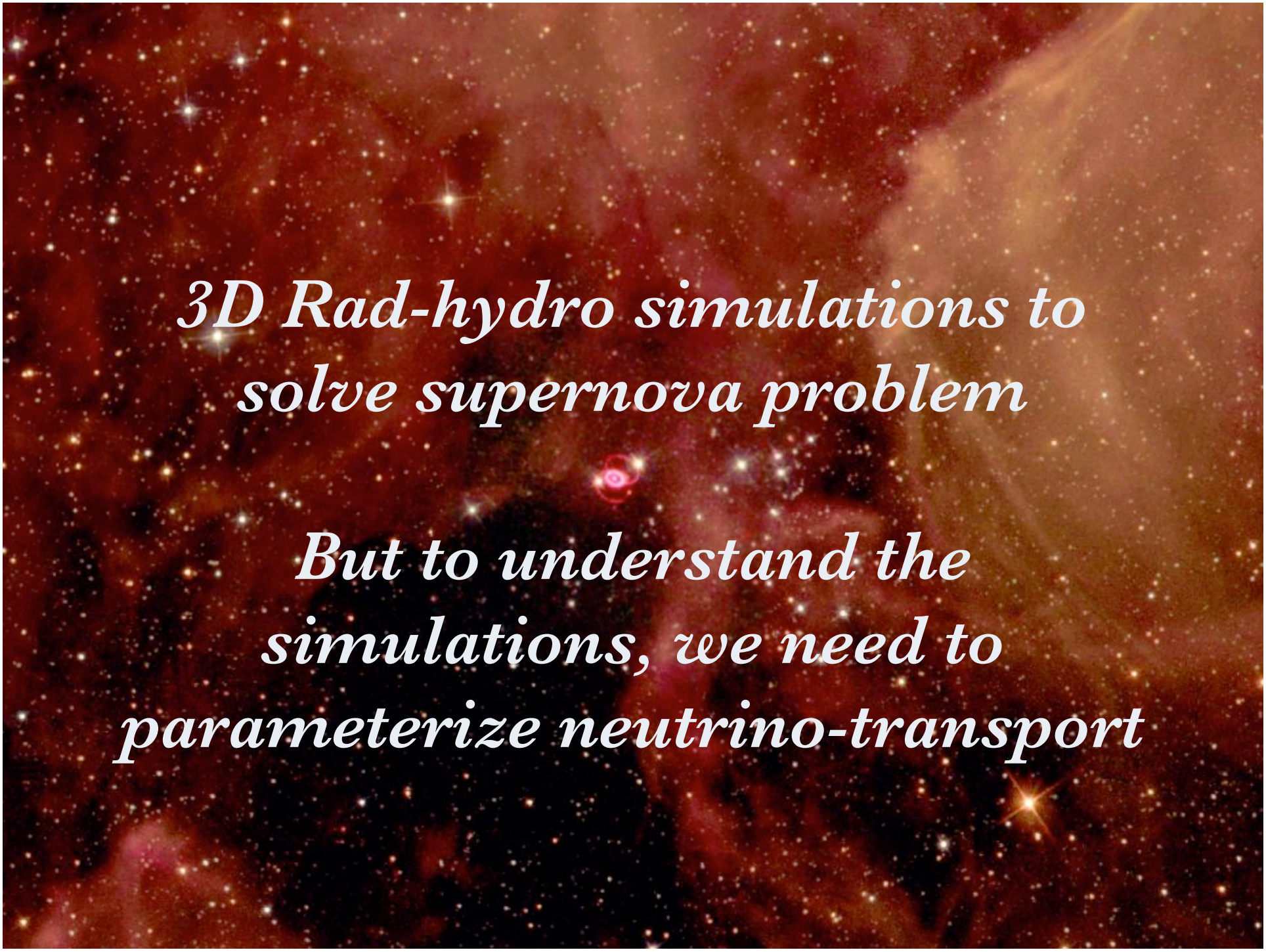
3D Rad-hydro simulations to solve supernova problem
But to understand the simulations, we need to parameterize neutrino-transport

Critical Conditions for Successful Neutrino-Driven Explosions

A Model for the Gravitational Wave Emission

by

Jeremiah W. Murphy

NSF AAP Fellow

(University of Washington)

Thank you…

Adam Burrows	Princeton U.
Randy LeVeque	Applied Math., UW
Christian Ott	Caltech / (NBI, Copenhagen)
Luc Dessart	OAMP (Marseille, Fr.)
Ivan Hubeny	Steward, U.A.
Raphael Loubere	CNRS, Fr.
Misha Shashkov	LANL
Milan Kucharik	LANL
Burton Wendroff	LANL
Casey Meakin	U. Arizona

JINA

SciDAC
Scientific Discovery through Advanced Computing

NSF

AAPF

Cor ova:
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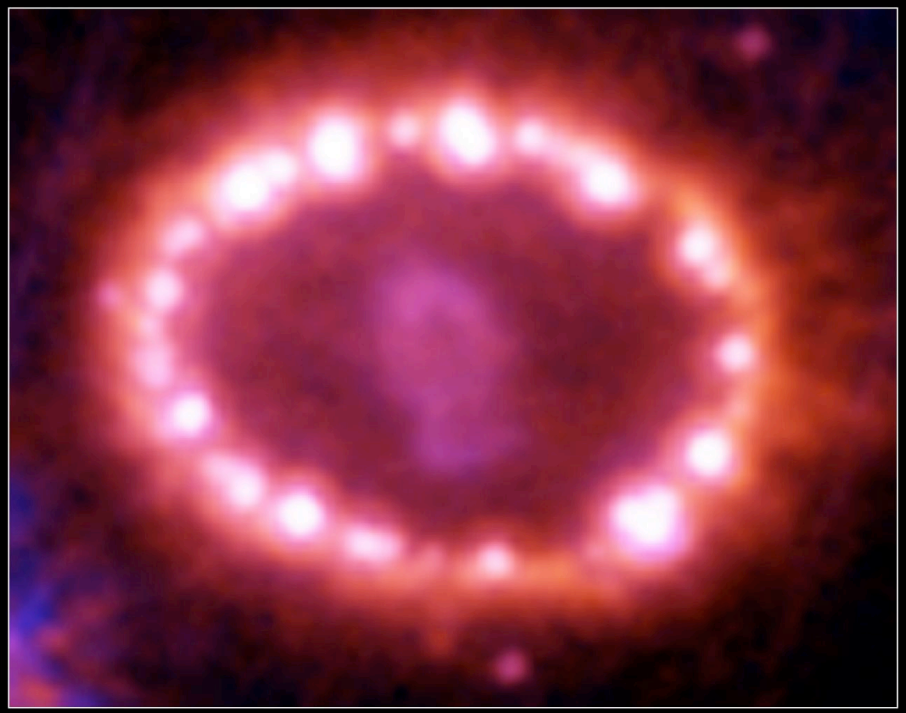

Supernova 1987A • November 28, 2003
Hubble Space Telescope • ACS

NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics) STScI-PRC04-09a

1D simulations (Rad-hydro)

Wilson ‘85
Bethe & Wilson ‘85

} Neutrino mechanism suggested

Liebendoerfer et al. ‘01
Rampp & Janka ‘02
Buras et al. ‘03
Thompson et al. ‘03
Liebendoer et al. ‘05
Kitaura et al. ‘06
Burrows et al. ‘07

} No Explosions
(Except lowest masses)

Relax 1D assumption?

Neutrino Mechanism:

- Neutrino-heated convection
- Standing Accretion Shock Instability (SASI)
- Explosions? maybe

Magnetic Jets:

- Only for very rapid rotations

Acoustic Mechanism:

- Explosions but caveats.

Neutrino Mechanism:

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- Explosions? maybe

Magnetic Jets:

- Only for very rapid rotations

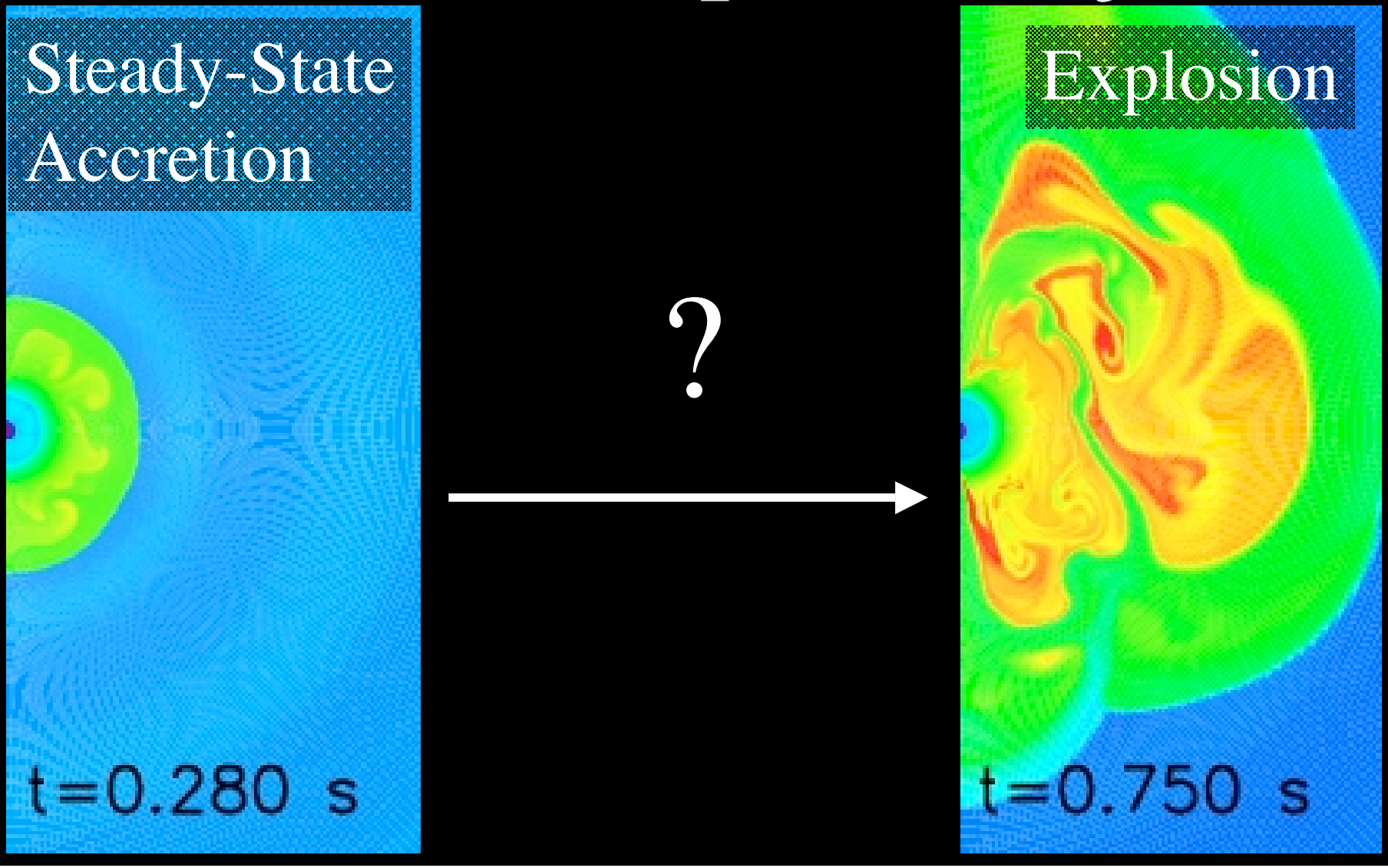
Acoustic Mechanism:

- Explosions but caveats.

Note…

- Stalled shock
- Begins 1D, but…
- Convection
- Standing Accretion Shock Instability (SASI)

Fundamental Question of Core-Collapse Theory



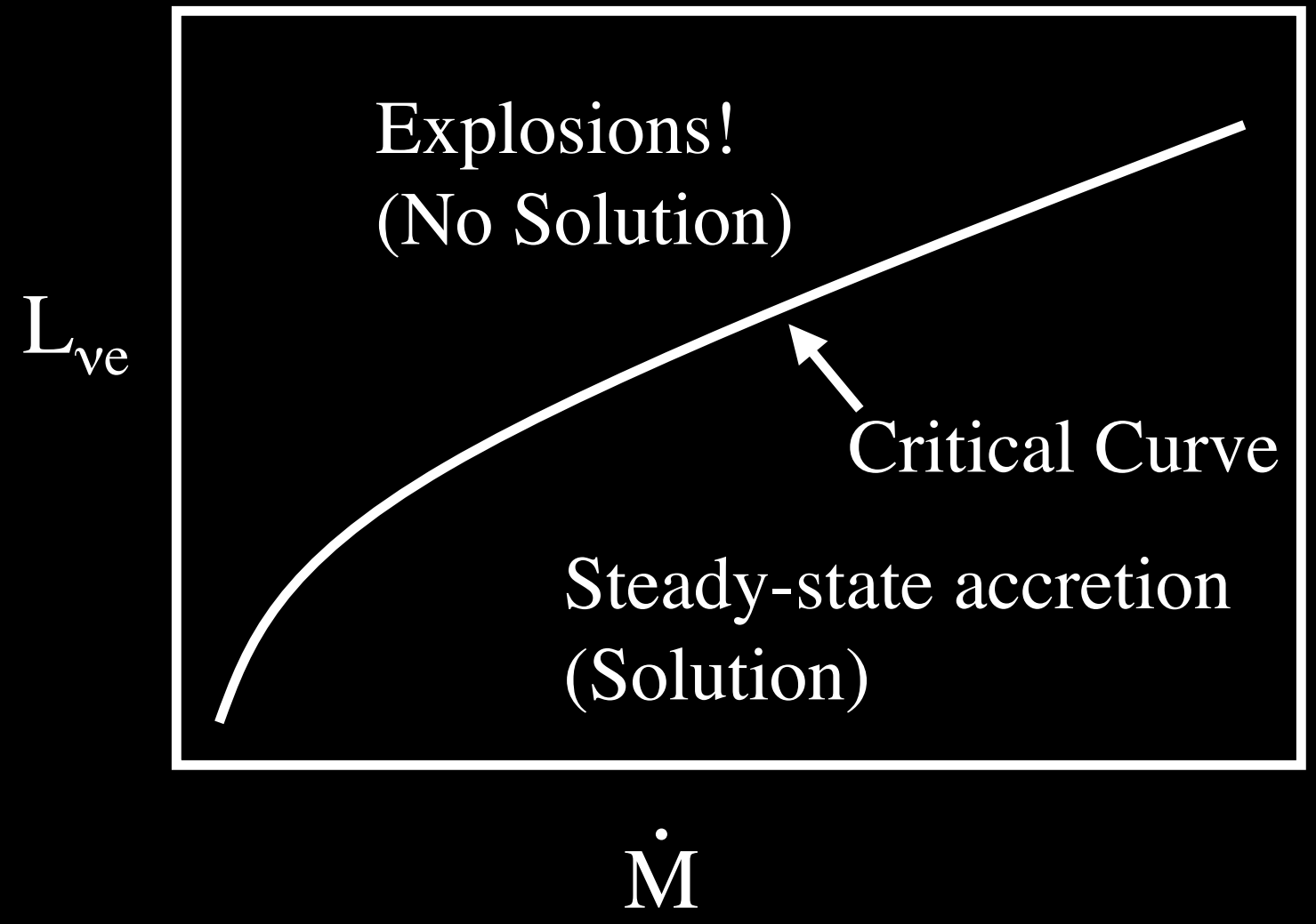
And why is it easier to explode in 2D compared to 1D?

Murphy & Burrows ‘08

Two Paths to the Solution

- Detailed 3D radiation-hydrodynamic simulations ("Accurate" energies, NS masses, nucleo., etc.)
- Parameterizations that capture essential physics (Tease out fundamental mechanisms)

Burrows & Goshy ‘93
Steady-state solution (ODE)



Conditions for Explosions by the Neutrino Mechanism

Murphy & Burrows, 2008

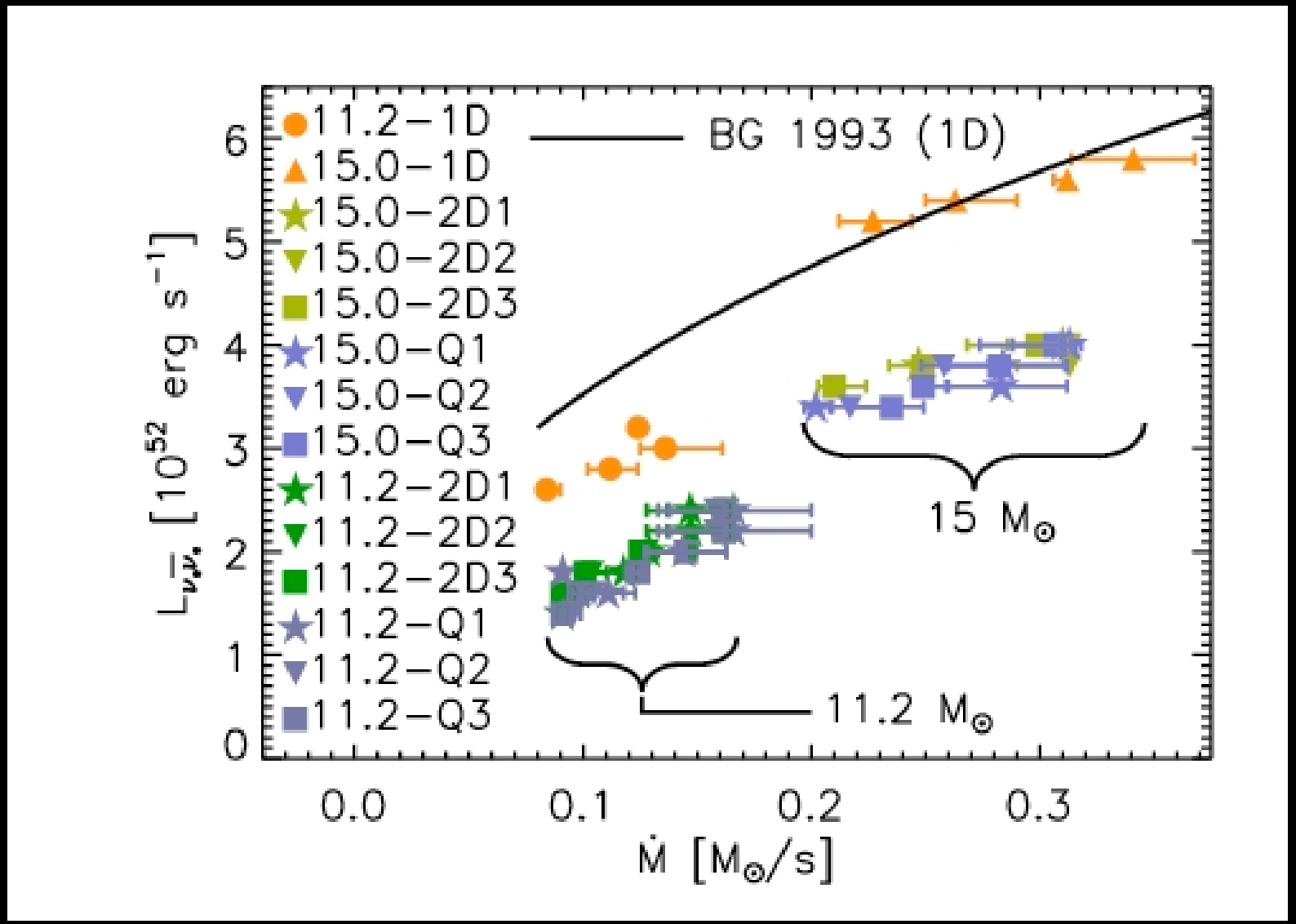
Parameter Study

- Neutrino Luminosity (Local heating and cooling)
- 1D, 2D (90^o and 180^o)
- 11.2 and 15 $M_\odot$ (range of accretion rates)
- Resolution
- ~100 simulations

Is a critical luminosity relevant in hydrodynamic simulations?

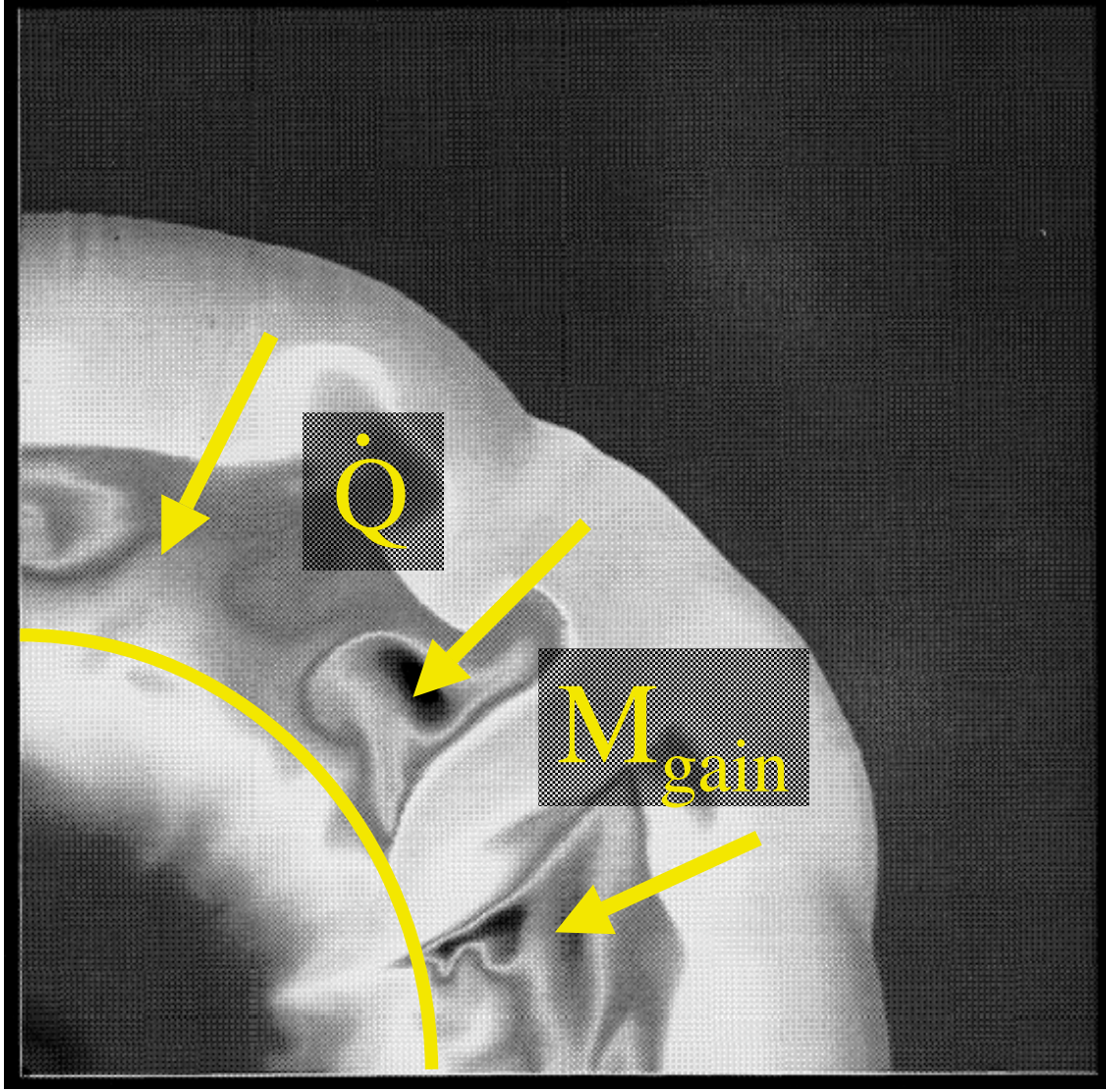
- 1D
- 2D Convection and SASI?

How do the critical luminosities differ between 1D and 2D?


11.2−1D
15.0−1D
15.0−2D1
15.0−2D2
15.0−2D3
15.0−Q1
15.0−Q2
15.0−Q3
11.2−2D1
11.2−2D2
11.2−2D3
11.2−Q1
11.2−Q2
11.2−Q3
BG 1993 (1D)
15 M⊙
11.2 M⊙
$L_{\nu_e,\bar{\nu}_e}$ [10^{52} erg s^{-1}]
$\dot{M}$ [$M_\odot$/s]
0
1
2
3
4
5
6
0.0
0.1
0.2
0.3

Why is critical luminosity of 2D simulations ~70% of 1D?

Conditions during Explosion



$$\tau_{adv} = \frac{\Delta r_{gain}}{v_r}$$

$$\tau_q = \frac{E}{\dot{Q}}$$

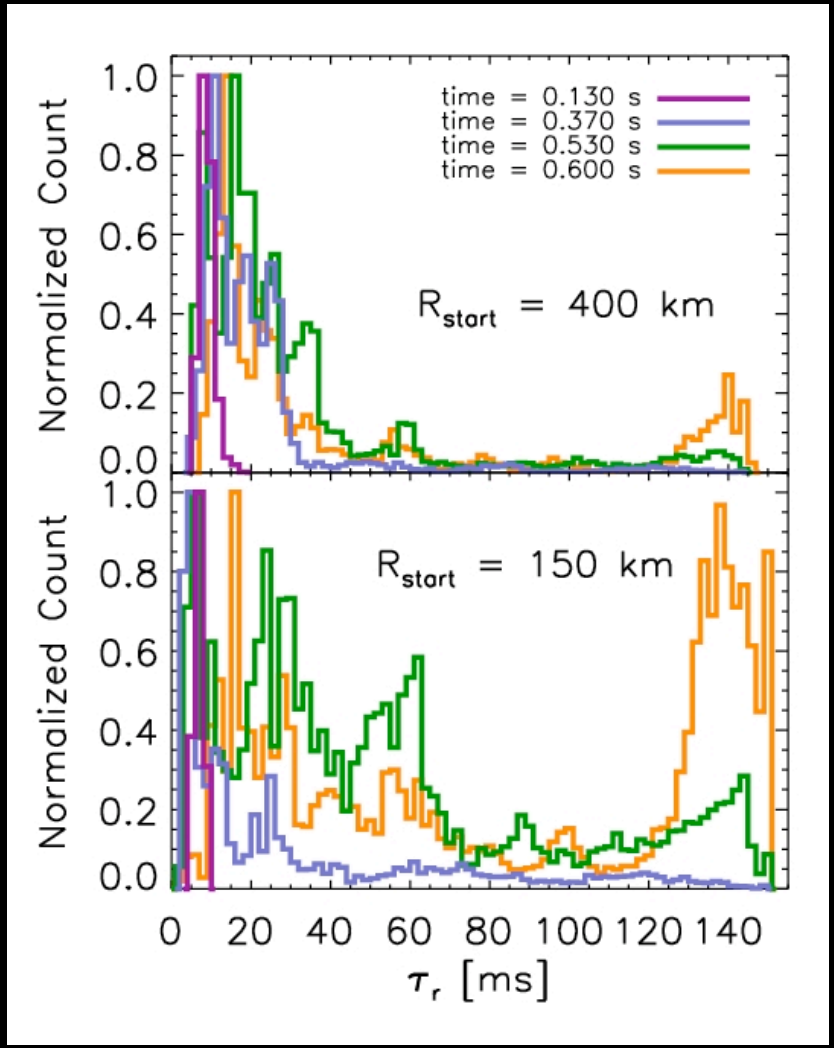
$$\frac{\tau_{adv}}{\tau_q} \gtrsim 1$$

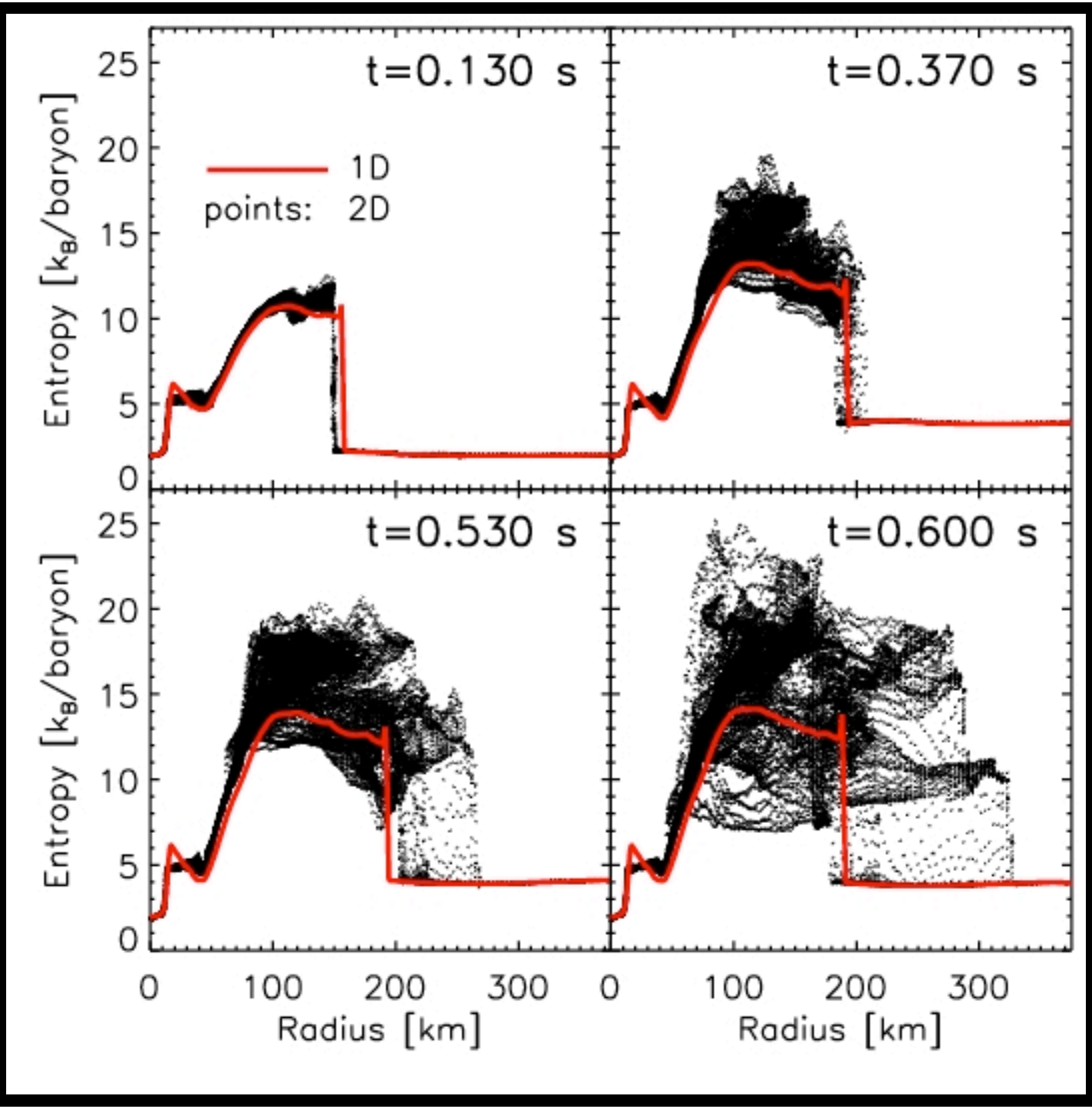
1D → one time

2D → distribution of times

More heating?

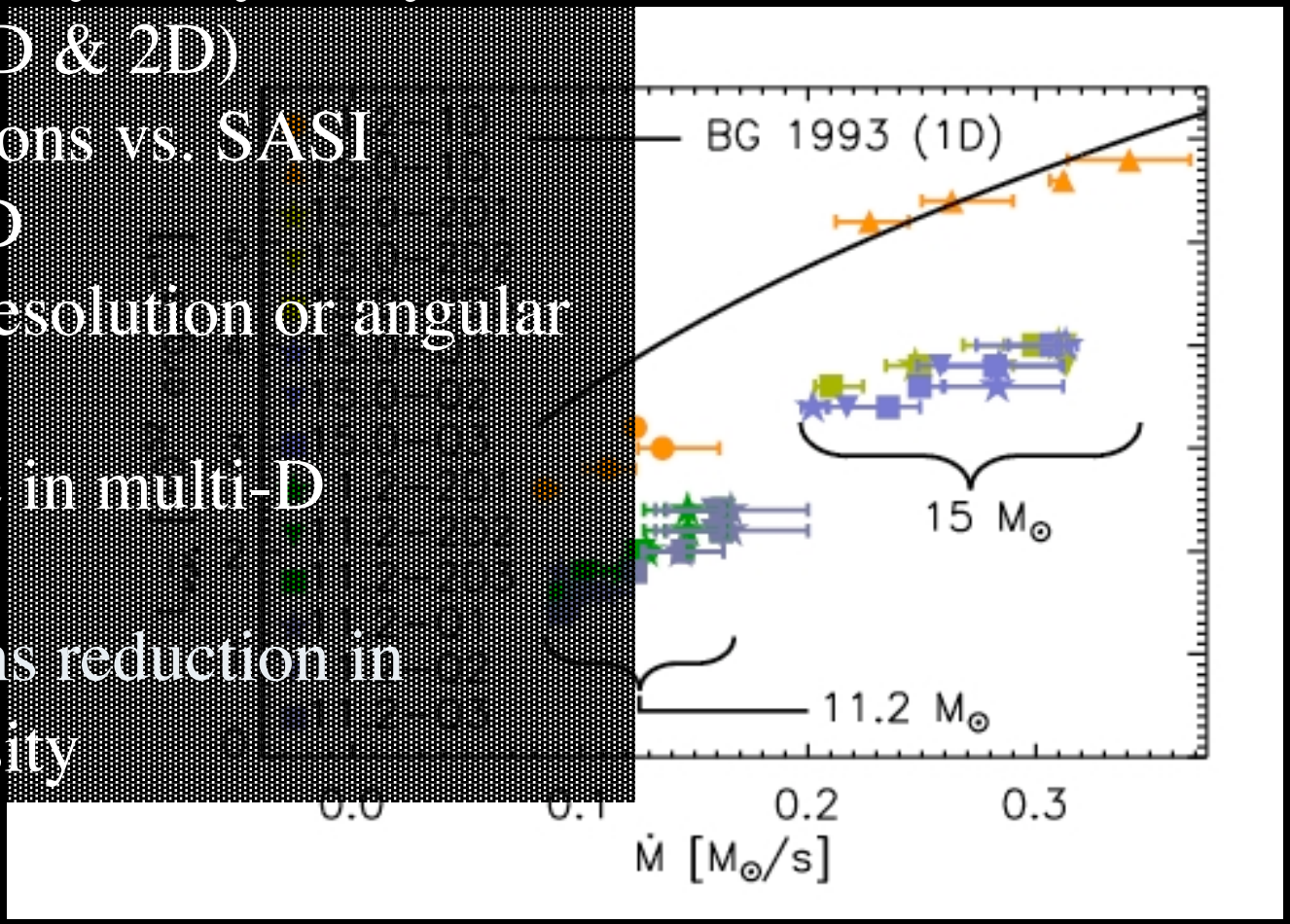
$$\Delta S \propto \frac{\dot{Q}}{T}$$

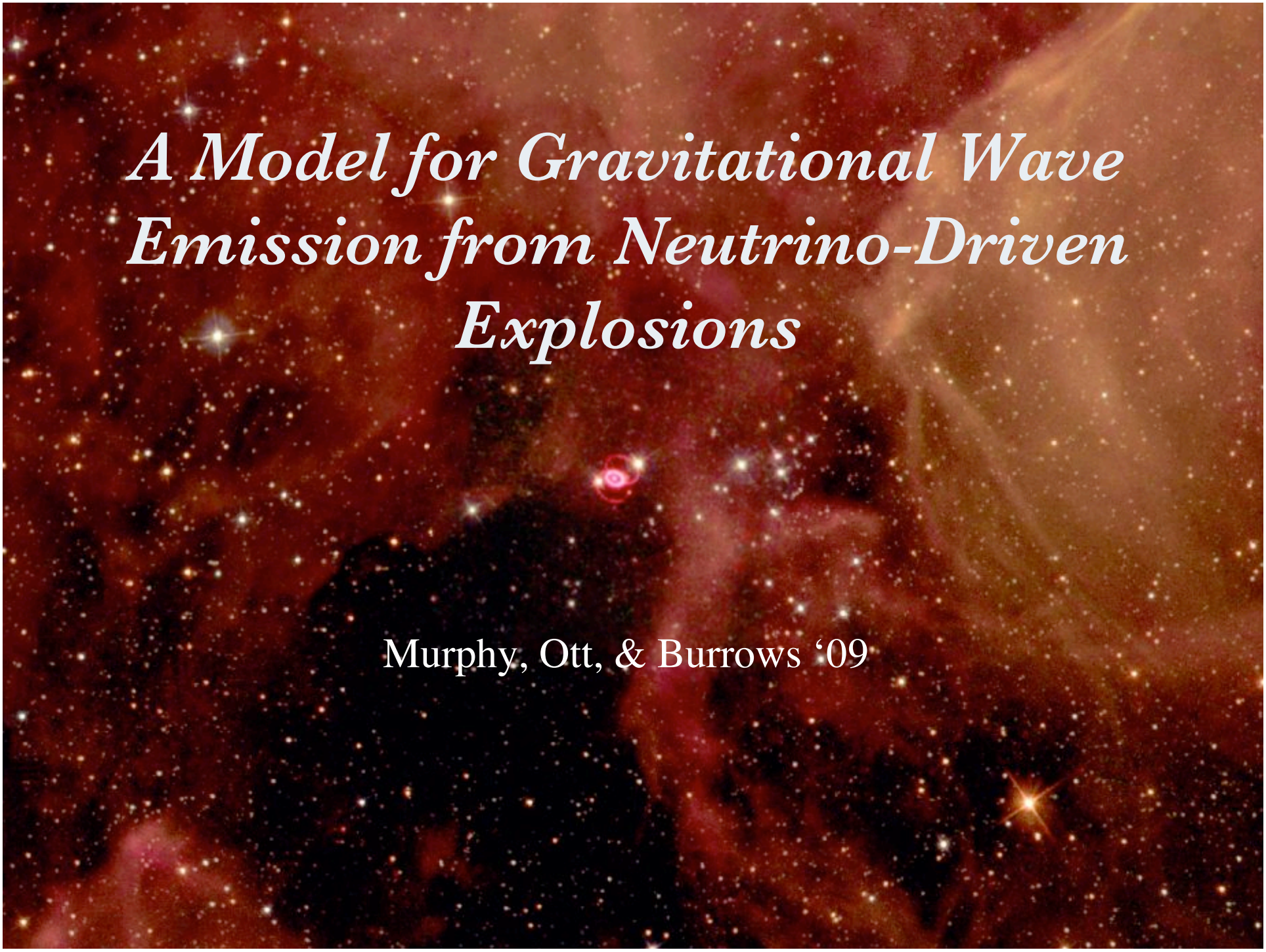



t=0.130 s
t=0.370 s
t=0.530 s
t=0.600 s
1D
points: 2D
Entropy [k_B/baryon]
Radius [km]
0
5
10
15
20
25
0
100
200
300

Conclusions

- Critical luminosity in hydrodynamic simulations (1D & 2D)
- Radial oscillations vs. SASI
- 2D ~70% of 1D
- Insensitive to resolution or angular domain
- Residence time in multi-D simulations
- Long τ_r explains reduction in critical luminosity





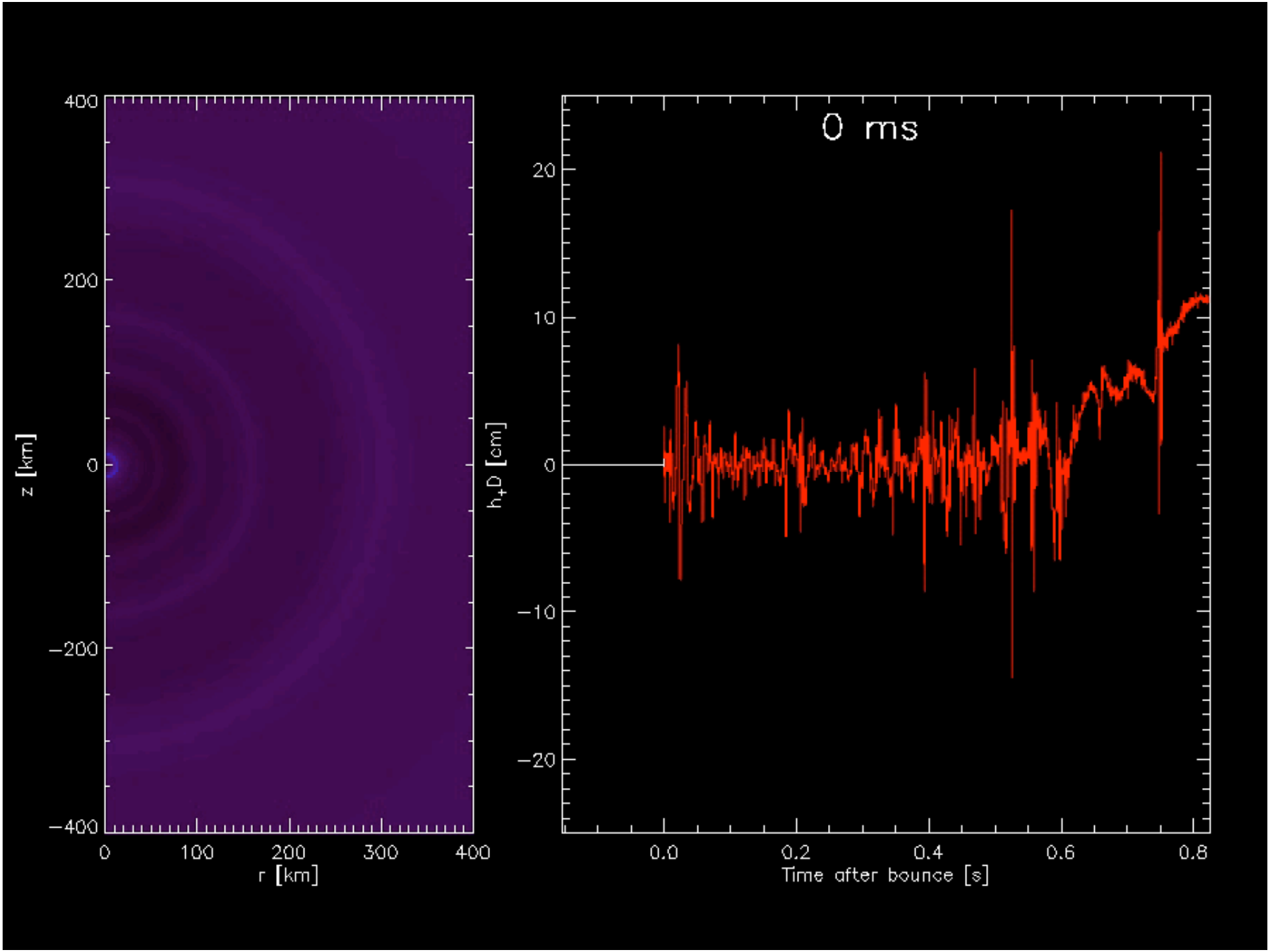
A Model for Gravitational Wave Emission from Neutrino-Driven Explosions

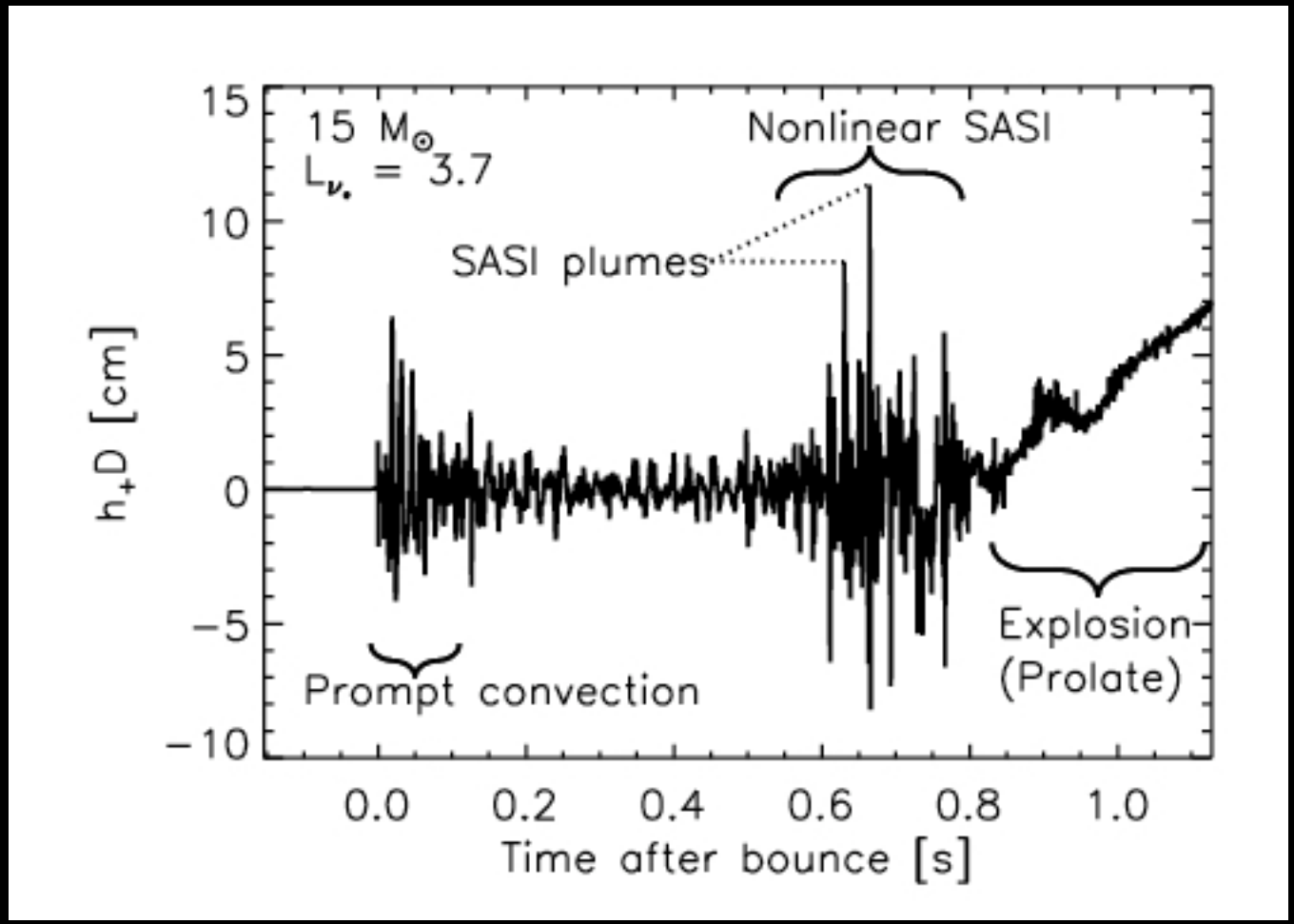
Murphy, Ott, & Burrows ‘09

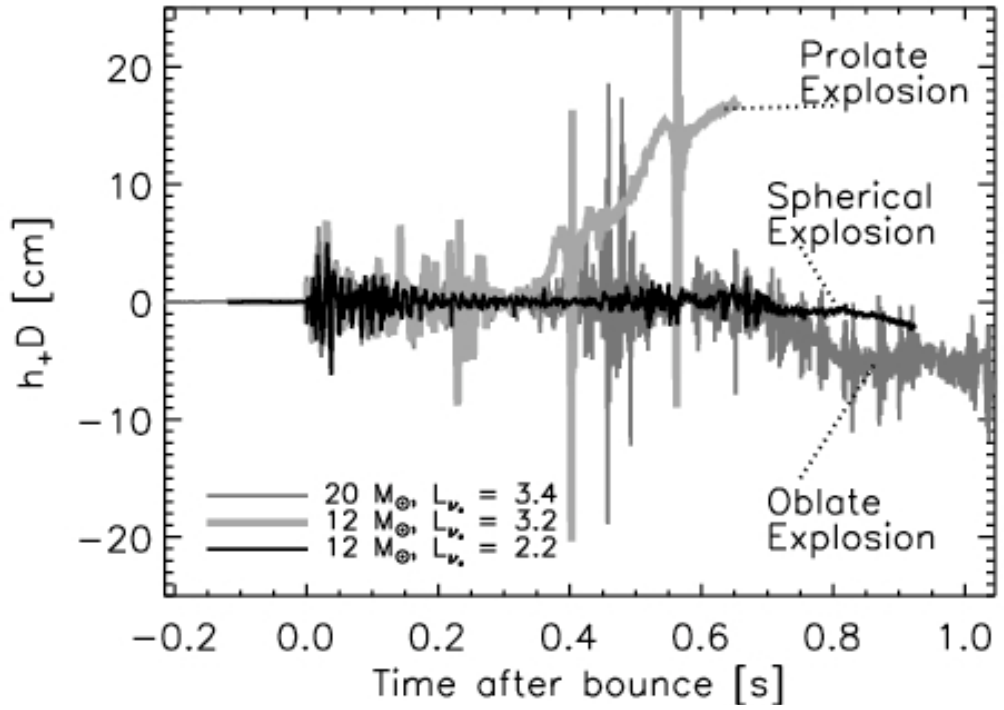
Murphy, Ott, & Burrows, 2009

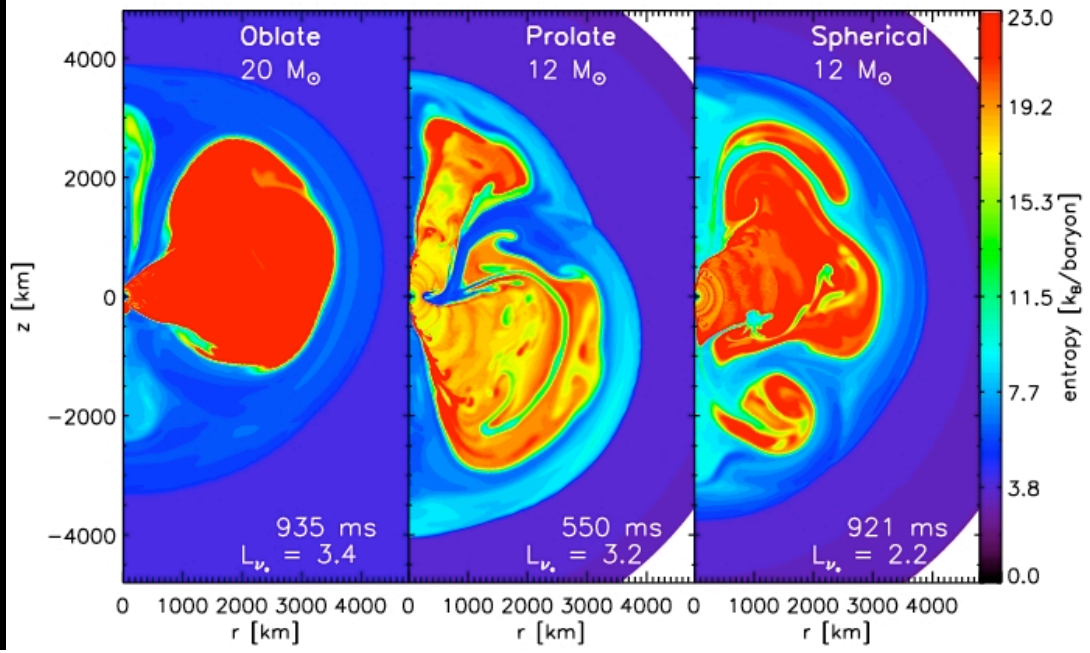
Another Parameter Study

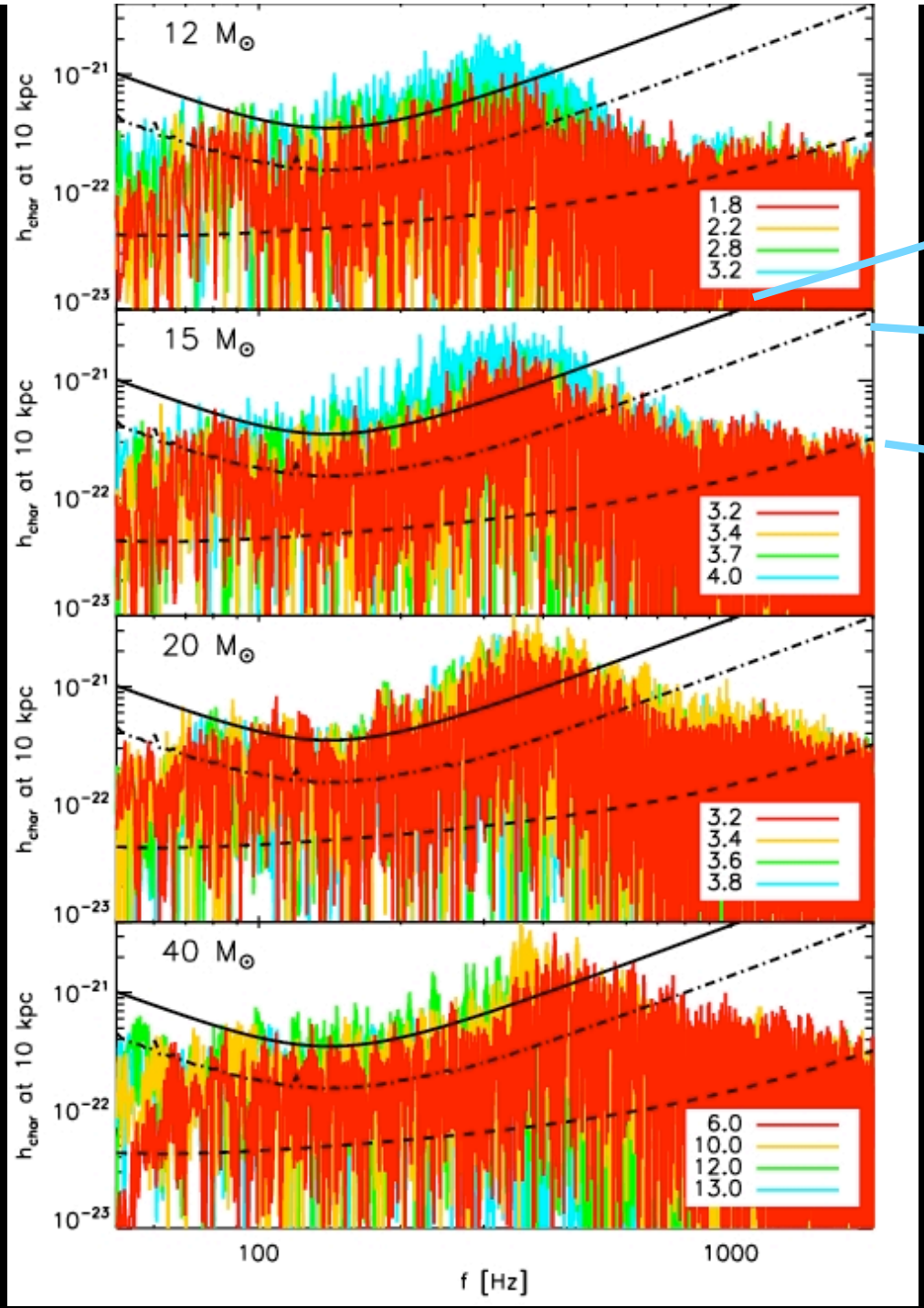
- Neutrino Luminosity (Local heating and cooling)
- 2D
- 12, 15, 20, and 40 $M_{\odot}$ (Woosley & Heger '07)


0 ms
400
200
0
−200
−400
z [km]
0
100
200
300
400
r [km]
20
10
0
−10
−20
h+D [cm]
0.0
0.2
0.4
0.6
0.8
Time after bounce [s]


15 M⊙
Lν = 3.7
Nonlinear SASI
SASI plumes
Prompt convection
Explosion
(Prolate)
h+D [cm]
Time after bounce [s]
15
10
5
0
−5
−10
0.0
0.2
0.4
0.6
0.8
1.0


Prolate
Explosion
Spherical
Explosion
Oblate
Explosion
20 M⊙, Lνe = 3.4
12 M⊙, Lνe = 3.2
12 M⊙, Lνe = 2.2
h+D [cm]
Time after bounce [s]

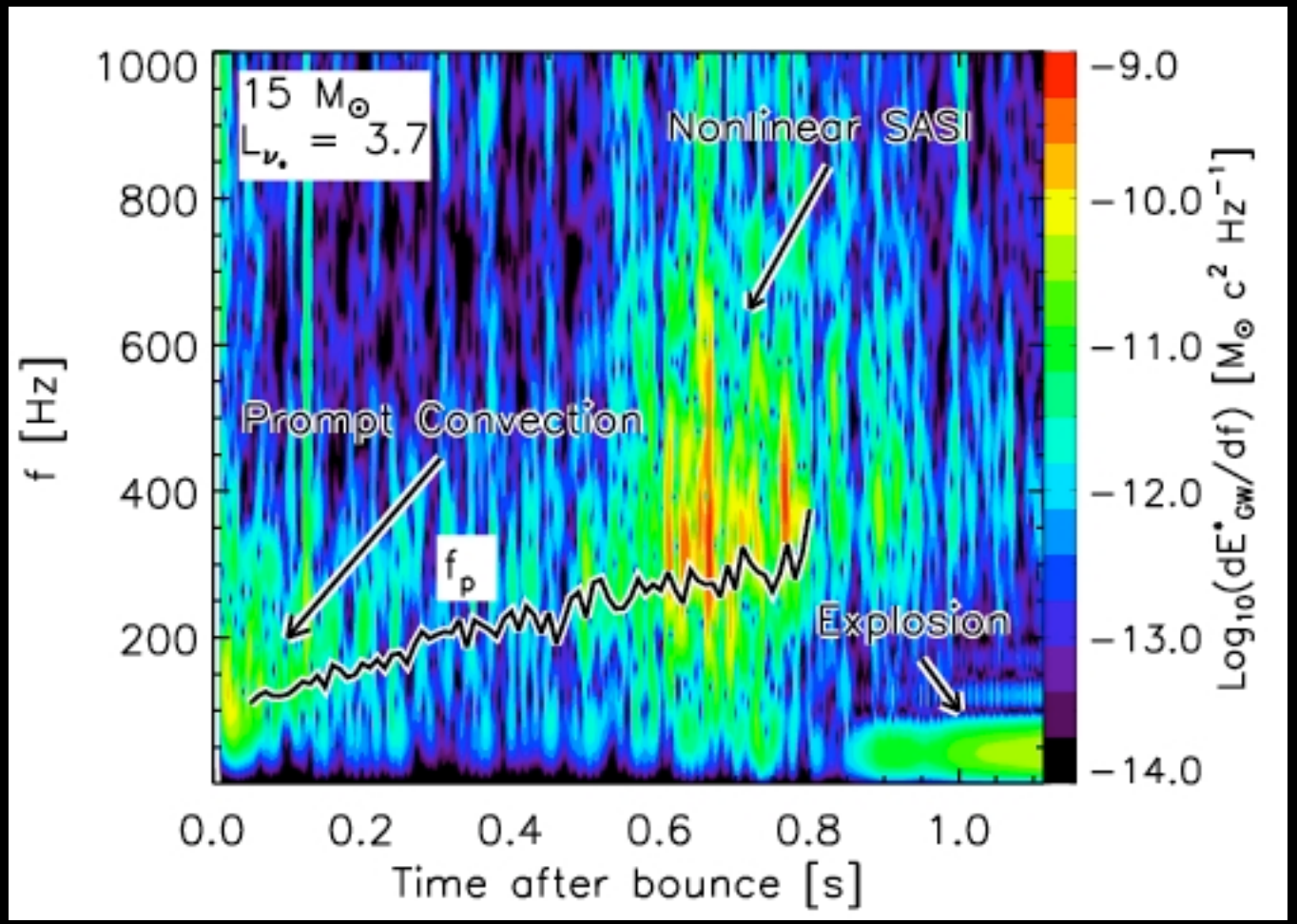

Oblate
20 M⊙
Prolate
12 M⊙
Spherical
12 M⊙
935 ms
Lνe = 3.4
550 ms
Lνe = 3.2
921 ms
Lνe = 2.2
z [km]
r [km]
entropy [kB/baryon]



Initial LIGO

Enhanced LIGO

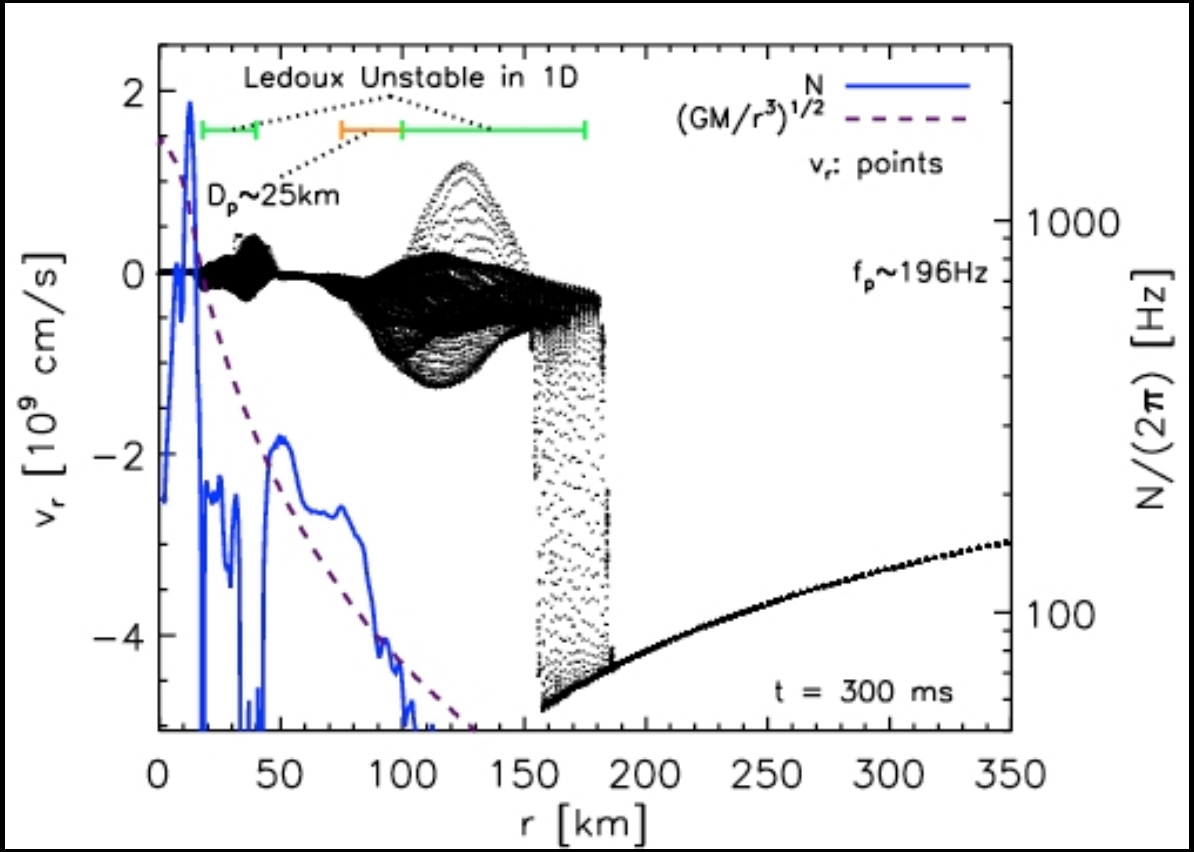
Advanced LIGO


15 M⊙
Lνe = 3.7
Nonlinear SASI
Prompt Convection
fp
Explosion
f [Hz]
1000
800
600
400
200
0.0
0.2
0.4
0.6
0.8
1.0
Time after bounce [s]
−9.0
−10.0
−11.0
−12.0
−13.0
−14.0
Log10(dE*GW/df) [M⊙ c2 Hz−1]

Characteristic GW frequencies and amplitudes?

The Model: Buoyant Impulse

$$b(r) = \int N^2 dr$$



$$R_b = \frac{\Delta b \, D_p}{v_p^2}$$

$$D_p \sim v_p / N$$

$$f_p \sim N/(2\pi)$$

$$h_+ \propto f_p \, v_p$$

Similar analysis for 3D convection in stellar interiors
(Meakin & Arnett 2007, Arnett & Meakin 2009)

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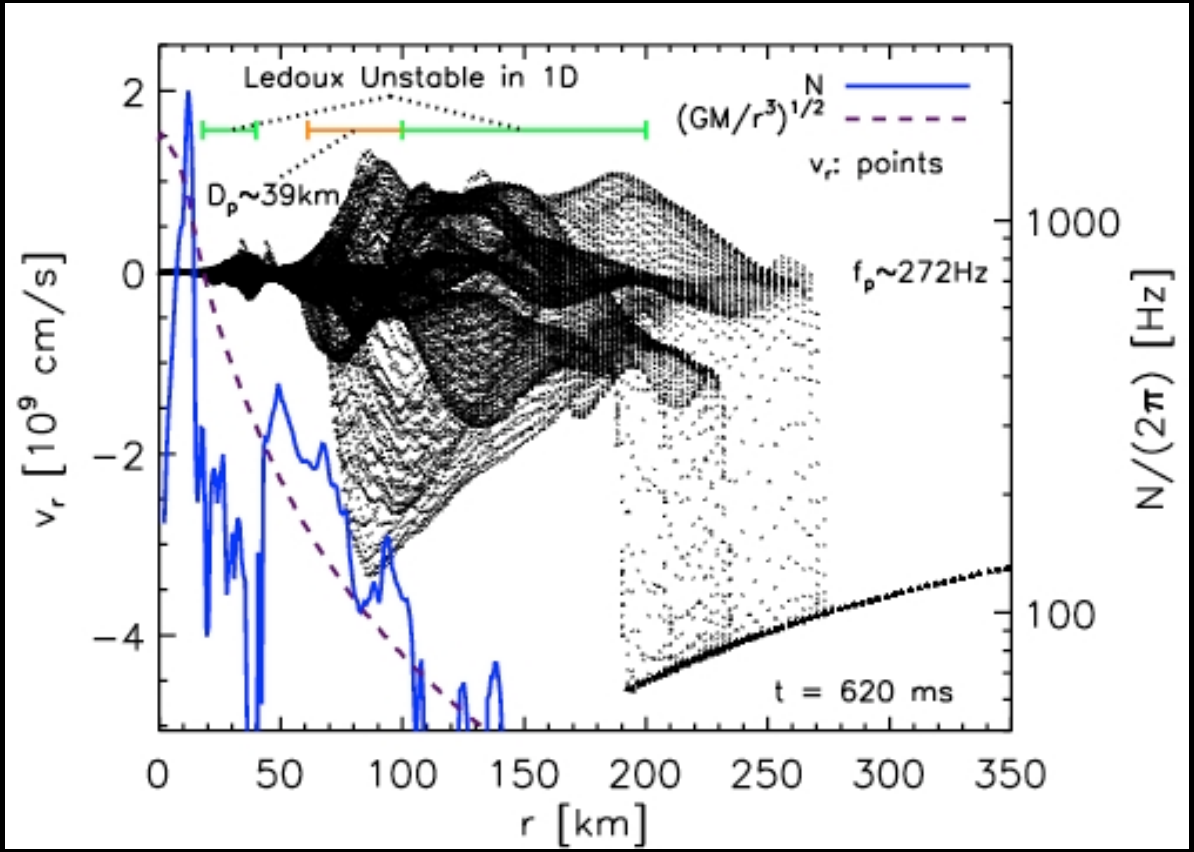

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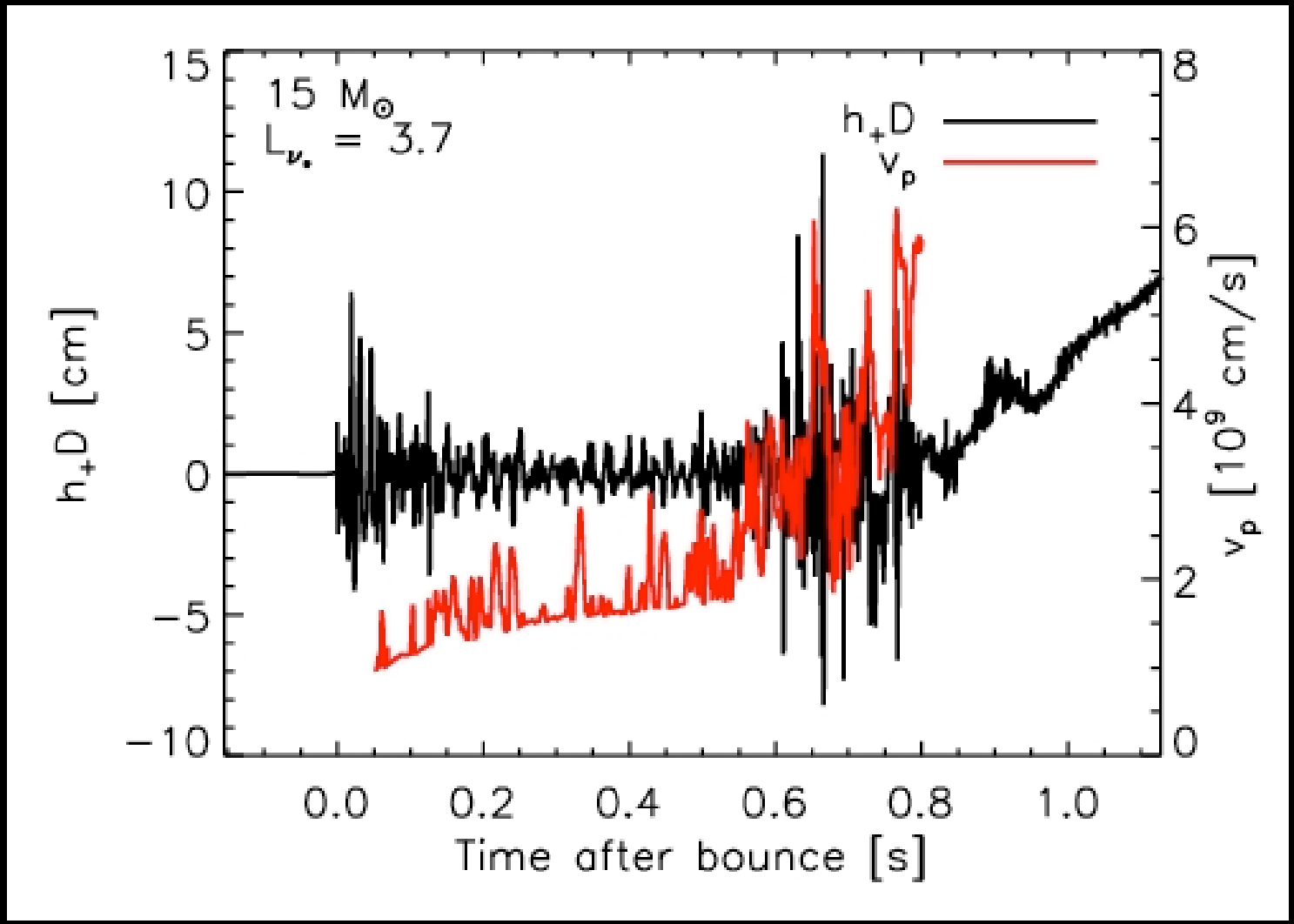
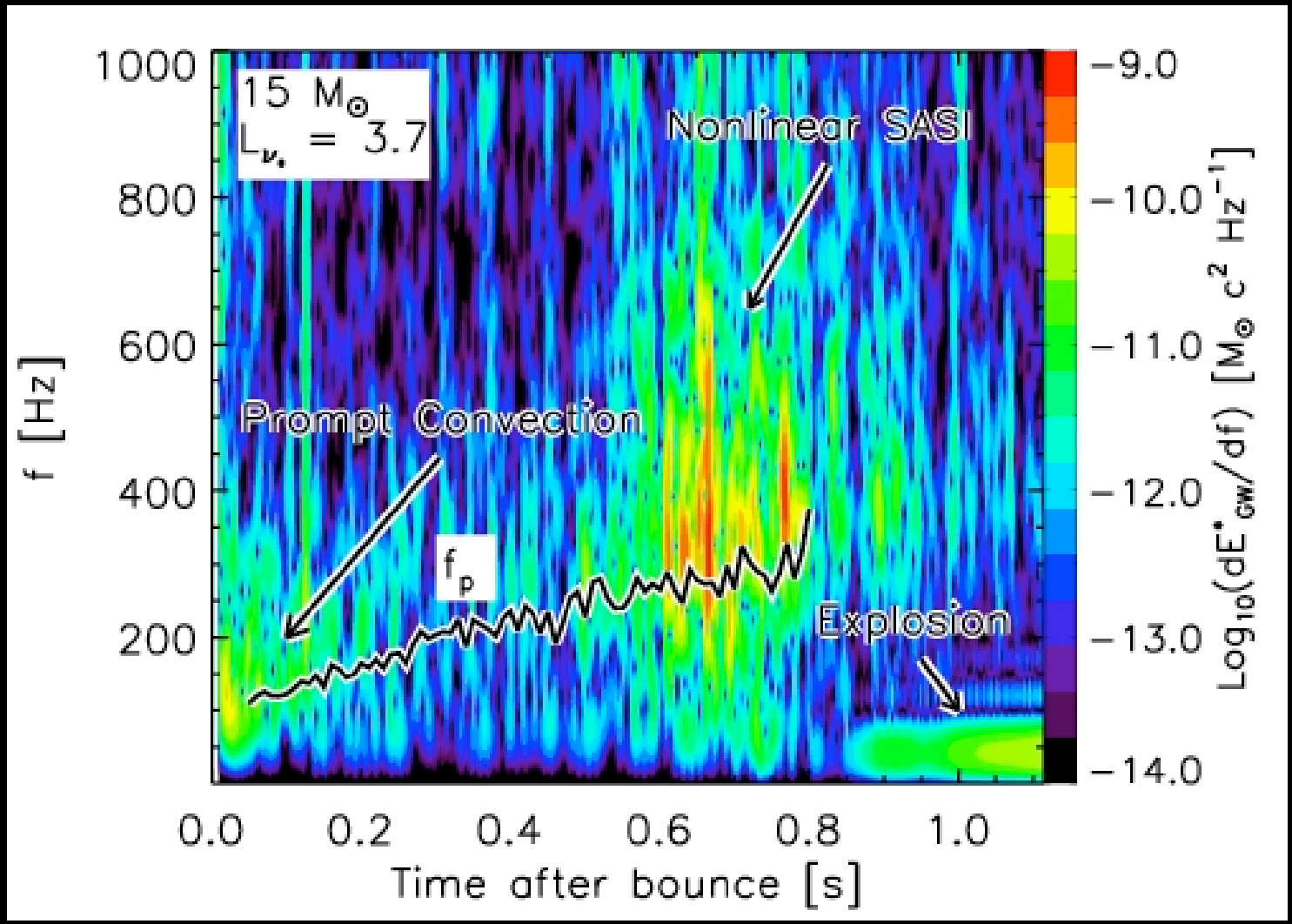
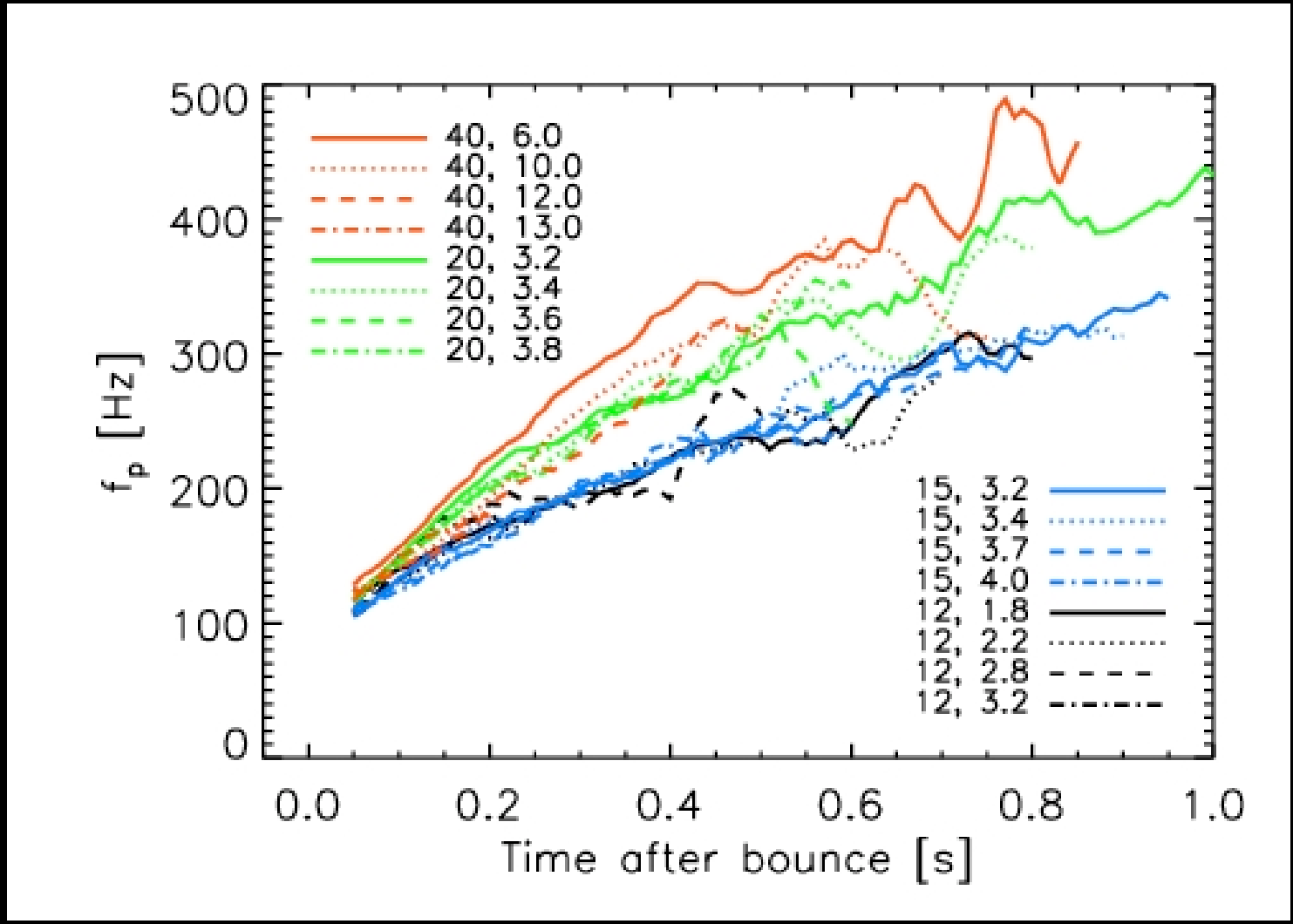


$f_p \sim N/(2\pi)$

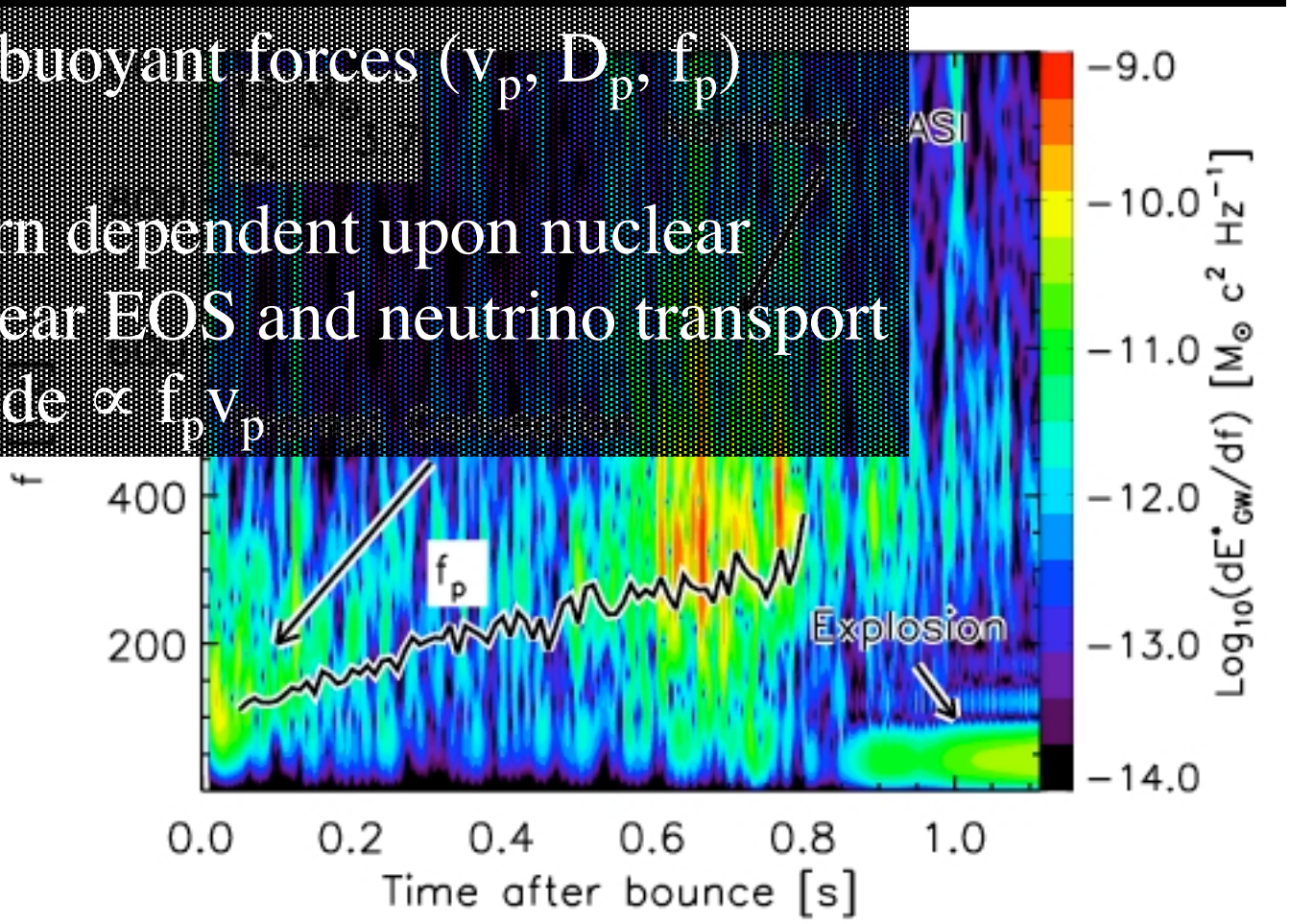

15 M⊙
Lνe = 3.7
Nonlinear SASI
Prompt Convection
fp
Explosion
f [Hz]
1000
800
600
400
200
0.0
0.2
0.4
0.6
0.8
1.0
Time after bounce [s]
−9.0
−10.0
−11.0
−12.0
−13.0
−14.0
Log10(dE*GW/df) [M⊙ c2 Hz−1]

Progenitor Mass and ν Luminosity Dependence



Conclusions

- GW emission of asymmetric explosions
- A model for GW emission
  - Plumes and buoyant forces (v_p, D_p, f_p)
  - $f_p \propto N_{turn}$
  - N_{turn} is in turn dependent upon nuclear and subnuclear EOS and neutrino transport
  - GW amplitude $\propto f_p v_p$



Future Directions

The Condition for successful explosions

- Better approximate neutrino physics
- L_{crit}, $\dot{M}$, and M relation!?
  - Where does it come from?
  - relate to τ_{adv} and τ_{q} condition?
- Distribution of residence times?
  - long and short
  - inherent asymmetry
  - Convection & SASI in context of Accretion?
- Analytic and numerical techniques
- 3D?

Why is it easier to explode in 2D compared to 1D?

Why is it easier to explode in 2D compared to 1D?

Because it's 2D

3D?

3D Simulations

Convection, SASI, & Accretion (in 3D)?
Distribution of residence times?
Lower critical luminosites?
Randy LeVeque et al.
CLAWPACK