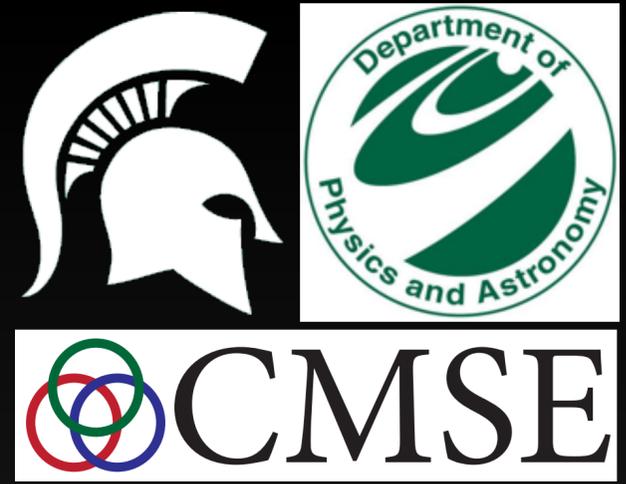
A large, semi-transparent image of a stellar explosion simulation is centered in the background. It shows a bright purple core surrounded by a blue ring, all within a larger, turbulent orange and red structure. The text is overlaid on this image.

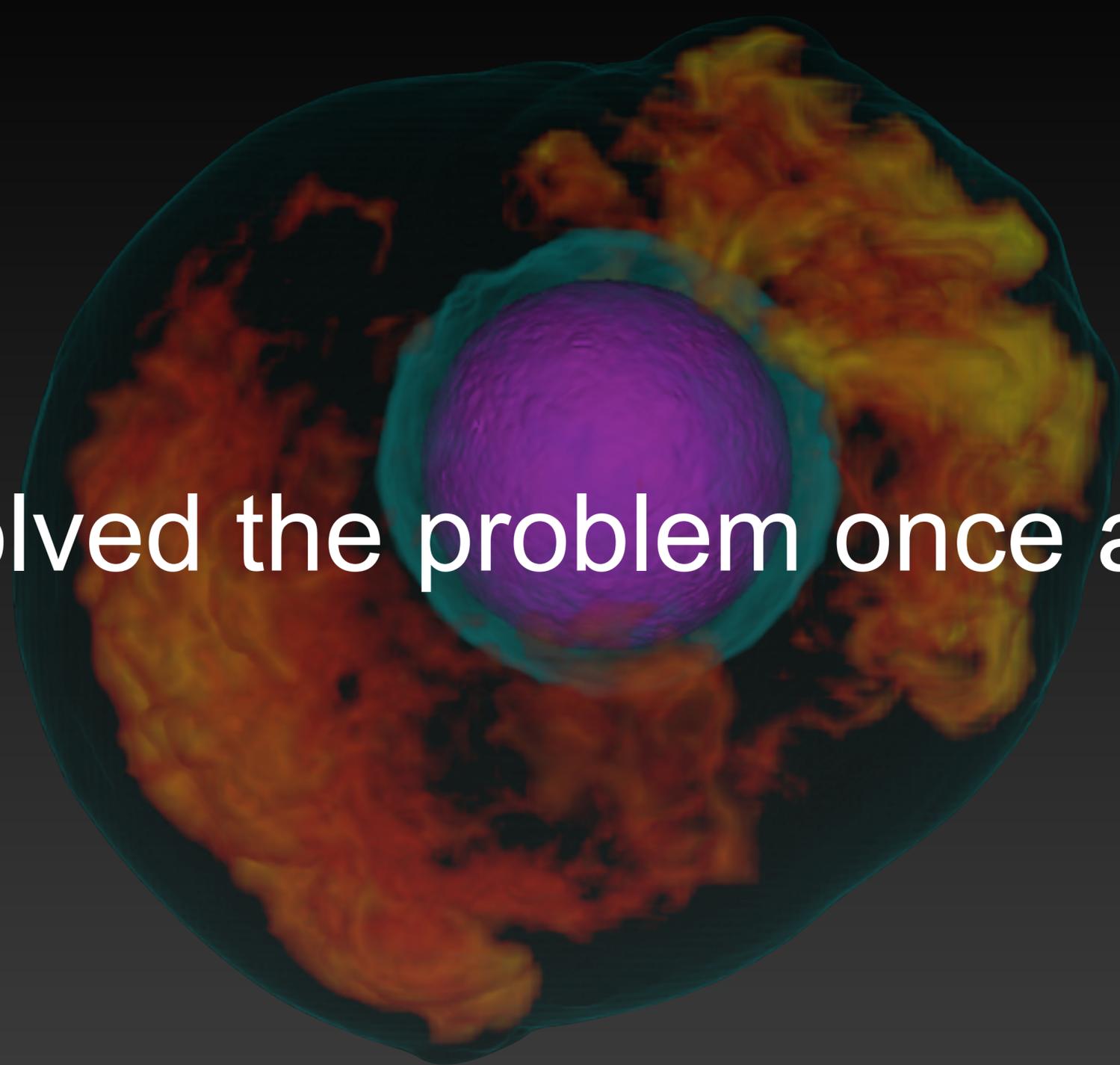
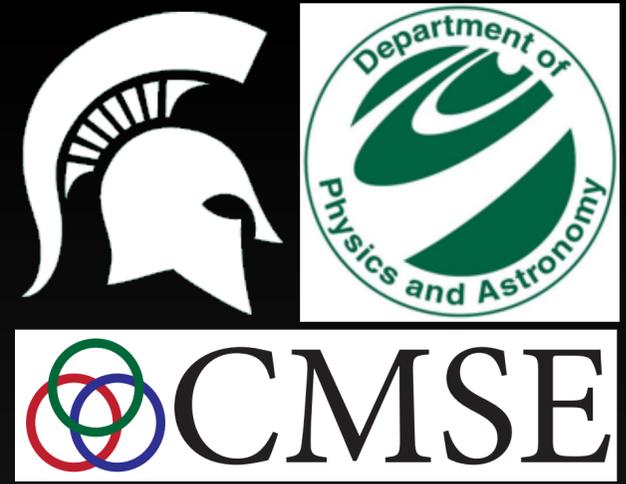
# Stellar Explosions: Core-collapse Supernovae and Nuclear Theory

Sean M. Couch  
Michigan State University

FRIB Theory Alliance Meeting  
1 April 2016



We've solved the problem once and for all!!



We've solved the problem once and for all!!

Sorry.... April Fool's!

# Nucleosynthesis from CCSNe

<p><b>Big Bang nucleosynthesis</b> spallation</p> <p>evolved giant stars</p>										<p><math>\alpha</math>-rich freeze-out, <math>\nu p</math>-process, weak s-process?</p> <p><b>s-process</b></p> <p>light neutron-capture primary process</p> <p><b>r-process</b></p>											
IA																	VIIIA				
1																	2				
H																	He				
1.008																	4.003				
										$\alpha$ -elements							iron group elements				
3	4															5	6	7	8	9	10
Li	Be															B	C	N	O	F	Ne
6.939	9.012															10.811	12.011	14.007	15.999	18.998	20.183
11	12															13	14	15	16	17	18
Na	Mg															Al	Si	P	S	Cl	Ar
22.990	24.312															26.982	28.086	30.974	32.064	35.453	39.948
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36				
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr				
39.102	40.08	44.956	47.88	50.942	51.996	54.938	55.847	58.933	58.69	63.54	65.37	69.72	72.59	74.922	78.96	79.909	83.80				
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54				
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe				
85.47	87.62	88.905	91.22	92.906	95.94	(99)	101.07	102.91	106.42	107.87	112.40	114.82	118.69	121.75	127.60	126.90	131.30				
55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86				
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn				
132.91	137.34	138.91	178.49	180.95	183.85	186.2	190.2	192.2	195.09	196.97	204.59	204.38	209.17	208.98	(210)	(210)	(222)				
87	88	89																			
Fr	Ra	Ac																			
(223)	(226)	(227)																			
			58	59	60	61	62	63	64	65	66	67	68	69	70	71					
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu					
			140.12	140.91	144.24	(145)	150.36	151.96	157.25	158.92	162.50	164.93	167.26	168.93	173.04	174.97					
			90	91	92	93	94	95	96	97	98	99	100	101	102	103					
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr					
			232.04	(231)	238.03	(237)	(242)	(243)	(247)	(249)	(251)	(254)	(253)	(256)	(253)	(257)					

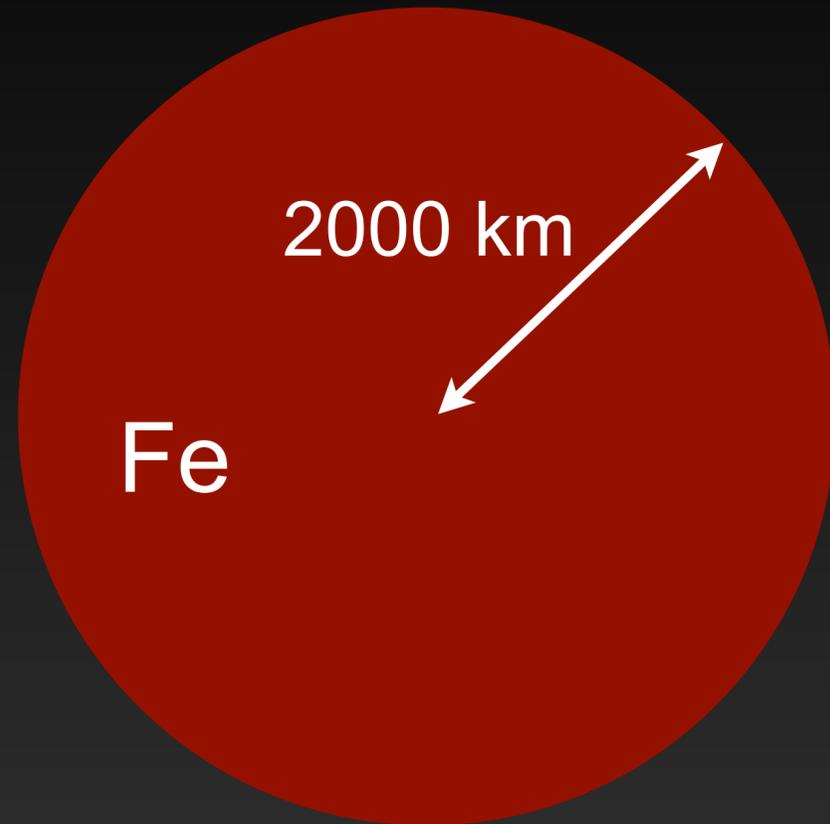
CCSNe dominate the chemical evolution of the universe

A. Frebel, MIT

# Nuclear Physics Labs

- Matter at most extreme densities, temperatures, isospin
- Produce most elements in Nature
- Complimentary to experiment at, e.g., NSCL, FRIB, JLAB, ATLAS, RHIC, GSI, TRIUMF,...
- Neutrino and gravitational wave signals encode info about nuclear EOS
- Test BSM physics of neutrinos

# Basic Picture of Stellar Collapse

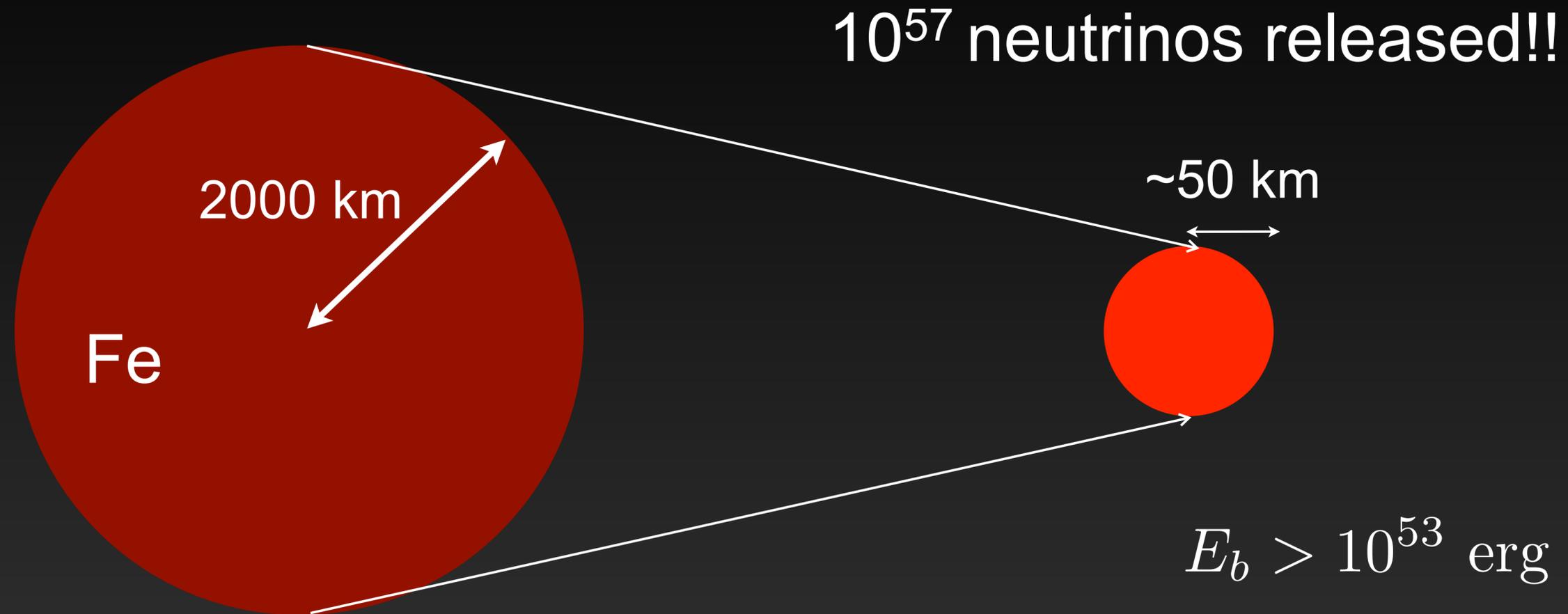


$$M_{Fe} \sim M_{Ch} \sim 1.4 M_{\odot}$$

$$\rho_c \sim 10^{10} \text{ g cm}^{-3}$$

$$Y_e \sim 0.43$$

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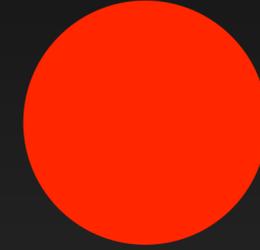
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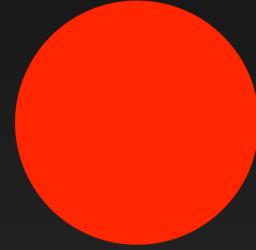
$$\rho_c > 10^{14} \text{ g cm}^{-3}$$

$$Y_e \sim 0.27$$

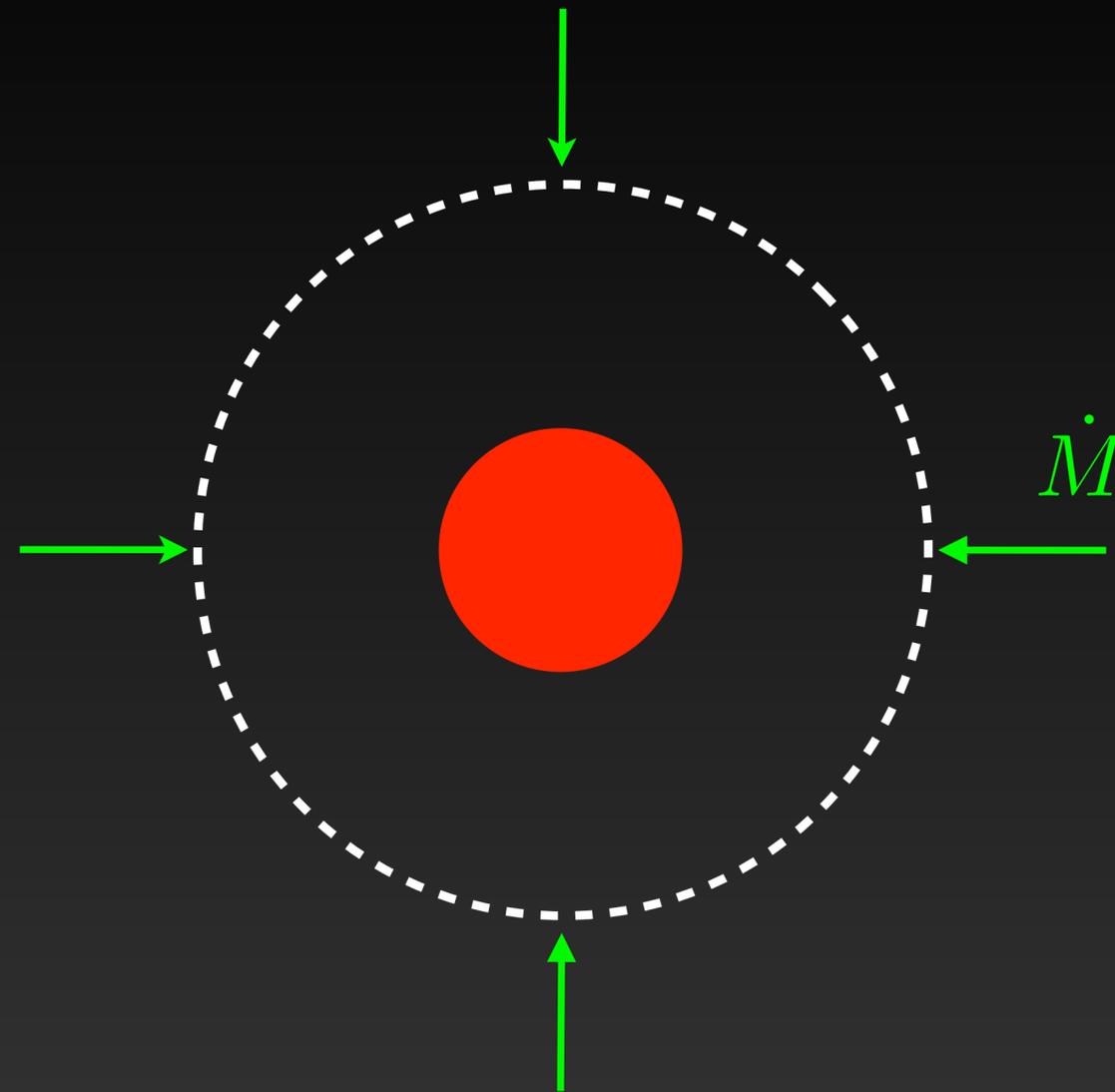
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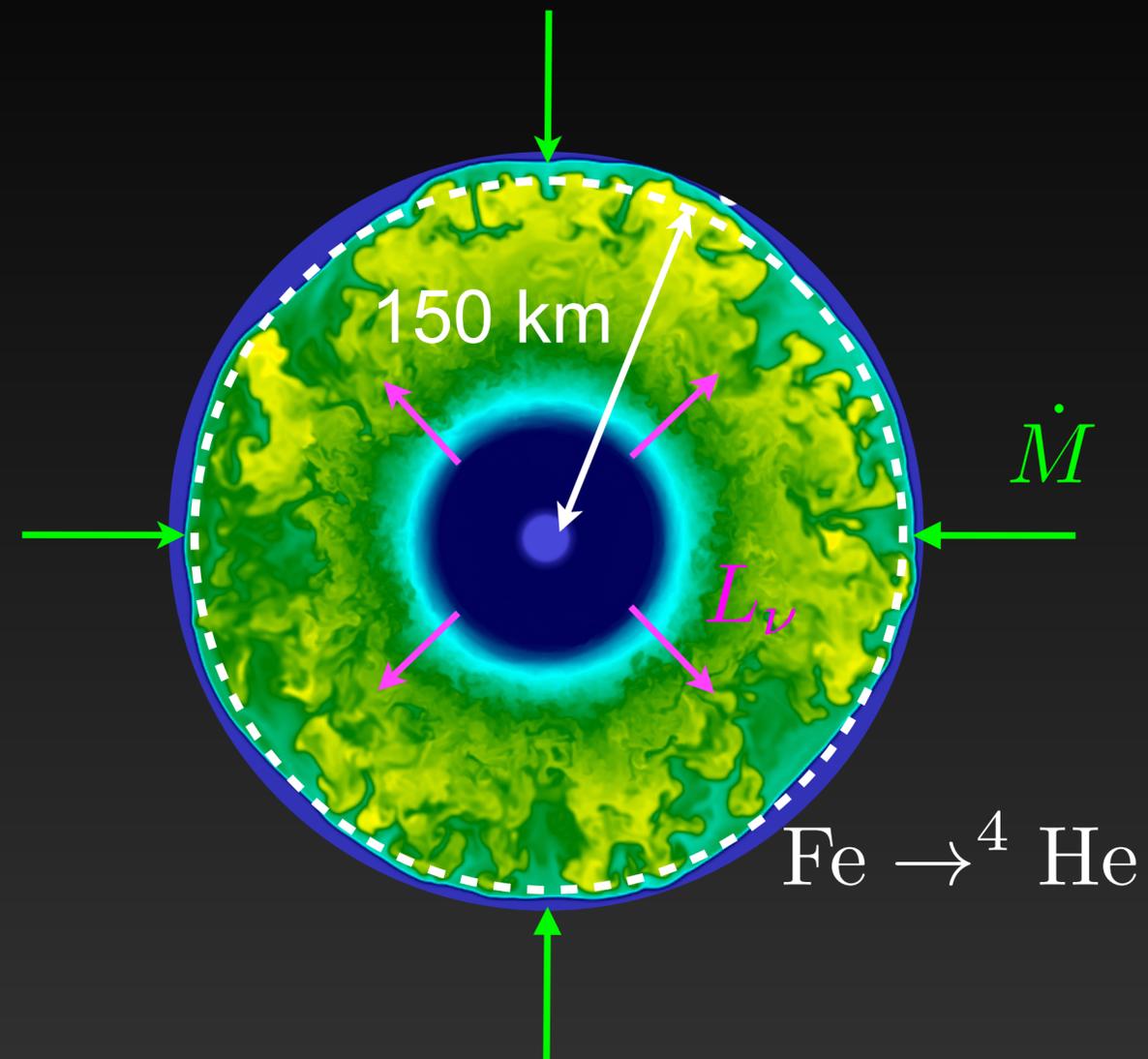
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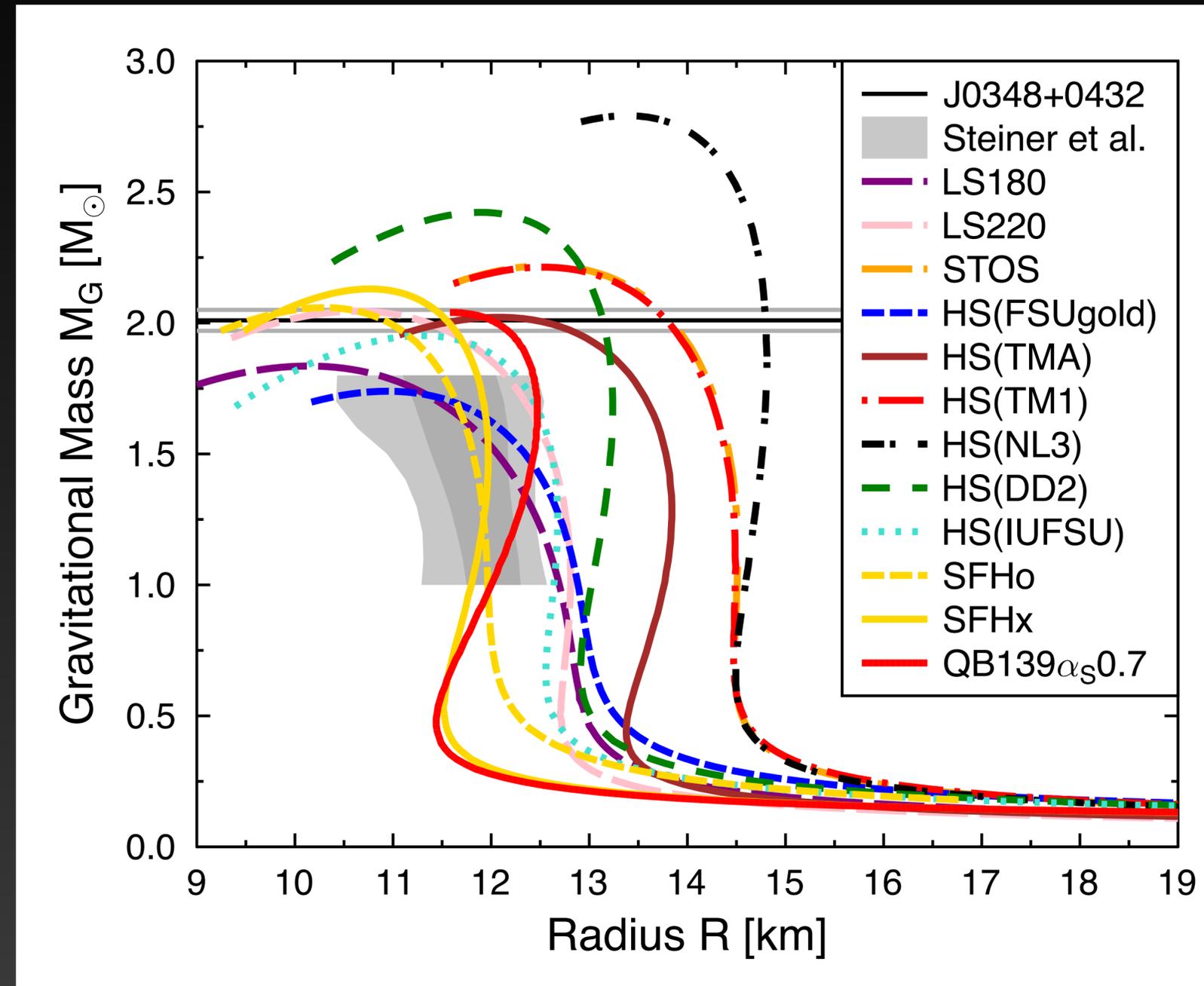
# Basic Picture of Stellar Collapse



Shock stalls... What revives it??  
=> The CCSN "Problem"

# Dense Matter Equation of State

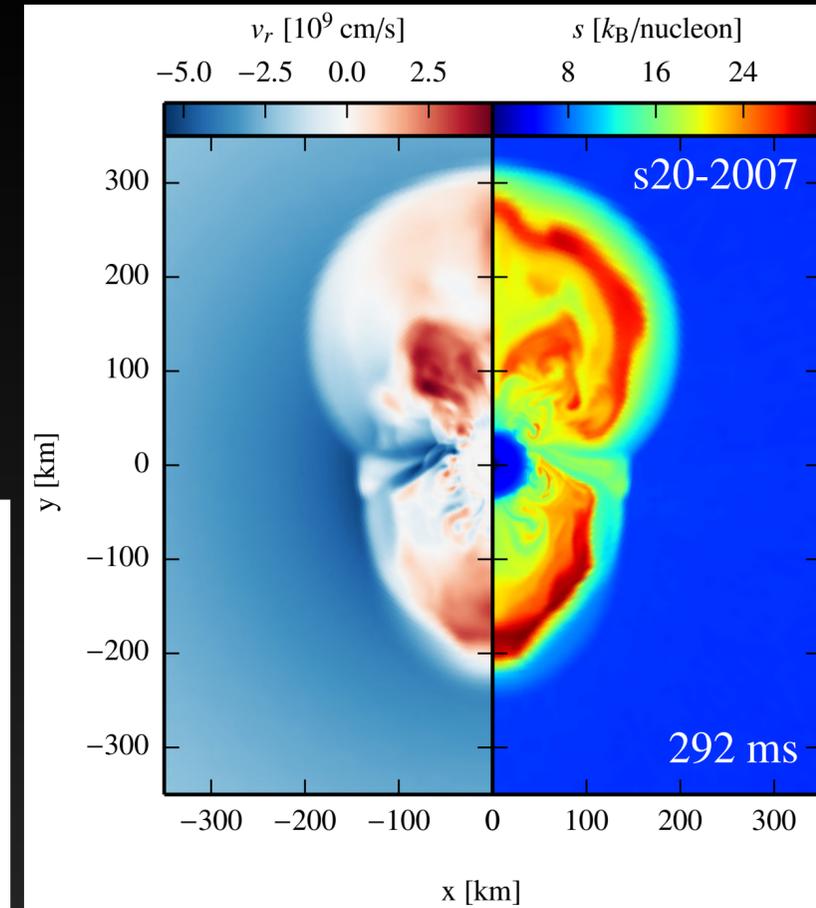
- Can impact:
  - Explosion (Marek et al. 2009; SMC 2013; Suwa et al. 2013)
  - Gravitational wave emission (Marek et al. 2009; Mueller et al. 2013)
  - Neutrino emission (O'Connor & Ott 2013)



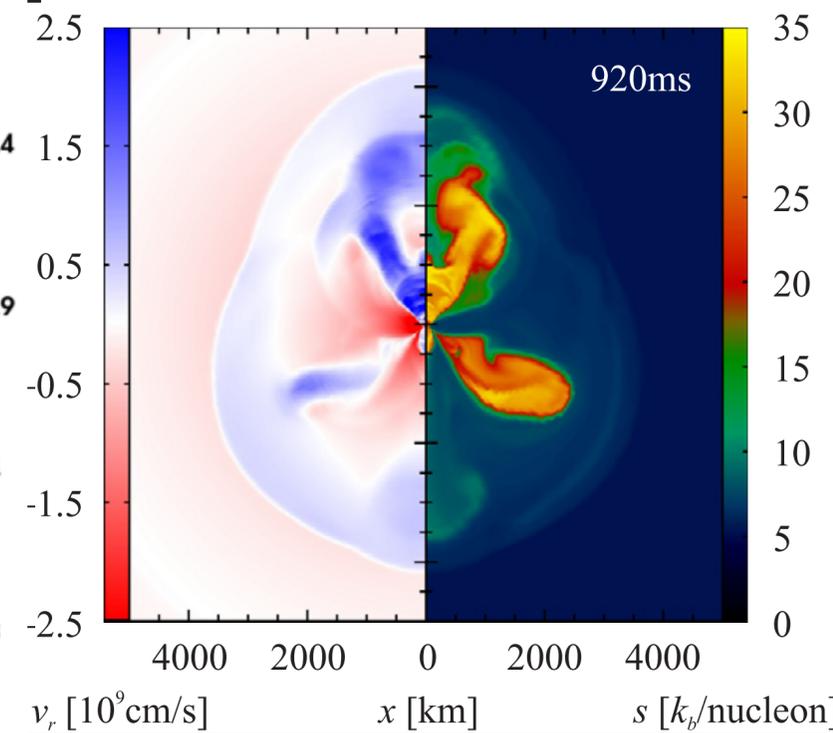
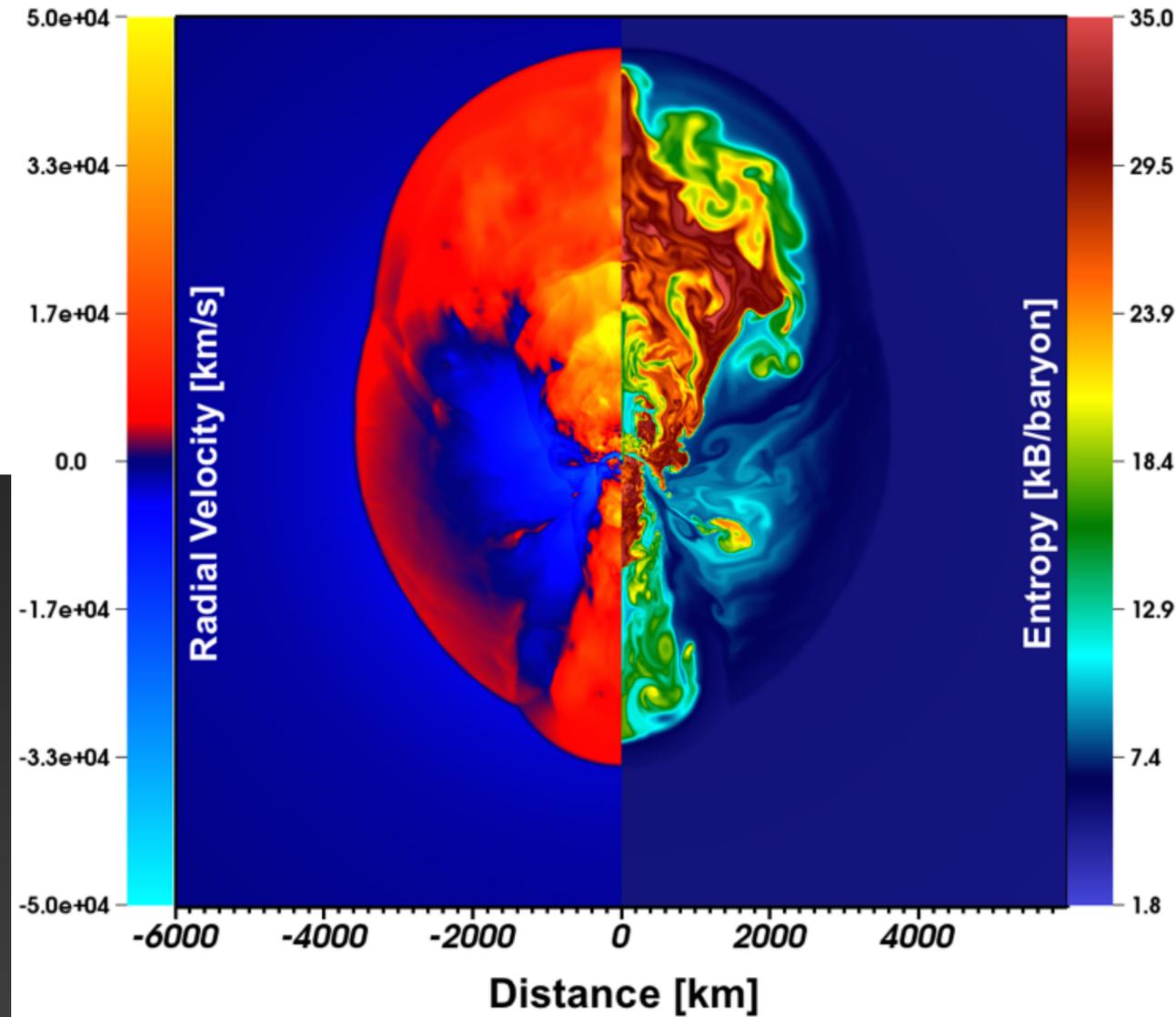
Fischer et al. 2014

# High-Fidelity Explosions in 2D

Summa et al. (2015)

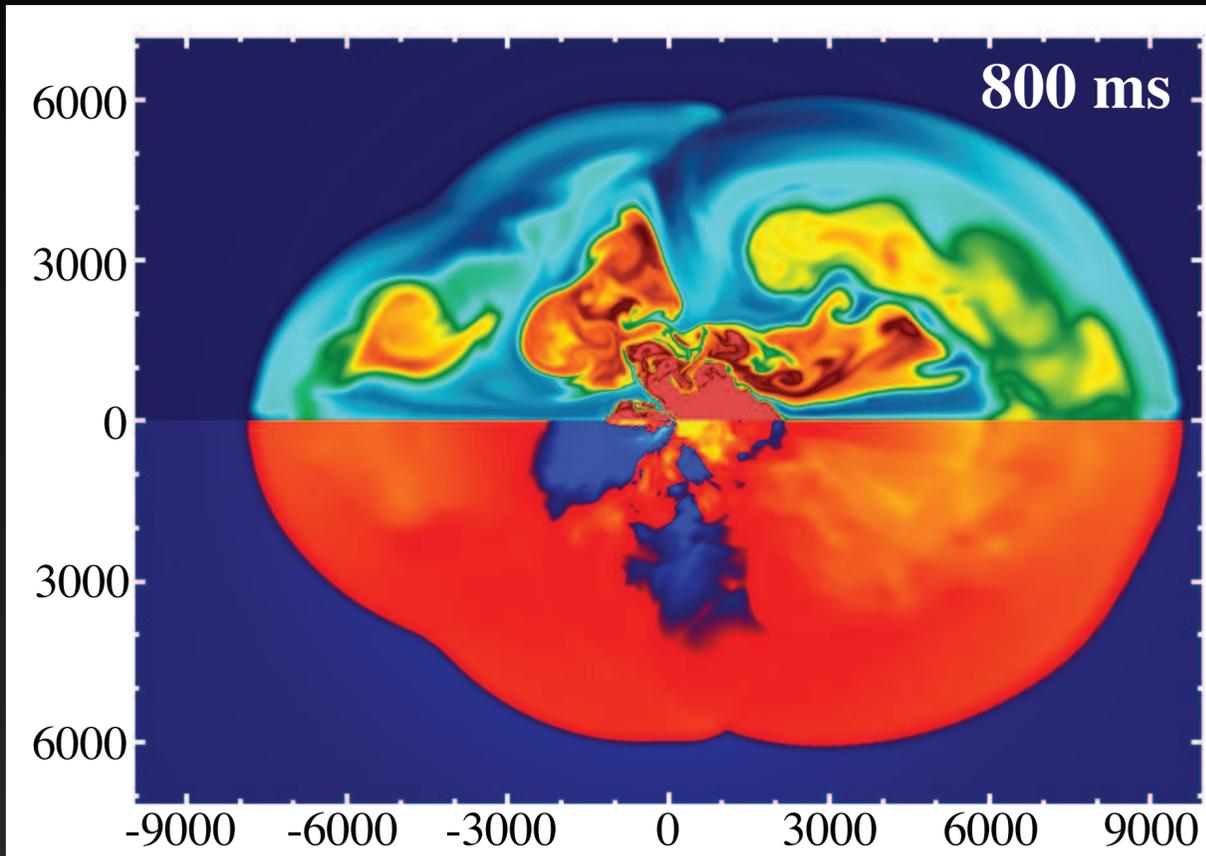


E. O'Connor & SMC (2016)



Mueller et al. (2012)

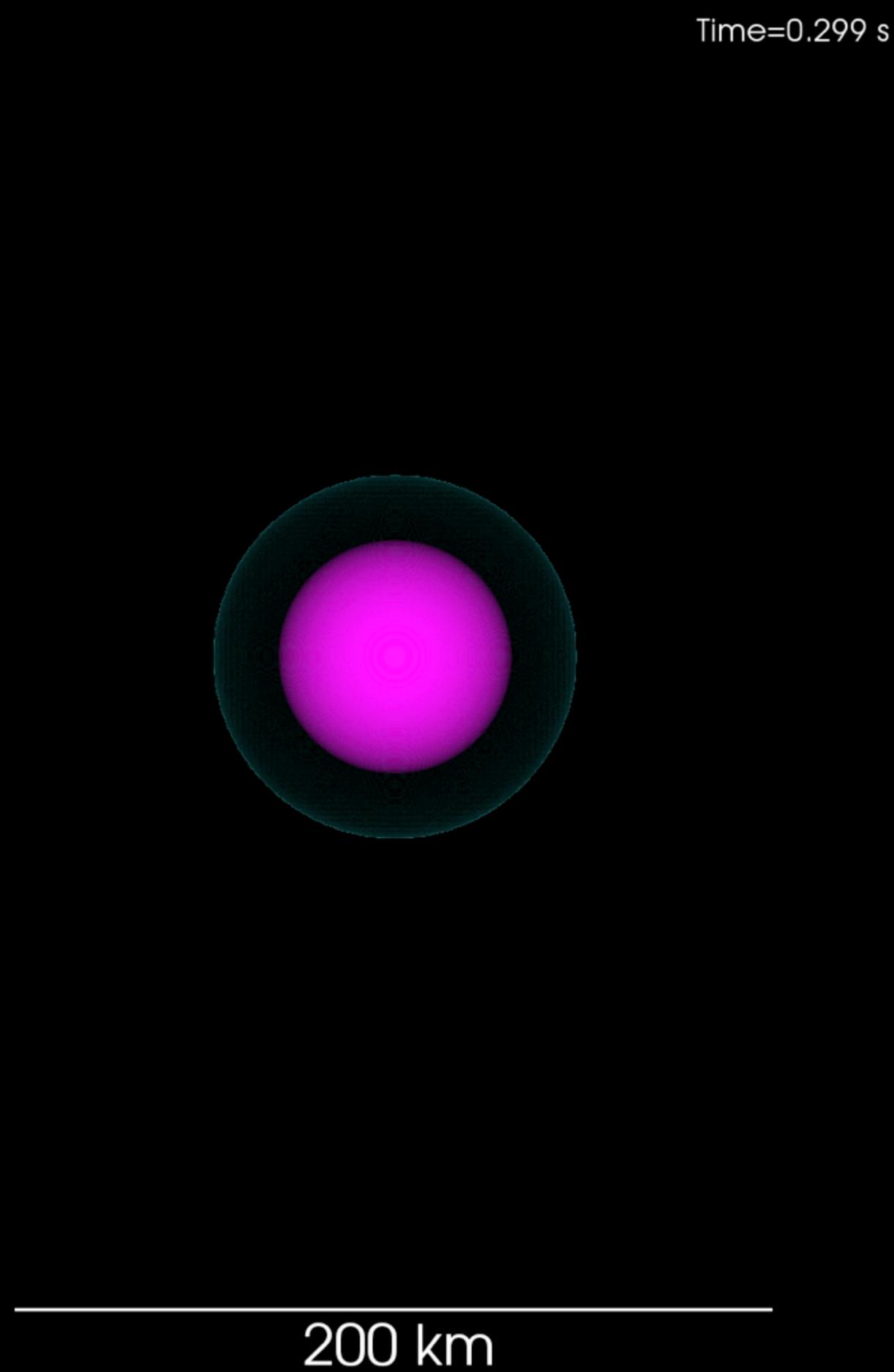
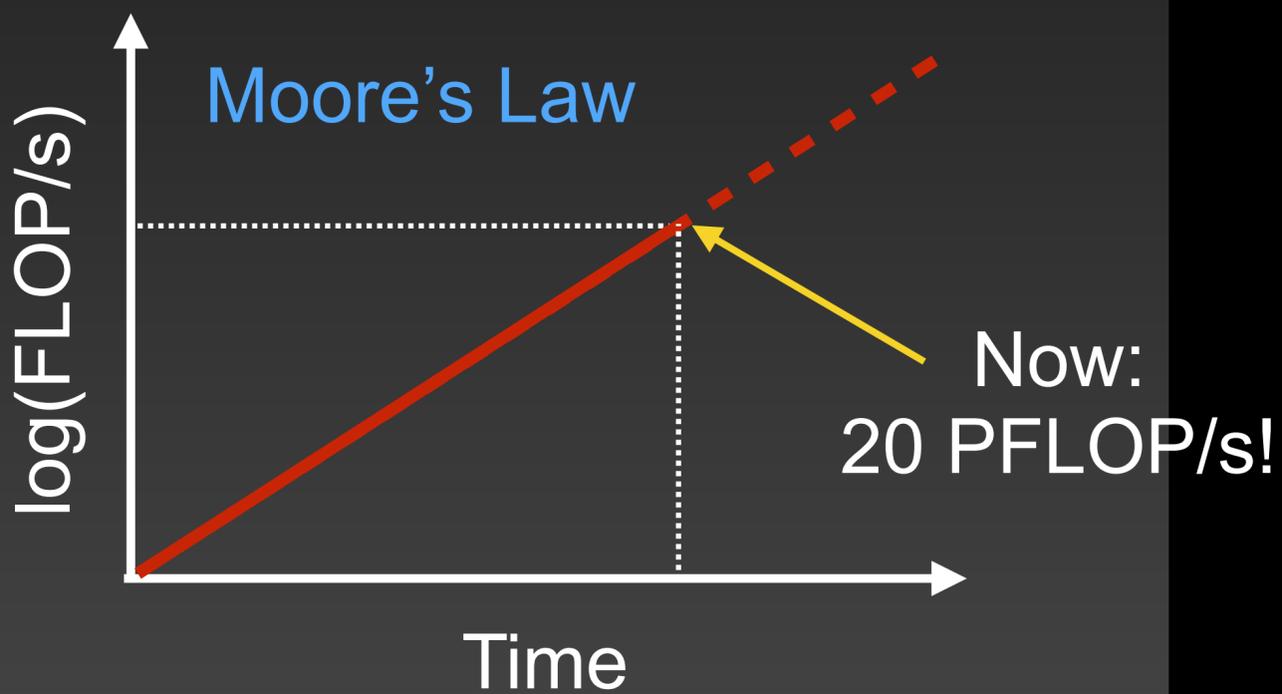
S.M. Couch



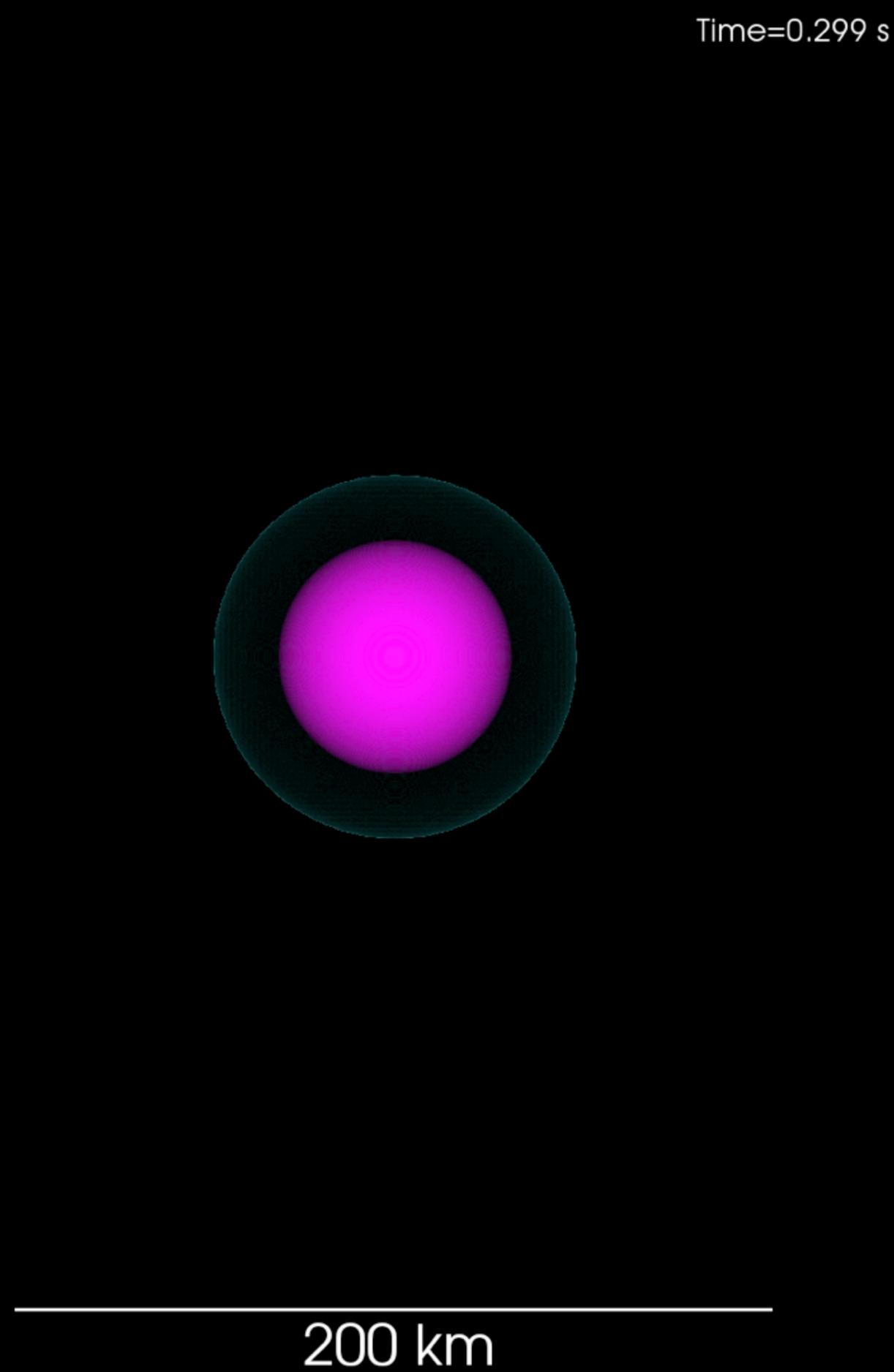
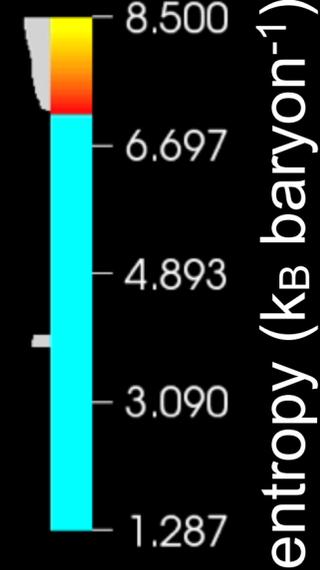
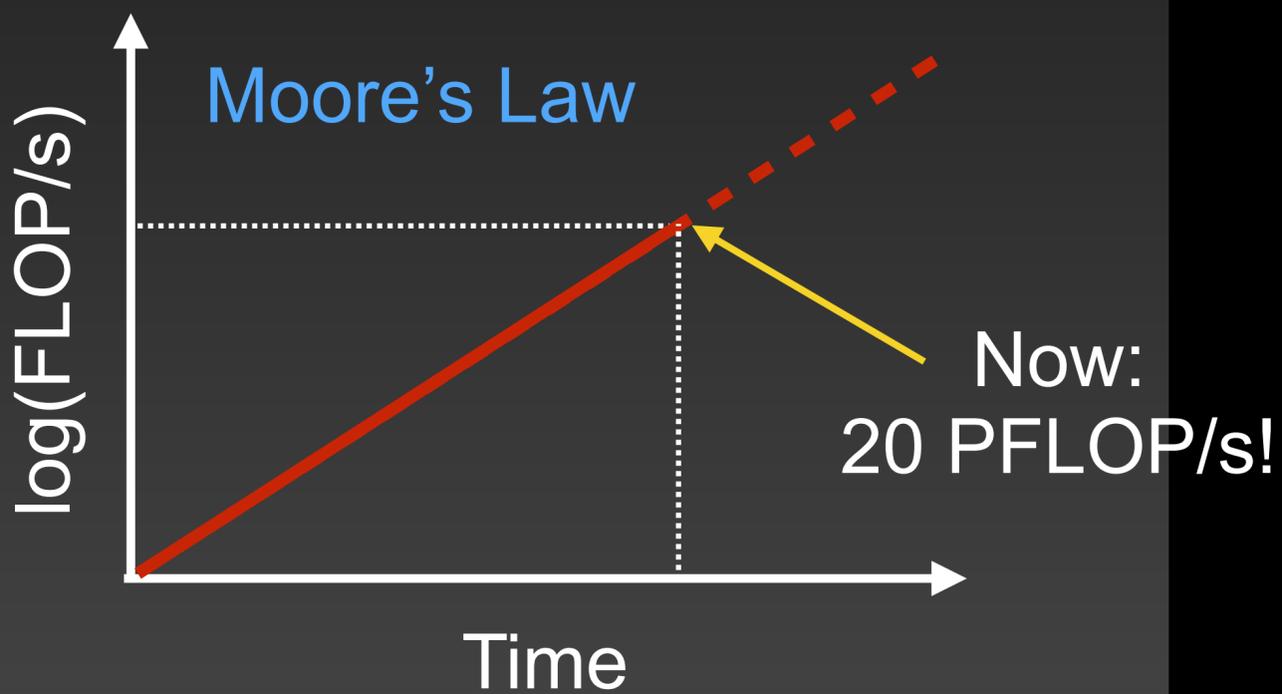
Bruenn et al. (2013,2014)

- Princeton group: no 2D explosions (Dolence et al. 2015).
- But see Skinner et al., arXiv:1512.00113

# 3D CCSN Simulations



# 3D CCSN Simulations

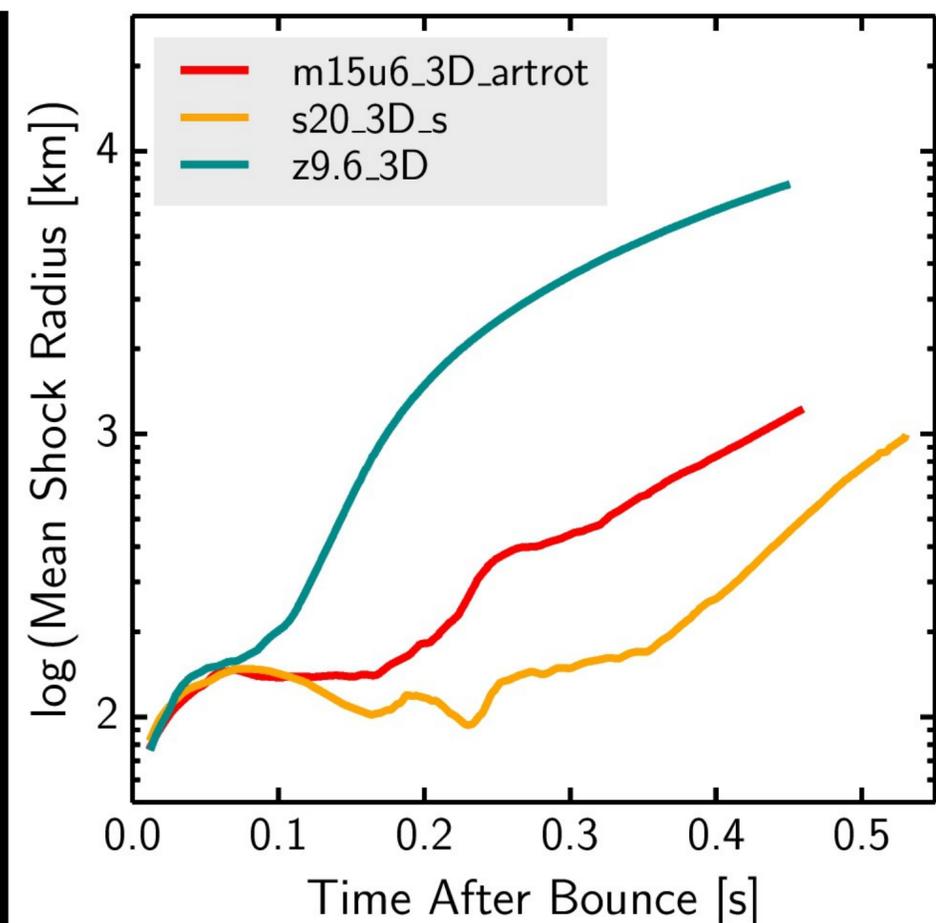
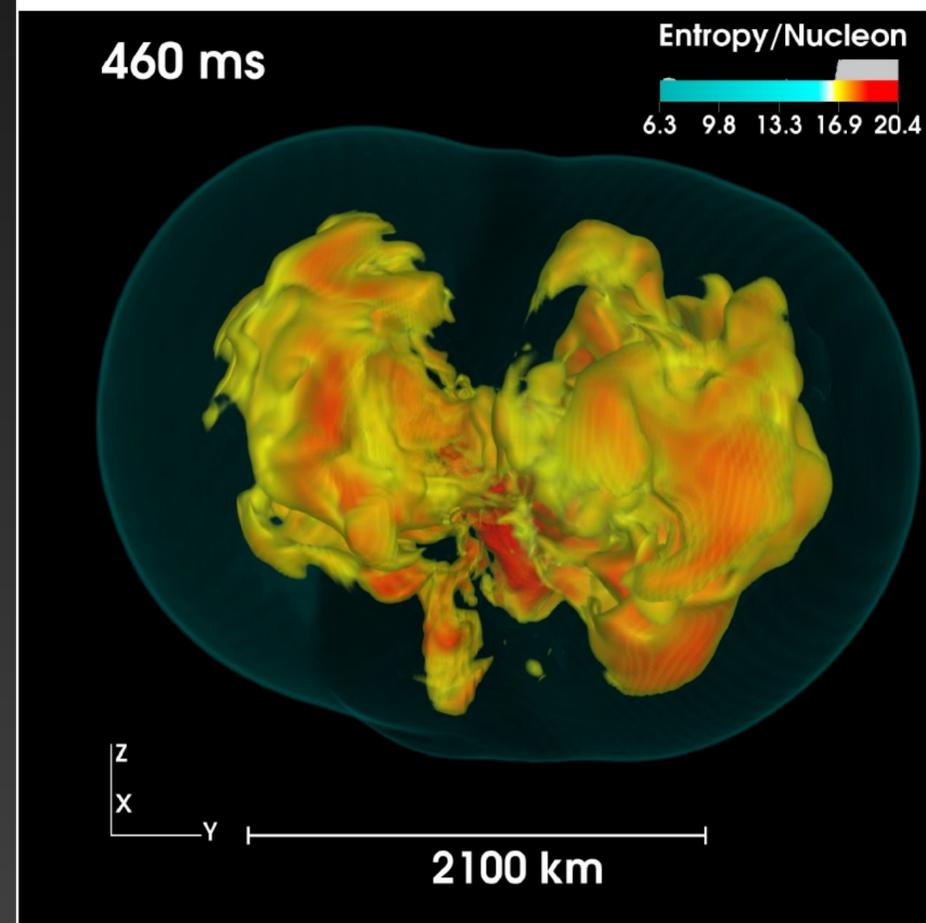
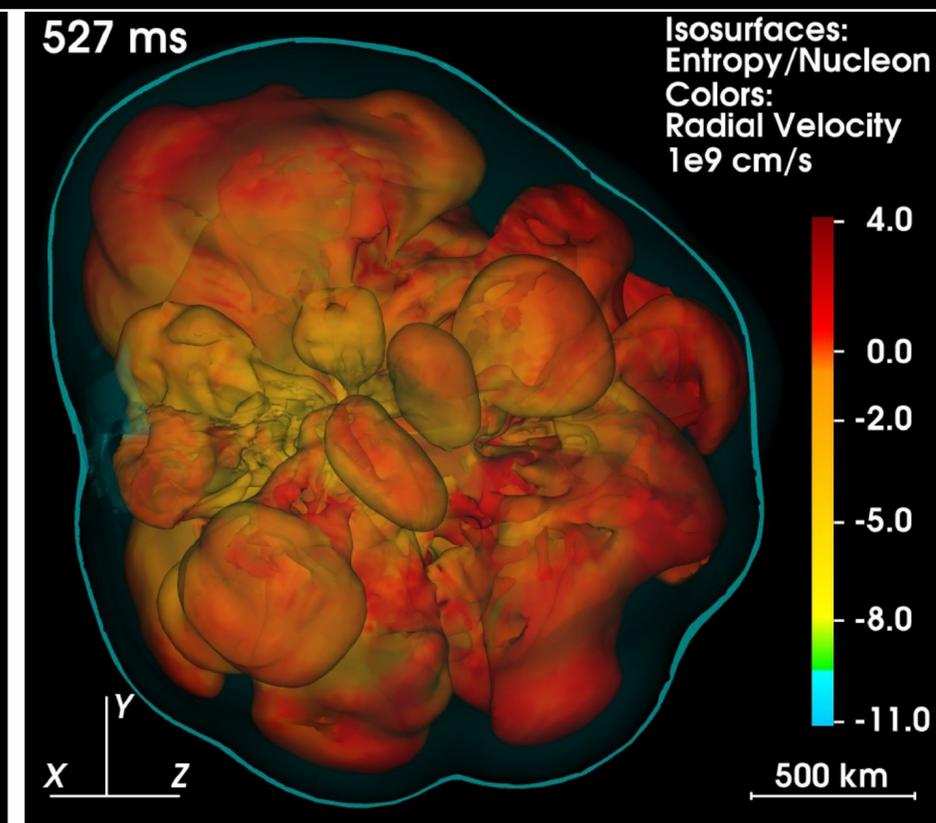
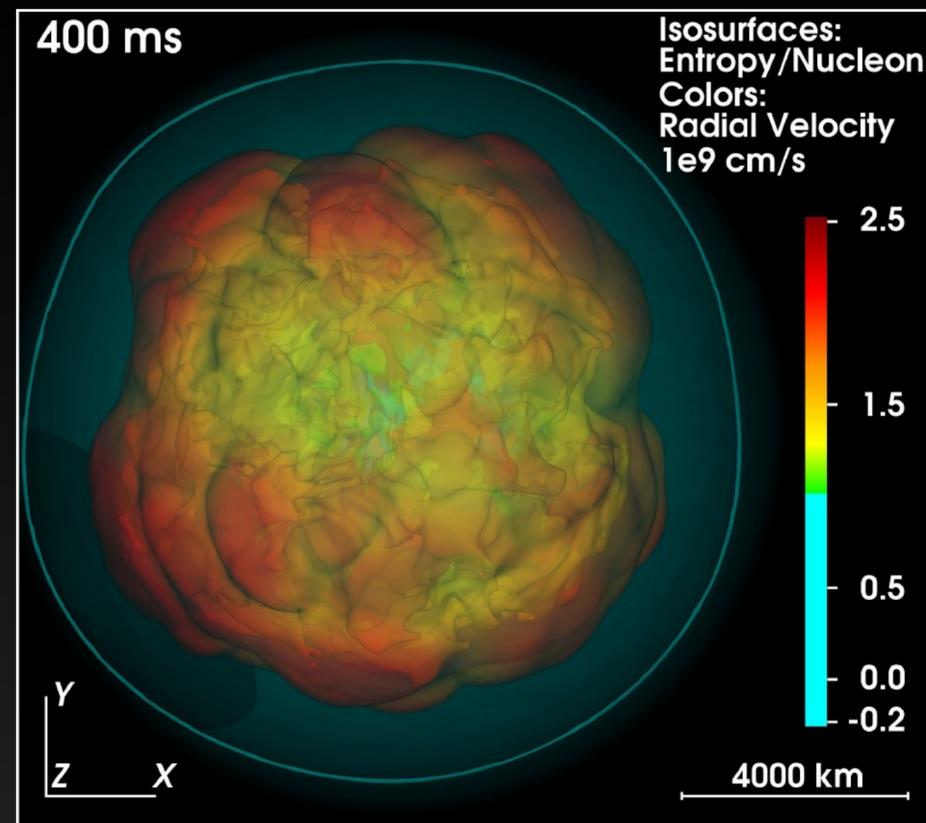


# 3D with Full Nu Transport

Janka, Melson, & Summa (2016)

3D explosions required:

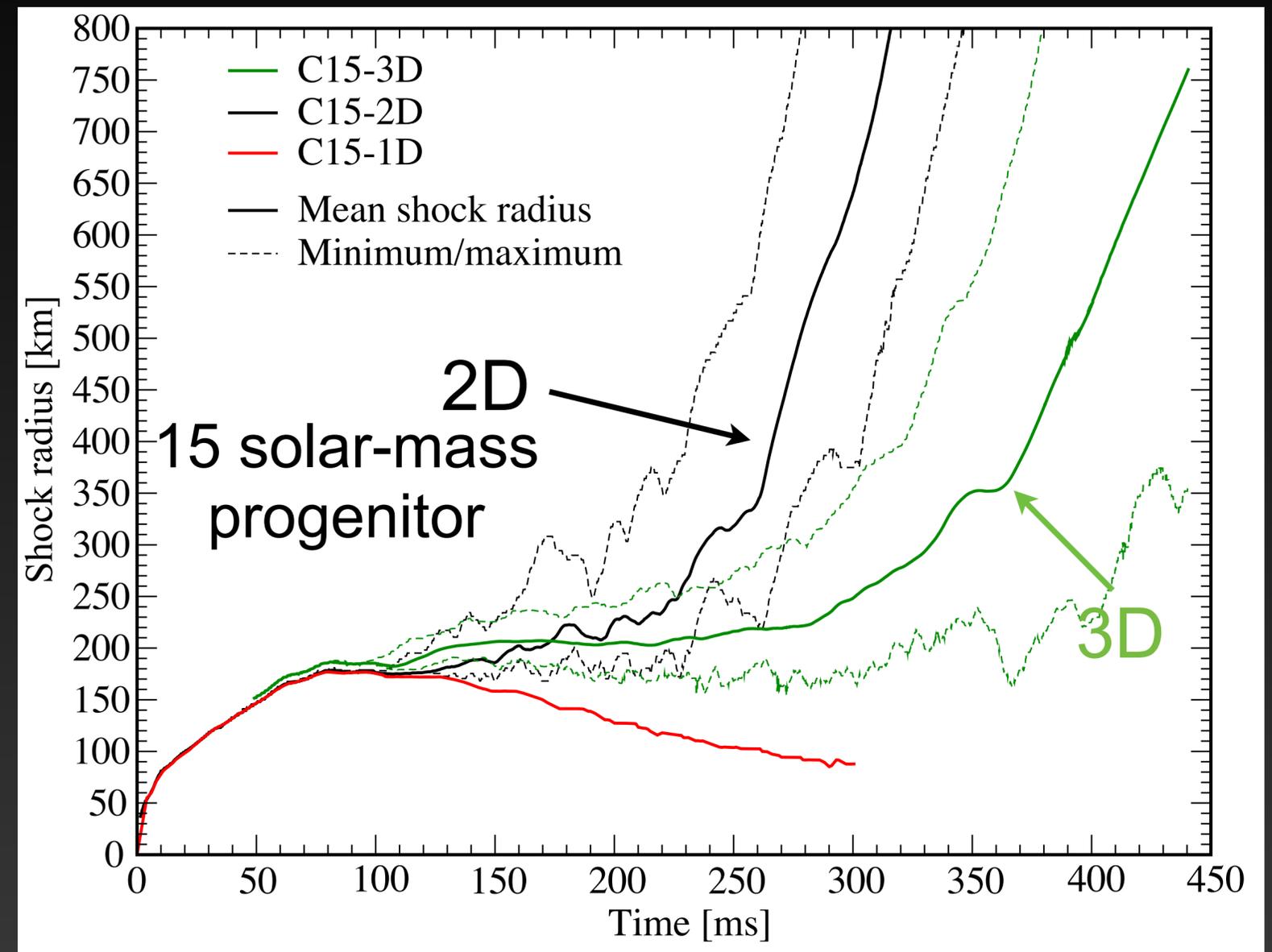
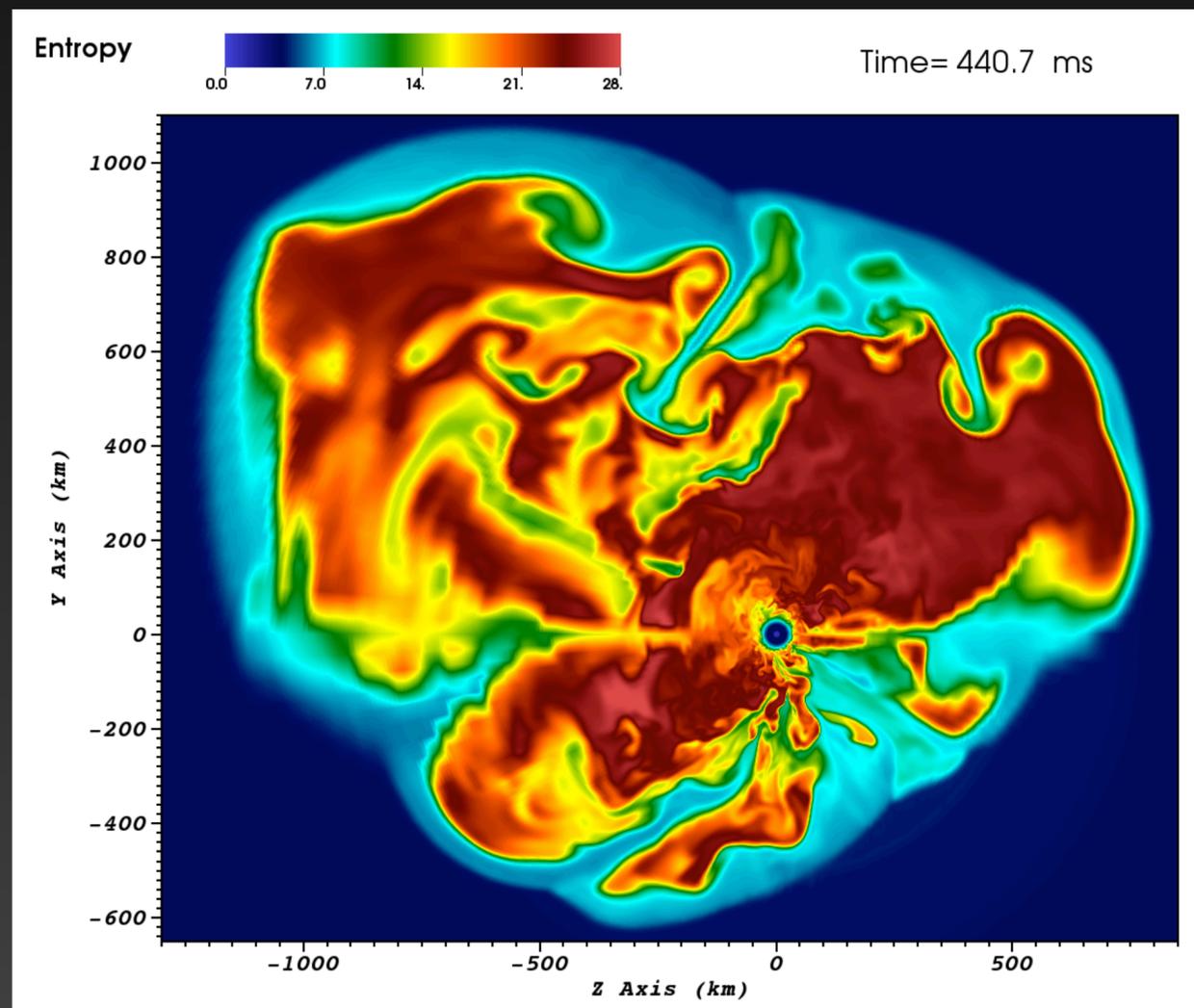
- low-mass progenitor
- (unphysically) large strangeness correction
- rapid rotation



# 3D with Full Nu Transport

Mezzacappa et al. (2015), Lentz et al. (2015)

## Results from Oak Ridge Ridge Group



3D explodes later than 2D

Only 2° resolution...

# Resolution Dependence

D. Radice, C. Ott, SMC, et al., ApJ, 820, 76

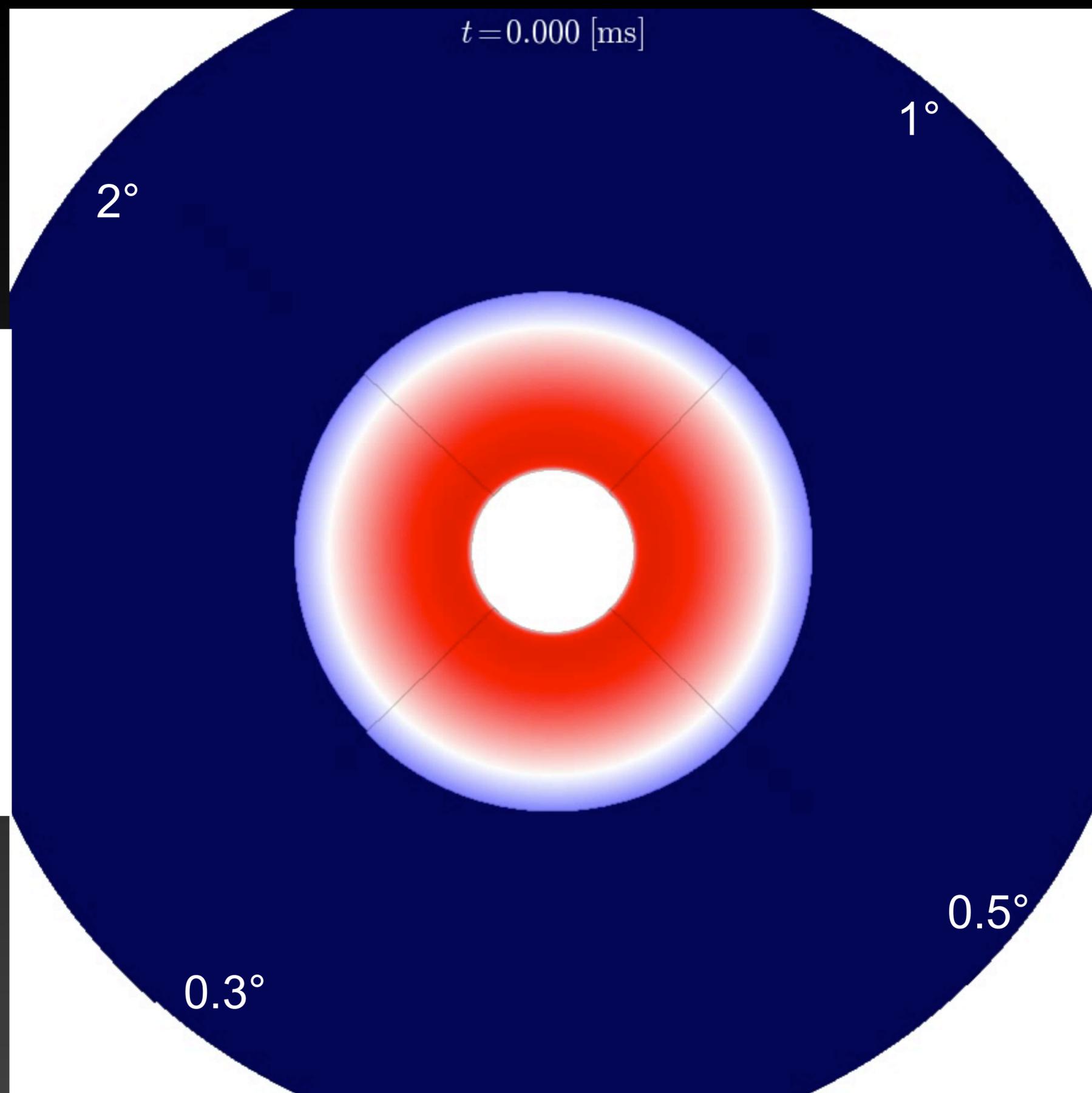
- Analytic accretion shock IC's
- Inner boundary
- Lightbulb heating/cooling
- Fixed-metric GR

3D Slices

High  
Entropy



Low  
Entropy



# Resolution Dependence

D. Radice, C. Ott, SMC, et al., ApJ, 820, 76

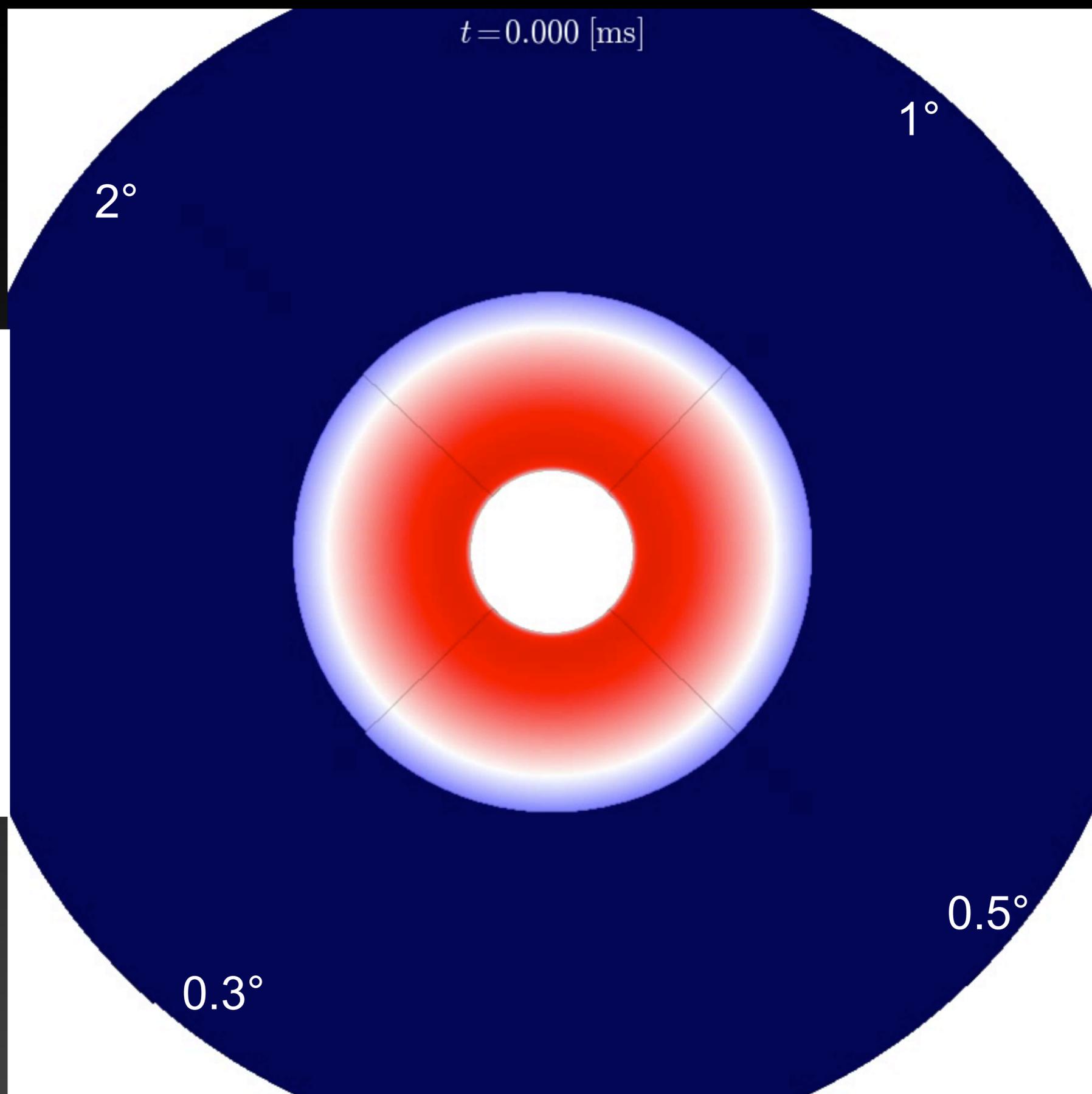
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3D Slices

High Entropy



Low Entropy



# 3(D) steps forward, 1(D) step back?

- Success of explosions in 2D may not be recovered in 3D... We must be missing physics, or getting the physics wrong...
- Possibilities:
  - Progenitor structure
  - MHD/rotation
  - Behavior of turbulence/low-resolution
  - Neutrino effects (i.e., oscillation, x-sections, sterile)
  - Equation of state
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# CCSN is an Initial Value Problem

...And we have problems with our initial values

- Stars are **not** (perfectly) **spherical**
- All stars **rotate**
- All stars have **magnetic fields**
- >50% of SN progenitors in interacting **binaries**

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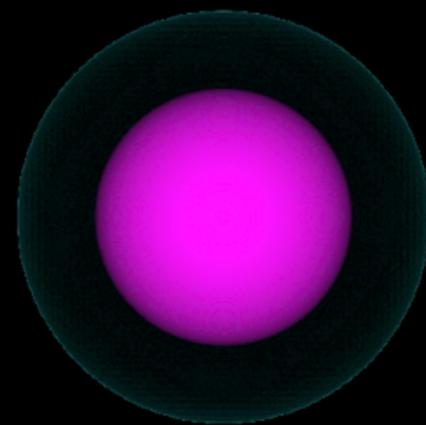
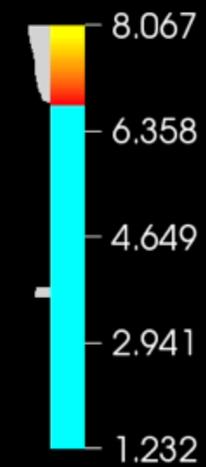
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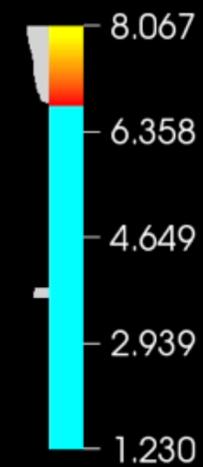
# Progenitor Asphericity in 3D

SMC & Ott (2013, 2015); SMC et al. (2015)

## Unperturbed

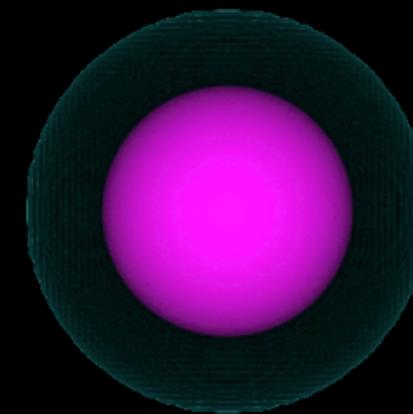


Time=0.251 s



## Perturbed

Time = 2 ms



200 km

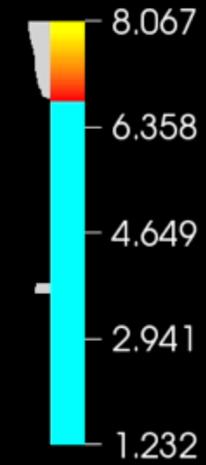
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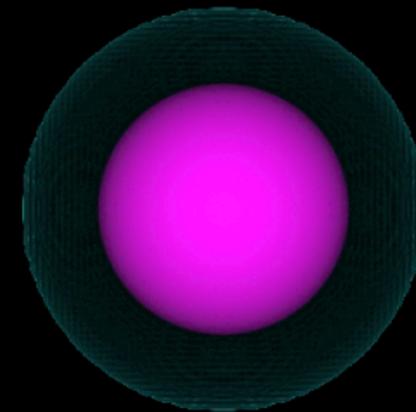
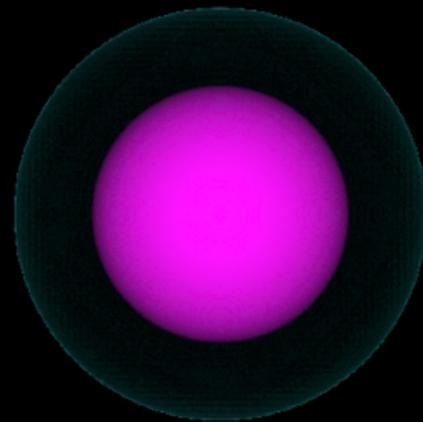
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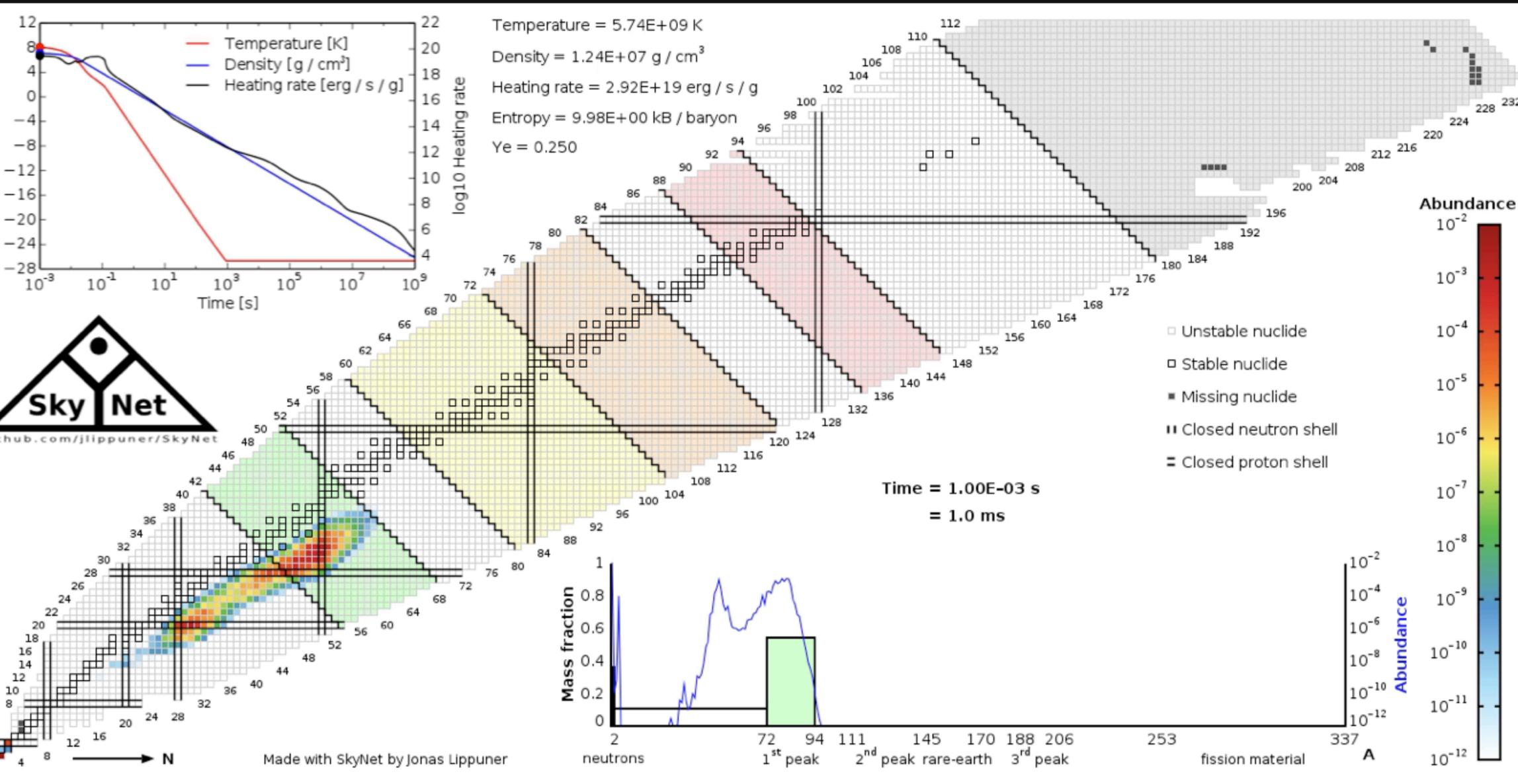


200 km

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# Connecting to Observation

GW strain  
With an explosion model:

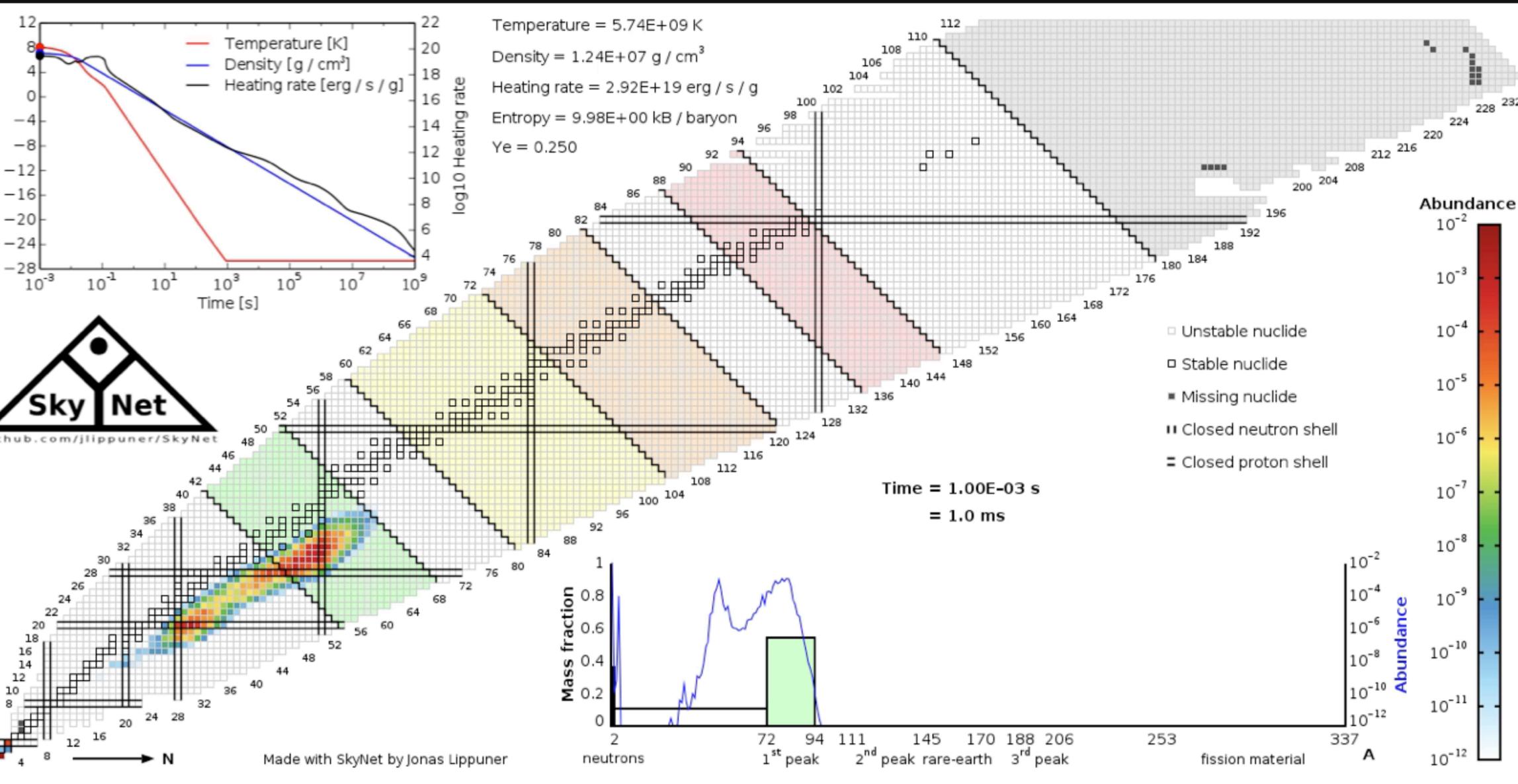


- Gravitational Waves
- Neutrinos
- NS/BH mass distributions
- Nucleosynthesis
- Light curves/spectra
- Nuclear data

J. Lippuner, L. Roberts

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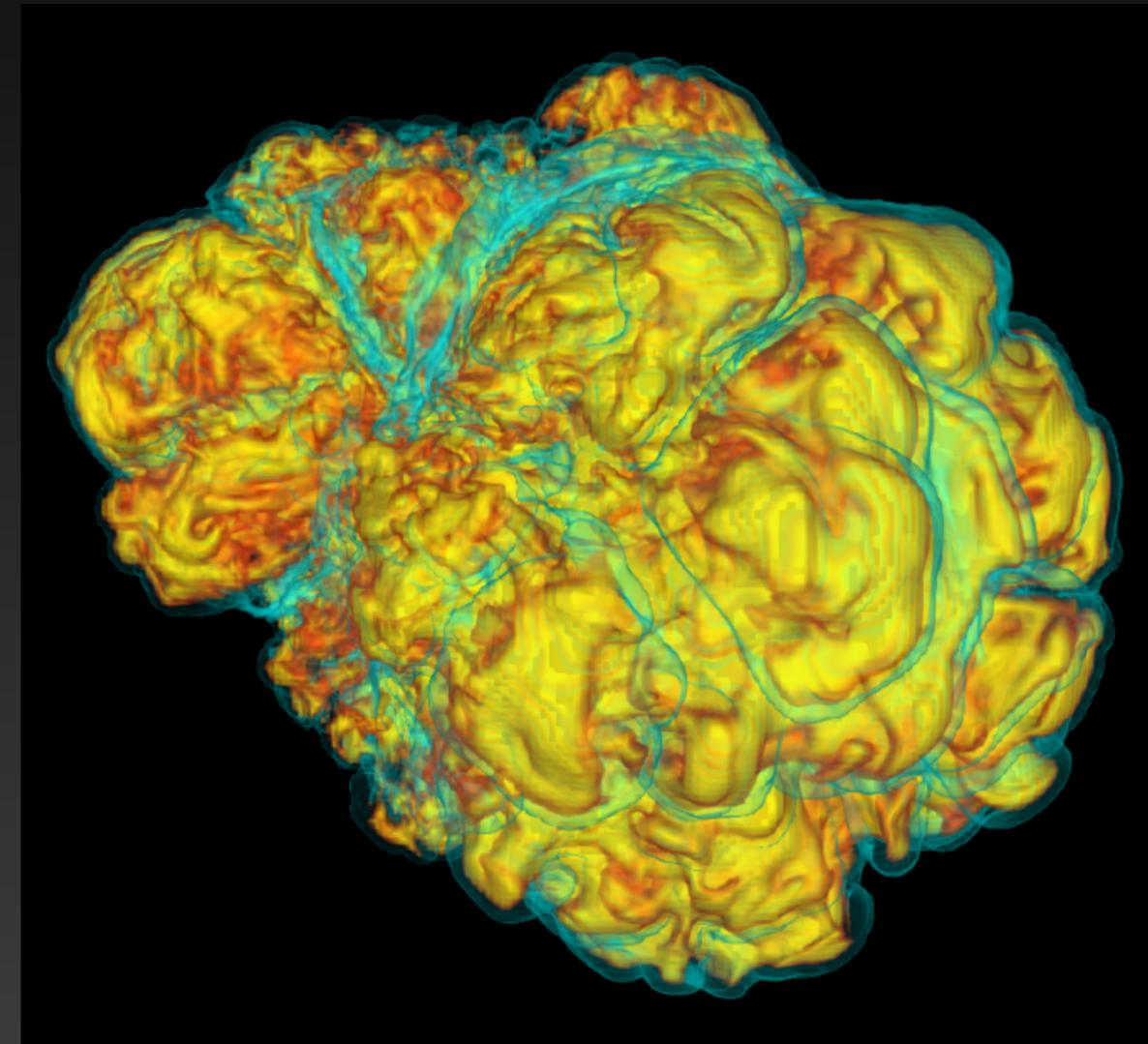


- Gravitational Waves
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J. Lippuner, L. Roberts

# Toward predictive CCSN theory

- Modern high-performance computing revolutionizing CCSN theory
- CCSN mechanism depends critically on nuclear theory input
- Understanding sensitivity to nuclear physics requires robust explosion model
- Goal of predictive CCSN theory within reach!



SMC & Ott (2013)