0606616

neutrino flavor transformation ⟷ **hydro/transport, T, S, nuclear composition/EOS**

feedback goes *both ways*

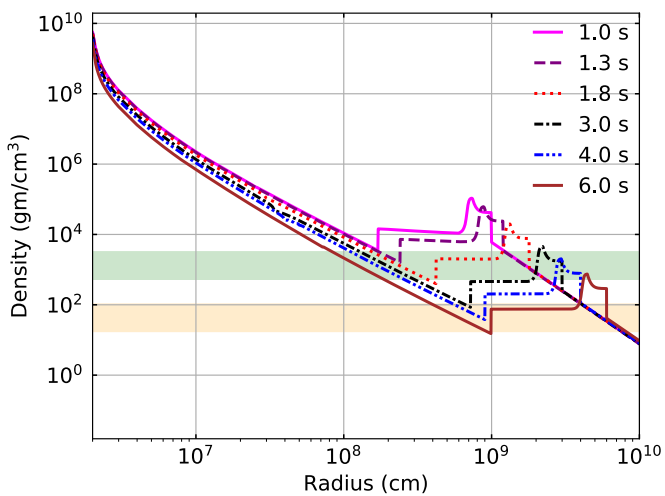
Cannot ignore feedback of flavor conversion on the medium and *vice versa*

Example: Shock/adiabaticity-modulation of the supernova neutrino flavor conversion signal

Schirato, Fuller arXiv:astro-ph/0205390

Friedland, Payel arXiv:2009.10059

Ekinci, Pehlivan, Patwardhan PRD **103**, 043016 (2021)



Friedland, Payel arXiv:2009.10059

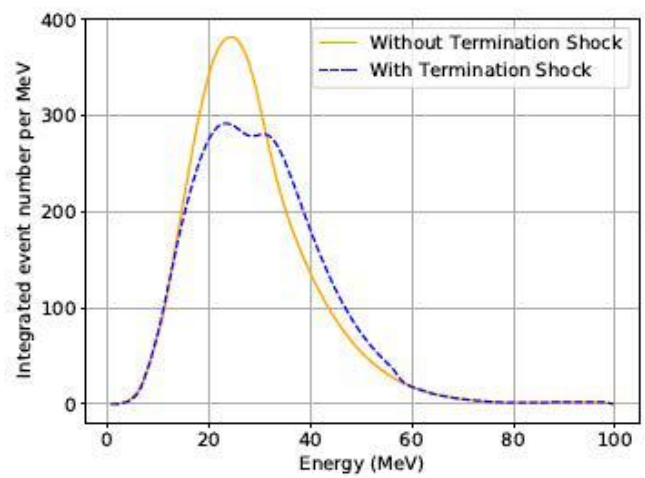


FIG. 3. Number of events expected between 2.2 and 3.2 s in a 40 kton liquid argon detector, from a supernova at 3 kpc, with (*dashed*) and without (*solid*) the termination shock.

"Coherent": $\hat{H} \neq 0, \hat{C} = 0$

Flavor Field Instabilities: may or may not lead to large-scale conversion

Type

"**Slow**" instability stemming from different oscillation frequencies for ν & $\bar{\nu}$

Kostelecky & Samuel PRD (1995)

"**Fast**" instability stemming from different angular distributions for ν_e & $\bar{\nu}_e$

R. Sawyer PRD (2005, 08); PRL (2016)

"**Collisional**" instability, e.g., stemming from differing scattering rates for ν & $\bar{\nu}$

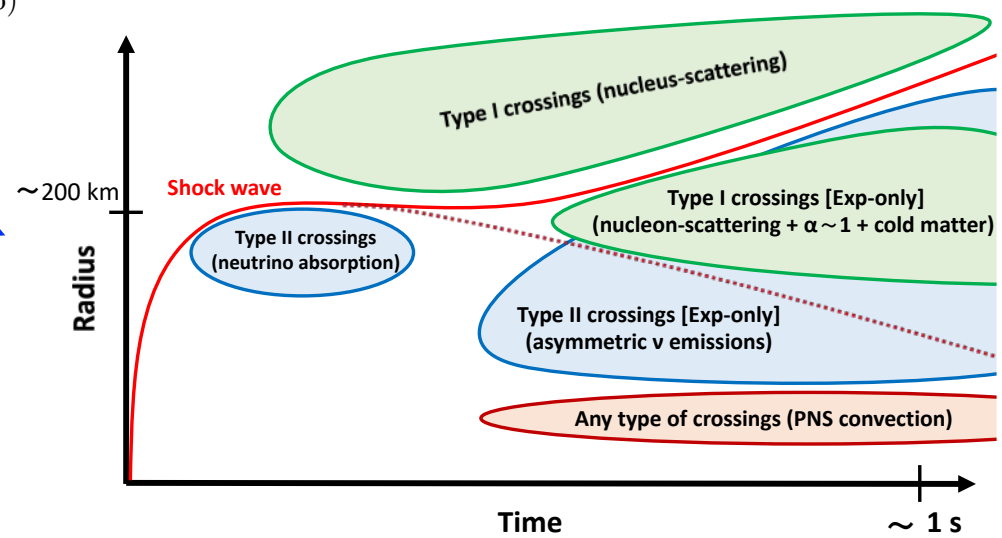
L. Johns 2104.11369; Capozzi, Dasgupta, Mirizzi JCAP (2019); etc.

Neutrino Flavor Field Instability

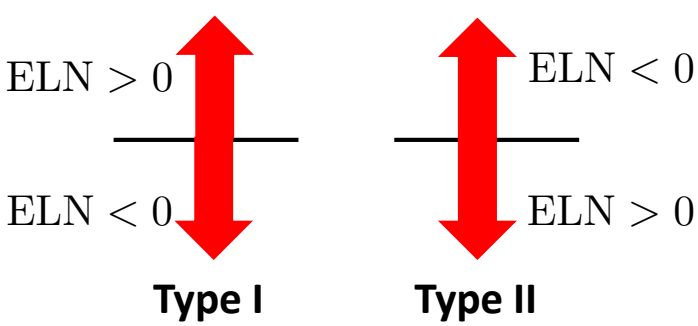
- Boltzmann neutrino transport in large supernova simulations shows differing angular distributions the neutrino flavors/types and this, in turn, reveals ***electron lepton number*** **(ELN)** ***crossings*** where ***Fast Flavor Conversion*** could arise

Chakraborty, Hansen, Izaguirre, Raffelt, Nucl. Phys. B (2016)
Tamborra, Shalgar, Annu. Rev. Nucl. Part. Sci. (2021)
Morinaga 2103.15267
Nagakura, Burrows, Johns, Fuller (2021)

Space-time diagram of ELN-angular crossings in CCSNe



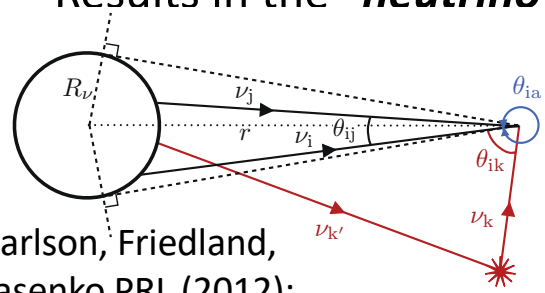
$$\mathrm{ELN} = \nu_e - \bar{\nu}_e$$



Classical + "Coherent"

Introduce neutrino scattering-induced alteration of the neutrino flavor field:

- Results in the "***neutrino halo***"



Cherry, Carlson, Friedland, Fuller, Vlasenko PRL (2012); Cirigliano, Paris, Shalgar (2018); Cherry et al (2021);

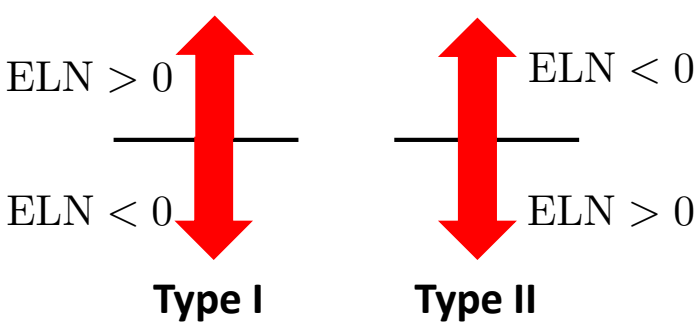
Small number (1 in 10^3) of "down-scattered" neutrinos make an outsized contribution to transformation potential

- *introduces composition (nuclear size) dependence and converts ν flavor transformation problem from an initial value problem into a boundary value problem*

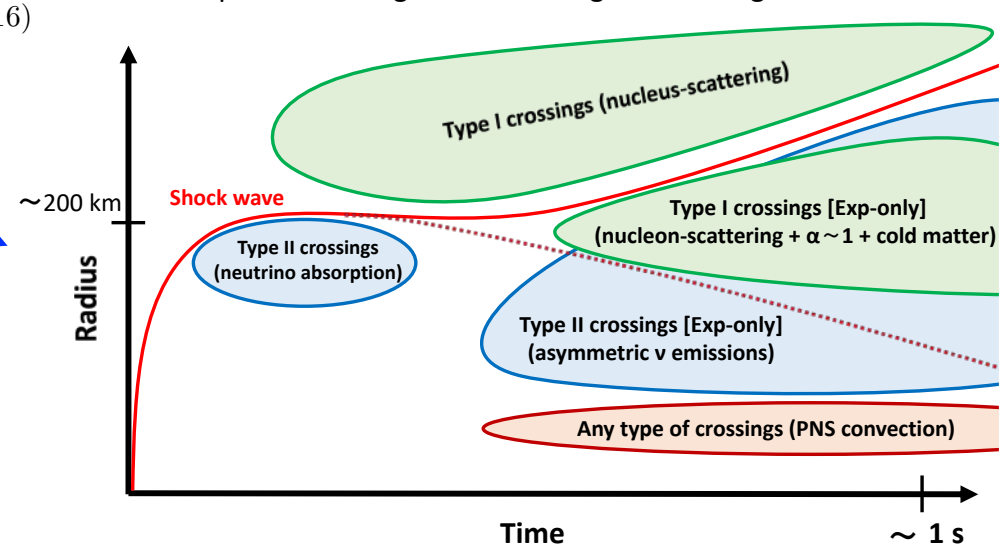
- Boltzmann neutrino transport in large supernova simulations shows differing angular distributions the neutrino flavors/types and this, in turn, reveals ***electron lepton number*** **(ELN)** ***crossings*** where ***Fast Flavor Conversion*** could arise

Chakraborty, Hansen, Izaguirre, Raffelt, Nucl. Phys. B (2016)
Tamborra, Shalgar, Annu. Rev. Nucl. Part. Sci. (2021)
Morinaga 2103.15267
Nagakura, Burrows, Johns, Fuller (2021)

$$\mathrm{ELN} = \nu_e - \bar{\nu}_e$$



Space-time diagram of ELN-angular crossings in CCSNe



Full Quantum (QKE solutions)

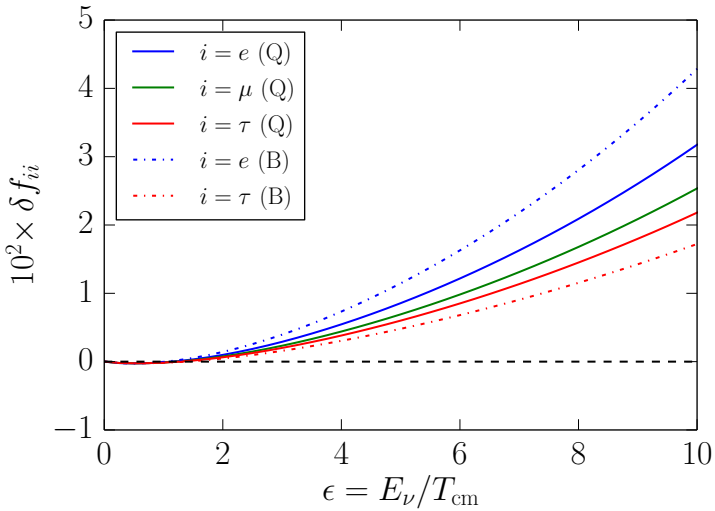
Early universe/weak decoupling-BBN

J. Froustey 2110.11296. N_{eff} = 3.044 (instead of 3.046)

J. Froustey, C. Pitrou, and C. Volpe 2020 JCAP 12 015 (Preprint 2008.01074)

E. Grohs et al. 2022

E. Grohs, preliminary



Core collapse supernovae

isotropic case: Richers, McLaughlin, Kneller, Vlasenko PRD **99**, 123014 (2019)

Particle-in-cell techniques;
(no collisions): Richers, Wilcox, Ford, Myers, PRD **103**, 083013 (2021)

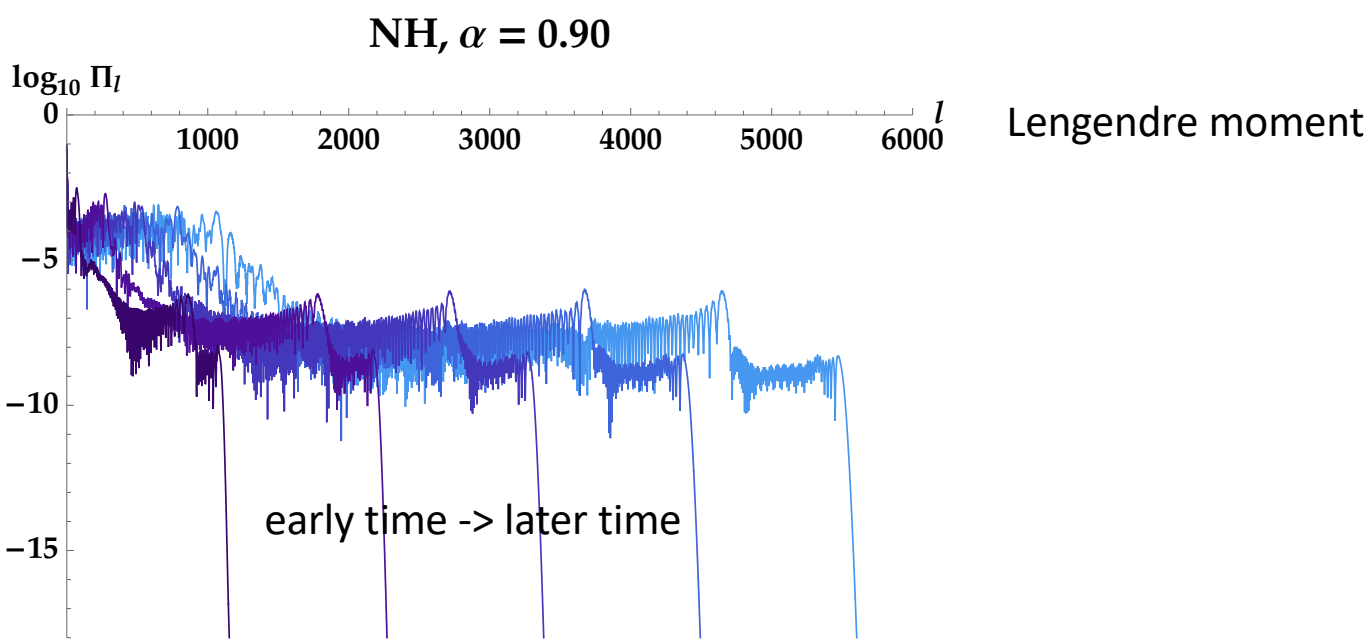
Monte Carlo Techniques: Chinami, Nagakura, Taiki, ApJ Suppl **257**, Issue 2, id.55 (2021)

Moment methods are employed in Boltzmann neutrino transport.
Could those techniques give insight into flavor transformation?

Duan, Shalgar JCAP (2014)
Johns, Nagakura, Fuller Burrows PRD (2020ab)

closing the tower of quantum moment equations is problematic

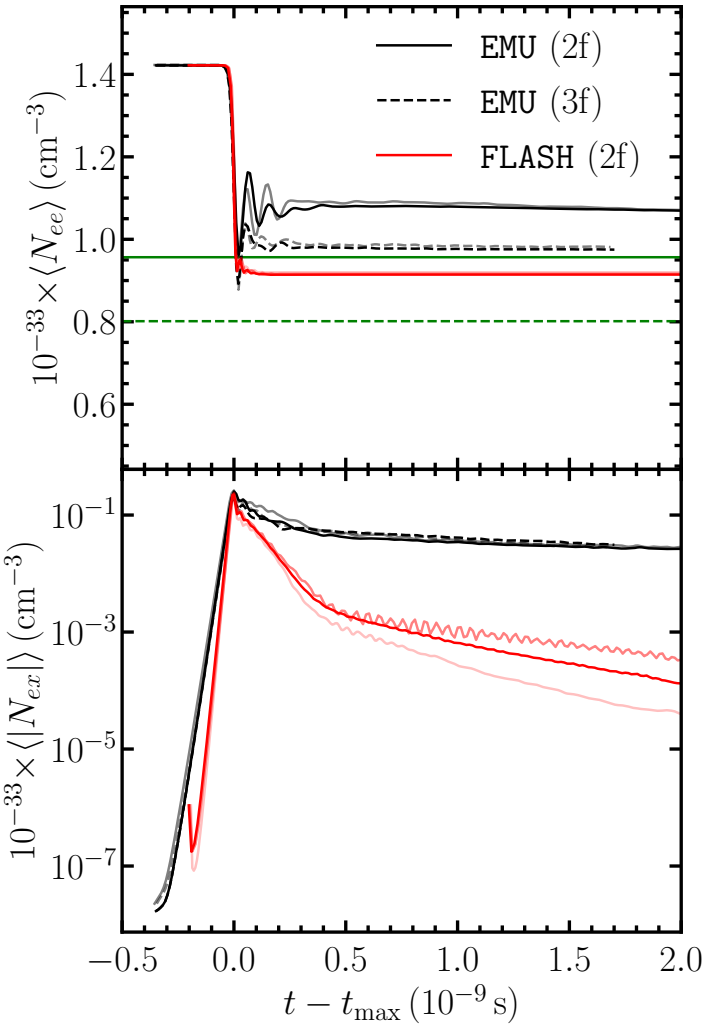
What emerges from these studies:
cascade with time of flavor-field power from large angular scales in momentum space down to small ones

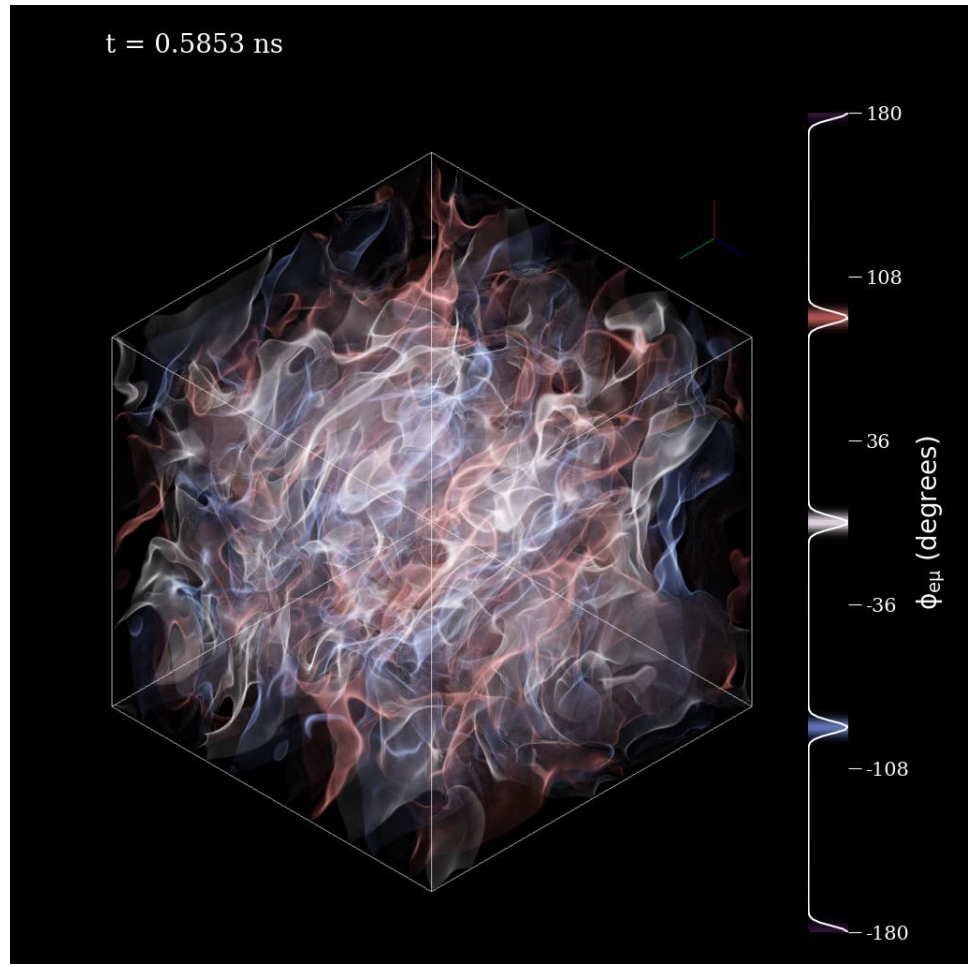


Lengendre moment

moment calculations with FLASH can replicate with fair fidelity QKE calculations -- *very promising*!

E. Grohs, S. Richers, G. McLauglin, in preparation 2023





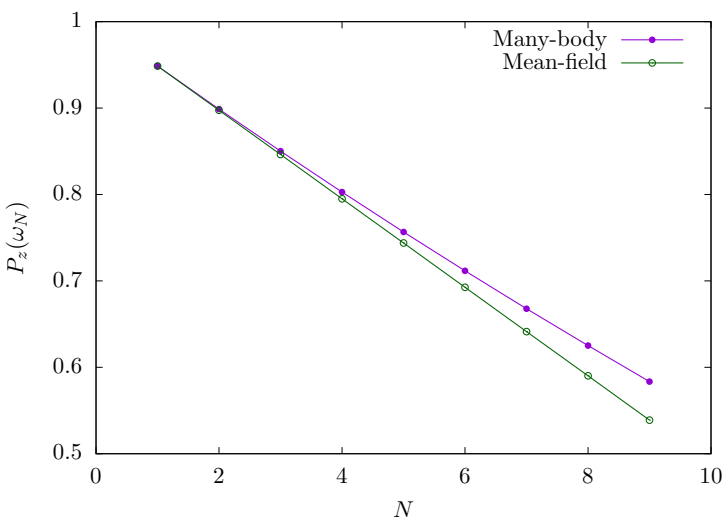
Phase of off-diagonal density matrix elements ("still" from a movie)

Efficacy of the 'Mean Field" Treatment? – *many-body correlations and entanglement* ?

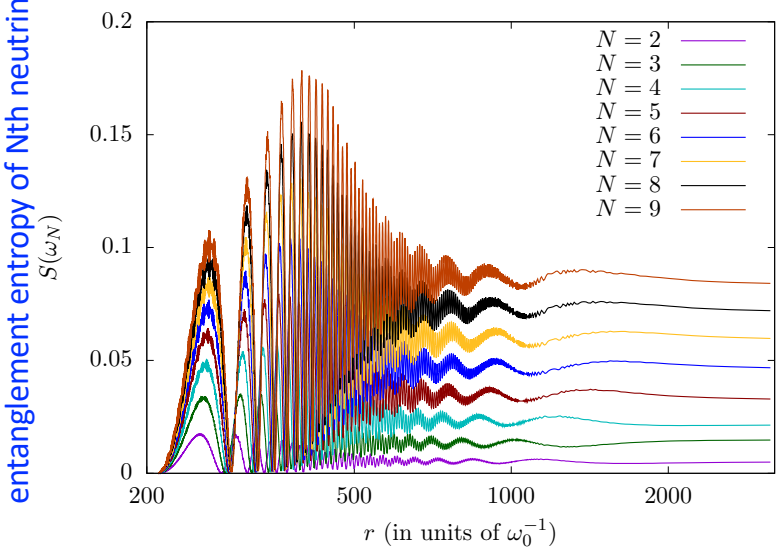
see for example: M. J. Cervia, A. V. Patwardhan, A. B. Balantekin, S. N. Coppersmith, Calvin W. Johnson, "*Entanglement and collective flavor oscillations in a dense neutrino gas*" Physical Review D **100**, 083001 (2019)

They considered *coherent* 2X2 neutrino flavor evolution in a simple 1-D "supernova" environment

Probability that neutrino remains electron flavor



entanglement entropy of Nth neutrino



N-neutrino wave function $|\Psi\rangle$ defined on a Hilbert space $\mathcal{H} = \mathcal{H}_1 \otimes \cdots \otimes \mathcal{H}_{\rm N}$

Density operator $\hat{\rho} = |\Psi\rangle\langle\Psi|$. Partition Hilbert space as $\mathcal{H} = \mathcal{H}_{\rm A} \otimes \mathcal{H}_{\rm B}$ and take partition A to be *one neutrino*, partition B includes the rest.

Reduced density operator for partition A is $\hat{\rho}_{\rm A} = {\rm Tr}_{\rm B}\,[\hat{\rho}]$. Bipartite entanglement entropy is $S_{({\rm A}|{\rm B})} = -{\rm Tr}\,[\hat{\rho}_{\rm A}\,\log\hat{\rho}_{\rm A}]$

entanglement entropy gives a measure of the extent entanglement and non-mean field effects

Beyond Standard Model (BSM)

Much of the standard picture of SN collapse
could be sensitive to lepton number violation and neutrino NSIs

BSM murder weapons?

A take-away message from the experiments is that neutrinos have *non-zero rest masses*

This fact begs the question: Are there sterile neutrino states?

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_s\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

If sterile neutrinos mix with active neutrinos in vacuum like this, then they are not really ***sterile*** !!

active neutrino cross section $\sigma \sim G_F^2\, E_\nu^2$

"sterile" neutrino cross section $\sigma \sim (G_F^2\, \sin^2\theta)\, E_\nu^2$

Bruno Pontecorvo

recognized that the handedness of the weak interaction meant that non-zero neutrino rest mass could enable neutrino spin flip from active, left-handed states, to **sterile**, right-handed states.

Soviet Physics – JETP **26**, 984 (1968)

Is there a rich neutrino "dark sector"?

Sterile neutrino dark matter contribution?

active work on this issue at UCSD:
Jake Spisak, Lukas Graf, Amol Patwardhan, Chad Kishimoto, GMF,

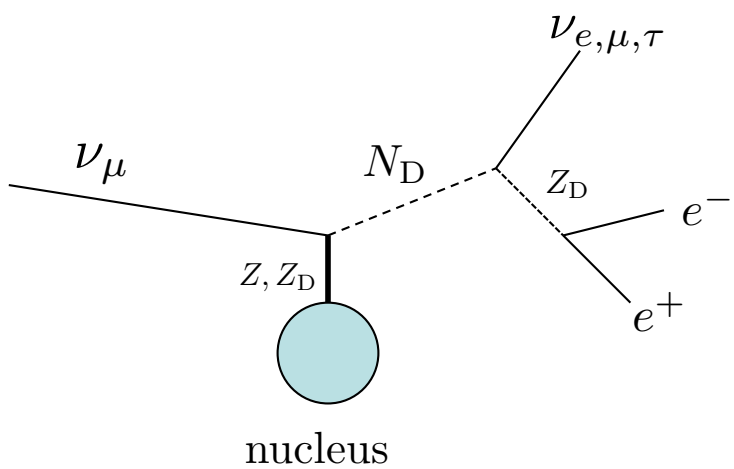
cosmologically-safe (?) Dark Sector "explanations" of the anomalies?

Examples include:

E. Bertuzzo, S. Jena, P. Machado, R. Funchal, PRL **121**, 241801 (2018)
Dark Z (small coupling to standard model quarks), Dark (i.e., sterile) neutrino

A. Datta, S. Kamali, D. Marfatia, arXiv:2005.08920
light scalar singlet (electromagnetic decay gives miniBooNE low energy excess) coupled to a sterile neutrino

For a general "lay of the land" see
"White Paper on New Opportunities at the Next-Generation Neutrino Experiments", C. A. Aguelles et al, arXiv:1907.08311



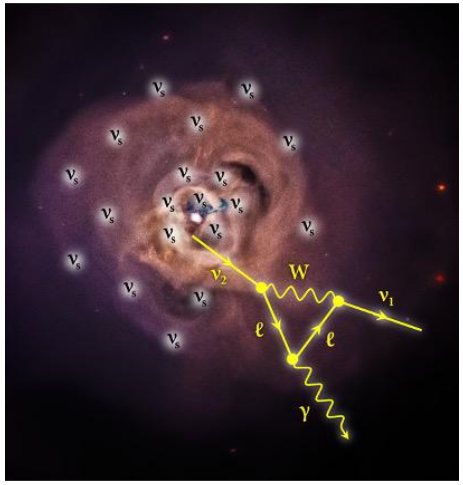
Sterile neutrino $N_{\rm D}$, mass $\sim 400\,{\rm MeV}$??
Dark Z, $Z_{\rm D}$, mass $\sim 100\,{\rm MeV}$??

NSIs quark-quark coupling? A.Suliga, S. Shalgar, GMF 2021

BSM Neutrino Sector Examples

(1) Heavy sterile neutrinos – dark matter component?

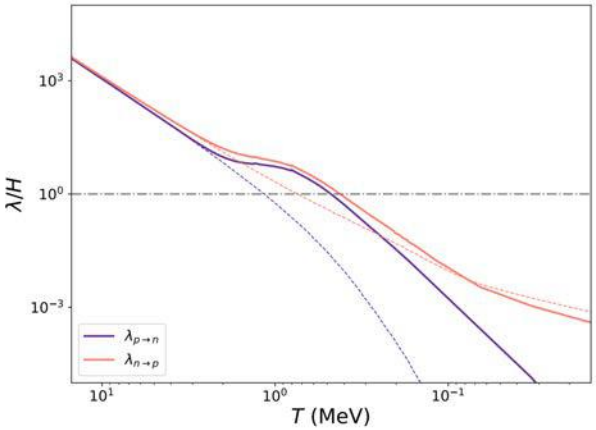
Motivation:
sterile neutrino dark matter ideas
See Abazajian & Kusenko review (2020)
Abazajian, Kusenko, GMF, Dodelson/Widrow. Gelmini, Takhistov, Patwardhan, etc.

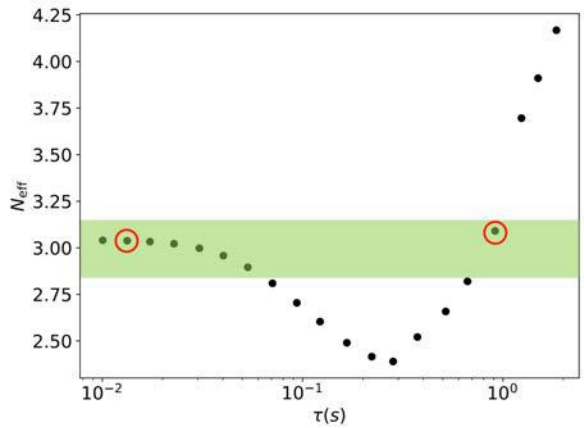


~ keV mases produced by
active neutrino scattering-induced decoherence in the Early Universe,
but X-rays can give them away (Abazajian, GMF, Tucker 2001)

-- decaying during/after BBN ?

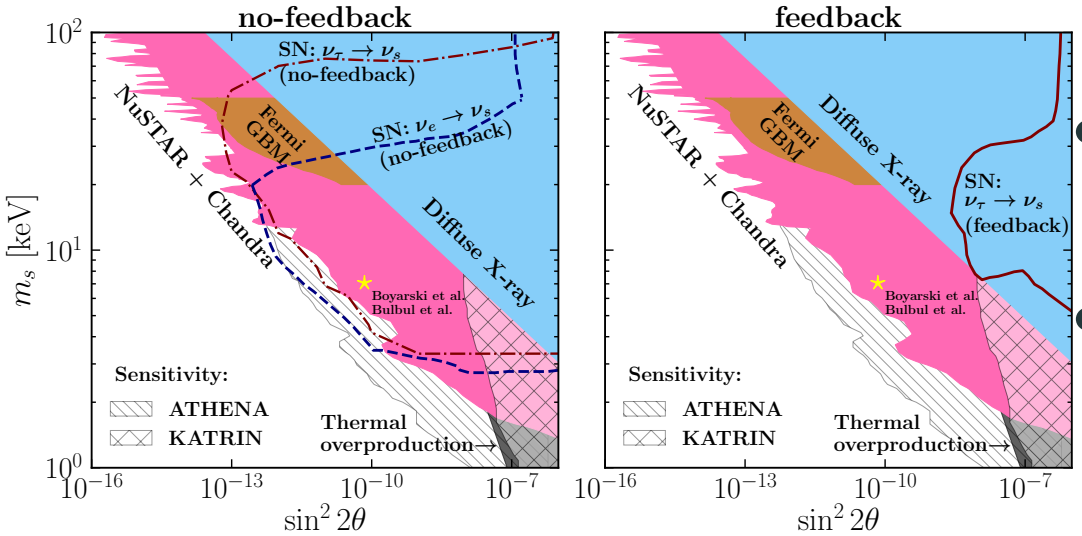
GMF, Kishimoto, Kusenko 2012; Rasmussen et al. 2021 (Chad's USD group); Gelmini et al. 2021;



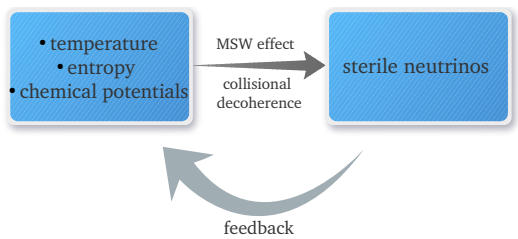


CMB and BBN constraints
-- CMB Stage-4 *will be very restrictive*

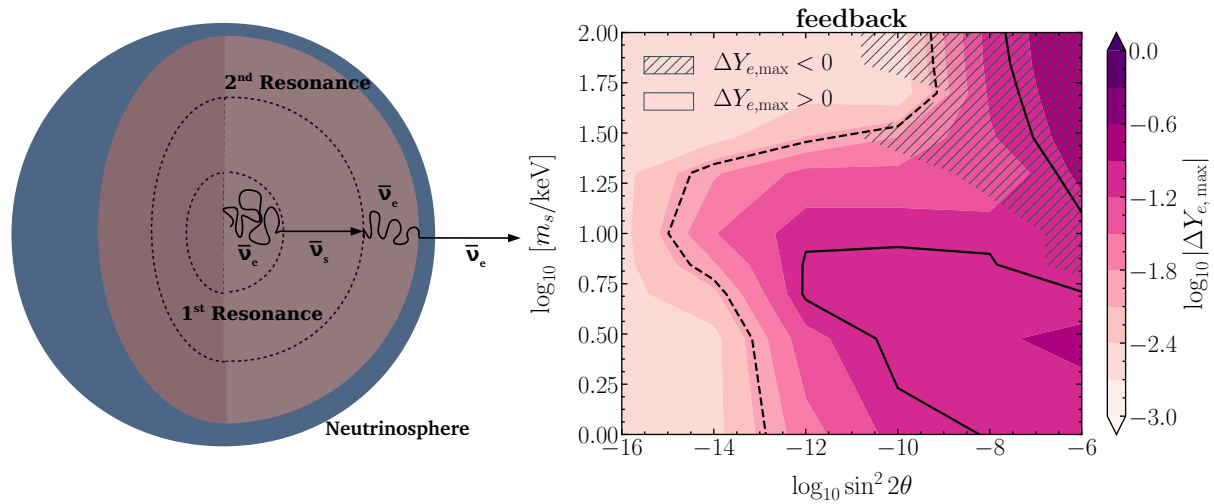
KeV sterile neutrinos in core-collapse supernovae *Anna Suliga's slide*



- The inclusion of feedback: reduction of the excluded region
- CC-SNe do not exclude any region of the DM parameter space



- The inclusion of feedback: growth of asymmetries
- Neutrino spectrum affected



Raffelt & Sigl (1992), Shi & Sigl (1994), Nunokawa et al. (1997), Hidaka & Fuller (2006), Hidaka & Fuller (2007), Raffelt & Zhou (2011), Warren et al. (2014), Argüelles et al. (2016), Suliga, Tamborra, Wu (2019), Syvolap et al. (2019), Suliga, Tamborra, Wu (2020)

BSM Neutrino Sector Examples

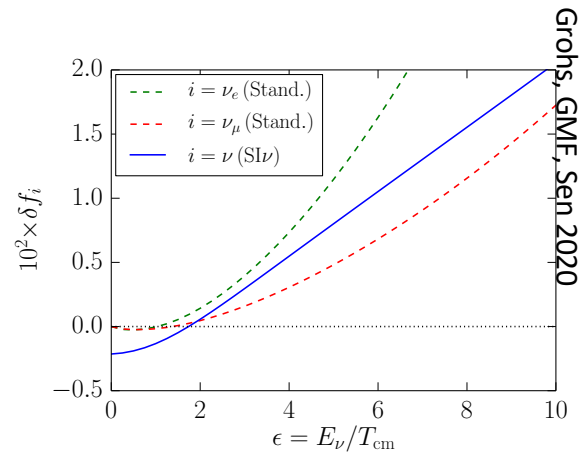
(2) NSIs (non-standard interactions)**: "secret" neutrino-neutrino interactions**

neutrino-neutrino scattering via new, possibly stronger than *weak* interactions?
Could these interactions *change flavor*?

For example see: Huang, Ohlsson, Zhou 2018; Grohs, GMF, Sen 2020; Grohs, Sen, Graf, GMF 2023

$$\mathcal{L}_{\rm int} = g_{ij}\overline{\nu_{iL}^c}\,\nu_{jL}\varphi + g_{ij}\overline{\nu_{iL}}\,\nu_{jL}^c\varphi, \quad G_{ij} = \frac{g_{ij}^2}{m_\varphi^2}, \qquad [g_{ij}] = \begin{pmatrix} g_{ee} & g_{e\mu} & g_{e\tau} \\ g_{\mu e} & g_{\mu\mu} & g_{\mu\tau} \\ g_{\tau e} & g_{\tau\mu} & g_{\tau\tau} \end{pmatrix} \Rightarrow g\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}.$$

Recent Motivation:
Reconciling discordant
Hubble parameters: Kreisch et al 2019



Grohs, GMF, Sen 2020

Little Effect on BBN
but . . . ***collapse might be a different story***

Low Entropy Collapse

entropy per baryon $s/k_{\rm b} \approx 1$

Temperature $T \sim 2\,{\rm MeV}$

Lepton Fermi levels: $\mu_e \approx 11.1\,{\rm MeV}\,(\rho_{10}\,Y_e)^{1/3} \sim 40\,{\rm MeV}$

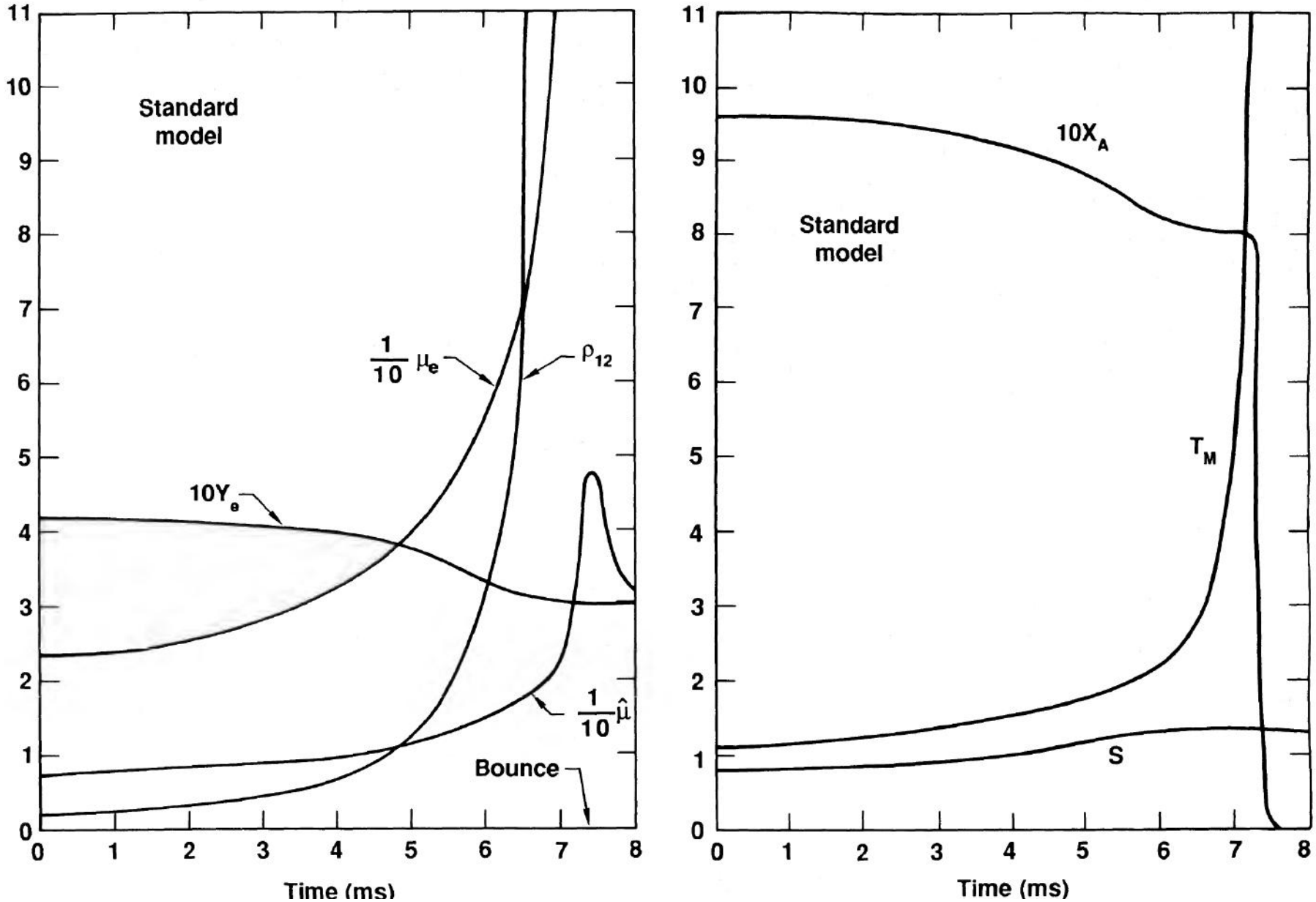
weak equilibrium: $e^- + p \rightleftharpoons n + \nu_e \quad \Rightarrow \quad \mu_e - \mu_{\nu_e} = (\mu_n - \mu_p) + \delta m_{np}$

electron capture on heavy nuclei leaves them in highly excited non-thermal states: **generates entropy !**

$\Delta s > 3 \quad \Rightarrow$ melt nuclei!

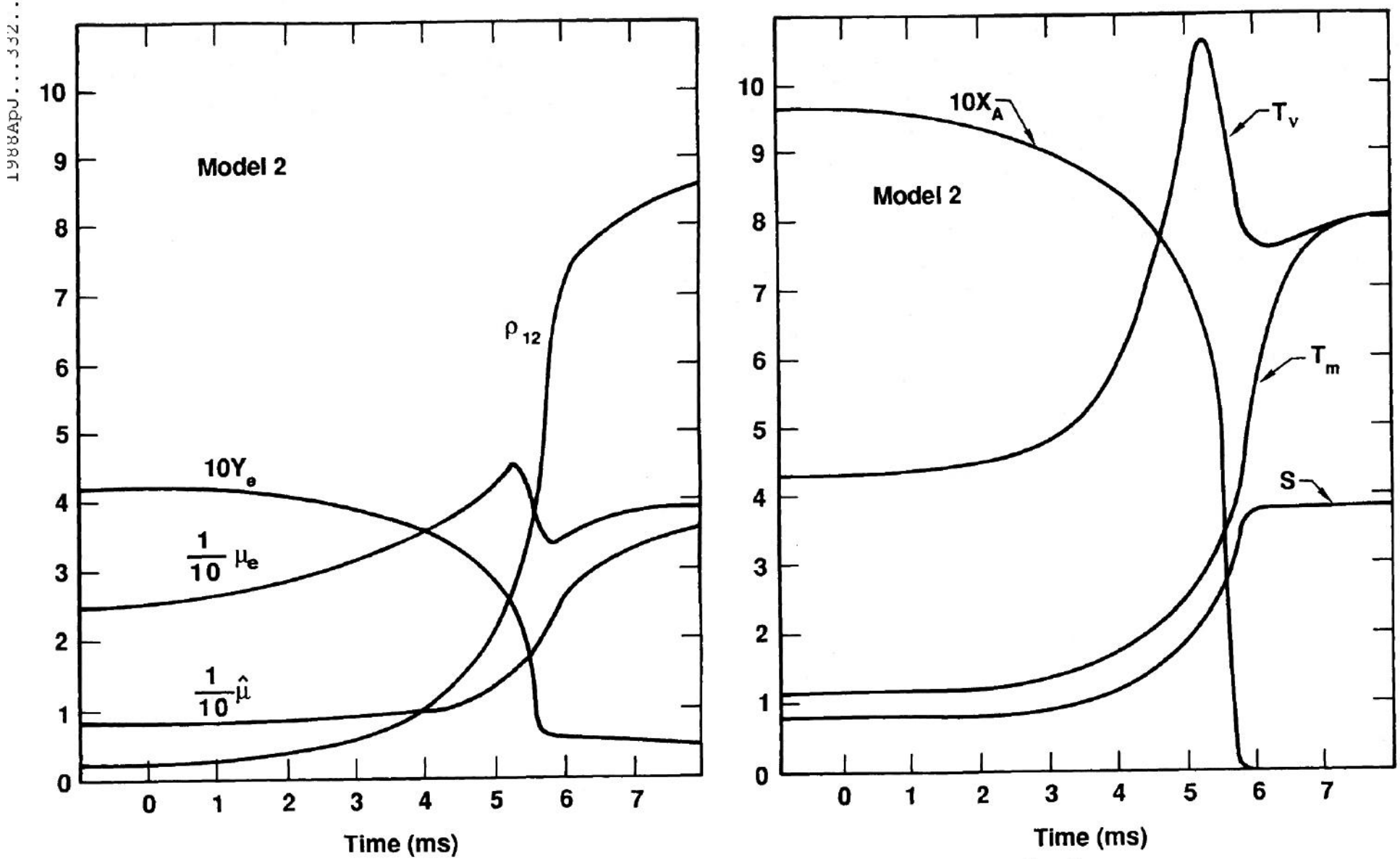
But if we turn on rapid flavor-changing NSIs $\nu_e \to \nu_{\mu,\tau}$, unblocks electron capture, leads to entropy generation. Anna Suliga, Lukas Graf, Kyle Kehrer, Shashank Shalgar, Oliver Sholer - 2023

Standard Model Collapse



GMF, R. Mayle, J. R. Wilson, Astrophys. J. **332**, 826 (1988)

neutrino-neutrino NSI – lepton number violation



GMF, R. Mayle, J. R. Wilson, Astrophys. J. **332**, 826 (1988)

Black Hole "Mass Gaps"

Evidence for BHs with awkward masses?

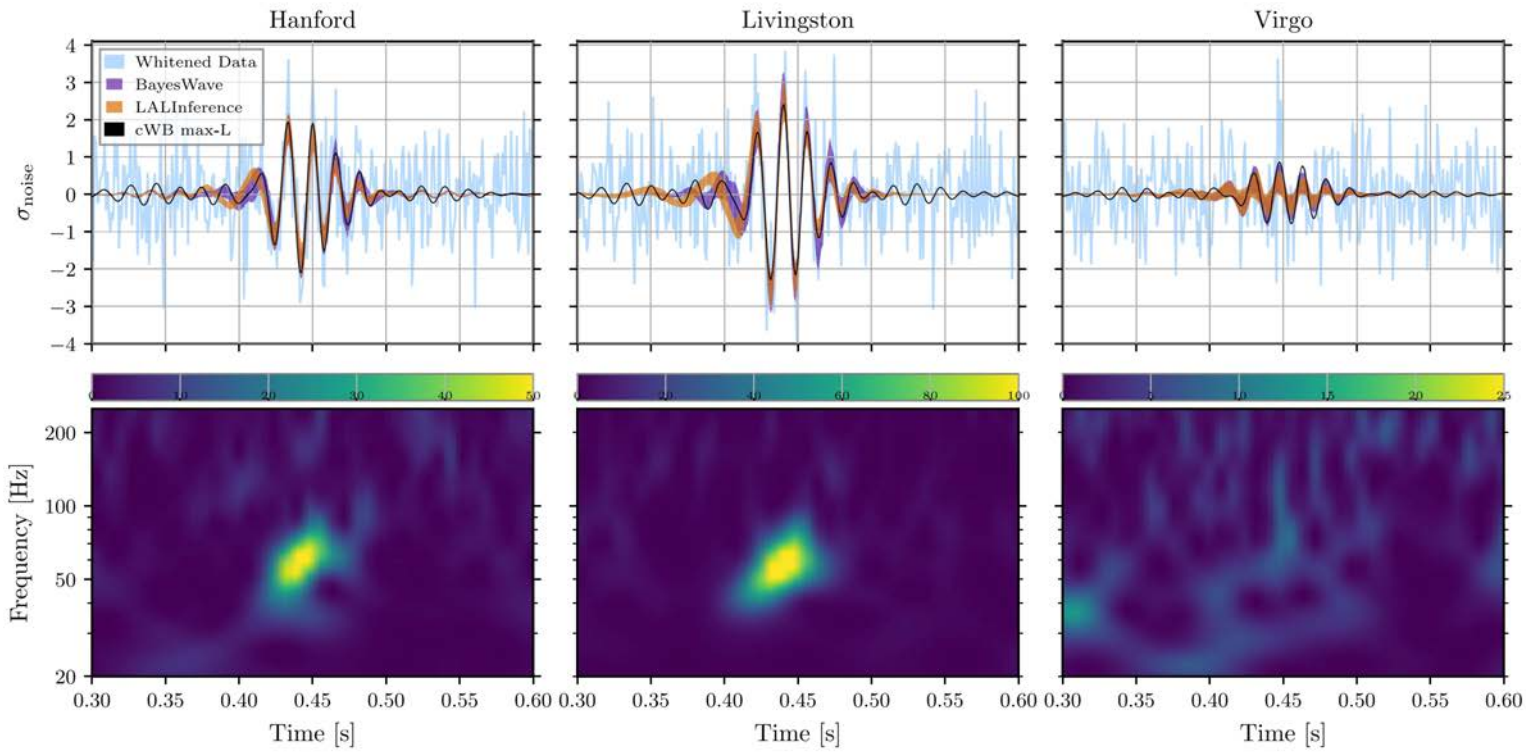
Black hole "mass gaps" – where ordinary stellar evolution/collapse lore would suggest it is hard to produce these masses

Low Mass Gap: $\sim 1\,\mathrm{M}_\odot$ to $\sim 5\,\mathrm{M}_\odot$

High Mass Gap: $\sim 50\,\mathrm{M}_\odot$ to $\sim 150\,\mathrm{M}_\odot$

More murder?
By dark matter?
By BSM physics?

GW190521



https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.125.101102 https://doi.org/10.1103/PhysRevLett.125.101102

$86M_\odot + 65M_\odot \to 142\,M_\odot$
– plus $9M_\odot$ radiated in
gravitational waves

Best fit redshift $z = 0.82 \pm 0.3$

How do you get a black hole of $86M_\odot$? Two so-called black hole "mass gaps" where it it is not clear that stellar progenitors could give rise to these holes: 2 to $5M_\odot$; and ~ 50 to $\sim 150M_\odot$. The latter, upper mass gap, has its origin in the pair instability in very massive objects. Pair instability supernovae that leave no remnant can occur for progenitor stars with masses $\sim 130M_\odot$ to $\sim 250M_\odot$. Stars above this mass will likely collapse to black holes without exploding.

Neutron Star Implosion

“transmutation” of neutron stars into low mass black holes?

Other dark matter models: see work by Anupam Ray; Yudai Tsai; V. Takhistov

Primordial Black Holes -- *a dark matter component?*

Radiation-dominated early universe –

-***any horizon volume is poised on the verge of instability and collapse***

Zeldovich & Novikov 67; Hawking 71; Carr, Hawking 74

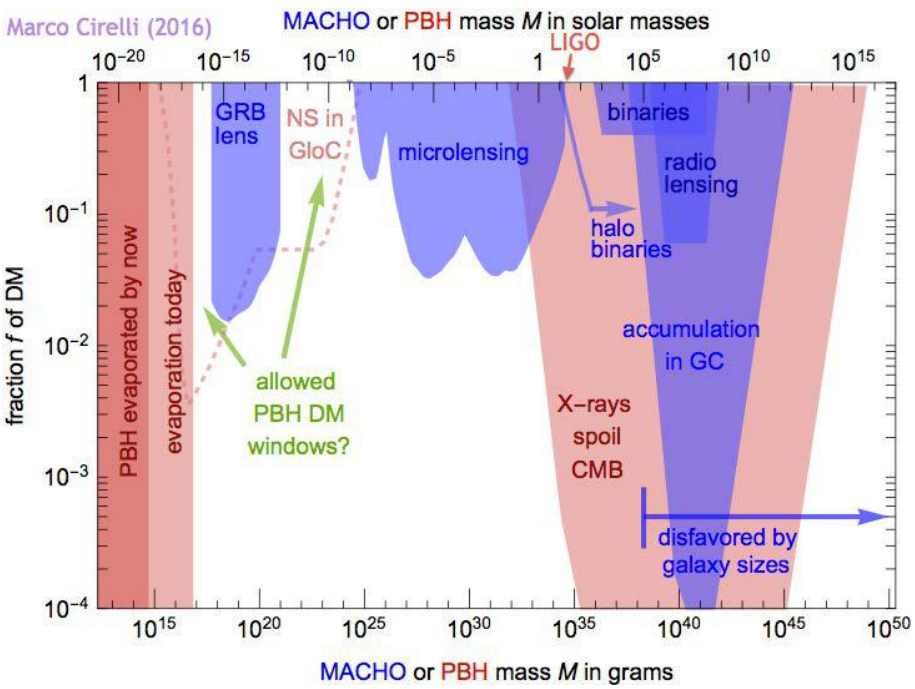
-***fluctuations can evolve to trapped surface formation***

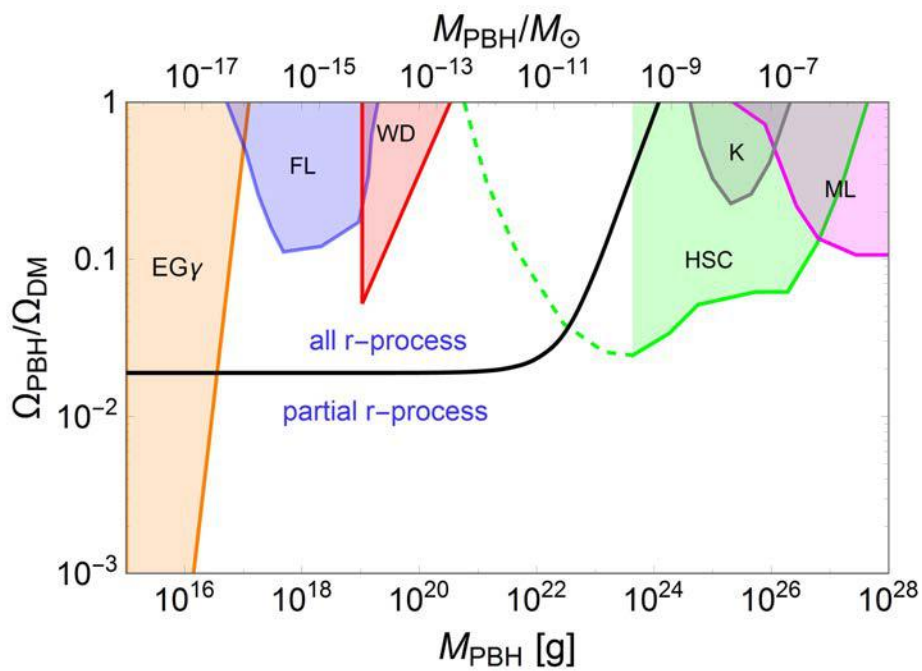
-Inflation (Carr; Garci-Bellido; Linde et al.; Kawasaki et al; . . .) may produce non-scale invariant fluctuations with extra power on some scales – can collapse to holes when they re-enter the horizon

-Vacuum phase transitions

- baryon isocurvature fluctuations (Dolgov; Silk)

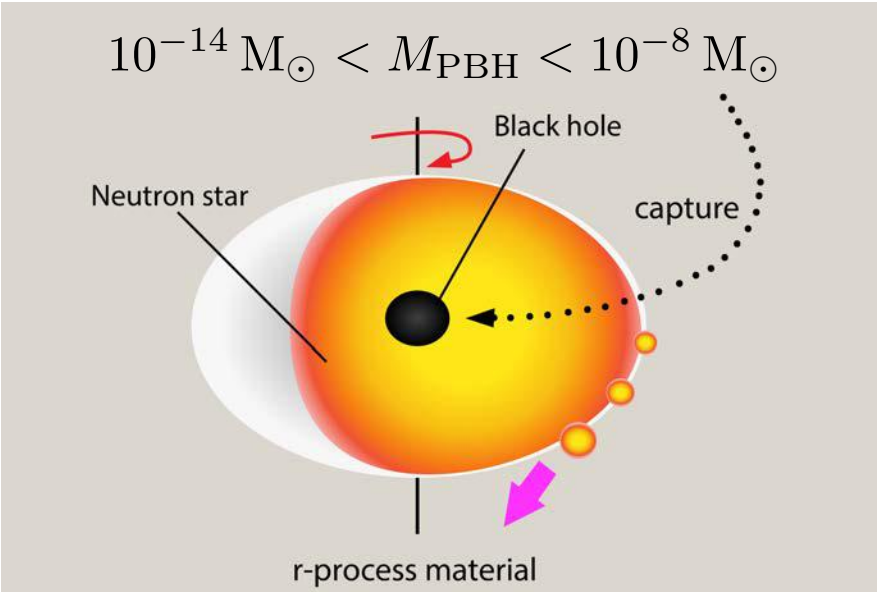
-Scalar field fragmentation, e.g., Cotner & A. Kusenko PRL **119**, 031103 (2017)





Small primordial black holes captured by neutron stars consume them from the inside.

If this happens in a *millisecond period pulsar* (MSP):cold neutron matter could be (centrifugally) ejected, decompress and make a very neutron-rich *r*-process (similar to the "tidal tails" in BNS merger scenarios); orphaned kilonova; FRB; positrons



GMF, A. Kusenko, V. Takhistov, PRL, **119**, 061101 (2017)

Capture Physics: F. Capela, M. Pshirkov, P. Tinyakov
PRD **87**, 123524 (2013)

Capture rate per neutron star: $F = (\Omega_{\mathrm{PBH}}/\Omega_{\mathrm{DM}}) \cdot F_0$, where
$F_0 \approx 1.5 \times 10^{-11}\,\mathrm{yr}^{-1}$ for the Milky Way;
$F_0 \approx 6.0 \times 10^{-10}\,\mathrm{yr}^{-1}$ for Ultra Faint Dwarfs (UFDs).

Pulsar lifetimes against PBH capture-induced destruction
$\langle t_{\mathrm{NS}} \rangle = 1/F + t_{\mathrm{loss}} + t_{\mathrm{con}}$
$t_{\mathrm{loss}} \sim 10^4\,\mathrm{yr}\,\left(M_{\mathrm{PBH}}/10^{-11}\,\mathrm{M}_\odot\right)^{-3/2}$ BH settling time
$t_{\mathrm{con}} \sim 1\,\mathrm{day}\,\left(10^{-11}\,\mathrm{M}_\odot/M_{\mathrm{PBH}}\right)$ NS consumption time

MSP with a BH inside
spinning near mass shedding limit:

Bondi accretion onto PBH maintained by *rigid rotation*: viscosity sufficient even without magnetic fields [Kouvaris, Tinyakov];
more so if magnetic field flux tubes are considered

very little heating and ***scant neutrino emission*** will accompany the consumption process (so long as material is *not* quark gluon plasma -- quark nova? -- Keranen et al arXiv:0406448)

CONSEQUENCES:

Other dark matter models: see work by Anupam Ray; Yudai Tsai

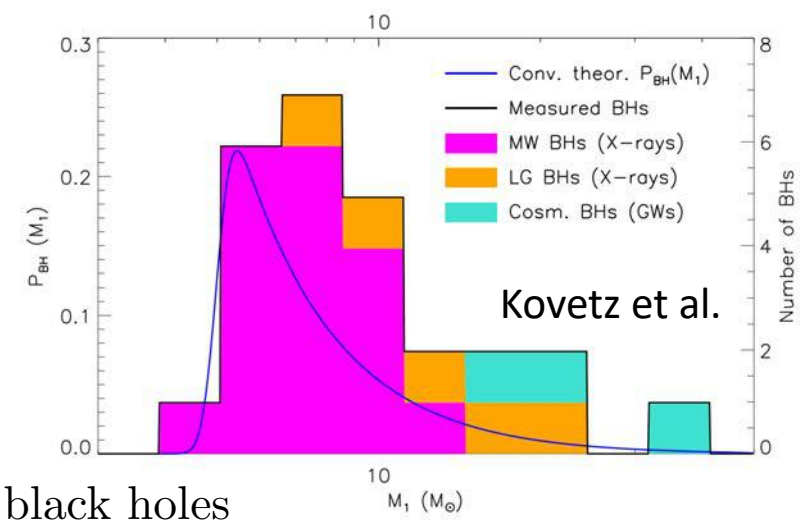
NS destruction will be most significant where the dark matter and MSP densities both high

$$\text{Destruction rate} \propto \rho_{\rm DM} \cdot \rho_{\rm NS}$$

In the age of the Galaxy expect $\mathcal{O}(1-10)\%$ of NS destroyed

This is consistent with the observed under-abundance of pulsars in the Galactic Center (GC) [Dexter, O'Leary, 14]

Production of low mass black holes
unexpected from conventional stellar evolution



PBH-NS implosion + ejected mass $= 1\,\mathrm{M}_\odot$ to $2\,\mathrm{M}_\odot$ black holes

If this happens in a binary system,
Will GW detectors find these holes in a binary in-spiral signal?

Test for the Origin of Solar Mass Black Holes

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Solar-mass black holes with masses in the range of $\sim$1–2.5 $M_\odot$ are not expected from conventional stellar evolution, but can be produced naturally via neutron star (NS) implosions induced by capture of small primordial black holes (PBHs) or from accumulation of some varieties of particle dark matter. We argue that a unique signature of such "transmuted" solar-mass BHs is that their mass distribution would follow that of the NSs. This would be distinct from the mass function of black holes in the solar-mass range predicted either by conventional stellar evolution or early Universe PBH production. We propose that analysis of the solar-mass BH population mass distribution in a narrow mass window of $\sim$1–2.5 $M_\odot$ can provide a simple yet powerful test of the origin of these BHs. Recent LIGO/VIRGO gravitational wave (GW) observations of the binary merger events GW190425 and GW190814 are consistent with a BH mass in the range $\sim$1.5–2.6 $M_\odot$. Though these results have fueled speculation on dark matter-transmuted solar-mass BHs, we demonstrate that it is unlikely that the origin of these particular events stems from NS implosions. Data from upcoming GW observations will be able to distinguish between solar-mass BHs and NSs with high confidence. This capability will facilitate and enhance the efficacy of our proposed test.

DOI: 10.1103/PhysRevLett.126.071101

PHYSICAL REVIEW LETTERS **126,** 071101 (2021)

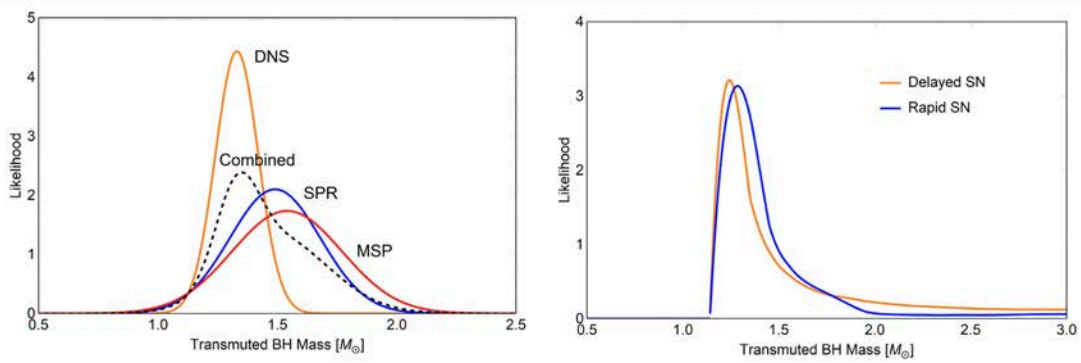
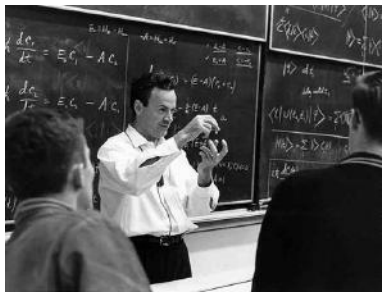


FIG. 1. Expected mass distribution of transmuted solar-mass BHs assuming that these track their NS progenitors. Left: Considered subpopulations of imploding NSs from slow pulsars (SPR, blue), recycled millisecond pulsars (MSP, red) and double neutron stars (DNS, orange) as well as combined distribution (black dashed) are shown. Input parameters for Gaussian distributions of the NS populations are taken from Refs. [73,74]. Right: Imploding NSs from models of delayed and rapid collapse supernovae [47], assuming solar metallicity of stellar progenitors.

whenever the pressure support for the star is from particles moving near the speed of light the star is "**trembling on the verge of instability**"

MASS in $M_\odot$	**Main Seq. Entropy per baryon** s/k_B	**Collapse Entropy per baryon** s/k_B	**degenerate core mass** in $M_\odot$	**Instability Mechanism**	**Fraction of rest mass radiated as neutrinos**	**Neutrino Trapping / Thermal equilibrium**
10 to ~ 100	**~ 10**	**~ 1**	**~ 1.4**	**Electron capture / NSE Feynman-Chandrasekhar G.R. instab.**	**~ 10% of collapsing core mass**	**Yes**
~ 100 to ~ 10^4	**~ 100**	**~ 100**	**NONE**	**$e^\pm$ pair instability**	**~ 10% C/O burning core**	**Yes**
~ 10^4 to ~ 10^8	**~ 1000 no main seq.**	**~ 1000**	**NONE**	**Feynman-Chandrasekhar G.R. Instability**	**~ 3%**	**No**



BSM channels to ***ruin*** pair instability explosions – guaranteeing collapse to a black hole

-- **add energy** via, e.g., dark matter particle annihilation

NORDITA 2020-088
UTTG-12-2020

Filling the Black Hole Mass Gap: Avoiding Pair Instability in Massive Stars through Addition of Non-Nuclear Energy

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In standard stellar evolution, stars with masses ranging from approximately 150 to $240M_\odot$ are expected to evolve to a pair instability supernova with no black hole (BH) remnant. This evolutionary behavior leads to a predicted gap in the black hole mass function from approximately 50 to $140M_\odot$. Yet the LIGO and Virgo Collaborations[1] recently discovered black holes of masses $66M_\odot$ and $85M_\odot$ in the gravitational wave event GW190521. We propose a new method to populate the BH mass gap. If an energy source is added throughout the star in addition to nuclear fusion, it is possible for the altered evolution to avoid the complete destruction of a pair instability supernova, and instead a BH remnant is left behind. An example of an extra energy source is dark matter annihilation within the star, but our results hold more generally. We show this phenomenon by exploring the effect of adding an energy source independent of temperature and density to a $180M_\odot$ star, using the MESA one-dimensional stellar evolution software. If ~50% of the star's energy is due to this new source, the star is capable of avoiding the pair instability entirely and evolving towards a core-collapse supernova and ultimately a BH remnant with mass $\sim 120M_\odot$.

arXiv:2010.00254

-- Extra **energy loss** channels through emission of new light degrees of freedom

- causes star to consume fuel more quickly (negative heat capacity!)
- ends He burning earlier, less 16O available to fuel nuclear burning-driven pulsational instability

e.g., Croon, McDermott, Sakstein arXiv: 2007.00650; 2007.07889

Supermassive Stars

$$\sim 10^6\,\mathrm{M}_\odot$$

Jung-Tsung Li, GMF, Chad T. Kishimoto arXiv:1708.05292

$*$ High entropy means that these objects are radiation/$e^{\pm}$-pair dominated

$*$ Neutrino pairs produced copiously via $e^- + e^+ \rightarrow \nu + \bar{\nu}$

$*$ Neutrino energy emission rate scales as **nine** power of temperature, $\sim T^9$, meaning that most of the neutrino radiation comes out just before black hole formation.

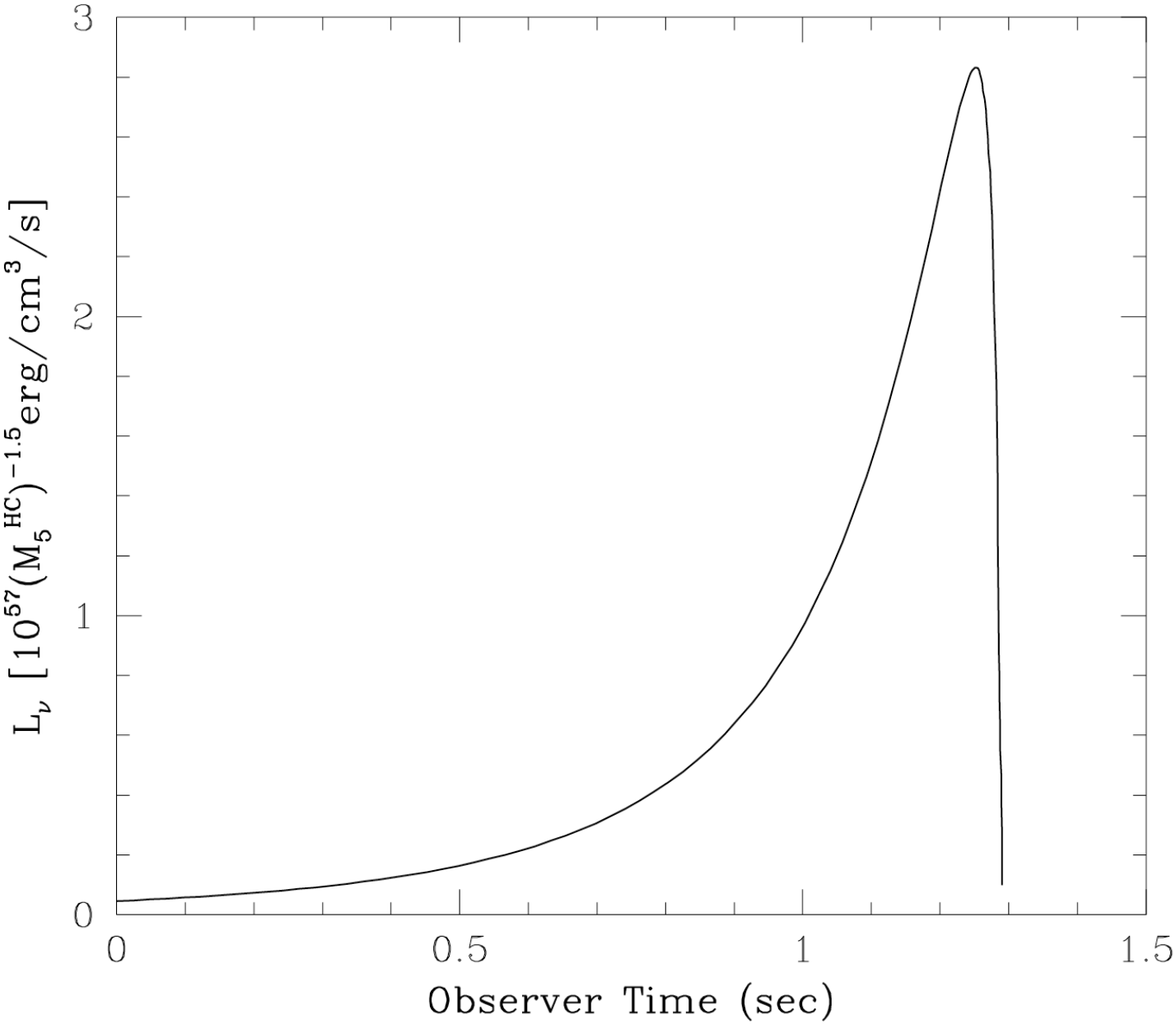
$*$ Stars with homologous core masses $M_{\rm HC} < 5 \times 10^4\,{\rm M}_\odot$ will have neutrino mean free paths smaller than the core size and therefor trap neutrinos via scattering – lower neutrino emission over a longer time scale.

$*$ Stars with homologous core masses $M_{\rm HC} > 5 \times 10^5\,{\rm M}_\odot$ will not get hot enough to radiate a significant fraction of the star's rest mass before they become black holes.

These stars go unstable as a result of the Feynman-Chandrasekhar General Relativistic instability and (for zero initial metals) collapse to a black hole.

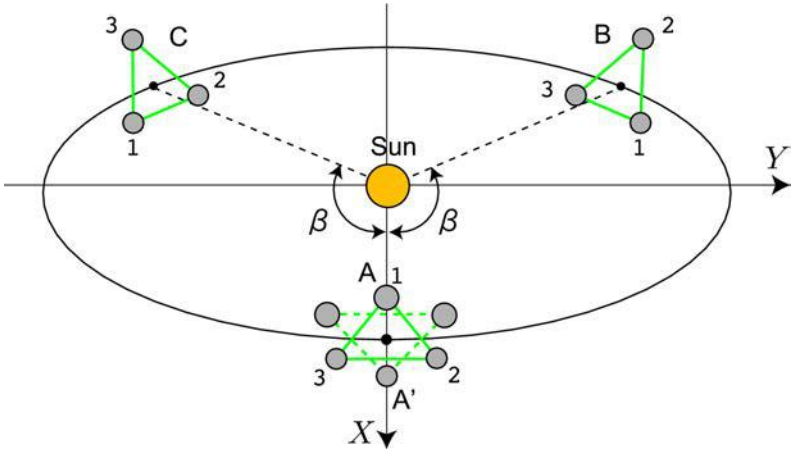
This collapse is non-homologous on account of prodigious neutrino-pair production/loss.
Fuller, Woosley, Weaver Ap. J., 307, 675 (1986)

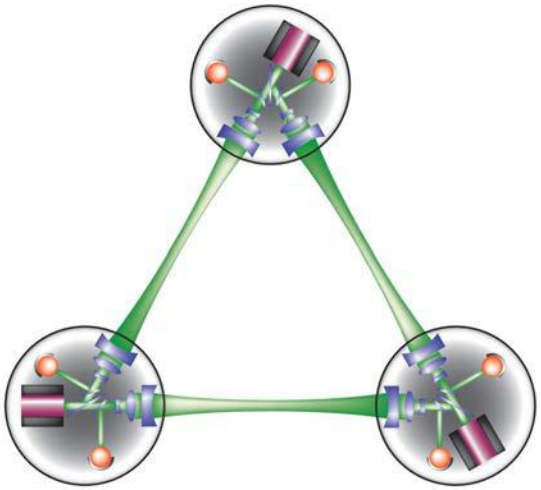
The star largely is transparent to neutrinos until a trapped surface forms.



$$M_5^{\rm HC} \equiv \frac{M_{\rm homol.\ core}}{10^5\,{\rm M}_\odot}$$

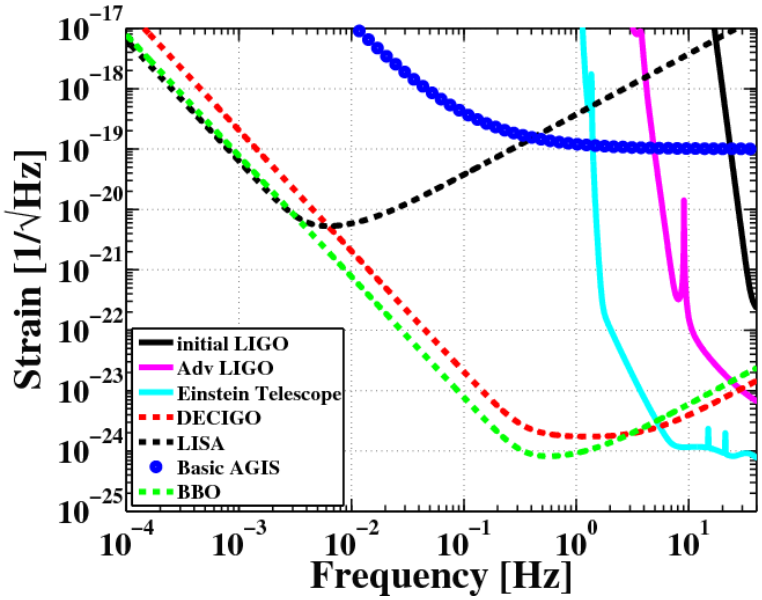
X. Shi & G. M. Fuller, Astrophys. J. 503, 307 (1998).

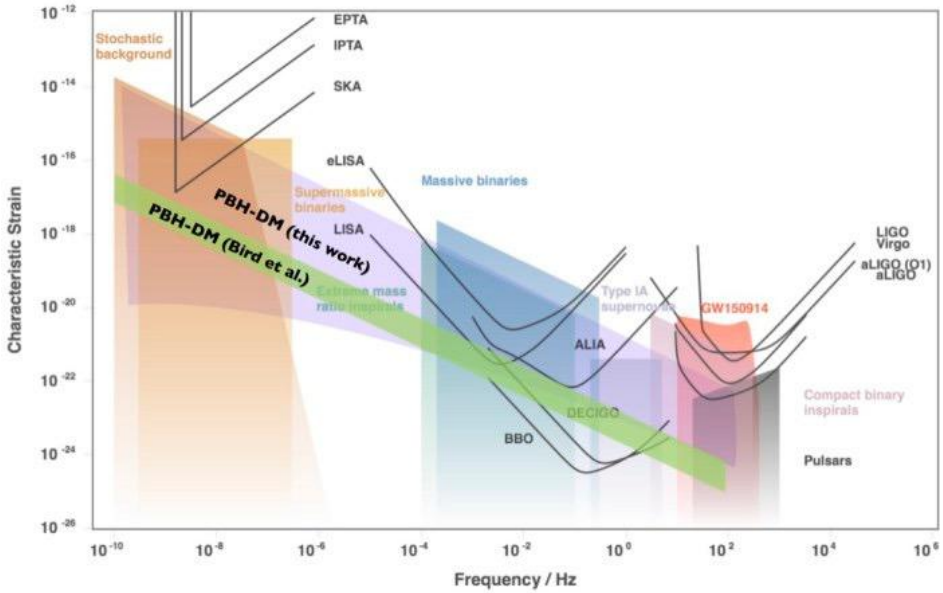




Cosmological test of gravity with polarizations of stochastic gravitational waves around 0.1-1 Hz - Nishizawa, Atsushi *et al.*
Phys.Rev. D81 (2010) 104043 arXiv:0911.0525 [gr-qc]

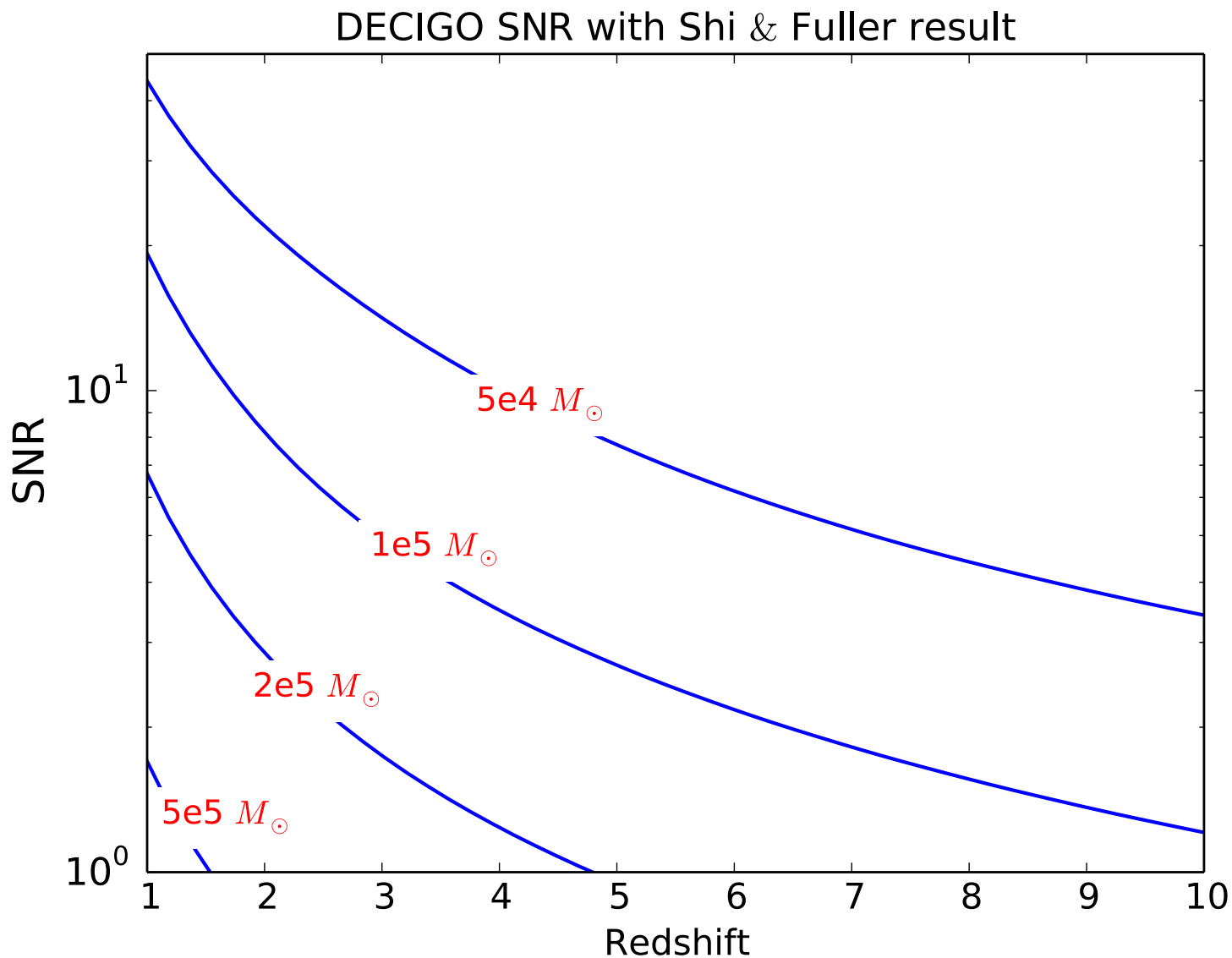
DECIGO constellation concept~\cite{Sato:DECIGO2009}

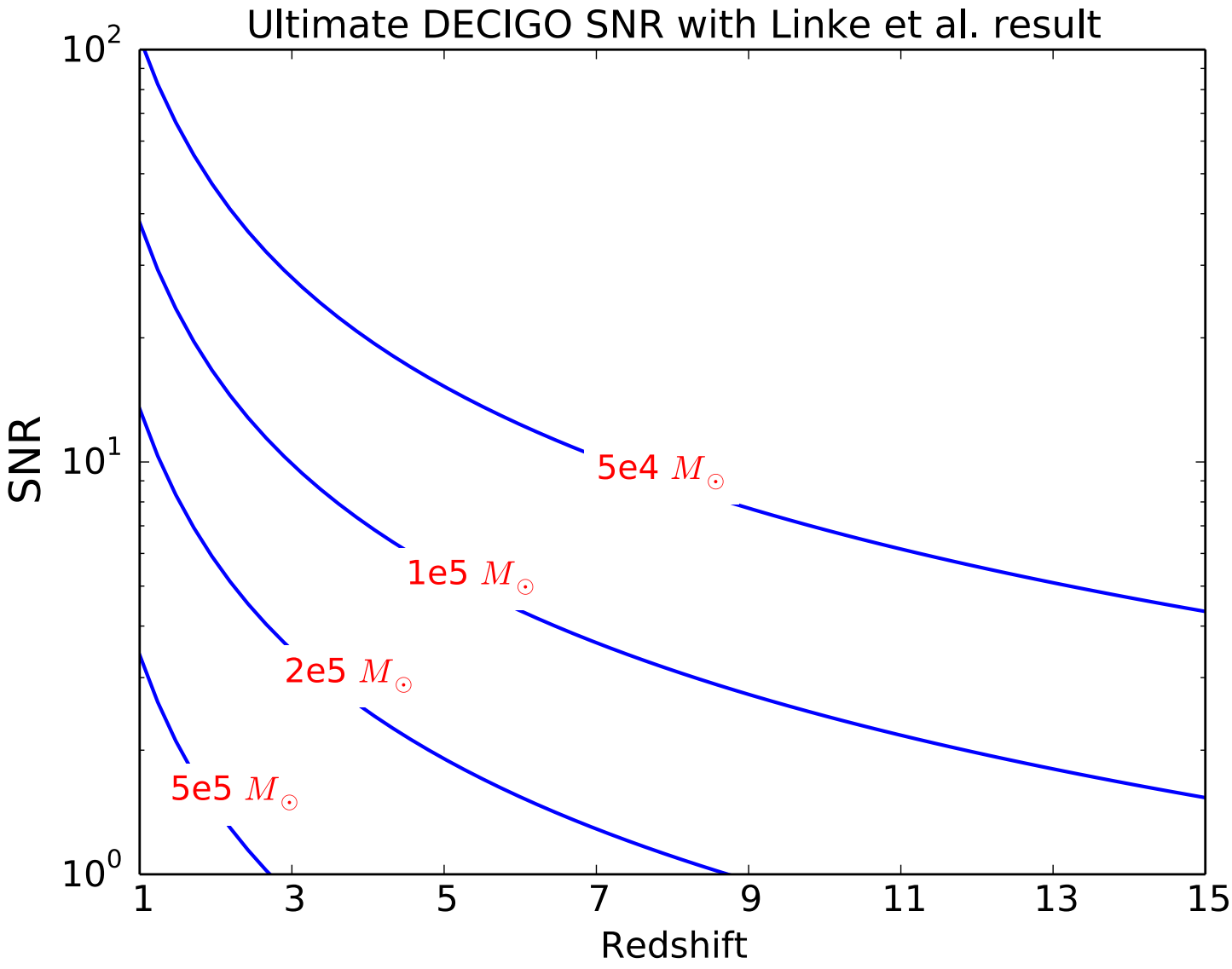




Left:
Adhikari, Rana X Rev.Mod.Phys. 86 (2014) 121 arXiv:1305.5188 [gr-qc] LIGO-P1200121

Right:
https://arxiver.wordpress.com/2016/10/27/detecting-the-gravitational-wave-background-from-primordial-black-hole-dark-matter-cea/#jp-carousel-203276

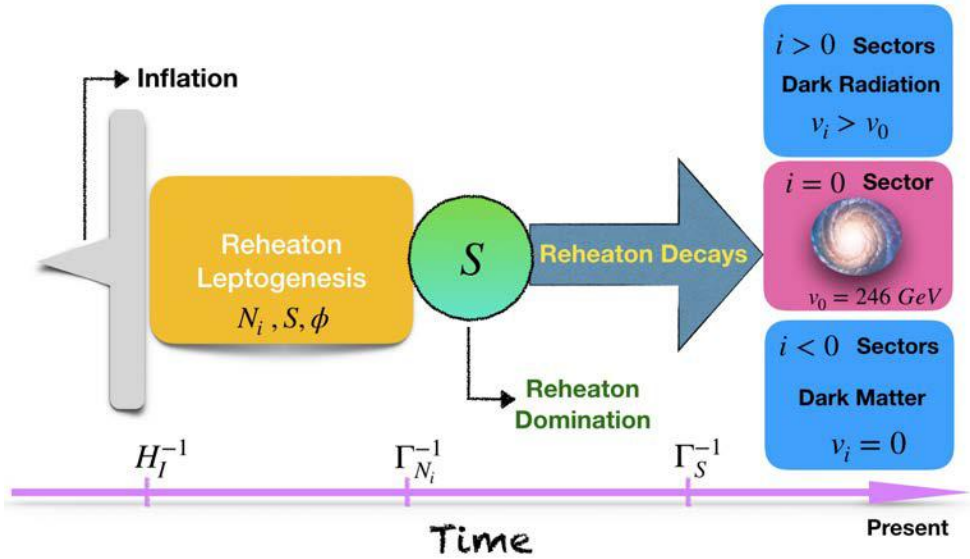

DECIGO SNR with Shi & Fuller result
SNR
Redshift
10^1
10^0
1
2
3
4
5
6
7
8
9
10
5e4 $M_\odot$
1e5 $M_\odot$
2e5 $M_\odot$
5e5 $M_\odot$


Ultimate DECIGO SNR with Linke et al. result
SNR
Redshift
10^2
10^1
10^0
1
3
5
7
9
11
13
15
5e4 $M_\odot$
1e5 $M_\odot$
2e5 $M_\odot$
5e5 $M_\odot$

Compact Dark Objects (CDOs)?

Dark Sectors – see Daniel Stolarski's paper for an example:

"Baryogenesis and Dark Matter in Multiple Hidden Sectors", Easa, Gregoire, Stolarski, Cosme arXiv:2206.11314



Can there be dissipation in this sector,
along the lines of the way baryons can change their phase space density by radiating?

CDO sizes? Planet-sized masses to supermassive objects?

See the 3G Science book: detect in-spiral of even small objects right to the causal horizon

Gordy Kane; Fred Adams – more fuel for the fire