Explosions In The Sky:
Core-collapse Supernova Theory

arxiv:2009.14157

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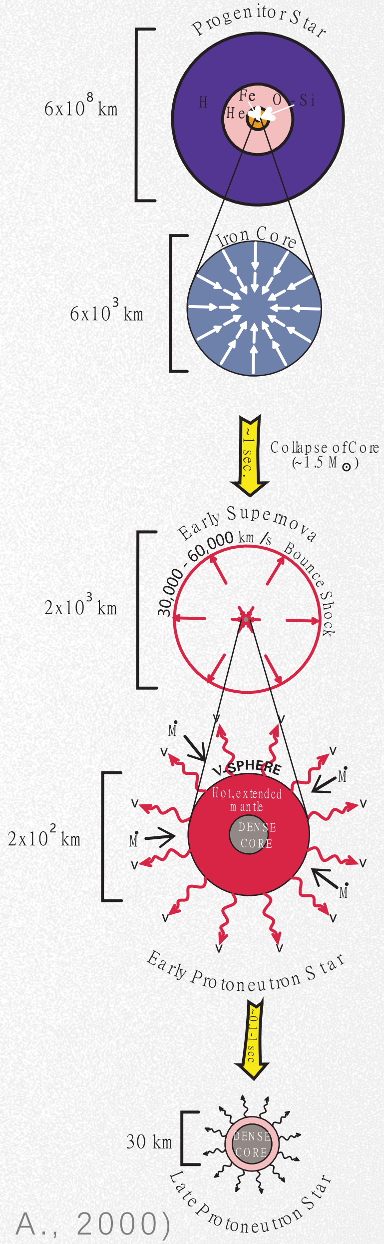
Quick introduction


凡十一日没三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屛星西北凡七十五日入濁没明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日没至和元年五月己丑出天關東南可數寸歲餘
稍没熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁
宋史志卷九

Supernova Classes

Low-mass Stars (White Dwarfs)	Massive Stars (Supergiants)
Thermonuclear ↓	↓ Core-Collapse
Type Ia	**Type II** Ib, Ic

Progenitor: $\mathbf{8 \sim 20}\ M_{\odot}$



(Burrows, A., 2000)

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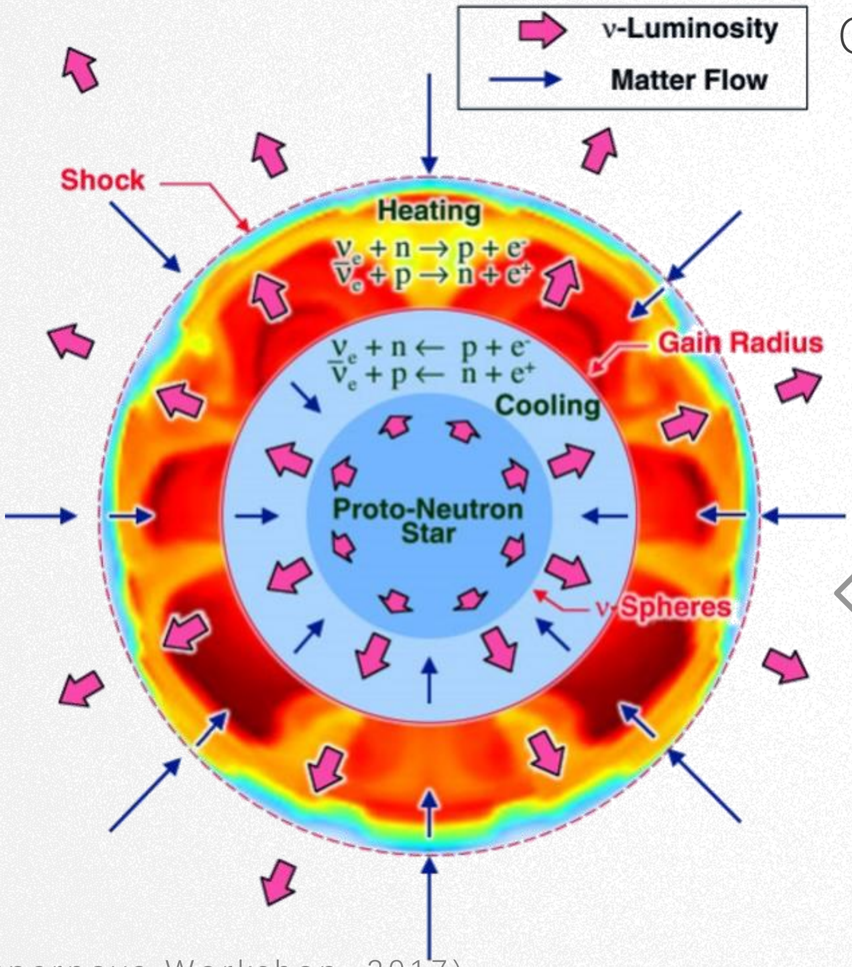
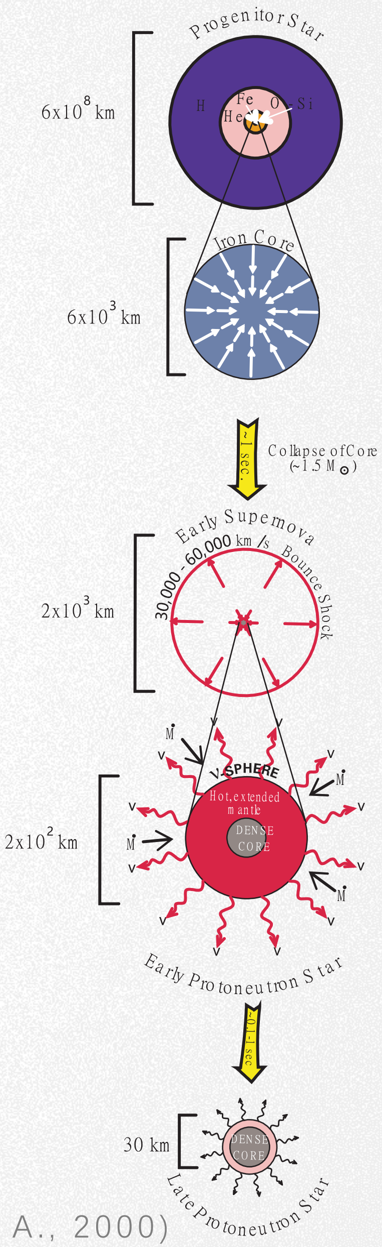


(LVC Supernova Workshop, 2017)

Q: How to explode, due to balance between $\boldsymbol{\nu}$ heating and accretion? Stalled shock or outward one?



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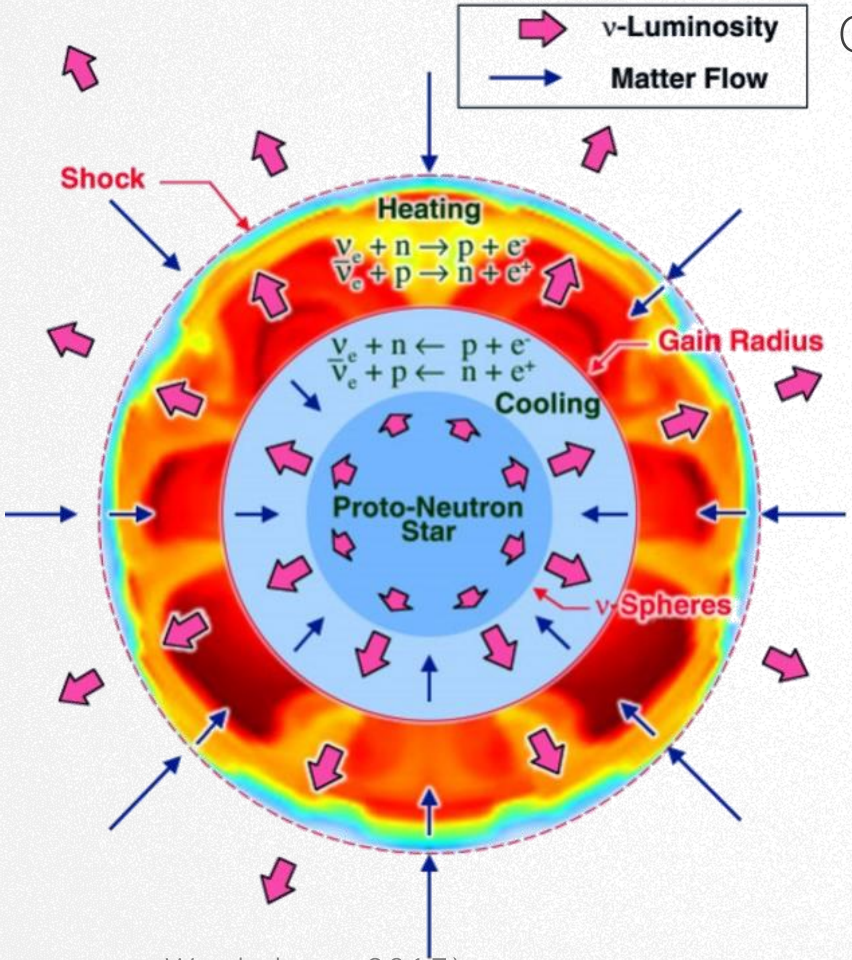

Q: How to explode, due to balance between $\boldsymbol{\nu}$ heating and accretion? ~~Stalled shock~~ or outward one?

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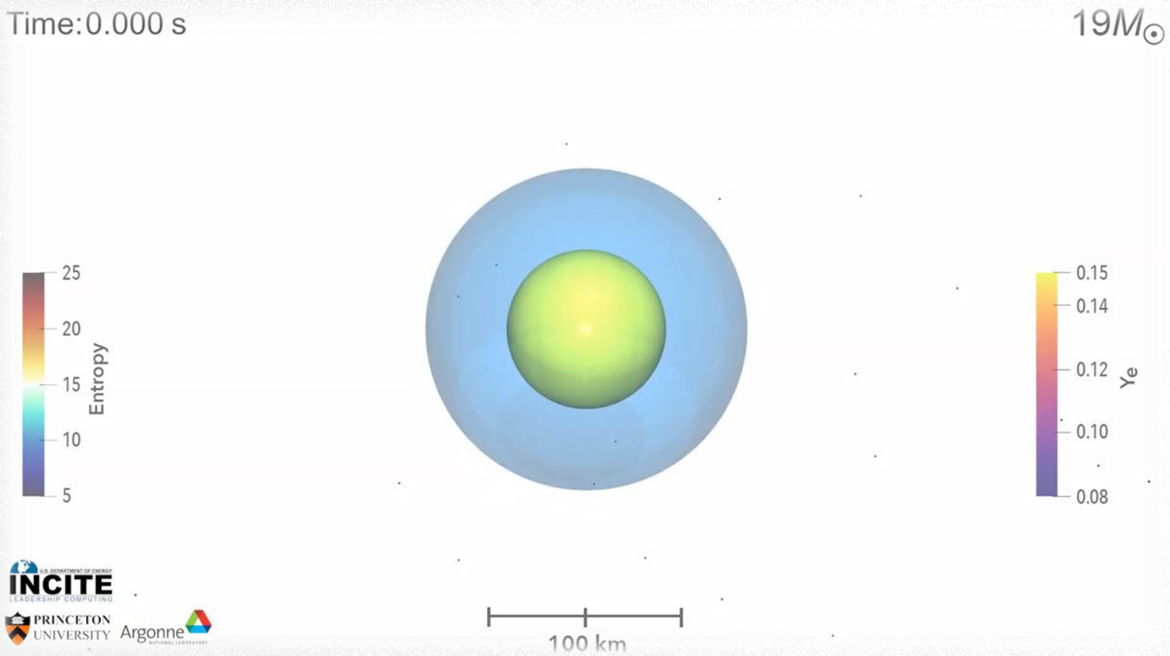
(LVC Supernova Workshop, 2017)

(Cendes, Y.+, 2018)

How to explode?



(Burrows, A. & Vartanyan D., 2021)

- ν from the inner core heats the “gain region” behind the shock, where ν is collisional → turbulent convection
- Energy from ν behind the shock & turbulent pressure together overcome the accretion pressure
- Key: Gravitational-energy sourced, neutrino-driven, and turbulence-aided → Delayed explosion

Physics behind explosions

- Neutrino mechanism (inelastic scattering, many-body effect)
- Turbulence (multi-dimension)
- Progenitor model
- General relativity
- Rotation
- Magnetic field (hypernova)
- Thermonuclear
- EoS for the inner core

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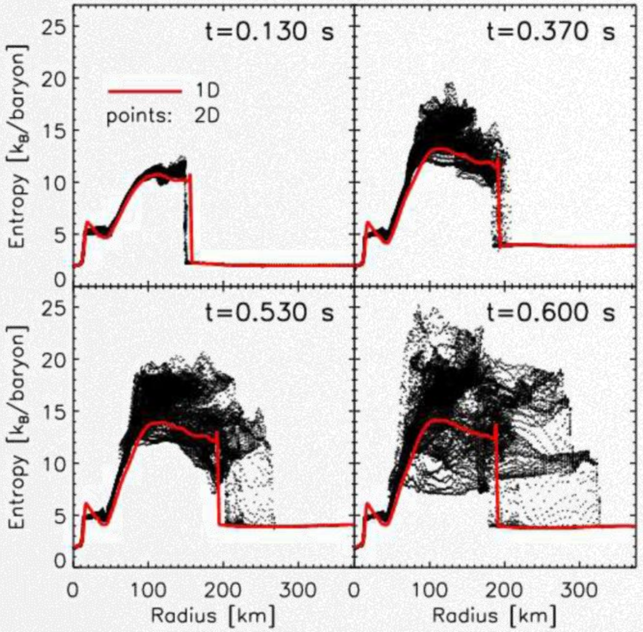
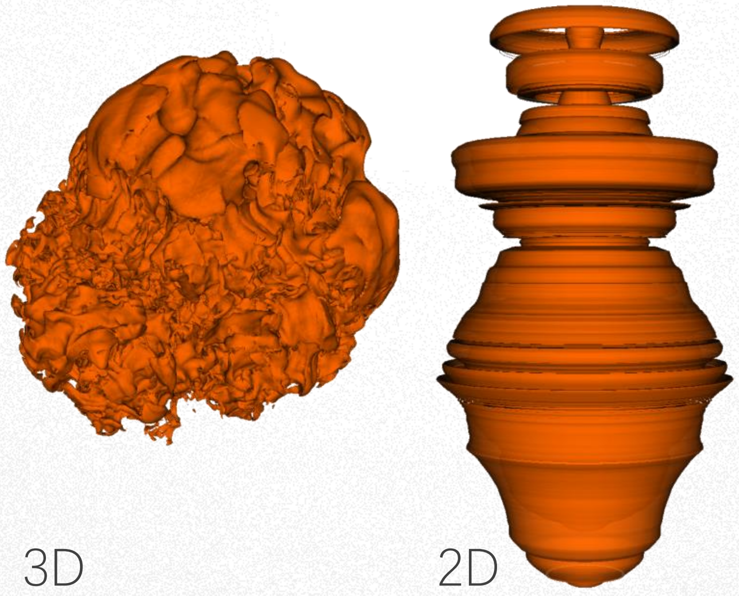
Turbulence

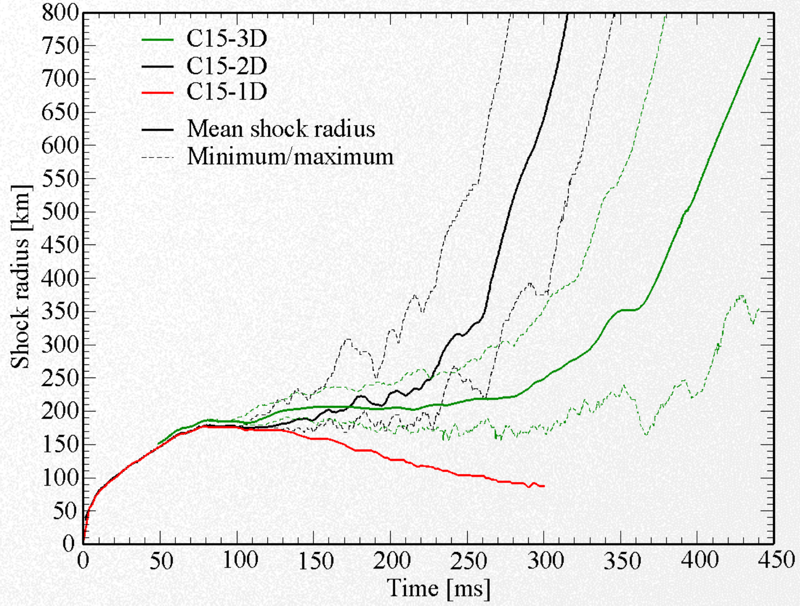
- Asymmetry: 1D is meaningless; 2D appoaches to reality but not precisely; 3D works best



(Murphy, J &.Burrows, A., 2008)



(Couch, S, 2012)



(Lentz+, 2015)

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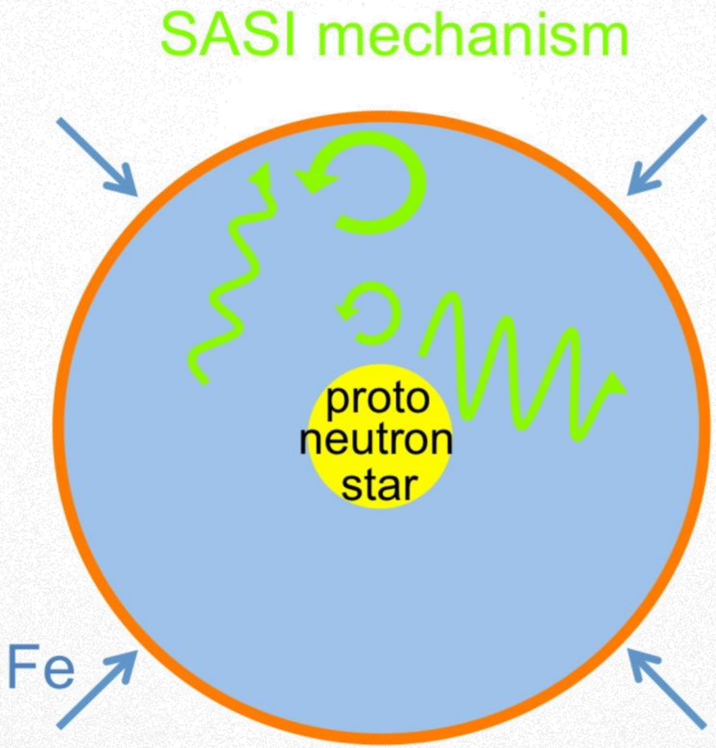

(Foglizzo, T.+, 2015)

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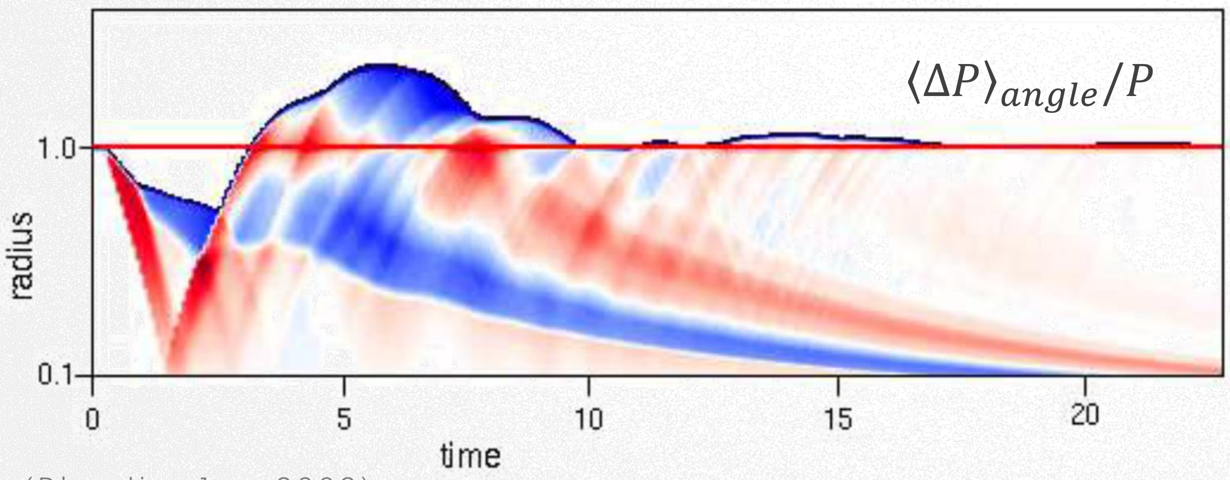
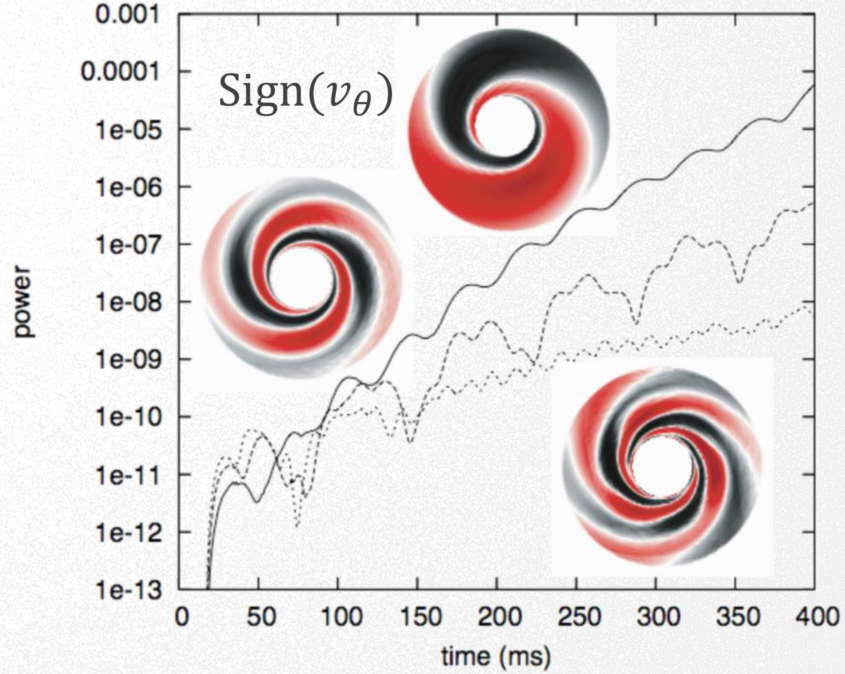
GW & ν signals

Axisymmetric SASI



(Blondin, J.+, 2003)

Non-axisymmetric SASI

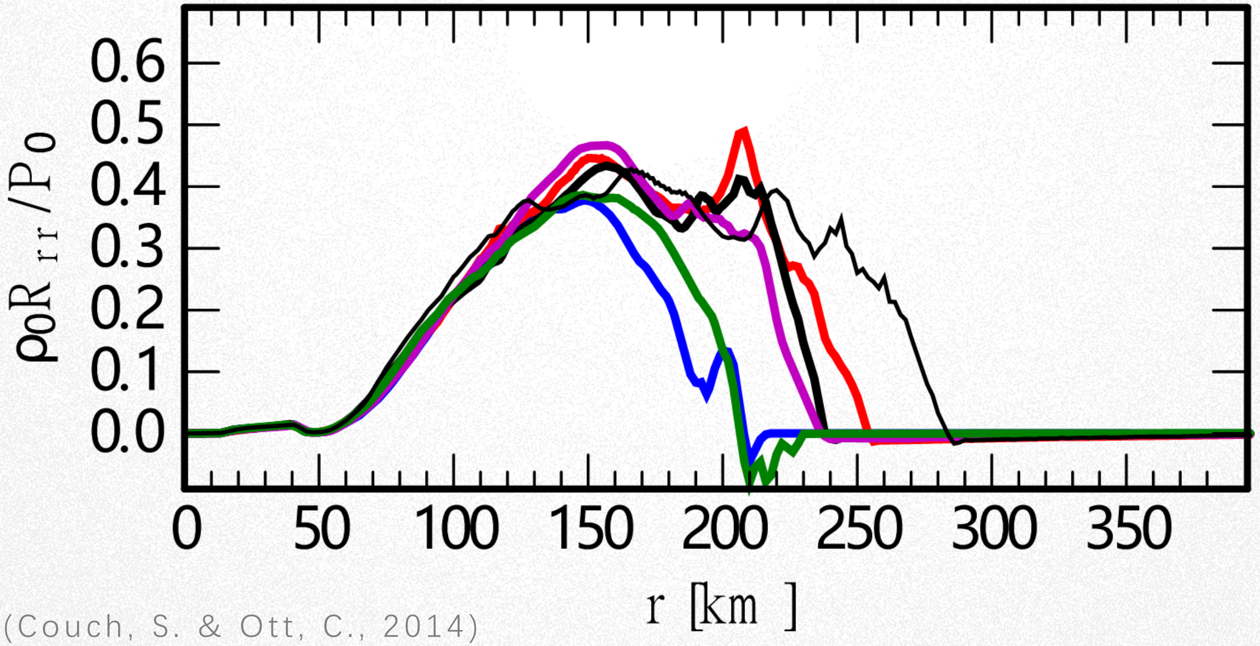


(Blondin, J.& Shaw, S., 2007)

Turbulence

- Asymmetry: 1D is meaningless; 2D appoaches to reality but not precisely; 3D works best
- Instabilities: standing accretion shock (SASI), convective, Rayleigh–Taylor, Kelvin–Helmholtz …
- Offer ~30-50% of the stress behind the stalled shock

$$R_{ij} = \langle \rho \langle u_i \rangle (\langle u_j \rangle - u_j) \rangle / \rho_0$$



(Couch, S. & Ott, C., 2014)

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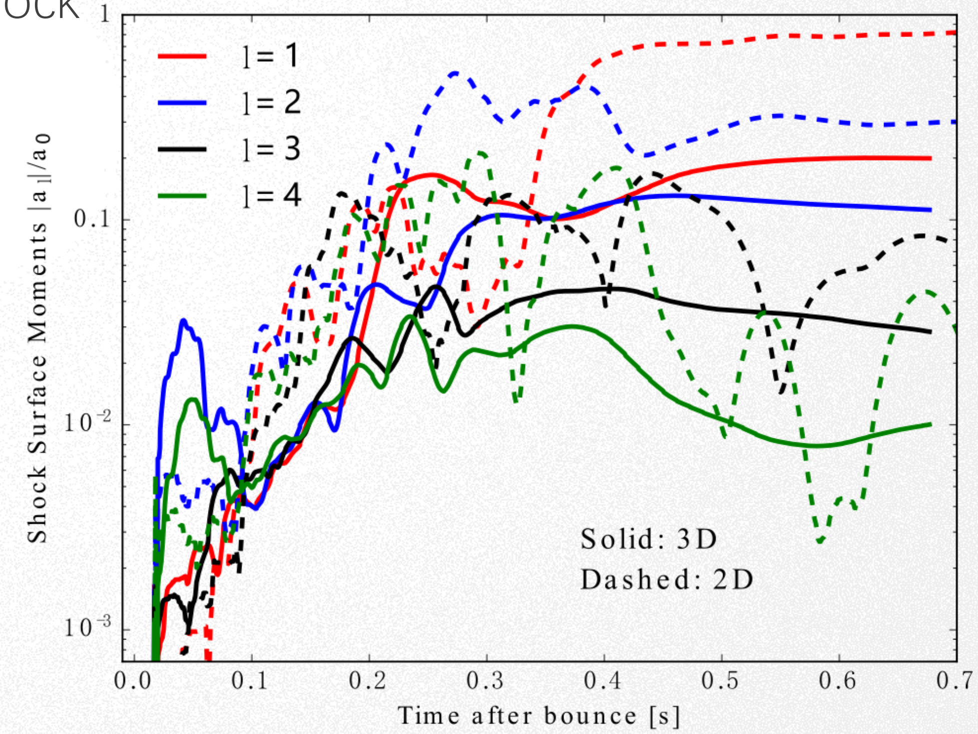
- Offer ~30-50% of the stress behind the stalled shock
- A roughly dipolar component w/ a random axis

$$a_{lm} = \frac{(-1)^m}{\sqrt{4\pi(2l+1)}} \oint R_s(\theta,\phi) Y_l^m(\theta,\phi)\, d\Omega$$

$$P_l = \sqrt{\textstyle\sum_{m=-l}^{l} a_{lm}^2} \,/ a_{00}$$



(Vartanyan, D.+, 2019)

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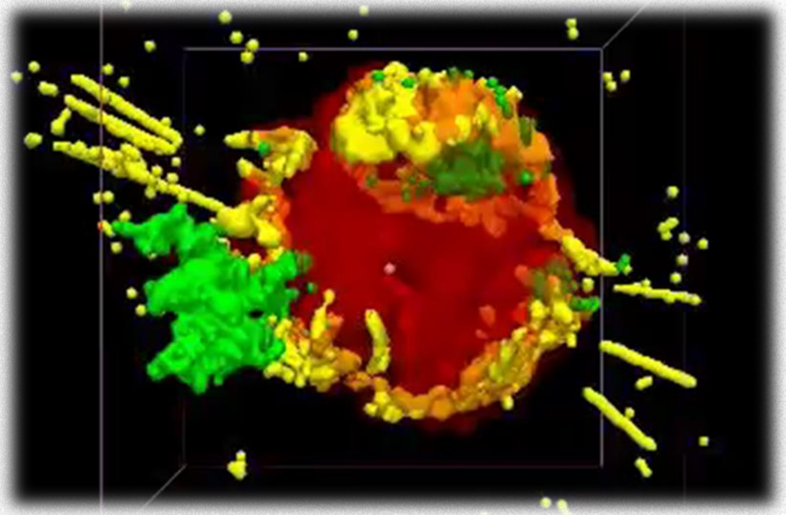
Cas A

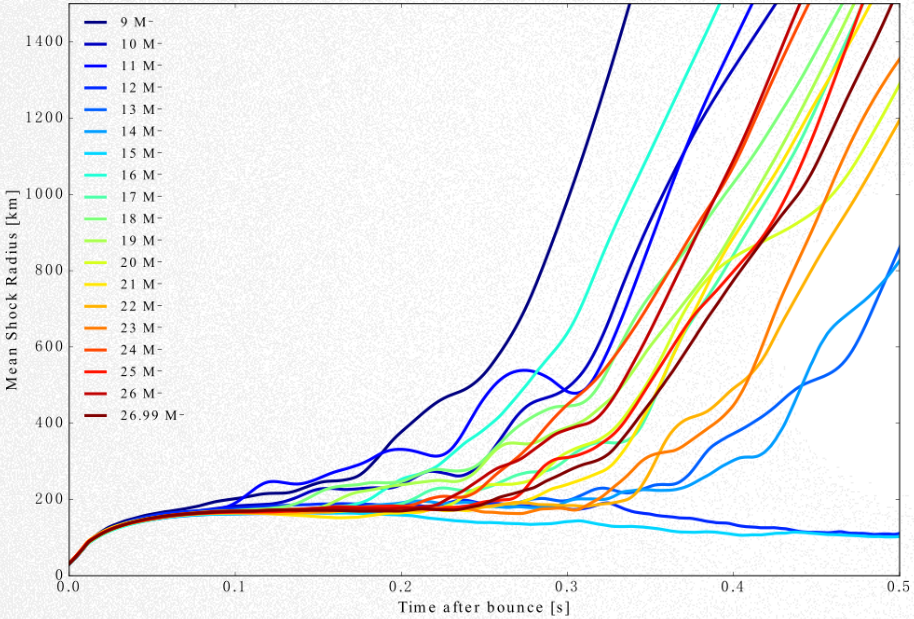


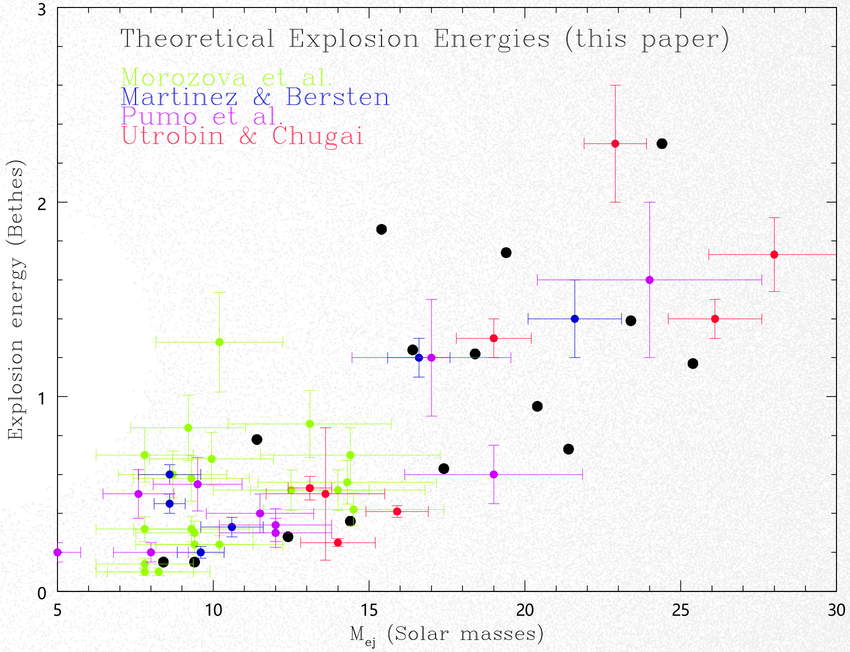
(DeLaney, T.+, 2010)

(Burrows, A. & Vartanyan D., 2021)

Summary (for core-collapse supernova)

(Burrows, A. & Vartanyan D., 2021)





- Gravitational-energy sourced, neutrino-driven, and turbulence-aided → Delayed explosion
- There are still too many effectors to draw reliable conclusions.
- If lucky, we can observe one event with EM, GW, ν and cosmic ray signals simultaneously.

Possible questions

- Can we apply the mixing layer theory (MLT) directly? Do we need to modify MLT in supernova?
- Any local simulation approaches? Shearing-box? Shock tube? Expanding box?
- If a BH is formed finally, how does the envelope structure change to a disk one?
- If neutrino can interact with dark matters, what will happen for core-collapse supernovae?