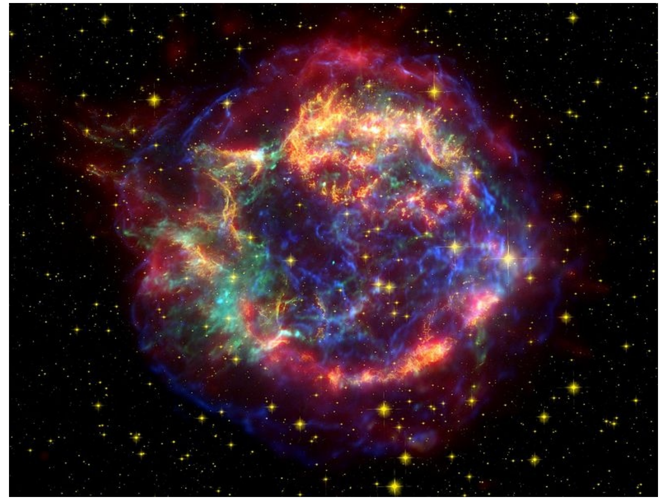
Australian Government
Australian Research Council



Queen's University Belfast

Core-Collapse Supernova Simulations from 3D Progenitor Models

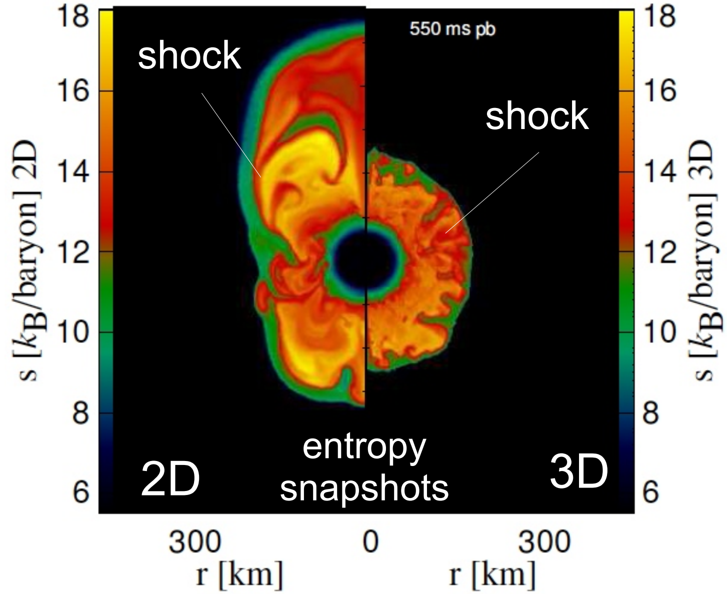
NCI PROVIDING AUSTRALIAN RESEARCHERS WITH WORLD-CLASS HIGH-END COMPUTING SERVICES

DiRAC
Distributed Research utilising Advanced Computing

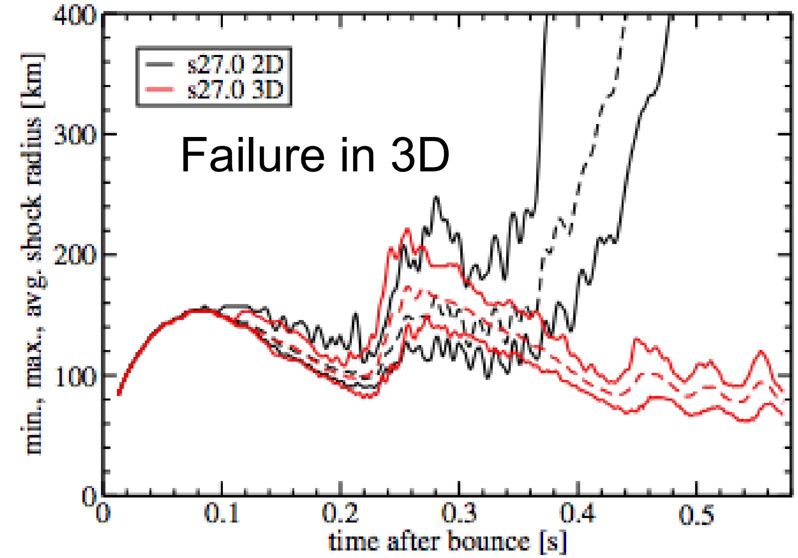
Bernhard Müller
Monash University/QUB

C. Collins (QUB), A. Heger (Monash), H.-Th. Janka, T. Melson, M. Viallet (MPA)

Problems: Shock revival by the ν-driven mechanism in 3D



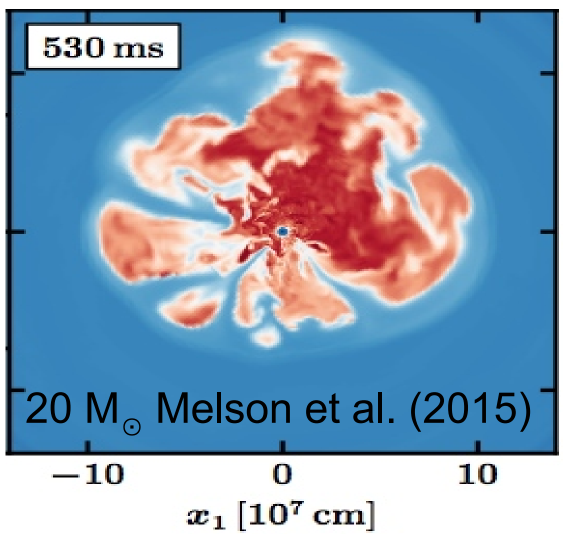
Simplified 3D “light-bulb” model from Hanke et al. (2012): Turbulent convection in 2D and 3D



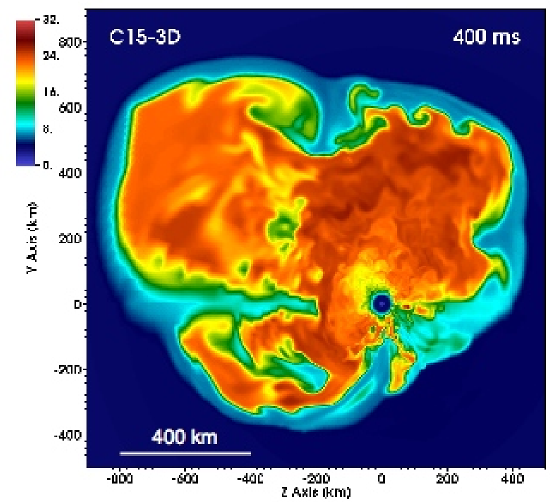
27 $M_\odot$ Hanke et al. (2013)

First-principle 3D models:

- Mixed record: failures or **delayed explosions compared to 2D**
- Still no proof that mechanism is *robust*
- Delay of shock revival → too small explosion energies & too large neutron star masses?



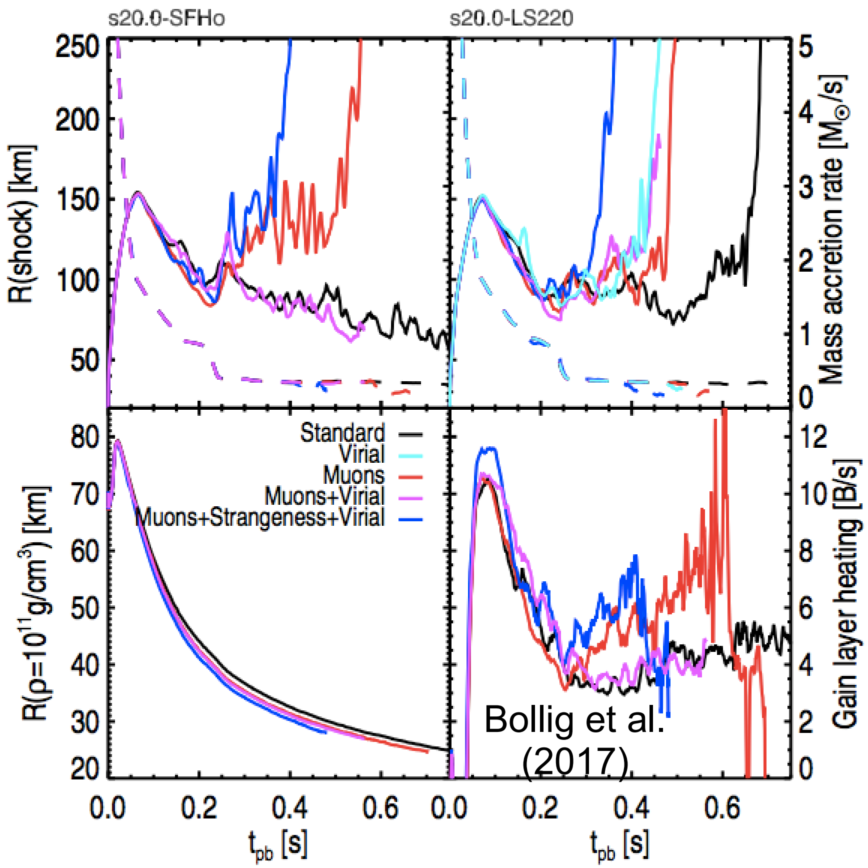
20 $M_\odot$ Melson et al. (2015)



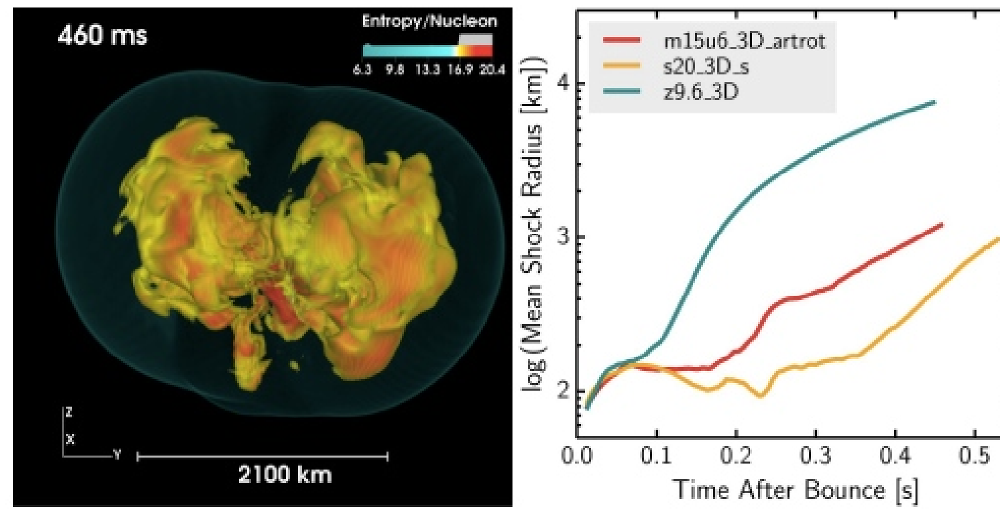
15 $M_\odot$ Lentz et al. (2015)

Or with simpler schemes: e.g. IDSA+leakage Takiwaki et al. (2014)

Possible Ingredients for More Robust Explosions



Bollig et al. (2017)



Janka et al. (2016)

Rapid rotation (Janka et al. 2016, Takiwaki 2016) – conditions likely not met in generic progenitor

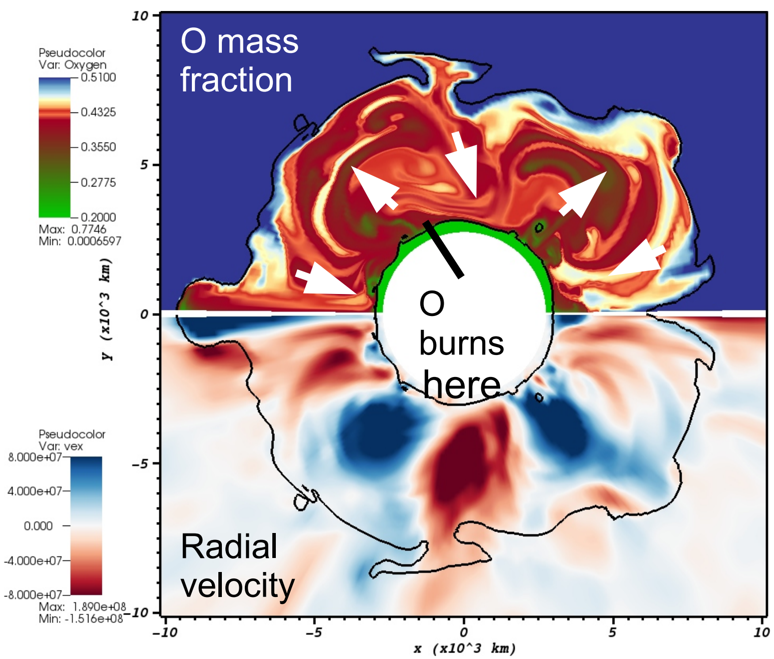
Better/different microphysics needed in models?

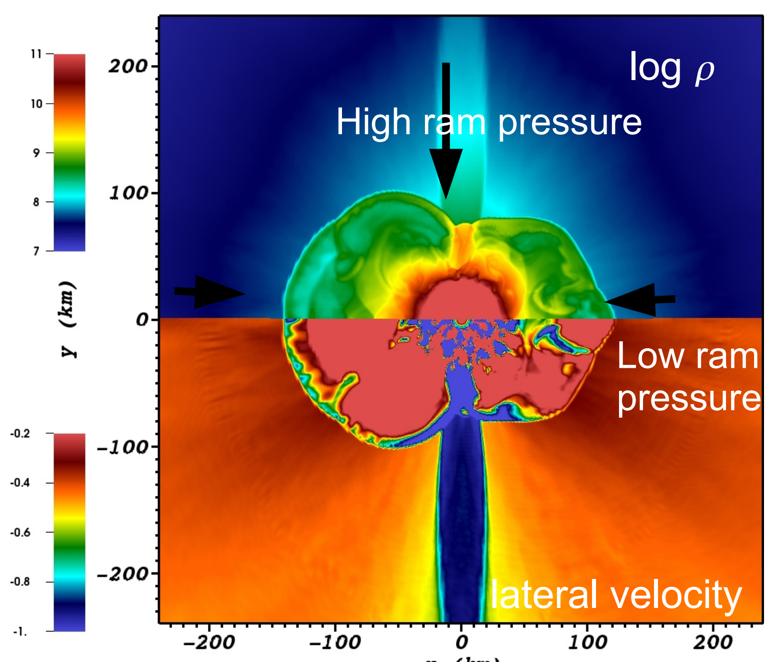
- Muon creation (Bollig et al. 2017)
- Effect of nucleon strangeness on ν opacity (Melson et al. 2015)
- Uncertainties in nucleon correlations (Horowitz et al. 2017)?

Individual effects may be small, but can add up!

Do we need 3D progenitor models?

Collapse: vortical perturbations → acoustic perturbations





Müller & Janka (2015)

- Some interior shells in progenitor convective at collapse → impact on instabilities during SN (Couch&Ott 2013, Müller & Janka 2015)?
- Expected effect of injection of extra turbulent kinetic energy:

$$\frac{\Delta L_{\mathrm{crit}}}{L_{\mathrm{crit}}} \sim \boxed{\frac{(2\ldots4)\times \mathrm{Ma}_{\mathrm{conv}}}{\text{multipole order } \ell}}$$

(Müller et al. 2016, cp. also Abdikamalov et al. 2016 and parameter study of Müller & Janka 2015)

- Mixing length theory and linear theory: $\mathrm{Ma}_{\mathrm{conv}}$~0.1 and ℓ~2-4 in **some (not all!)** progenitors

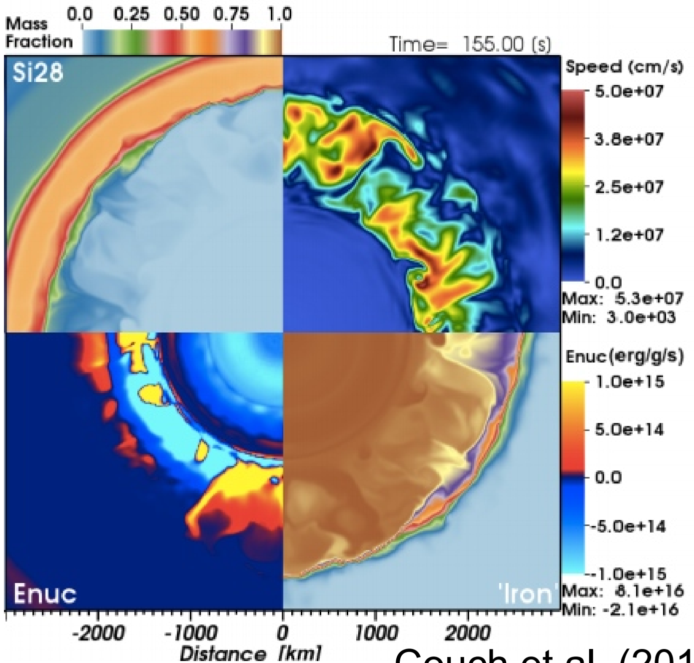
$\delta P_{\mathrm{ram}}/P_{\mathrm{ram}} \sim \mathrm{Ma}_{\mathrm{conv}}$ (cp. Lai & Goldreich 2000

→ **"forced shock deformation"**

Understanding of “perturbation-aided explosions” so far

- Parametric initial conditions
  - Couch & Ott (2013, 2015): acoustic perturbations, 3D+leakage scheme
  - Müller & Janka (2015), Burrows et al. (2016): quasi-solenoidal velocity perturbations, 2D+neutrino transport
  - Anything from negligible to huge effect of perturbations
- Initial conditions from 3D shell burning models:
  - Couch et al. (2015): 1 progenitor, 3D+leakage scheme, no *qualitative* change compared to non-perturbed baseline model (also explodes)
  - Müller (2016) & Müller, Melson, Heger & Janka (2017)
- Need to explore:
  - 3D simulations of “perturbation-aided explosions” with multi-group transport (otherwise we're studying a setup where shock revival is not a problem!)
  - Qualitative impact of realistic initial conditions?
  - Energetics & compact remnant properties for perturbation-aided explosions
  - Scan parameter space (different progenitor masses & shell configurations)

Aside on 3D Progenitor Models

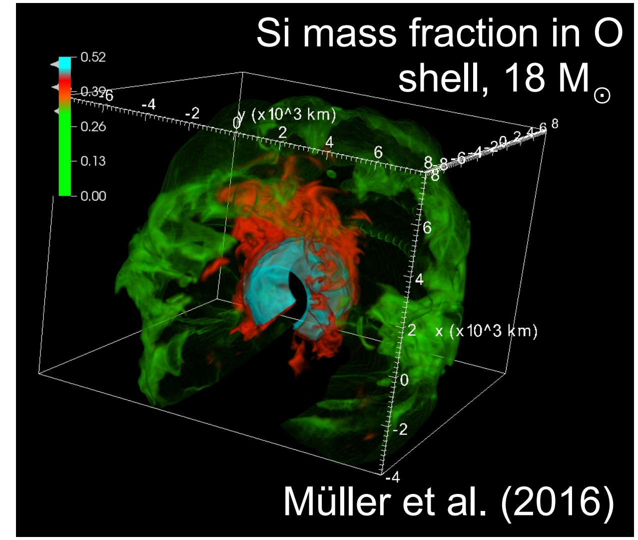


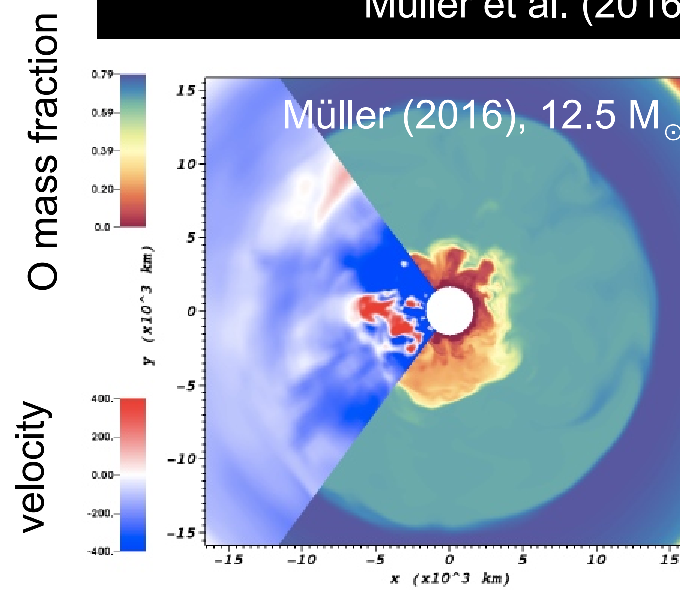
Couch et al. (2015)

Couch et al. (2015):

- Silicon shell burning, 15$M_\odot$
- Octant symmetry
- 21 species network (extended alpha-chain)
- Core **deleptonisation rate artificially increased** (by ~1000) → keeps Si shell alive until collapse
- ~8 turnover times

Models are yet in their infancy, especially concerning evolution of core & Si shell
(But is this critical?)





Monash/QUB/MPA group:

- O burning, several progenitors
- Overset Yin-Yang grid, 4π solid angle
- 19 species network
- **Contracting inner boundary** (using mass shell trajectory from KEPELER code) as excised core in non-convective
- >15 turnover times

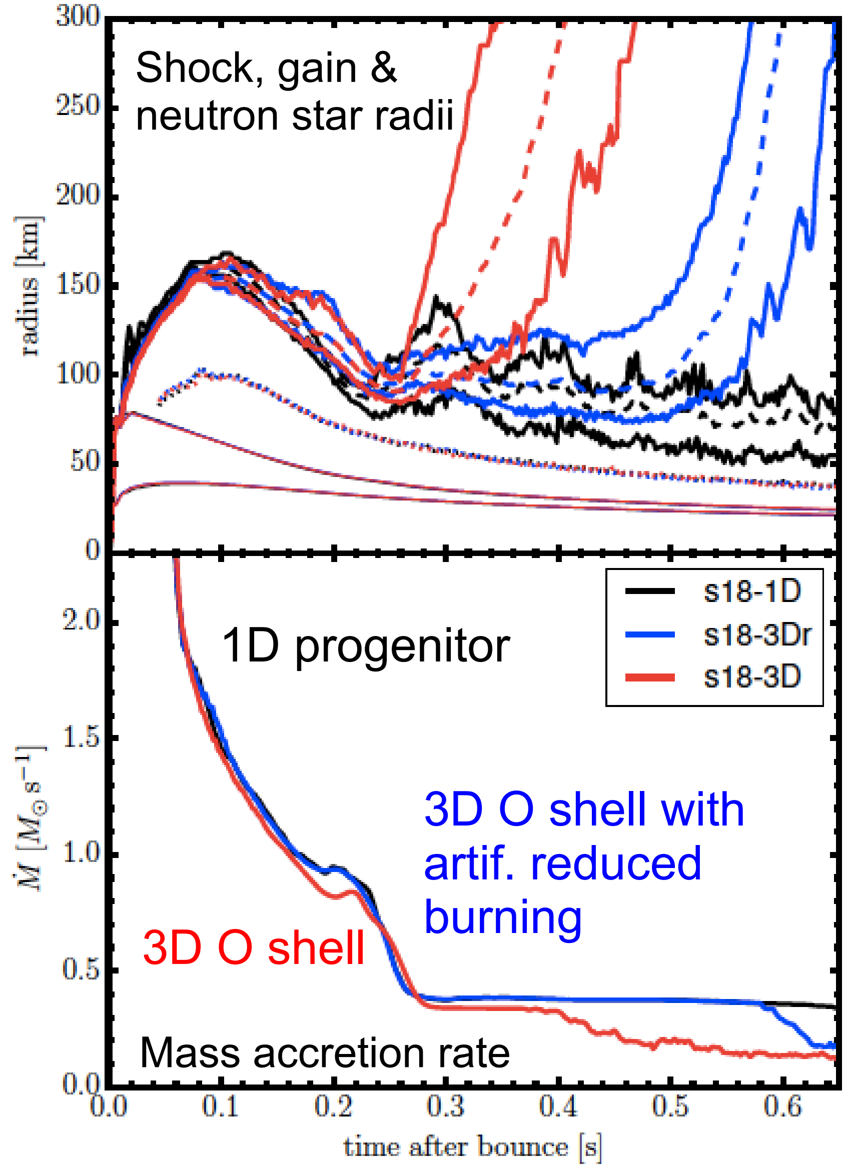
Effect of Perturbations on Shock Revival

3 models of $18M_{\odot}$ progenitor with FMT multi-group transport scheme (Müller et al. 2017):

- 3D initial conditions from O shell burning simulation (convective Mach number ~0.1)
- 3D initial conditions assuming reduced burning in O shell (convective Mach number ~0.04)
- 1D progenitor + small random seed perturbations

Clear impact on shock revival:

$$\frac{\Delta L_{\mathrm{crit}}}{L_{\mathrm{crit}}} \sim 0.2$$ (difficult to quantify)

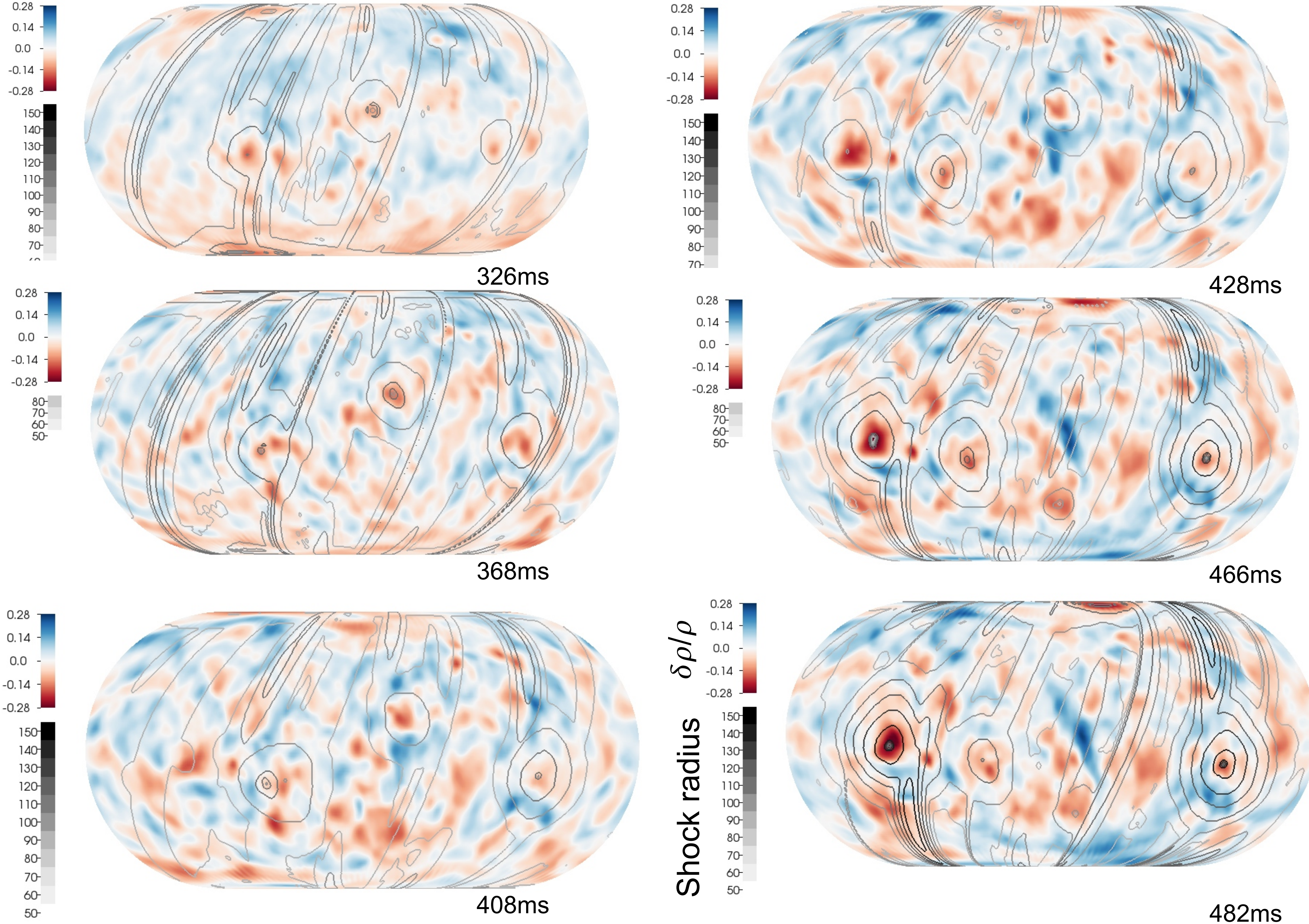


Forced Shock Deformation in 3D

1D progenitor (with tiny random seed perturbations)

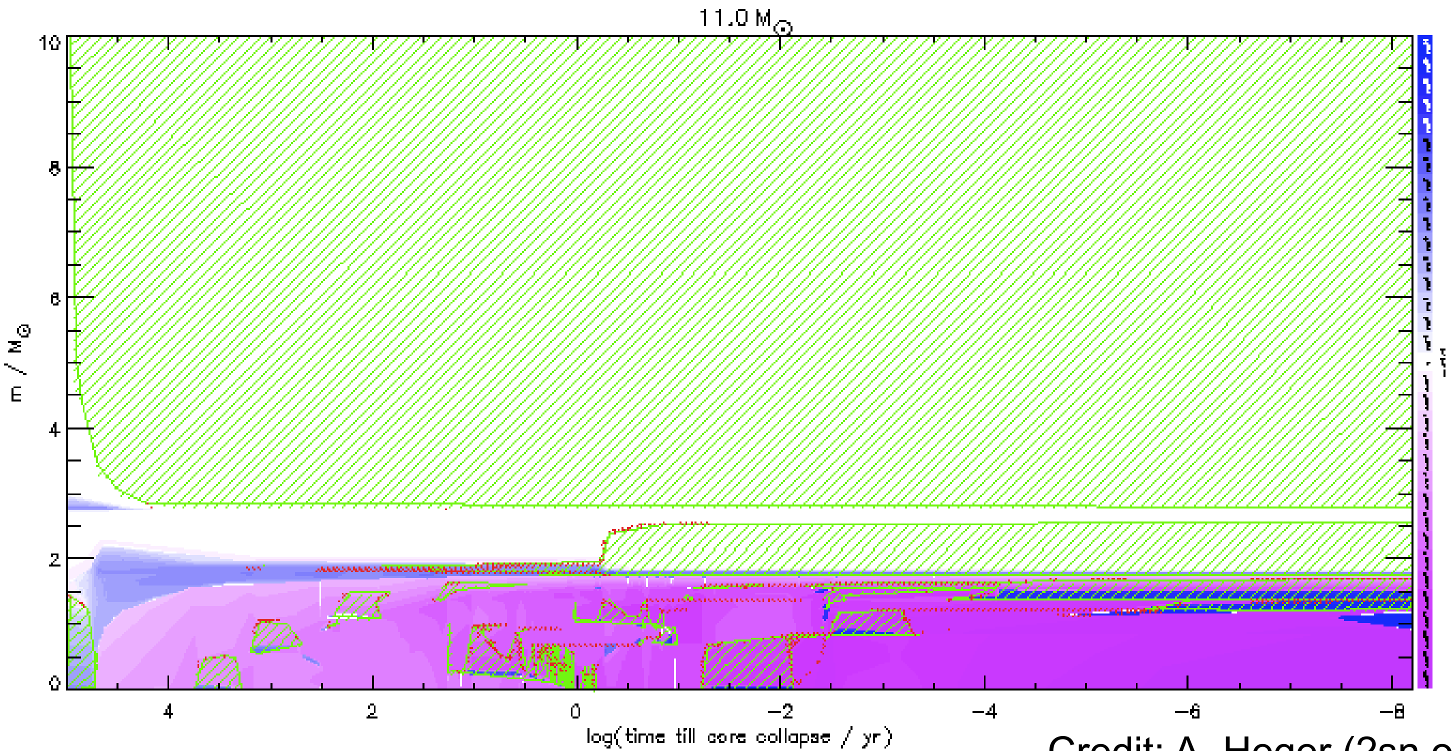
3D initial conditions

- Shock expands into directions of lower ram pressure & density in the collapsing shells
- SASI oscillations inhibited once perturbations become strong
- Interplay of perturbations & instabilities too complicated to validate proposed analytic models for perturbation-aided explosion yet



18M$_{\odot}$ progenitor with with artif. reduced O burning

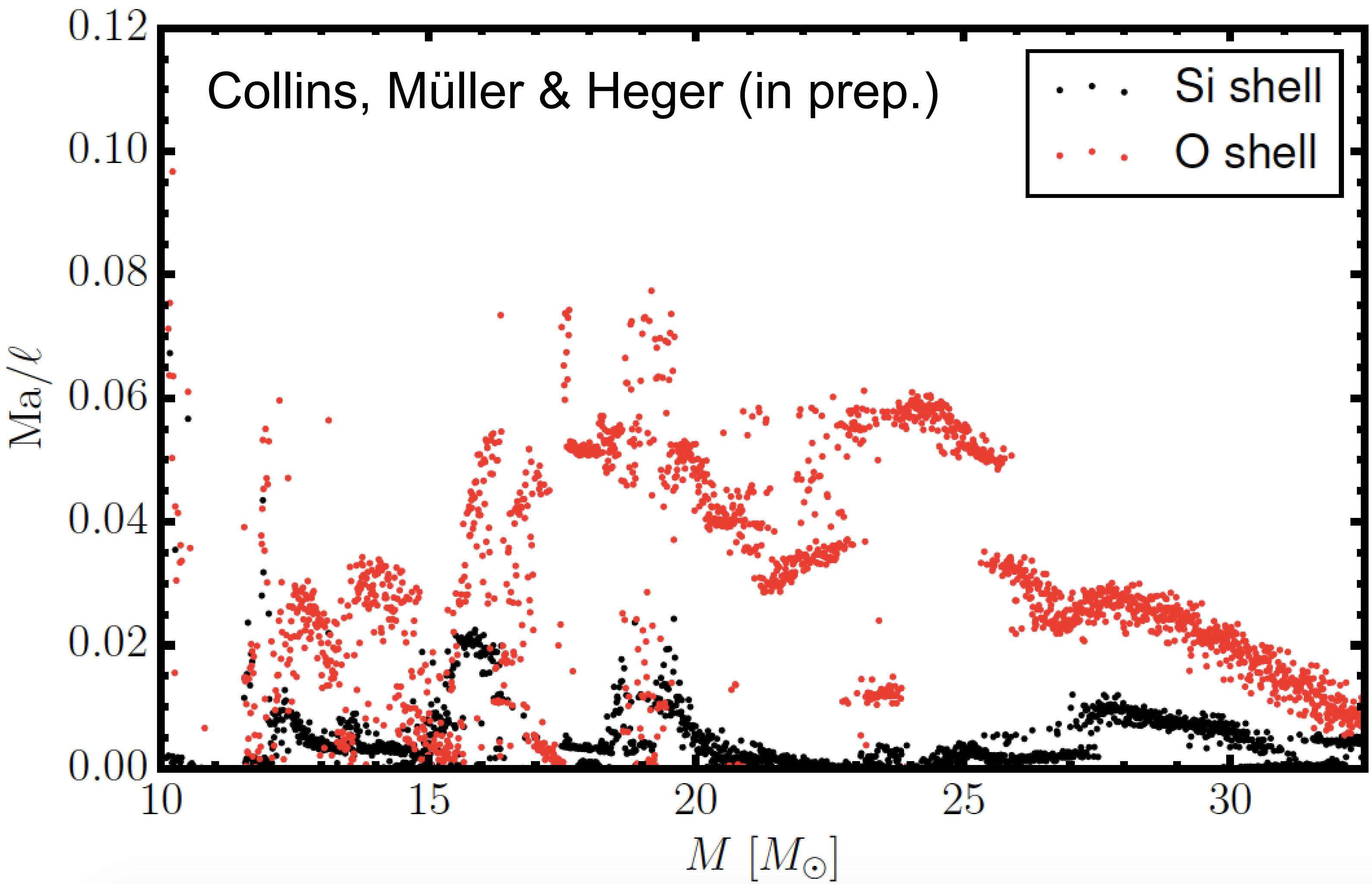
Perturbations-Aided Mechanism as a Panacea?



Credit: A. Heger (2sn.org)

- Tremendous variations in shell configuration (more complex than "compactness")
- Conditions for perturbation-aided explosions do not obtain in all progenitors (Collins, Müller & Heger in prep.):
  - Region around 18$M_\odot$ is one the sweet-spots
  - Sufficiently strong Si shell burning seems rare

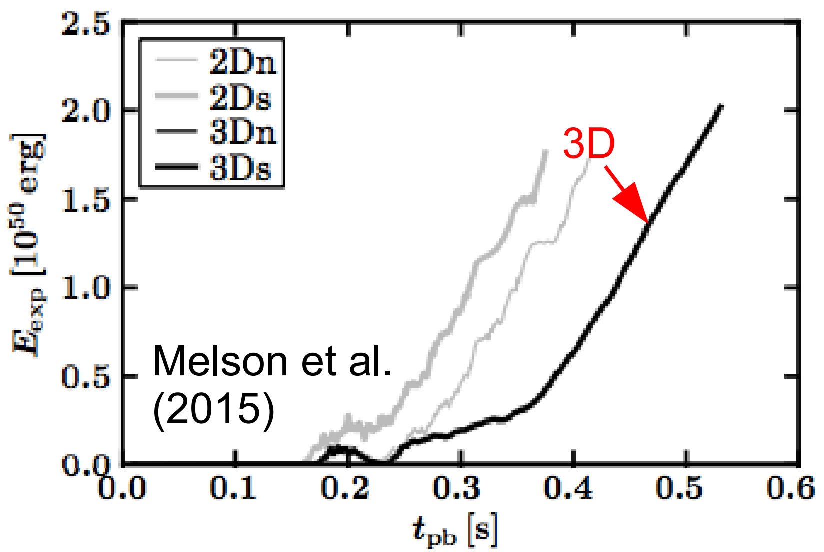
Variation of Effects Sizes

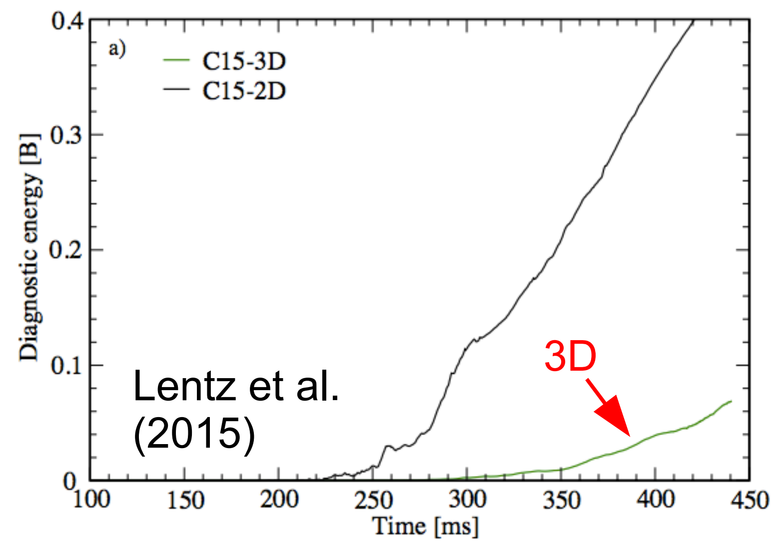


→ neglecting initial perturbations in Si shell seems justified for now

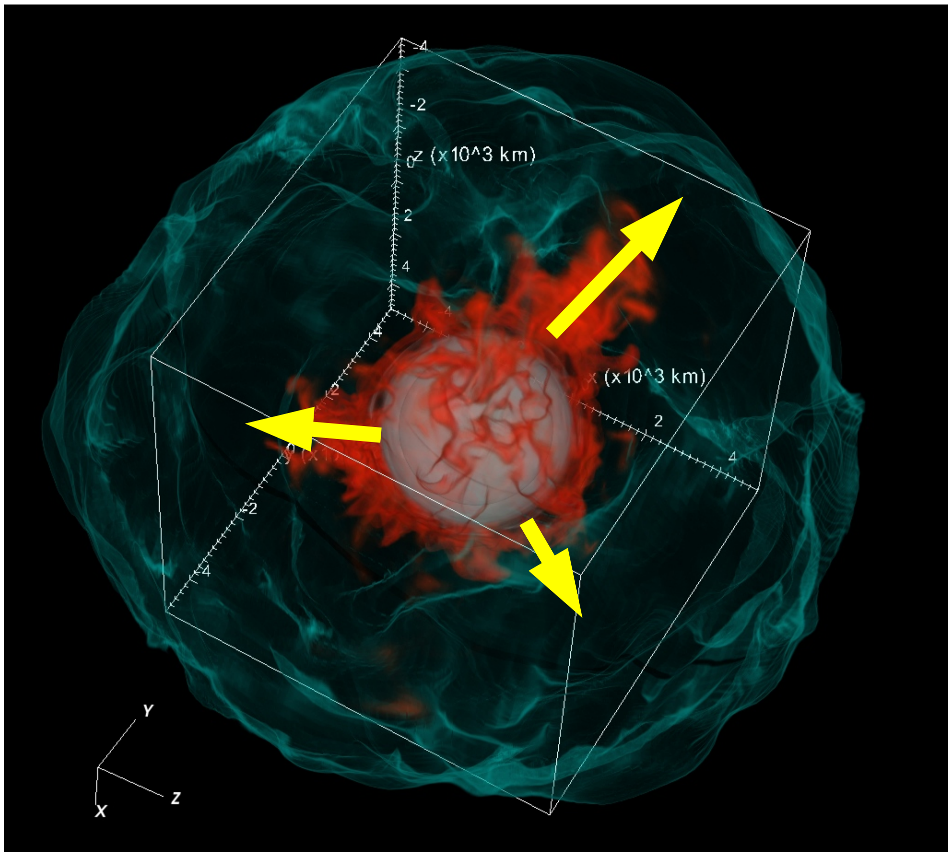
Explosion Phase

- Yet to be demonstrated that 3D models can reach plausible explosion energies, neutron star masses, etc.
- Simply a numerical challenge need to go to >1s
- Highly problematic to rely on 2D models (Müller 2015)
- Pushed 18$M_\odot$ model to 2.5s to give first insights into long-term evolution





Long-Time Evolution of the Explosion

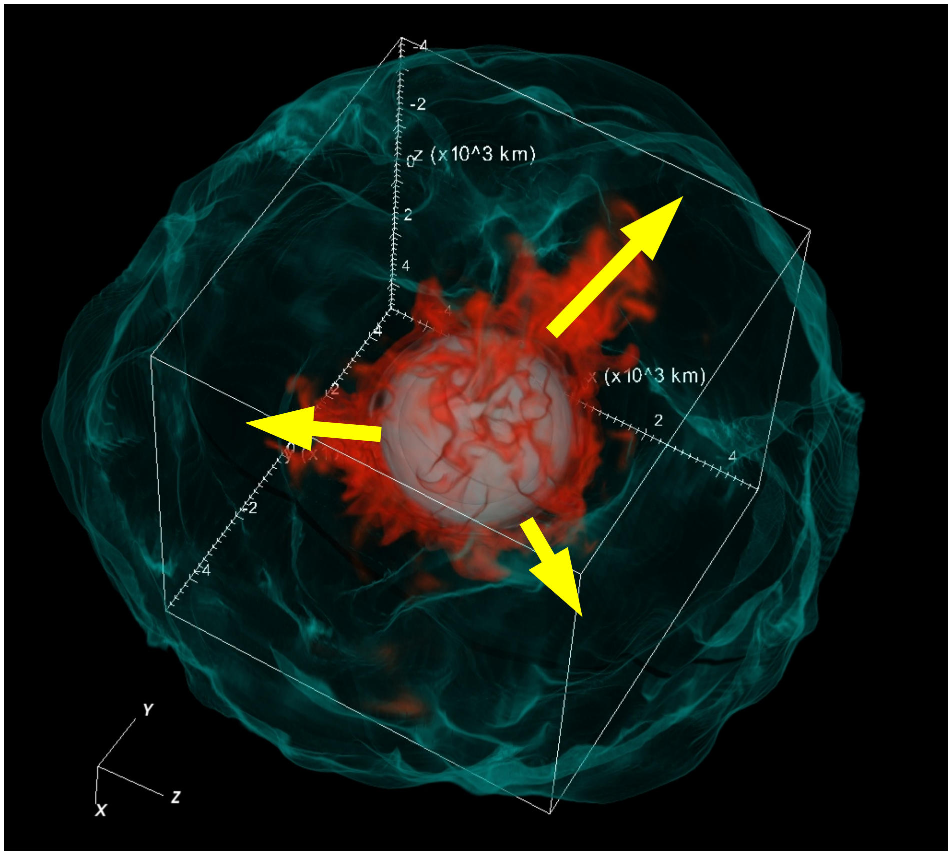


Red: Si-rich ashes
Cyan: Outer O shell boundary
Grey: Si core

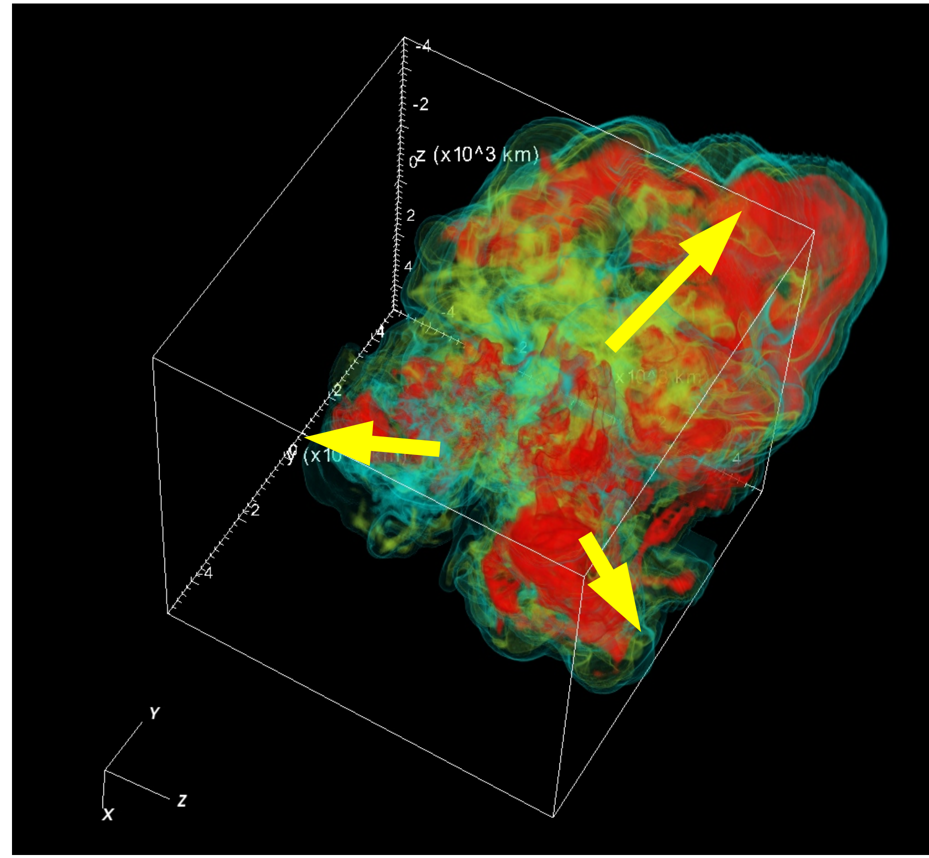
Neutrino-heated bubbles in ensuing supernova (red/yellow)

Geometry of convective flow in progenitor remains imprinted on explosion

Long-Time Evolution of the Explosion



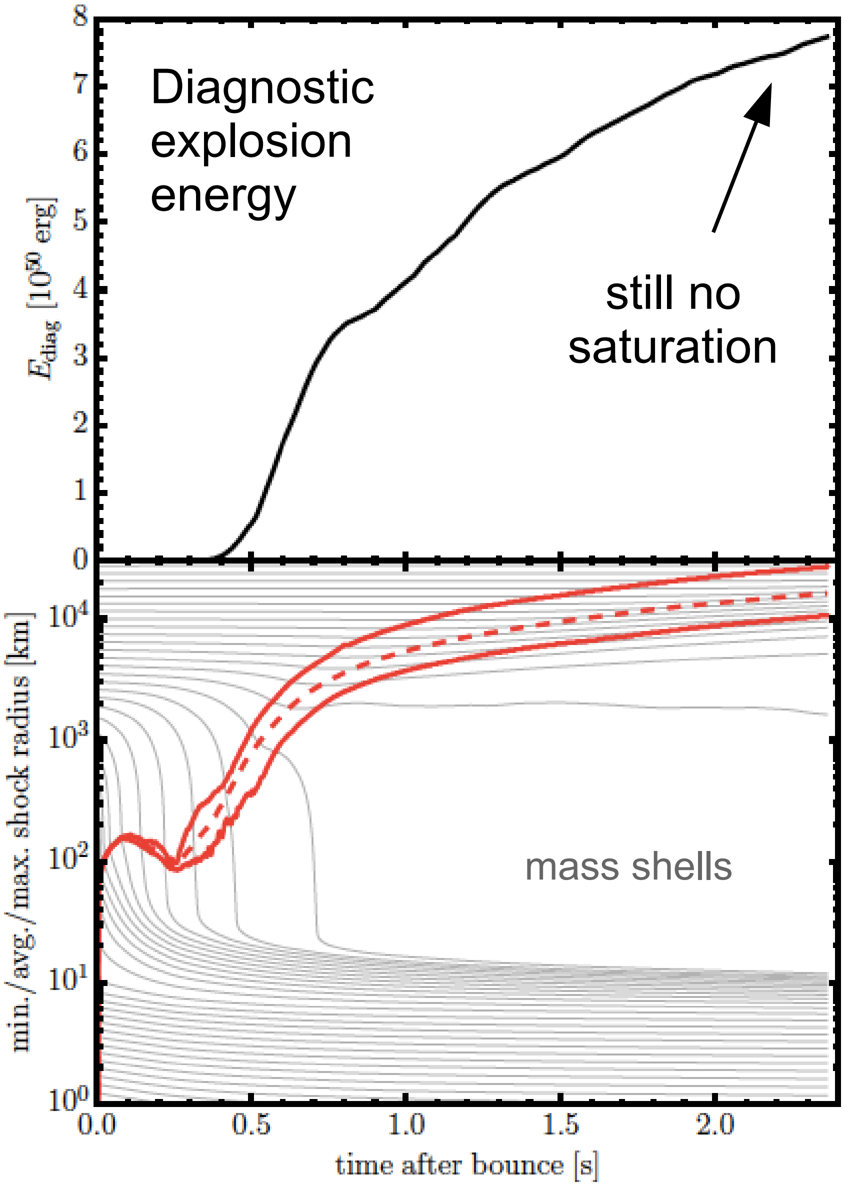
Red: Si-rich ashes
Cyan: Outer O shell boundary
Grey: Si core



Neutrino-heated bubbles in ensuing supernova (red/yellow)

Geometry of convective flow in progenitor remains imprinted on explosion

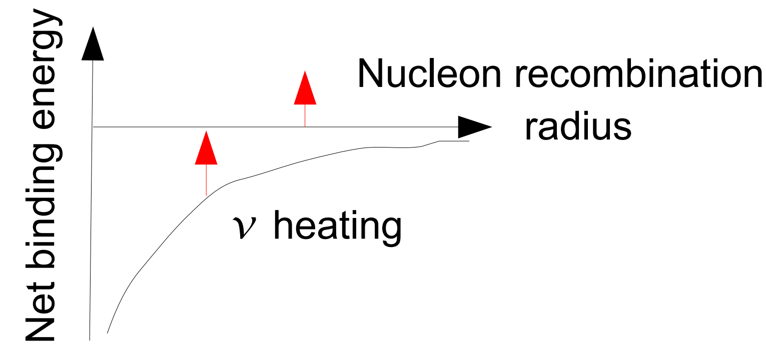
Energetics

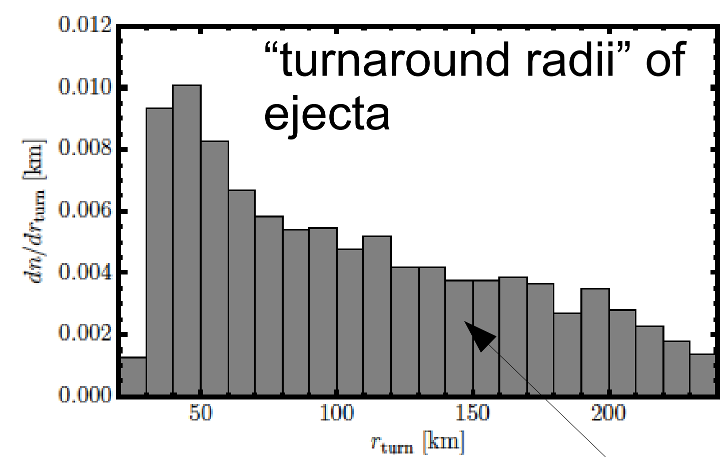


Even correction for “overburden” of envelope gives lower limit of E_{exp}>0.5foe
→ not far from “typical” energies (~0.9foe; Kasen & Woosley 2009)

Don't need much neutrino heating for late-time growth of explosion energy:

$$\frac{\dot{E}_{\mathrm{diag}}}{0.5\,\dot{Q}_\nu} \approx 0.5$$ (much higher than in 2D!)

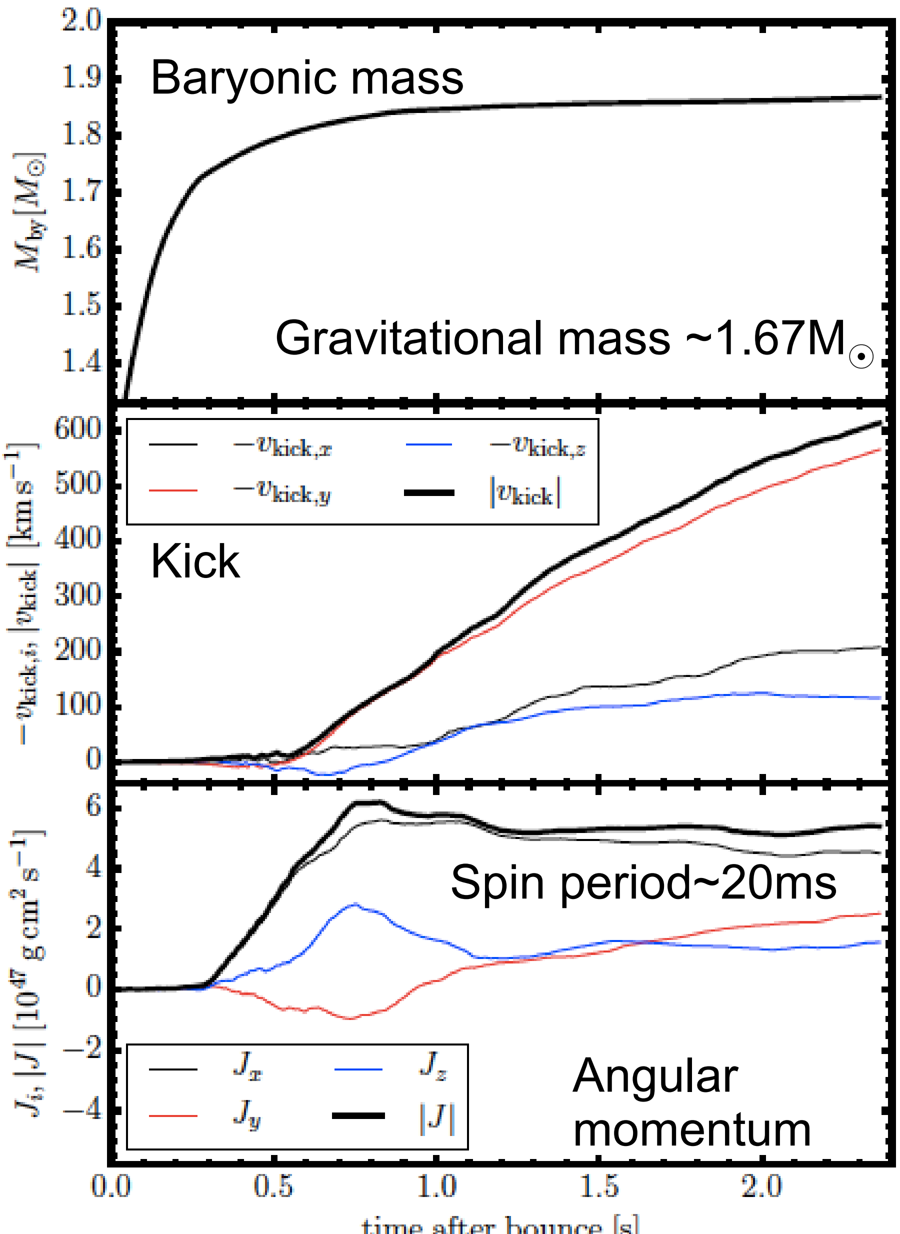




Large turnaround radii due to braking of downflows in 3D

Confirms trend towards more robust growth of explosion energy in 3D (Melson et al. 2015, Müller 2015, Kazeroni)

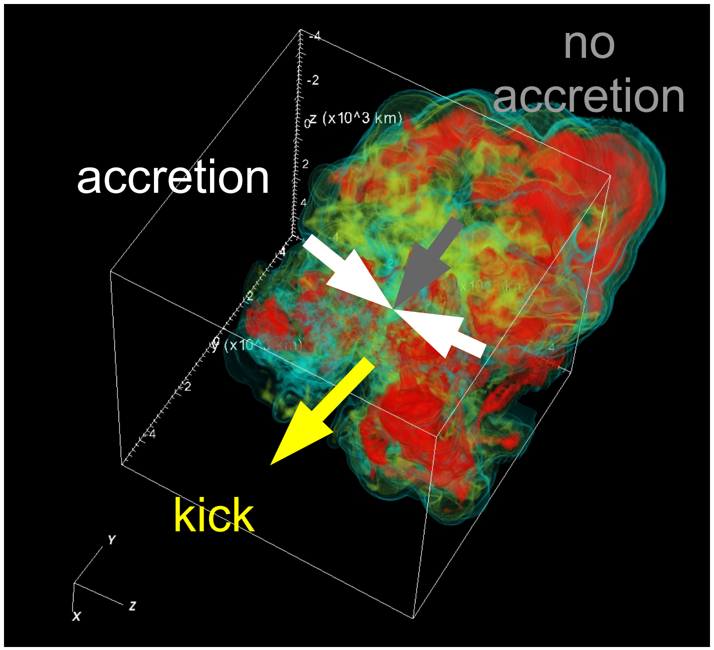
Neutron Star Mass, Kick & Spin

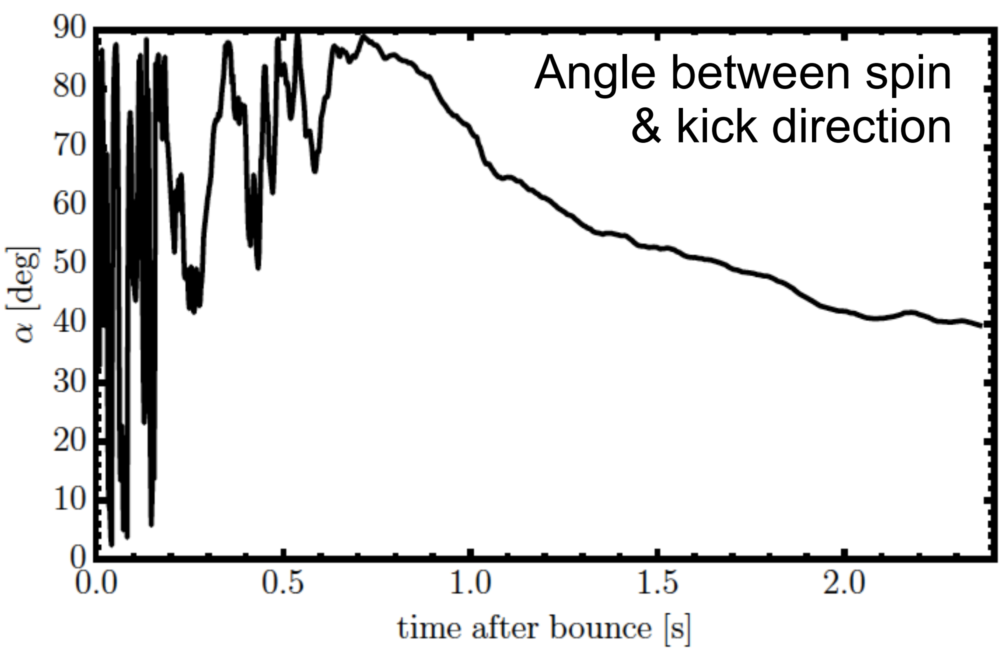


- Mass, kick & angular momentum somewhat on high side, but not implausible
- Same "gravitational tug-boat mechanism" for kick as in parameterised 3D models (Wongwathanarat et al. 2010, 2013)
- But much faster spin than in parameterised 3D models (← sustained accretion)

→ another mechanism that may reset the angular momentum of the progenitor core... (cp. spin-up by SASI)

Neutron Star Mass, Kick & Spin





- Mass, kick & angular momentum somewhat on high side, but not implausible
- Same "gravitational tug-boat mechanism" for kick as in parameterised 3D models (Wongwathanarat et al. 2010, 2013)
- But much faster spin than in parameterised 3D models (← sustained accretion)

  → another mechanism that may reset the angular momentum of the progenitor core...
- Trend towards spin-kick alignment? Judgement seems premature...

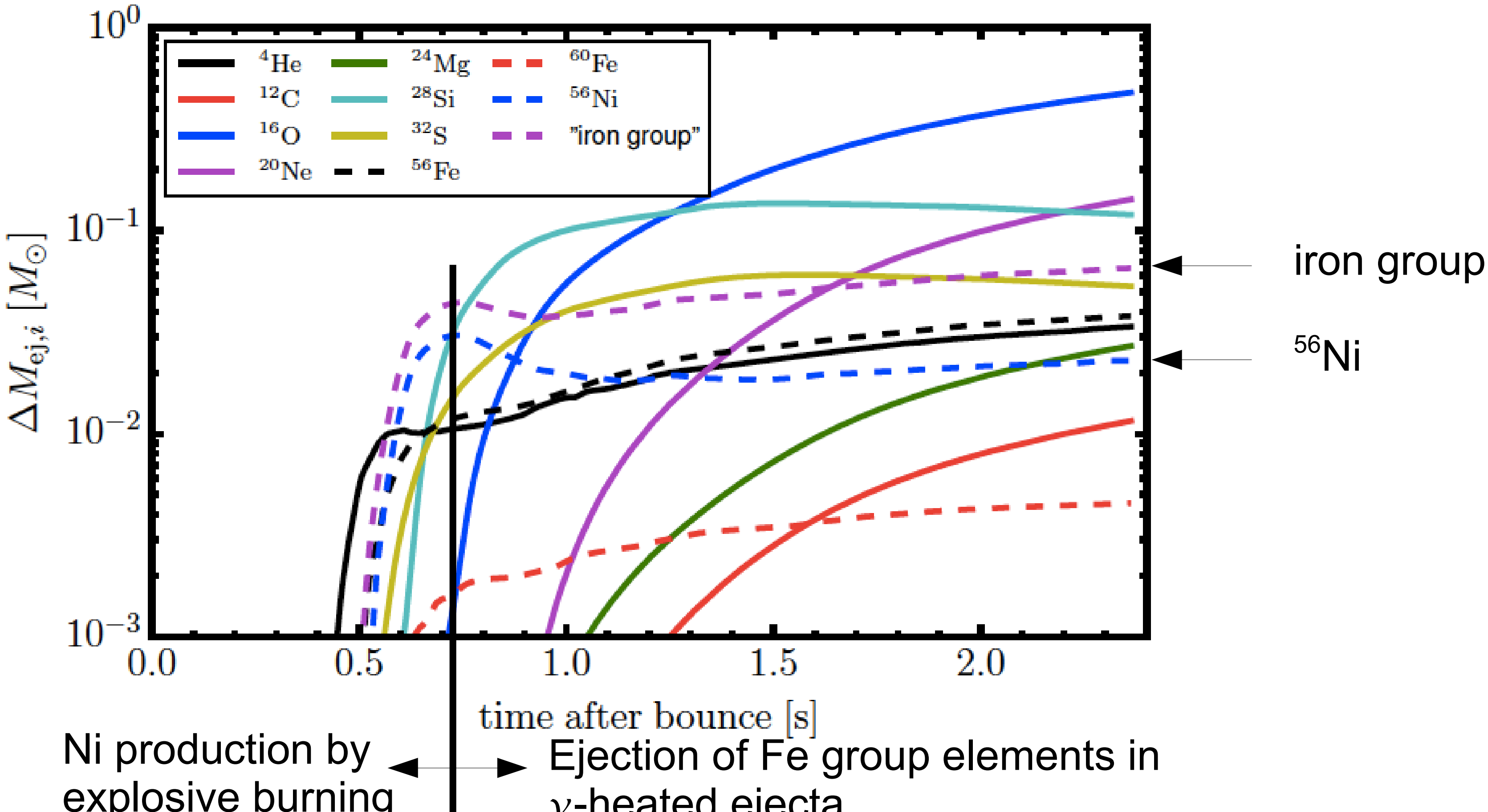
Conclusions

- First multi-group neutrino hydrodynamics simulations of CCSNe with 3D initial conditions available
- Huge effect of initial perturbations from convective O shell on shock revival in $18M_\odot$ progenitor
- But: Conditions for perturbation-aided explosions generally less favourable according to stellar evolution models

  → **need to simulate more progenitors in 3D**
- Long-time simulation of $18M_\odot$ explosion to 2.5s suggests 3D models can reach plausible explosion & remnant properties
- But may need a bit of a “boost” to make 18 model “typical” (higher E_{expl}, lower M_{NS})

  → Perturbations *one among many ingredients* for accurate SN models (“complete” microphysics, more accurate transport, GR)

Nucleosynthesis



Some caveats concerning this simulation:

- Fixed "flashing" temperatures for various burnings and freeze-out from NSE (no network)
- Y_e underestimated with FMT transport solver
  $\rightarrow$ ^{56}Fe, ^{60}Fe could actually be ^{56}Ni