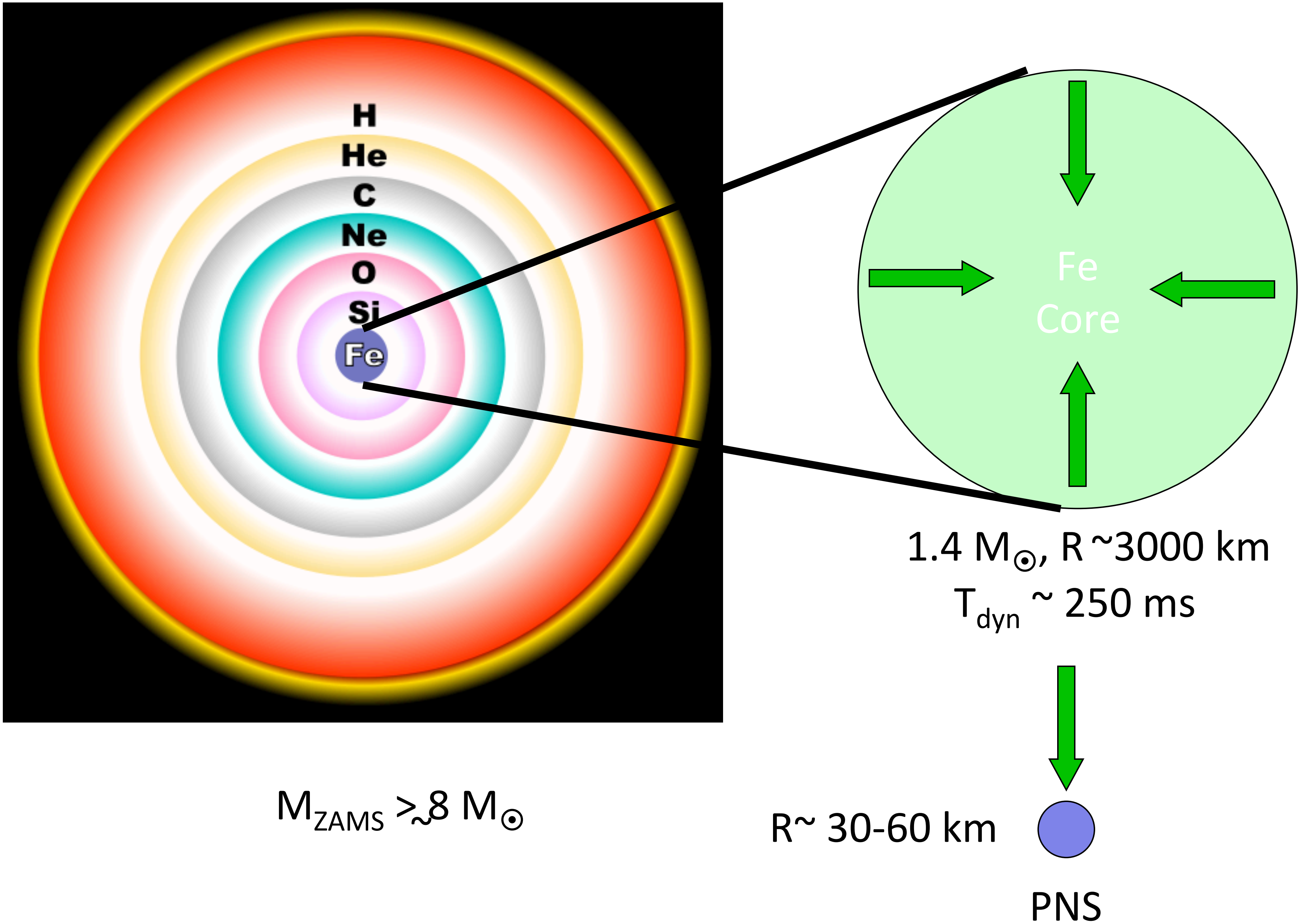
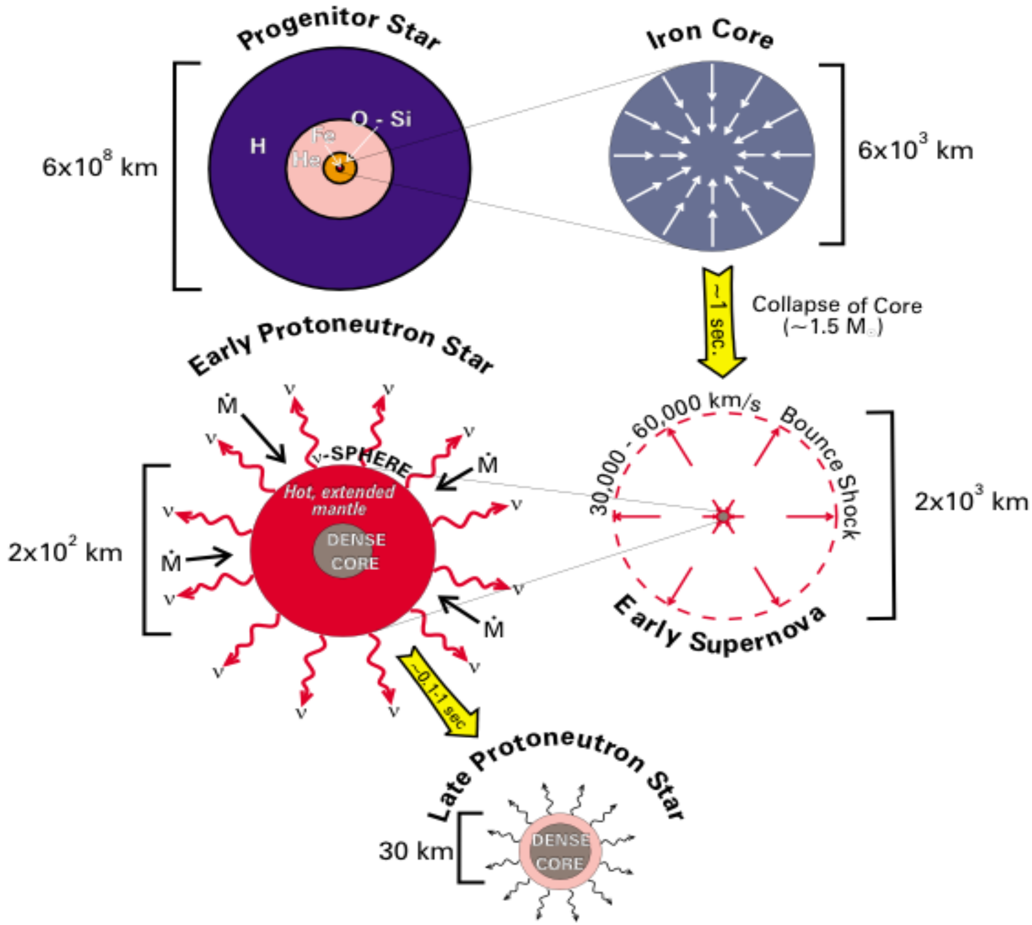
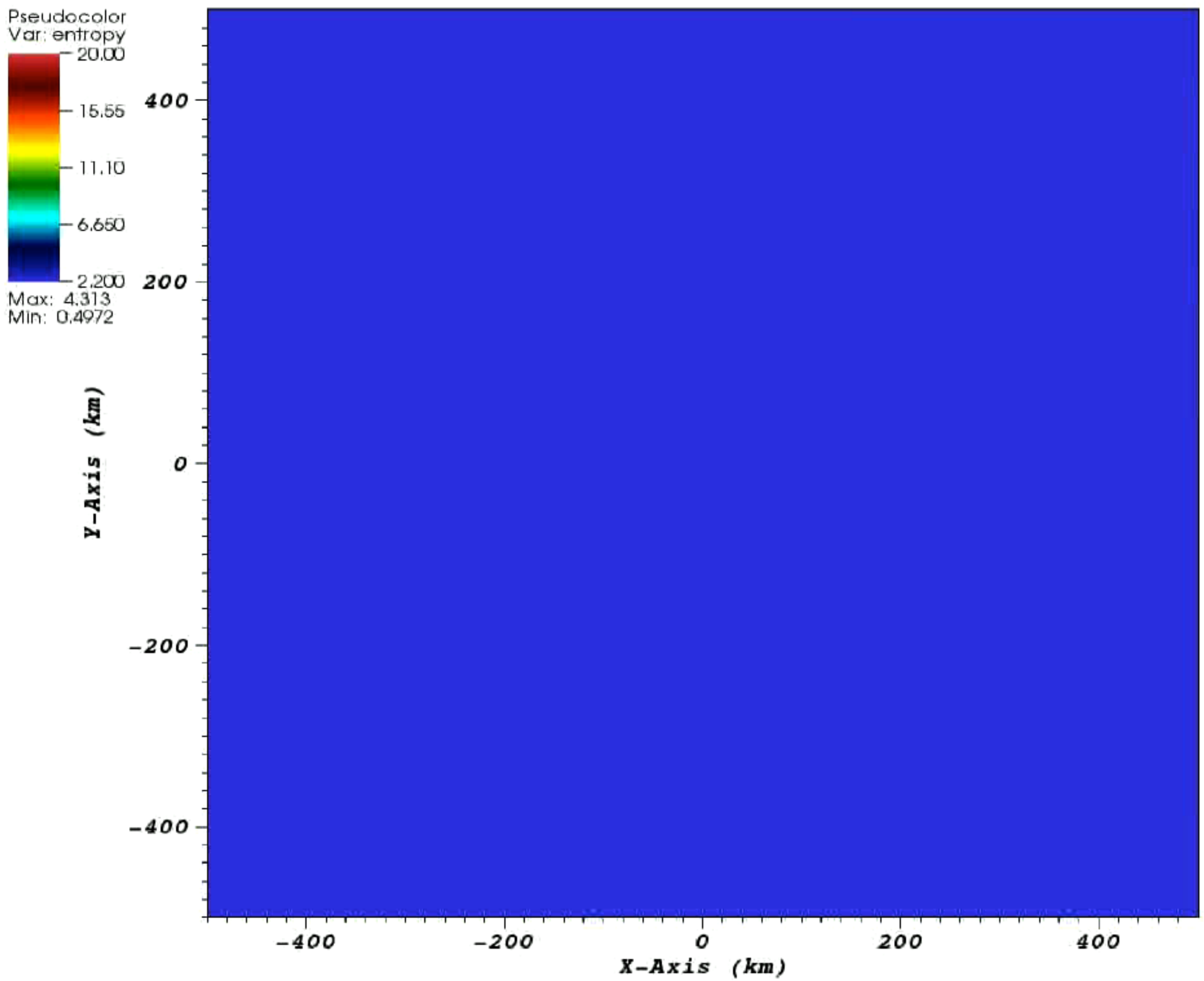
A History of Supernova Neutrinos

Adam Burrows, Princeton University


H
He
C
Ne
O
Si
Fe
Fe
Core
1.4 M⊙, R ~3000 km
T_dyn ~ 250 ms
M_ZAMS ≳ 8 M⊙
R~ 30-60 km
PNS


Progenitor Star
Iron Core
6x10^8 km
H
O - Si
Fe
He
6x10^3 km
~1 sec.
Collapse of Core
(~1.5 M☉)
Early Protoneutron Star
ν-SPHERE
Hot, extended mantle
DENSE CORE
2x10^2 km
30,000 - 60,000 km/s
Bounce Shock
2x10^3 km
Early Supernova
~0.1-1 sec
Late Protoneutron Star
30 km
DENSE CORE

Neutrino Transport; 3D turbulence; Explosion is Neutrino-driven



Parallel Evolution: 1930's

Neutrino Physics

- Pauli's suggestion of the ν
- Discovery of the neutron
- Fermi – β decay

Supernova Physics

- Baade & Zwicky 1933-1934: Neutron stars and supernovae

Parallel Evolution: 1940's

Neutrino Physics

Supernova Physics

- Gamow & Schoenberg 1941 (April 1, Poisson d'Avril!): hot stellar interiors lead to copious emission of neutrinos (URCA?), rapid contraction, rapid outer layer expansion (?), binding energy radiated as neutrinos – supernovae (and novae?)

Parallel Evolution: 1950's

Neutrino Physics

- Parity violation (Yang & Lee 1956)
- Parity Experiment (Wu 1957)
- Helicity (Goldhaber et al. 1957)
- Cowan & Reines 1957
- ν oscillations and e^-/μ^- universality (Pontecorvo)
- V-A theory (Feymann & Gell Mann 1957-1958)

Supernova Physics

- Origin of the elements (Burbidge, Burbidge, Fowler, & Hoyle 1957; Cameron 1950's)

Parallel Evolution: 1960's

Neutrino Physics

- ν_μ neutrino discovered (Lederman et al. 1962)
- Weinberg-Salam-Glashow (1967-1968)

Supernova Physics

- H.Y. Chiu (1961, 1964) and neutrinos in stars (and supernovae!)
- Colgate & White 1966
- Arnett 1967 – neutrino transport

Parallel Evolution: 1970's

Neutrino Physics

- Weak neutral current discovery (1973)
- Weak Neutral current scattering neutrino processes (Dicus 1972; Freedman (1974) scattering off nuclei, …)
- ν_τ discovered (M. Perl 1975)
- Nuclear EOS progress
- Wolfenstein (1978-1979) and neutrino oscillations in matter

Supernova Physics

- J. Wilson (including ν_μ transport)
- Wilson and LeBlanc (rapid rotation and MHD)
- Neutrino trapping (Mazurek [1974, without NC]; Sato [1975, with NC]) – ν_e degeneracy/high initial lepton number
- Chandrasekhar mass core of massive stars (neutrino cooling)

Parallel Evolution: 1980's

Neutrino Physics

- Discovery of the W/Z (Rubbia & van de Meer 1984)
- MSW oscillation resonant oscillation theory (1985)
- Solar neutrino puzzle solved??

Supernova Physics

- Relevant Neutrino-matter interaction rates (scattering and absorption) coming into focus
- 1D neutrino radiative transport maturing (e.g., Bruenn 1985)
- Delayed mechanism of explosion (Wilson 1985)
- Burrows & Lattimer (1986) (long duration, softer spectrum of burst)
- SN 1987A!!

To the present……

- Multi-D hydrodynamics (Burrows et al., Herant et al., 1990's…); multi-D transport ….
- Sophisticated multi-D radiation/hydrodynamics models: Burrows, Janka, Mezzacappa, Kotake, Yamada, Couch, Ott, Roberts, ……….
- Modern Explosion Theory: Neutrino-Powered

Neutrino Reactions in Supernovae

Beta processes:	• $e^- + p \rightleftharpoons n + \nu_e$
	• $e^+ + n \rightleftharpoons p + \bar{\nu}_e$
	• $e^- + A \rightleftharpoons \nu_e + A^*$
Neutrino scattering:	• $\nu + n, p \rightleftharpoons \nu + n, p$
	• $\nu + A \rightleftharpoons \nu + A$
	• $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
Thermal pair processes:	• $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$
	• $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$
Neutrino-neutrino reactions:	• $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$ ($\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau$, or $\bar{\nu}_\tau$)
	• $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Important Ingredients/Physics

- Progenitor Models (and initial seed perturbations?)
- Multi-D Hydrodynamics (3D)
- Multi-D Neutrino Transport (most challenging aspect)
- Instabilities - Neutrino-Driven Convection (+ SASI)
- Neutrino-Matter Processes - Cross sections, emissivities, inelasticities, Many-body, etc.
- General Relativity (May & White; Schwartz; Bruenn et al.; Mueller et al.; Kotake et al.; Roberts et al. 2016; Skinner et al. 2016; Radice et al. 2017)
- Rotation (!)

Some Microphysics Issues

Sub-Dominant Terms/Effects Add “Non-linearly” when near Criticality:

- Nucleon-nucleon Bremsstrahlung (suppression effect at high densities) – effect on ν_μ luminosities and spectra
- Electron capture on heavies – known to a factor of five (?)
- EOS at high densities – affecting core radii and contraction
- Strange quark effect on S_A for neutral current scattering (Melson, but …)
- Full ν_μ, ν_τ, and antiparticle transport
- Many-body corrections to neutral- and charged-current scattering and absorption rates

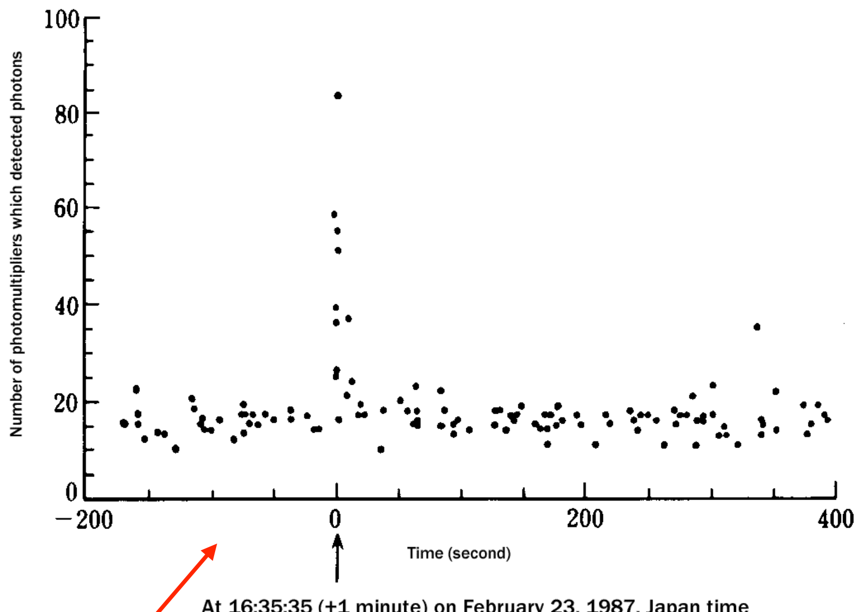
Supernova Neutrino Detection

SUPERK, HYPERK, DUNE, JUNO, ICE CUBE

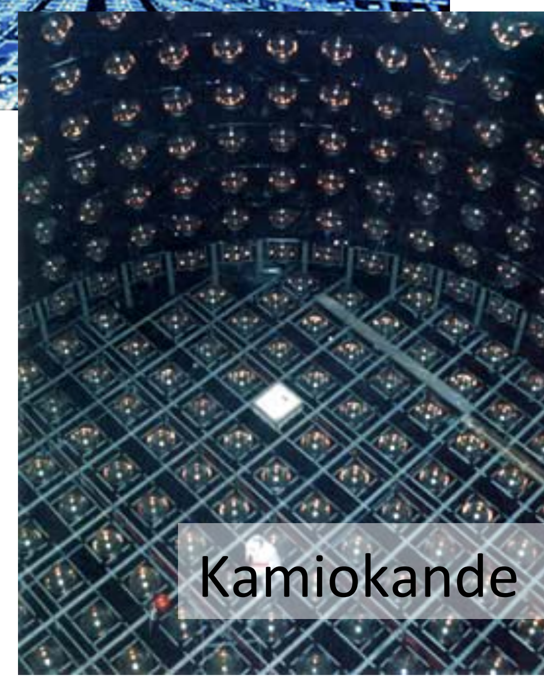
Consequences of Neutrino Trapping

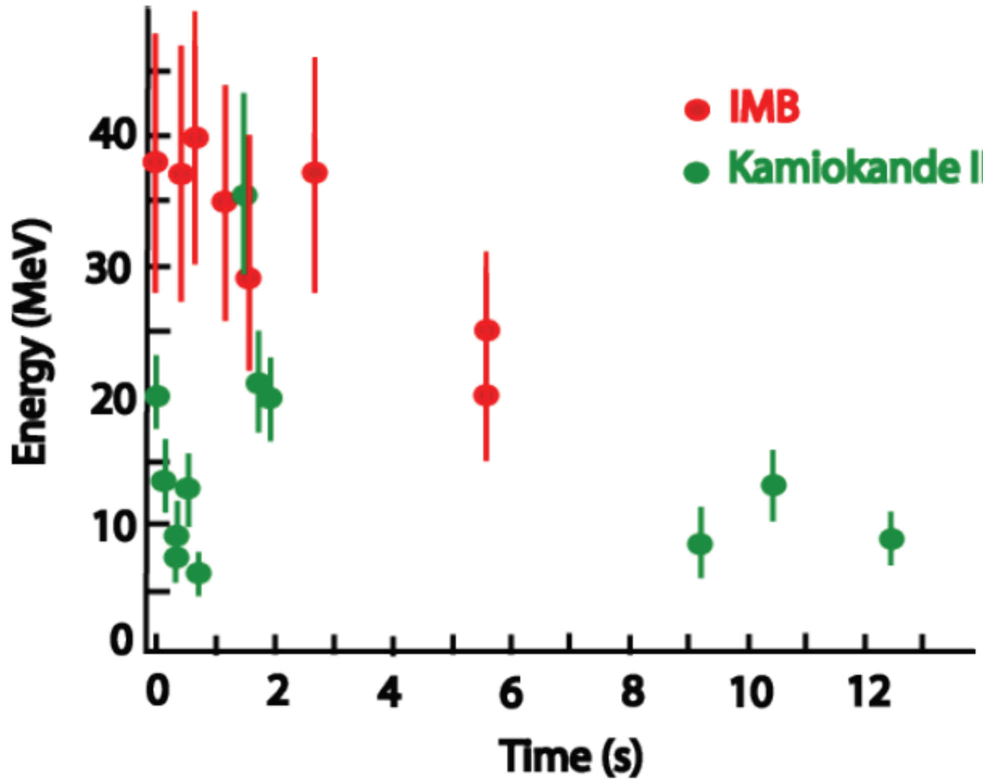
- ..of lepton number (electrons plus ν_e's)
- Results in degenerate ν_e's in core – high average neutrino energies (~250 MeV) – high opacity (τ ~10^5)
- As a result energy and lepton number diffuse out of the core on long time scales (many seconds to ~1 minute)
- Binding energy of a neutron star (~10^{53} ergs) sets the total energy scale
- Therefore, lower average emergent neutrino energies
- Old theory without trapping: burst duration tens of milliseconds, average energy ~50+ MeV
- New theory with trapping: duration of many seconds, average energy of 10-20 MeV – SN1987A!

Core-Collapse Neutrinos Detected

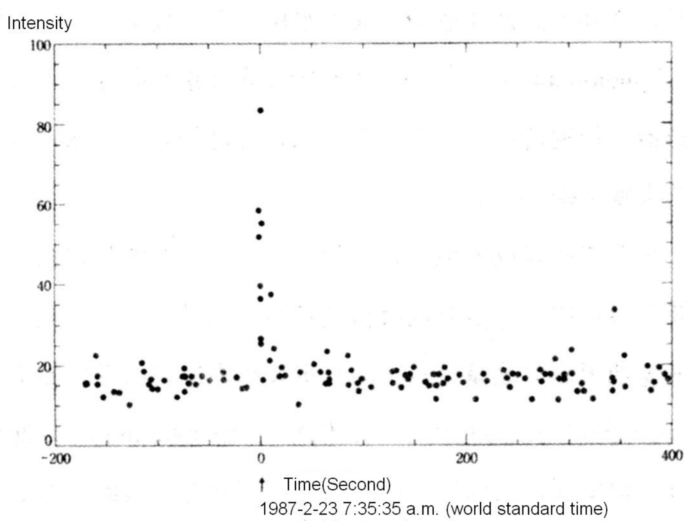


Kamioka II

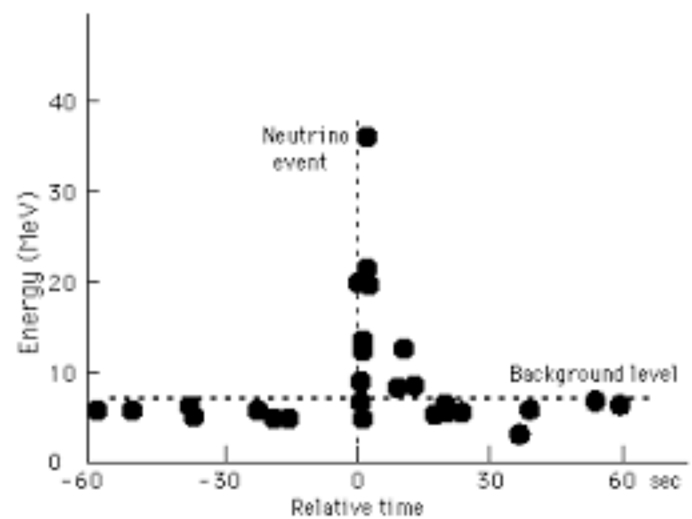



IMB
Kamiokande II
Energy (MeV)
0
10
20
30
40
Time (s)
0
2
4
6
8
10
12

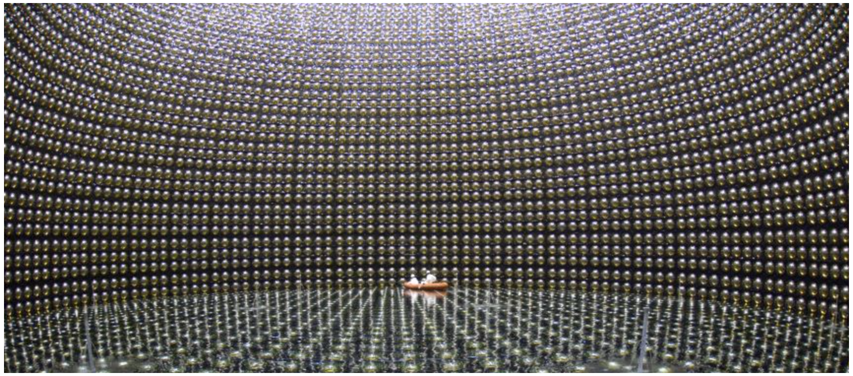
KII:


Intensity
100
80
60
40
20
0
-200
0
200
400
Time(Second)
1987-2-23 7:35:35 a.m. (world standard time)

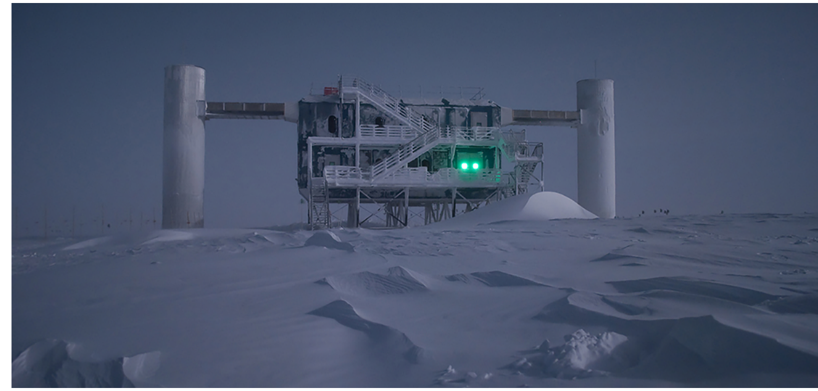
IMB:


Energy (MeV)
40
30
20
10
0
Neutrino event
Background level
-60
-30
0
30
60 sec
Relative time

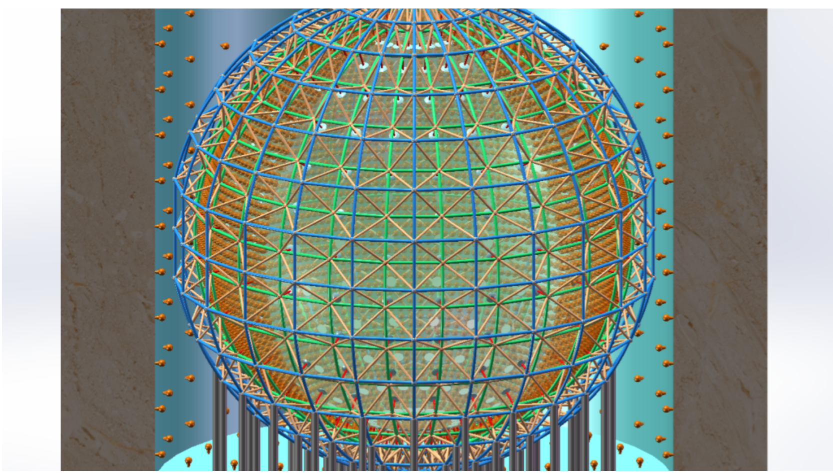
SN Neutrino Observatories



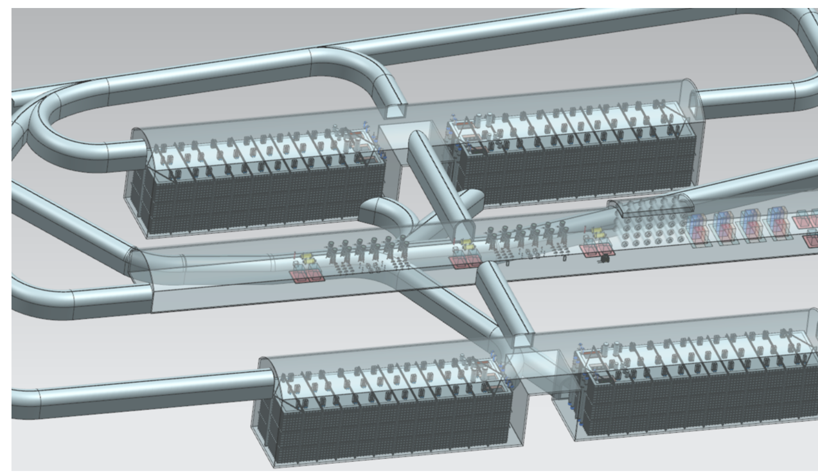
Super-Kamiokande
(Water Cherenkov)



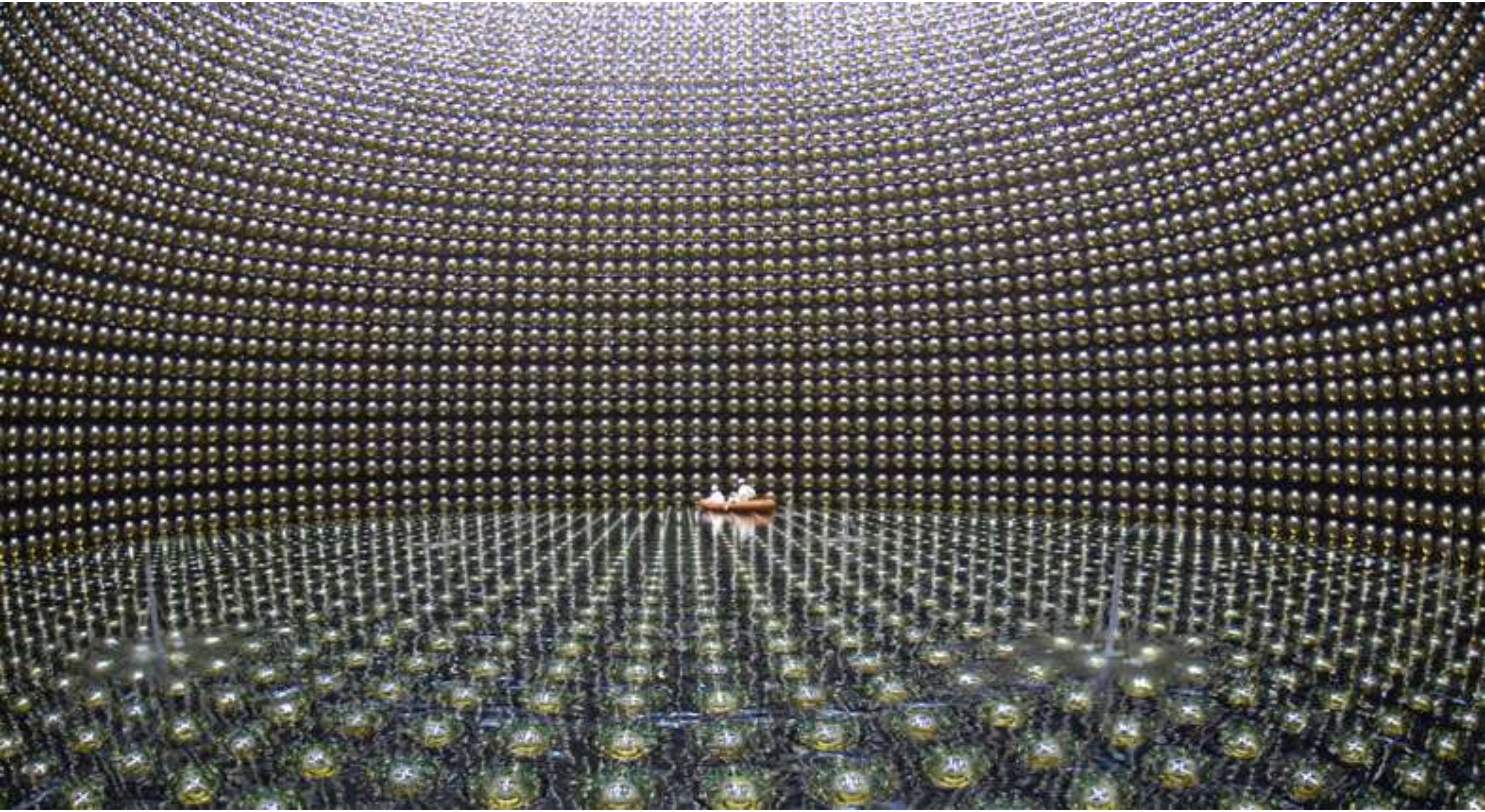
ICECUBE
(Longstring Ice)



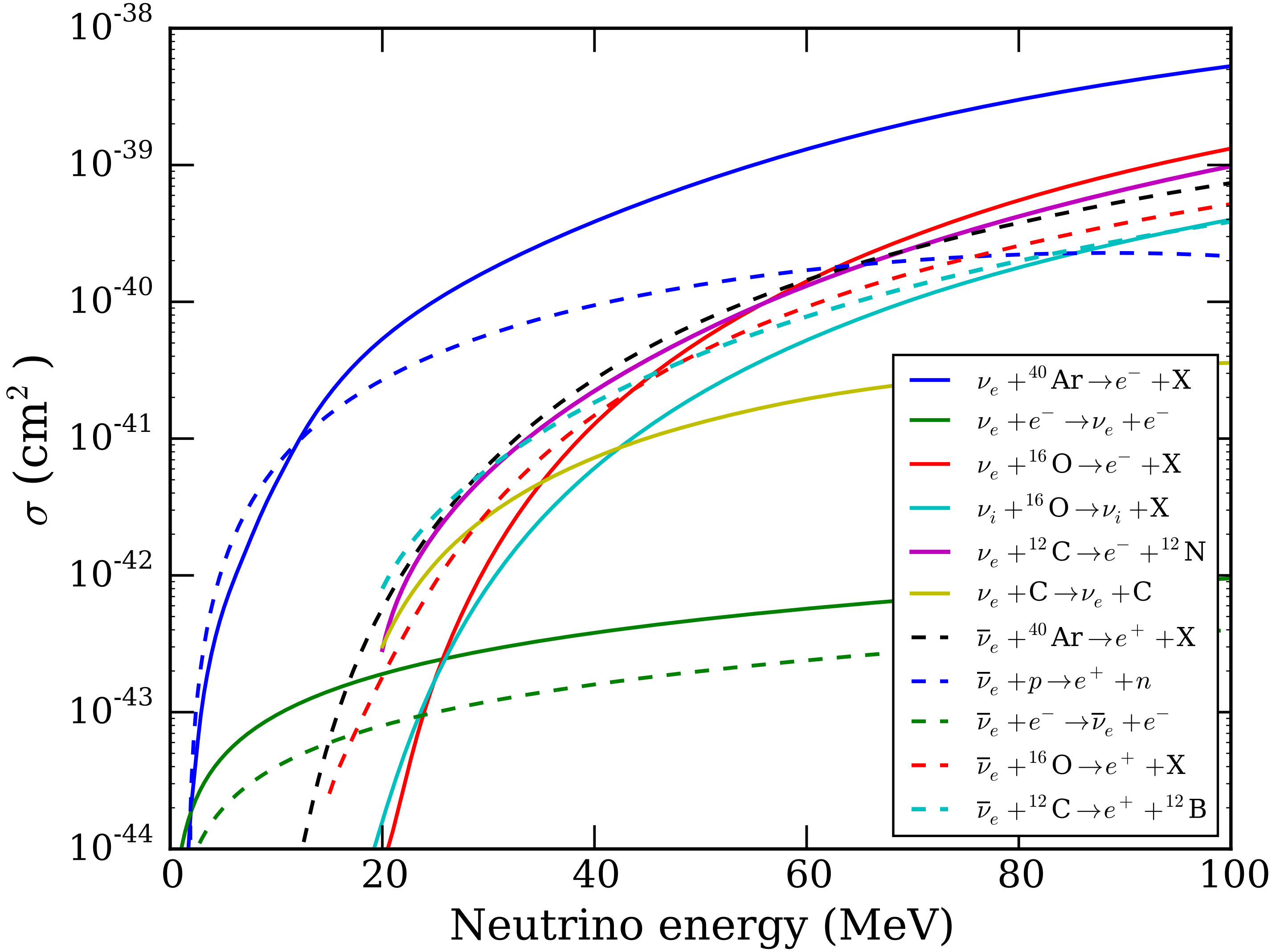
JUNO
(Hydrocarbon Scintillator)



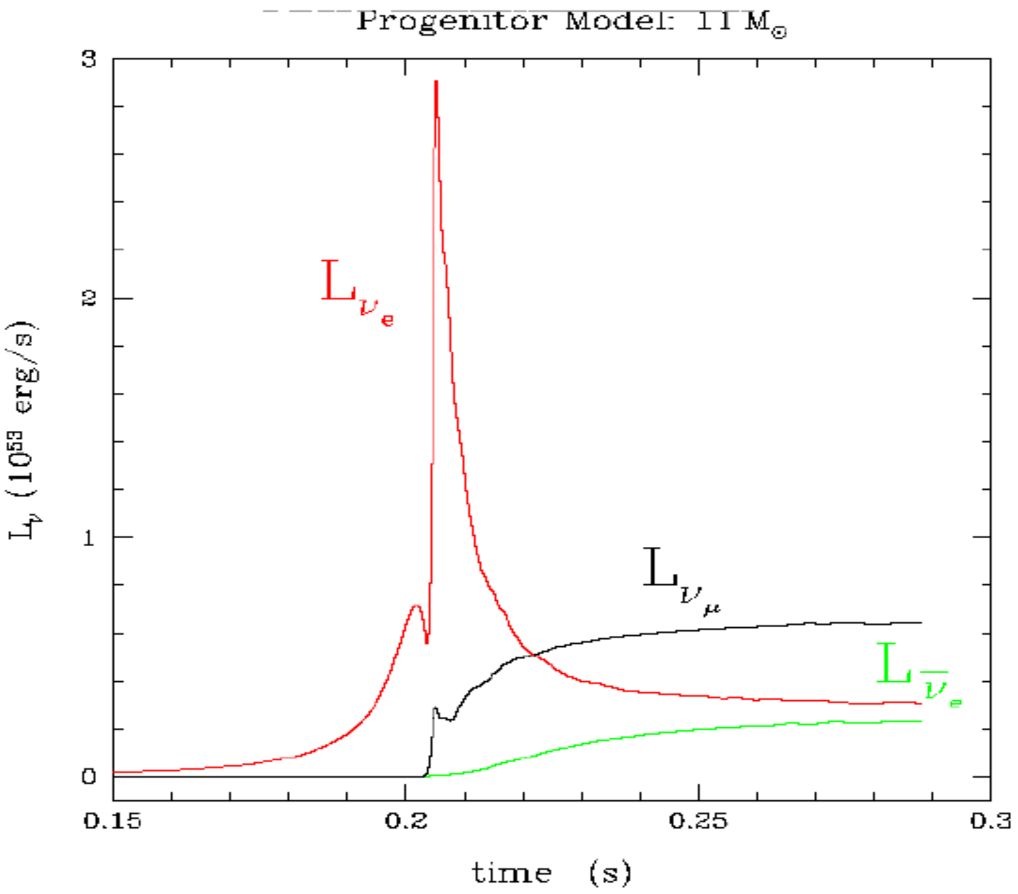
DUNE
(Liquid Argon TPC)

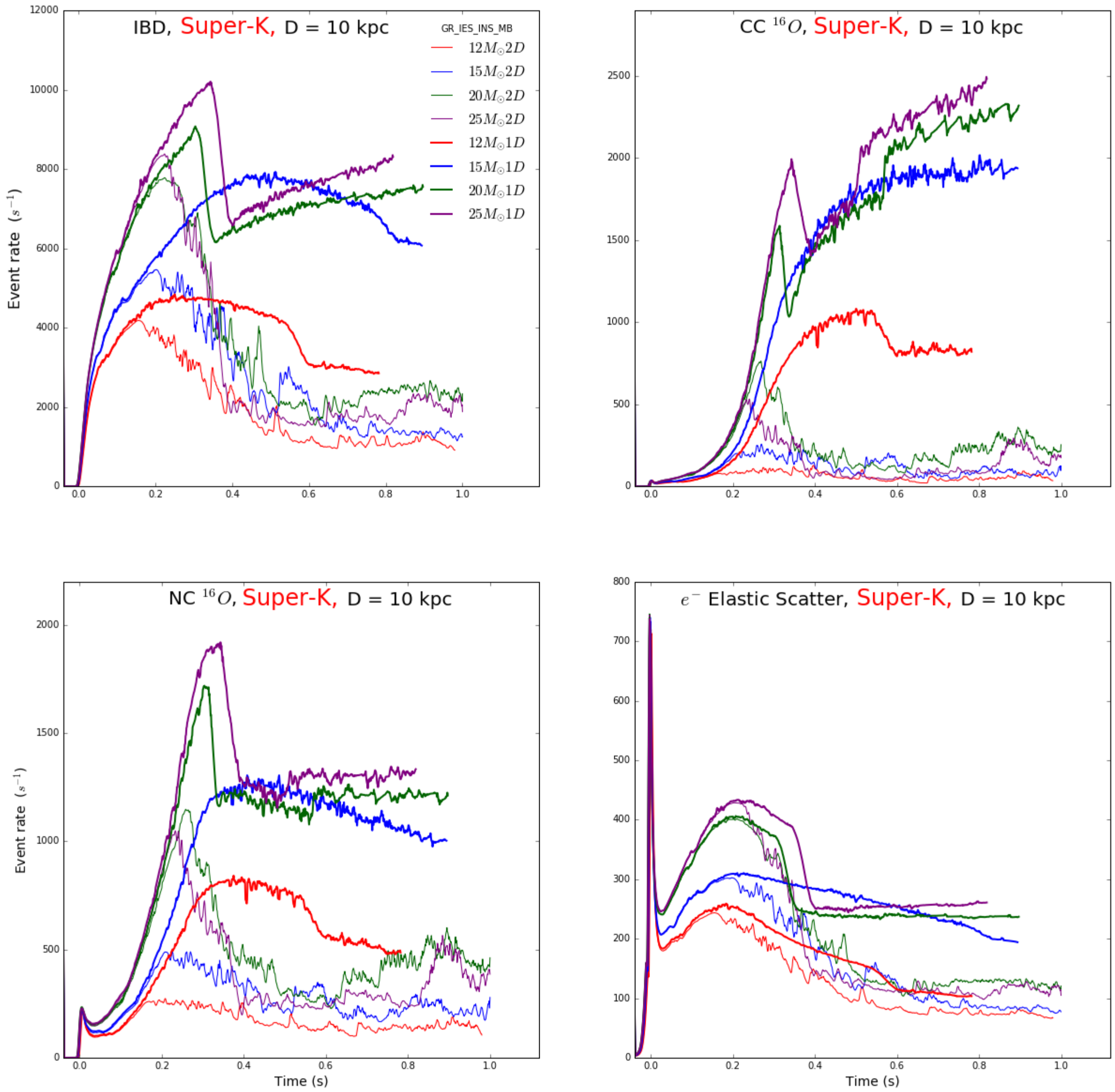


Reactions in Detectors

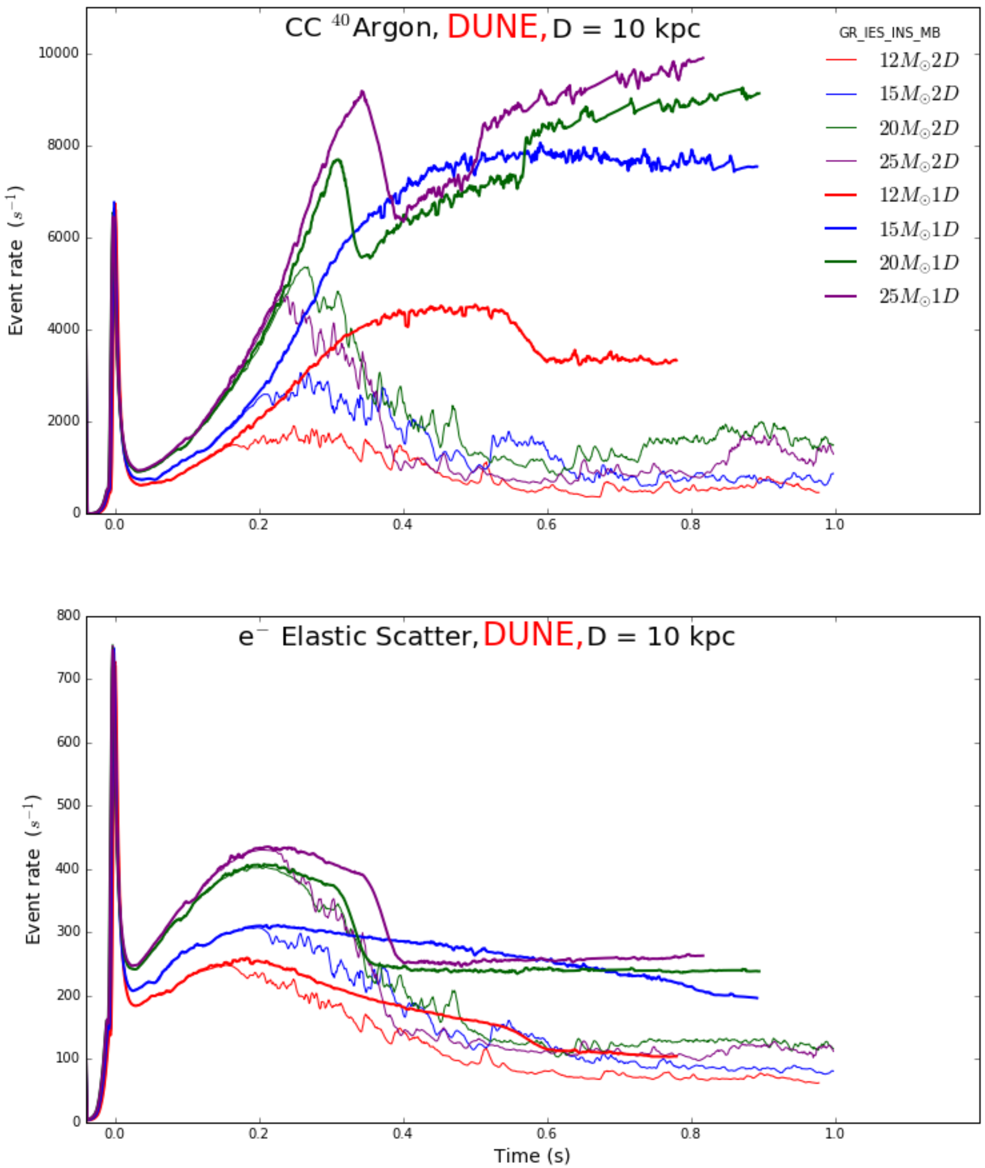


Breakout Burst of Neutrinos: Precision Boltzmann Transfer

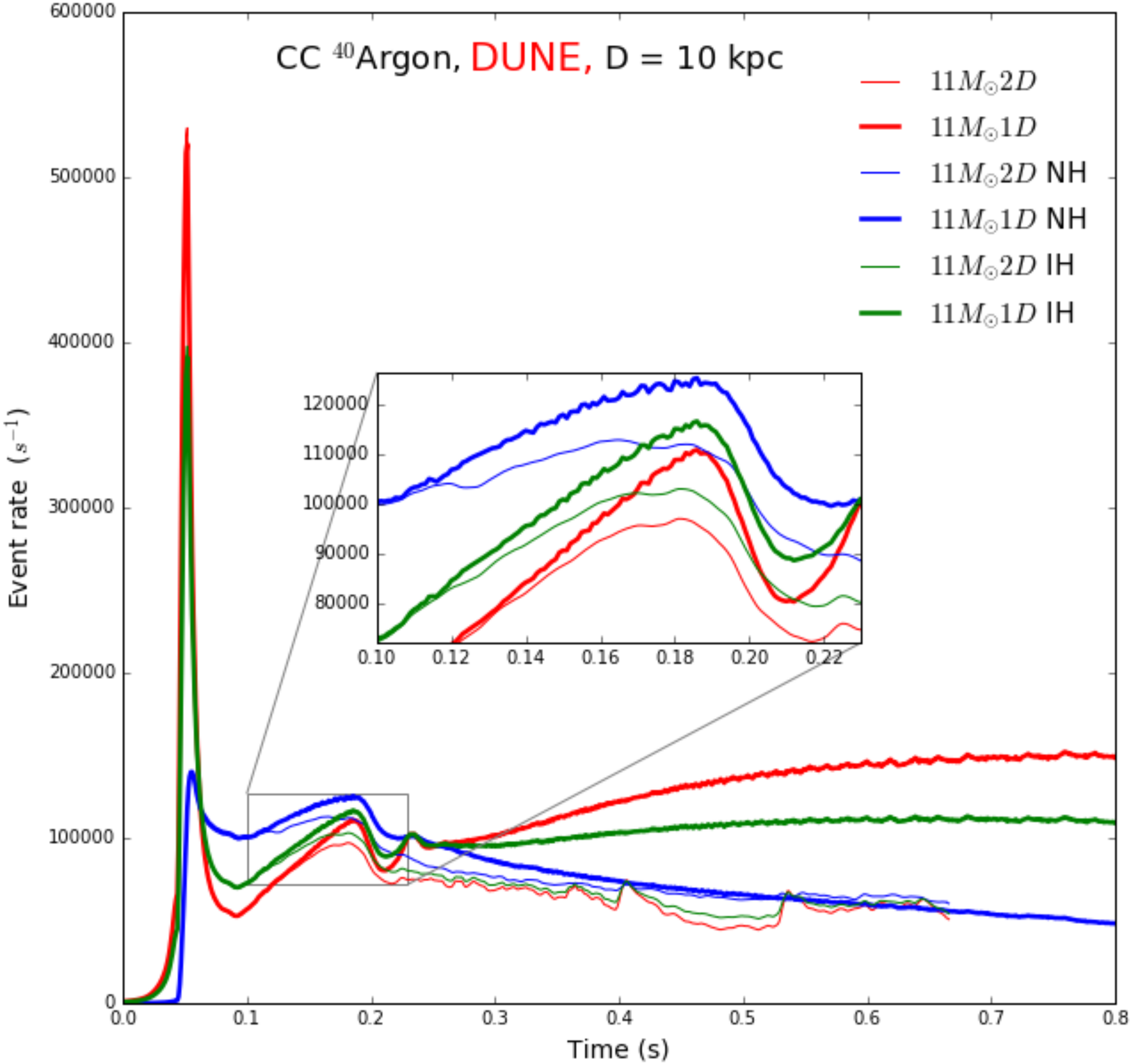




Seadrow et al. 2018

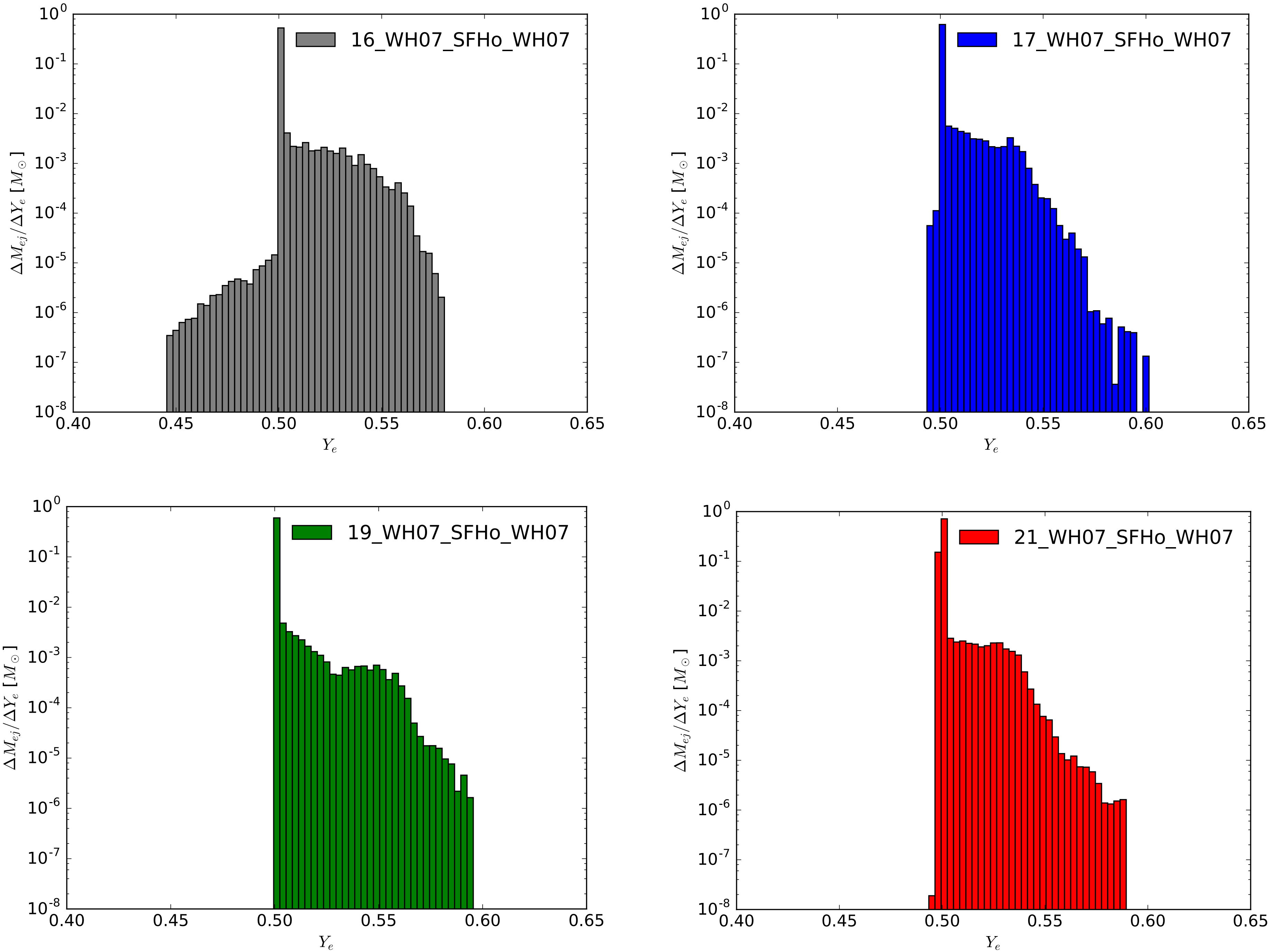


Seadrow et al. 2018

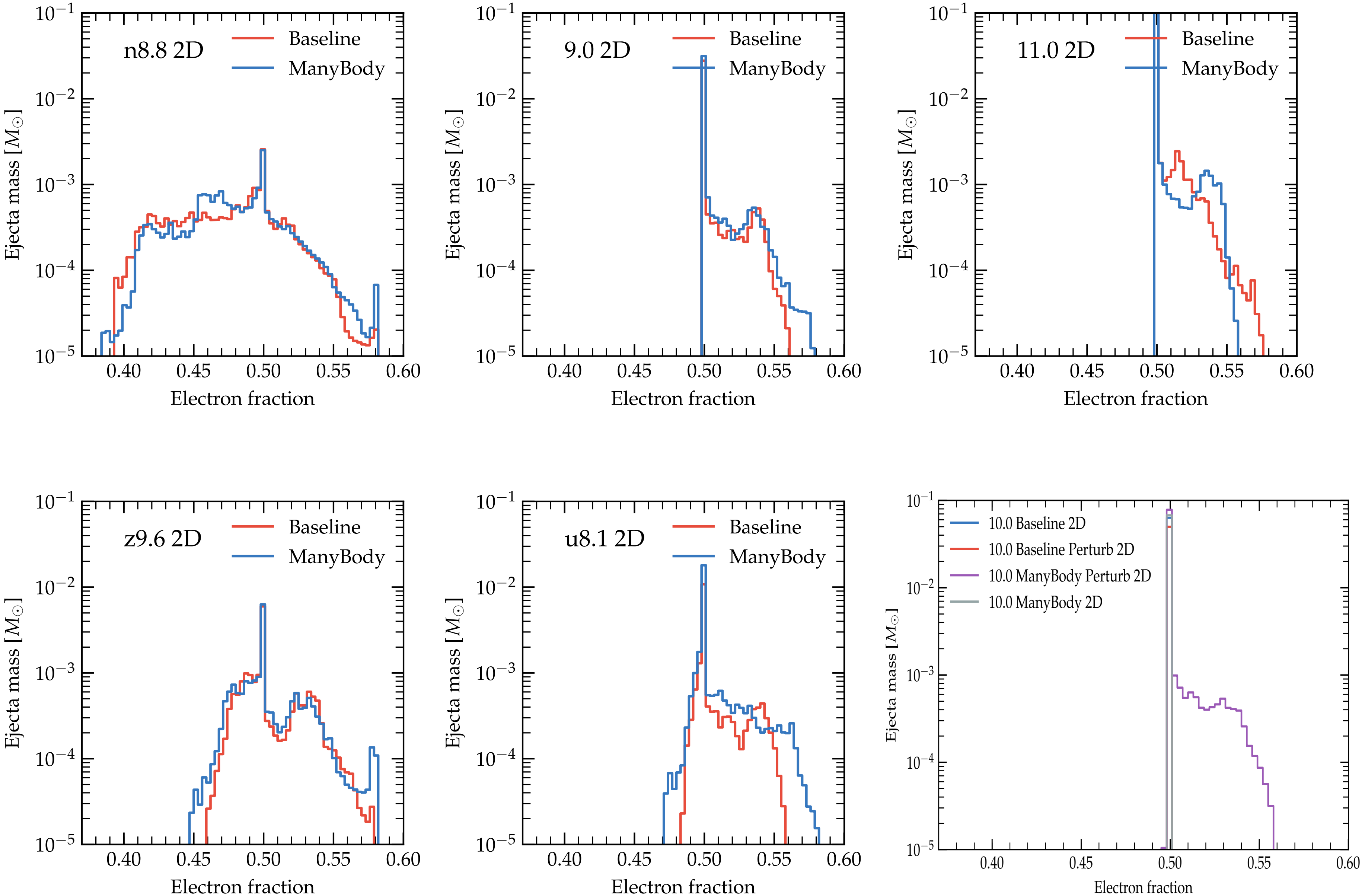


Seadrow et al. 2017

Nucleosynthesis – The effect of neutrino absorption on ejecta



16_WH07_SFHo_WH07
17_WH07_SFHo_WH07
19_WH07_SFHo_WH07
21_WH07_SFHo_WH07
$\Delta M_{ej}/\Delta Y_e\ [M_\odot]$
Y_e
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0.40
0.45
0.50
0.55
0.60
0.65


n8.8 2D
9.0 2D
11.0 2D
z9.6 2D
u8.1 2D
Baseline
ManyBody
10.0 Baseline 2D
10.0 Baseline Perturb 2D
10.0 ManyBody Perturb 2D
10.0 ManyBody 2D
Ejecta mass [$M_\odot$]
Electron fraction

Y_e Histograms: 16-solar-mass model

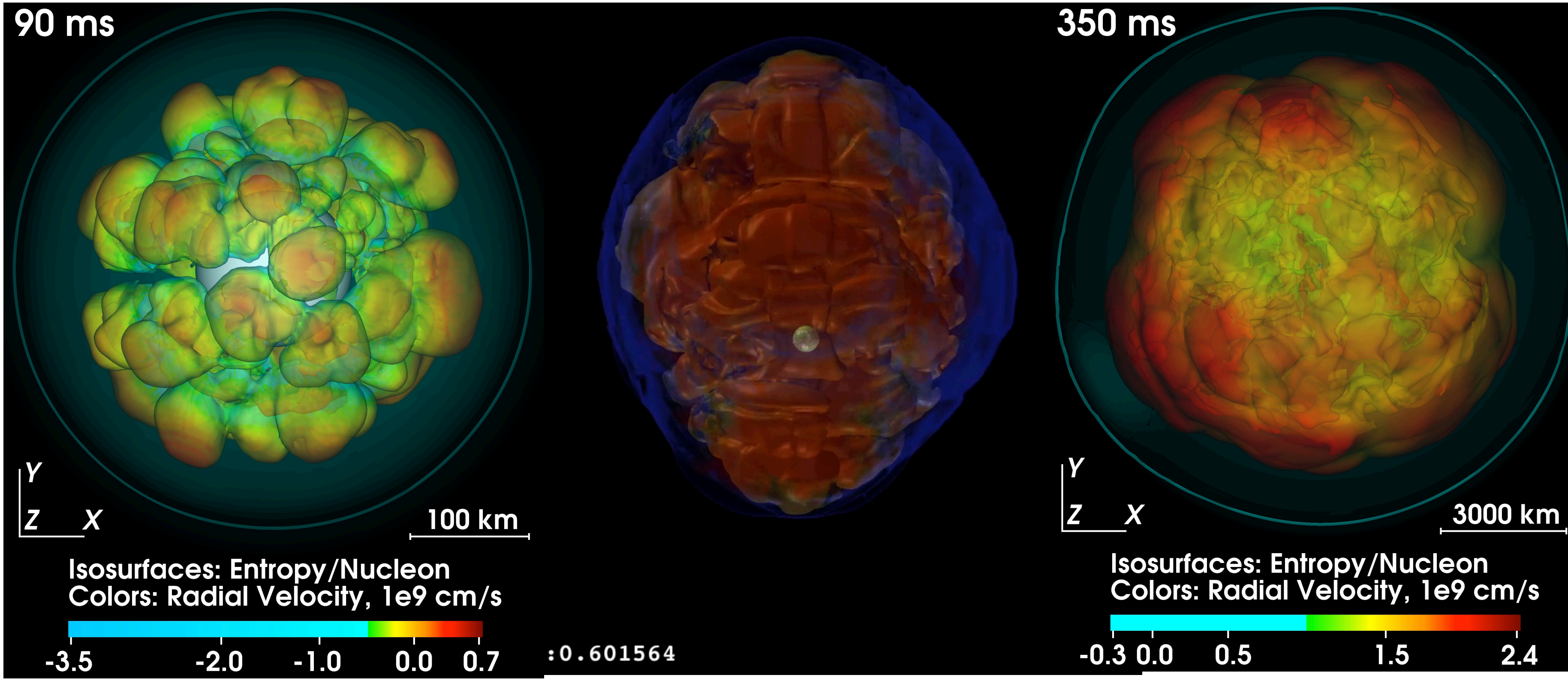
2D

3D

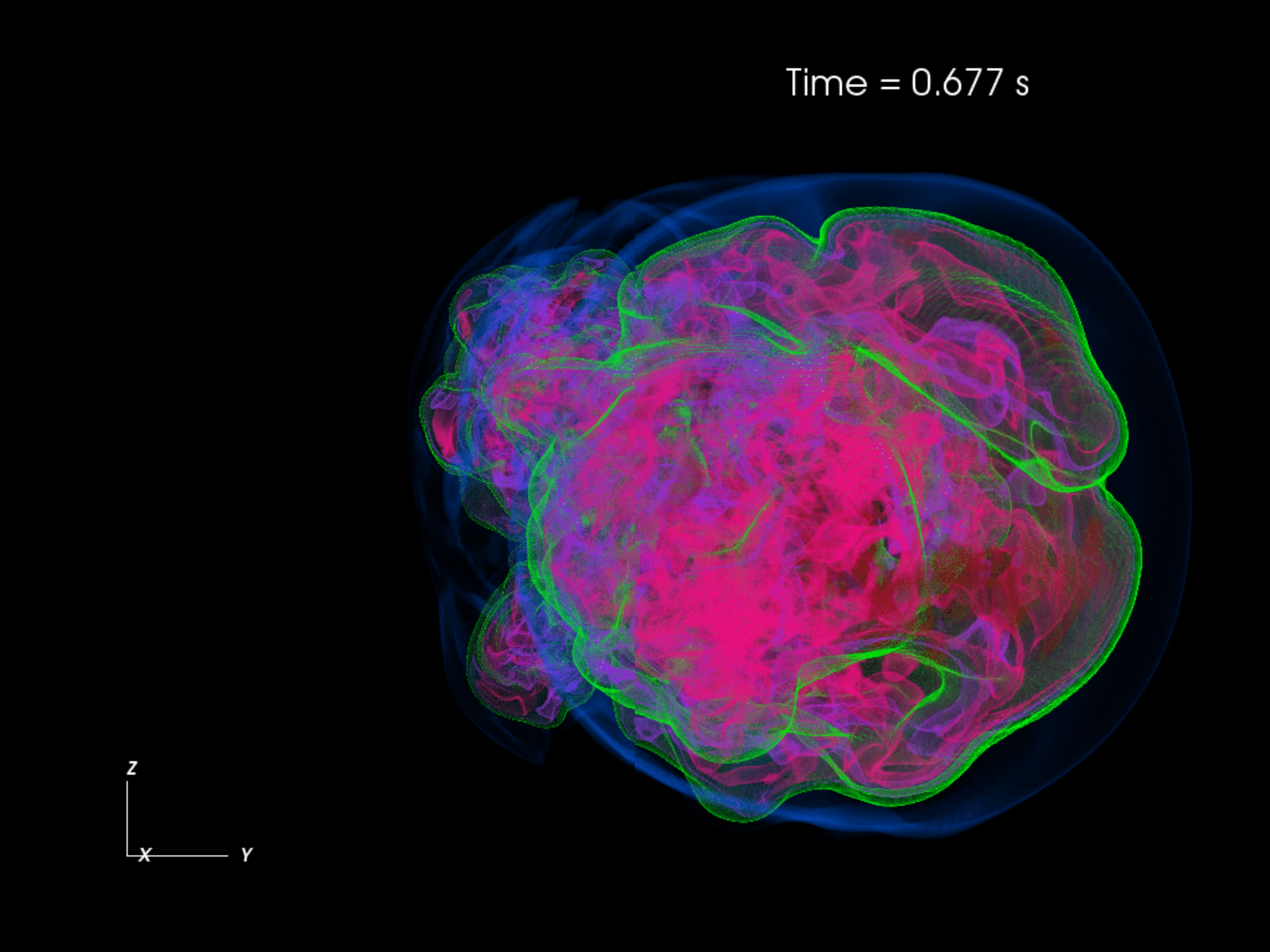
Vartanyan et al. 2018

Melson et al. (2015, MPA) – 3D (with strangeness correction - likely too large)

Lentz et al. (2015) - ORNL



Summa et al. 2017 (MPA) – rapidly rotating 3D models (but pulsar birth spins?)



Time = 0.677 s
Z
X
Y

Radice, Burrows et al. (2018) –
11 solar mass