Neutrino flavor mixing in supernovae & mergers

Luke Johns
NASA Einstein Fellow
UC Berkeley

The past & promise of neutrino astronomy

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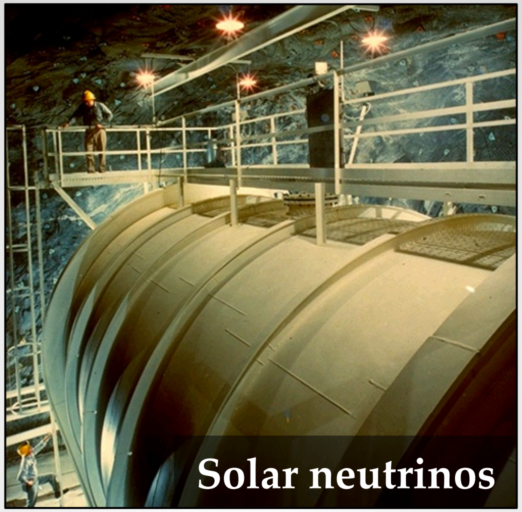
Homestake



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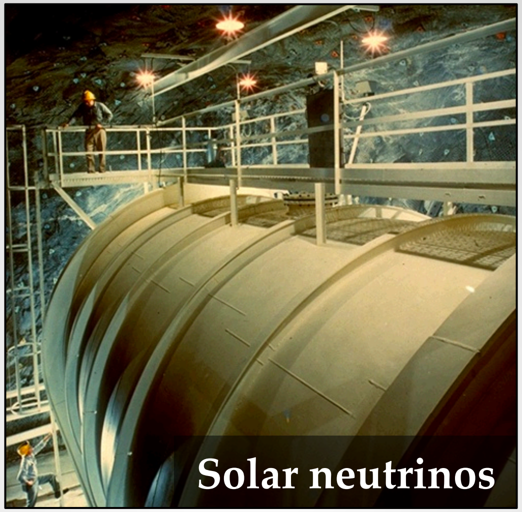

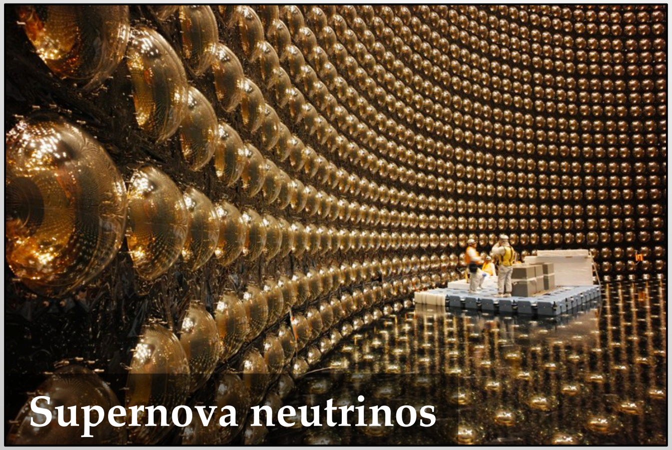

Super-Kamiokande

The past & promise of neutrino astronomy

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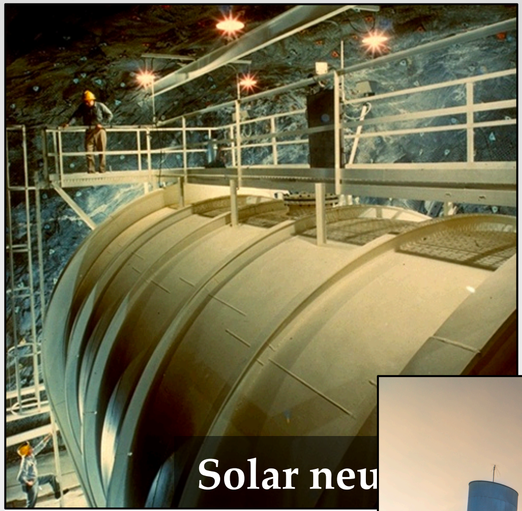
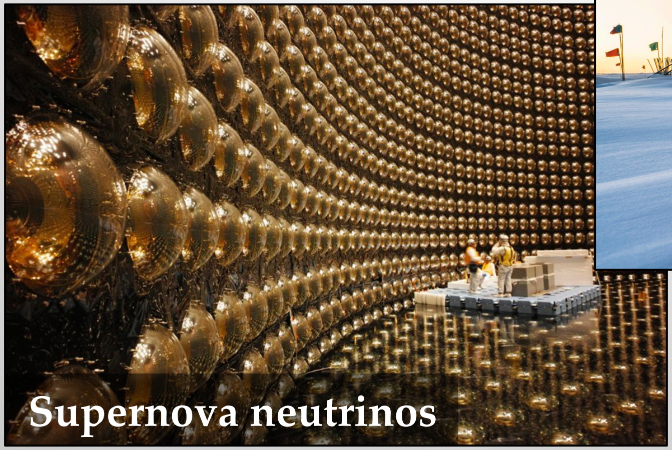
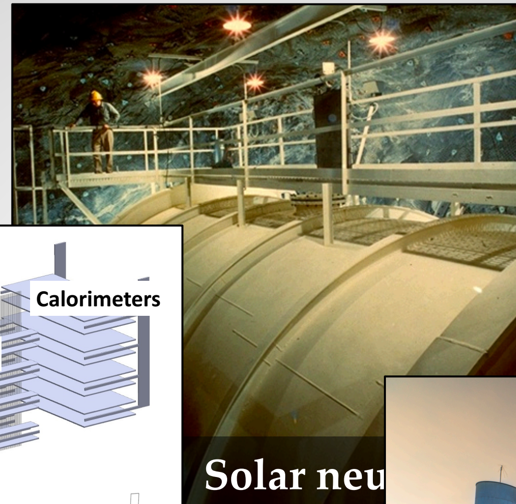


IceCube



Super-Kamiokande

The past & promise of neutrino astronomy



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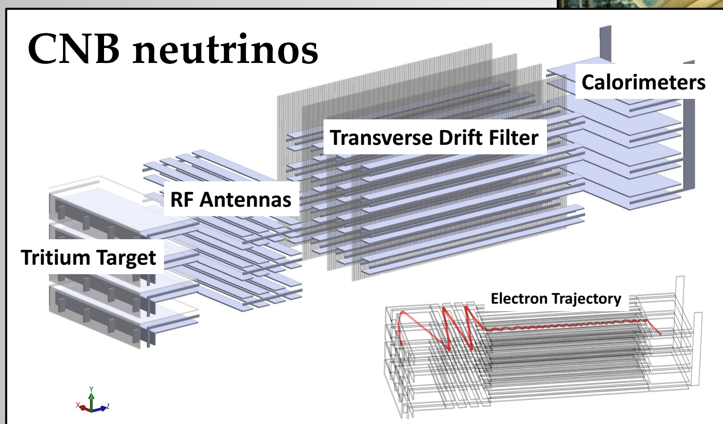

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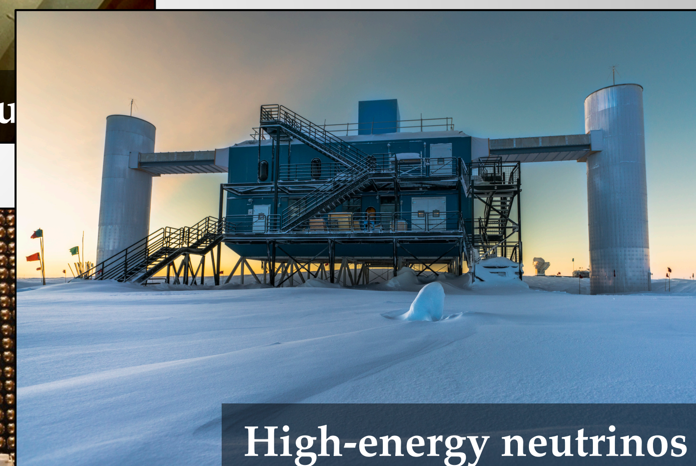

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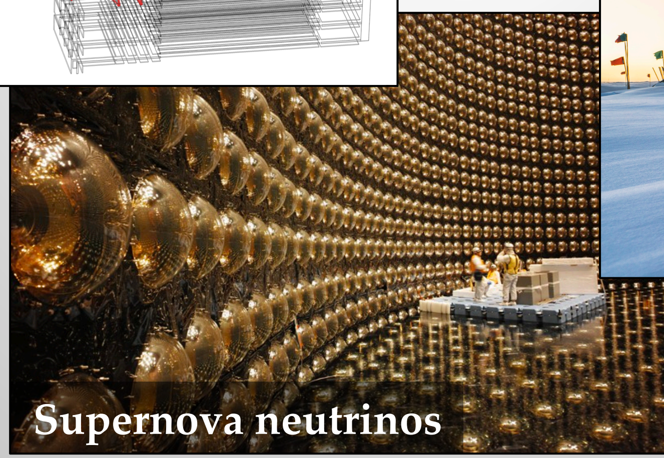

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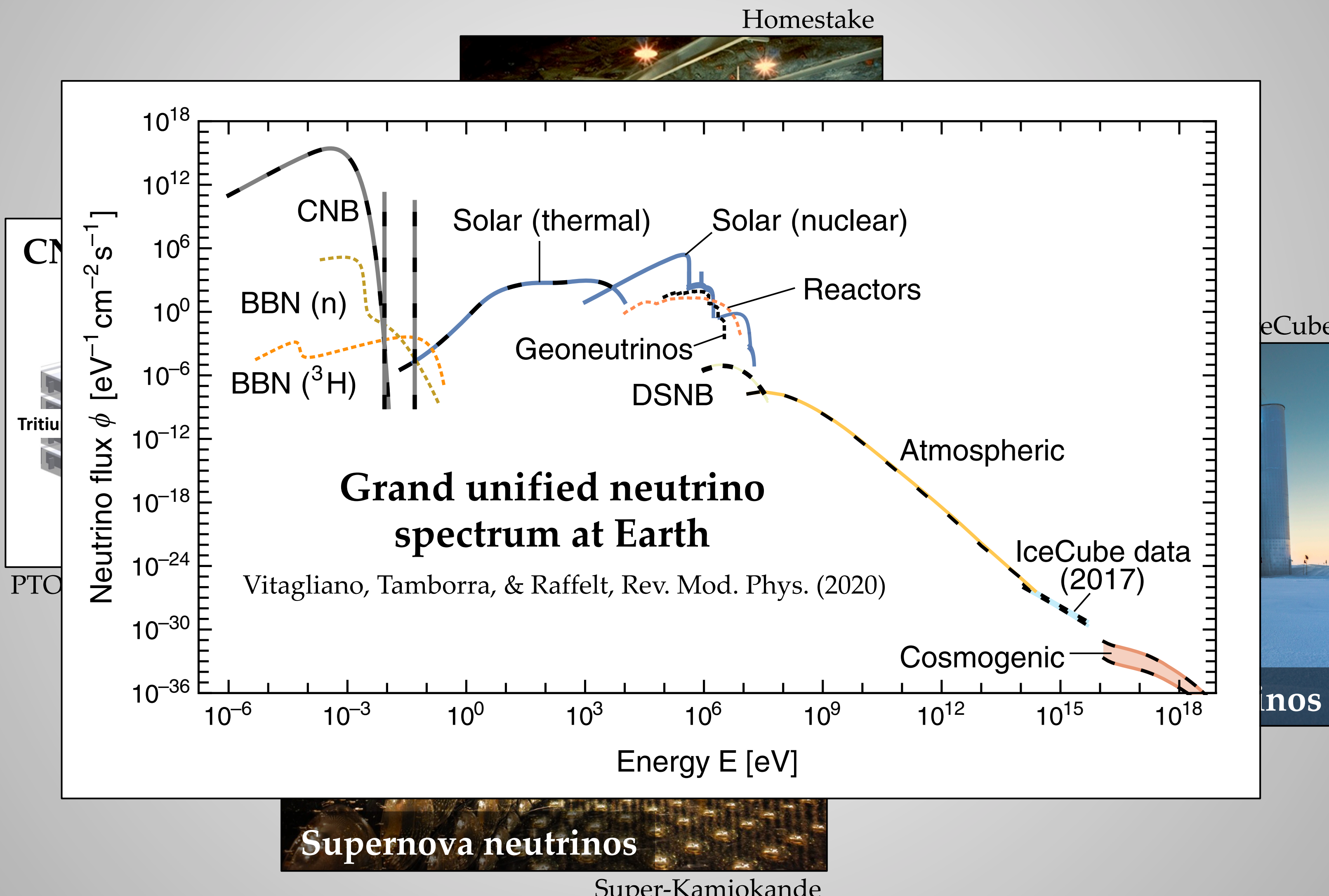


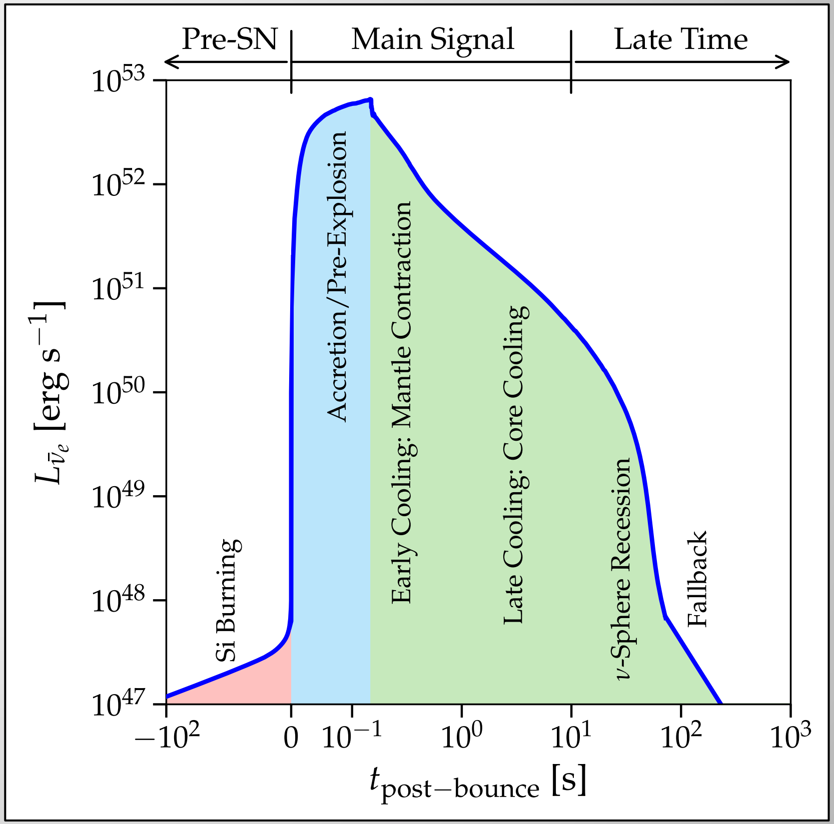
Table 3 Measured properties of neutrino events observed in water Cherenkov detectors[a]

Event	Event time (s)	Electron energy (MeV)	Electron angle (degrees)
Kamiokande II:			
1	0.0	20.0 ± 2.9	18 ± 18
2	0.107	13.5 ± 3.2	40 ± 27
3	0.303	7.5 ± 2.0	108 ± 32
4	0.324	9.2 ± 2.7	70 ± 30
5	0.507	12.8 ± 2.9	135 ± 23
6	0.686	6.3 ± 1.7	68 ± 77
7	1.541	35.4 ± 8.0	32 ± 16
8	1.728	21.0 ± 4.2	30 ± 18
9	1.915	19.8 ± 3.2	38 ± 22
10	9.219	8.6 ± 2.7	122 ± 30
11	10.433	13.0 ± 2.6	49 ± 26
12	12.439	8.9 ± 1.9	91 ± 39
IMB:			
1	0.0	38 ± 7	80 ± 10
2	0.41	37 ± 7	44 ± 15
3	0.65	28 ± 6	56 ± 20
4	1.14	39 ± 7	65 ± 20
5	1.56	36 ± 9	33 ± 15
6	2.68	36 ± 6	52 ± 10
7	5.01	19 ± 5	42 ± 20
8	5.58	22 ± 5	104 ± 20

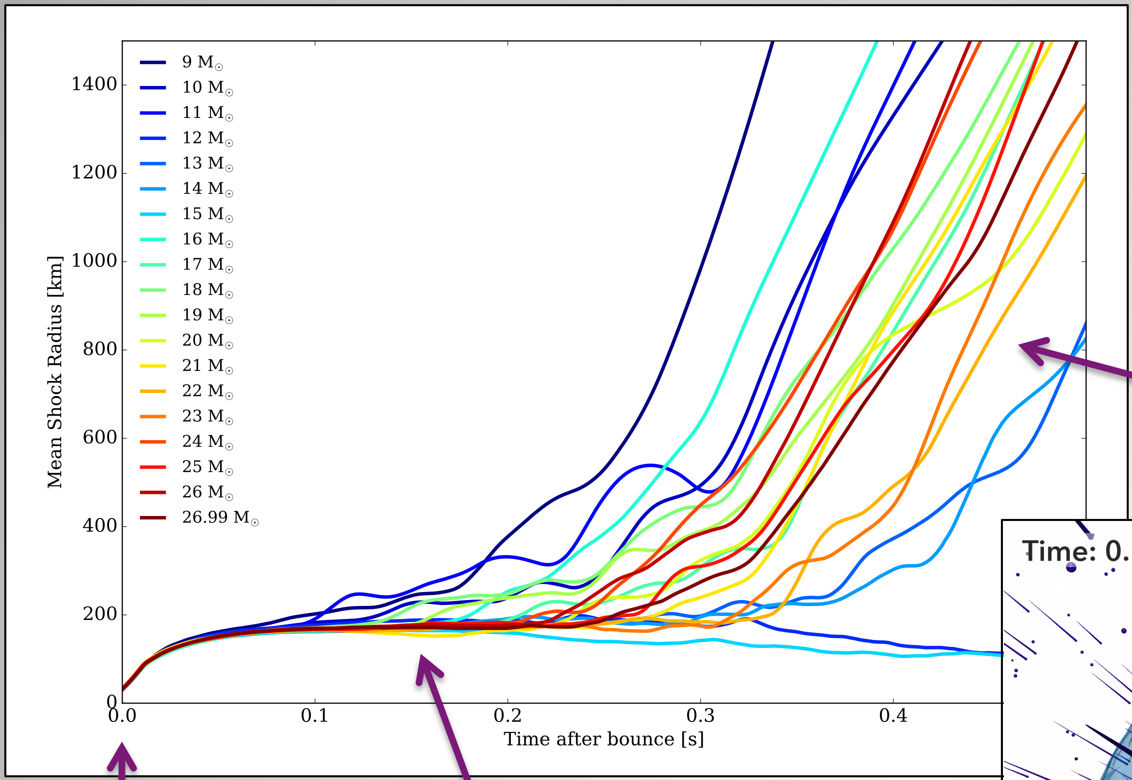
[a] The first events were detected on February 23, 1987, at about 7 hr 36 m UT. The angle in the last column is relative to the direction of the LMC. The errors are estimated 1σ uncertainties.

Arnett, Bahcall, Kirshner, & Woosley, Annu. Rev. Astron. Astrophys. (1989)

SN 1987A evinced the birth & early cooling of a hot neutron star. The next nearby event will reveal far more.

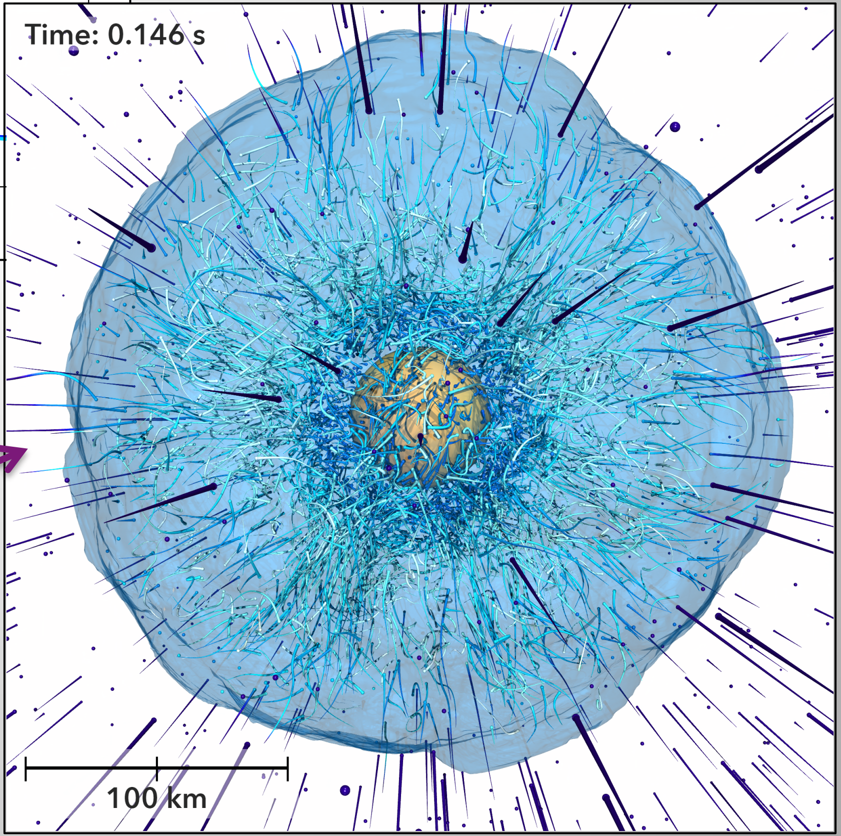


Li, Roberts, & Beacom, PRD (2021)



The delayed neutrino-heating mechanism likely explains most CCSN explosions

Explosion



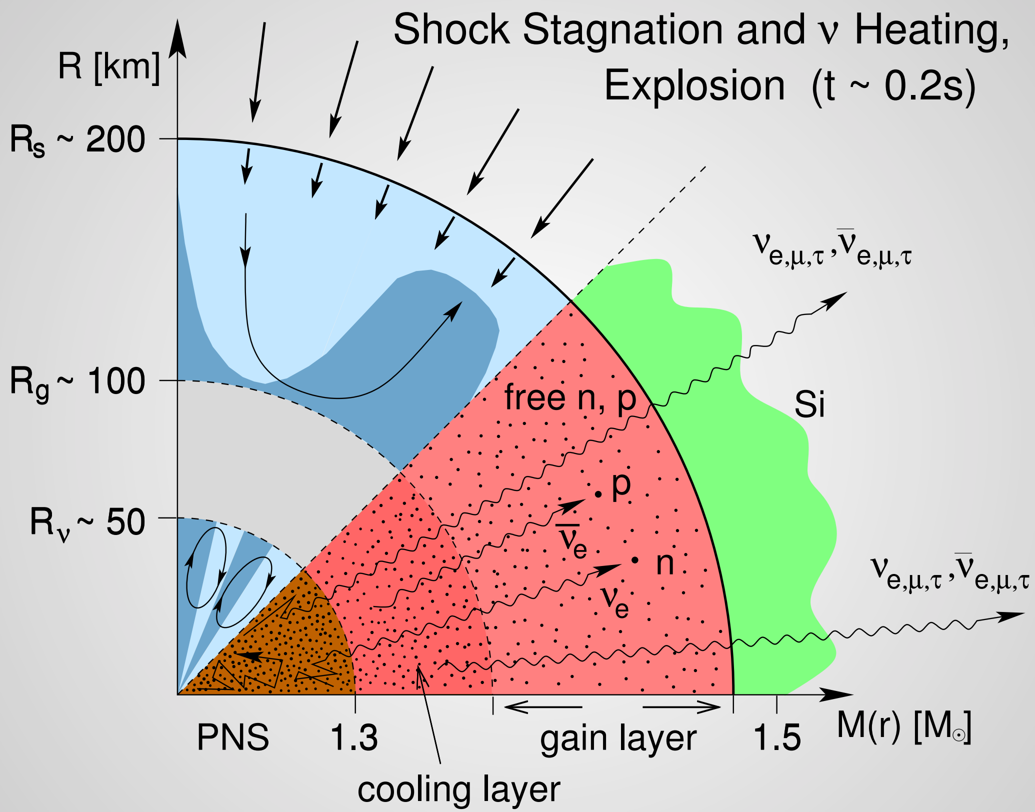
The collapsing core of the star **bounces**

The shock **stalls** while neutrinos attempt to re-energize it

Burrows & Vartanyan, Nature (2021)

A closer look at the pivotal accretion/revival phase…

Janka, 1702.08713

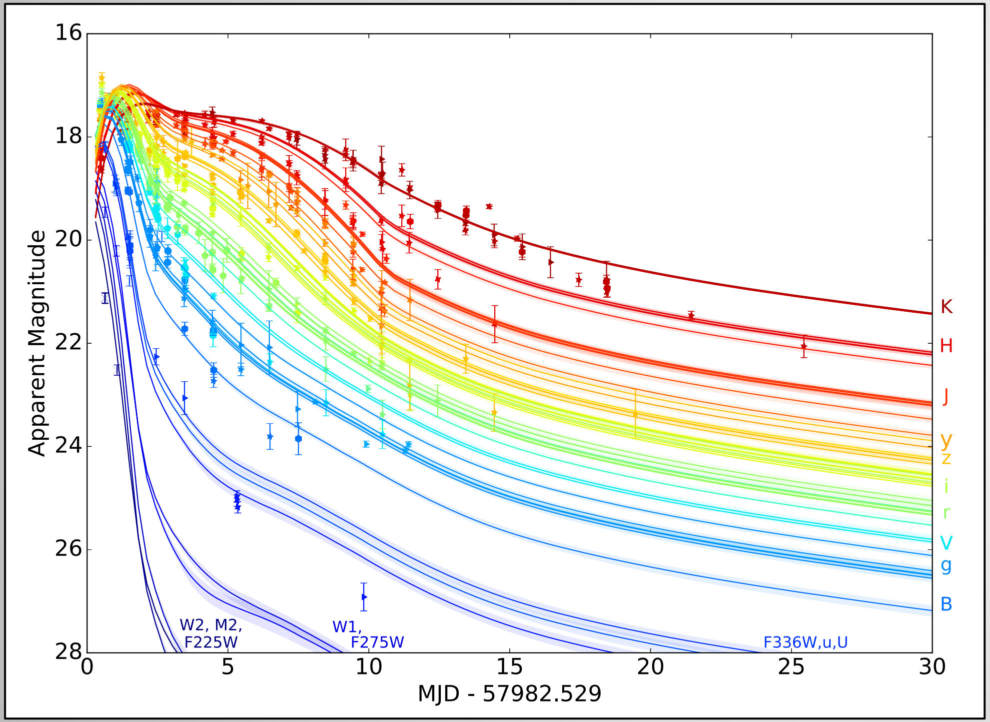


Flavor conversion might occur as neutrinos radiate out from the core.

Mazurek, *Neutrino-79* conference proceedings (1979)
Wolfenstein, Phys. Rev. D (1979)
Fuller, Mayle, Wilson, & Schramm, Astrophys. J. (1987)
Raffelt, *Stars as Laboratories for Fundamental Physics* (1996)

Kilonovae accompanying NSMs inform us about neutrino astrophysics even when the neutrinos themselves are not detected.

AT2017gfo: An EM counterpart of GW170817
(UVOIR light curves fit by 3-component models)



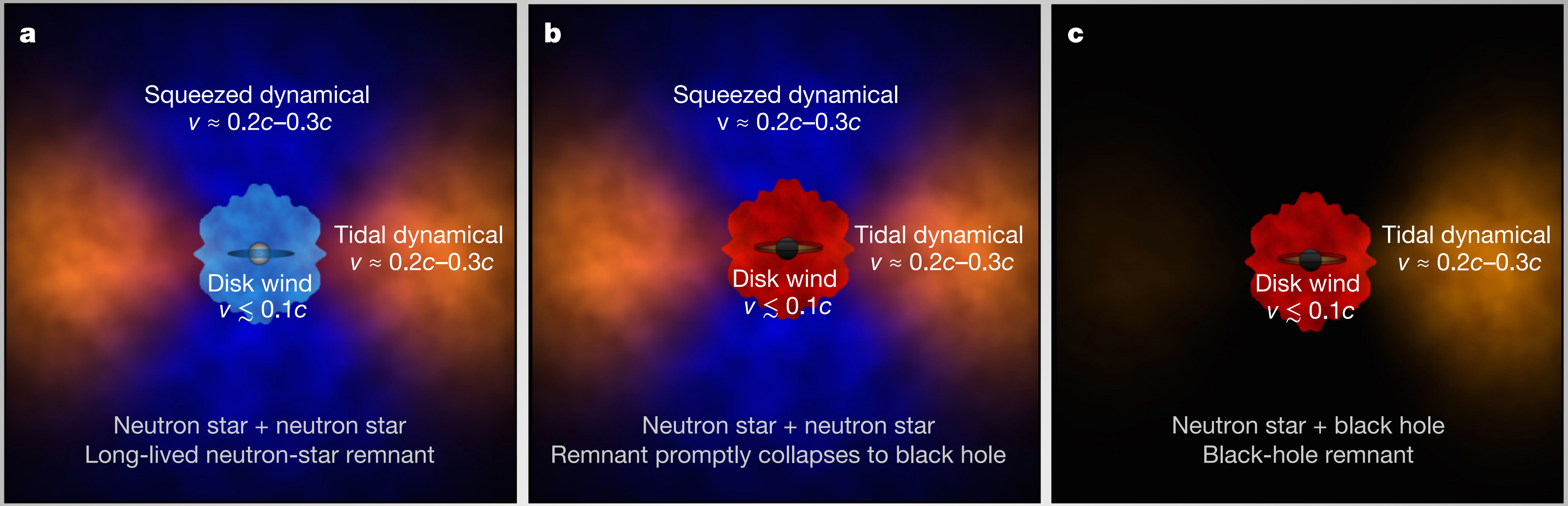
Villar et al., Astrophys. J. Lett. (2017)
(see references for original data sets)

A significant amount of the ejecta is thought to have come from the post-merger accretion-disk outflow.

In general, such material is **irradiated by neutrinos** from the disk & the central remnant (if a NS).

Recent reviews:
Baiotti & Rezzolla, RPP (2017); Siegel, EPJA (2019); Metzger, LRR (2020); Radice et al., ARNPS (2020); Margutti & Chornock, ARAA (2021); & others

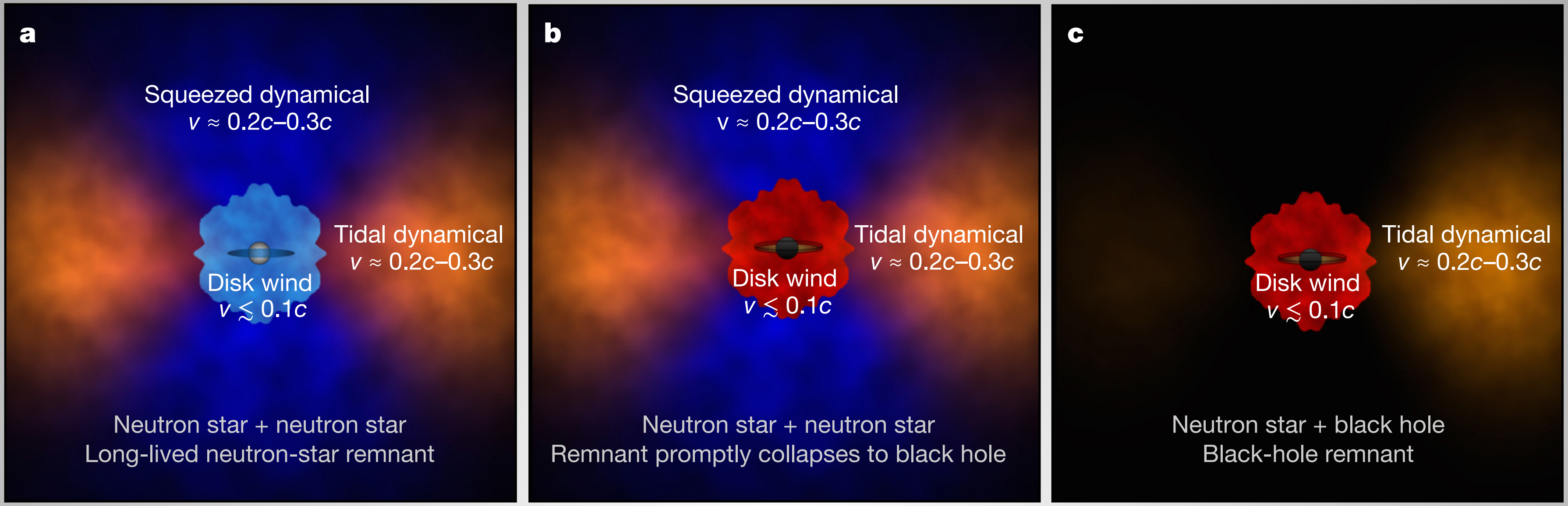
Kasen, Metzger, Barnes, Quataert, & Ramirez-Ruiz, Nature (2017)



NS–NS: A longer-lived remnant equals more disk ejecta at higher electron fraction.

NS–BH: A single tidal tail, plus disk ejecta at low electron fraction.

Kasen, Metzger, Barnes, Quataert, & Ramirez-Ruiz, Nature (2017)



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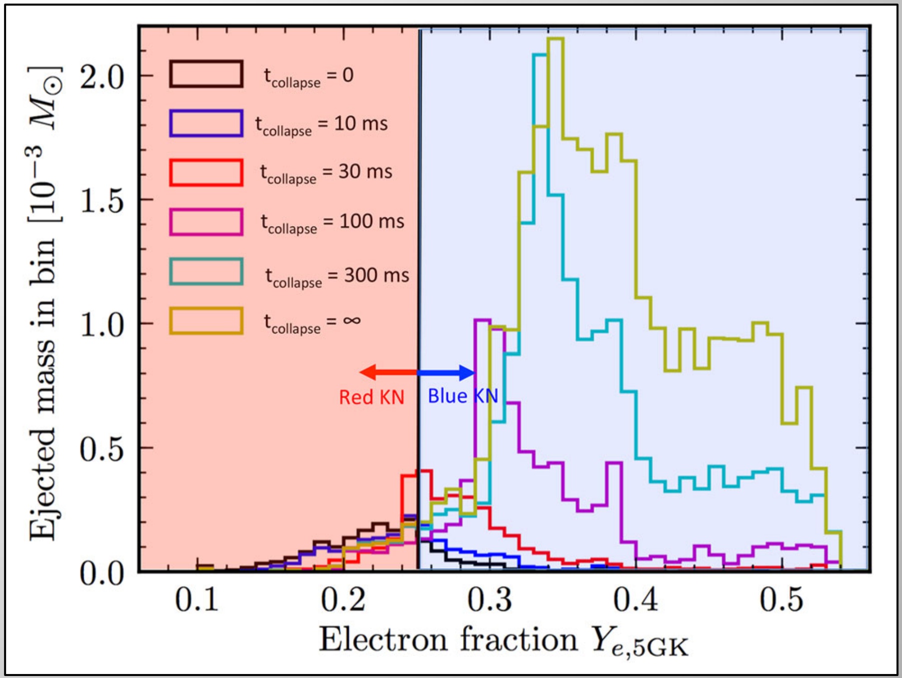

Lippuner et al., MNRAS (2017); Metzger, Living Rev. Relativ. (2020)

Some common themes of CCSNe & NSMs:

- Matter at high temperatures & extreme densities
- Nucleosynthesis
- Extreme spacetime curvature & detectable GW emission
- Powerful & (indirectly) observable neutrino emission
- Neutrinos are dynamically & chemically important
- Neutrino trapping, self-interactions, & collective oscillations

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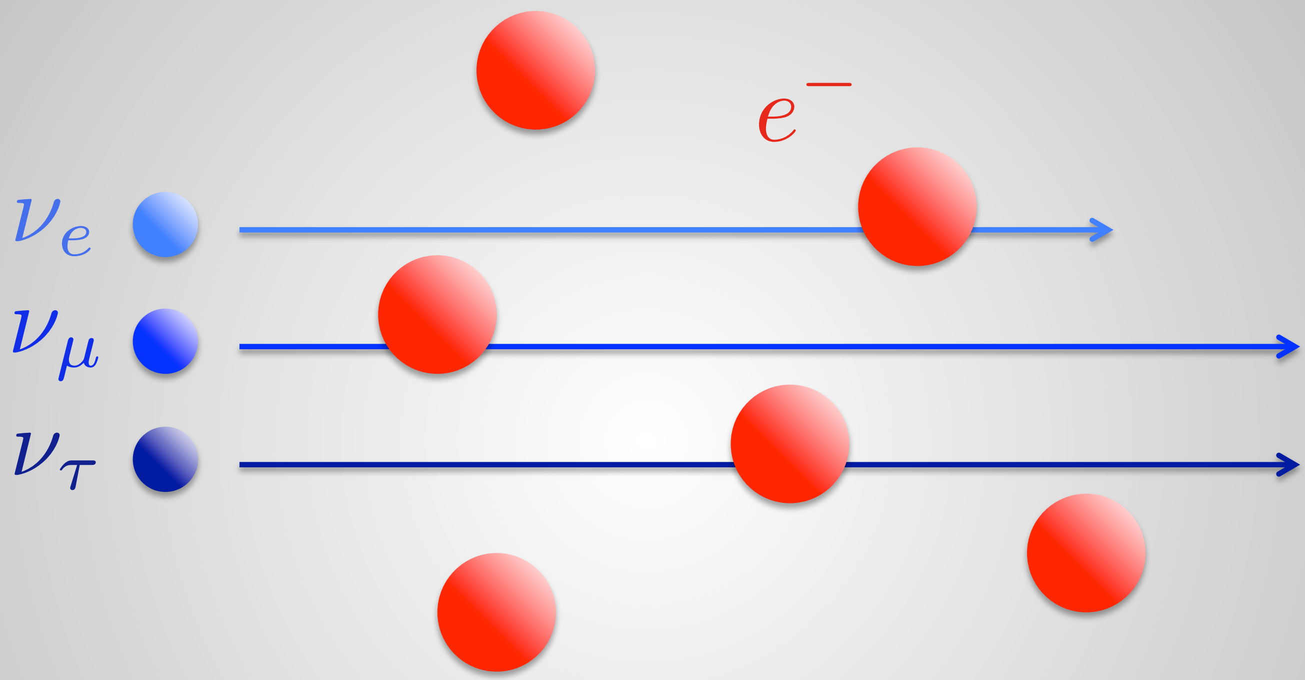
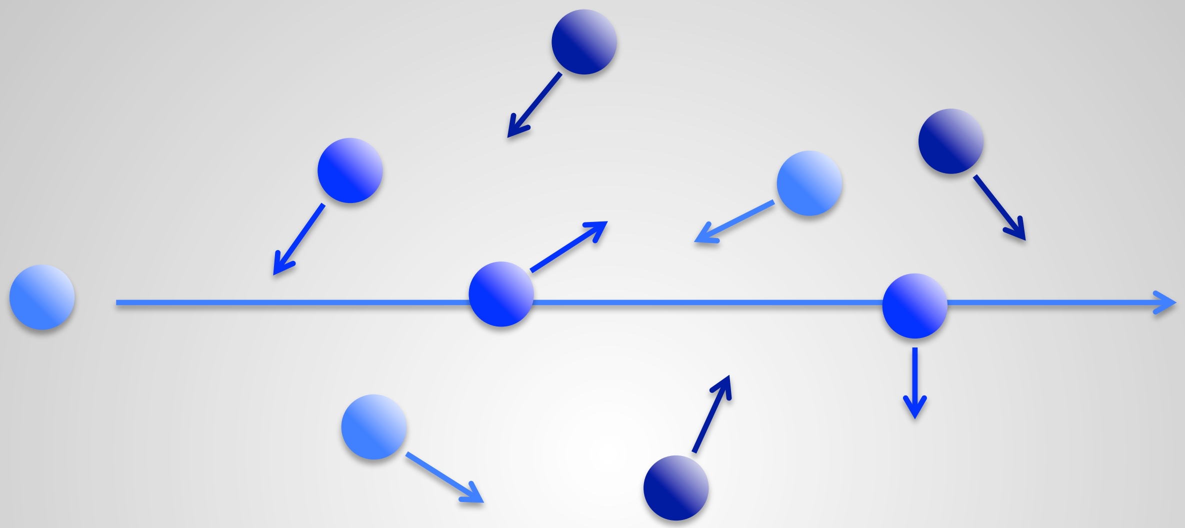
There's currently a strong push to incorporate neutrino mixing—*established physics*—into the theory/simulation of these events.



When neutrinos **forward scatter** on background particles,
they acquire in-medium effective masses.



Neutrinos contribute to **their own background**. As a result, forward scattering changes oscillations in a nonlinear way.

Collective oscillations

Generally, the high densities in SNe & NSMs *suppress* mixing because

interaction eigenstates $\cong$ **energy eigenstates**.

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interaction eigenstates ≅ **energy eigenstates**.

The two main exceptions occur in regions with

- **(avoided) level crossings** or
- **flavor instabilities**.

MSW resonance is the classic example

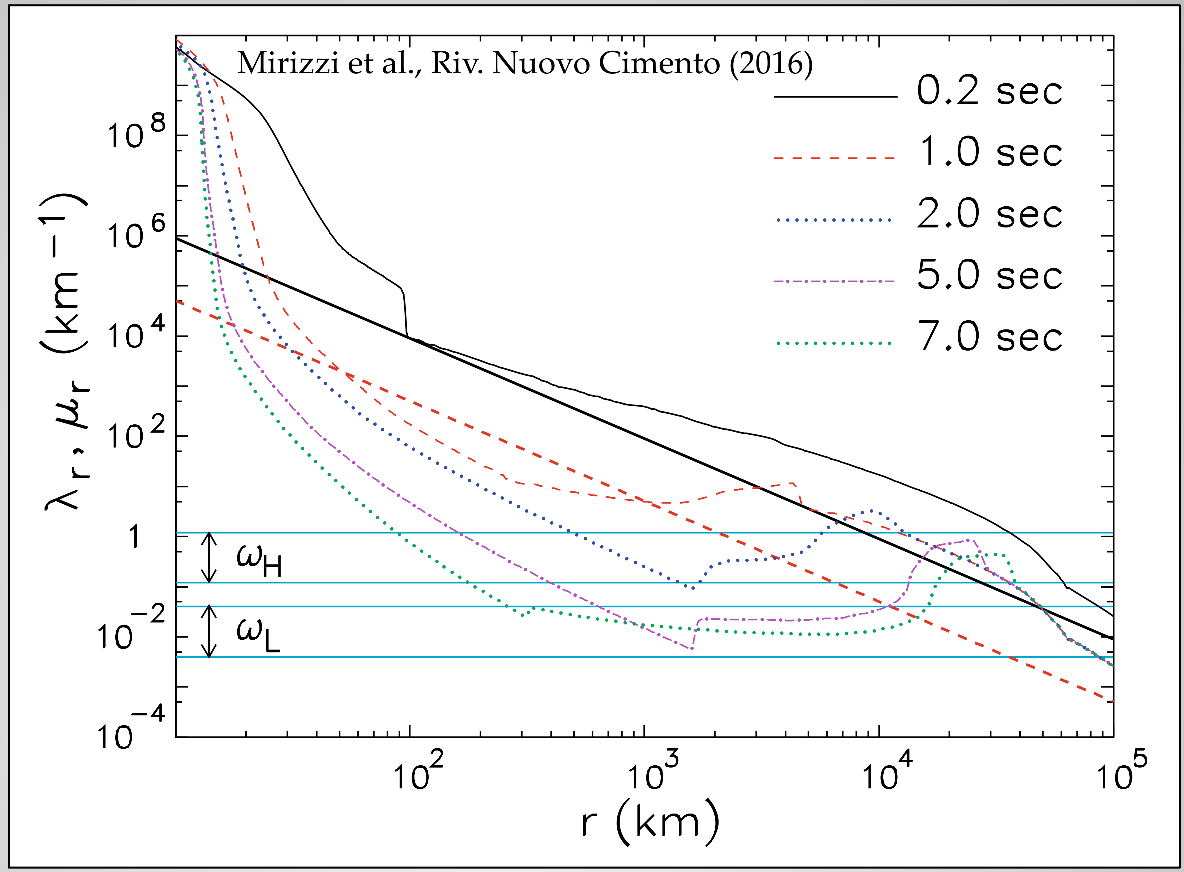
Wolfenstein, PRD (1978); Mikheyev & Smirnov, SJNP (1985)

Forward-scattering potentials in a CCSN

λ = Matter pot'l (*thin curves*)

μ = Neutrino pot'l (*thick curves*)

ω = Vacuum osc. frequencies (*blue bands*)



Time after core bounce

Radius

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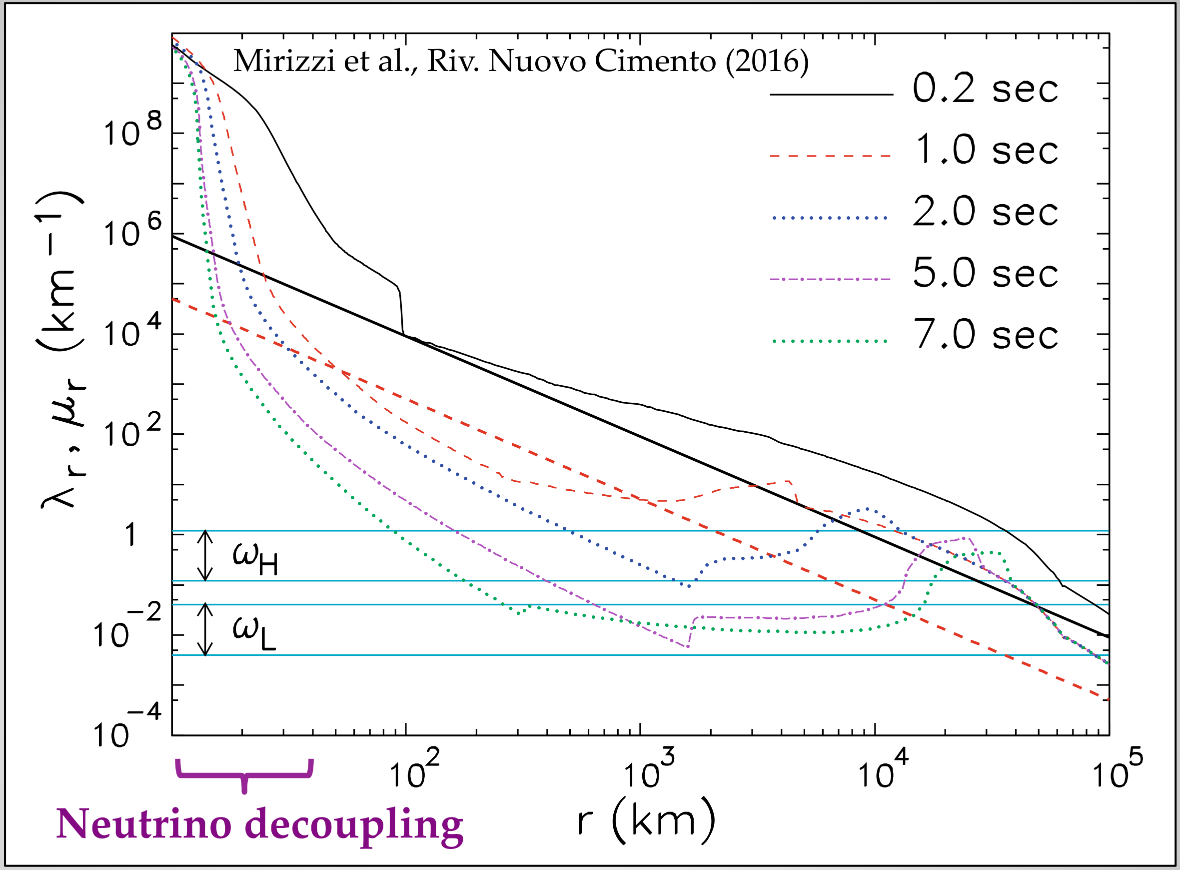

Time after core bounce

Radius

Level crossings: MSW, spectral swaps, MNR (mergers only?)

Duan et al., PRL (2007); Raffelt & Smirnov, PRD (2007); Dasgupta et al., PRL (2009); Gava et al., PRL (2009); Friedland, PRL (2010); Galais & Volpe, PRD (2011); Malkus et al., PRD (2012); Zhu et al., PRD (2016); Wu et al., PLB (2016); & many more

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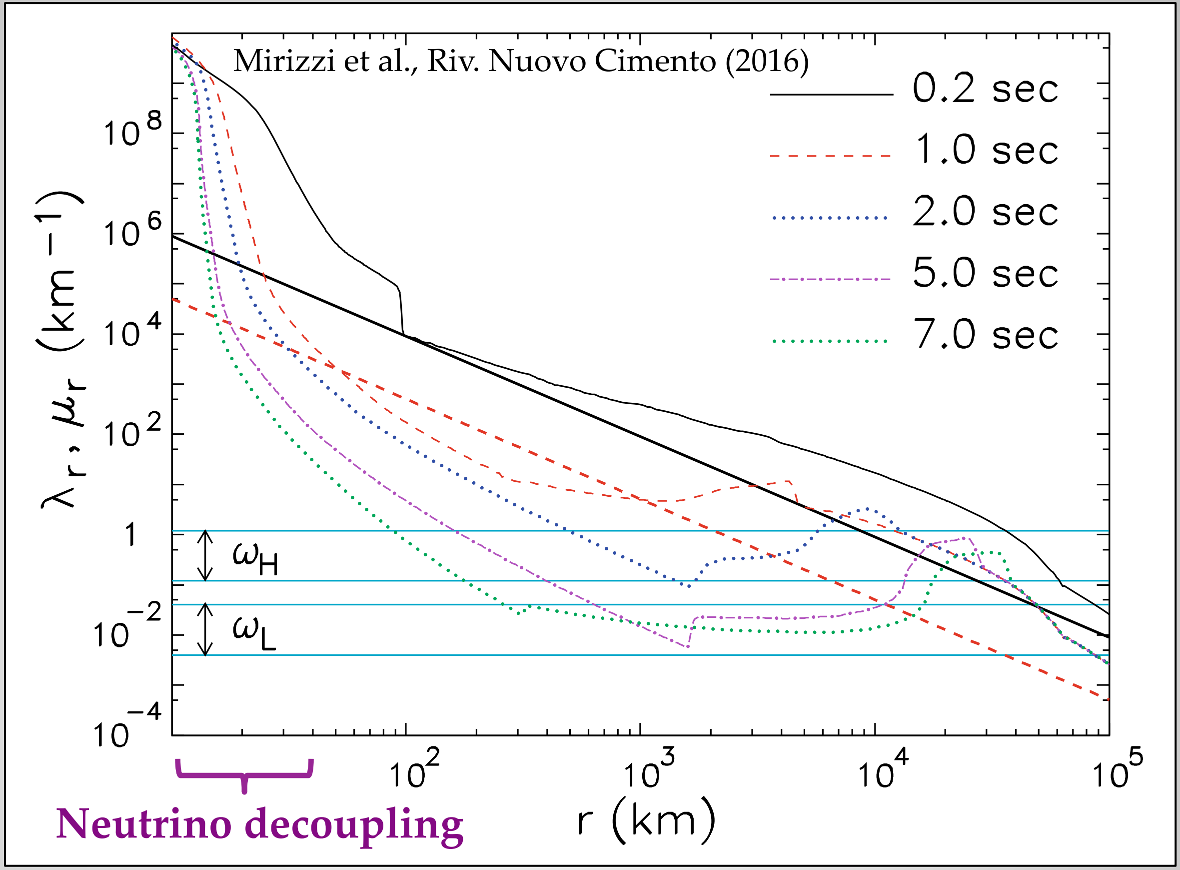

Neutrino decoupling

***λ* = Matter pot'l (*thin curves*)**

***μ* = Neutrino pot'l (*thick curves*)**

***ω* = Vacuum osc. frequencies (*blue bands*)**

Time after core bounce

Radius

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***Flavor instabilities* can occur just about anywhere in or beyond the decoupling region, as we'll see…**

Three types of instabilities are known, each related to some kind of **asymmetry between neutrinos and antineutrinos**.

Collective oscillations are sensitive to physics that distinguishes between neutrinos and antineutrinos because

$$H_{\mathbf{p},\nu\nu} \sim G_F \int d^3\mathbf{q}\,(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})\boxed{(\rho_{\mathbf{q}}-\bar{\rho}_{\mathbf{q}})}$$

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Slow instabilities. Vacuum oscillation frequencies: $\omega_{E_\nu} \neq \omega_{E_{\bar{\nu}}}$

Kostelecký & Samuel, PRD (1995)

Fast instabilities. Neutrino angular distributions: $g_\nu \neq g_{\bar{\nu}}$

Sawyer, PRD (2005, 2008), PRL (2016)

Collisional instabilities. Interaction rates: $\Gamma_\nu \neq \Gamma_{\bar{\nu}}$

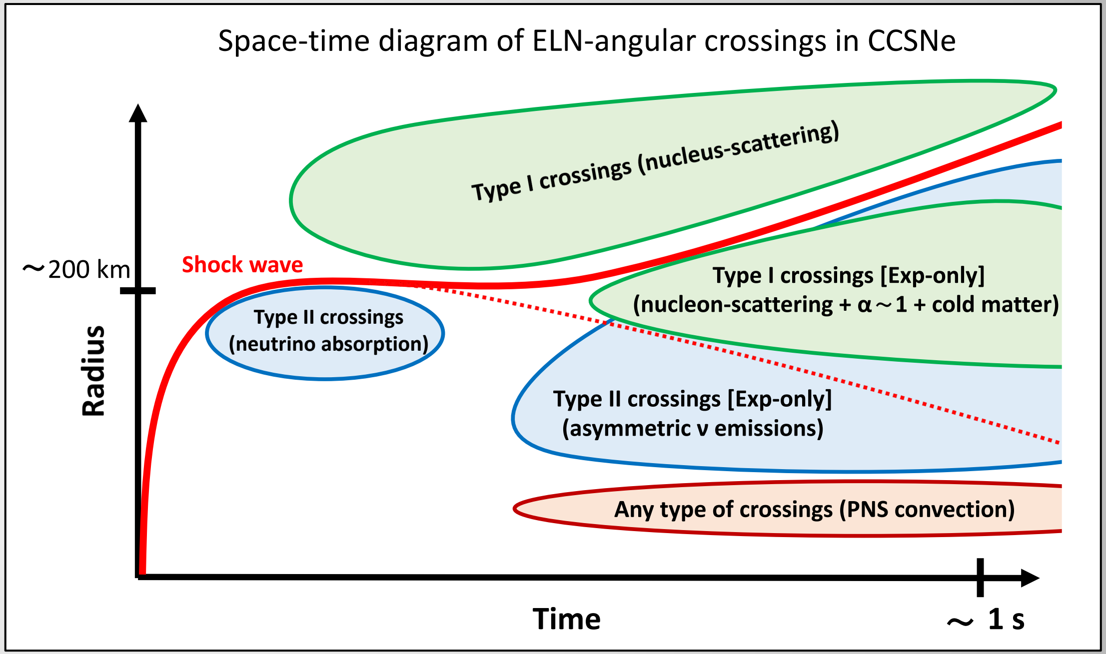
Johns, 2104.11369

There's strong evidence that **fast instabilities** occur in CCSNe & NSMs.

(The situation is less clear with **slow** & **collisional**.)

Fast (in)stability is determined by various aspects of the SN physics:

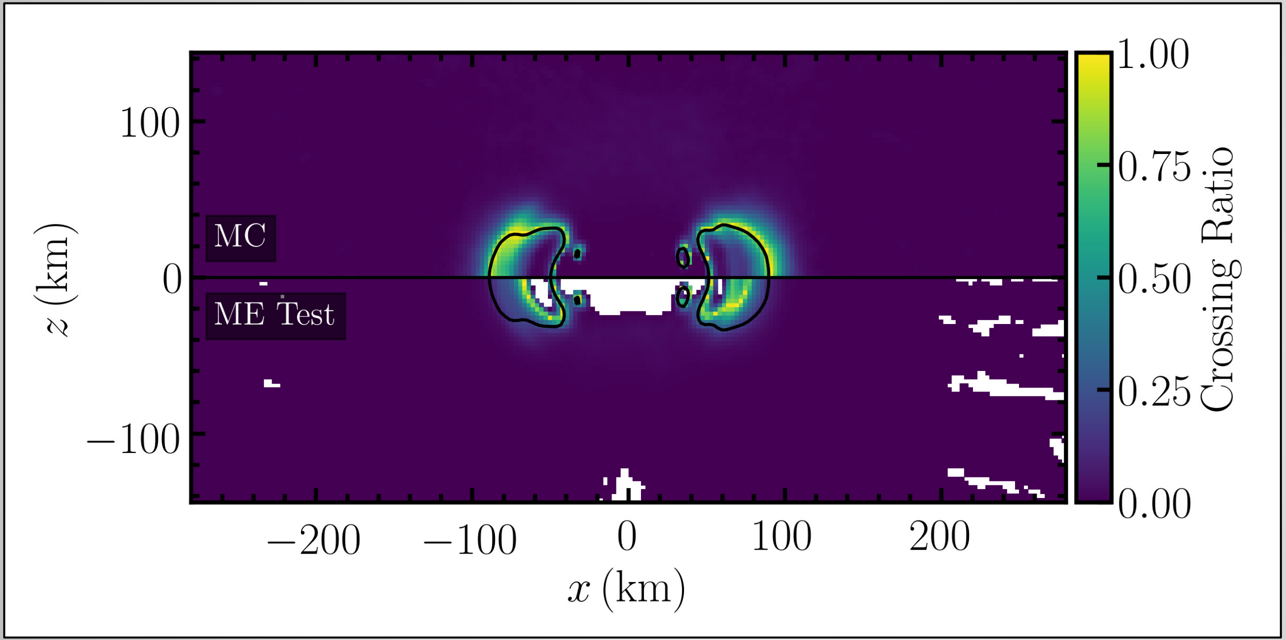
- ✧ Flavor-dependent decoupling
- ✧ Scattering & absorption in optically thin regions
- ✧ Fluid entropy & density
- ✧ Accretion rate
- ✧ Asymmetric emission (e.g., LESA, PNS kicks)
- ✧ PNS convection
- ✧ Thermal muons



Nagakura, Burrows, **Johns**, & Fuller, PRD (2021)

Sawyer, PRD (2005); Banerjee et al., PRD (2011); Chakraborty et al., JCAP (2016); Izaguirre et al., PRD (2017); Capozzi et al., PRD (2017); Dasgupta et al., JCAP (2017); Delfan Azari et al., PRD (2019); Abbar et al., PRD (2020); Glas et al., PRD (2020); Morinaga et al., PRR (2020); Xiong et al., ApJ (2020); **Johns** & Nagakura, PRD (2021); Nagakura & **Johns**, PRD (2021a); Nagakura & **Johns**, PRD (2021b); Capozzi et al., PRD (2021); Shalgar & Tamborra, Annu. Rev. Nucl. Part. Sci. (2021); Morinaga, PRD (2022); Harada & Nagakura, ApJ (2022); & others

Fast instabilities appear almost everywhere surrounding merger remnants, largely due to protonization of neutron-rich matter.



Richers, 2206.08444

Indicative of the extent of flavor conversion (*white = stable*)

Wu & Tamborra, PRD (2017); Wu et al., PRD (2017); George et al., PRD (2020); Li & Siegel, PRL (2021); Padilla-Gay et al., JCAP (2021); Just et al., PRD (2022); Fernández et al., 2207.10680

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Approximations

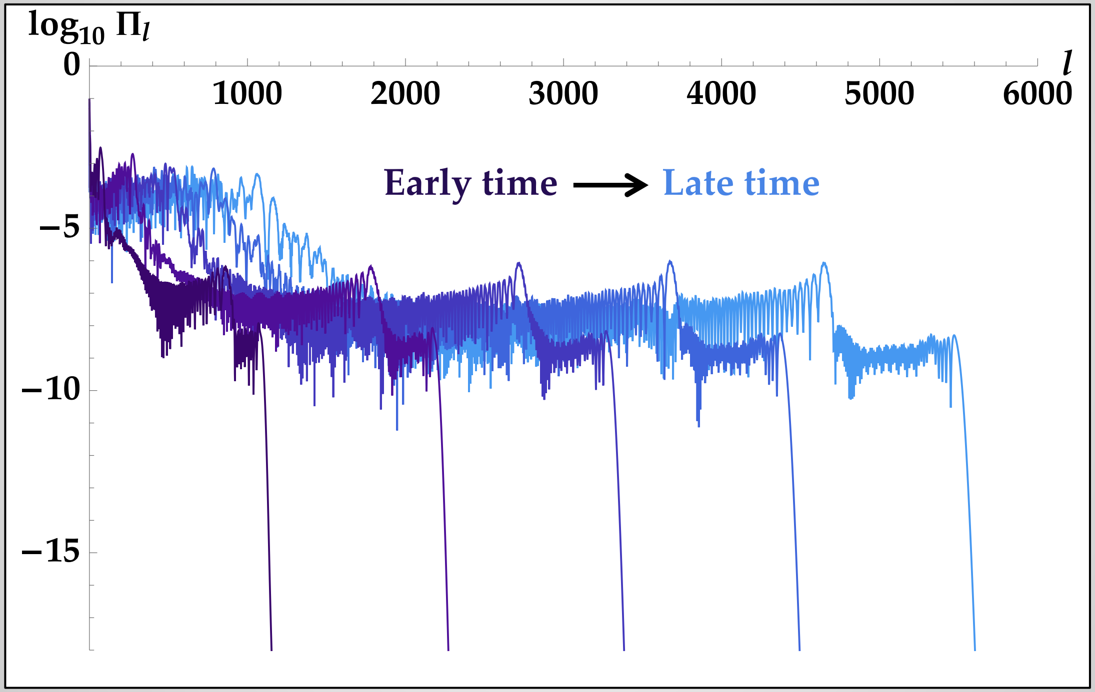
- ✧ Enforce **flavor equilibrium** in unstable regions:
  - Flavor equipartition
  - Other analytic prescription
  - Local numerical solution
- ✧ Solve **moments** of the QKEs

Raffelt & Sigl, PRD (2007); Duan & Shalgar, JCAP (2014); **Johns** et al., PRD (2020a); **Johns** et al., PRD (2020b); Padilla-Gay et al., JCAP (2021), Dasgupta & Bhattacharyya, PRL (2021); Xiong & Qian, PLB (2021); Padilla-Gay et al., PRL (2022); Myers et al., PRD (2022); Just et al., PRD (2022); Nagakura & Zaizen, 2206.04097; Nagakura, 2206.04098; Grohs et al., 2207.02214; & others

Flavor equilibration occurs through the development of small-scale features in phase space.

Sawyer, PRD (2005)
Raffelt & Sigl, PRD (2007)
Mangano et al., PRD (2014)
Mirizzi et al., PRD (2015)
Johns et al., PRD (2020b)
Bhattacharyya & Dasgupta, PRL (2021)

Cascade of power to smaller angular scales



Legendre moment in momentum space

Johns, Nagakura, Fuller, & Burrows, PRD (2020b)

Similar phenomena occur in other systems—*violent relaxation* in grav. systems, *filamentation* in plasmas, *turbulence* in fluids—but we're still developing the theory for neutrino flavor fields.

Flavor mixing exerts two countervailing influences:

1. The **reduction in number** of electron flavor *decreases* ν irradiation & energy deposition.
2. The **effective heating** of electron flavor *increases* them.

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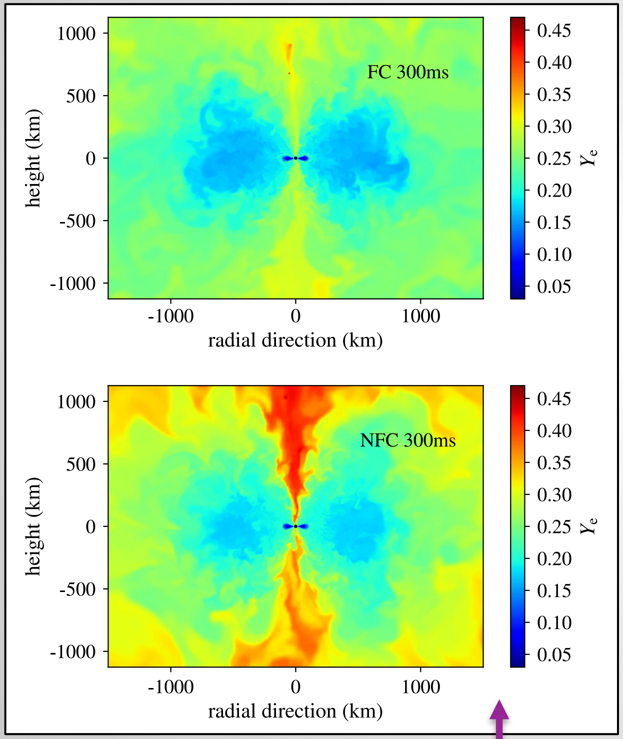

Li & Siegel, PRL (2021)

Accretion-disk winds: Enhanced *r*-process yields.

NS winds: Increased mass & Y_e of ejected material.

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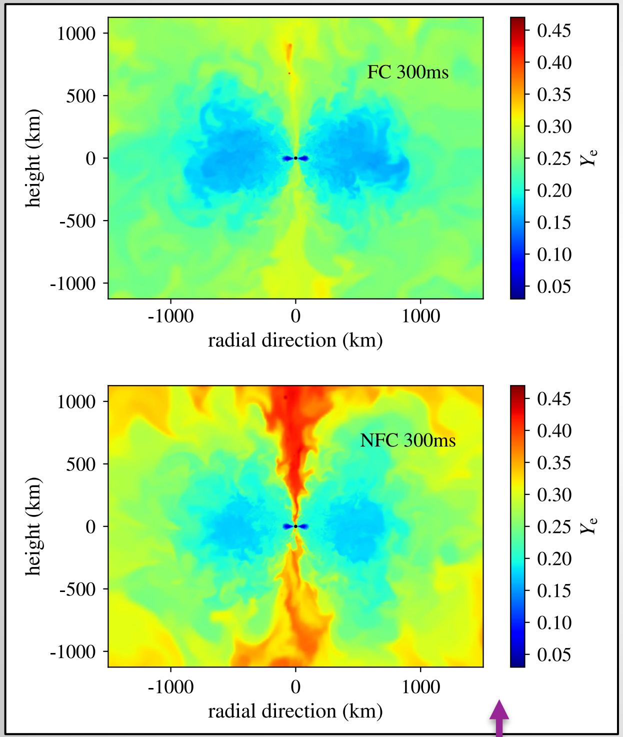

Li & Siegel, PRL (2021)

Neutrino signals

MSW: Detectable in neutronization burst from CCSN.

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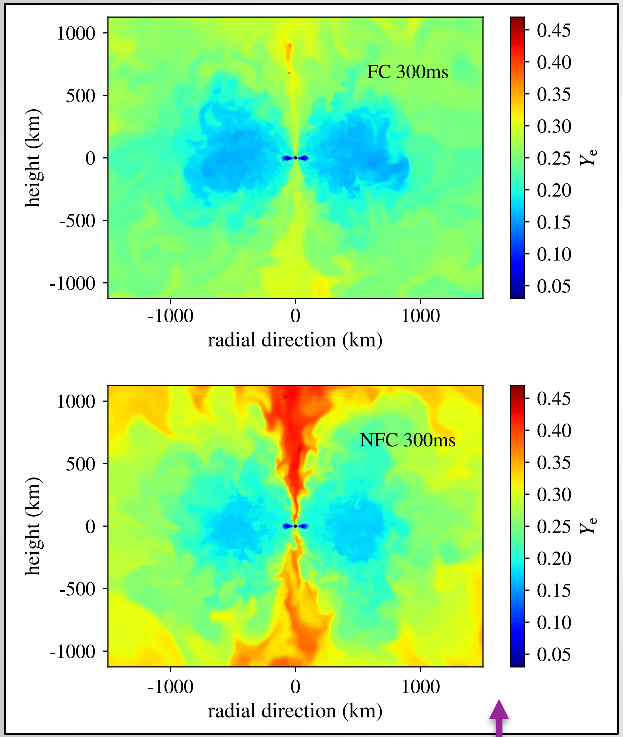

Li & Siegel, PRL (2021)

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Collective effects: Presently unclear whether there will be smoking guns.

Dynamics

Presently unclear, even qualitatively.

Accretion-disk winds: Enhanced *r*-process yields.

NS winds: Increased mass & Y_e of ejected material.

Summary

- **Where does this research area stand?**
  - A comprehensive flavor-mixing phenomenology is emerging (though surprises are always possible).
  - For *some* of these phenomena, we have a good idea of when & where they occur, and we have suggestions as to their effects.

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  - Helicity/chirality mixing (**B** fields, magnetic moments, anomalies) & other BSM effects (sterile species, decay, NSIs).
  - Many-body corrections (or at least many-body foundations) & quantum computing.

Friedland & Lunardini, PRD (2003); Bell et al., PLB (2003); Pehlivan et al., PRD (2011); Patwardhan et al., PRD (2019); Rrapaj, PRC (2020); Roggero, PRD (2021); Martin et al., PRD (2022); Xiong, PRD (2022); & many others