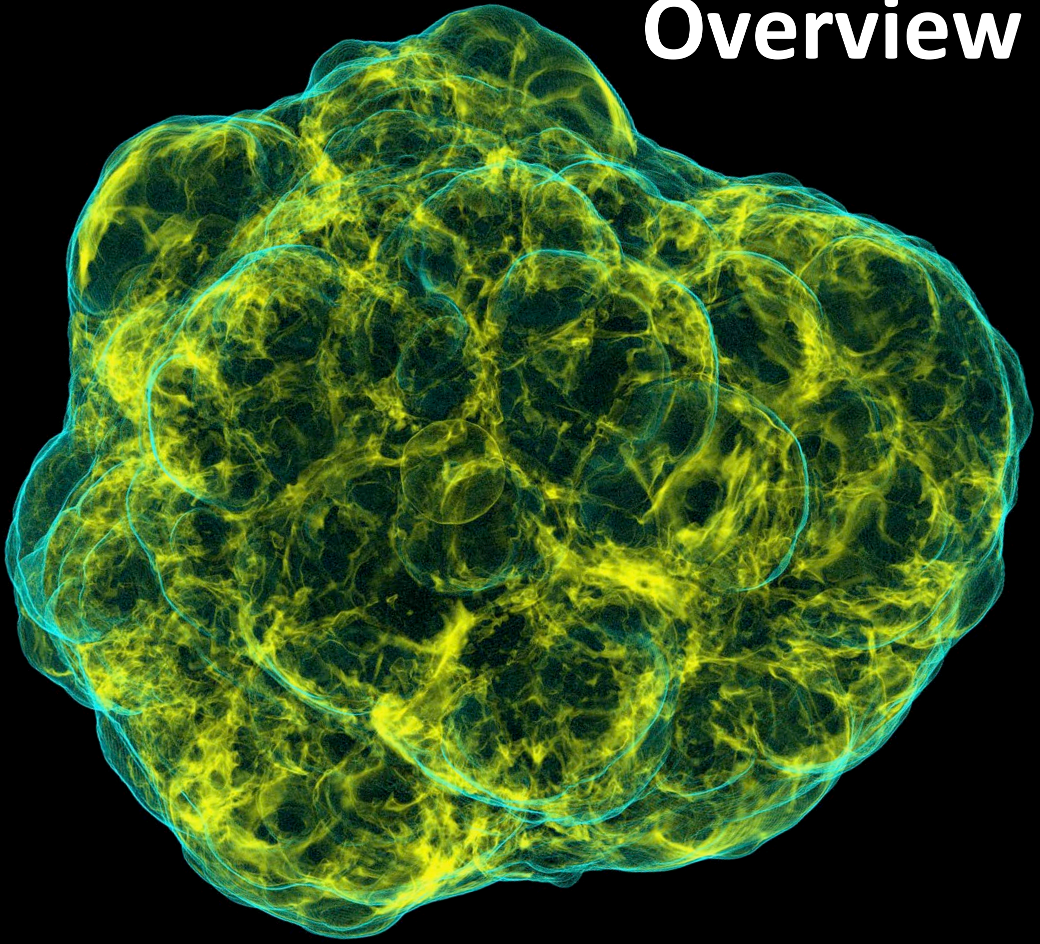
Core-Collapse Supernova Simulations: Overview & Status



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Caltech

OAK RIDGE
National Laboratory

Core-Collapse Supernovae:

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

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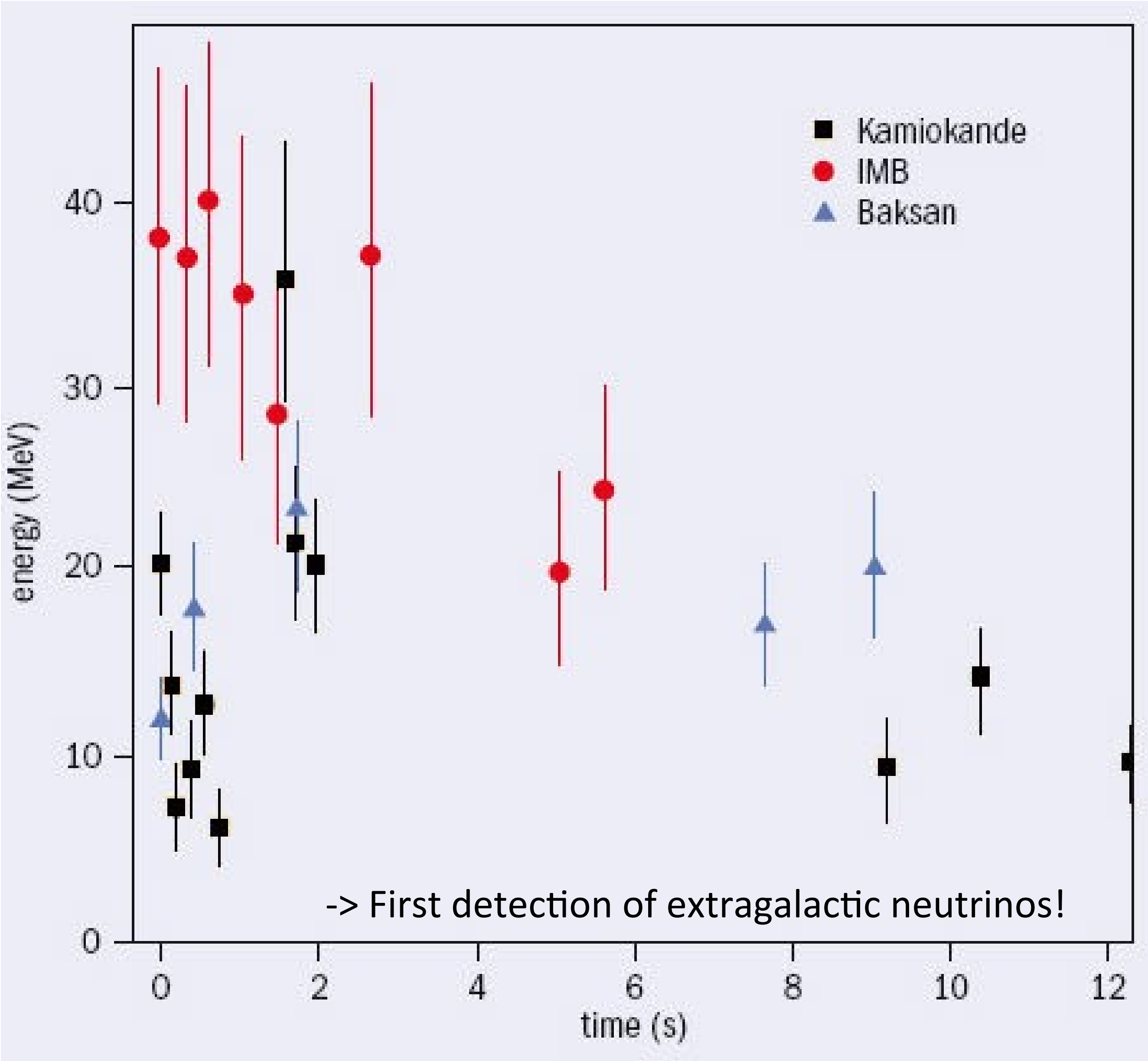
Supernova 1987A
Large Magellanic Cloud
Progenitor:
BSG Sanduleak -69° 220a, ≈18 M_{SUN}

SN 1987A: Neutrino Detection

Hirata+87
Bionta+87



-> First detection of extragalactic neutrinos!

Stellar Death & Supernova Explosions

- ~10 SN/s in the Universe
- ~multiple 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

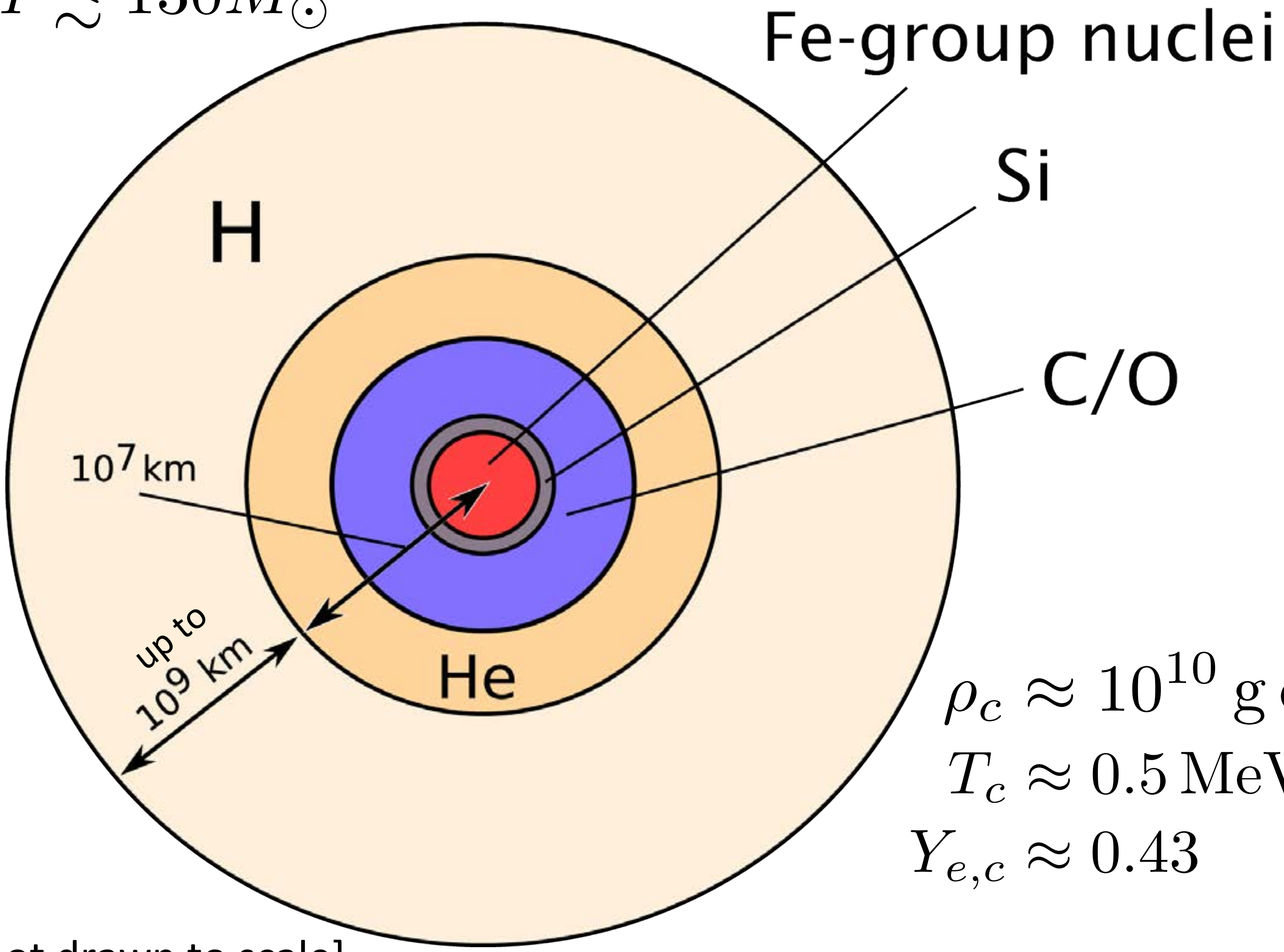
- Class of energetic "stripped-envelope" explosions: Type Ic-bl ("broad lines")
- Some (>11) SNe Ic-bl associated with long gamma-ray bursts.

Chandra

G1.9+0.3
Explosion ~140 yrs ago.
@ 8 kpc in Sgr

The Basic Theory of Core Collapse

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

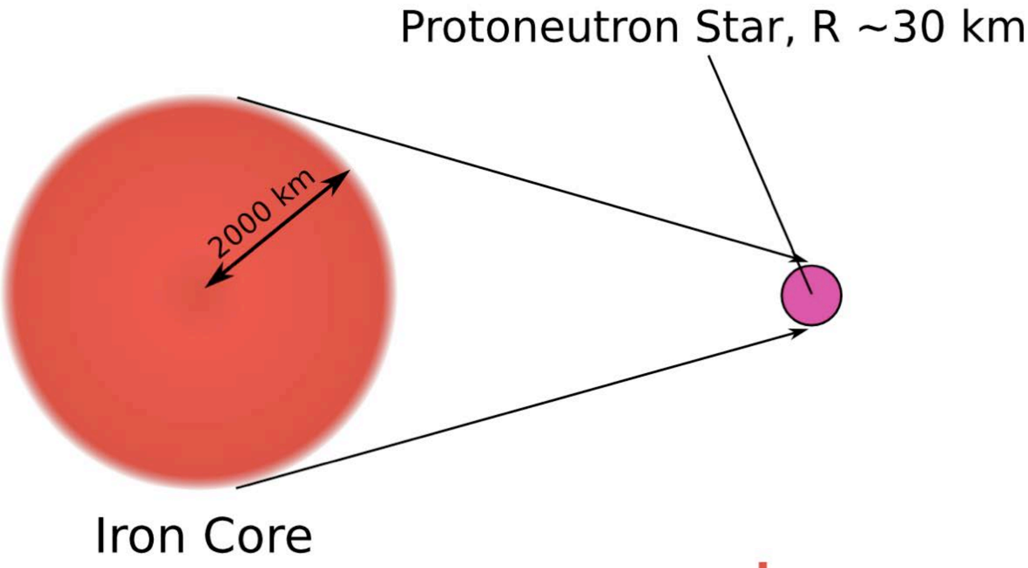


[not drawn to scale]

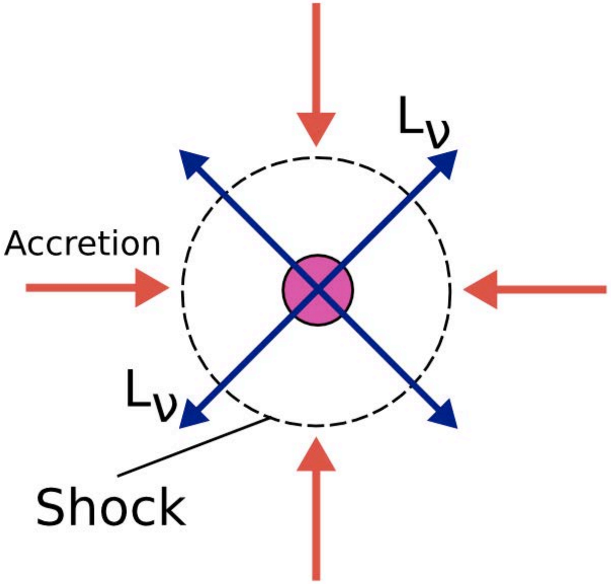
$$\rho_c \approx 10^{10}\,\mathrm{g\,cm^{-3}}$$
$$T_c \approx 0.5\,\mathrm{MeV}$$
$$Y_{e,c} \approx 0.43$$

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

Reminder: Core Collapse Basics



Reviews:
Bethe'90
Janka+'12



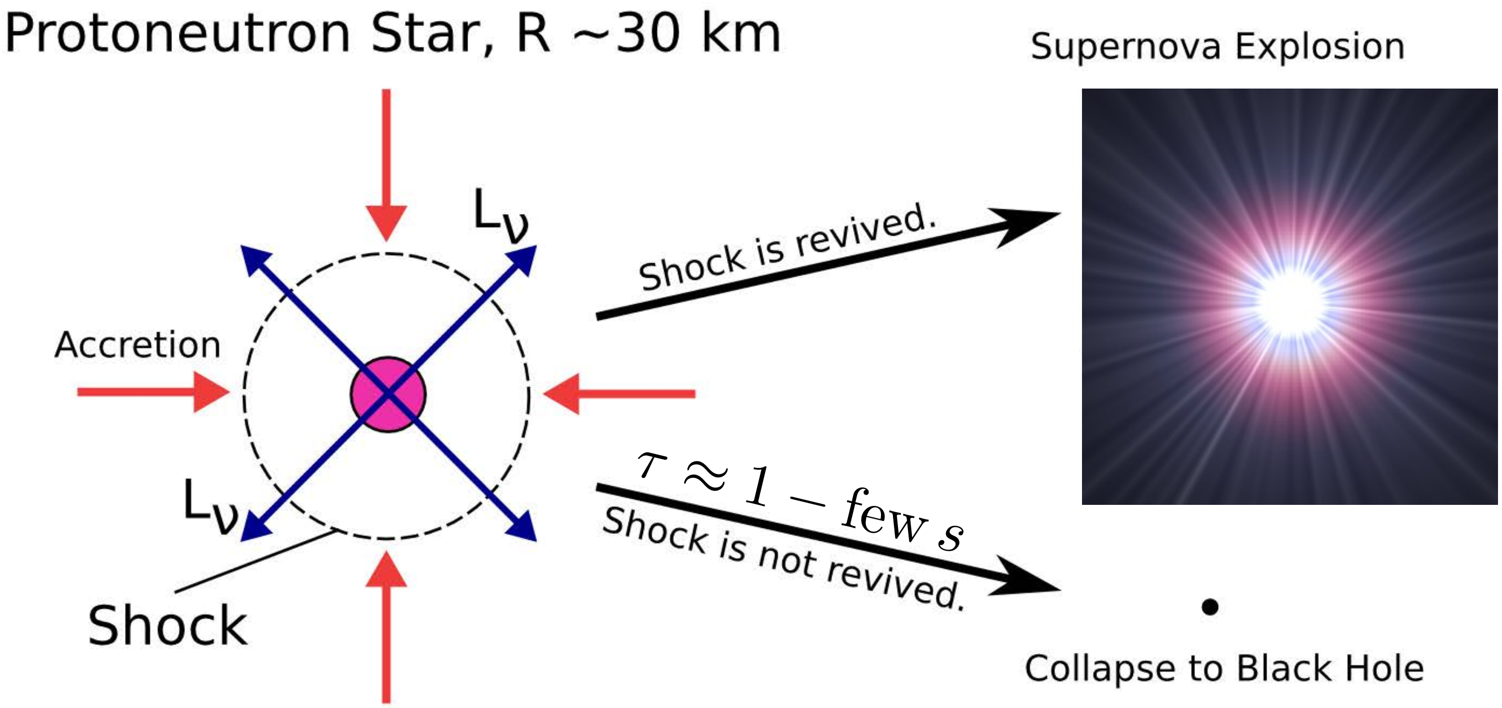
Nuclear equation of state (EOS) stiffens at nuclear density.

Inner core (~0.5 M_{Sun})
-> protoneutron star core.
Shock wave formed.

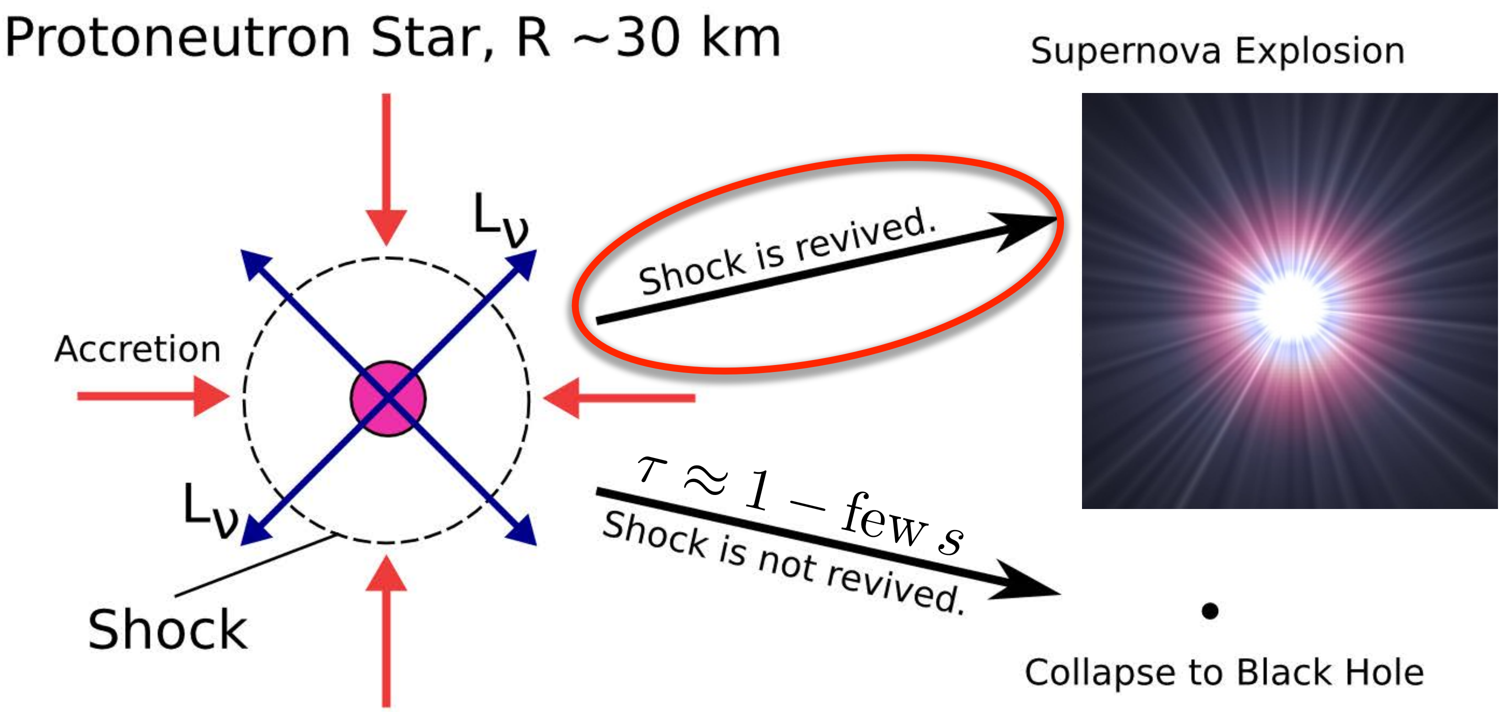
Outer core accretes onto shock & protoneutron star with O(1) $M_{\odot}$/s.

-> **Shock stalls at ~100 km, must be "revived" to drive explosion.**

“Postbounce” Evolution



"Postbounce" Evolution



What is the mechanism that revives the shock?

Core-Collapse Supernova Energetics

- Collapse to a neutron star: ~3 x 10^{53} erg = 300 [B]ethe **gravitational energy** (≈0.15 $M_{Sun}c^2$).
  -> 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 on $\mathcal{O}$(10)s

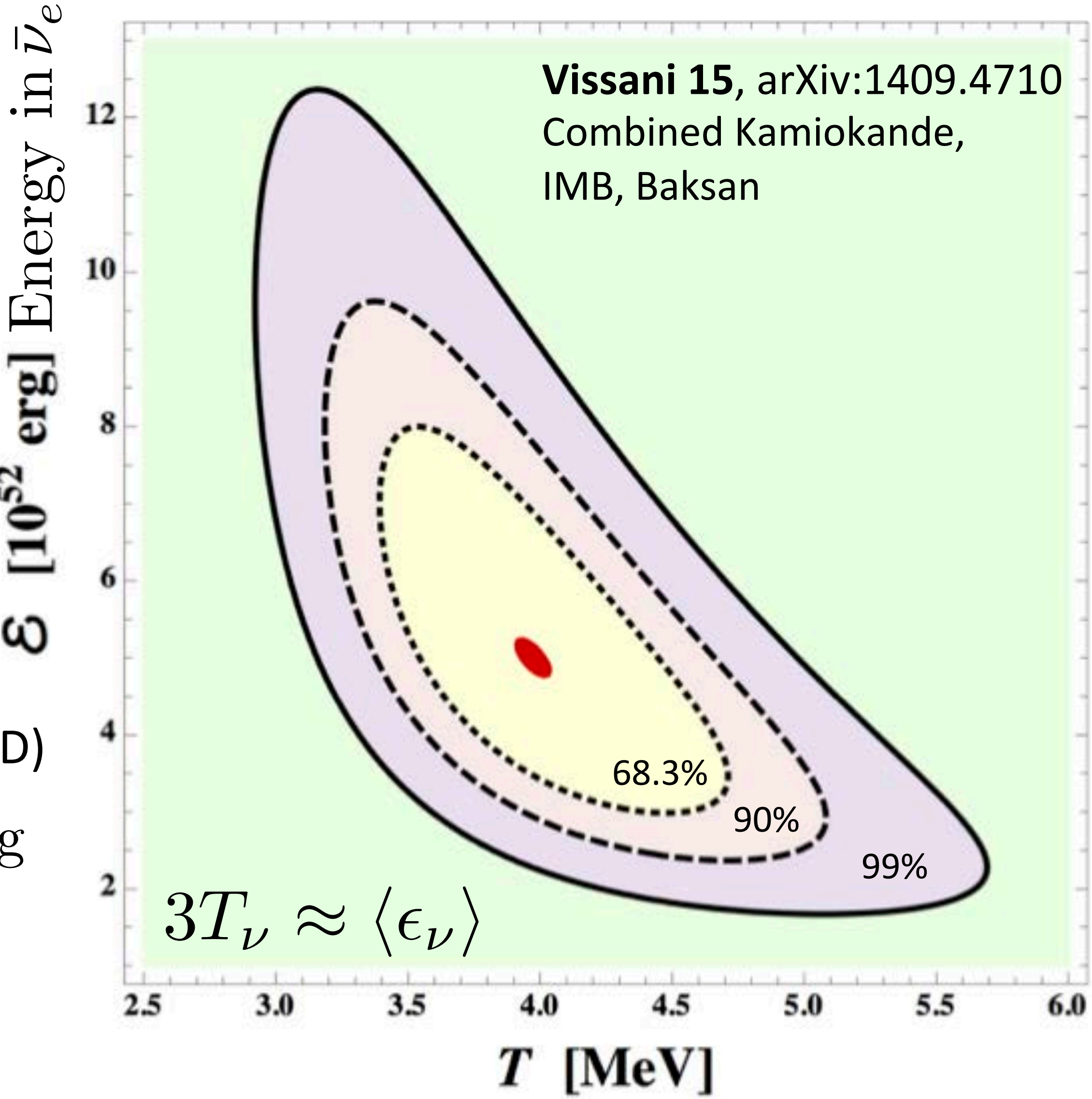
SN 1987A & Basics of CCSN Theory

SN 1987A

Kamiokande II,
IMB, Baksan:

$$\bar{\nu}_e + p \rightarrow n + e^+ \text{ (IBD)}$$

$$E_{\text{tot}} \approx 6\mathcal{E} \approx 3 \times 10^{53}\,\text{erg}$$



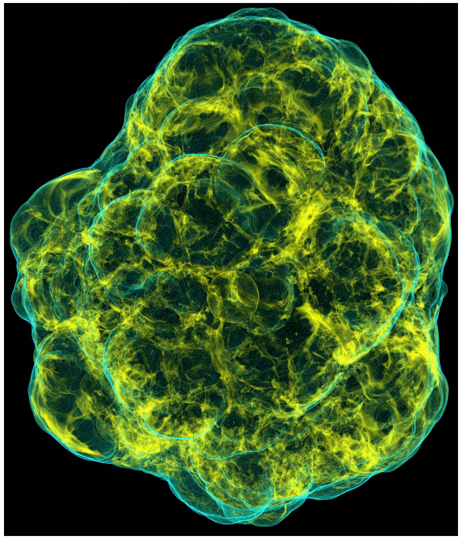
Vissani 15, arXiv:1409.4710
Combined Kamiokande,
IMB, Baksan

$$3T_\nu \approx \langle \epsilon_\nu \rangle$$

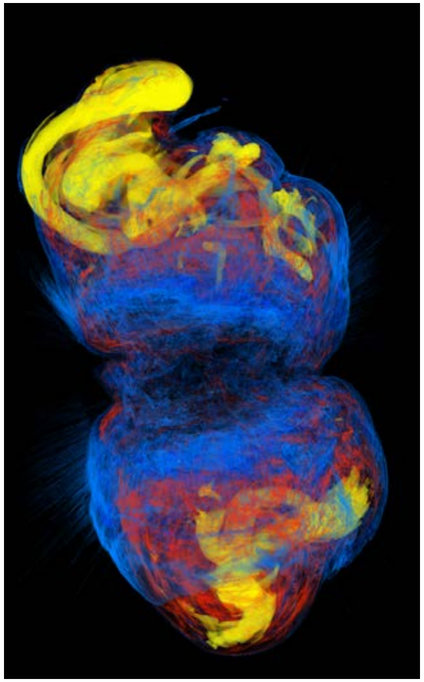
Overview: Supernova Mechanisms

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 structure.
- Inefficient ($\eta \lesssim 10\%$); difficulty explaining $E_{explosion}$?



Ott+13



Mösta+14

Magnetorotational Mechanism

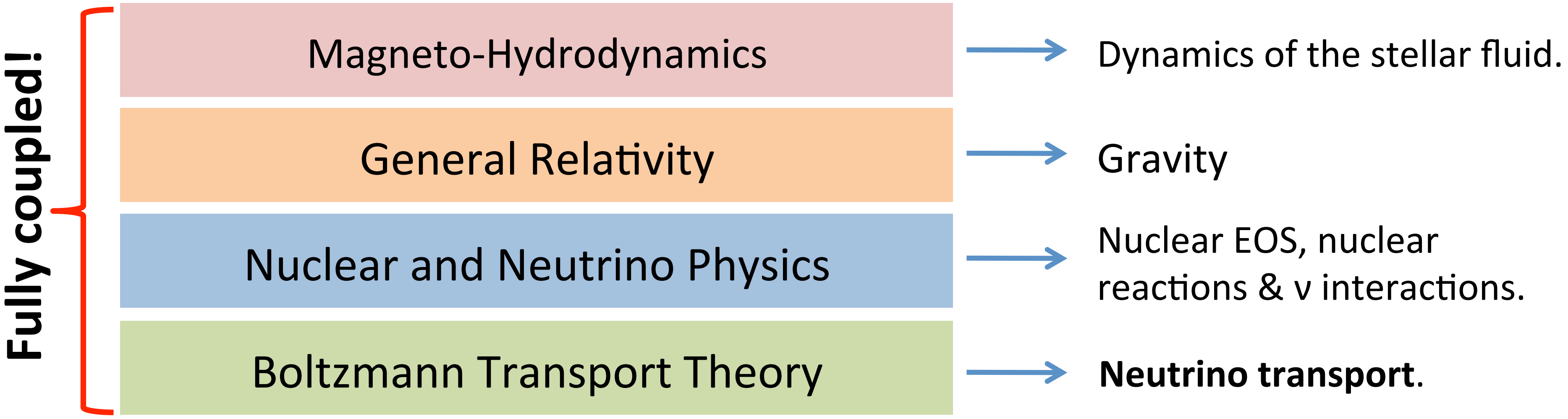
- Magneto-centrifugal forcing, hoop stresses.
- For energetic explosions and CCSN-LGRB connection?
- Very rapid core rotation + magnetorotational instability + dynamo for large-scale field.
- Needs "special" progenitor evolution.
- Jets unstable, may fail to explode in proto-NS phase; black hole formation,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

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.

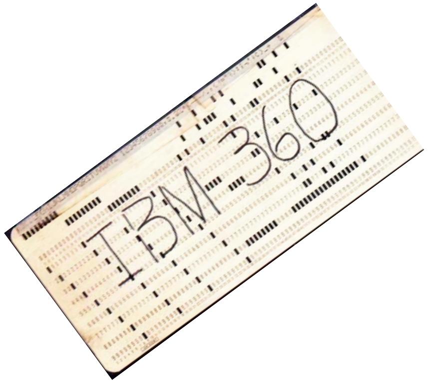
Boltzmann Transport Theory → **Neutrino transport**.

- Additional Complication: **Core-Collapse Supernovae are 3D**
  - Rotation, **fluid instabilities**, **magnetic fields**, multi-D stellar structure from convective burning, etc.

- Route of Attack: **Computational simulation.**
  - Full problem is 3 (space) + 3 (momentum space) + 1 (time) dimensional
  - Approach: employ reduced dimensionality in space and momentum space.

Core-Collapse Supernova Simulations

1D (spherical symmetry)



- First simulations: 1960-70 by Colgate & White,
  Wilson, Arnett, Nadyozhin

- Bethe & Wilson '85: "**Neutrino Mechanism**"

Cray-I

Neutrino Mechanism: Heating

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

Cooling:

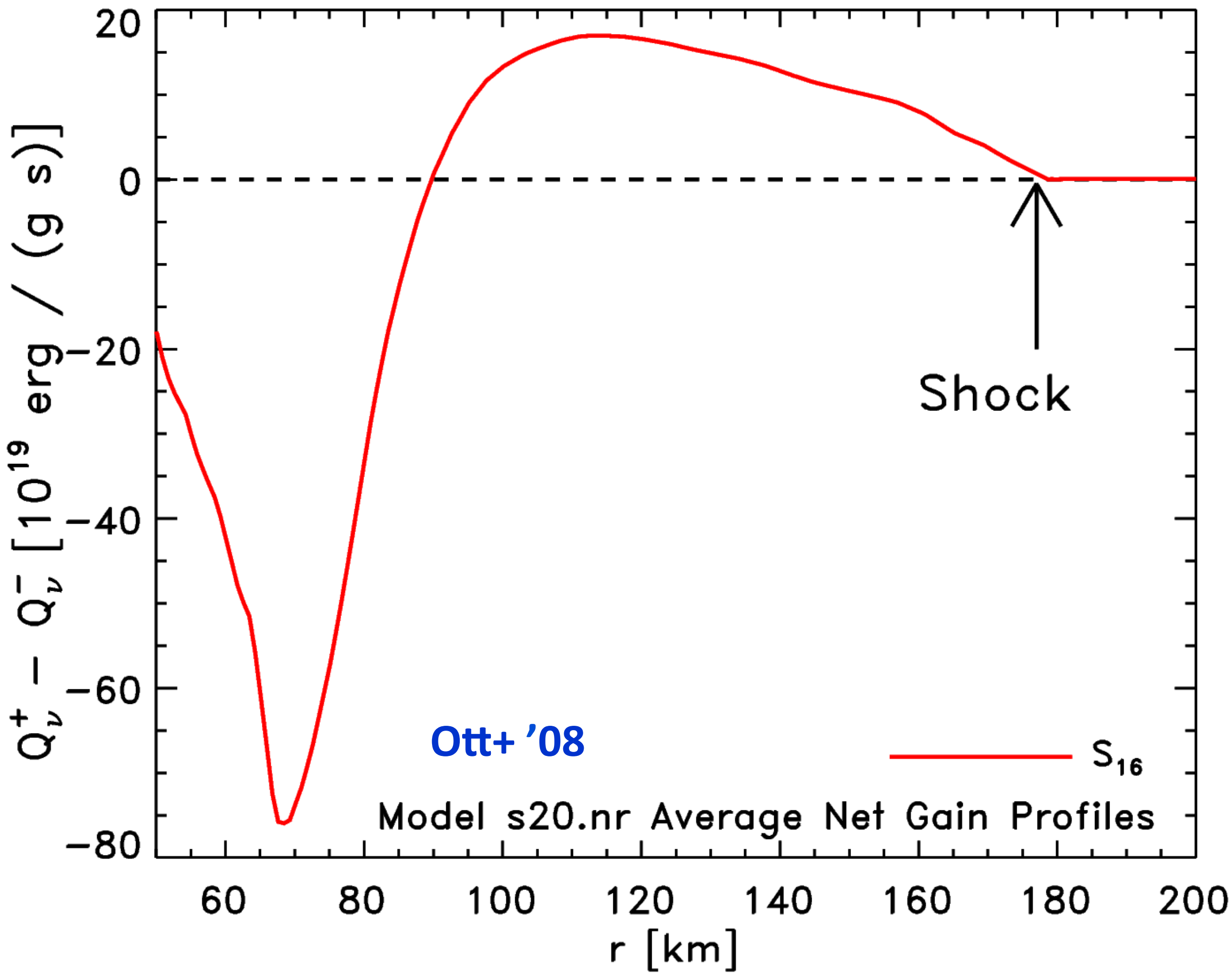
$$Q_\nu^- \propto T^6, T^9$$

Heating via charged-current absorption:

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

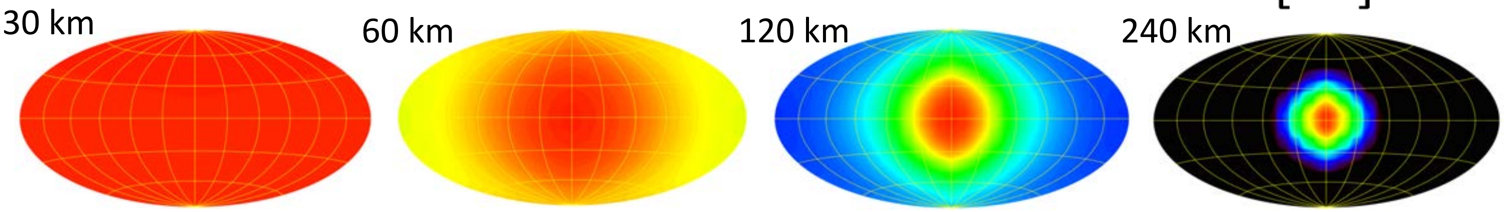
$$\bar{\nu}_e + p \rightarrow n + e^+$$

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



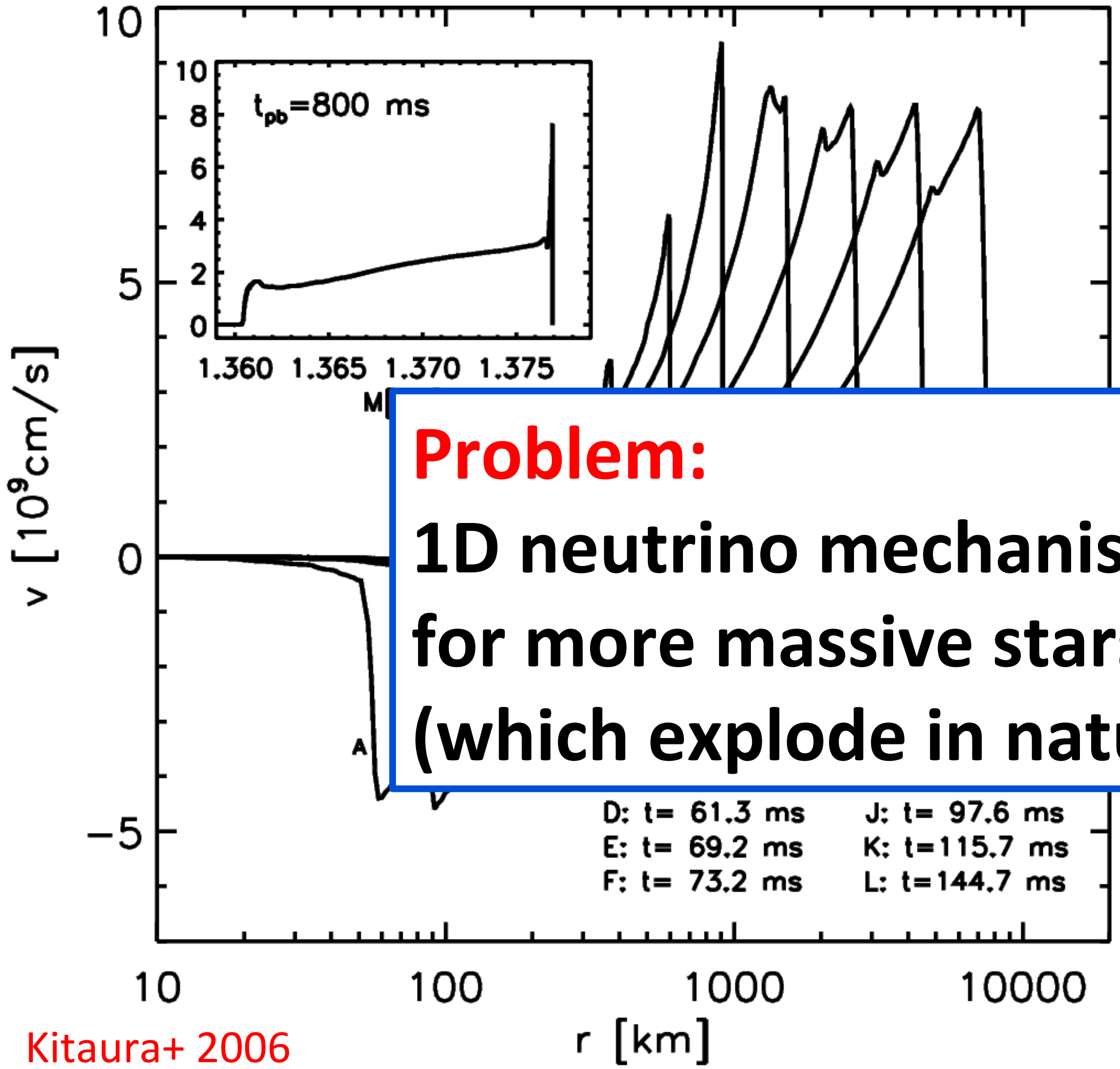
Ott+ ’08

Neutrino radiation field:



1D Neutrino-Driven Explosions

Kitaura+ ‘06, Hüdepohl+ ’10, Fischer+ ’10, ‘12



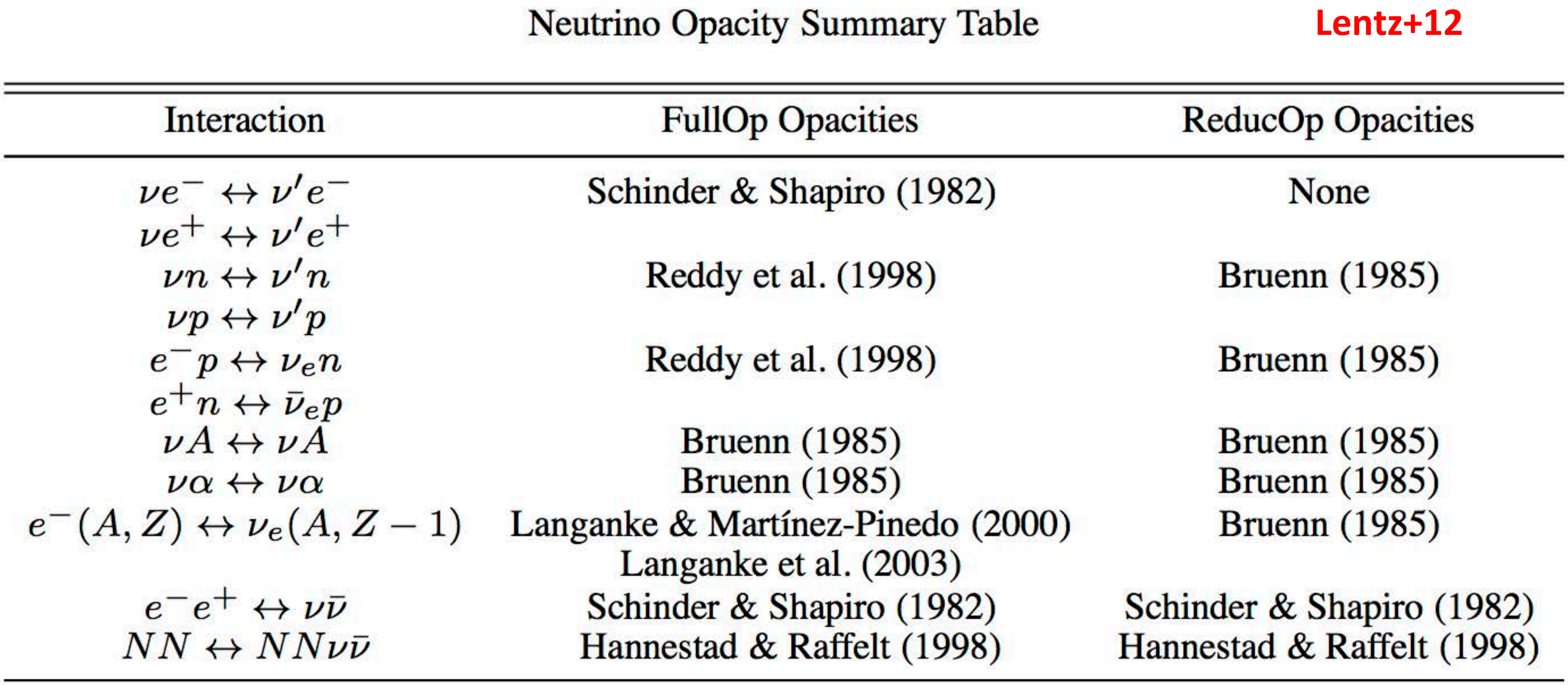
Problem:
1D neutrino mechanism fails for more massive stars (which explode in nature).

8.8 M_{SUN} progenitor star
O-Ne-Mg core

Kitaura+ 2006

Status: 1D Simulations

- Full physics 1D simulations: 2000s –> no explosions!
- Current codes: spectral transport, differences in included microphysics (->effects on ν spectra). **Some can simulate O(10)s**.



Neutrino Opacity Summary Table

Lentz+12

Interaction	FullOp Opacities	ReducOp Opacities
$\nu e^- \leftrightarrow \nu' e^-$	Schinder & Shapiro (1982)	None
$\nu e^+ \leftrightarrow \nu' e^+$		
$\nu n \leftrightarrow \nu' n$	Reddy et al. (1998)	Bruenn (1985)
$\nu p \leftrightarrow \nu' p$		
$e^- p \leftrightarrow \nu_e n$	Reddy et al. (1998)	Bruenn (1985)
$e^+ n \leftrightarrow \bar{\nu}_e p$		
$\nu A \leftrightarrow \nu A$	Bruenn (1985)	Bruenn (1985)
$\nu \alpha \leftrightarrow \nu \alpha$	Bruenn (1985)	Bruenn (1985)
$e^-(A, Z) \leftrightarrow \nu_e(A, Z-1)$	Langanke & Martínez-Pinedo (2000)	Bruenn (1985)
	Langanke et al. (2003)	
$e^- e^+ \leftrightarrow \nu \bar{\nu}$	Schinder & Shapiro (1982)	Schinder & Shapiro (1982)
$NN \leftrightarrow NN\nu\bar{\nu}$	Hannestad & Raffelt (1998)	Hannestad & Raffelt (1998)

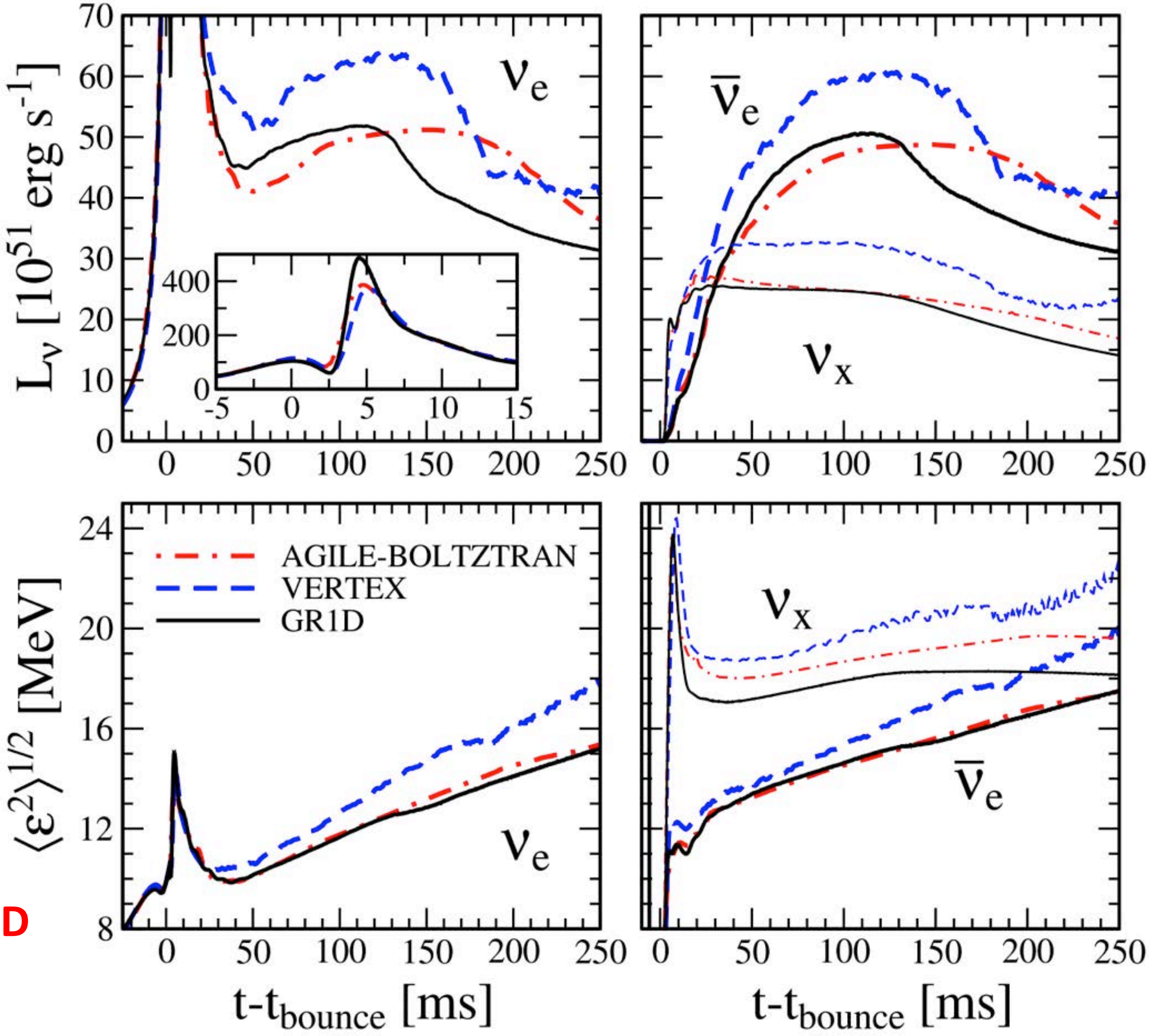
Status: 1D Simulations

Code/Group	Gravity	Transport	X sections	Note	Recent Refs.
Roberts (Caltech/MSU)	GR	GR,Mom+glob. closure	Bruenn 85 / Reddy 99	LT cooling	Roberts 2012
Prometheus-Vertex (Garching)	Approx. GR	Approx. GR,Mom +glob. closure	Full (Lentz+12)	LT cooling	Hüdepohl+10
CoCoNuT-Vertex (Garching/Monash)	GR	Approx. GR,Mom +glob. closure	Full		Müller +10,12,14
Agile-Boltztran (ORNL/Basel/ Wraclaw[Fischer])	GR	GR, Boltzmann	Full (ORNL) or reduced (Fischer)	LT cooling (Fischer)	Lentz+12 Fischer+12
Chimera	Approx. GR	Approx GR, MGFLD	Full		Bruenn +13,15,16
Waseda/Yamada/ Sumiyoshi	GR	GR, Boltzmann or MGFLD	Bruenn 85 + NN/plasmon	LT cooling	Sumiyoshi+05 Nakazato+13
νGR1D (O'Connor, NCSU)	GR	GR, M1	Bruenn 85 + NuLib	open source	O'Connor 15
Fornax (Princeton)	Newt.	Newt., M1	?		Wallace+15

+ several other codes: Pan (Basel), Just/Obergaulinger, Wilson/Mathews, Burrows/Thompson

1D Simulations: Physics Benchmarks

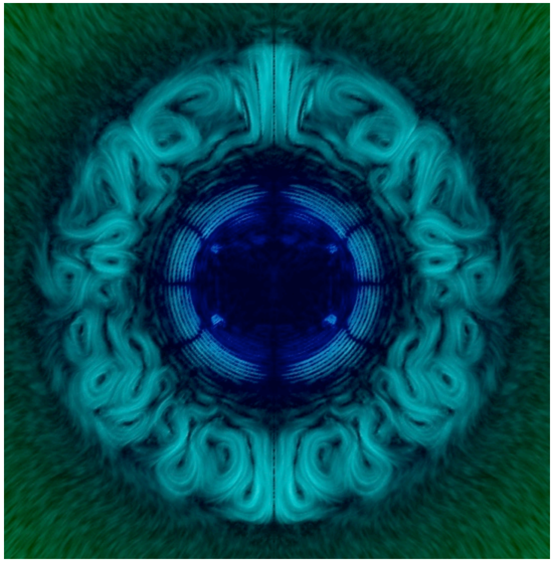
- Liebendörfer+05: First detailed comparison study ORNL-Garching.
- Results available and serve as community benchmark for new codes.



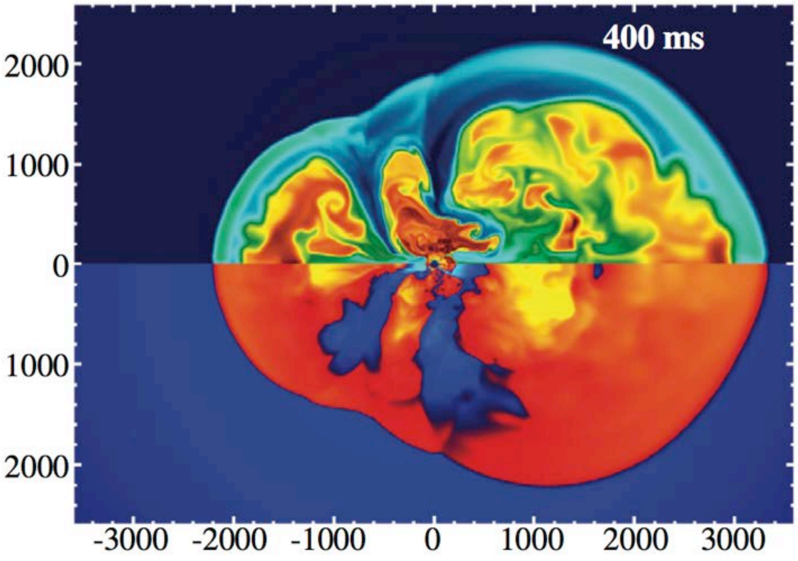
O'Connor 2015, νGR1D

2D and 3D Core-Collapse Supernovae

- **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 fully self-consistent & from first principles.
  E.g.: Bruenn+13,14 (ORNL), Dolence+14 (Princeton), B. Müller+12ab (MPA Garching)
- Simulations to O(1) s after core bounce.



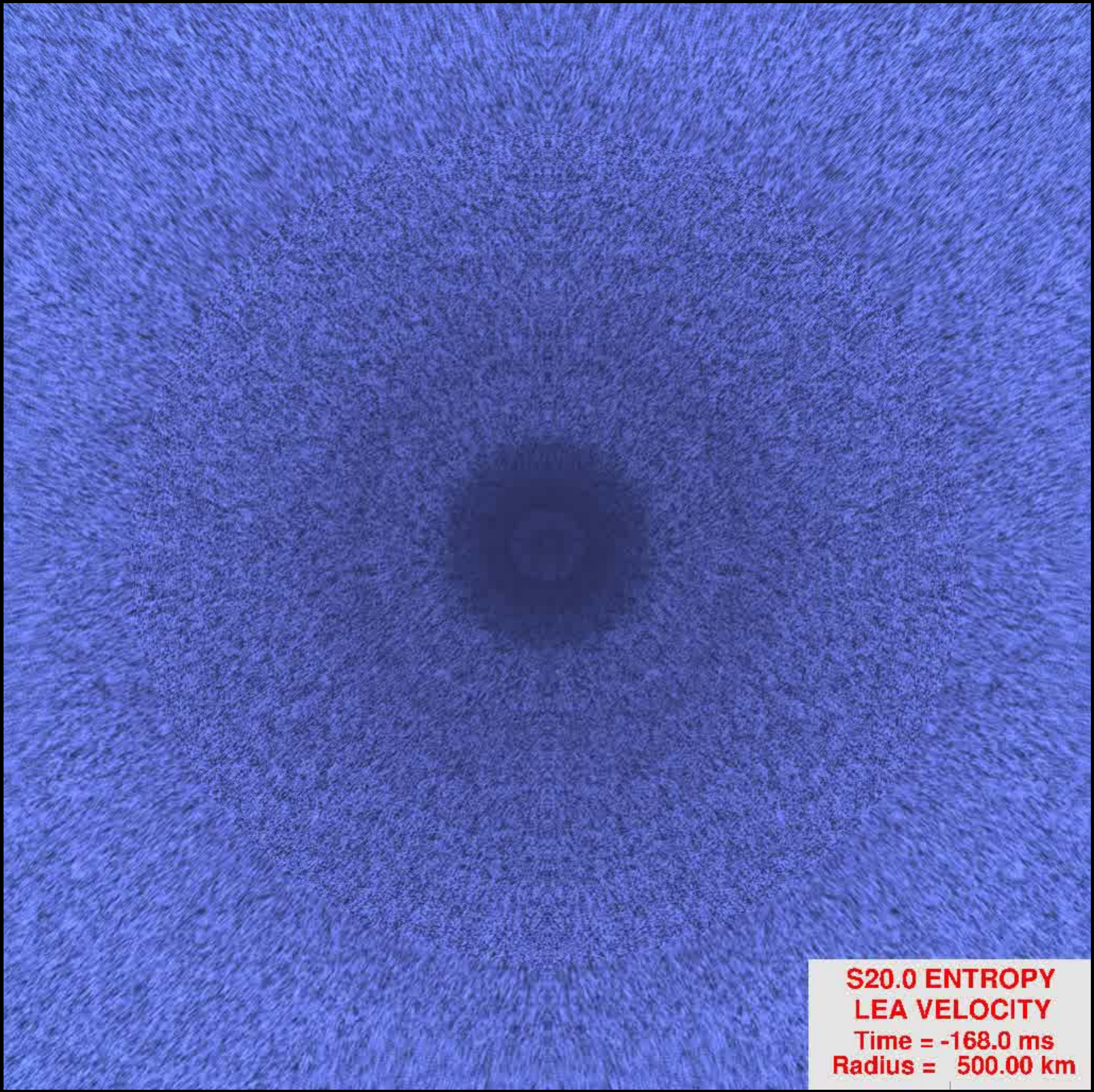
Dessart+05



Bruenn+13

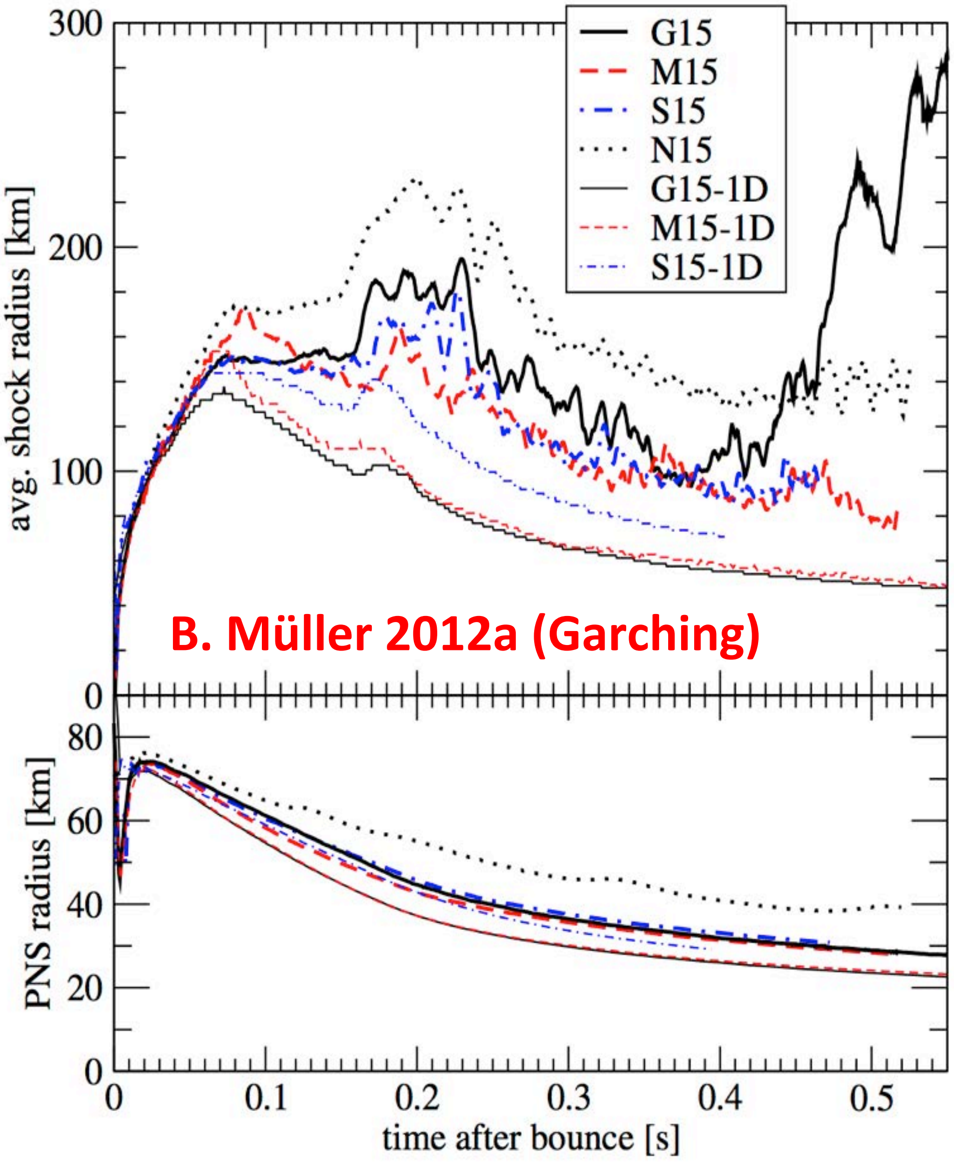
Standing Accretion Shock Instability (SASI)

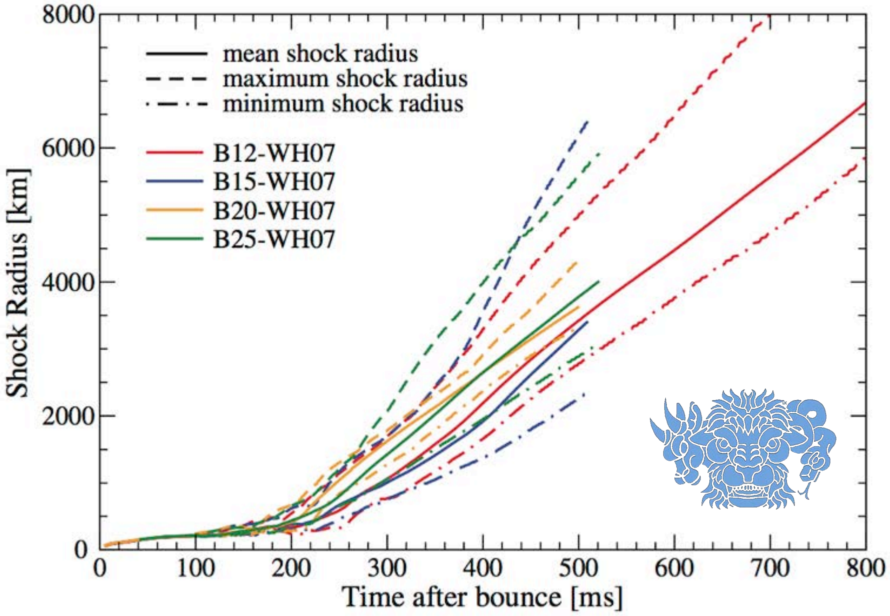
Blondin+'03
Foglizzo+'06
Scheck+ '08
and many
others

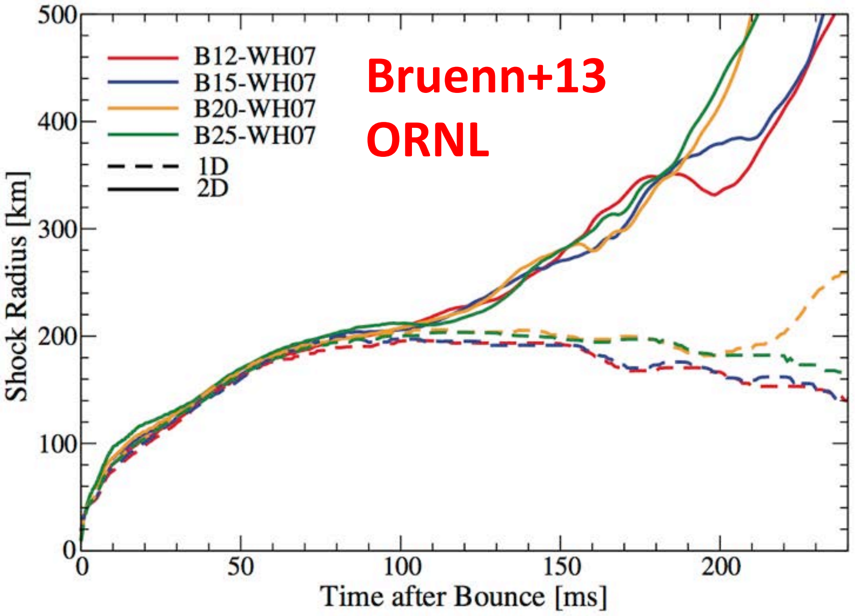


Movie by
Burrows,
Livne,
Dessart,
Ott, Murphy'06

2D Full-Physics CCSN Simulations

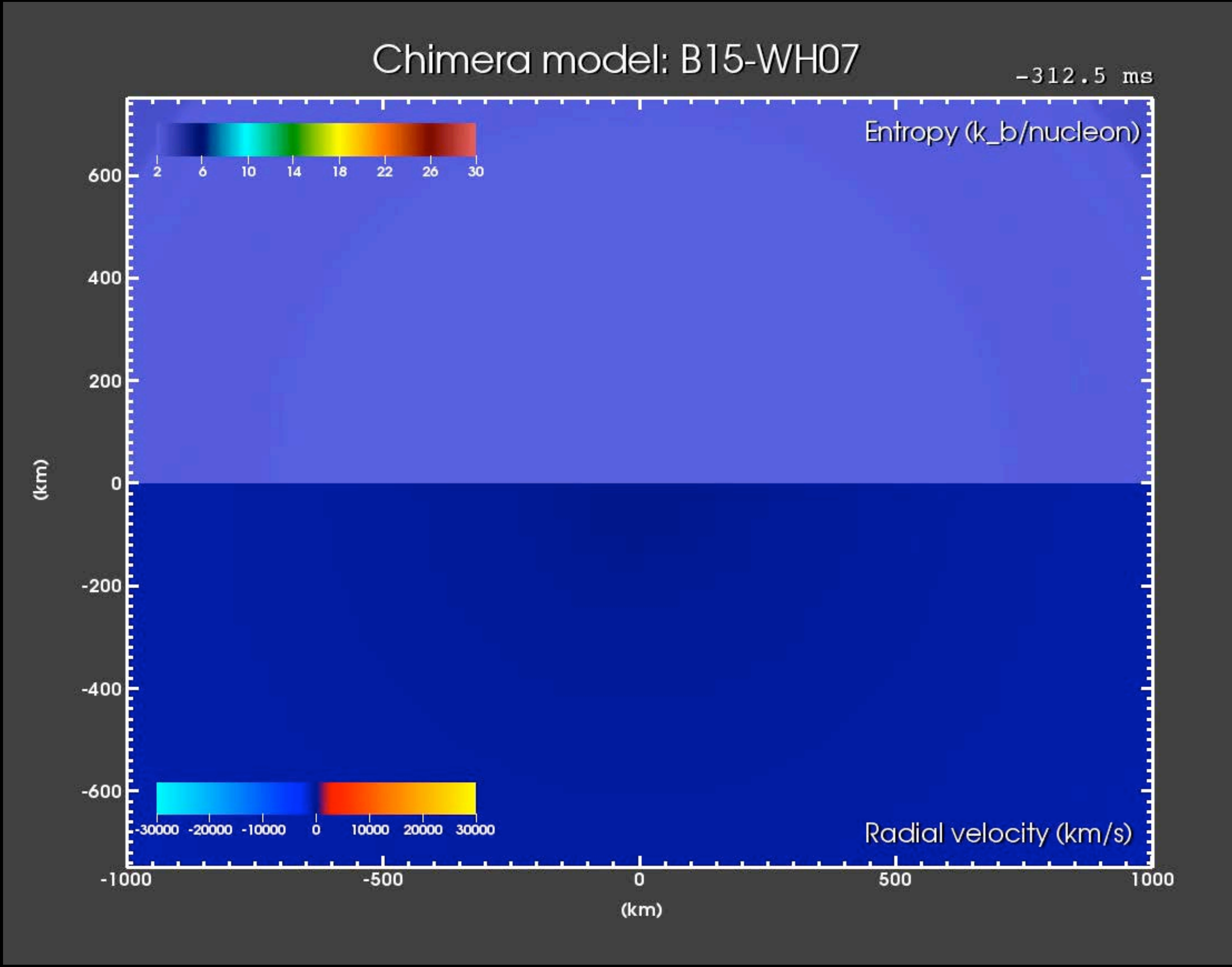

B. Müller 2012a (Garching)



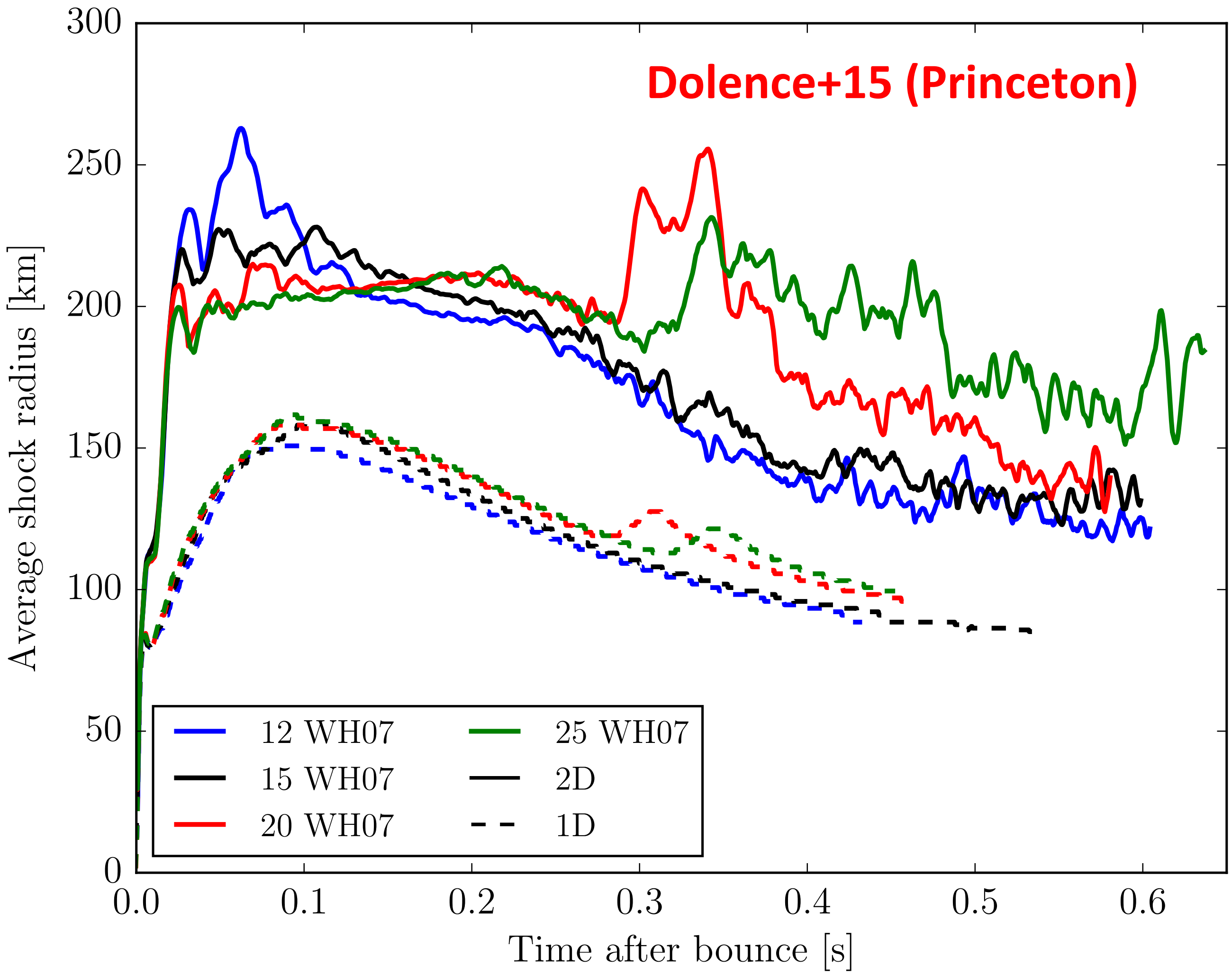

Bruenn+13
ORNL

ν-driven convection and SASI

Bruenn+15
ORNL



2D Full-Physics CCSN Simulations



Differences: stiff EOS (Shen vs. LS), Newtonian, full 2D MGFLD.

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**

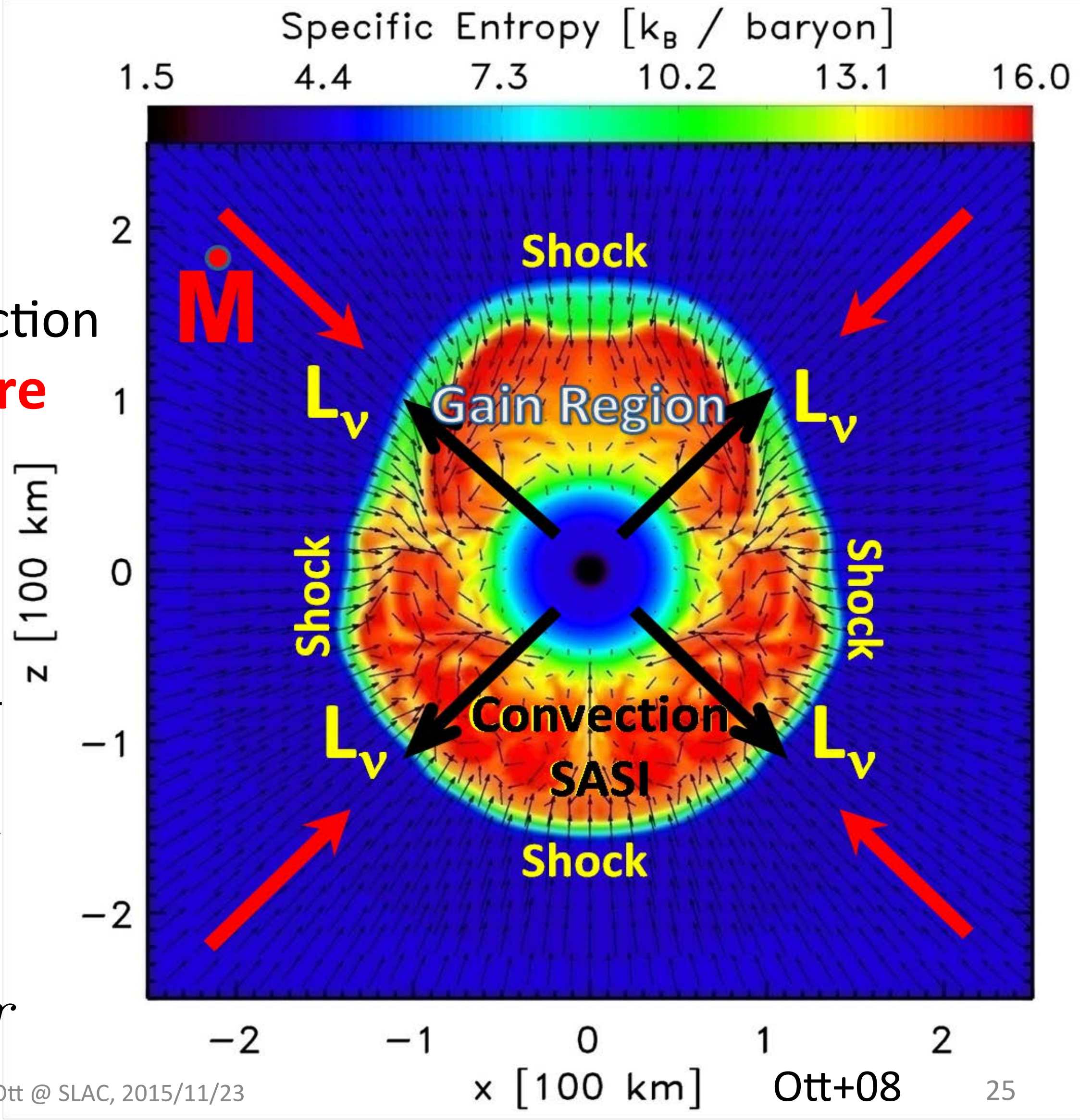
(Radice+15ab,Couch&Ott 15, Murphy+13)

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

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

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

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



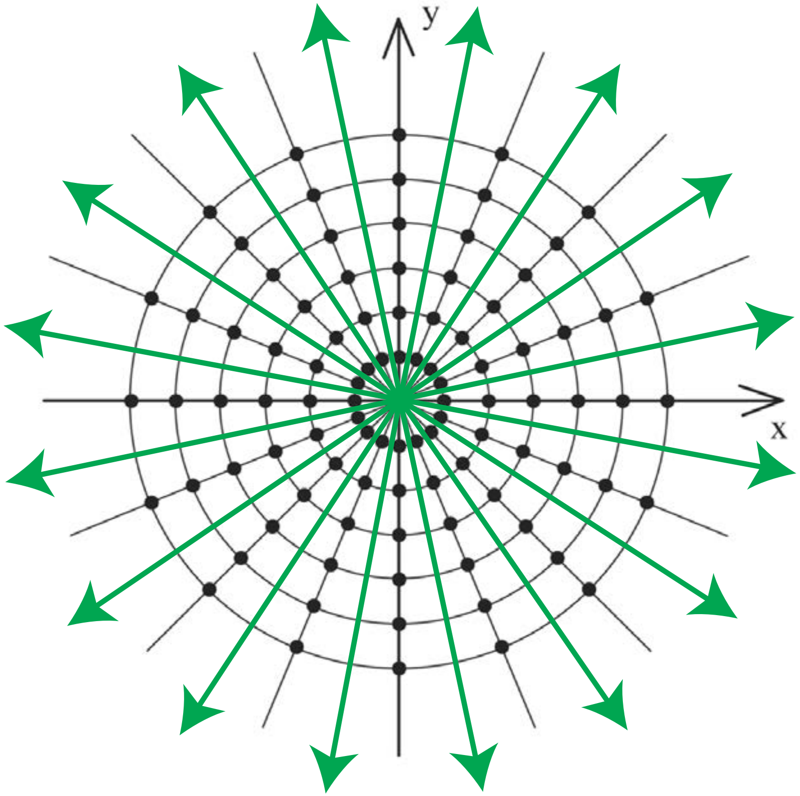
Ott+08

Status: 2D Simulations

Code/Group	Gravity	Transport	X sections	Note	Recent Refs.
Prometheus-Vertex (Garching)	Approx. GR	Approx. GR, Mom. +Glob. closure, RBR	Full (Lentz+12)	also 1D&3D	Hanke+13, Melson+15ab
CoCoNuT-Vertex (Garching/Monash)	CFC GR	Approx. GR, Mom., RBR (ray-by-ray)	Full	also 1D	Müller +10,12ab,13,14
Chimera	Approx. GR	Approx. GR, MGFLD, RBR	Full	also 1D&3D	Bruenn +13,15,16
FLASH (MSU/NCSU)	Approx. GR	Approx. GR, M1, full 2D	Bruenn 85 + NuLib	also 1D&3D	O'Connor & Couch 15
Fornax (Princeton)	Newt.	Newt., M1, full 2D	?	also 1D&3D	Wallace+15 (1D)
CASTRO (Princeton/LBNL)	Newt.	Newt., MGFLD, full 2D	Bruenn 85 + NN/ plasmon		Dolence & Burrows 15
ZEUS+IDSA (Fukuoka/Kotake/ Suwa)	Approx. GR	IDSA, RBR	simplified Bruenn 85 - inelastic	also 1D&3D	Takiwaki+12,14, Suwa+10,14
FLASH+IDSA (Basel)	Newt.	IDSA, full 2D	Bruenn 85	also 1D&3D	Pan+15

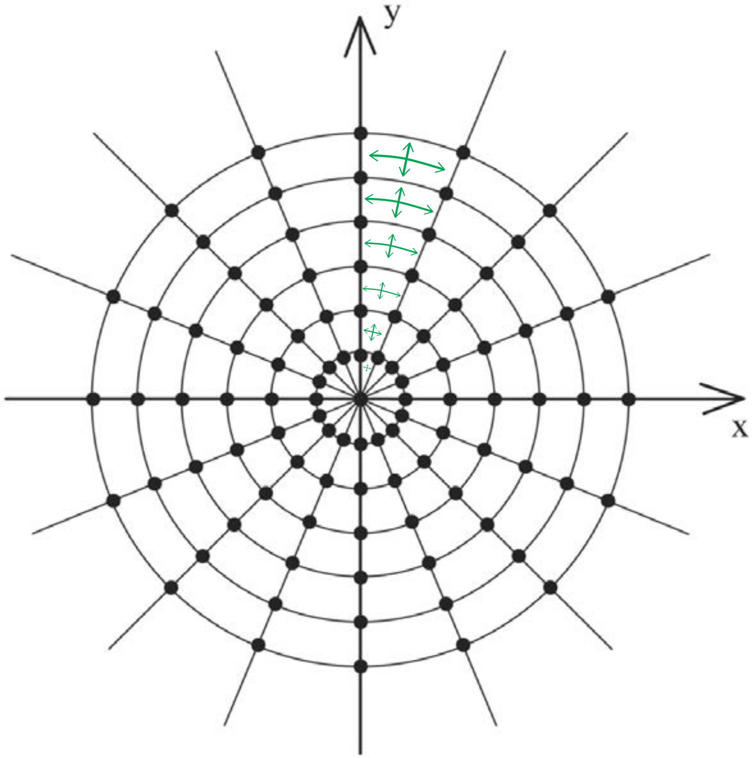
Ray-by-Ray vs. Multi-D Transport

Ray-by-Ray (plus)



- Solution of many 1D transport problems along rays. No nonradial fluxes.
- Coupling of neighboring rays through advection terms (RBR+).

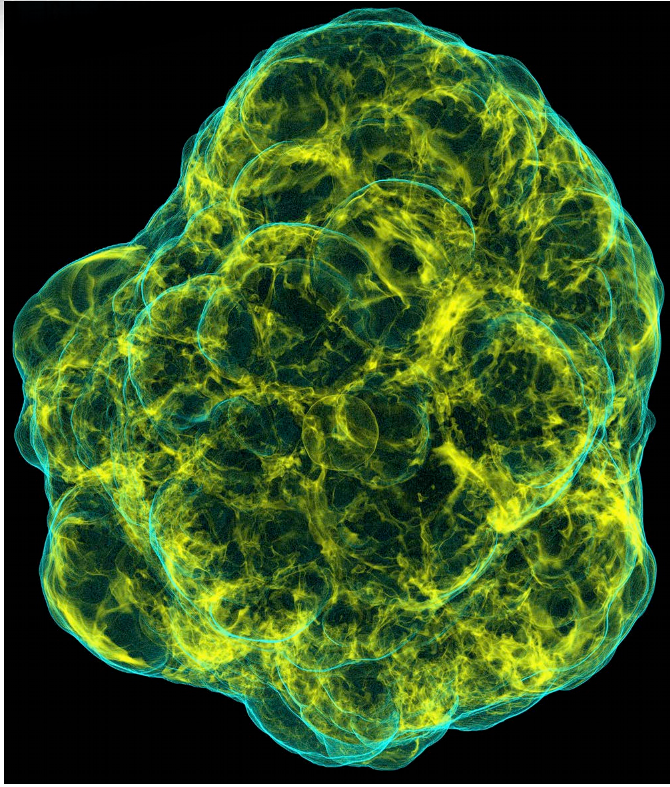
Multi-D Transport



- Full multi-dimensional solution.
- Radial and non-radial fluxes.

The 3D Frontier – **Petascale Computing!**

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



Ott+2013

Ott+2013
Caltech,
full GR,
parameterized
neutrino heating

-6.18 ms

Lentz+15 (ORNL), Chimera, full physics MGFLD, approx.GR

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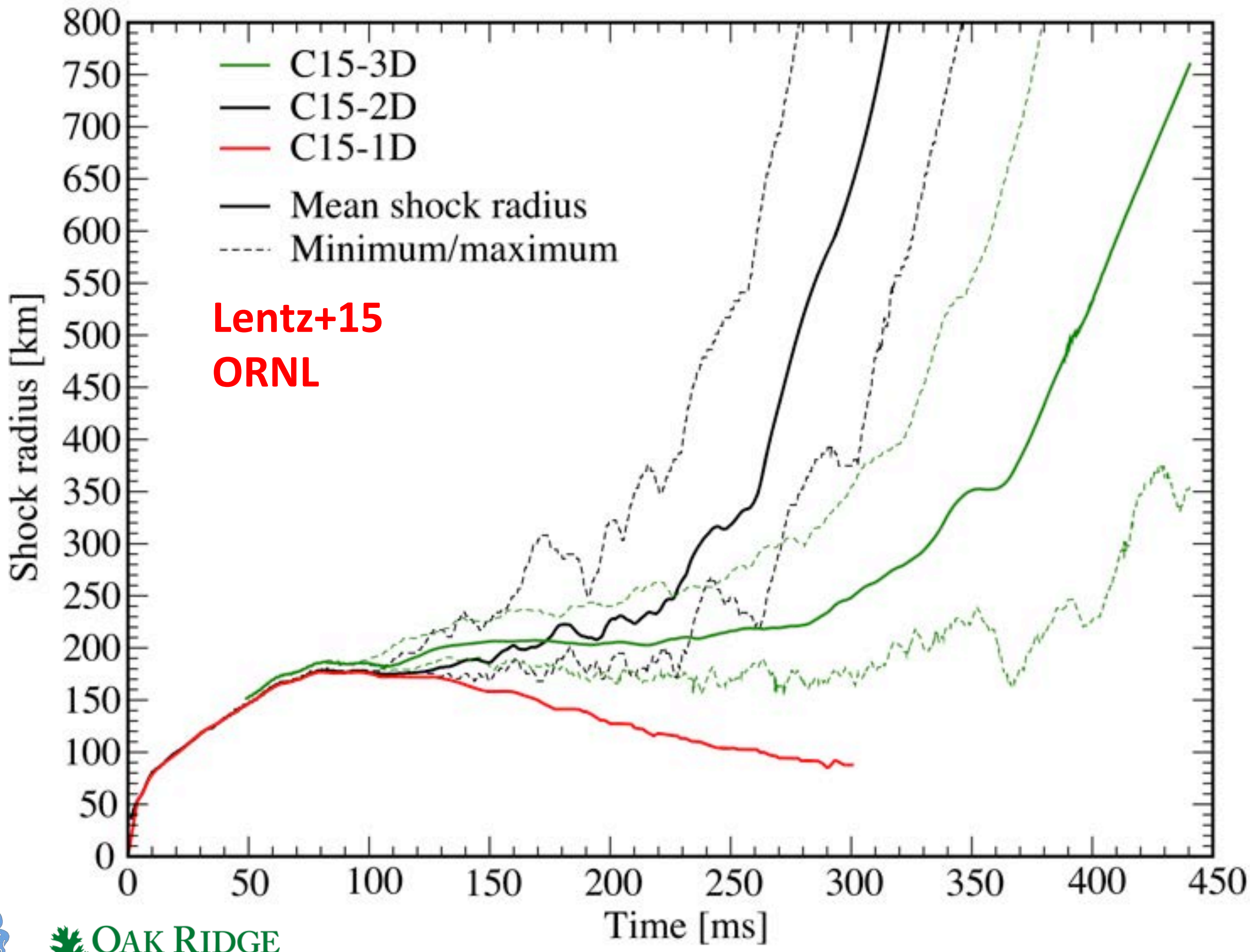
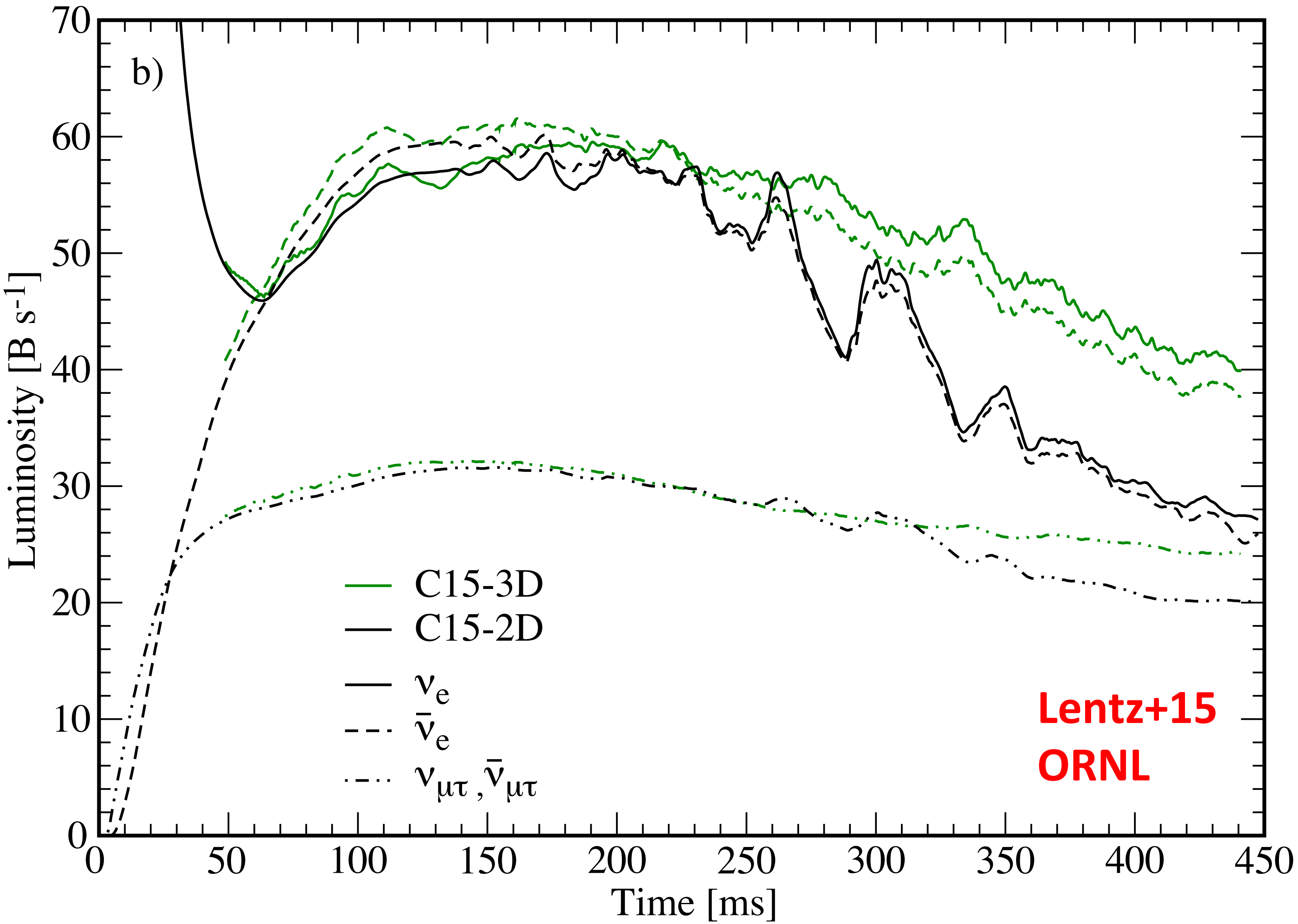
2D & 3D Explosions!



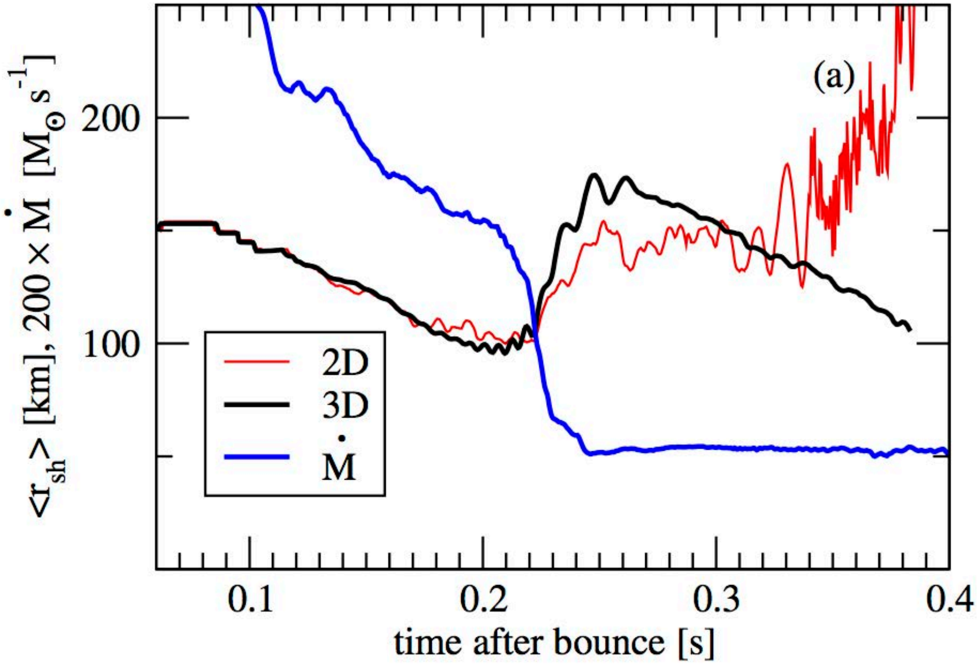
Lentz+15
ORNL

2D vs. 3D Neutrino Luminosities

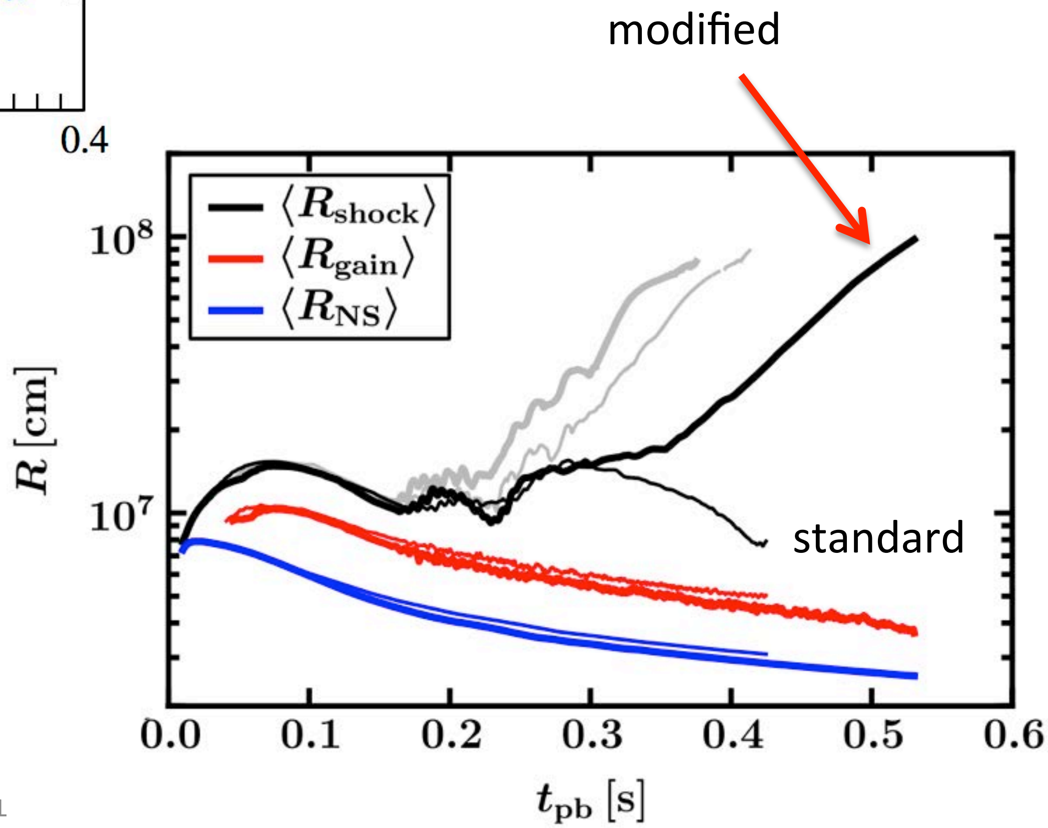


Lentz+15
ORNL

2D & 3D Explosions (or not)!



Hanke+13 (Garching)
Prometheus-Vertex (approx. GR)
27-$M_\odot$ progenitor.



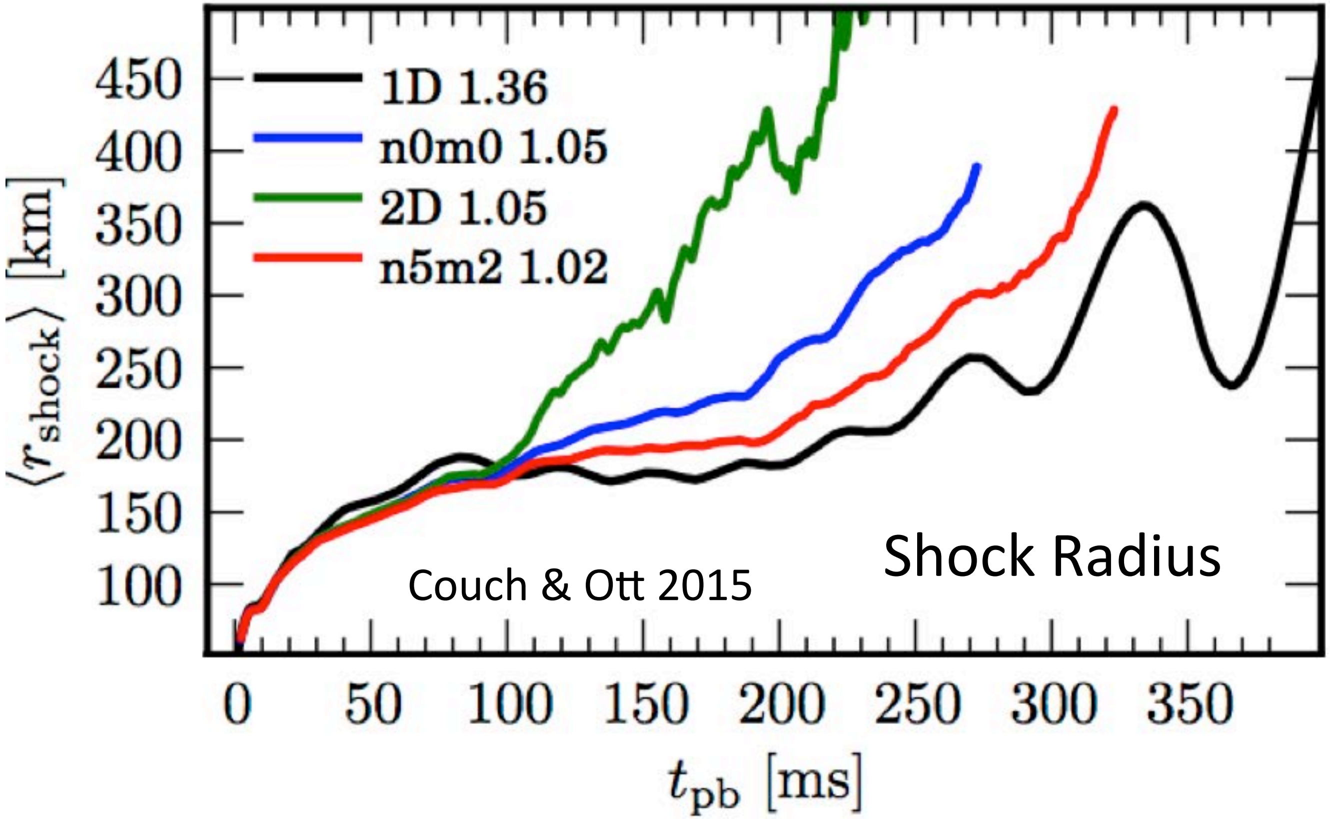
Melson+15b (Garching)
Prometheus-Vertex
(approx. GR)
20-$M_\odot$ progenitor.
Reduced ν-neutron scattering.

2D Simulations explode more easily

(e.g., Couch & Ott 2015, Couch 13, Couch & O'Connor 14, Hanke+13, Lentz+15, Takiwaki+14)

parameterized
neutrino heating

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



Couch & Ott 2015

Shock Radius

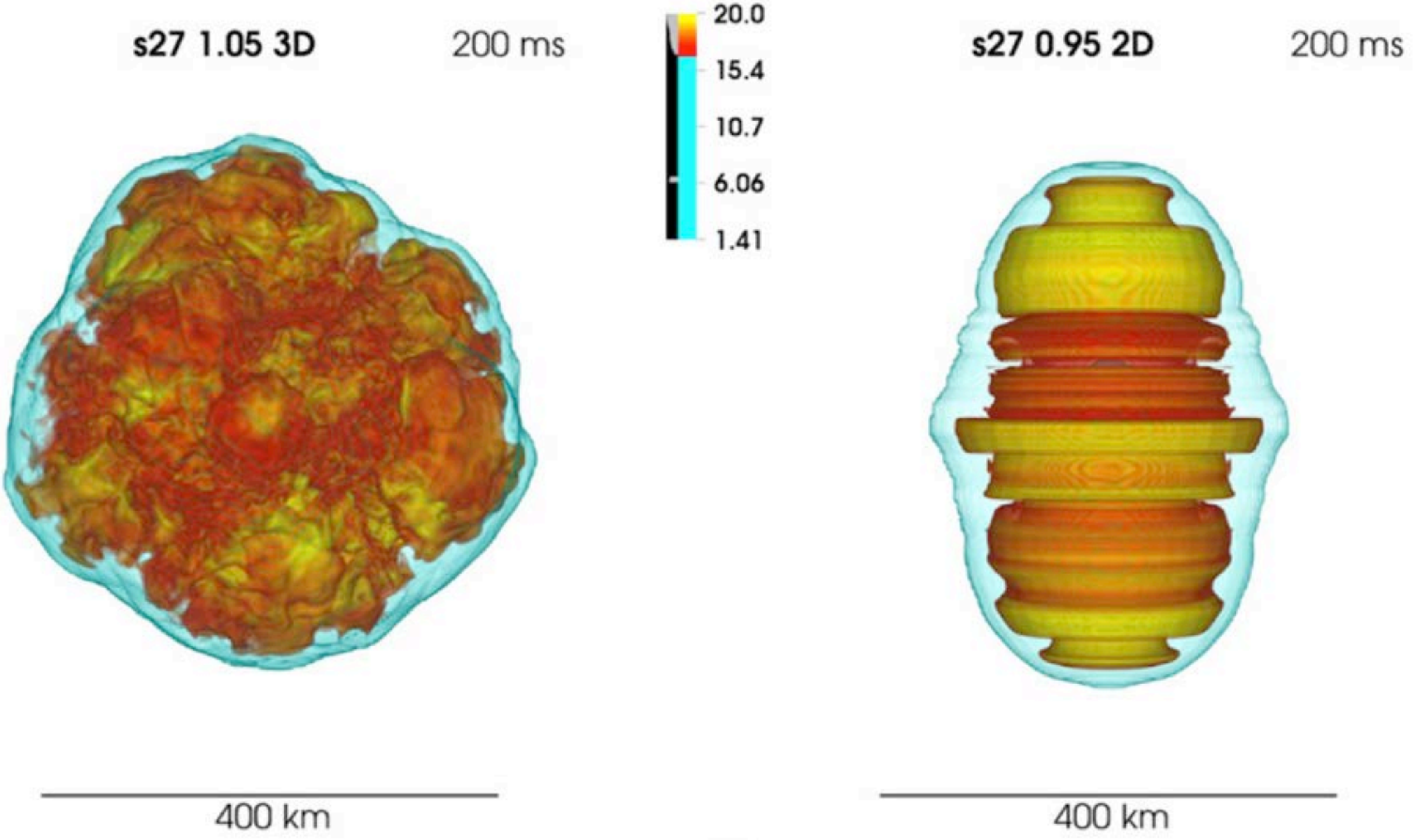
Note: 2D vs. 3D!

2D explodes more easily!

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

2D vs. 3D: Turbulence

(e.g., Couch 13, Couch & O’Connor 14)



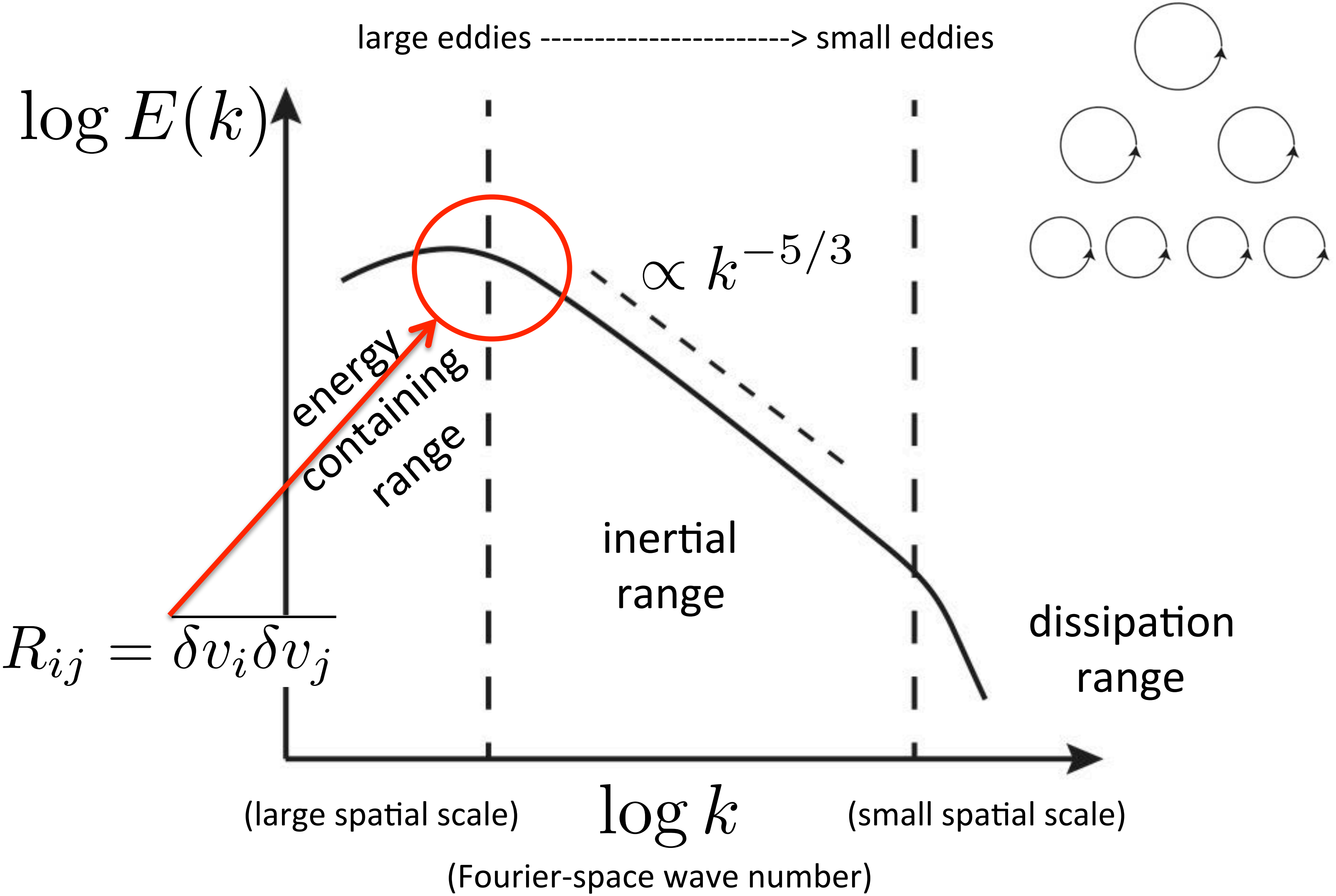
Some Facts about Supernova Turbulence

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

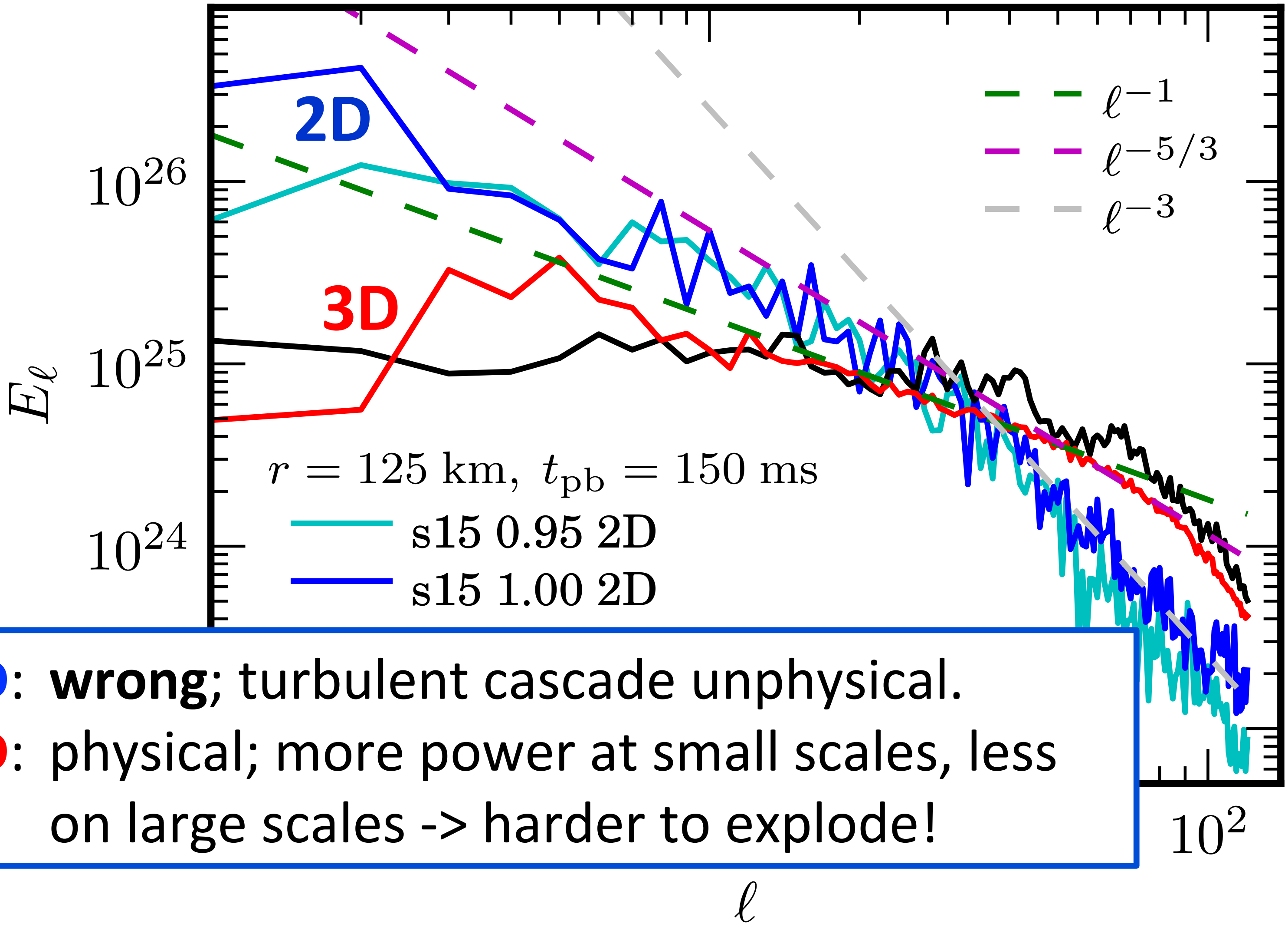
- Neutrino-driven convection is turbulent. $$\mathcal{R}e = \frac{lu}{\nu} \approx 10^{17}$$
- **Kolmogorov** turbulence: Kolmogorov 1941 isotropic, incompressible, stationary. $$E(k) \propto k^{-5/3}$$
- Supernova turbulence: anisotropic (buoyancy), mildly compressible, quasi-stationary.
- Reynolds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

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

Kolmogorov Turbulence



Turbulent Cascade: 2D vs. 3D

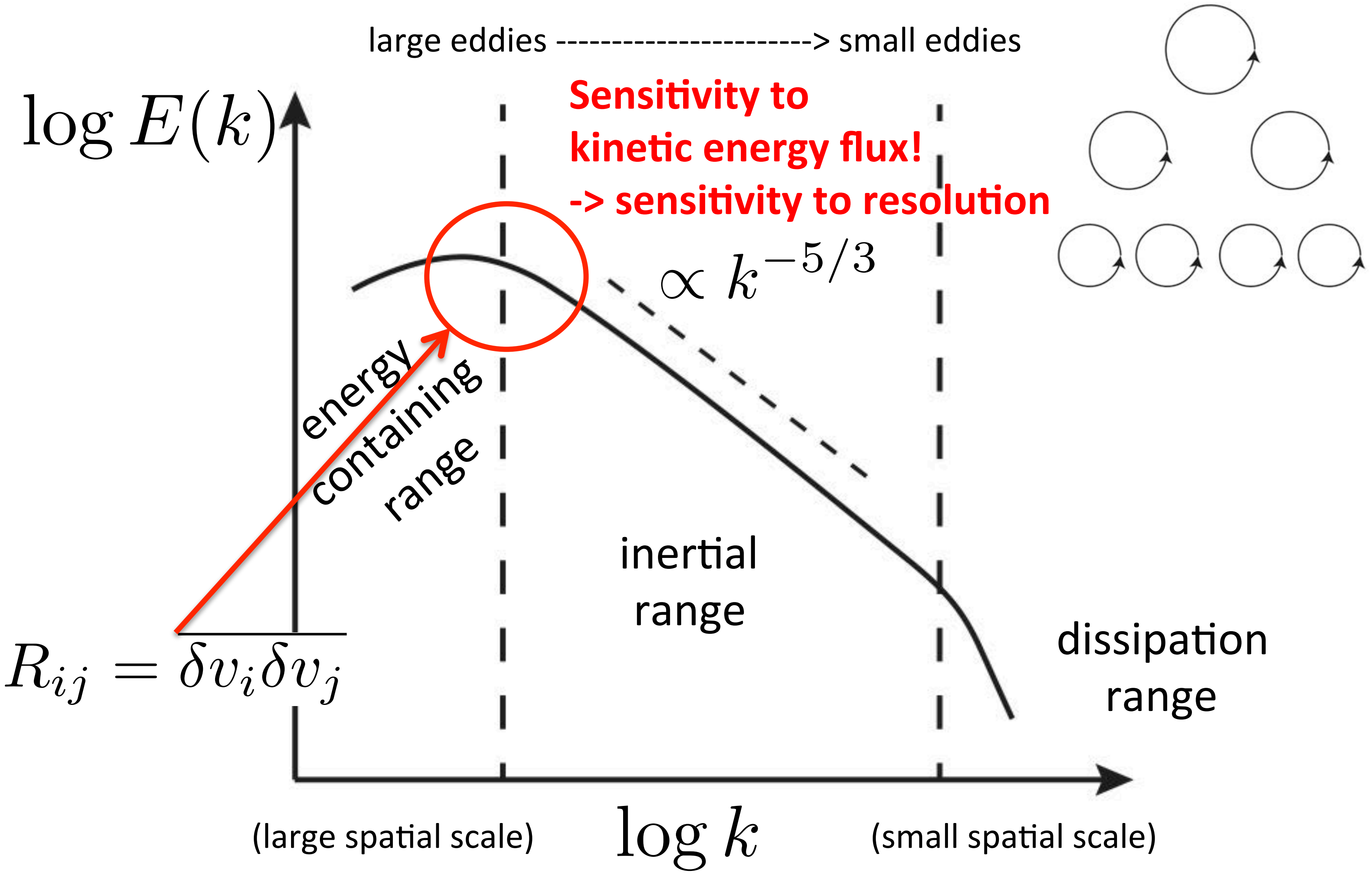


- **2D**: **wrong**; turbulent cascade unphysical.
- **3D**: physical; more power at small scales, less on large scales -> harder to explode!

Couch & O'Connor 14

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

Kolmogorov Turbulence

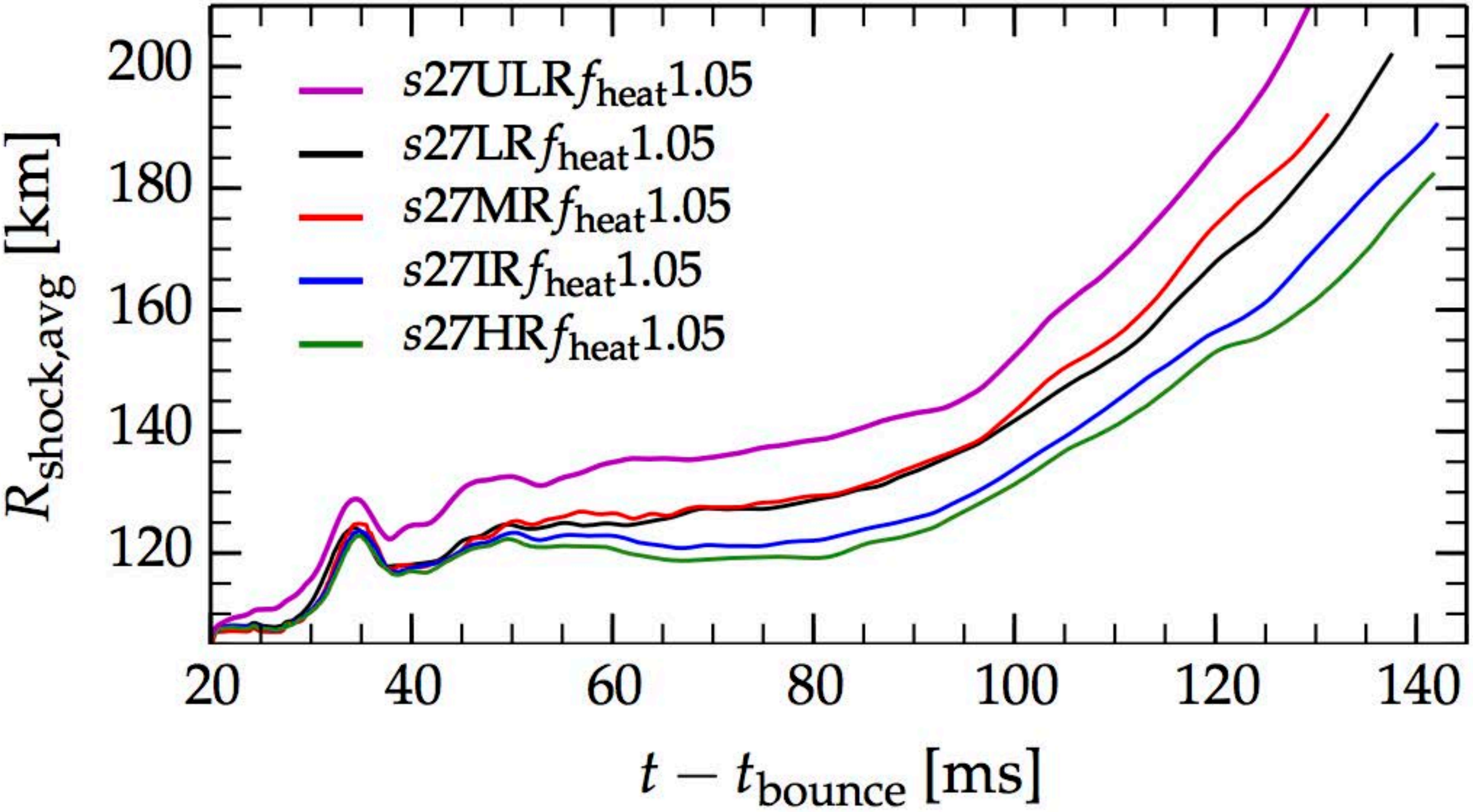


(Fourier-space wave number)

C. D. Ott @ SLAC, 2015/11/23

3D: Sensitivity to Resolution

Abdikamalov+15



low resolution -> less efficient turbulent cascade

-> kinetic energy stuck at large scales

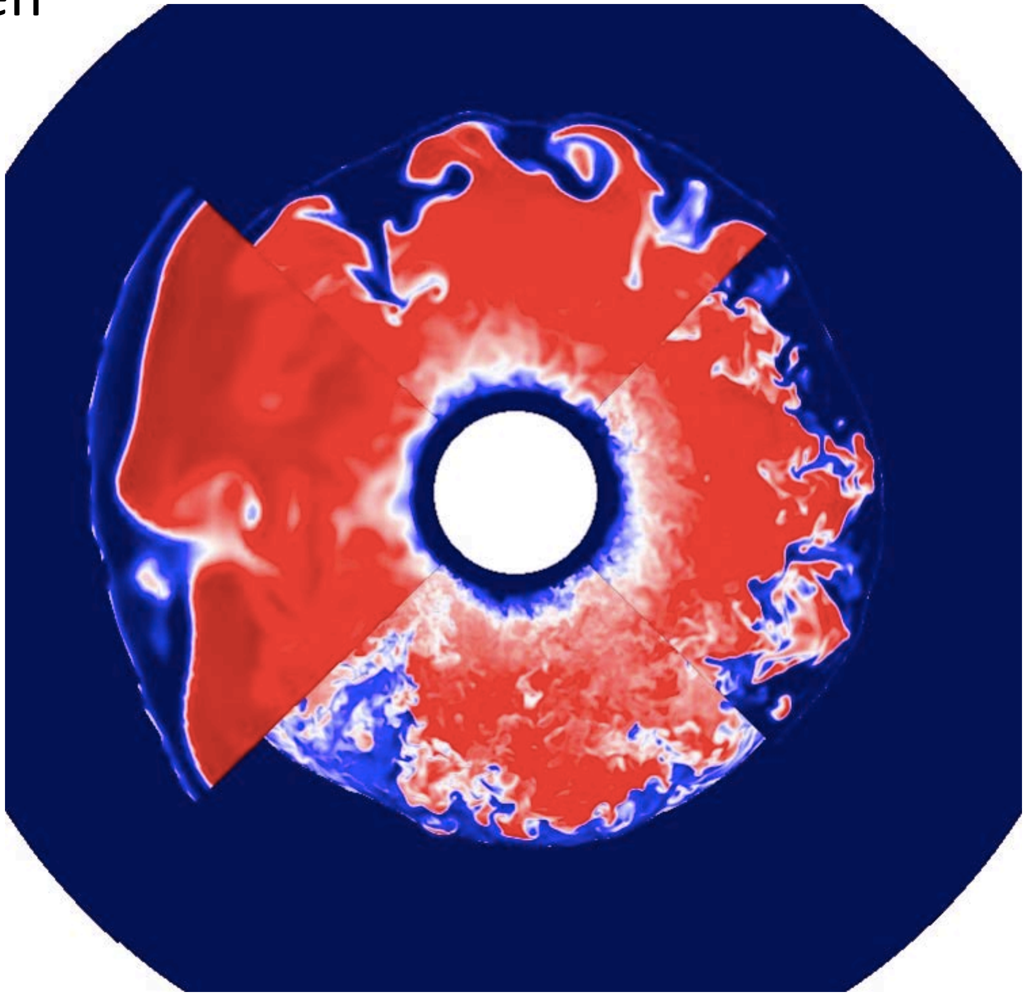
Resolution Comparison (Radice+15b)

- semi-global simulations of neutrino-driven turbulence.

dθ,dϕ = 0.9°
dr = 1.9 km

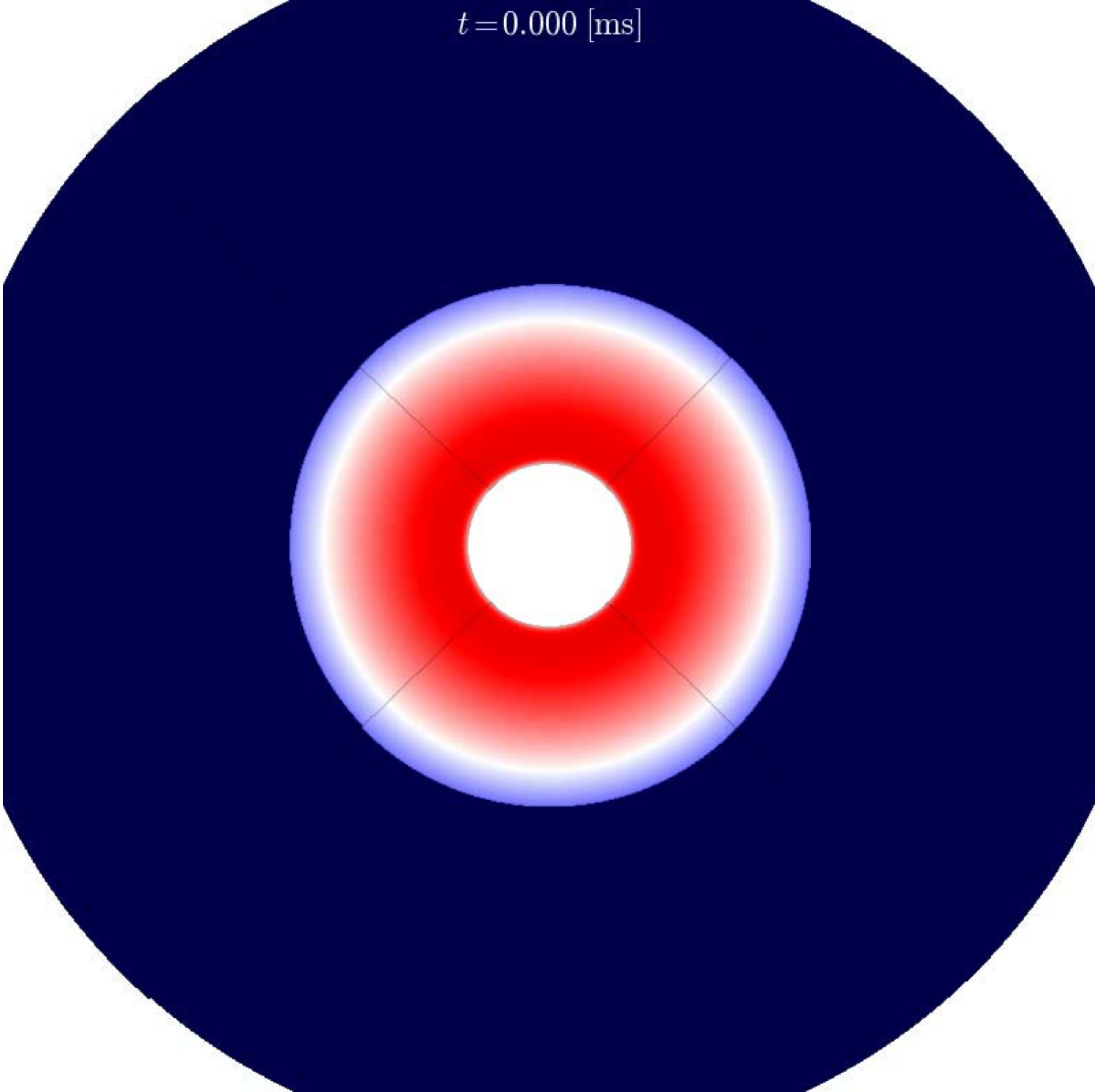
dθ,dϕ = 1.8°
dr = 3.8 km

(typical resolution of
3D rad-hydro sims)



dθ,dϕ = 0.45°
dr = 0.9 km

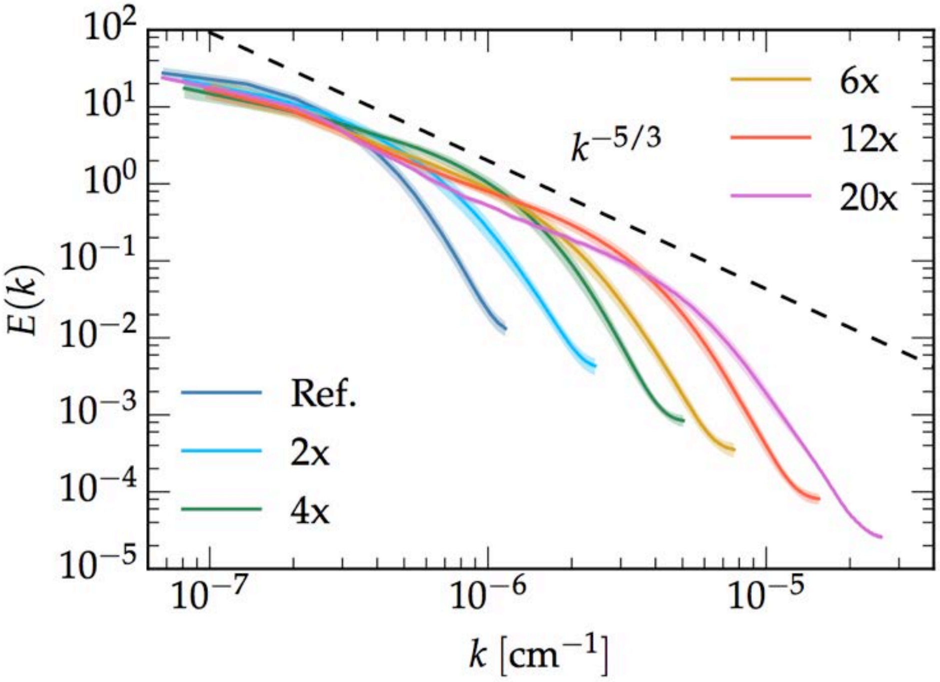
dθ,dϕ = 0.3°
dr = 0.64 km

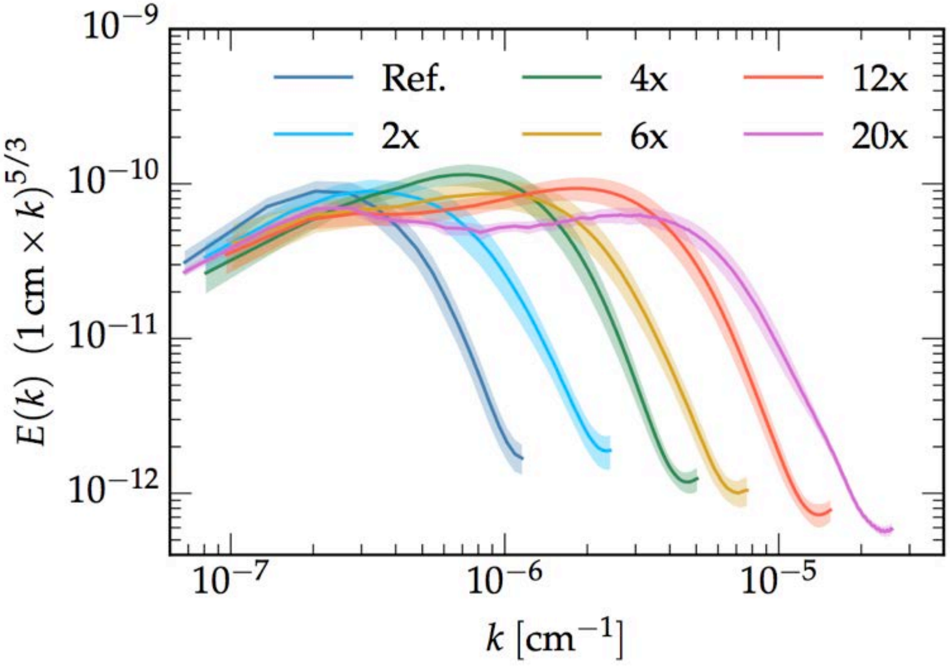


$t = 0.000$ [ms]

Turbulent Kinetic Energy Spectrum

(Radice+15b)




“compensated” spectrum

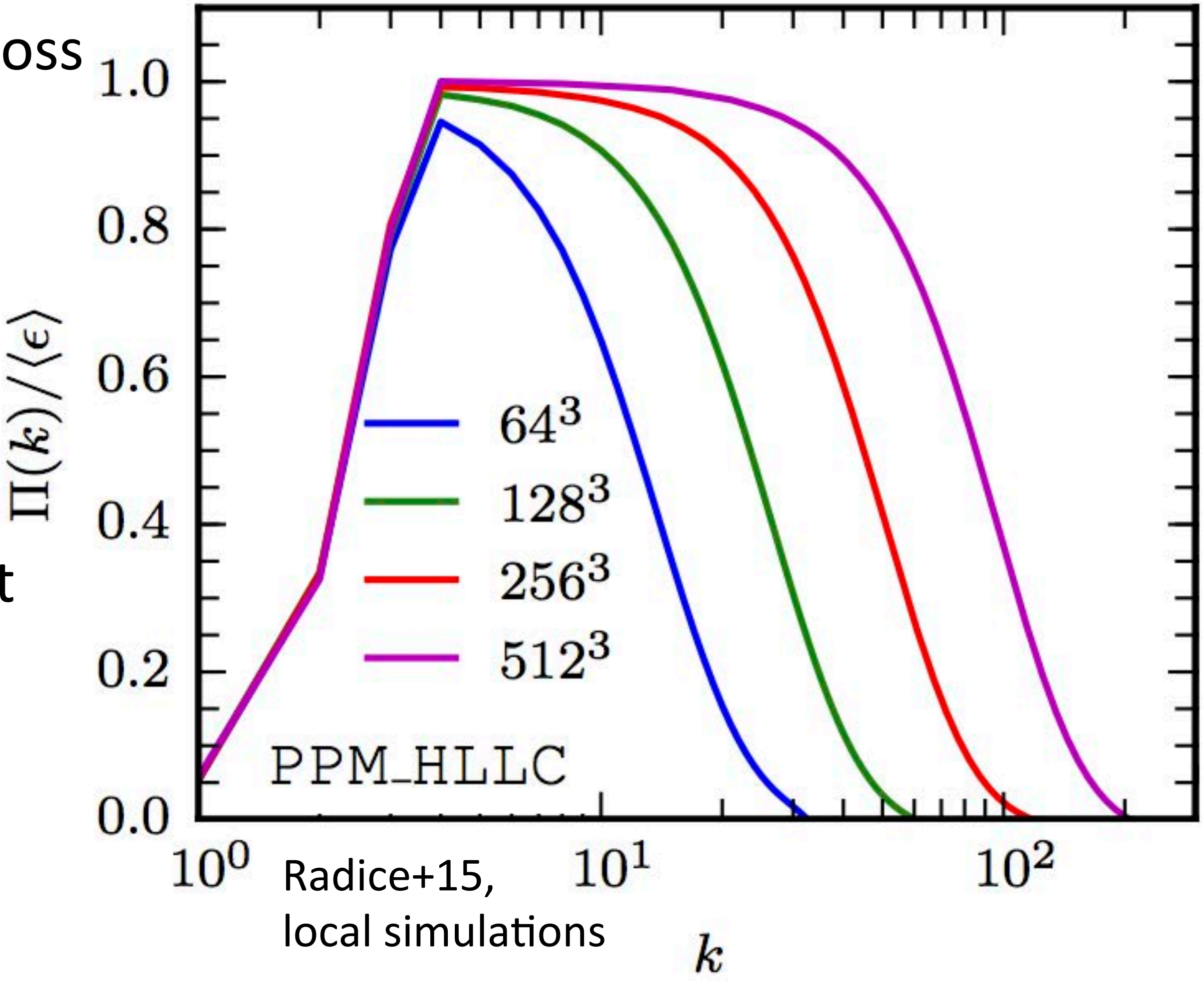
Core-collapse supernova turbulence obeys Kolmogorov scaling!

But: Can’t afford to run global simulations at necessary resolution to resolve inertial range!

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.



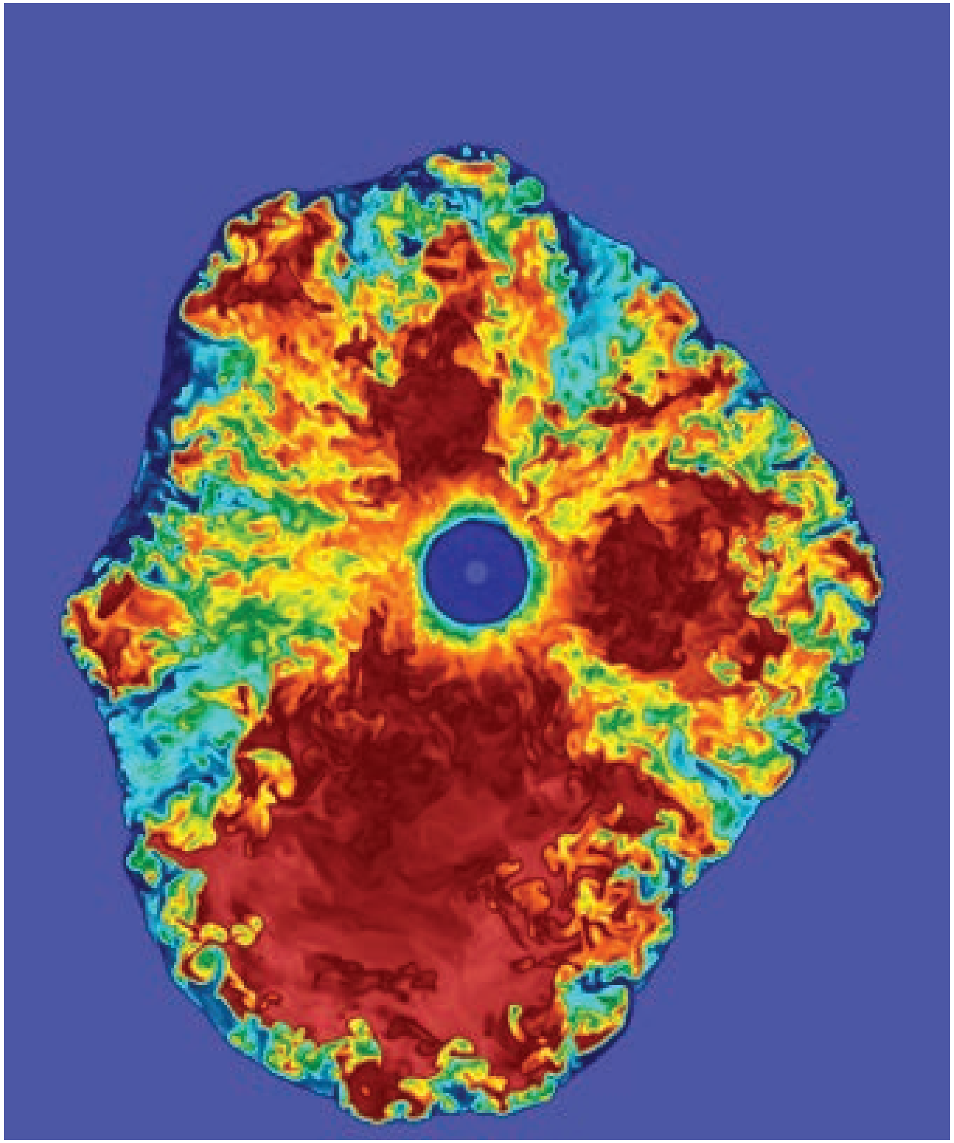
Radice+15, local simulations

Summary of 2D & 3D Simulations:

- **Better than 1D:**
  More efficient neutrino heating, turbulent ram pressure.

- **2D simulations** explode but can't really be trusted (unphysical turbulence, symmetry axis).

- **3D simulations**:
  (1) Most not yet fully self consistent (parameterized);
  (2) Numerical bottleneck in energy cascade due to low resolution.



Ott+13

Status: 3D Simulations

Code/Group	Gravity	Transport	X sections	Note	Recent Refs.
Prometheus-Vertex (Garching)	Approx. GR	Approx. GR, Mom. +Glob. closure, RBR	Full	also 1D&2D	Hanke+13, Melson+15ab
Chimera	Approx. GR	Approx. GR, MGFLD, RBR	Full	also 1D&3D	Bruenn +13,15,16
FLASH (MSU/NCSU)	Approx. GR	Approx. GR, M1, full 3D	Bruenn 85 + NuLib	also 1D&2D	O'Connor & Couch 15
Fornax (Princeton)	Newt.	Newt., M1, full 3D	?	also 1D&2D	Wallace+15 (1D)
ZEUS+IDSA (Fukuoka/Kotake/Suwa)	Approx. GR	IDSA, RBR	simplified Bruenn 85 - inelastic	also 1D&2D	Takiwaki+12,14, Suwa+10,14
FLASH+IDSA (Basel)	Newt.	IDSA, full 3D	Bruenn 85	also 1D&2D	Pan+15 (2D)
FISH+IDSA (Basel)	Approx. GR	IDSA, full 3D	Bruenn 85	only 3D	Winteler+12
ZelmaniM1 (Caltech)	full GR	GR, M1, full 3D	Bruenn 85 + NuLiB	only 3D	Roberts+16

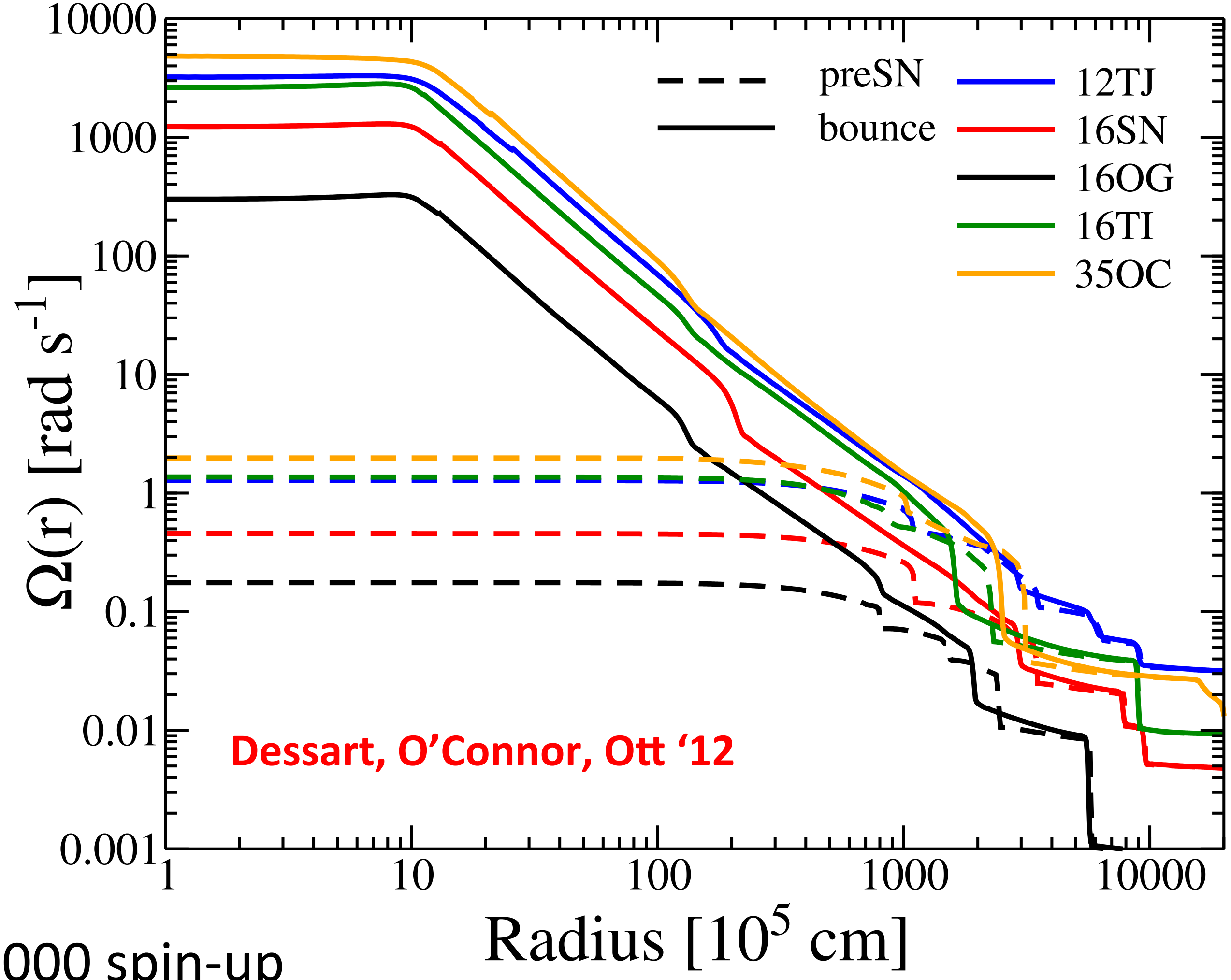
More Problems: Hypernovae & GRBs

- Hyper-energetic (up to >10 B) supernova explosions.
  Most: **type “Ic-bl”** (H, He free, broad lines <- relativistic velocities).
- ~1% of all core-collapse supernovae.
- Neutrino-driven mechanism is inefficient (~10% efficiency), cannot power hypernovae.
- 11 long gamma-ray burst – core-collapse supernova associations.
- **All GRB-SNe are of type “Ic-bl”**!

What drives hypernovae and GRBs?

SN 1998bw/GRB 980425

Magnetorotational Explosions



Dessart, O'Connor, Ott '12

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

Magnetorotational Mechanism

[LeBlanc & Wilson ‘70, Bisnovatyi-Kogan ’70,
Meier+76, Burrows+ ‘07, Takiwaki & Kotake ‘11, Winteler+ 12]

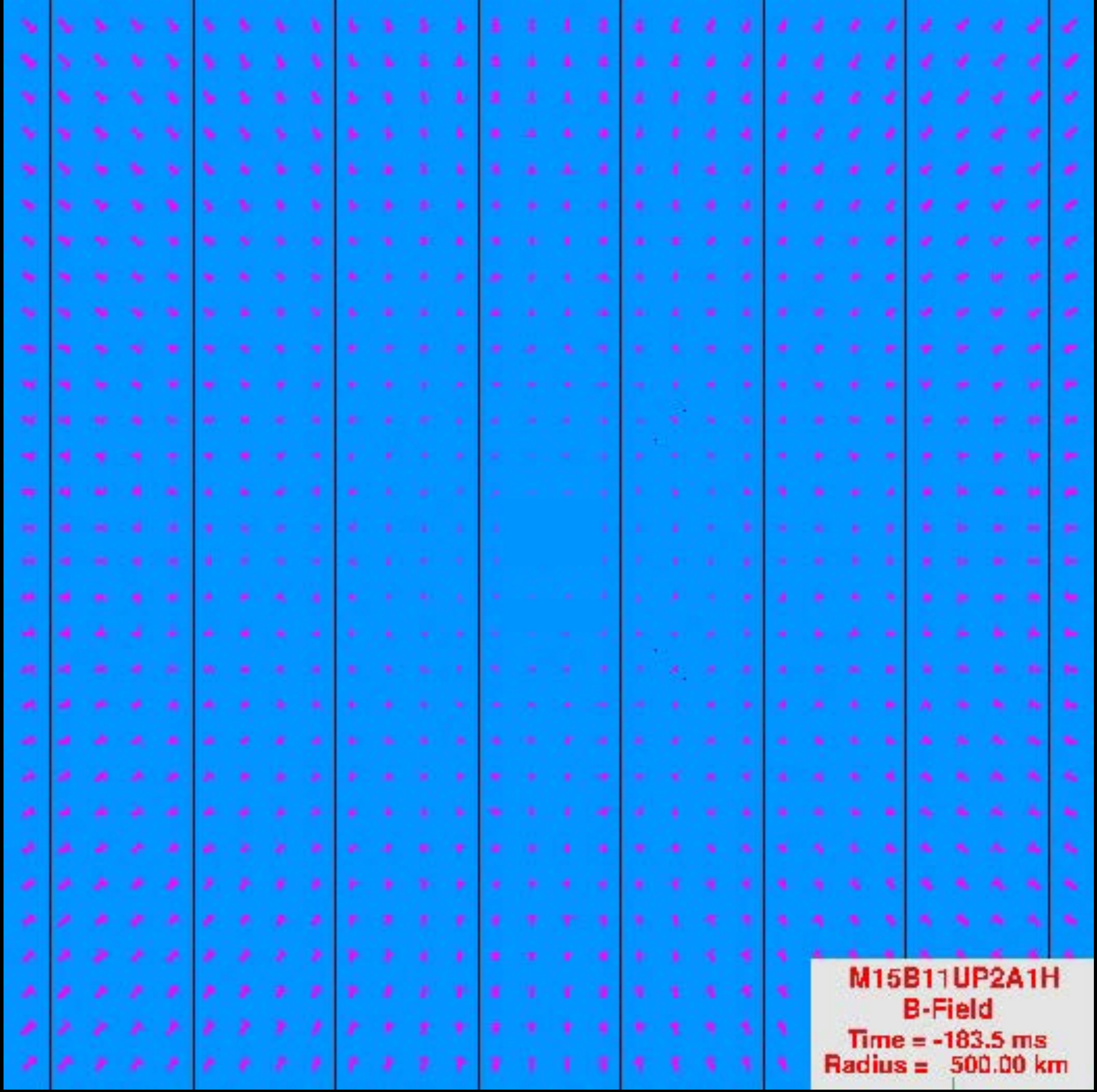
Burrows+’07

Rapid Rotation + B-field amplification
(need magnetorotational instability [MRI])

2D: Energetic “bipolar” explosions.

Results in ms-period “proto-magnetar.”
GRB connection?

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



Burrows+’07

(10^{11} G
seed field)

t = -3.00 ms

Mösta+ 2014
ApJL

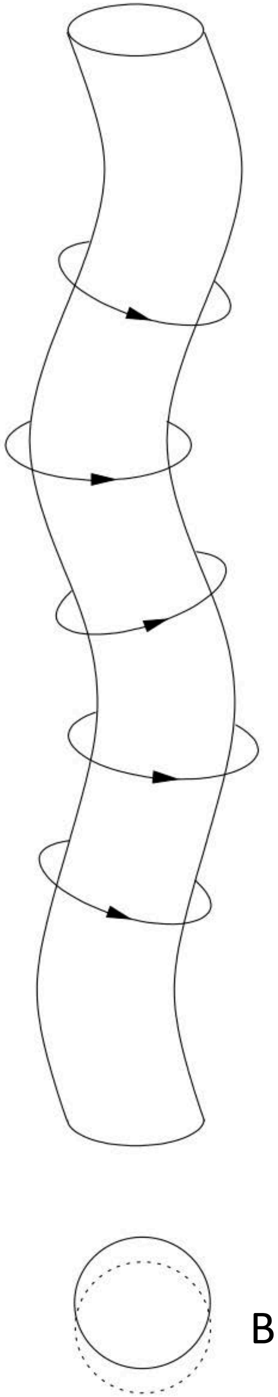
What is happening here?

Mösta+14, ApJL

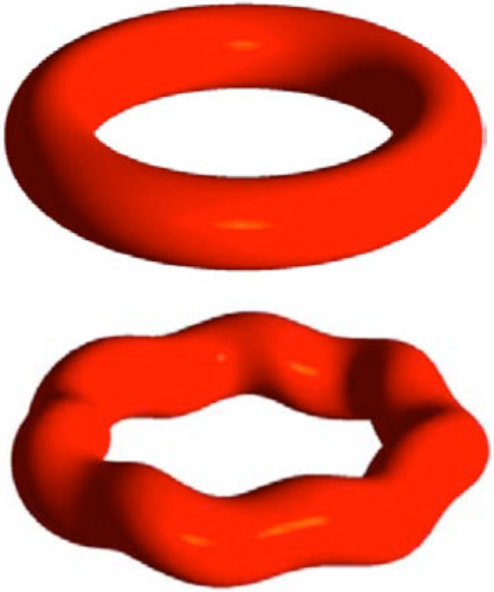
Philipp Mösta

Sherwood Richers

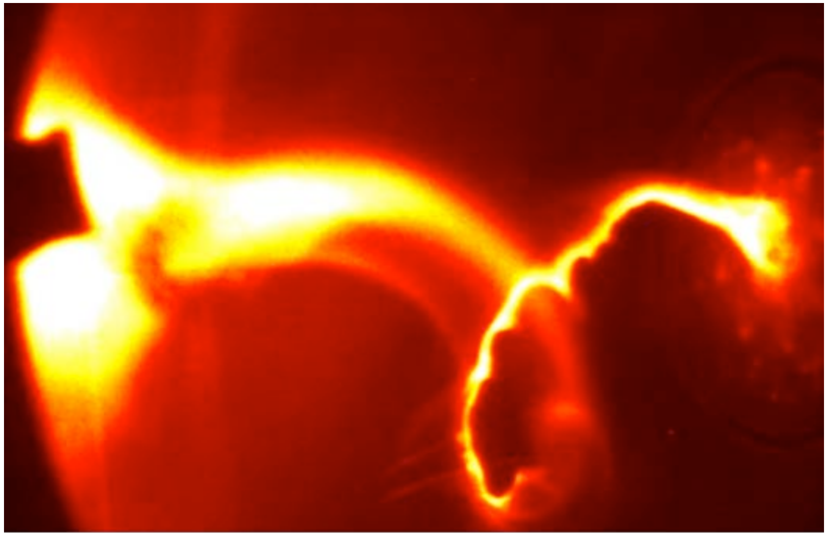
- B-field near proto-NS: $B_{tor} >> B_z$
- Unstable to MHD screw-pinch kink instability.
- Similar to situation in Tokamak fusion reactors!



Braithwaite+ ’06



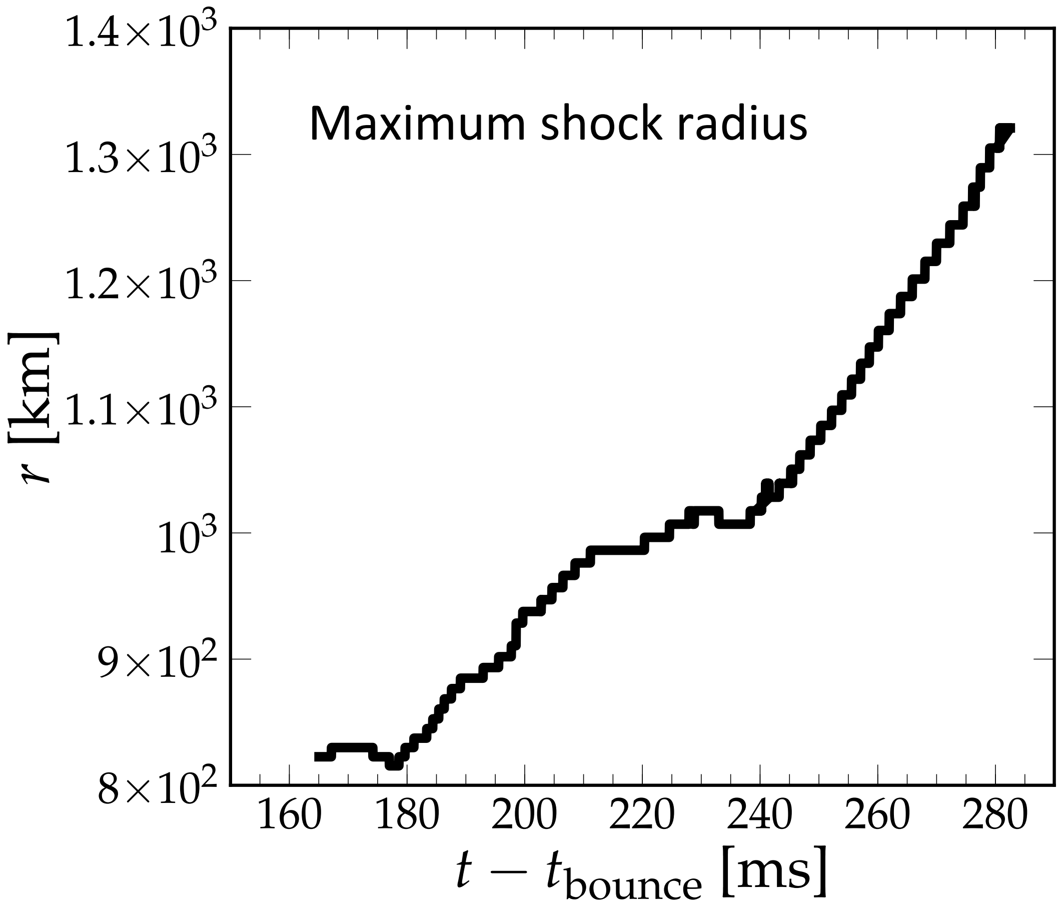
Sarff+13

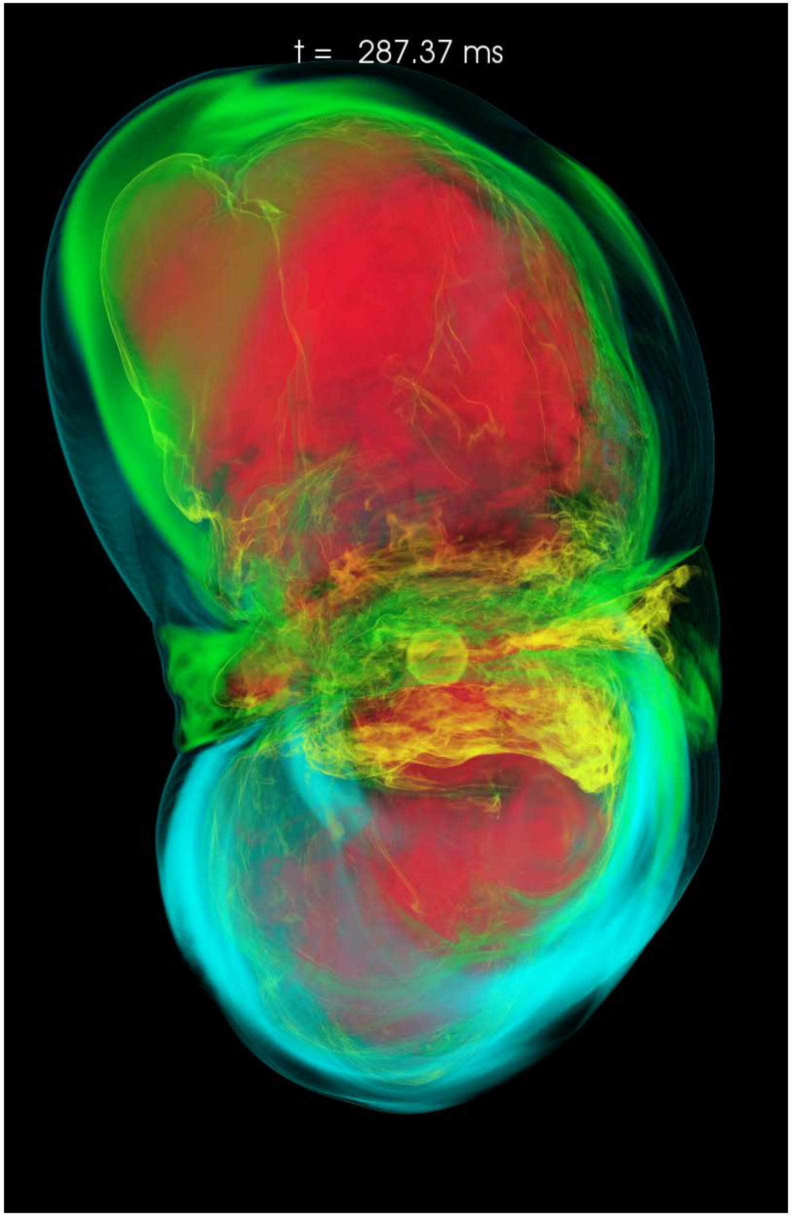


Credit: Moser & Bellan, Caltech

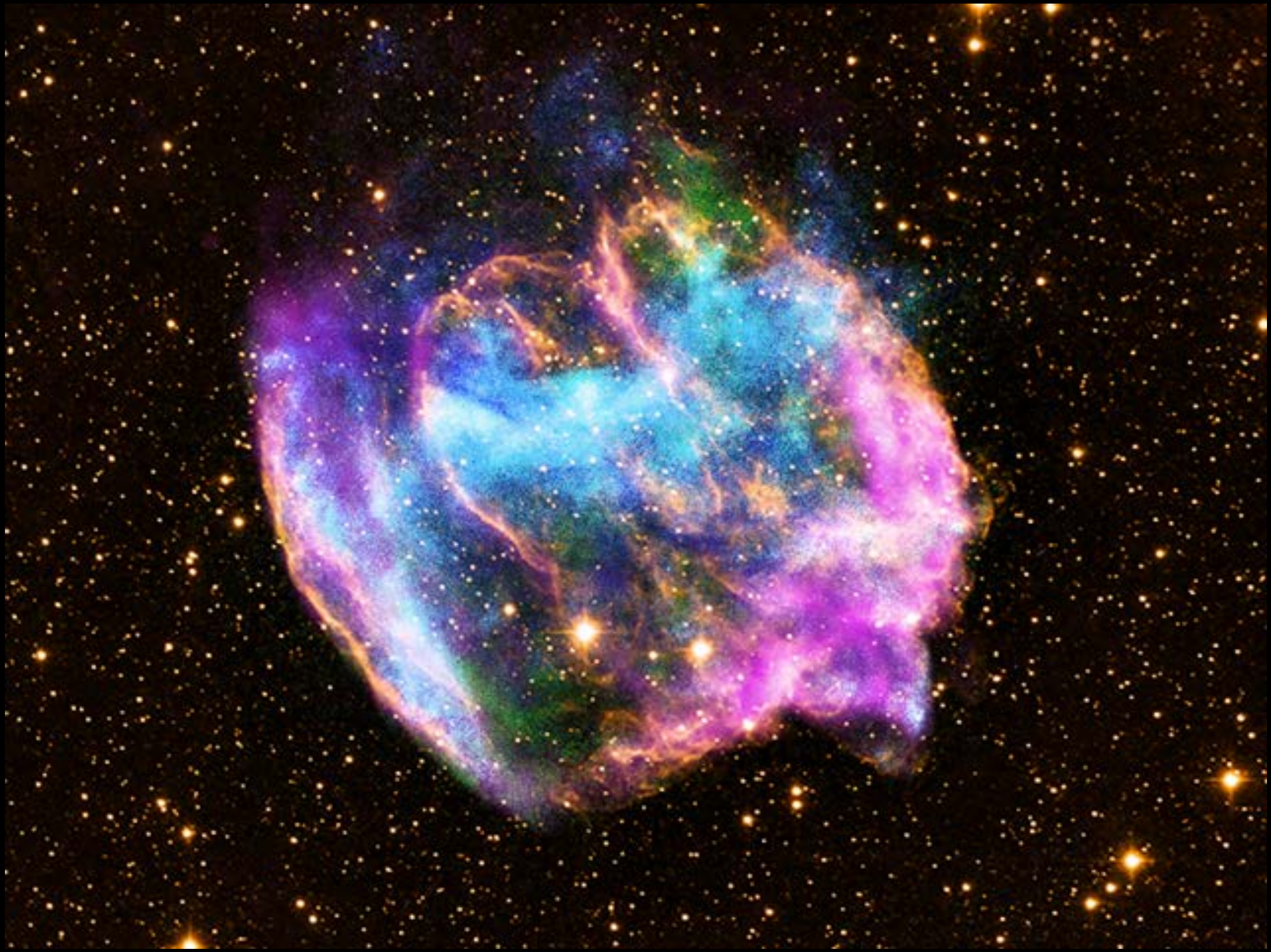
Continuing the Simulation

Mösta+15, in prep.





Implications?



SNR W49B; harboring a black hole? (Lopez+2013)

Image credit: Composite X/IR/Radio image NASA/CXC/MIT/Lopez et al./
Palomar/SF/NRAO/VLA

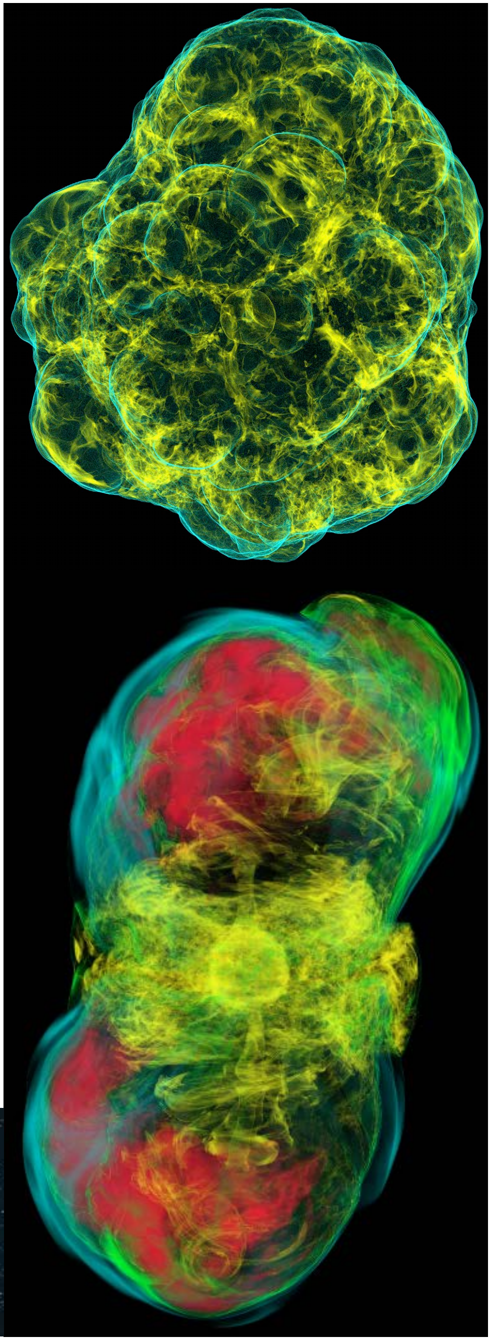
Summary: CCSN Simulatiosn

- 3D neutrino mechanism is the best bet for driving massive star explosions.
  Turbulence is crucial, but currently not resolved.

- 2D neutrino-driven explosions work; cannot be fully trusted.

- The 3D neutrino mechanism may need help.

- 3D magnetorotational mechanism for extreme CCSNe. 2D MHD jets broken in 3D. Final outcome unclear.



wikipedia.org/wiki/Magnetar

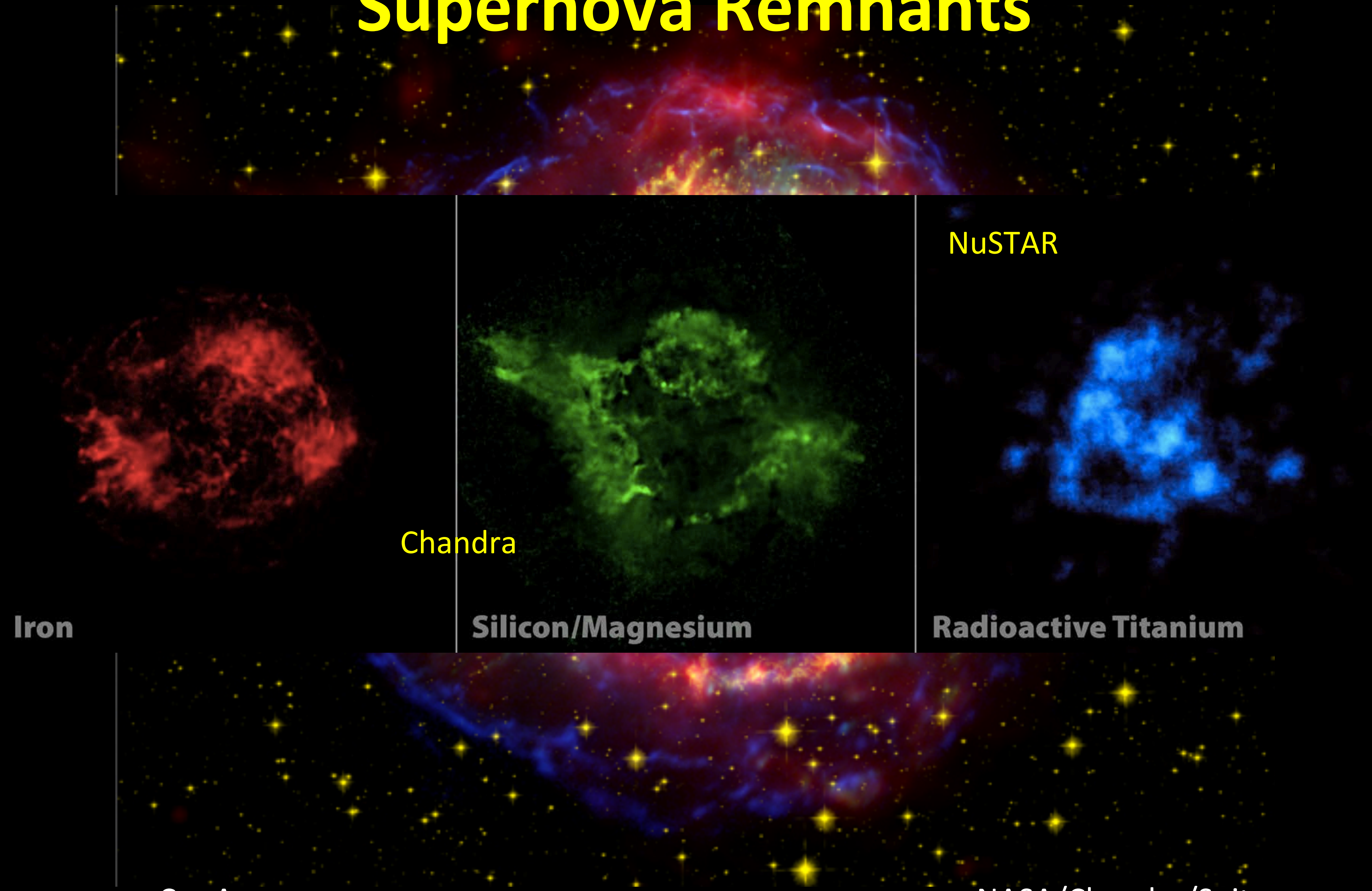
Supplemental Slides

Supernova Remnants

Cas A

NASA/Chandra/Spitzer

Supernova Remnants

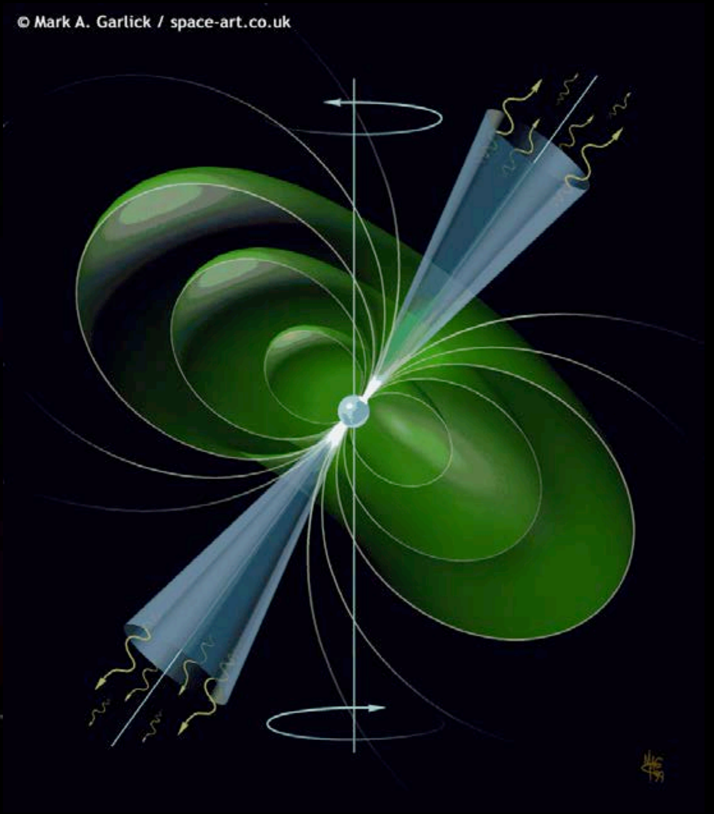


Cas A

NASA/Chandra/Spitzer

Neutron Stars; Pulsars and Magnetars, Stellar-Mass Black Holes

Crab; HST/Chandra



© Mark A. Garlick / space-art.co.uk

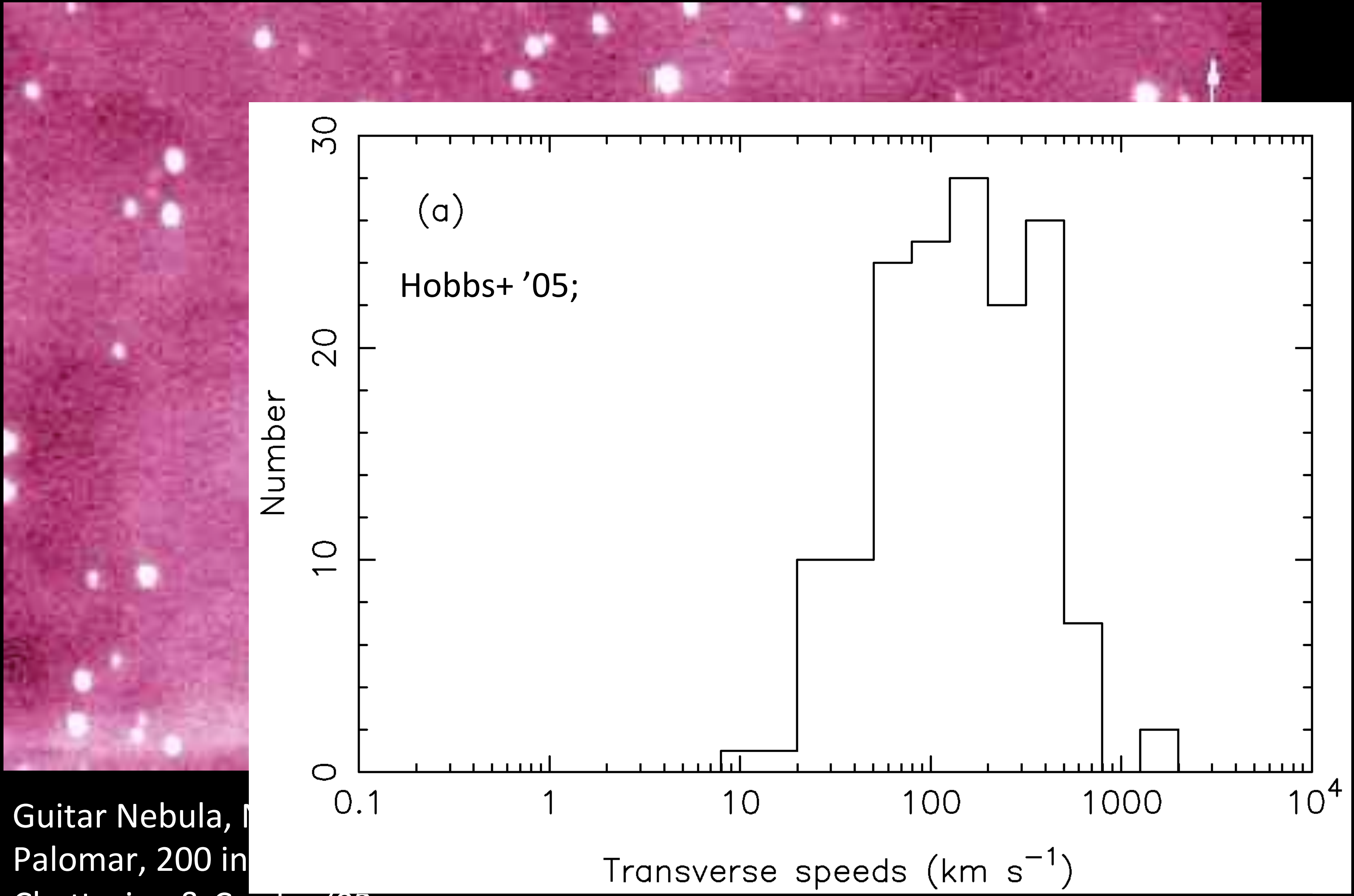
$B \sim 10^{8} - 10^{15}$ G

also: spin, mass distributions

Pulsar Birth Kicks

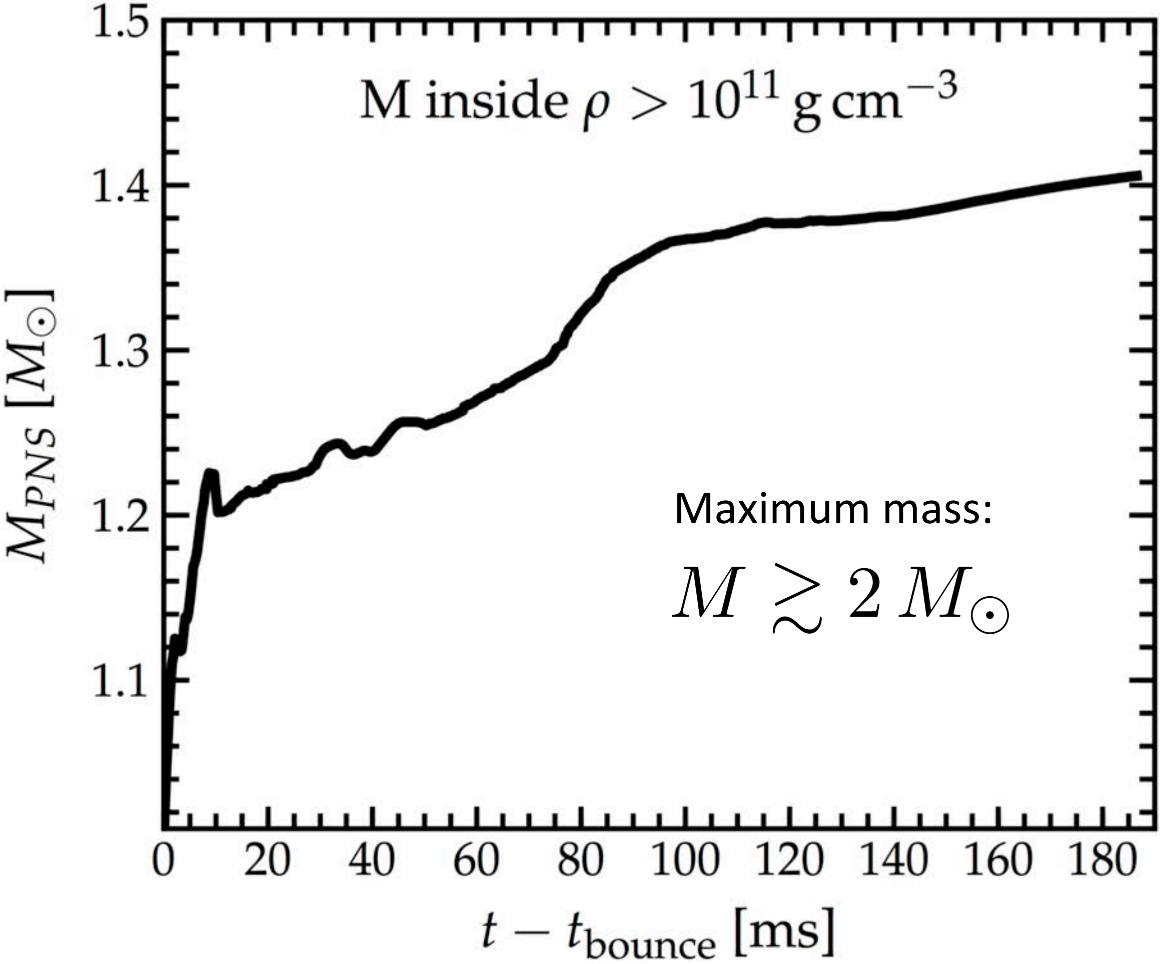
Guitar Nebula, NS v > ~1000 km/s
Palomar, 200 inch
Chatterjee & Cordes ‘02

Pulsar Birth Kicks



Guitar Nebula, N
Palomar, 200 in
Chatterjee & Cordes '02

Protoneutron Star Mass



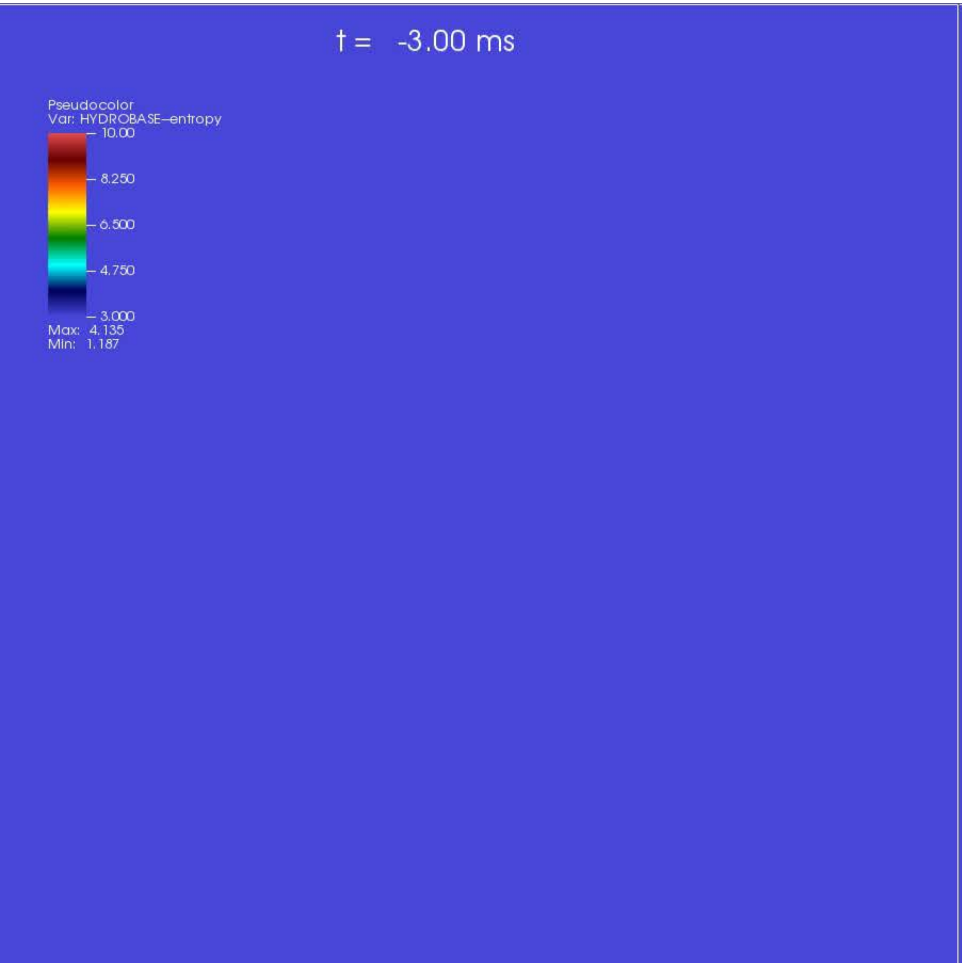
Maximum mass:

$$M \gtrsim 2\,M_\odot$$

3D Dynamics of Magnetorotational Explosions

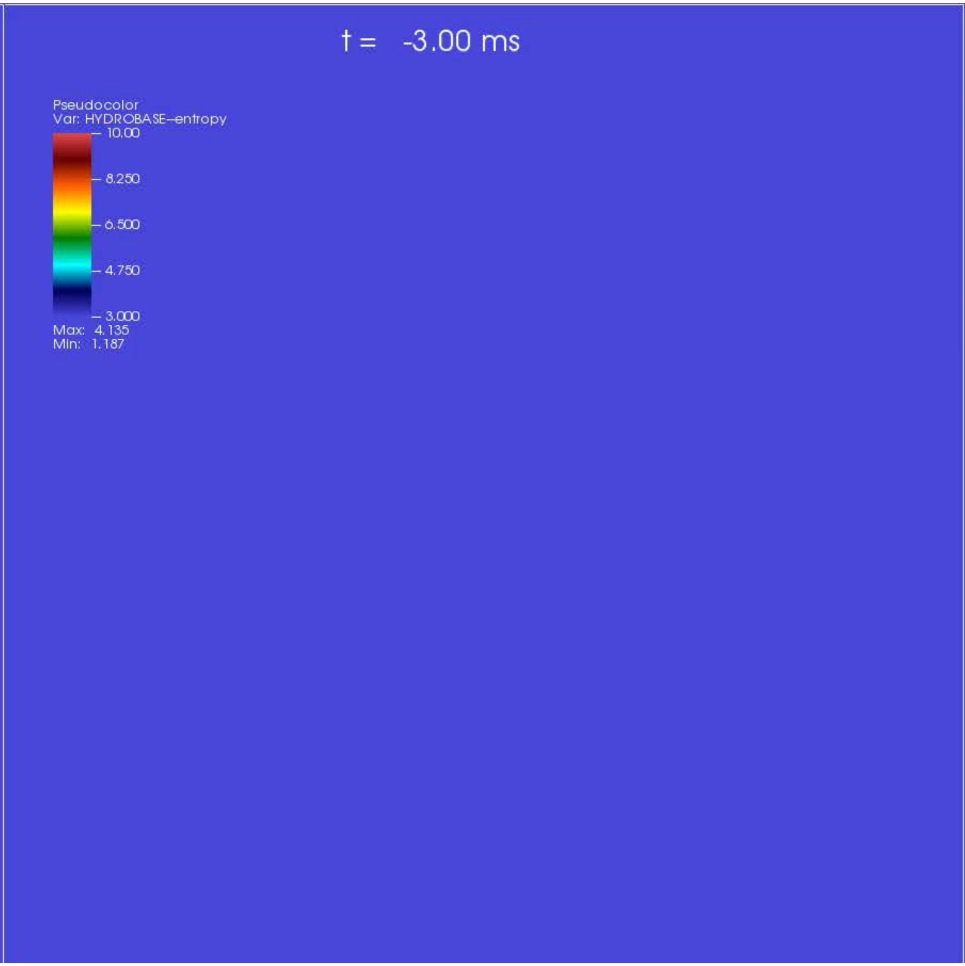
New, full 3D GRMHD simulations. **Mösta+ 2014**, ApJL.
Initial configuration as in Takiwaki+11, 10^{12} G seed field.

← 2000 km →



Octant Symmetry (no odd modes)

← 2000 km →



Full 3D

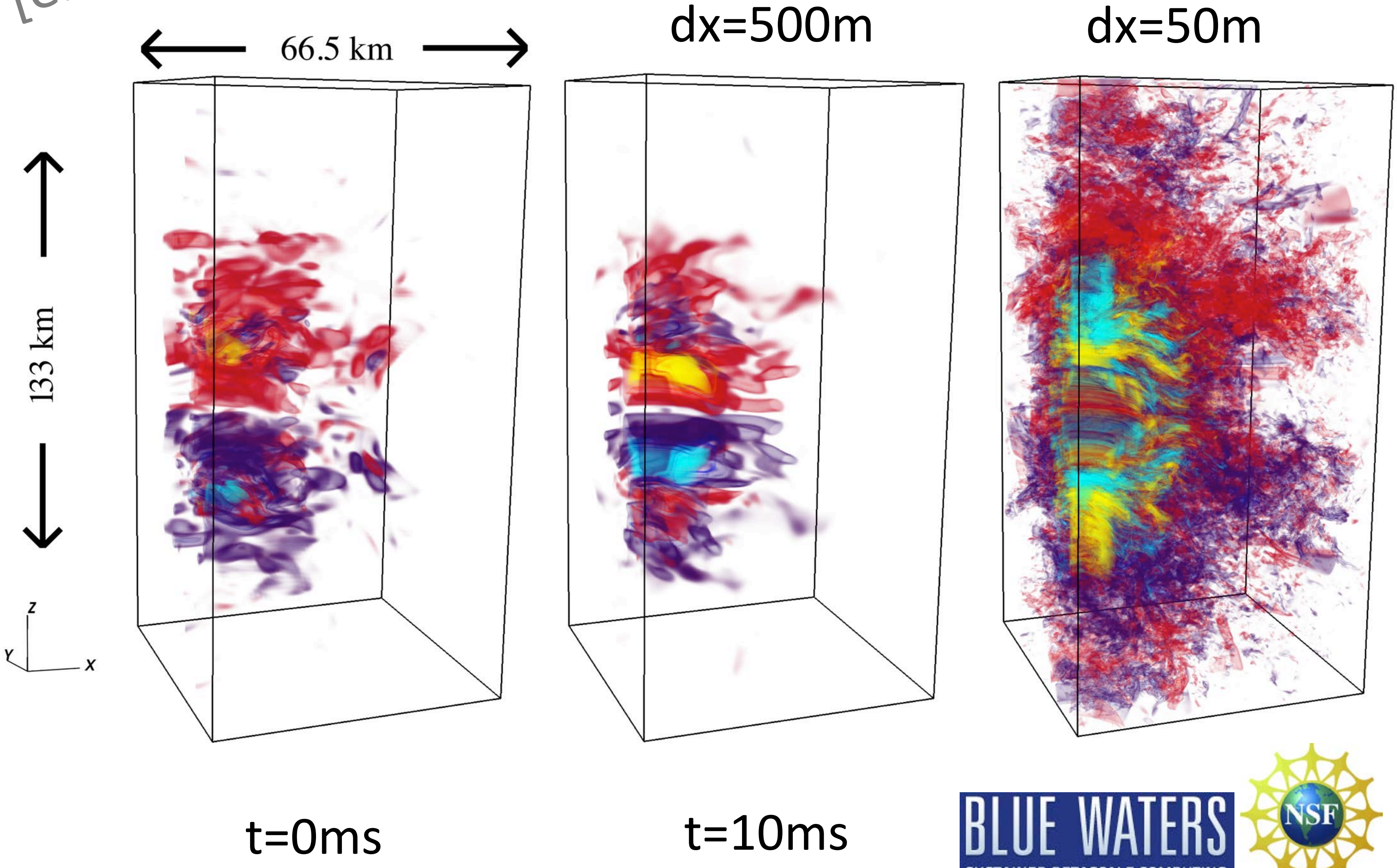
t = -4.95 ms

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

Mösta+ 2014
ApJL

Global Field Structure

Mösta+15, to appear in Nature



“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)

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

- Rankine-Hugoniot with turbulence:

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

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

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

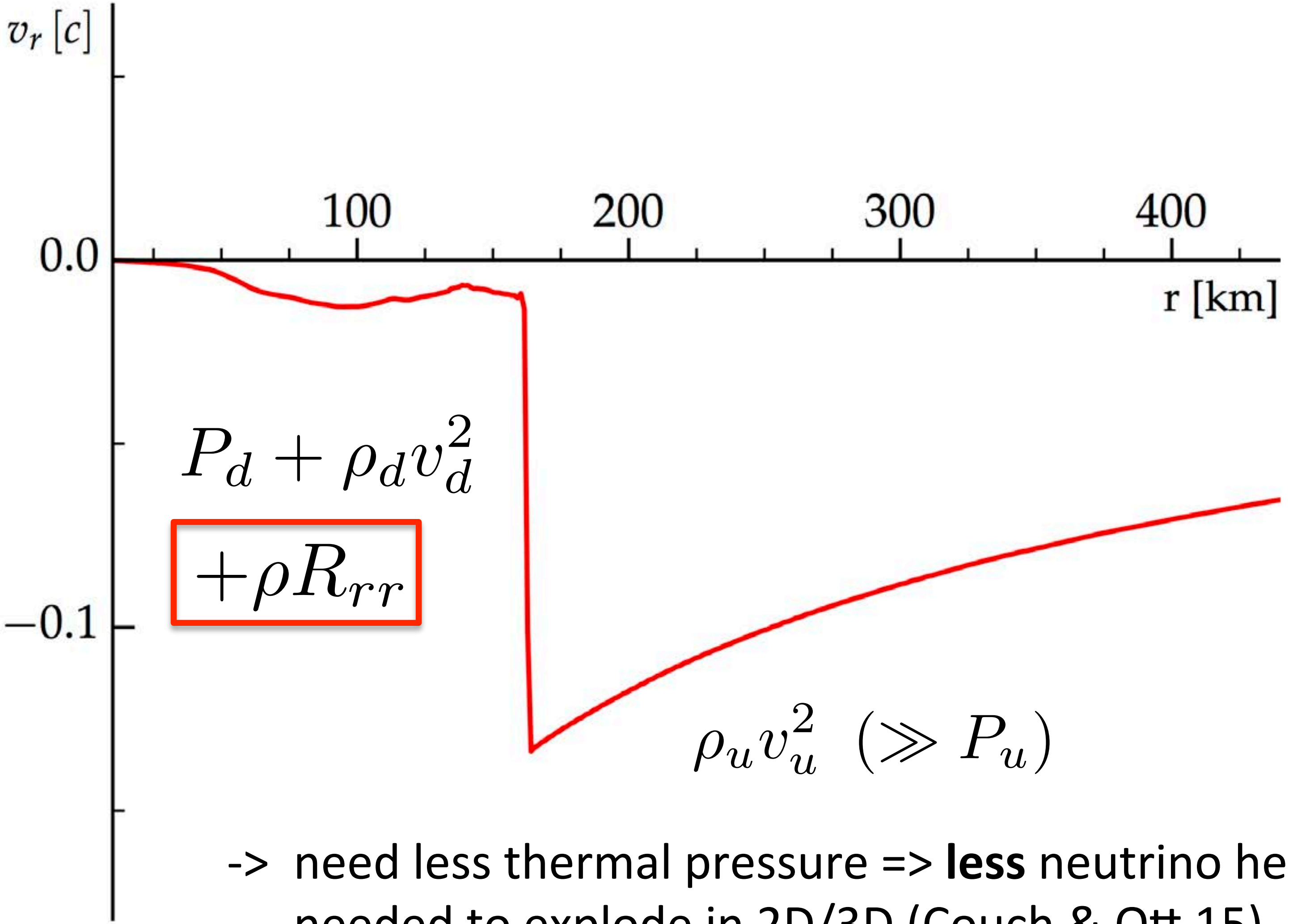
$$(\gamma_{\rm th} - 1)\rho\epsilon_{\rm th} + \rho_d v_d^2 + (\Gamma_{\rm turb} - 1)\rho\epsilon_{\rm turb} = \rho_u v_u^2$$

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

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

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/