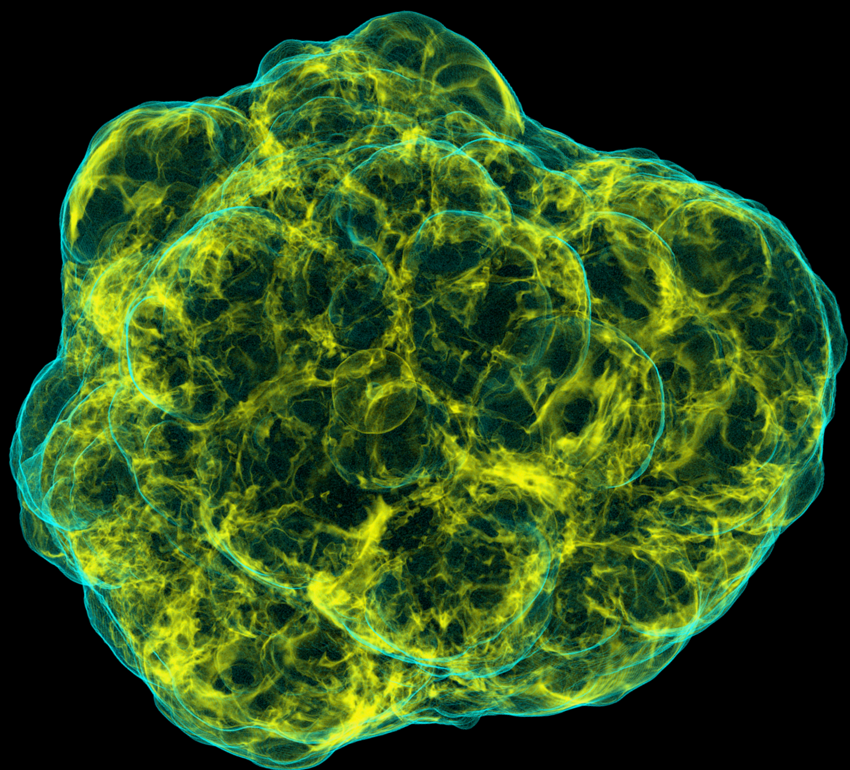
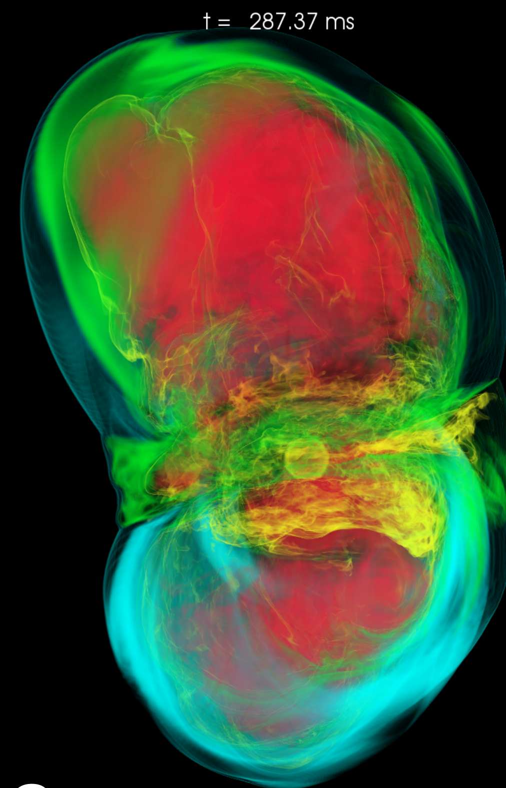
Core-Collapse Supernova Overview





Christian D. Ott
TAPIR, Caltech

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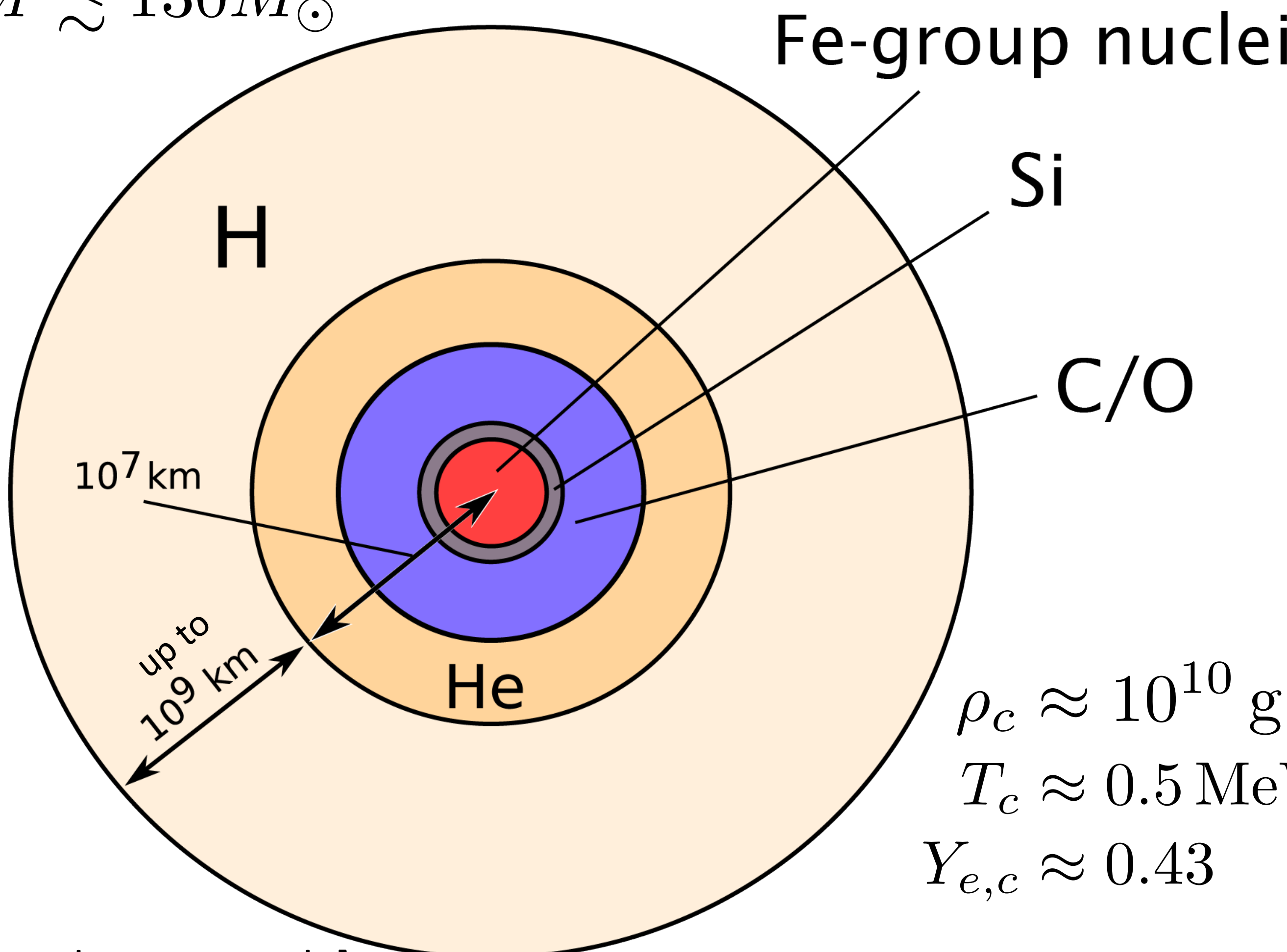
The Basic Theory of Core Collapse

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

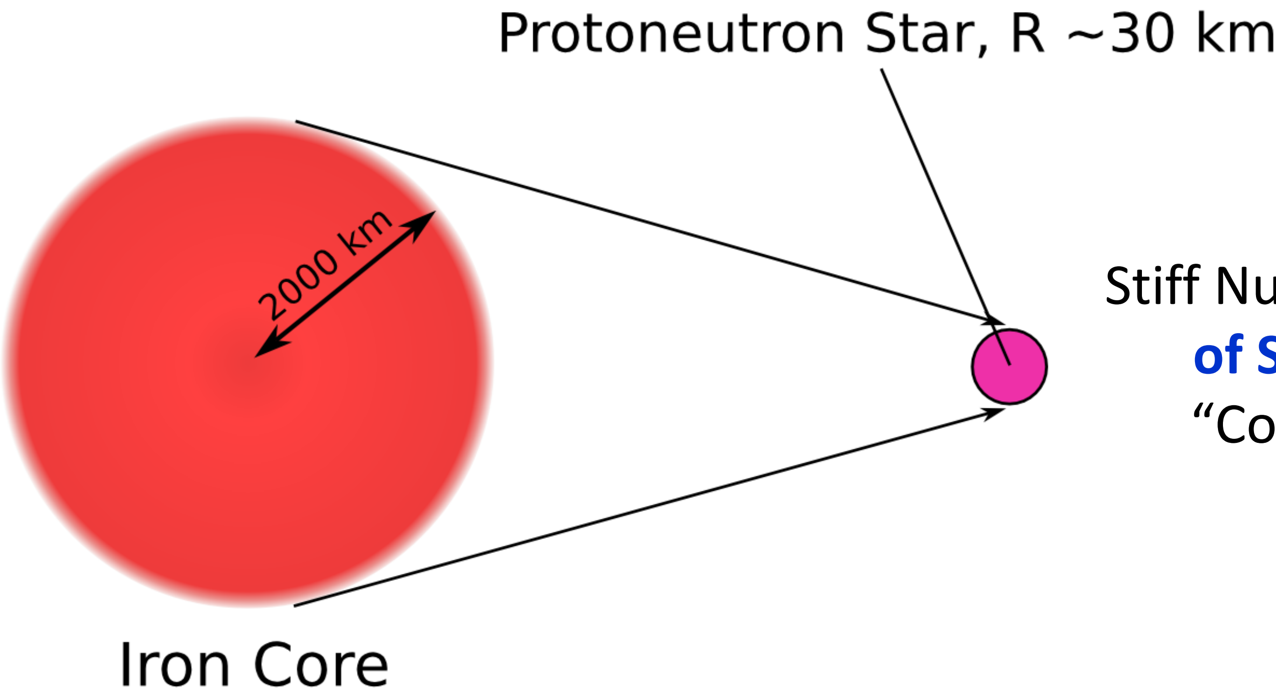


[not drawn to scale]

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

$$M_{\mathrm{Ch}} \approx 1.44 \left(\frac{Y_e}{0.5}\right)^2 M_\odot$$

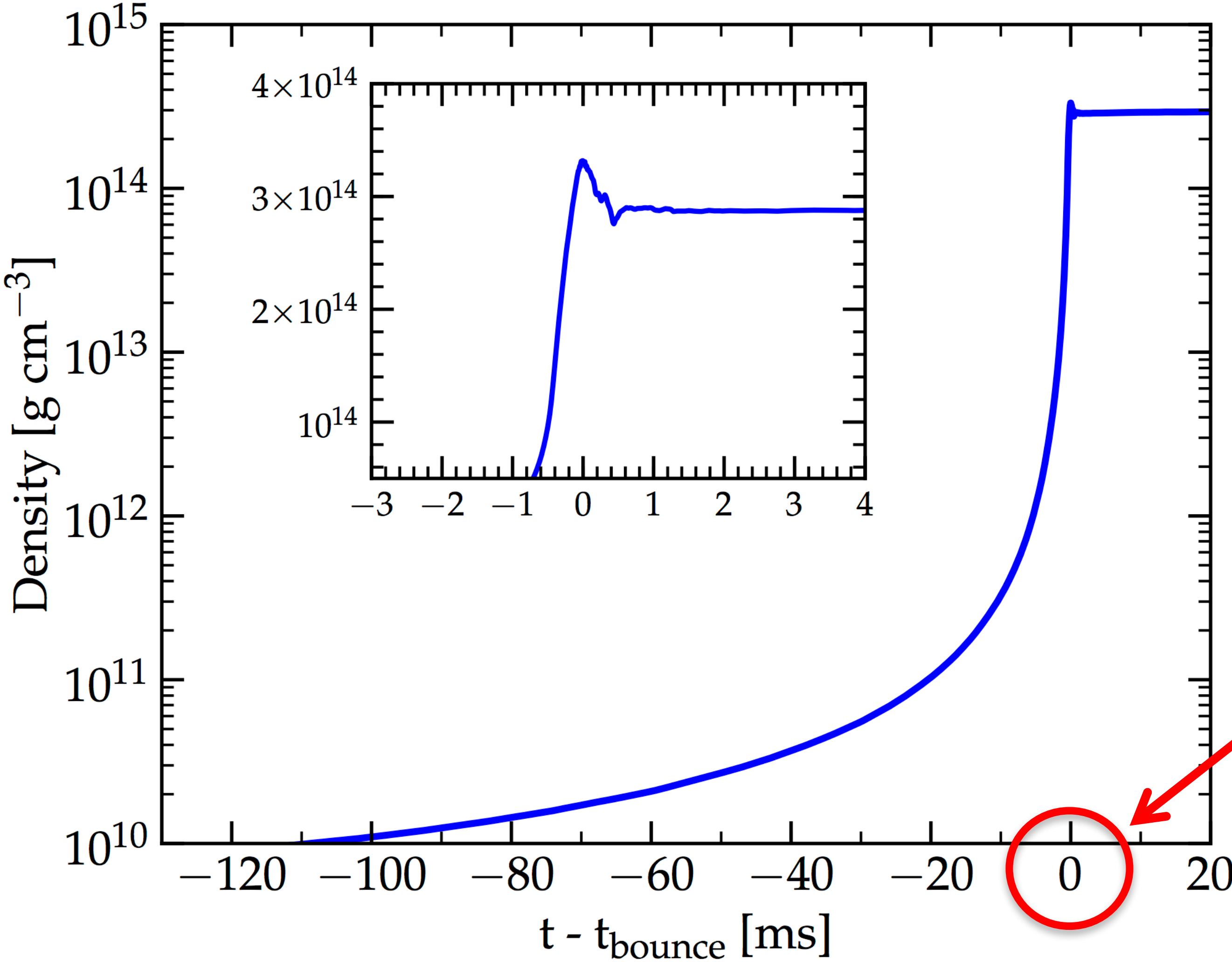
Collapse and Bounce



Stiff Nuclear **Equation of State** (EOS):
"Core Bounce"

Collapse and Core "Bounce"

Central rest-mass density in the collapsing core:

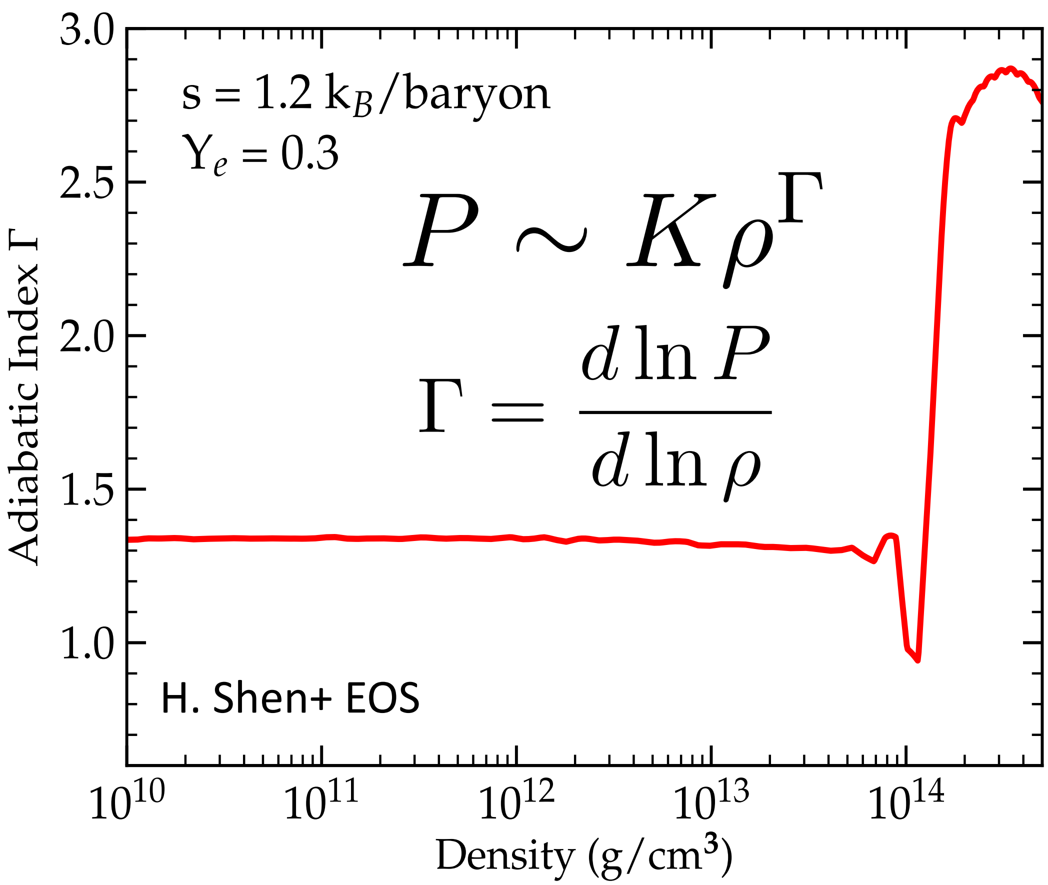


Stiff Nuclear **Equation of State** (EOS):
"**Core Bounce**"

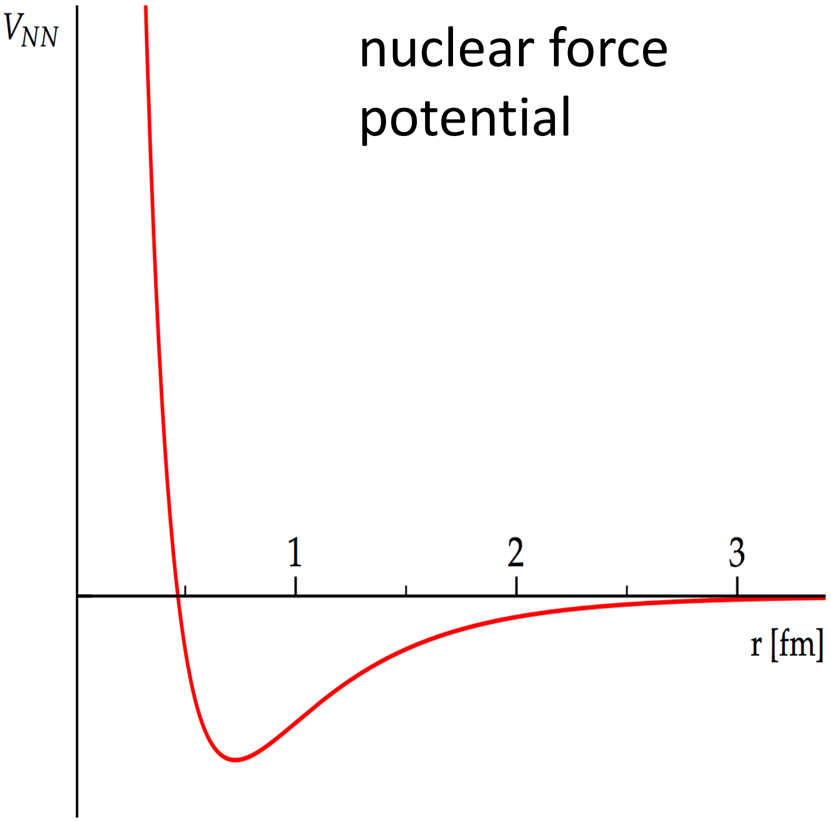
Bounce:
t=0 for SN theorists.

“Stiffening” of the Nuclear EOS

“Core Bounce”

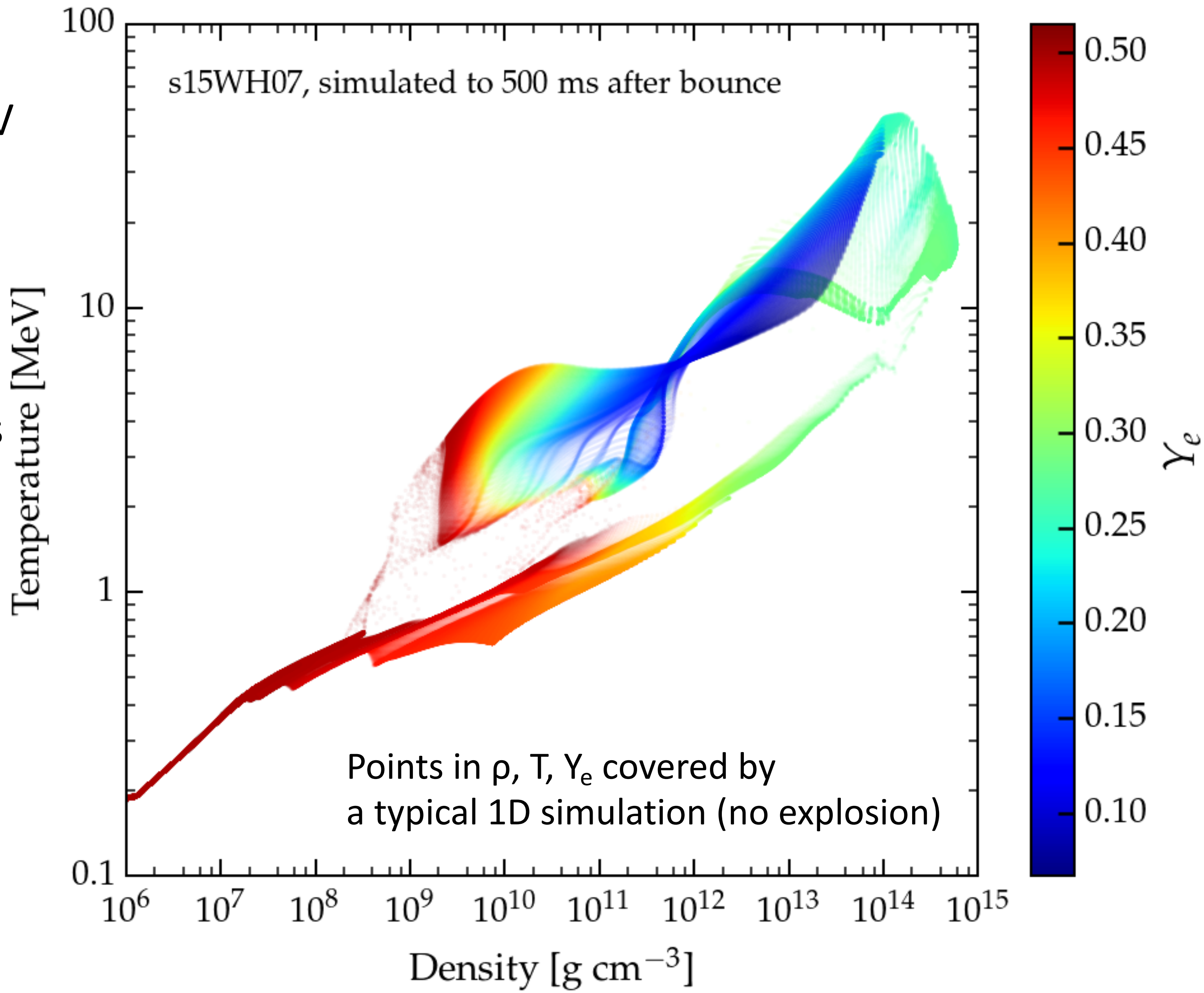


Schematic nuclear force potential



An Aside on the Nuclear EOS

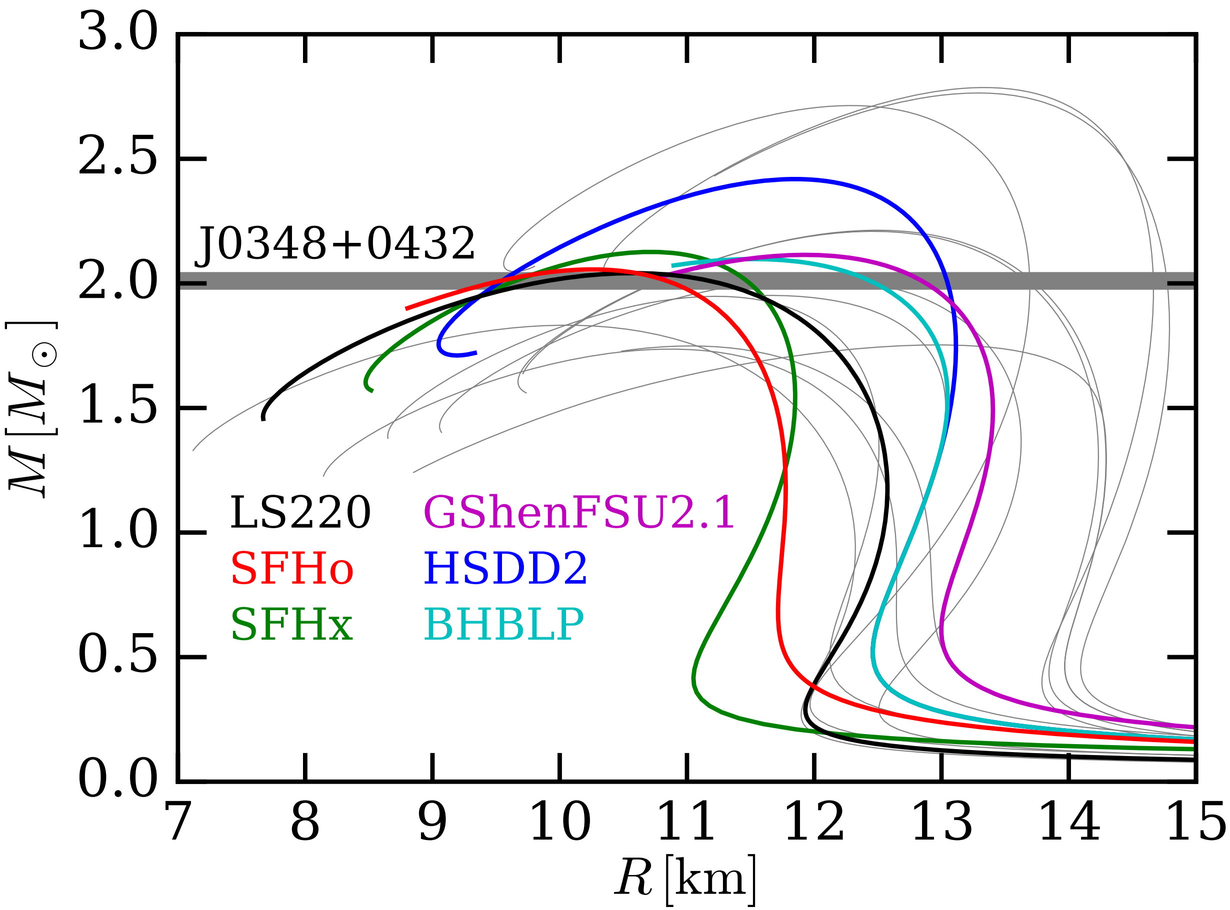
- Need hot EOS, T up to 100 MeV (BH formation!)
- EOS up to ~10 x n_0.
- Proton fractions Y_e of 0 – 0.6.



Points in ρ, T, Y_e covered by a typical 1D simulation (no explosion)

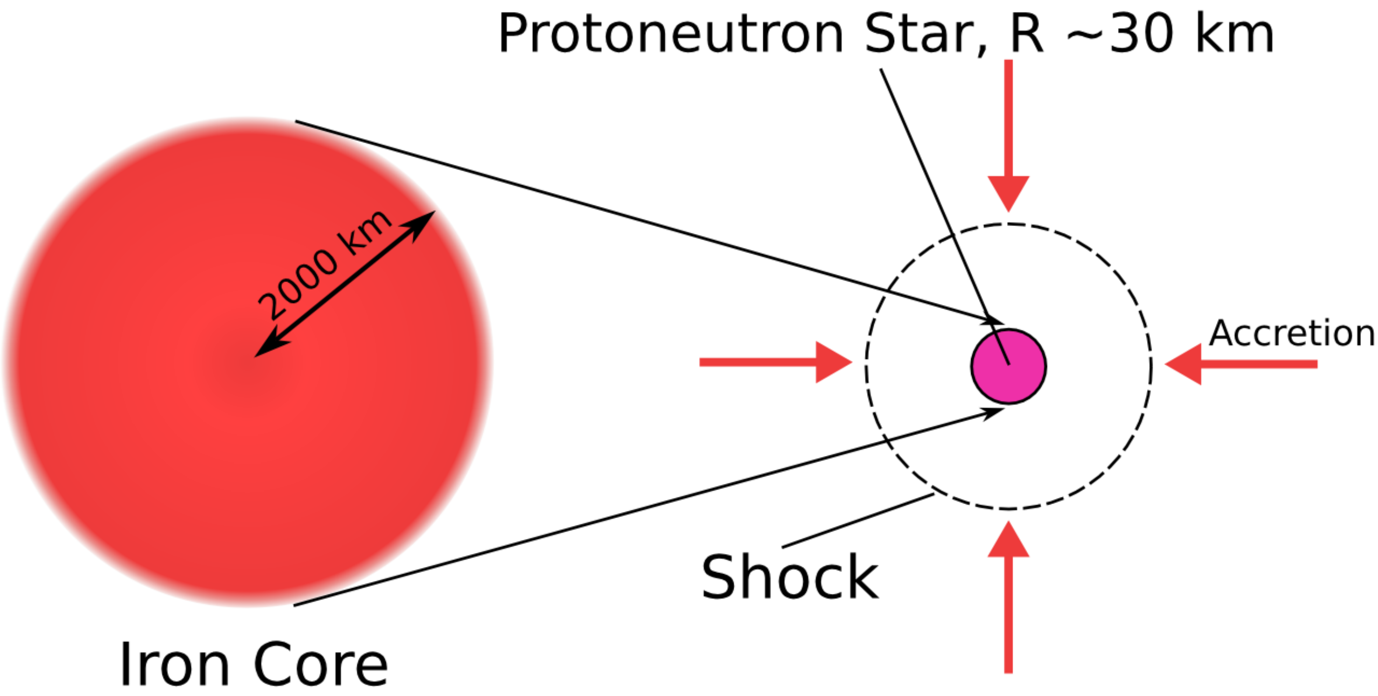
Available Core-Collapse Supernova EOS

Richer+16 in prep, see https://stellarcollapse.org for tables and references

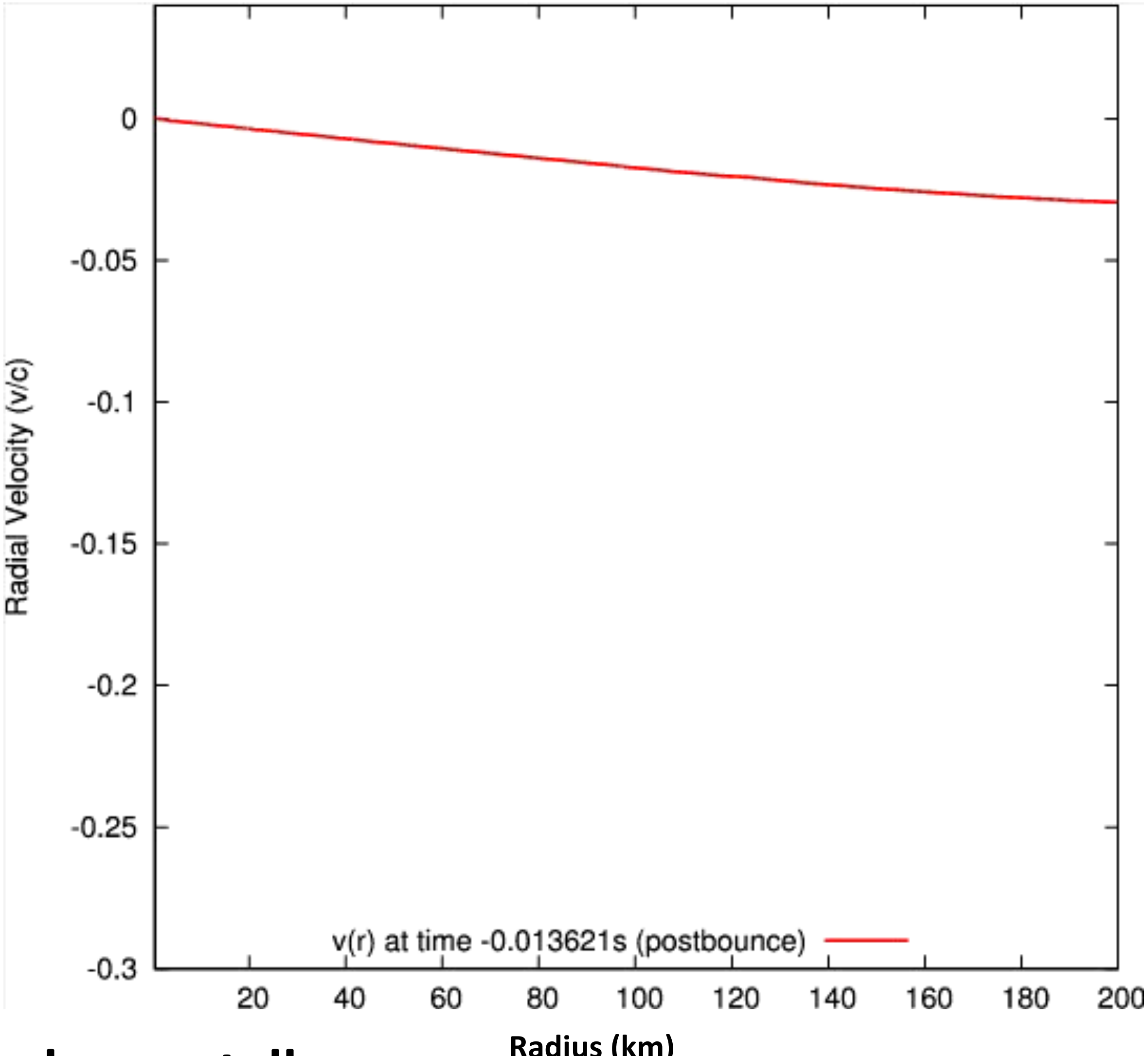


- ~18 hot nuclear EOS available for CCSN & NS merger simulations.
- Many ruled out by experiments / astrophysical constraints (-> Jim Lattimer's talk on November 1). **Need more EOS!**

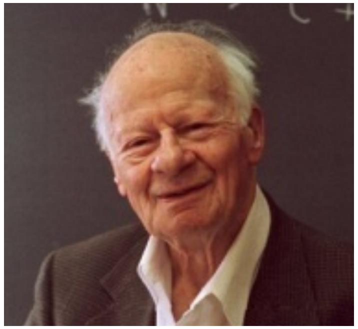
Situation after Core Bounce



Situation after Core Bounce



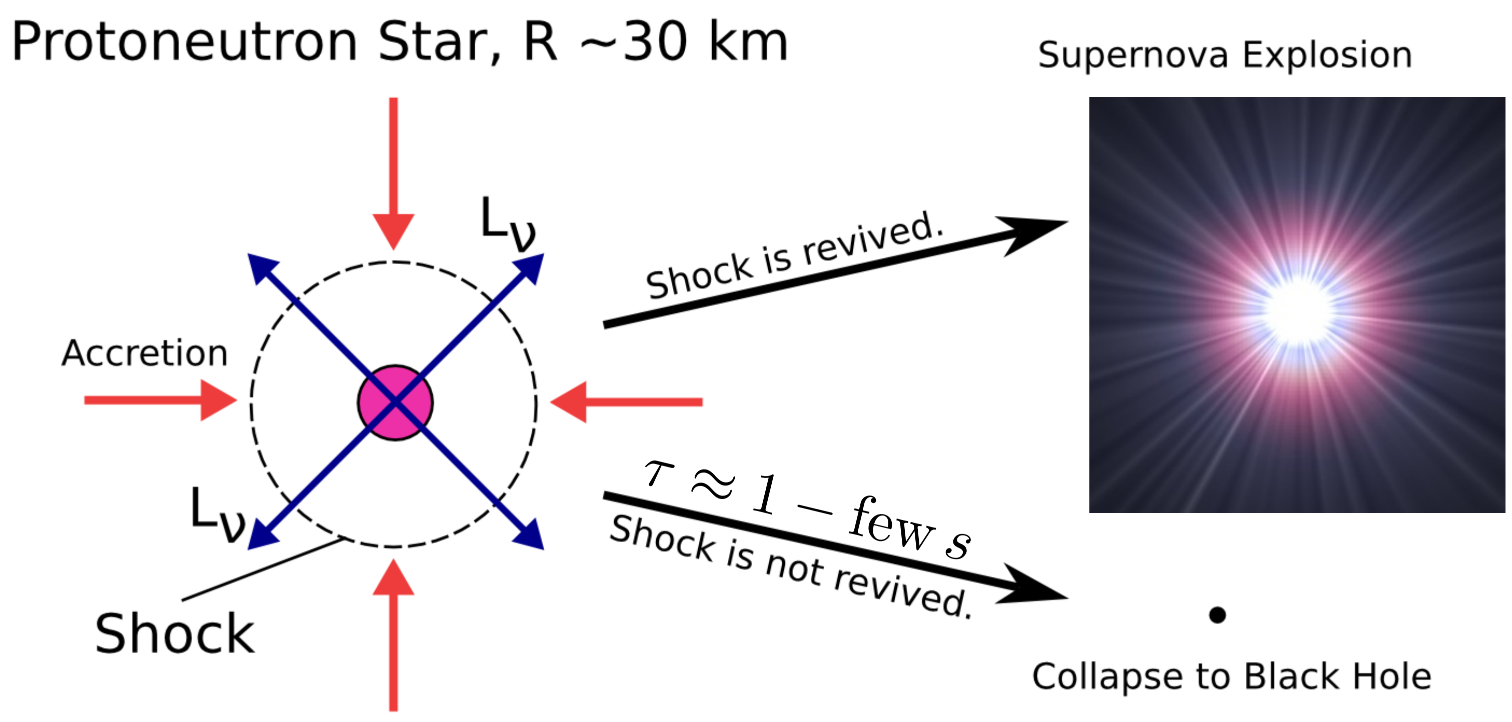
Animation
by Evan O'Connor
GR1D code
stellarcollapse.org



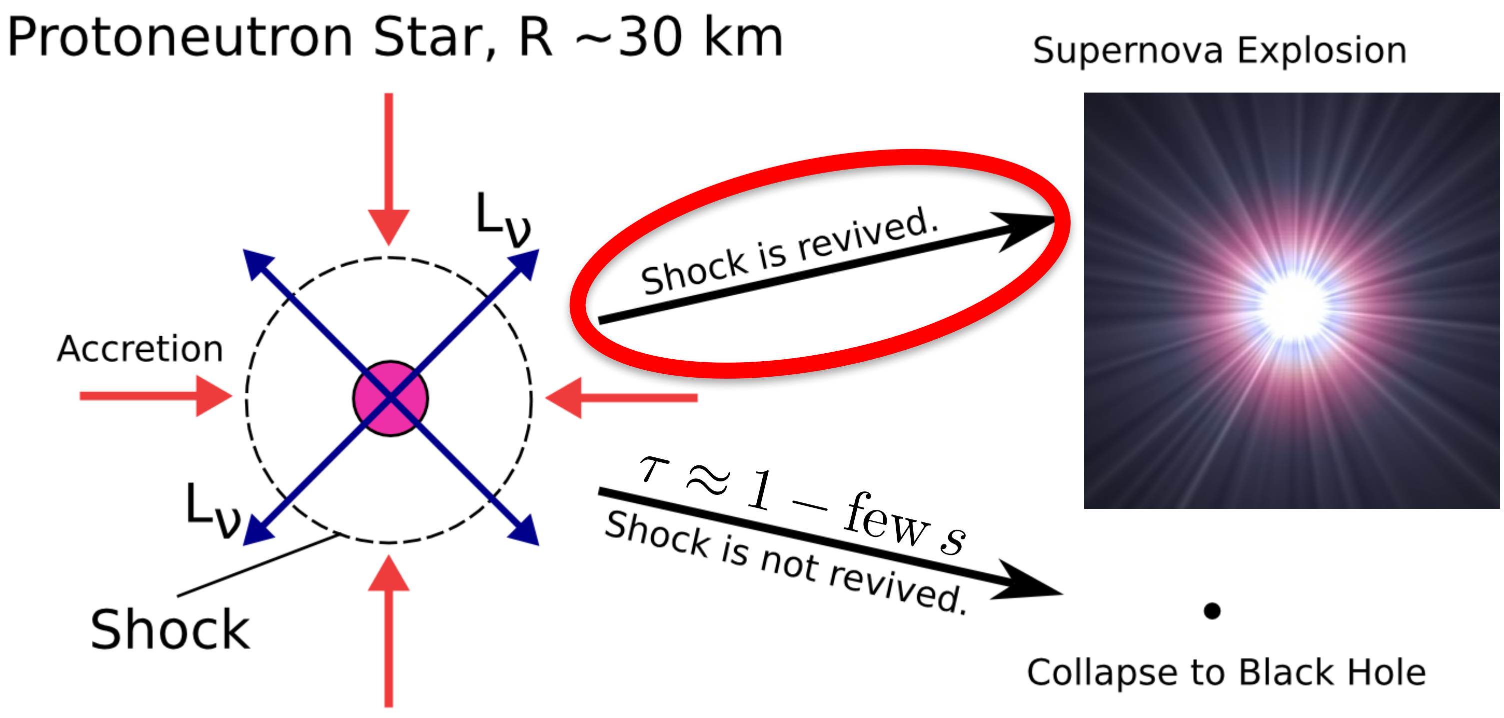
Hans Bethe
1906-2005

- **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

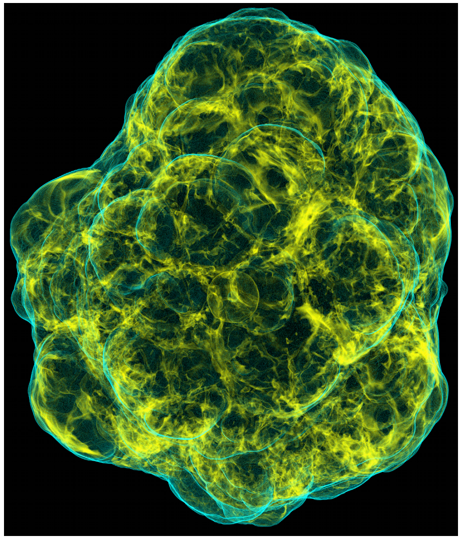


What is the mechanism that revives the shock?

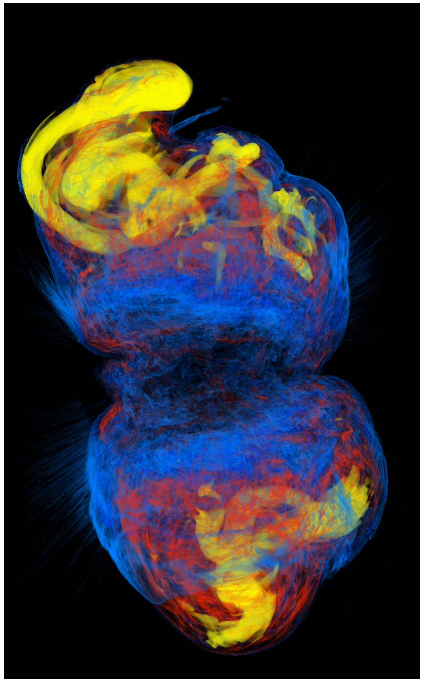
Supernova Mechanisms

Neutrino Mechanism

- Neutrino heating; **turbulent convection**, standing accretion shock instability (SASI).
- Works (even in 1D) for lowest mass massive stars.
- Sensitive to (multi-D) progenitor star structure.
- Inefficient ($\eta \lesssim 10\%$); difficulty explaining $E_{explosion}$?



Ott+13

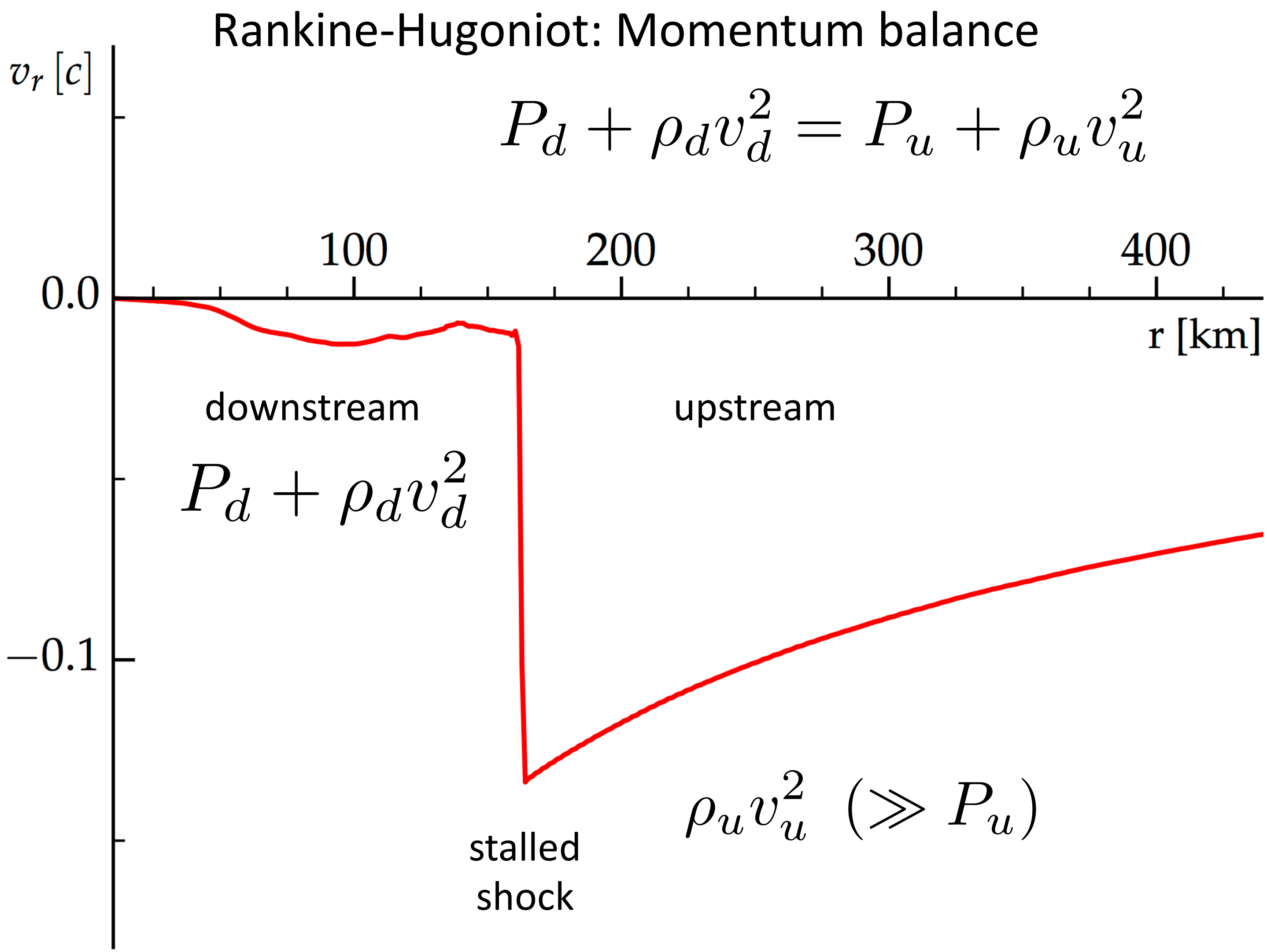


Mösta+14

Magnetorotational Mechanism

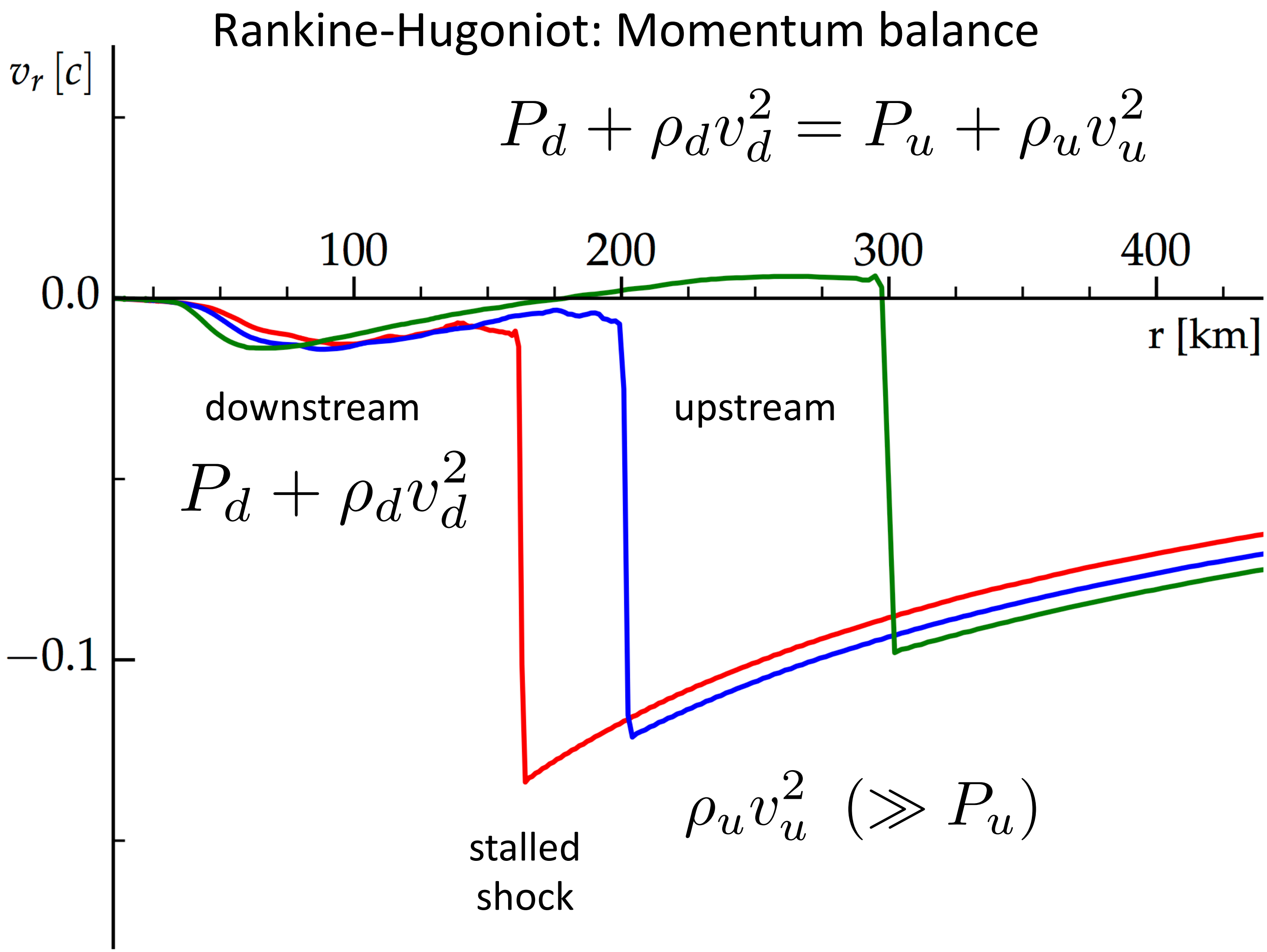
- Magneto-centrifugal forcing, hoop stresses.
- For energetic explosions and CCSN-LGRB connection?
- Very rapid core rotation + magnetorotational instability + dynamo for large-scale field.
- Needs "special" progenitor evolution.
- Jets unstable, may fail to explode in proto-NS phase; black hole formation, GRB central engine?

Basic Stalled-Shock Situation



GR1D simulation
http://stellarcollapse.org/

Basic Stalled-Shock Situation



GR1D simulation
http://stellarcollapse.org/

Neutrino Mechanism: Heating

Bethe & Wilson ’85; also see: Janka ‘01, Janka+ ’07

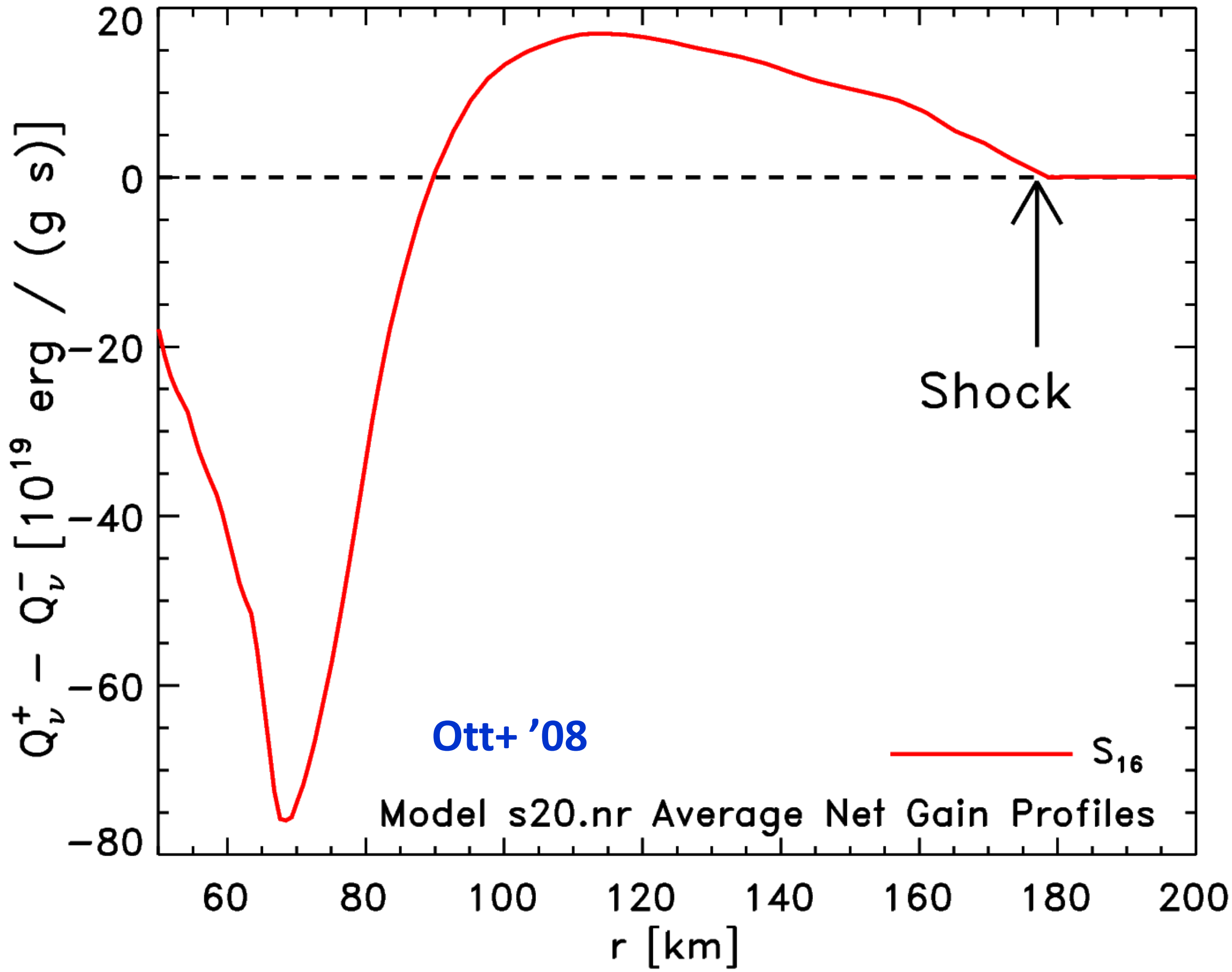
Cooling:

$$Q_\nu^- \propto T^6, T^9$$

Heating via charged-current absorption:

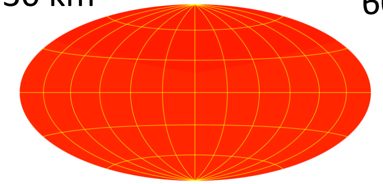
$$\nu_e + n \to p + e^-$$
$$\bar{\nu}_e + p \to n + e^+$$

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

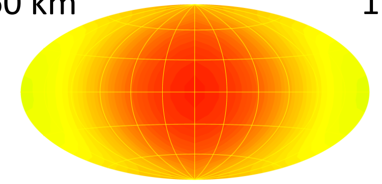


Neutrino radiation field:

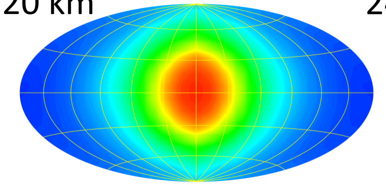
30 km



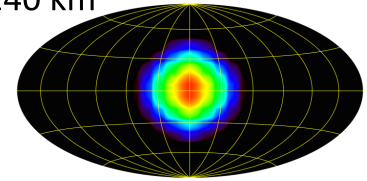
60 km



120 km



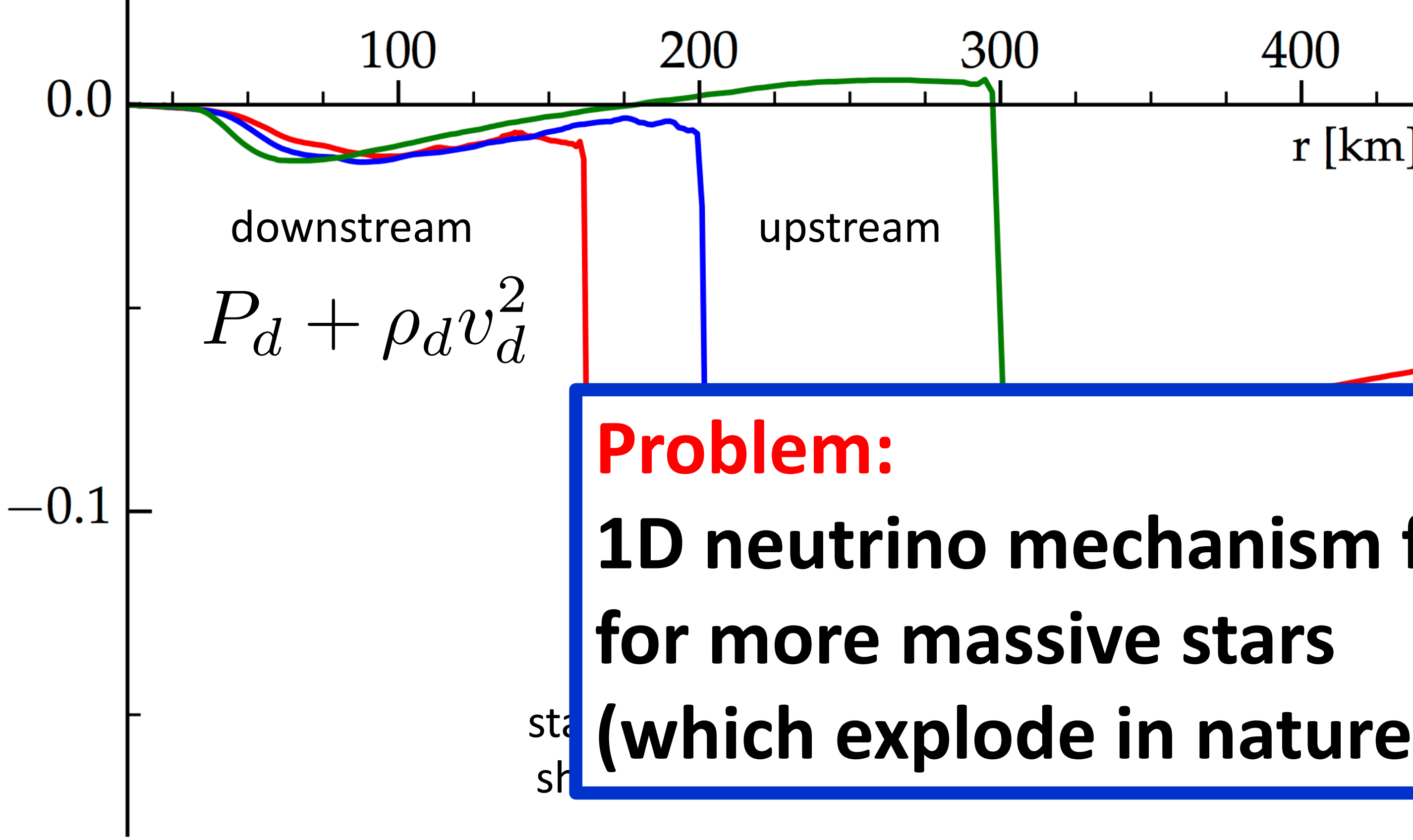
240 km



Basic Stalled-Shock Situation

Rankine-Hugoniot: Momentum balance

$$P_d + \rho_d v_d^2 = P_u + \rho_u v_u^2$$



Problem:

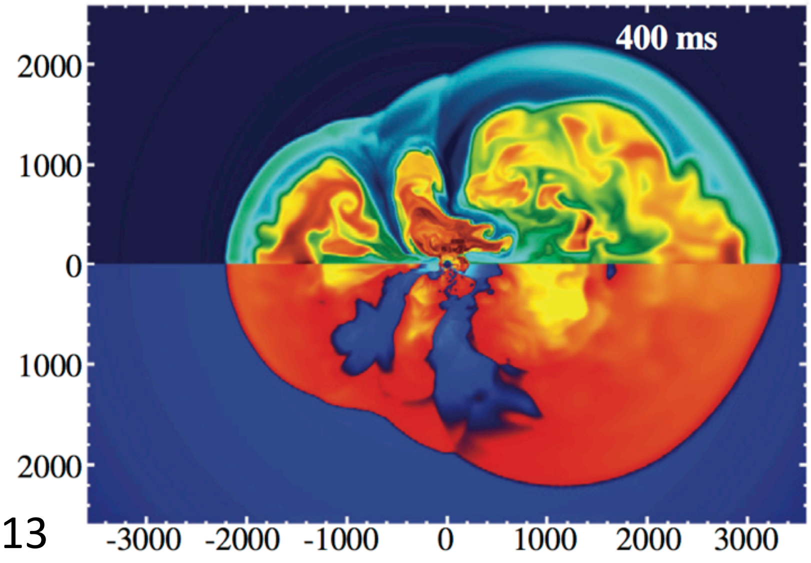
1D neutrino mechanism fails for more massive stars (which explode in nature).

GR1D simulation
http://stellarcollapse.org/

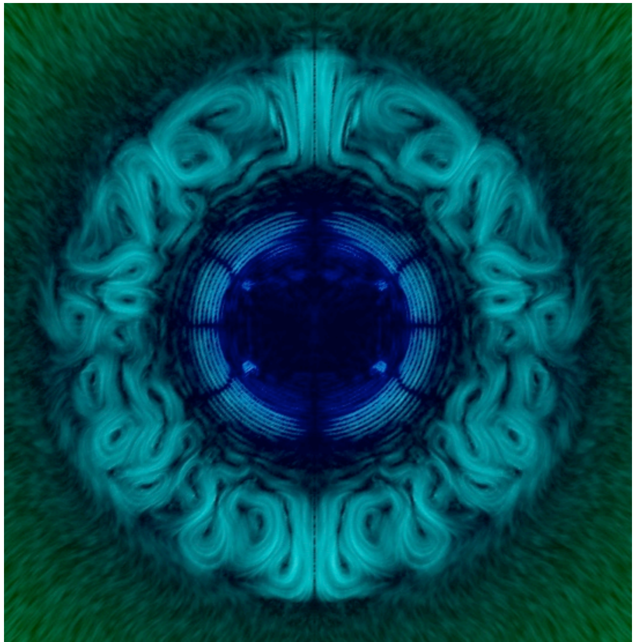
2D and 3D Neutrino-Driven CCSNe

- **Progress driven by advances in compute power**!
- First 2D (axisymmetric) simulations in the 1990s:
  Herant+94, Burrows+95, Janka & E. Müller 96.
- 2D simulations now self-consistent & from first principles.
  E.g.: Bruenn+13,16 (ORNL), Dolence+14 (Princeton),
  B. Müller+12ab (MPA Garching), Nagakura+16 (YITP/Waseda),
  Suwa+16 &Takiwaki+14 (YITP/NAOJ/Fukoka)

Dessart+ '05

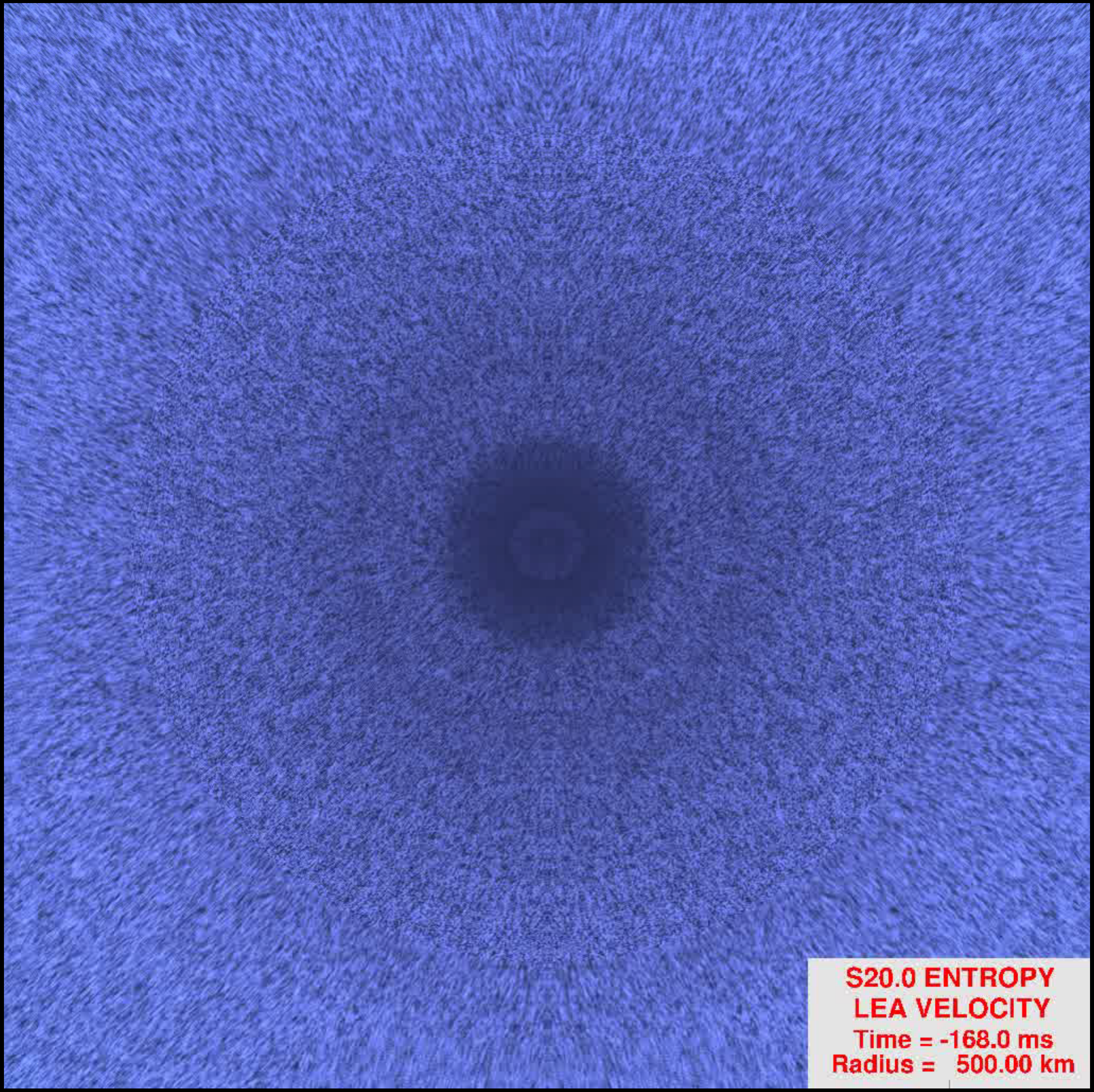


Bruenn+13



Standing Accretion Shock Instability (SASI)

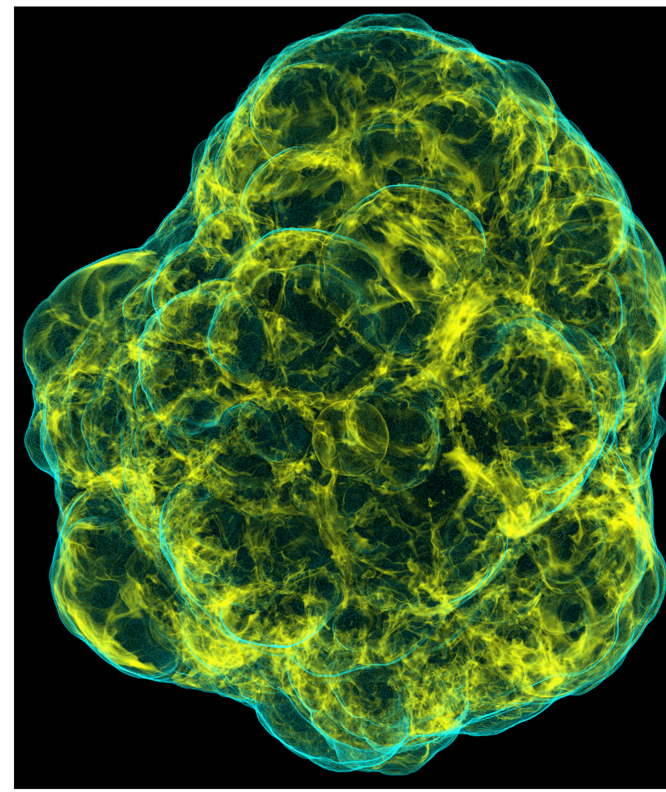
Blondin+'03
Foglizzo+'06
Scheck+ '08
and many others



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

The 3D Frontier – Petascale Computing!

- Some early work: Fryer & Warren 02, 04
- **Much work since ~2010**:
  Fernandez 10, Nordhaus+10, Takiwaki+11,13,14, Burrows+12, Murphy+13, Dolence+13, Hanke+12,13, Kuroda+12, Ott+13, Couch 13, Couch & Ott 13, 15, Abdikamalov+15, Couch & O'Connor 14, Lentz+15, Melson+15ab, Kuroda+16, Roberts+16
- Approximations currently made:
  (1) **Gravity** (2) Neutrinos (3) Resolution



Ott+13
Caltech,
full GR,
parameterized
neutrino heating

-6.18 ms

Caltech

Multi-Dimensional Simulations: Effects

(e.g., Hanke+13, Couch&Ott 15, Murphy+08, Murphy+13, Ott+13, Dolence+13)

(1) Lateral/azimuthal flow: "Dwell time" in gain region increases.

(2) New: Anisotropy of convection -> **Turbulent ram pressure**

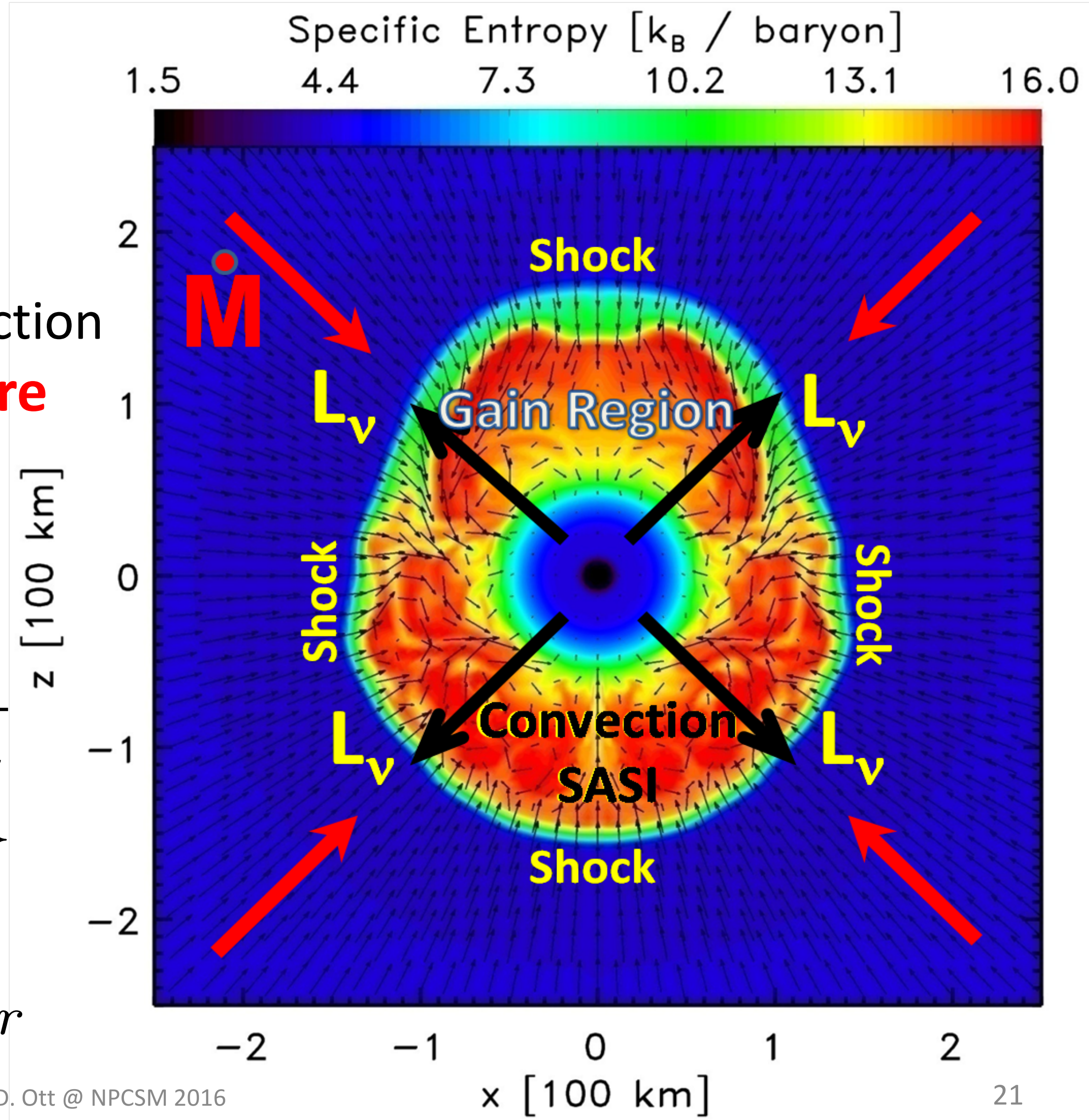
(Radice+15, 16, Couch&Ott 15, Murphy+13)

$$R_{ij} = \overline{\delta v_i \delta v_j}$$

$$\delta v_i = v_i - \overline{v_i}$$

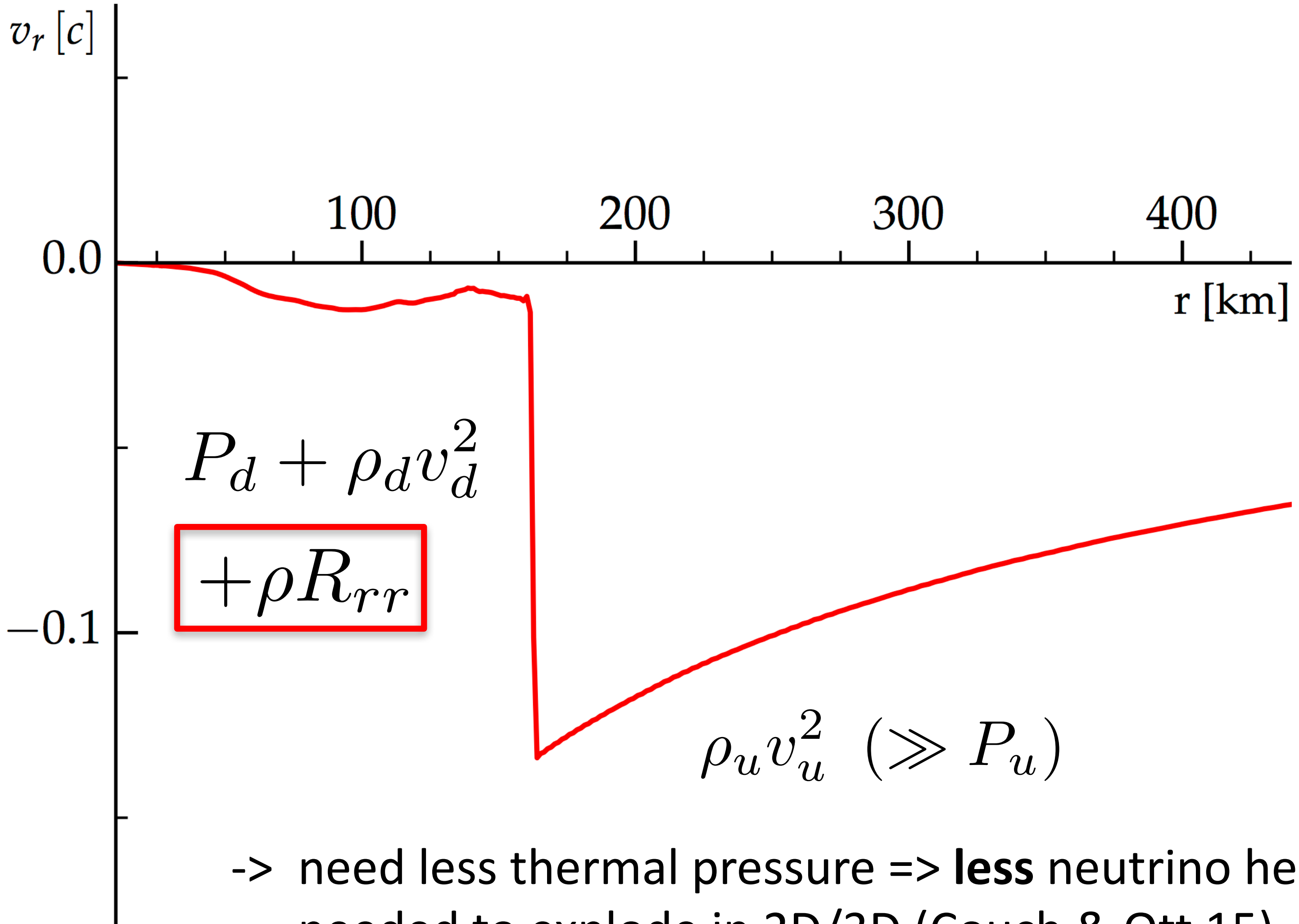
$$R_{rr} \sim 2\{R_{\theta\theta}, R_{\phi\phi}\}$$

effective turbulent pressure $$P_{\rm turb} = \rho R_{rr}$$



Accounting for Turbulent Ram

(Couch & Ott 2015, Murphy+13)

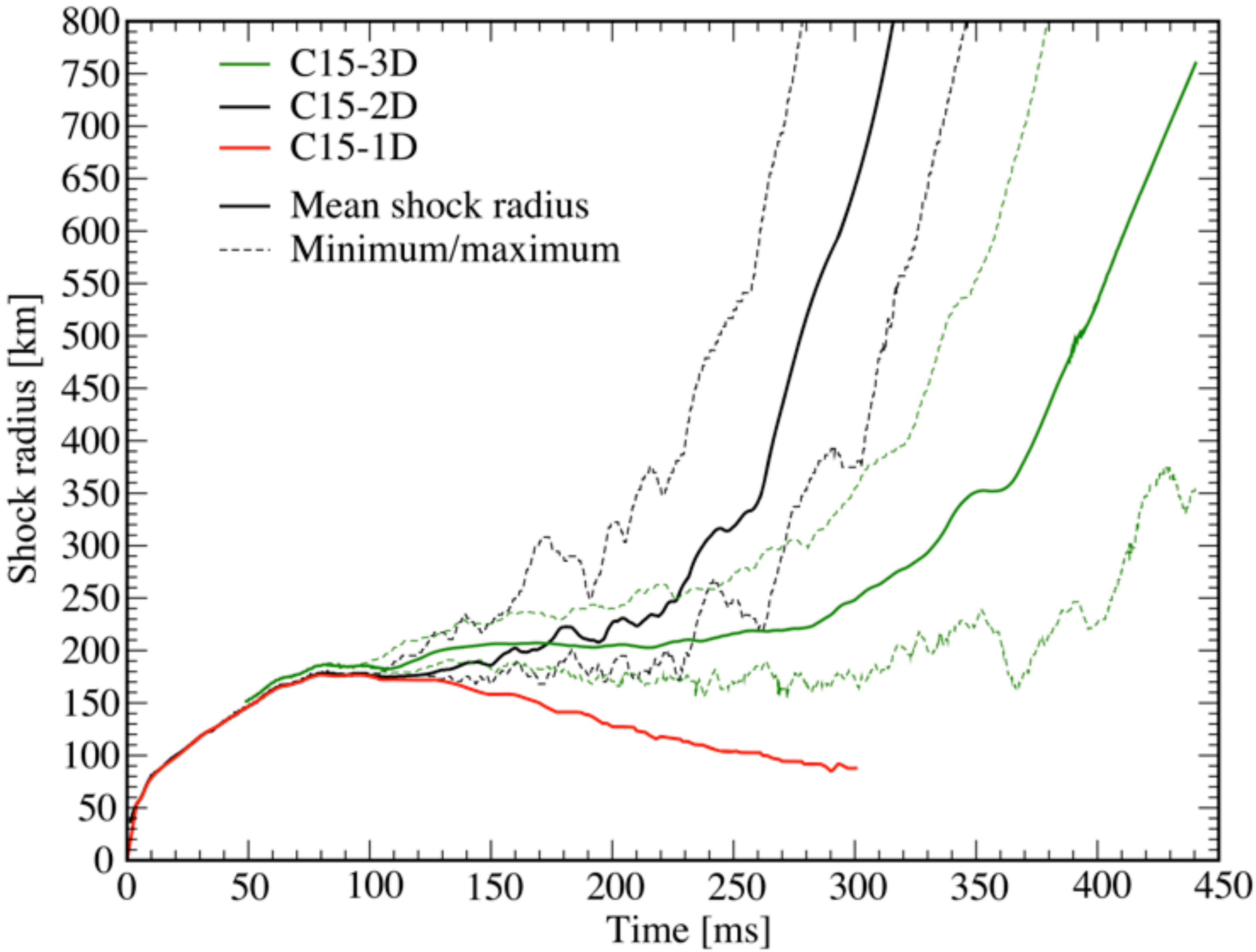


-> need less thermal pressure => **less** neutrino heating needed to explode in 2D/3D (Couch & Ott 15).

GR1D simulation
http://stellarcollapse.org/

2D & 3D Explosions!

(e.g., Lentz+15, Melson+15ab)

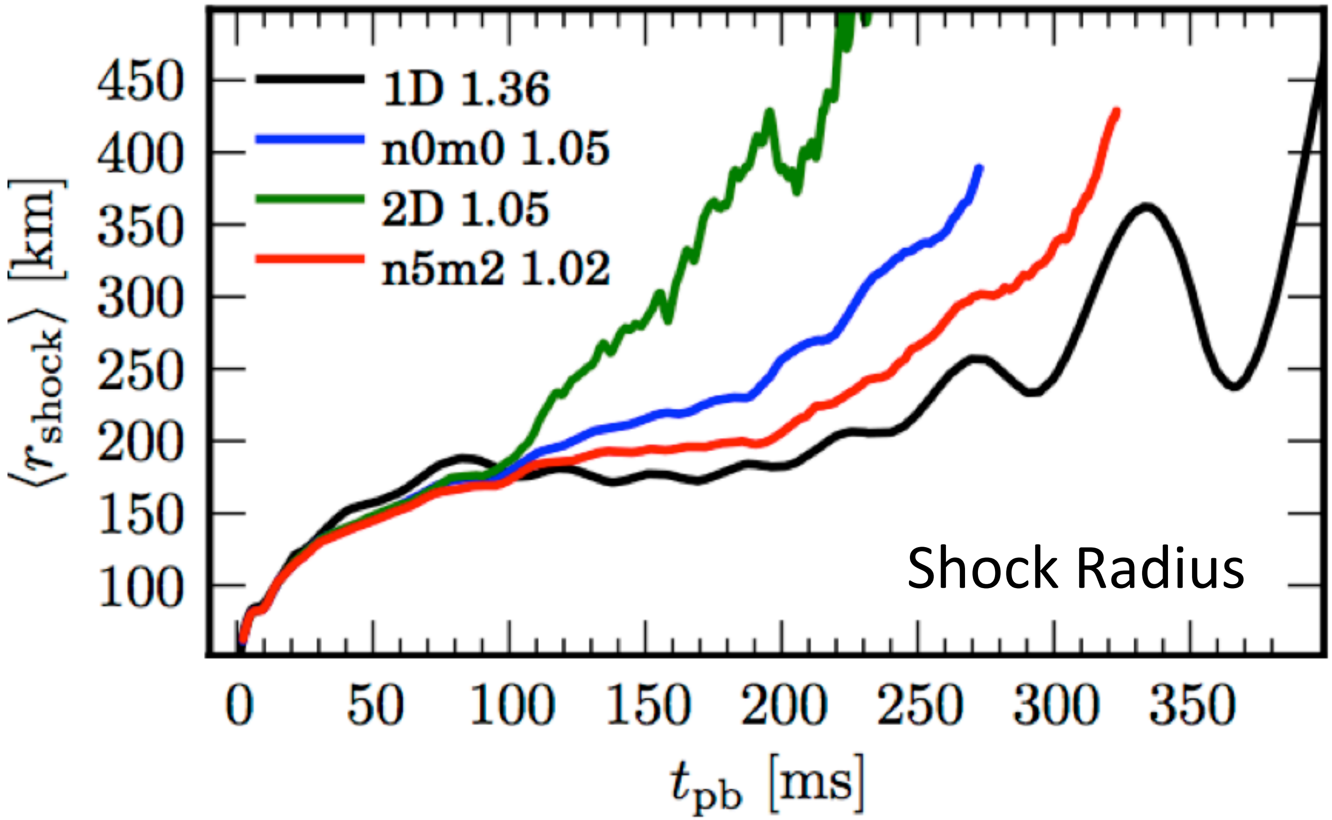


1D, 2D, 3D

(Couch & Ott 2015)

parameterized neutrino heating

black: 1D
green: 2D
red, blue: 3D



(1) 2D & 3D explode with less neutrino heating.

(2) 2D explodes more easily than 3D!

(see also: Couch & O'Connor 14, Hanke+13)

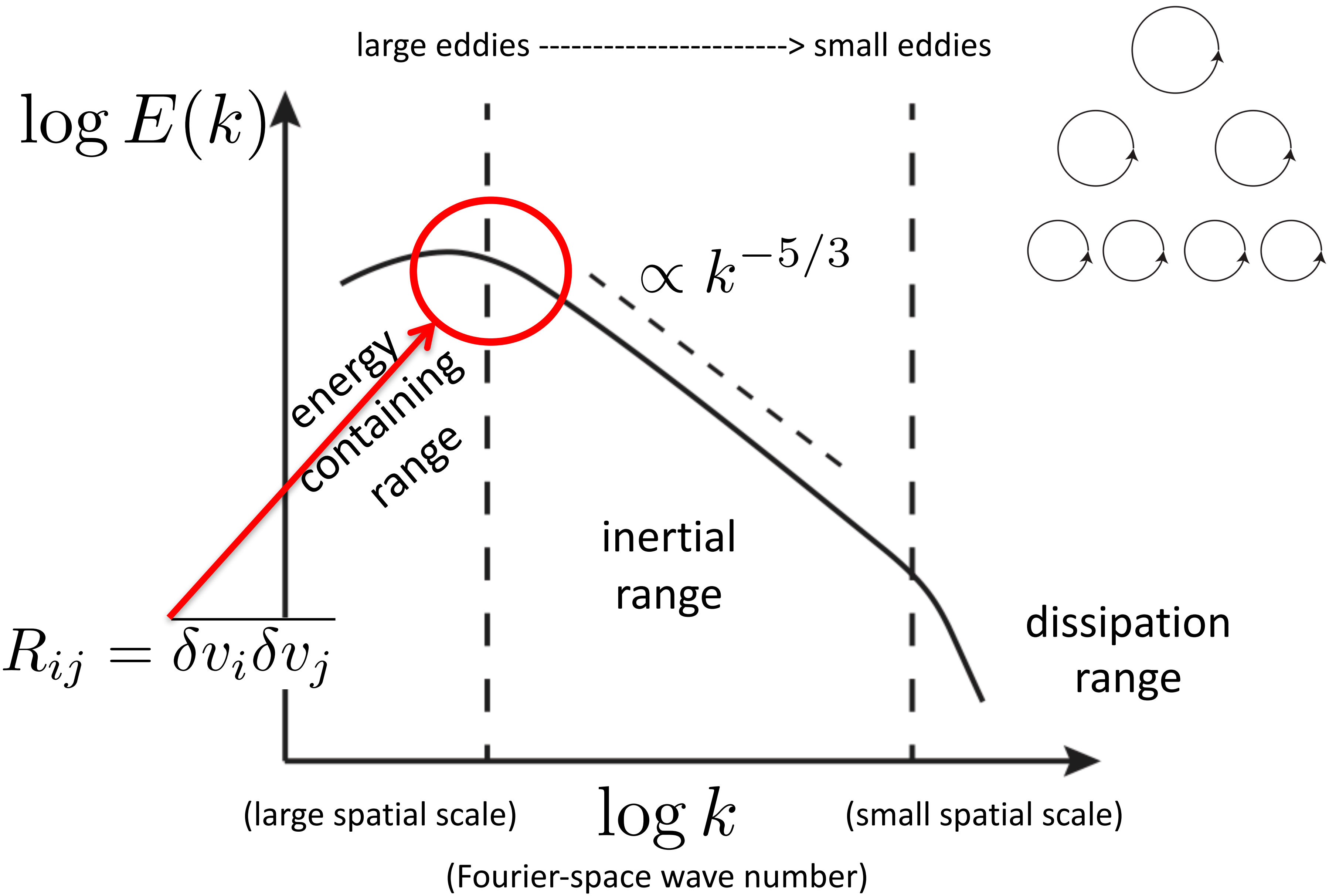
Some Facts about Supernova Turbulence

(e.g., Abdikamalov, Ott+ 15, Radice+15ab)

- Neutrino-driven convection is turbulent. $\mathcal{R}e = \frac{lu}{\nu} \approx 10^{17}$
- **Kolmogorov** turbulence: Kolmogorov 1941
  isotropic, incompressible, stationary. $E(k) \propto k^{-5/3}$
- Supernova turbulence:
  anisotropic (buoyancy), mildly compressible, quasi-stationary.
- Reynolds stresses (relevant for explosion!) dominated by dynamics at largest scales.

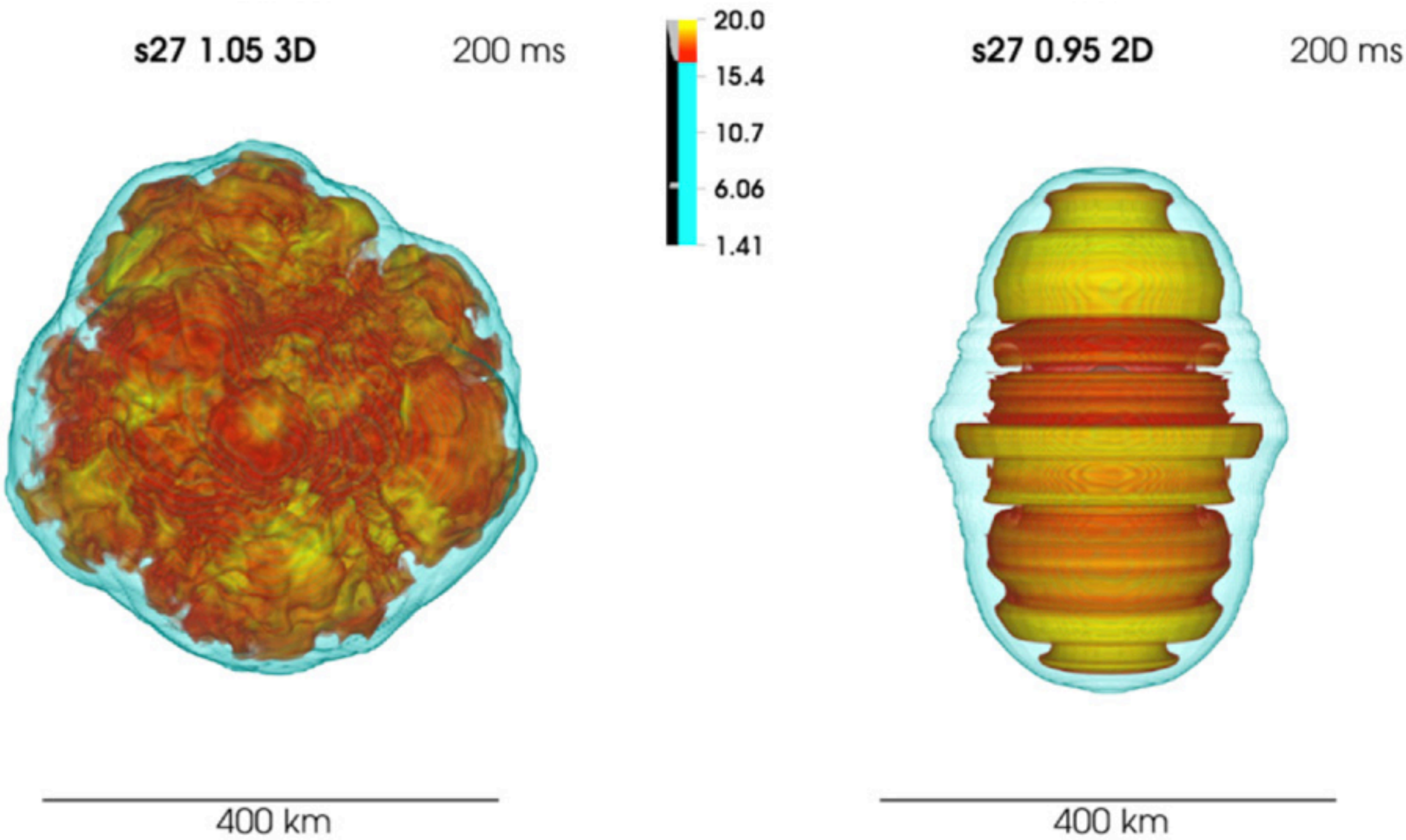
$$R_{ij} = \overline{\delta v_i \delta v_j}$$

Kolmogorov Turbulence

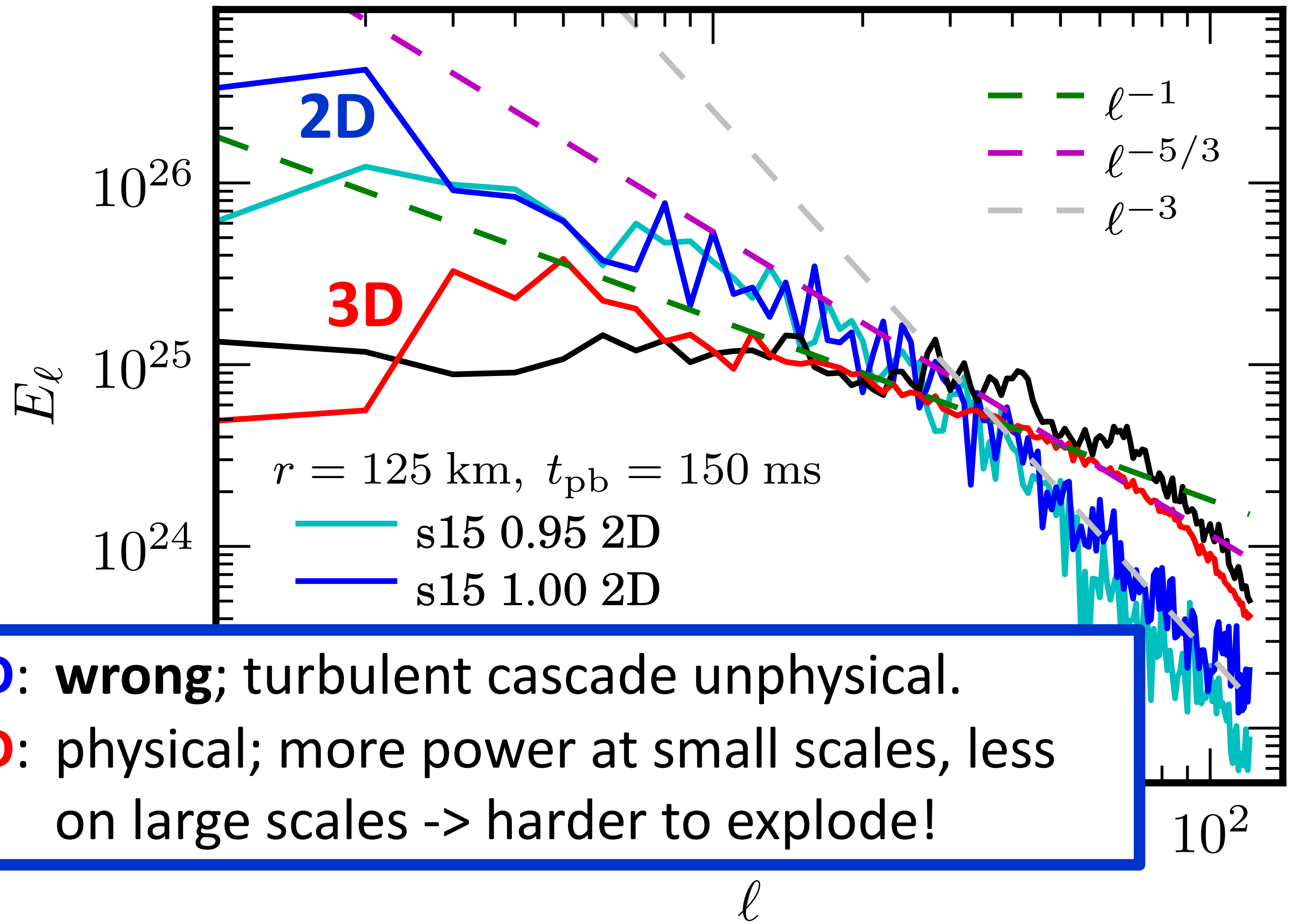


2D vs. 3D

(e.g., Couch 13, Couch & O'Connor 14)



Turbulent Cascade: 2D vs. 3D



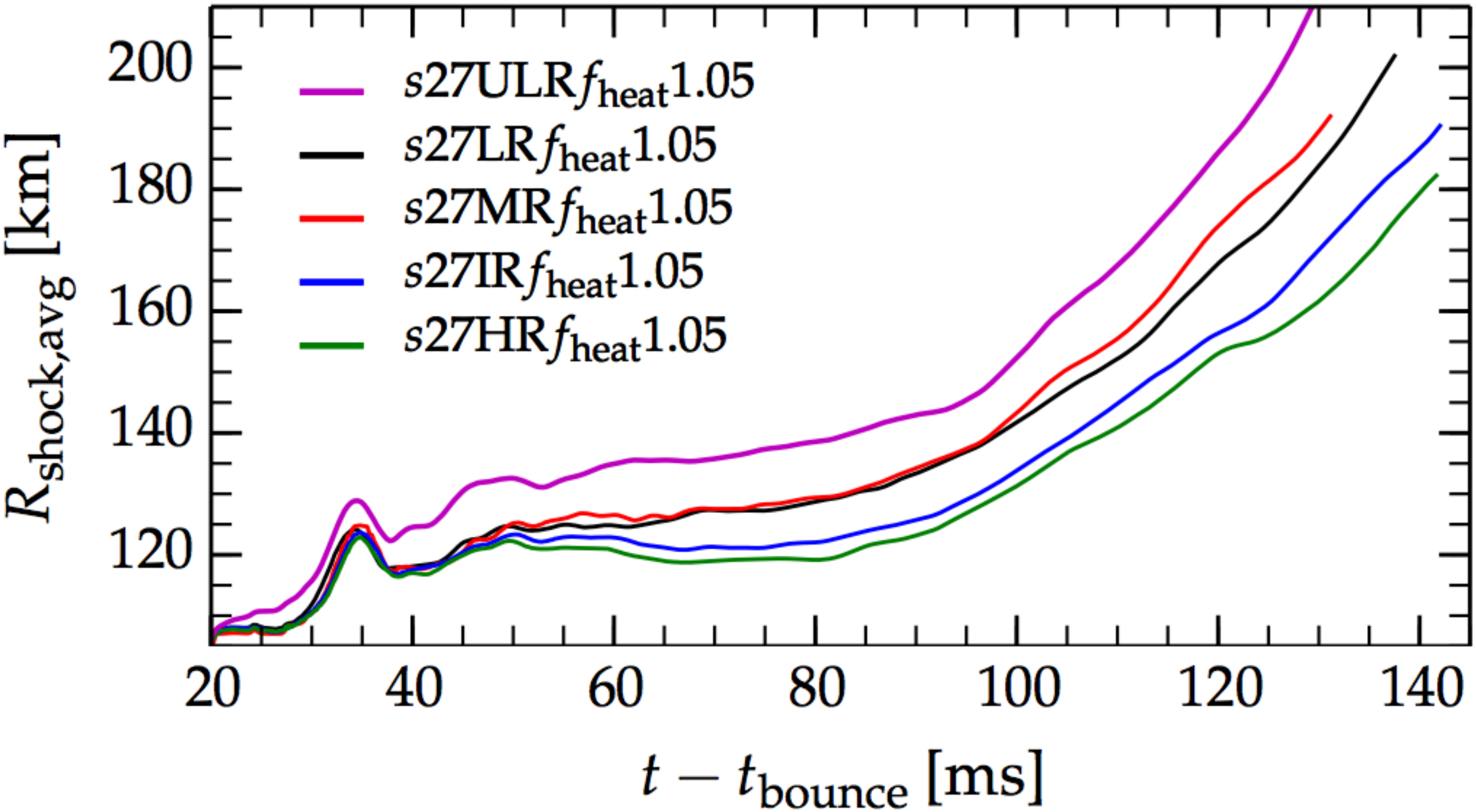
- **2D**: **wrong**; turbulent cascade unphysical.
- **3D**: physical; more power at small scales, less on large scales -> harder to explode!

Couch & O'Connor 14

see also: Dolence+13, Hanke+12,13, Abdikamalov+'15, Radice+15ab

3D: Sensitivity to Resolution

Abdikamalov+15



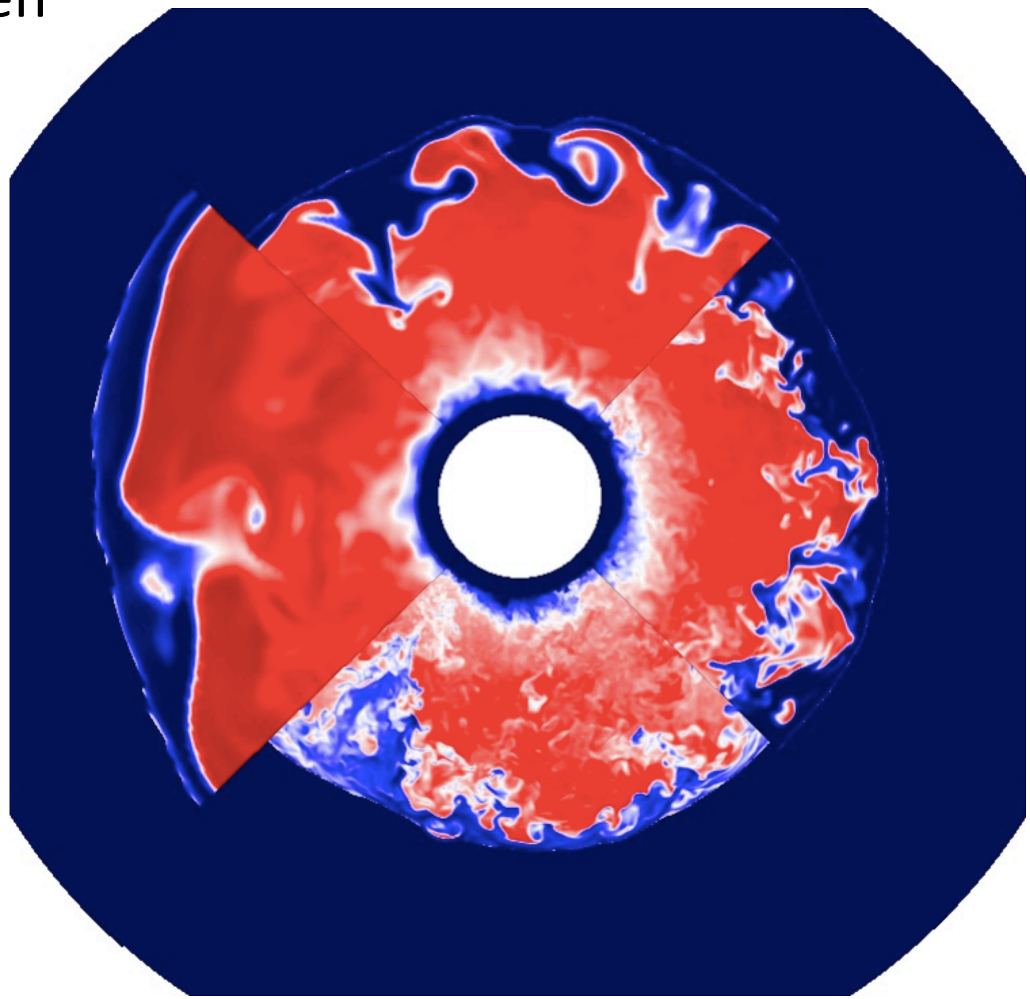
low resolution -> less efficient turbulent cascade

-> kinetic energy stuck at large scales

Resolution Comparison (Radice+16)

- semi-global simulations of neutrino-driven turbulence.

$d\theta, d\phi = 0.9°$
dr = 1.9 km

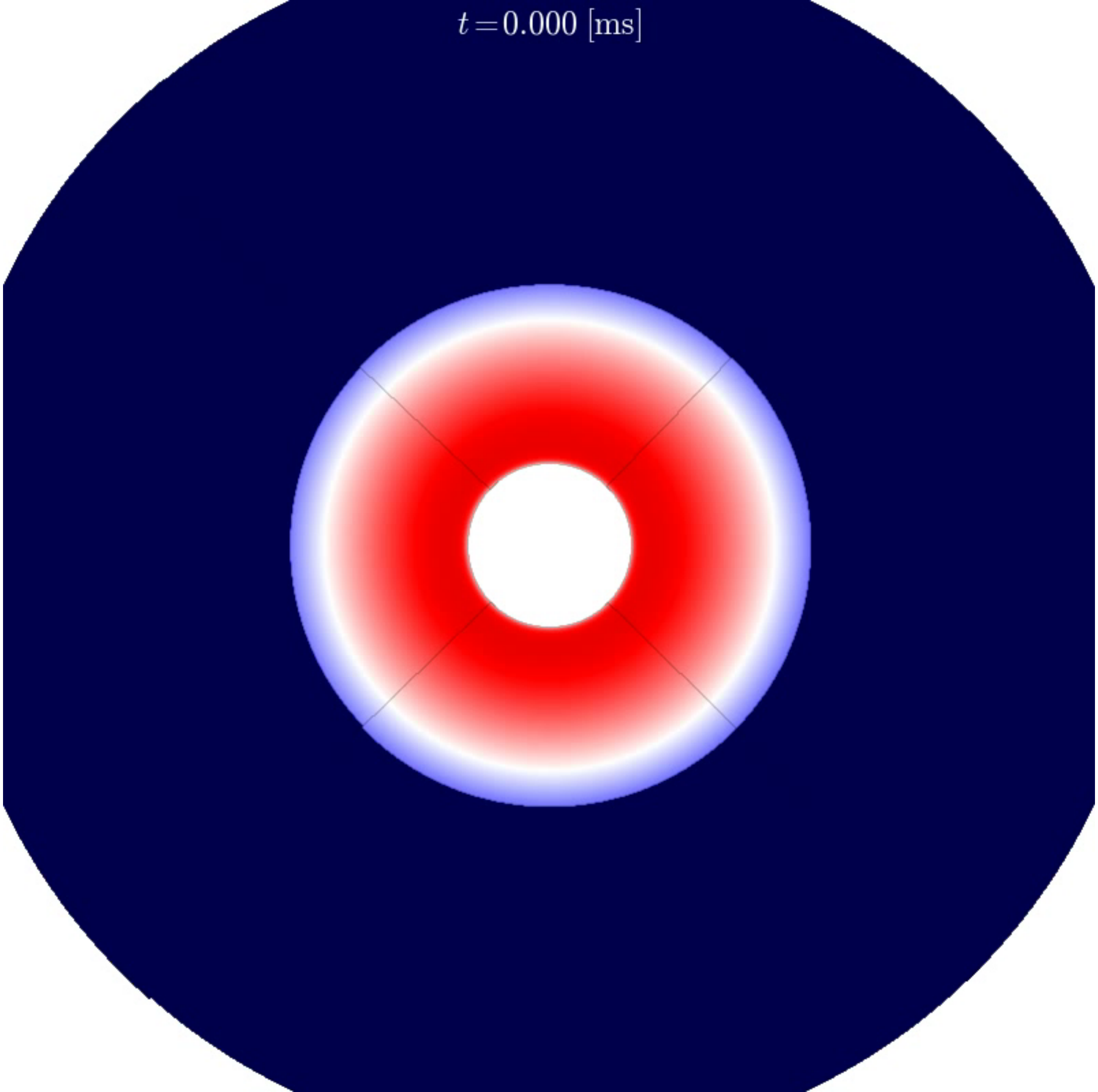


$d\theta, d\phi = 1.8°$
dr = 3.8 km

(typical resolution of 3D rad-hydro sims)

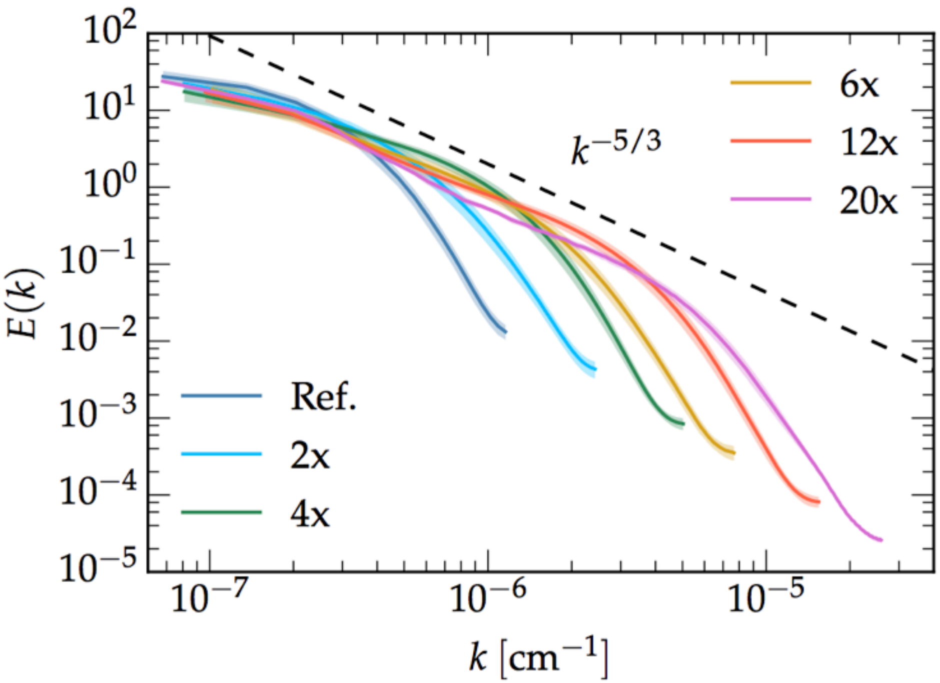
$d\theta, d\phi = 0.45°$
dr = 0.9 km

$d\theta, d\phi = 0.3°$
dr = 0.64 km

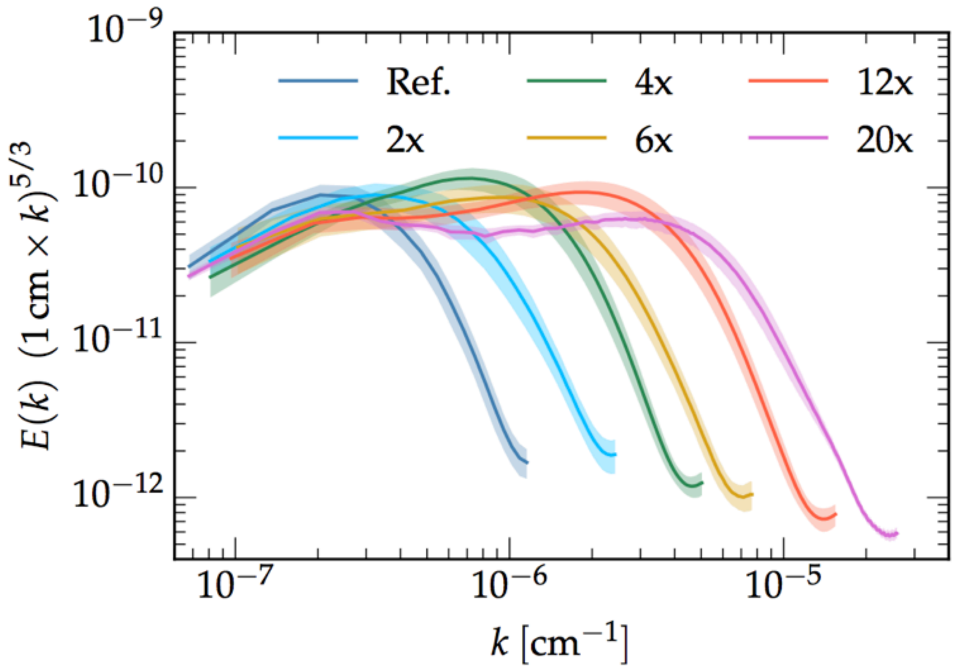

$t = 0.000$ [ms]

Turbulent Kinetic Energy Spectrum

(Radice+16)



"compensated" spectrum



Core-collapse supernova turbulence obeys Kolmogorov scaling!

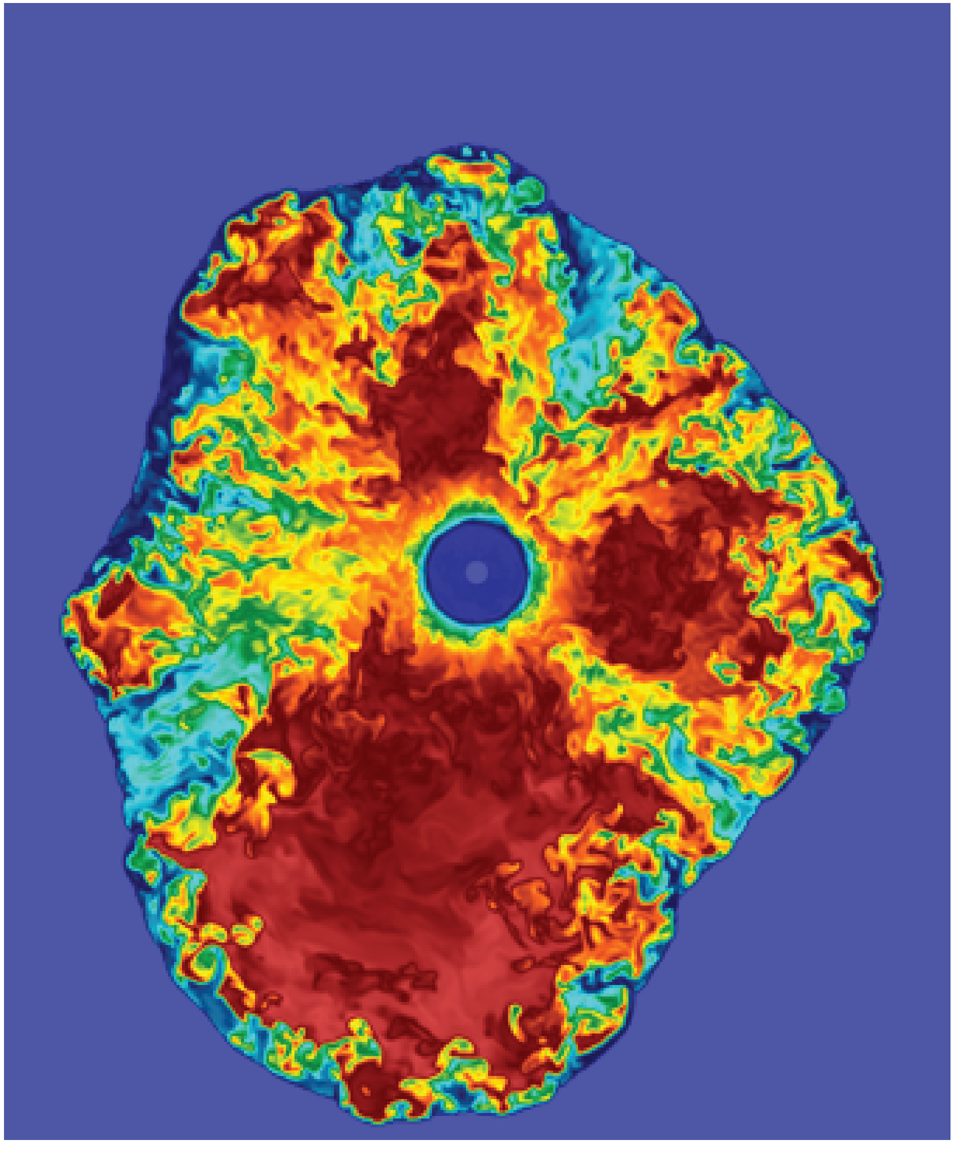
But: Global simulations at necessary resolution currently impossible!

Way forward? -> Subgrid modeling of neutrino-driven turbulence?

Summary of 2D & 3D Neutrino-Driven CCSNe

- **More efficient neutrino heating, turbulent ram pressure.**
- **2D simulations** explode but can't be trusted (unphysical turbulence).
- **3D simulations**:
  (1) most not yet fully self consistent (parameterized);
  (2) numerical bottleneck in energy cascade (resolution).
- How much resolution is necessary?
- Subgrid model for 3D neutrino-driven turbulence?

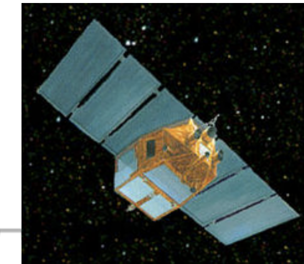
See also Luke Robert's conference talk on Nov. 4!



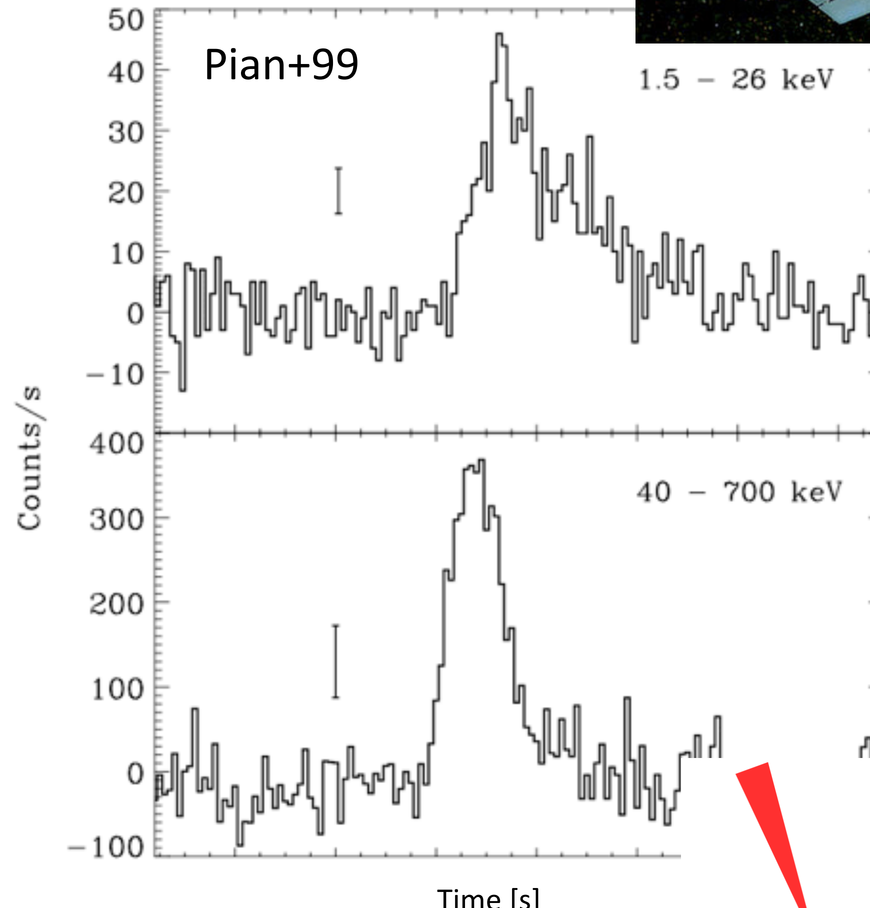
Ott+13

Hypernovae & Gamma-Ray Bursts

BeppoSAX



SN 1998bw/GRB 980425

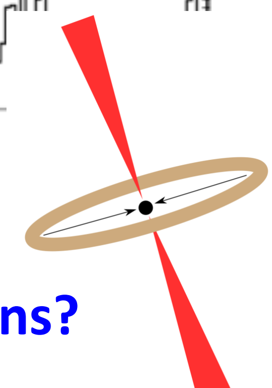


Type Ic-bl Hypernova – 10 x normal SN energy.

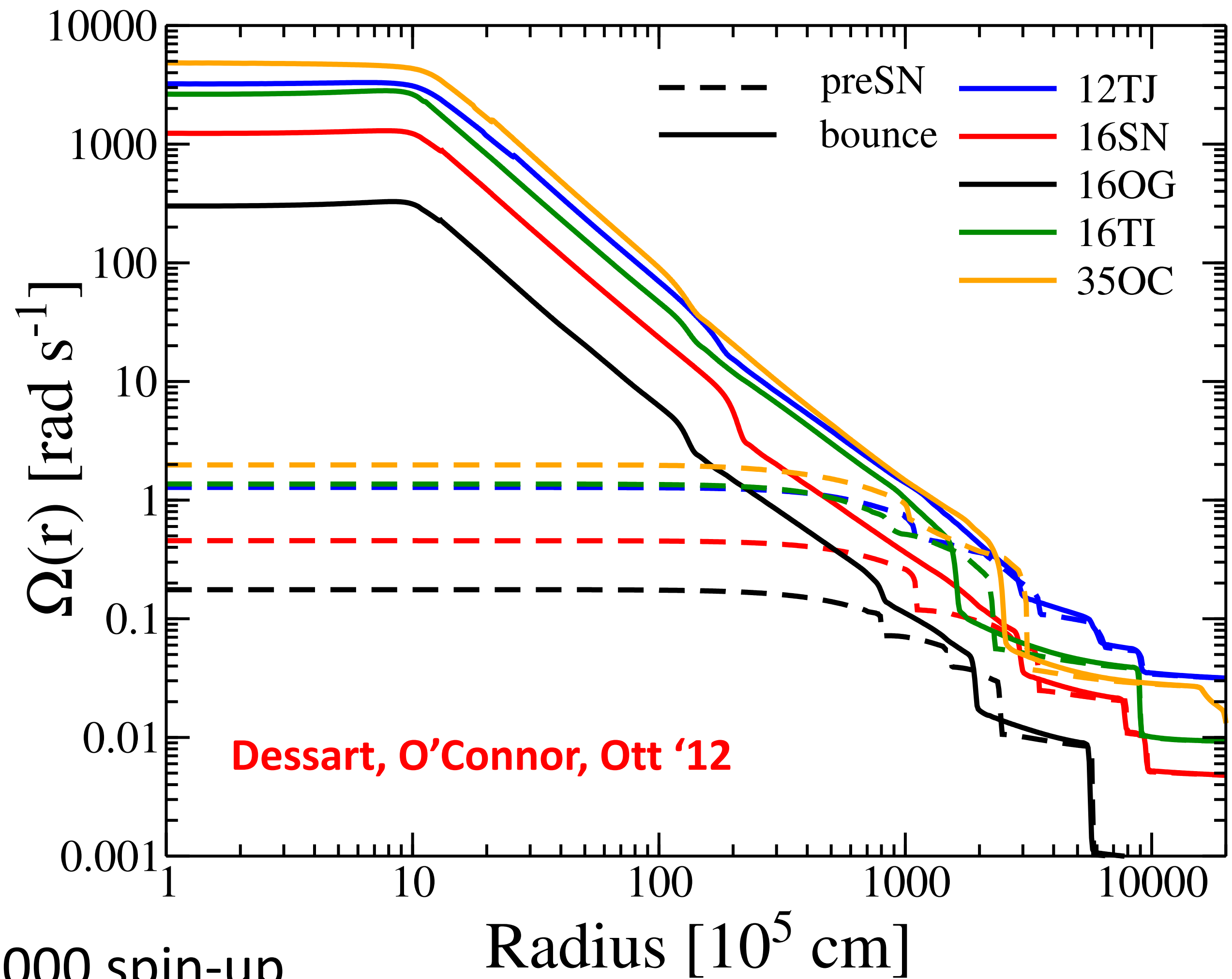
11 CCSN-long GRB associations.

1% of CCSNe are Ic-bl (very few with GRB)

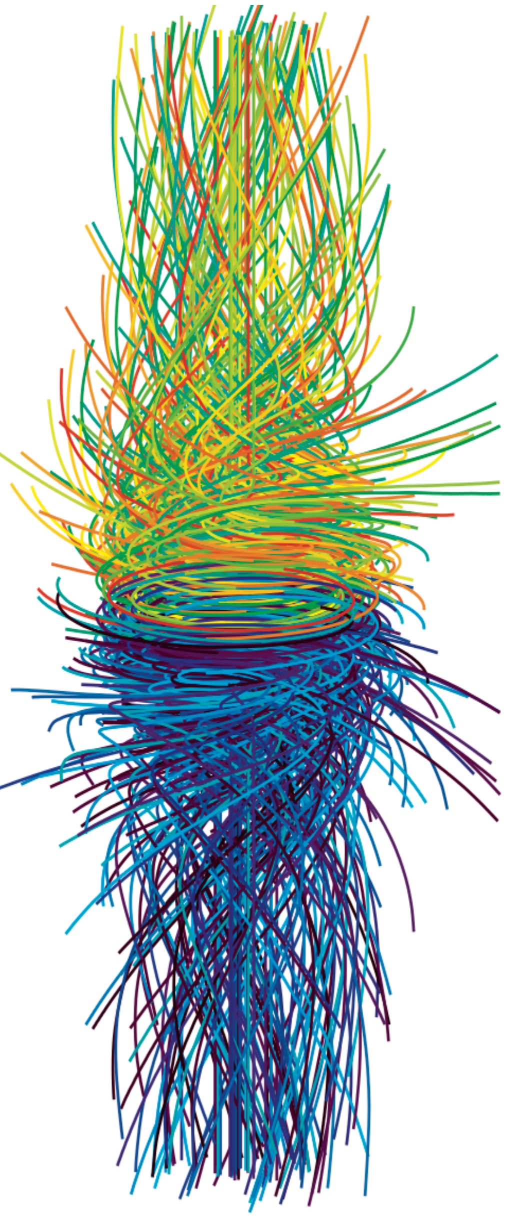
What drives explosions?



Magnetorotational Explosions



- Core: x 1000 spin-up
- Differential rotation -> reservoir of free energy.
- Spin energy tapped by **magnetorotational instability** (MRI)?



Burrows+’07

Magnetorotational Mechanism

[LeBlanc & Wilson ‘70, Bisnovatyi-Kogan ’70 & ‘74, Meier+76, Ardeljan+’05, Moiseenko+’06, Burrows+‘07, Bisnovatyi-Kogan+’08, Takiwaki & Kotake ‘11, Winteler+ 12, Mösta+14,15]

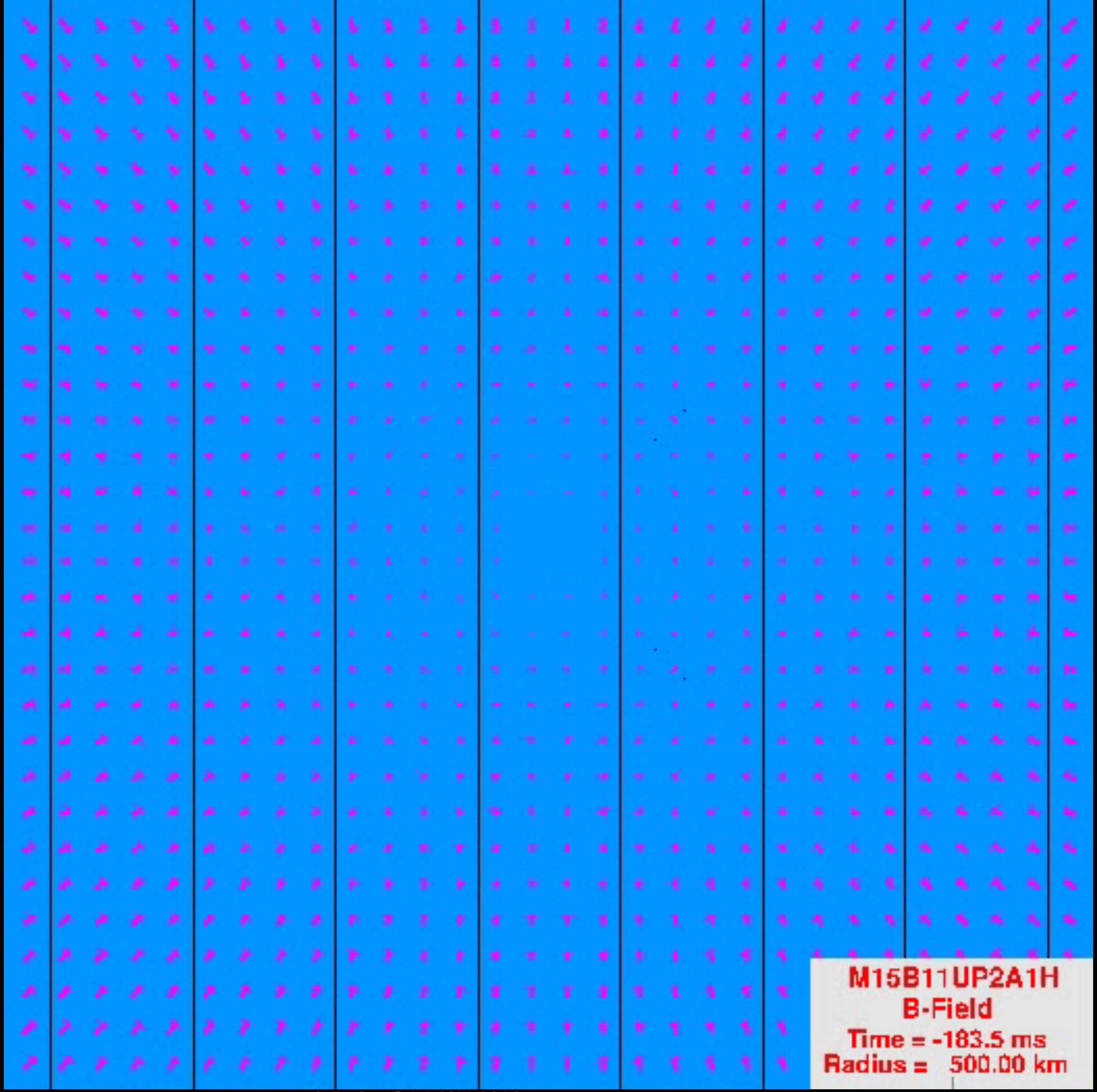
Rapid Rotation + B-field amplification to > 10^{15} G
(need magnetorotational instability [MRI])

MHD stresses lead to outflows.

2D: Energetic “bipolar” explosions.

Results in ms-period “proto-magnetar.”
-> connection to GRBs, Superluminous SNe?

Problem: Need high core spin;
only in very few progenitor stars?



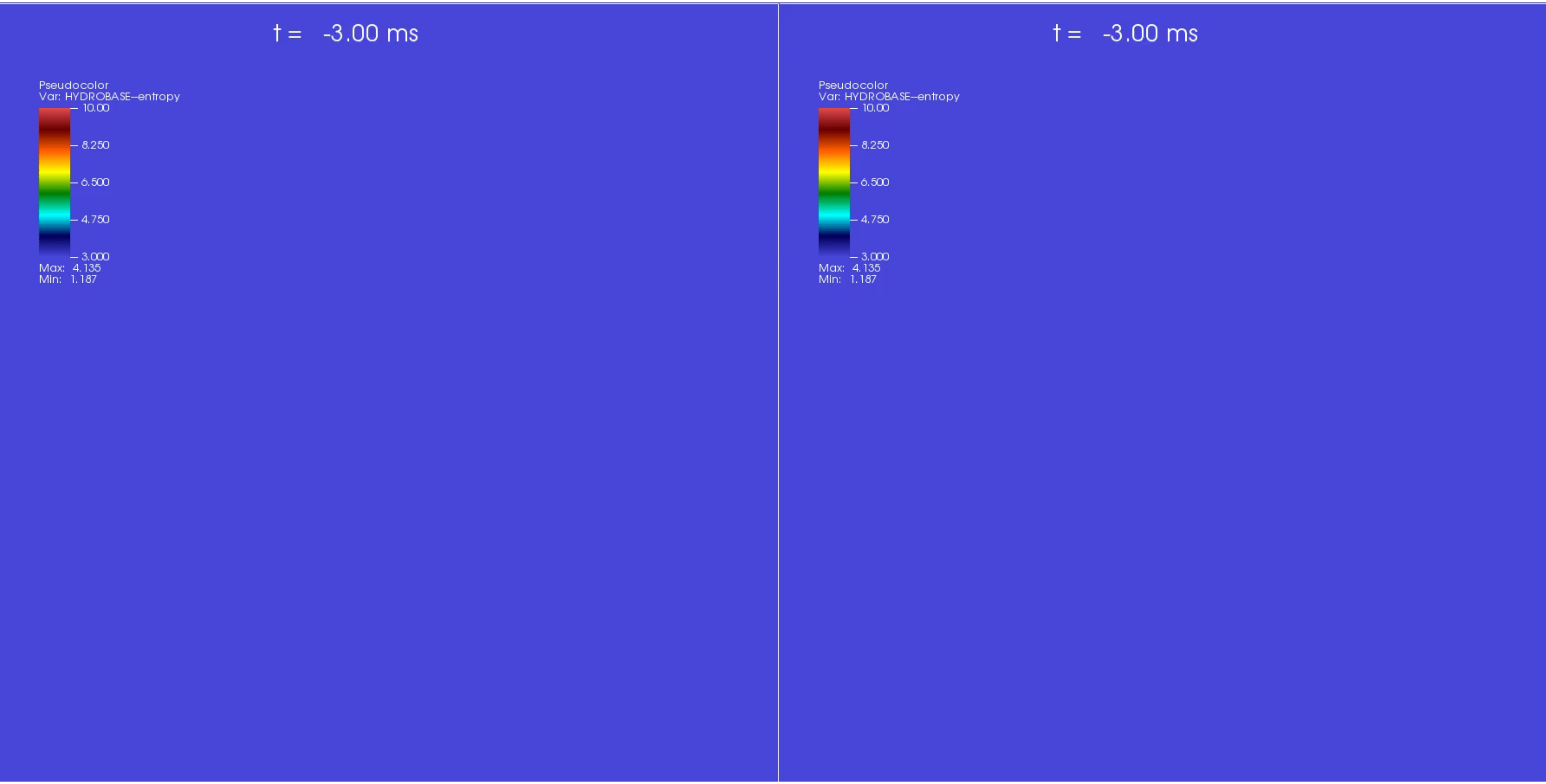
Burrows+'07

(10^{11} G
seed field)

3D Dynamics of Magnetorotational Explosions

New, full 3D GRMHD simulations. **Mösta+ 2014**, ApJL.
Initial configuration as in Takiwaki+11, 10^{12} G seed field.

← 2000 km → ← 2000 km →



Octant Symmetry (no odd modes) Full 3D

Mösta+ 2014
ApJL

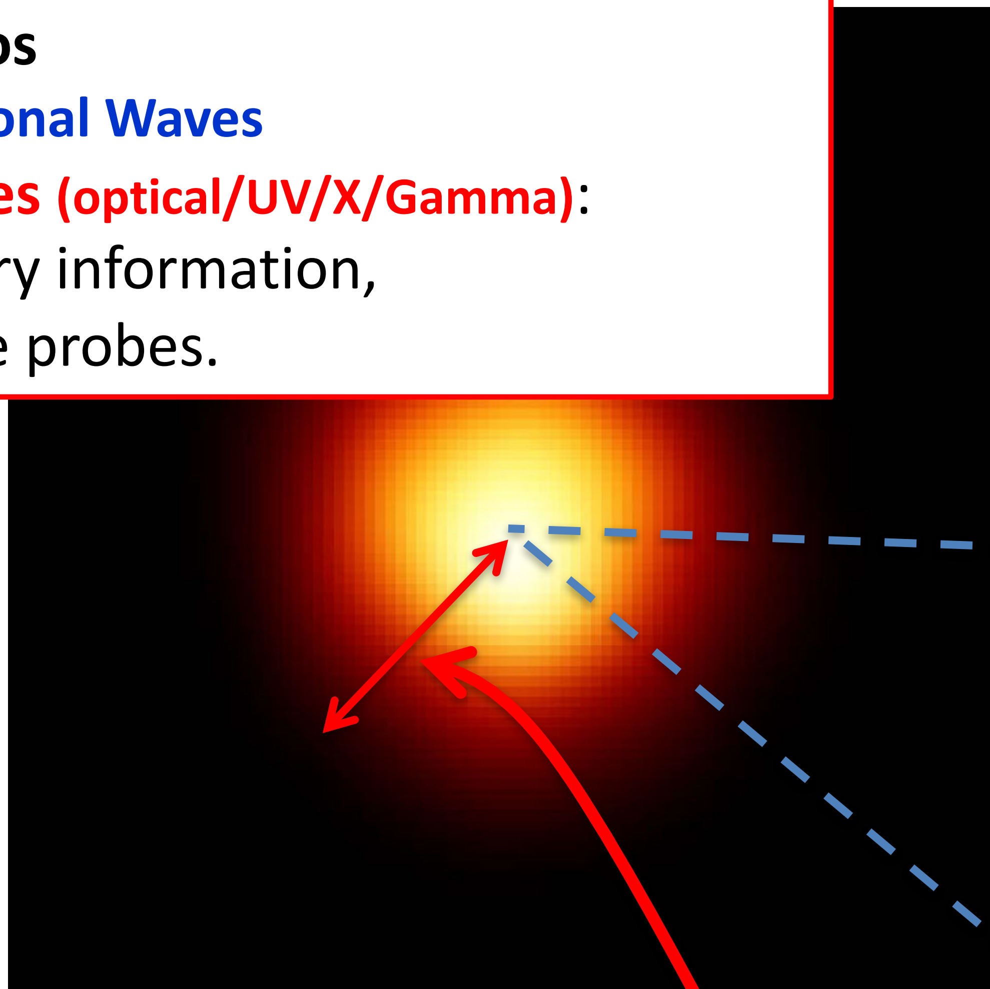
t = -3.00 ms

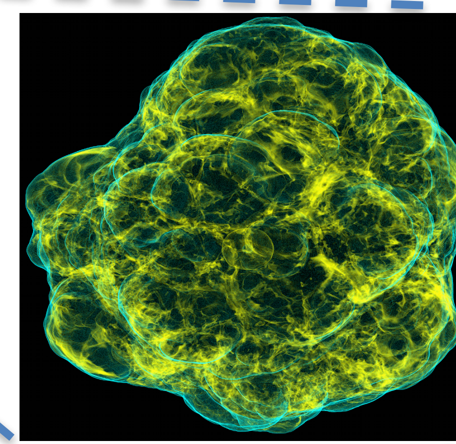
Caltech

Observing the Heart of a Supernova

Probes of Supernova & Nuclear Physics:
- **Neutrinos**
- **Gravitational Waves**
- **EM waves (optical/UV/X/Gamma)**: secondary information, late-time probes.

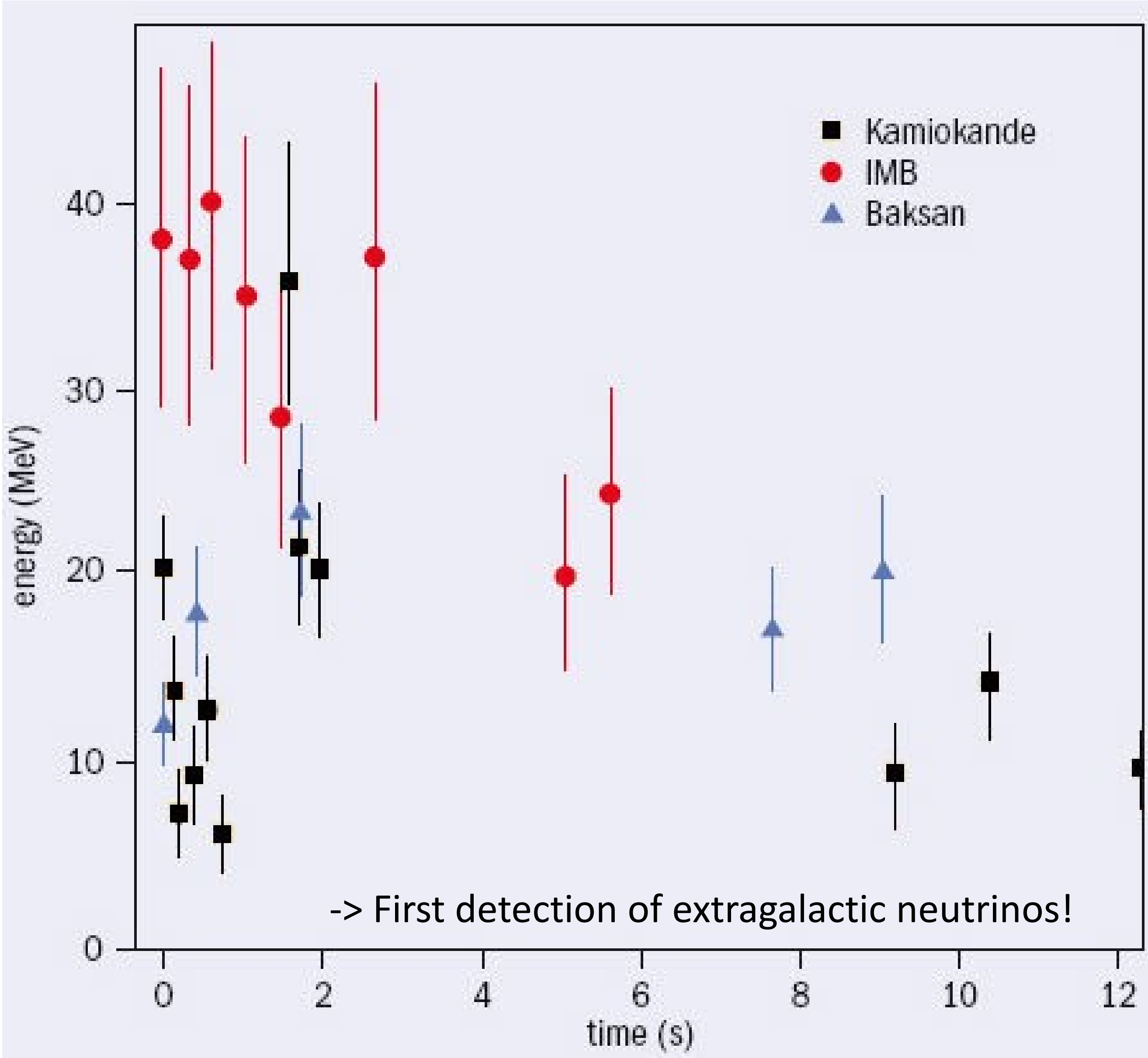
Red Supergiant
Betelgeuse





SN 1987A: Neutrino Detection!

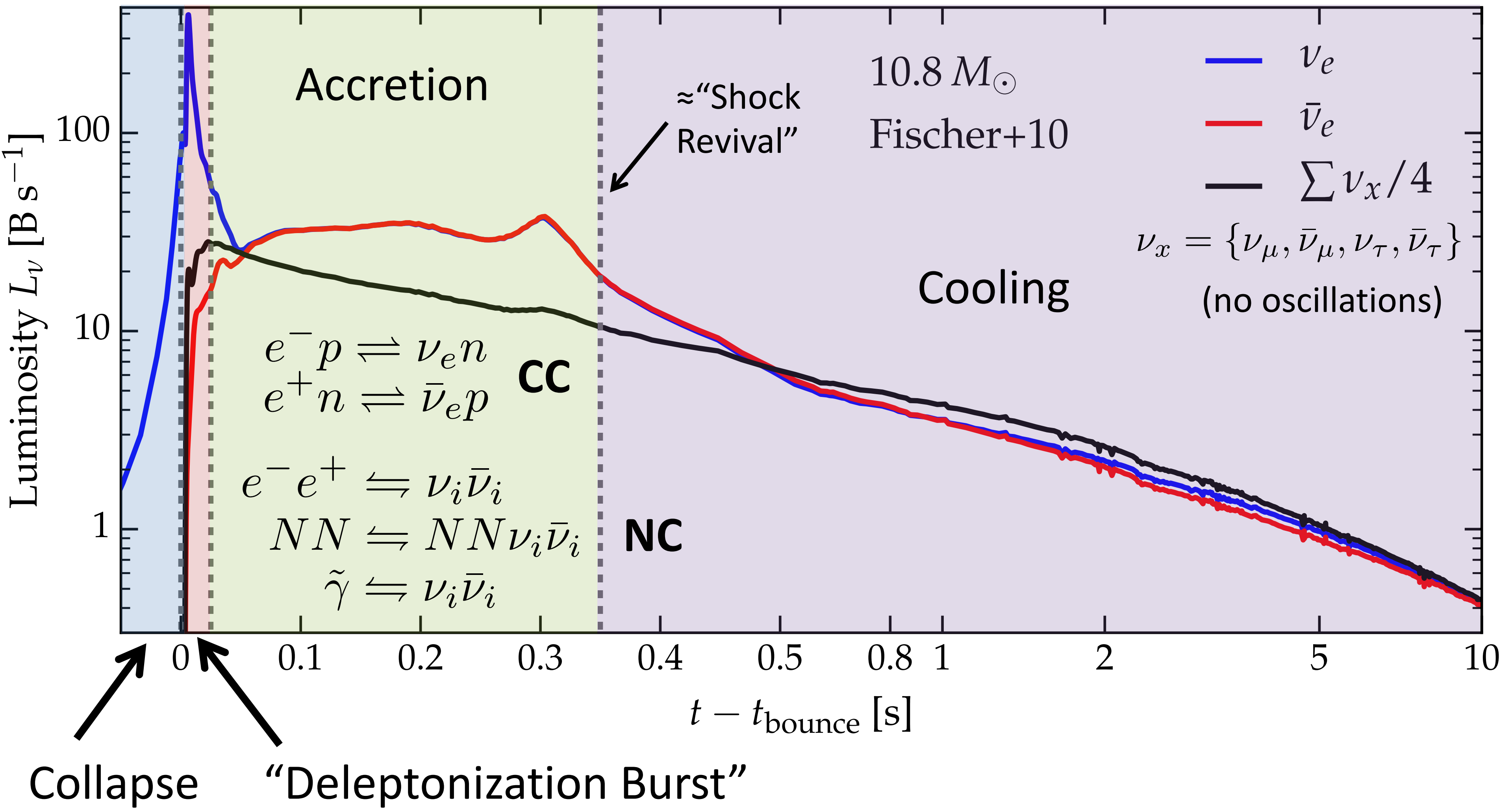
Hirata+87
Bionta+87
Alekseev+87



-> First detection of extragalactic neutrinos!

http://images.iop.org/objects/ccr/cern/47/1/28/CCEsup3_01-07.jpg

Supernova Neutrino "Lightcurves"



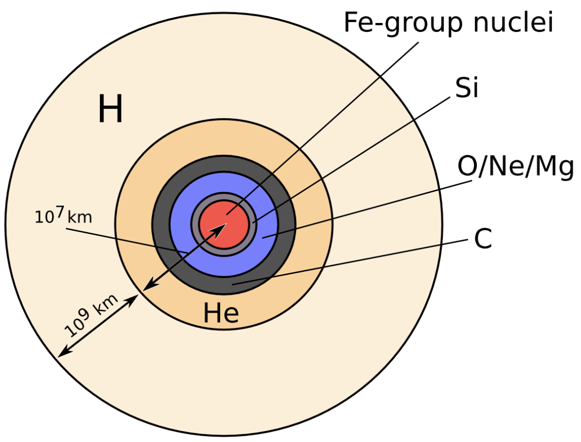
$$e^- + p \to n + \nu_e$$

Probing Stellar Structure and the Nuclear EOS with Pre-Explosion Neutrinos

O'Connor & Ott '13, ApJ

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

- EOS dependence:
  softer EOS -> more compact proto-NS -> harder spectrum, higher luminosity

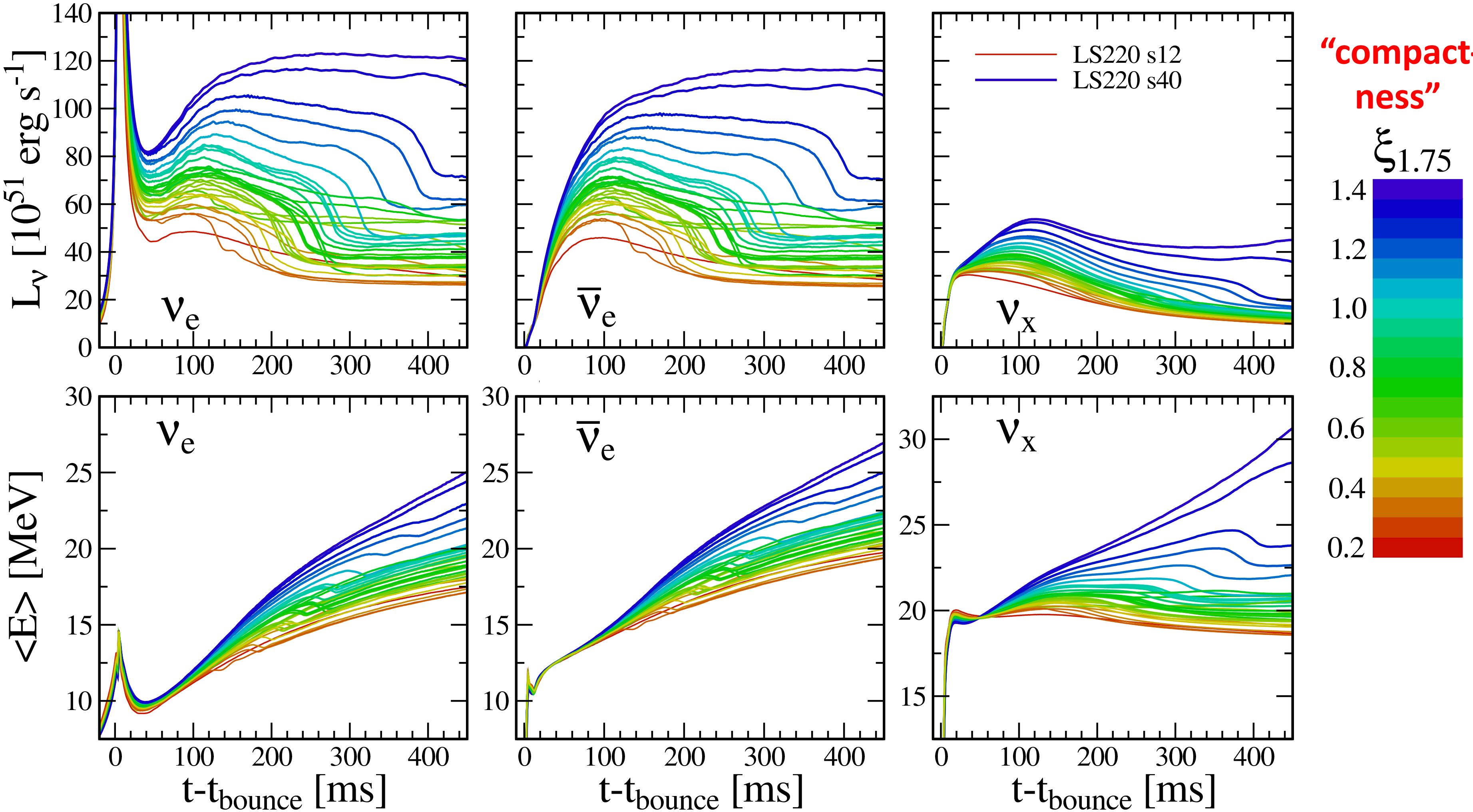


$$\xi_M = \frac{M/M_\odot}{R(M_{\rm bary}=M)/1000\,{\rm km}}\Big|_{t=t_{\rm bounce}}$$

"compactness parameter" (O'Connor & Ott '11)

Probing Stellar Structure with Pre-Explosion Neutrinos

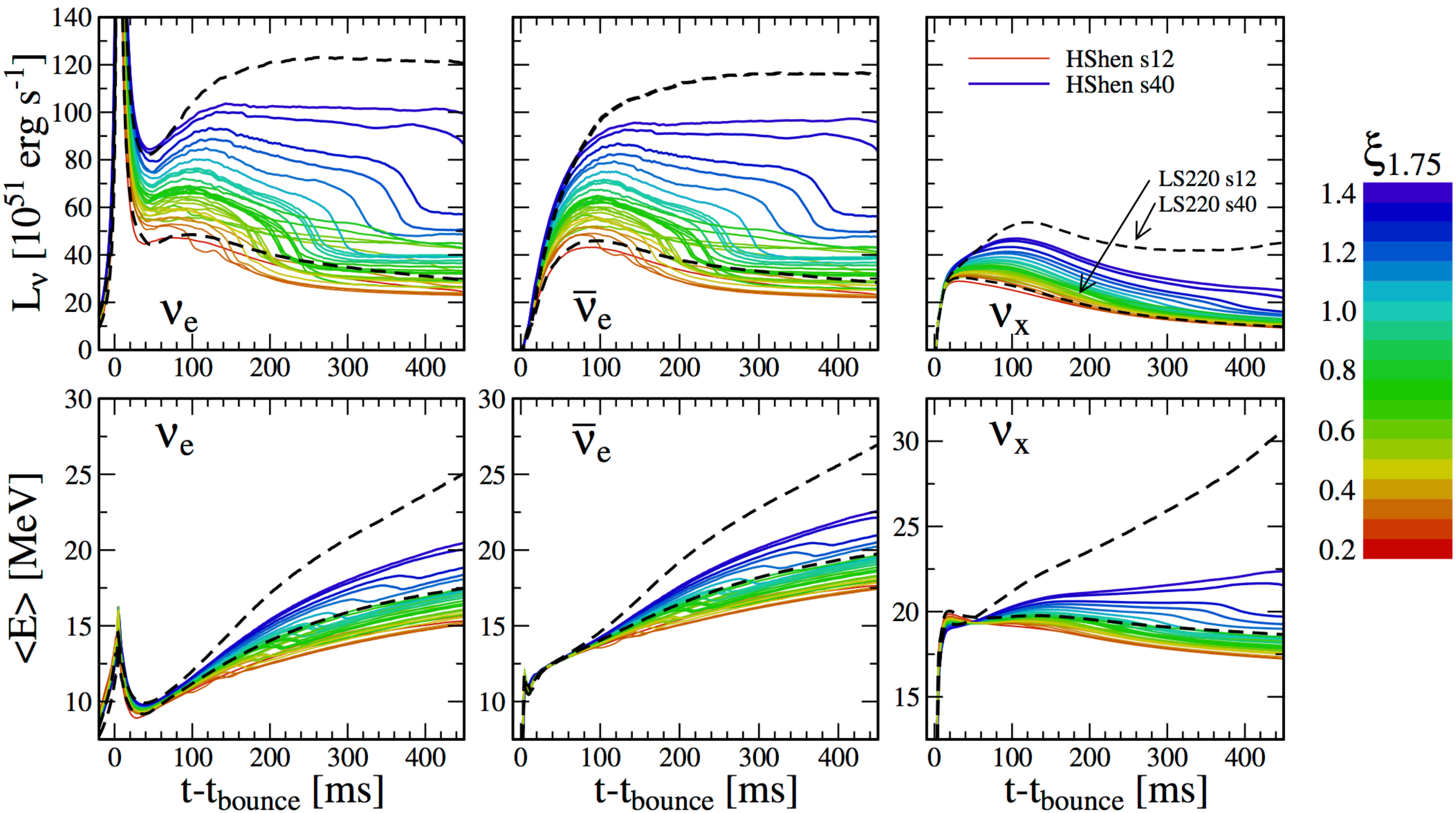
O'Connor & Ott '13, ApJ



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

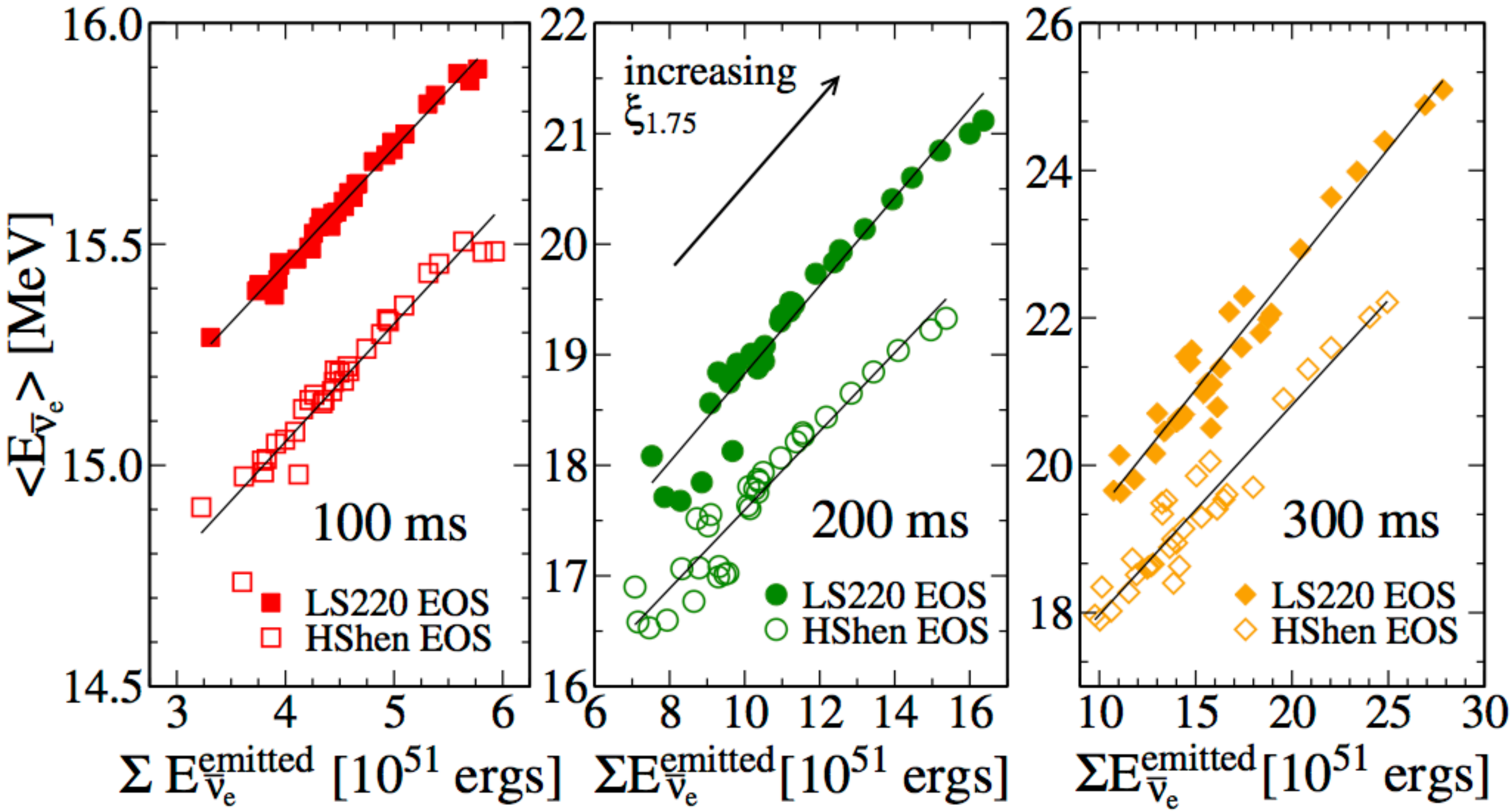
EOS Dependence of the Early Neutrino Signal

O'Connor & Ott '13, ApJ



EOS Dependence of the Early Neutrino Signal

O'Connor & Ott '13, ApJ



Note: Extracting EOS information will require precise knowledge of distance to source.

Gravitational Wave (GW) Refresher

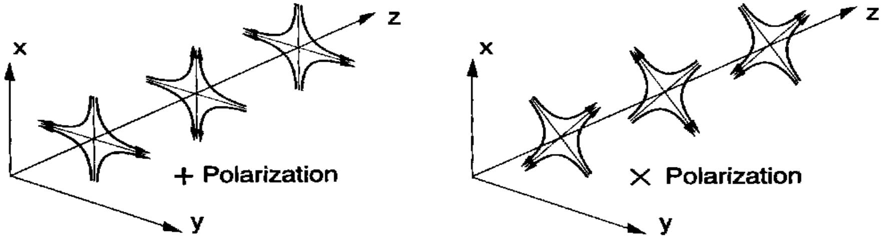
- **Emission**: **Accelerated quadrupole bulk mass-energy motion.**

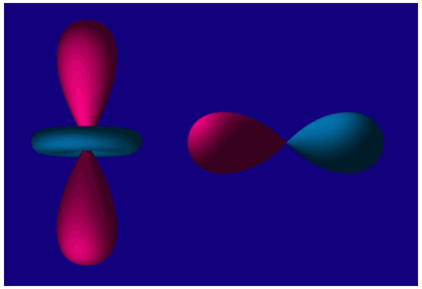
Quadrupole approximation

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

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

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





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

- **Detection**:
  Measure changes in separations of test masses with laser interferometry.
  -> Advanced LIGO, Kagra
  Advanced Virgo,
  LIGO India.

Gravitational-Waves from Core-Collapse Supernovae

Reviews: Kotake 11, Fryer & New 11, Ott 09

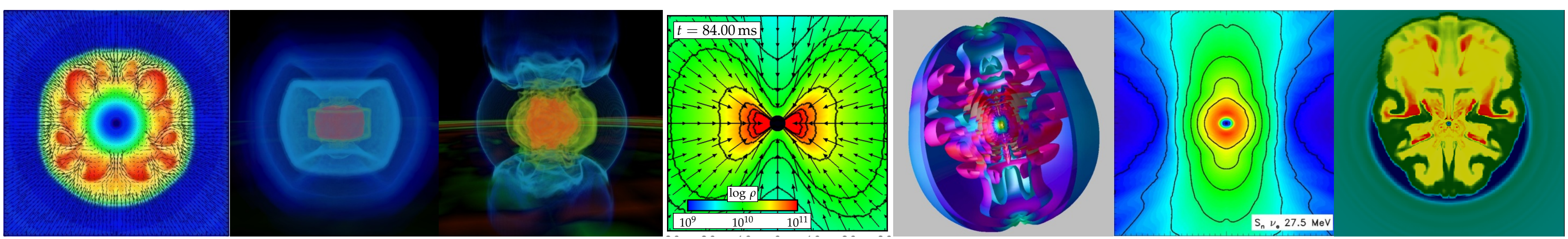
Need:

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

accelerated aspherical (quadrupole) mass-energy motions

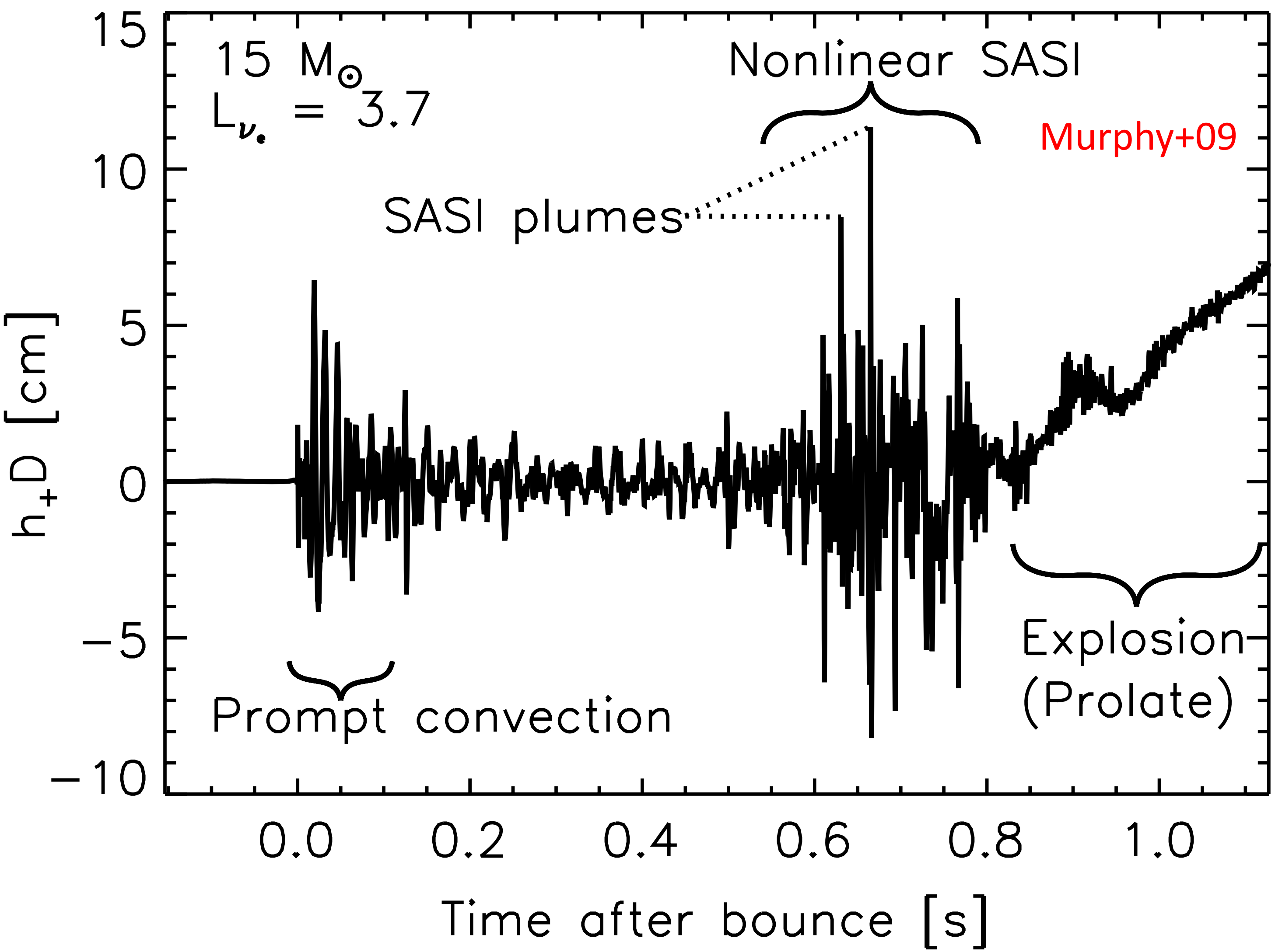
Candidate Emission Processes:

- Turbulent convection
- Rotating collapse & bounce
- 3D MHD/HD instabilities
- Aspherical mass-energy outflows



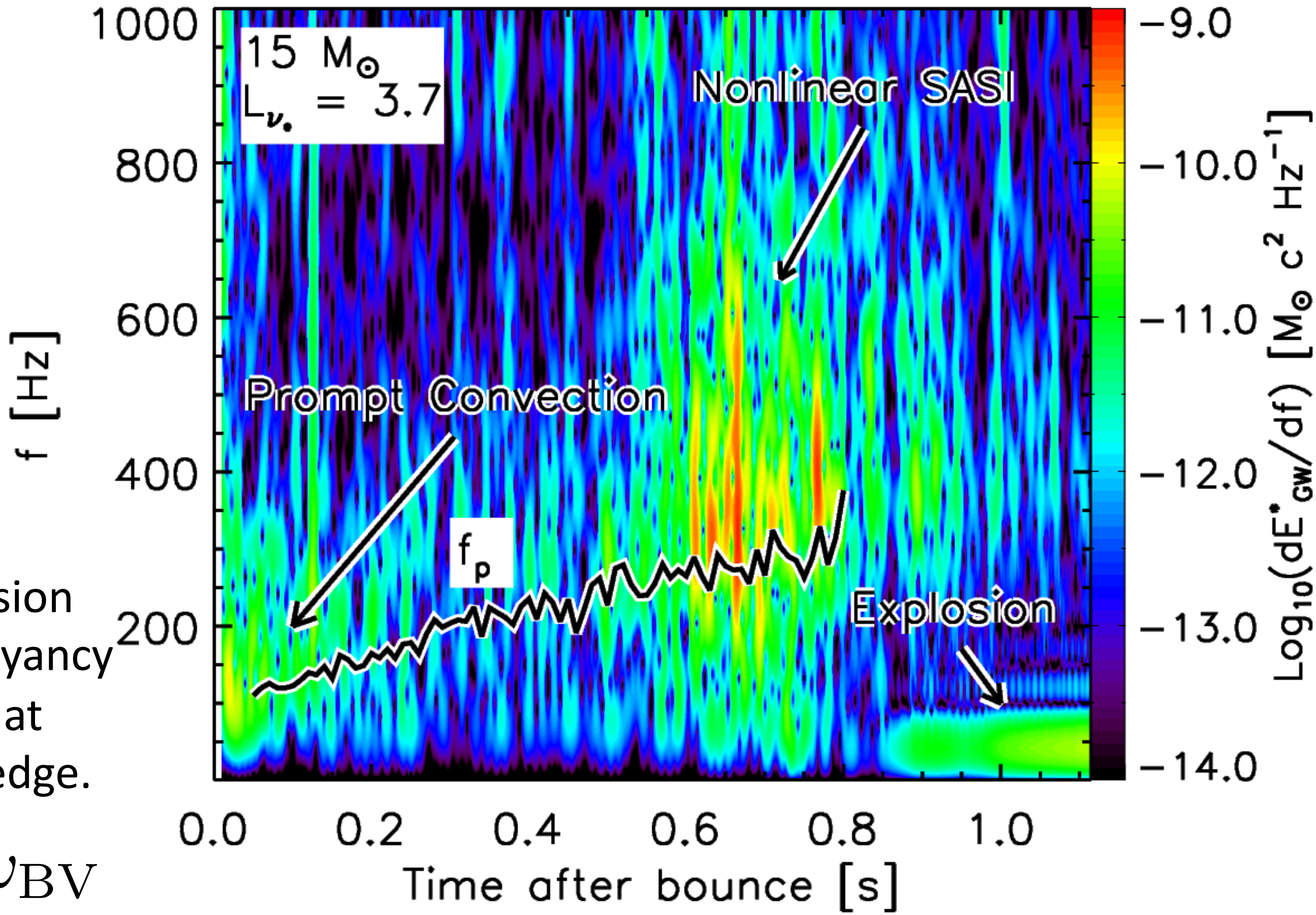
GWs from Convection & Standing Accretion Shock Instability

Recent work: Murphy+09, Kotake+09, 11, Yakunin+10,16, E. Müller+12, B.Müller+13



Time-Frequency Analysis of GWs

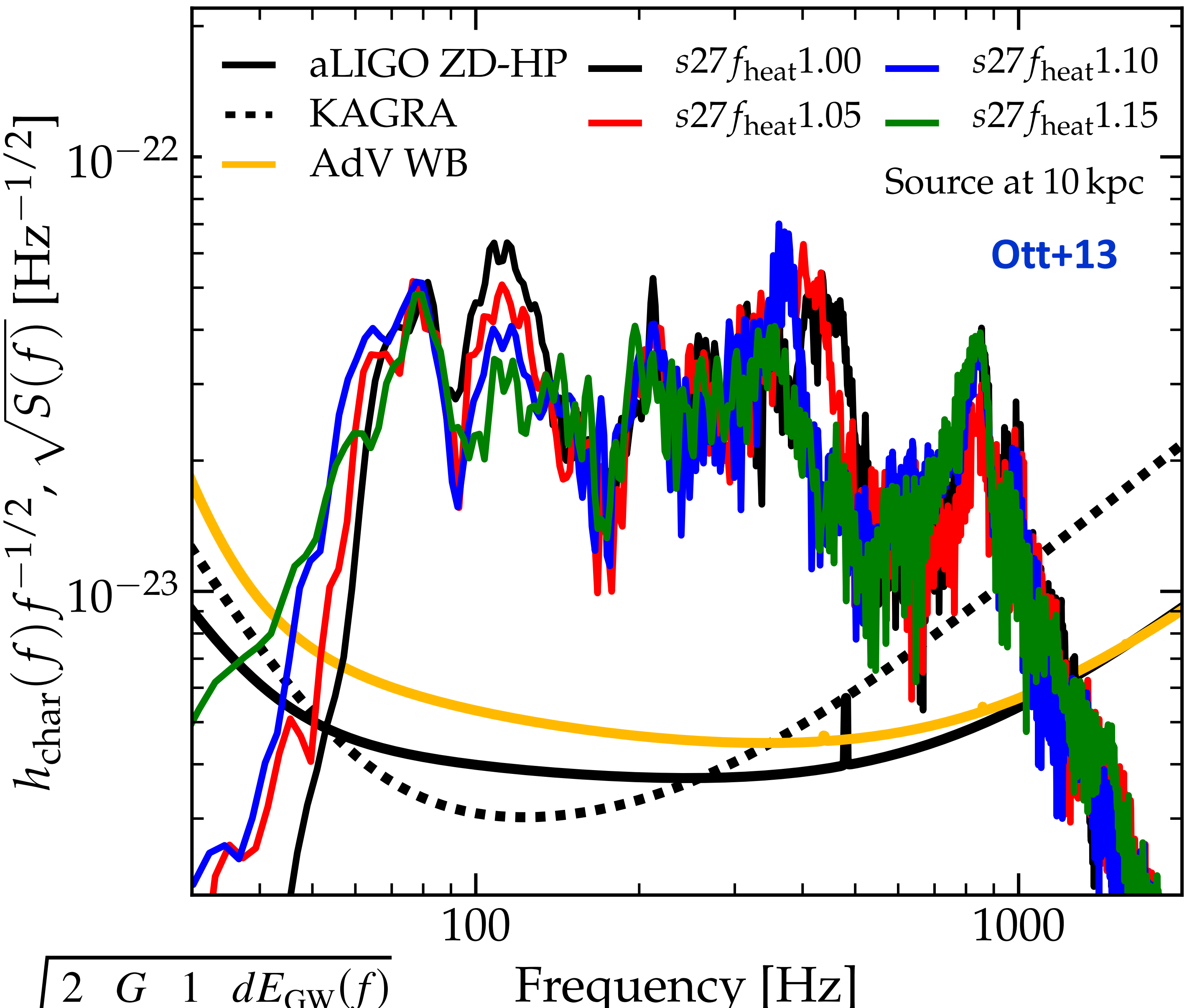
Murphy, Ott, Burrows 09, see also B. Müller+13, Sotani & Takiwaki 16



Peak emission traces buoyancy frequency at proto-NS edge.

$$f_p \sim \frac{\omega_{\rm BV}}{2\pi}$$ (buoyancy frequency)

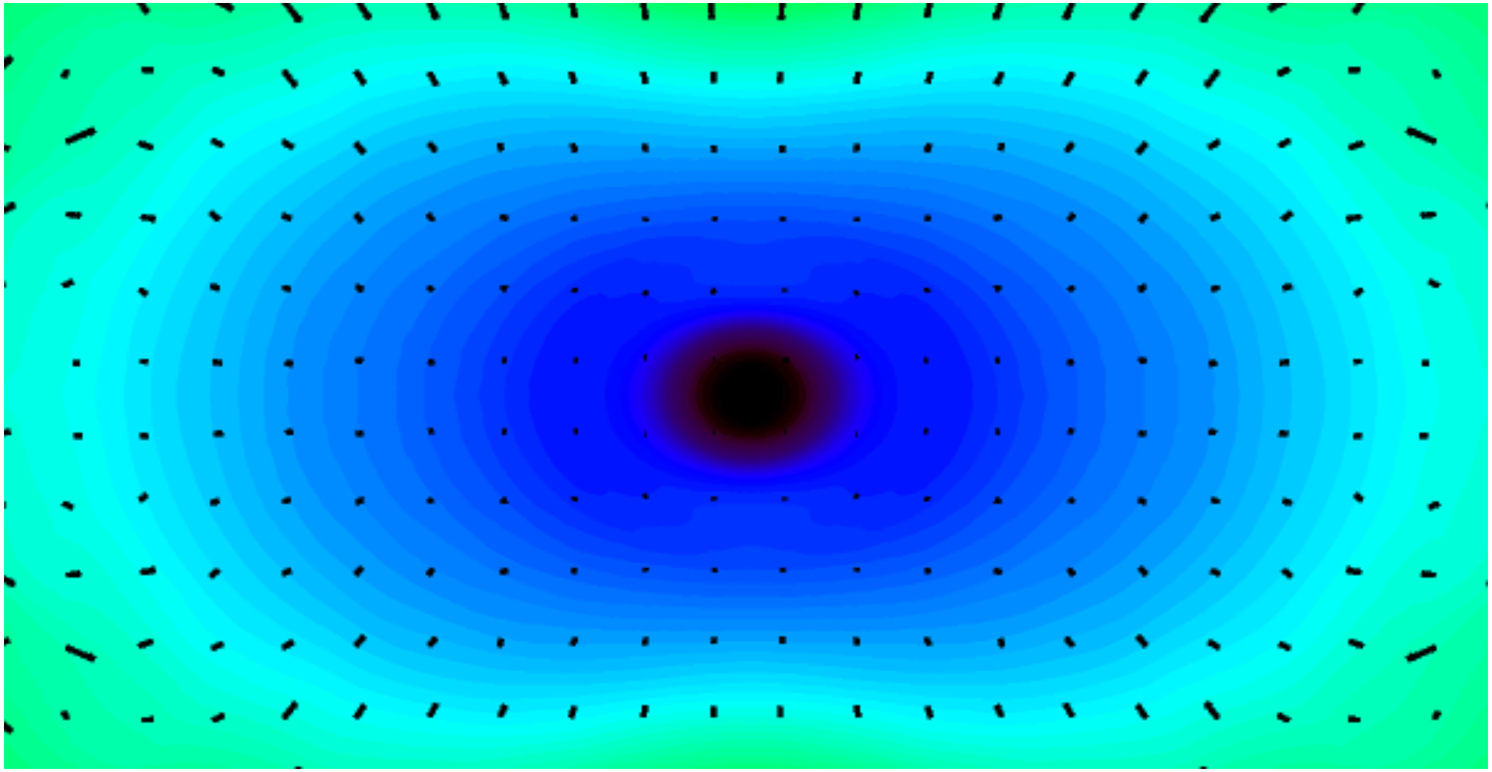
Detectability?



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

GWs from Rotating Collapse & Bounce

Recent work: Dimmelmeier+08, Scheidegger+10, Ott+12, Abdikamalov+14

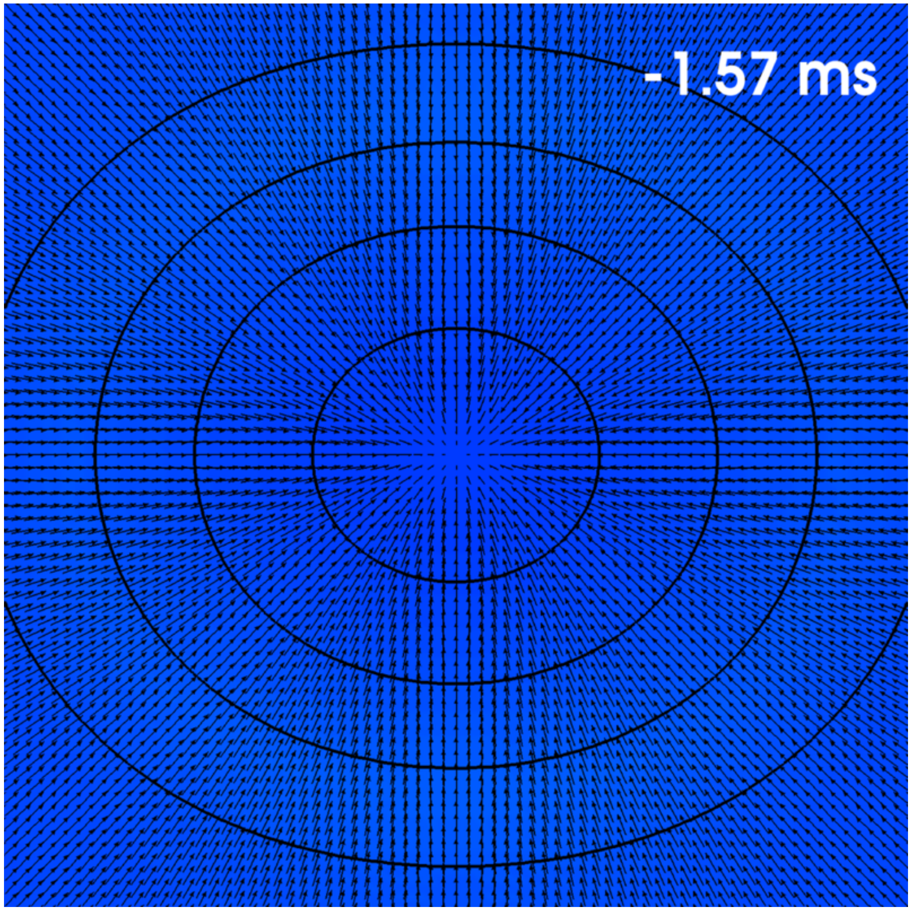


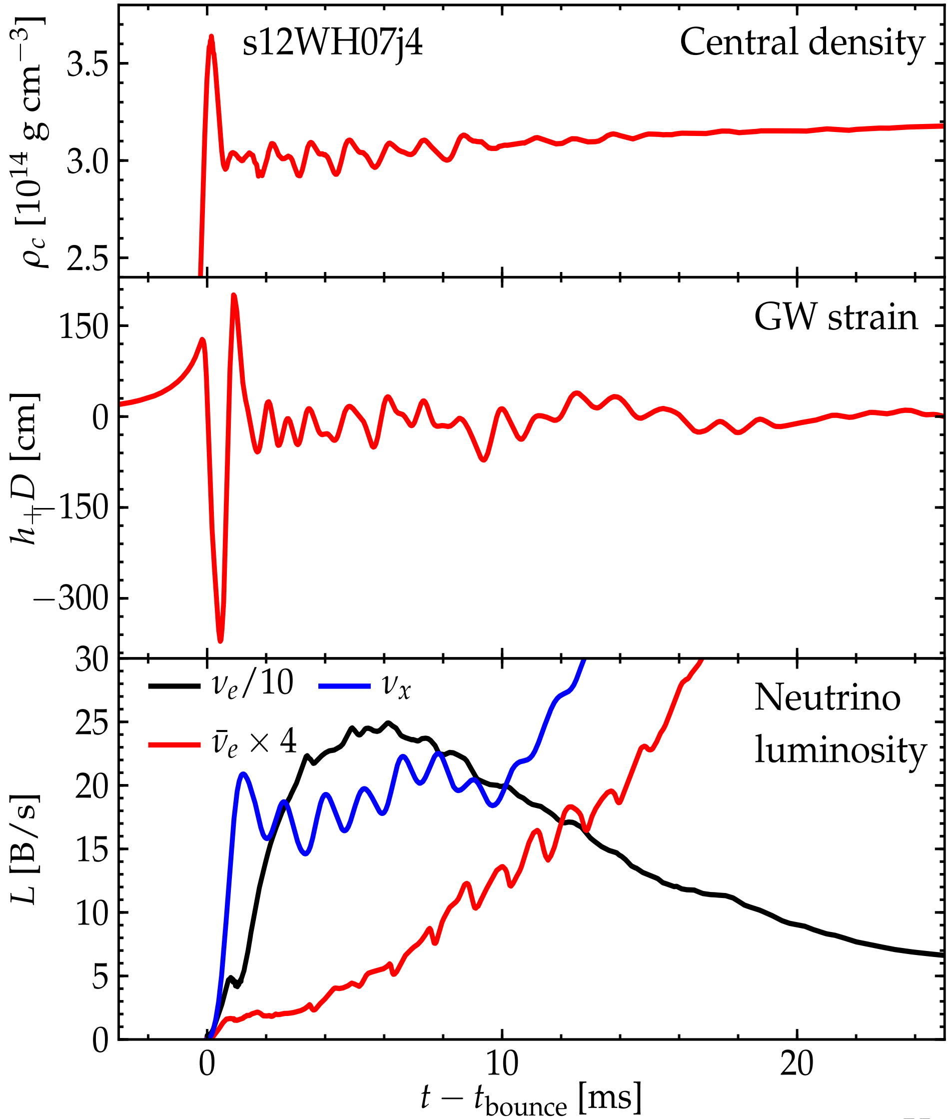
- **Axisymmetric:** **ONLY h_+**
- Simplest GW emission process: **Rotation** + mass of the inner core + **gravity** + **stiffening of nuclear EOS**
- Strong signals for rapid rotation (-> millisecond proto-NS).
- Magnetorotational mechanism.

Probing Multi-Dimensional Supernova Dynamics

- Rotating core collapse: Correlated neutrino and gravitational-wave signal.

  Ott+2012

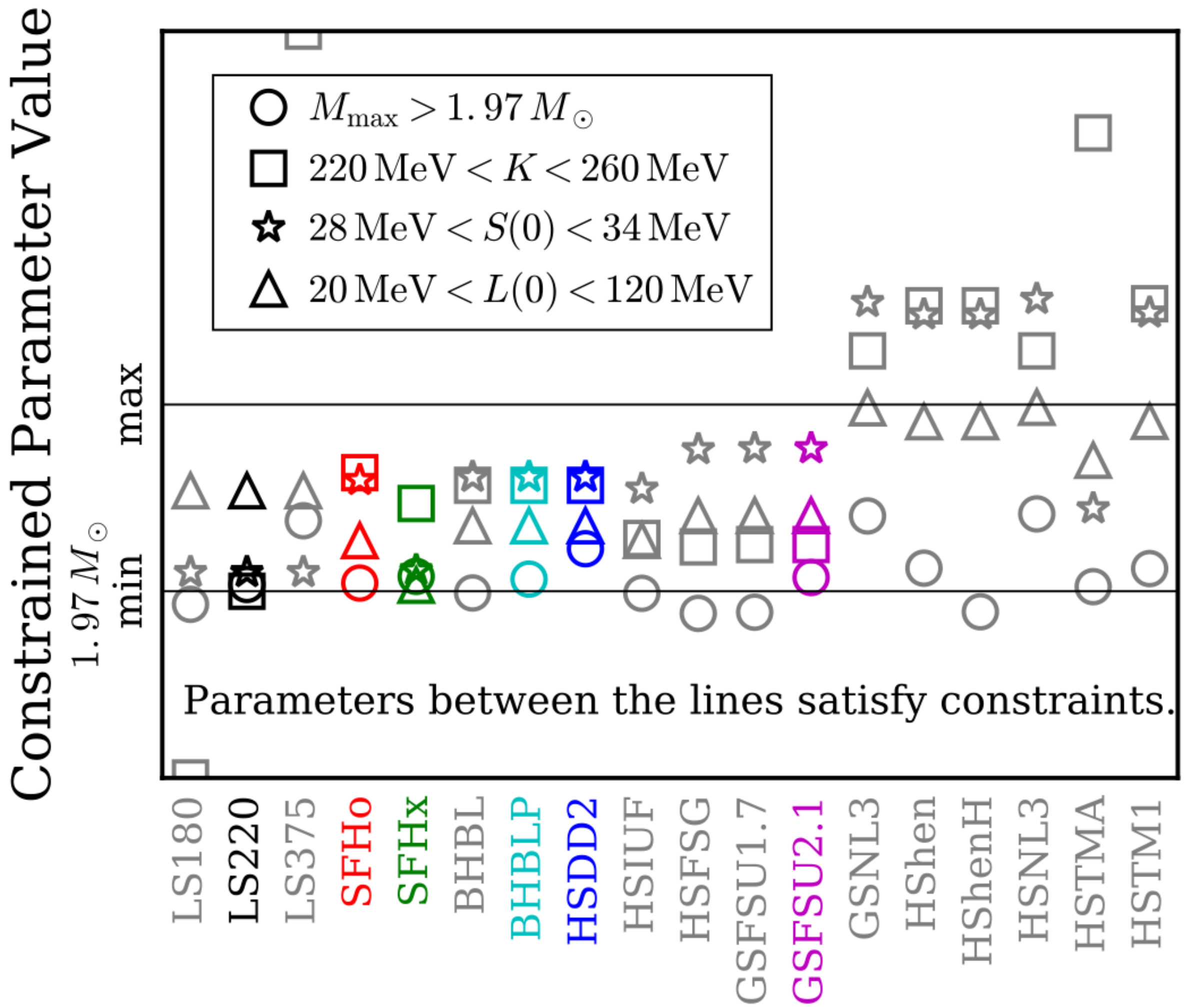




EOS Dependence of the GW Signal?

Richers+2016, in preparation, **talk on November 10**.

- 2D general-relativistic hydrodynamics.
- 18 EOS, taken from http://stellarcollapse.org
- ~1800 simulations.

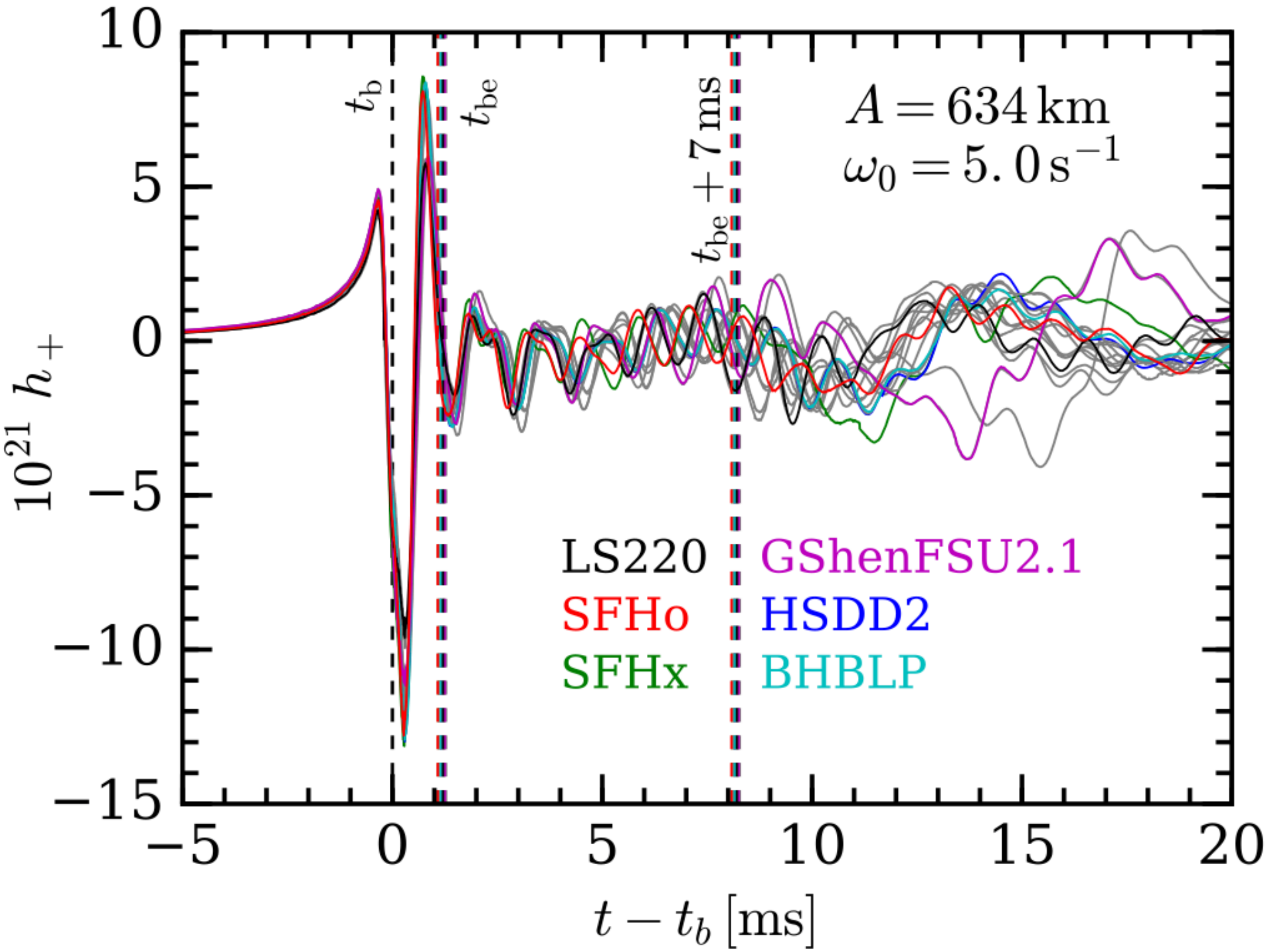


Sherwood Richers

EOS Dependence of the GW Signal?

Richers+2016, in preparation, **talk on November 10**.

Example result:

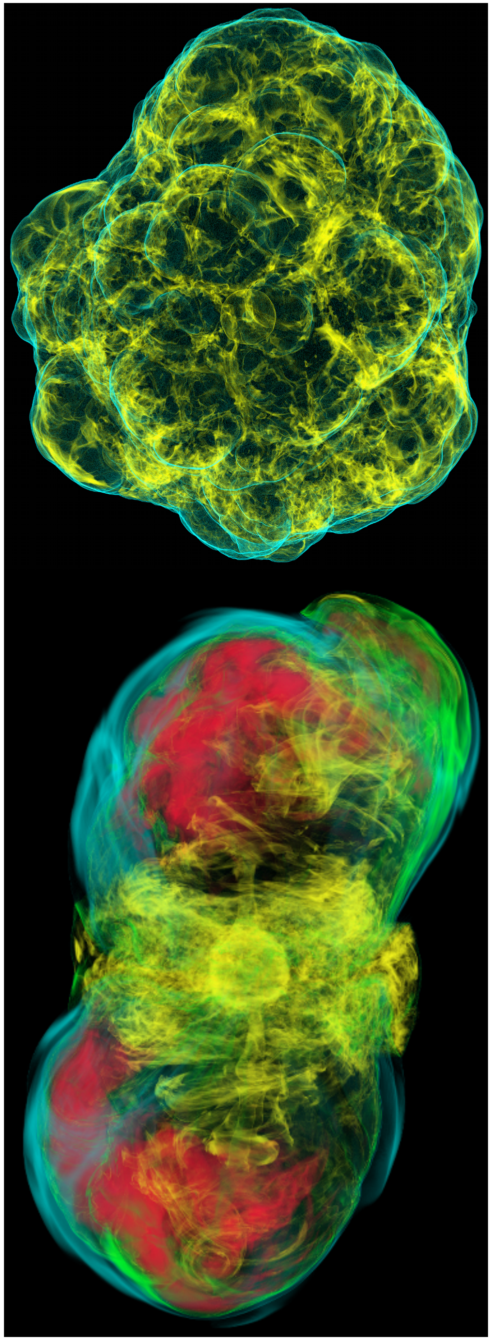


Sherwood Richers

- Rotating core collapse GW signal: determined by mass and angular mom. of inner core.
- Dependence on nuclear EOS is weak.

Summary

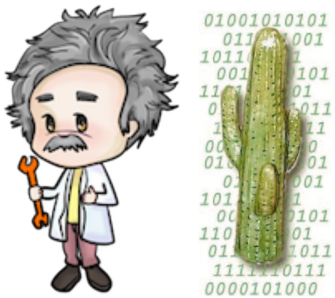
- Core-Collapse Supernovae are fundamentally 3D: Turbulence (not resolved!), magnetic field
- 2D/3D simulations: neutrino-driven explosions with limitations -> “supernova problem” not yet solved. Main issues:
  - Progenitor star structure (-> Suwa & Müller 16).
  - Neutrino transport & gravity approximations.
  - Numerical resolution.
  - Neutrino oscillations? (ν-ν interactions)
  - Input microphysics (EOS, ν interactions).
- Probably need magnetorotational mechanism to explain hypernovae.
- Neutrino and GW signals carry information on supernova thermodynamics, dynamics, and nuclear EOS.



Supplemental Slides

Technical Details: The Caltech CCSN Code

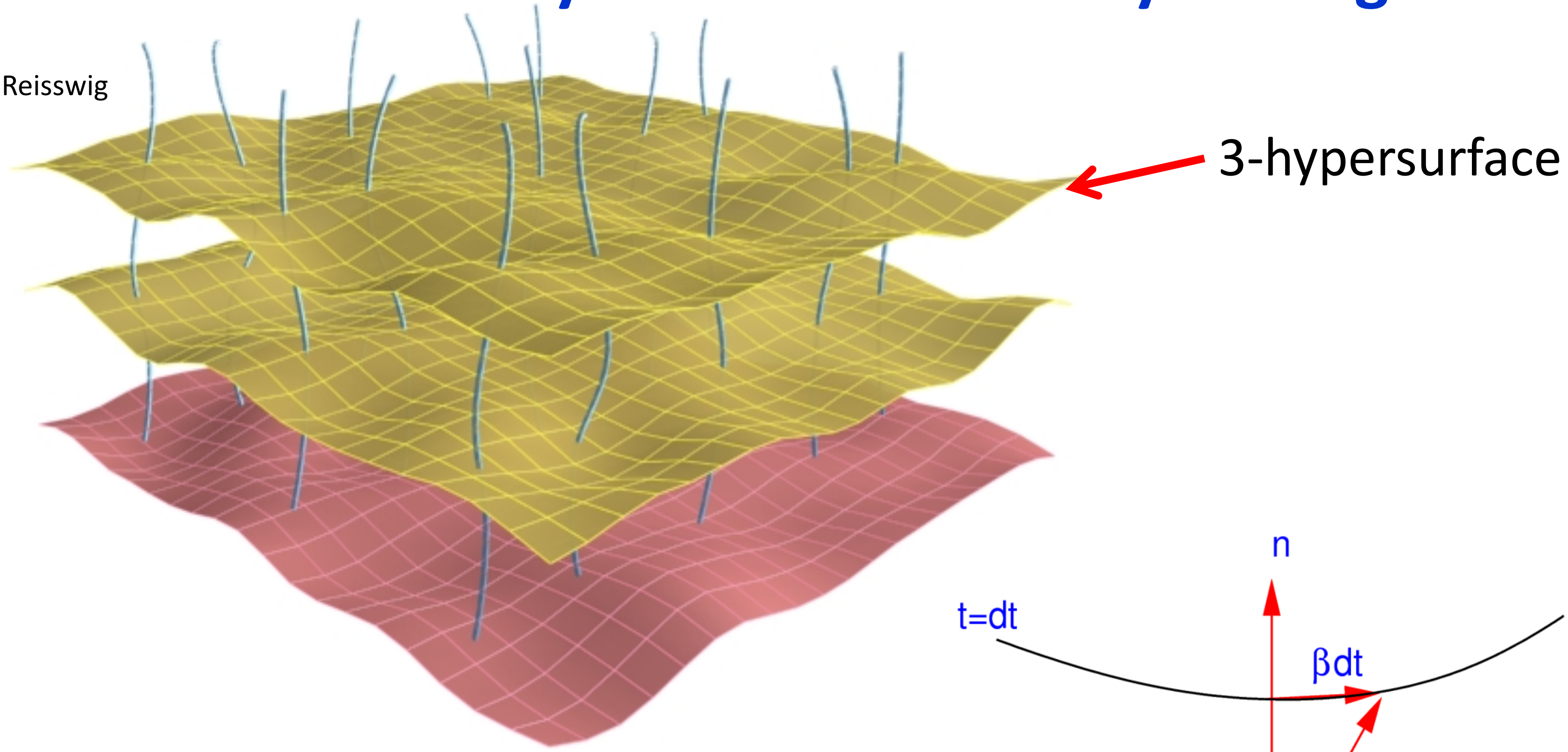
[Ott+09, Ott+12, Reisswig+13, Ott+13, Roberts+16]

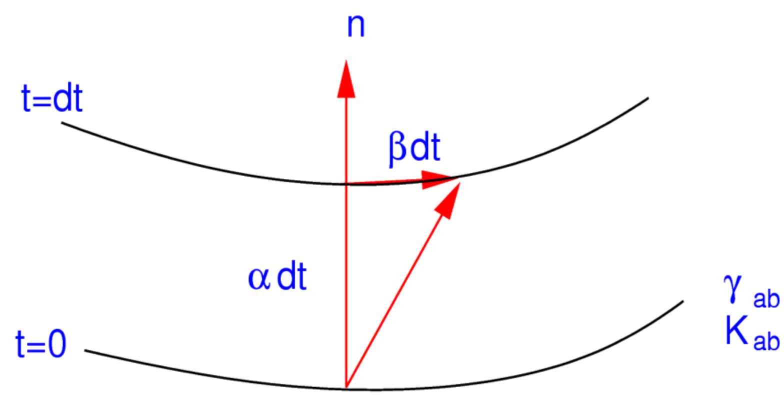


- Based on the open-source Einstein Toolkit (http://einsteintoolkit.org) and the Cactus Framework.
- Fully general-relativistic using numerical relativity.
- Cartesian AMR grids, cubed-sphere generalized grids.
- Spacetime solvers based on BSSN formalism of numerical relativity.
- Finite-volume GR hydrodynamics, magnetohydrodynamics.
- Microphysical finite-temperature nuclear equations of state.
- Neutrino treatment:
  (1) Multi-group two-moment + analytic closure relation.
  (2) Extremely efficient gray "leakage"+heating scheme.

Numerical Relativity: How to do Gravity the Right Way

Figure: C. Reisswig





$$G^{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu}$$

- 12 first-order hyperbolic *evolution* equations.
- 4 elliptic *constraint* equations
- 4 coordinate gauge degrees of freedom: α, β^i.

"Equation of State" of Turbulent Pressure

(Radice+15a)

- Reynolds tensor: $R_{rr} \approx R_{\theta\theta} + R_{\phi\phi}$ (buoyancy)

$$R_{ij} = \delta v_i \delta v_j$$

- Specific turbulent energy: $\epsilon_{\rm turb} = \frac{1}{2}|\delta \mathbf{v}|^2$

$$|\delta \mathbf{v}^2| = (\delta v_r)^2 + (\delta v_\theta)^2 + (\delta v_\phi)^2 \approx 2(\delta v_r)^2$$ (buoyancy)

$$(\delta v_r)^2 \approx \frac{1}{2}|\delta \mathbf{v}|^2 = \epsilon_{\rm turb}$$

- Rankine-Hugoniot with turbulence:

$$P_d + \rho_d v_d^2 + \rho_d(\delta v_r)^2 = \rho_u v_u^2$$

$$(\gamma_{\rm th} - 1)\rho\epsilon_{\rm th} + \rho_d v_d^2 + \rho(\delta v_r)^2 = \rho_u v_u^2$$

$$(\gamma_{\rm th} - 1)\rho\epsilon_{\rm th} + \rho_d v_d^2 + \rho\epsilon_{\rm turb} = \rho_u v_u^2$$

$$(\gamma_{\rm th} - 1)\rho\epsilon_{\rm th} + \rho_d v_d^2 + (\Gamma_{\rm turb} - 1)\rho\epsilon_{\rm turb} = \rho_u v_u^2$$

$$\Gamma_{\rm th} \approx 4/3$$

$$\Gamma_{\rm turb} \approx 2$$

How much resolution is needed?

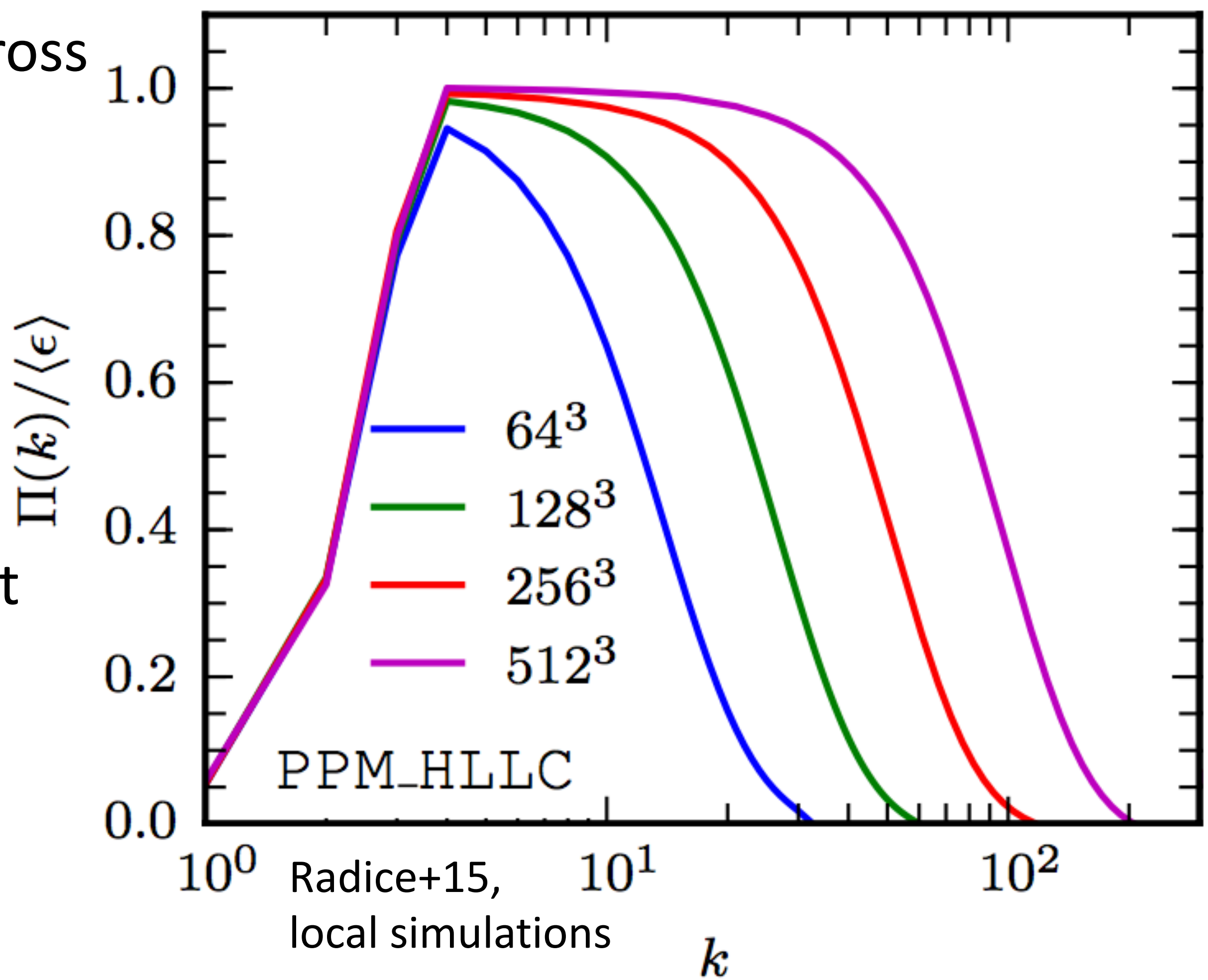
- Must (at least) capture correct rate of kinetic energy flux from largest scales.

- Need ~128^3 zones across turbulent layer.

- Roughly 2 x current high-resolution global simulations.

- Resolve inertial range: 10-20 x current resolution needed.

Normalized kinetic energy flux.



Radice+15, local simulations

Can this work at all?

Mösta+15, Nature

- All simulations of the magnetorotational mechanism **assume**: MRI works + large-scale field created by dynamo.

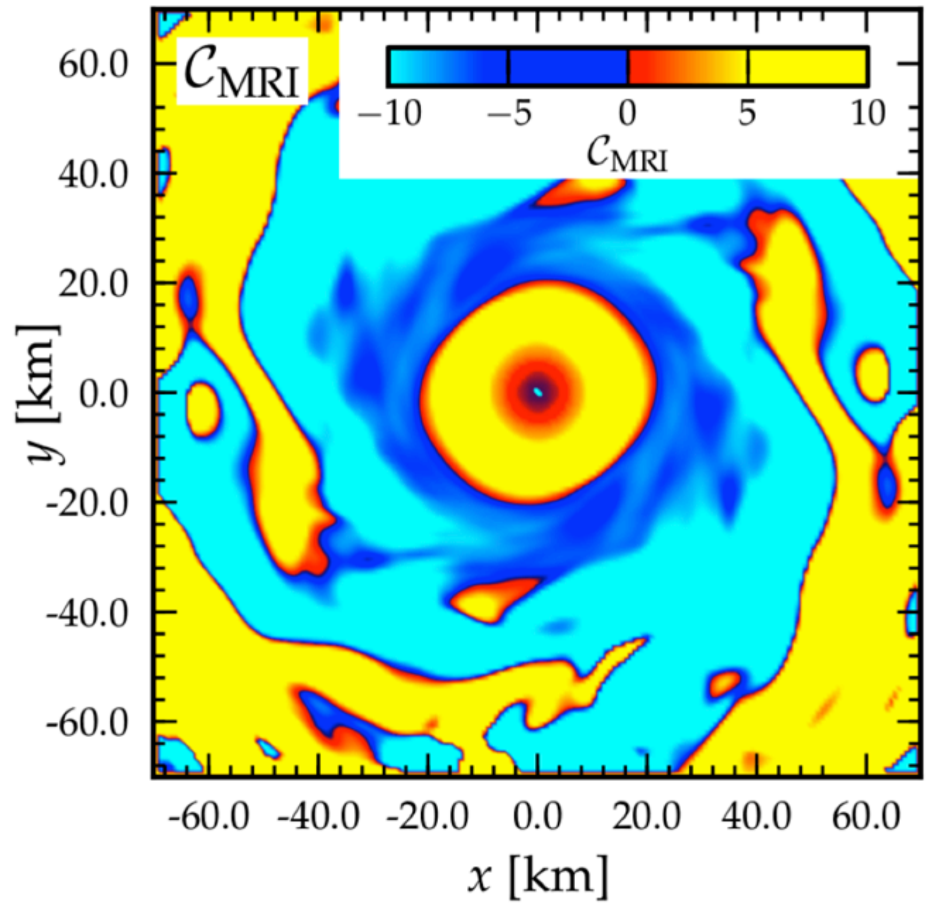
- So far impossible to resolve fastest-growing MRI mode in global 3D simulations.

- Unstable regions (roughly):

$$\frac{d\ln\Omega}{dr} < 0$$

- Precollapse field 10^{10} G, $\sim 10^{14}$ G at bounce.

- Fastest growing mode: $\lambda \sim 1$ km.



dark blue: most MRI unstable

Simulation Setup

Mösta+15, Nature

- Rapidly spinning, magnetized proto-NS.
- Global simulation in quadrant symmetry: 70 km x 70 km x 140 km box
- Resolutions: 500 m/200 m/100 m/50 m
- hot nuclear eq. of state, neutrinos, fixed gravity, GRMHD.
- Simulations on 130,000 CPU cores on NSF Blue Waters, simulate for 10-20 ms.

BLUE WATERS
SUSTAINED PETASCALE COMPUTING

Key questions:

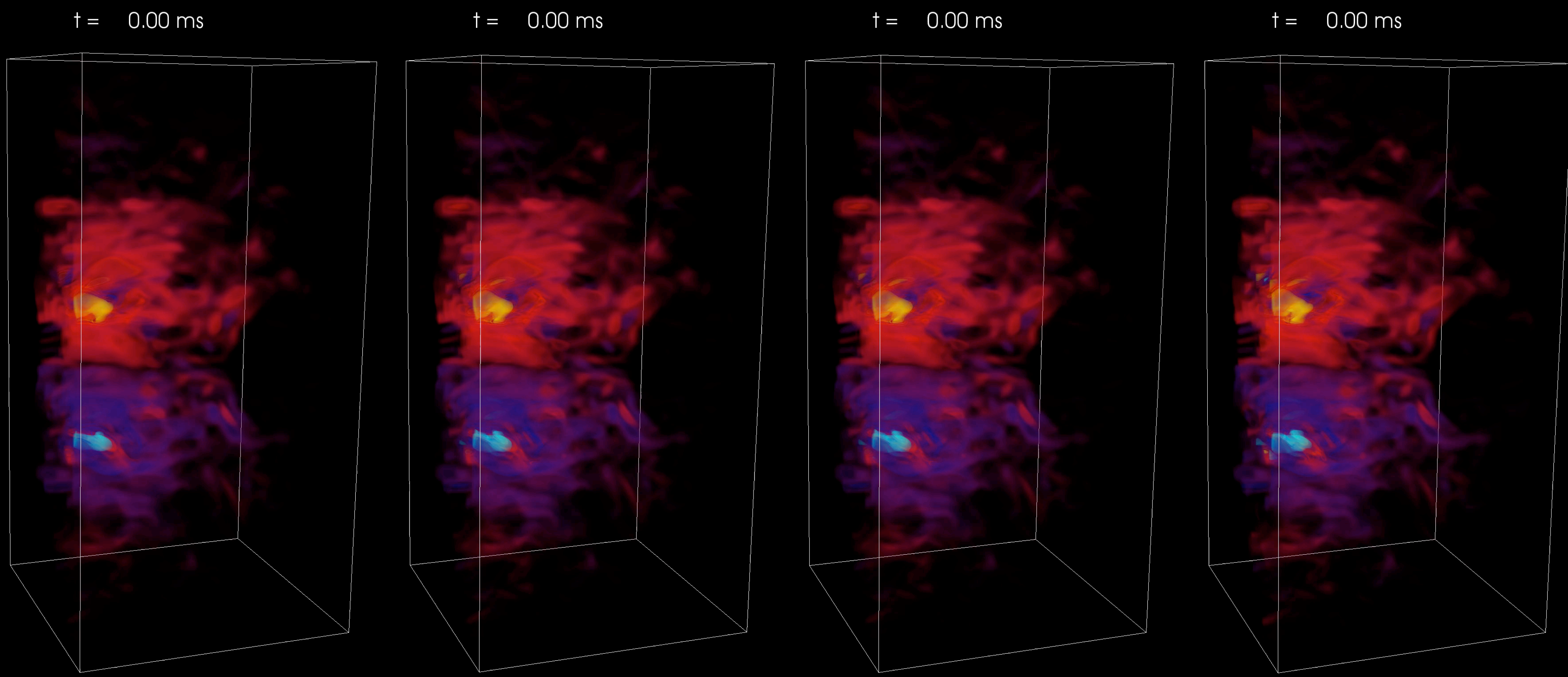
- Does the MRI efficiently build up dynamically relevant field?
- Saturation field strength? Global field structure?

NSF

Global Field Structure

Caltech

Mösta+15, Nature



dx = 500 m   dx = 200 m   dx = 100 m   dx = 50 m

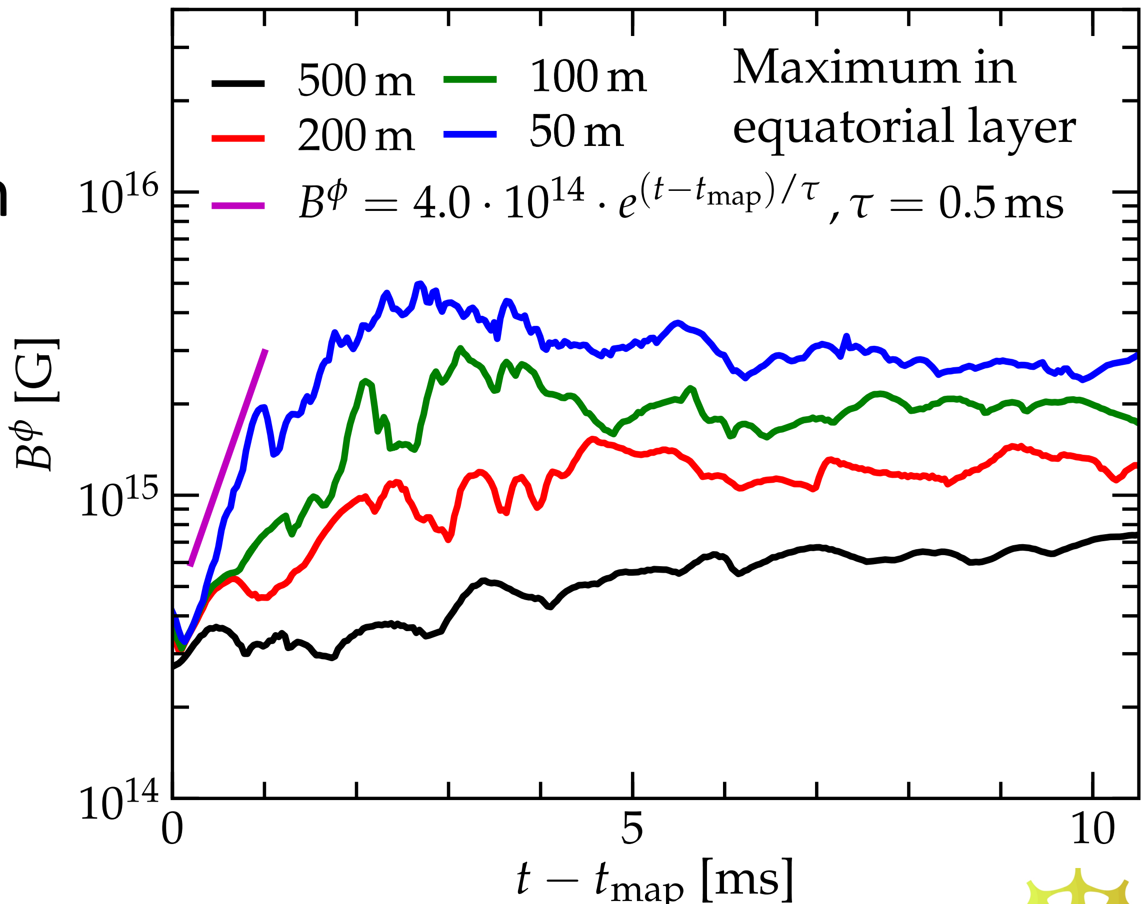
BLUE WATERS
SUSTAINED PETASCALE COMPUTING

NSF

Local Magnetic Field Saturation

Mösta+15, Nature

- Initial exponential growth resolved with 100m/50m simulations.
- Saturated turbulent state within 5 ms.

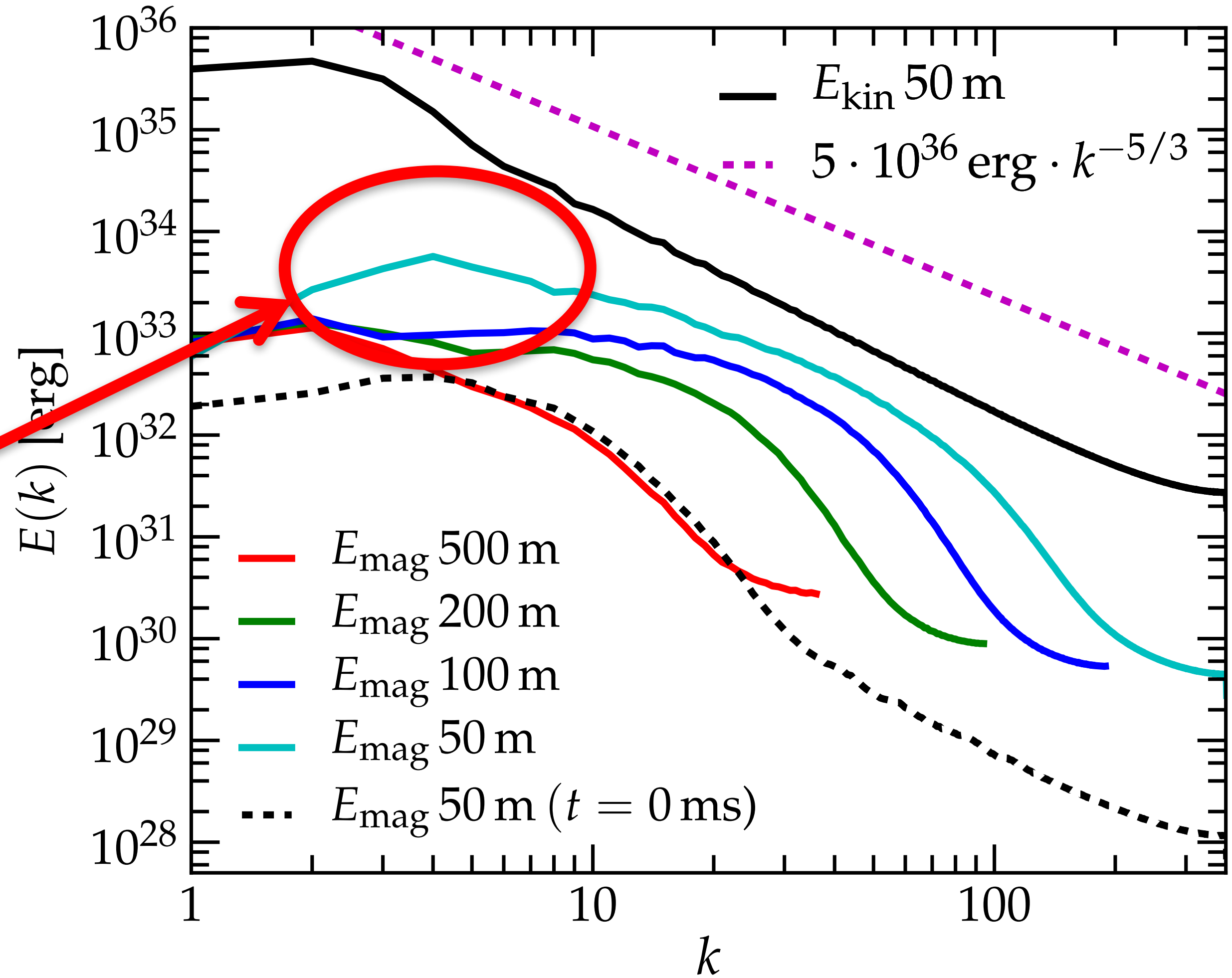


Energy Spectra

Mösta+15, Nature

Caltech

Inverse Cascade: Dynamo!



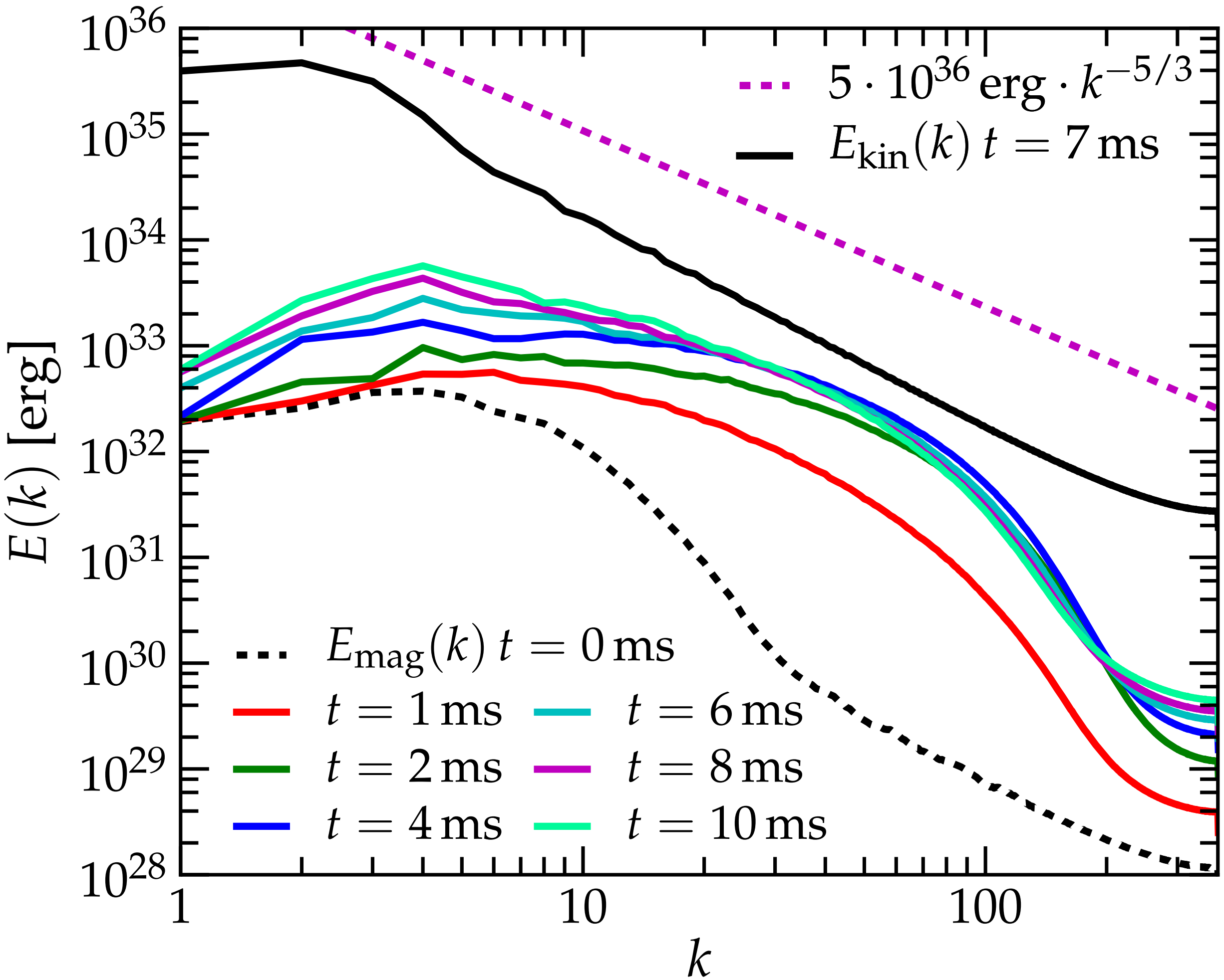
Magnetic energy spectrum very resolution dependent.

BLUE WATERS SUSTAINED PETASCALE COMPUTING

NSF

Energy Spectra

Mösta+15, Nature

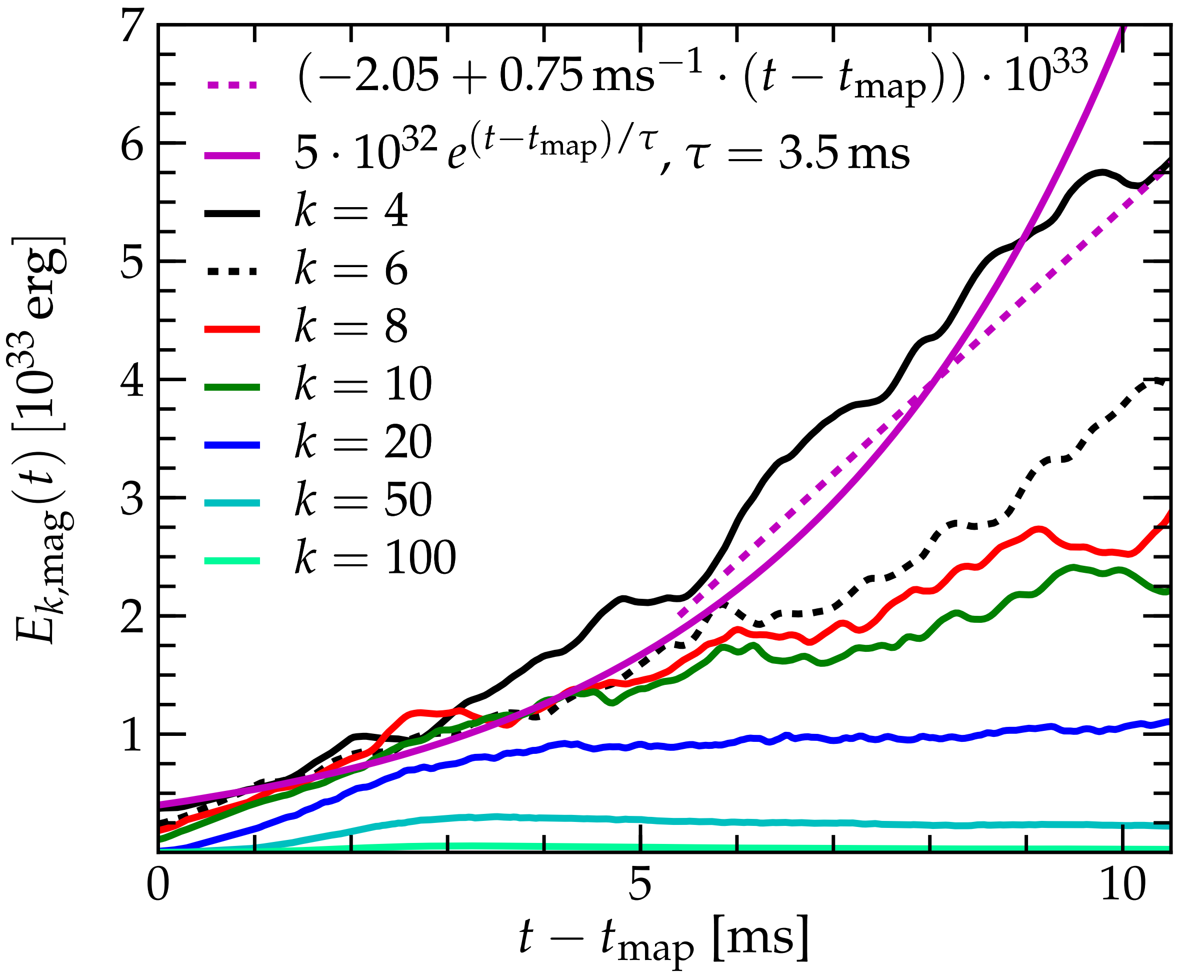


- Turbulent saturated state after ~3 ms.
- Inverse cascade (dynamo) afterwards.

B-Field Growth at Large Scales

Mösta+15, Nature

- k=4; corresponding roughly to width of shear layer
- Field will grow to saturation at large scales within ~60 ms.



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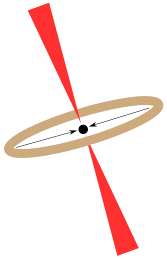
BLUE WATERS
SUSTAINED PETASCALE COMPUTING

NSF

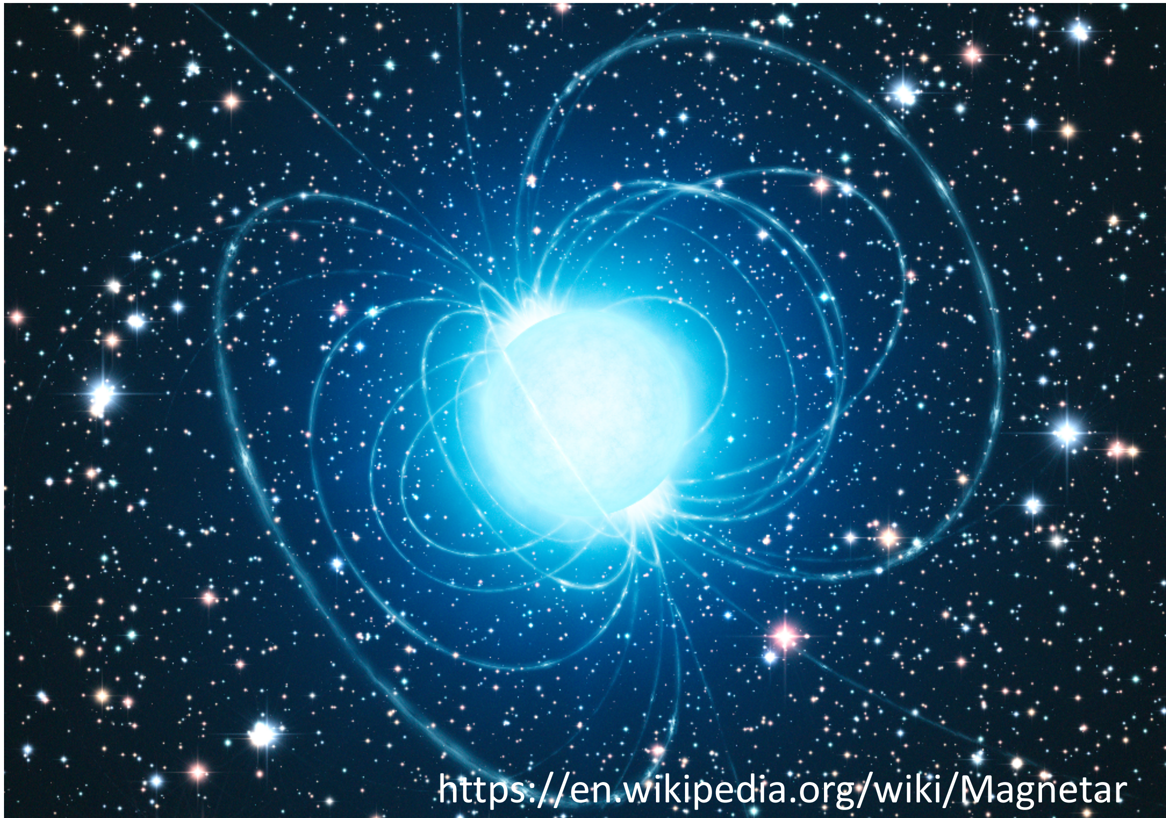
Implications: Magnetars, Hypernovae, GRBs

- MRI+dynamo -> prompt formation of "proto-magnetar."



-> magnetorotational explosions possible -> hypernovae?
-> could drive relativistic jet at late times -> GRB? (Metzger+11)

Artist's impression of the magnetar in Westerlund 1



- Power "superluminous supernovae"? (Kasen & Bildsten 10)
- ~10% of Milky Way neutron stars are magnetars.

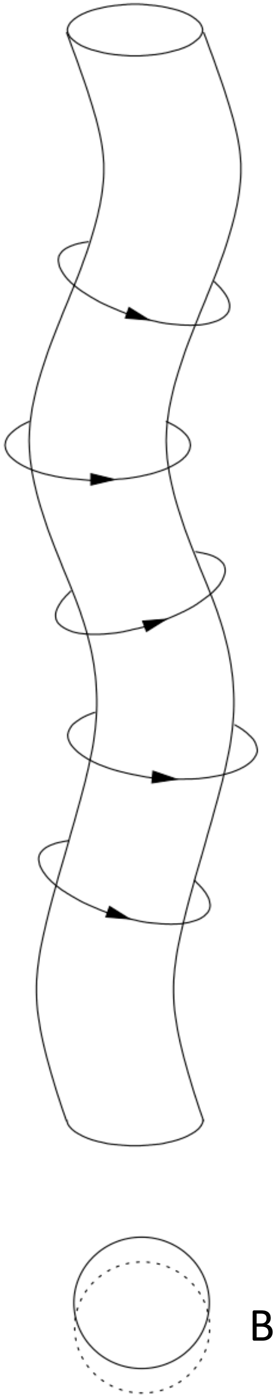
What is happening here?

Mösta+14, ApJL

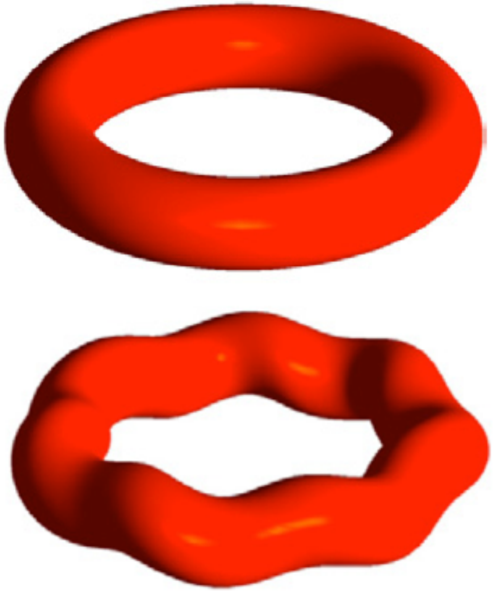
Philipp Mösta

Sherwood Richers

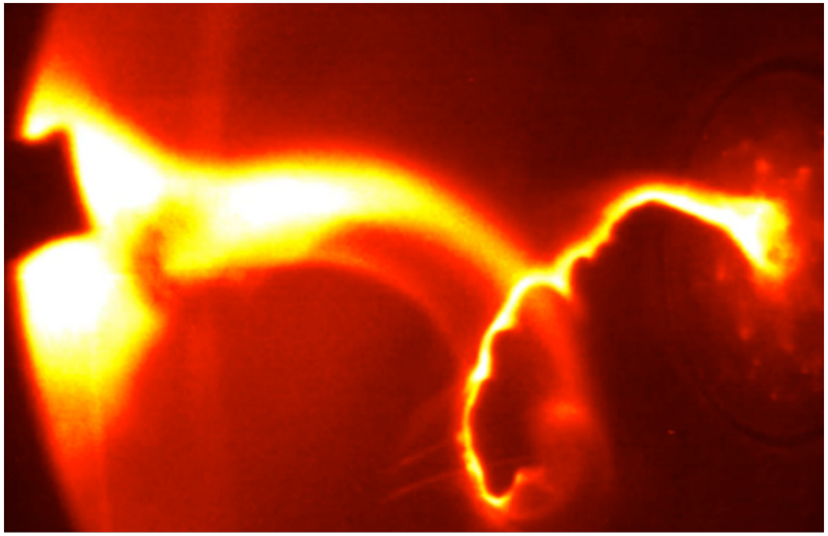
- B-field near proto-NS: $B_{tor} >> B_z$
- Unstable to MHD screw-pinch **kink** instability.
- Similar to situation in Tokamak fusion reactors!



Braithwaite+ '06

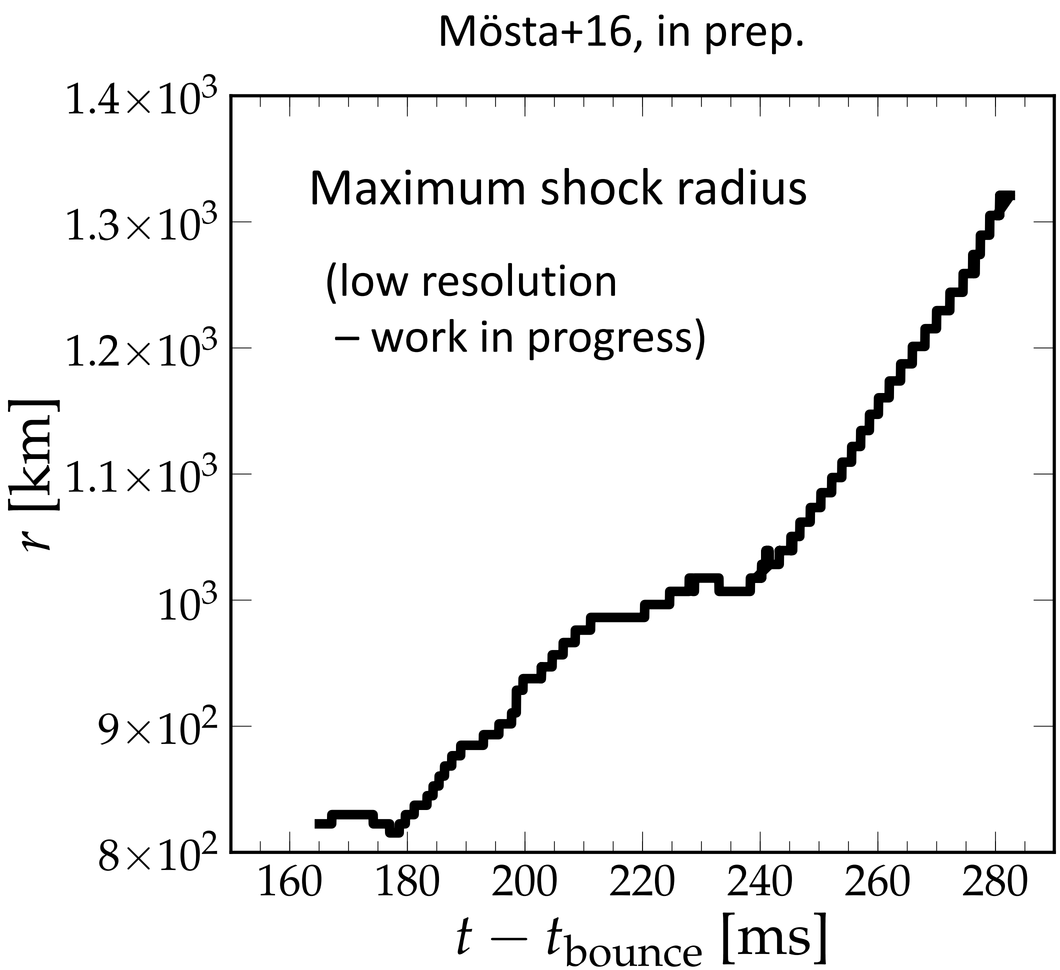


Sarff+13

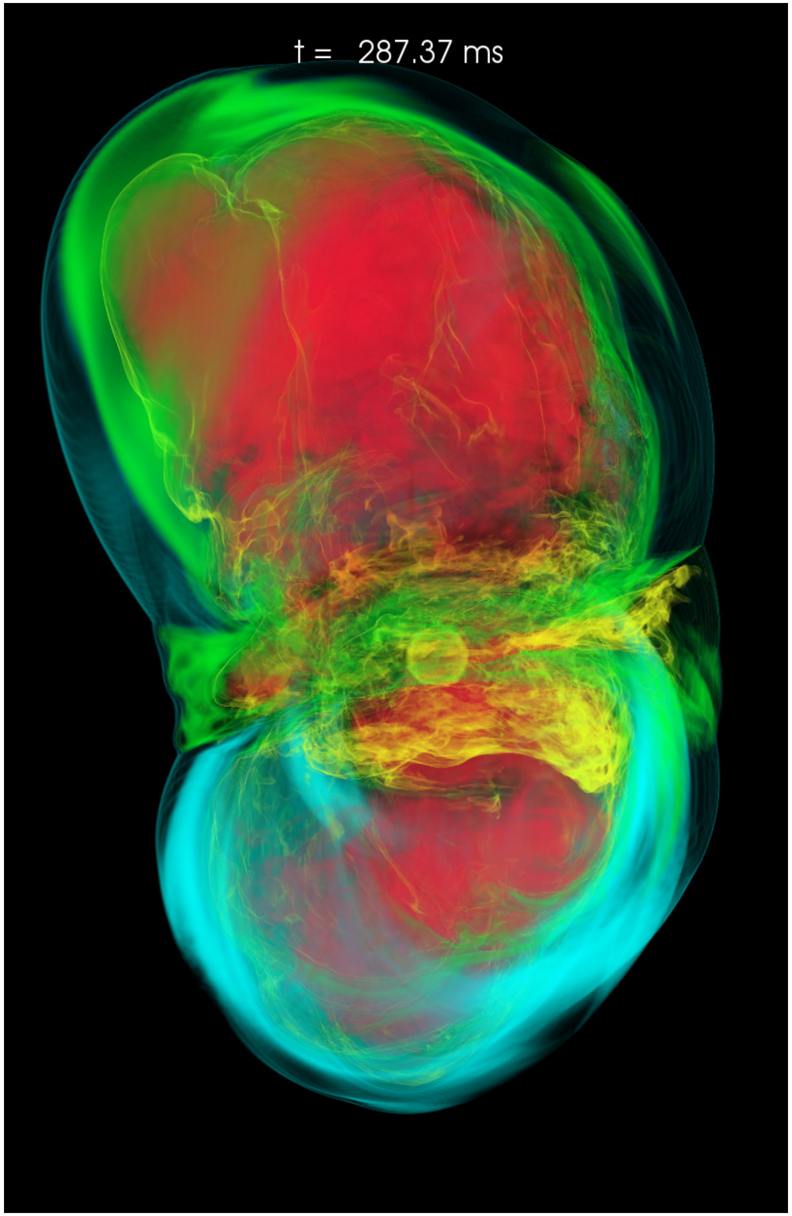


Credit: Moser & Bellan, Caltech

Explosion?



Mösta+16, in prep.
Maximum shock radius
(low resolution
– work in progress)
1.4×10³
1.3×10³
1.2×10³
1.1×10³
10³
9×10²
8×10²
r [km]
160
180
200
220
240
260
280
t − t_bounce [ms]



t = 287.37 ms

t =   -4.95 ms

Mösta+ 2014
ApJL
Plasma β

$$\beta = \frac{P_{\rm gas}}{P_{\rm mag}}$$

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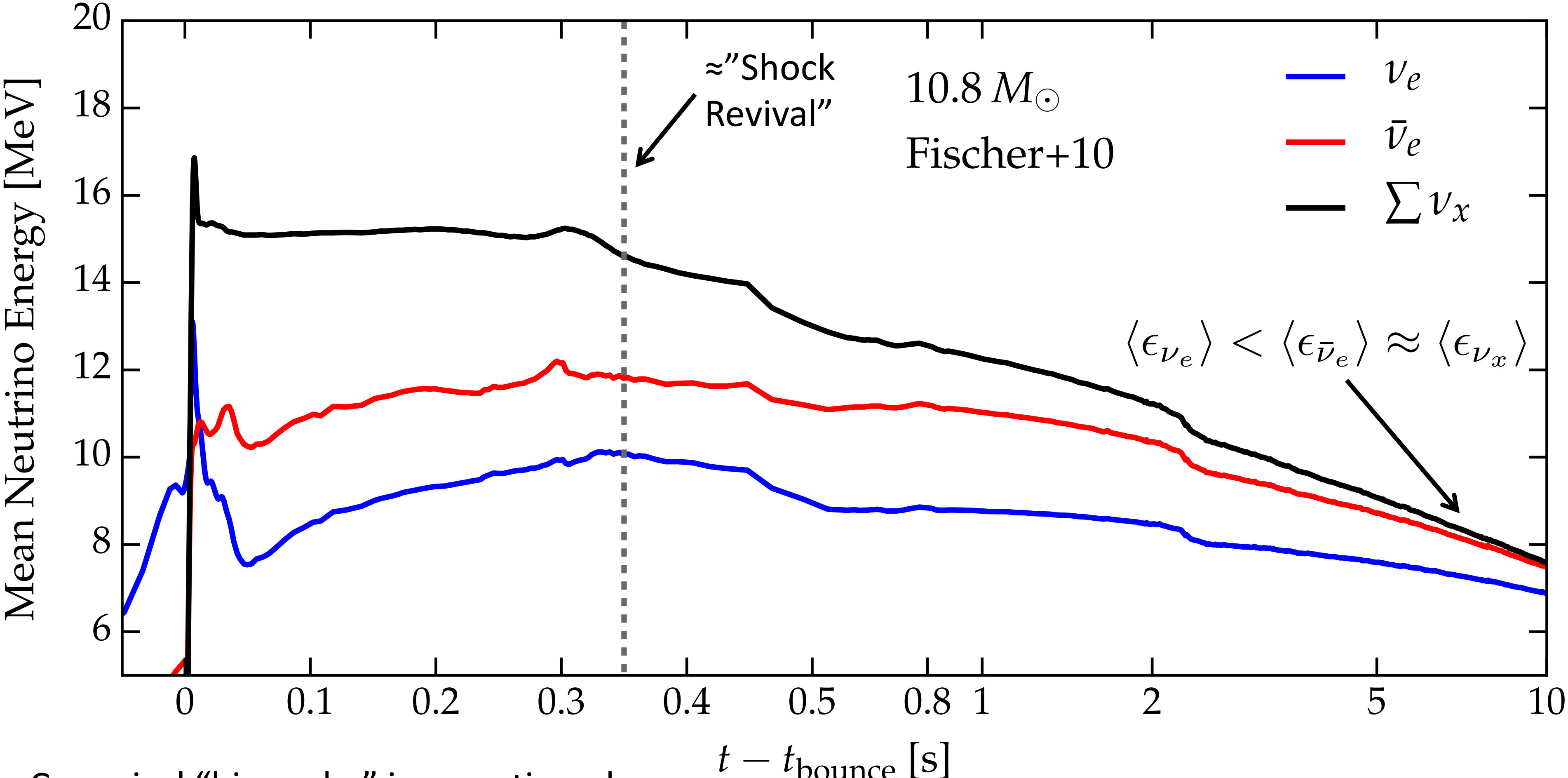
Neutrinos: Mean Energies



Canonical "hierarchy" in accretion phase:

$$\langle \epsilon_{\nu_e} \rangle < \langle \epsilon_{\bar{\nu}_e} \rangle < \langle \epsilon_{\nu_x} \rangle$$

(at least at early times & lower-mass stars)

$$\langle \epsilon_{\nu_e} \rangle < \langle \epsilon_{\nu_x} \rangle \lesssim \langle \epsilon_{\bar{\nu}_e} \rangle$$

(late accretion phase, more massive stars)