Supernovae & Neutrinos

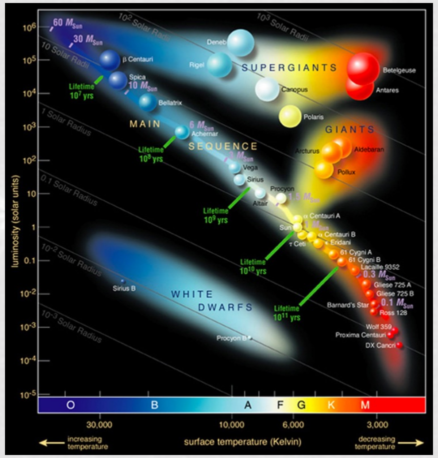
<u>Outline</u>

- SN Theory from a neutrino perspective
  - Collapse Phase
  - Neutronization Burst
  - Accretion/Explosion Phase
  - Cooling Phase
  - Black Holes
- Earth-based Neutrino Detection
- Neutrinos from other supernovae

Evan O’Connor
Stockholm University
July 21, 2022

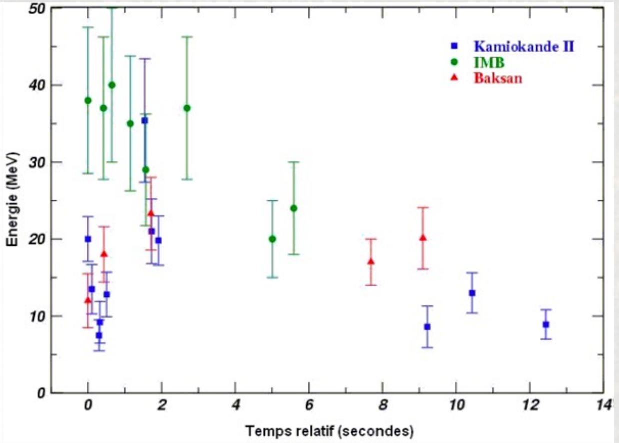
Supernovae have a broad connection to the Universe

Stellar Evolution

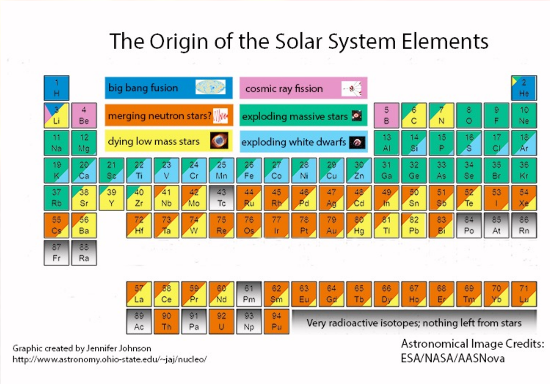


ESO

Neutrinos & Gravitational Waves

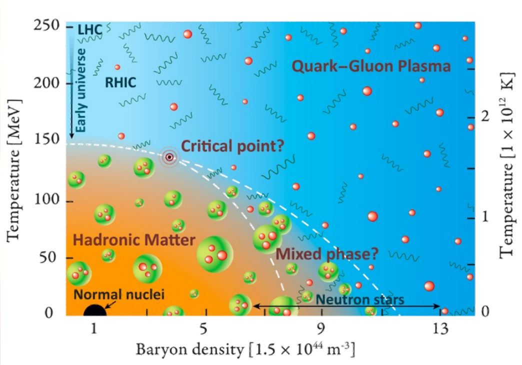


Nucleosynthesis



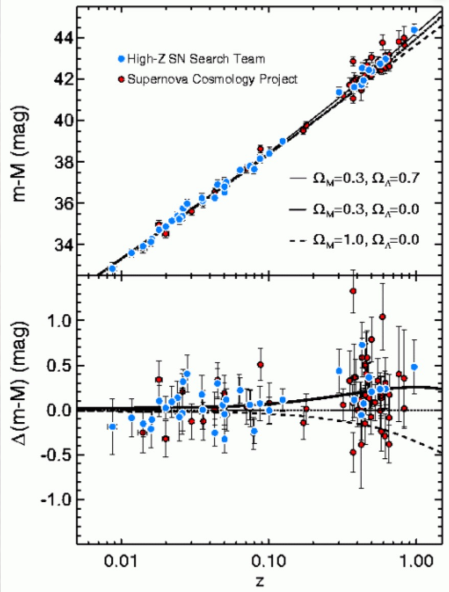
Jennifer Johnson

Extreme Physics



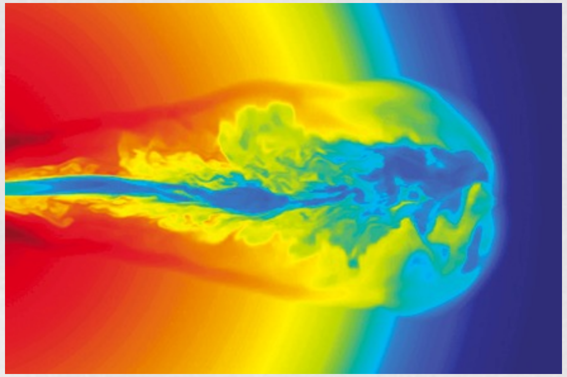
Contemporary Physics Education Project (CPEP)

Cosmology



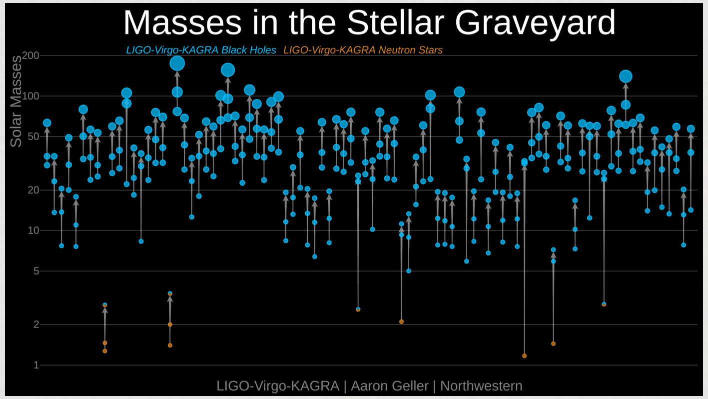
High-Z & SCP

Long gamma-ray burst



Science/MacFadyen

Neutron Star & Black Holes



LIGO/VIRGO

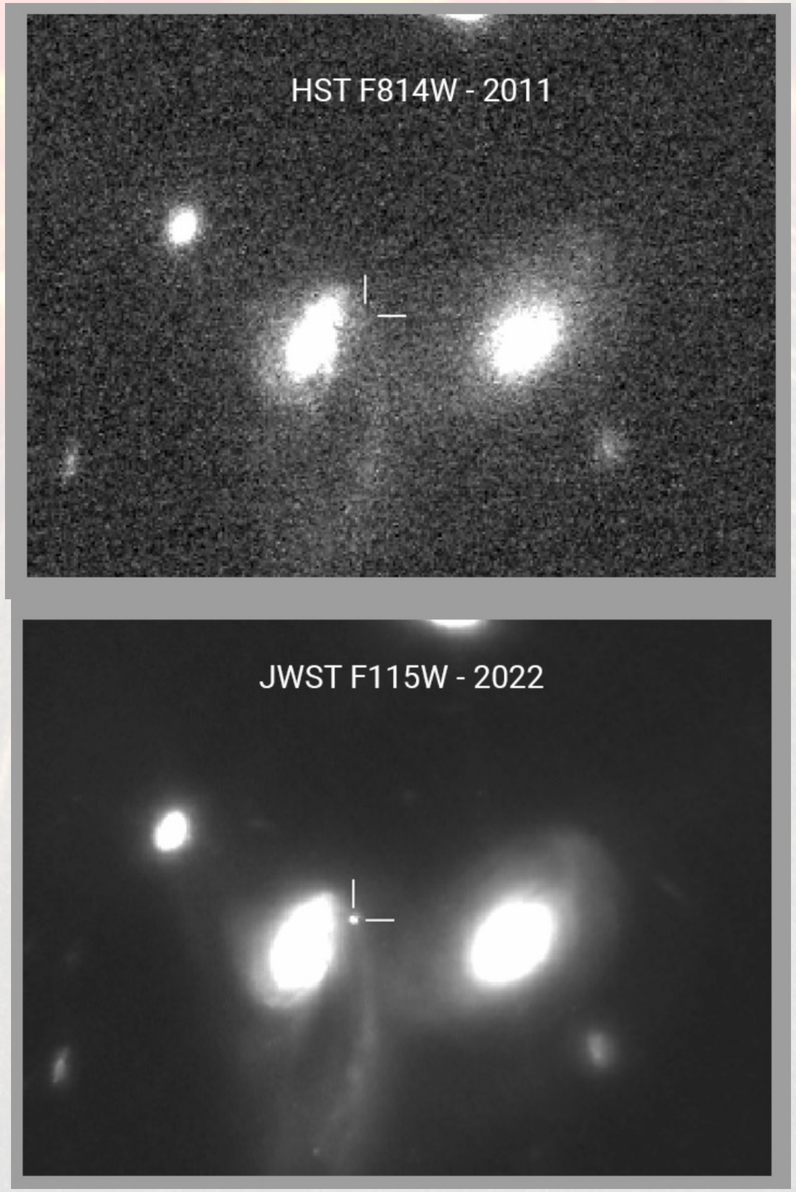
Galaxy Evolution

Hubble

Supernovae

- Thermonuclear Supernovae: Type Ia
  - caused by runaway thermonuclear burning of white dwarf fuel to Nickel
  - roughly of 10^{51} ergs released
  - very bright, used as standard candles
  - no remnant

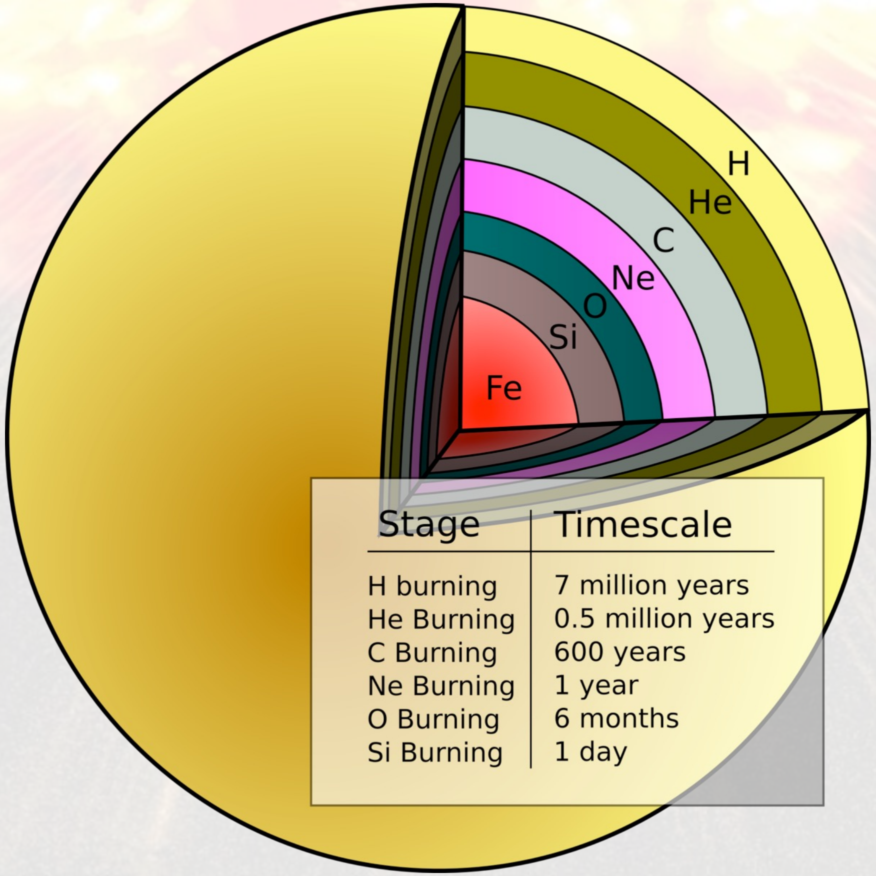
- Core-Collapse Supernovae: Type II, Ib, Ic
  - result from the collapse of an iron core in an evolved massive star (M_{ZAMS} > 8-10M_{sun})
  - 10^{53} ergs released in gravitational collapse, most (99%) radiated in neutrinos
  - neutron star or black hole remnant



Engesser et al. (2022)

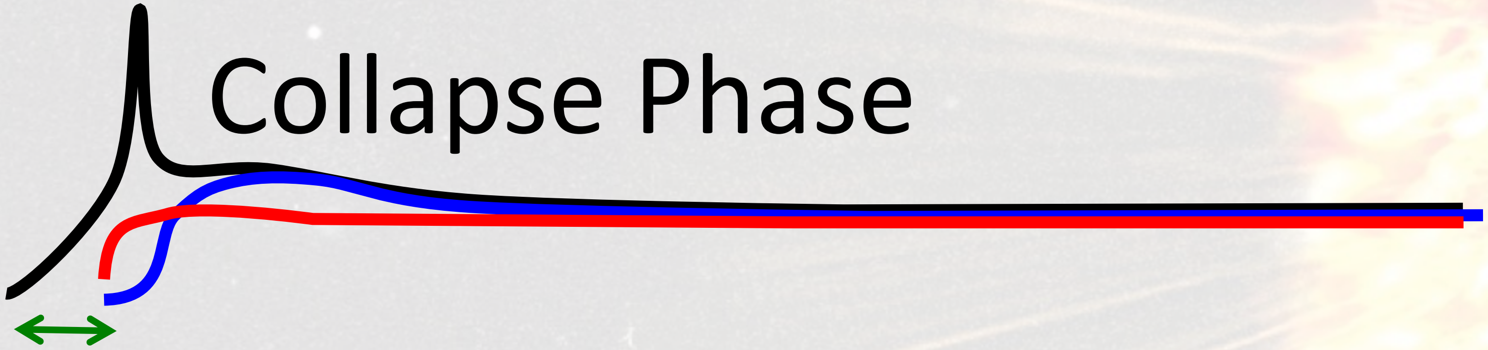
Massive Stars: Burning Stages

- Stars spend most of their lives burning hydrogen.
- For massive stars ($M > 8\text{-}10 M_{sun}$), the process continues through helium, carbon, … , up to iron.
- This process does not continue past iron as iron is one of the most tightly bound nuclei.
- Iron cores however are supported by electron degeneracy pressure, much like a white dwarf, there is a maximum mass that electron degeneracy pressure can support.



Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

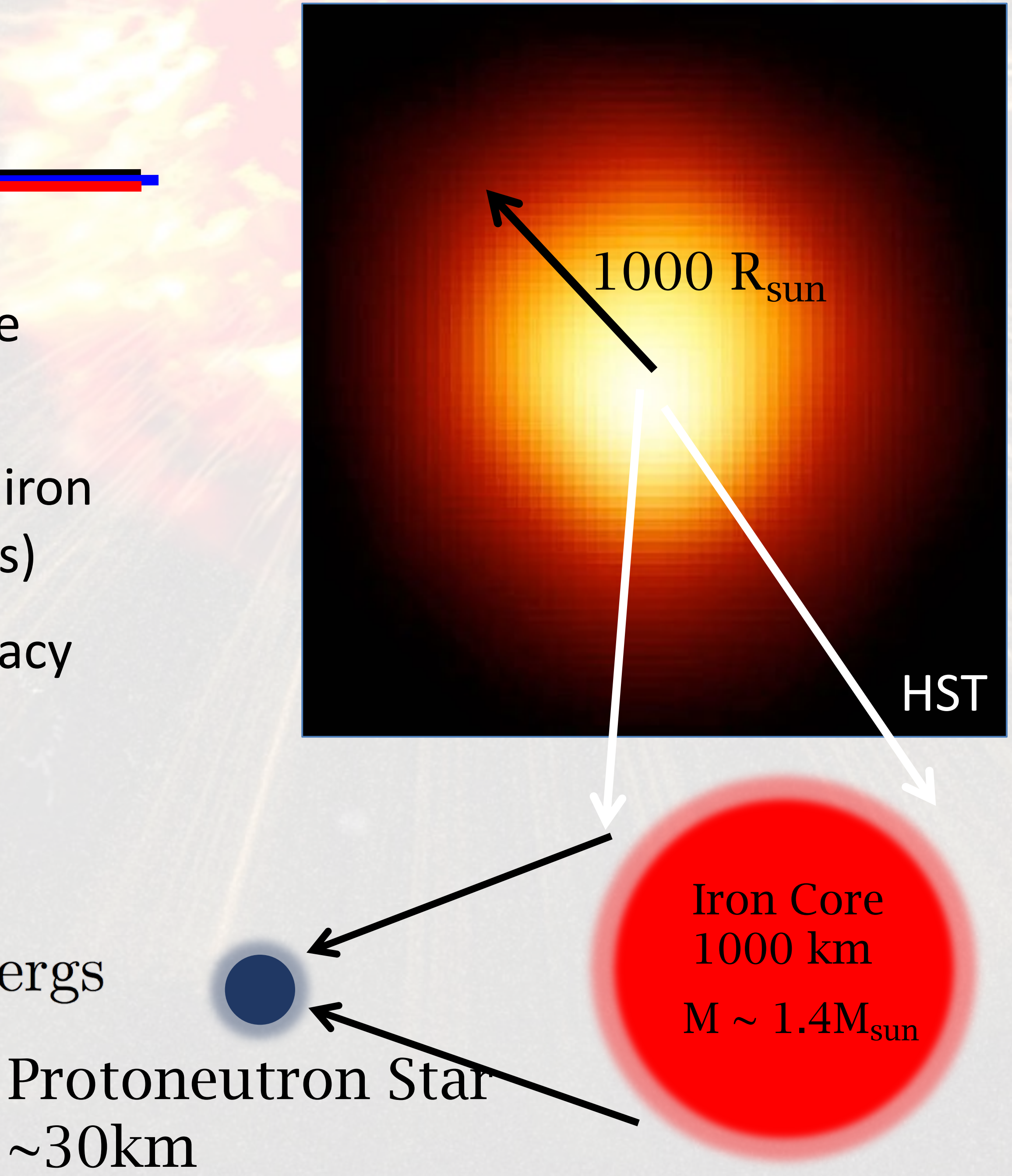
A. C. Phillips, *The Physics of Stars*, 2nd Edition (Wiley, 1999).



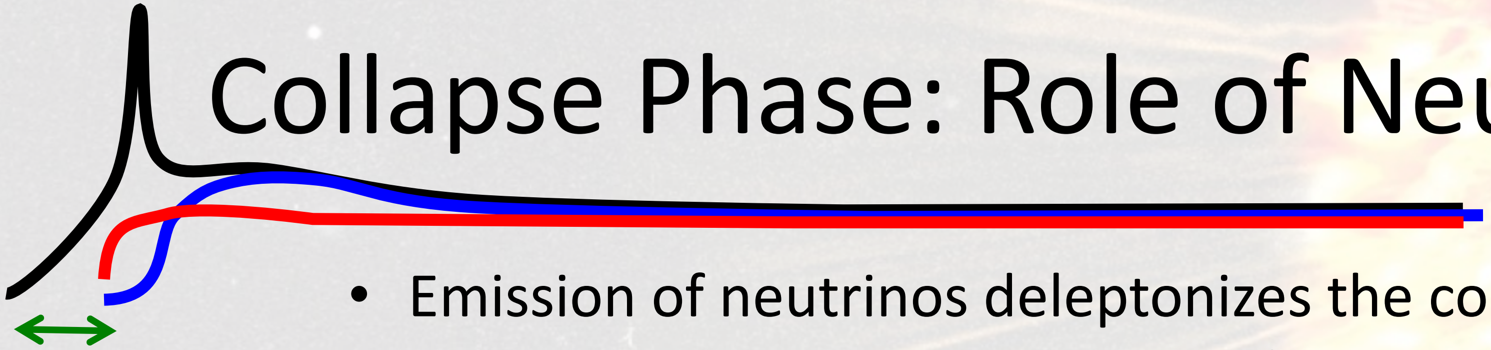
Collapse Phase

- Most massive stars core collapse during the red supergiant phase
- CCSNe are triggered by the collapse of the iron core (~1000km, or 1/10^6 of the star's radius)
- Collapse ensues because electron degeneracy pressure can no longer support the core against gravity

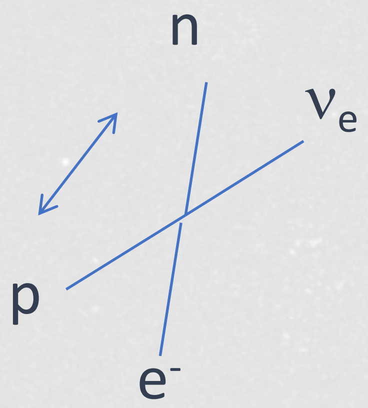
$$-\frac{3}{5}\left[\frac{GM^2}{1000\text{km}} - \frac{GM^2}{12\text{km}}\right] \sim 300 \times 10^{51}\text{ergs}$$



Collapse Phase: Role of Neutrinos

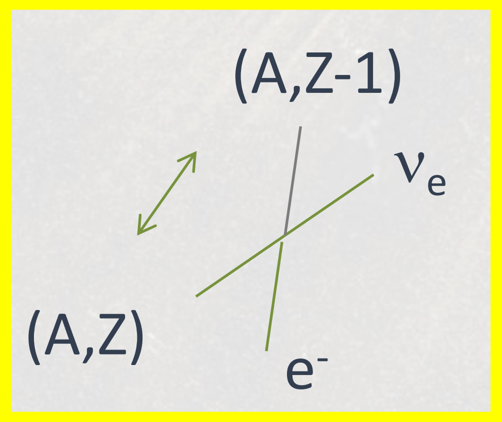


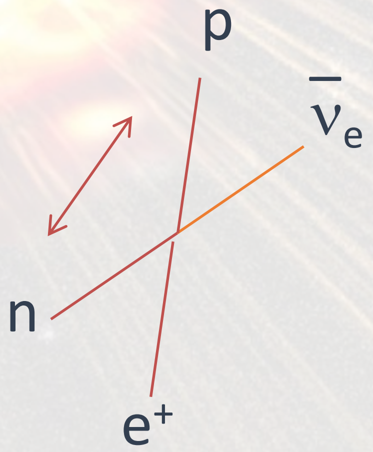
- Emission of neutrinos deleptonizes the core and accelerates collapse
- The emission ultimately sets the final Ye of the core



Electron capture on free protons. Cross section is very high, but suppressed because number of free protons is low

- Heavy-lepton neutrino production is highly suppressed because temperature is so low

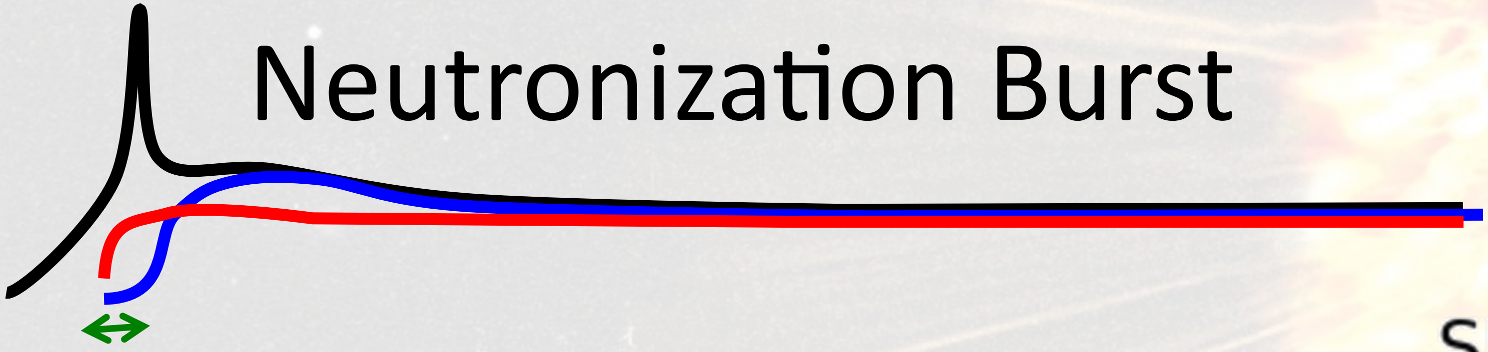




Positron capture on free neutrons. Suppressed because positron density is very low due to high electron chemical potential

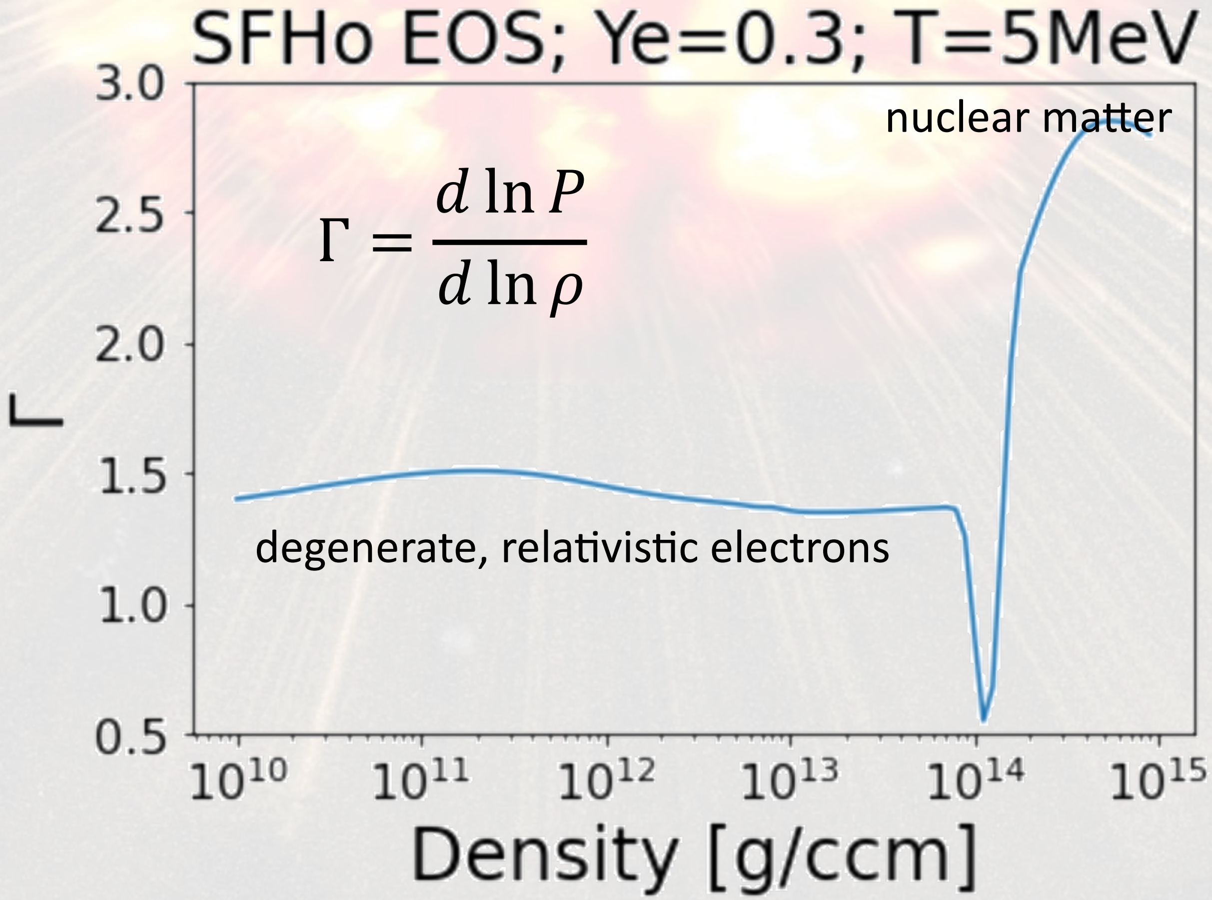
Electron capture on heavy nuclei. Abundance is very high, cross section is somewhat suppressed because of energetic cost of converting proton to neutron in a nucleus.

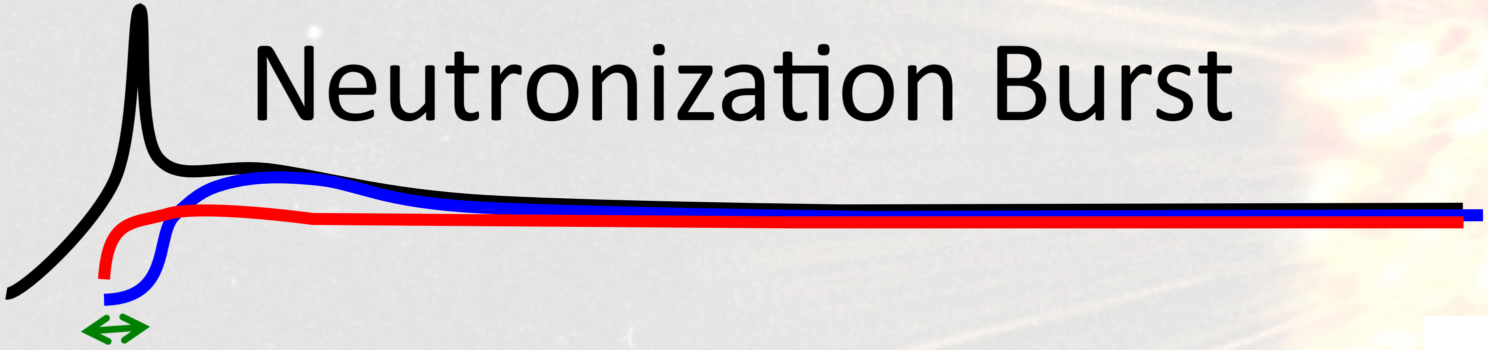
Neutronization Burst



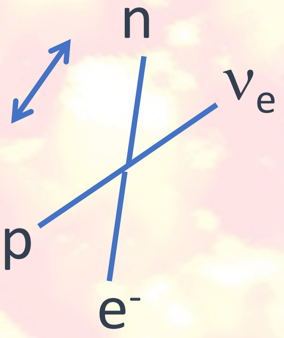
- When the matter reaches nuclear density the “stiffening” of the EOS halts the collapse

- The core elastically rebounds and drives a shock into the infalling matter





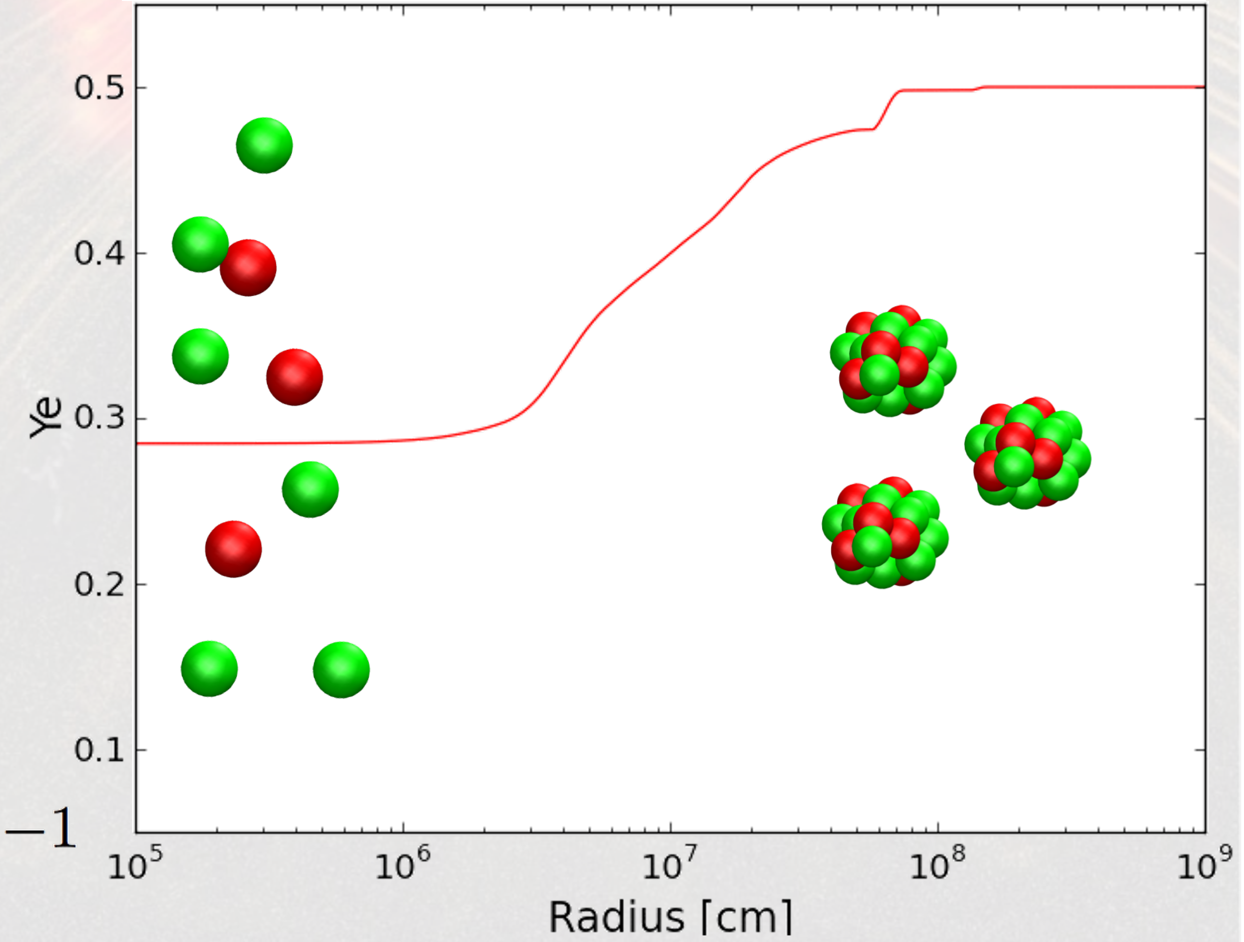
Neutronization Burst



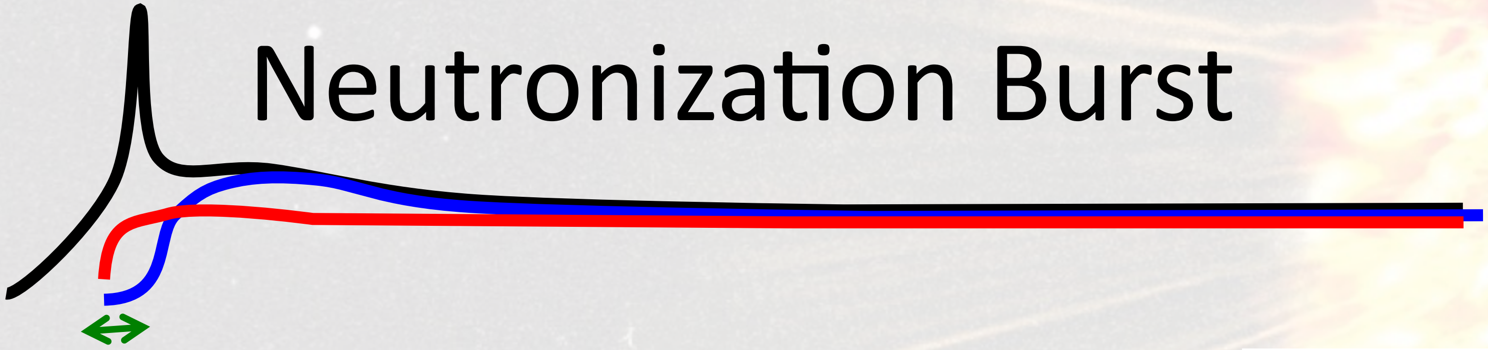
- Recently freed and no longer suppressed, protons now rapidly capture electrons, producing a burst of ν_e

- This neutronization burst is universal across core-collapse progenitors

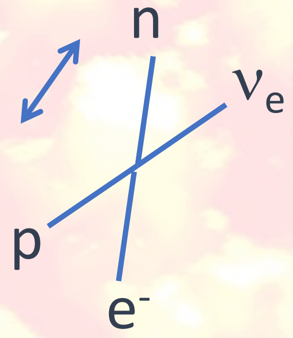
from 3ms before bounce to 6 ms after



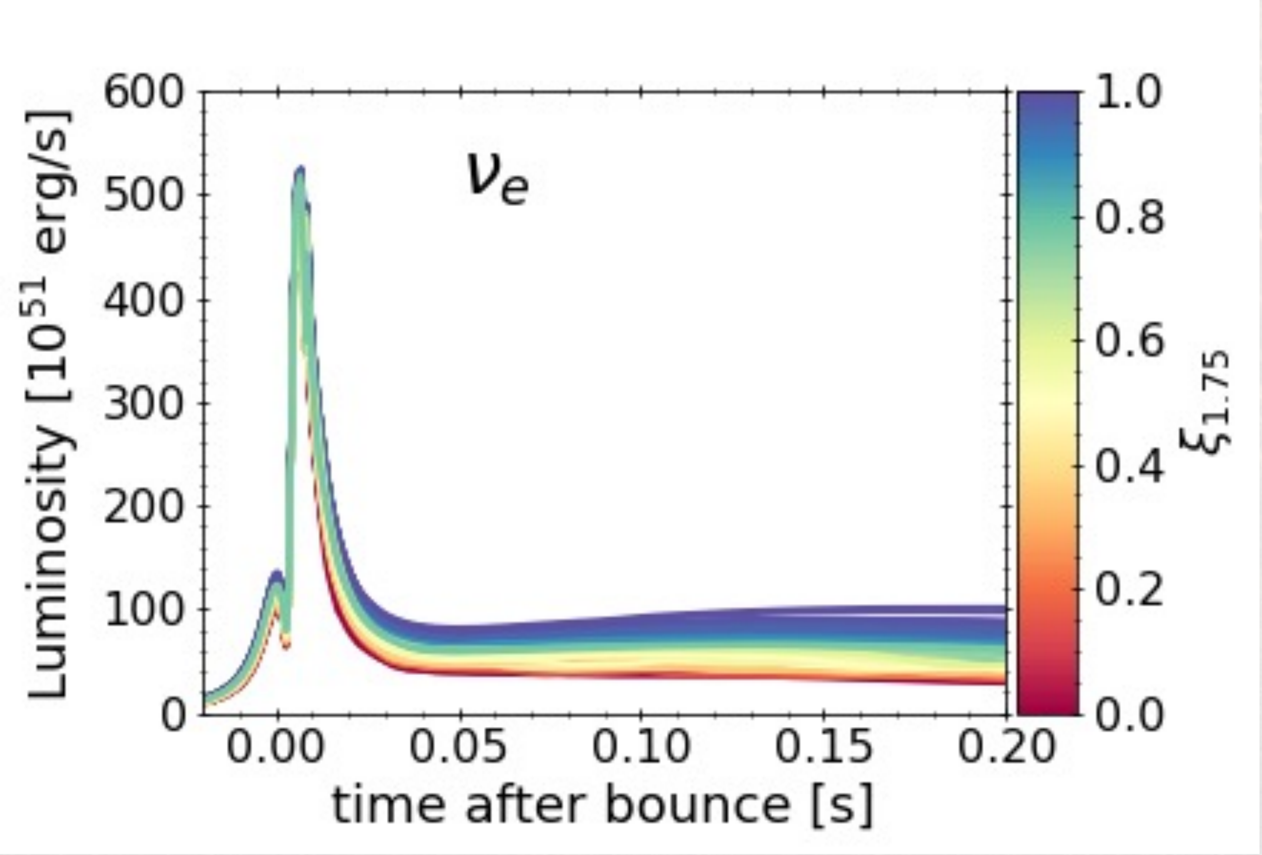
$$\frac{1}{2}\frac{M_\odot}{m_N} \times 0.2 \times \frac{10\,\mathrm{MeV}}{5\,\mathrm{ms}} \sim 4 \times 10^{53}\,\mathrm{erg\,s^{-1}}$$



Neutronization Burst

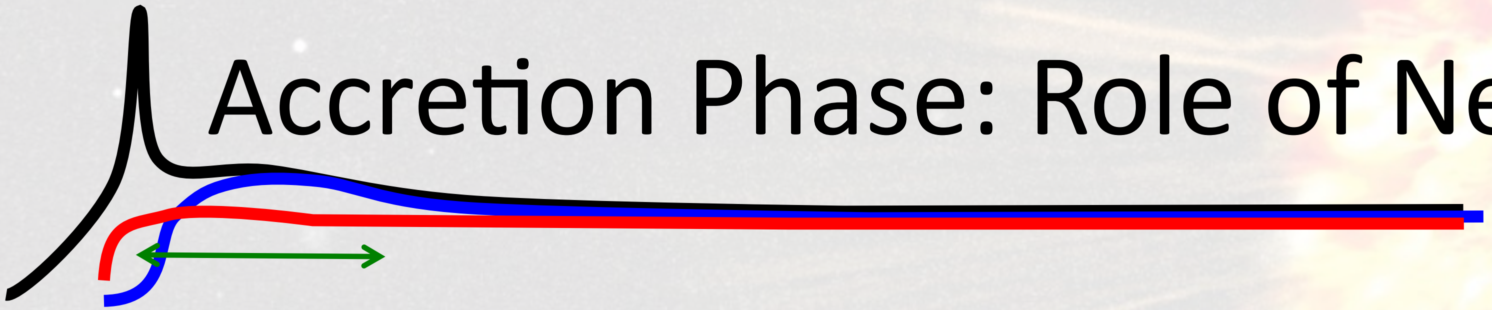


- Recently freed and no longer suppressed, protons now rapidly capture electrons, producing a burst of ν_e
- This neutronization burst is universal across core-collapse progenitors

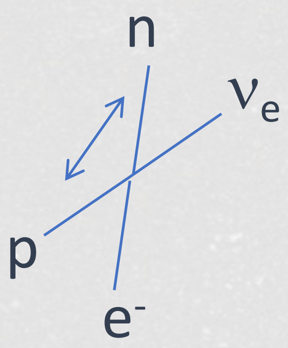


$$\frac{1}{2}\frac{M_\odot}{m_N} \times 0.2 \times \frac{10\,\mathrm{MeV}}{5\,\mathrm{ms}} \sim 4 \times 10^{53}\,\mathrm{erg\,s^{-1}}$$

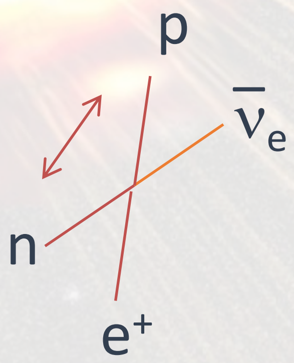
Accretion Phase: Role of Neutrinos



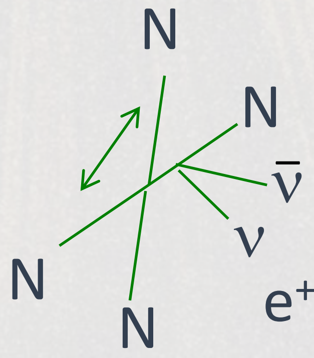
- After the burst, ν_e and anti-ν_e emission is powered by accretion
- Infalling matter is shock heated and then is cooled via neutrino emission

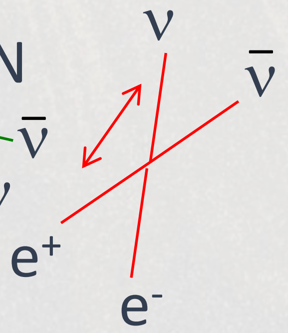


- Charged current processes dominant production
- Thermal production processes dominate at high densities where neutrinos are trapped for seconds



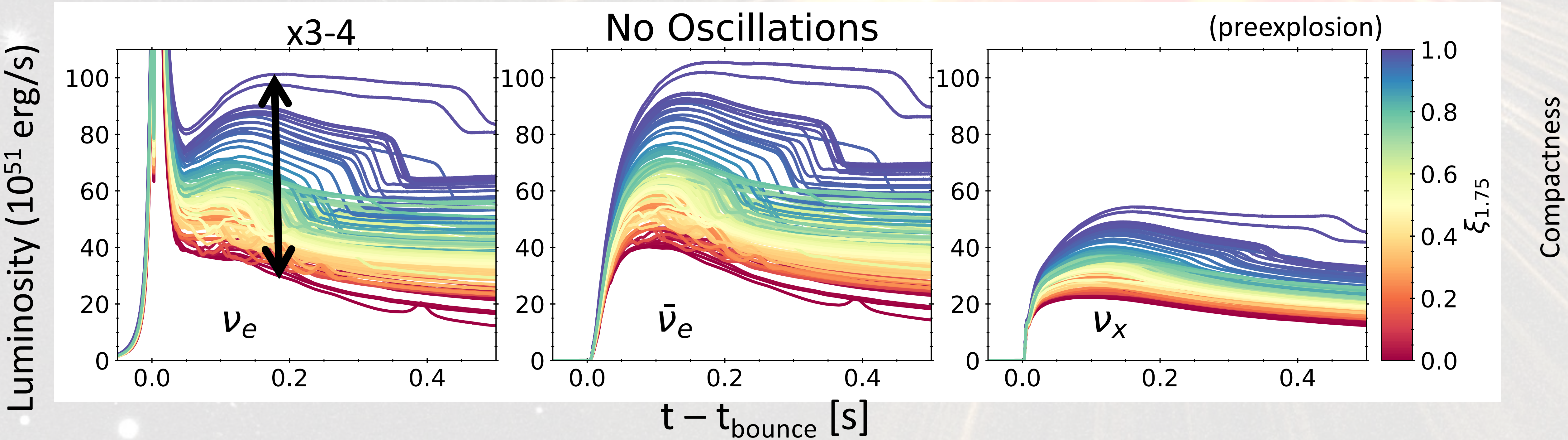
- Thermal emission is dominant production process for heavy lepton neutrinos as T is too low for charged-current processes with μ's and τ's





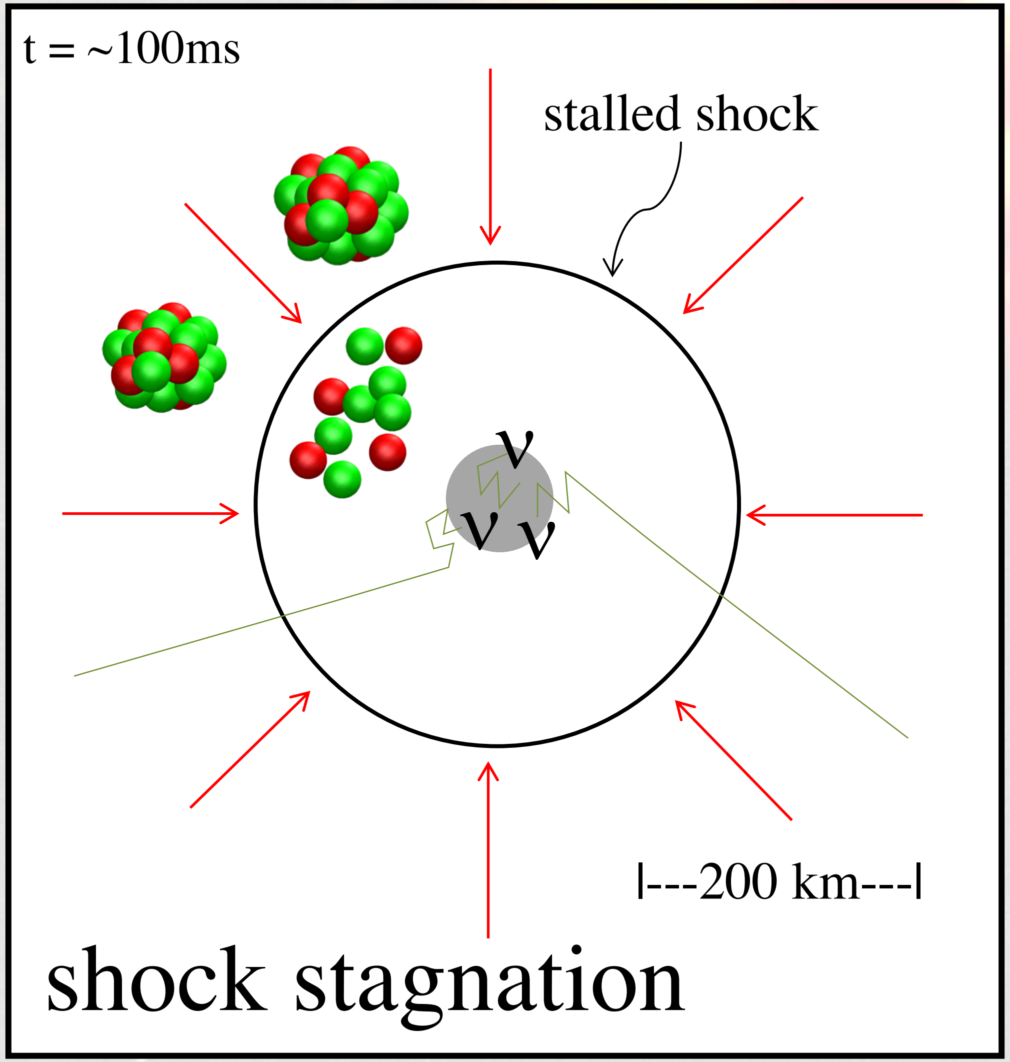
Accretion Phase

FLASH simulations, 149 progenitors, SFHo EOS, Segerlund et al. (2021)

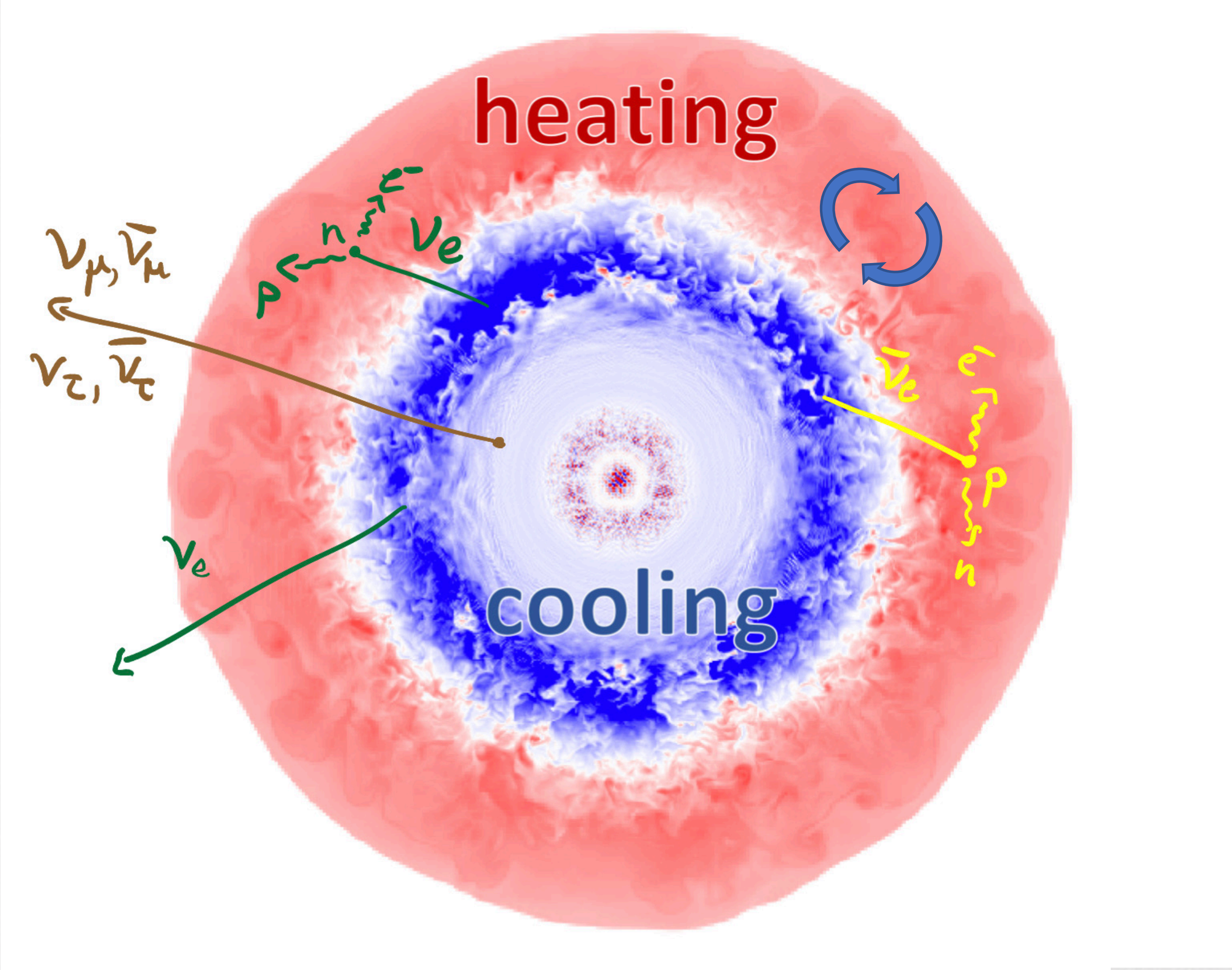


Learn about progenitor structure from neutrino observation of a galactic supernova

CCSNe: The Explosion?



The Core-Collapse Supernova Problem



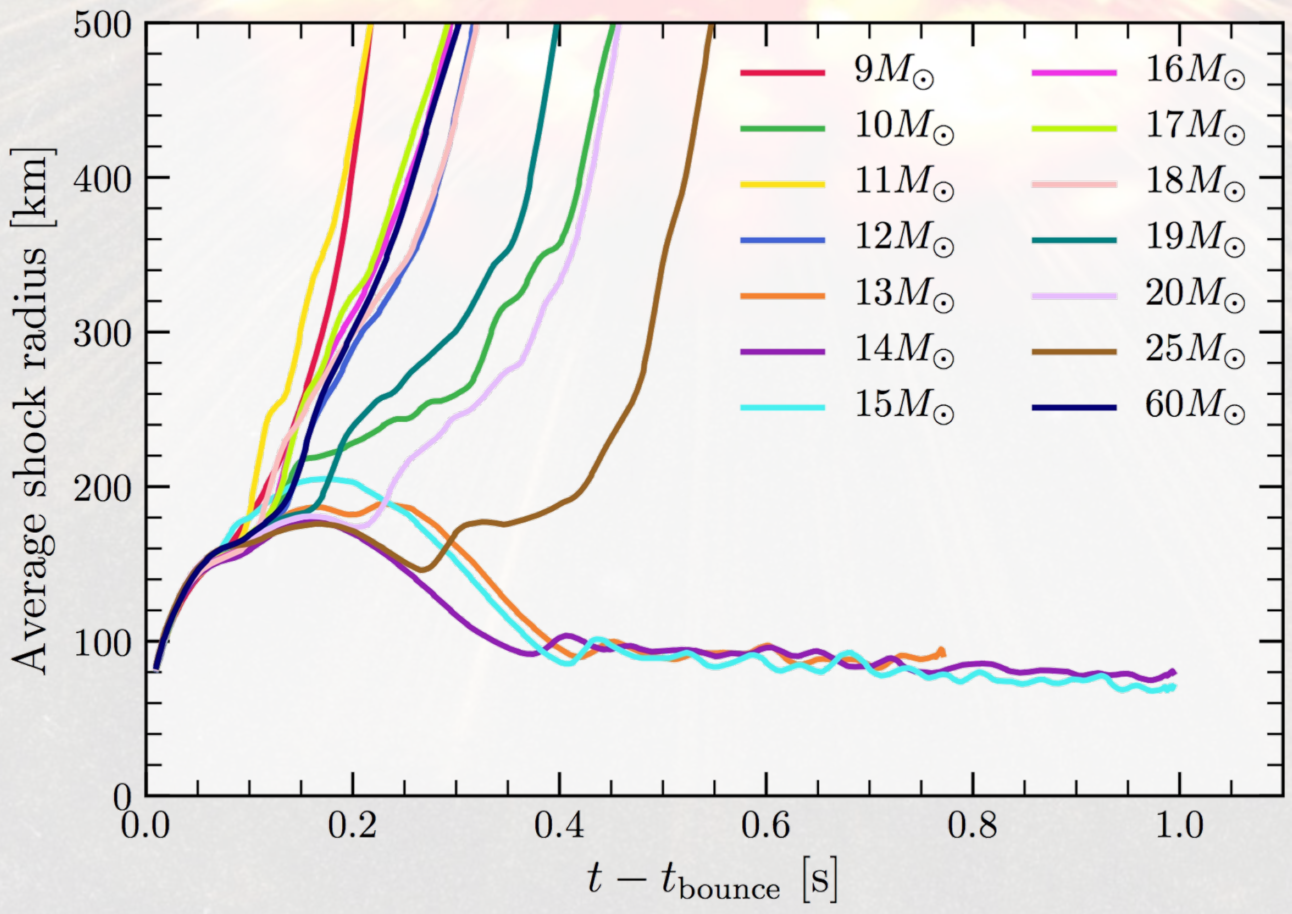
- The naive `prompt` mechanism fails
- The prevailing mechanism is the **turbulence-aided neutrino mechanism**
  - Neutrinos from core heat outer layers
  - Drives convection
  - Turbulence pressure support aids heating and drive explosion
- Very successful in 2D*, many successful explosions, also successful in 3D although fewer simulations

Successful CCSN explosions

Burrows et al. (2019)

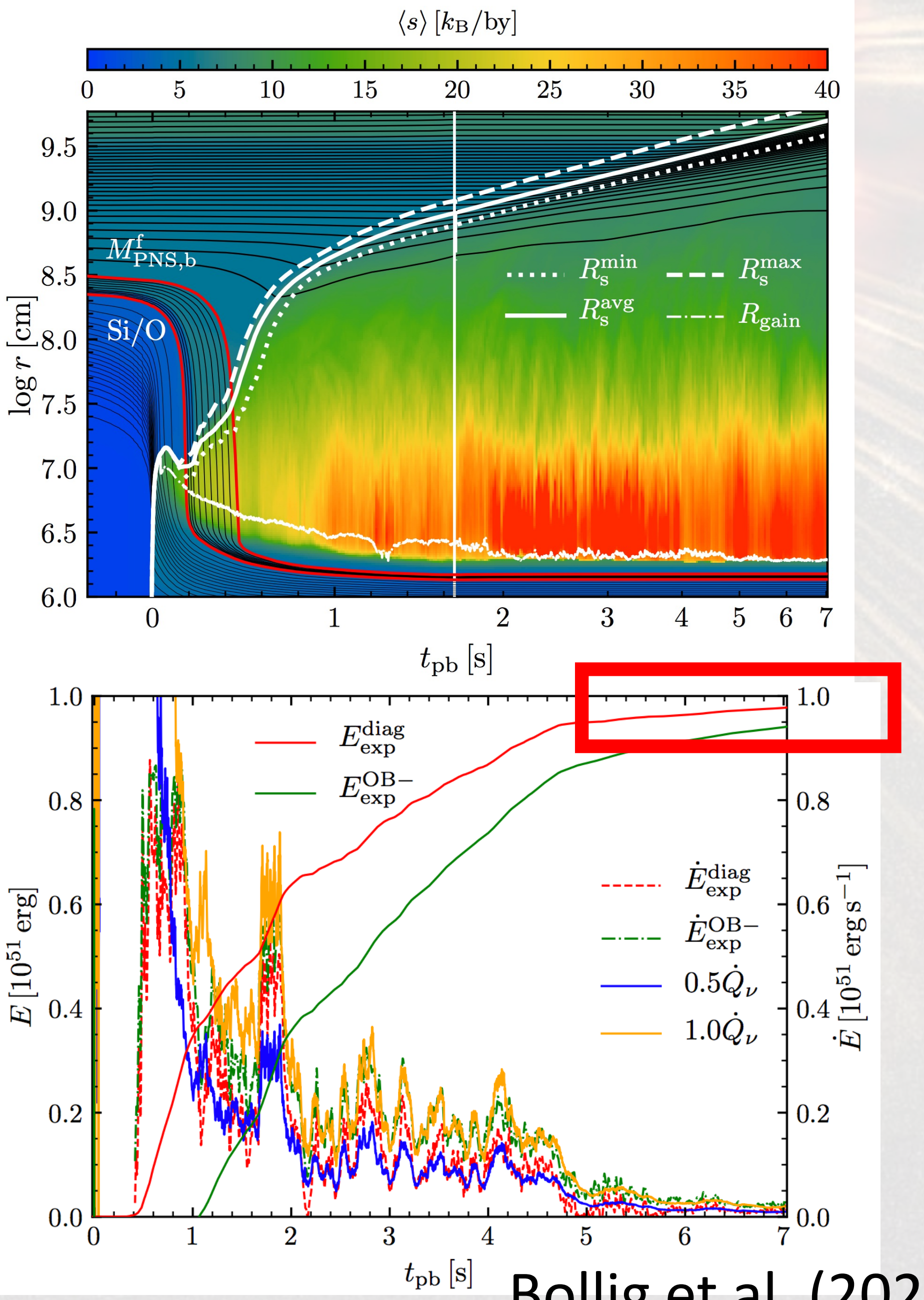
- Routinely, modern, state-of-the-art, symmetry-free, simulation codes obtain explosions across the progenitor spaces

- Suggest that canonical observed energies (0.5-1 Bethe) are achievable in the turbulence-aided neutrino mechanism, if you wait long enough



Successful CCSN explosions

- Routinely, modern, state-of-the-art, symmetry-free, simulation codes obtain explosions across the progenitor spaces
- Suggest that canonical observed energies (0.5-1 Bethe) are achievable in the turbulence-aided neutrino mechanism, if you wait long enough

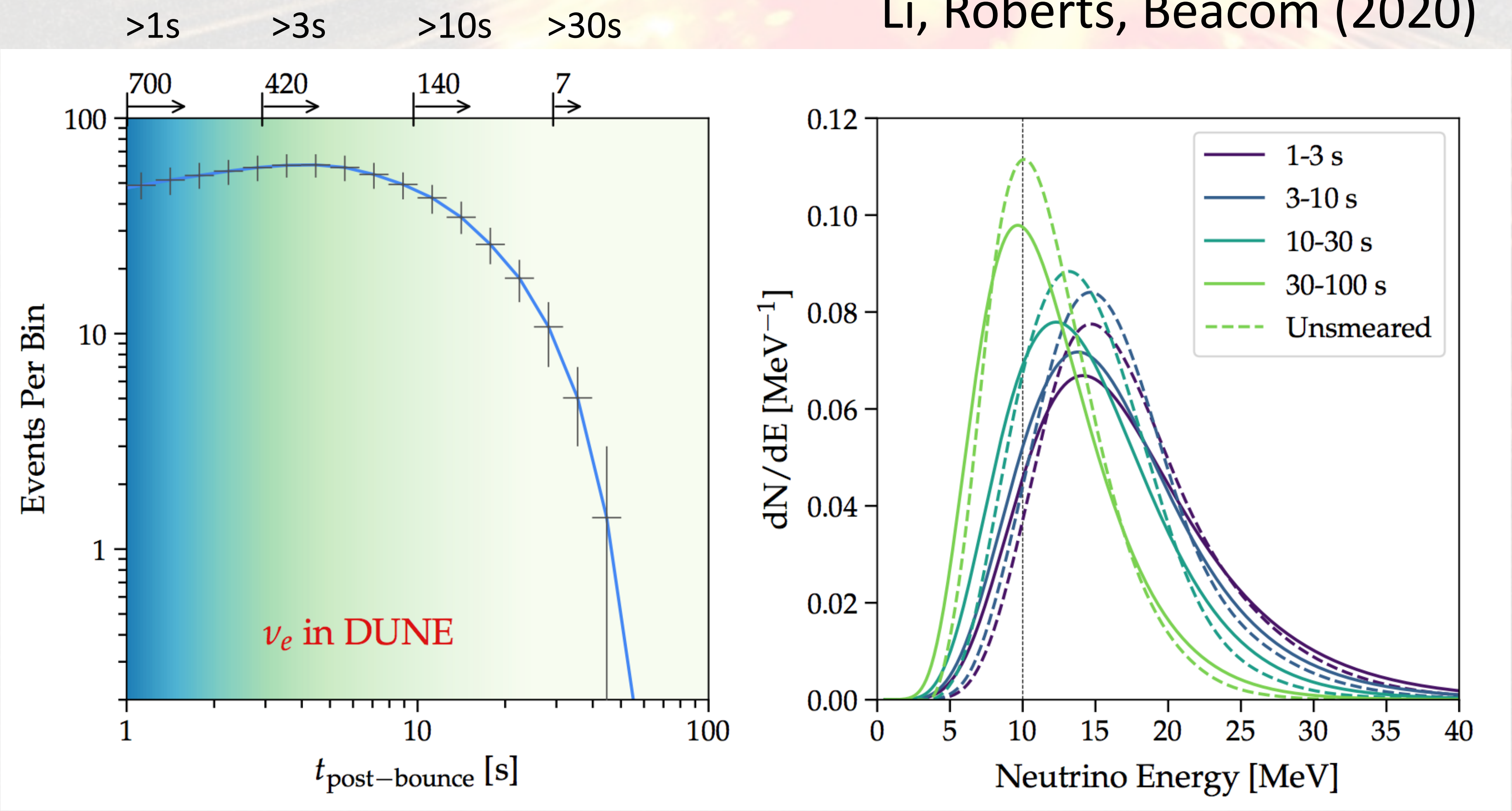


Bollig et al. (2020)

Cooling Phase

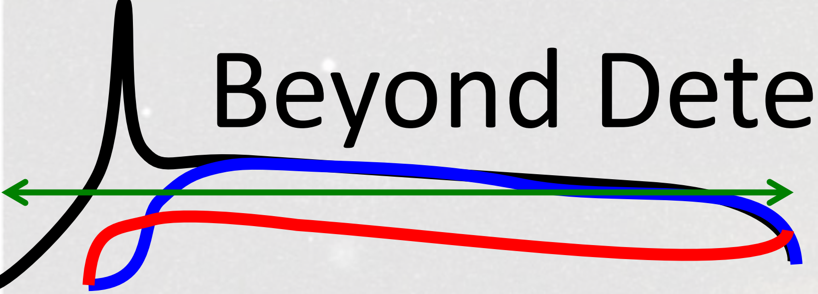
Li, Roberts, Beacom (2020)

- Late time neutrinos critical to probe neutron star transparency regime, and high-density nuclear EOS. Flavor important here!
- Li et al. also probe black hole formation during cooling phase

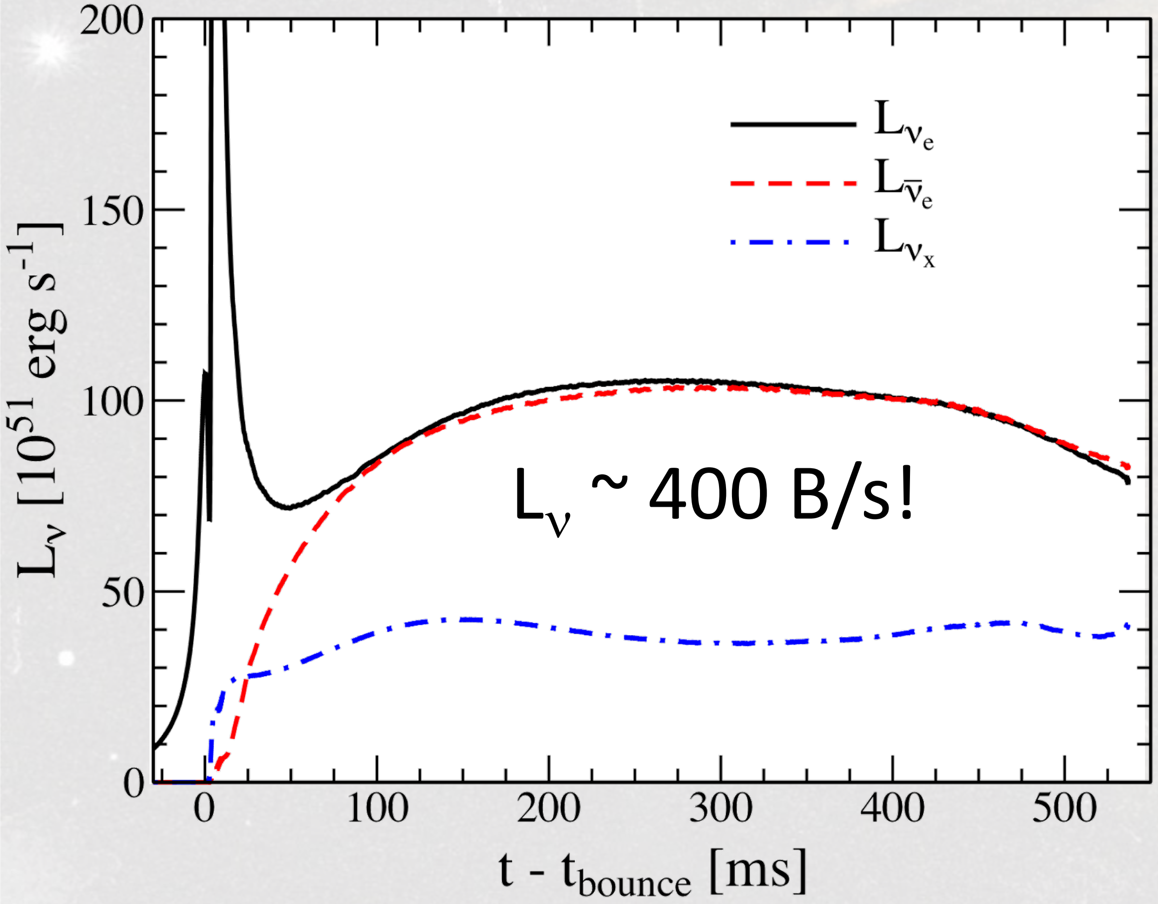


*Optimistic scenario, assumes abilities to reconstruct electrons and deexcitation gammas, electrons only limits late time due to background noise.

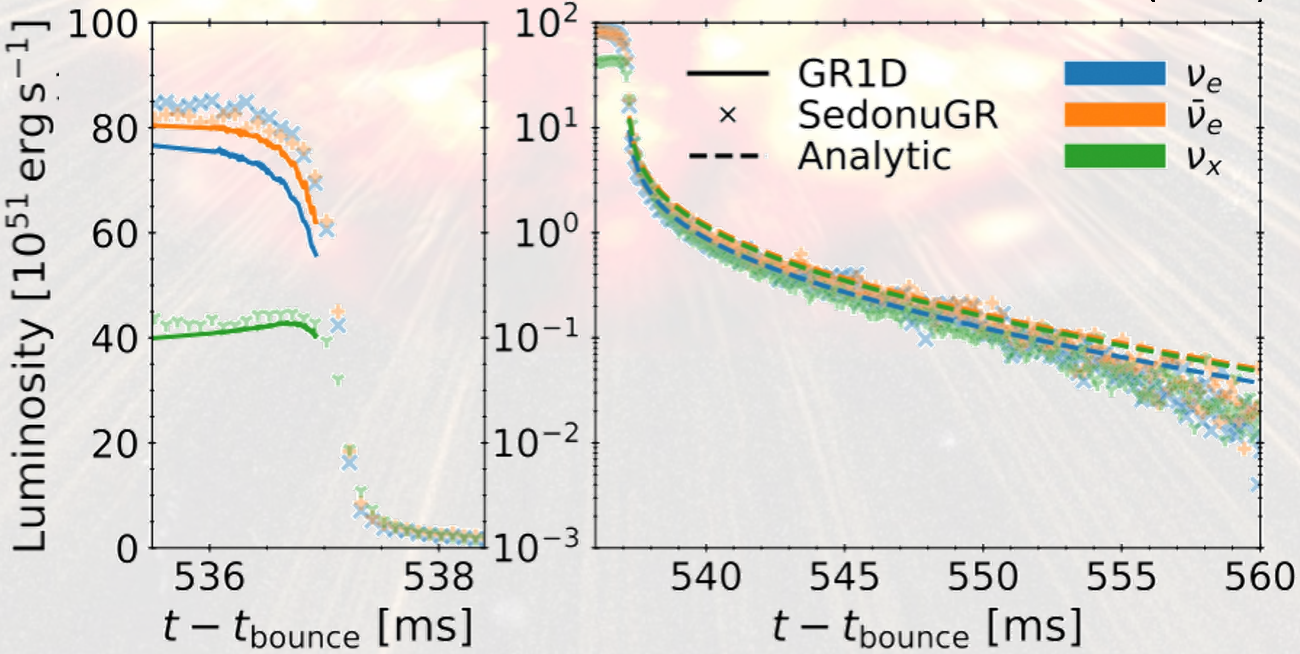
Beyond Detection: Black Holes



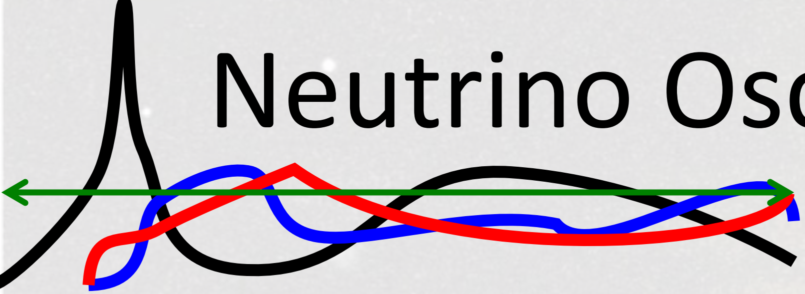
O'Connor (2015)



Gullin et al. (2022)



Probe PNS collapse to black hole and observe echos from progenitor

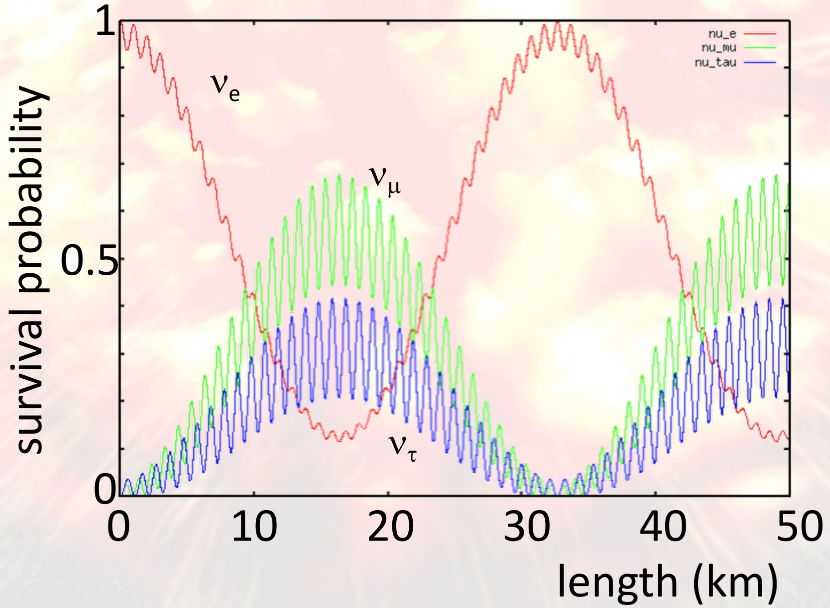


Neutrino Oscillations

- *Vacuum Oscillations*

$$\begin{pmatrix} |\nu_1(t)\rangle \\ |\nu_2(t)\rangle \\ |\nu_3(t)\rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\Delta m^2_{21} t/2E} & 0 \\ 0 & 0 & e^{-i\Delta m^2_{31} t/2E} \end{pmatrix} \begin{pmatrix} |\nu_1(0)\rangle \\ |\nu_2(0)\rangle \\ |\nu_3(0)\rangle \end{pmatrix}$$

  - Not relevant for supernovae



- *Matter Oscillations*

Matter introduces a potential in Hamiltonian due to forward scattering of electrons and neutrinos, the MSW potential:

$$\mathcal{H}_{\text{matter}} = \sqrt{2} G_{\text{F}} (N_{e^-} - N_{e^+})$$

- *Collective Oscillations*

High neutrino densities in the core-collapse supernova environment leads to appreciable neutrino-neutrino forward scattering

$$\mathcal{H}_{\text{collective}} = G_{\text{F}} \frac{R^2_{\nu_e}}{2r^2 - R^2_{\nu_e}} \int \frac{R^2_{\nu_e}}{r^2} [\Phi_{\nu_e} - \Phi_{\bar{\nu}_e}] dE$$

Neutrino Oscillations: Impact

- Collective oscillations, or some variant of them, may impact the dynamics if they occur deep enough in the supernovae, i.e. within the region where the neutrino heating occurs

- MSW and collective oscillations occuring far out don't impact the dynamics, but do impact the detection signal

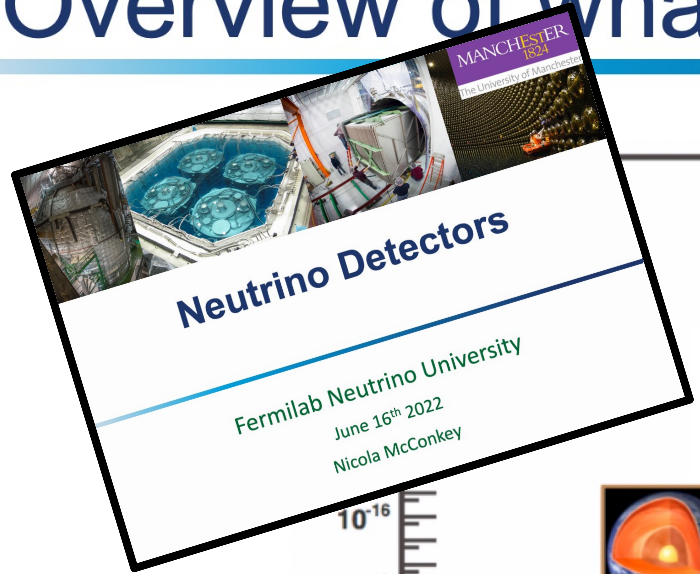
Supernovae & Neutrinos

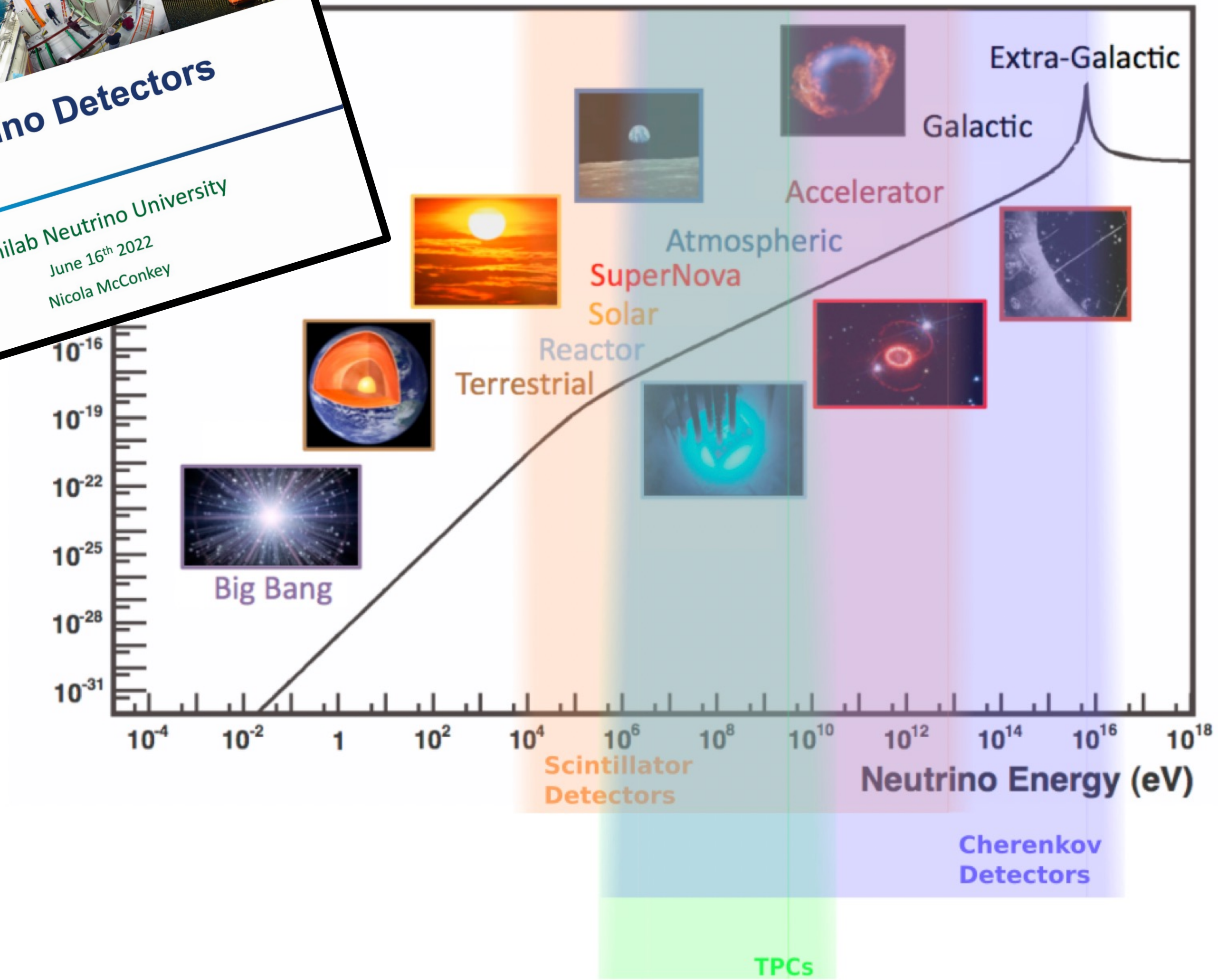
Outline

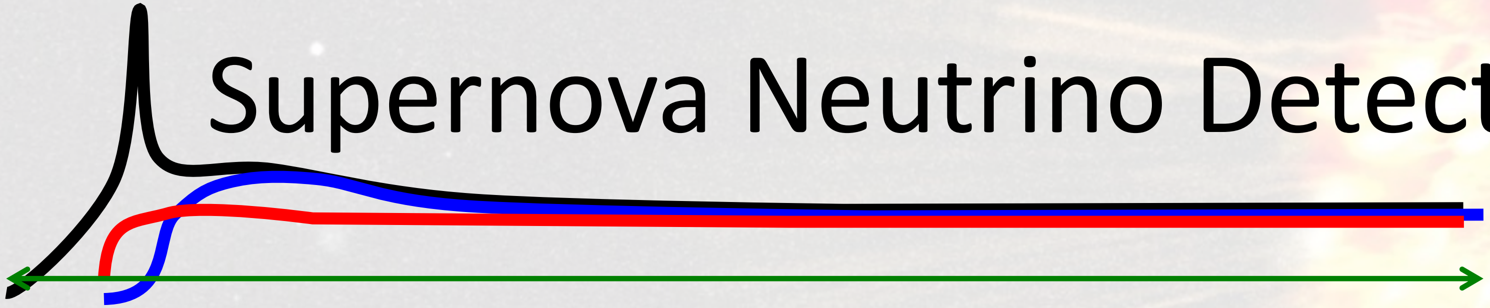
- **SN Theory from a neutrino perspective**
  - **Collapse Phase**
  - **Neutronization Burst**
  - **Accretion/Explosion Phase**
  - **Cooling Phase**
  - **Black Holes**
- **Earth-based Neutrino Detection**
- **Neutrinos from other supernovae**

Evan O'Connor
Stockholm University
July 21, 2022

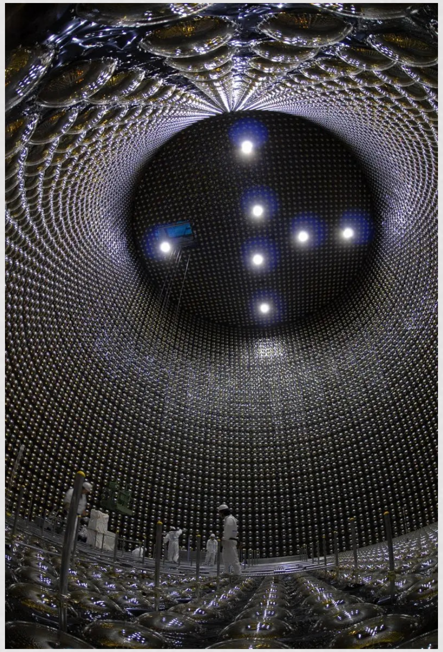
Overview of what we've seen so far







Supernova Neutrino Detection: Detectors



Super-K

⬅️ Water Cherenkov

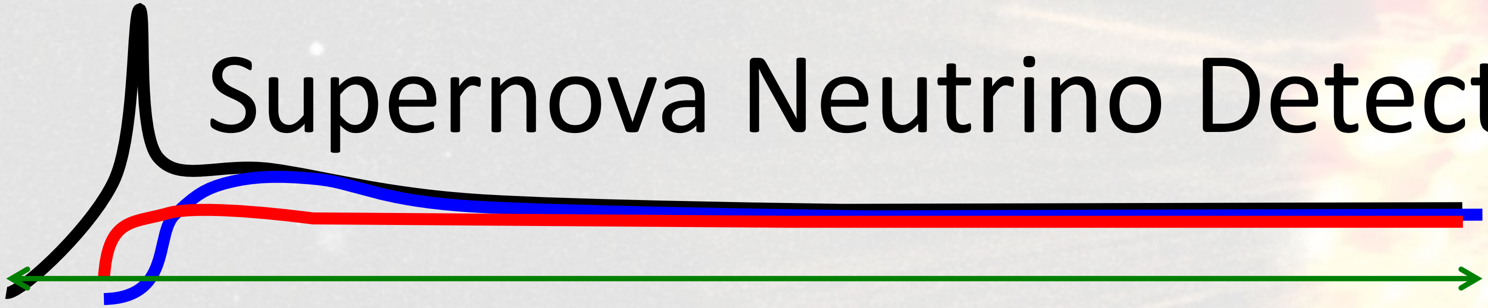
- Main reaction: inverse beta decay on p in water
- Main secondary reaction: Electron scattering of all types of neutrinos
- Can see individual events and tag to some extent
- Reconstruct energy and direction of leptons (sometimes neutrino)

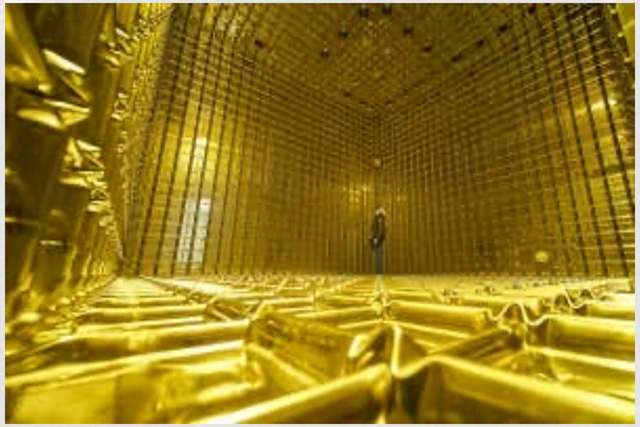
Scintillator ➡️

- Main reaction: inverse beta decay on p in scintillator
- Main secondary reaction: neutral current on carbon (also protons)
- Individual events, excellent energy resolution, low threshold

Daya Bay

Supernova Neutrino Detection: Detectors





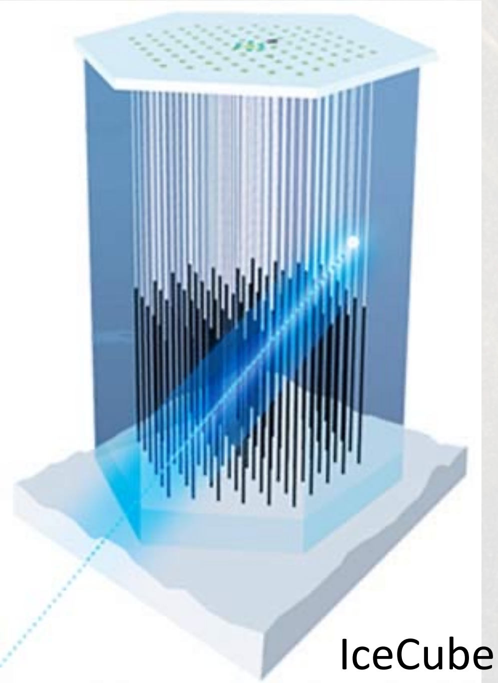
Proto-DUNE

⬅️ Liquid Argon

- Main reaction: electron neutrino charged current ^{40}Ar
- Secondary: elastic scattering on electrons, neutral current ^{40}Ar
- Individual events, good energy resolution
- Key: electron flavour sensitive

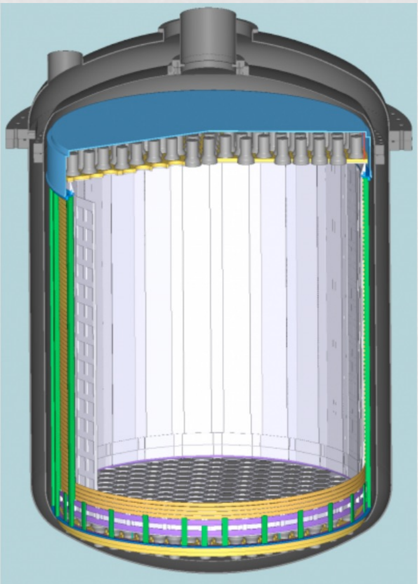
Long-String Water Cherenkov ➡️

- Main reaction: inverse beta decay on p in water
- Secondary reactions: elastic scattering & oxygen reactions
- Sensitive only to rate of neutrinos, not individual ones
- Large size gives excellent statistics



IceCube

Supernova Neutrino Detection: Detectors



XENONnT

Coherent Scattering (Nobel Gases)

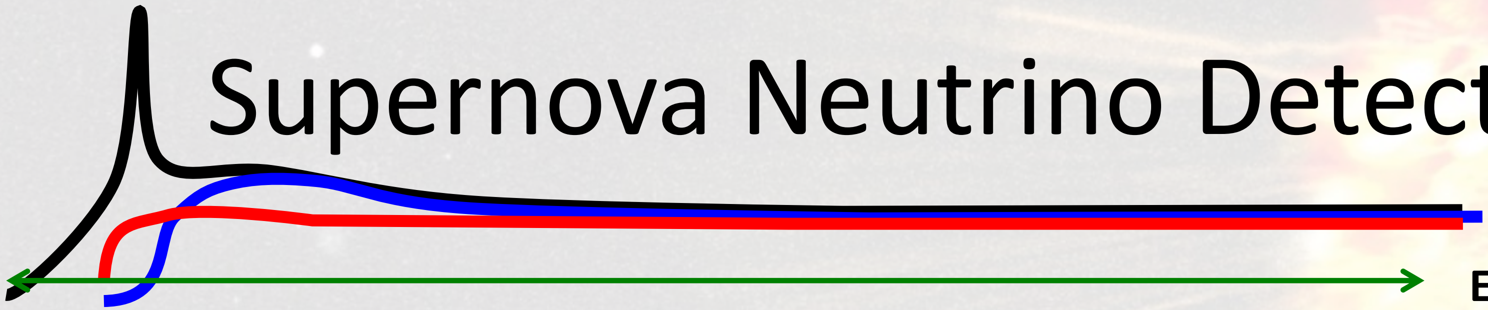
- Main reaction: coherent scattering on nucleus
- Neutral current: no flavour preference
- High specific rate (events/ton), but detectors small

Lead

- Main reaction: one (and two) neutron spalltion in lead
  - Sensitive to electron neutrinos (like liquid Argon)

HALO

Supernova Neutrino Detection: Rates



Example Supernovae at 10kpc

Experiment	Type	Mass [kt]	Location	$11.2\,M_\odot$	$27.0\,M_\odot$	$40.0\,M_\odot$
Super-K	$H_2O/\bar{\nu}_e$	32	Japan	4000/4100	7800/7600	7600/4900
Hyper-K	$H_2O/\bar{\nu}_e$	220	Japan	28K/28K	53K/52K	52K/34K
IceCube	String/$\bar{\nu}_e$	2500*	South Pole	320K/330K	660K/660K	820K/630K
KM3NeT	String/$\bar{\nu}_e$	150*	Italy/France	17K/18K	37K/38K	47K/38K
LVD	$C_nH_{2n}/\bar{\nu}_e$	1	Italy	190/190	360/350	340/240
KamLAND	$C_nH_{2n}/\bar{\nu}_e$	1	Japan	190/190	360/350	340/240
Borexino	$C_nH_{2n}/\bar{\nu}_e$	0.278	Italy	52/52	100/97	96/65
JUNO	$C_nH_{2n}/\bar{\nu}_e$	20	China	3800/3800	7200/7000	6900/4700
SNO+	$C_nH_{2n}/\bar{\nu}_e$	0.78	Canada	150/150	280/270	270/180
NOνA	$C_nH_{2n}/\bar{\nu}_e$	14	USA	1900/2000	3700/3600	3600/2500
Baksan	$C_nH_{2n}/\bar{\nu}_e$	0.24	Russia	45/45	86/84	82/56
HALO	Lead/ν_e	0.079	Canada	4/3	9/8	9/9
HALO-1kT	Lead/ν_e	1	Italy	53/47	120/100	120/120
DUNE	Ar/ν_e	40	USA	2700/2500	5500/5200	5800/6000
MicroBooNe	Ar/ν_e	0.09	USA	6/5	12/11	13/13
SBND	Ar/ν_e	0.12	USA	8/7	16/15	17/18
DarkSide-20k	Ar/any ν	0.0386	Italy	-	250	-
XENONnT	Xe/any ν	0.006	Italy	56	106	-
LZ	Xe/any ν	0.007	USA	65	123	-
PandaX-4T	Xe/any ν	0.004	China	37	70	-

Supernovae & Neutrinos

<u>Outline</u>

- **SN Theory from a neutrino perspective**
  - **Collapse Phase**
  - **Neutronization Burst**
  - **Accretion/Explosion Phase**
  - **Cooling Phase**
  - **Black Holes**
- **Earth-based Neutrino Detection**
- **Neutrinos from other supernovae**

Evan O’Connor
Stockholm University
July 21, 2022

Neutrinos from other Supernovae

Wright et al. (2016, 2017a,c)

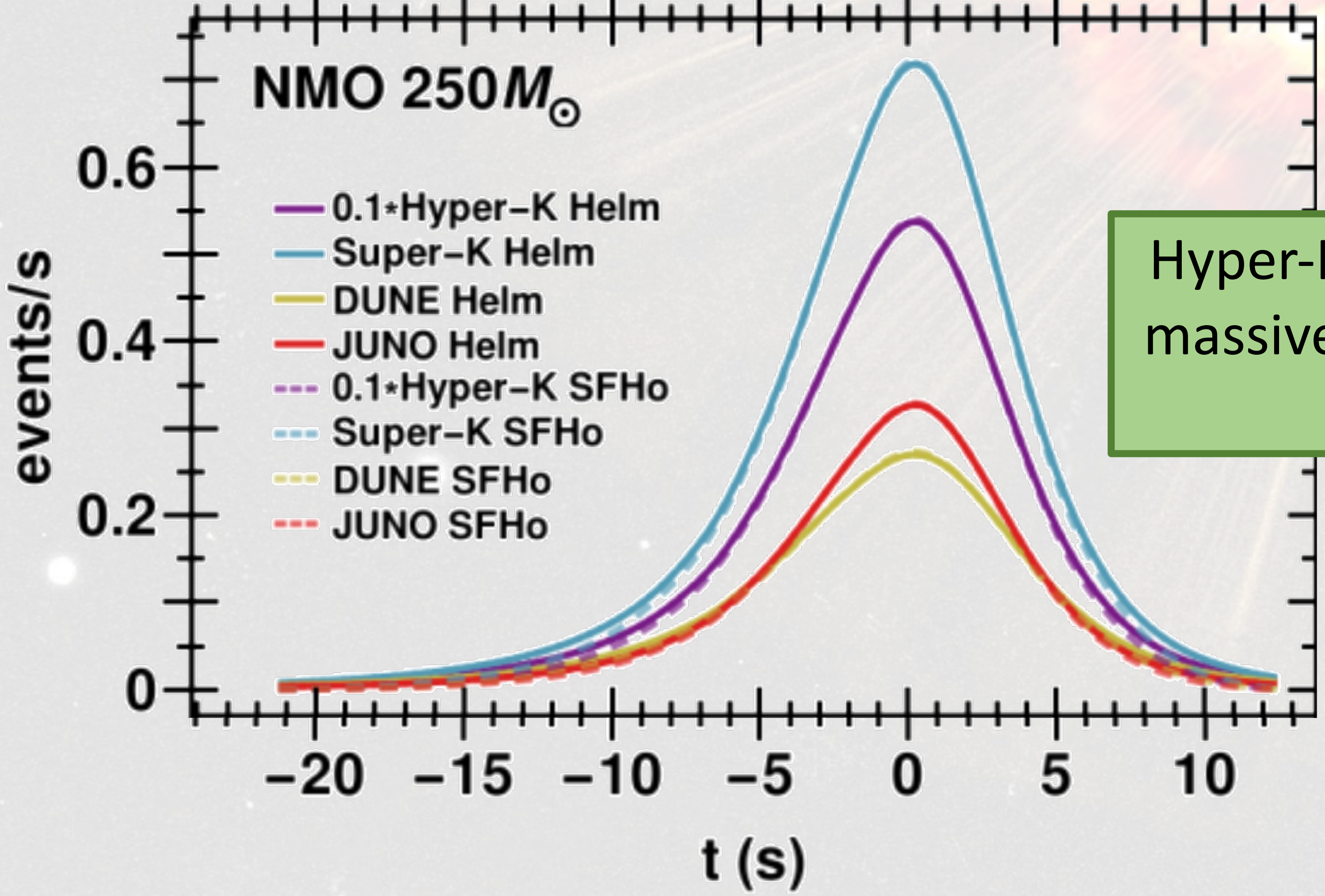
- All other supernovae are 'thermonuclear' energy comes from runaway burning of carbon & oxygen
- Do not get to nuclear densities and therefore not as hot and not nearly the same number of neutrinos

Pair-Instability Supernovae
Type Ia – unknown mechanism

Neutrinos from other Supernovae

Wright et al. (2016, 2017a,c)

Pair-Instability Supernovae

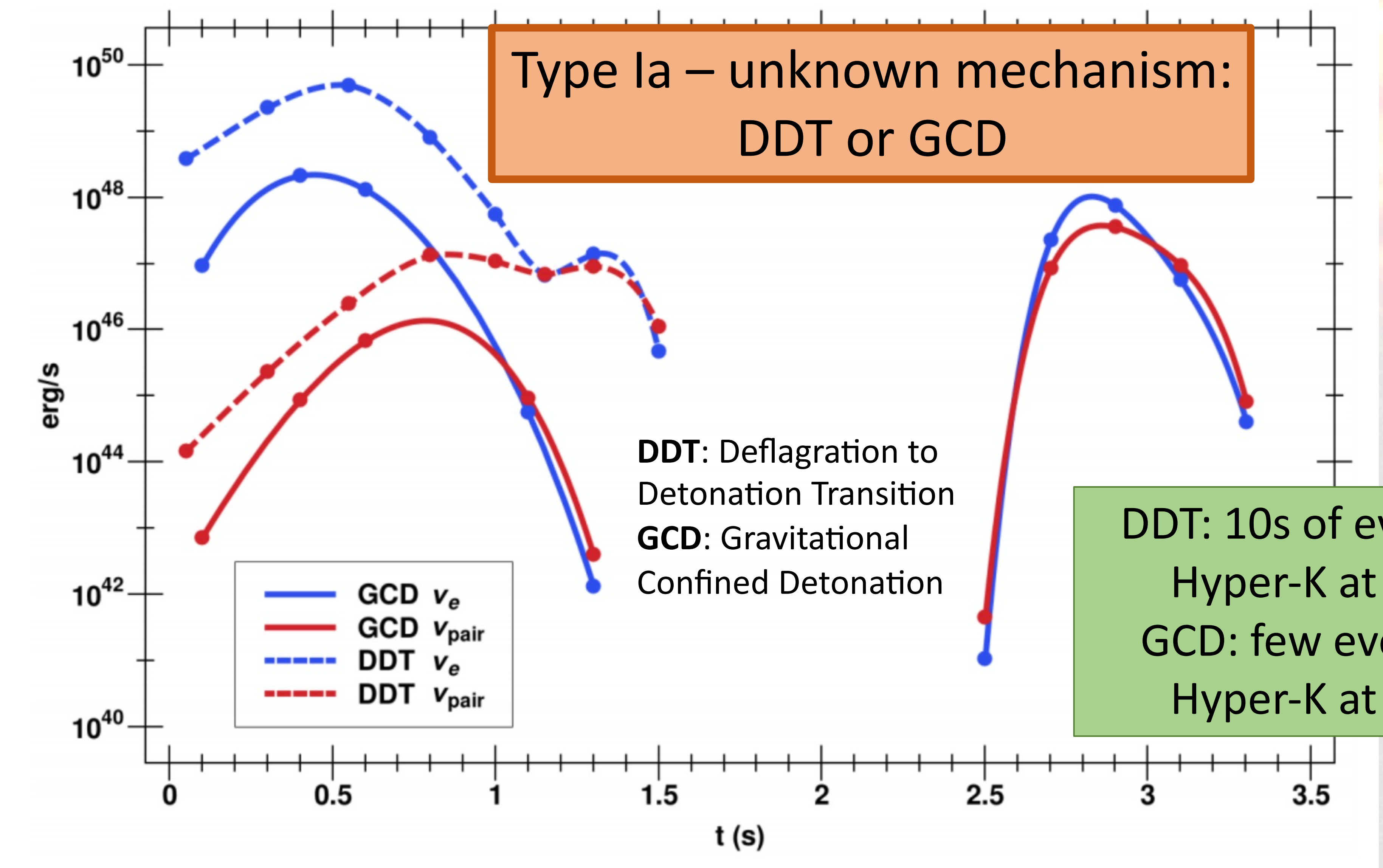


Hyper-K: 40-50 events for massive (250M_{sun}) PISN at 10kpc

Caveat: Very Low Energy requires low threshold: 2MeV -> 50% efficiency

Neutrinos from other Supernovae

Wright et al. (2016, 2017a,c)



Type Ia – unknown mechanism:
DDT or GCD

DDT: Deflagration to Detonation Transition
GCD: Gravitational Confined Detonation

DDT: 10s of events in Hyper-K at 1kpc
GCD: few events in Hyper-K at 1kpc

Supernovae & Neutrinos

<u>Outline</u>

- **SN Theory from a neutrino perspective**
  - **Collapse Phase**
  - **Neutronization Burst**
  - **Accretion/Explosion Phase**
  - **Cooling Phase**
  - **Black Holes**
- **Earth-based Neutrino Detection**
- **Neutrinos from other supernovae**

Evan O'Connor
Stockholm University
July 21, 2022