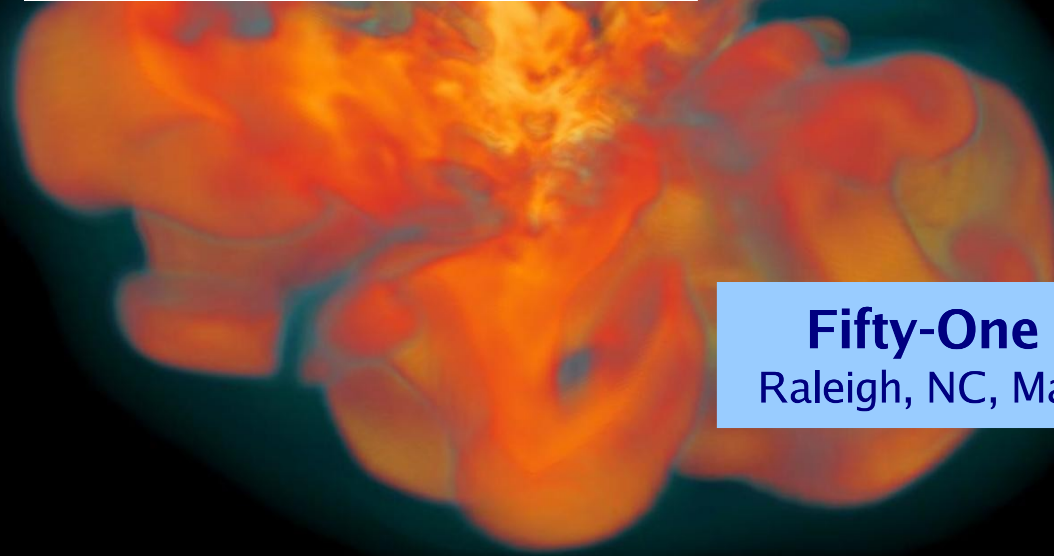
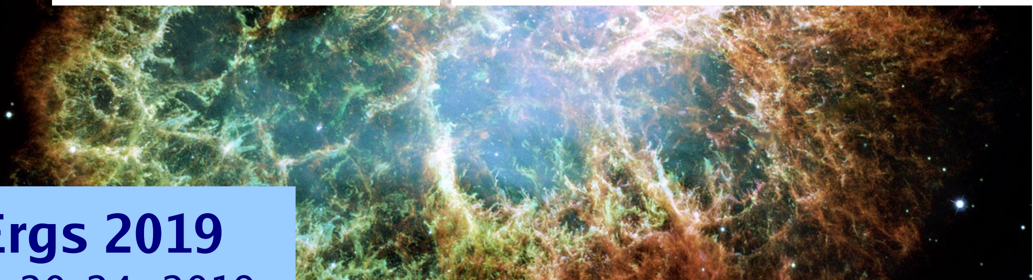
Max-Planck-Institut für Astrophysik

TUM LMU ORIGINS Excellence Cluster ESO lrz

SFB 1258 Neutrinos Dark Matter Messengers





Fifty-One Ergs 2019

Raleigh, NC, May 20–24, 2019

Core-Collapse Supernova Modeling in Three Dimensions

Recent Progress @ Garching

European Research Council

Established by the European Commission

Supporting top researchers from anywhere in the world

Hans-Thomas Janka

MPI for Astrophysics

COCO2CASA

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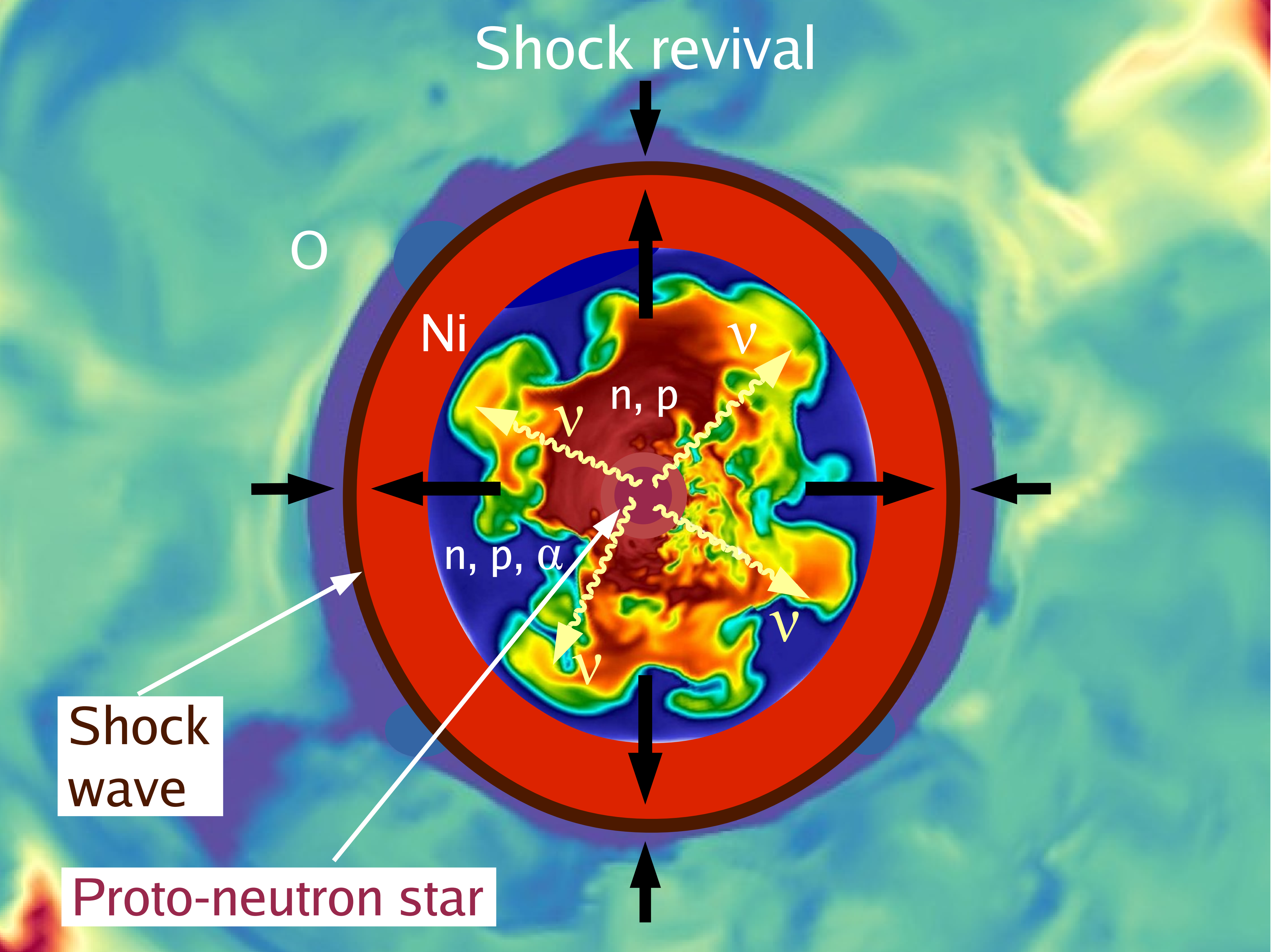
- <u>**Brief overview:**</u> **Status of 3D CCSN modeling**

- **1. Pre-collapse progenitor asymmetries**
- **2. Resolution dependence of 3D CCSN simulations (with the Garching *Prometheus-Vertex* code)**
- **3. Ray-by-ray (RbR+) versus fully multi-dimensional (FMD-M1) neutrino transport in 3D**


Shock revival
O
Ni
ν
n, p
ν
n, p, α
ν
ν
Shock wave
Proto-neutron star

Status of Neutrino-driven Mechanism in 3D Supernova Models

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  3D differs from 2D in many aspects, explosions more difficult than in 2D.

- M <~ 12–13 M_{sun} stars explode by neutrino-driven mechanism in 3D.
- First neutrino-driven 3D explosions of 15–40 M_{sun} progenitors
  (with rotation, 3D progenitor perturbations, or slightly modified neutrino opacities).
- Explosion energy can take several seconds to saturate !

3D Core-Collapse SN Explosion Models

Oak Ridge (Lentz+ ApJL 2015): **15 M_{sun} nonrotating progenitor** (Woosley & Heger 2007)

Tokyo/Fukuoka (Takiwaki+ ApJ 2014): **11.2 M_{sun} nonrotating progenitor** (Woosley et al. 2002)

Caltech/NCSU/LSU/Perimeter (Roberts+ ApJ 2016; Ott+ ApJL 2018):

27 M_{sun} nonrotating progenitor (Woosley et al. 2002),

15, 20, 40 M_{sun} nonrotating progenitors (Woosley & Heger 2007)

Princeton (Vartanyan+ MNRAS 2019a, Burrows+ MNRAS 2019):

9, 10, 11, 12, 13, 16 M_{sun} nonrot. progenitors (Woosley & Heger 2007, Sukhbold+2016)

Garching/QUB/Monash (Melson+ ApJL 2015a,b; Müller 2016; Janka+ ARNPS 2016, Müller+ MNRAS 2017, Summa+ ApJ 2018):

9.6, 20 M_{sun} nonrotating progenitors (Heger 2012; Woosley & Heger 2007)

18 M_{sun} nonrotating progenitor (Heger 2015)

15 M_{sun} rotating progenitor (Heger, Woosley & Spuit 2005, modified rotation)

9.0 M_{sun} nonrotating progenitor (Woosley & Heger 2015)

3D Core-Collapse SN Explosion Models

Monash/QUB (Müller+ MNRAS 2018, Müller+MNRAS 2019):

z9.6, s11.8, z12, s12.5 M_{sun} nonrotating progenitors (Heger 2012),

he2,8, he3.0, he3.5 M_{sun} He binary stars, ultrastripped SN progenitors (Tauris 2017)

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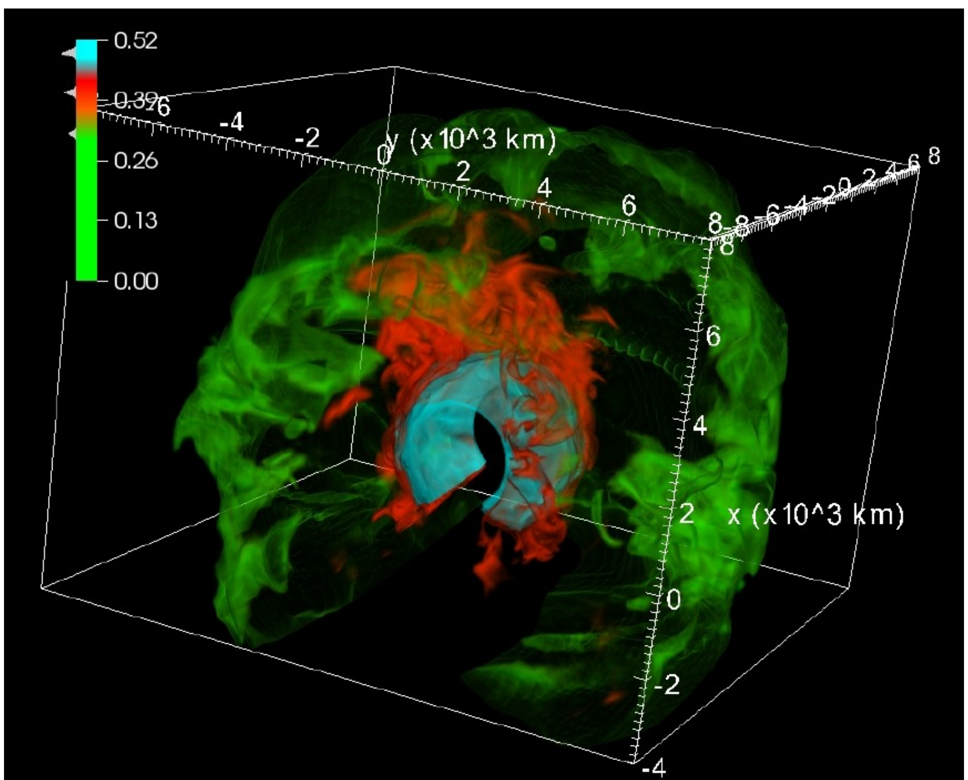
1. Pre-collapse 3D Asymmetries in Progenitors

With Naveen Yadav (postdoc), Tobias Melson (ex-postdoc) and Bernhard Müller and Alex Heger (Monash University); arXiv:1905.04378

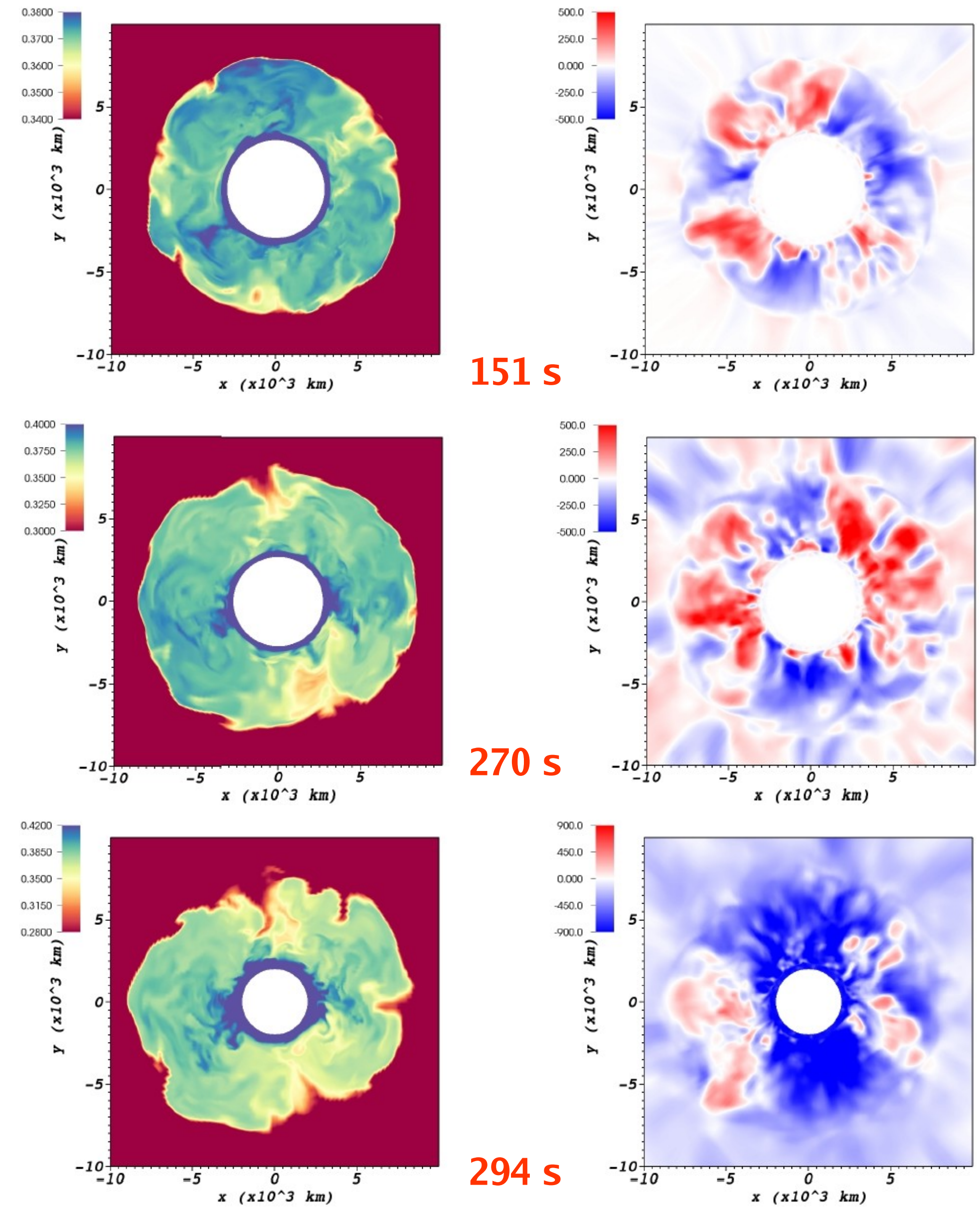
3D Core-Collapse SN Progenitor Model

18 M_{sun} (solar-metallicity) progenitor (Heger 2015)

3D simulation of last 5 minutes of O-shell burning. During accelerating core contraction a quadrupolar (l=2) mode develops with convective Mach number of about 0.1.



B. Müller, Viallet, Heger, & THJ, ApJ 833, 124 (2016)



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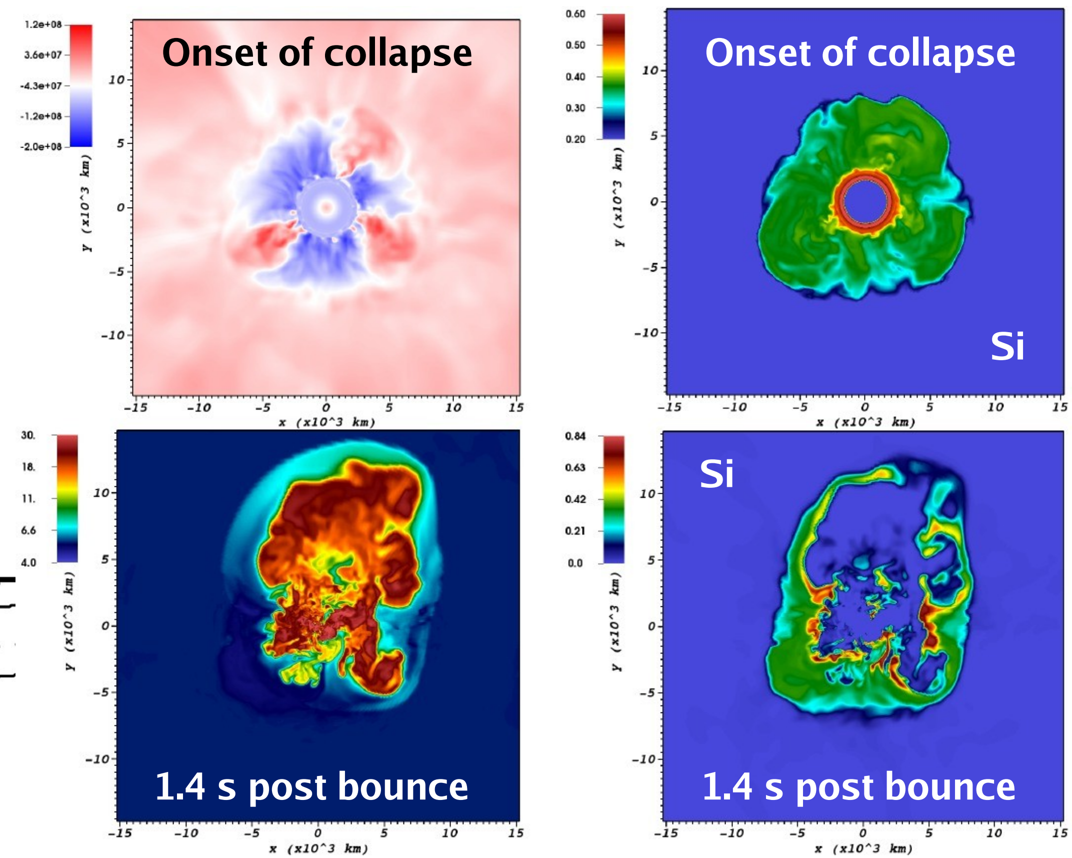
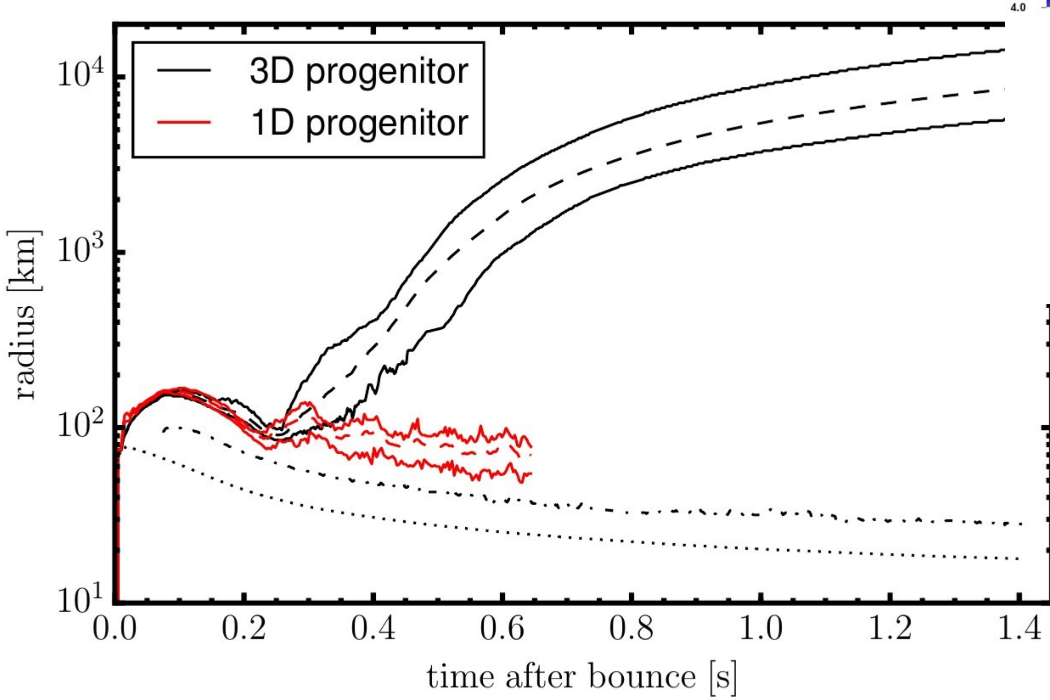
This fosters strong postshock convection and could thus reduces the criticial neutrino luminosity for explosion.





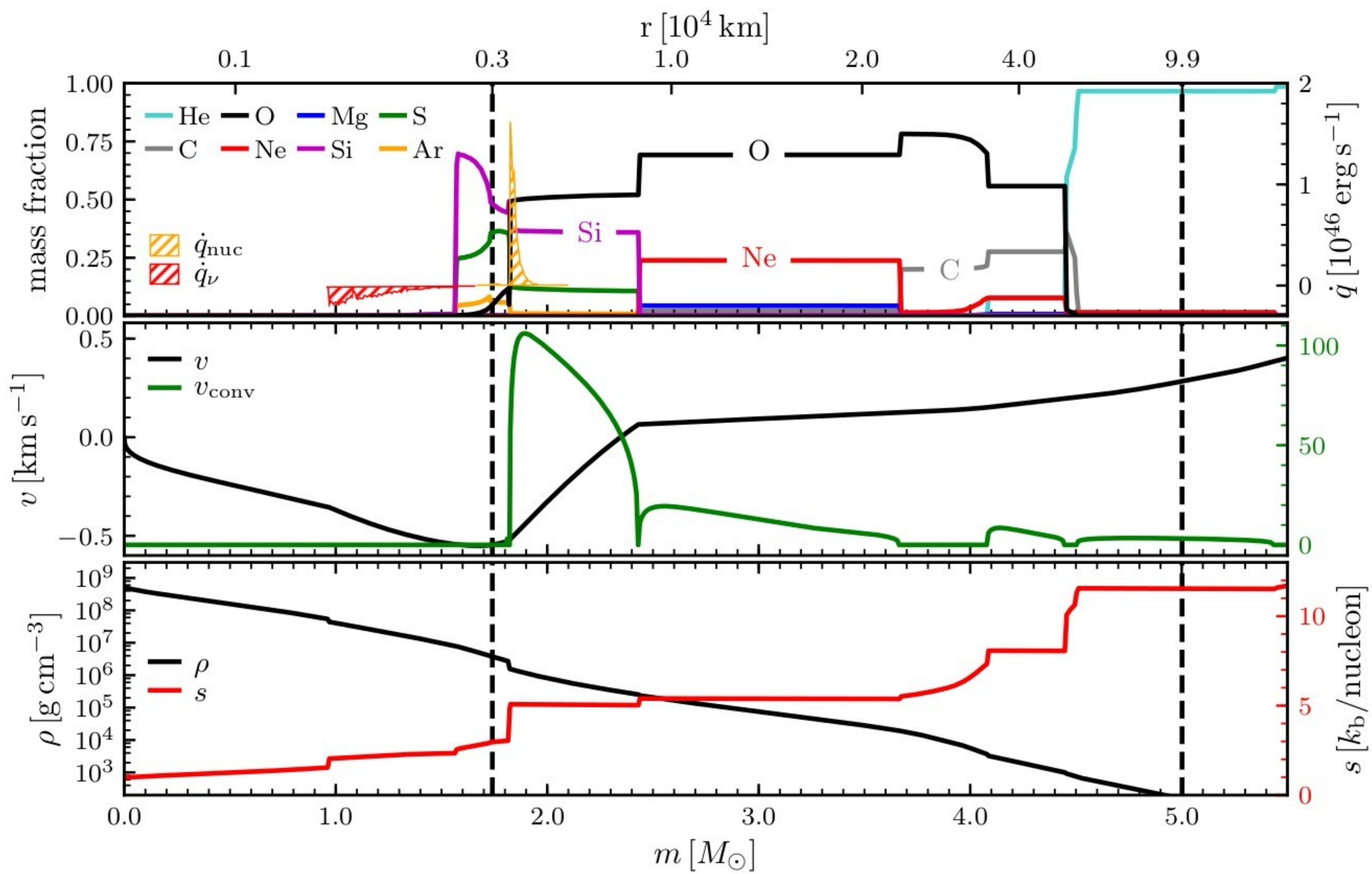
$\delta\rho/\rho \sim Ma_{conv}$

$$(L_\nu E_\nu^2)_{\mathrm{crit,pert}} \approx (L_\nu E_\nu^2)_{\mathrm{crit,3D}} \left(1 - 0.47 \frac{\mathrm{Ma_{conv}}}{\ell \eta_{\mathrm{acc}} \eta_{\mathrm{heat}}}\right)$$

B. Müller, PASA 33, 48 (2016);
Müller, Melson, Heger & THJ, MNRAS 472, 491 (2017)

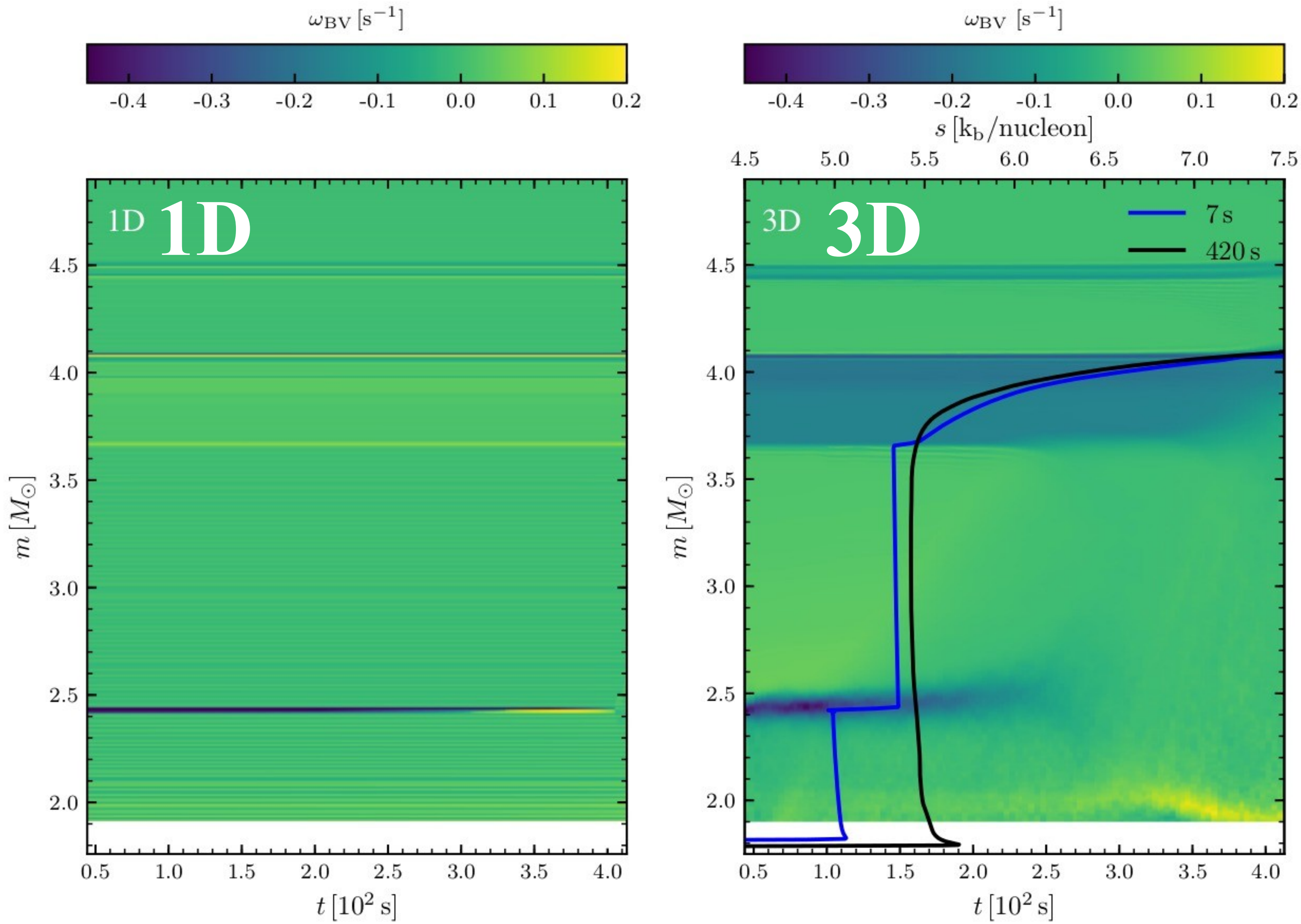
3D Simulations of Convective Oxygen Burning in ~19 M_{sun} Pre-collapse Star

Initial (1D) conditions 7 minutes prior to core collapse.



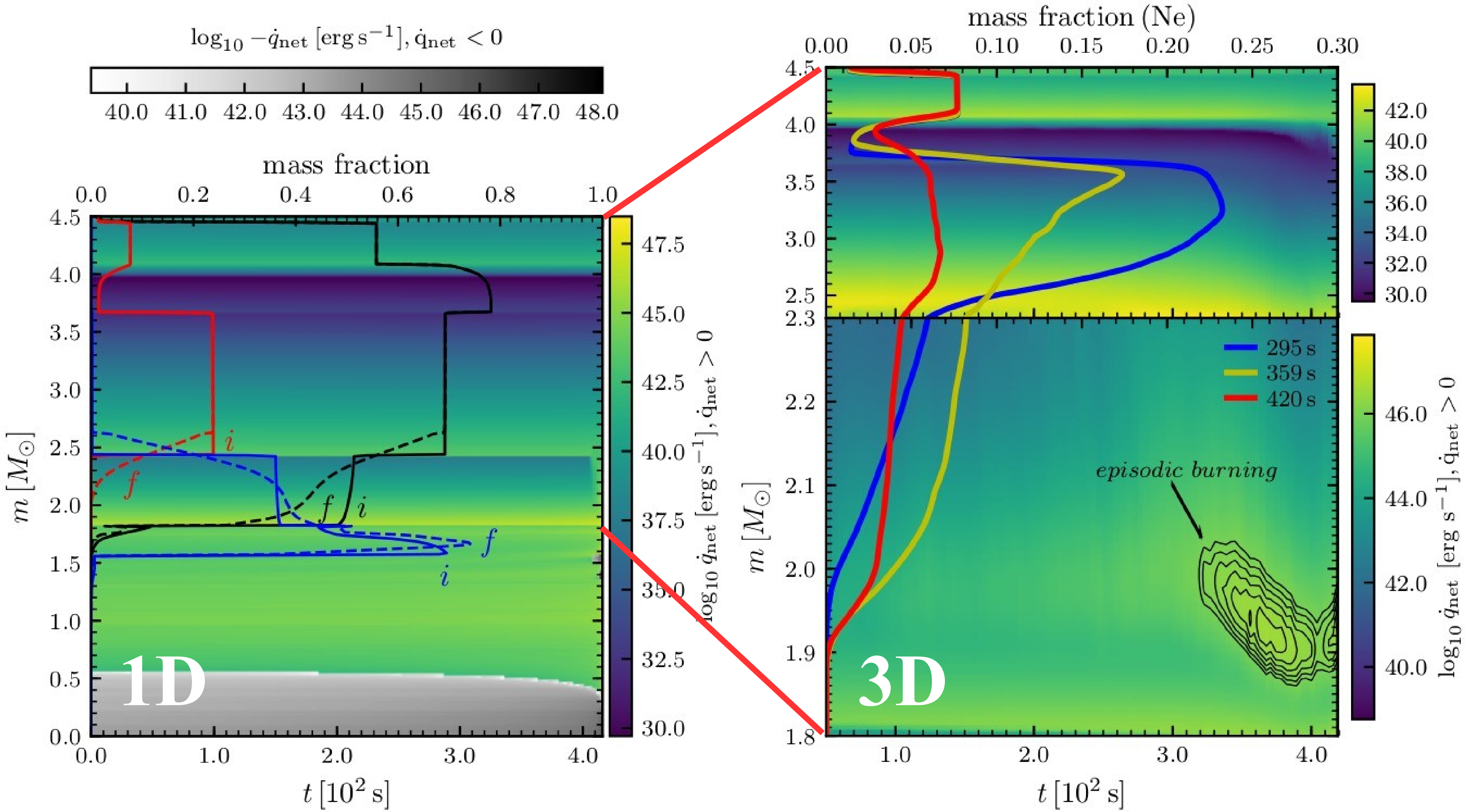
Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M_{sun}

Convectively Ledoux-stable (BV frequency < 0) and Ledoux-unstable regions (BV frequency > 0) regions.



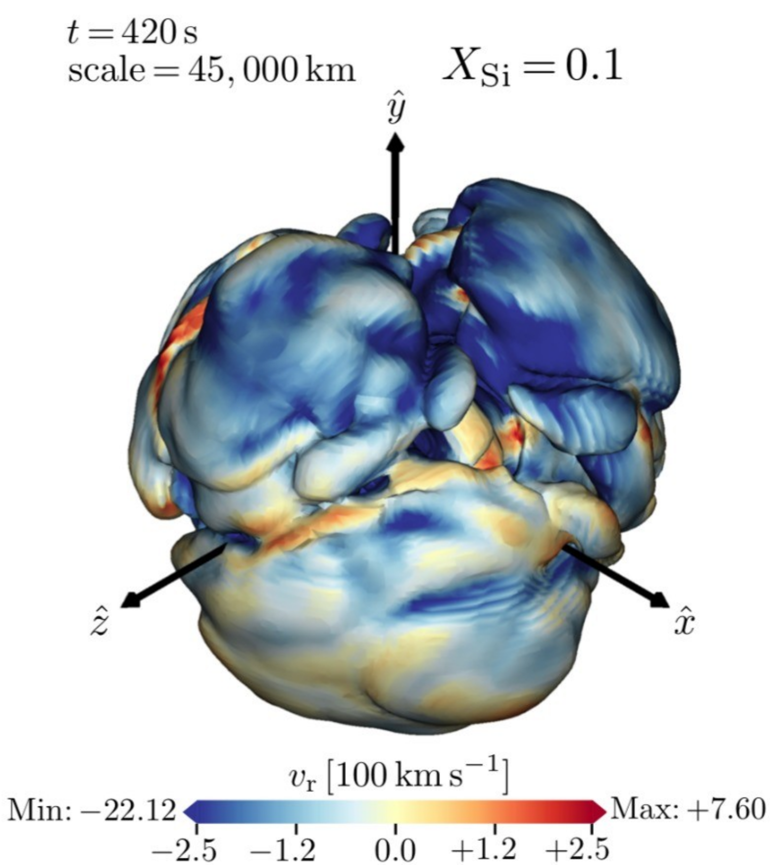
Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M$_{sun}$

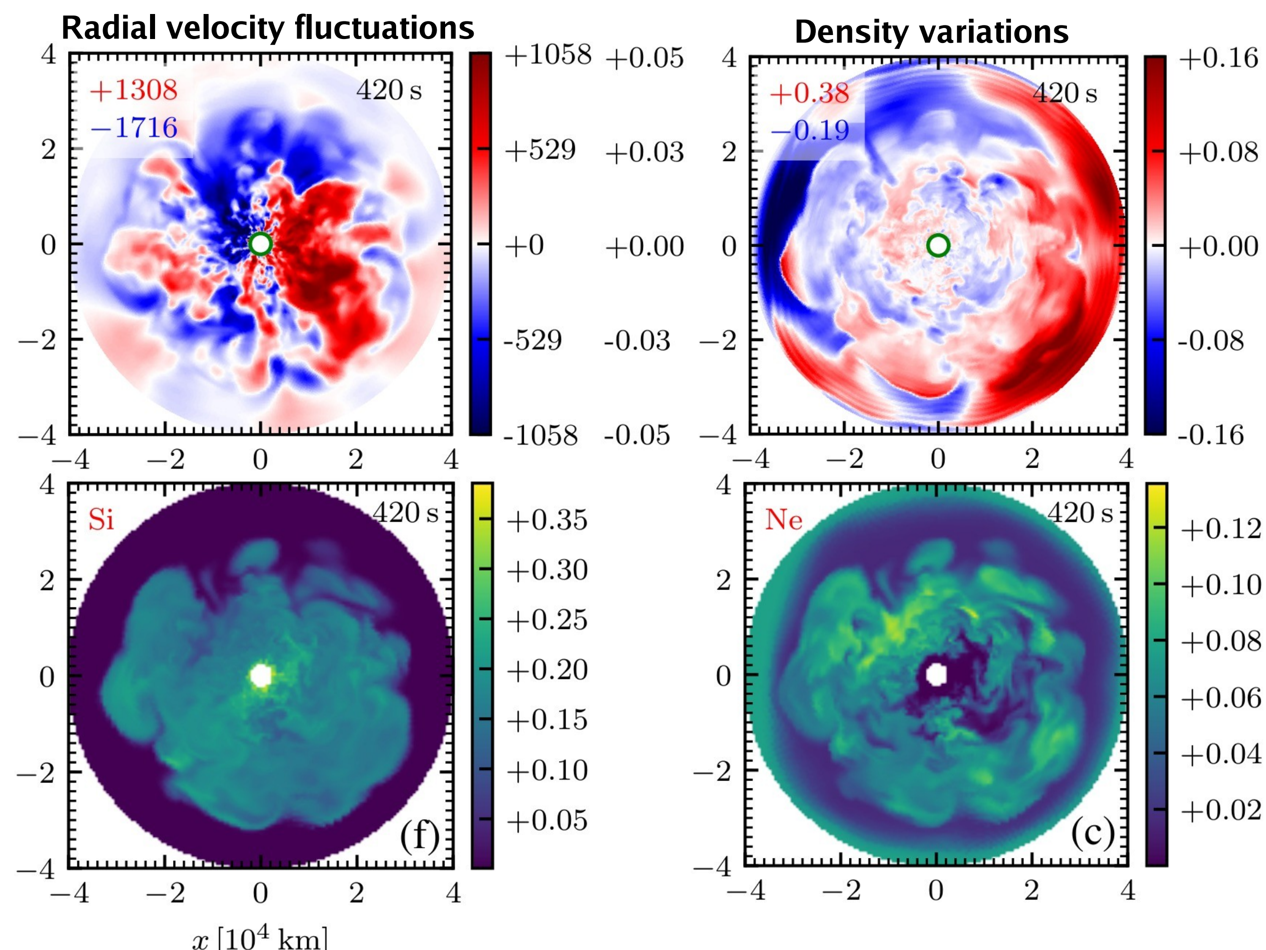
Net energy generation rate (nuclear burning minus neutrino cooling).

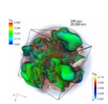


Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M_{sun}

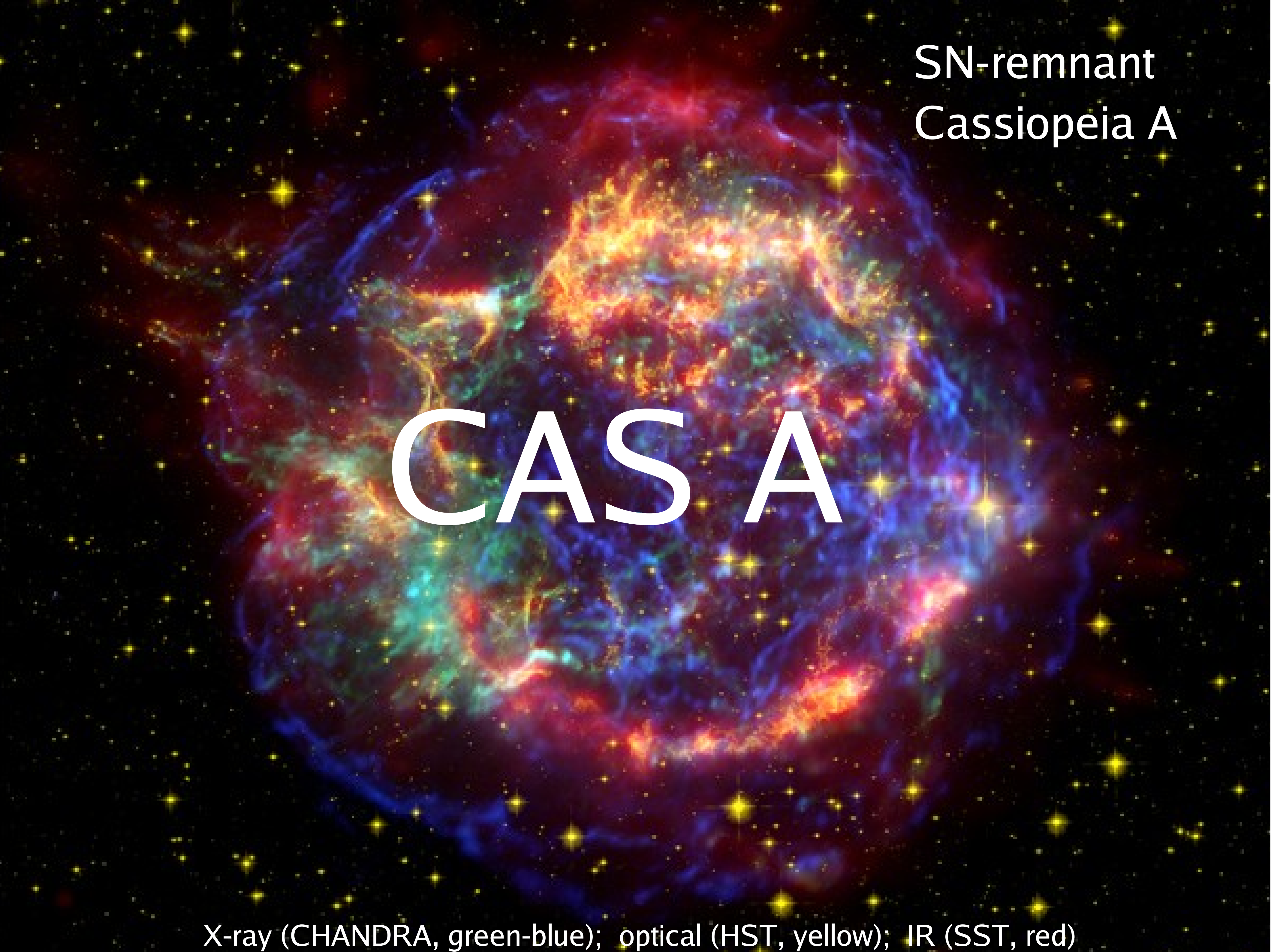
Flash of Ne+O burning creates large-scale asymmetries in density, velocity, Si/Ne composition





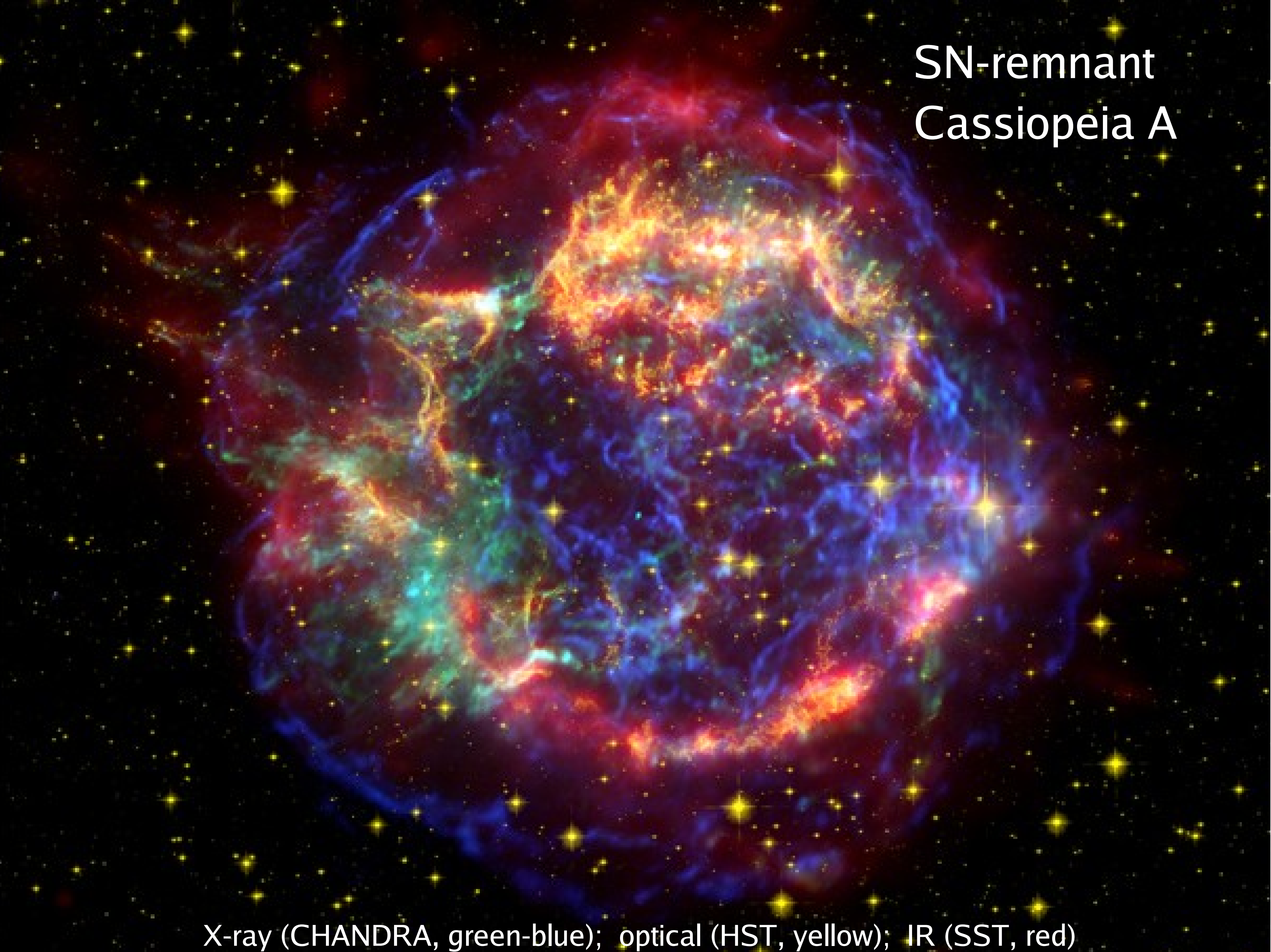


Yadav et al., arXiv:1905.04378



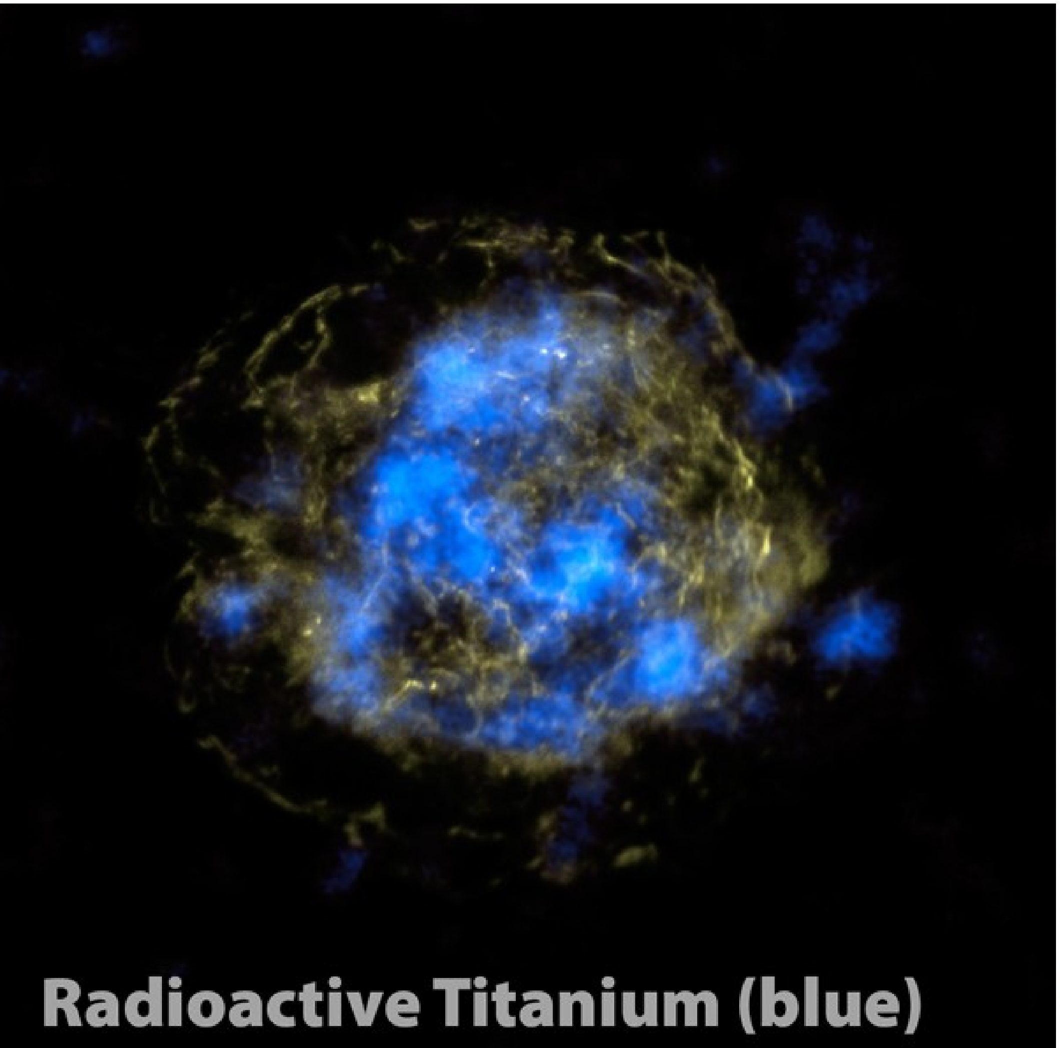
X-ray (CHANDRA, green-blue); optical (HST, yellow); IR (SST, red)

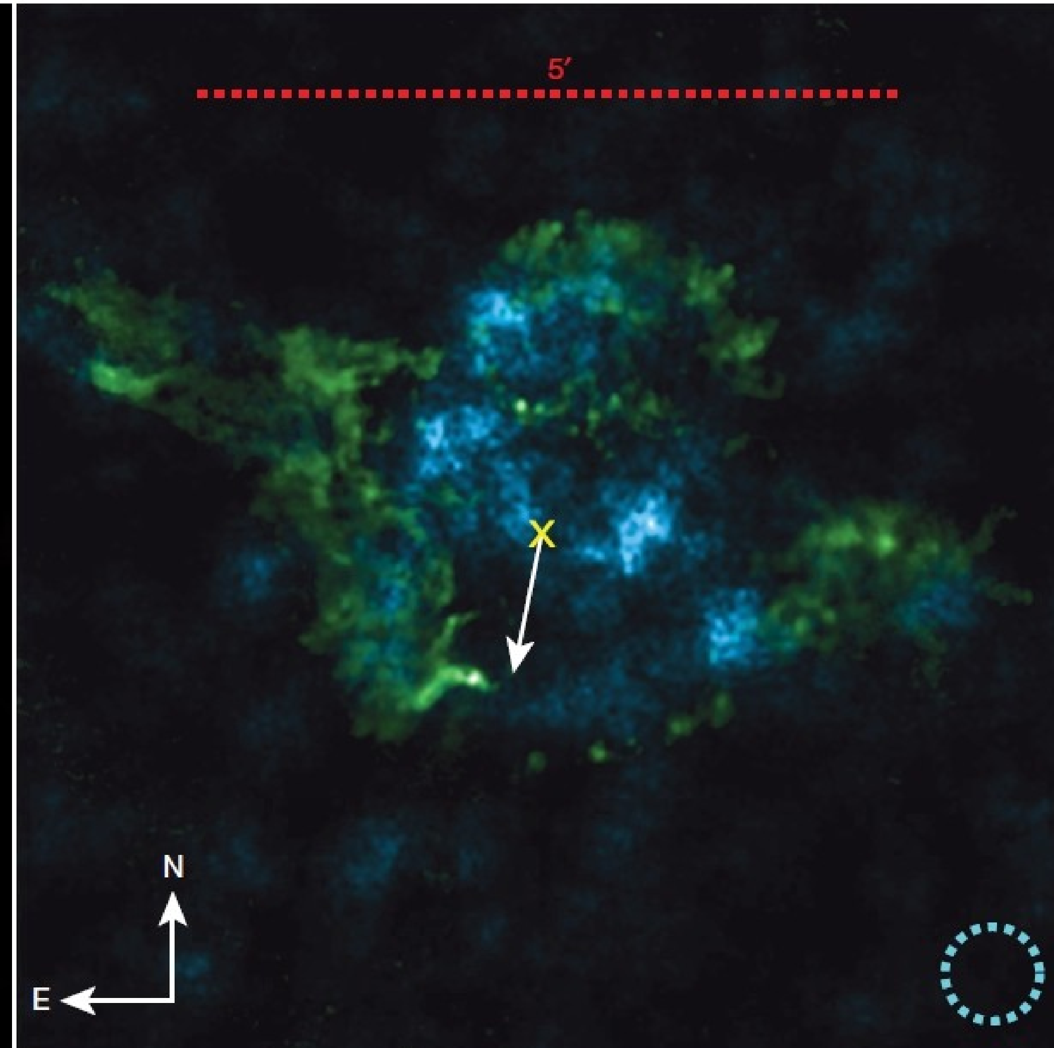
SN-remnant Cassiopeia A



X-ray (CHANDRA, green-blue); optical (HST, yellow); IR (SST, red)

^{44}Ti Asymmetry in the CAS A Remnant

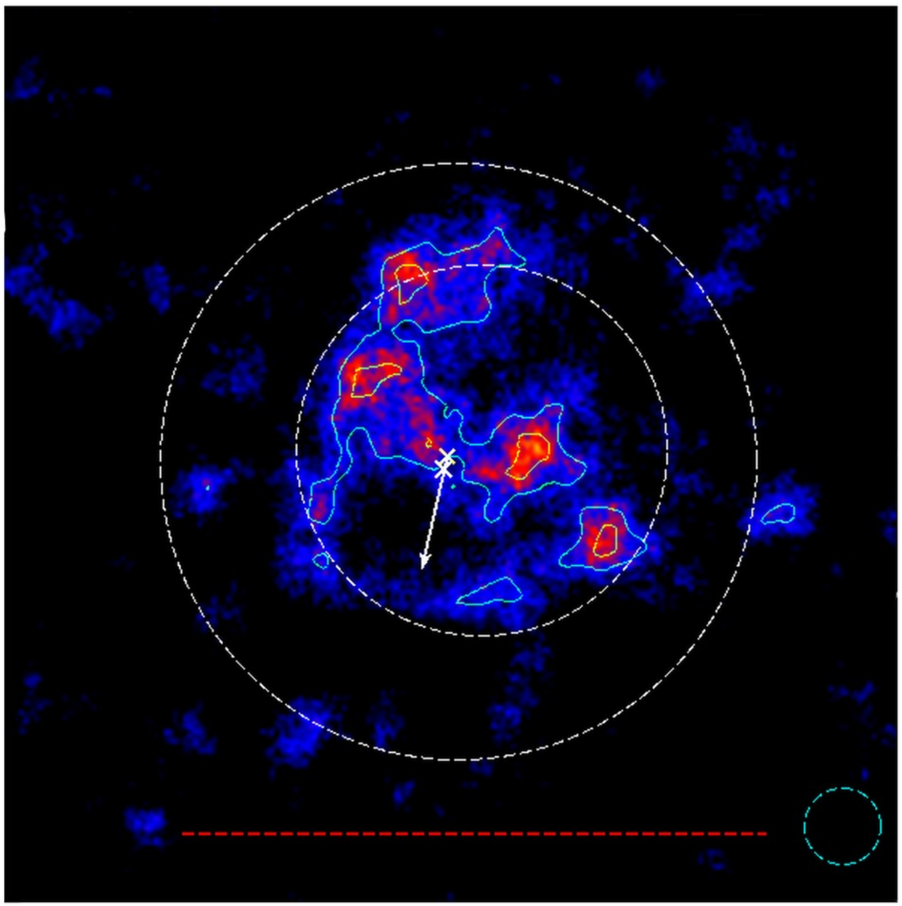




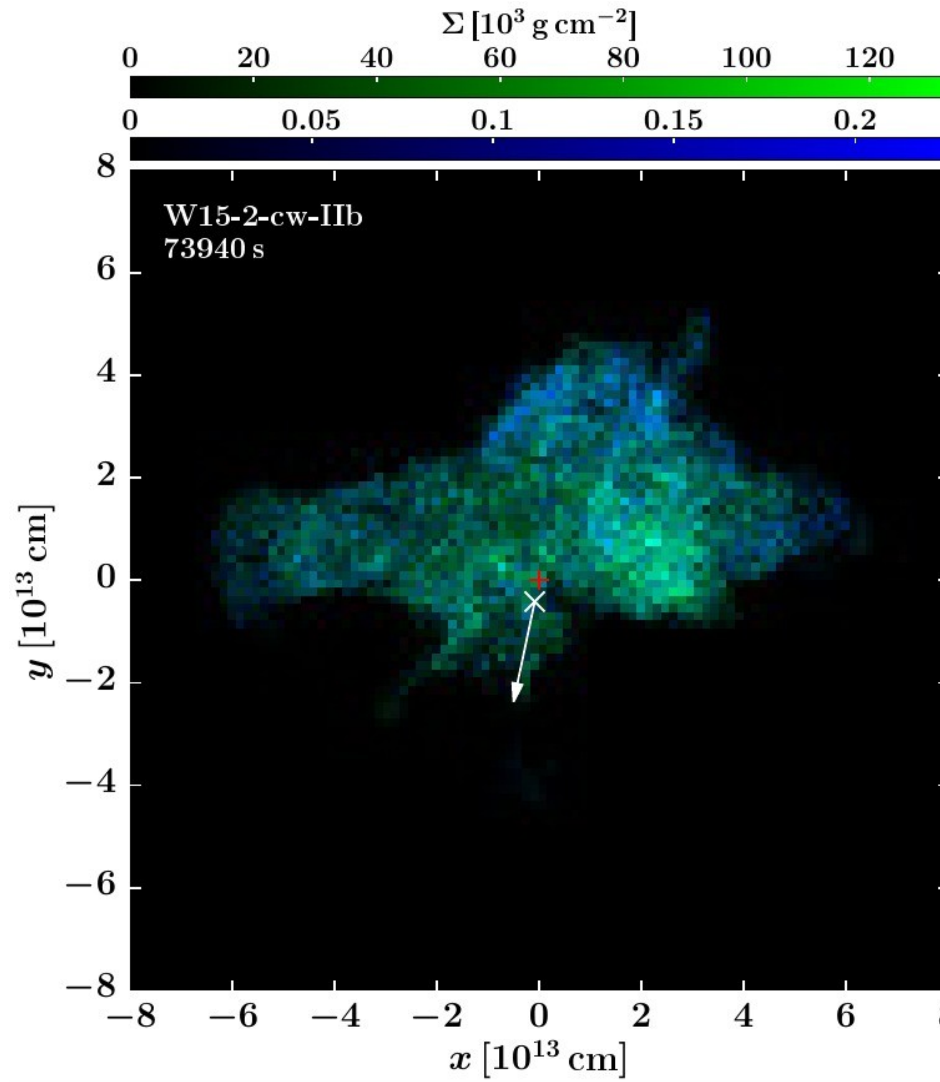
Grefenstette et al., Nature 506 (2014) 340

NuSTAR observations

Neutron Star Recoil and Nickel & 44Ti Distribution

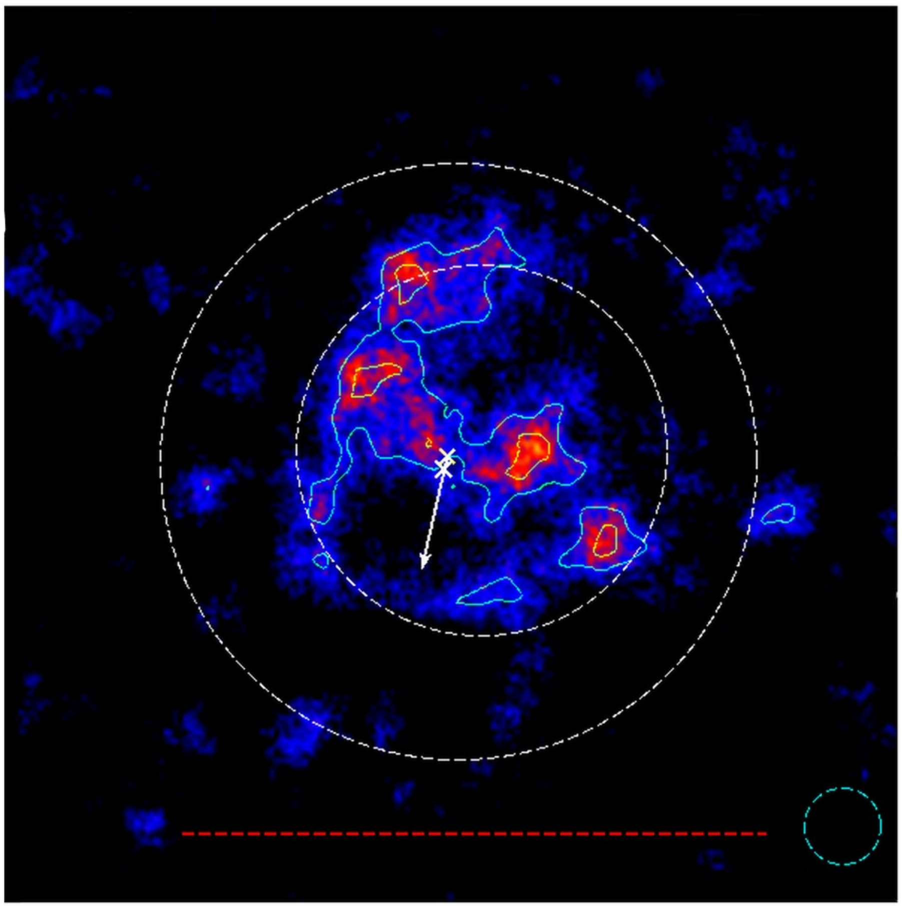


Grefenstette et al., Nature 506 (2014) 340

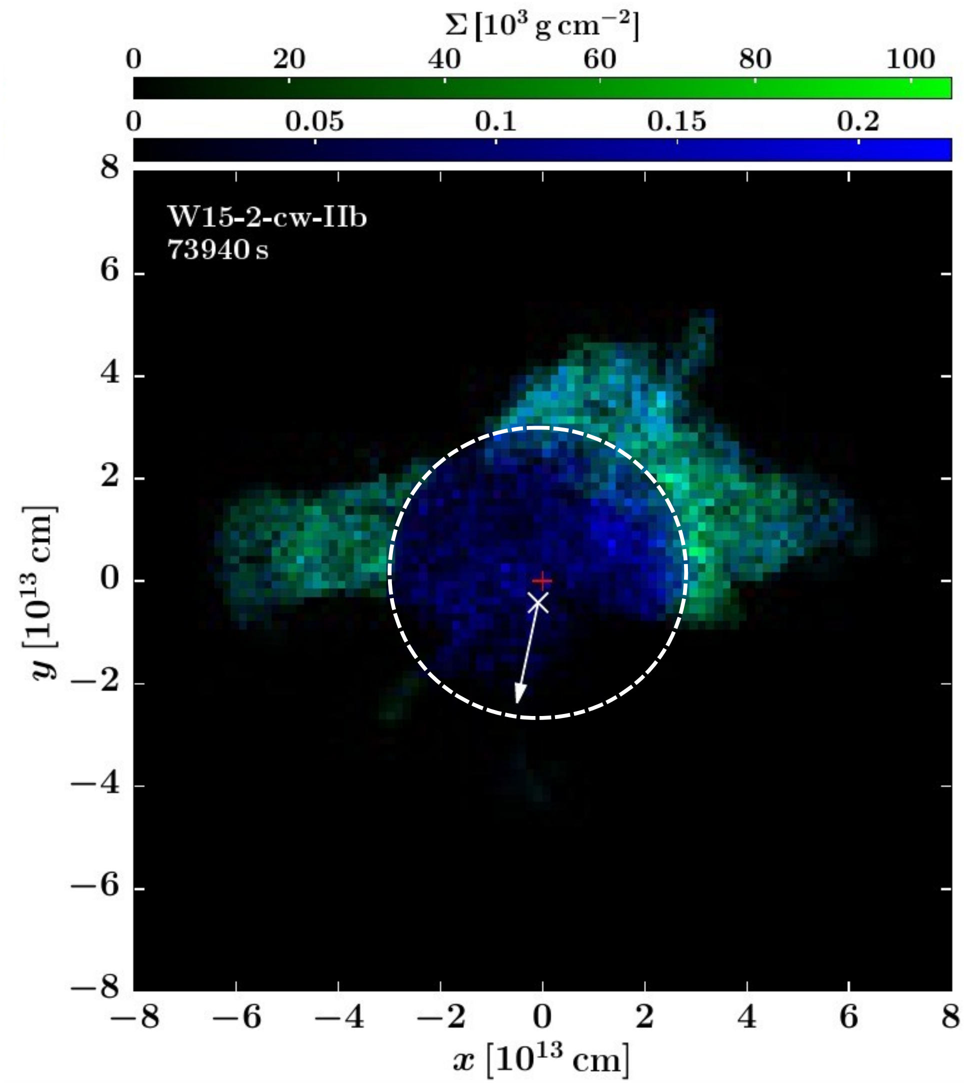


Wongwathanarat et al., ApJ 842 (2017) 13

Neutron Star Recoil and Nickel & 44Ti Distribution



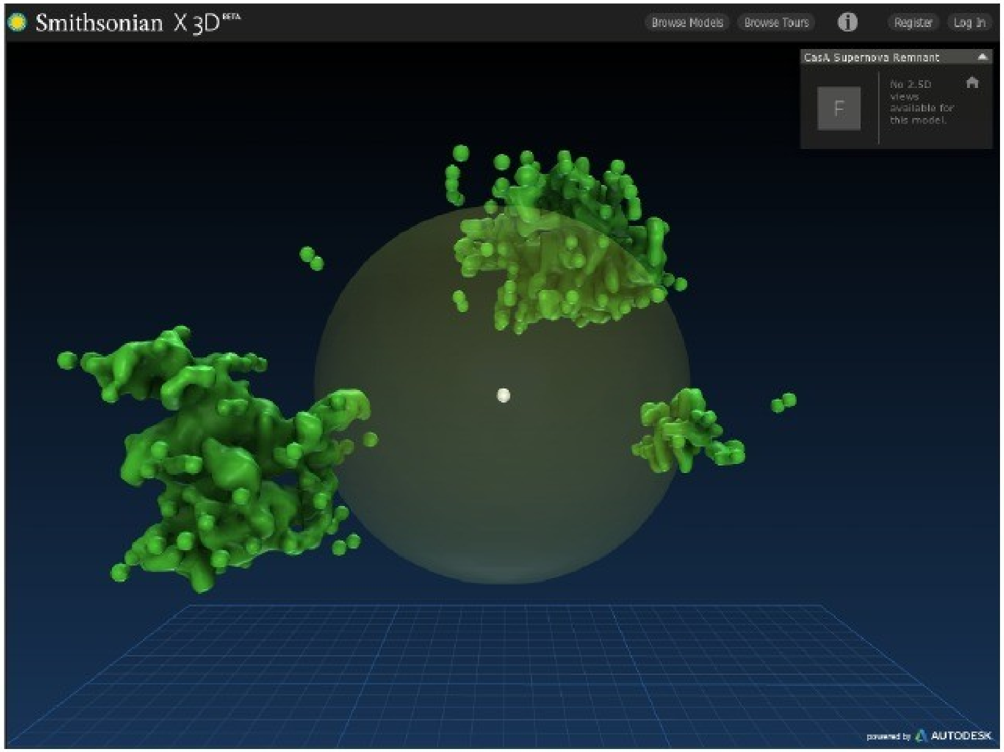
Grefenstette et al., Nature 506 (2014) 340

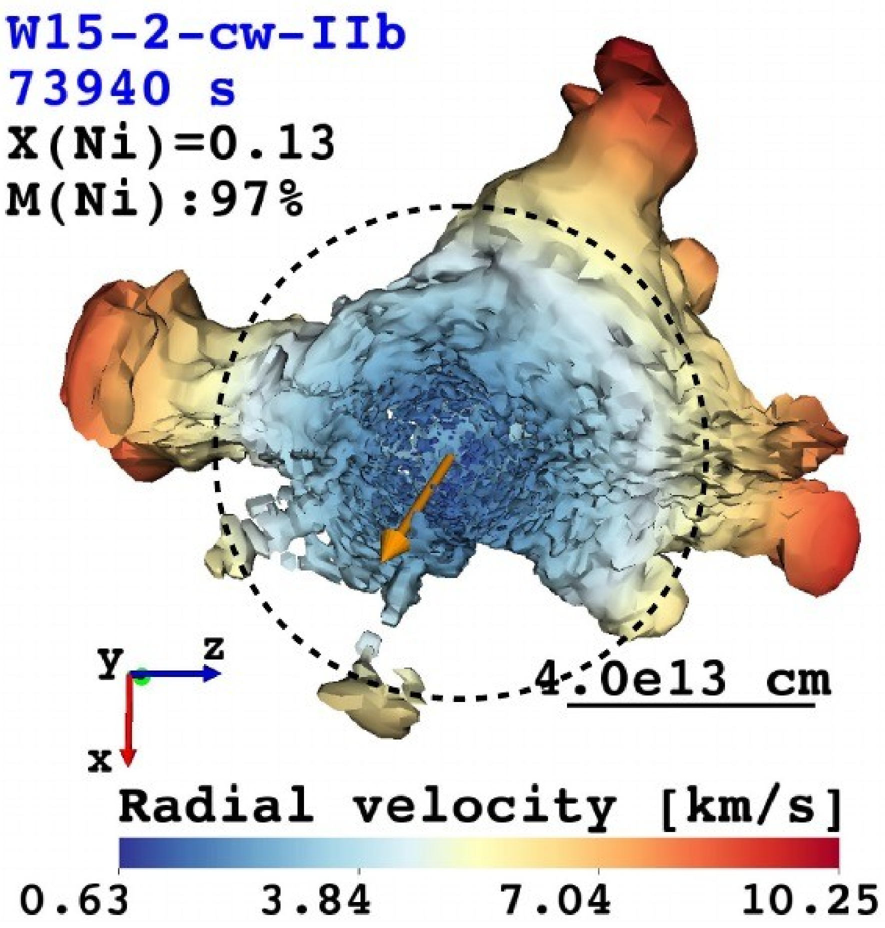


Wongwathanarat et al., ApJ 842 (2017) 13

Chemical Asymmetries in CAS A Remnant

Reverse-shock heated iron is visible in three big "fingers"





Wongwathanarat et al., ApJ 842 (2017) 13

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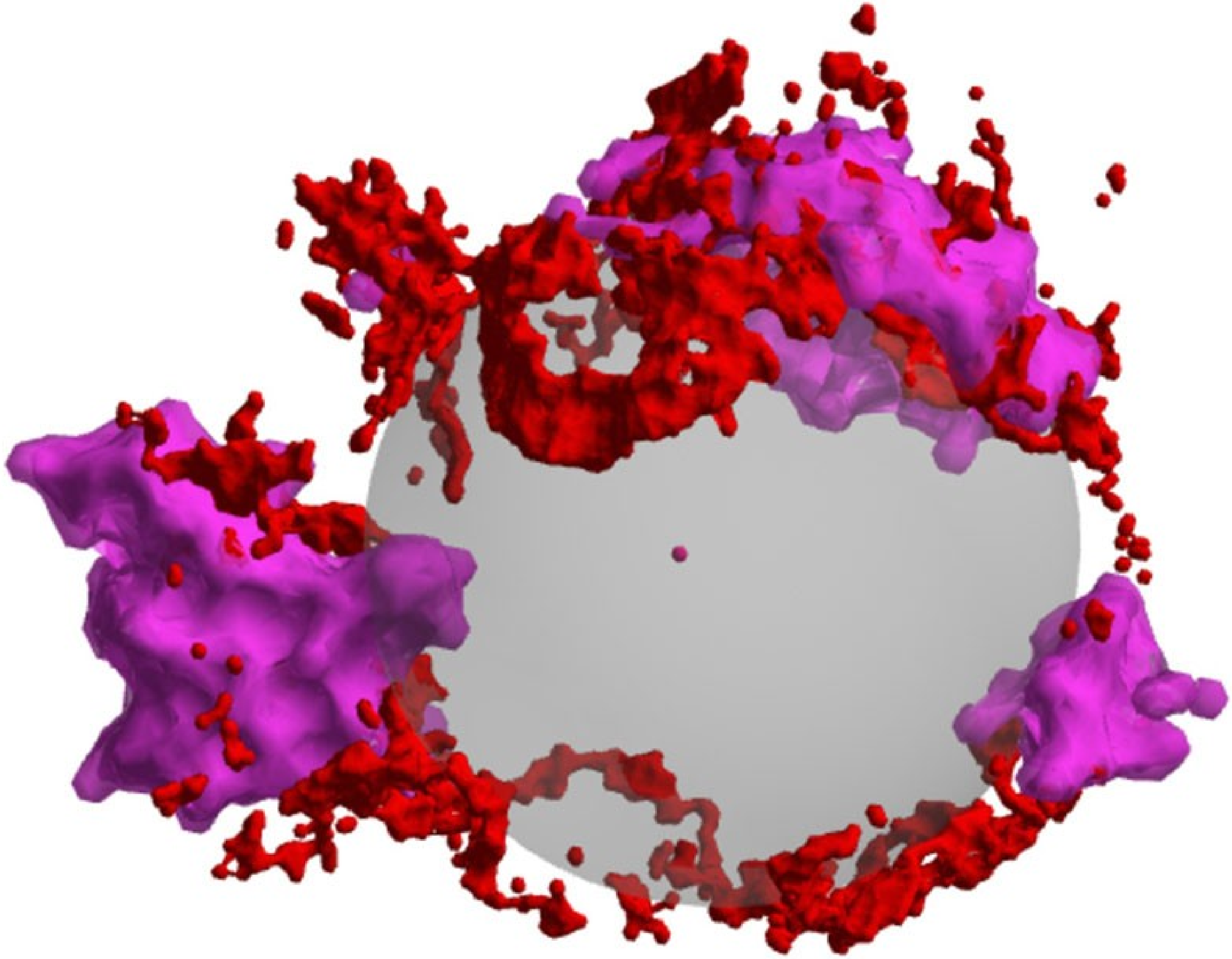
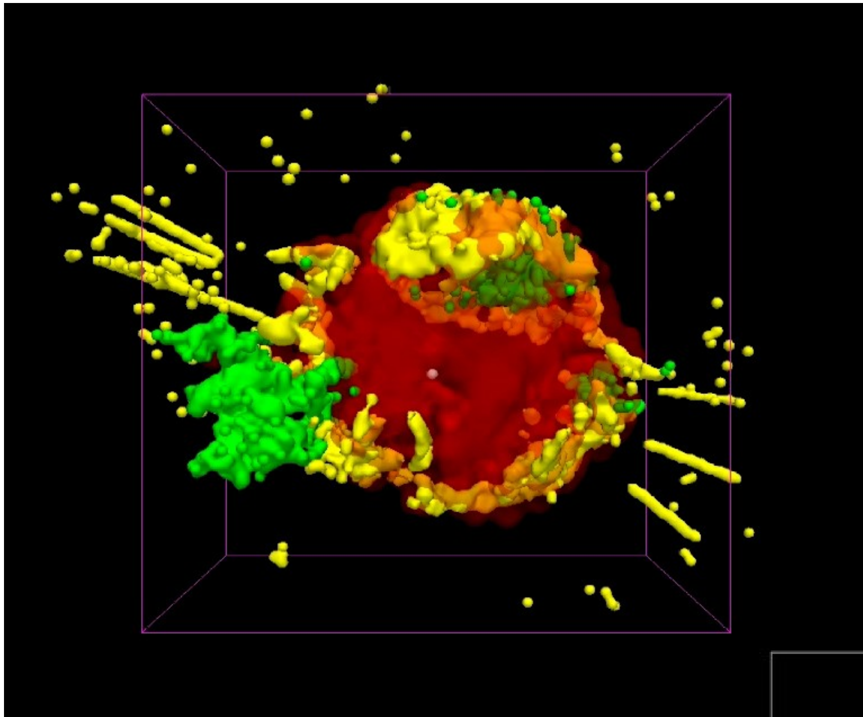


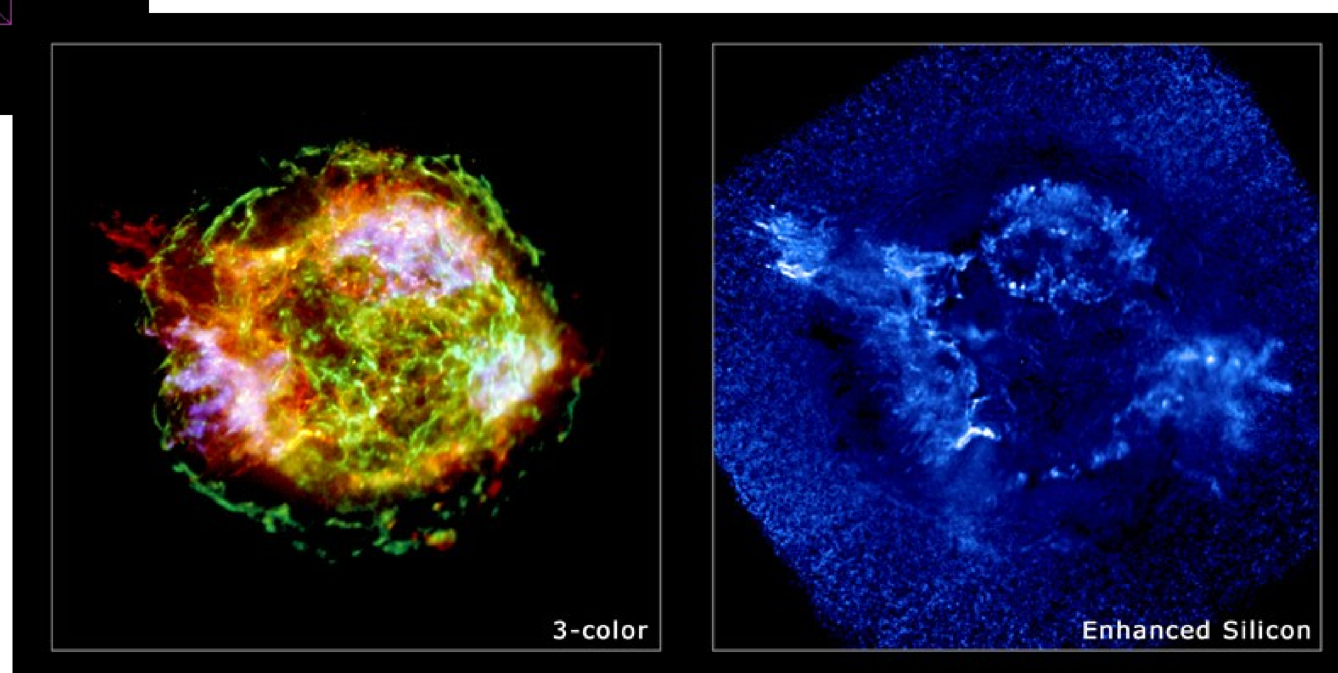
Red: Ar, Ne, and O (optical)
Purple: Iron (X-ray)

Image: Robert Fesen and Dan Milisavljevic, using iron data from DeLaney et al. (2010)

CAS A Si-Ne-rich Wide-angle "Jets"



- Wide-angle features in NE and SW directions with up to 15,000 km/s expansion velocity.
- Rich in Si and Ne, but poor in iron.



Credit: NASA/CXC/GSFC/U.Hwang et al.

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2. Resolution Dependence of CCSN Simulations With PV Code

With Tobias Melson (ex-postdoc);
arXiv:1904.01699

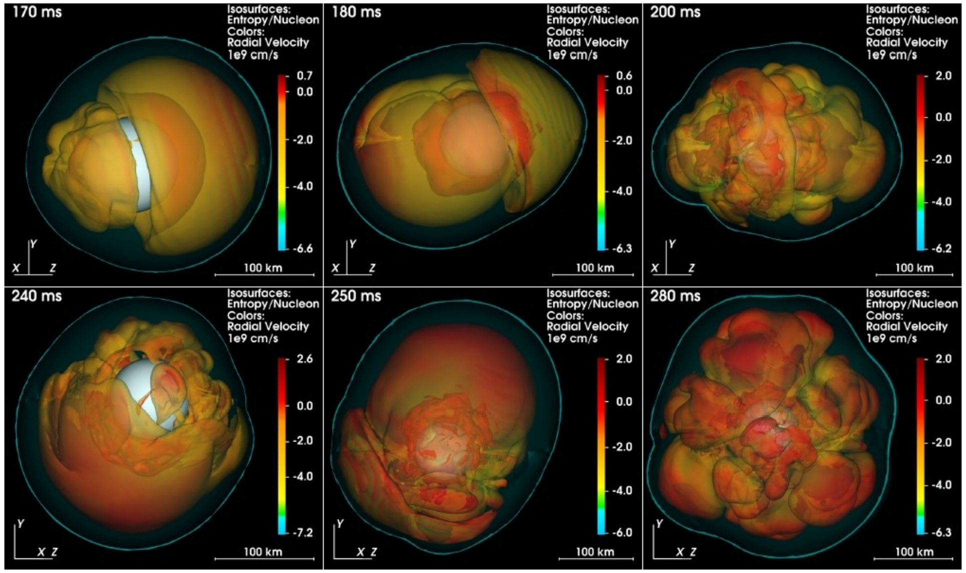
Exploding 3D Core-Collapse SN Model

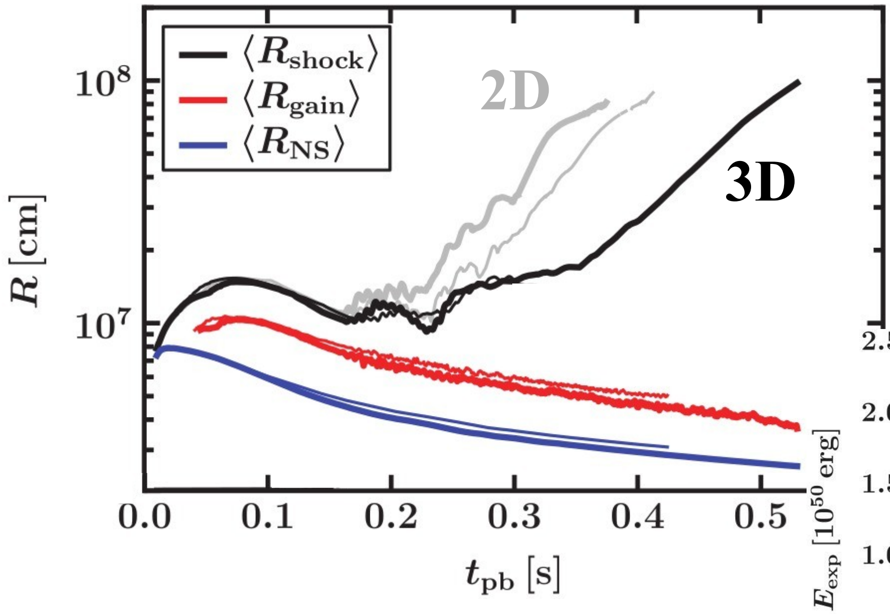
20 M_{sun} (solar-metallicity) progenitor (Woosley & Heger 2007)

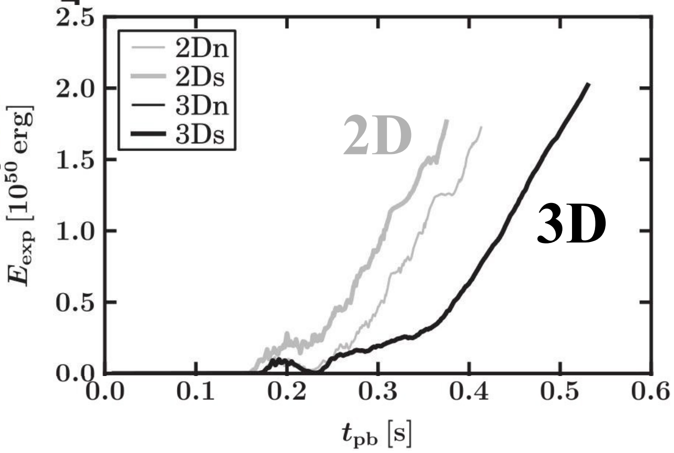
Explore uncertain aspects of microphysics in neutrinospheric region:

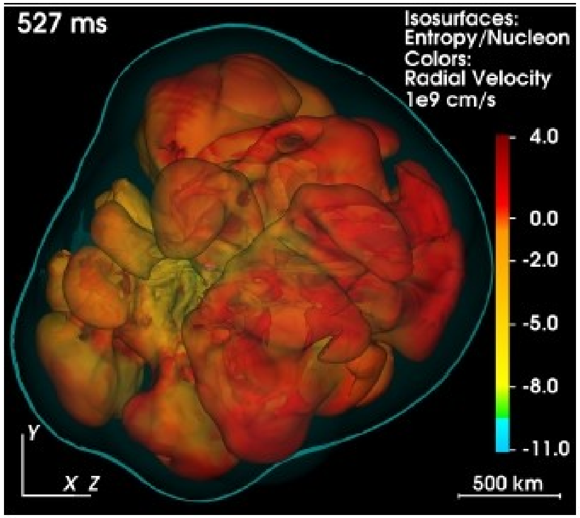
Example: strangeness contribution to nucleon spin, affecting axial-vector neutral-current scattering of neutrinos on nucleons

Effective reduction of neutral-current neutrino-nucleon scattering by ~15%





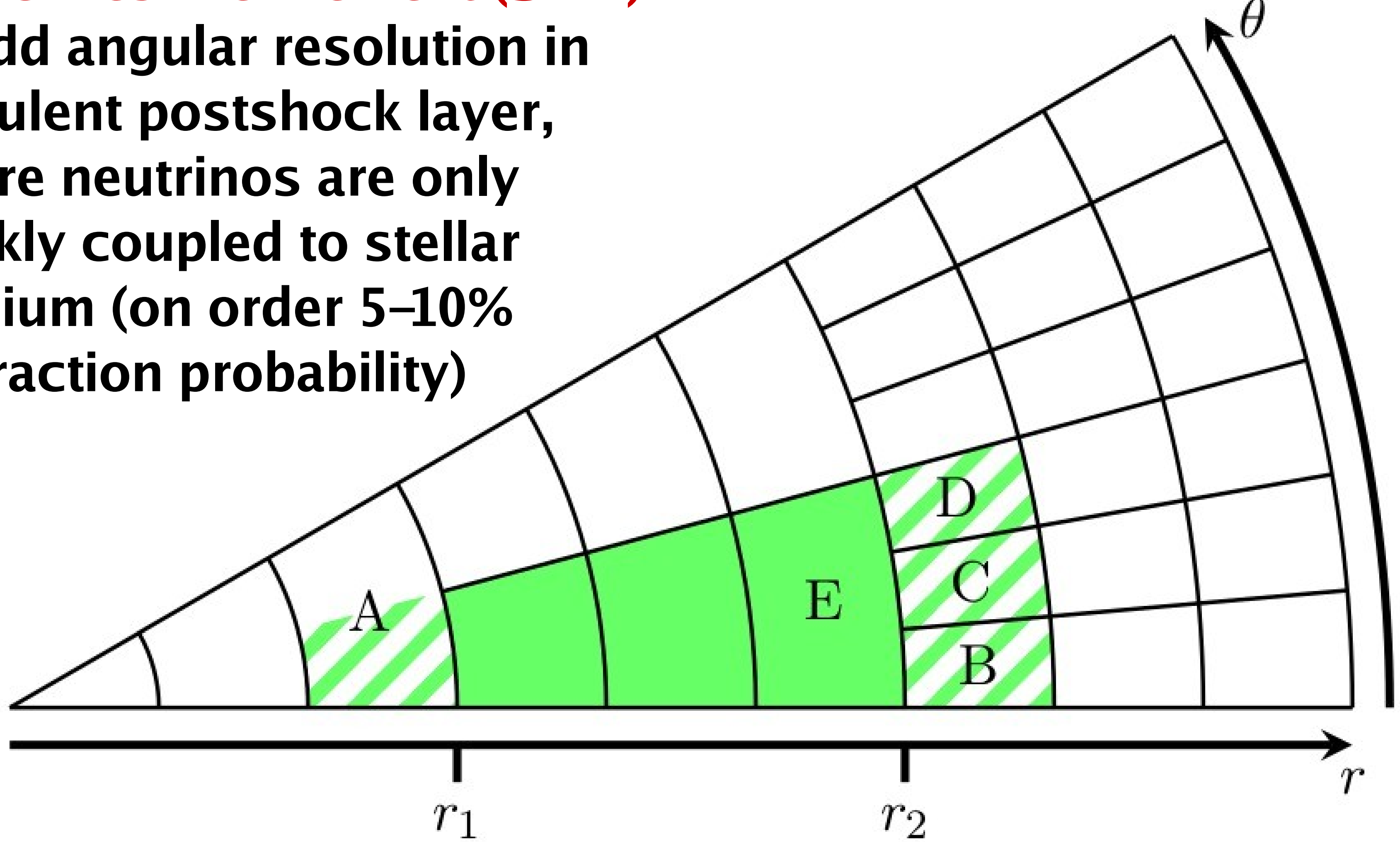




Melson et al.,
ApJL 808 (2015) L42

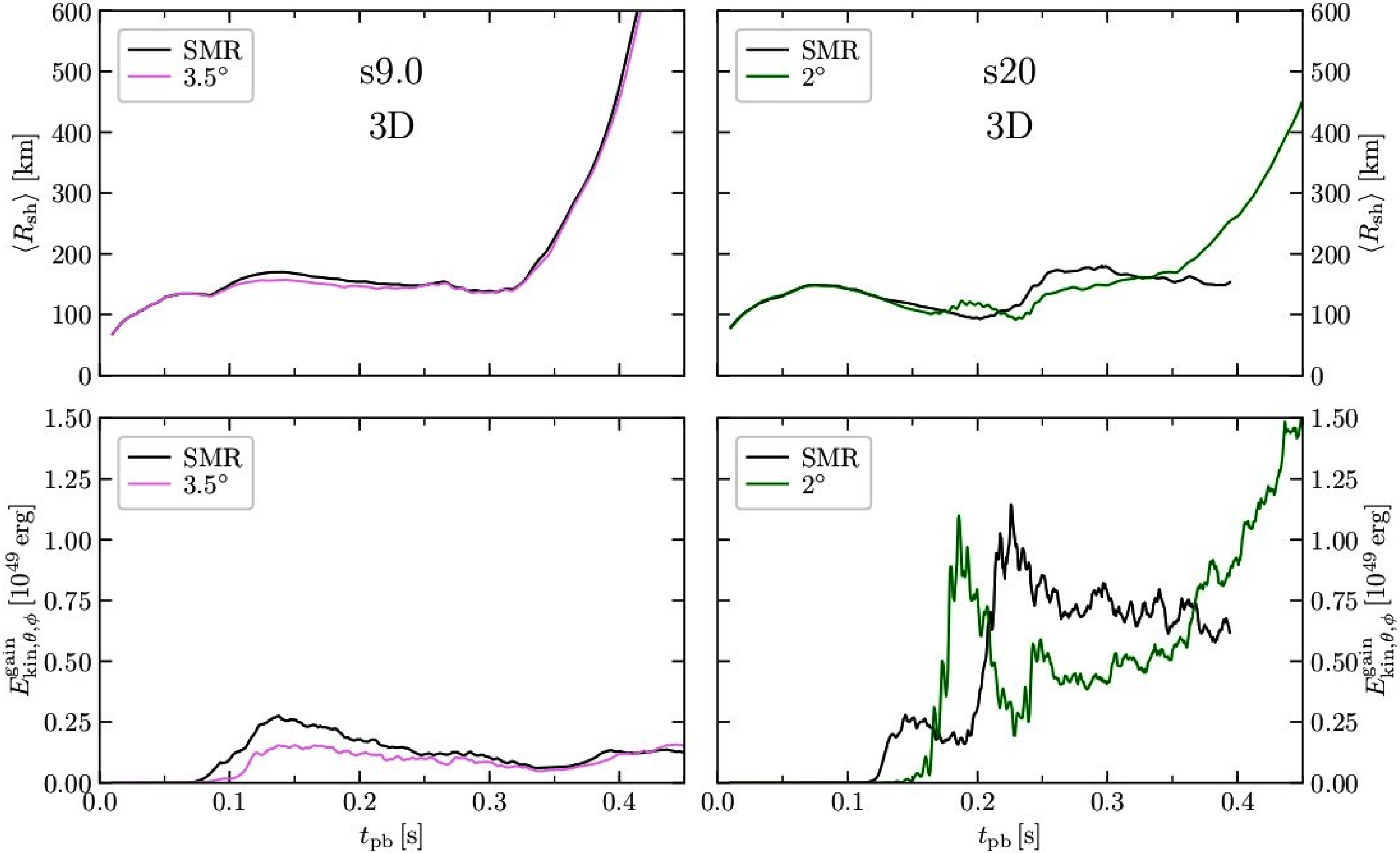
Improved Angular Resolution in 3D: Newly Implemented SMR Grid

Static mesh refinement (SMR) to add angular resolution in turbulent postshock layer, where neutrinos are only weakly coupled to stellar medium (on order 5–10% interaction probability)

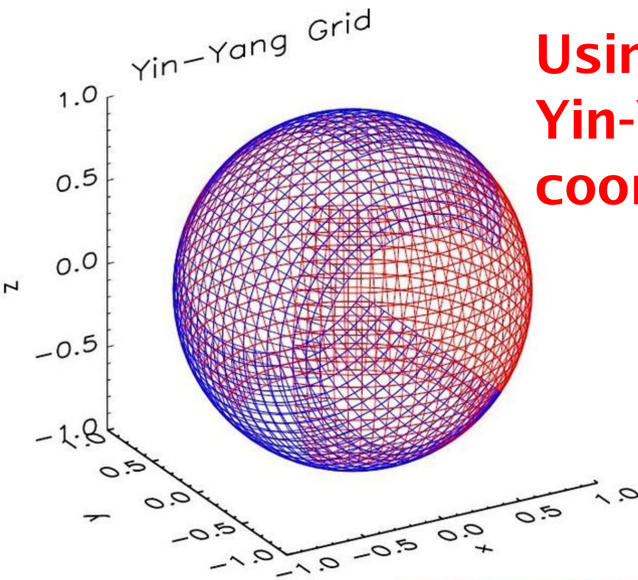


Melson et al., arXiv:1904.01699

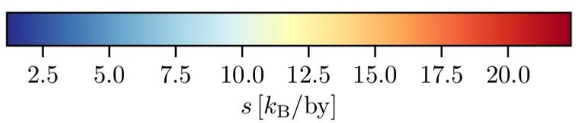
Comparing Explosions With Full Neutrino Transport and Different Angular Resolution

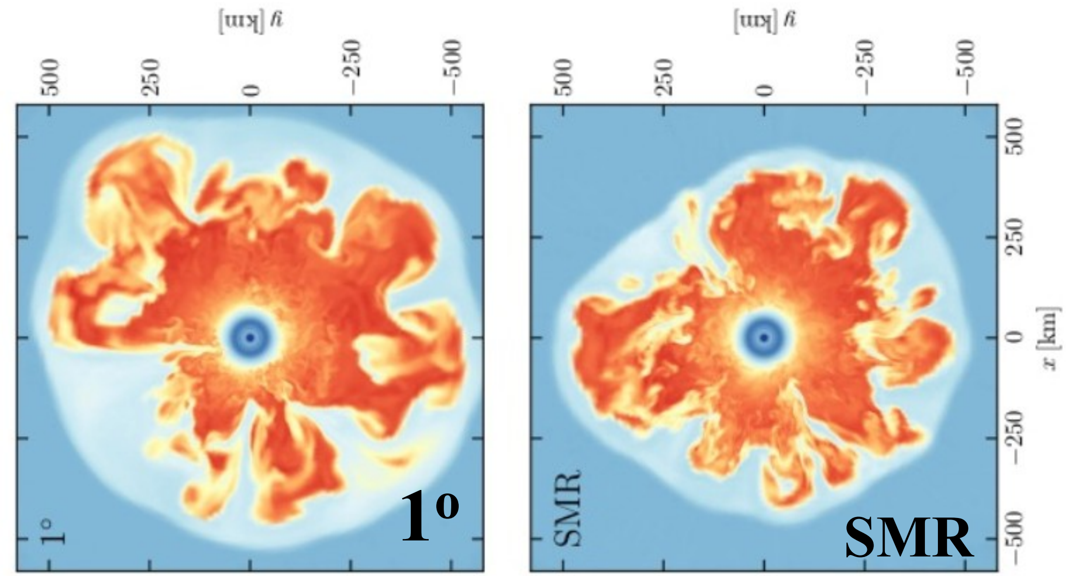


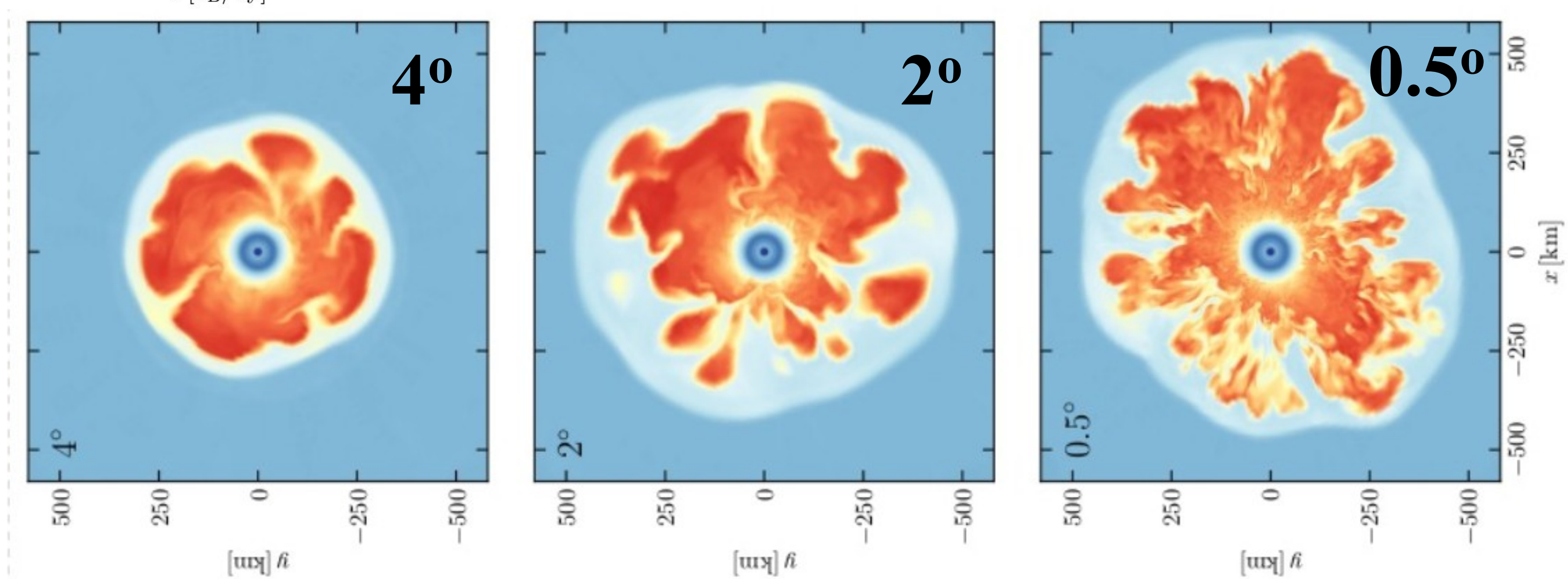
Resolution Study of 20 Msun Model With Simple Neutrino Heating & Cooling Treatment



Using axis-free Yin-Yang coordinate grid







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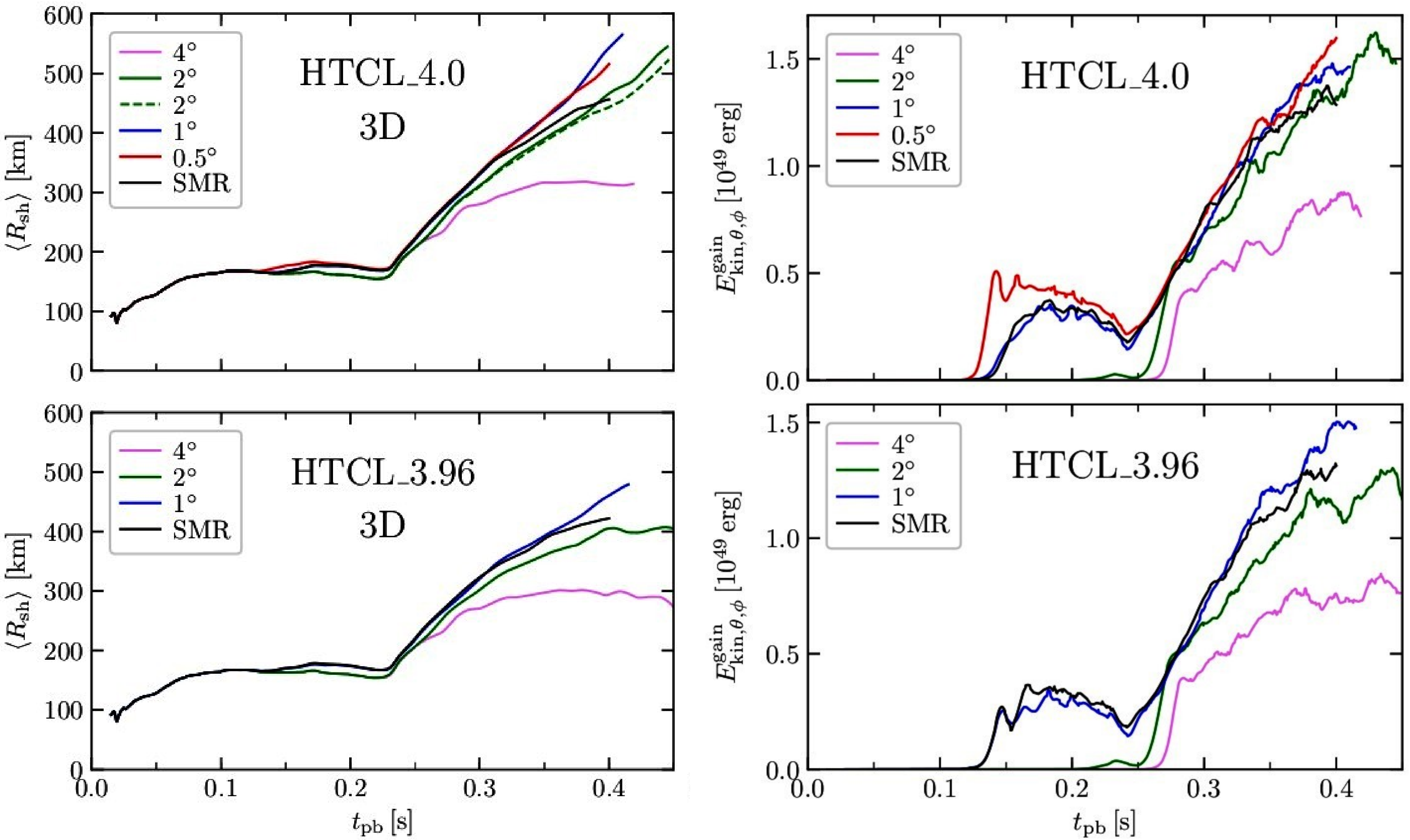
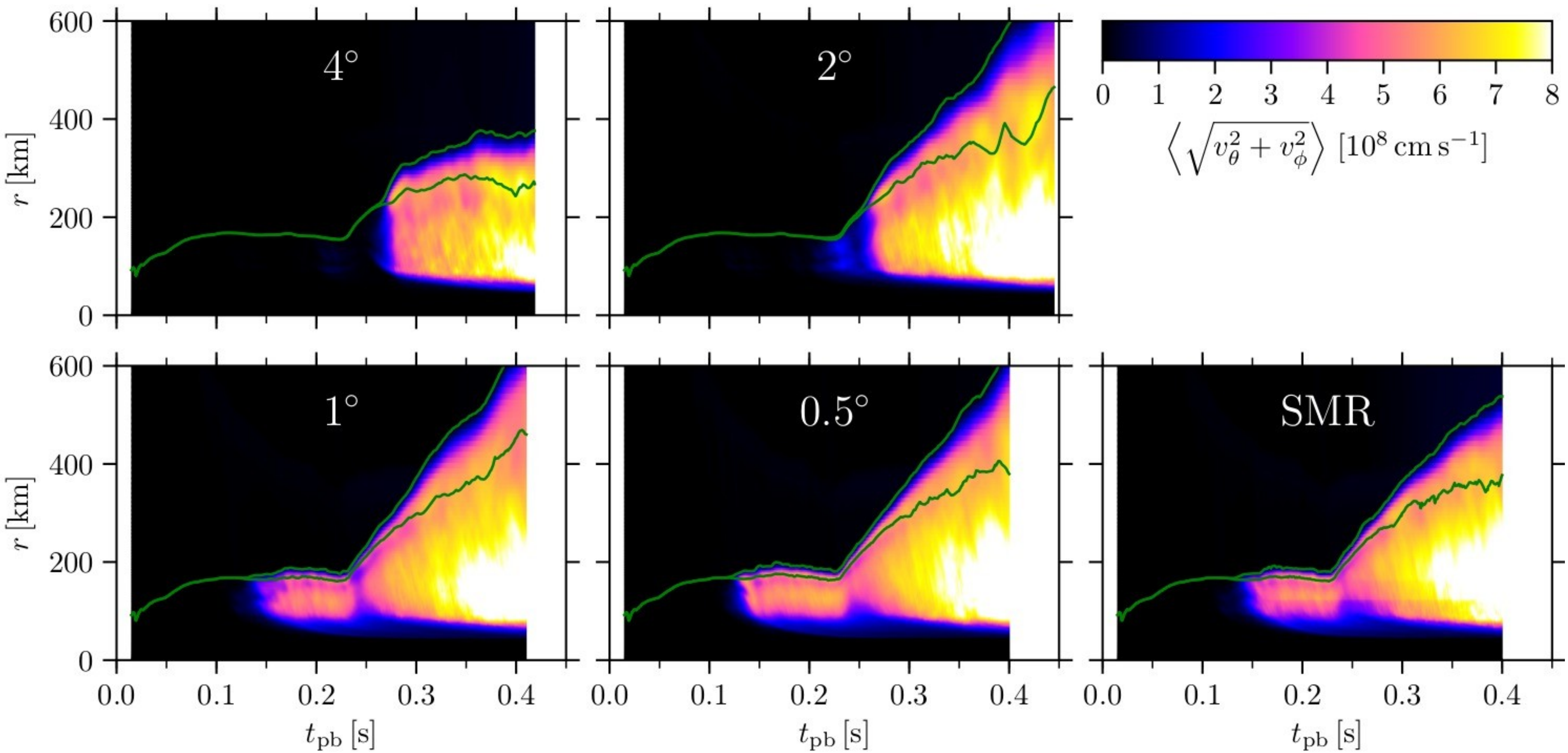


Resolution Study of 20 Msun Model With Simple Neutrino Heating & Cooling Treatment

Higher angular resolution and lower numerical viscosity leads to faster growth of hydrodynamic instabilities (convection, SASI) in postshock layer, seeded by the same small (0.1% cell-to-cell) density perturbations.



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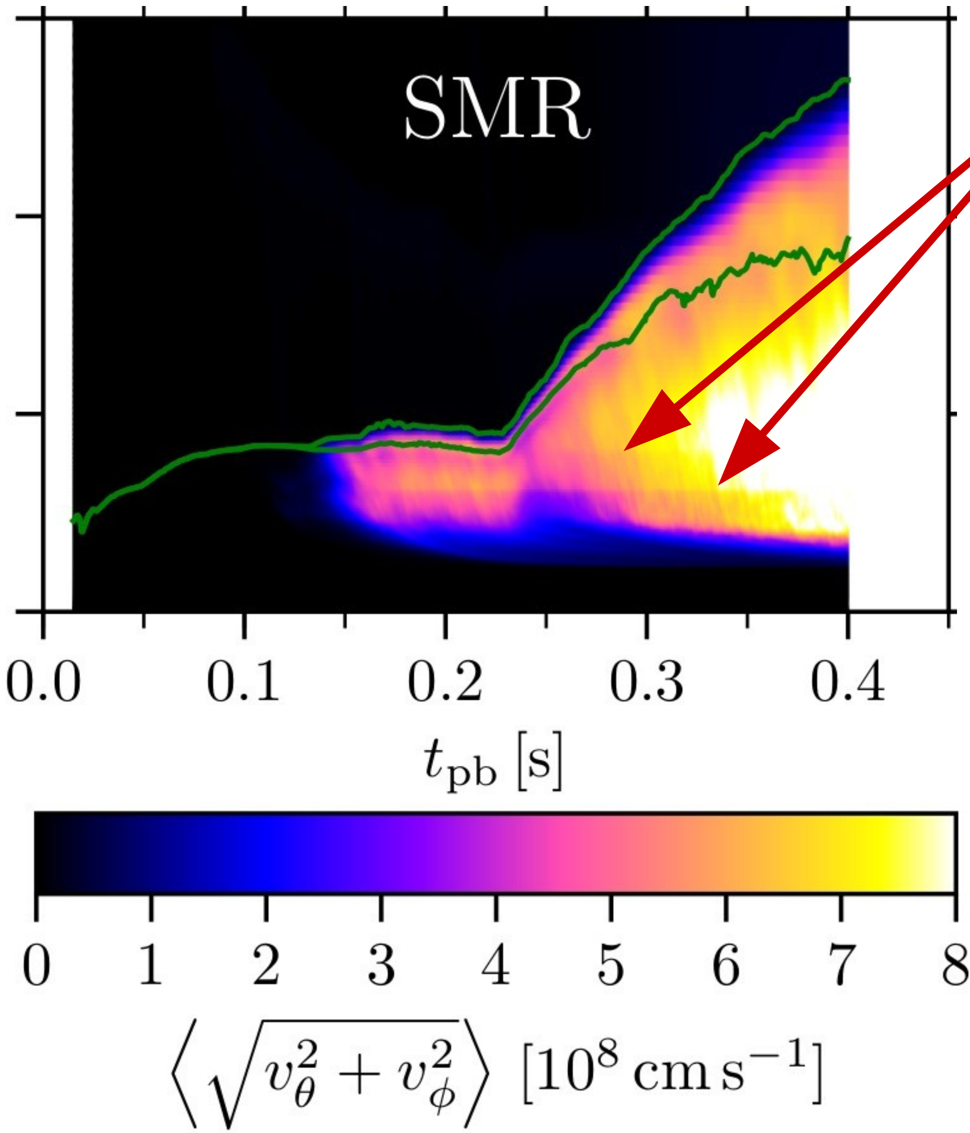
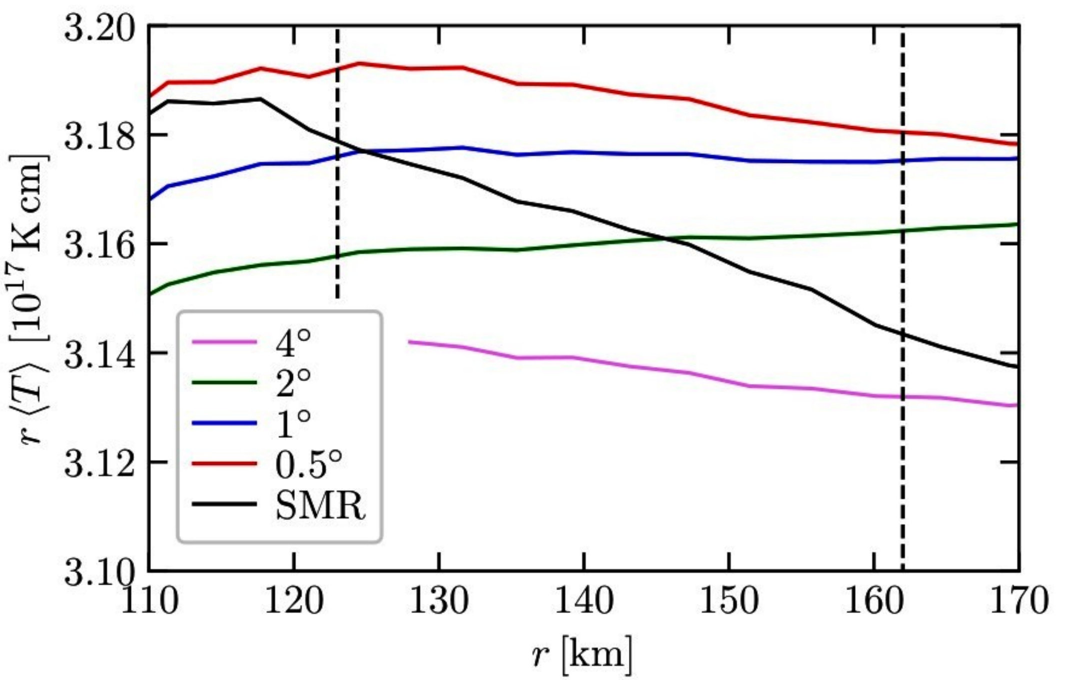


Static mesh refinement (SMR) boundaries create artifacts:
convert kinetic energy to thermal energy while the sum of both is conserved ===> turbulent pressure is reduced, enhanced thermal pressure cannot compensate



Resolution Dependence With Polar Coordinate Grid

Polar coordinate grid: Higher angular resolution near the poles can trigger faster growth of hydrodynamic instabilities (convection, SASI) in the postshock layer.

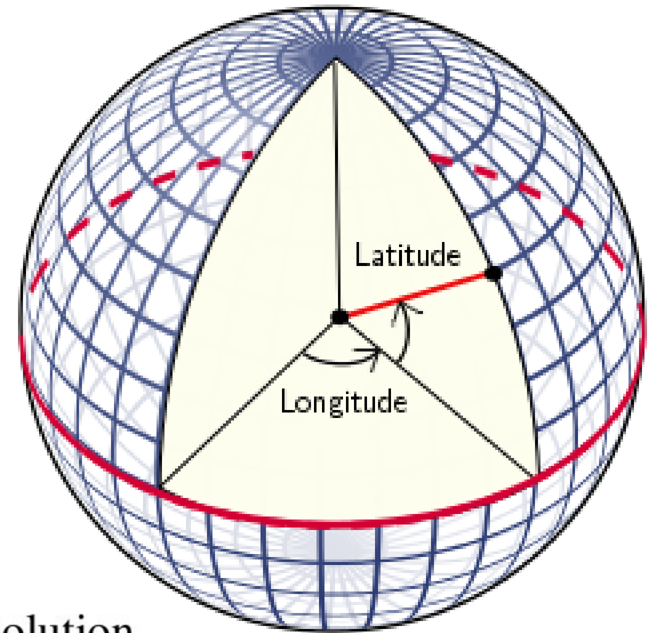


Table 2
Multi-dimensional Models with Different Resolution

Mass[a] ($M_\odot$)	Dim[b]	L_{ν_e}[c] (10^{52} erg s^{-1})	Ang.[d] Res.	N_r[e]	t_{exp}[f] (ms)	$\dot{M}_{exp}$[g]	t_{sim}[h] (ms)
11.2	2D	0.8	3°	400	⋯	⋯	1017
11.2	2D	0.8	2°	400	⋯	⋯	979
11.2	**3D**	**0.8**	**3°**	**400**	⋯	⋯	**915**
11.2	**3D**	**0.8**	**2°**	**400**	⋯	⋯	**758**
11.2	2D	0.9	3°	400	⋯	⋯	1006
11.2	2D	0.9	2°	400	⋯	⋯	985
11.2	**3D**	**0.9**	**3°**	**400**	**731**	**0.085**	**954**
11.2	**3D**	**0.9**	**2°**	**400**	⋯	⋯	**819**
11.2	2D	1.0	3°	400	563	0.082	1053
11.2	2D	1.0	2°	400	527	0.086	1053
11.2	**3D**	**1.0**	**3°**	**400**	**537**	**0.086**	**684**
11.2	**3D**	**1.0**	**2°**	**400**	**572**	**0.082**	**761**

Hanke et al., ApJ 755: 138 (2012)

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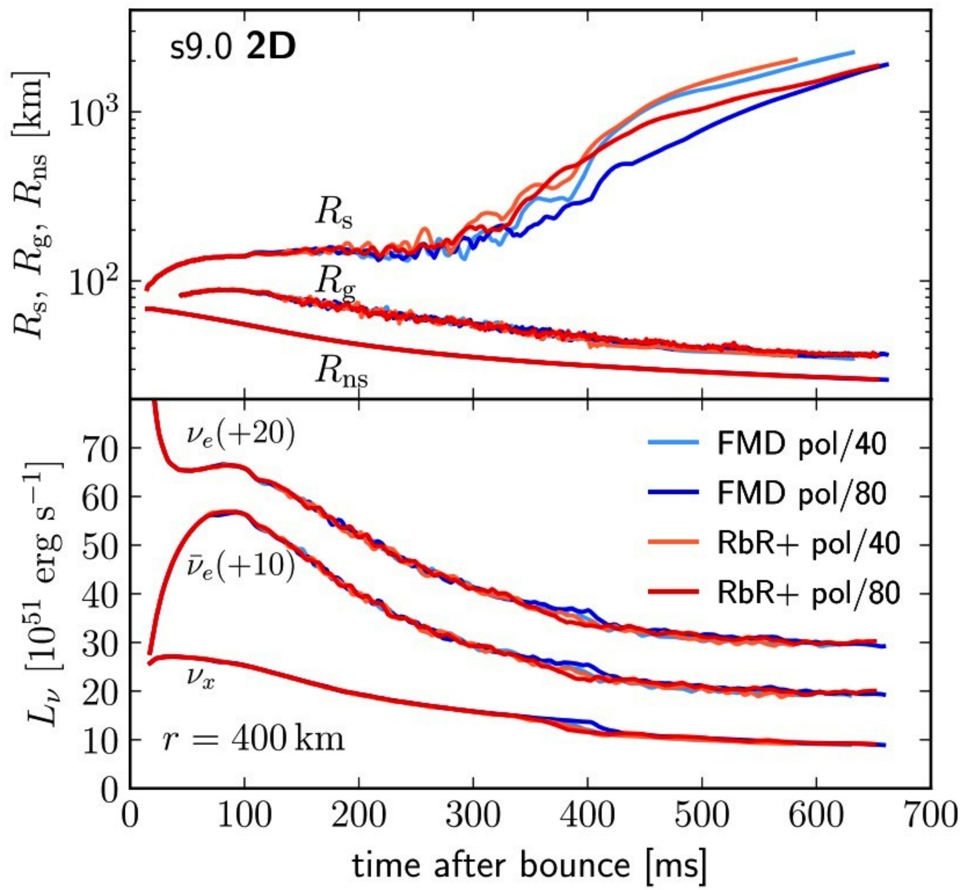
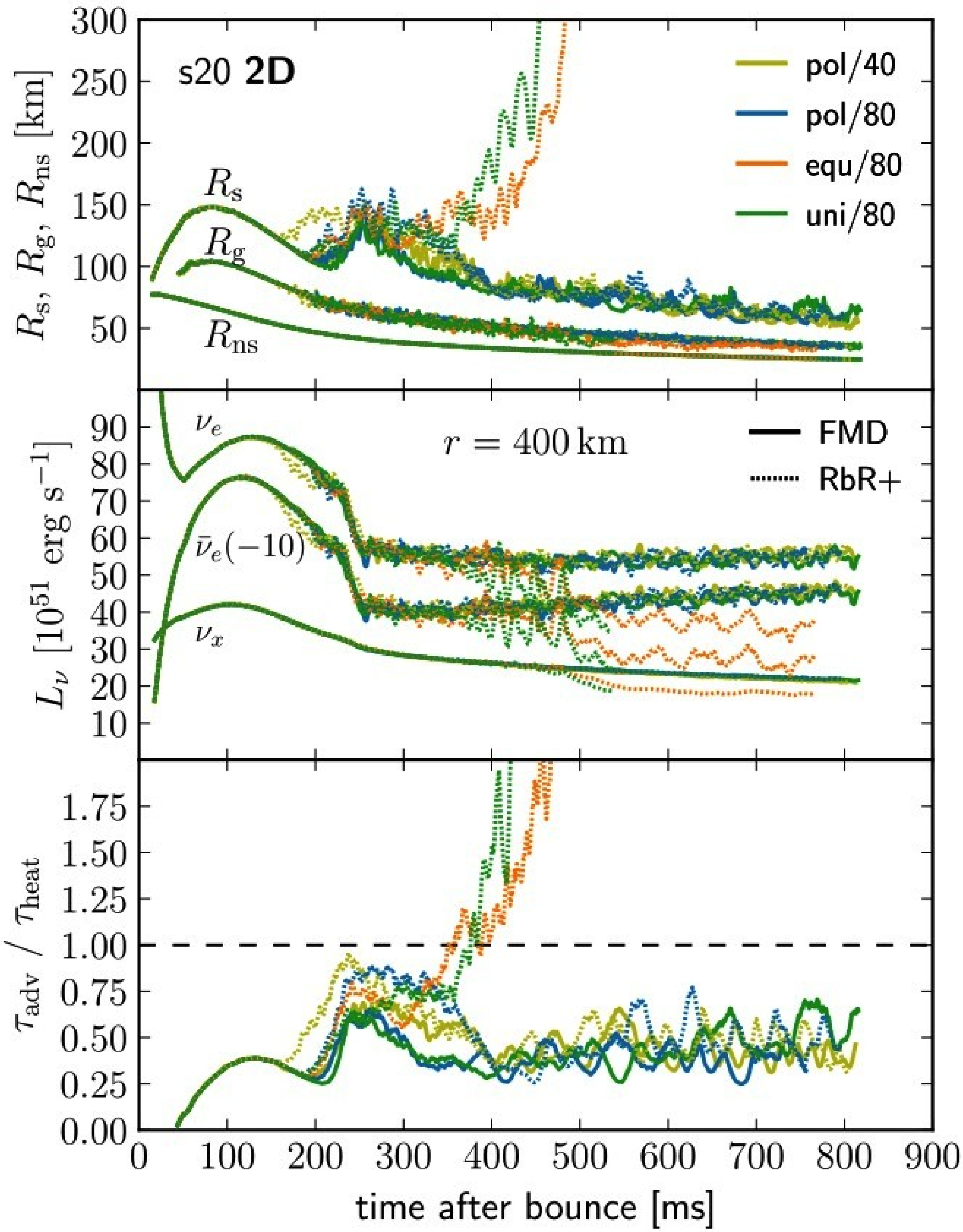
3. RbR+ vs. FMD-M1 3D Neutrino Transport

With Robert Glas (PhD student);
ApJ 873:45 (2019)

RbR+ vs. FMD-M1 Transport in 2D: 9 & 20 M_{sun} Stars

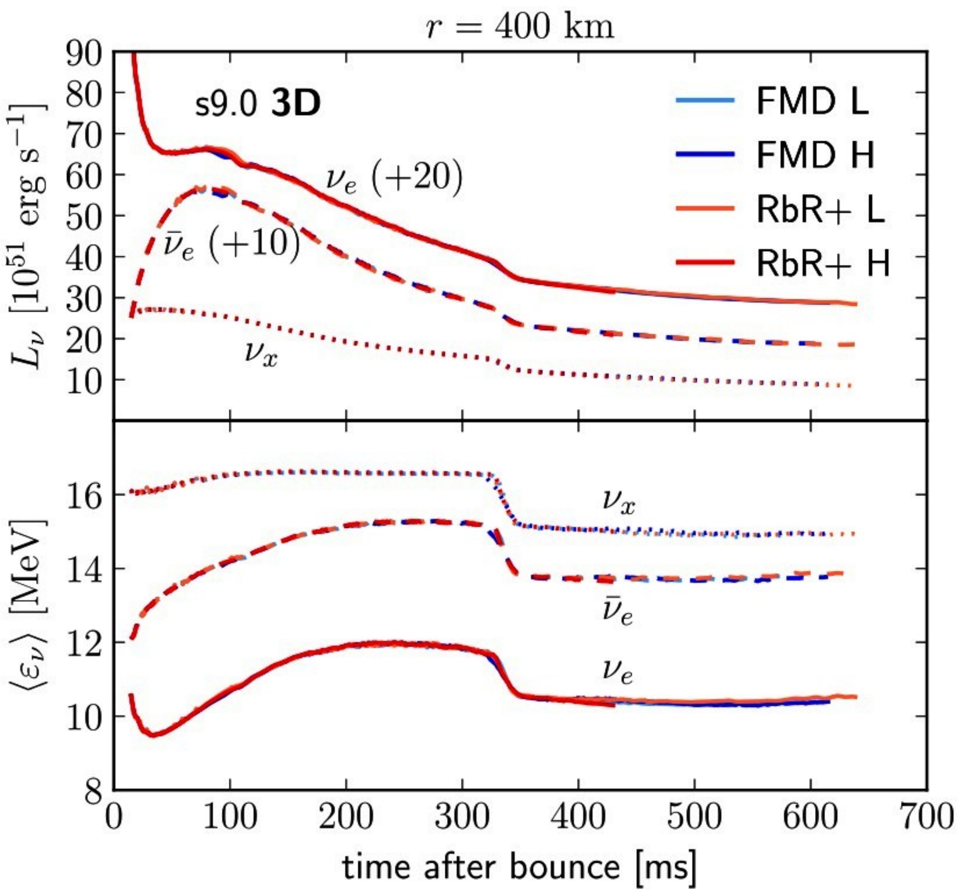
Using polar coordinate grid;
RbR+ results depend strongly on resolution and coordinate setup.
Severe differences between RbR+ and fully multi-dimensional (FMD) transport. **(See also Dolence+2015, Sumiyoshi+2015, Skinner+2016, Just+2018)**

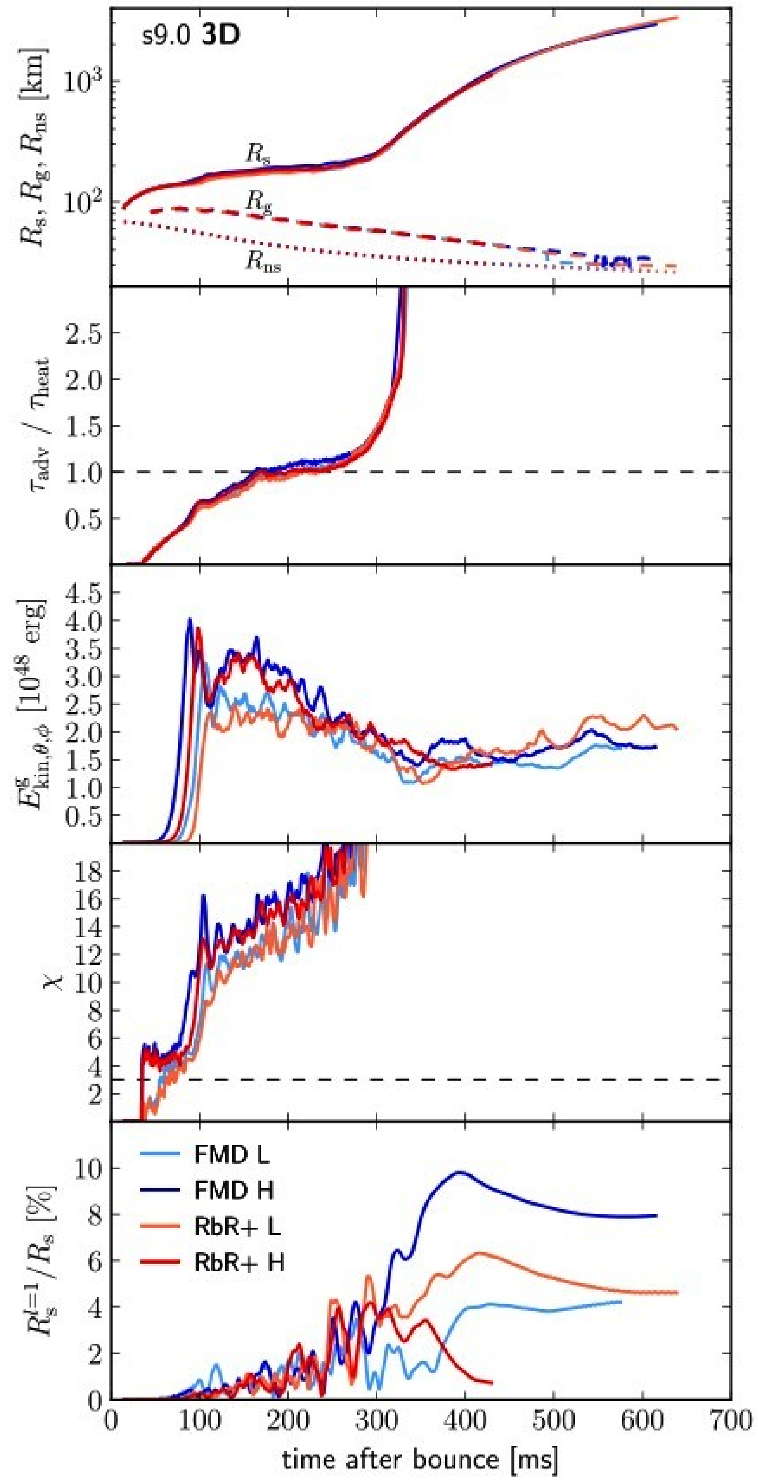




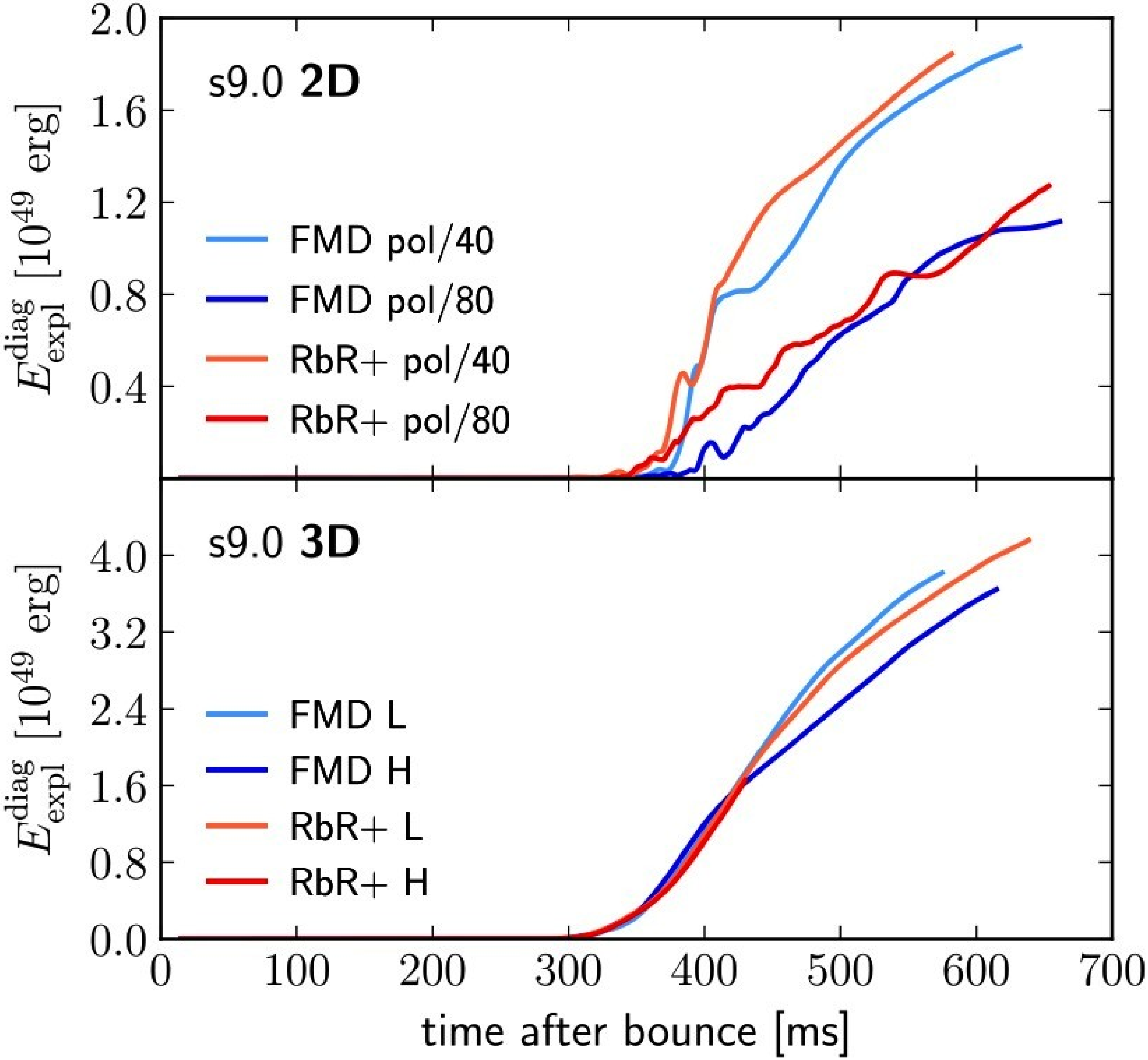
RbR+ vs. FMD-M1 Transport in 3D: Exploding 9 M_{sun} Star

Using polar coordinate grid;
RbR+ results show minor quantitative and no qualitative differences compared to fully multi-dimensional (FMD-M1) transport.





RbR+ vs. FMD-M1 Transport in 2D and 3D: Exploding 9 M_{sun} Star

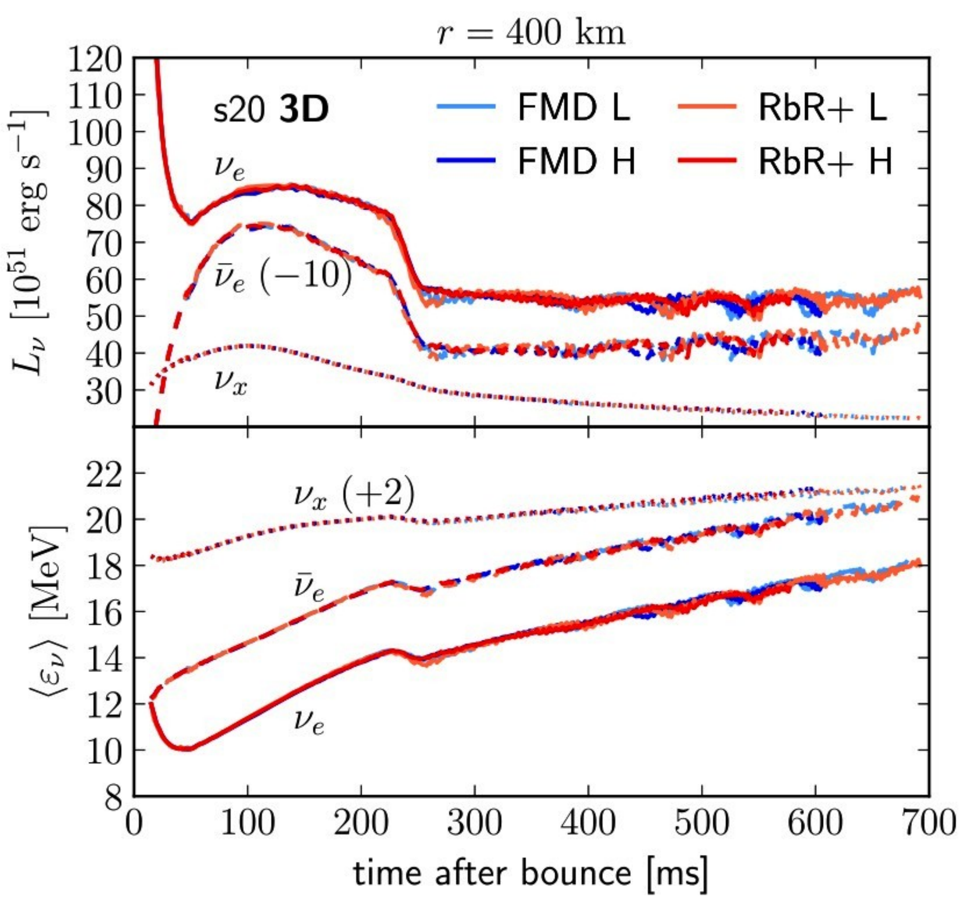


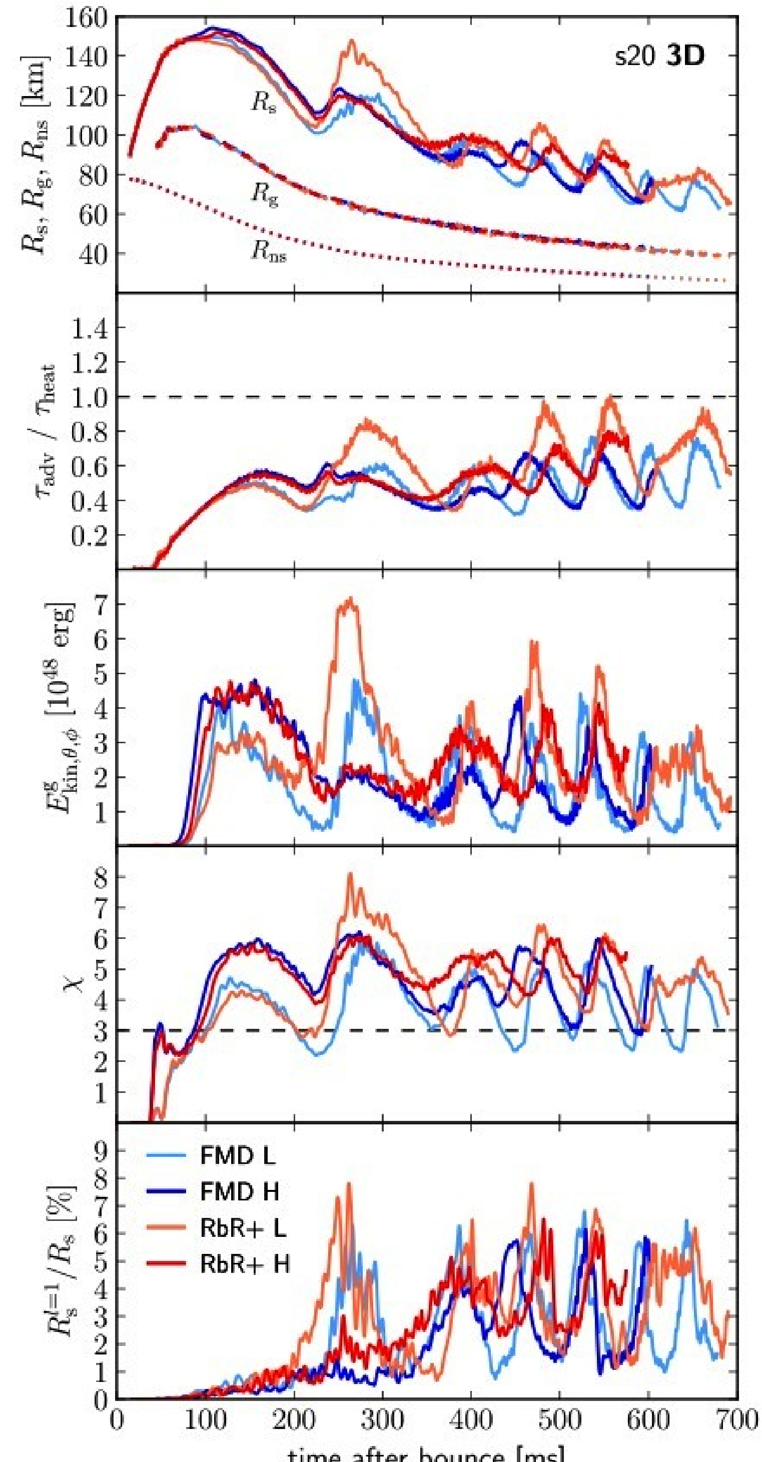
Severe differences in 2D of RbR+ vs. FMD-M1 transport.

Small differences in 3D of RbR+ vs. FMD-M1 transport.

RbR+ vs. FMD-M1 Transport in 3D: Nonexploding 20 M_{sun} Star

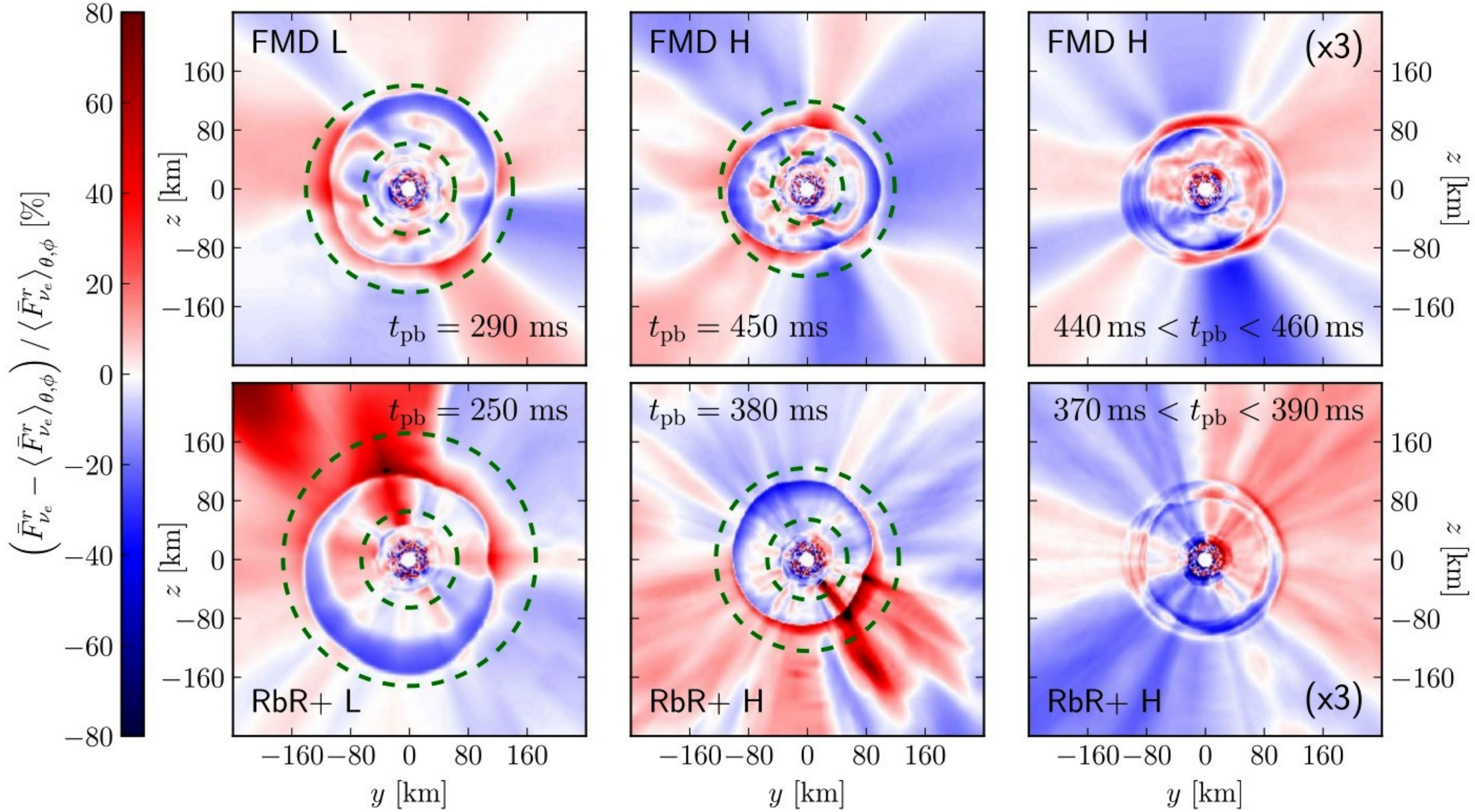
Using polar coordinate grid;
RbR+ results show moderate quantitative but no qualitative differences compared to fully multi-dimensional (FMD-M1) transport.





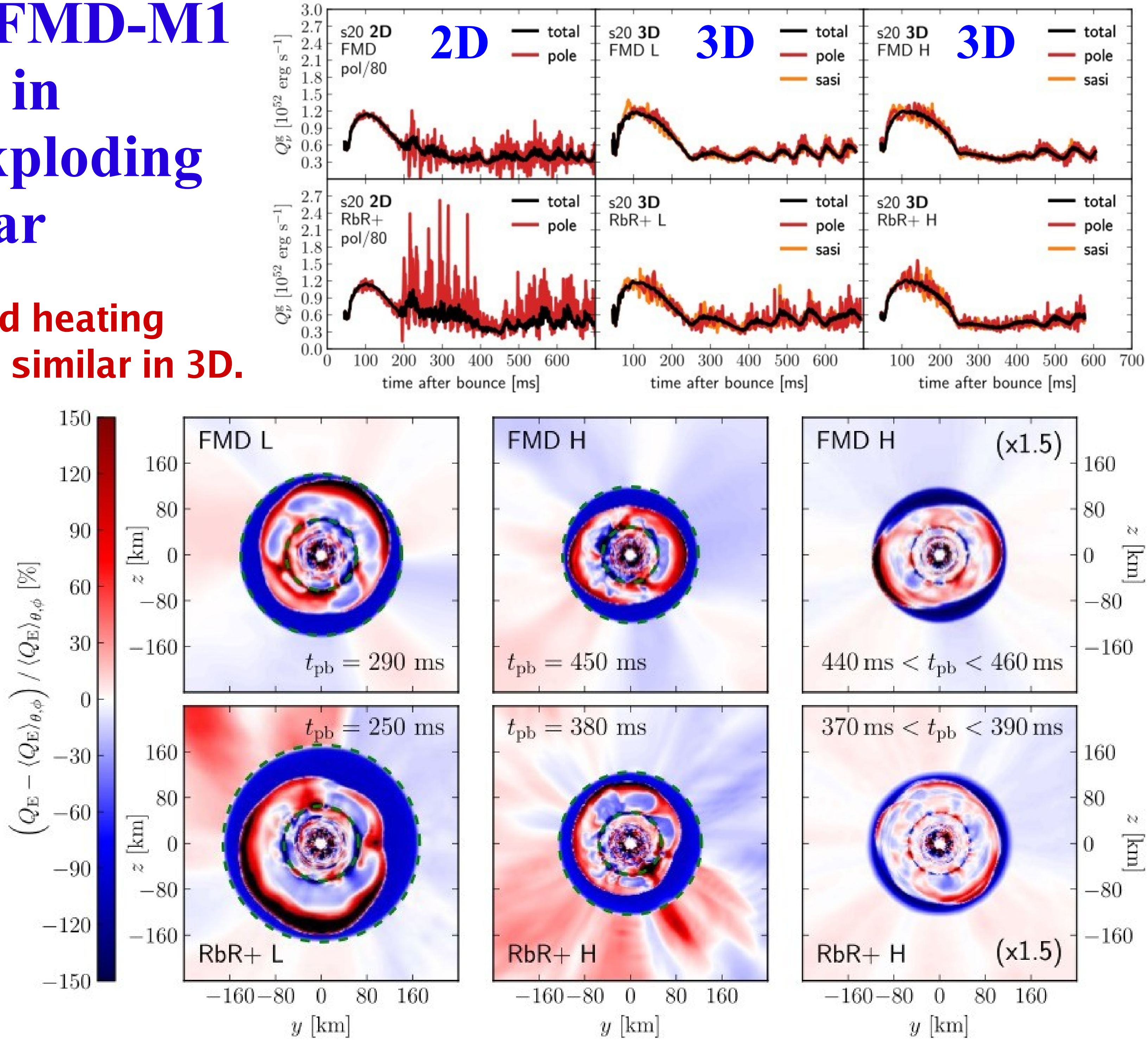
RbR+ vs. FMD-M1 Transport in 3D: Nonexploding 20 M_{sun} Star

Relative neutrino-flux variations with direction for electron neutrinos. Time-averaged variations very similar for RbR+ and FMD-M1 transport.



RbR+ vs. FMD-M1 Transport in 3D: Nonexploding 20 M_{sun} Star

Time-averaged heating rates are very similar in 3D.



Summary

1. 3D asymmetries in the pre-collapse progenitor are supportive to explosion, affect explosion asymmetry.

2. 3D CCSN simulations with the Garching *Prometheus-Vertex* code tend to converge around 1º angular resolution.

3. Dynamical evolution of 3D models does not critically depend on differences of RbR+ and FMD-M1 transport.