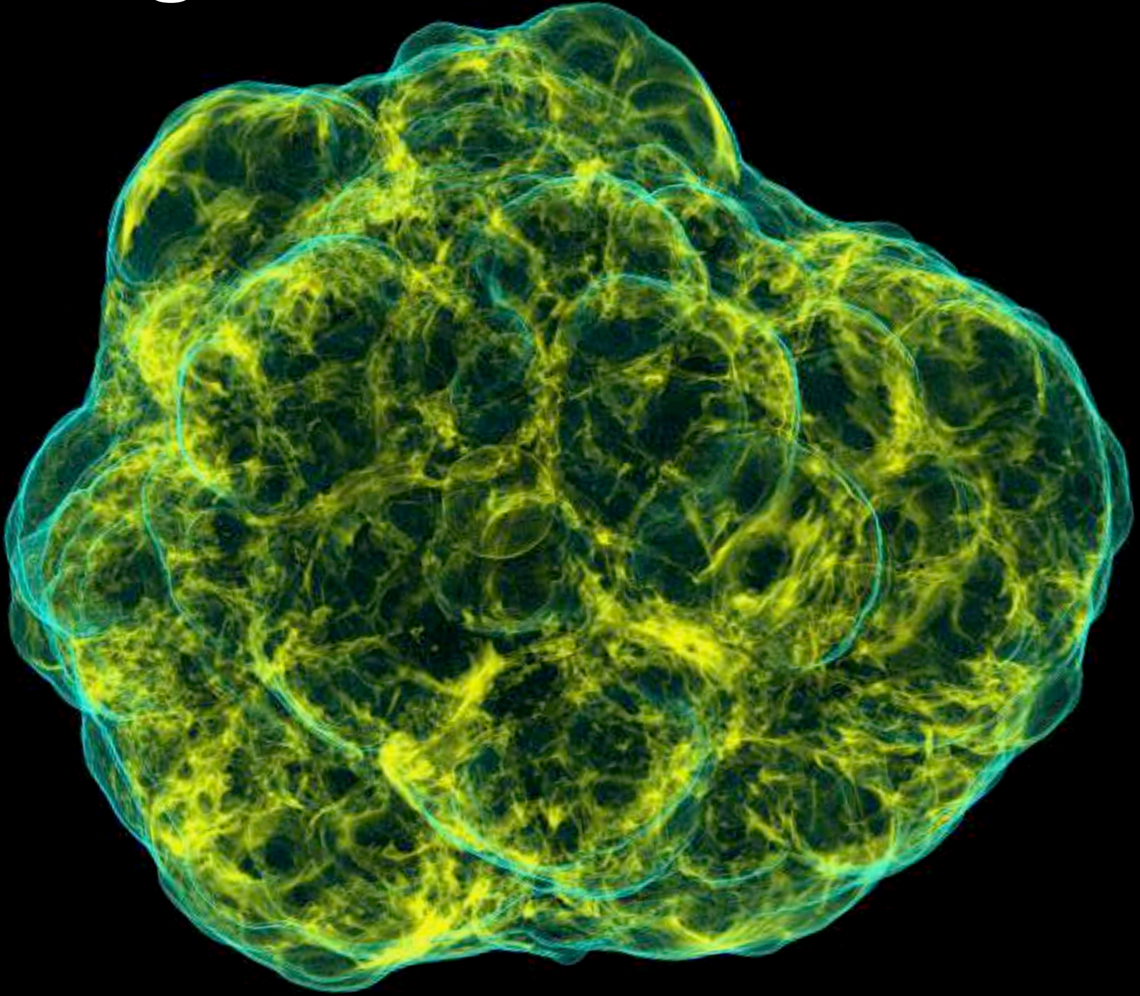
Modeling The Death of Massive Stars



Sherman
Fairchild
Foundation

Christian D. Ott,
TAPIR, California Institute of Technology
Simulating eXtreme Spacetimes (SXS) Collaboration

Fritz Zwicky
1898-1974

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891

Walter Baade
1893-1960

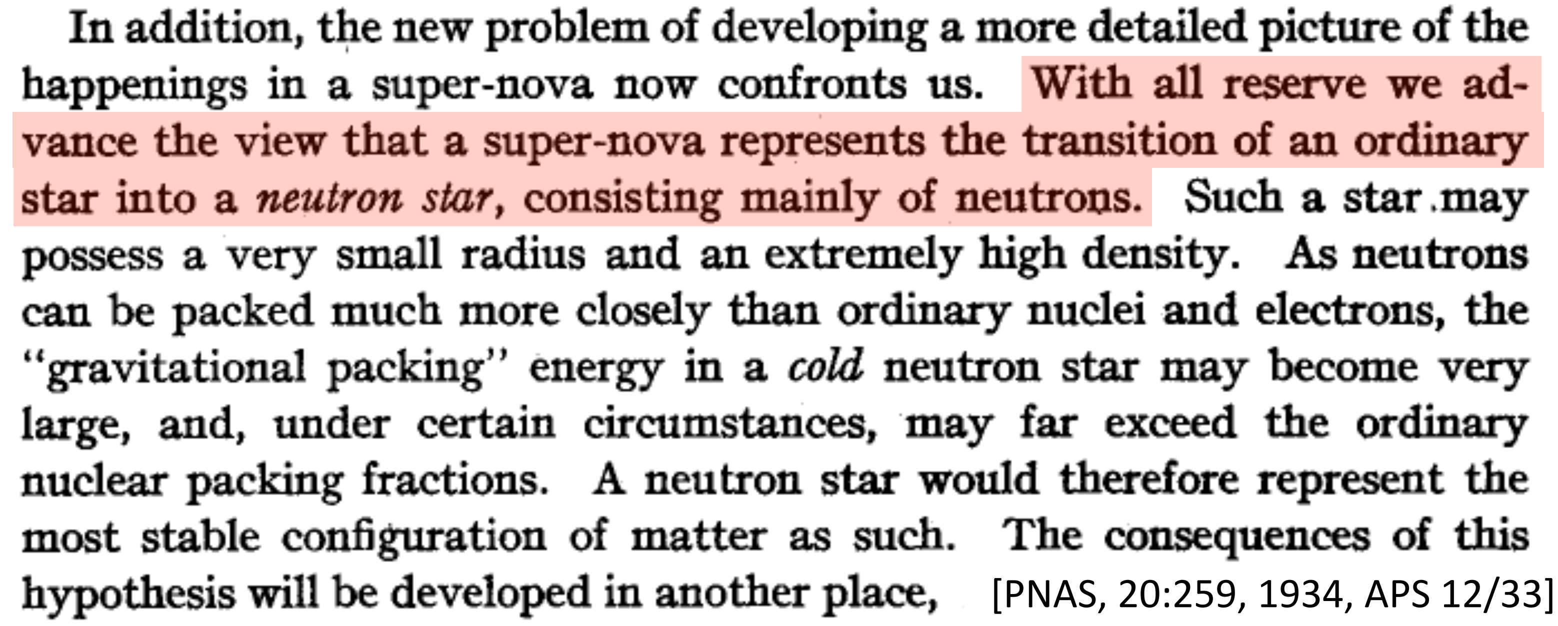
CARNEGIE OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON

Palomar 18” Schmidt telescope

Fritz Zwicky
1898-1974

Walter Baade

“Supernova” (1934)



In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the “gravitational packing” energy in a *cold* neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such. The consequences of this hypothesis will be developed in another place,

[PNAS, 20:259, 1934, APS 12/33]

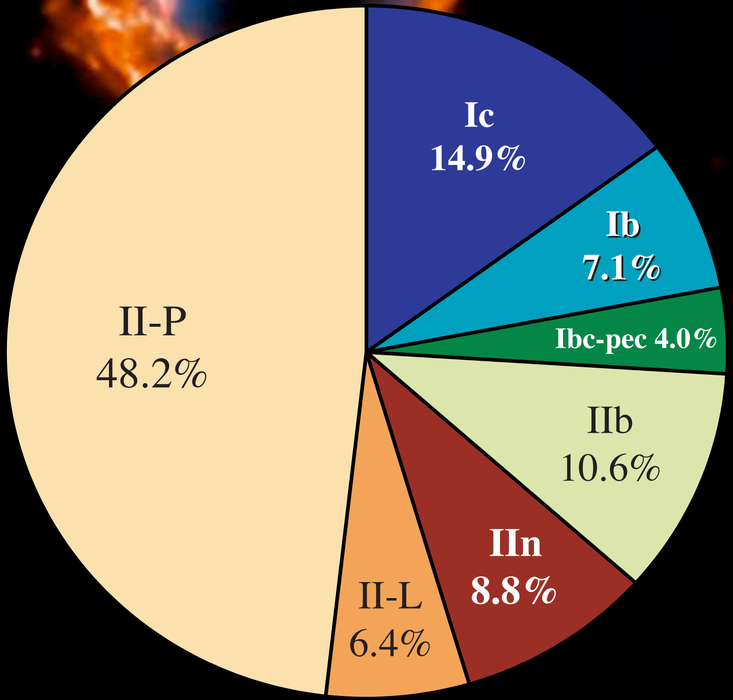
Stellar Death & Supernova Explosions

- ~1 SN/s in the Universe
- ~1 SN/day discovered
- ~1 SN/50-100 yrs (?) in the Milky Way
- >1 SN/year within 10 Mpc

- ~20% thermonuclear SNe (Type Ia)
  -> exploding white dwarfs
- ~80% core-collapse SNe (CCSNe)
  -> exploding massive stars

- Class of energetic stripped-envelope explosions: Type Ic-bl ("broad lines")
- Some (>8) SNe Ic-bl associated with long gamma-ray bursts.


Chandra



Smith+ 11, LOSS sample

Core-Collapse Supernovae:

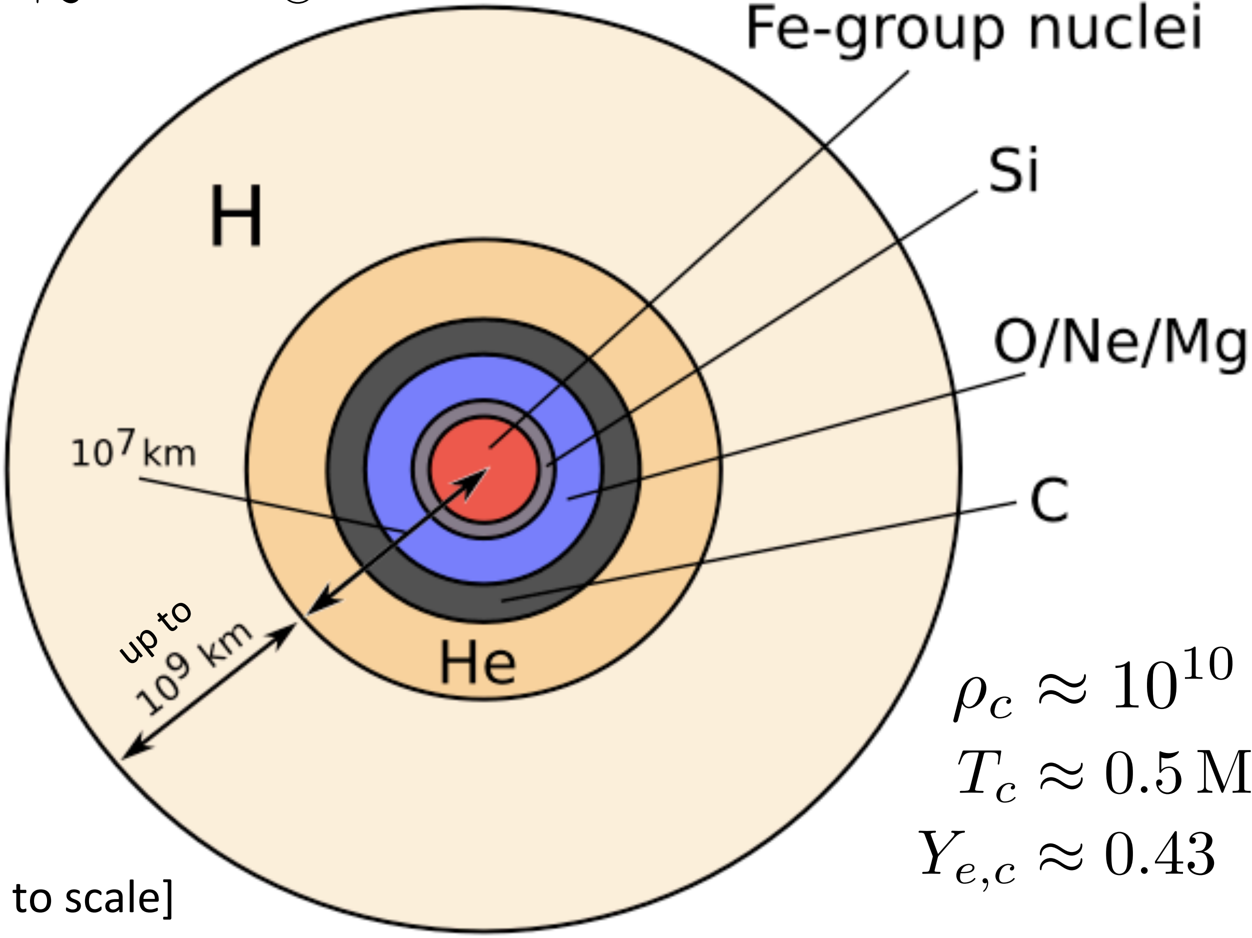
Explosions of Massive Stars $8M_\odot \lesssim M \lesssim 130M_\odot$

© Anglo-Australian Observatory

Supernova 1987A
Large Magellanic Cloud
Progenitor:
BSG Sanduleak -69° 220a, ≈18 M_{SUN}

The Basic Theory of Core Collapse

$8M_\odot \lesssim M \lesssim 130M_\odot$

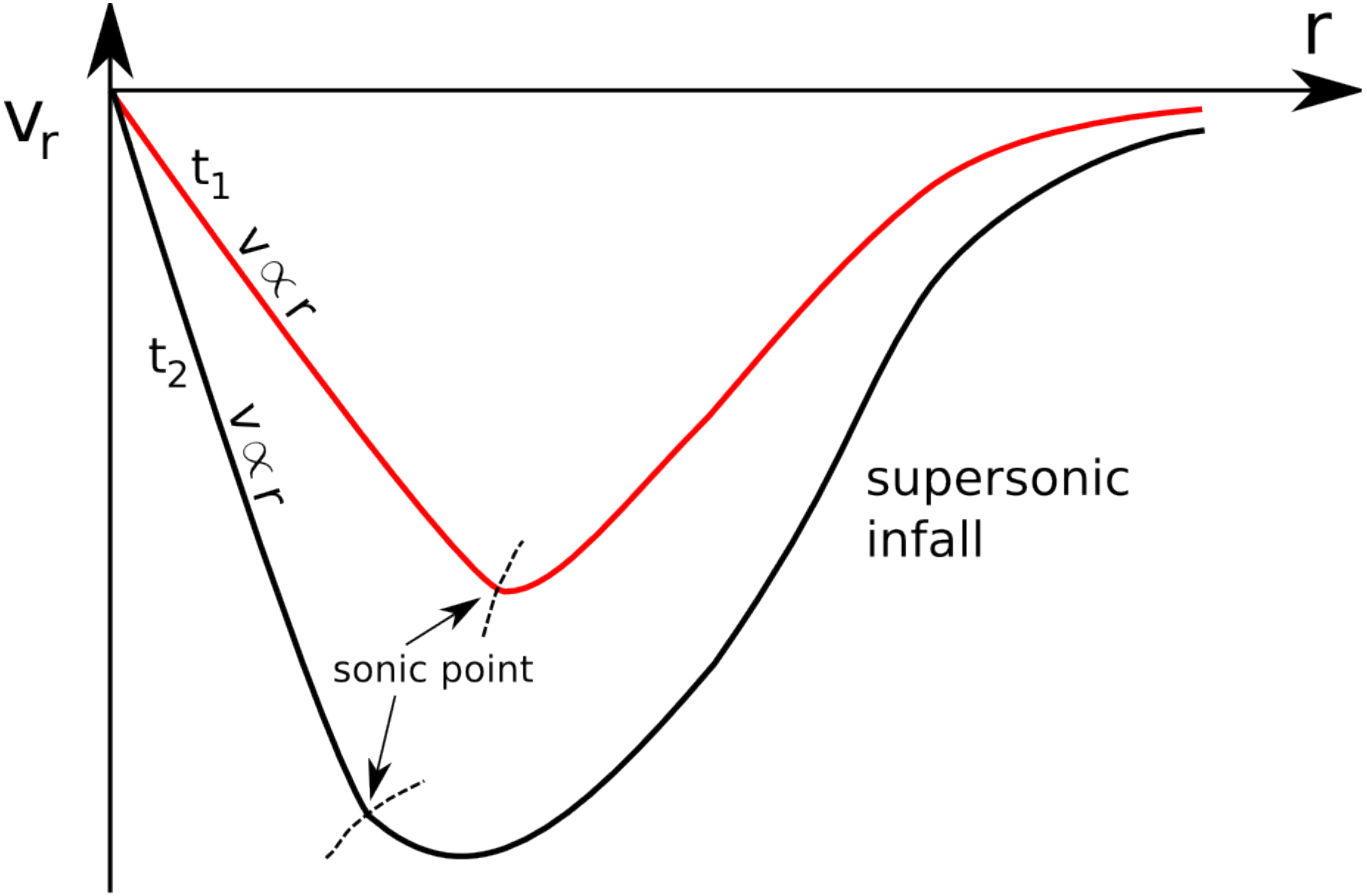


[not drawn to scale]

$$\rho_c \approx 10^{10}\,\mathrm{g\,cm^{-3}}$$
$$T_c \approx 0.5\,\mathrm{MeV}$$
$$Y_{e,c} \approx 0.43$$

$$M_{\mathrm{Ch}} \approx 1.44 \left(\frac{Y_e}{0.5}\right)^2 \left[1 + \left(\frac{s_e}{\pi Y_e}\right)^2\right]$$

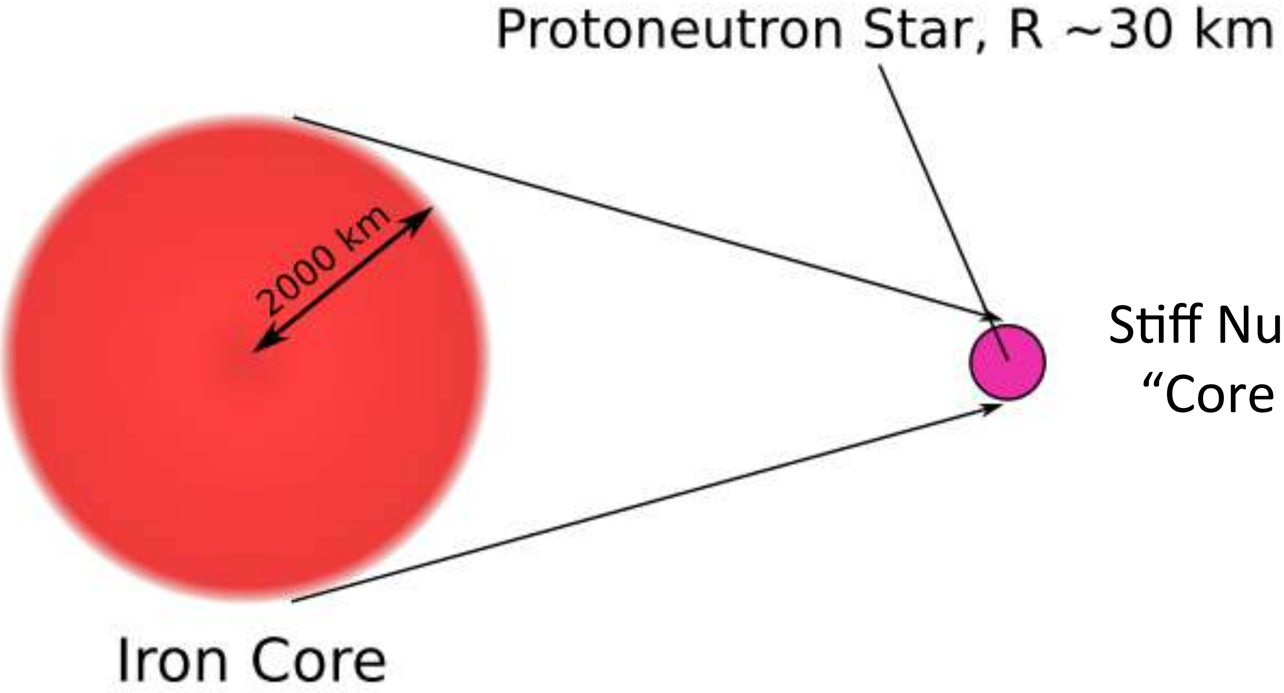
Self-Similarity of Collapse



Homologously ($v \propto r$) collapsing **inner core**.
Supersonically collapsing **outer core**.

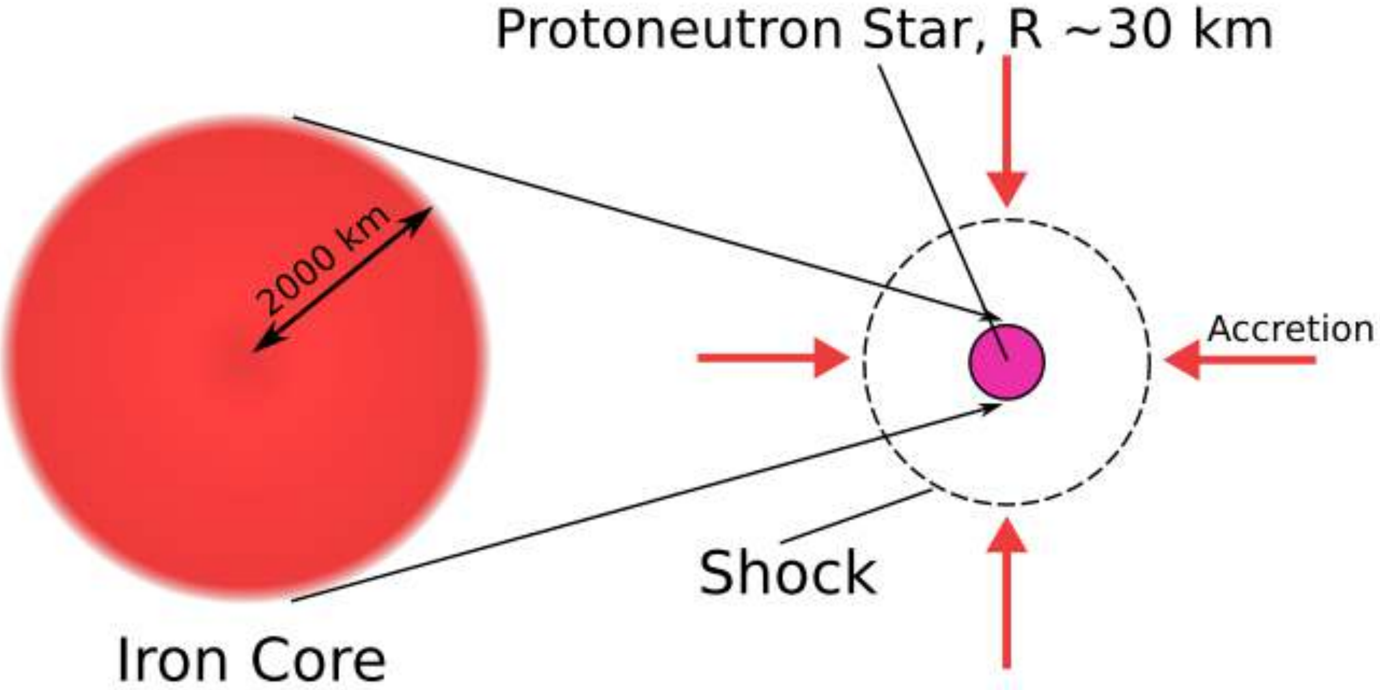
Analytic similarity solutions:
Goldreich & Weber 1980
Yahil & Lattimer 1982
Yahil 1983

Collapse and Bounce

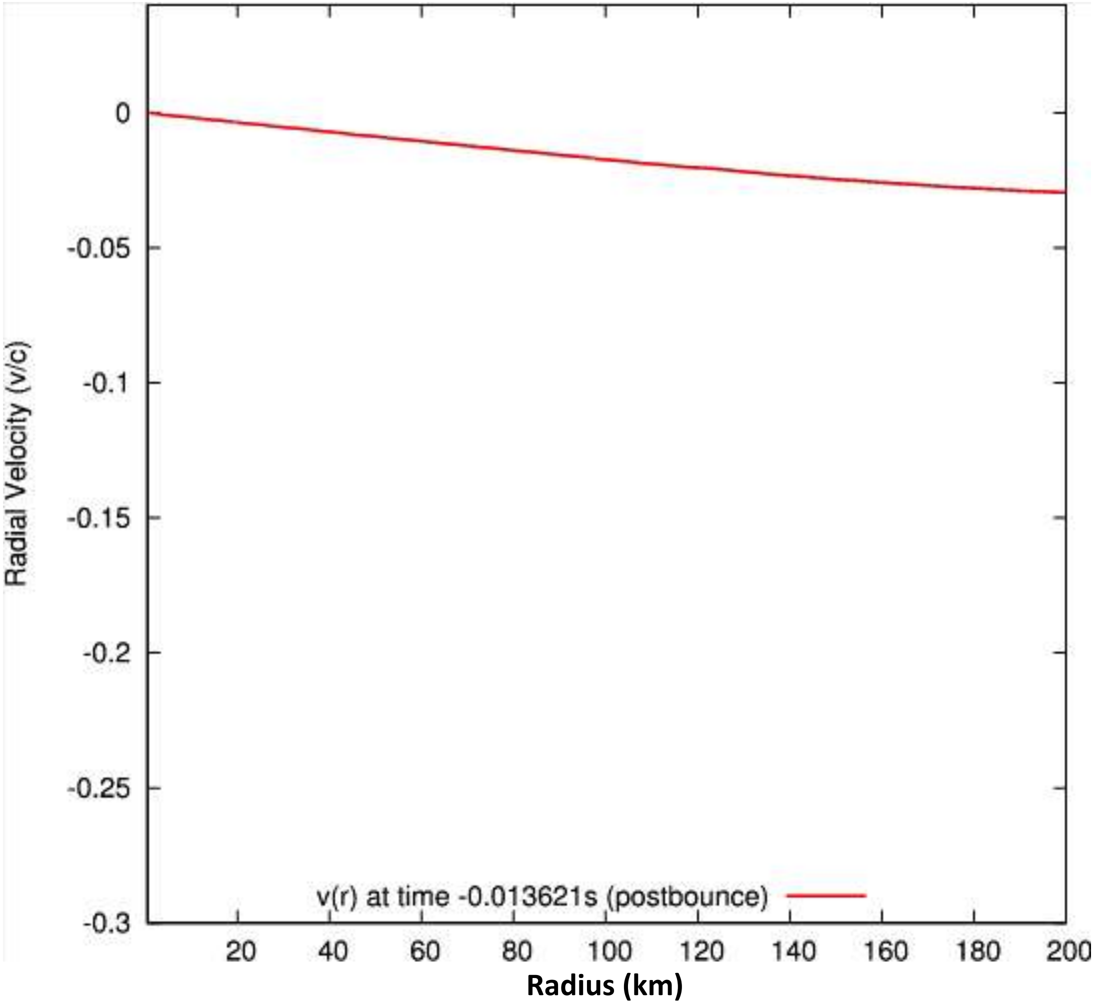


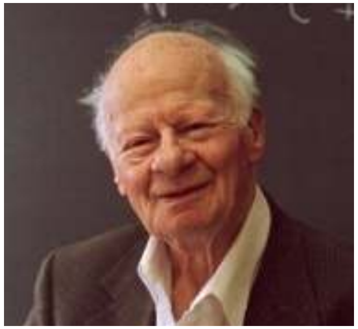
Stiff Nuclear EOS:
“Core Bounce”

Situation after Core Bounce



The Core-Collapse Supernova Problem



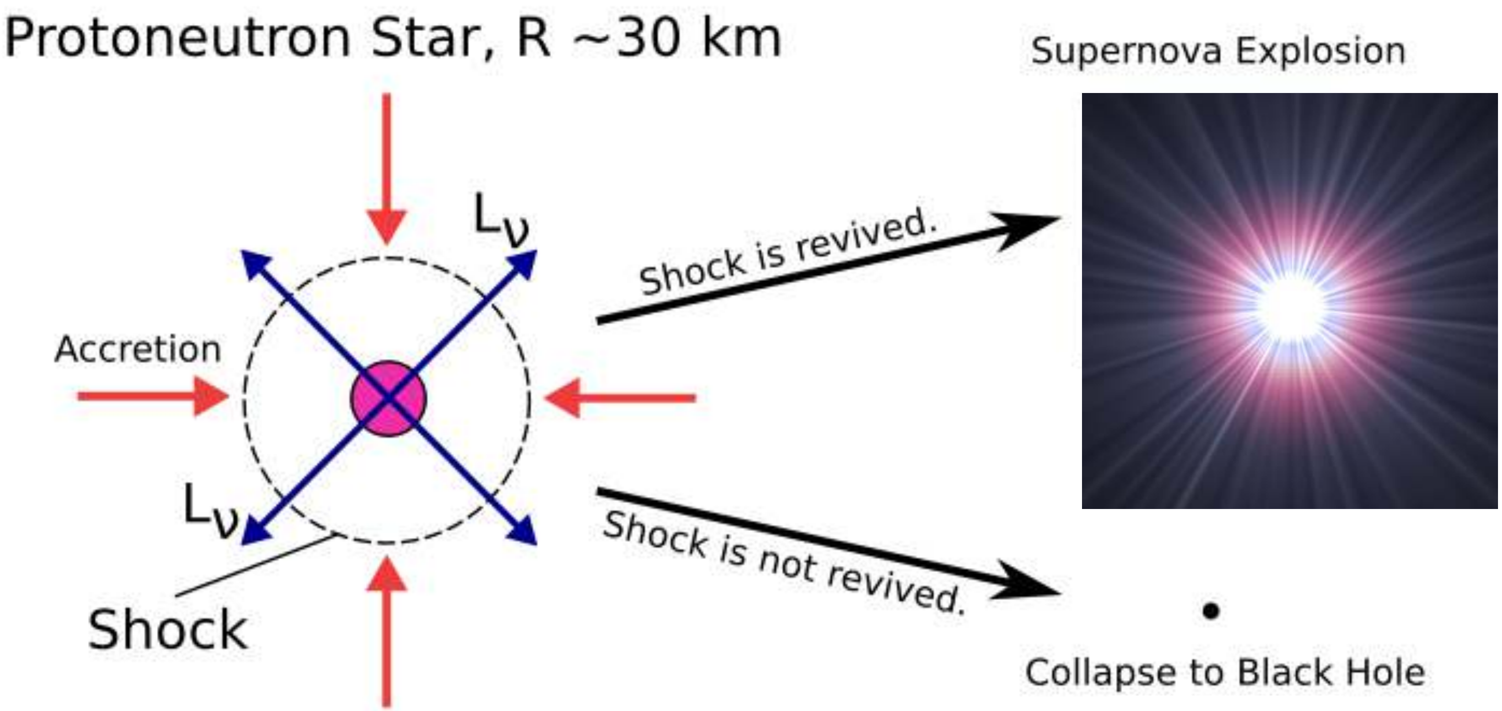


Hans Bethe
1906-2005

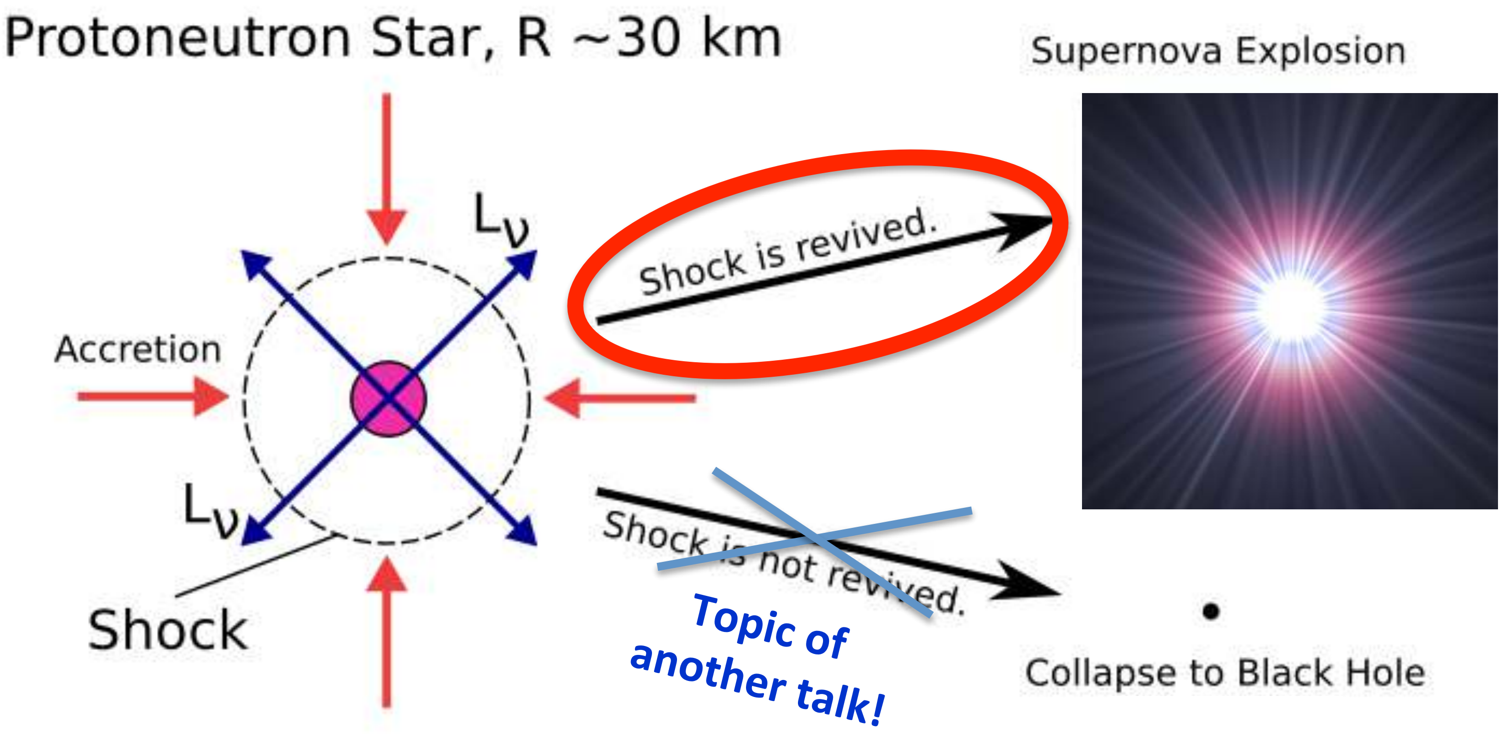
Animation
by Evan O'Connor
Caltech GR1D code
(open source!)

- **The shock always stalls:**
  Dissociation of Fe-group nuclei @ ~8.8 MeV/baryon (~17 B/M_{Sun}).
  Neutrino losses initially @ >100 B/s (1 [B]ethe = 10^{51} ergs).

Postbounce Evolution



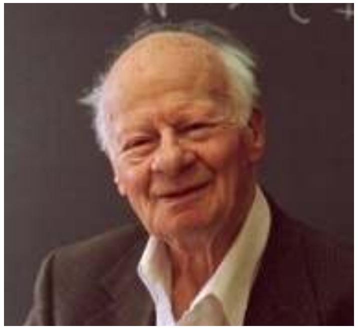
Postbounce Evolution



Topic of another talk!

What is the mechanism that revives the shock?

Core-Collapse Supernova Energetics



Hans Bethe
1906-2005

- Collapse to a neutron star:
  ~3 x 10^{53} erg = 300 [B]ethe
  gravitational energy (≈0.15 $M_{Sun}c^2$) released.
  Initially stored in protoneutron star.
  -> Any explosion mechanism must tap this reservoir.

- ~10^{51} erg = 1 B kinetic and internal energy of the ejecta.
  (Extreme cases: 10 B; "hypernova")

- 99% of the energy is radiated in neutrinos over tens of seconds in protoneutron star cooling.
  -> Strong evidence from SN 1987A neutrino observations.

Detailed Models: Ingredients

Fully coupled!

Magneto-Hydrodynamics	→ Dynamics of the stellar fluid.
General Relativity	→ Gravity
Nuclear and Neutrino Physics	→ **Nuclear EOS**, nuclear reactions & ν interactions.
Boltzmann Transport Theory	→ **Neutrino transport**.

Detailed Models: Ingredients

Fully coupled!

Magneto-Hydrodynamics	Dynamics of the stellar fluid.
General Relativity	Gravity
Nuclear and Neutrino Physics	**Nuclear EOS**, nuclear reactions & ν interactions.
Boltzmann Transport Theory	**Neutrino transport**.

- Additional Complication: **Core-Collapse Supernovae are 3D**
  - Rotation, **fluid instabilities** (convection, turbulence, advective-acoustic, rotational), **MHD**, multi-D structure from convective burning.
    -> **Need multi-D (ideally 3D) treatment.**

- Route of Attack: **Computational Modeling**

– Complexity dominated by neutrino transport:
Full problem is 3 (space) + 3 (momentum space) + 1 (time) dimensional

– Approach: employ reduced dimensionality in space and momentum space.

Next Step: Computation

1D (spherical symmetry)

- First simulations: 1960-70 by Colgate & White, Wilson, Arnett
- Bethe & Wilson '85: "**Neutrino Mechanism**"

Neutrino Mechanism

Bethe & Wilson ’85; also: Janka ‘01, Janka+ 07, Pejcha & Thompson ‘12

Cooling:

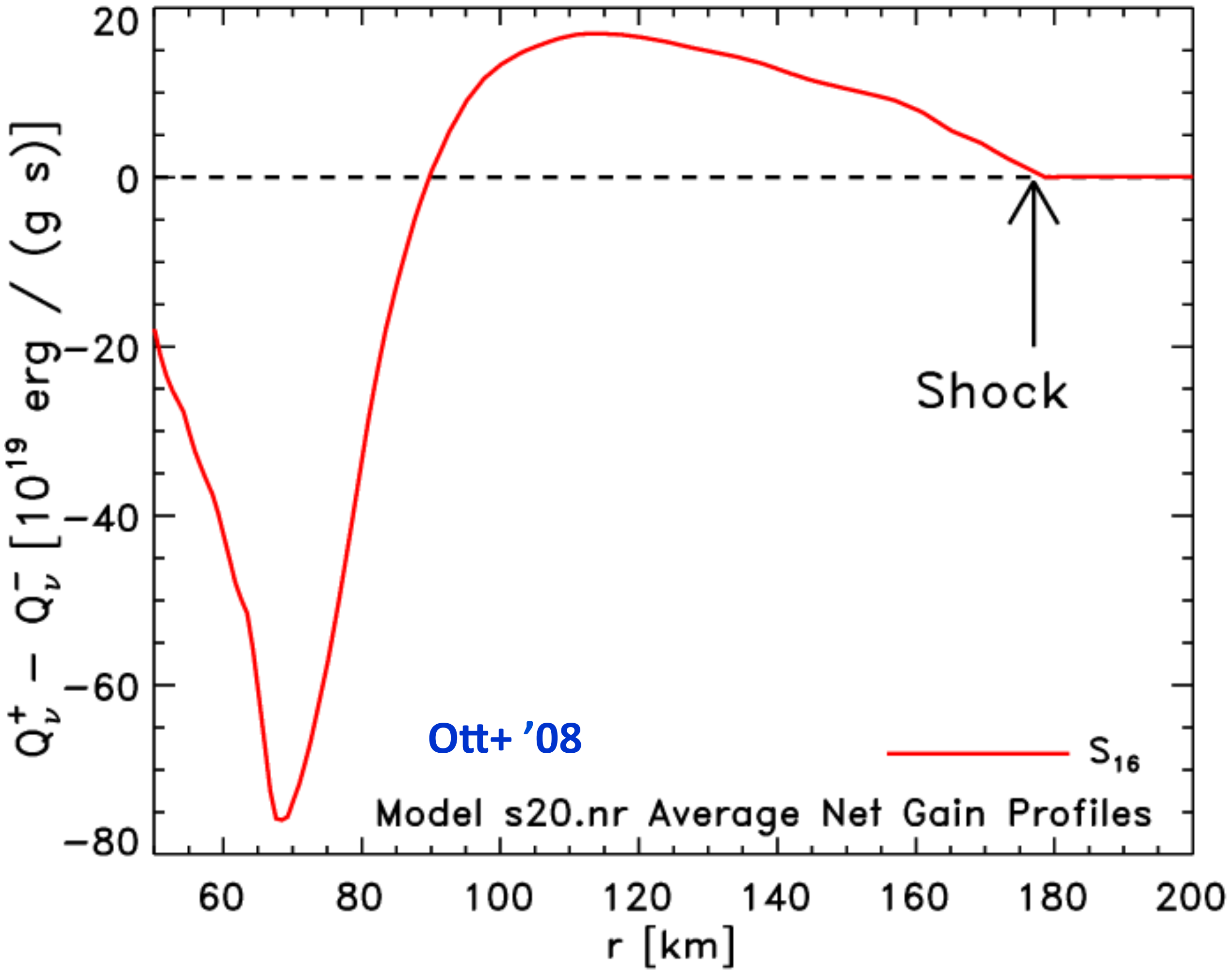
$$Q_\nu^- \propto T^6$$

Heating via charged-current absorption:

$$\nu_e + n \rightarrow p + e^-$$

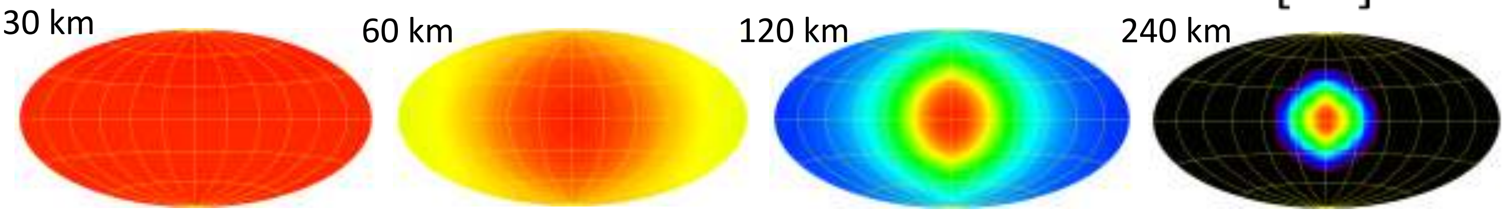
$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$Q_\nu^+ \propto \left\langle \frac{1}{\mathrm{F}_\nu} \right\rangle L_\nu r^{-2} \langle \epsilon_\nu^2 \rangle$$



Ott+ ’08

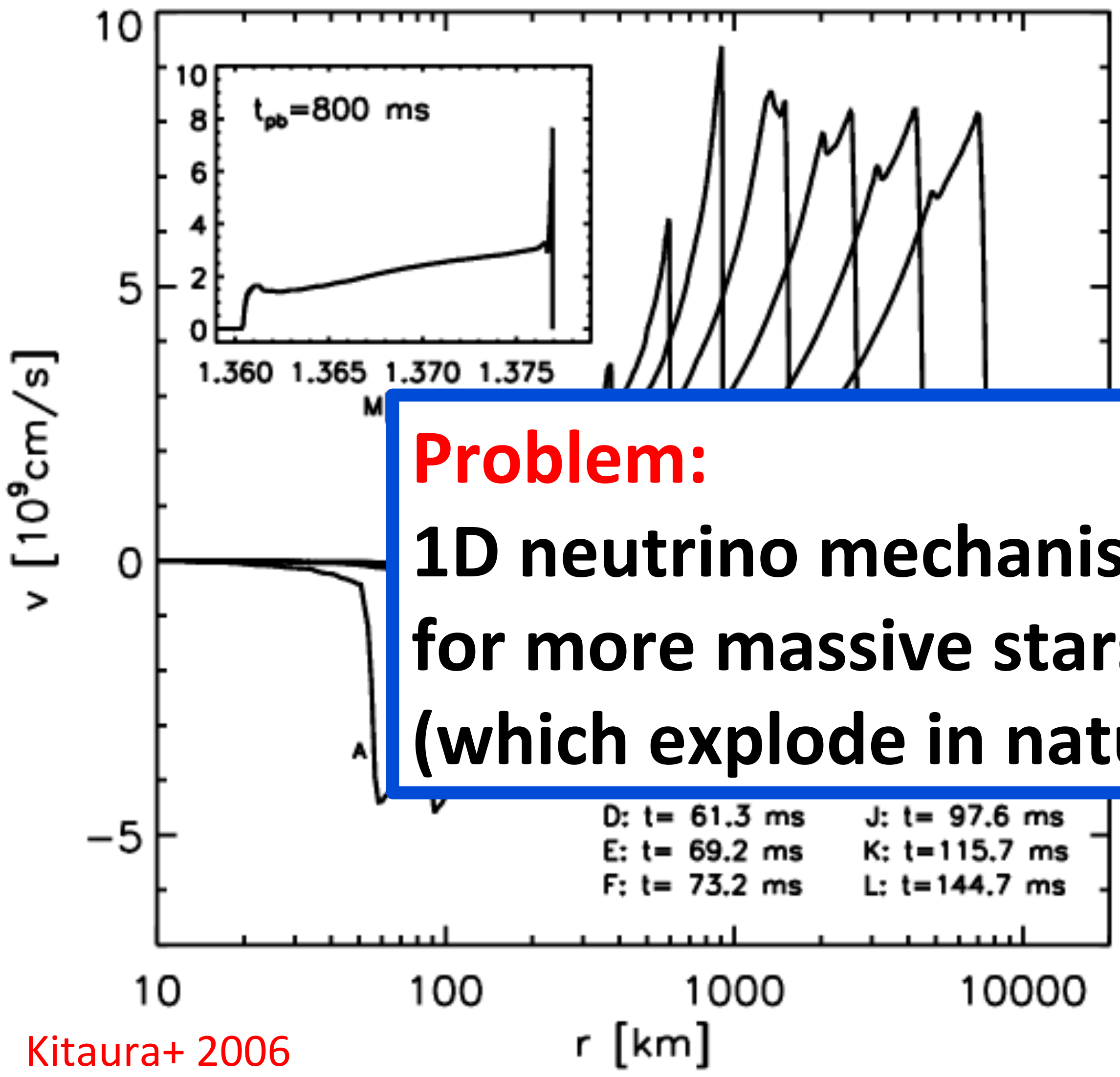
Neutrino radiation field:



C. D. Ott @ ICTS, 2013/06/27

1D Neutrino-Driven Explosions

Kitaura+ '06, Hüdepohl+ '10, Fischer+ '10, '12



Kitaura+ 2006

8.8 M_{SUN} progenitor star

O-Ne-Mg core

Problem:

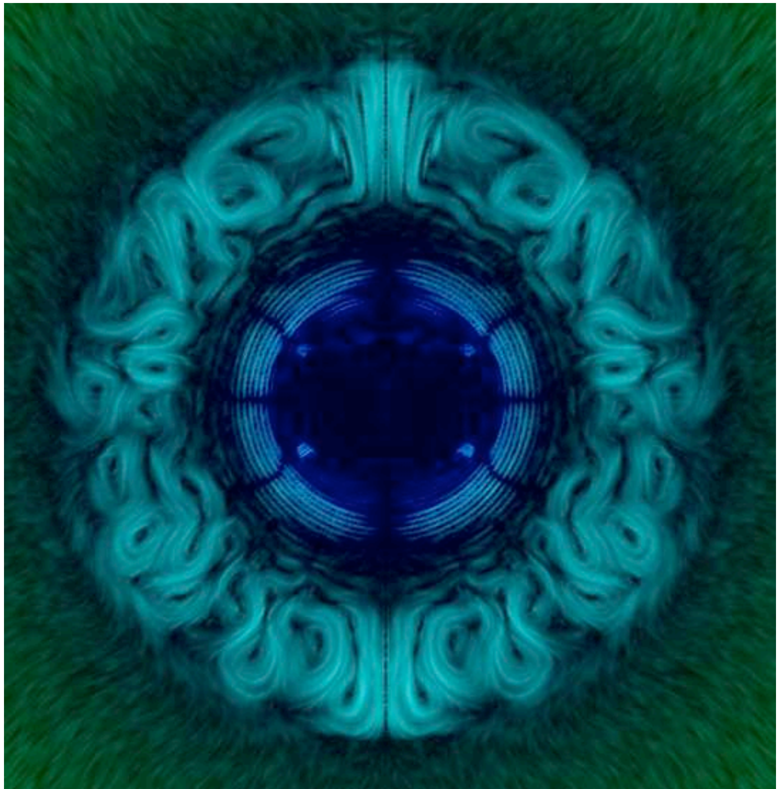
1D neutrino mechanism fails for more massive stars (which explode in nature).

Overview of Core-Collapse Supernova Models

1D -> 2D (axisymmetry)

- First simulations in 1990s:
  Herant+ ‘94, Burrows+ ’95, Janka & Müller ’96
- Multi-D dynamics:
  - **Convection** in proto-NS and in the heating region.
  - Instability of the stalled shock (“**SASI**”).
  - Rotation & magnetic fields.

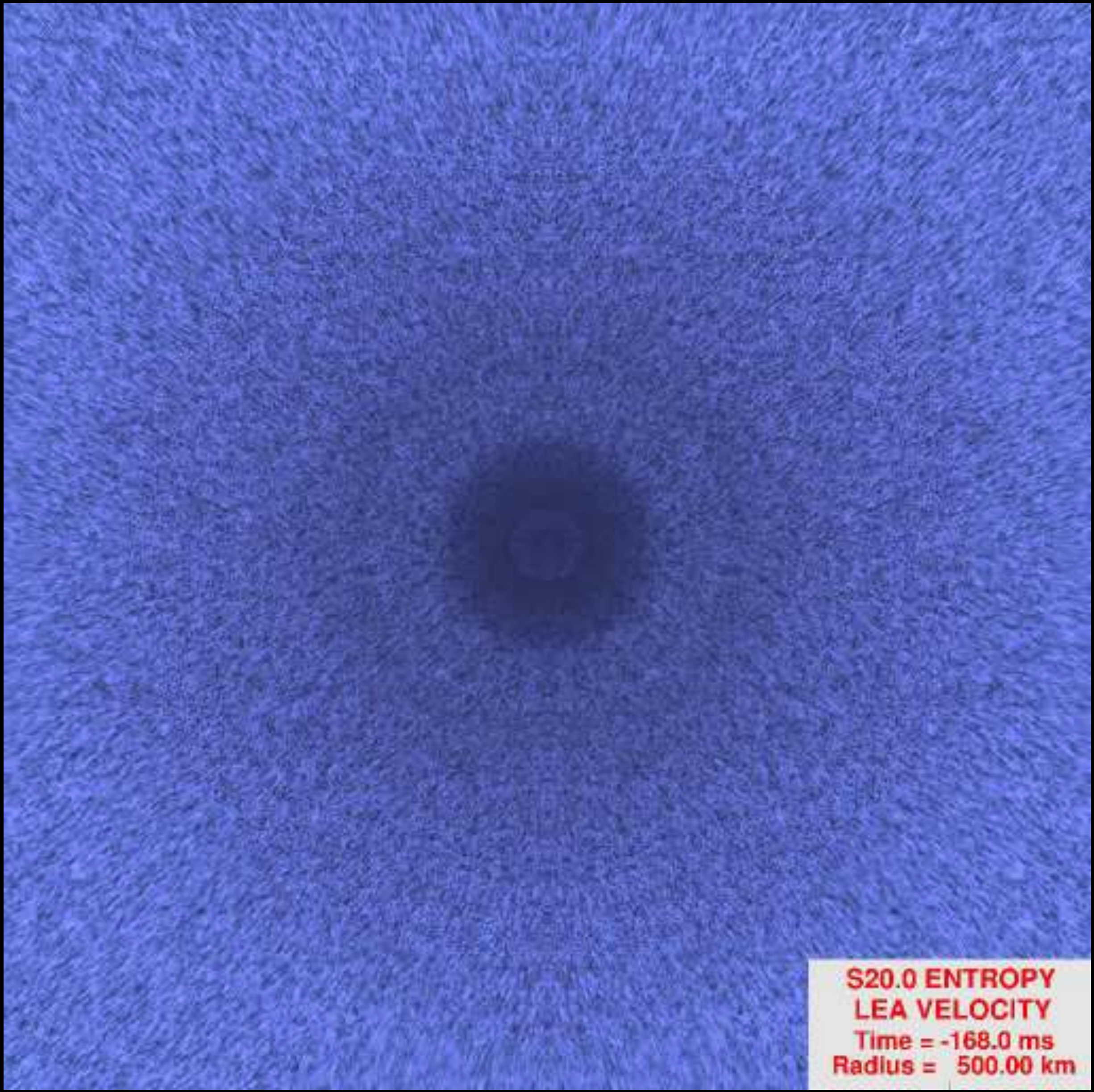
Proto-NS convection



Dessart+ ‘05

Standing Accretion Shock Instability (SASI)

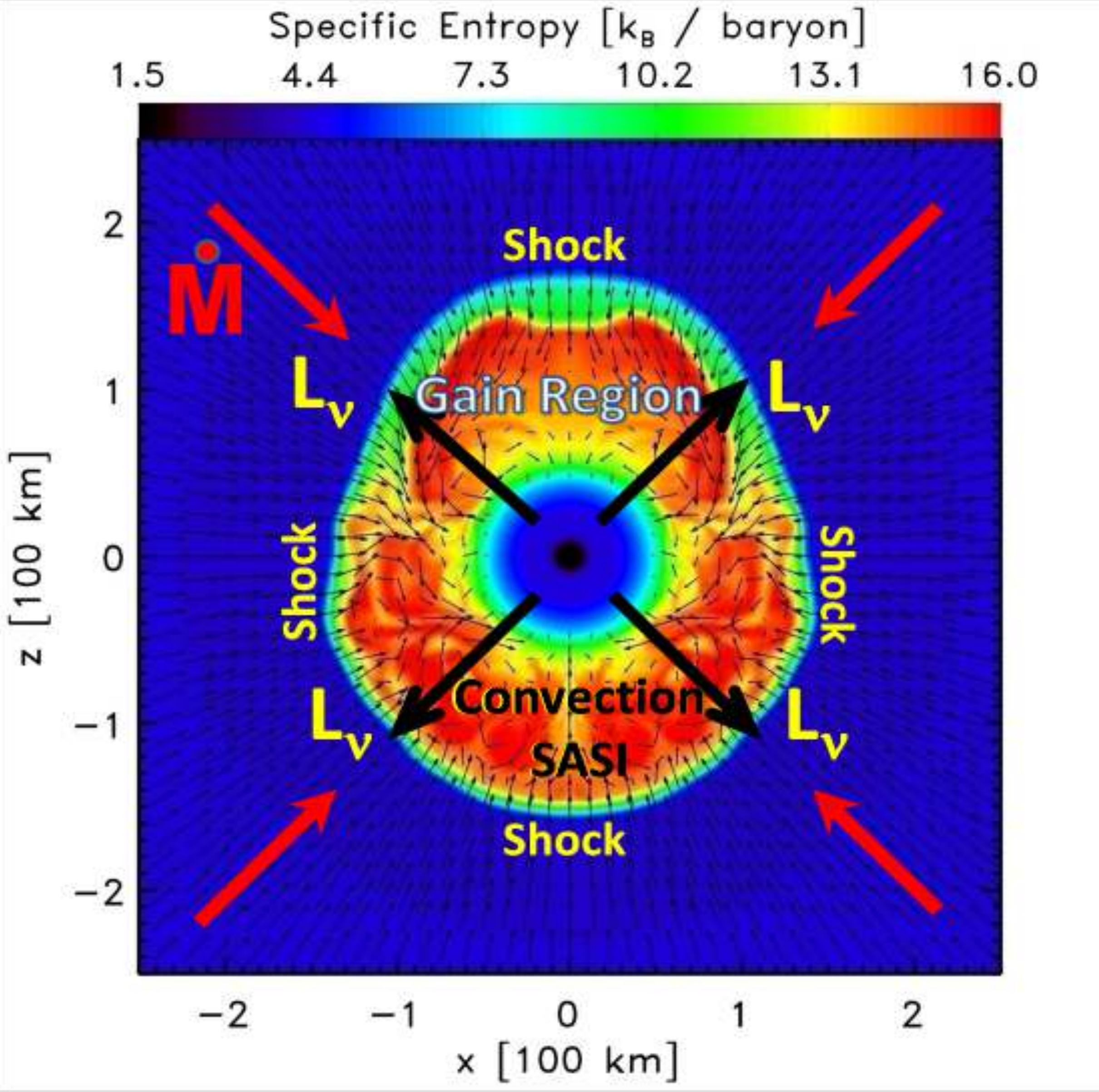
Blondin+'03
Foglizzo+'06
Scheck+ '08
and many
others



Movie by
Burrows,
Livne,
Dessart,
Ott, Murphy'06

Results of 2D Simulations

Recent 2D work: Buras+06, Ott+08, Marek+09, Murphy+08, Suwa+10, Müller+12abc, Bruenn+12



Net effect of 2D:
"Dwell time" in heating region increases.

-> 2D models explode more easily.

-> **BUT explosions not robust**:
- marginal,
- require fine-tuning,
- not reproducible across codes.

What are we missing?

Dimensionality?

2D -> 3D

Physics?

Missing Physics: Neutrino Oscillations!?

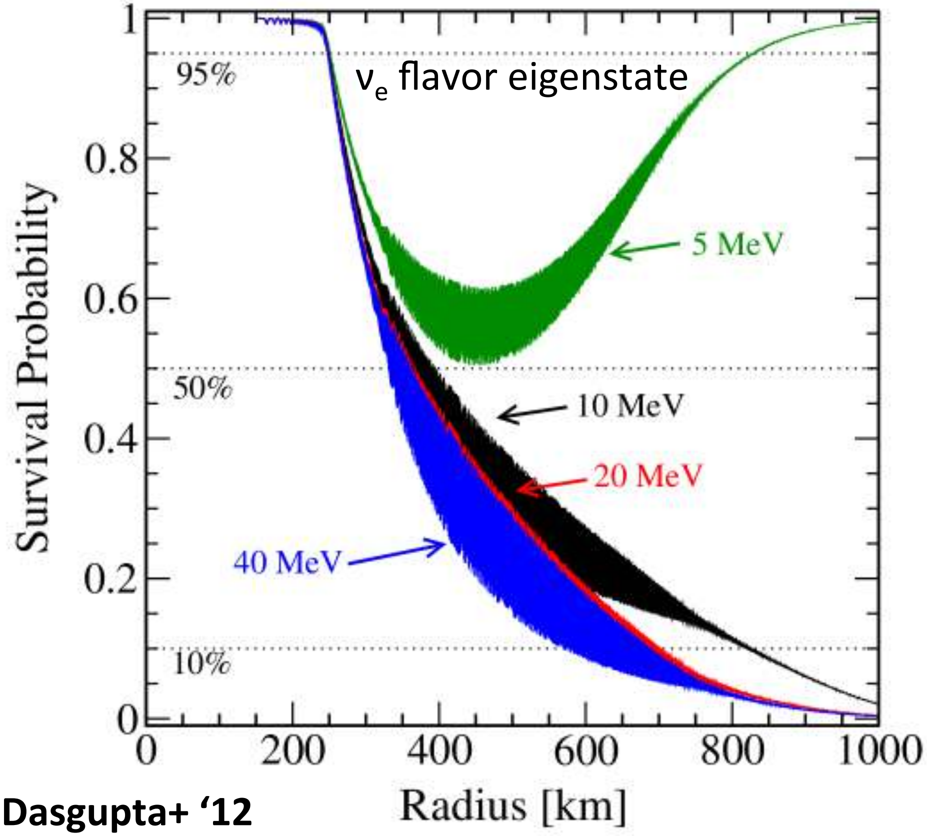
Neutrino Oscillations

[**Dasgupta, O'Connor, & Ott'12**]

- Multiple kinds of oscillations:
  Vacuum oscillations
  Mikheyev–Smirnov–Wolfenstein (MSW) effect: ν-e$^-$ scattering
  New: Self-induced "collective" oscillations: ν-ν scattering

[Pantaleone '92, Hannestad/Raffelt et al. '06, Duan/Fuller et al. '06-'10, Dasgupta/Dighe '07-'11]

- Collective oscillations need high neutrino density
  -> *near the core of a core-collapse supernova*.

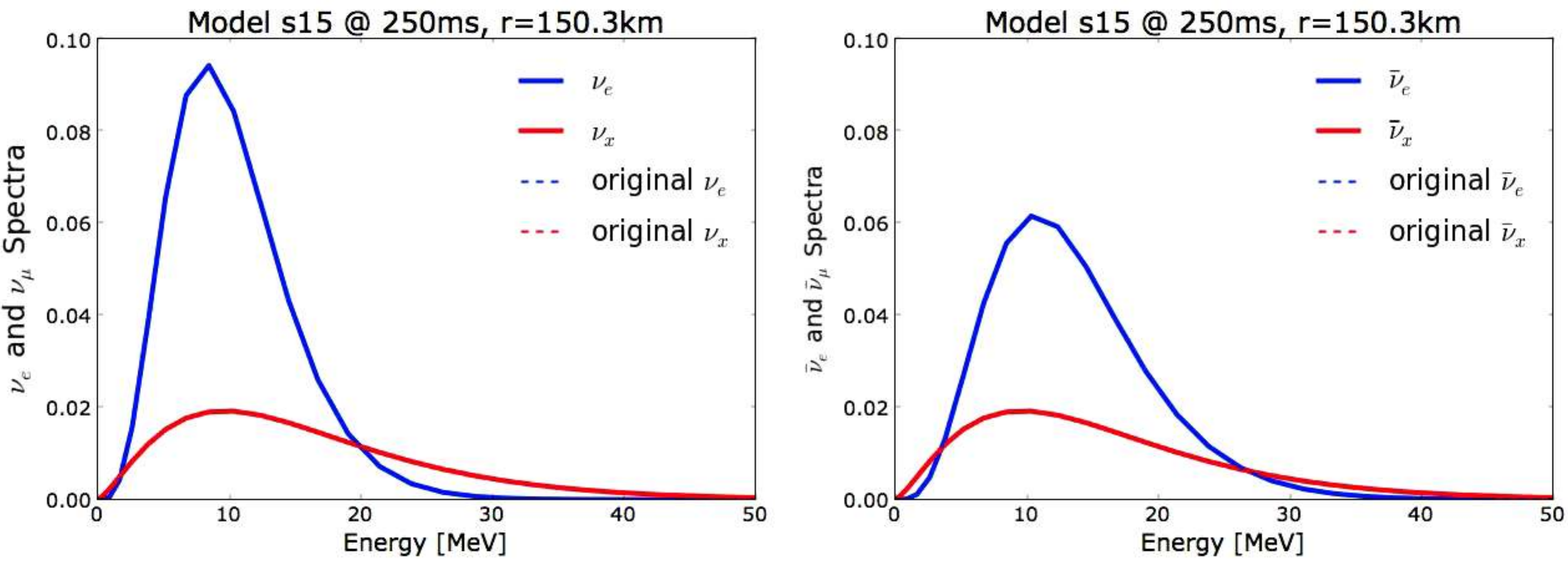


Dasgupta+ '12

Collective Oscillations

[Dasgupta, O’Connor, & Ott 2012]

- Example from Dasgupta, O’Connor & Ott ’12 – single-angle, multi-energy, effective 2-flavor approach: ν_e, ν_x
- First oscillation calculation tagging on to 2D radiation-hydro simulations. Work in 1D by Hamburg & Munich groups.



Spectral swaps!

Movie by Evan O’Connor

Impact of Collective Oscillations

[**Dasgupta, O'Connor, & Ott '12**]

- **What is the effect on the CCSN mechanism?**

Neutrino heating:

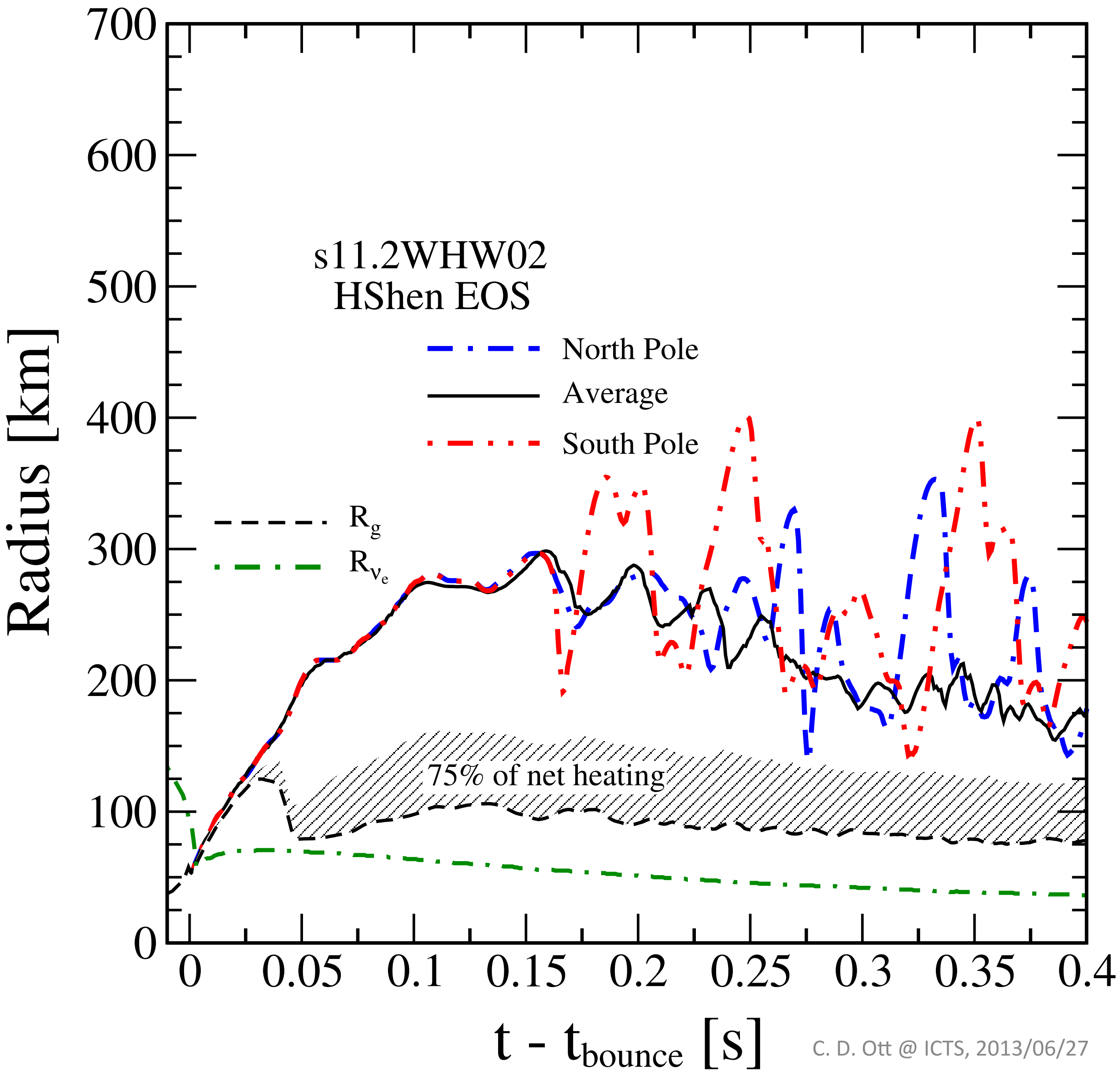
$$Q_\nu^+ = \frac{X_n}{\lambda_0^a}\frac{L_{\nu_e}}{4\pi r^2}\underset{\uparrow}{\langle E_{\nu_e}^2\rangle}\left\langle\frac{1}{\mathsf{F}}\right\rangle + \frac{X_p}{\bar{\lambda}_0^a}\frac{L_{\bar{\nu}_e}}{4\pi r^2}\underset{\uparrow}{\langle E_{\bar{\nu}_e}^2\rangle}\left\langle\frac{1}{\bar{\mathsf{F}}}\right\rangle$$

Messer et al. '98
Janka '01

- **Basic idea**: swap of ν_e/ν_x and anti-ν_e/anti-ν_x spectra -> **harder ν_e/anti-ν_e spectra** -> increased heating.
- Key prerequisite:
  Oscillations must occur below shock radius,
  ideally below gain radius.

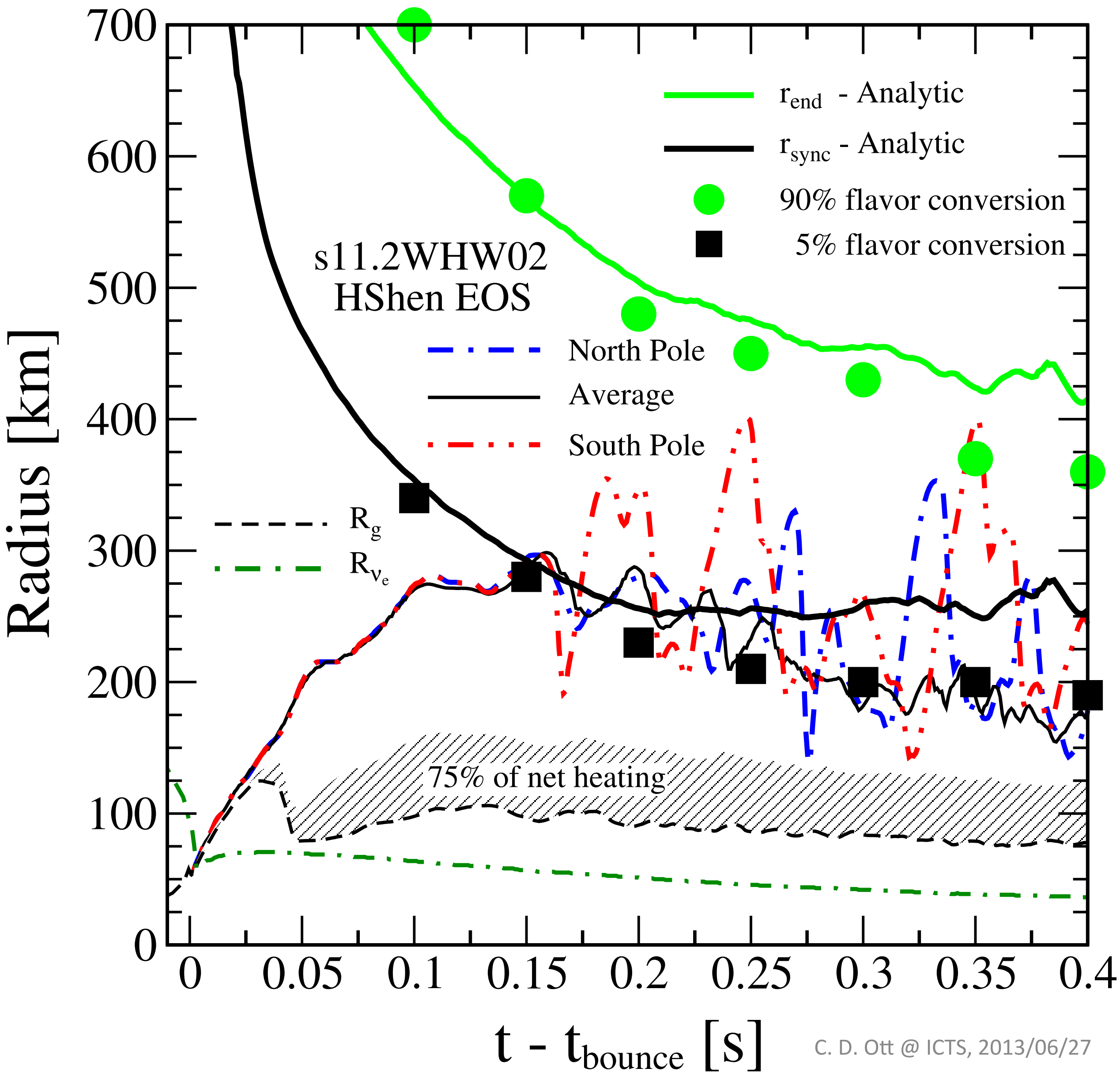
Impact of Collective Oscillations (2)

[**Dasgupta, O'Connor, & Ott '12**]



Impact of Collective Oscillations (3)

[**Dasgupta, O'Connor, & Ott '12**]



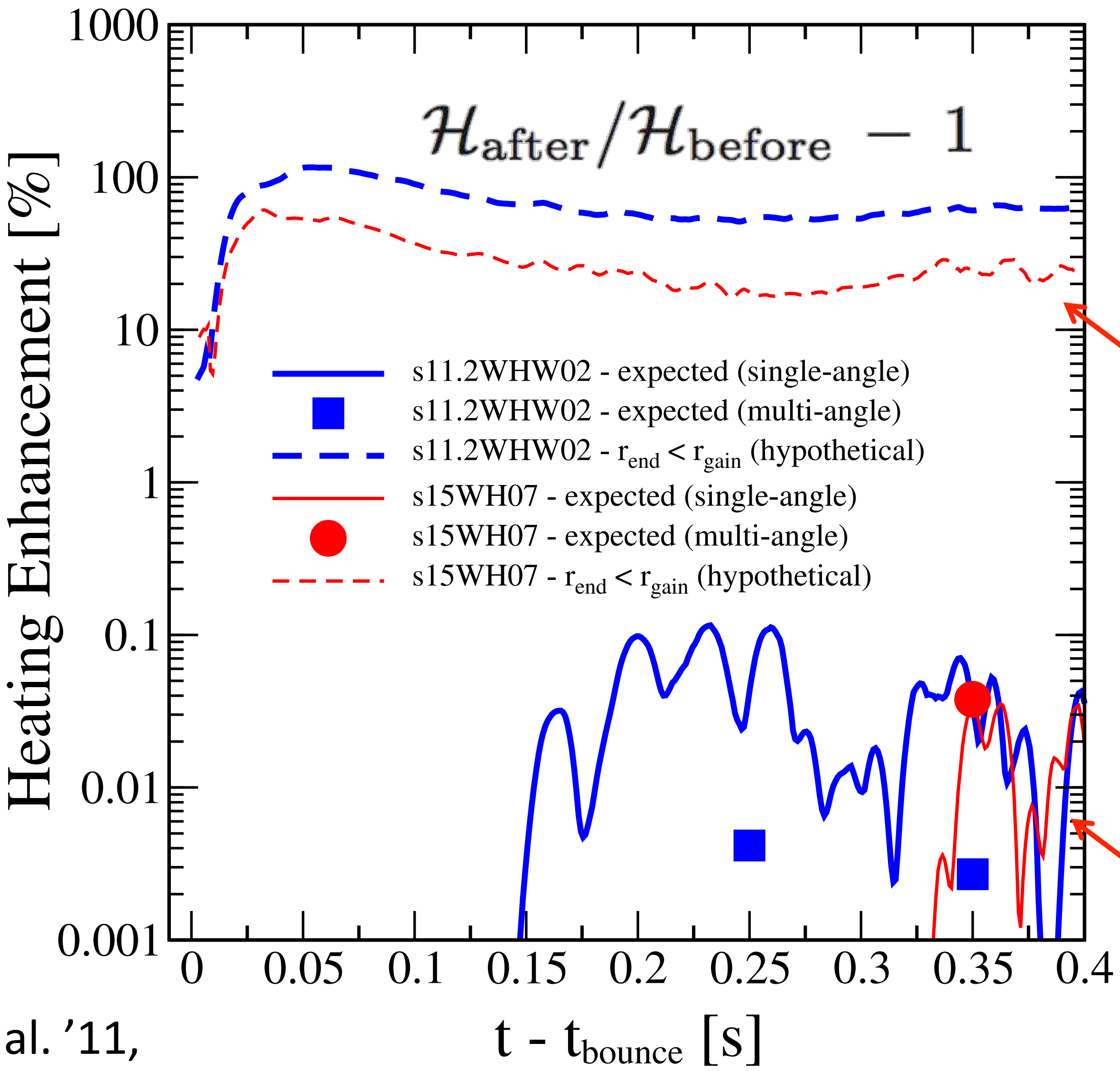
Analytic & numerical oscillation calculations based on 2D radiation fields

See also:
Chakraborty et al. '11ab
Suwa et al. '11
Pejcha et al. '11

Heating Enhancement?

[Dasgupta, O'Connor, & Ott '12]

Progenitors:
11.2 M_{Sun}
15 M_{Sun}
Woosley et al. '02



optimistic guess by Suwa et al. (wrong!)

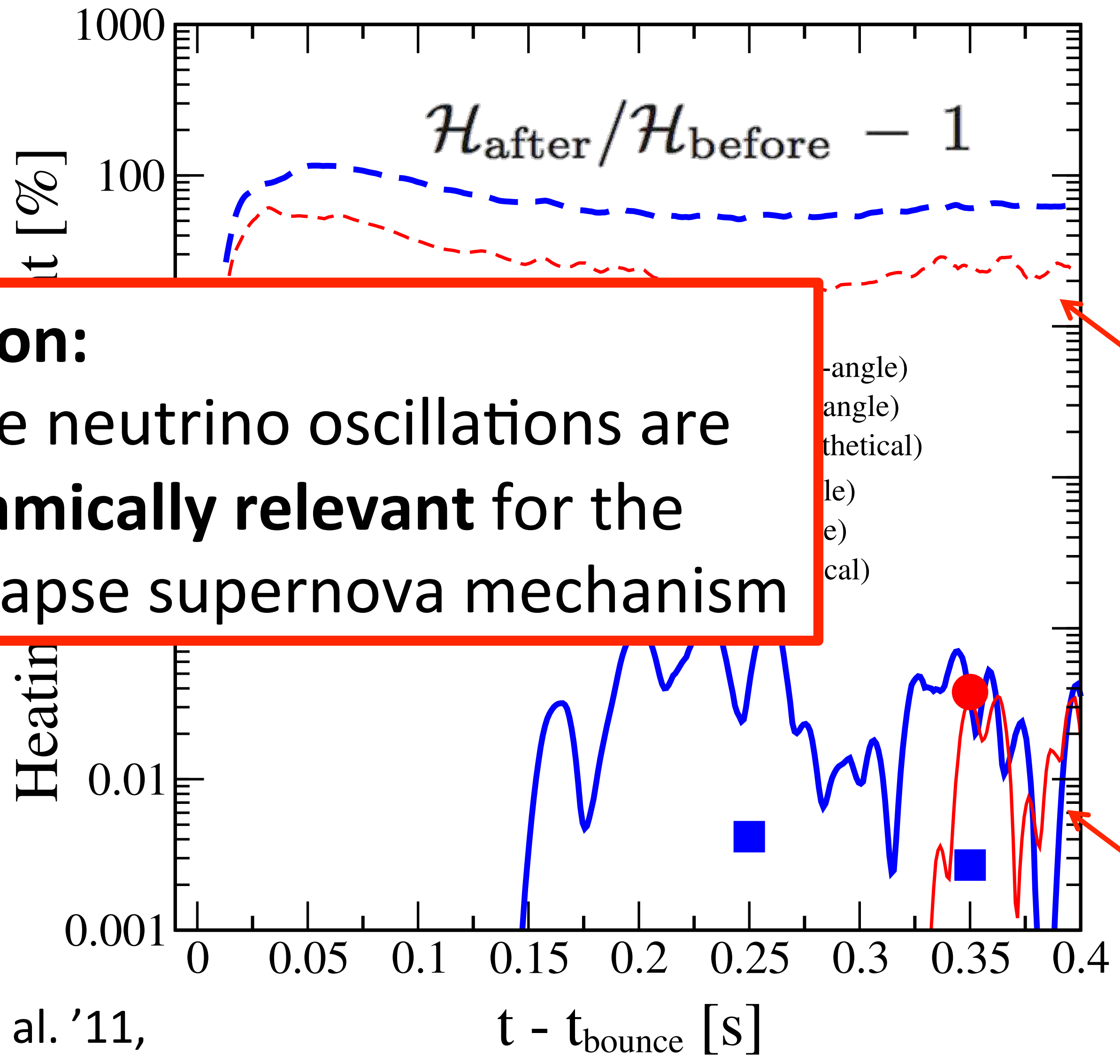
results from actual calculations

See also Suwa et al. '11, Chakraborty et al. '11ab

Heating Enhancement?

[Dasgupta, O'Connor, & Ott '12]

Progenitors:
11.2 M_{Sun}
15 M_{Sun}
Woosley et al. '02



Conclusion:
Collective neutrino oscillations are **not dynamically relevant** for the core-collapse supernova mechanism

optimistic guess by Suwa et al. (wrong!)

results from actual calculations

See also Suwa et al. '11, Chakraborty et al. '11ab

What are we missing?

Dimensionality?

2D -> 3D

Physics?

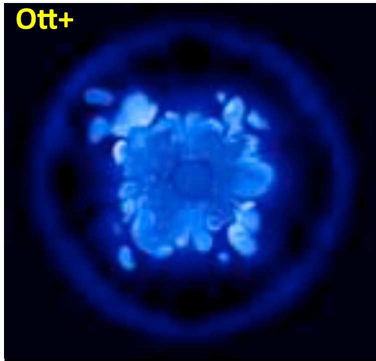
The Frontier: 3D Core-Collapse Supernovae

- 1D -> 2D: neutrino heating more efficient, some models explode.
- 2D -> 3D: (1) Character of turbulence changes;
  energy cascades to small scales (large scales in 2D).
  (2) Additional degree of freedom:
  nonaxisymmetric flow.

- **Is the neutrino mechanism robust in 3D?**

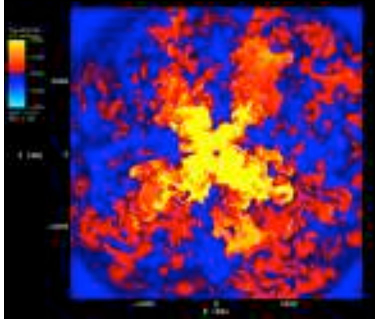
- **Computational challenge**:
  - **Multi-scale**: Resolve 10 m (turbulence) - 10000 km (outer core)
  - **Multi-physics**: GR, MHD, neutrinos, nuclear EOS, nuclear reactions
  - 3D estimates: Memory footprint: ~10-100 Terabytes
    Total # of floating point operations: ~10^5 Petaflops

  -> Approximations must be made!



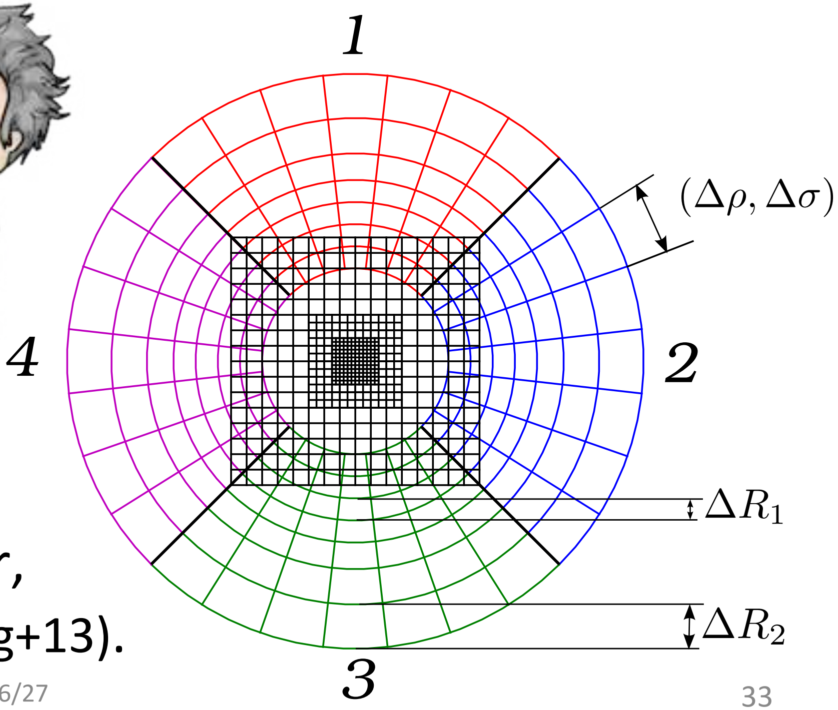
Ott+

Nordhaus+, Princeton



3D Core-Collapse Supernova Simulations

- Some “early” work: Fryer & Warren ‘02, ‘04 (SPH)
- Lots of new work: Fernandez ’10, Nordhaus+10, Takiwaki+11, Burrows+12, Dolence+13 (Princeton), Hanke+12,13 (Garching), Kuroda+12 (Tokyo), Ott+13 (Caltech), Couch ‘13
- Approximations made:
  (1) **Gravity**: full GR (Ott+, Kuroda+) vs. 1D Newtonian.
  (2) Neutrinos: “light-bulb” (Princeton,Garching), “leakage” (Caltech), grey transport (Kuroda+), multi-group (Takiwaki+)
  (3) Resolution
- Some details of our work:
  - Open-source & based on Einstein Toolkit (einsteintoolkit.org)
  - Full 3D GR using BSSN system.
  - Neutrino leakage scheme, $\nu_e\,, \bar{\nu}_e\,, \nu_x$ with heating & deleptonization.
  - Multi-patch scheme with spherical outer, central Cartesian grid with AMR (Reisswig+13).



Results of 3D Simulations

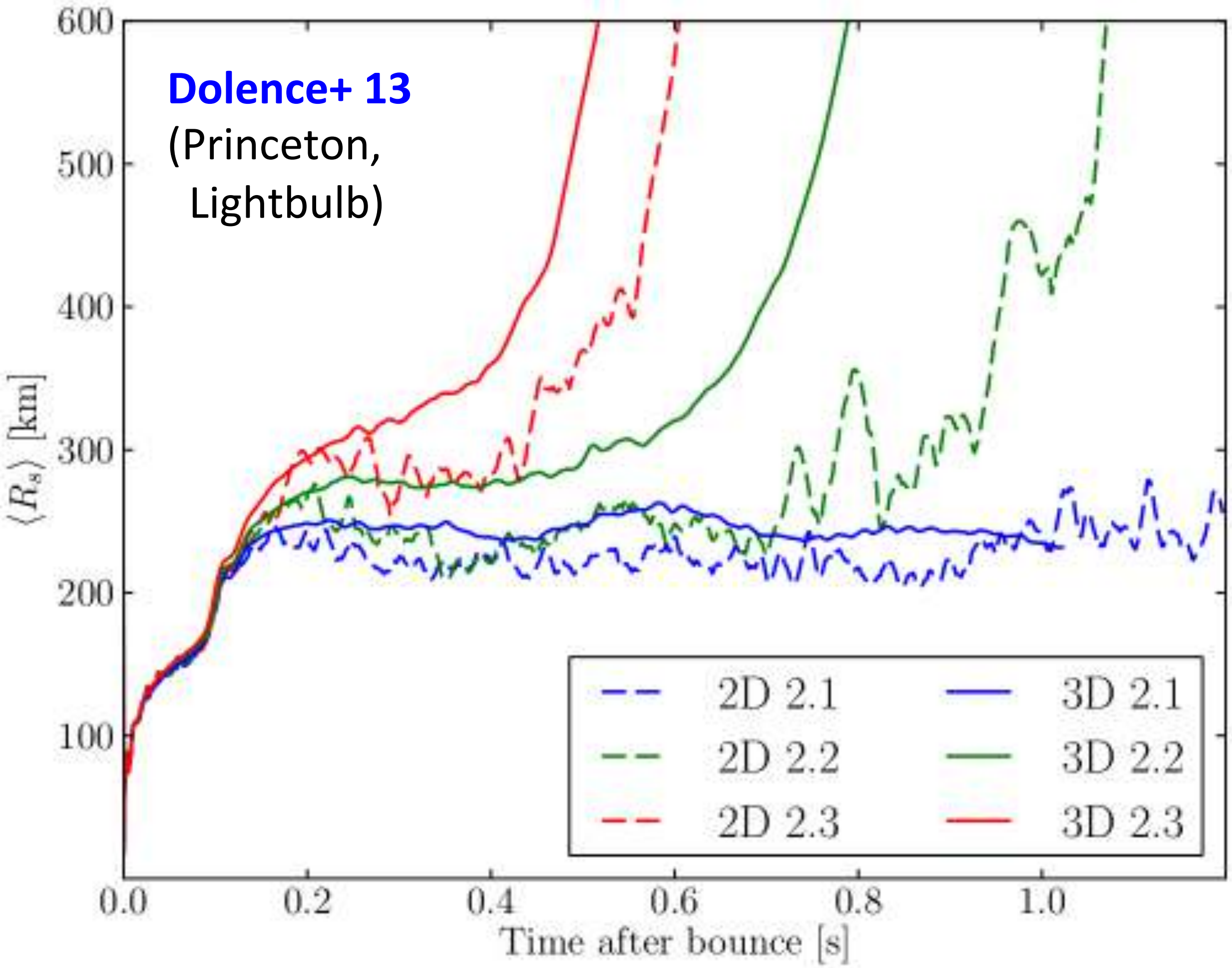
(Warning: This is as of June 27, 2013 and is evolving quickly)

Does 3D help the explosion?

Yes:

Explosions start earlier in 3D

Nordhaus+10,
Burrows+12,
Dolence+13,
Takiwaki+12



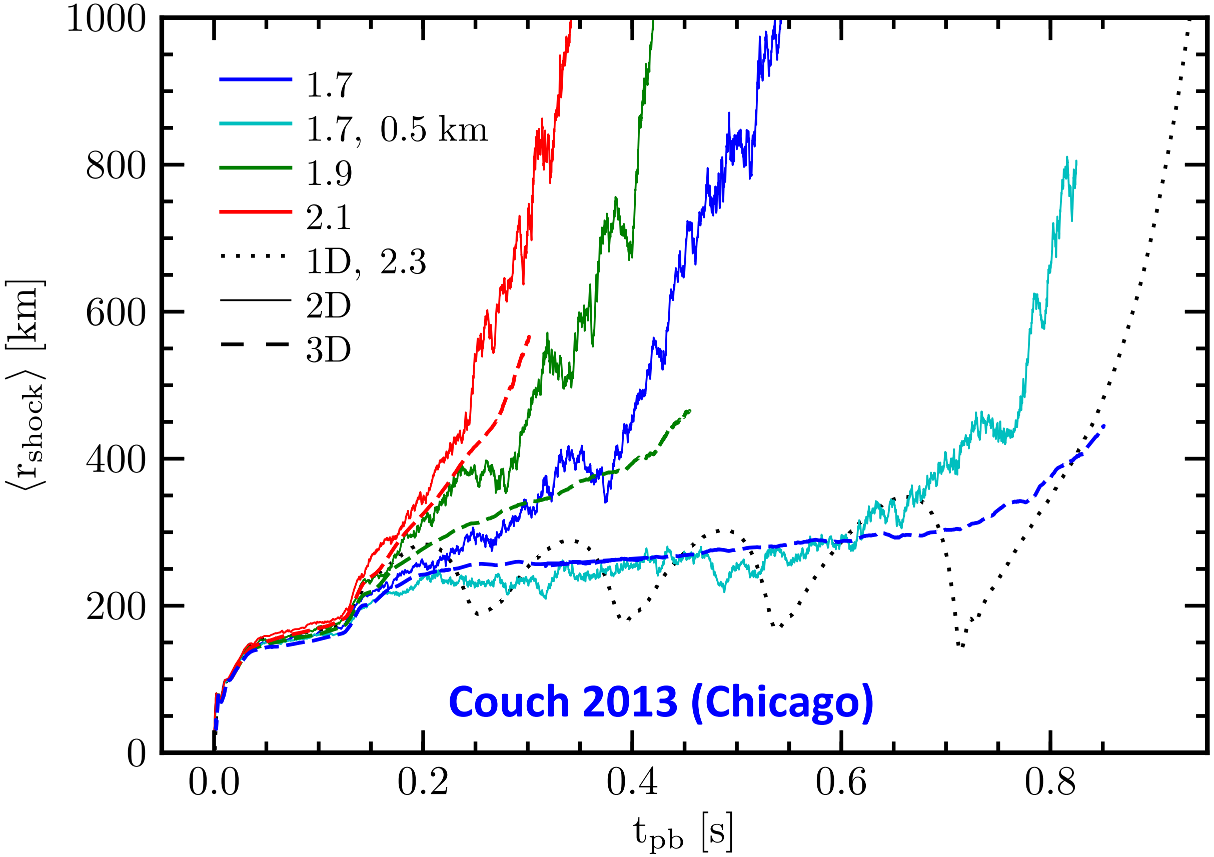
Results of 3D Simulations

(Warning: This is as of June 27, 2013 and is evolving quickly)

Does 3D help the explosion?

No:

Hanke+12,13 (Garching)
Couch 13 (Chicago)
3D simulations explode later than 2D ones.



Couch 2013 (Chicago)

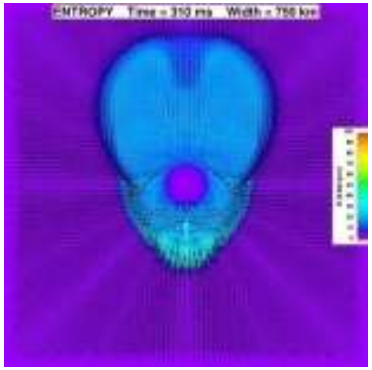
Explanation(s)?

-> Hanke+12: Higher resolution makes it harder to explode in 3D.
Consequence of turbulent cascade? (answer not clear)

Results of 3D Simulations

(Warning: This is as of June 27, 2013 and is evolving quickly)

Burrows+06



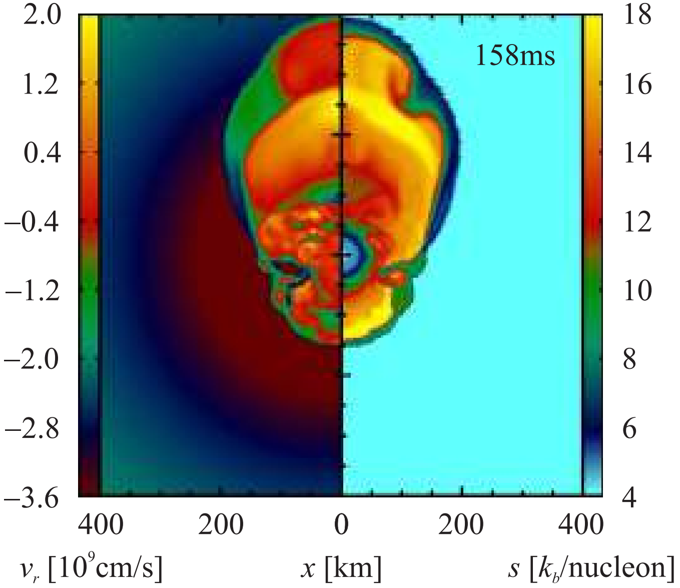
What does the SASI do in 3D?

- Absent / suppressed by convection or 3D effects?
  (Burrows+12,Murphy+12, Dolence+12)
- Present, but with different mode structure than in 2D, perhaps spiral mode?
  (Blondin&Mezzacappa 07, Iwakami+09, Fernandez 10, Hanke+13, Kuroda+13)

Motivation for Ott+ 13:

2D simulation by B. Müller+12 of 27-M_{Sun} progenitor star showing very strong SASI.

B. Müller+12b

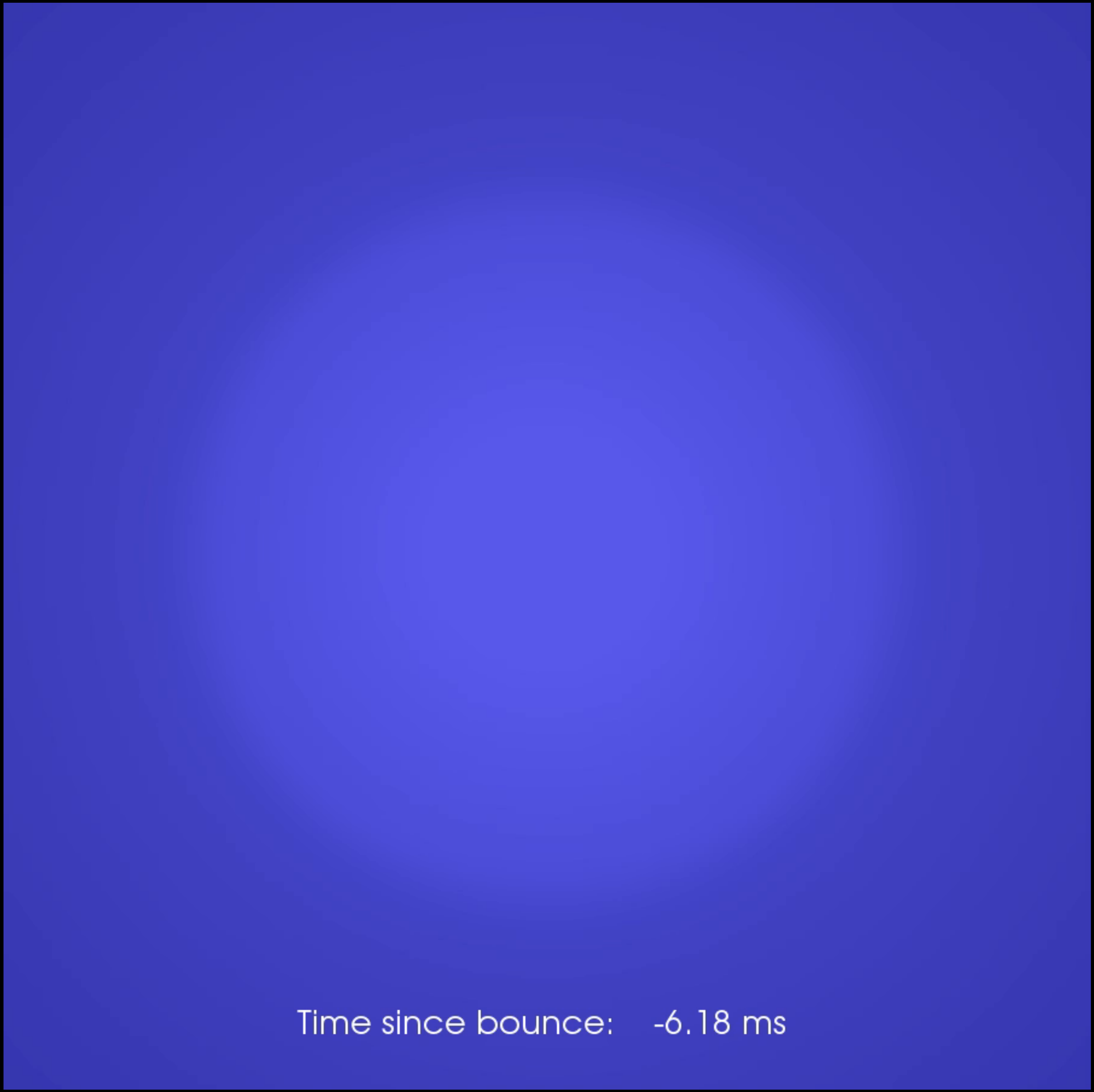


Ott+13, ApJ

3D GR with neutrino leakage scheme

27-M_{Sun} progenitor, shows strong SASI in 2D (Müller+12)

rendered by S. Drasco



Ott+13,
ApJ

3D GR
with
neutrino
leakage
scheme

27-M_{Sun}
progenitor,
shows
strong SASI
in 2D
(Müller+12)

rendered by
S. Drasco

-6.18 ms

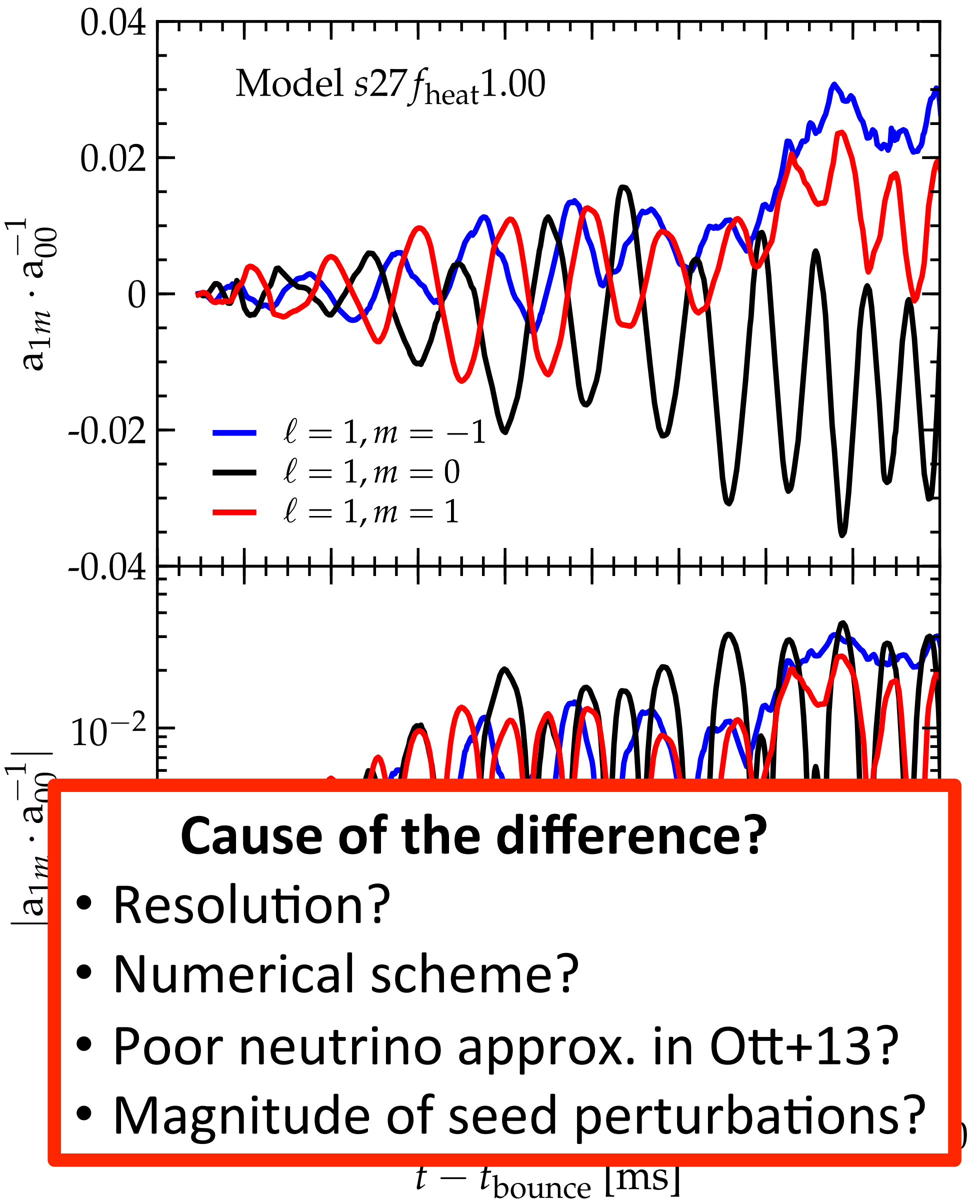
SASI in 3D?

Ott+13:

- SASI present in 3D, but weaker than in 2D.
- 10 x smaller saturation amplitudes.
- Appears suppressed by convection in exploding models.

BUT: Hanke+13:

- Growth of spiral mode.
- ~3 x larger amplitudes than Ott+13.
- Comparable amplitudes to their 2D run (which disagrees with the B. Müller+12 simulation by the same group).

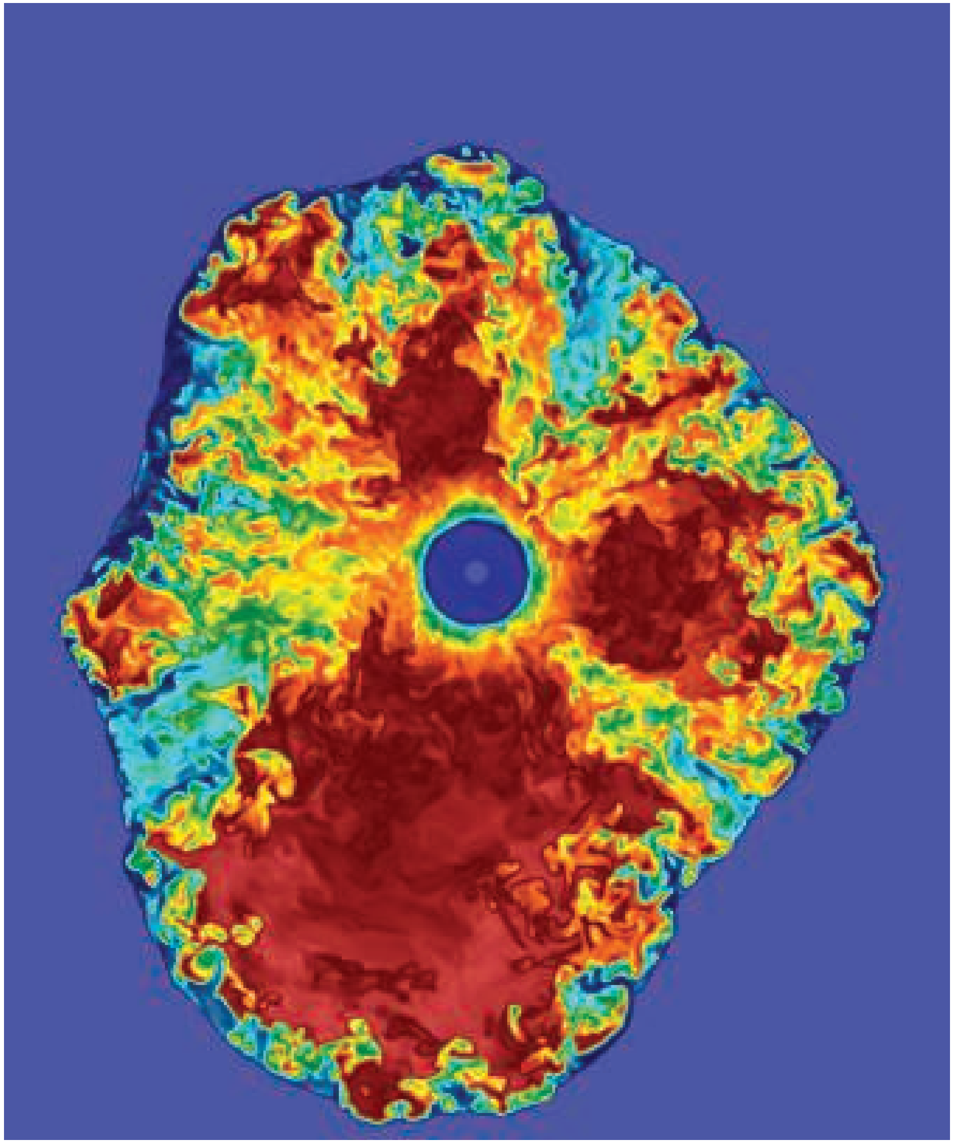


Cause of the difference?

- Resolution?
- Numerical scheme?
- Poor neutrino approx. in Ott+13?
- Magnitude of seed perturbations?

Summary of 3D Simulations

- Explosions developing with **non-oscillatory, low-mode asymmetry** and fine structure in shock front.
- Downside of current 3D models: Either underresolved or parameterized.
- Not yet clear if 3D key to robust neutrino-driven explosions. Increasing resolution in 3D appears to delay explosion (Hanke+'12).

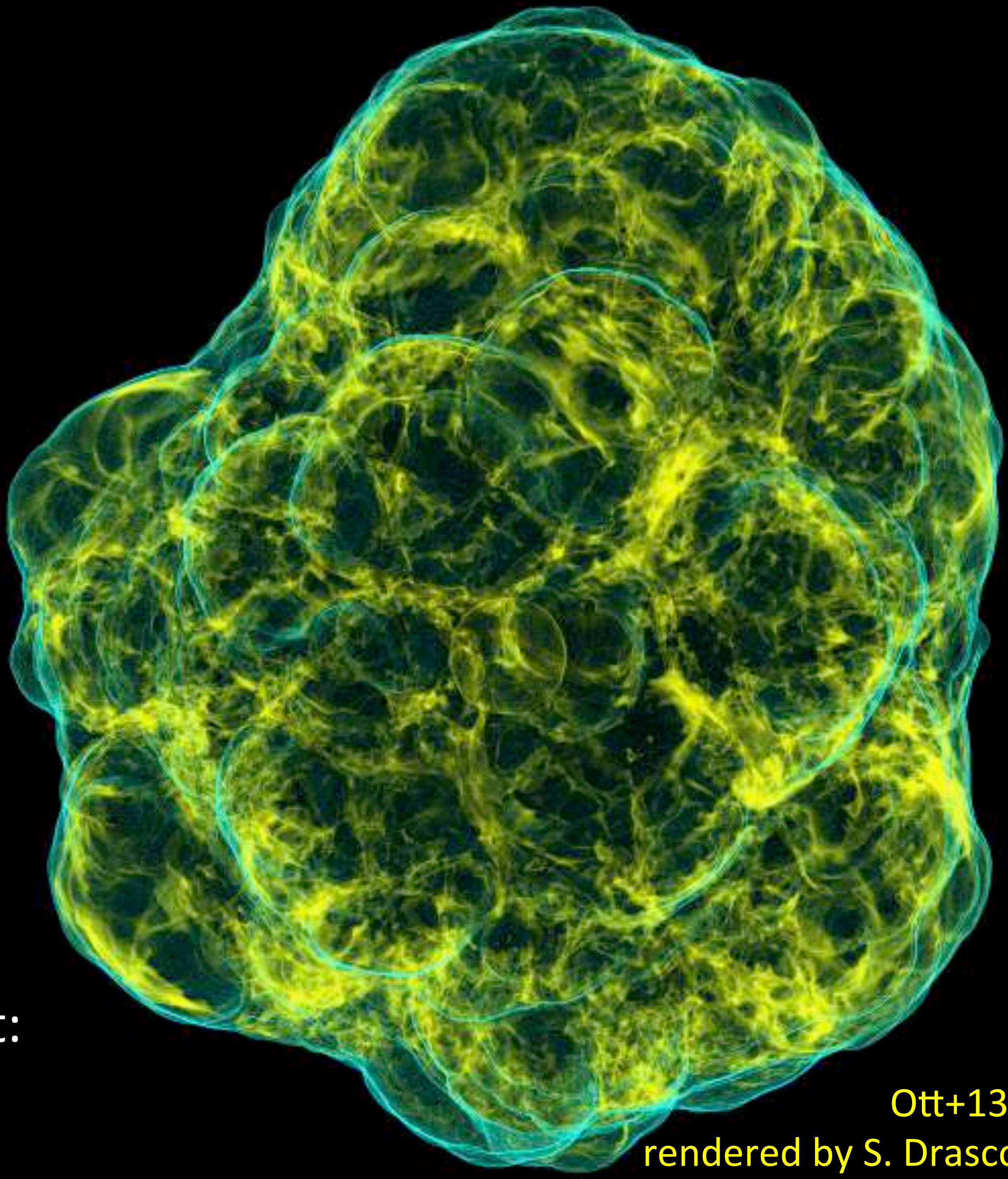


Asymmetric explosions generic outcome in 3D (and even in 2D).

-> May explain pulsar kicks hydrodynamically.
(Scheck+06, Nordhaus+10,12, Wongwathanarat+10,12)

But what about strong neutron star B-fields, extreme SNe and long GRBs?

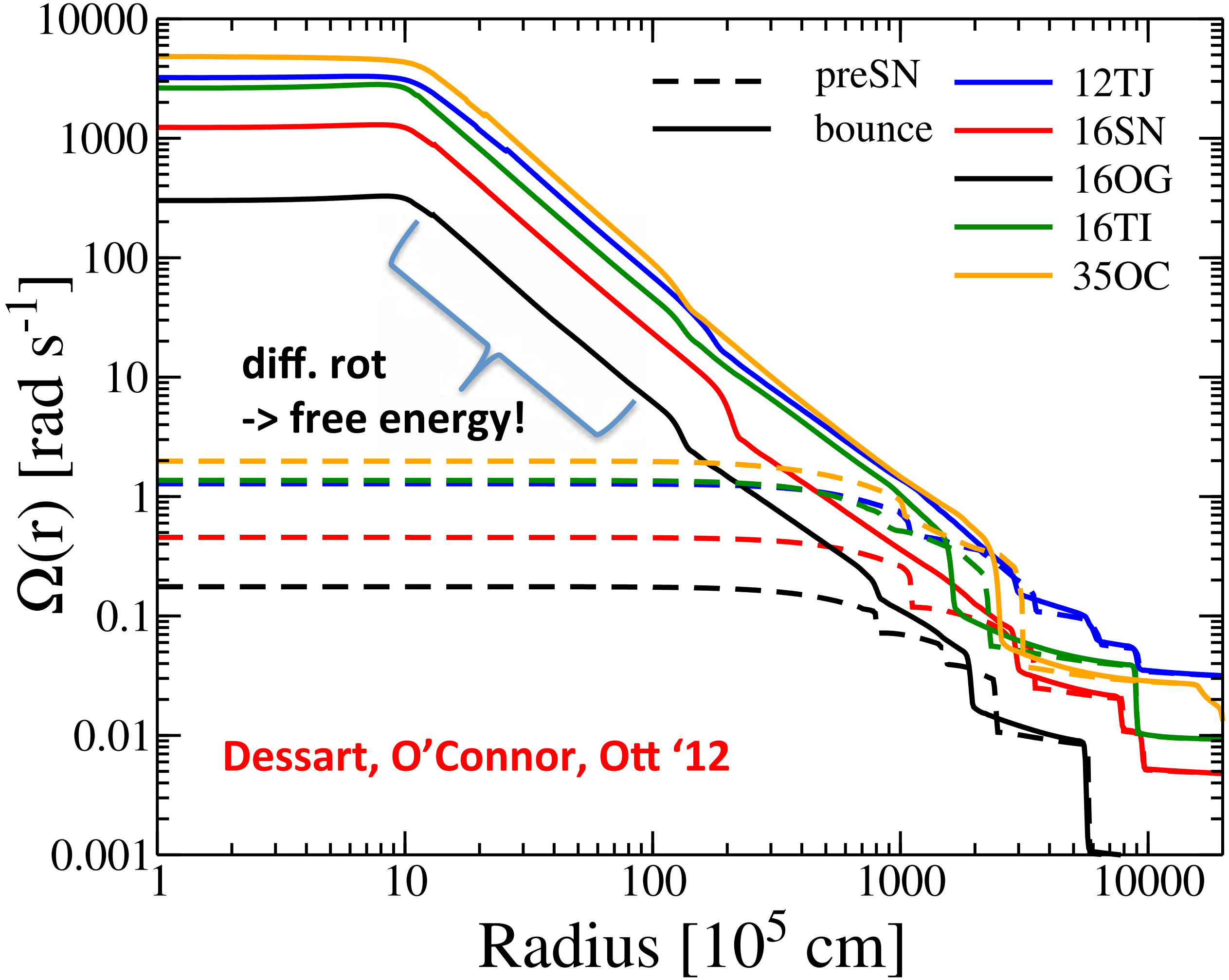
-> possible key ingredient:
rapid rotation



Ott+13,
rendered by S. Drasco

Rotating Core Collapse

see, e.g., Fryer & Heger ‘02, Ott+ ’06, Thompson+ ‘05, Burrows+ ’07, Cerda-Duran+ ‘08, Ott+ ‘08, Dessart+ ‘08, ‘12



diff. rot
-> free energy!

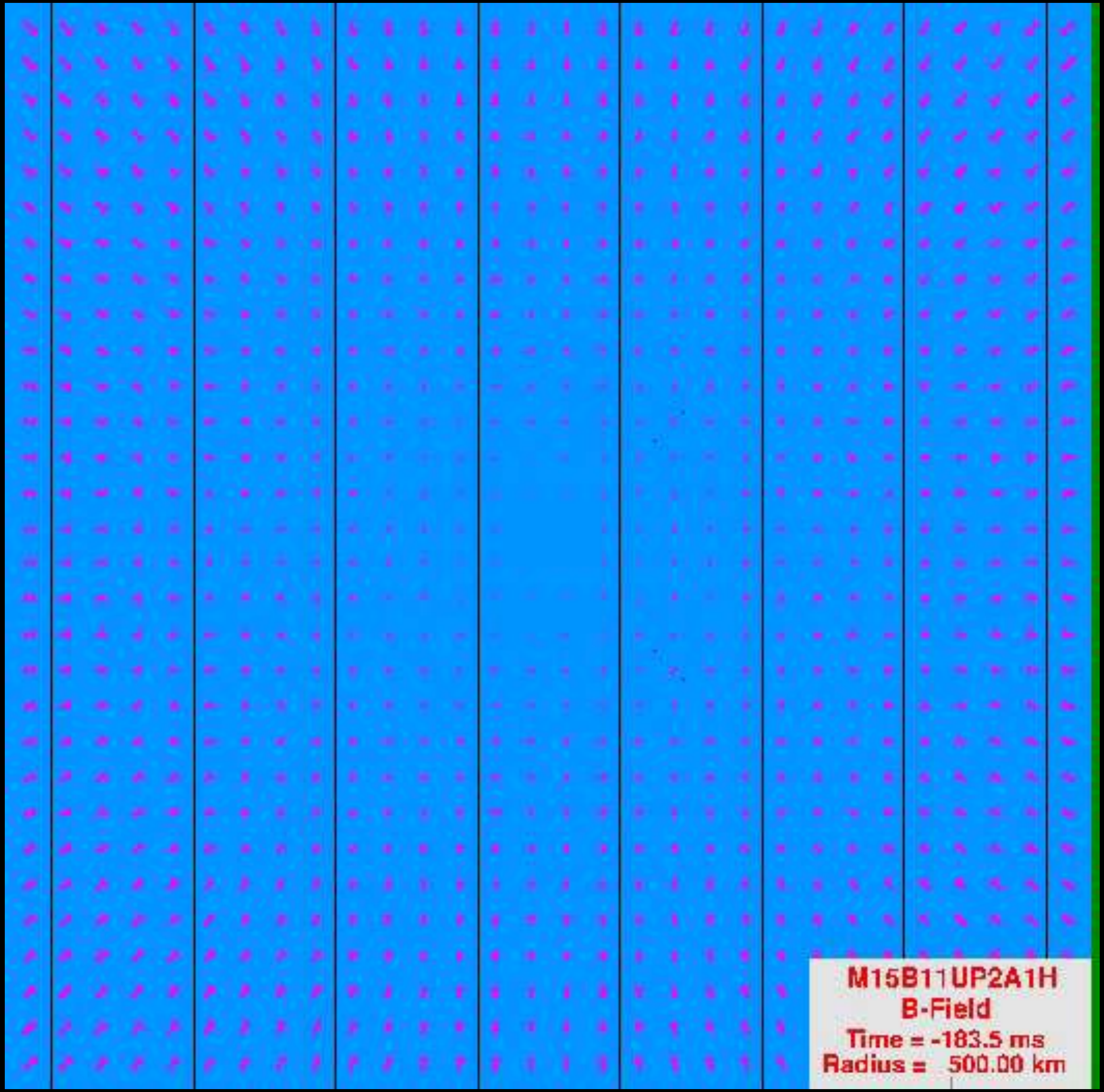
Dessart, O’Connor, Ott ‘12

- Core: x 1000 spin-up
- Differential rotation -> reservoir of free energy

Magnetorotational Explosions

e.g., Bisnovatyi-Kogan '70, Burrows+ '07, Dessart+ '08, Takiwaki & Kotake '11, Winteler+ '12

- **Rapid rotation**:
  P_0<4-6 s -> millisecond PNS
- PNS rotational energy:
  ~10 B = 10^{52} erg
- *Free energy of differential rotation.*
- Amplification of B fields up to equipartition:
  compression, winding, magnetorotational instability (MRI)
- BUT: MRI not resolved.
- Jet-driven outflows.
- Hypernova-scale explosion energies.
- Magnetar left behind.

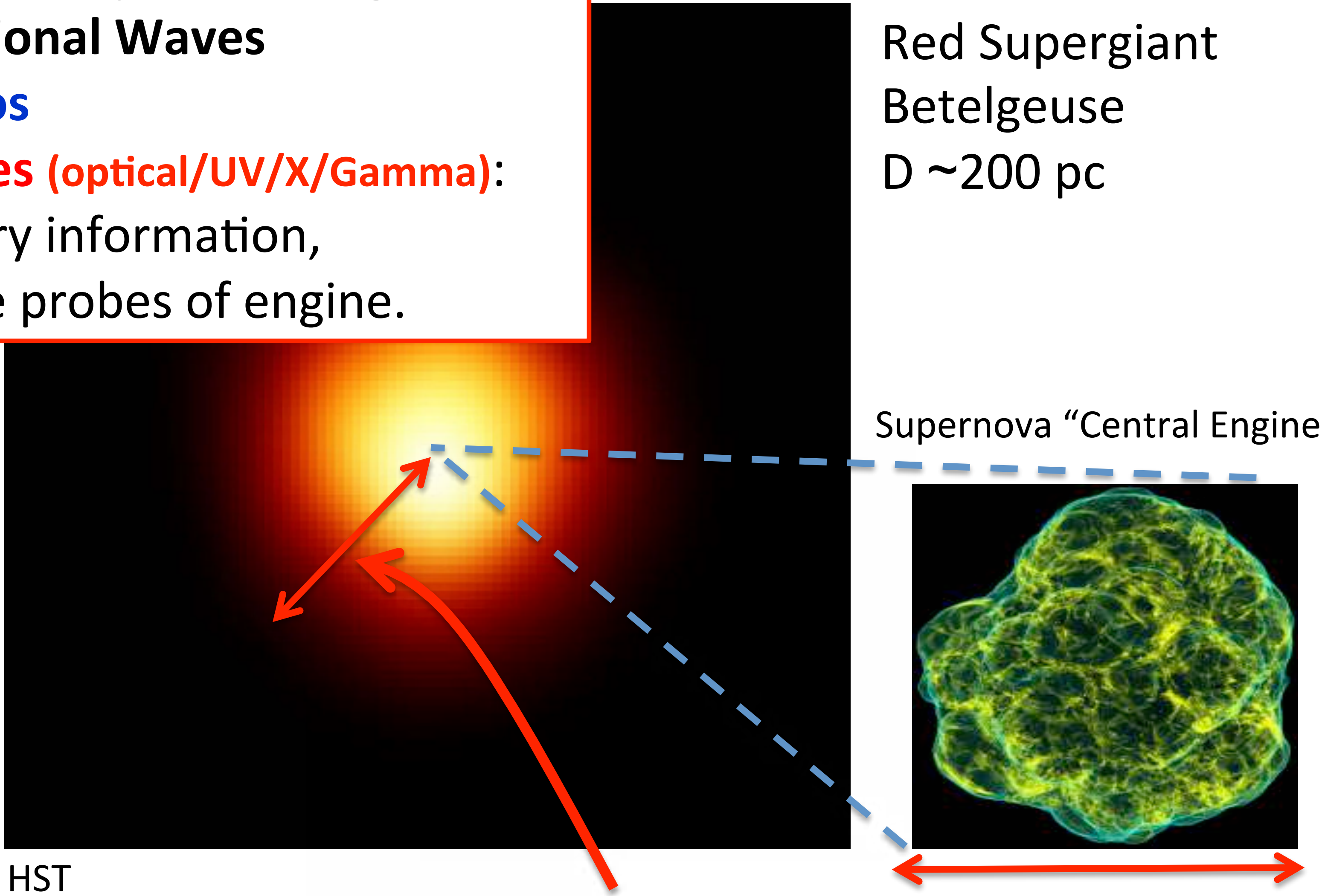


VULCAN 2D R-MHD code, Livne+ '07, Burrows+ '07.

Observing the CCSN Engine

Probing the “Supernova Engine”
- **Gravitational Waves**
- **Neutrinos**
- **EM waves (optical/UV/X/Gamma)**: secondary information, late-time probes of engine.

Red Supergiant
Betelgeuse
D ~200 pc



Neutrino Refresher

- Emission: Charged current & neutral current weak interactions.

$$\nu_e, \nu_\mu, \nu_\tau$$

+ mixing

$$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$$

- Detection: (see Scholberg '12)

$$\bar{\nu}_e + p \rightarrow n + e^+$$

-> primary reaction in Water Cherenkov detectors Super-K & IceCube.

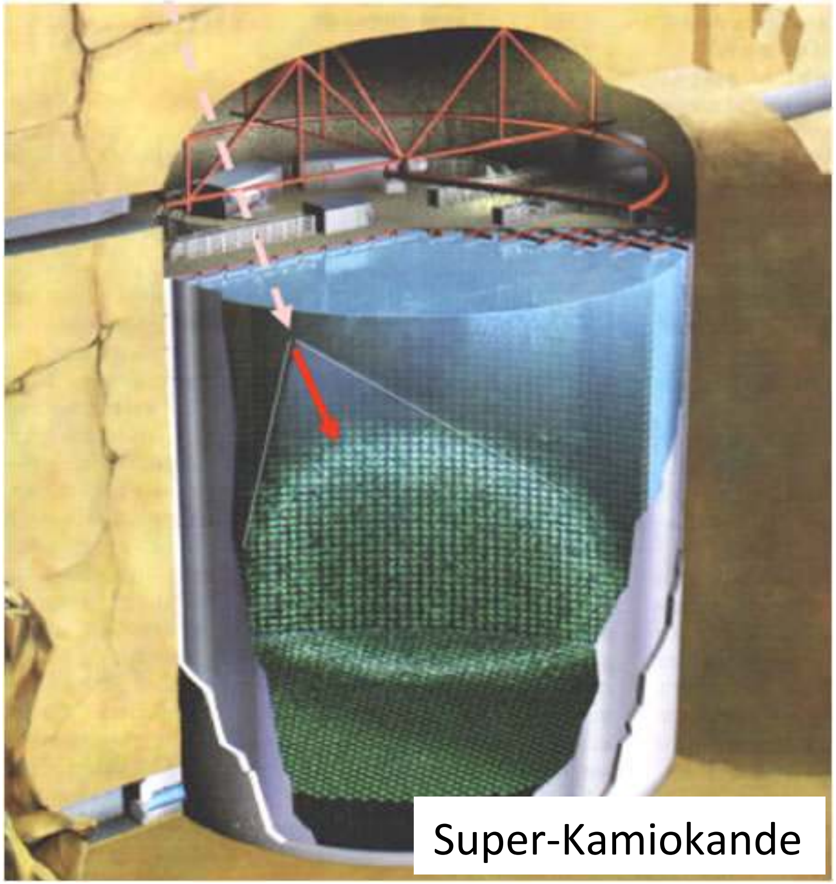
Other relevant interactions:

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

$$\nu_e + (N,Z) \rightarrow (N-1, Z+1) + e^-$$

$$\bar{\nu}_e + (N,Z) \rightarrow (N-1, Z-1) + e^+$$

Water Cherenkov, liquid scintillator, liquid argon, lead detectors.



Most detectors will provide flux and spectral information.

Core-Collapse Supernova Neutrinos

- Carry 99% of the energy: ~300 B (3 x 10^{53} erg).
- Neutrinos and antineutrinos of ALL species:

$$\nu_e\,,\bar{\nu}_e$$

$$"\nu_\mu" = "\nu_x"$$

$$= \{\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$$

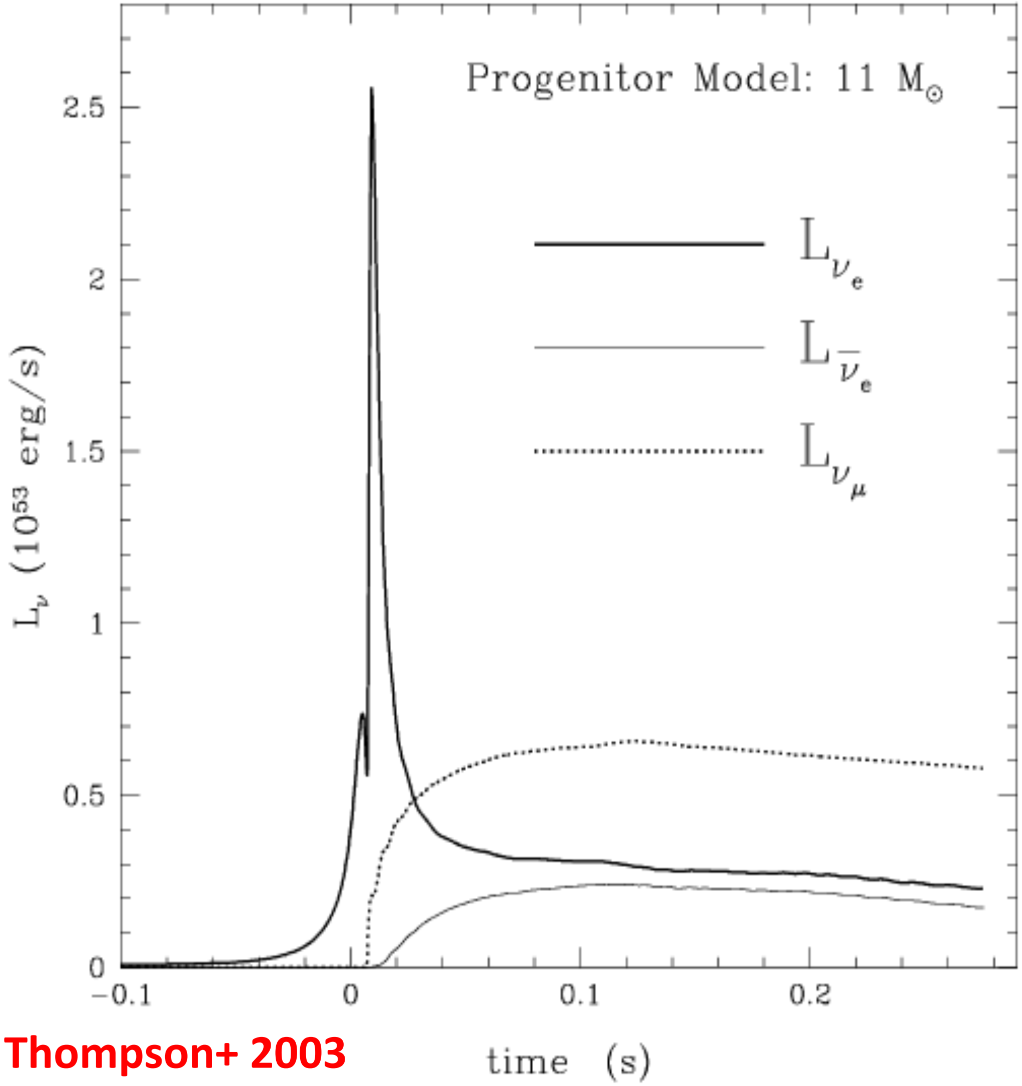
- Emission at ~1-100 MeV:

$$e^- p \rightleftharpoons \nu_e n \quad e^- e^+ \rightleftharpoons \nu_i \bar{\nu}_i$$

$$e^+ n \rightleftharpoons \bar{\nu}_e p \quad NN \rightleftharpoons \nu_i \bar{\nu}_i$$

$$\tilde{\gamma} \rightleftharpoons \nu_i \bar{\nu}_i$$

- 3 emission phases:
  1) neutronization burst
  2) accretion phase (< 1 s)
  3) cooling phase (10+ s)



Thompson+ 2003

Probing Stellar Structure with Pre-Explosion Neutrinos

O'Connor & Ott '13, ApJ

- Neutrino signal in the pre-explosion phase is determined by
  (1) the accretion rate of the stellar envelope and
  (2) by the core temperature of the collapsing star.

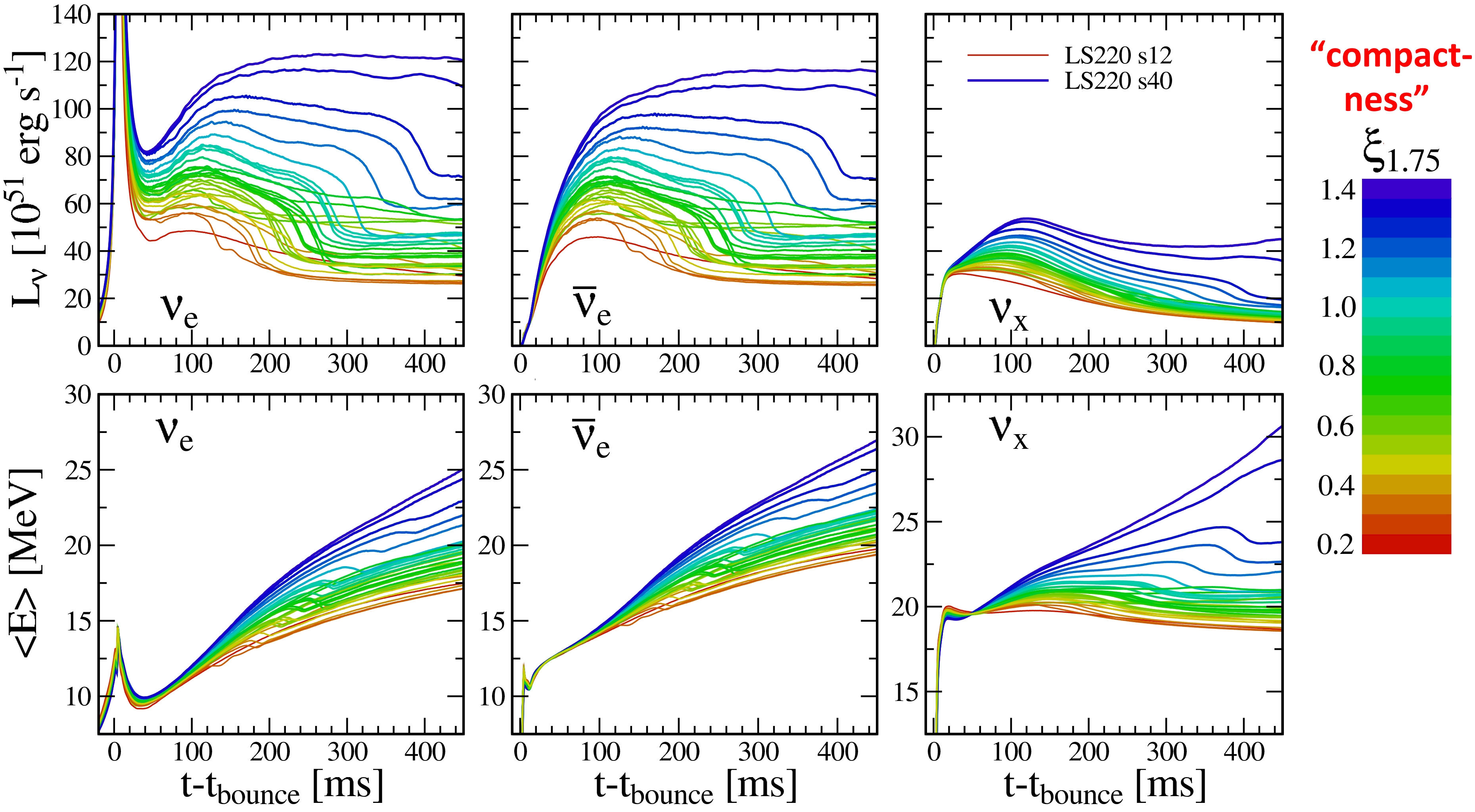
Parameter encapsulating both (1) and (2):

$$\xi_M = \frac{M/M_\odot}{R(M_\mathrm{bary}=M)/1000\,\mathrm{km}}\bigg|_{t=t_\mathrm{bounce}}$$

"compactness parameter" measured at bounce.
(O'Connor & Ott '11)

Probing Stellar Structure with Pre-Explosion Neutrinos

O’Connor & Ott ’13, ApJ

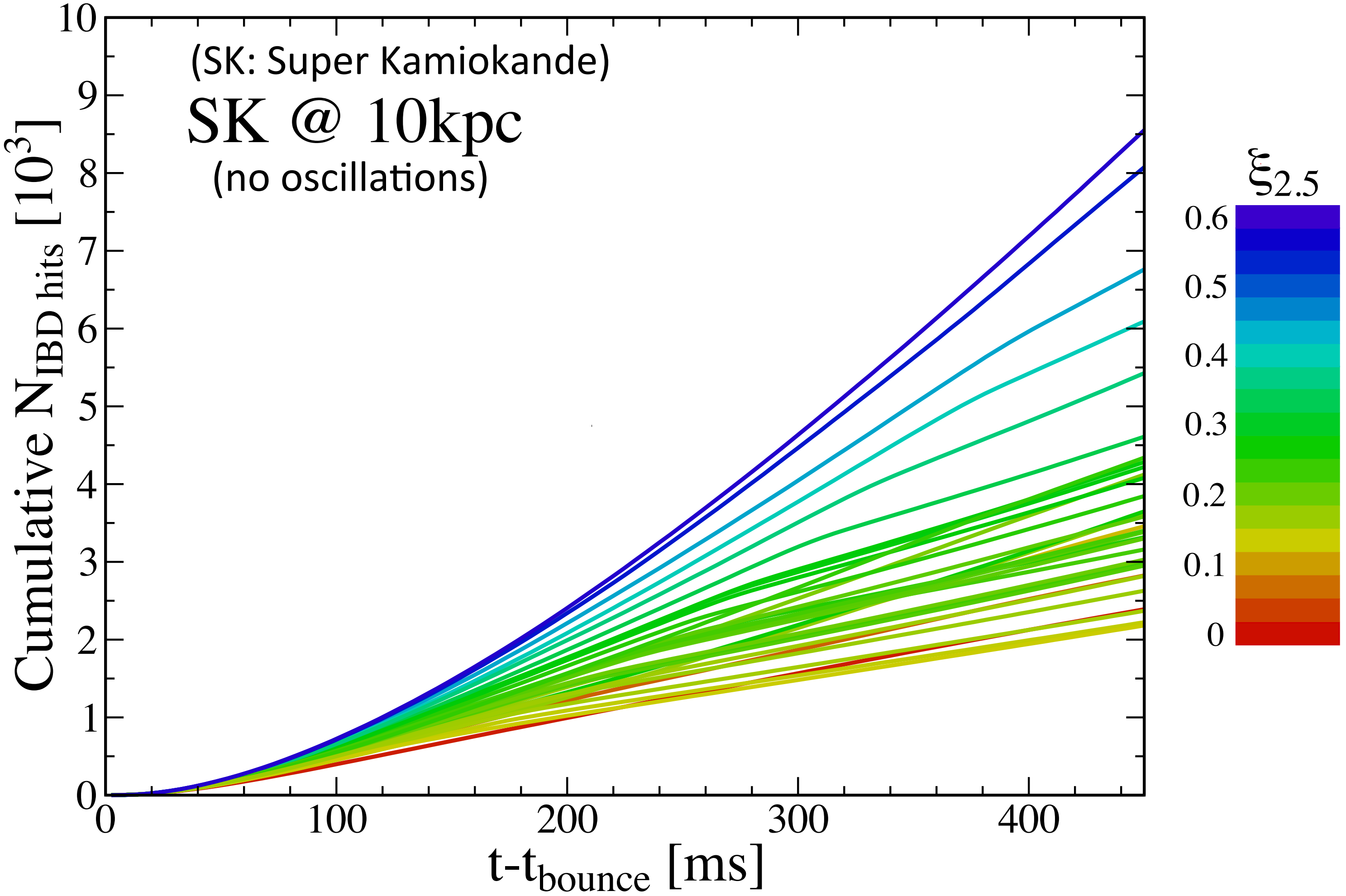


- Consider pre-explosion phase: clean, “collective oscillations” suppressed (?)

$$\xi_M = \left.\frac{M/M_\odot}{R(M_{\rm bary}=M)/1000\,\mathrm{km}}\right|_{t=t_{\rm bounce}}$$

Probing Stellar Structure with Pre-Explosion Neutrinos

O'Connor & Ott '13, ApJ



- Expected inverse beta decay events in Super-K using SNOwGLoBES (Scholberg '12). http://www.phy.duke.edu/~schol/snowglobes

$$\xi_M = \frac{M/M_\odot}{R(M_{\rm bary} = M)/1000\,\rm km}\Big|_{t=t_{\rm bounce}}$$

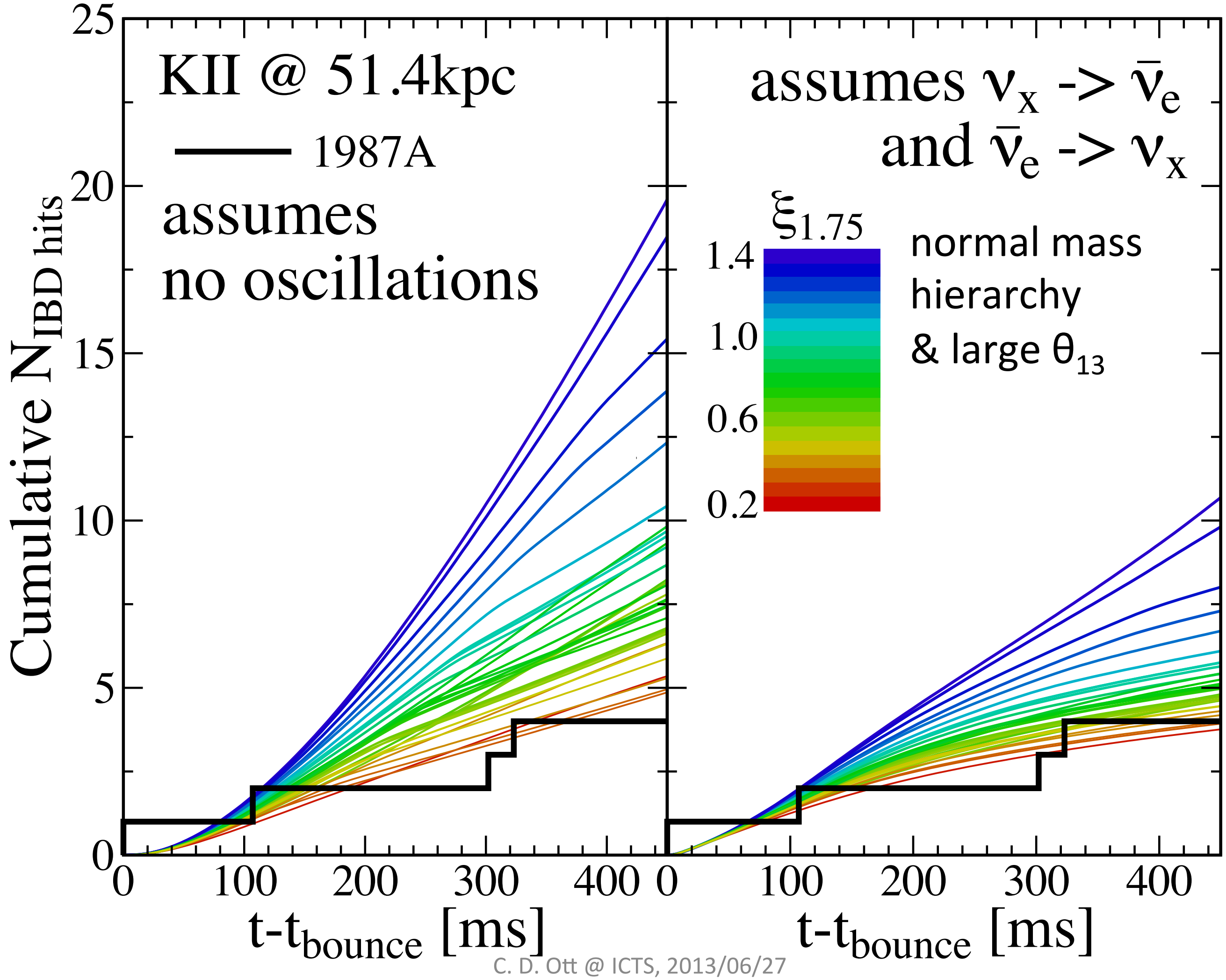
Progenitor Structure of SN 1987A

O'Connor & Ott '13

Comparison with early phase of the observed SN 1987A neutrino signal.

-> Potential Conclusion: **early explosion OR low-compactness progenitor core!**

But: beware of small-number statistics!!



Gravitational Wave (GW) Refresher

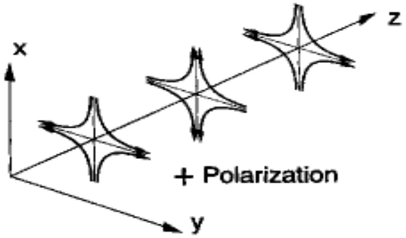
- Emission: **Accelerated quadrupole bulk mass-energy motion.**

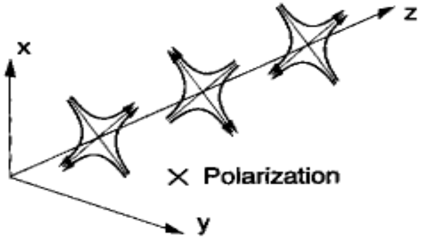
Quadrupole approximation

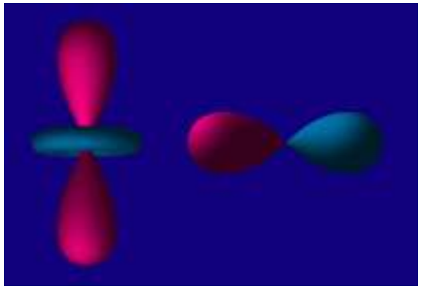
$$h_{jk}^{TT}(t,\vec{x}) = \left[\frac{2}{c^4}\frac{G}{|\vec{x}|}\ddot{I}_{jk}\left(t-\frac{|\vec{x}|}{c}\right)\right]^{TT}$$

$$\frac{G}{c^4} \approx 10^{-49}\,\mathrm{s}^2\,\mathrm{g}^{-1}\,\mathrm{cm}^{-1}$$

$$10\,\mathrm{kpc} \approx 3\times 10^{22}\,\mathrm{cm}$$





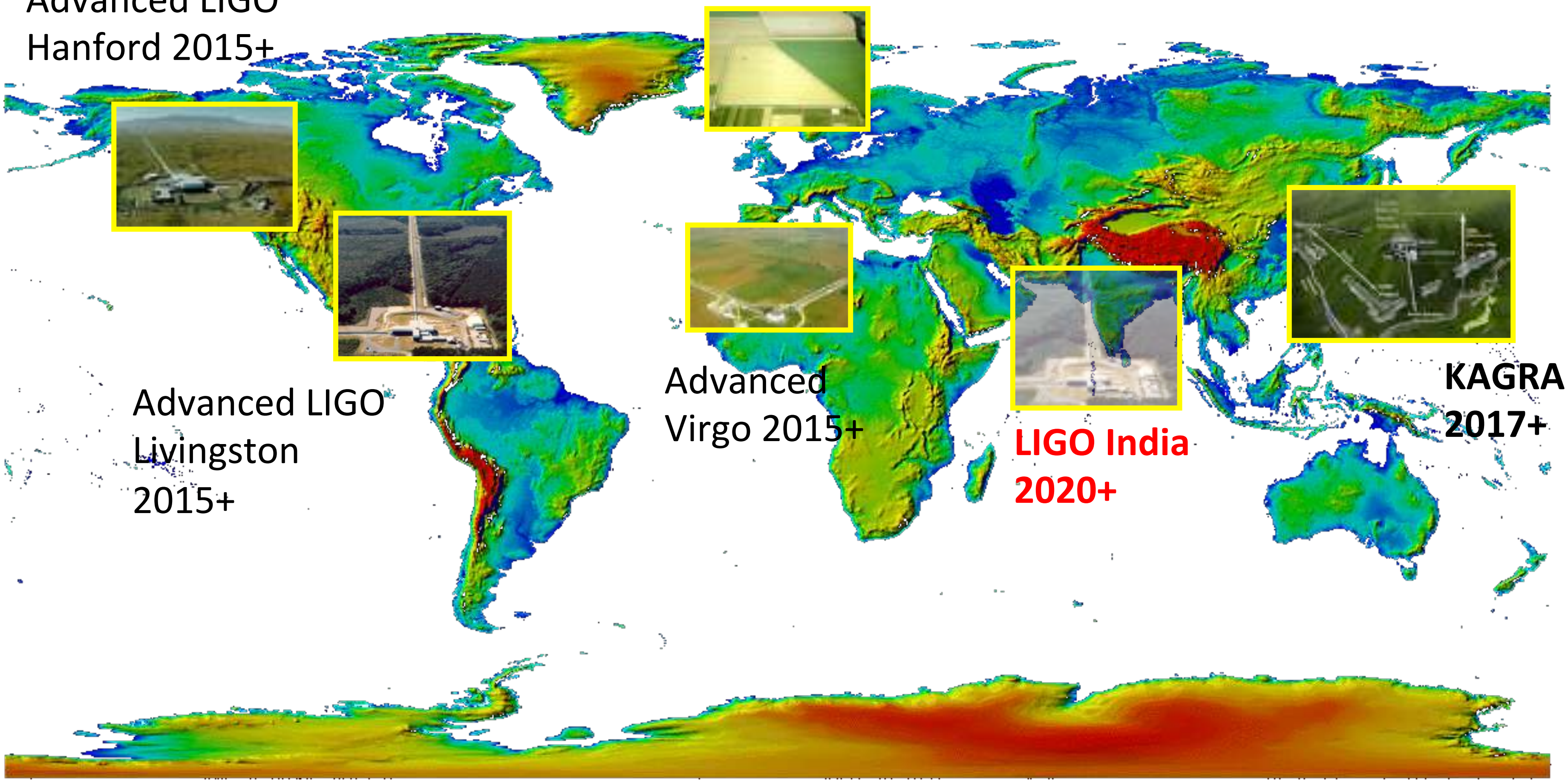


-> must measure relative displacements of 10^{-22}

- Detection:
  Measure changes in separations of test masses with laser interferometry.
  -> Advanced LIGO in 2015+,
  LIGO India (2020+),
  + international partners.

LIGO Livingston, Louisiana

The Advanced GW Detector Network: 2020+



Advanced LIGO
Hanford 2015+

GEO 600 (operating)

Advanced LIGO
Livingston
2015+

Advanced
Virgo 2015+

**LIGO India
2020+**

**KAGRA
2017+**

Gravitational-Waves from Core-Collapse Supernovae

Recent reviews: Ott '09, Kotake '11, Fryer & New '11

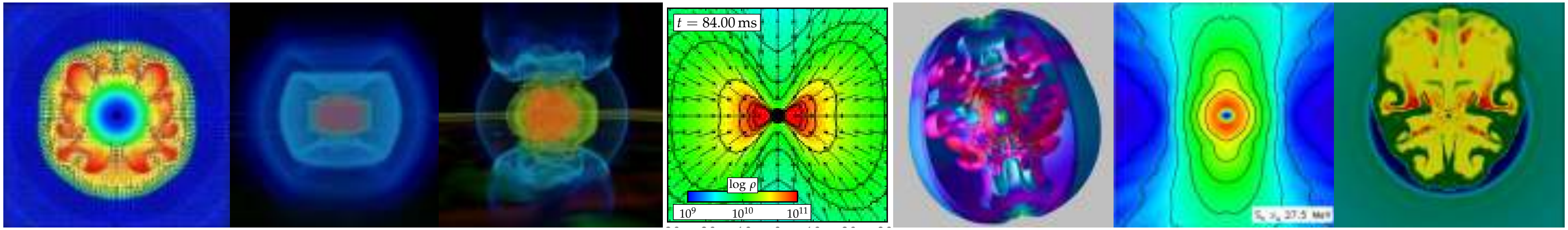
Need:

$$h^{TT}_{jk}(t,\vec{x}) = \left[\frac{2}{c^4}\frac{G}{|\vec{x}|}\ddot{I}_{jk}\left(t-\frac{|\vec{x}|}{c}\right)\right]^{TT}$$

→ accelerated aspherical (quadrupolar) mass-energy motions

Candidate Emission Processes:

- Convection and SASI
- Rotating collapse & bounce
- Rotational 3D instabilities
- Black hole formation
- Pulsations of the protoneutron star
- Anisotropic neutrino emission
- Aspherical accelerated outflows
- Magnetic stresses



Gravitational-Waves from Core-Collapse Supernovae

Recent reviews: Ott ‘09, Kotake ‘11, Fryer & New ‘11

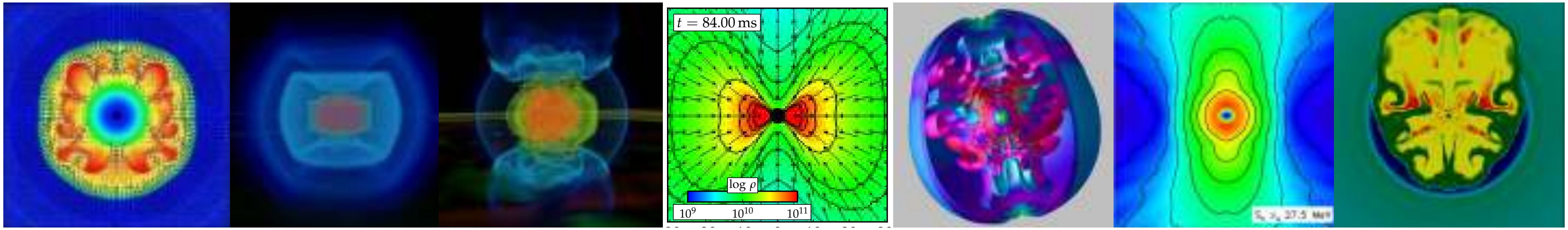
Need:

$$h_{jk}^{TT}(t,\vec{x}) = \left[\frac{2}{c^4}\frac{G}{|\vec{x}|}\ddot{I}_{jk}\left(t-\frac{|\vec{x}|}{c}\right)\right]^{TT} \rightarrow$$

accelerated aspherical (quadrupolar) mass-energy motions

Candidate Emission Processes:

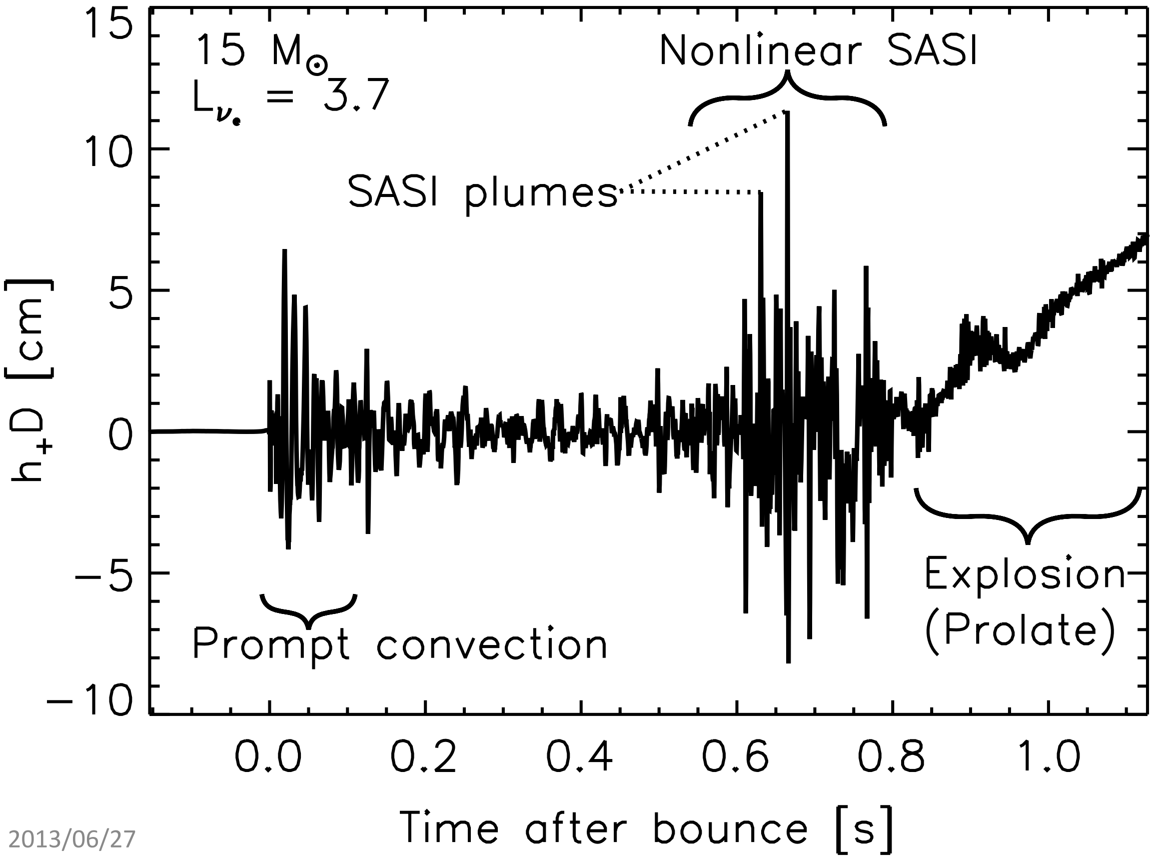
- **Convection and SASI**
- **Rotating collapse & bounce**
- Rotational 3D instabilities
- Black hole formation
- Pulsations of the protoneutron star
- Anisotropic neutrino emission
- Aspherical accelerated outflows
- Magnetic stresses



GWs from Convection & SASI

Recent work: Kotake+ ‘09, ‘11, Murphy+’09, Yakunin+’10 E. Müller+’12, B.Müller+‘13

- Prompt convection soon after bounce (Marek+ ‘09, Ott ‘09).
- Neutrino-driven convection & SASI (recent: Murphy+’09, Yakunin+10, Müller+12).
- Protoneutron star convection (e.g., Keil+ ’96, Müller+’04)

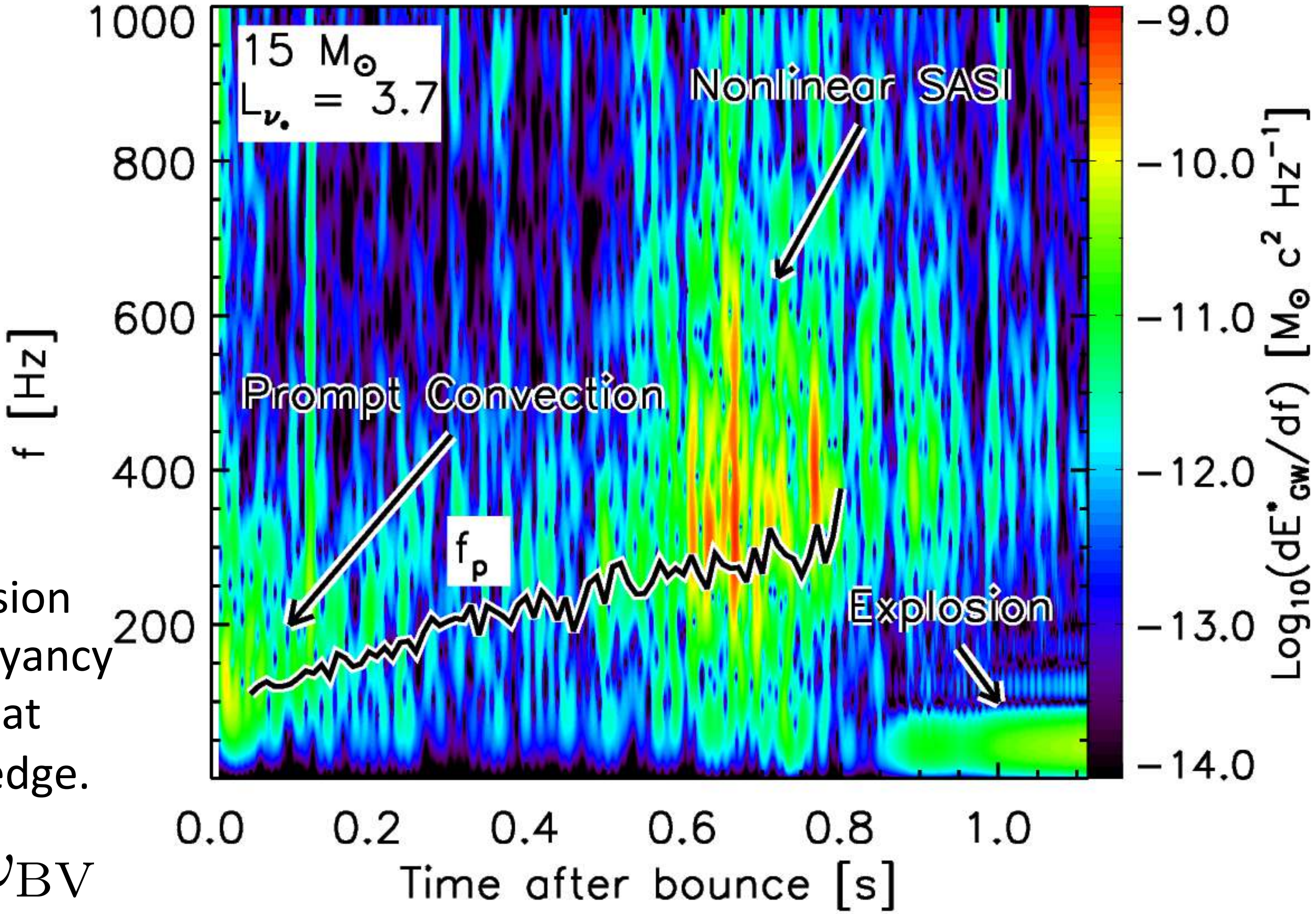


Murphy+ ’09, using simplified heating/cooling scheme.

Expect also: Correlations with neutrino signal. Lund+ ’10,’12, Marek+’09, Brandt+’11

Time-Frequency Analysis of GWs

Murphy, Ott, Burrows ’09, see also B. Müller+‘13



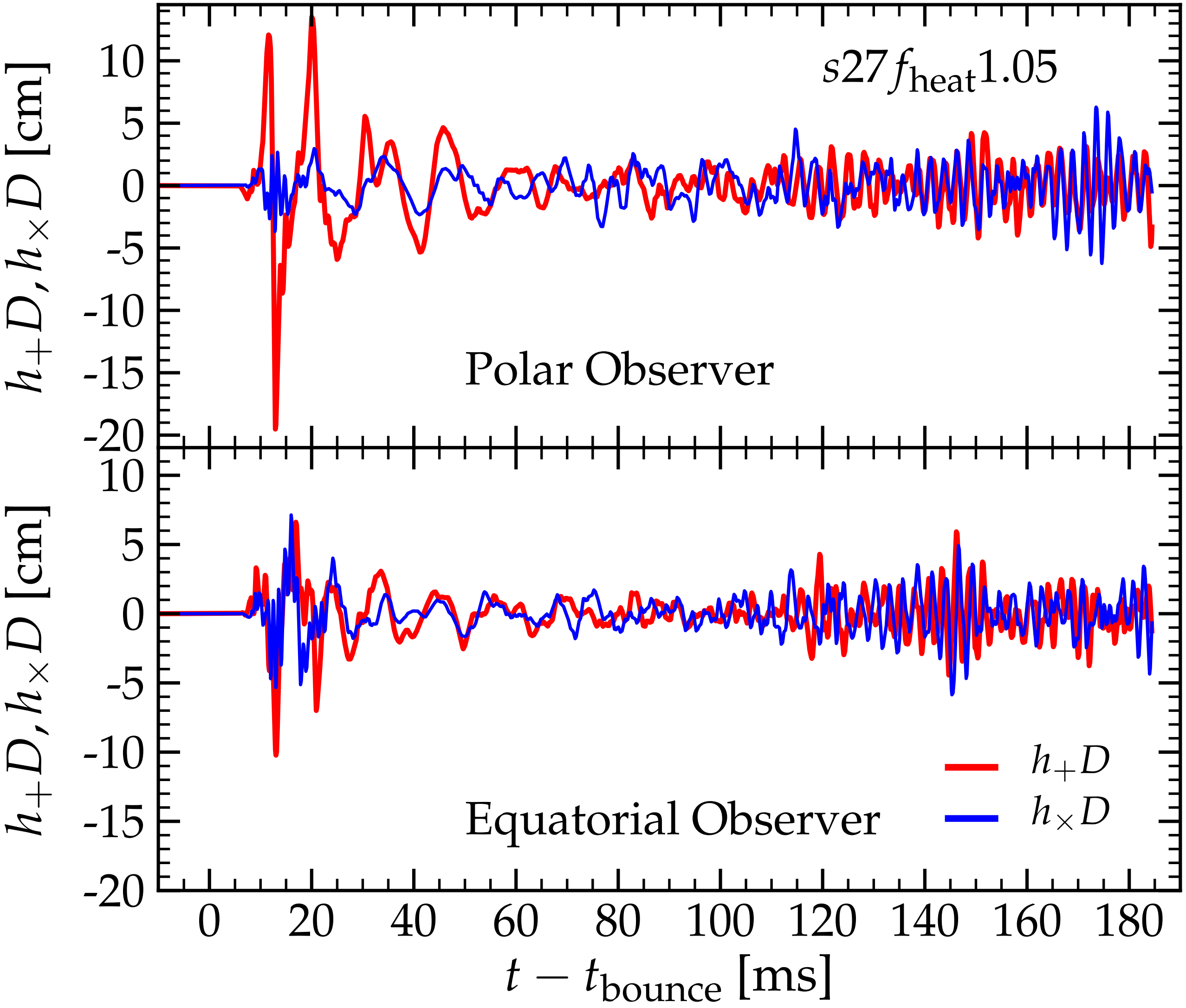
Peak emission traces buoyancy frequency at proto-NS edge.

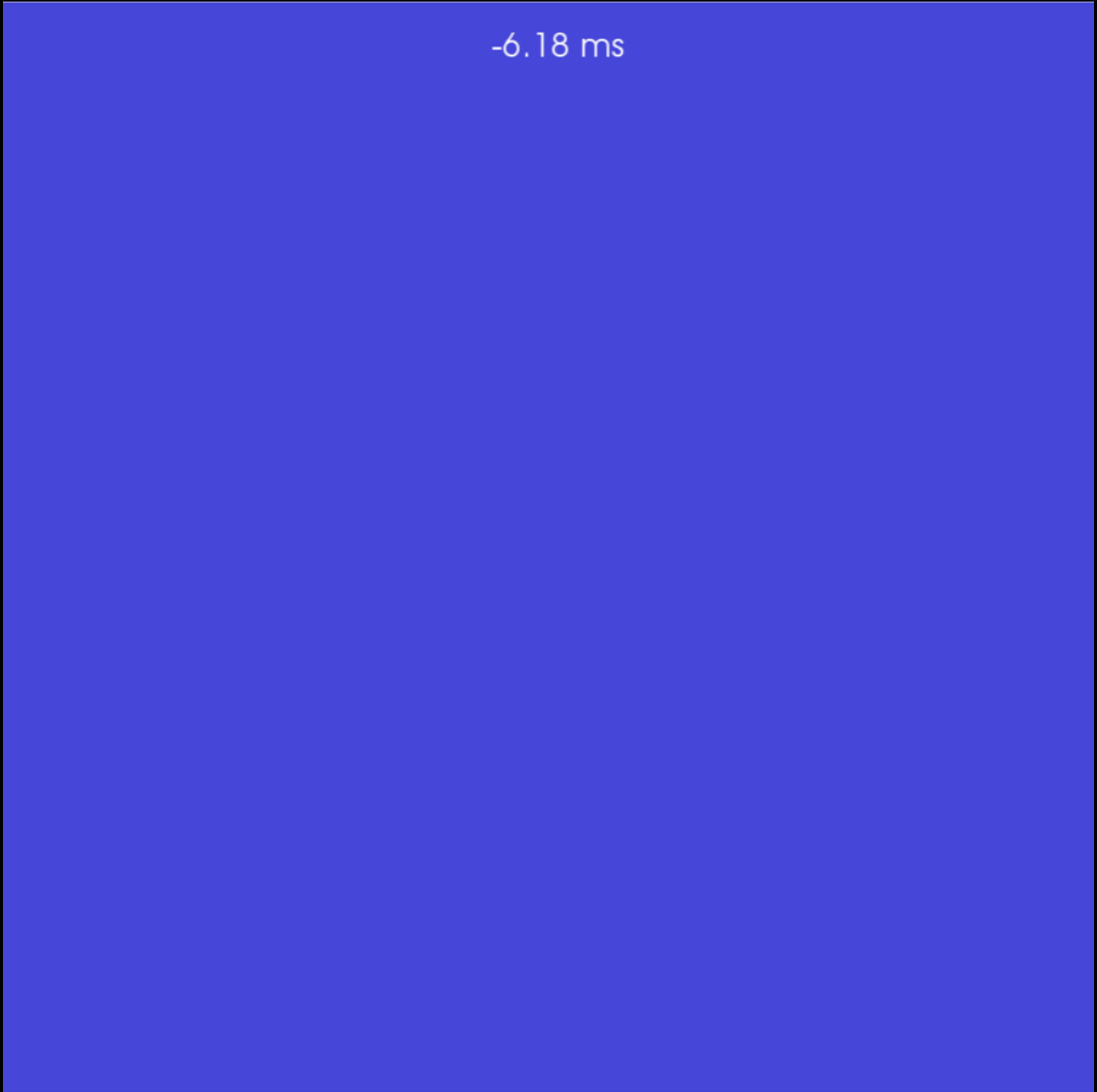
$$f_p \sim \frac{\omega_{\mathrm{BV}}}{2\pi}$$

New Results from General-Relativistic 3D Simulations

Ott+ 2013, ApJ 768:115

- Both polarizations: h_+ and h_x .
- Prompt convection GWs: larger |h| than 2D results of B. Müller+'13
  -> sensitive to seed perturbations.
- Subsequent signal ~1/5 |h| of 2D (3D: absence of large-scale SASI).



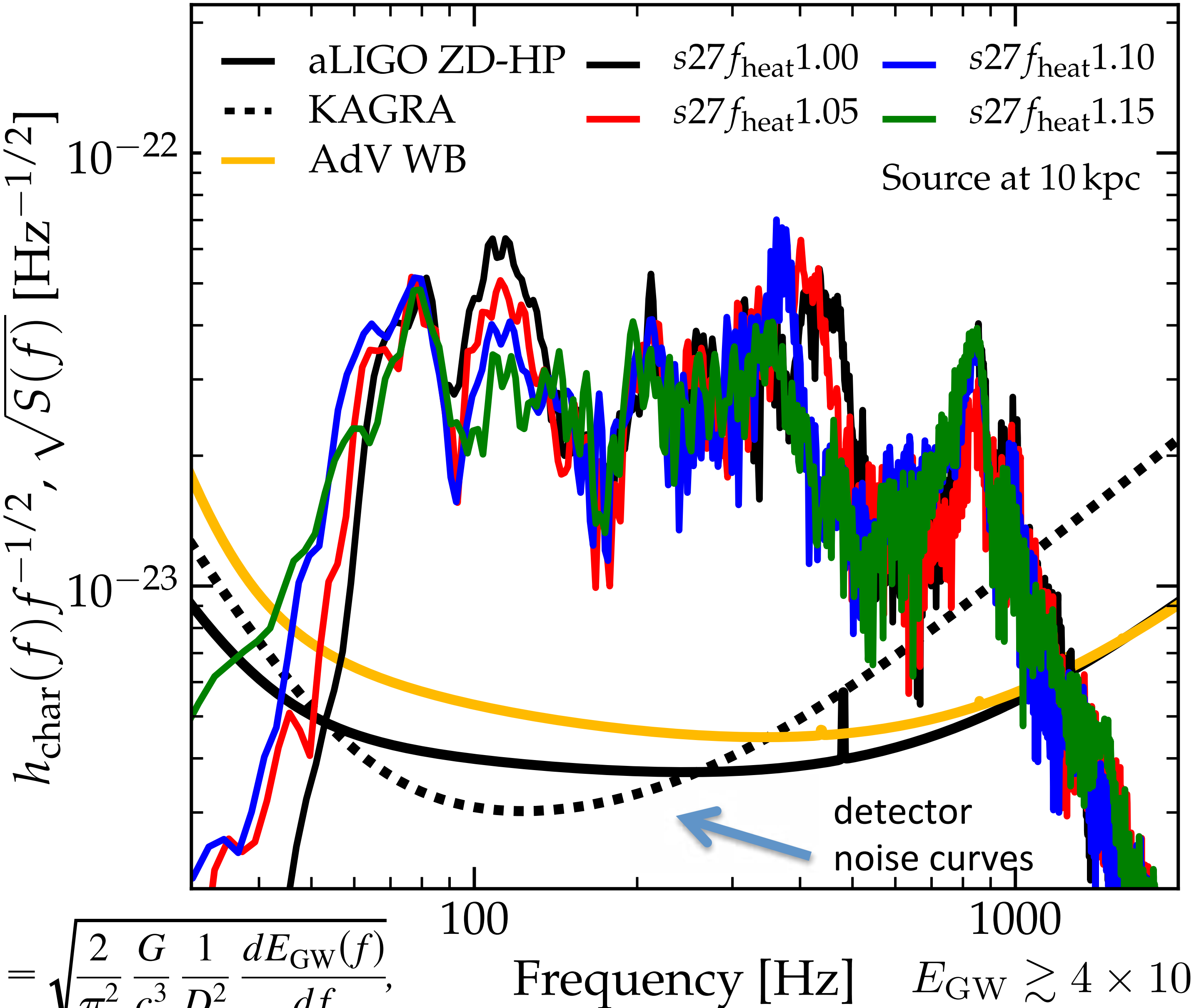


Ott+13
s27 simulation

rendered
by S. Drasco

New Results from General-Relativistic 3D Simulations

Ott+13, ApJ 768:115



detector
noise curves

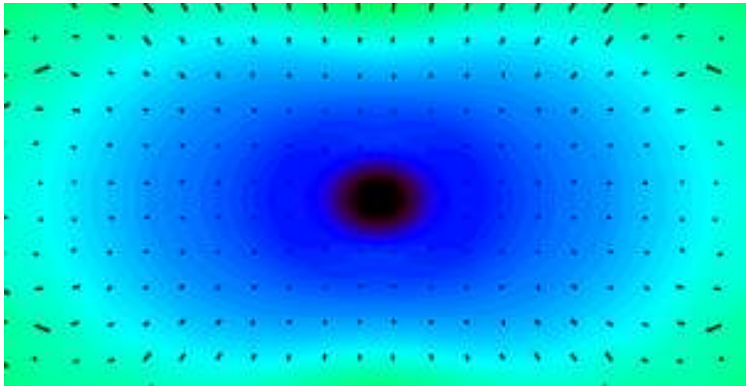
$$h_{\mathrm{char}}(f) = \sqrt{\frac{2}{\pi^2}\,\frac{G}{c^3}\,\frac{1}{D^2}\,\frac{dE_{\mathrm{GW}}(f)}{df}},$$

$$E_{\mathrm{GW}} \gtrsim 4 \times 10^{-10}\,M_\odot c^2$$

GWs from Rotating Collapse & Bounce

Recent work: Dimmelmeier+ ’08, Scheidegger+ ‘10, Ott+ ’12, Kuroda+ ‘13

Rapid rotation:
Oblate deformation of the inner core

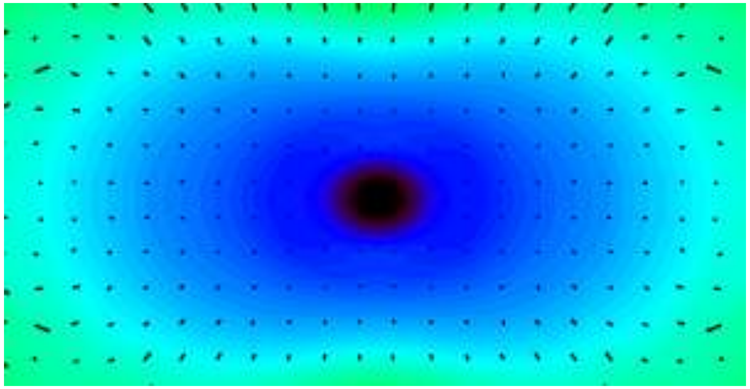


- Most extensively studied GW emission in core collapse
- **Axisymmetric: ONLY h_+**
- Simplest GW emission process: **Rotation** + **Gravity** + **Stiffening of nuclear EOS**.
- Strong signals for rapid rotation (-> millisecond proto-NS).

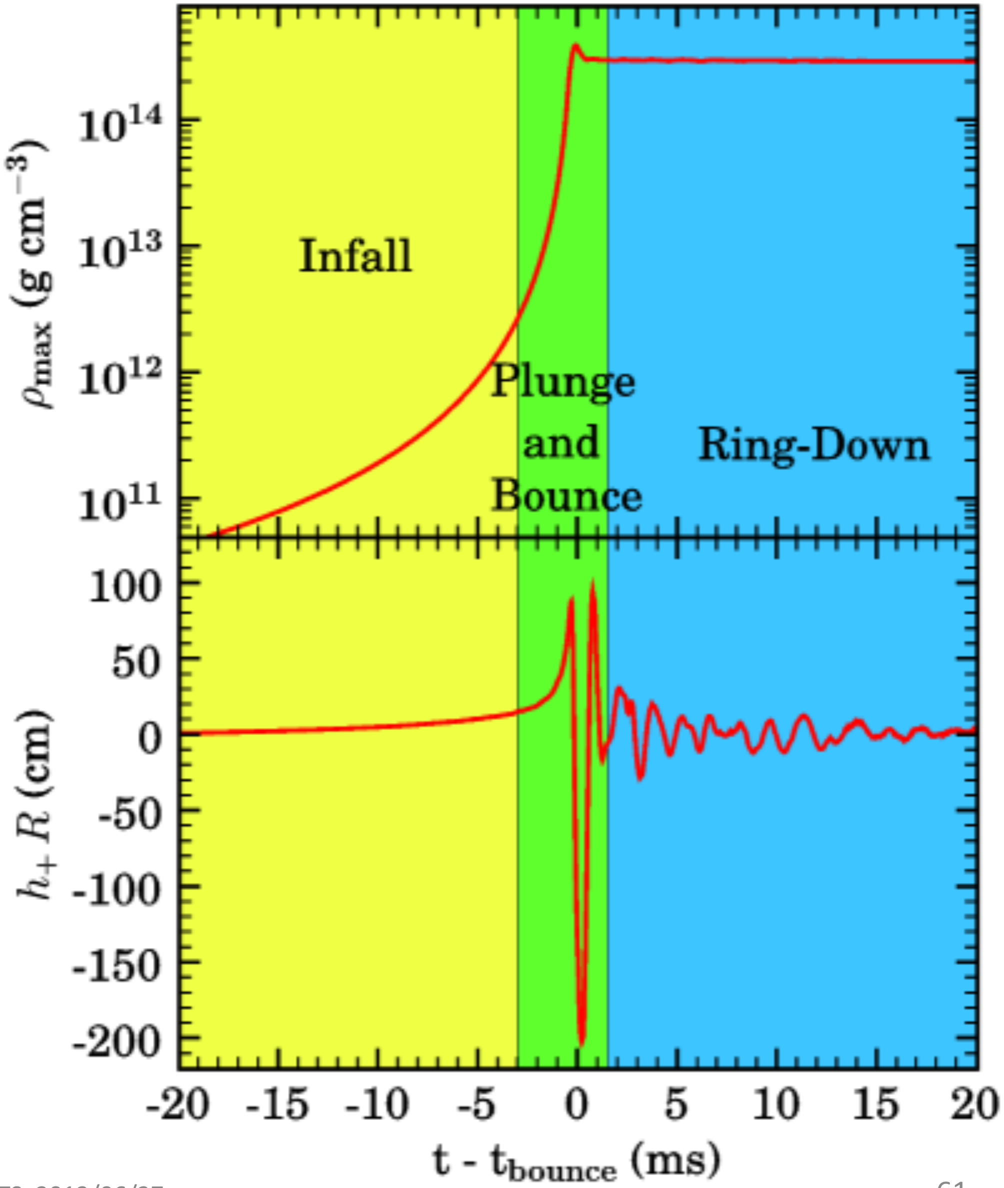
GWs from Rotating Collapse & Bounce

Recent work: Dimmelmeier+ '08, Scheidegger+ '10, Ott+ '12, Kuroda+ '13

Rapid rotation:
Oblate deformation of the inner core

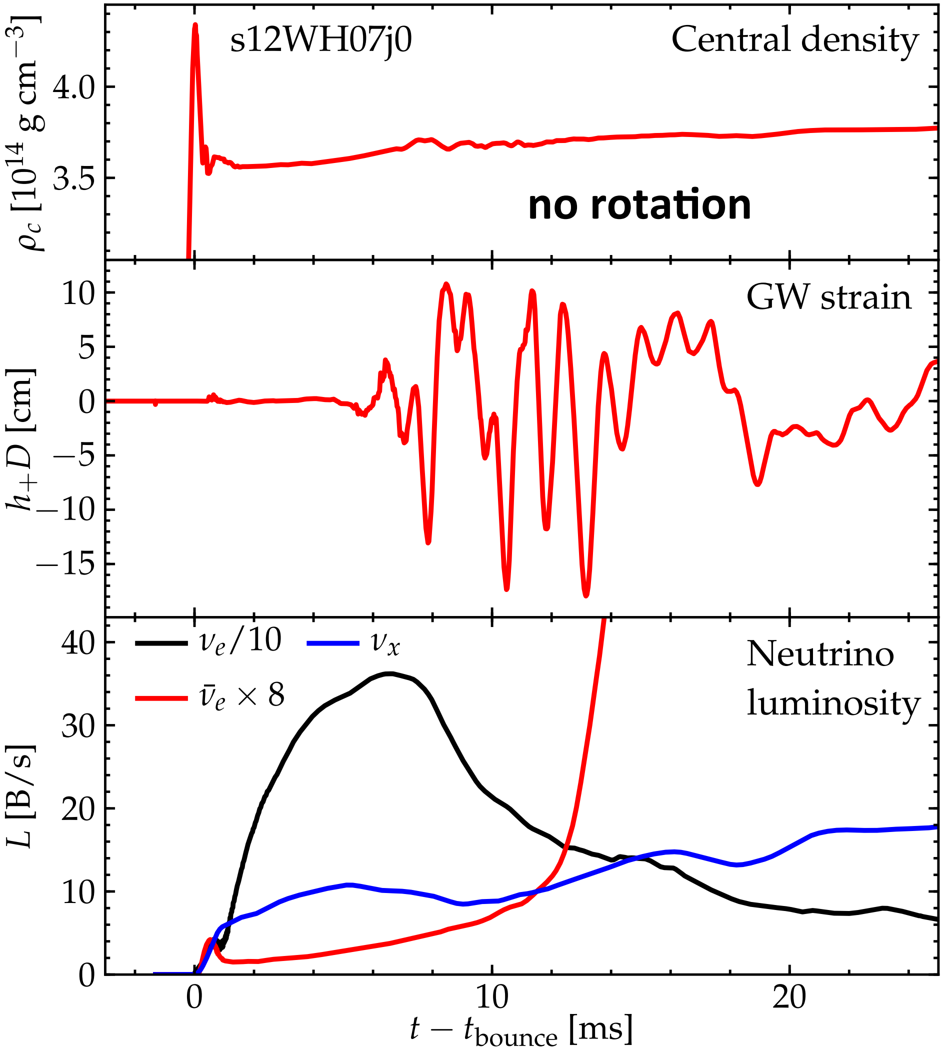


- Most extensively studied GW emission in core collapse
- **Axisymmetric: ONLY h_+**
- Simplest GW emission process: **Rotation** + **Gravity** + **Stiffening of nuclear EOS**.
- Strong signals for rapid rotation (-> millisecond proto-NS).

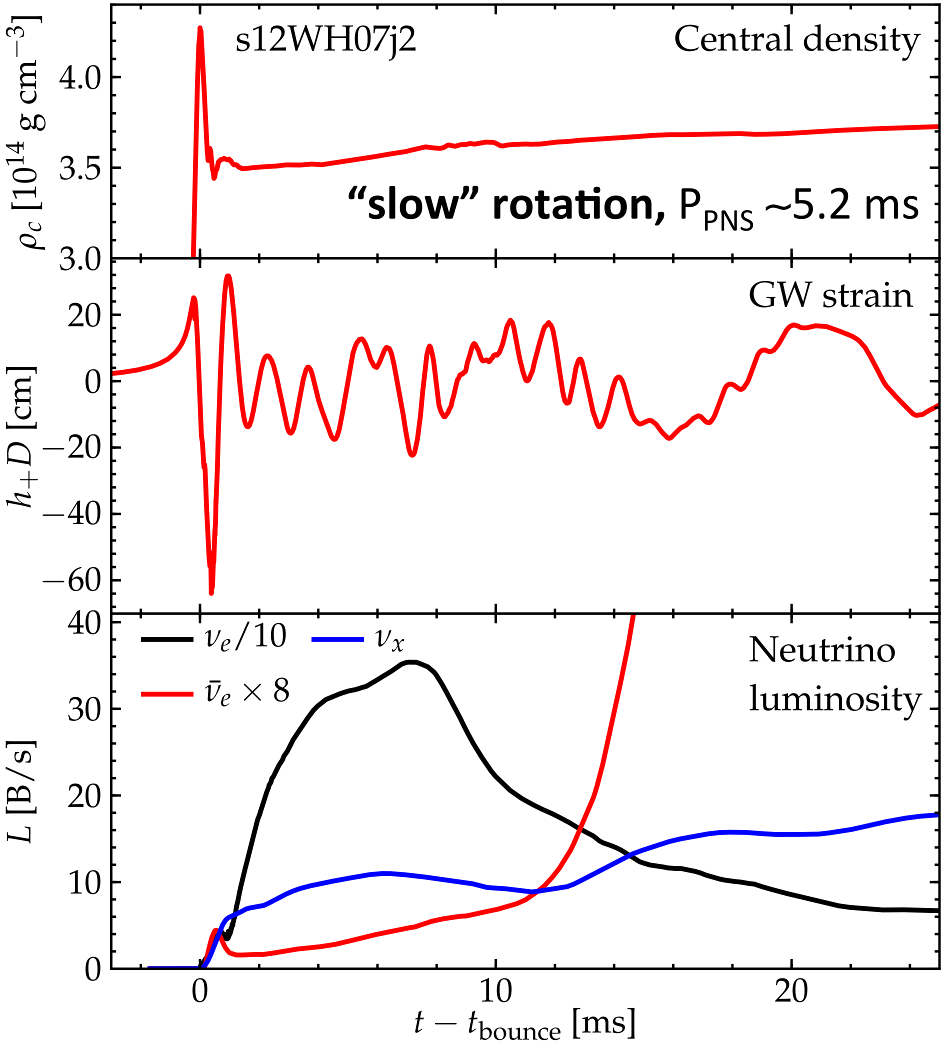


Correlated GW and Neutrino Signals: Rotation

Ott+'12, PRD



no rotation

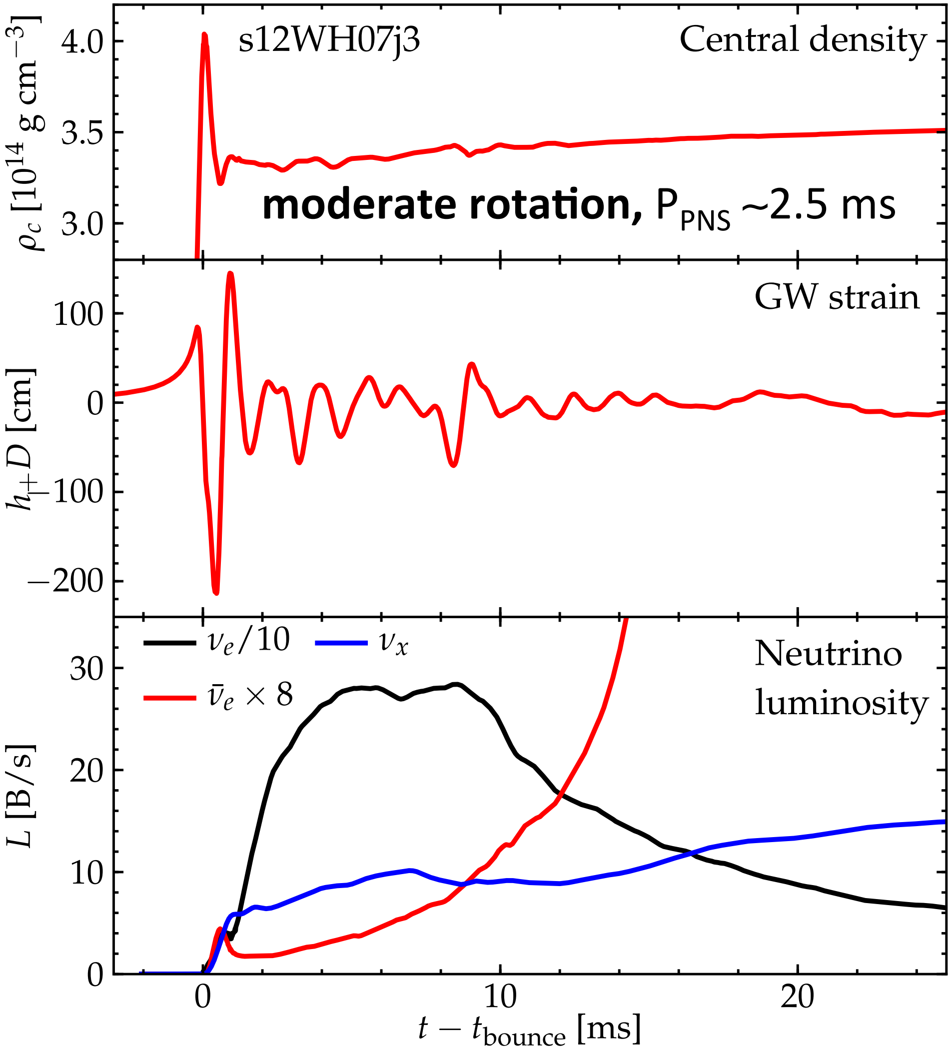


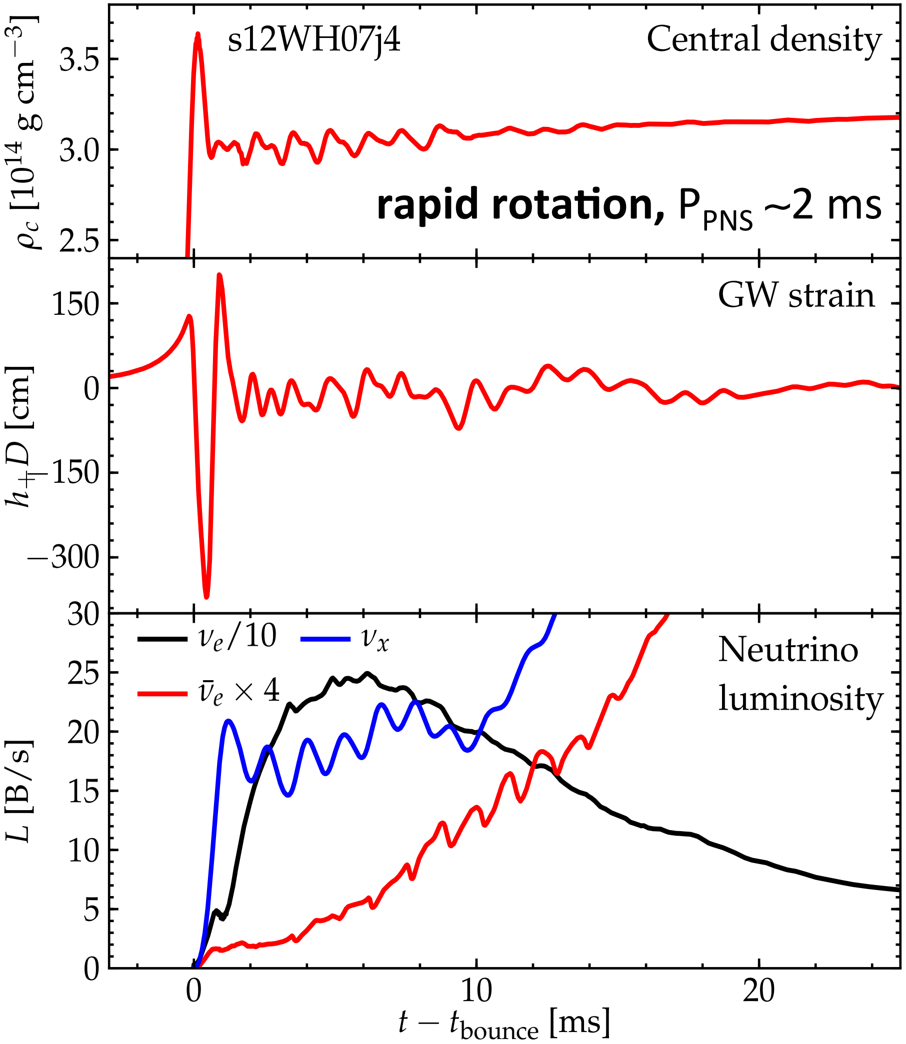
"slow" rotation, P_{PNS} ~5.2 ms

-> Using simple neutrino "leakage" scheme.

Correlated GW and Neutrino Signals: Rotation

Ott+'12, PRD

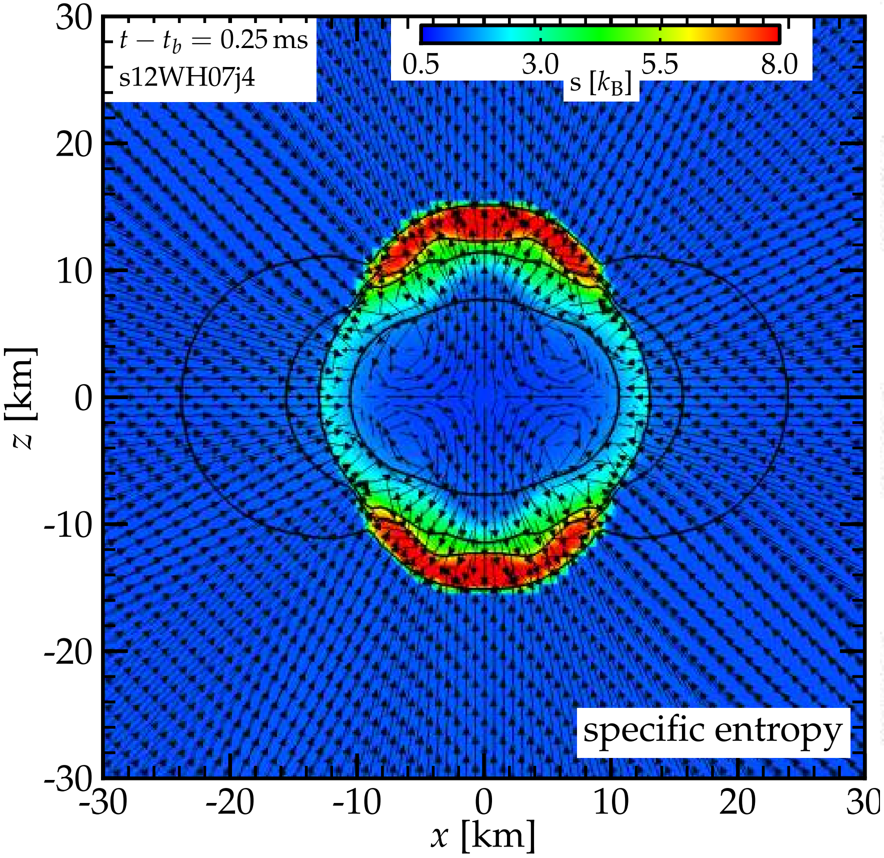


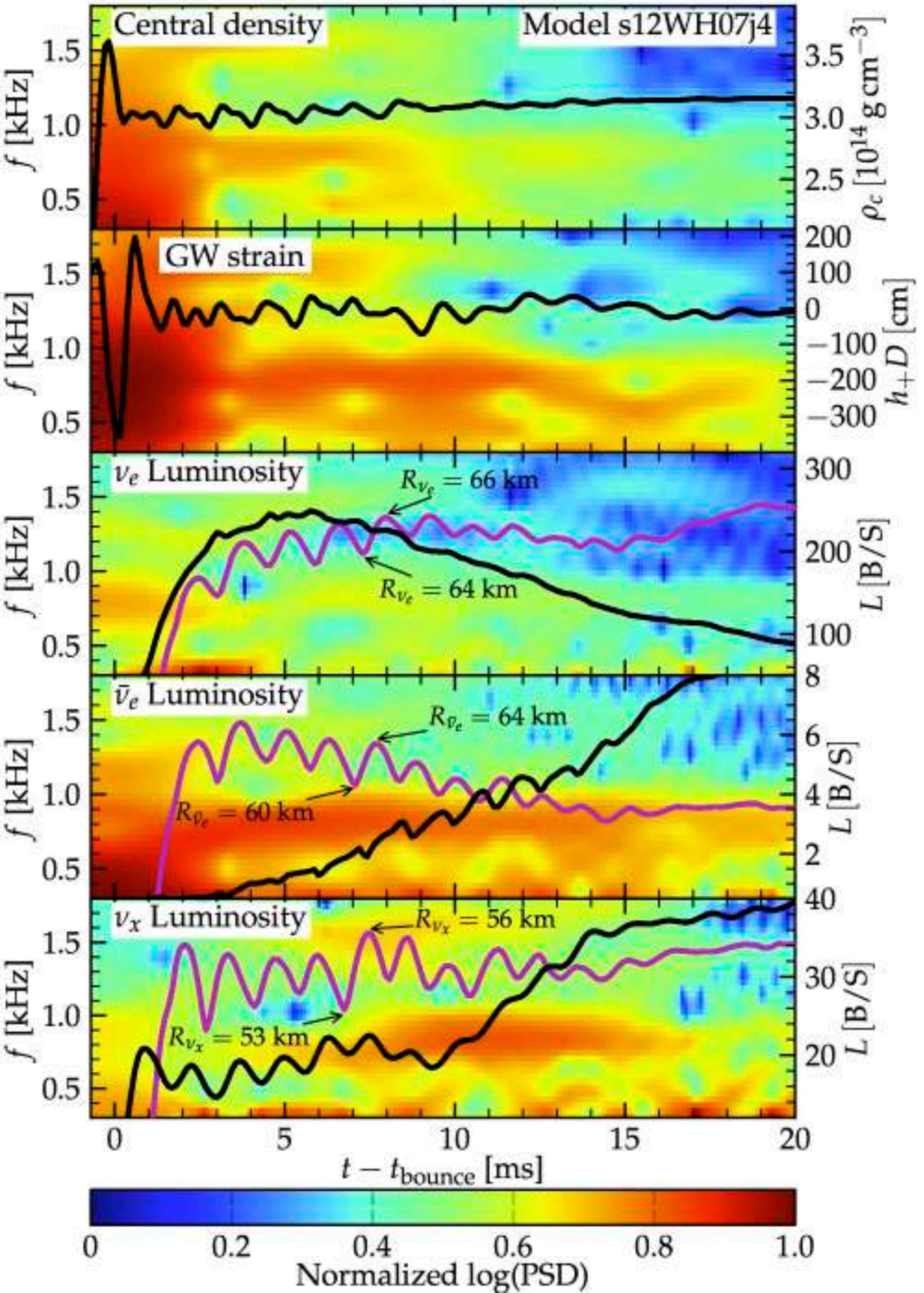


-> Using simple neutrino "leakage" scheme <- results must be checked w/ transport.

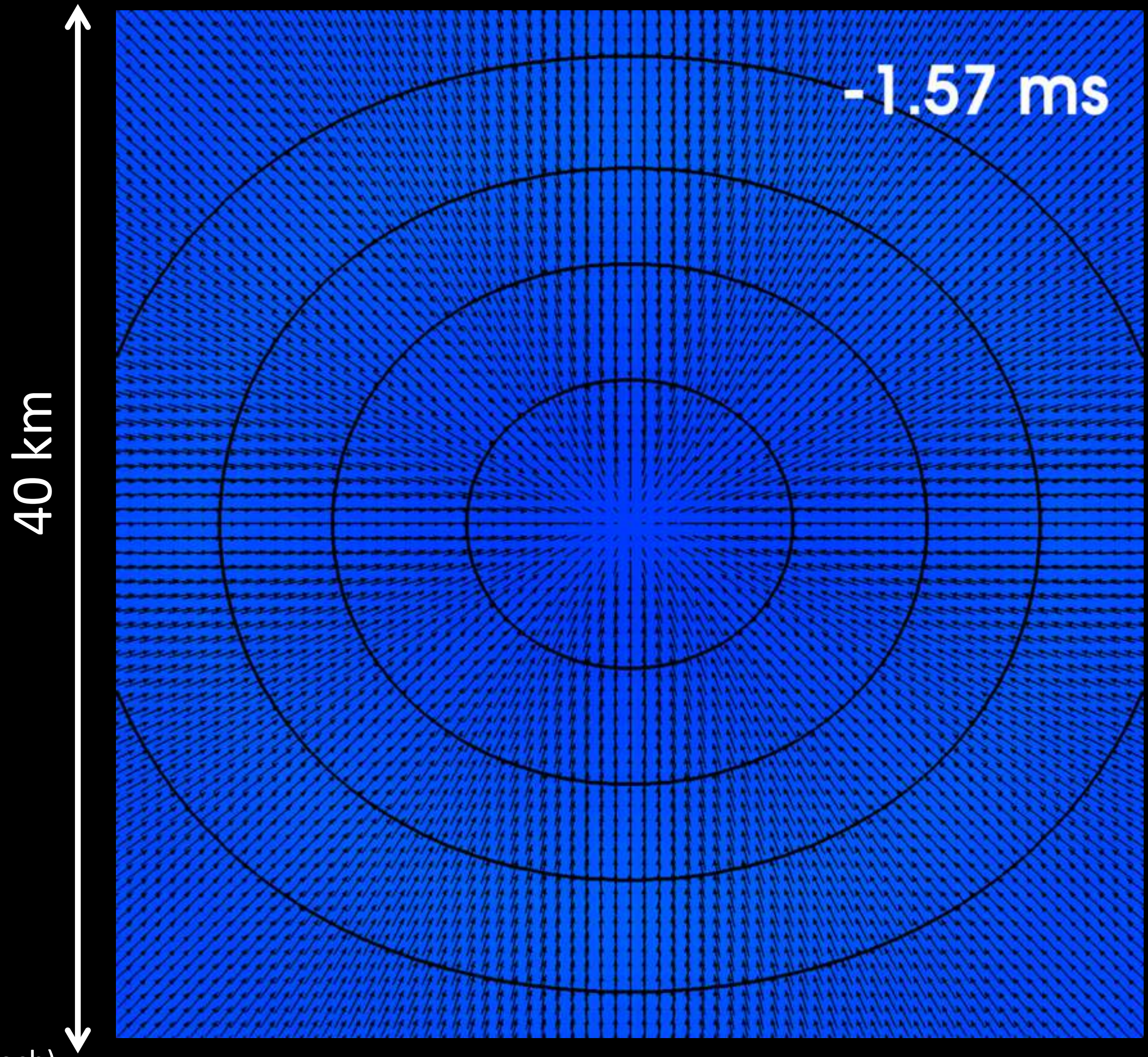
What is going on?

Ott+ ‘12, PRD





-> prolate bounce of oblate core excites fundamental quadrupole oscillation mode.

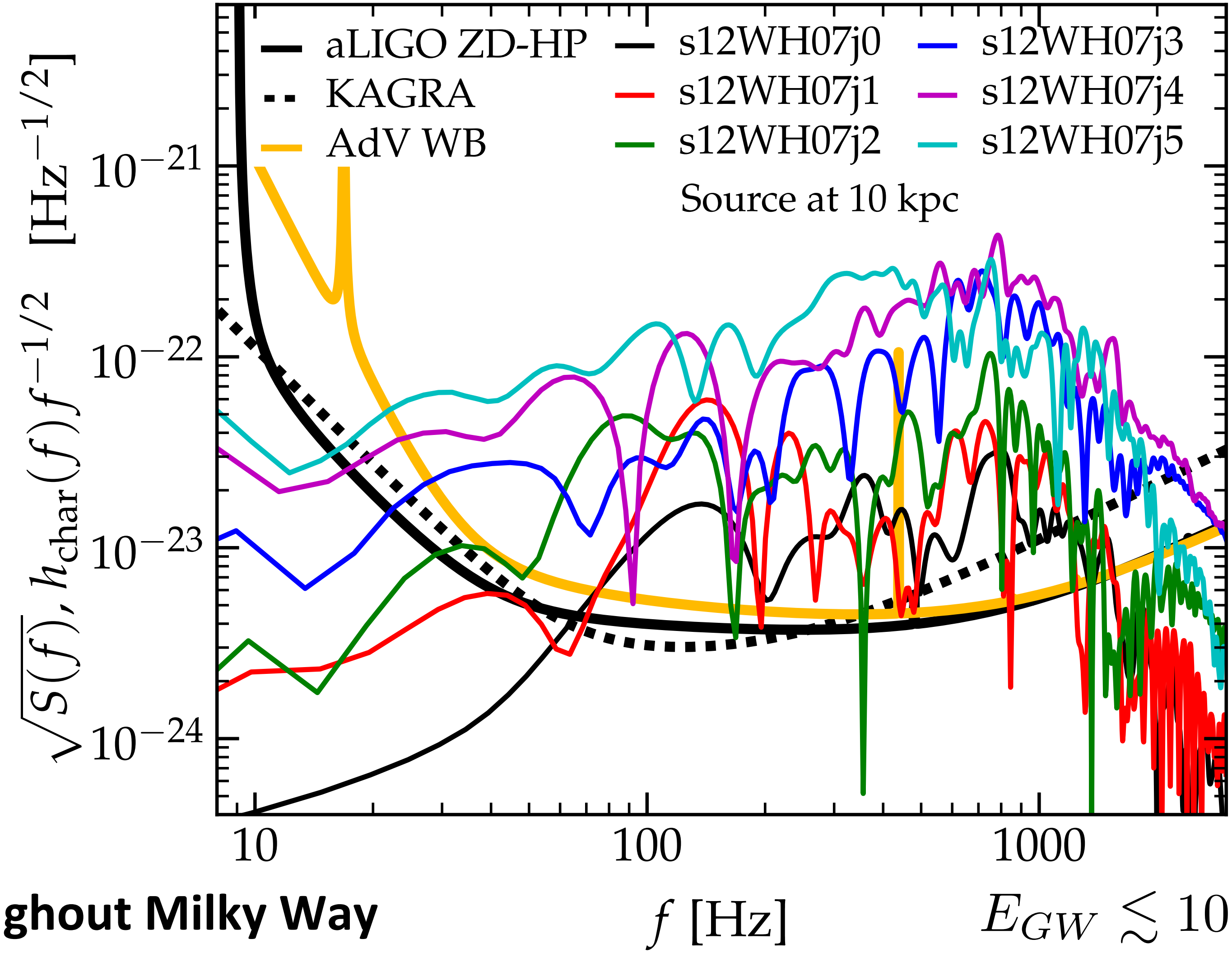


Movie by
Steve Drasco
(Grinnell/Caltech)

Can we observe this?

Ott+ ‘12, PRD

Gravitational Waves

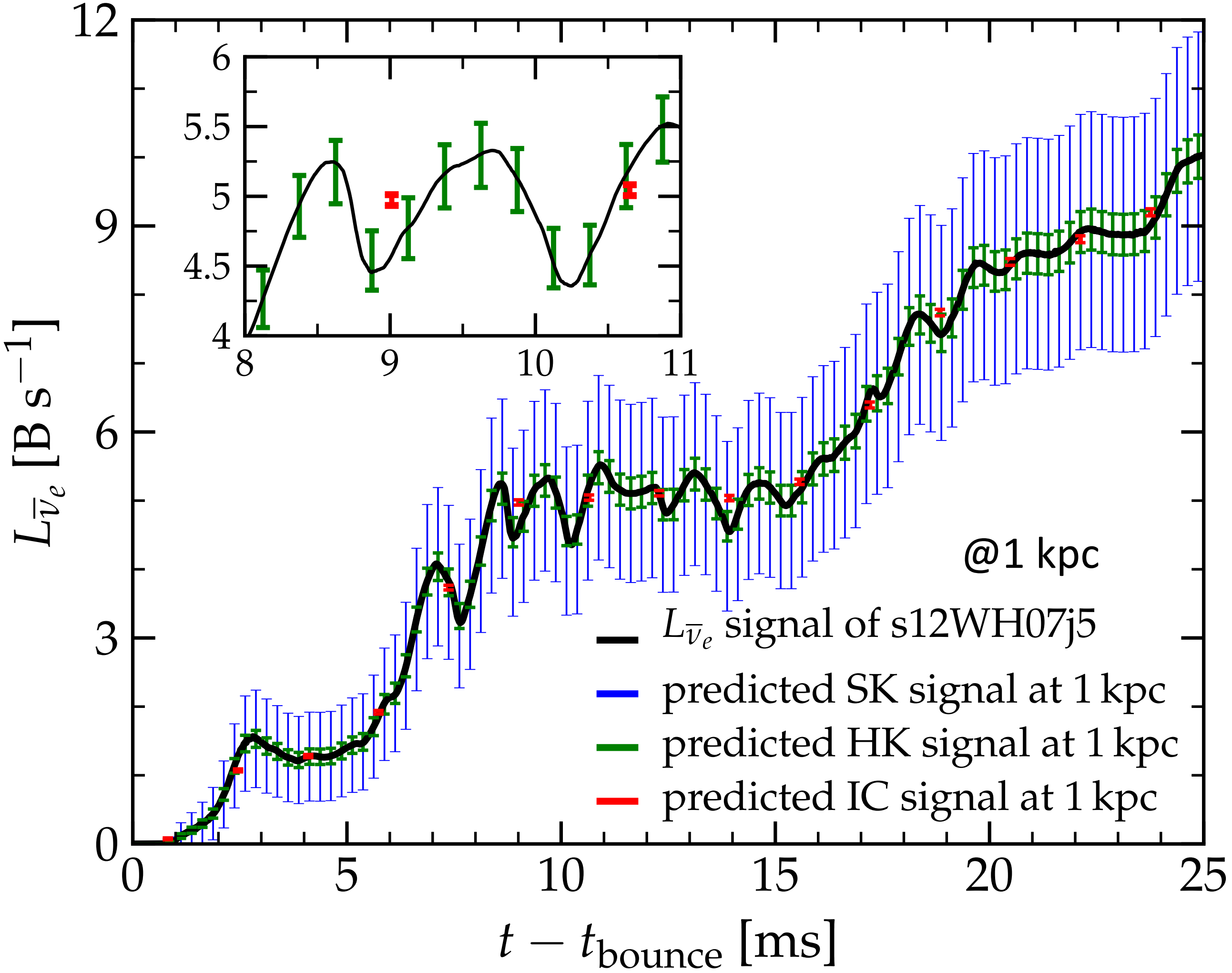


$E_{GW} \lesssim 10^{-8} M_\odot c^2$

-> Throughout Milky Way with aLIGO

Can we observe this? **Neutrinos**

Ott+ '12, PRD



~1 kpc with a megaton water-Cherenkov detector.
IceCube limited by readout rate.

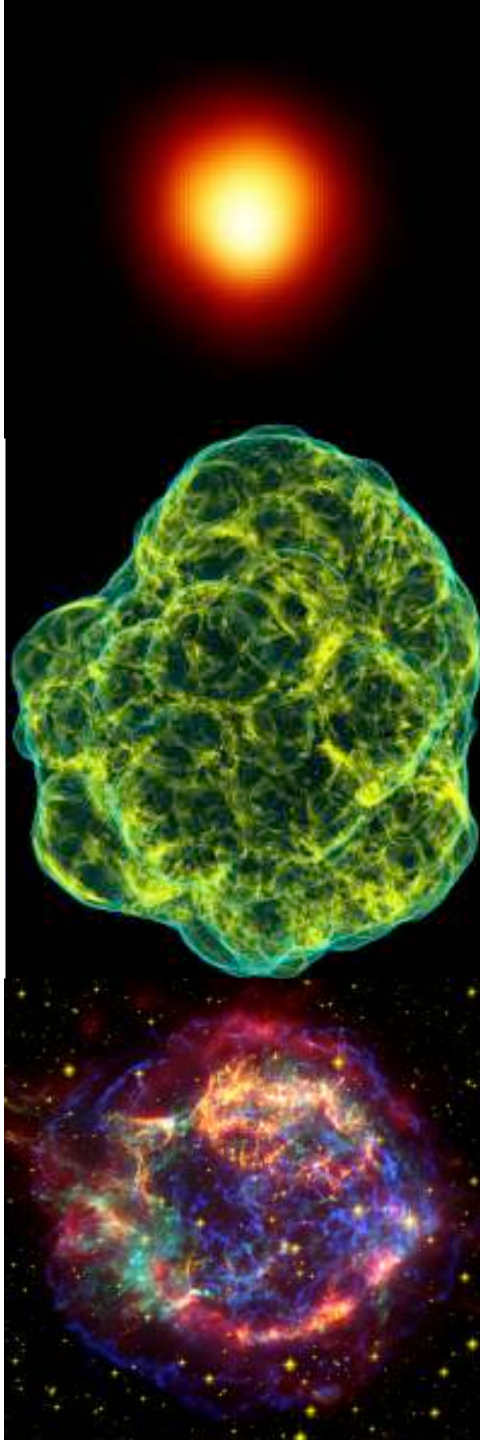
Summary

- Basics of core-collapse supernova theory on solid foundation; details to be worked out.

- Multi-D (3D?) neutrino mechanism best bet for blowing up ordinary massive stars.
  Next: Self-consistent 3D models.

- **The next galactic core-collapse supernova has already exploded.**
  (But its GWs/neutrinos/EM waves better not get here until 2015+ [-> advanced LIGO].)

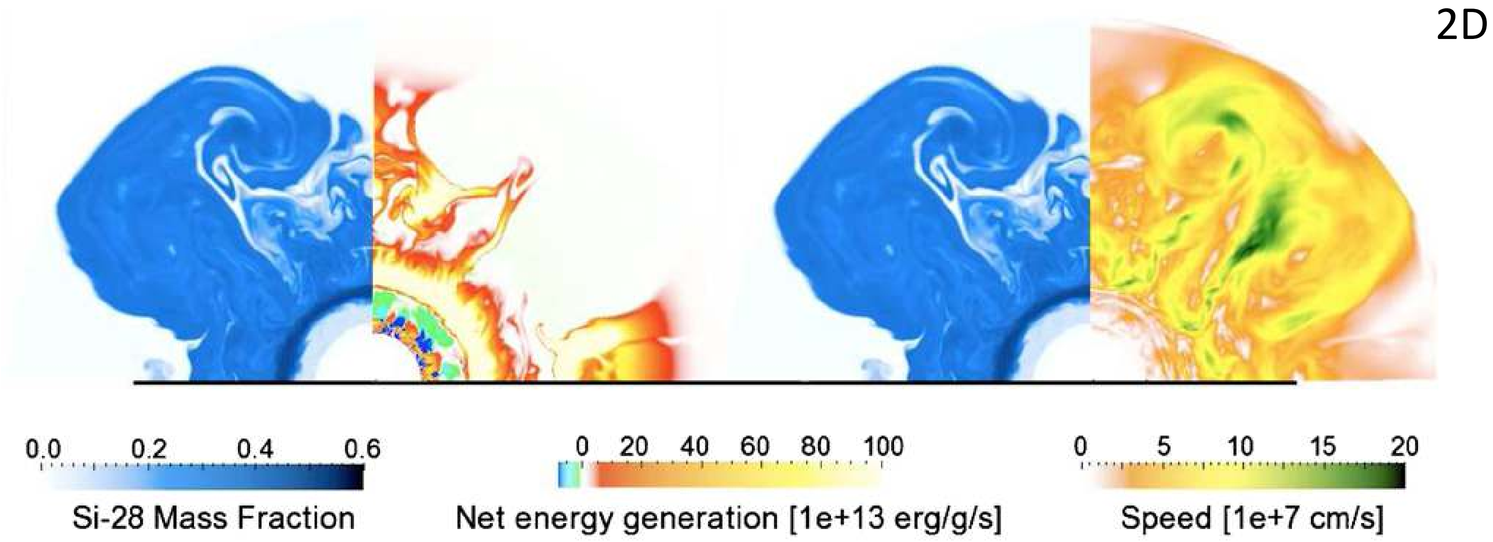
- Gravitational waves and neutrinos probe the supernova engine and progenitor star properties.



Supplemental Slides

Perhaps: Multi-D Stellar Evolution

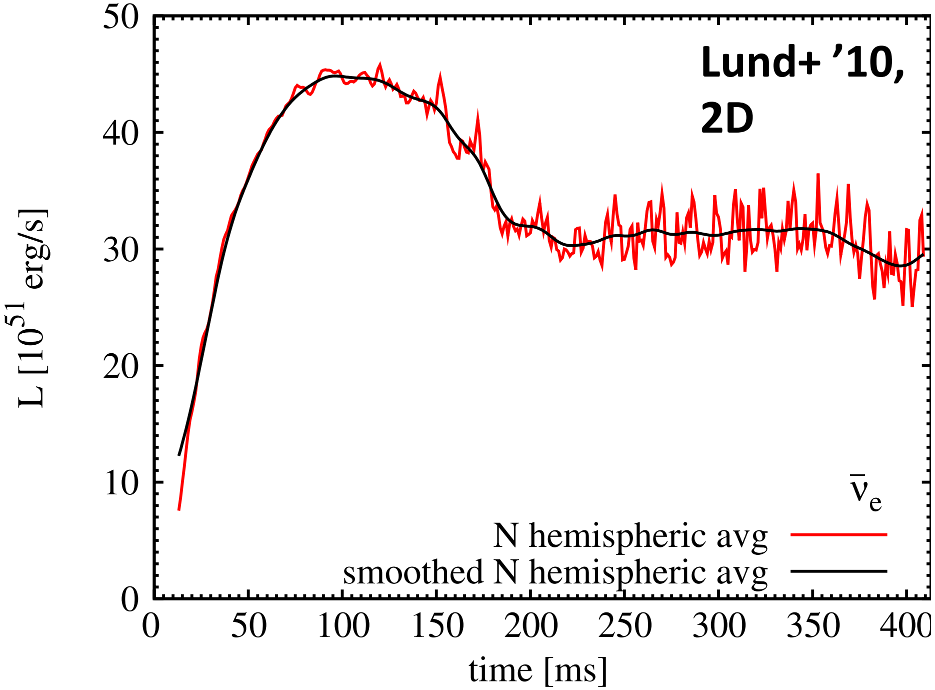
- All presently available presupernova stellar models are spherically symmetric with convection algorithms based on mixing-length theory.

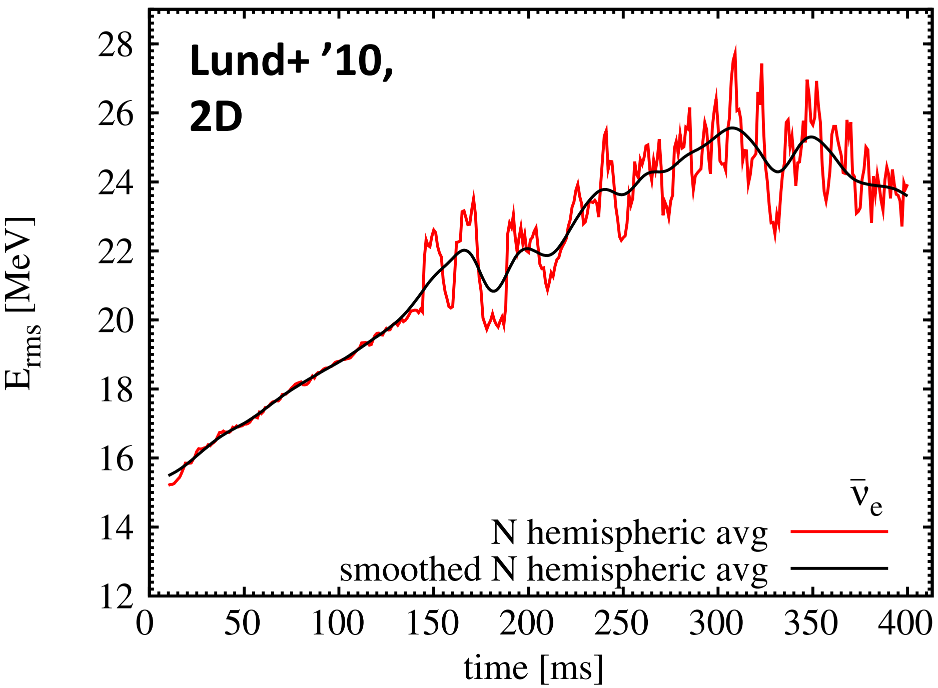


Arnett & Meakin 2011

- Late-stage oxygen burning very violent
  -> may lead to large-scale inhomogeneities in O/Si layer.
- Supernova evolution sensitive to local (and global) variations in the accretion rate -> potentially large effect, but presently ignored.

Neutrino Signature of Convections/SASI

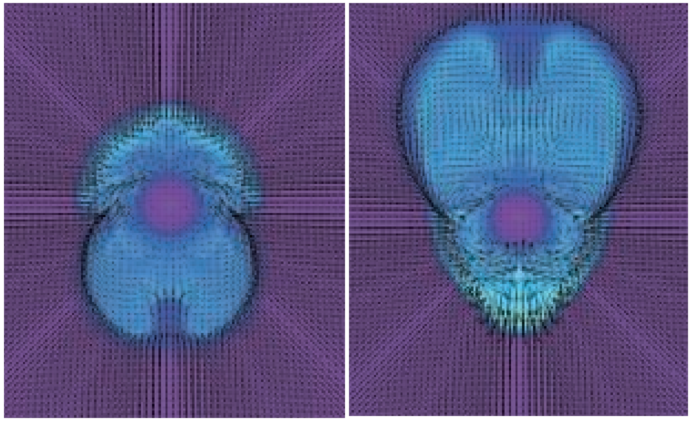




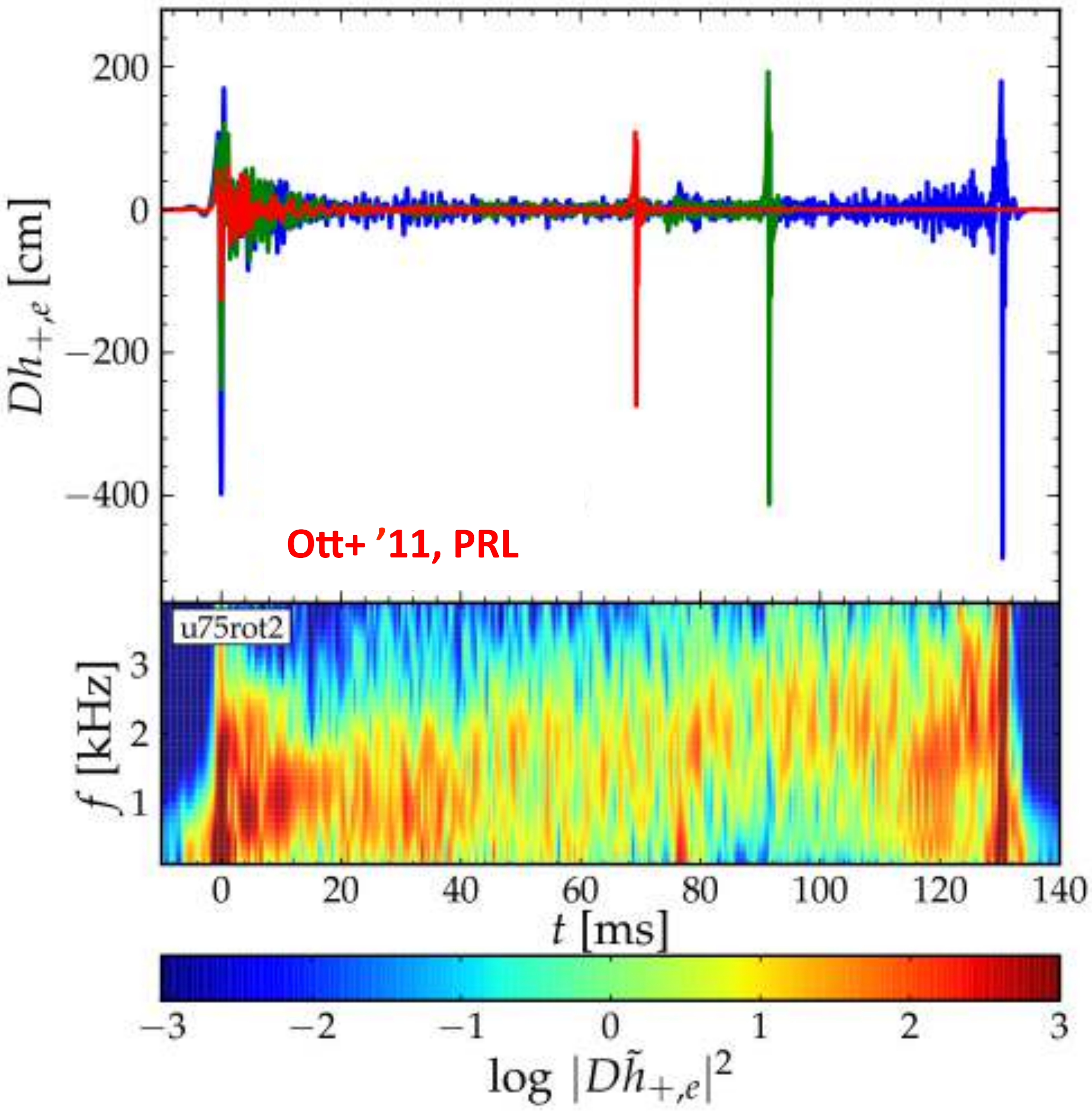
See: Ott+ '08, Marek & Janka '09, Lund+ '10, '12, Brandt +'11

- Neutrino signal can be used to probe supernova dynamics.

- Lund et al. '10:
  IceCube can detect SASI for galactic event.
  Effect smaller in 3D simulations (Lund+12)



Gravitational Waves from BH Formation



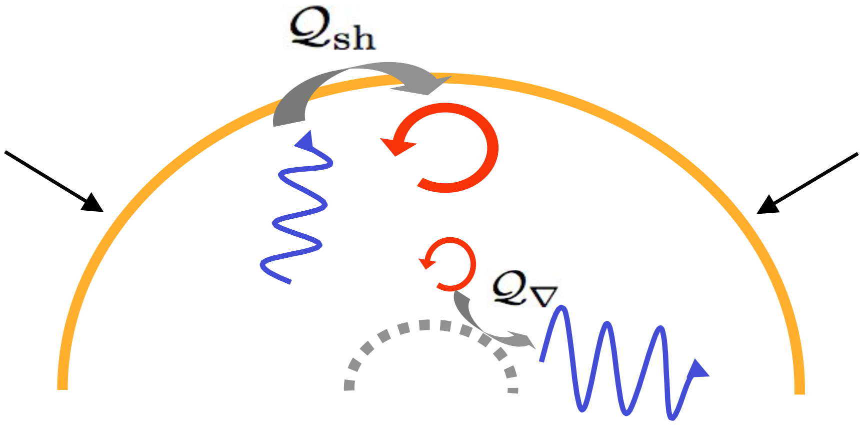
Ott+ ’11, PRL

Rotating
Black Hole
Formation

$E_{\rm GW} \sim 10^{-7}\, M_\odot\, c^2$

How Does the SASI work?

for details: see, e.g., Fernandez & Thompson ‘09ab, Foglizzo+ ‘06, ‘07, Scheck+ ‘08



(Source: Foglizzo)

Advective-acoustic cyle.

Fastest growing mode in linear analysis: l = 1

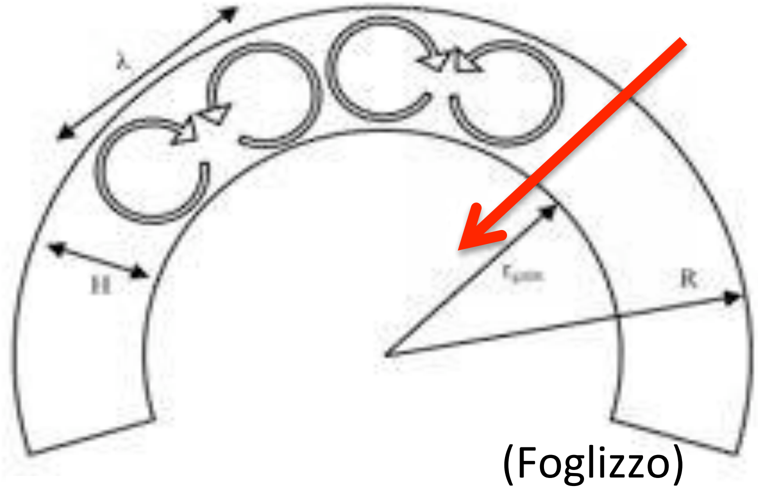
Non-linear saturation: sourcing of Kelvin-Helmholtz and Rayleigh-Taylor instability

SASI strongest if neutrino-driven convection absent, e.g., in idealized simulations w/o neutrin heating.

Interplay of SASI and ν-driven Convection

for details: see, e.g., Fernandez & Thompson '09b, **Foglizzo+ '06**, '07, Scheck+ '08

- Turbulence may damp advective acoustic mode (Foglizzo+).
- Gain region: neutrino-driven convection – early growth may inhibit SASI.



(Foglizzo)

In CCSN context, neutrino-driven convection will have most unstable mode at l=5-8.

But: non-standard setting -> advection
Perturbations must grow to non-linear scale and become buoyant before advected out of unstable region.

$$\chi \equiv \frac{\tau_{\rm adv}}{\tau_{\rm buoy}} \sim \frac{H\omega_{\rm buoy}}{v}$$

$\chi \gtrsim 3$ required for small (< 1%) perturbation to grow before it is advected out.

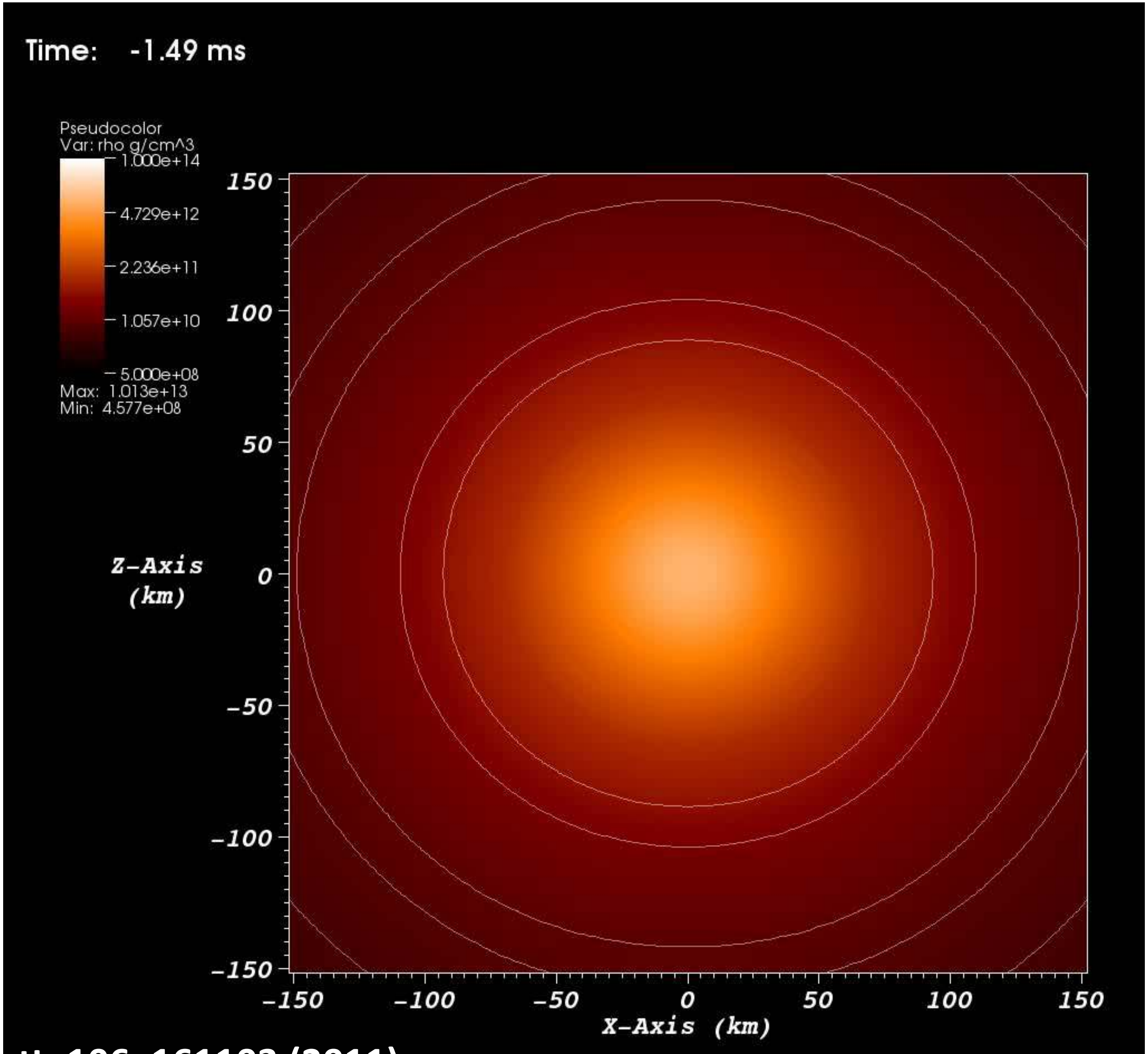
Alternative: Larger perturbation!

Role of the Nuclear EOS and GR

Ott, O'Connor, & Dasgupta '11, Marek et al. '09

$$Q_\nu^+ = \frac{X_n}{\lambda_0^a}\frac{L_{\nu_e}}{4\pi r^2}\boxed{\langle E_{\nu_e}^2\rangle}\left\langle\frac{1}{\mathrm{F}}\right\rangle + \frac{X_p}{\bar{\lambda}_0^a}\frac{L_{\bar{\nu}_e}}{4\pi r^2}\boxed{\langle E_{\bar{\nu}_e}^2\rangle}\left\langle\frac{1}{\bar{\mathrm{F}}}\right\rangle$$

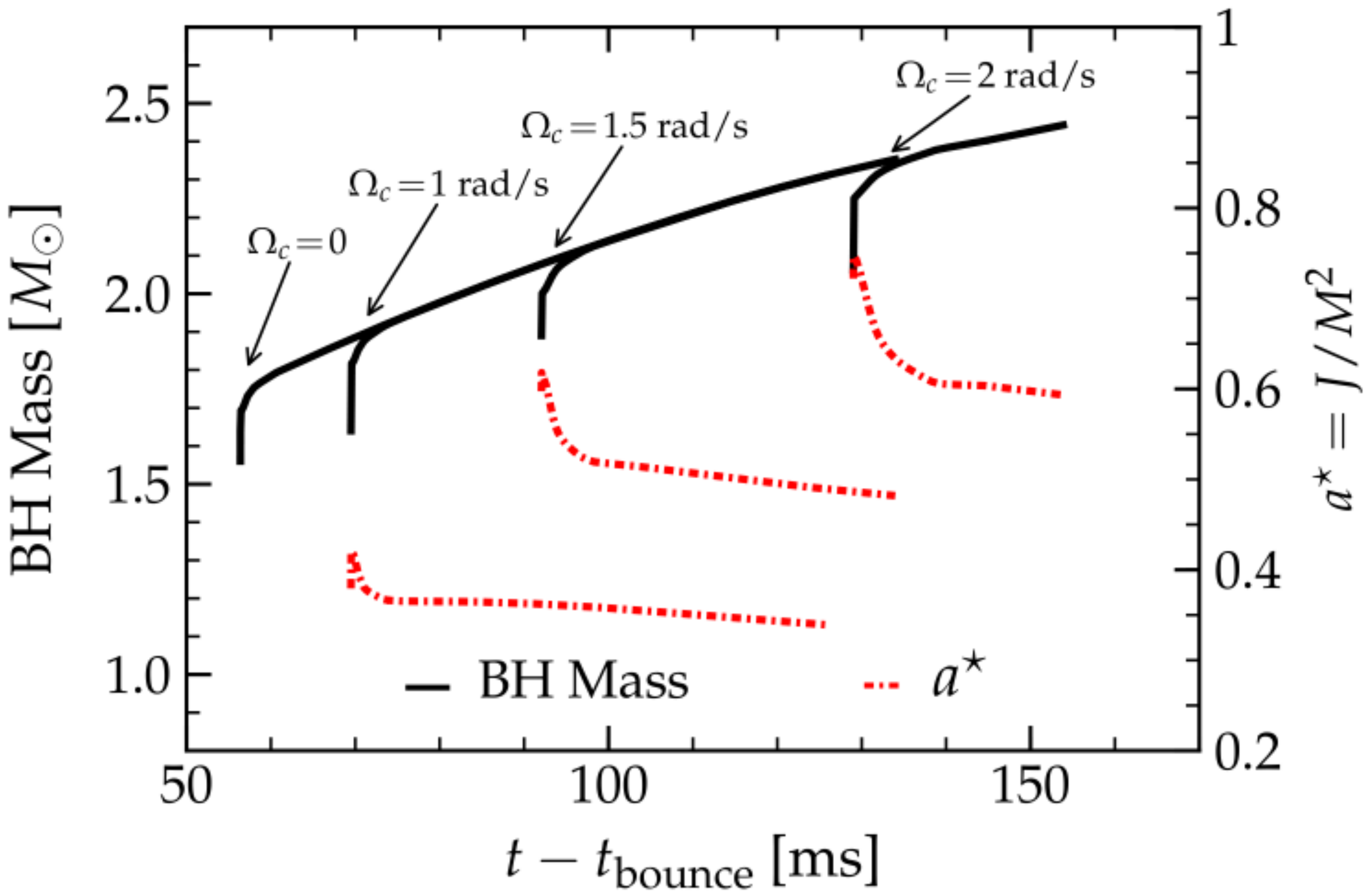
- "Soft" EOS
  -> compact protoneutron star, ν decouple at smaller radius,
  -> harder neutrino spectrum.
  -> increased neutrino heating.
- "Stiff" EOS
  -> more extended protoneutron star, ν decouple at larger radius,
  -> softer neutrino spectrum,
  -> increased neutrino heating.
- General relativity: Effective softenting -> harder ν spectrum.
- "Favorite EOS": Lattimer & Swesty '91, K_0 = 180 MeV
- Problem: Discovery of 2-$M_\odot$ neutron star (Demorest et al. '10) *rules out many soft EOS*, including LS180.



ett. 106, 161103 (2011)

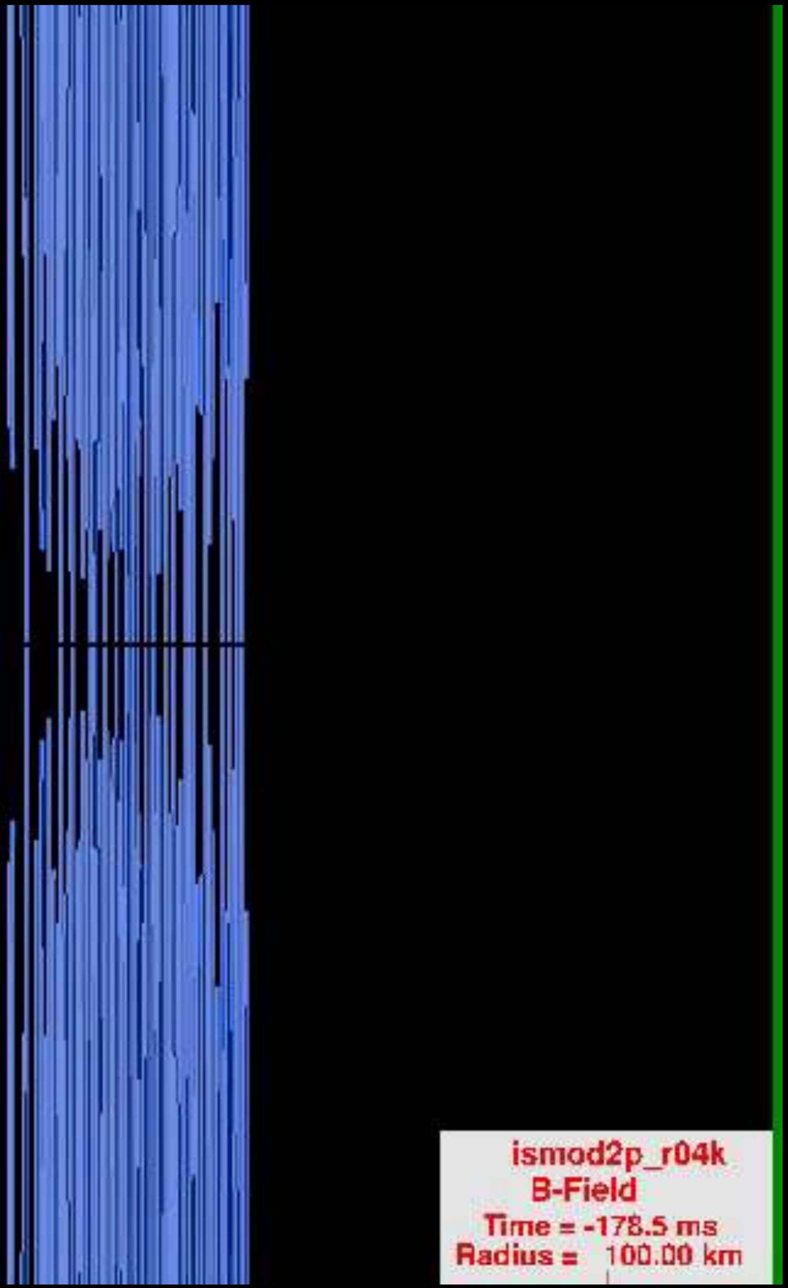
Nascent BH Spin and Mass Evolution

Ott+ 2011, PRL

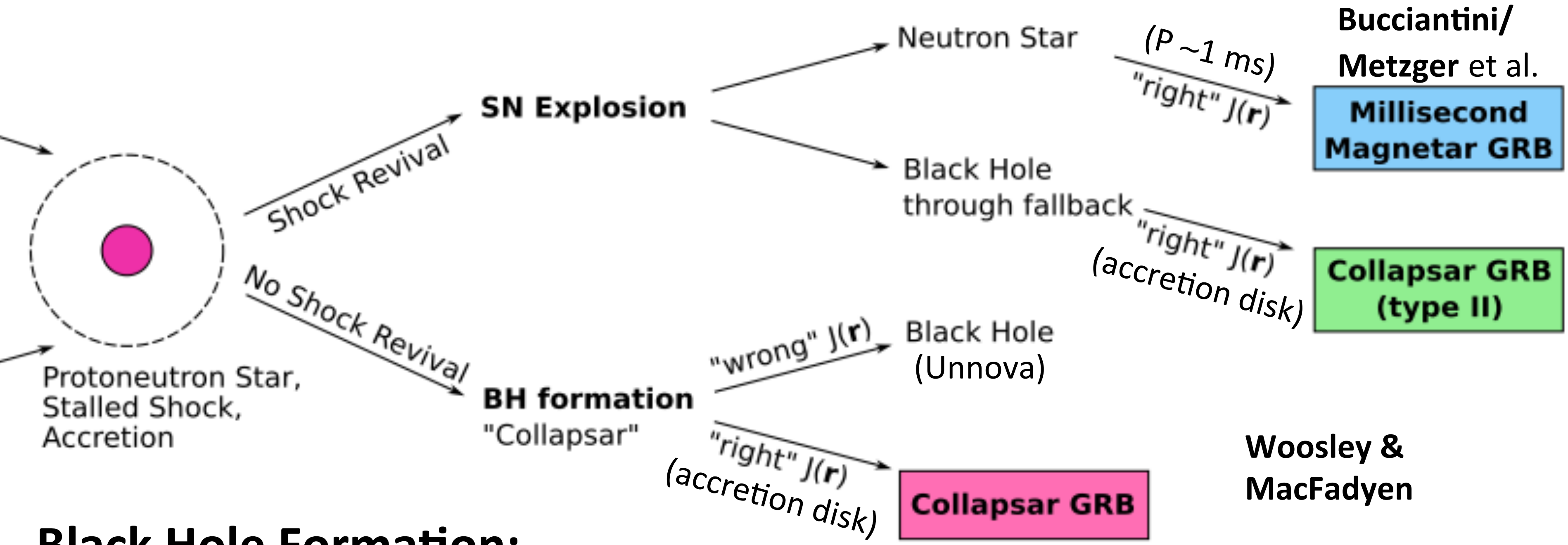


Newtonian
Radiation-MHD
Simulations with
VULCAN/2D

Magnetic field lines in
Burrows, Dessart,
Livne, Ott, Murphy ‘07.



Black Hole Formation and Connection to Long GRBs



Protoneutron Star,
Stalled Shock,
Accretion

Shock Revival

SN Explosion

Neutron Star

(P ~1 ms)
"right" $J(\mathbf{r})$

Bucciantini/
Metzger et al.

Millisecond Magnetar GRB

Black Hole
through fallback

"right" $J(\mathbf{r})$
(accretion disk)

Collapsar GRB (type II)

No Shock Revival

BH formation
"Collapsar"

"wrong" $J(\mathbf{r})$

Black Hole
(Unnova)

"right" $J(\mathbf{r})$
(accretion disk)

Collapsar GRB

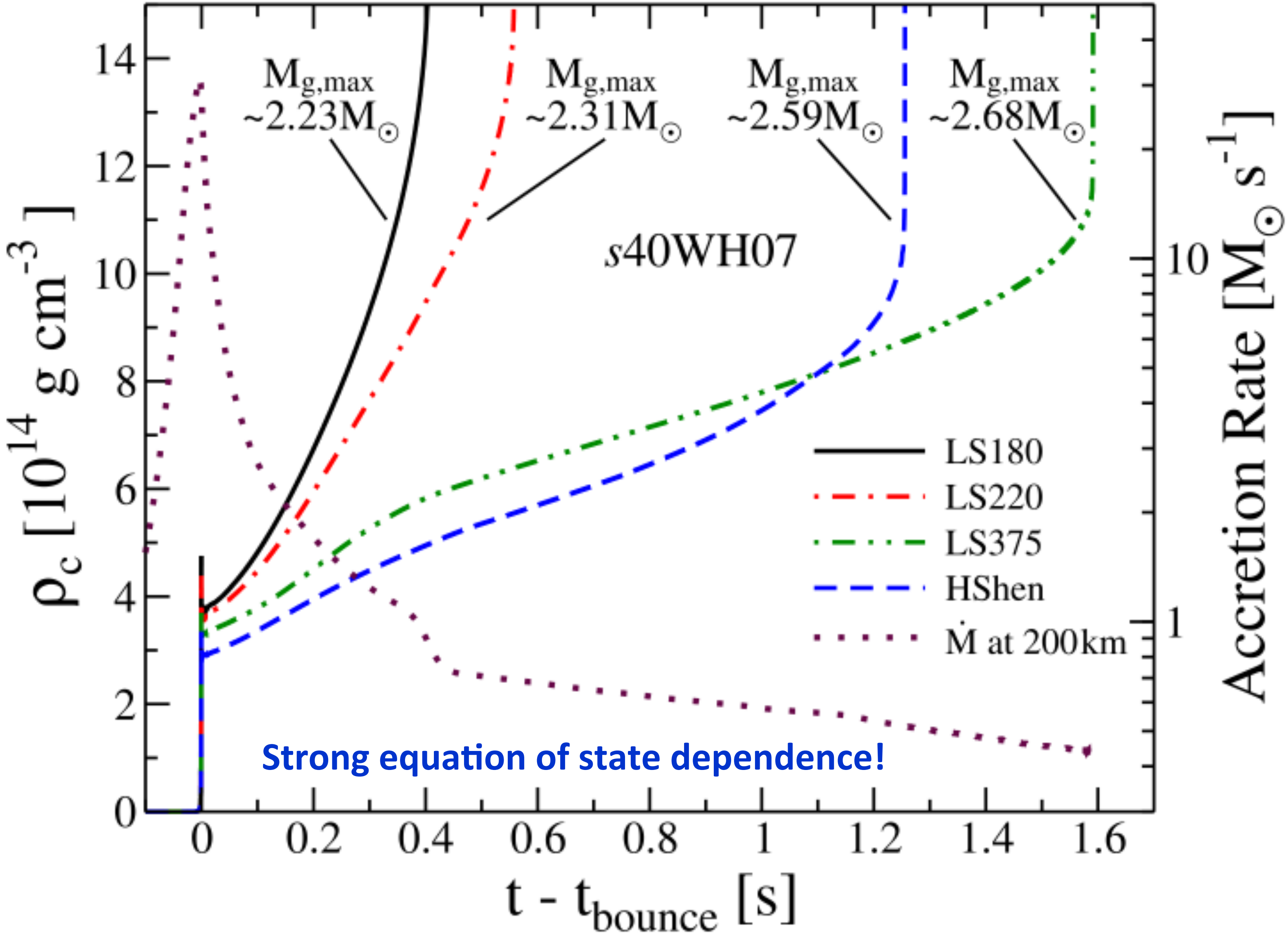
Woosley &
MacFadyen

Black Hole Formation:

- **A protoneutron star always forms, but has a maximum mass!**
  Exact value unknown, but $M_{max} > 2\ M_{Sun}$ (J1614-2230, Demorest+'10)
- BH formation: (1) explosion fails, (2) fallback accretion
  [(3) softening of nuclear equation of state].
- What stars make black holes?

Explosion Failure and BH Formation

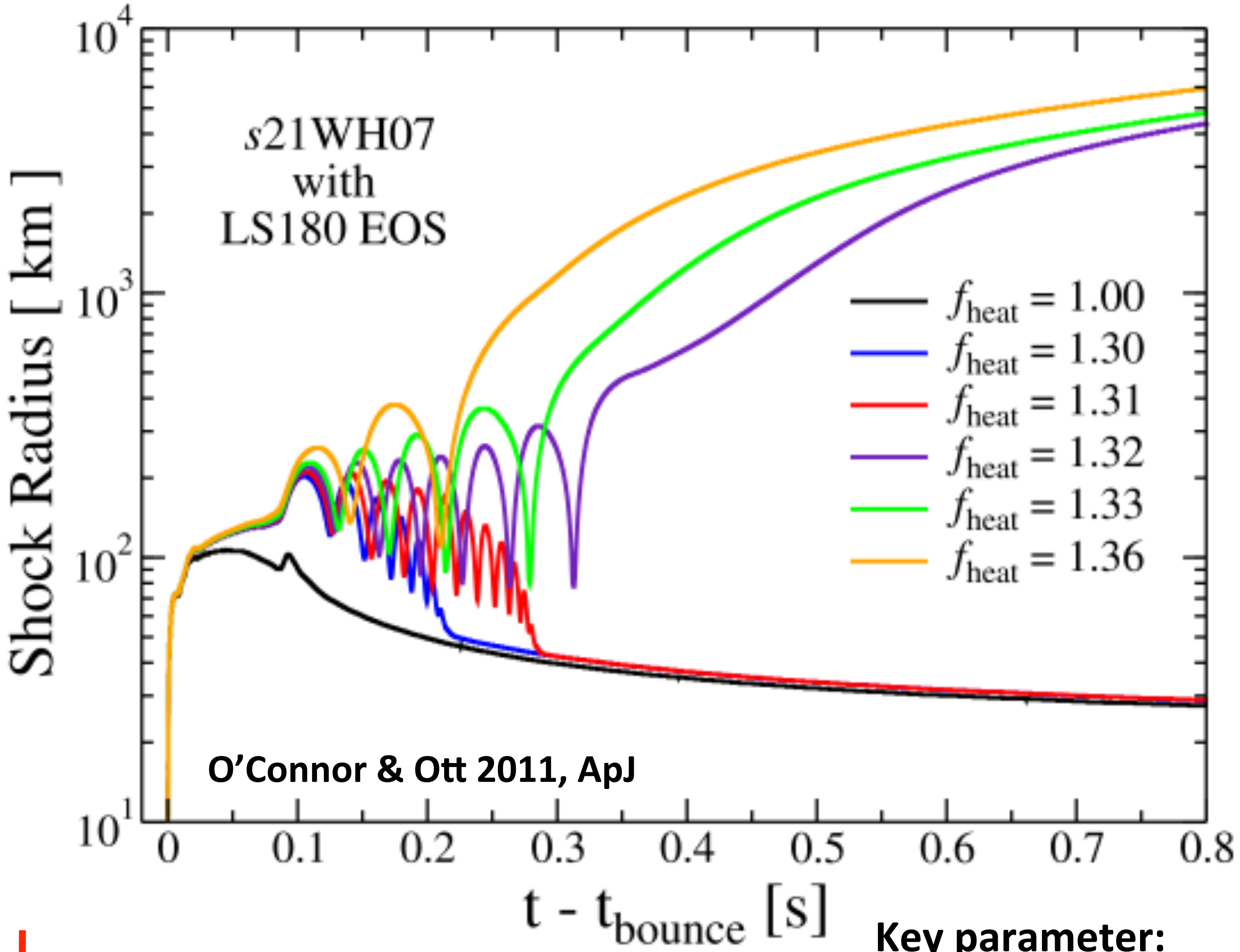
O'Connor & Ott 2011, GR1D code @ `http://www.stellarcollapse.org`



Strong equation of state dependence!

See also
Fischer+ '09, Sumiyoshi+ '08

How hard can it be to blow up a star?



O’Connor & Ott 2011, ApJ

$$Q^{\mathrm{heat}}_{\nu_i}(r) = f_{\mathrm{heat}} \frac{L^{\mathrm{FRF}}_{\nu_i}(r)}{4\pi r^2} \sigma_{\mathrm{heat},\nu_i} \frac{\rho}{m_u} X_i \left\langle \frac{1}{F_{\nu_i}} \right\rangle e^{-2\tau_{\nu_i}}$$

Key parameter:

$$\eta_\nu = \frac{Q^+_\nu}{L_{\nu_e} + L_{\bar{\nu}_e}}$$

Heating Efficiency

How to Characterize Progenitor Stars

O'Connor & Ott 2011

Compactness Parameter

$$\xi_M = \frac{M/M_\odot}{R(M_\mathrm{bary} = M)/1000\,\mathrm{km}}\bigg|_{t=t_\mathrm{bounce}}$$

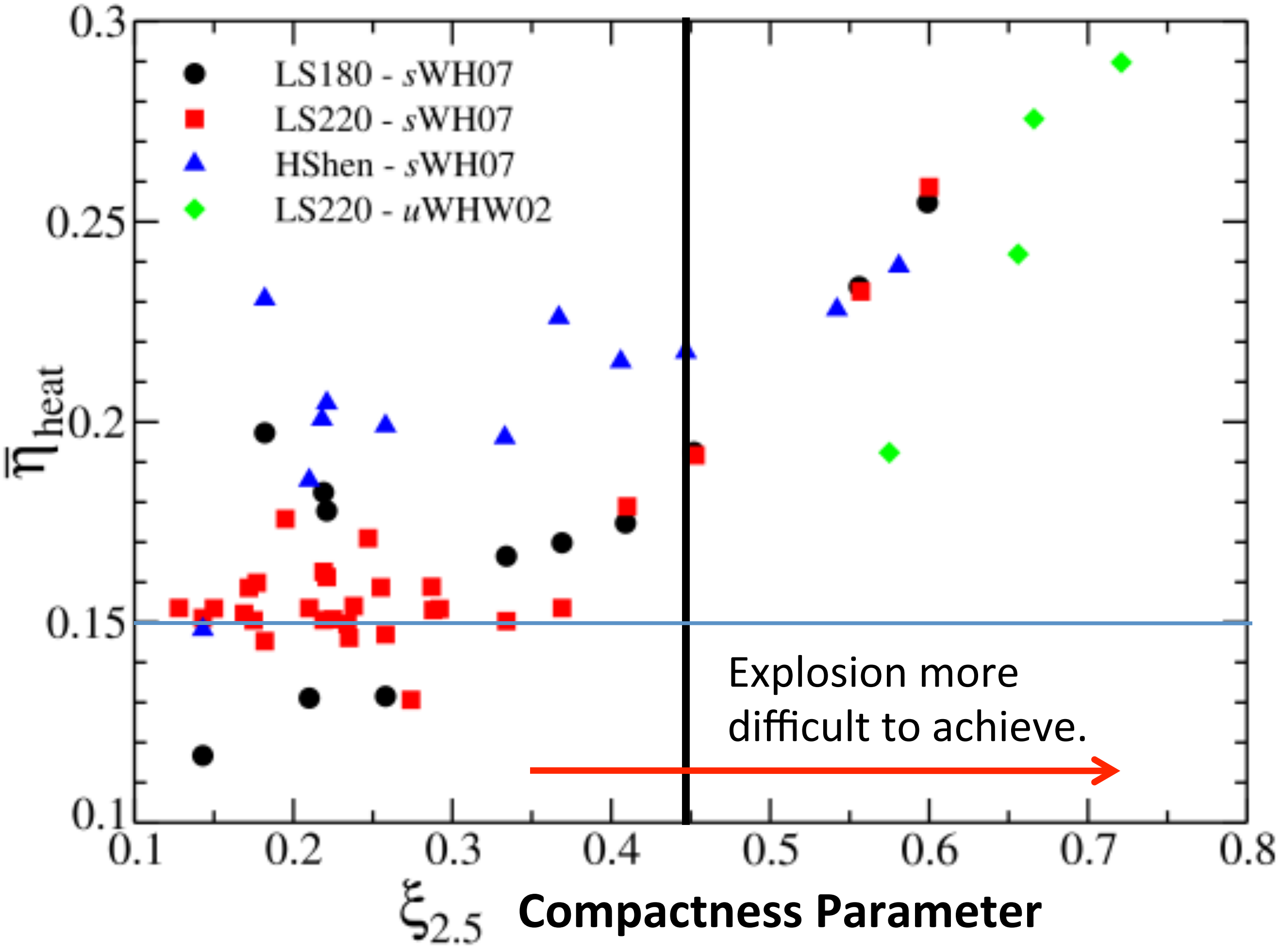
here: use $M = 2.5 M_\odot$ (typical mass scale for BH Formation)

Baseline set of simulations: **no rotation, 4 equations of state, ~100 progenitor models.**

-> compactness parameter + EOS completely control the dynamics.

What does it take to blow up a star?

O'Connor & Ott 2011



Heating Efficiency

Compactness Parameter

Explosion more difficult to achieve.

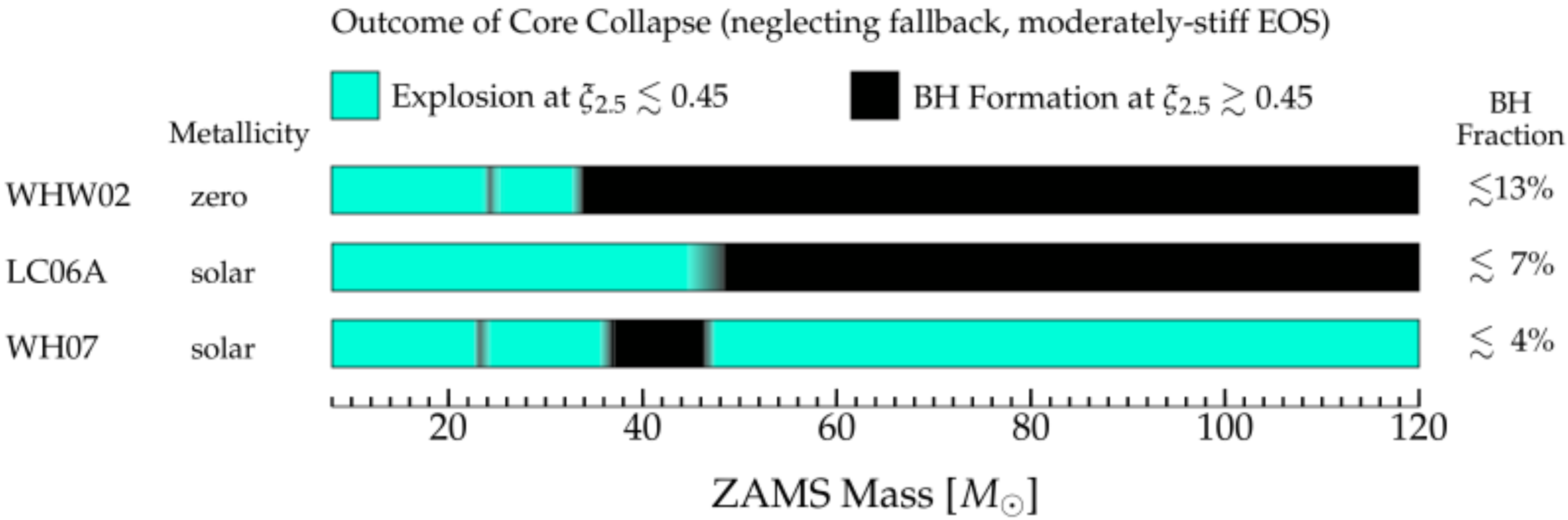
- Heating efficiency in multi-D simulations: 0.05 - 0.15

[Marek & Janka '09, Ott et al. '08]

Mapping ZAMS Mass to Outcome

[O’Connor & Ott 2011]

What stars make black holes?

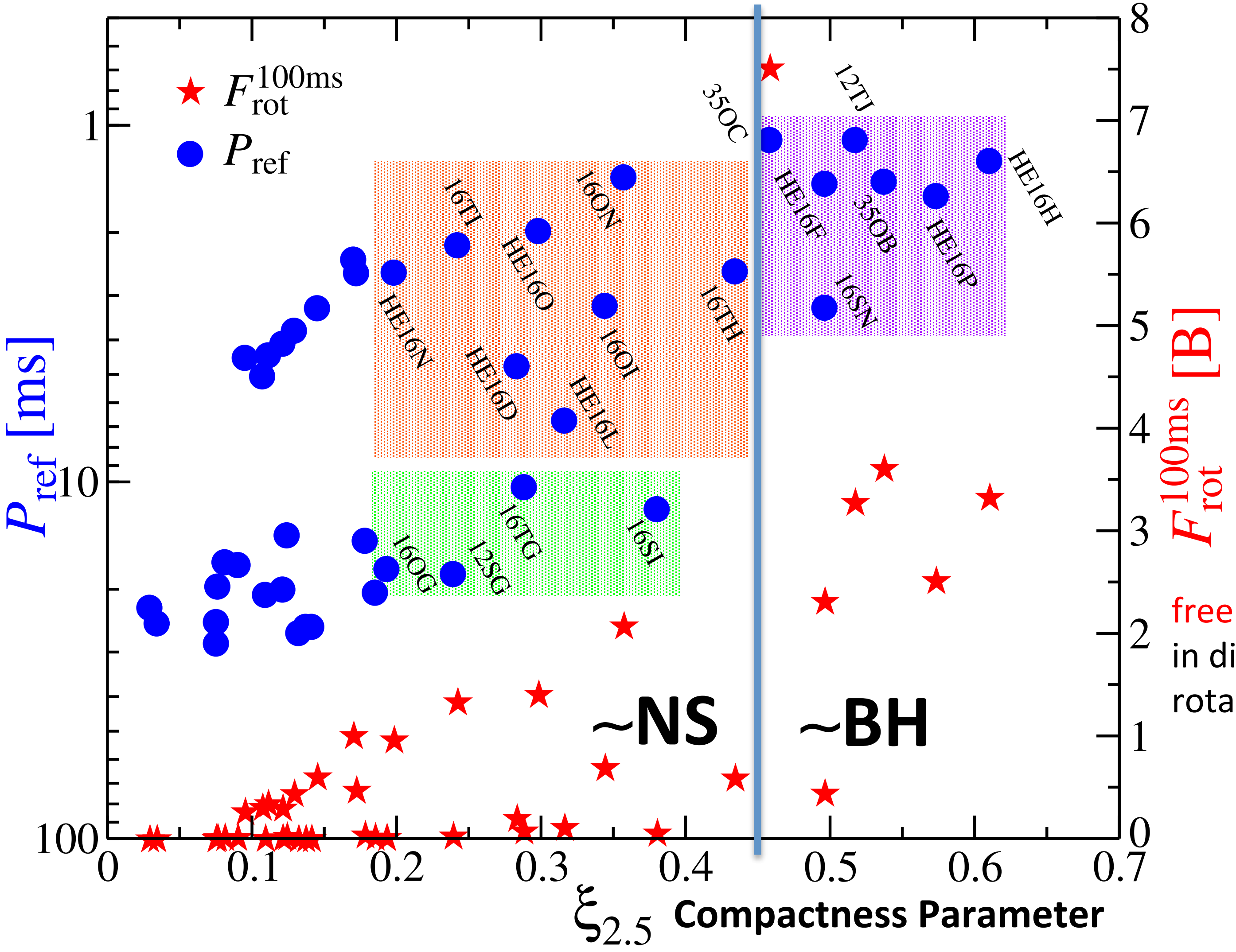


Large uncertainty at solar metallicity: **Physics of mass loss highly uncertain!**

Adding in Rotation: Testing Collapsar Progenitors

Dessart, O'Connor, Ott '12, ApJ

Models of Woosley & Heger '06



free energy in differential rotation

Vast majority of long-GRB progenitors -> NS.

BH-producing models have extreme spin -> magnetorotational explosion + NS?