Core-Collapse Supernova Explosions: Some Observables and Diagnostics

Adam Burrows, Josh Dolence, Jeremiah Murphy, Jason Nordhaus, Christian Ott, John Bell, Ann Almgren, Luc Dessart, Eli Livne, Tim Brandt

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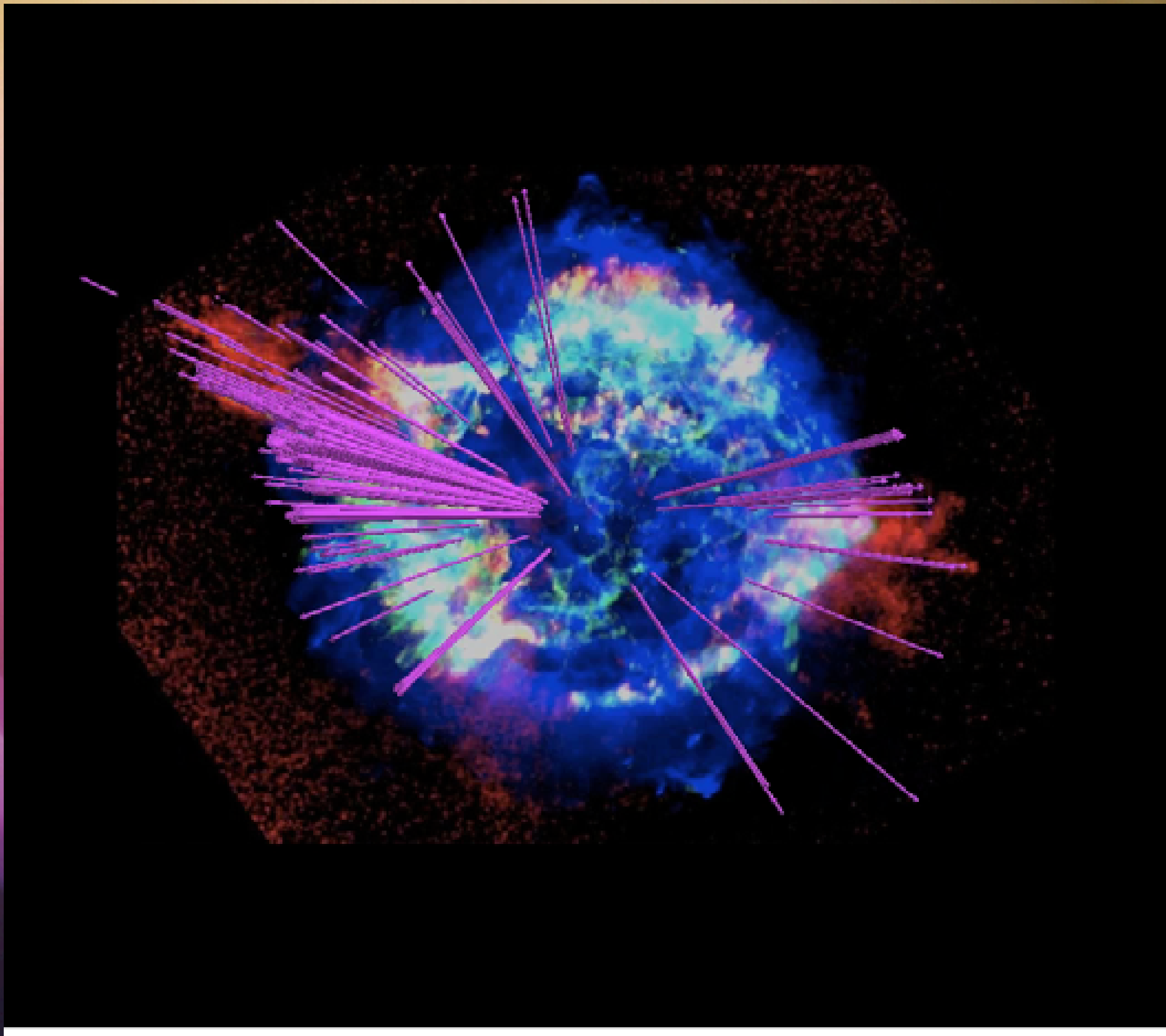
Diagnostics of Explosion

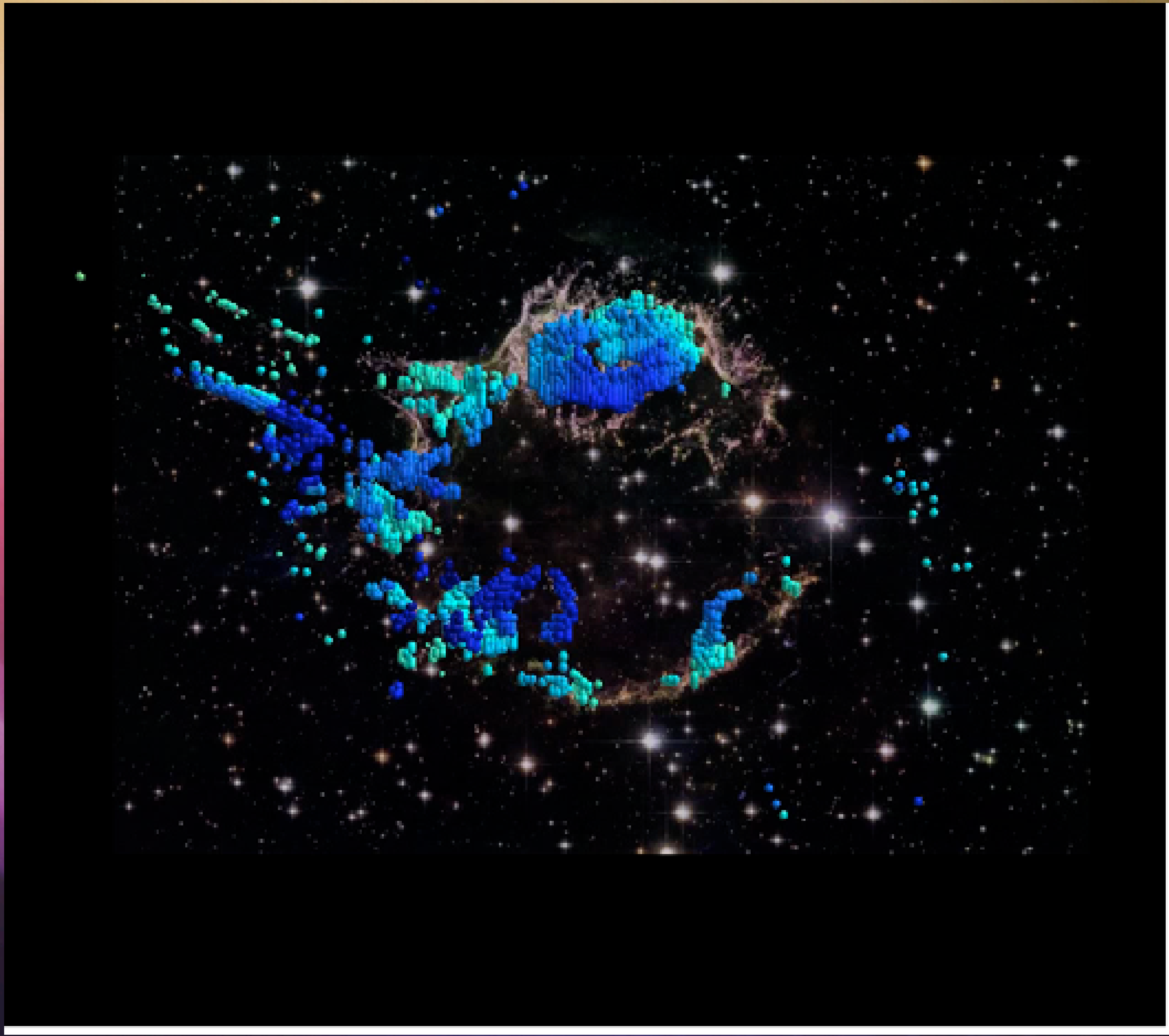
- Morphology of Blasts: Spatial Element/Debris Distribution
- Pulsar Proper Motions (“Kicks”)
- Pulsar Spin Periods
- Neutrinos
- Gravitational Waves
- Nucleosynthesis - R-process ?

Cas A Remnant



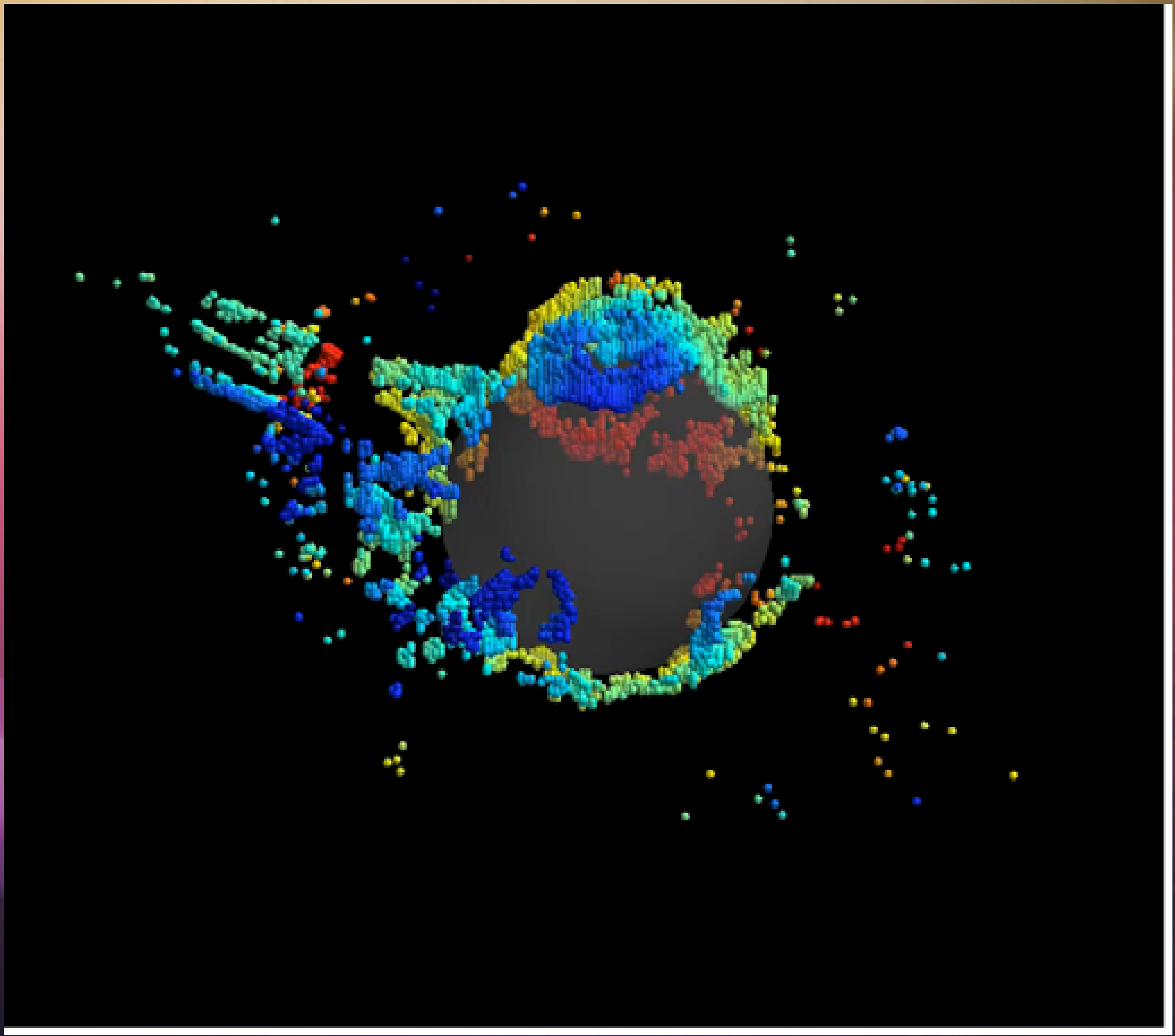
Fesen/Milisavljevic et al. 2011

Cas A Remnant



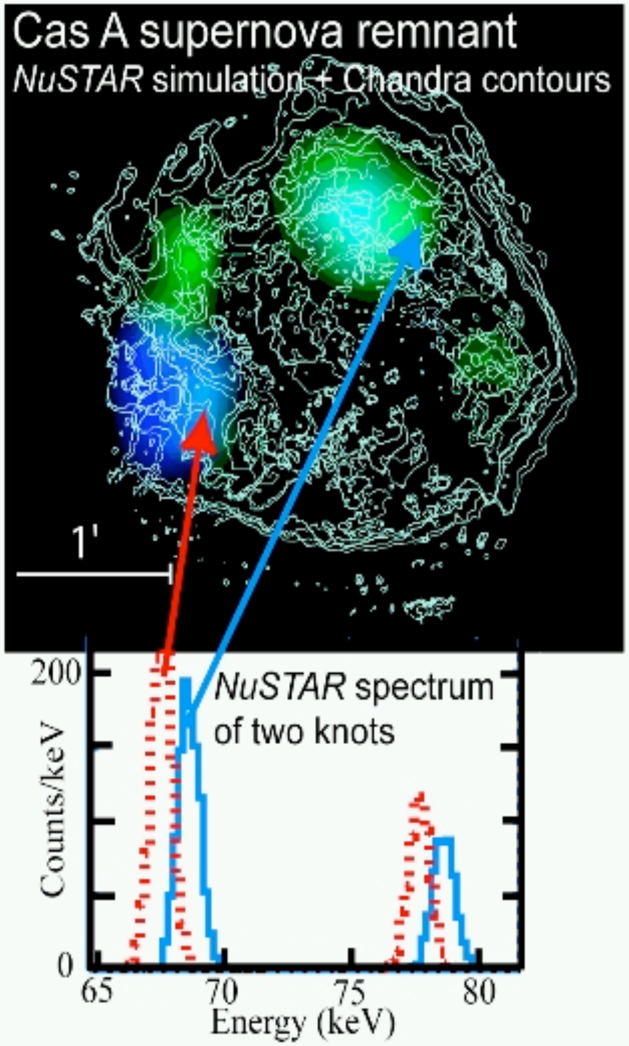
Fesen/Milisavljevic et al. 2011

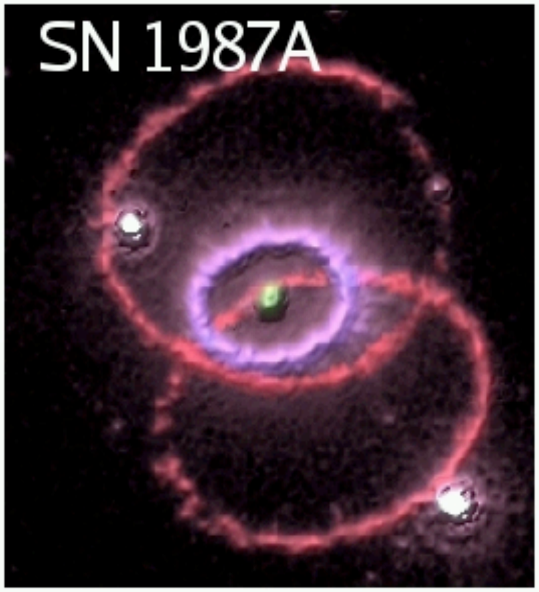
Cas A Remnant



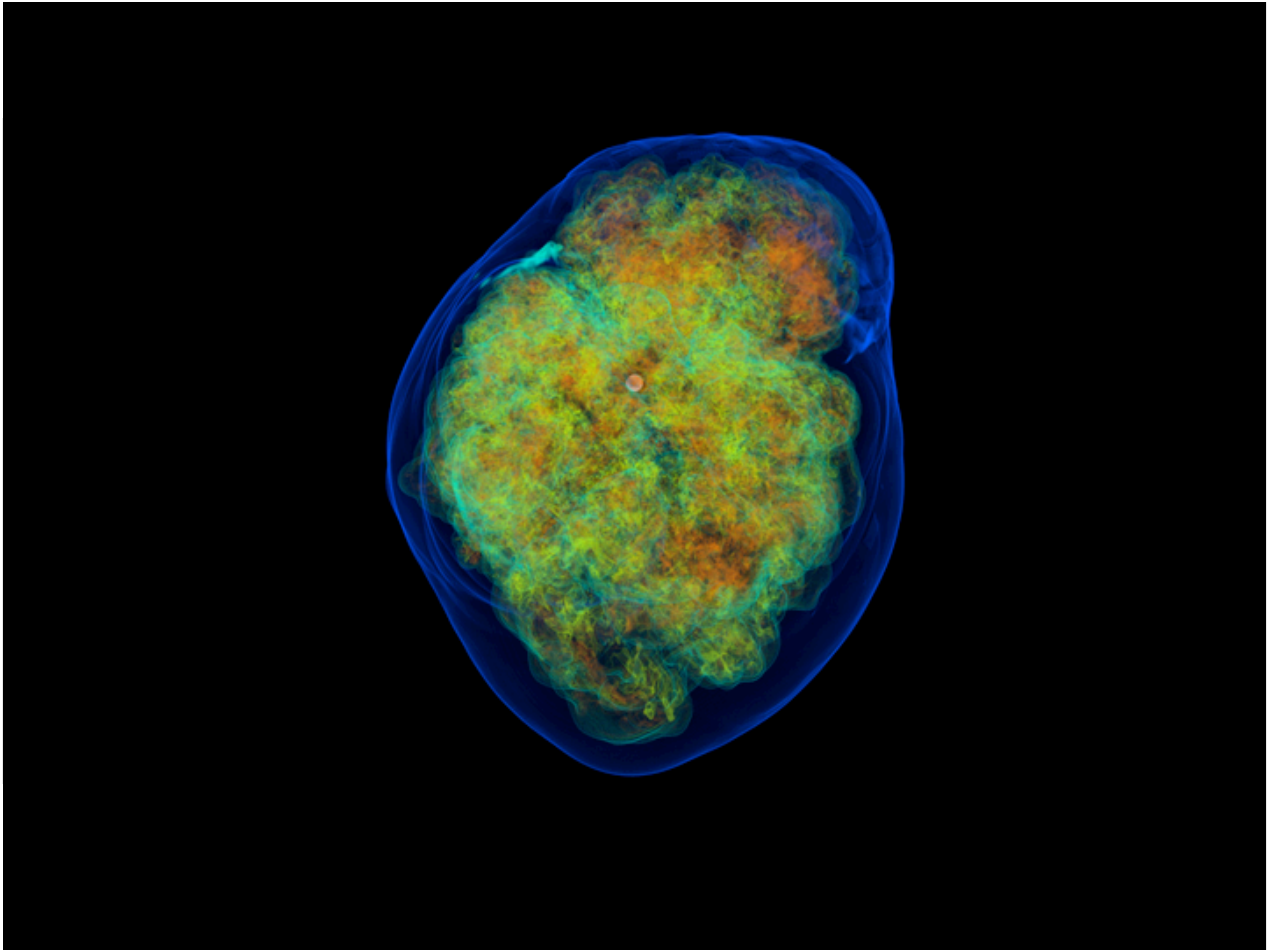
Fesen/Milisavljevic et al. 2011

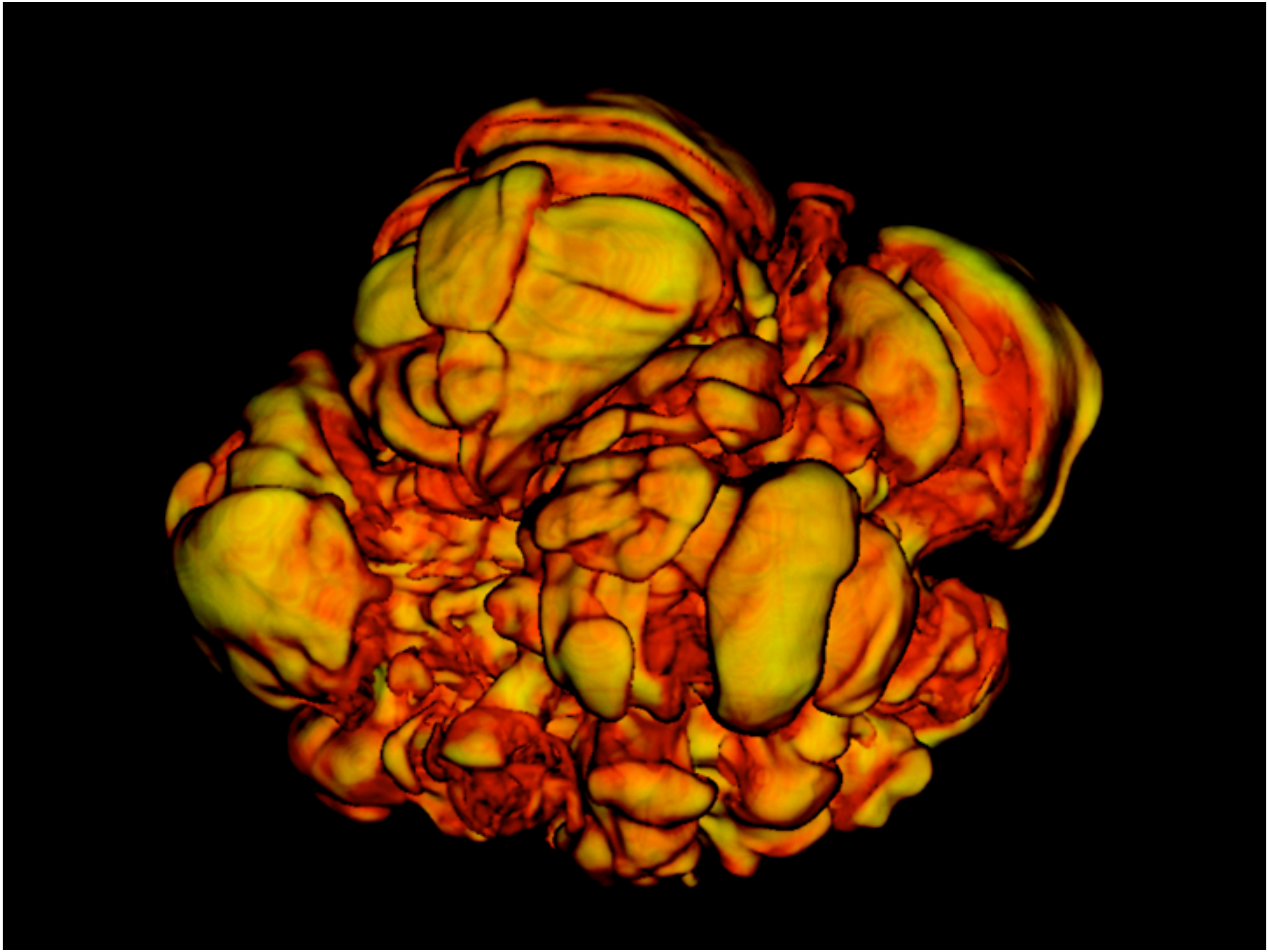
NuSTAR will map the remnants of recent supernova explosions, testing theories of where the elements are born





NuSTAR will measure and map the ^{44}Ti lines at 68 and 78 keV in historic remnants:
Tycho, Kepler, Cas A and SN1987A

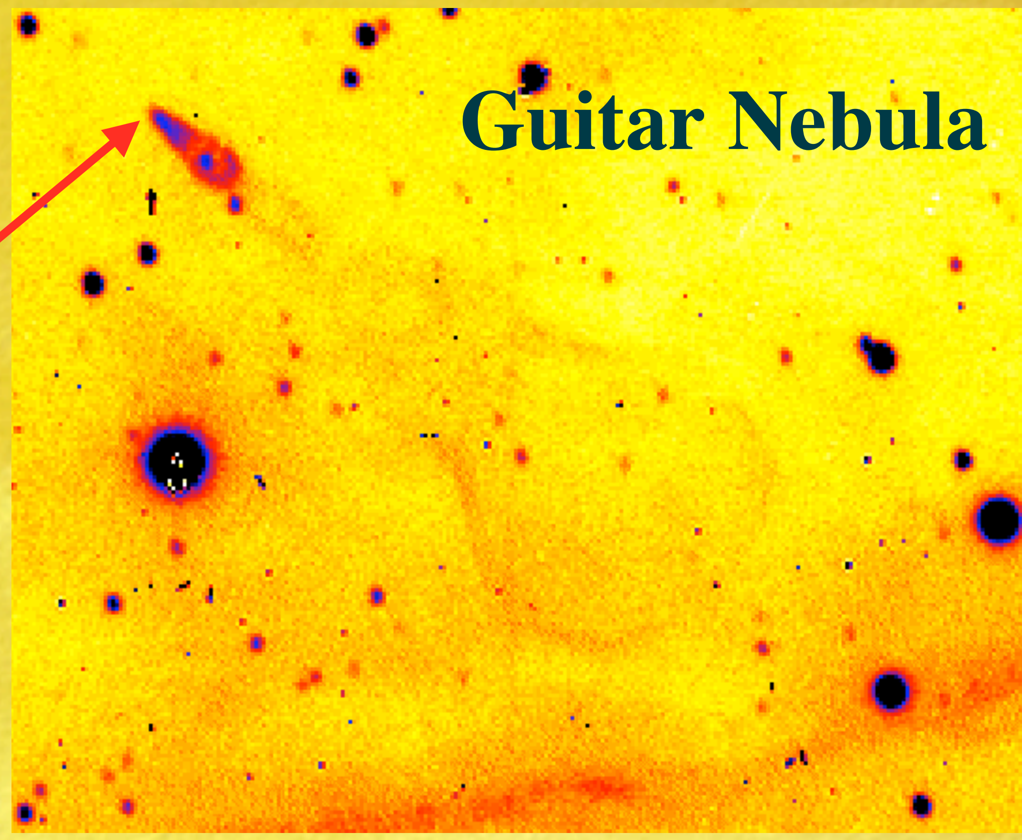




Pulsar Kicks

- Hydrodynamic Mechanism Seems Natural - “Simple” Recoil
- Net Neutrino momentum component may be small
- No need for exotic mechanisms (Harrison-Tademaru, parity violation, B-fields, ….)

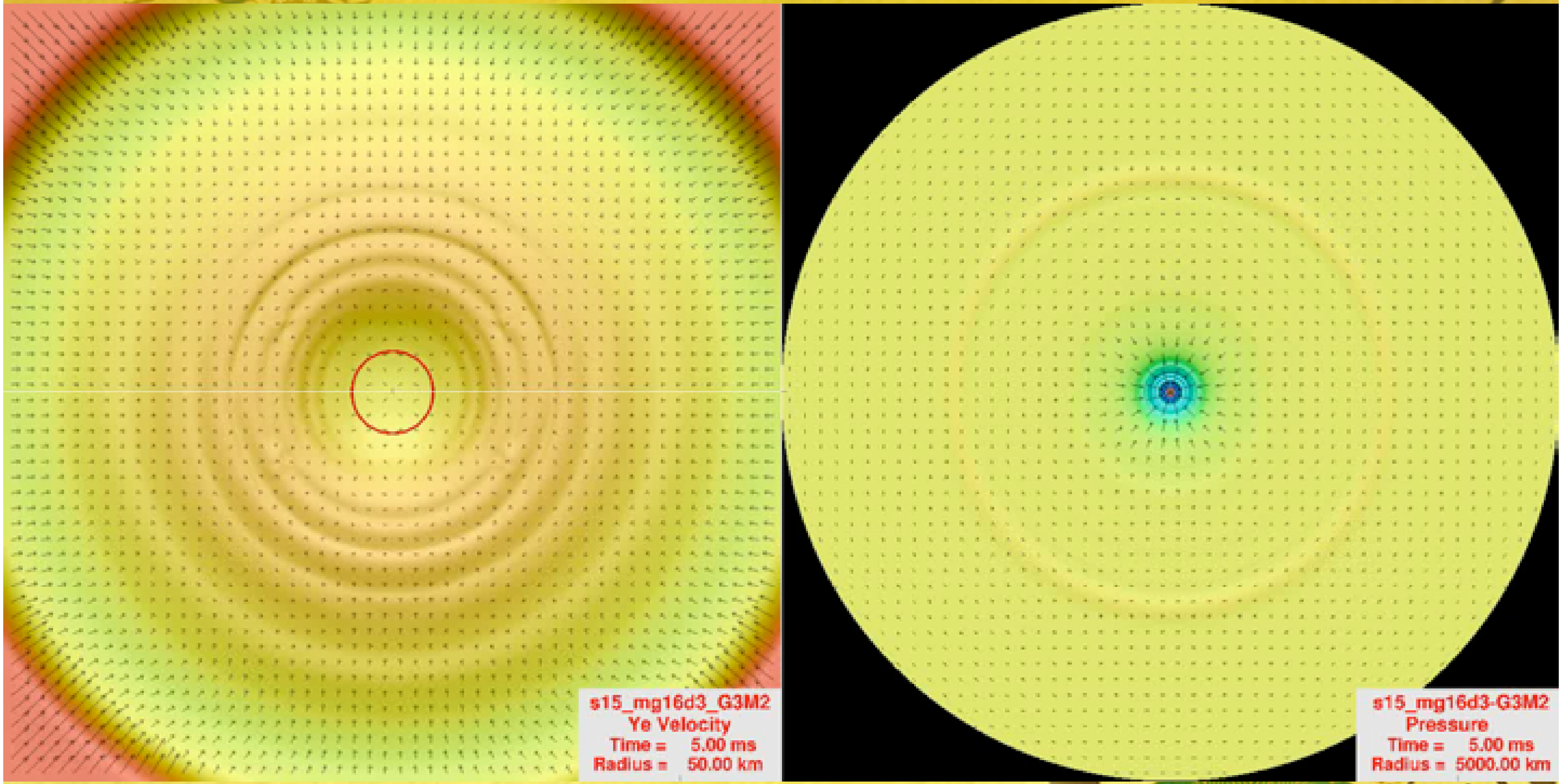
Pulsar Recoil: A Generic Feature



Cordes, Romani, Lundgren '93

<u>Pulsar Kicks:</u>
Pulsar B2224+65
and Bow Shock
$V \geq 1000$ km s^{-1}

The Origin of Pulsar Kicks in Hydrodynamic (and neutrino?) Recoil

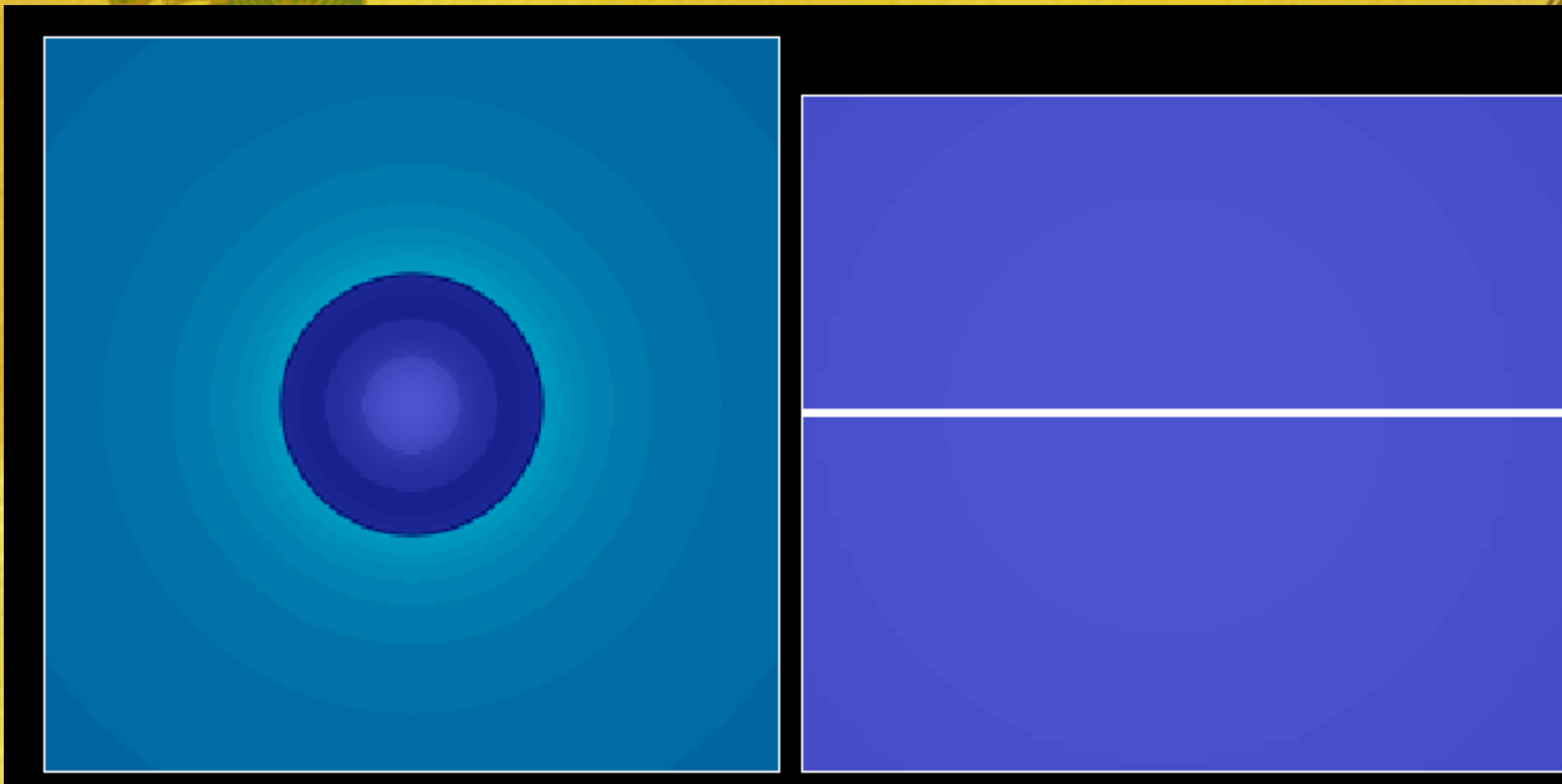


Nordhaus, Burrows, & Ott 2010

Acceleration ~ 500 km/s^2

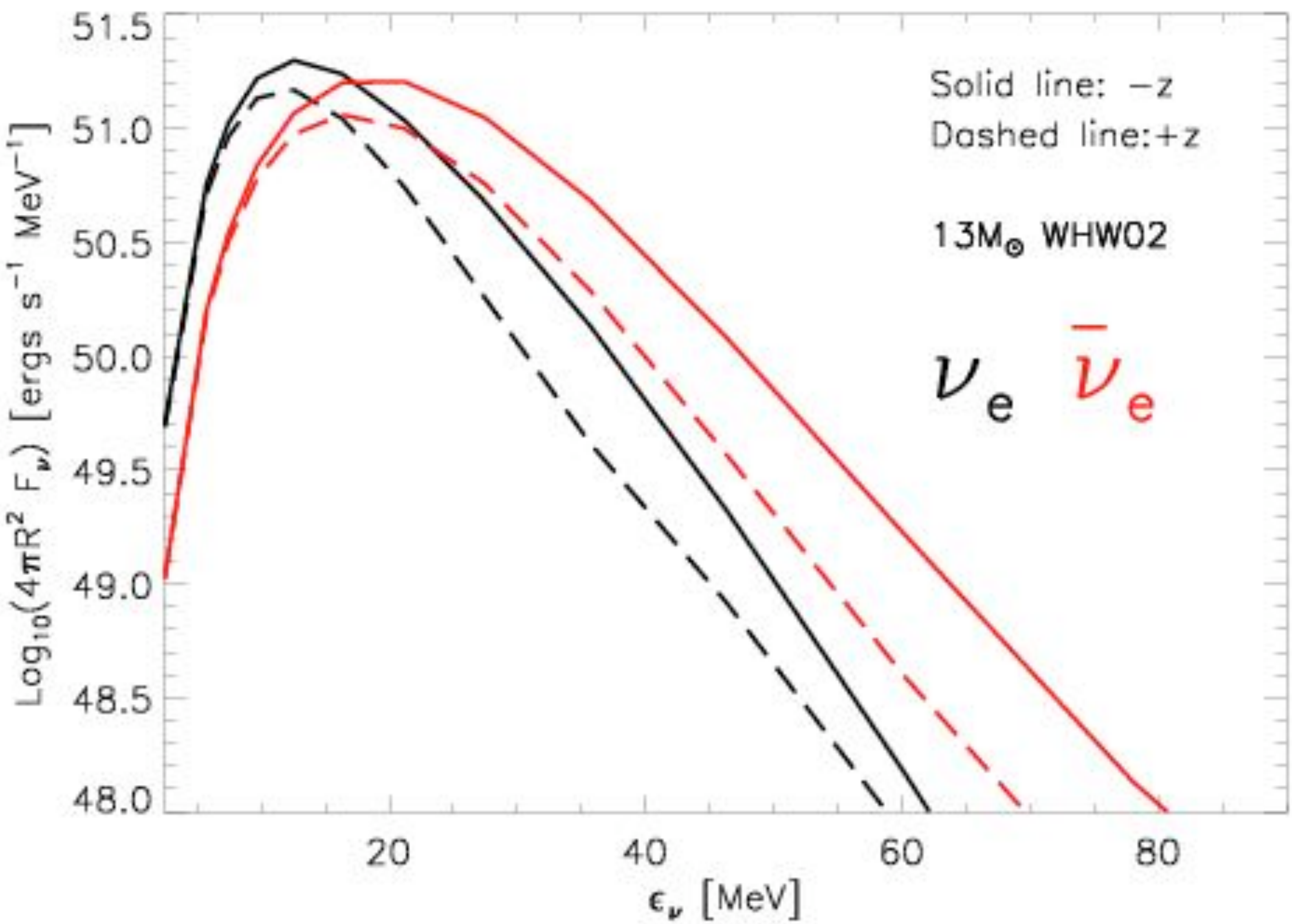
See also pioneering work of Scheck et al., for an extensive suite of related simulations

The Origin of Pulsar Kicks in Hydrodynamic Recoil



Nordhaus, Brandt, & Burrows 2012

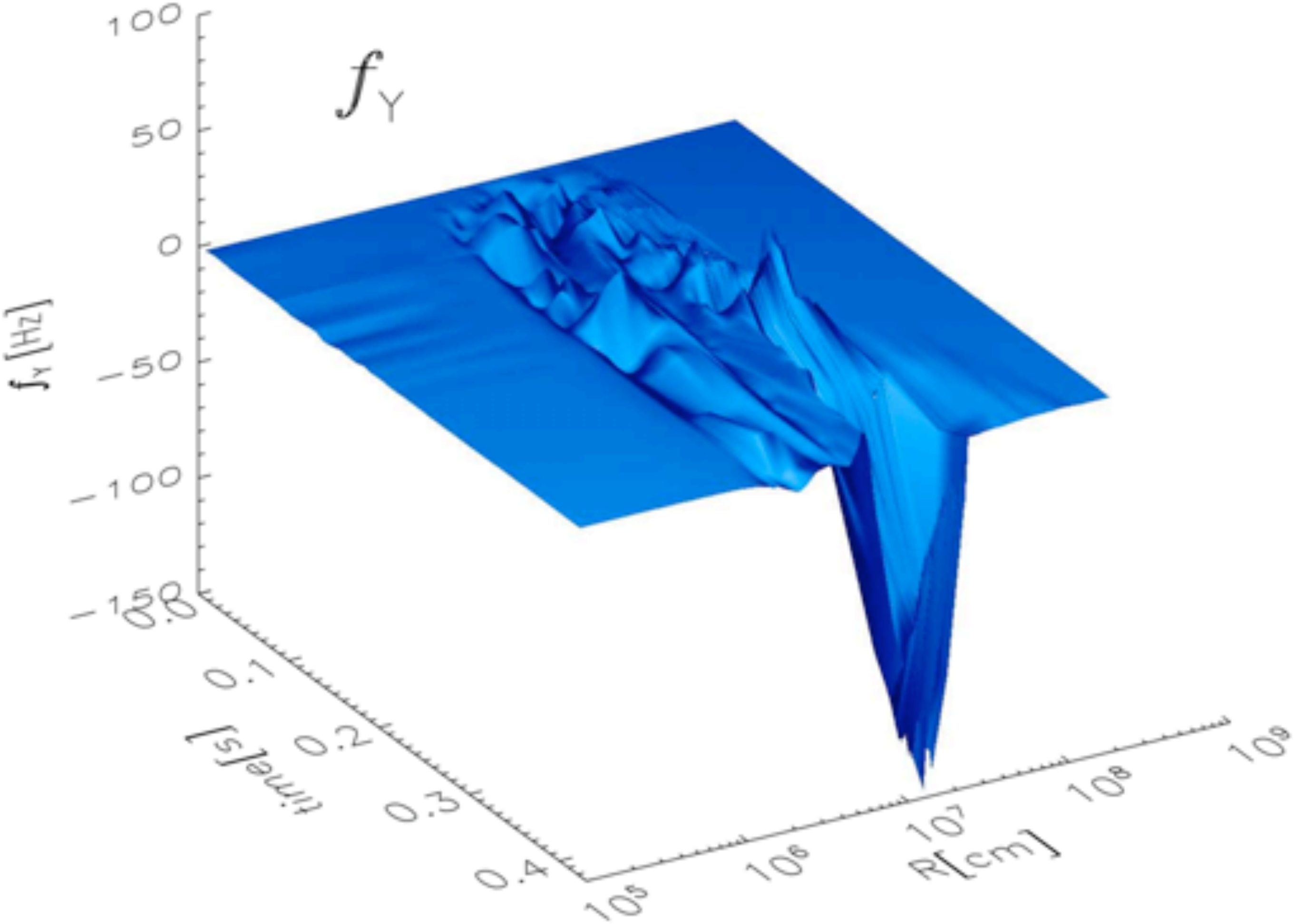
Top-Bottom Asymmetry in Neutrino Luminosity after Explosion: Kicks!



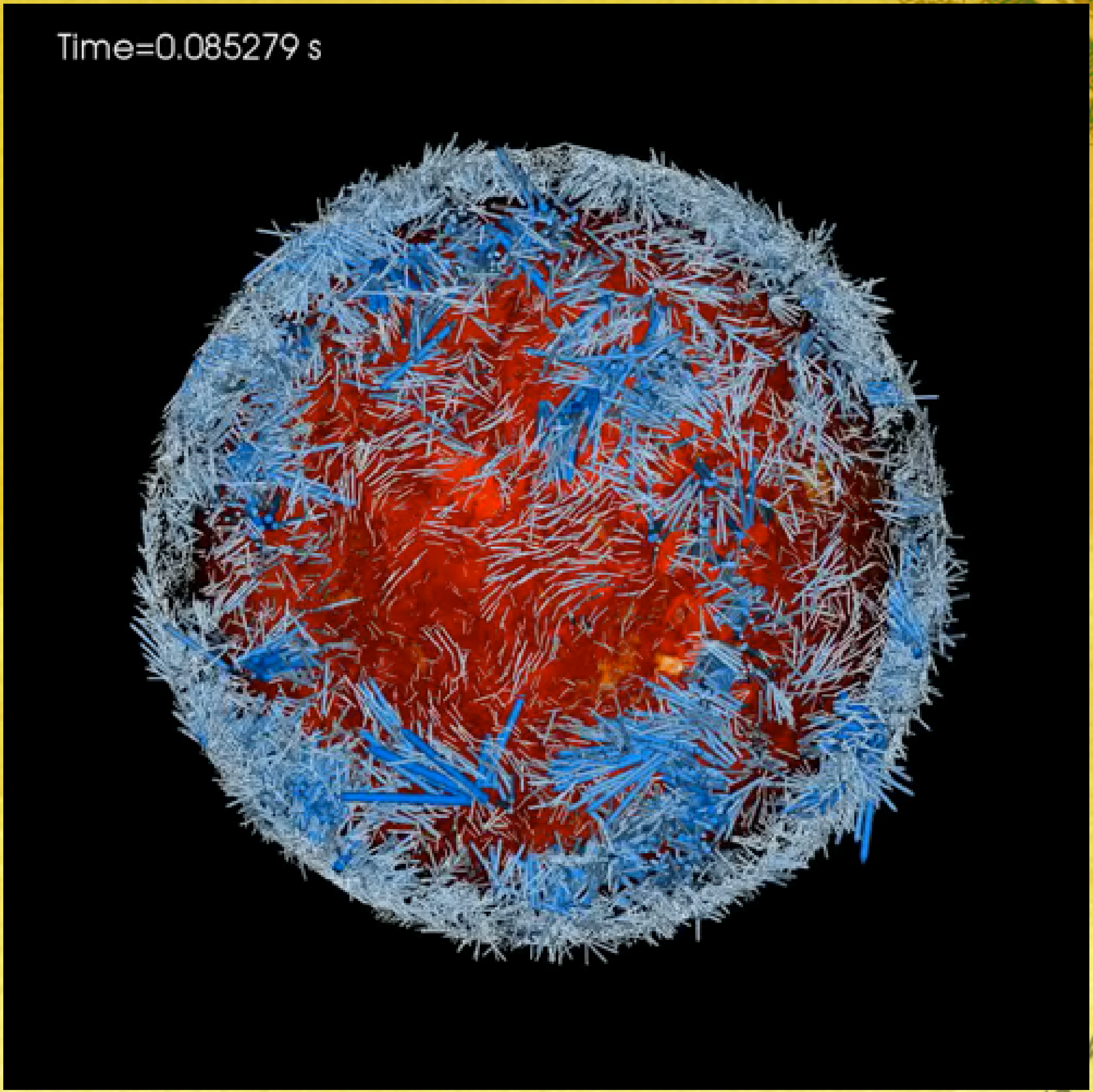
Induced Rotation?

Found and Pioneered by J. Blondin et al.

CASTRO 3D AMR Neutrino-Driven Explosion Model: Induced Spin?



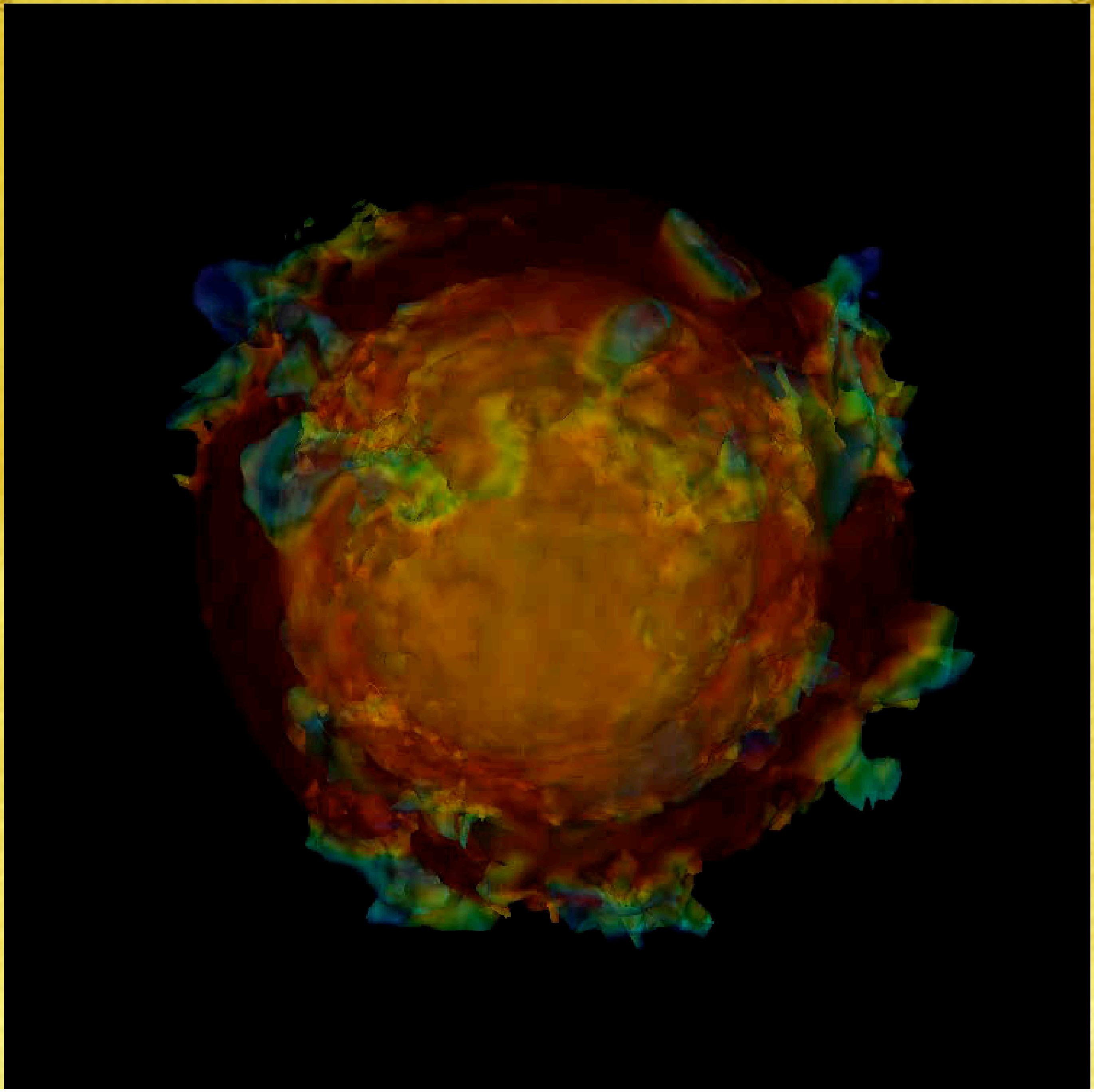
CASTRO 3D AMR Neutrino-Driven Explosion Model: Induced Spin?



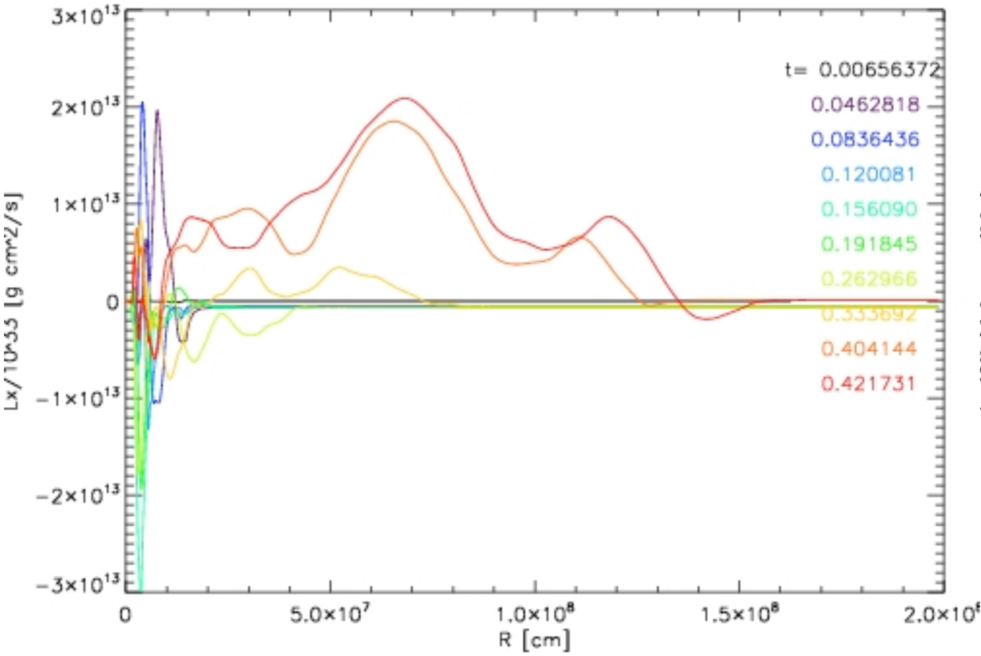
Rantsiou et al., Ap.J. 732, 57, 2010

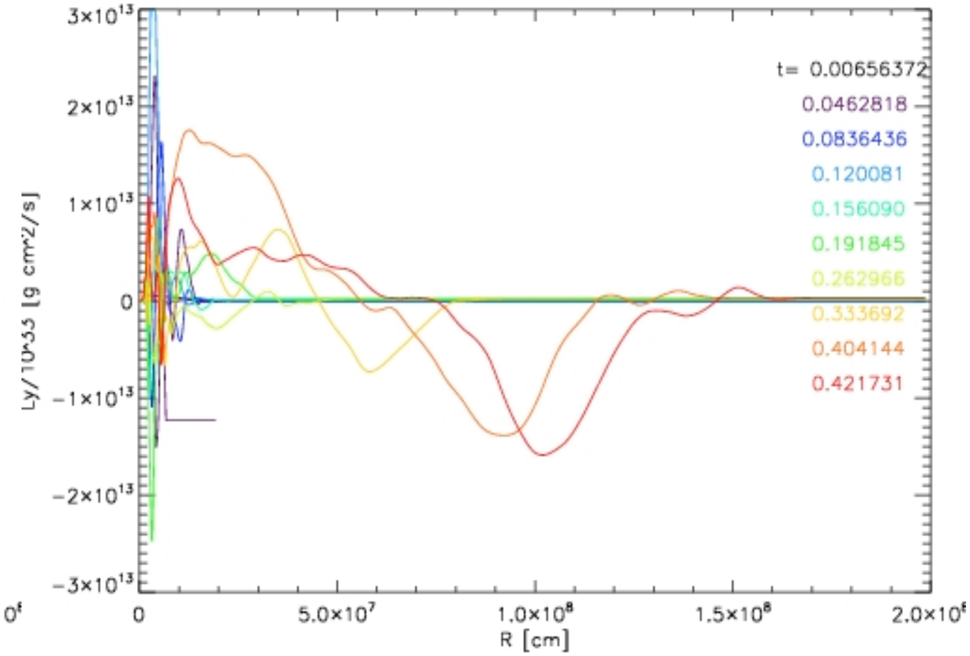
"1.7"

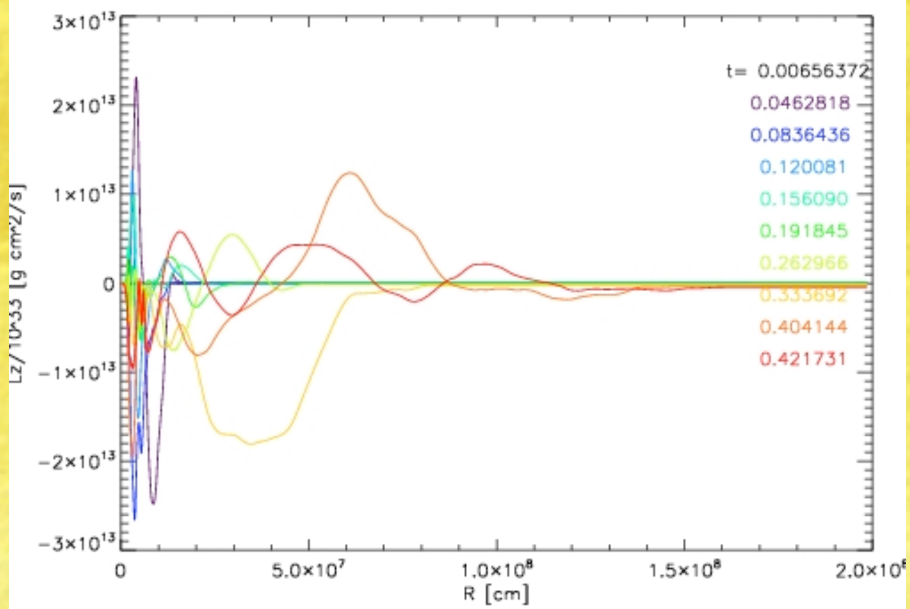
CASTRO 3D AMR Neutrino-Driven Explosion Model: Induced Spin?



Integrated Angular Momentum from 3D simulations: Induced Spin?

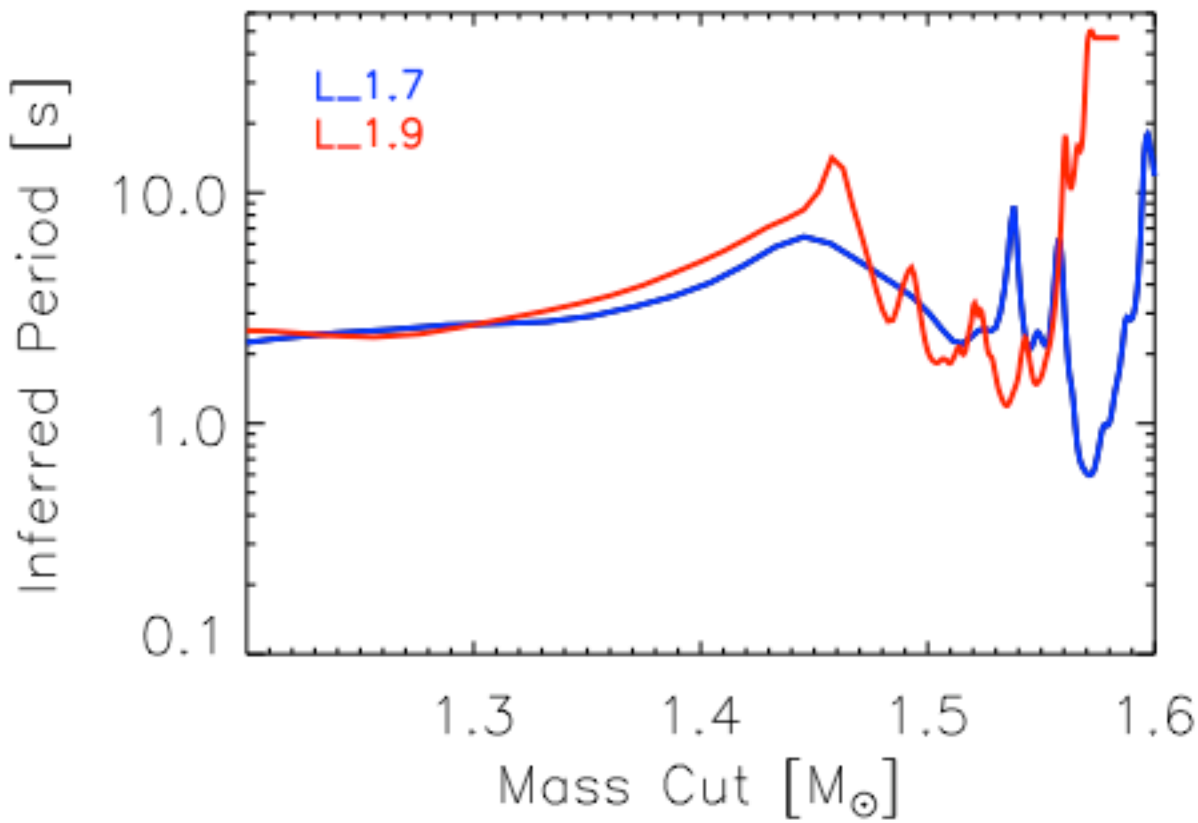






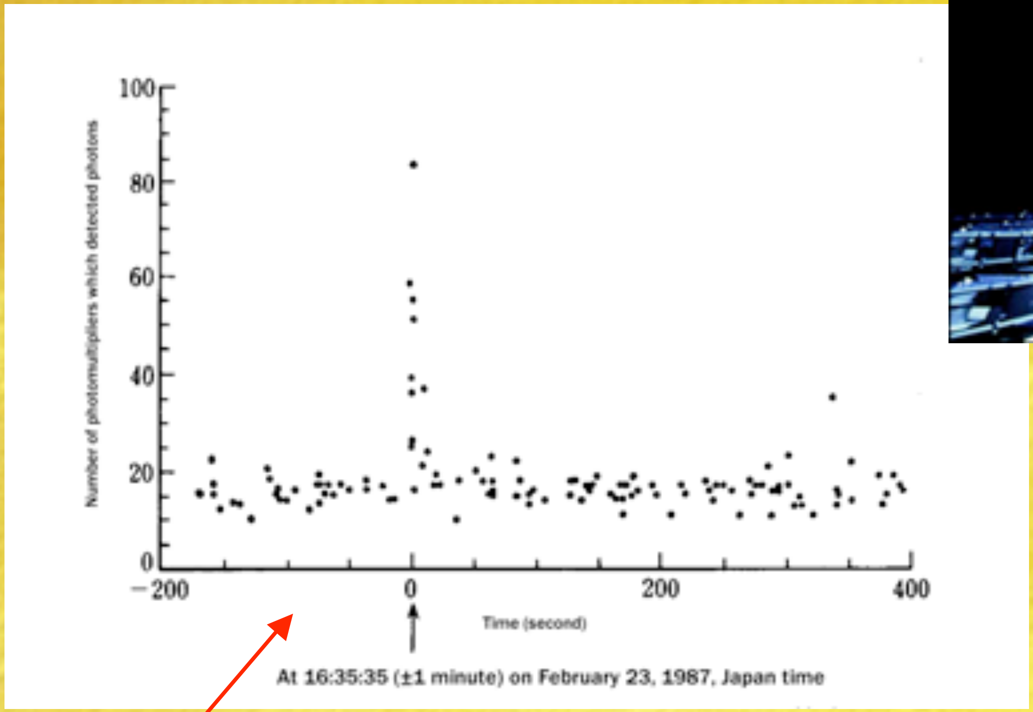
Rantsiou et al., Ap.J. 732, 57, 2010

CASTRO 3D AMR Neutrino-Driven Explosion Model: Induced Spin (1.7 vs. 1.9)?

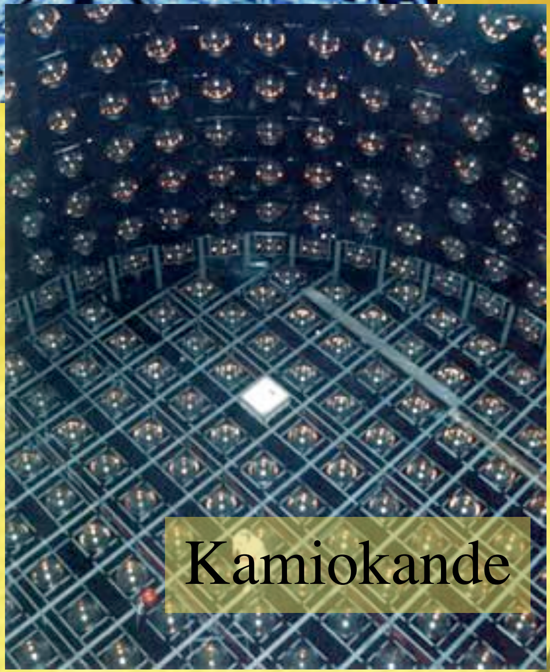


Neutrino Bursts/Signatures

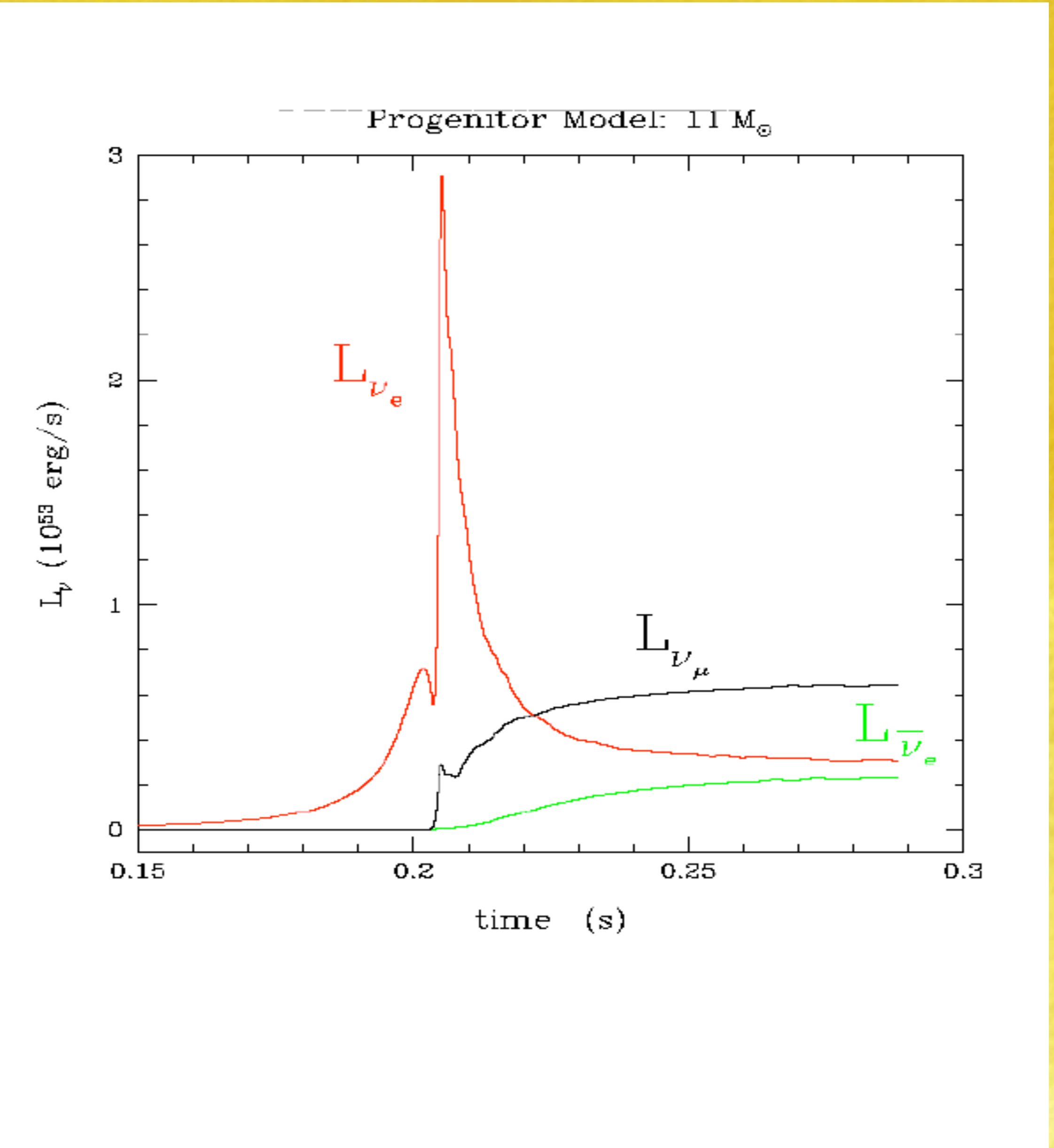
Core-Collapse Neutrinos Detected

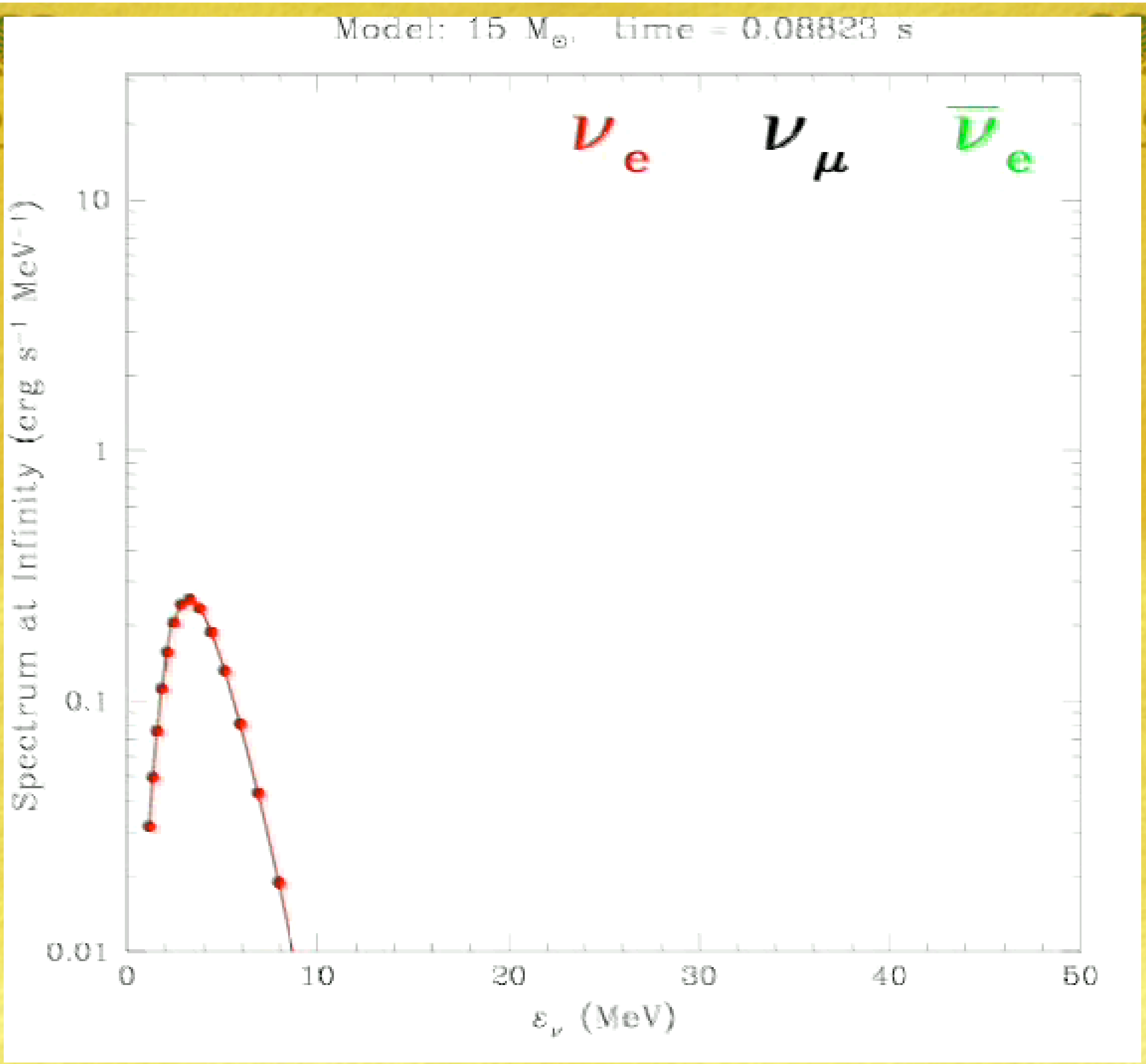


Kamioka II

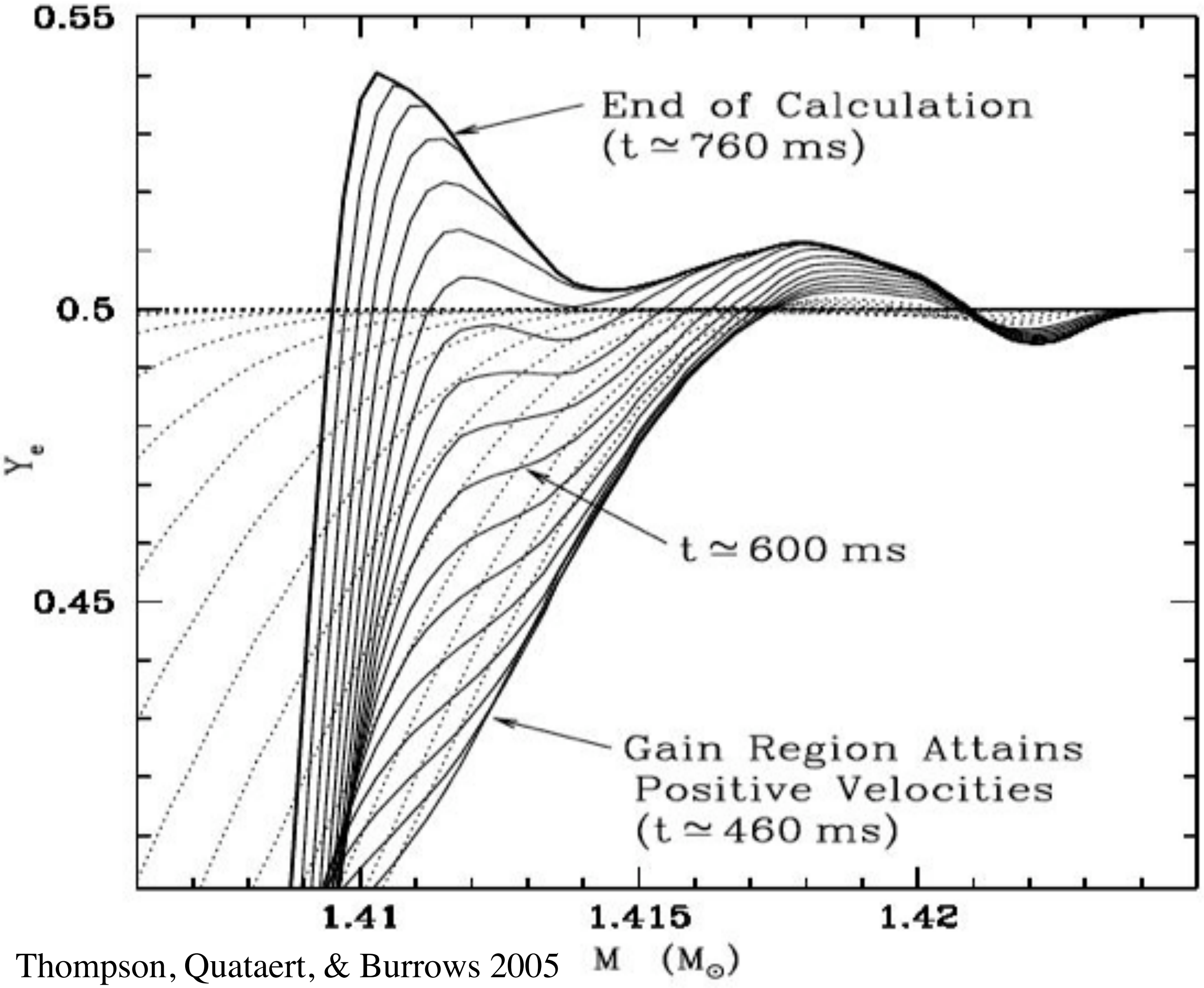


Breakout Burst of Neutrinos: Precision Boltzmann Transfer




Model: 15 M⊙ time = 0.08823 s
νe
νμ
ν̄e
Spectrum at Infinity (erg s⁻¹ MeV⁻¹)
10
1
0.1
0.01
0
10
20
30
40
50
εν (MeV)

Ejecting Some $Y_e > 0.5$ Material



Thompson, Quataert, & Burrows 2005

Multi-Angle, Multi-group, Time-Dependent Transport in 2D SN Simulations

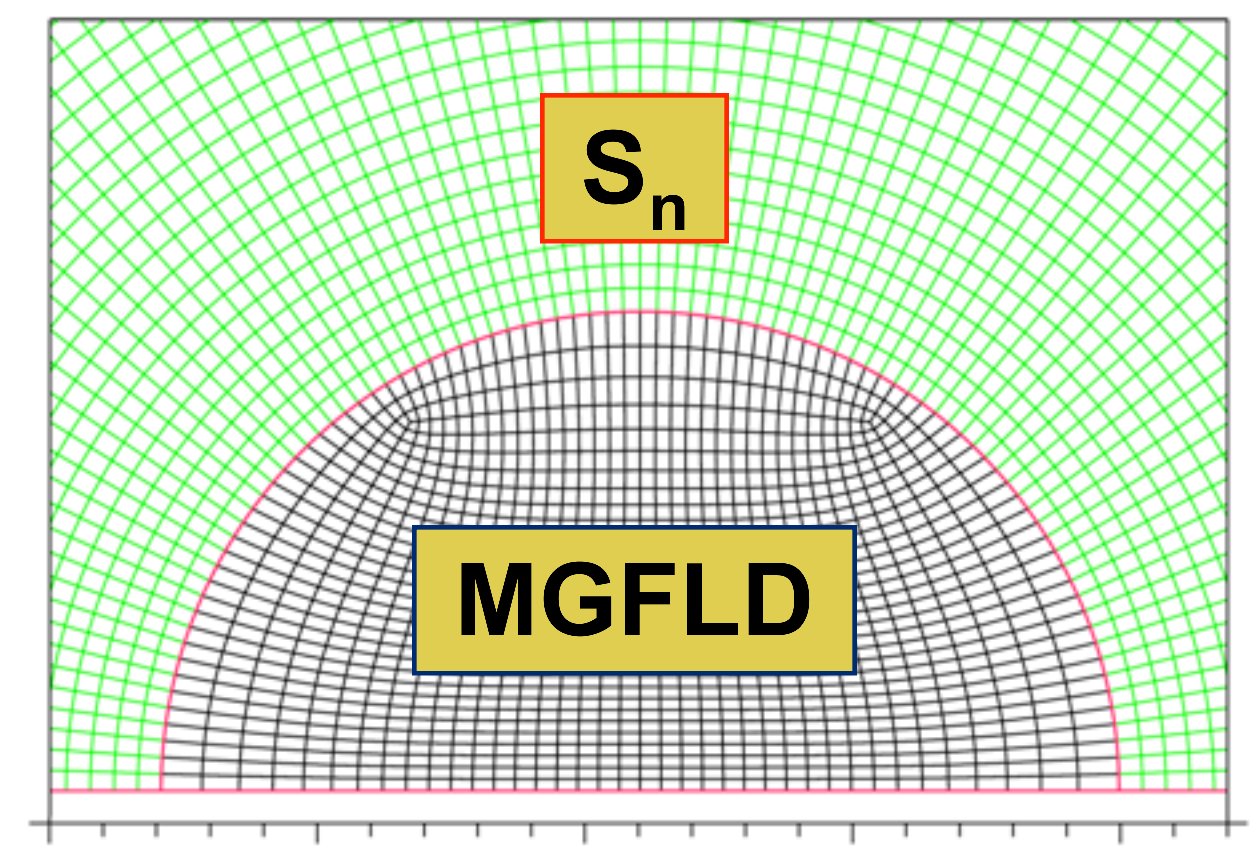
Ott et al. 2008

Modifications to the Solver

[Ott et al. 2008, arxiv:0804.239, ApJ 682, 1277, 2008]

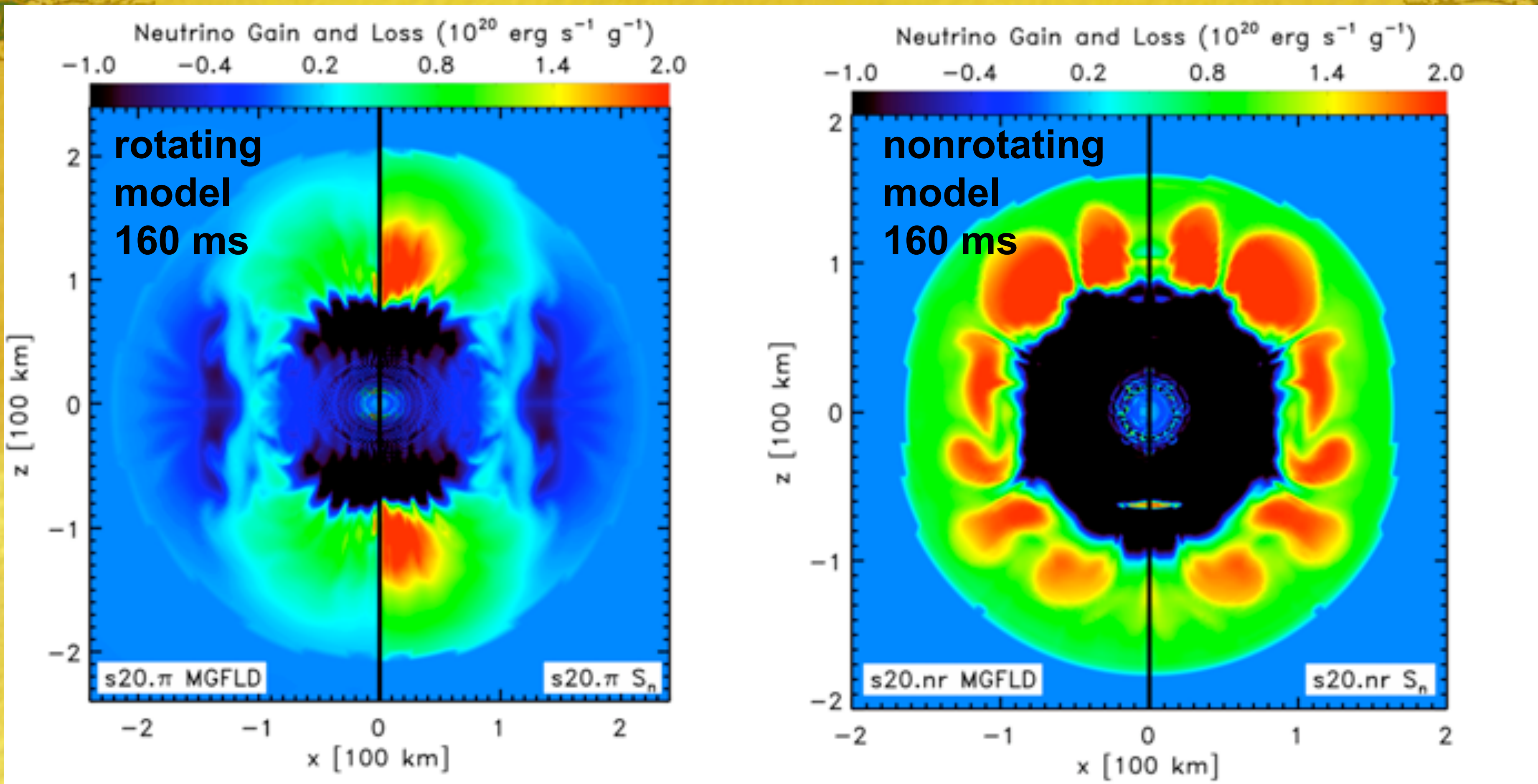
- S_n – MGFLD hybrid scheme:
  - S_n solver in VULCAN converges slowly at high optical depth.
    -> time step limitation.
  - Idea:
    Use MGFLD at high optical depths and transition to Sn at intermediate optical depth.
  - Set up boundary data using to Eddington approximation:

$$I(\vec{n}) = J_{\mathrm{MGFLD}} + 3(\vec{n} \cdot \vec{H}_{\mathrm{MGFLD}})$$



- Matching at τ ≥ 2, R = 20 km.
- Efficient at high optical depths and accurate in semi-transparent regions.

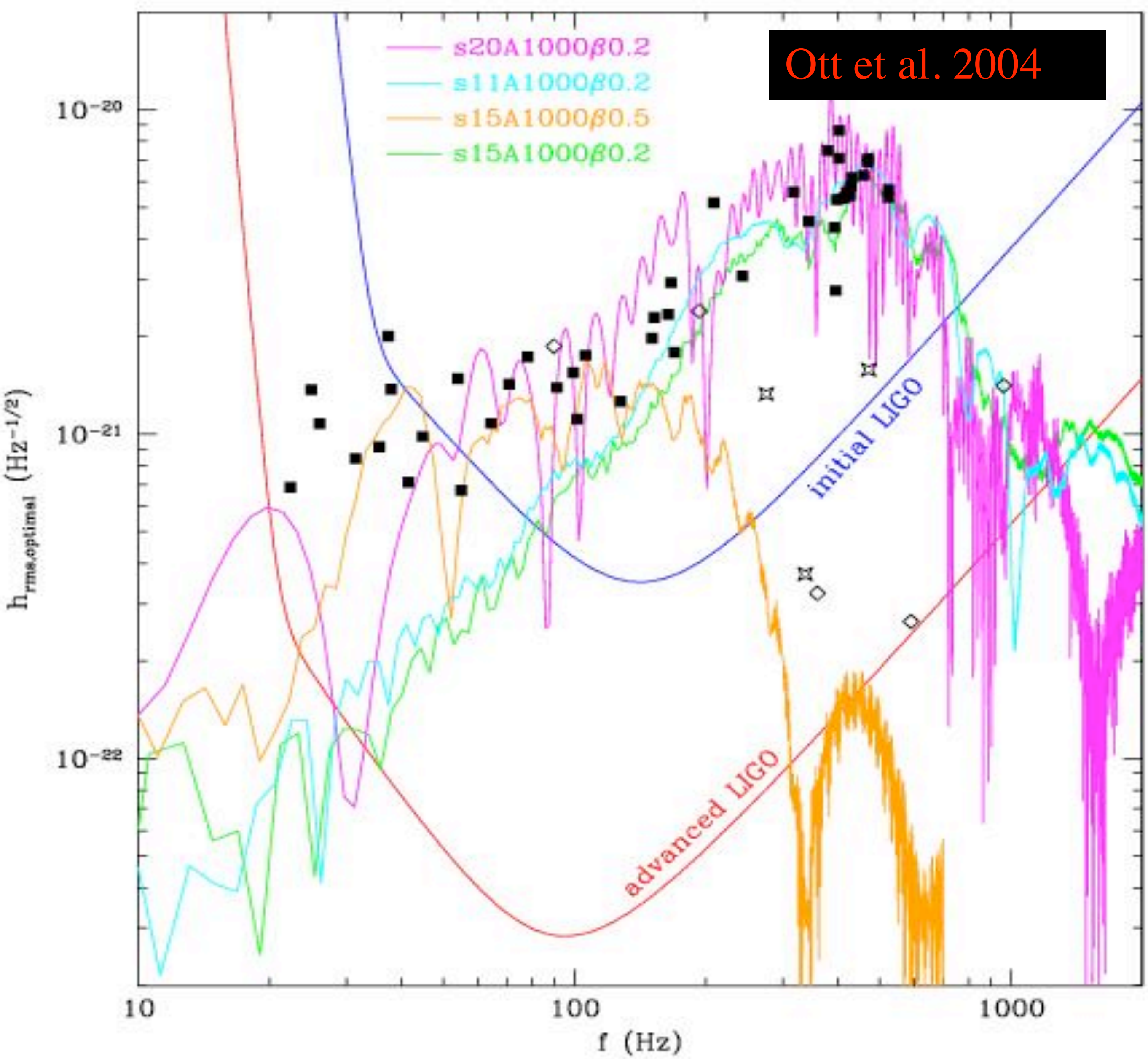
Neutrino Energy Deposition

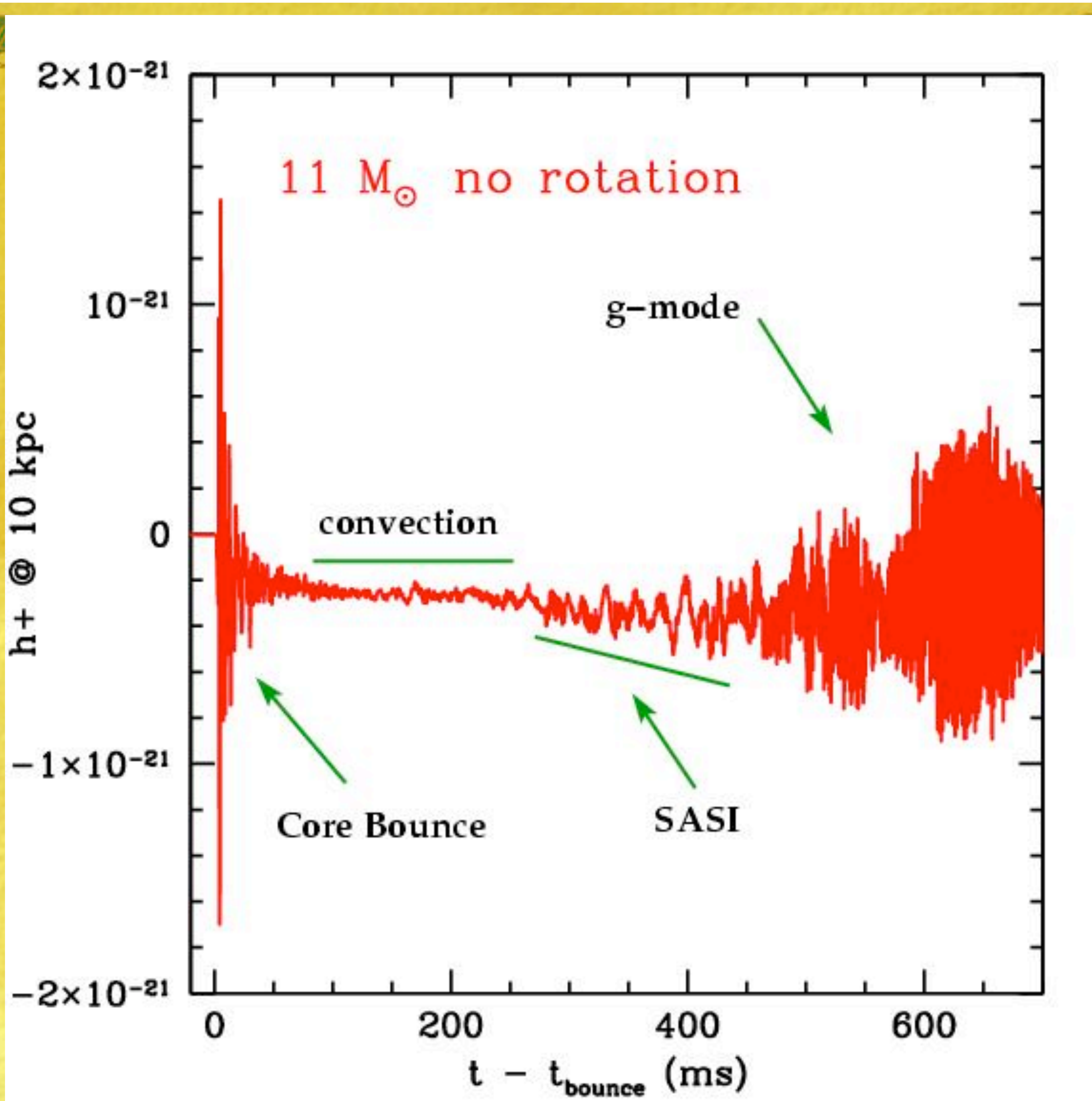


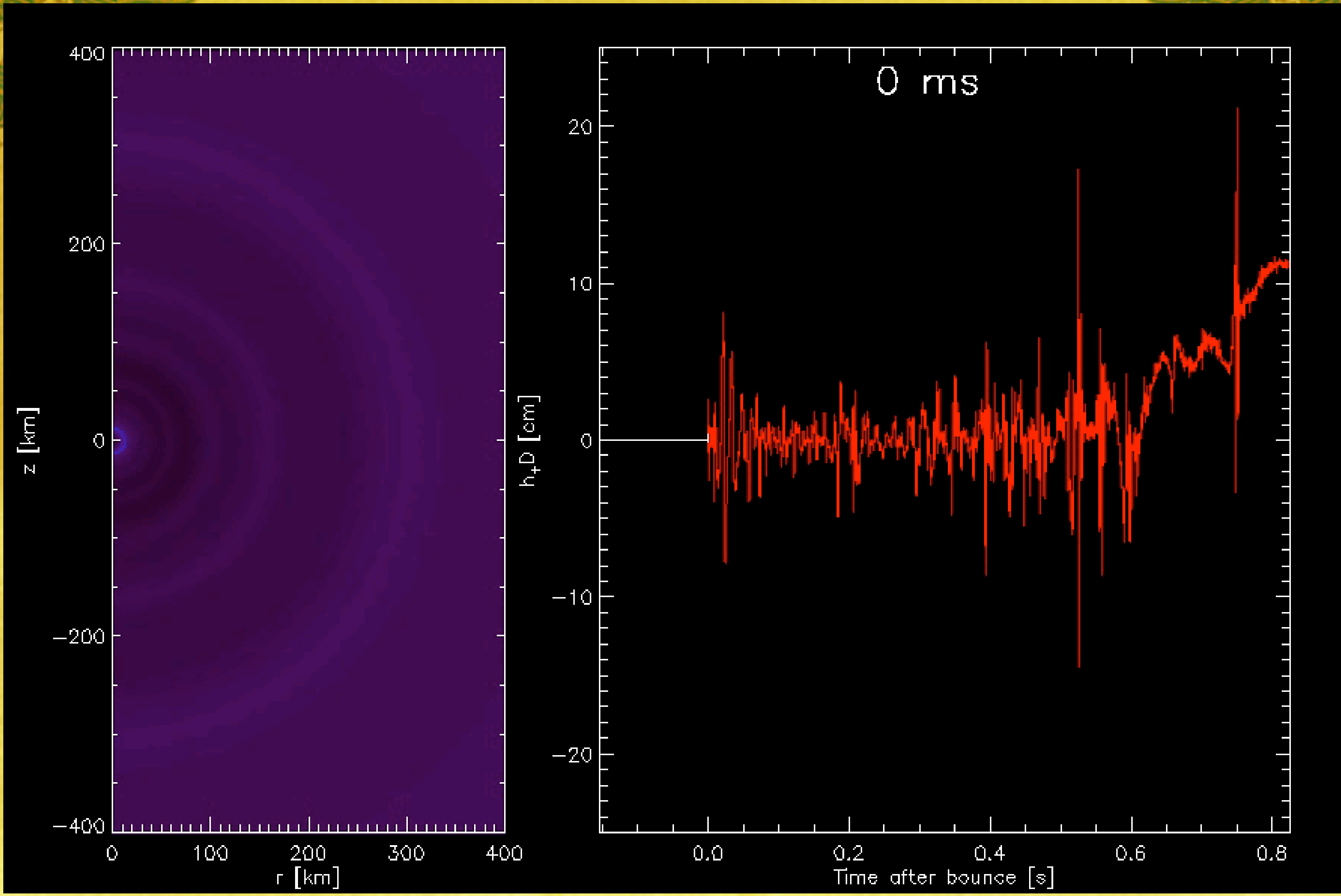
- s20.nr: Little difference between MGFLD and S_n at 160 ms after bounce.
- s20.π: Large (factor ~3) polar differences in specific heating rates.
    - (only ≈ 2% difference; S_n gain < MGFLD gain!)

Gravitational Radiation from Supernovae

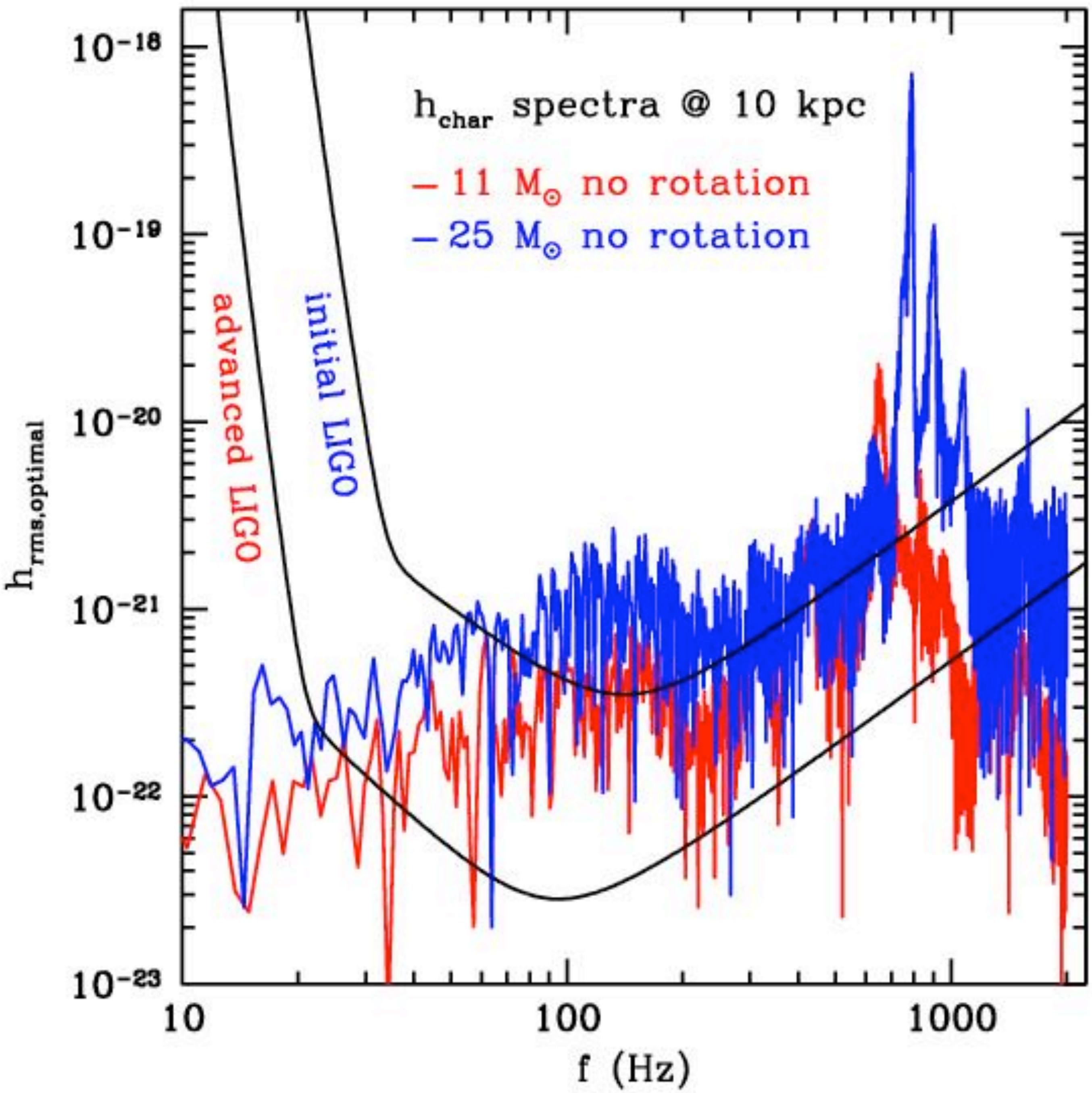
Ott et al. (2004,2006)


Ott et al. 2004
s20A1000β0.2
s11A1000β0.2
s15A1000β0.5
s15A1000β0.2
initial LIGO
advanced LIGO
10^-20
10^-21
10^-22
h_rms,optimal (Hz^-1/2)
10
100
1000
f (Hz)

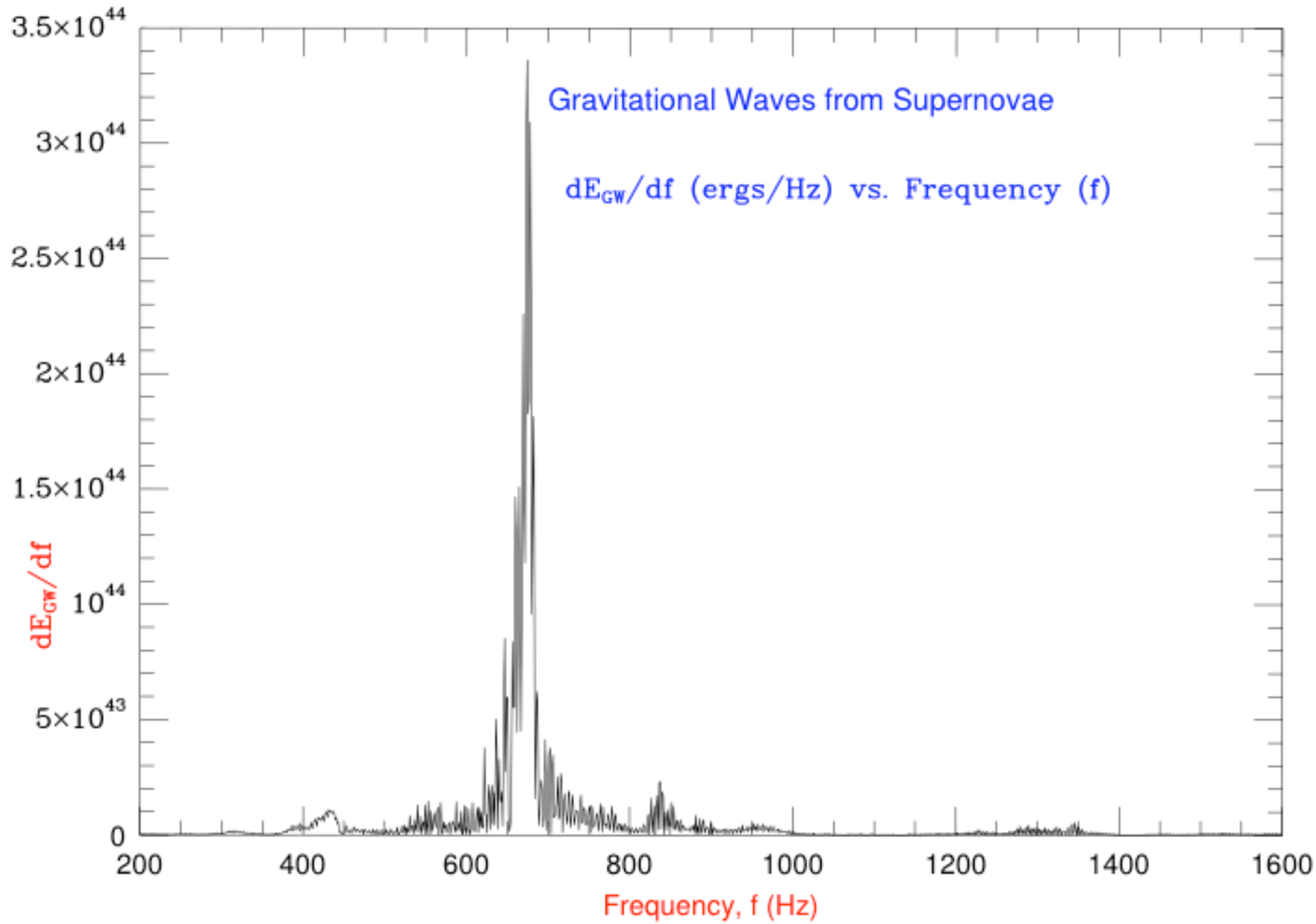

11 $M_\odot$ no rotation
2×10^{-21}
10^{-21}
0
-1×10^{-21}
-2×10^{-21}
h+ @ 10 kpc
g–mode
convection
Core Bounce
SASI
0
200
400
600
$t - t_{bounce}$ (ms)



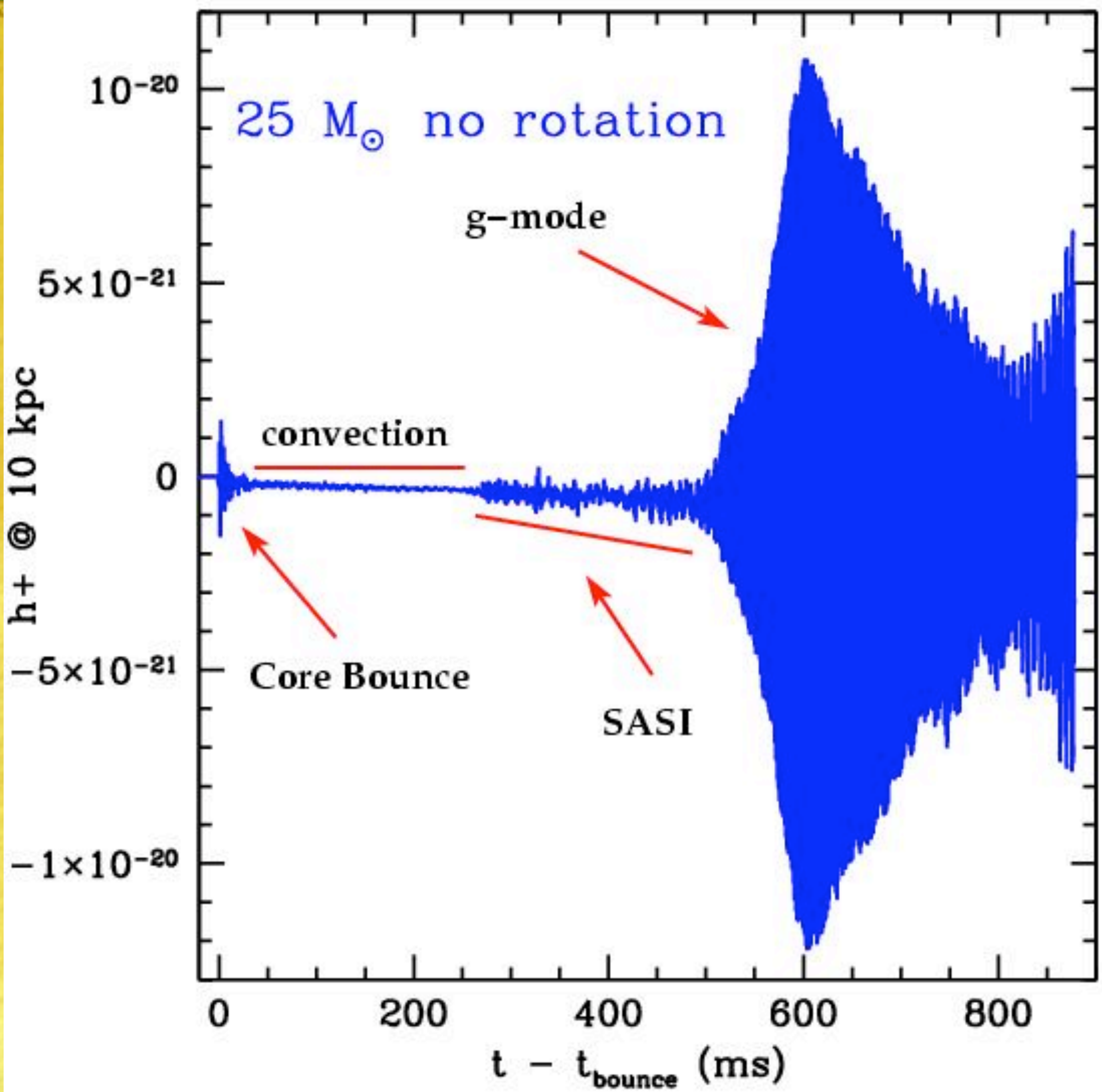
Murphy et al. 2009



h_char spectra @ 10 kpc
– 11 M☉ no rotation
– 25 M☉ no rotation
advanced LIGO
initial LIGO
h_rms,optimal
f (Hz)
10
100
1000
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23



Gravitational Waves from Supernovae
dE_GW/df (ergs/Hz) vs. Frequency (f)
3.5×10^44
3×10^44
2.5×10^44
2×10^44
1.5×10^44
10^44
5×10^43
0
dE_GW/df
200
400
600
800
1000
1200
1400
1600
Frequency, f (Hz)



25 M⊙ no rotation
g–mode
convection
Core Bounce
SASI
h+ @ 10 kpc
t − t_bounce (ms)
10^-20
5×10^-21
0
−5×10^-21
−1×10^-20
0
200
400
600
800

A Boltzmann Formalism for Oscillating Neutrinos

P. Strack and A. Burrows

Phys.Rev.D 71:093004,2005 (hep-ph/0504035) & hep-ph/0505056

Y. Zhang & A. Burrows 2013

I. Quasi-classical Boltzmann equations

- Quantum analog to the classical phase-space density

$$\rho(\mathbf{r},\mathbf{p},t) = \int \frac{d^3\mathbf{p}'}{(2\pi)^3} e^{-i\mathbf{p}'\mathbf{r}} a^\dagger(\mathbf{p}-\frac{1}{2}\mathbf{p}',t)\, a(\mathbf{p}+\frac{1}{2}\mathbf{p}',t)$$

Make operators to numbers

$$\mathcal{F} = \langle n_i|\rho|n_j\rangle = \begin{pmatrix} f_{\nu_e} & f_{e\mu} \\ f^*_{e\mu} & f_{\nu_\mu} \end{pmatrix}$$

→ Diagonal elements: real numbers: phase-space densities

→ Off-diagonal elements: complex numbers: macroscopic overlap

$$\begin{aligned} f_{e\mu} &= \langle n_{\nu_e}|\rho(\mathbf{r},\mathbf{p},t)|n_{\nu_\mu}\rangle \\ &= \int \frac{d^3\mathbf{p}'}{(2\pi)^3} e^{i\mathbf{p}'\mathbf{r}} \left\langle n_{\nu_e}\right| a^\dagger(\mathbf{p}-\frac{1}{2}\mathbf{p}',t)\, a(\mathbf{p}+\frac{1}{2}\mathbf{p}',t) \left|n_{\nu_\mu}\right\rangle \end{aligned}$$

II. Quasi-classical Boltzmann equations

- Merging the Boltzmann equation with the Heisenberg equation yields

$$\frac{\partial \mathcal{F}}{\partial t} + \frac{1}{2}\left\{\mathbf{v}, \frac{\partial \mathcal{F}}{\partial \mathbf{r}}\right\} + \frac{1}{2}\left\{\dot{\mathbf{p}}, \frac{\partial \mathcal{F}}{\partial \mathbf{p}}\right\} = -i\,[\Omega, \mathcal{F}] + C$$

Flavor Oscillation physics is implemented via

$$\Omega(\mathbf{r}, \mathbf{p}, \varepsilon, t) = \underbrace{\Omega_{\mathrm{vac}}(\varepsilon) + \Omega_{\mathrm{mat}}(\mathbf{r})} + \underbrace{\Omega_{\nu\nu}(\mathbf{r}, \mathbf{p}, t) - \tilde{\Omega}_{\tilde{\nu}\nu}(\mathbf{r}, \mathbf{p}, t)}$$

$$\Omega(\varepsilon, \mathbf{r}) = \frac{\pi c}{L}\begin{pmatrix} -\cos 2\theta + 2A & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

Nonlinearities through self-interactions.

$$L = \frac{4\pi\hbar c\varepsilon}{\Delta m^2 c^4}$$ & $$A = \left(\frac{L}{\pi c}\right)\frac{2\sqrt{2}G_F}{\hbar}n_e(\mathbf{r})$$

III. Quasi-classical Boltzmann equations

- Separation of scales (small de Broglie wavelength of the ν's when compared to density gradients & no density fluctuations)

  neglect off-diagonal Liouville terms

- New "customized" variables

  Macroscopic Overlap densities:

$$f_r = \frac{1}{2}\left(f_{e\mu} + f_{e\mu}^*\right)$$

$$f_i = \frac{1}{2i}\left(f_{e\mu} - f_{e\mu}^*\right)$$

Self-interactions

$$\frac{\partial f_{\nu_e}}{\partial t} + \mathbf{v}\cdot\frac{\partial f_{\nu_e}}{\partial \mathbf{r}} + \dot{\mathbf{p}}\cdot\frac{\partial f_{\nu_e}}{\partial \mathbf{p}} = -f_i\left(\frac{2\pi c}{L}\sin 2\theta + 2\beta\int(1-\cos\theta^{\mathbf{pq}})\left(f_r+\tilde{f}_r\right)d^3\mathbf{q}\right) + 2\beta f_r\int(1-\cos\theta^{\mathbf{pq}})\left(f_i+\tilde{f}_i\right)d^3\mathbf{q} + C_{\nu_e}$$

$$\frac{\partial f_{\nu_\mu}}{\partial t} + \mathbf{v}\cdot\frac{\partial f_{\nu_\mu}}{\partial \mathbf{r}} + \dot{\mathbf{p}}\cdot\frac{\partial f_{\nu_\mu}}{\partial \mathbf{p}} = f_i\left(\frac{2\pi c}{L}\sin 2\theta + 2\beta\int(1-\cos\theta^{\mathbf{pq}})\left(f_r+\tilde{f}_r\right)d^3\mathbf{q}\right) - 2\beta f_r\int(1-\cos\theta^{\mathbf{pq}})\left(f_i+\tilde{f}_i\right)d^3\mathbf{q} + C_{\nu_\mu}$$

$$\frac{\partial f_r}{\partial t} + \mathbf{v}\cdot\frac{\partial f_r}{\partial \mathbf{r}} + \dot{\mathbf{p}}\cdot\frac{\partial f_r}{\partial \mathbf{p}} = f_i\left[\frac{2\pi c}{L}(A-\cos 2\theta) + \beta\int(1-\cos^{\mathbf{pq}})\left(f_{\nu_e}-\tilde{f}_{\nu_e}-f_{\nu_\mu}+\tilde{f}_{\nu_\mu}\right)d^3\mathbf{q}\right] +$$

$$\left(f_{\nu_e}-f_{\nu_\mu}\right)\beta\int(1-\cos\theta^{\mathbf{pq}})\left(\tilde{f}_i-f_i\right)d^3\mathbf{q}$$

$$\frac{\partial f_i}{\partial t} + \mathbf{v}\cdot\frac{\partial f_i}{\partial \mathbf{r}} + \dot{\mathbf{p}}\cdot\frac{\partial f_i}{\partial \mathbf{p}} = \left(f_{\nu_e}-f_{\nu_\mu}\right)\left[\frac{\pi c}{L}\sin 2\theta + \beta\int(1-\cos^{\mathbf{pq}})\left(f_r-\tilde{f}_r\right)d^3\mathbf{q}\right] - f_r\left[\frac{2\pi c}{L}(A-\cos 2\theta) +\right.$$

$$\left.\beta\int(1-\cos^{\mathbf{pq}})\left(f_{\nu_e}-\tilde{f}_{\nu_e}-f_{\nu_\mu}+\tilde{f}_{\nu_\mu}\right)d^3\mathbf{q}\right]$$

Quasi-classical Boltzmann equations

- Wigner density matrix, ensemble-averaging →

$$\mathcal{F} = \langle n_i|\rho|n_j\rangle = \begin{pmatrix} f_{\nu_e} & f_{e\mu} \\ f^*_{e\mu} & f_{\nu_\mu} \end{pmatrix}$$

→ Diagonal elements: real numbers: Phase-Space densities

→ Off-diagonal elements: complex numbers: Macroscopic Overlap densities

$$f_r = \frac{1}{2}\left(f_{e\mu} + f^*_{e\mu}\right)$$ (Real part)

$$f_i = \frac{1}{2i}\left(f_{e\mu} - f^*_{e\mu}\right)$$ (Imaginary part)

$$L = \frac{4\pi\hbar c\varepsilon}{\Delta m^2 c^4}$$

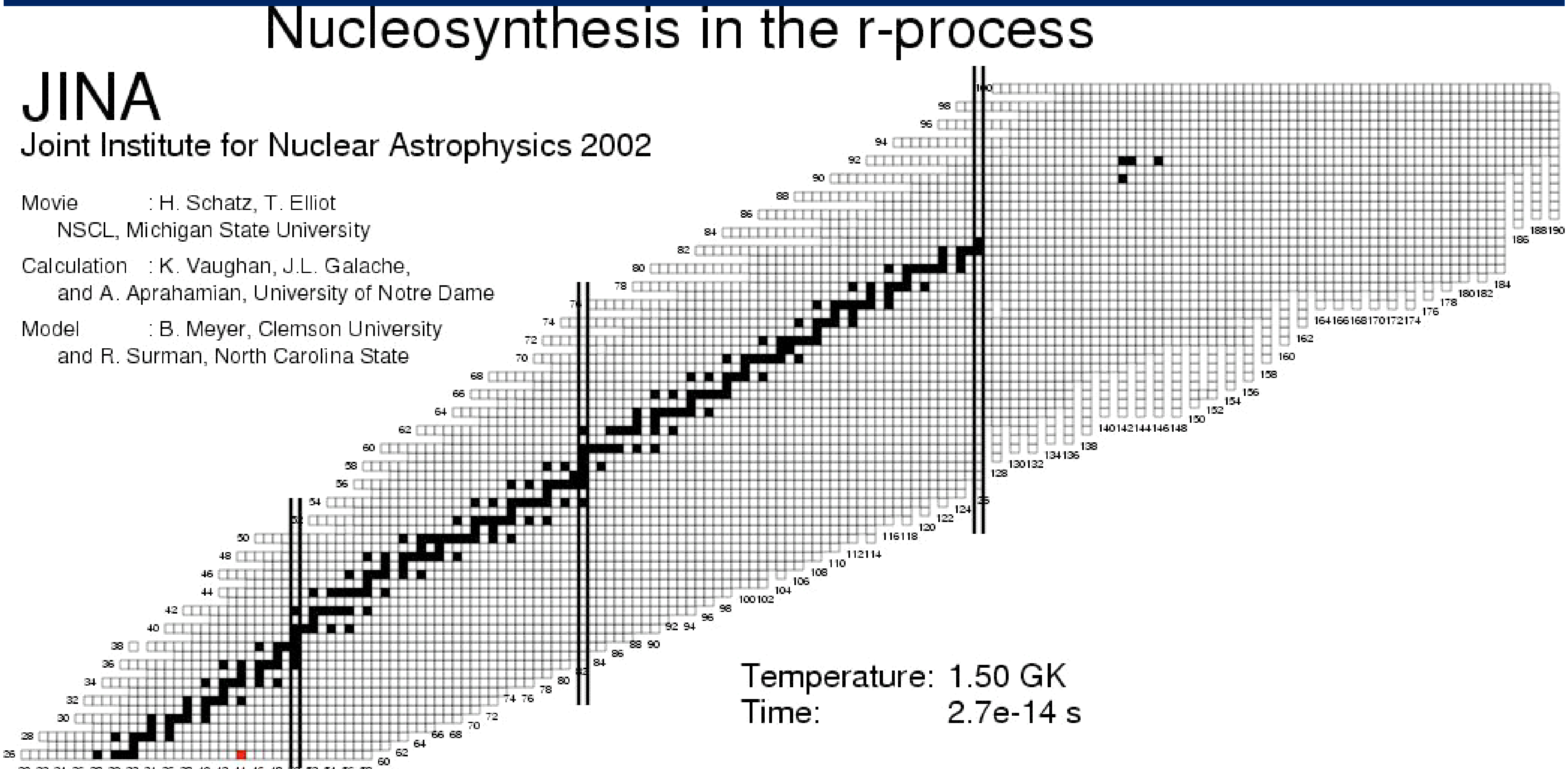
$$A = \left(\frac{L}{\pi c}\right)\frac{2\sqrt{2}G_F}{\hbar}n_e(\mathbf{r})$$

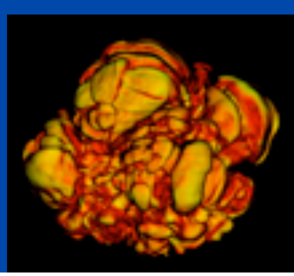
$$\begin{aligned}
\frac{\partial f_{\nu_e}}{\partial t} + \mathbf{v}\cdot\frac{\partial f_{\nu_e}}{\partial \mathbf{r}} + \dot{\mathbf{p}}\cdot\frac{\partial f_{\nu_e}}{\partial \mathbf{p}} &= -\frac{2\pi c}{L} f_i \sin 2\theta + C_{\nu_e} \\
\frac{\partial f_{\nu_\mu}}{\partial t} + \mathbf{v}\cdot\frac{\partial f_{\nu_\mu}}{\partial \mathbf{r}} + \dot{\mathbf{p}}\cdot\frac{\partial f_{\nu_\mu}}{\partial \mathbf{p}} &= \frac{2\pi c}{L} f_i \sin 2\theta + C_{\nu_\mu} \\
\frac{\partial f_r}{\partial t} + \mathbf{v}\cdot\frac{\partial f_r}{\partial \mathbf{r}} + \dot{\mathbf{p}}\cdot\frac{\partial f_r}{\partial \mathbf{p}} &= -\frac{2\pi c}{L} f_i (\cos 2\theta - A) \\
\frac{\partial f_i}{\partial t} + \mathbf{v}\cdot\frac{\partial f_i}{\partial \mathbf{r}} + \dot{\mathbf{p}}\cdot\frac{\partial f_i}{\partial \mathbf{p}} &= \frac{2\pi c}{L}\Big(\frac{f_{\nu_e} - f_{\nu_\mu}}{2}\sin 2\theta + \\
&\quad f_r (\cos 2\theta - A)\Big)
\end{aligned}$$

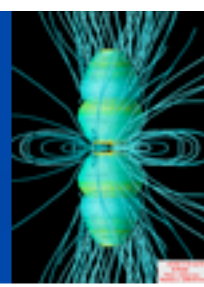
“R-process” Nucleosynthesis?

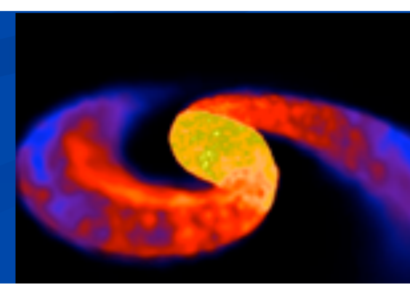
No natural site for 2nd or 3rd Peak in CCSNe (~ Solar Metallicity)?

R-Process Nucleosynthesis

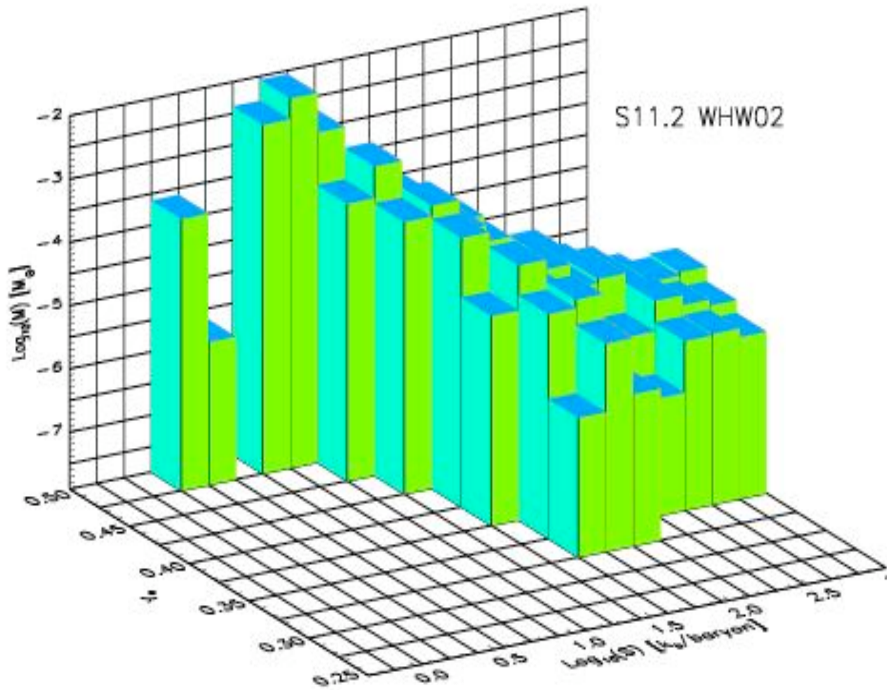


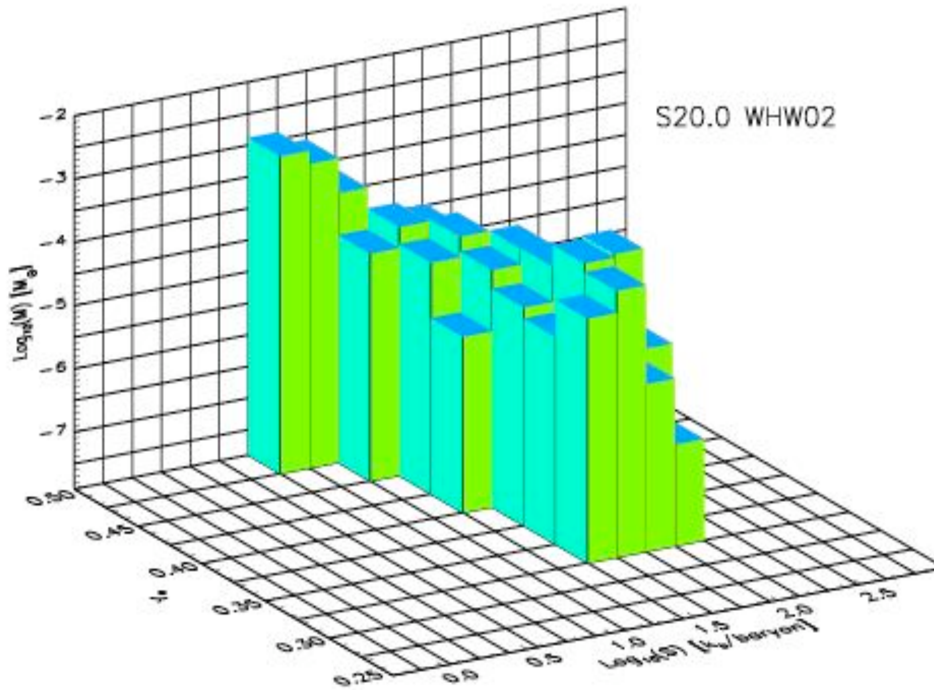






Ejecta mass versus Entropy and Y_e for Acoustic Mechanism: R-process?

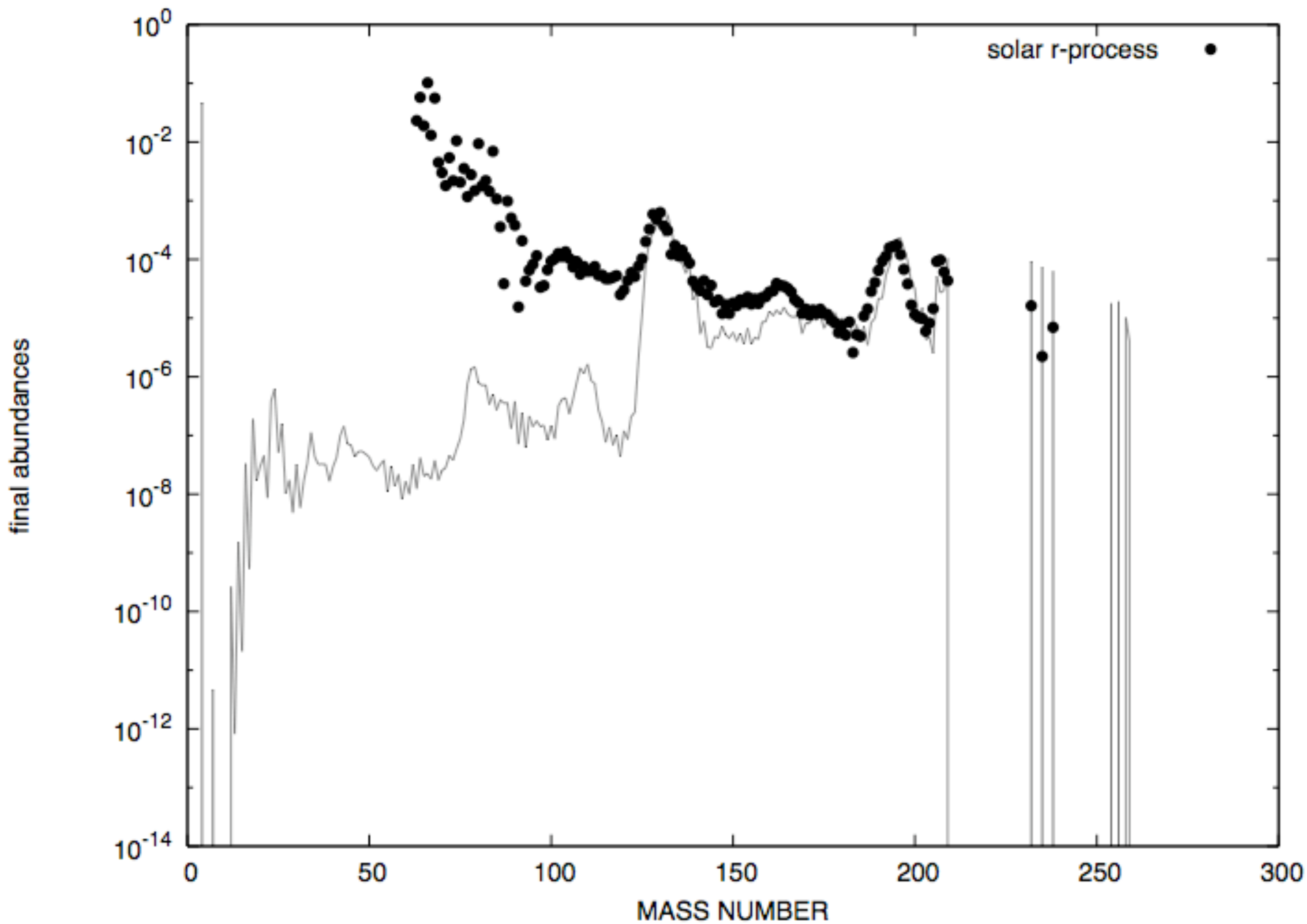




M (s > 300): $1.25 \times 10^{-4} M_\odot$?

M (s > 100): $1.07 \times 10^{-5} M_\odot$?

Preliminary R-process Calculations for the Long-term Acoustic Mechanism



K. Otsuki et al. 2008

Summary: Diagnostics of Explosion

- Morphology of Blasts: Spatial Element/Debris Distribution
- Explosion Energies and Nickel Yields
- Pulsar Proper Motions ("Kicks")
- Pulsar Spin Periods
- Neutrinos !!
- Gravitational Waves
- Nucleosynthesis - R-process ?   The first peak?