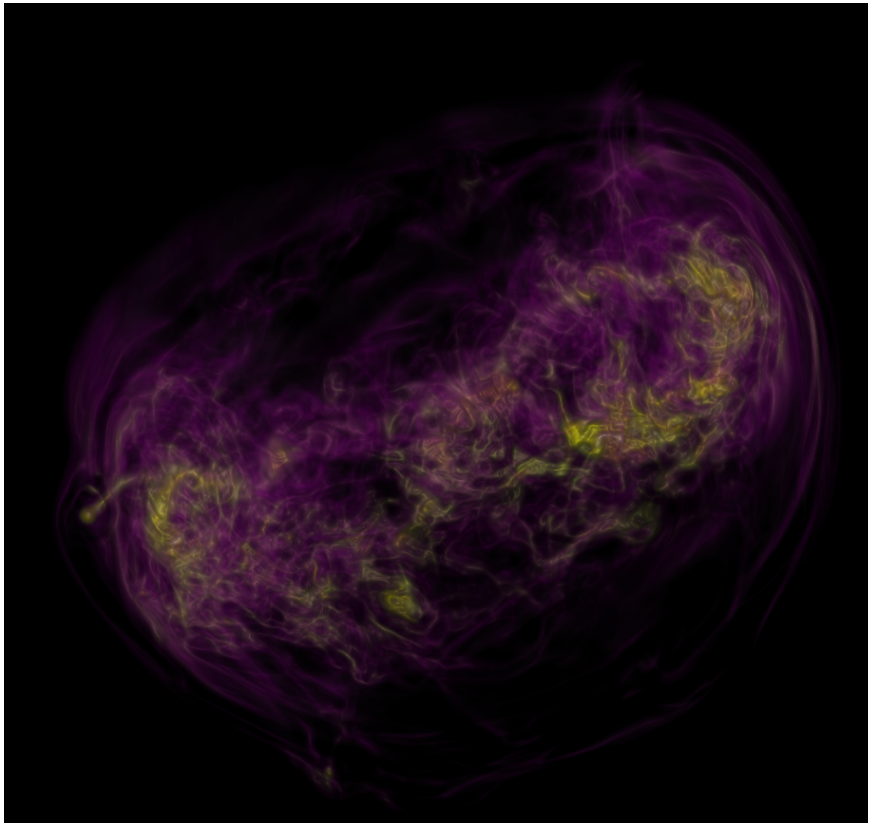
Toward End-to-End Simulation of SNe Ia

Chris Malone



Department of Astronomy and Astrophysics
UCSC
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Acknowledgments

Wetware

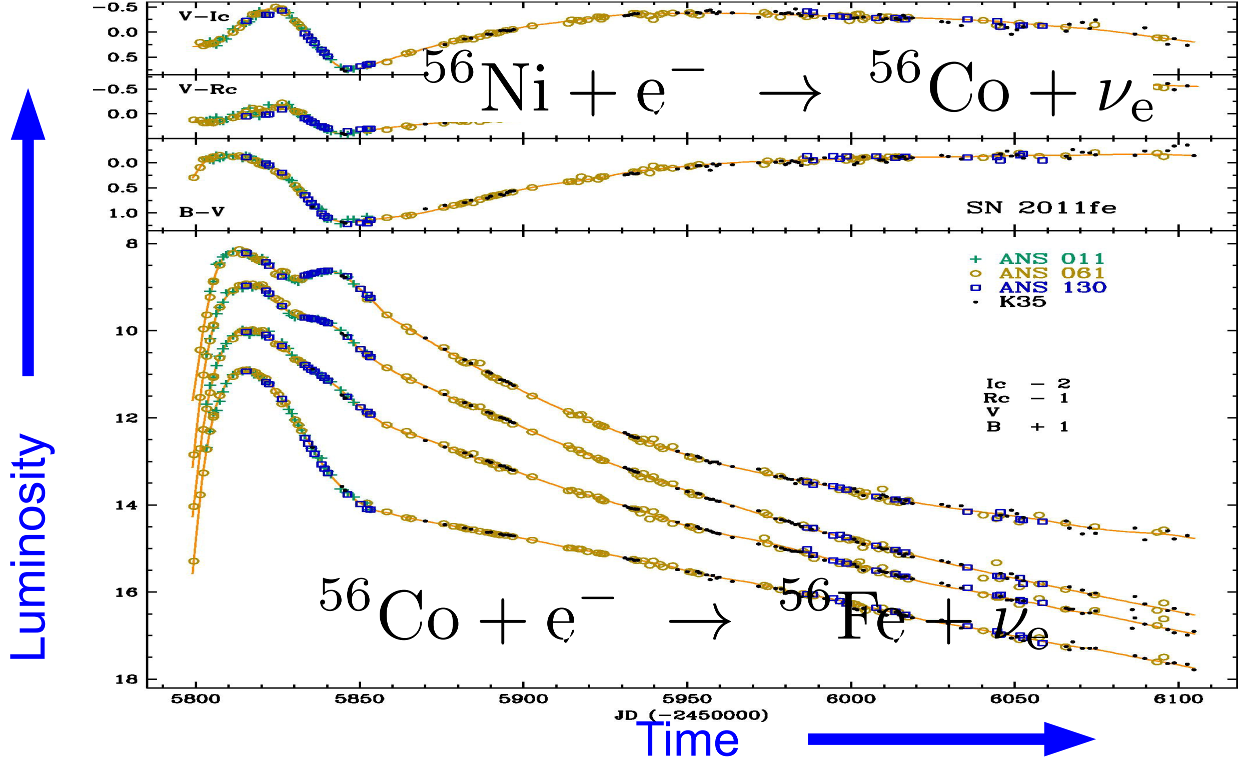
- UCSC
  - Stan Woosley
  - Shawfeng Dong
- SUNY Stony Brook
  - Mike Zingale
- LBNL
  - Ann Almgren
  - John Bell
  - Andy Nonaka

Hardware

- NERSC
  - Hopper
- OLCF
  - Jaguar
  - Titan
- NCSA
  - Blue Waters

What is a SN Ia?

- Transient event visible for months to years
- “I” means no significant Hydrogen
- “a” means strong Silicon lines



$$^{56}\mathrm{Ni} + \mathrm{e}^- \rightarrow {}^{56}\mathrm{Co} + \nu_\mathrm{e}$$

$$^{56}\mathrm{Co} + \mathrm{e}^- \rightarrow {}^{56}\mathrm{Fe} + \nu_\mathrm{e}$$

SN2011fe

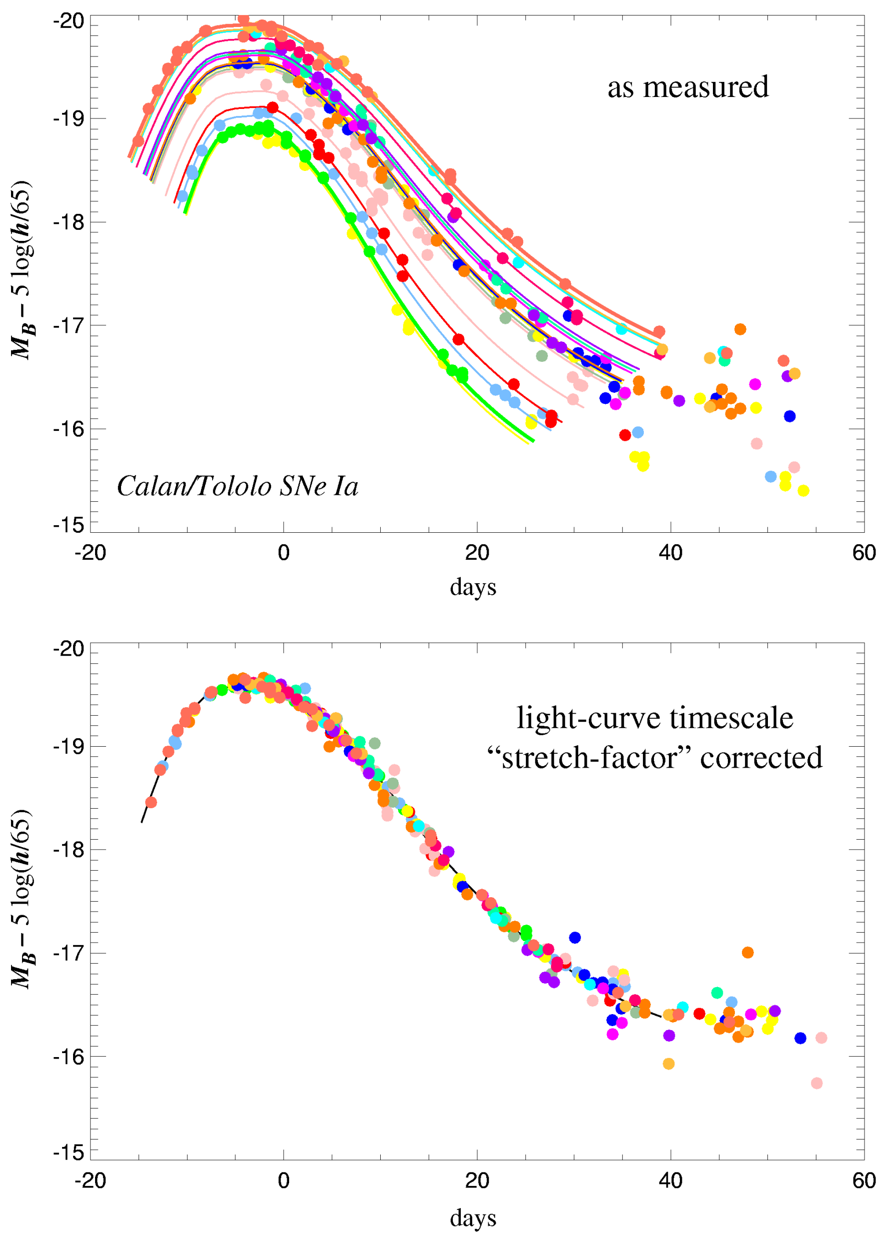
Munari+
2013

Standard(izable) Candles

- "Broader is brighter" – Phillips relation
- SN lightcurve width related to intrinsic brightness
- Allows for distance measure

2011 Nobel Prize in Physics: Perlmutter, Schmidt, and Riess

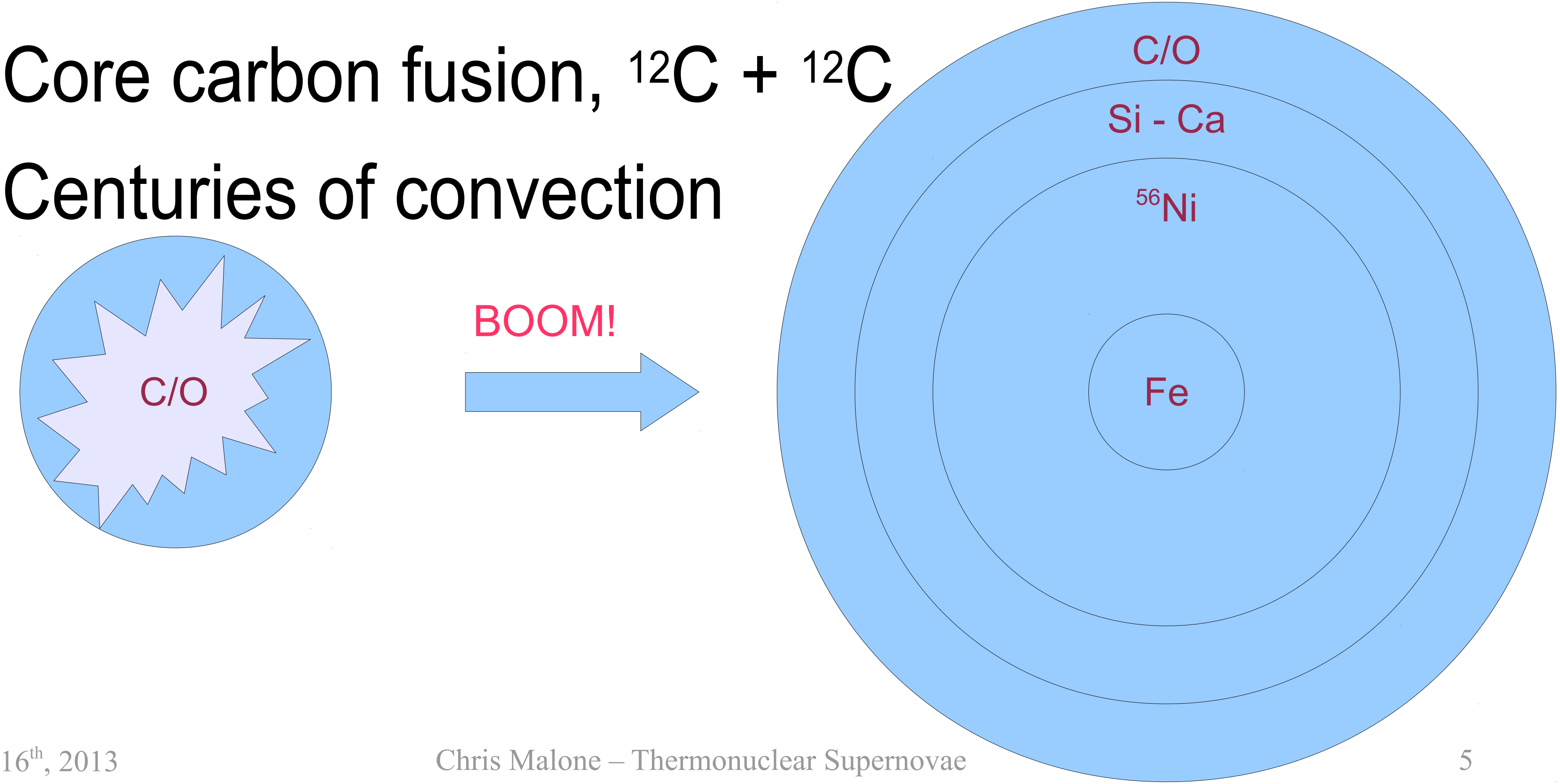
"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae."



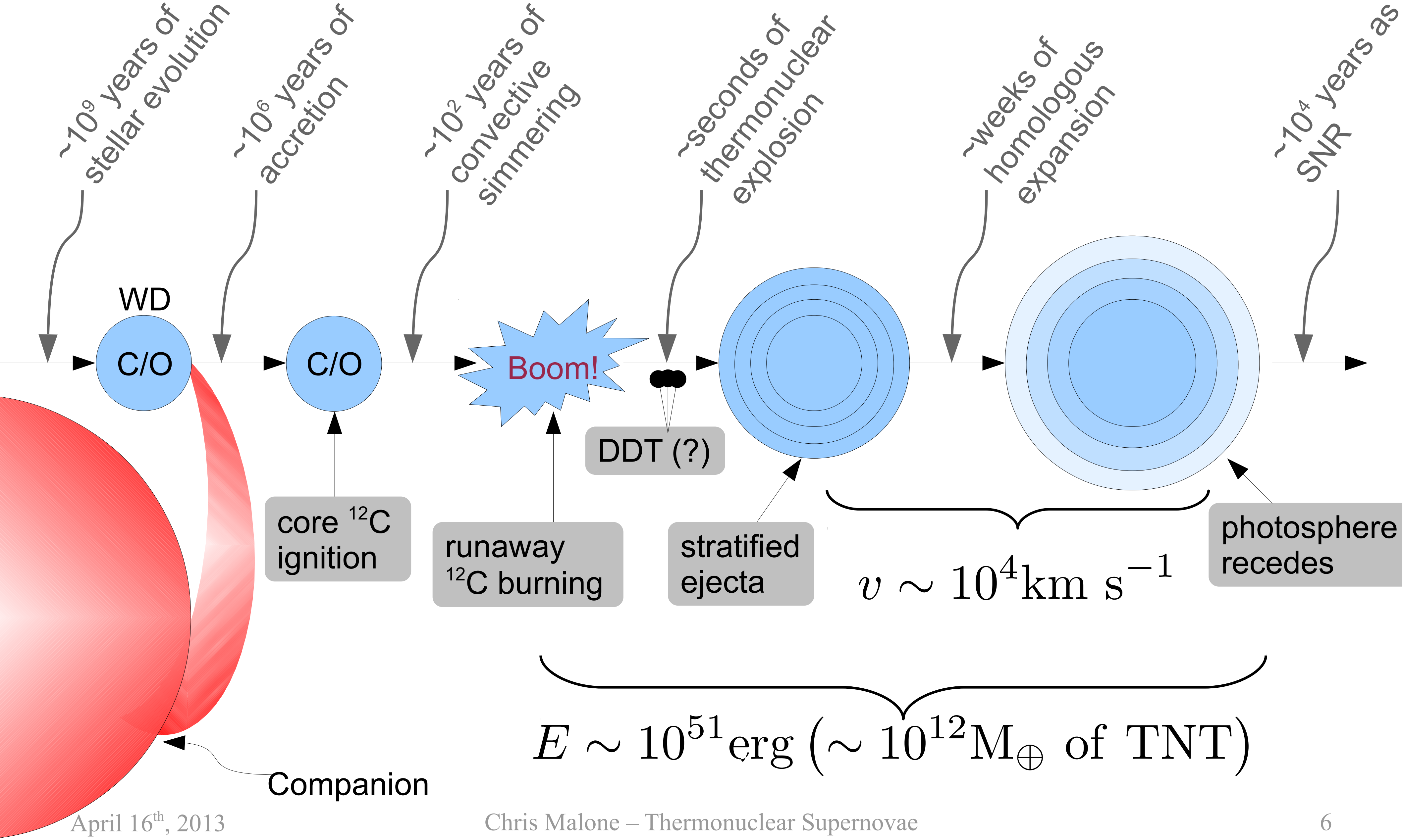
Kim, *et al.* (1997)

Single Degenerate Model

- C/O WD + companion
- WD approaches Chandrasekhar mass $(\sim 1.4 M_\odot)$
- Core carbon fusion, $^{12}C + ^{12}C$
- Centuries of convection



Single Degenerate Model



~10^9 years of stellar evolution

~10^6 years of accretion

~10^2 years of convective simmering

~seconds of thermonuclear explosion

~weeks of homologous expansion

~10^4 years as SNR

WD

C/O

C/O

Boom!

DDT (?)

core ^{12}C ignition

runaway ^{12}C burning

stratified ejecta

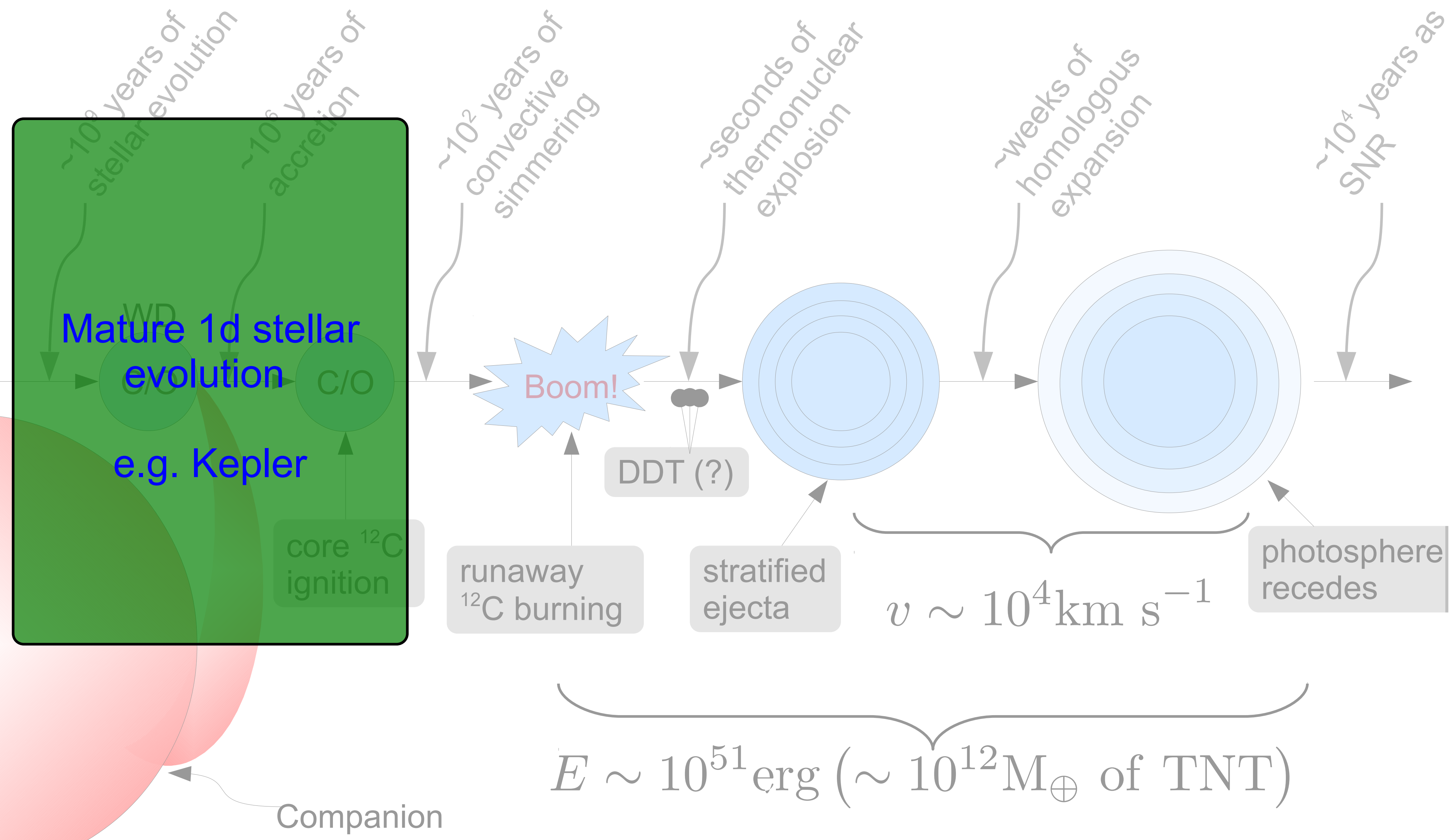
photosphere recedes

$$v \sim 10^4 \mathrm{km\ s}^{-1}$$

$$E \sim 10^{51} \mathrm{erg}\ (\sim 10^{12} \mathrm{M}_\oplus \text{ of TNT})$$

Companion

Single Degenerate Model



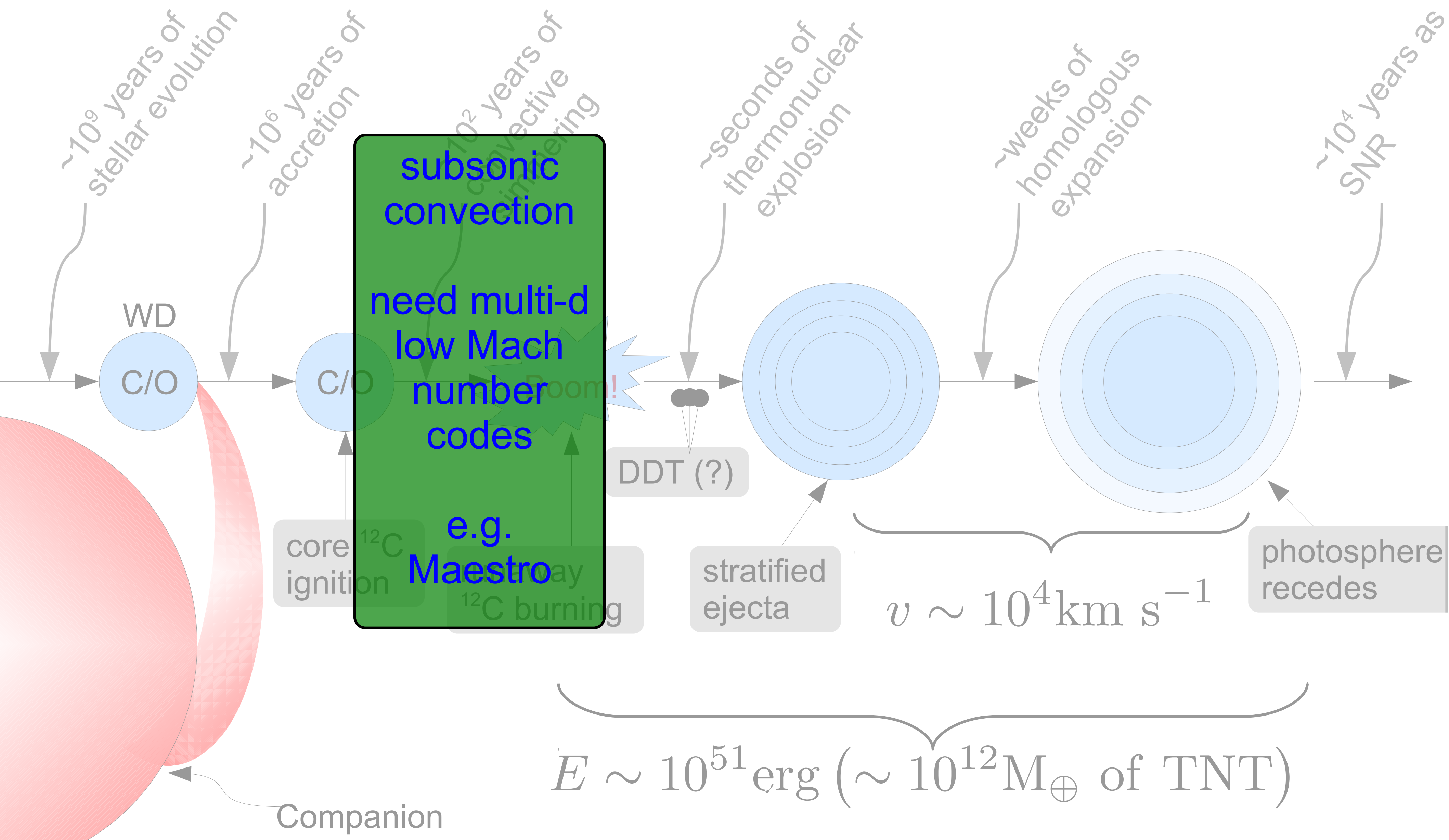
Mature 1d stellar evolution

e.g. Kepler

$$v \sim 10^4 \mathrm{km\ s}^{-1}$$

$$E \sim 10^{51}\mathrm{erg}\ (\sim 10^{12} \mathrm{M}_\oplus\ \text{of TNT})$$

Single Degenerate Model

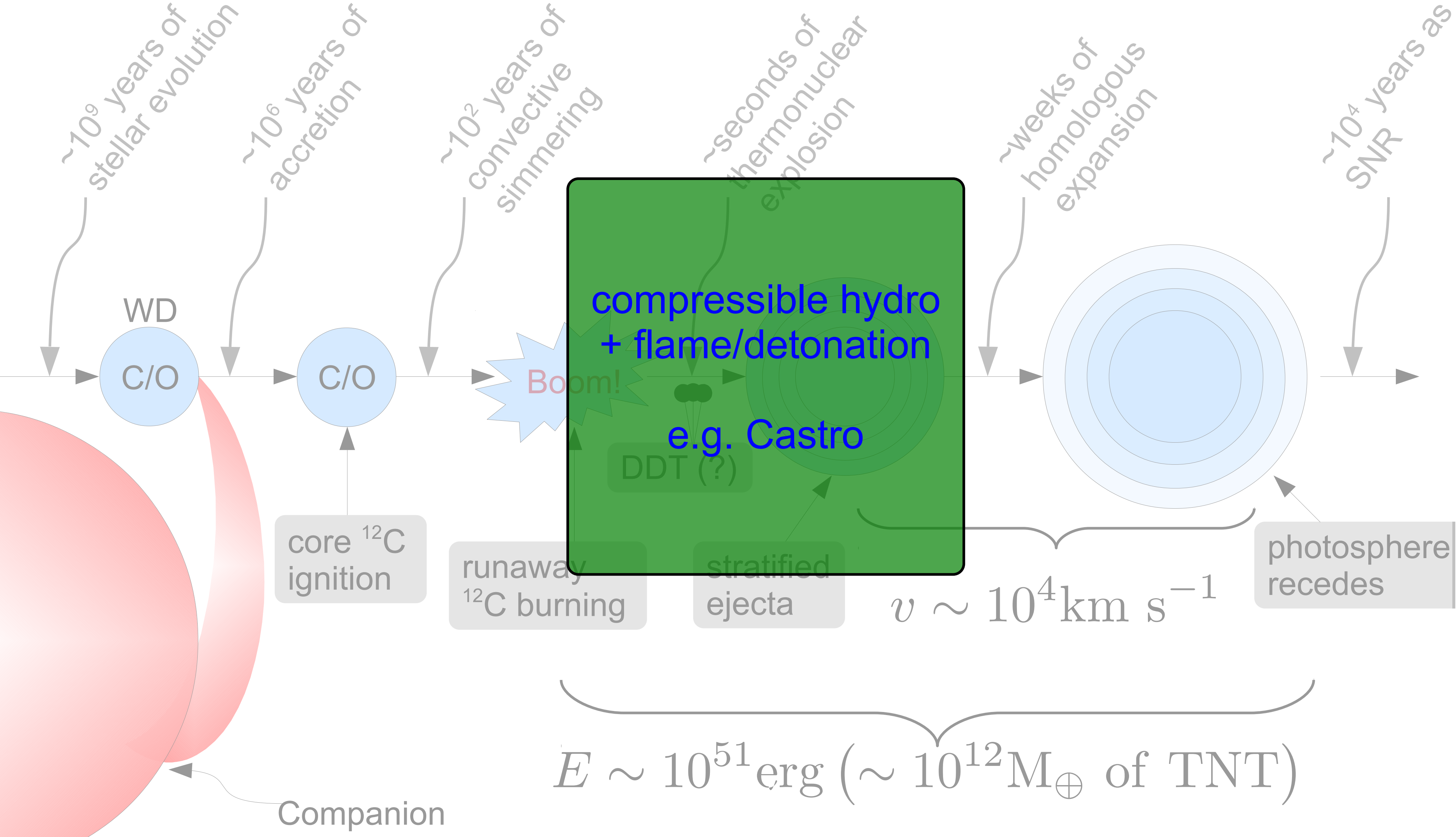


subsonic convection

need multi-d low Mach number codes

e.g. Maestro

Single Degenerate Model



~10⁹ years of stellar evolution

~10⁶ years of accretion

~10² years of convective simmering

~seconds of thermonuclear explosion

~weeks of homologous expansion

~10⁴ years as SNR

WD

C/O

C/O

Boom!

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photosphere recedes

$v \sim 10^4 \mathrm{km\ s}^{-1}$

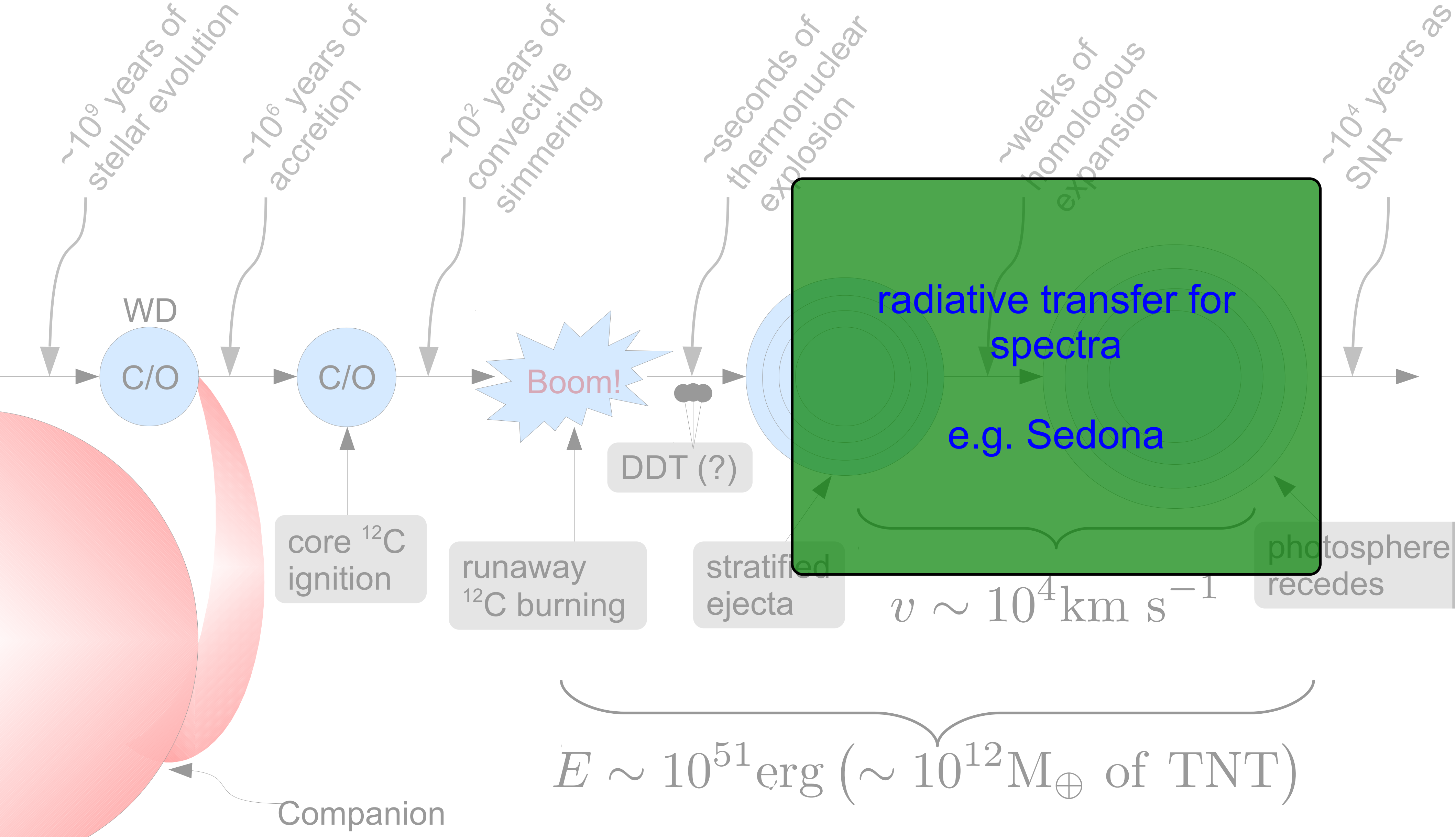
$E \sim 10^{51}\mathrm{erg}\ (\sim 10^{12} \mathrm{M}_\oplus \text{ of TNT})$

Companion

compressible hydro
+ flame/detonation

e.g. Castro

Single Degenerate Model



~10^9 years of stellar evolution

~10^6 years of accretion

~10^2 years of convective simmering

~seconds of thermonuclear explosion

~weeks of homologous expansion

~10^4 years as SNR

WD

C/O

C/O

Boom!

core ^{12}C ignition

runaway ^{12}C burning

DDT (?)

stratified ejecta

photosphere recedes

Companion

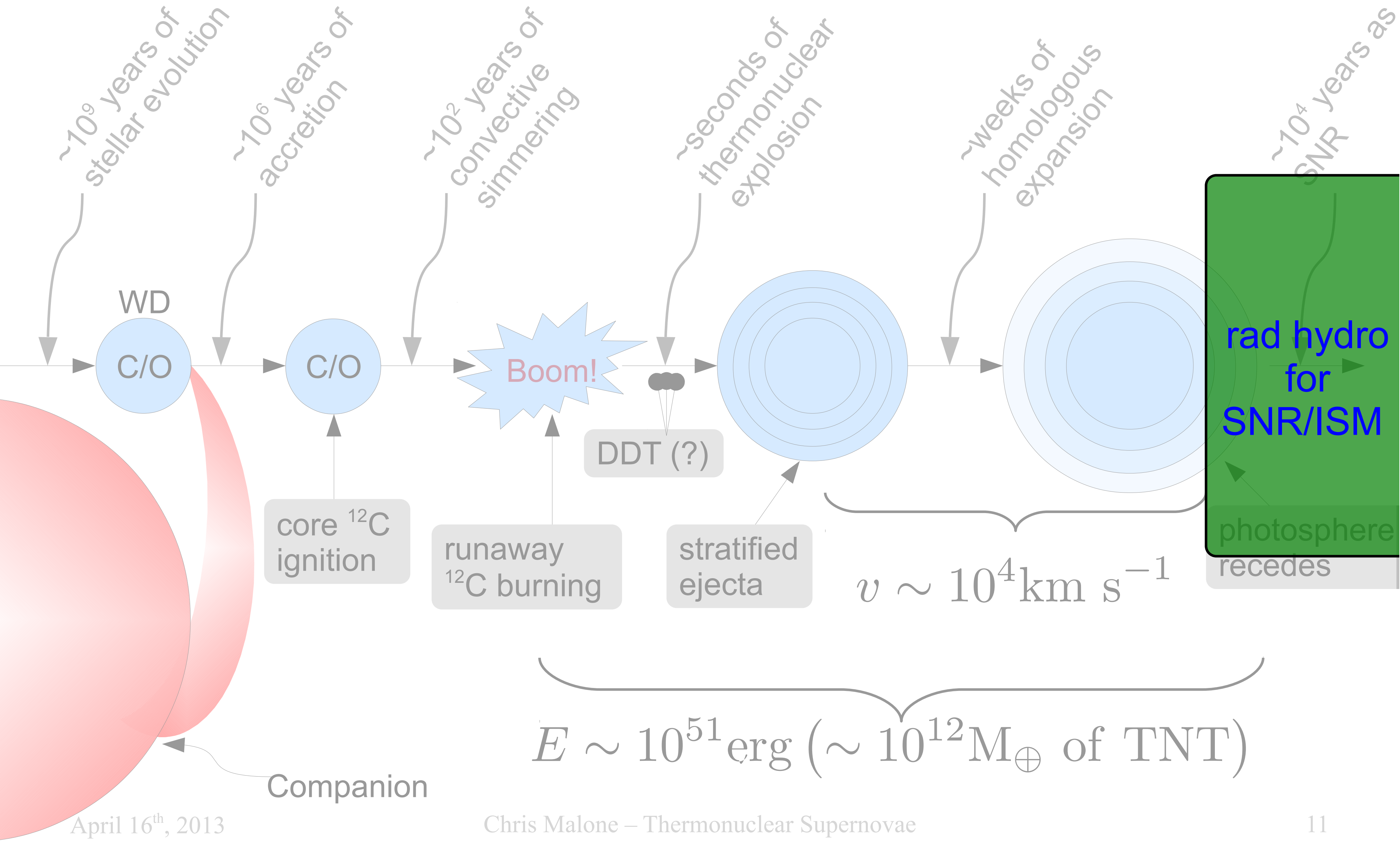
$v \sim 10^4 \mathrm{km\ s}^{-1}$

$E \sim 10^{51} \mathrm{erg}\ (\sim 10^{12} M_\oplus \text{ of TNT})$

radiative transfer for spectra

e.g. Sedona

Single Degenerate Model



~10^9 years of stellar evolution

~10^6 years of accretion

~10^2 years of convective simmering

~seconds of thermonuclear explosion

~weeks of homologous expansion

~10^4 years as SNR

WD

C/O

C/O

Boom!

core ^{12}C ignition

runaway ^{12}C burning

DDT (?)

stratified ejecta

rad hydro for SNR/ISM

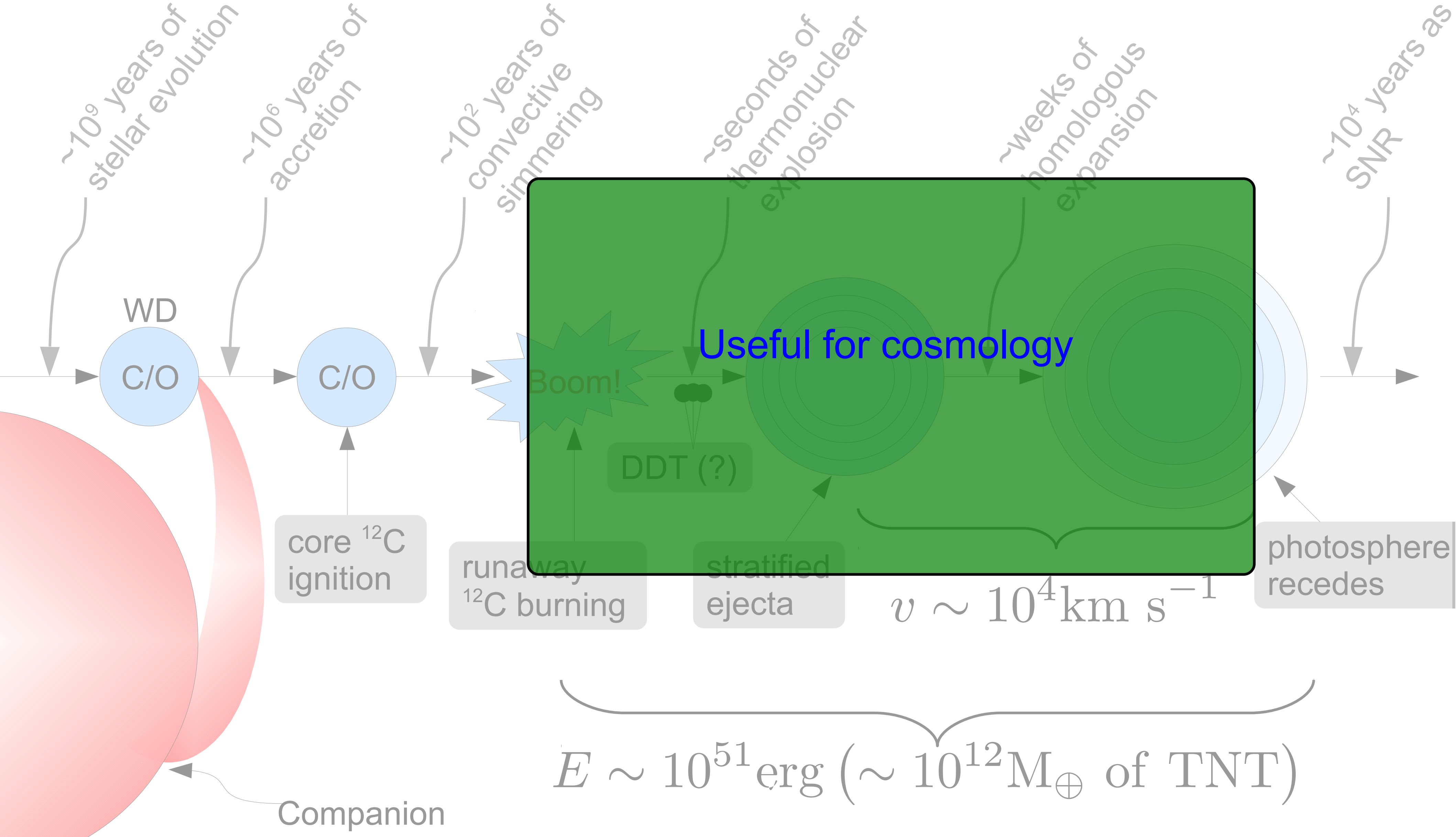
photosphere recedes

$v \sim 10^4 \mathrm{km\ s}^{-1}$

$E \sim 10^{51} \mathrm{erg}\ (\sim 10^{12} \mathrm{M}_\oplus \text{ of TNT})$

Companion

Single Degenerate Model



$$v \sim 10^4 \mathrm{km\ s}^{-1}$$

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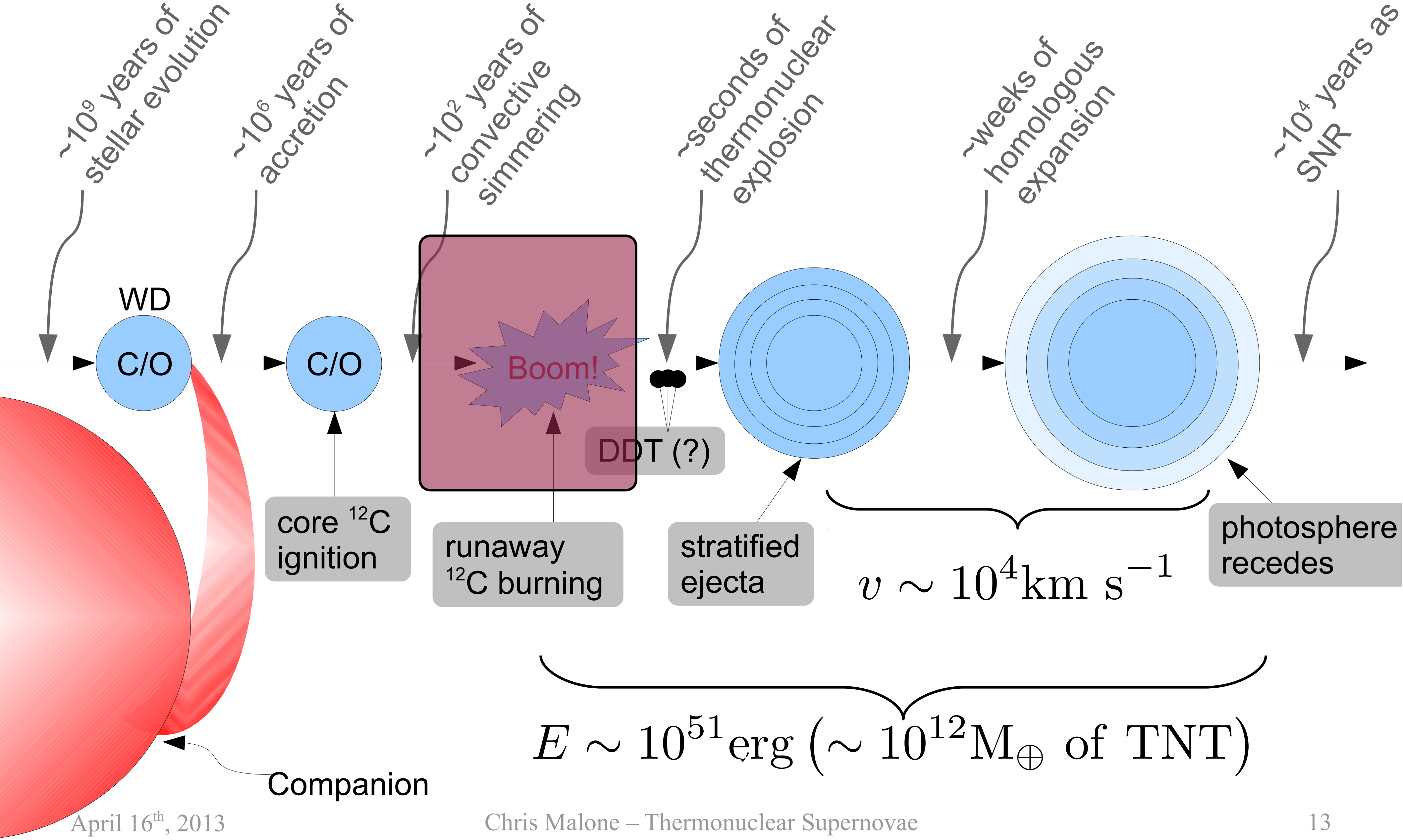
Single Degenerate Model



$$v \sim 10^4 \mathrm{km\ s}^{-1}$$

$$E \sim 10^{51}\mathrm{erg}\ (\sim 10^{12} \mathrm{M}_\oplus\ \mathrm{of\ TNT})$$

Centuries of Simmering

- Compression heats core

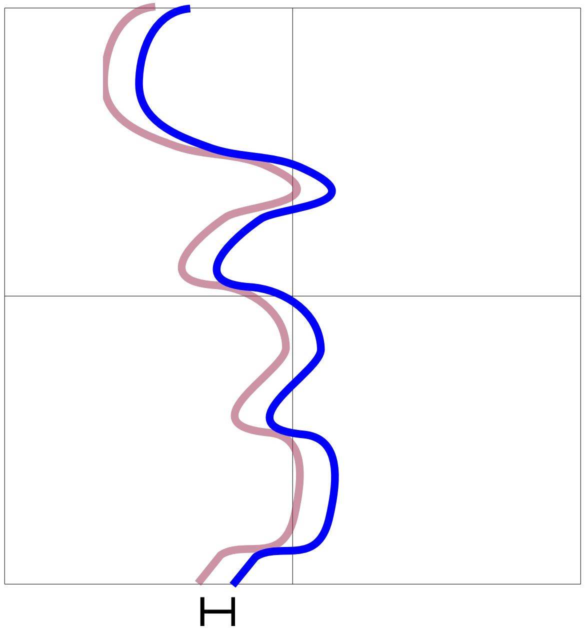
$$\rho_c \sim 2\times 10^9 \text{ g cm}^{-3} \qquad T_c \sim 4 \times 10^8 \text{ K}$$

- Core carbon burning drives low Mach number convection $(M \sim 0.01)$

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{20}\mathrm{Ne} + \alpha$$

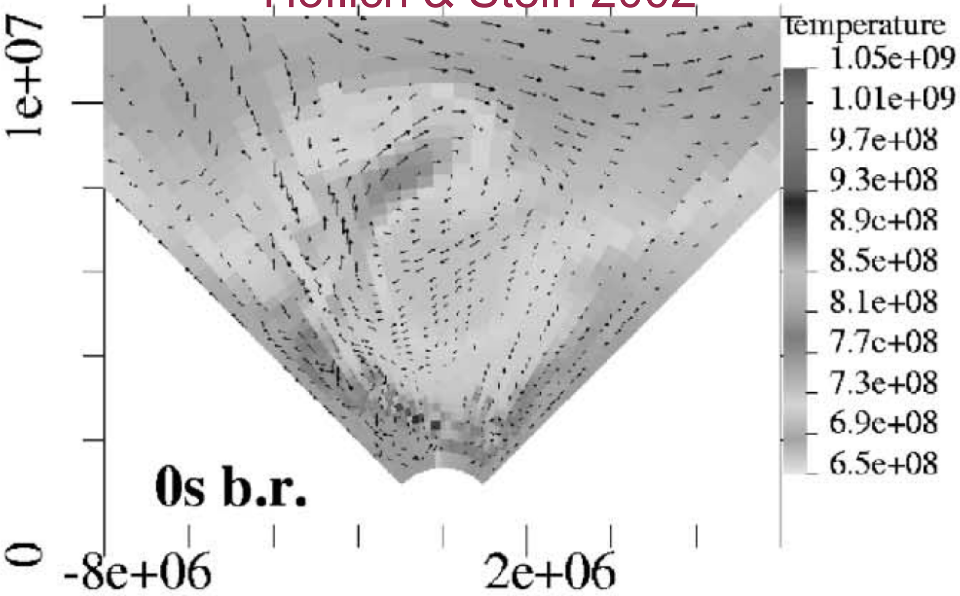
- Efficient simulation requires special care because of CFL condition

$$\Delta t_{\mathrm{CFL}} \lesssim \frac{\Delta x}{U_{c,\mathrm{max}}} \xrightarrow{(M \ll 1)} \frac{\Delta x}{c_s}$$



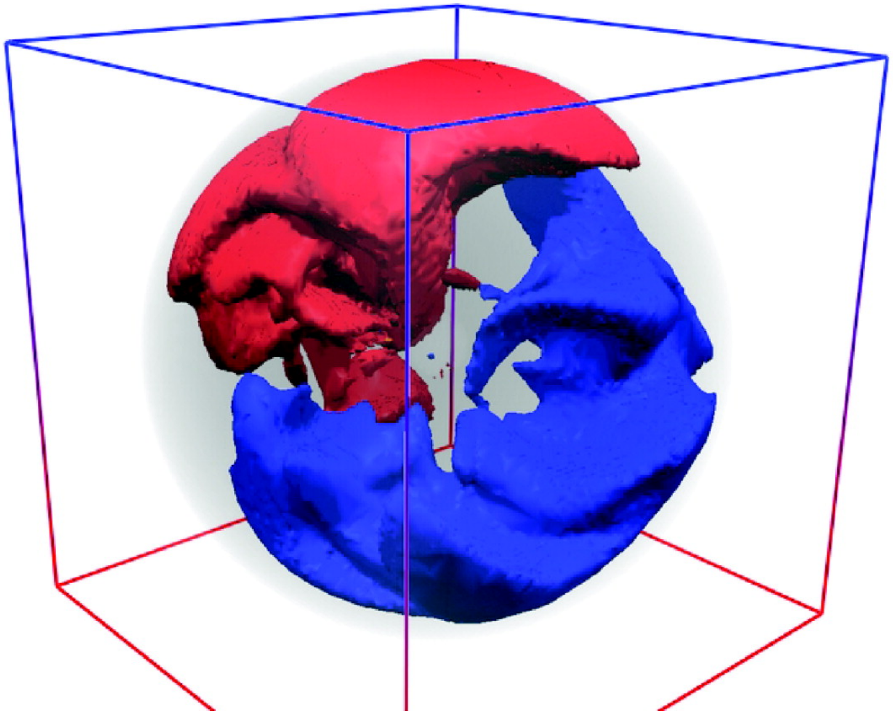
Previous Simulations of Simmering

Hoflich & Stein 2002



2d implicit hydro simulations; flows converged towards center suggesting central ignition

Kuhlen+ 2006



3d anelastic simulations of convection region; observed dipole flow that suggested off-center ignition

Maestro

Nonaka+ 2011

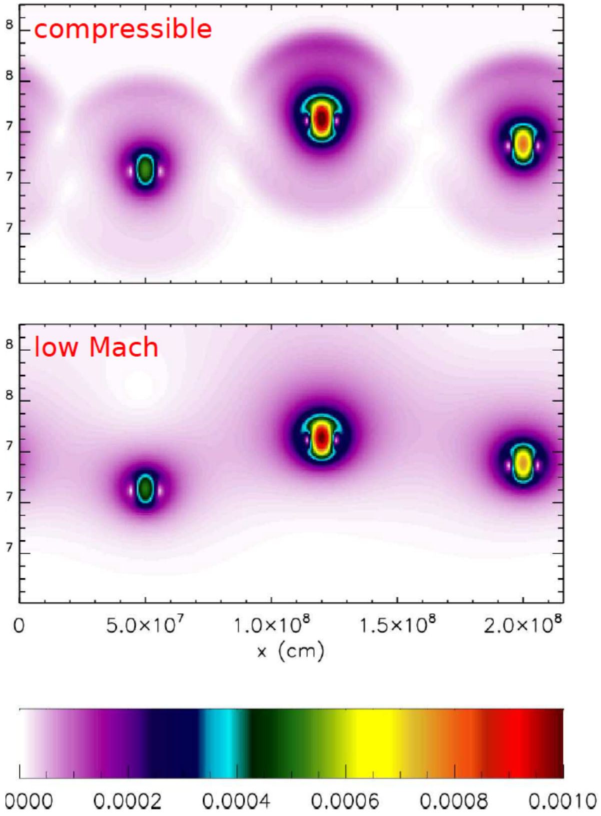
- Finite volume, AMR, low Mach hydro code that filters acoustic waves
- Retains important compressible effects from burning, diffusion, stratification
- Average HSE background state

$$\frac{|\pi|}{p_0} = \mathcal{O}\left(M^2\right)$$

$$p(x,t) = p_0(r,t) + \pi(x,t)$$

$$\nabla p_0 = -\rho_0 g$$

$$\boxed{\Delta t_{\rm CFL} \lesssim \frac{\Delta x}{U}}$$



Maestro

Nonaka+ 2011

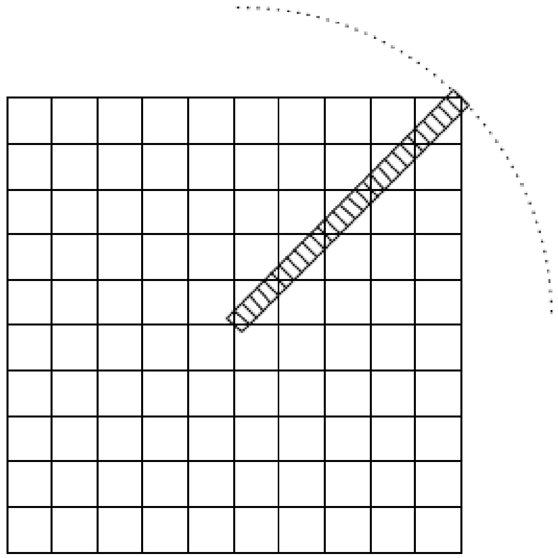
$$\frac{\partial\left(\rho X_k\right)}{\partial t} = -\nabla\cdot\left({}_k\mathbf{U}\right) + \rho\dot{\omega}$$

$$\frac{\partial\mathbf{U}}{\partial t} = -\mathbf{U}\cdot\nabla\mathbf{U} \quad - \quad \frac{1}{\rho}\nabla\pi \quad - \quad \frac{\rho-\rho_0}{\rho}g\mathbf{e}_r$$

$$\frac{\partial\left(\rho h\right)}{\partial t} = -\nabla\cdot\left(\rho h\mathbf{U}\right) + \frac{Dp_0}{Dt} + \rho H_{\mathrm{nuc}} + \nabla\cdot\left(\kappa\nabla T\right)$$

$$\nabla\cdot\left(\beta_0\mathbf{U}\right) = \beta_0\left(S - \frac{1}{\Gamma_1 p_0}\frac{\partial p_0}{\partial t}\right)$$

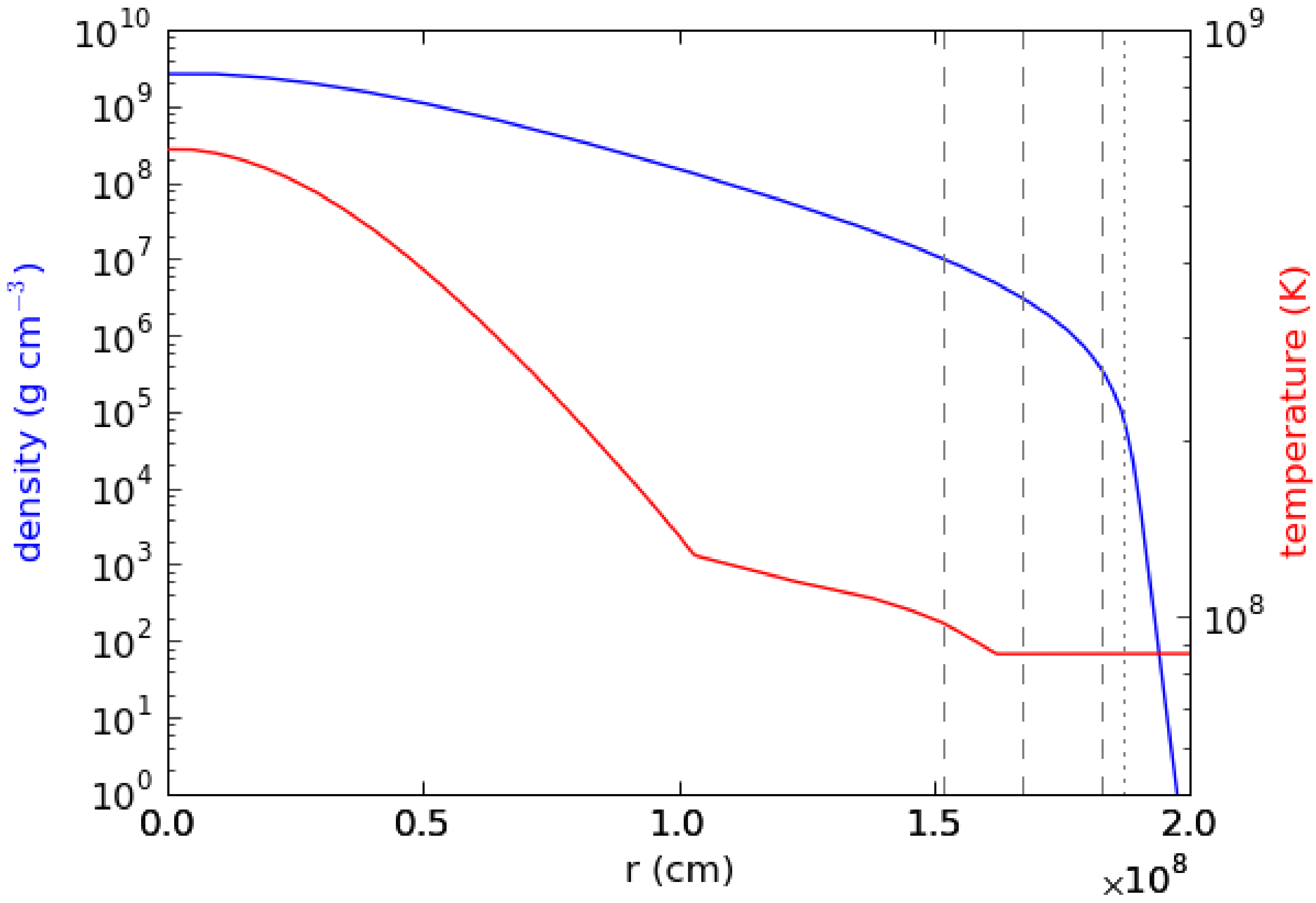
$$\beta_0(r,t) = \rho_0(r,t)\exp\left(\int_0^r \frac{1}{\Gamma_1 p_0}\frac{\partial p_0}{\partial r'}\,dr'\right)$$



- Advection using 2nd order Godunov
- Reactions using Strang splitting (Stiff ODEs)
- Diffusion semi-implicit (multigrid)
- Divergence constraint – elliptic solve (multigrid)

Initial Conditions

Zingale+ 2011

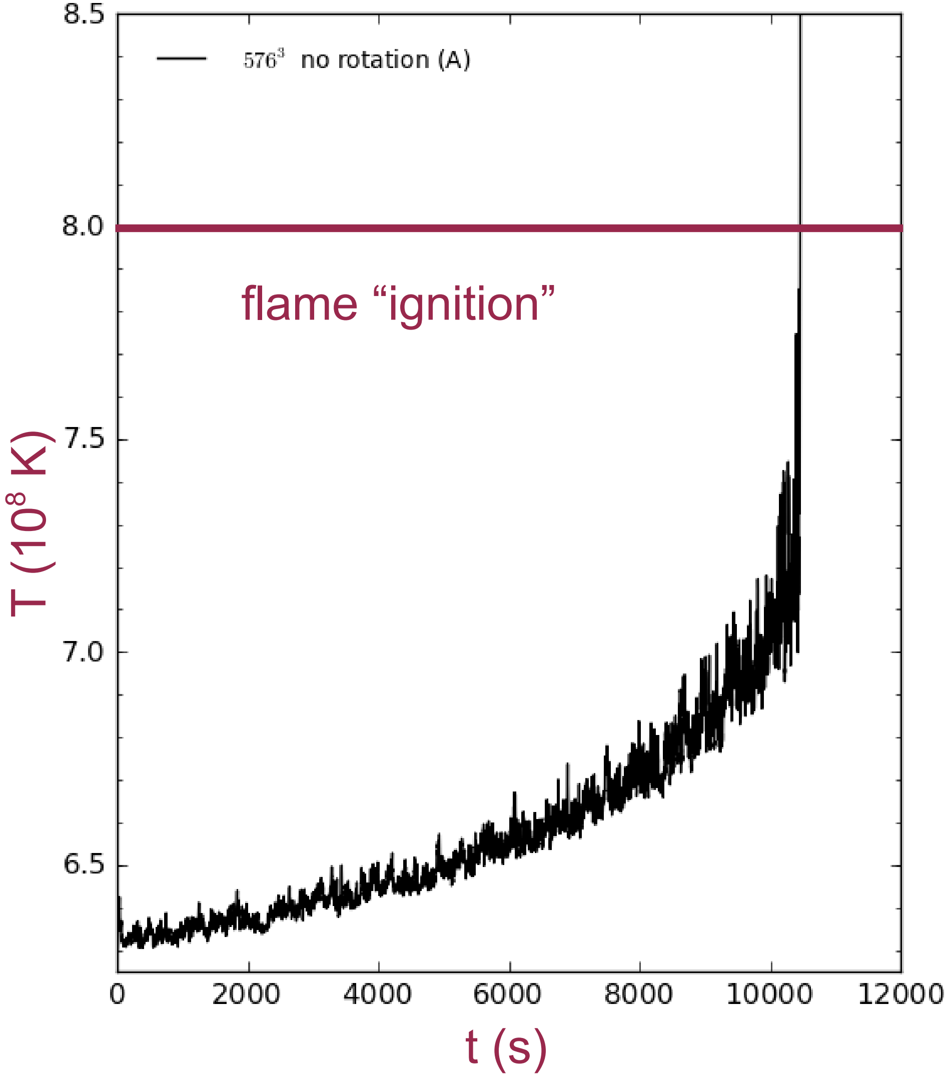


Based on Kepler model

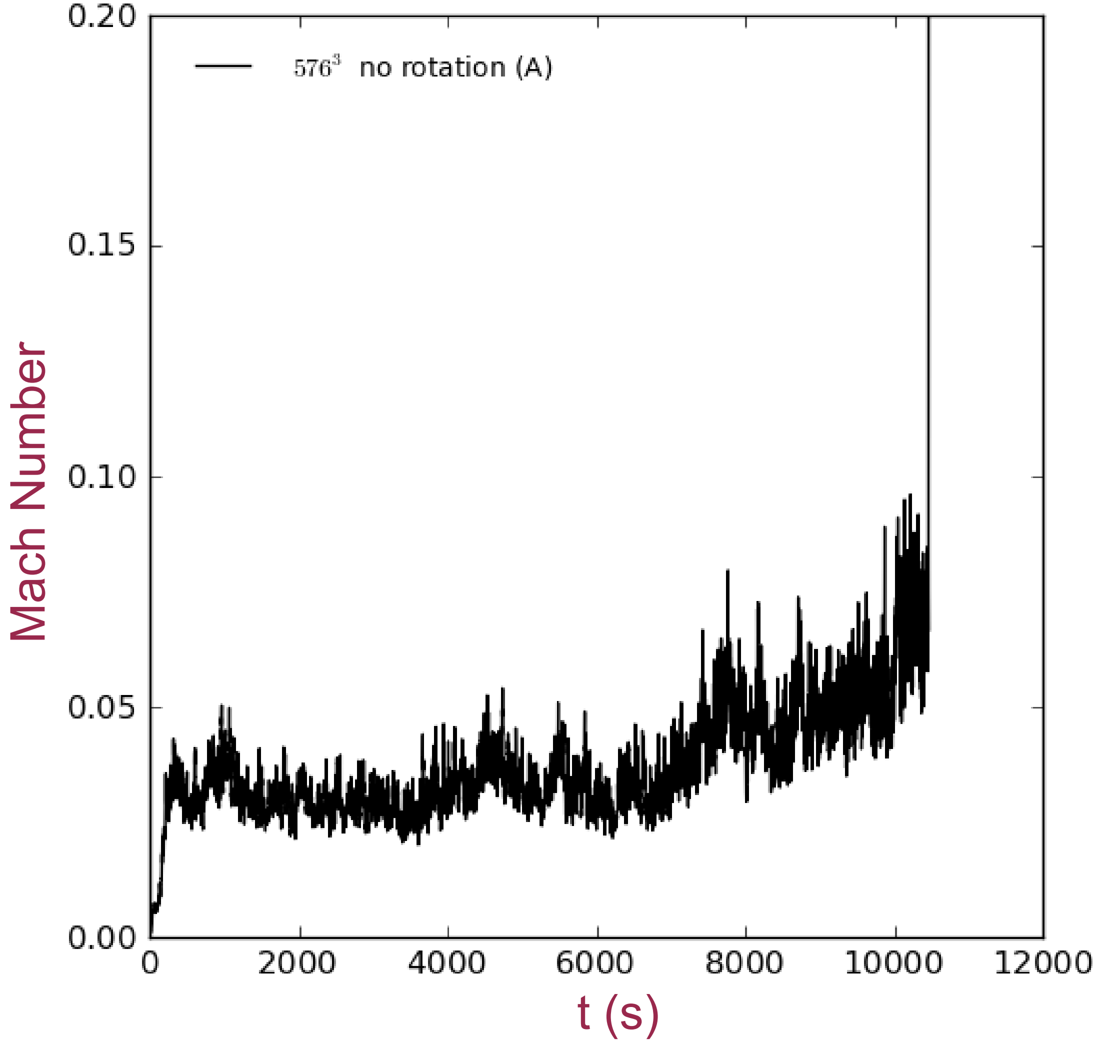
Simmering to Ignition

Zingale+ 2011

8.7 km / zone



flame “ignition”



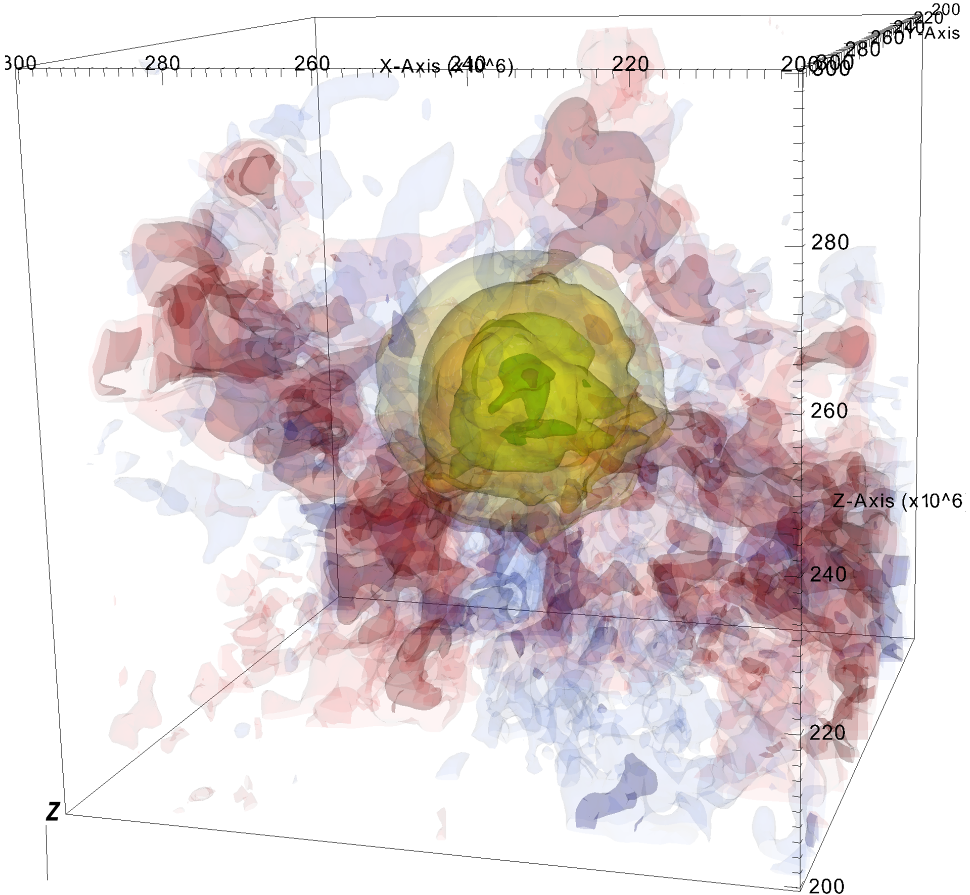
Simmering to Ignition

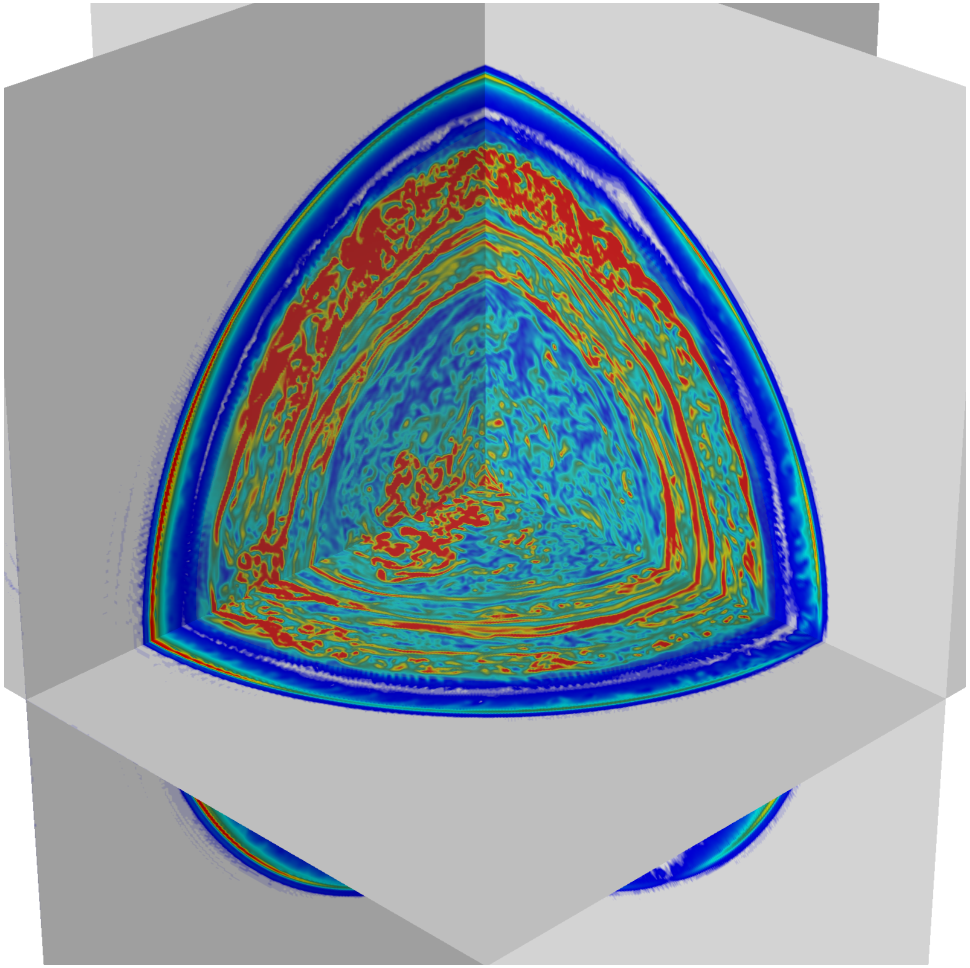
Zingale+ 2011

EGR – yellow/green/purple
Rad. Vel – red/blue

8.7 km / zone

Mag. vorticity



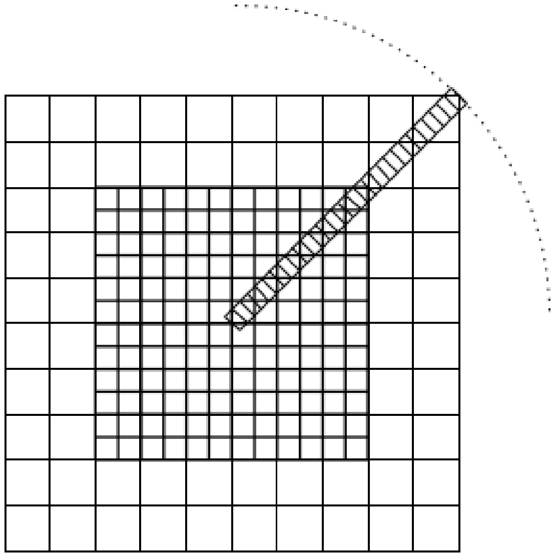


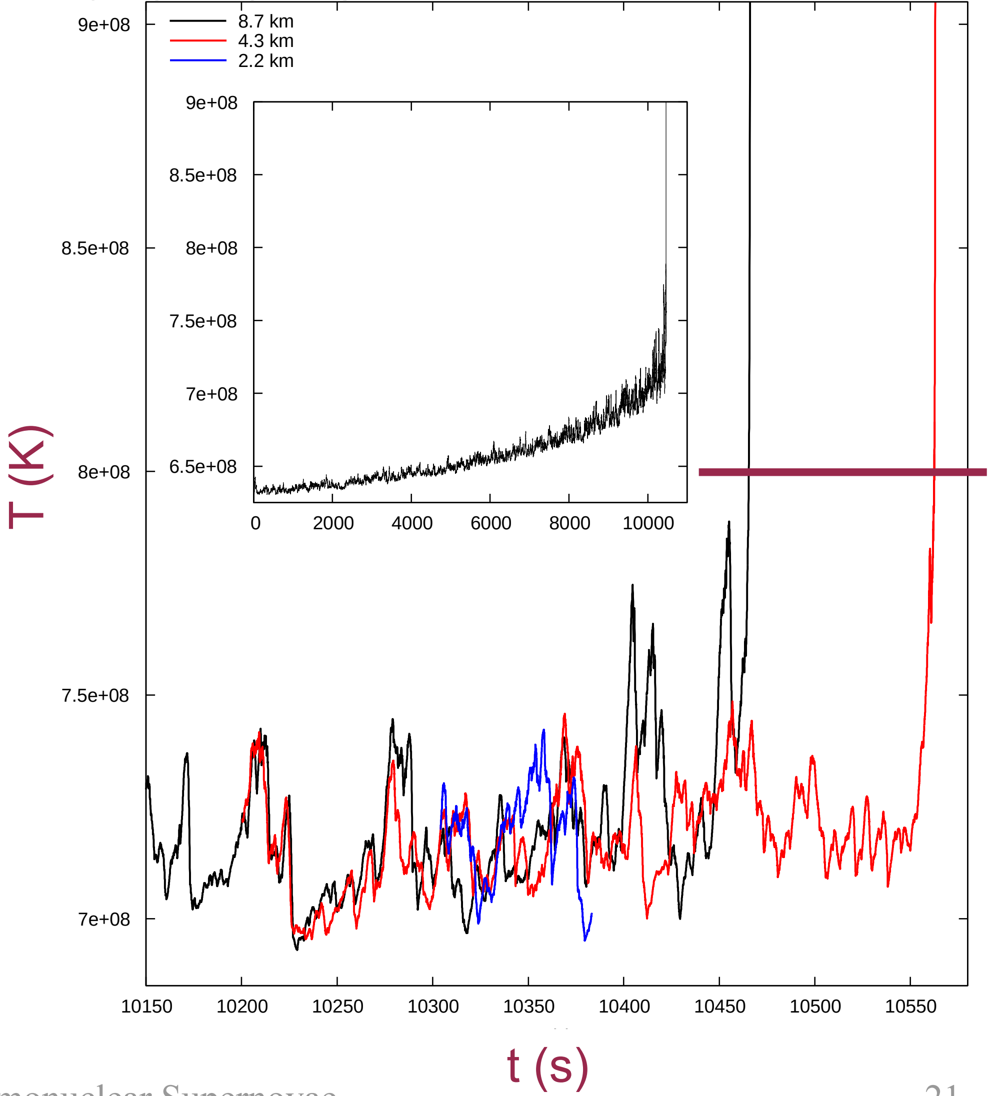
Inner 1000^3 km

Simmering to Ignition

Nonaka+ 2012

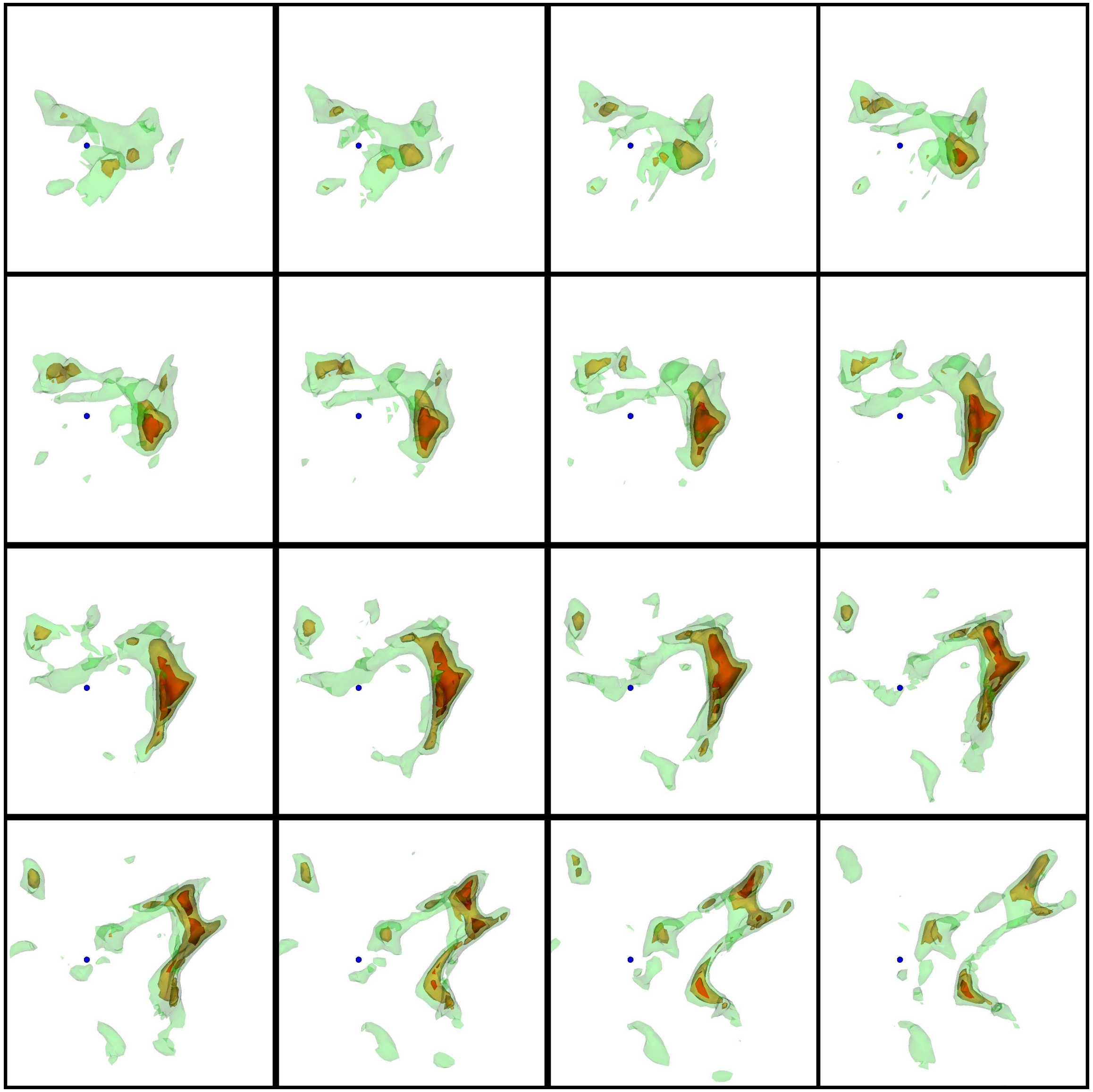
- Added refinement to simulations with AMR
- Up to effective 2304^3 (2.1 km / zone)





Simmering to Ignition

Nonaka+ 2012, 4.3 km / zone



Green: $T_8 = 7.5$
Yellow: $T_8 = 7.7$
Orange: $T_8 = 7.9$

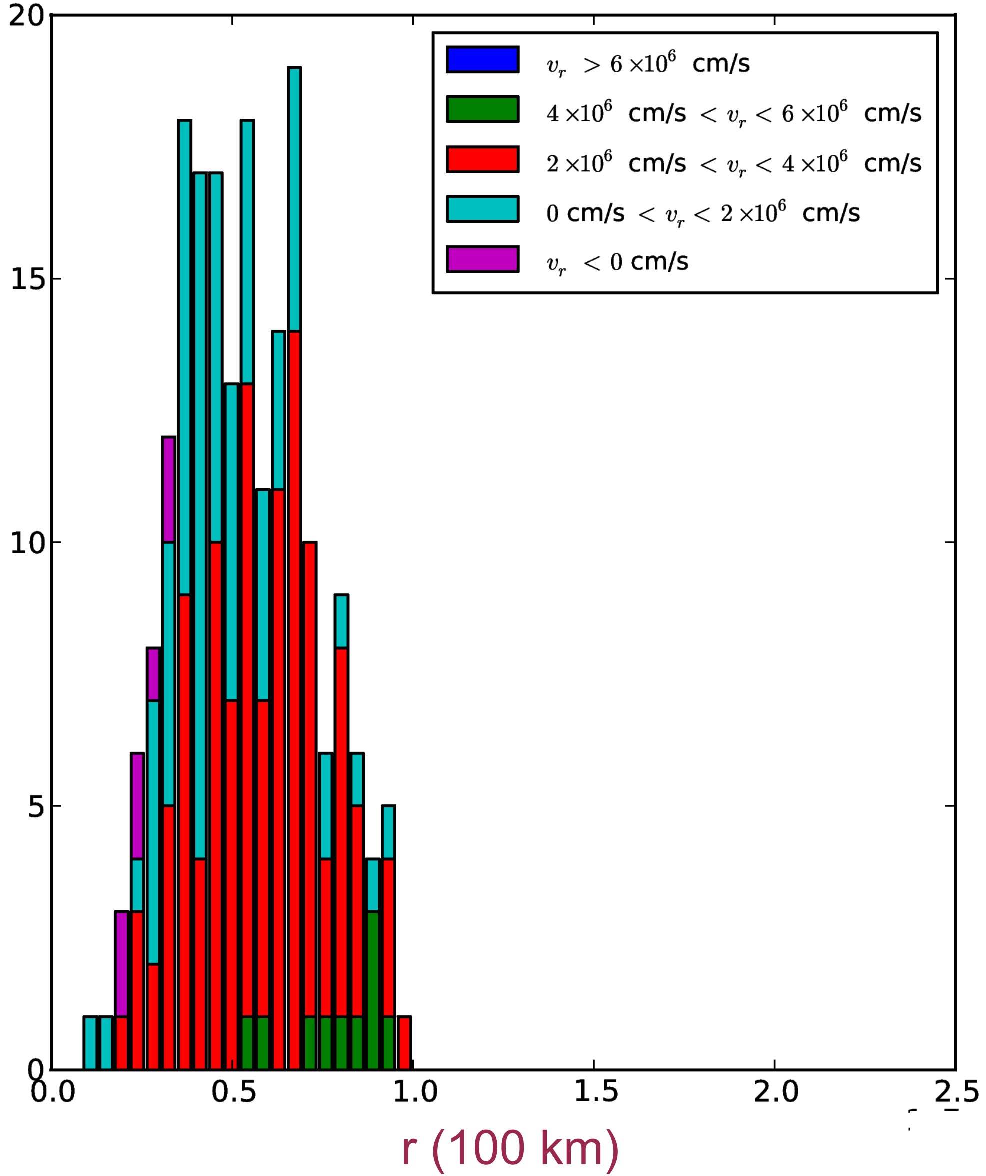
Ignition localized and off-center!

Simmering to Ignition

Zingale+ 2011, Nonaka+ 2013

Ignition occurs in region of outflow!

Ignition localized and off-center!



Castro

Almgren+ 2010,(Zhang+ 2011, 2013)

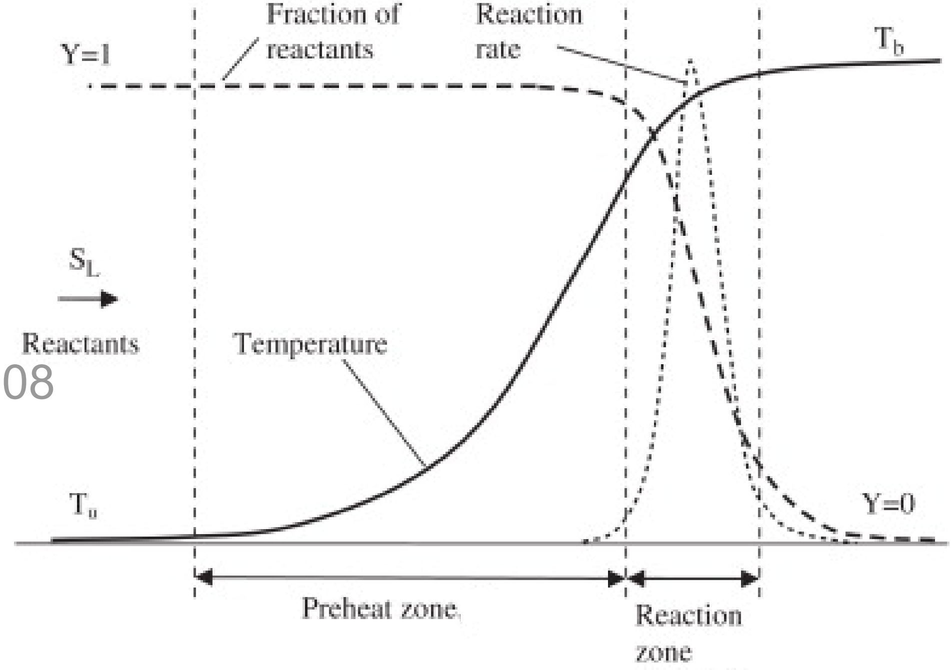
- Finite volume, AMR compressible (rad)-hydro code
- Sub-cycling in time
- Multigrid solvers for gravity/diffusion
- Same underlying data structures as Maestro (BoxLib)

Astrophysical Flames

- Flame thickness at ignition $\delta \sim 10^{-2}\ \mathrm{cm}$
- Radius of star $R_{\mathrm{WD}} \sim 10^{8}\ \mathrm{cm}$
- Thermal diffusion much more important than species diffusion $Le \gg 1$

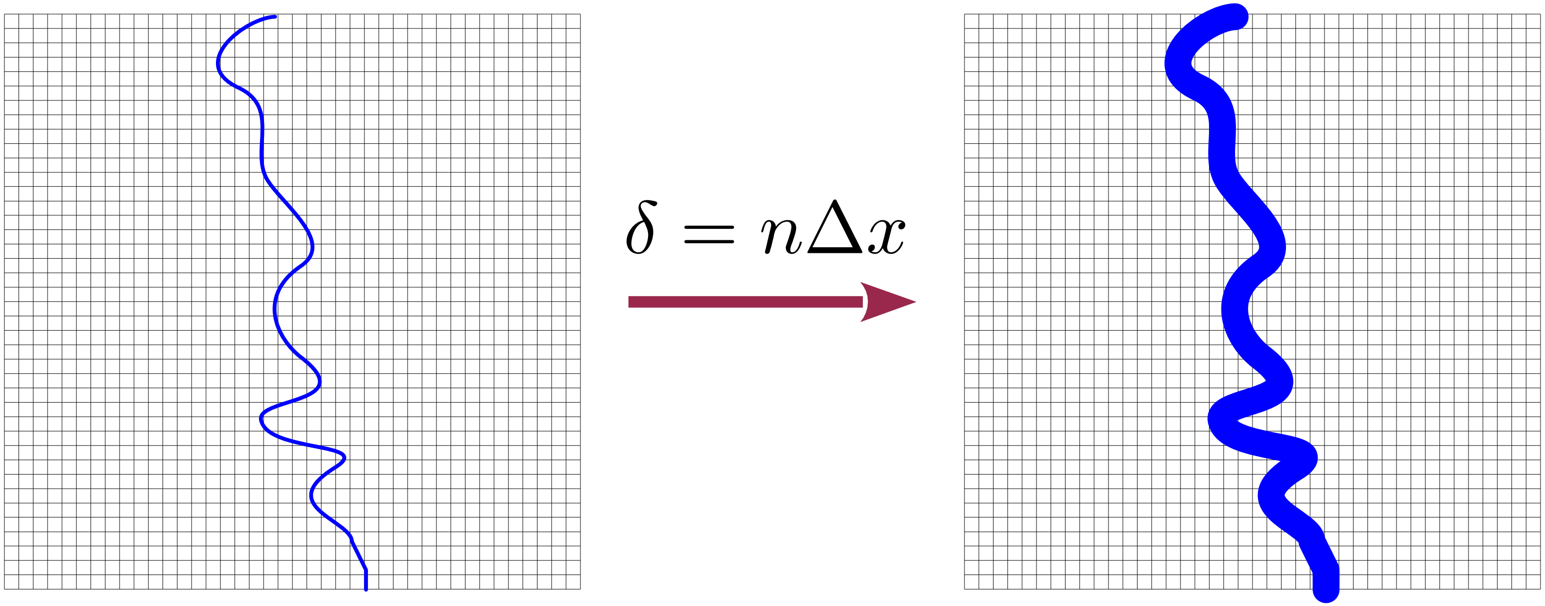
Laminar flame

after
Ciccarelli & Dorofeev 2008



Turbulence highly complicates the burning!

Thickened Flame



$$\delta = n\Delta x$$

$$\text{Steady state}: \quad \tau_{\mathrm{diff}} = \tau_{\mathrm{burn}}, \quad \mathrm{v_f} = \frac{\delta}{\tau_{\mathrm{diff}}}$$

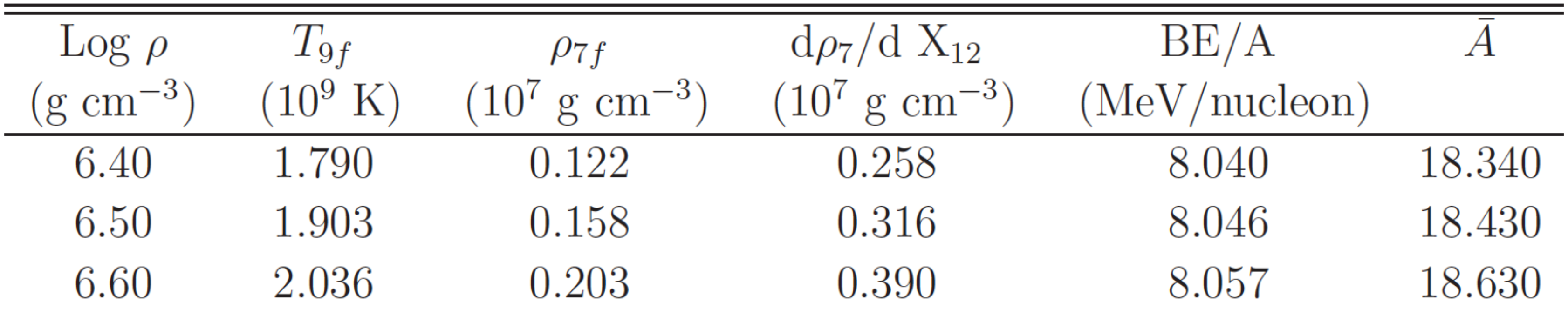
Given a flame speed and EGR, find a consistent diffusion coefficient

$$\kappa \simeq \frac{(\Delta x)^2}{\tau_{\mathrm{diff}}} \simeq \frac{(v_f \tau_{\mathrm{burn}}/n)^2}{\tau_{\mathrm{burn}}} \simeq \tau_{\mathrm{burn}} \left(\frac{v_f}{n}\right)^2$$

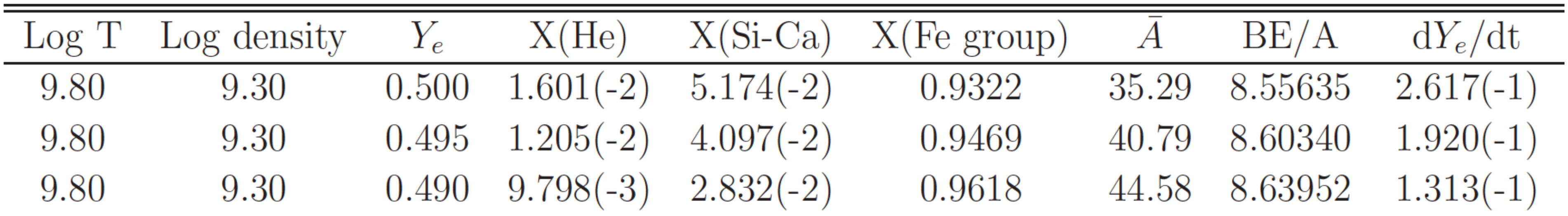
Thickened Flame

Ma+ 2013

- Burning timescale determined by table interpolation of off-line large reaction networks



Log ρ ($\mathrm{g\ cm^{-3}}$)	T_{9f} (10^9 K)	ρ_{7f} ($10^7\ \mathrm{g\ cm^{-3}}$)	$\mathrm{d}\rho_7/\mathrm{d}\ X_{12}$ ($10^7\ \mathrm{g\ cm^{-3}}$)	BE/A (MeV/nucleon)	$\bar{A}$
6.40	1.790	0.122	0.258	8.040	18.340
6.50	1.903	0.158	0.316	8.046	18.430
6.60	2.036	0.203	0.390	8.057	18.630

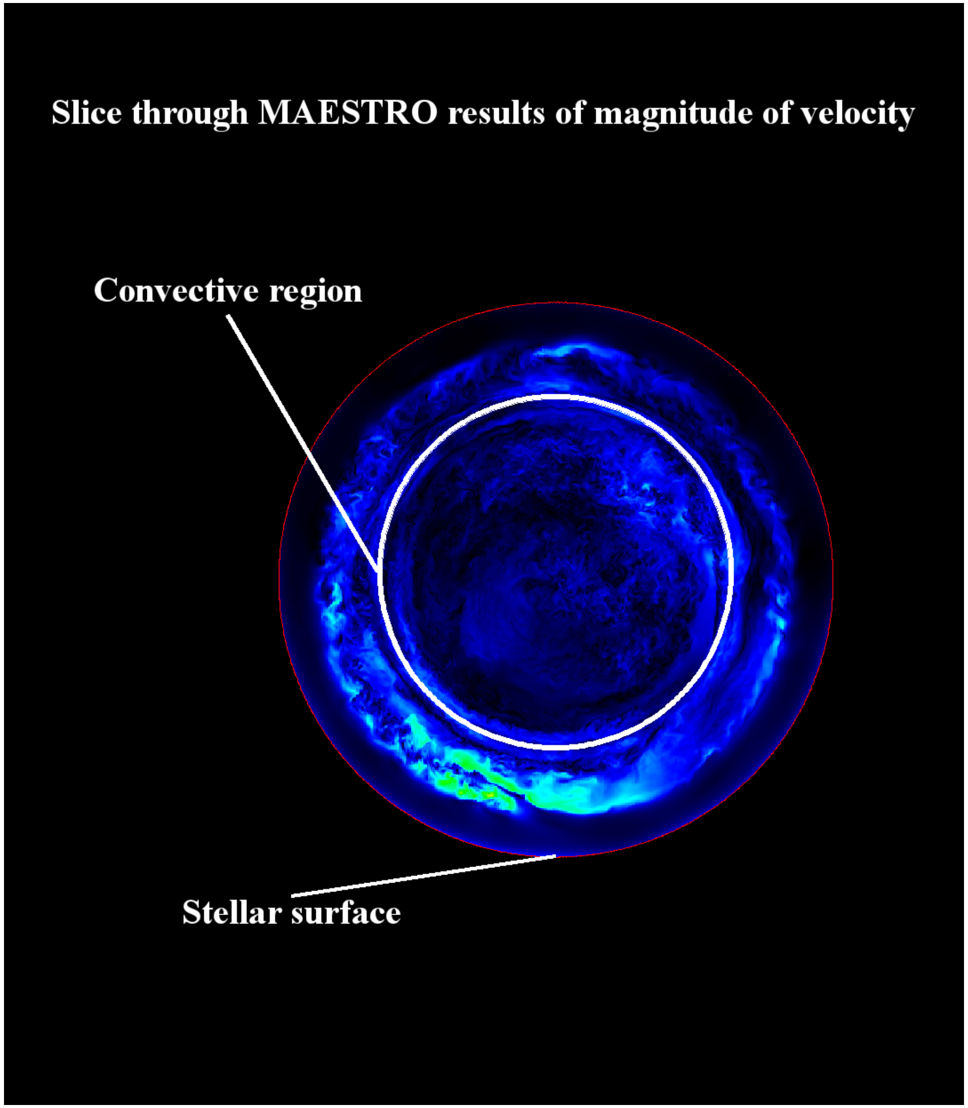


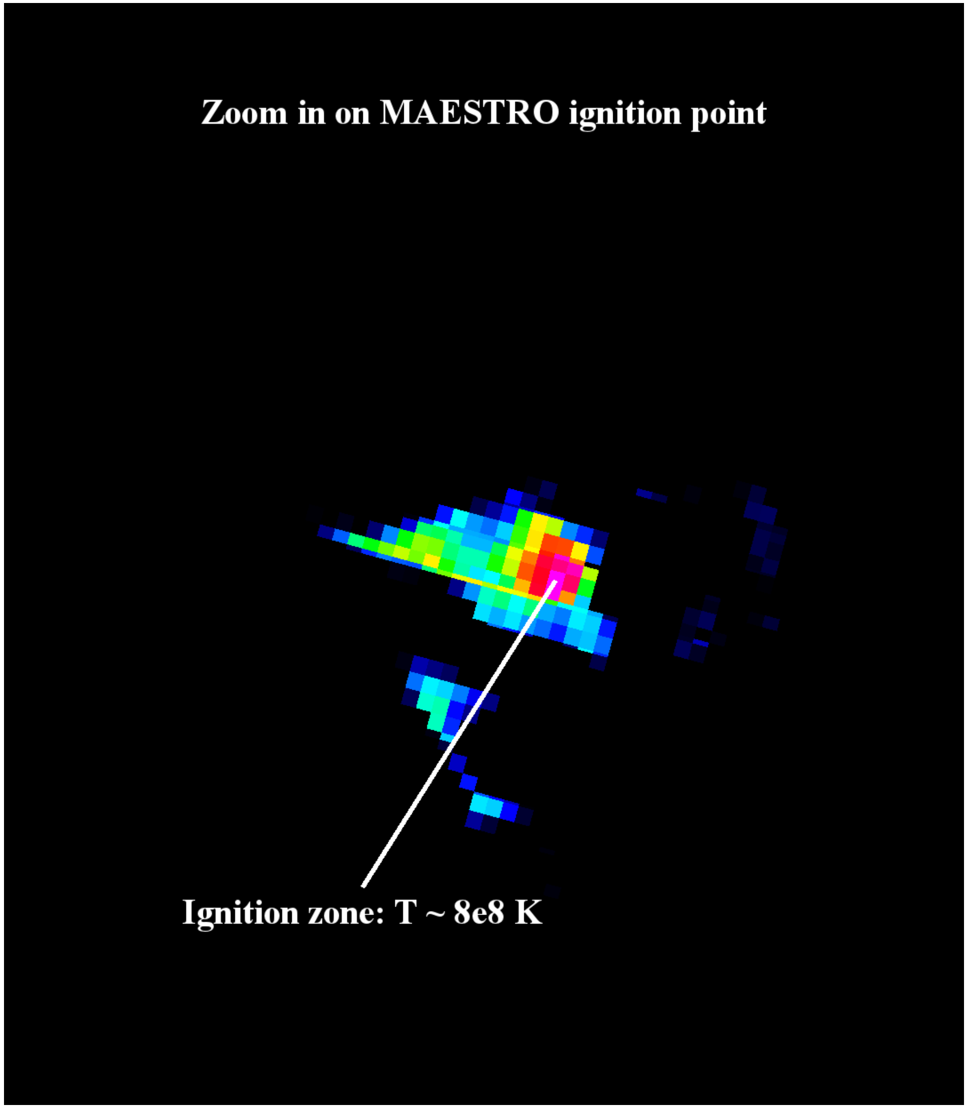
Log T	Log density	Y_e	X(He)	X(Si-Ca)	X(Fe group)	$\bar{A}$	BE/A	$\mathrm{d}Y_e/\mathrm{dt}$
9.80	9.30	0.500	1.601(-2)	5.174(-2)	0.9322	35.29	8.55635	2.617(-1)
9.80	9.30	0.495	1.205(-2)	4.097(-2)	0.9469	40.79	8.60340	1.920(-1)
9.80	9.30	0.490	9.798(-3)	2.832(-2)	0.9618	44.58	8.63952	1.313(-1)

- Flame speed currently set to constant*

Maestro to Castro

Malone+ 2013





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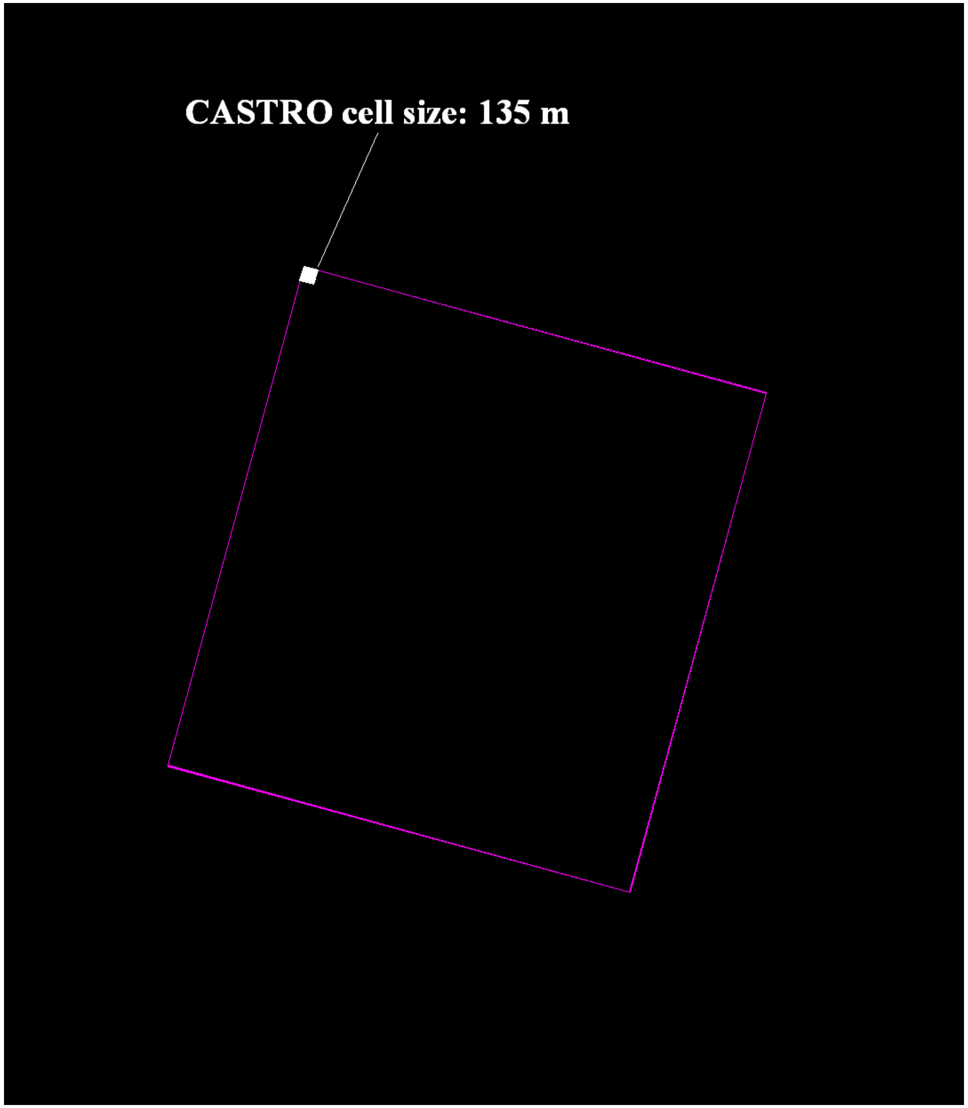

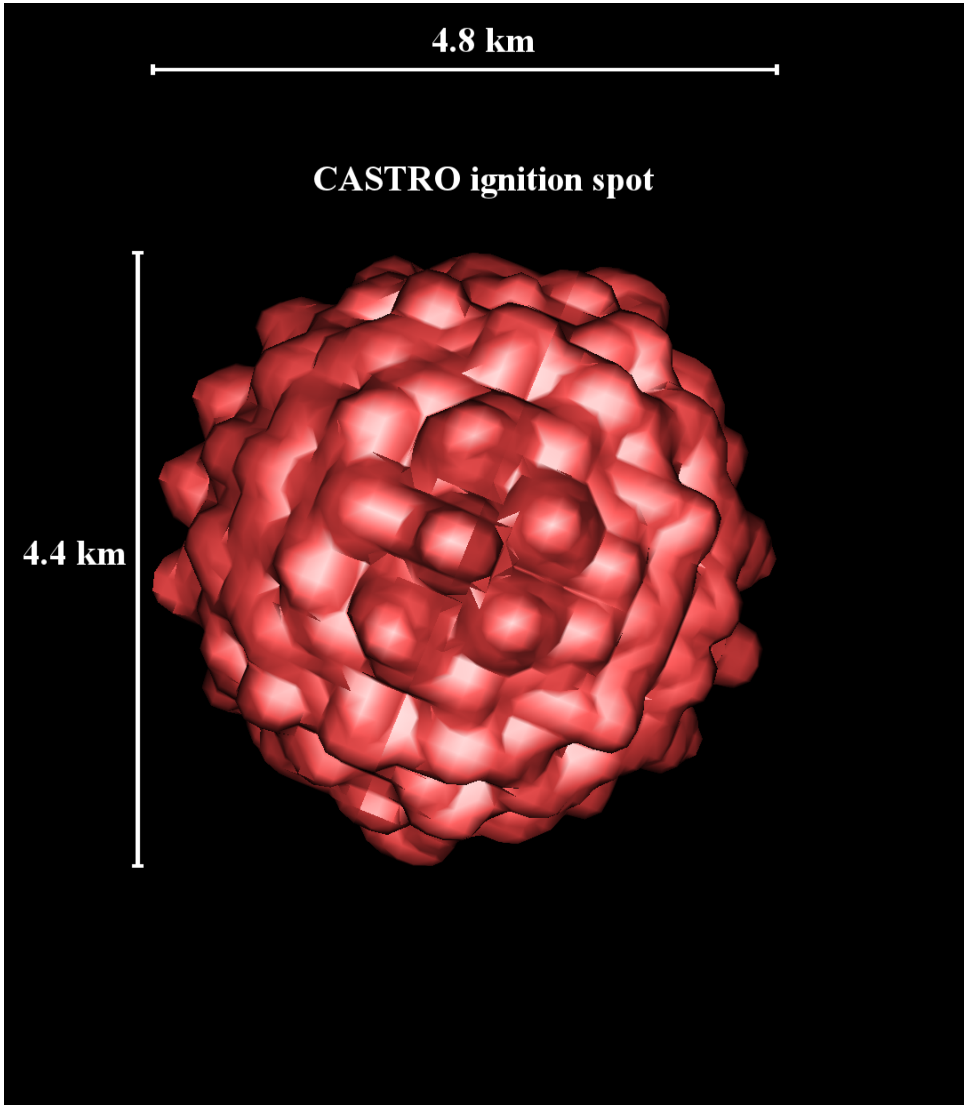

Bubble Rise

$X\left({}^{12}\mathrm{C}\right) = 0.49$ Malone+ 2013 $|\nabla \times \mathbf{U}|$

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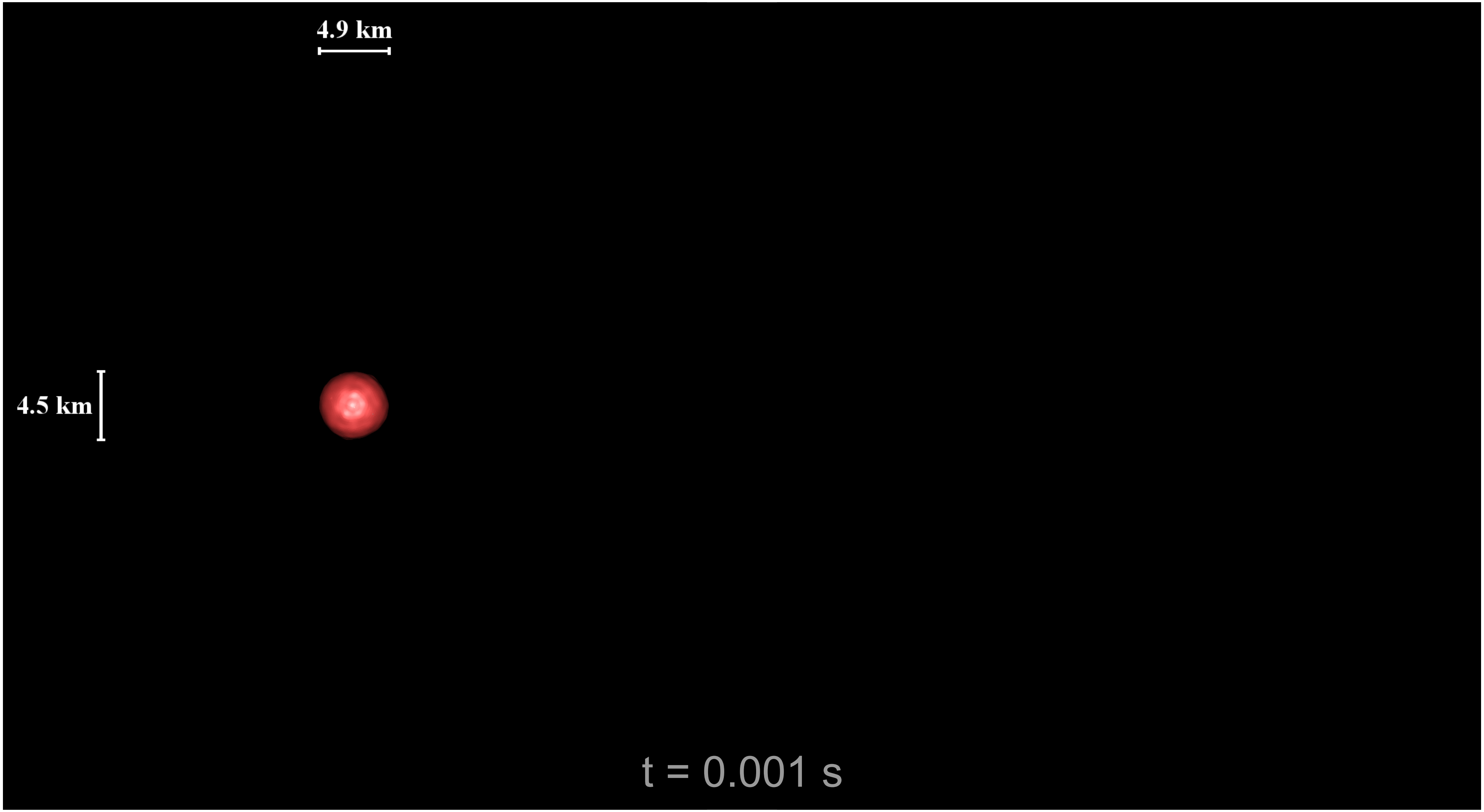

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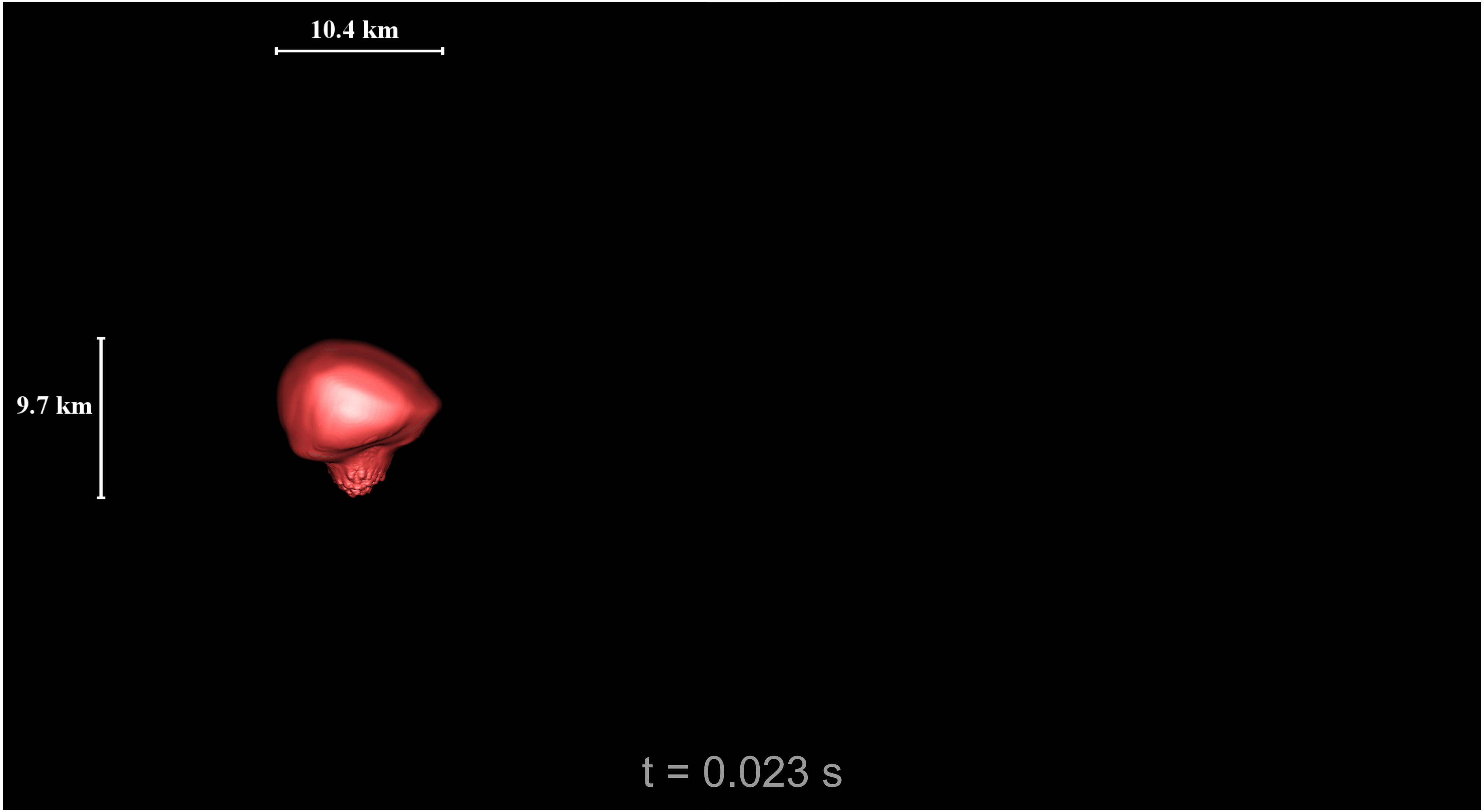

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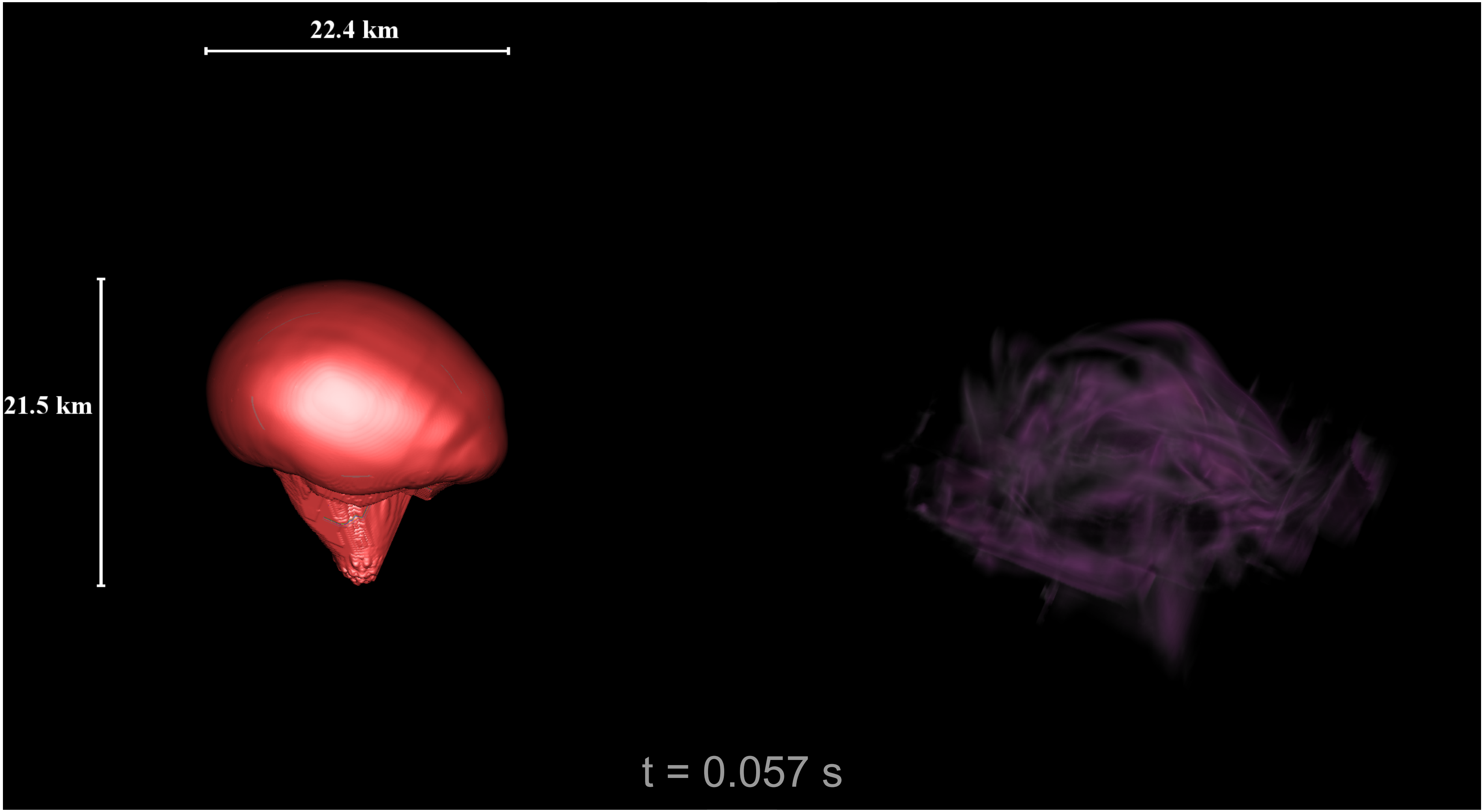

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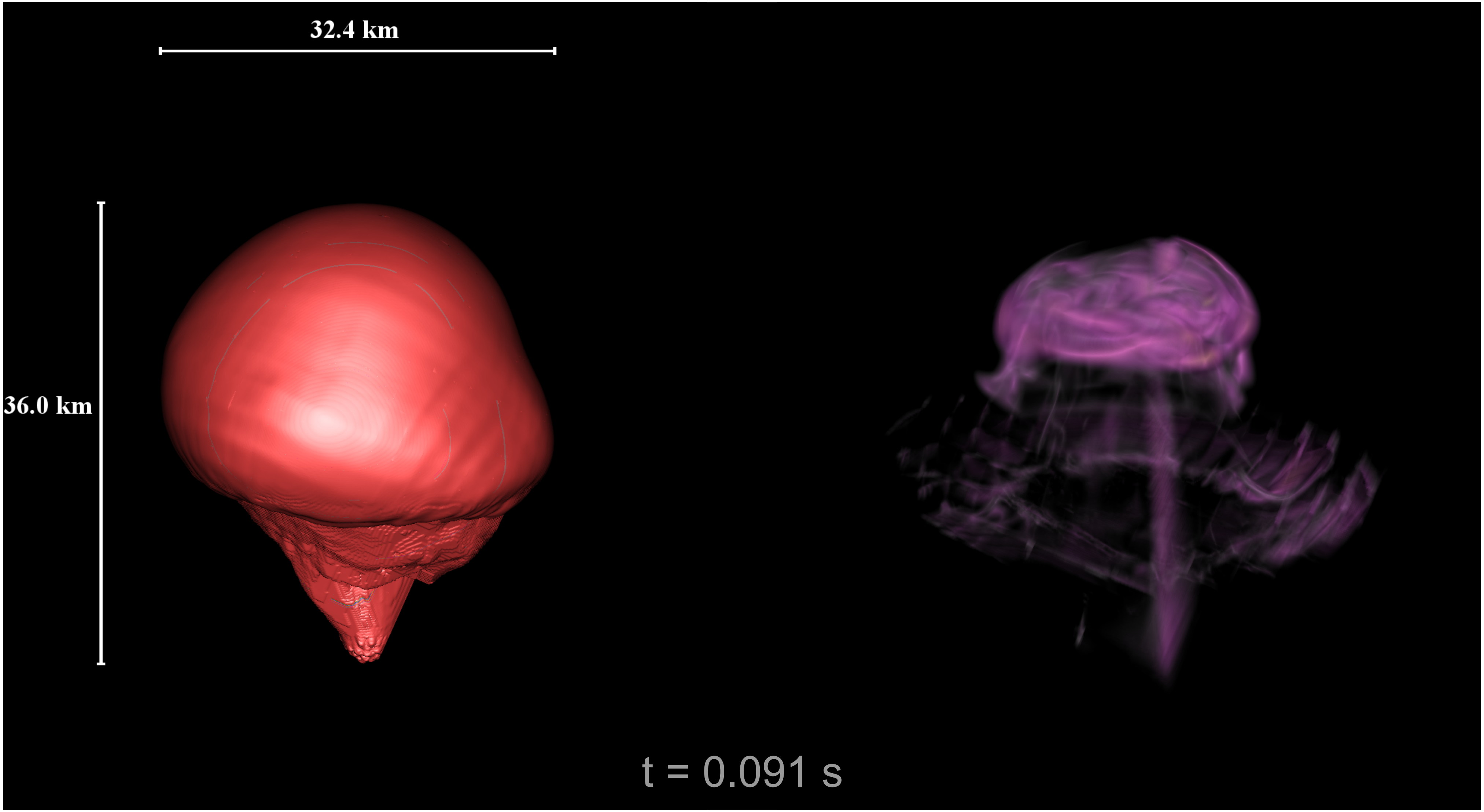

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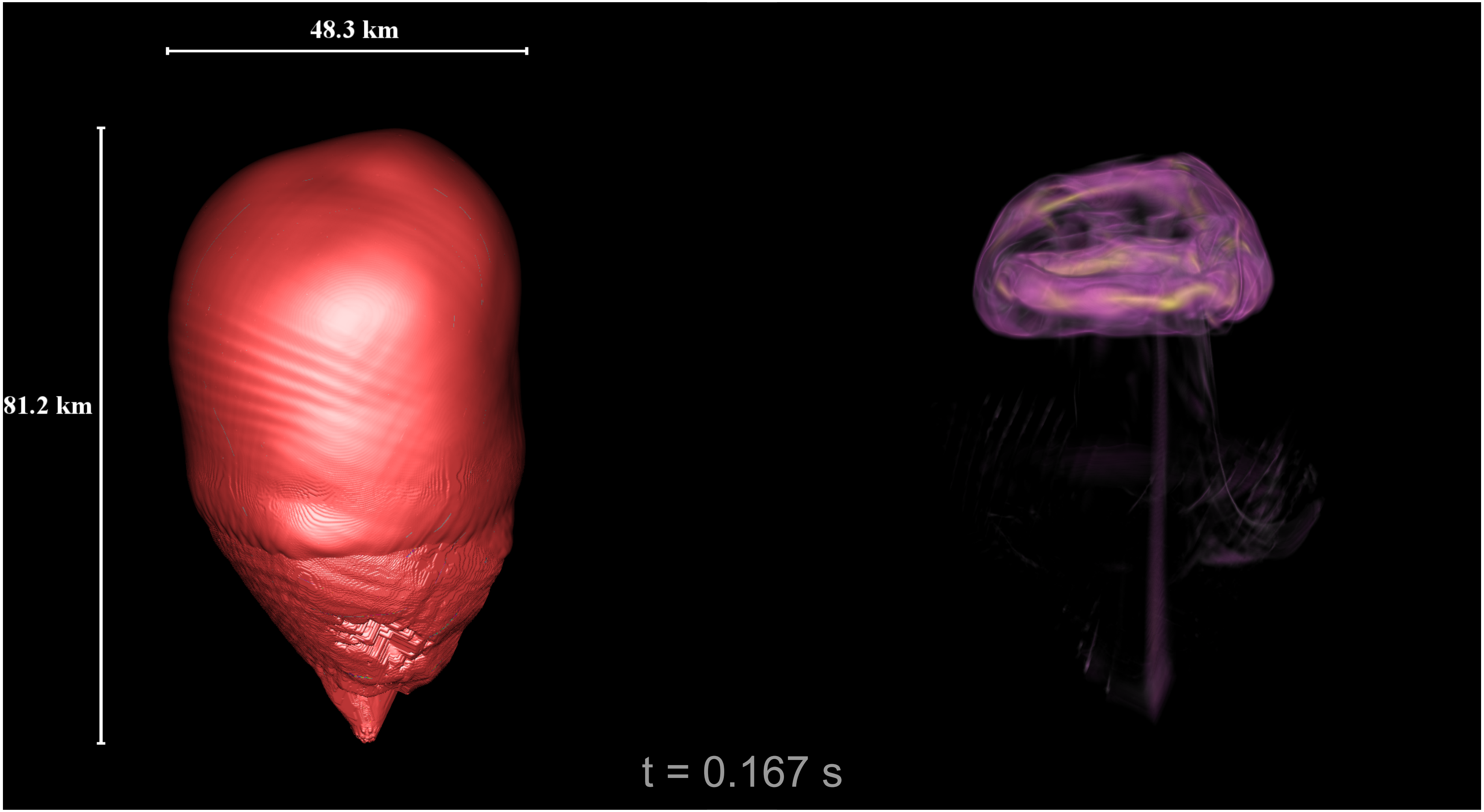

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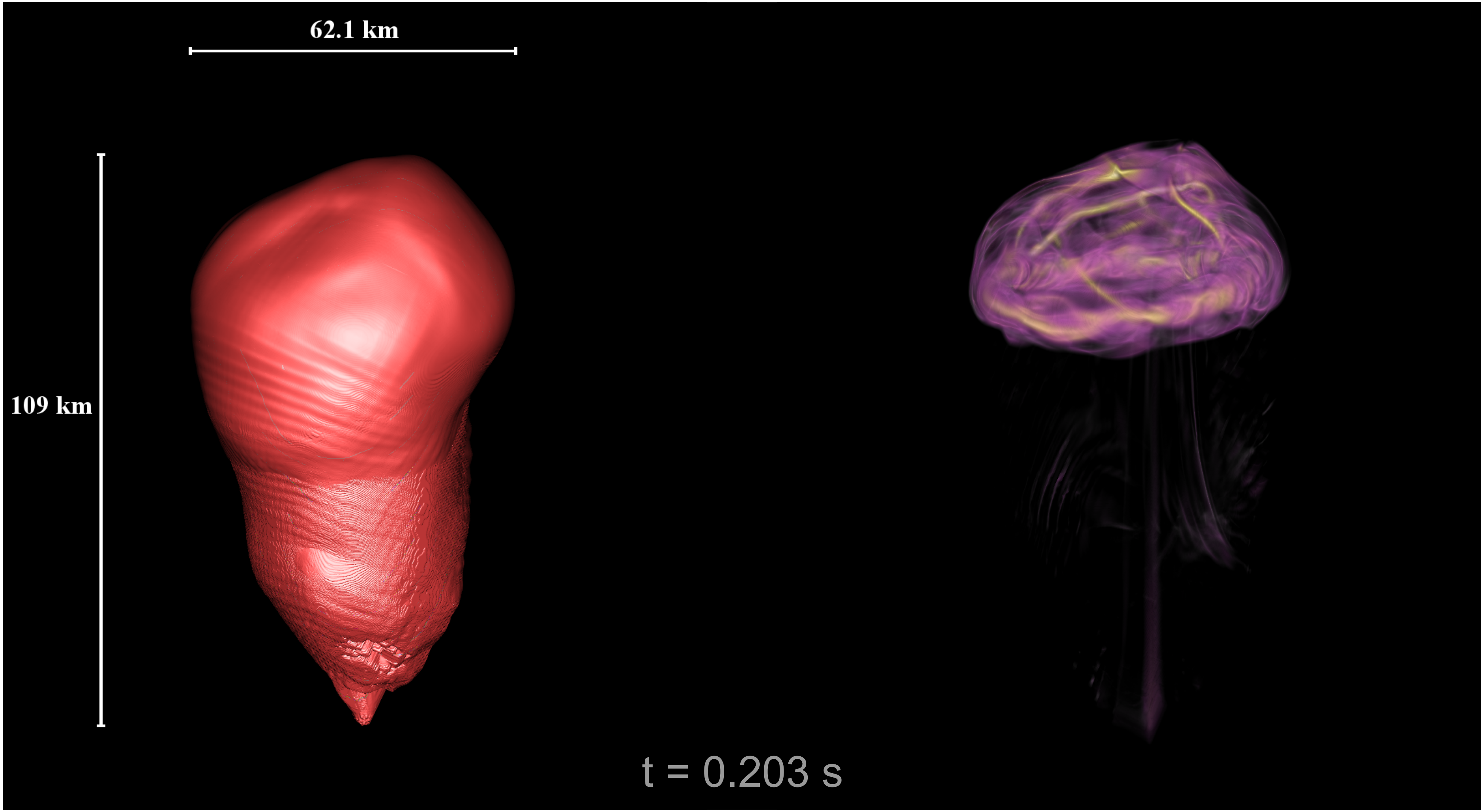

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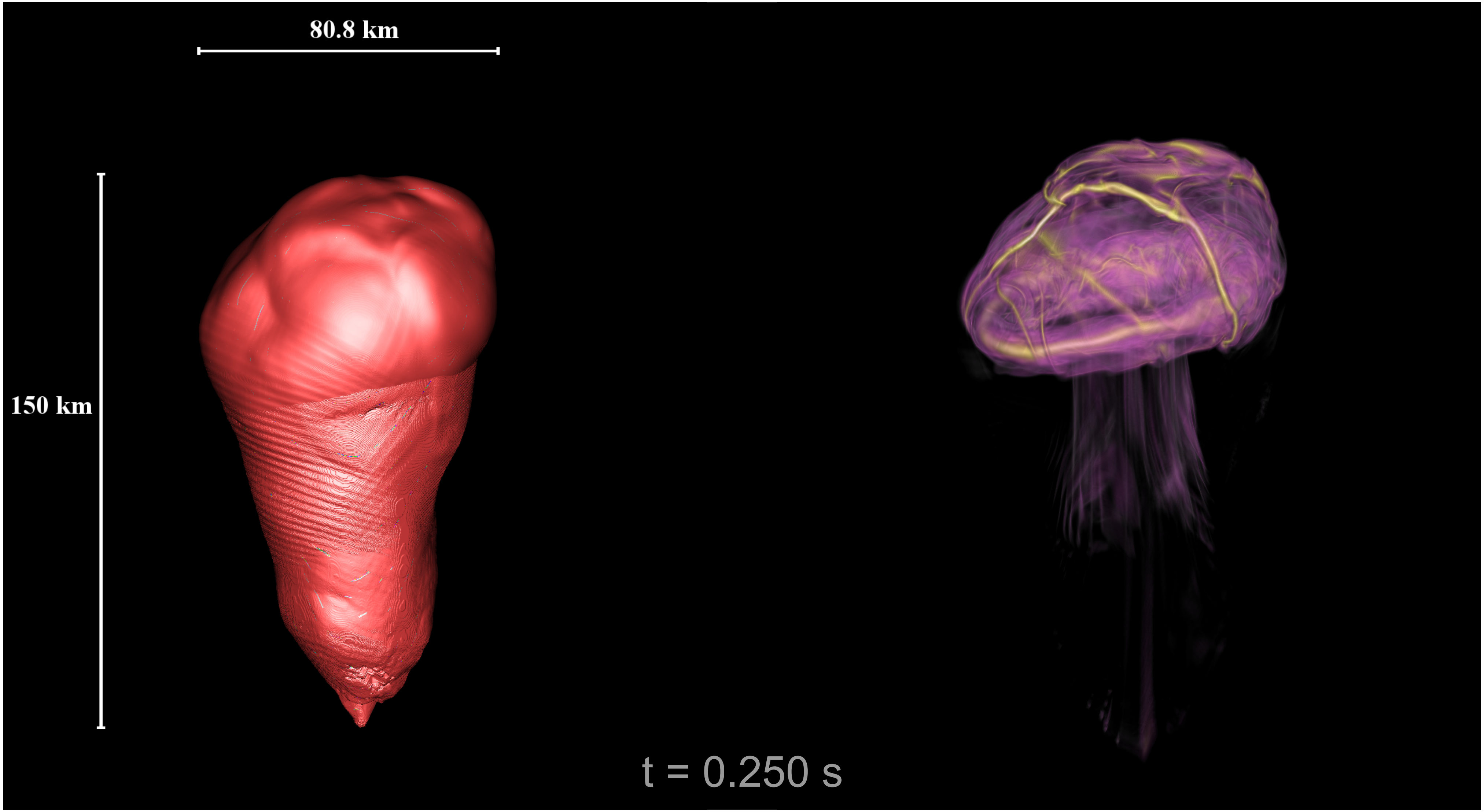

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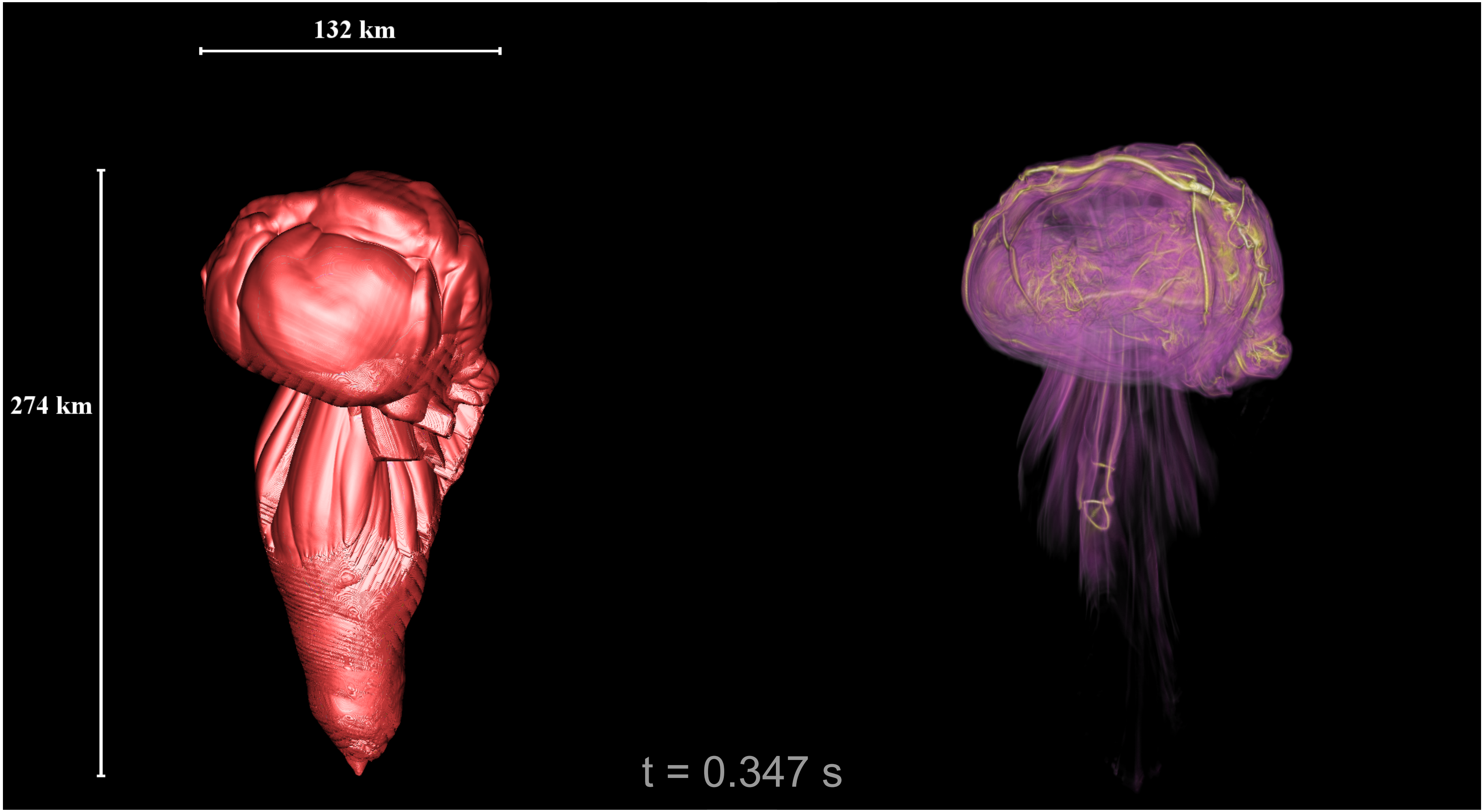

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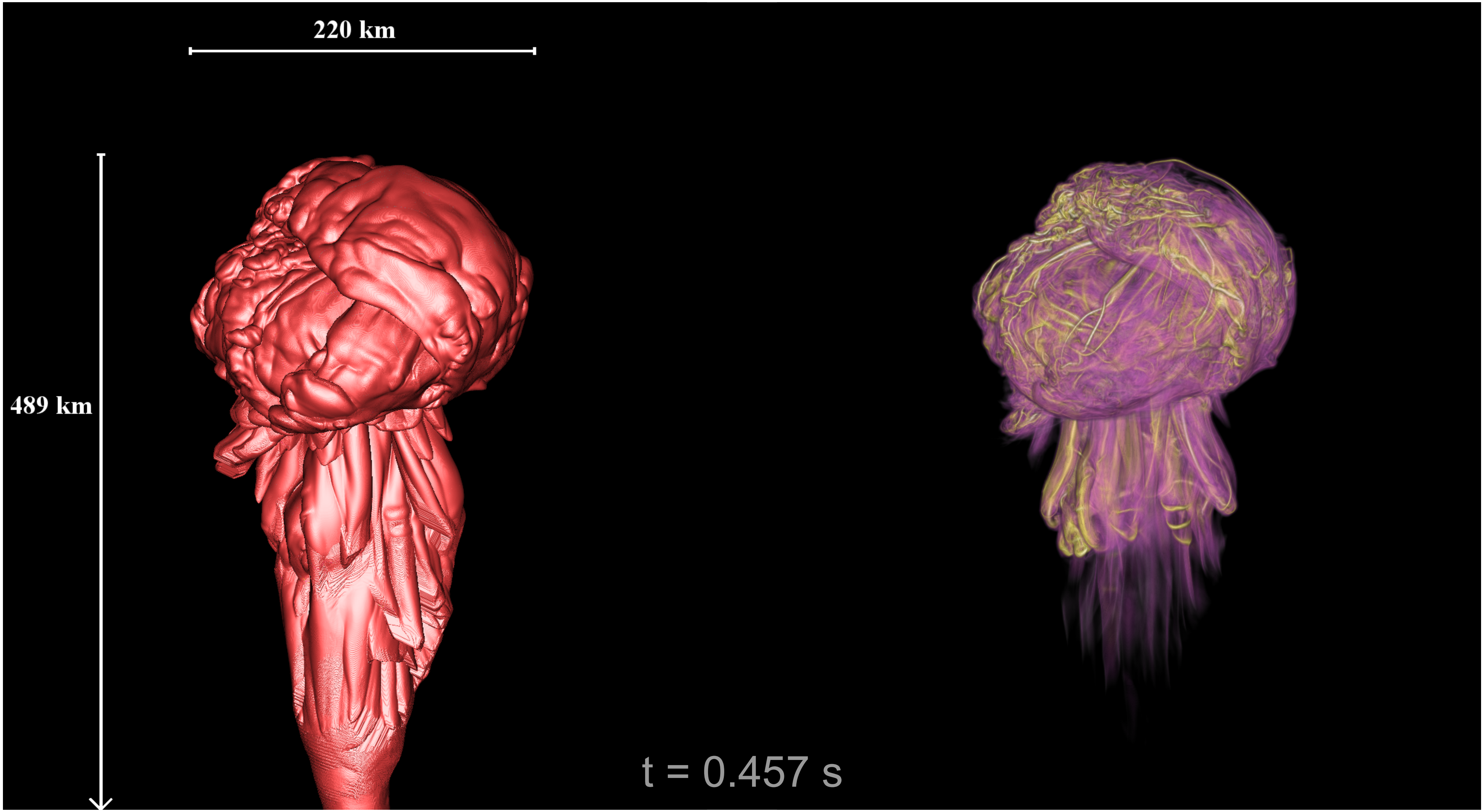
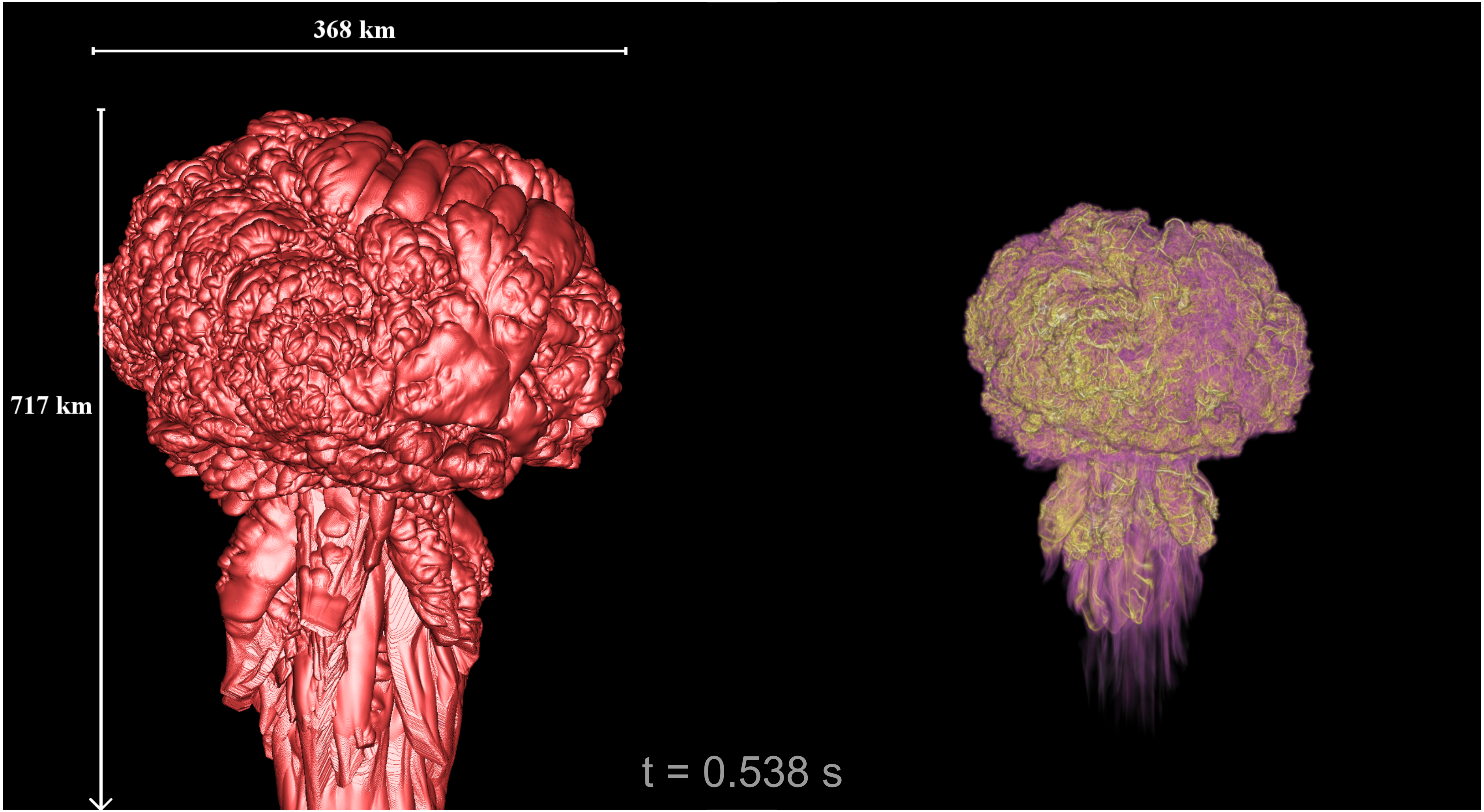
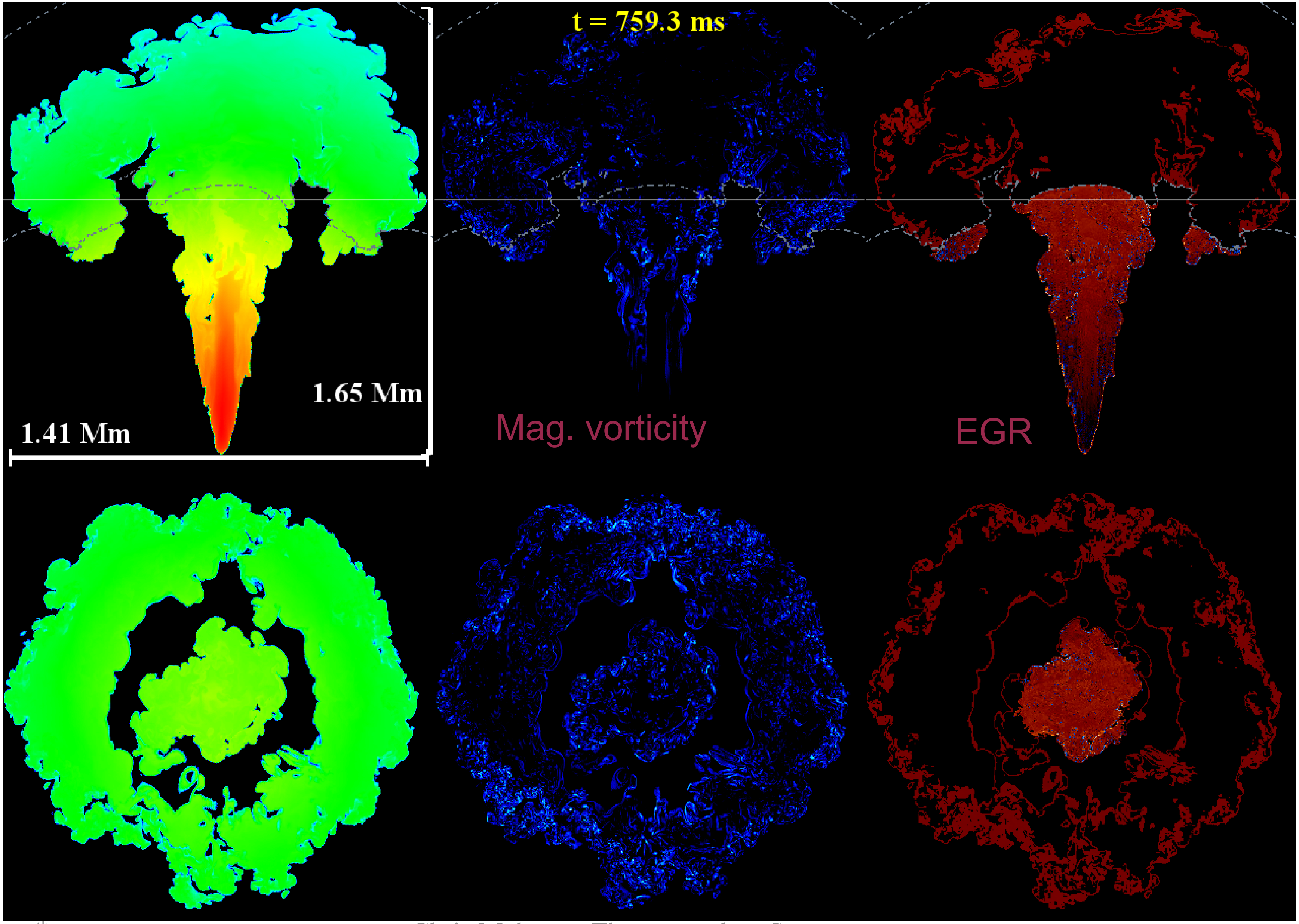


Bubble Rise

$X\left({}^{12}\mathrm{C}\right) = 0.49$ Malone+ 2013 $|\nabla \times \mathbf{U}|$



Slices – Interesting Burning



temperature

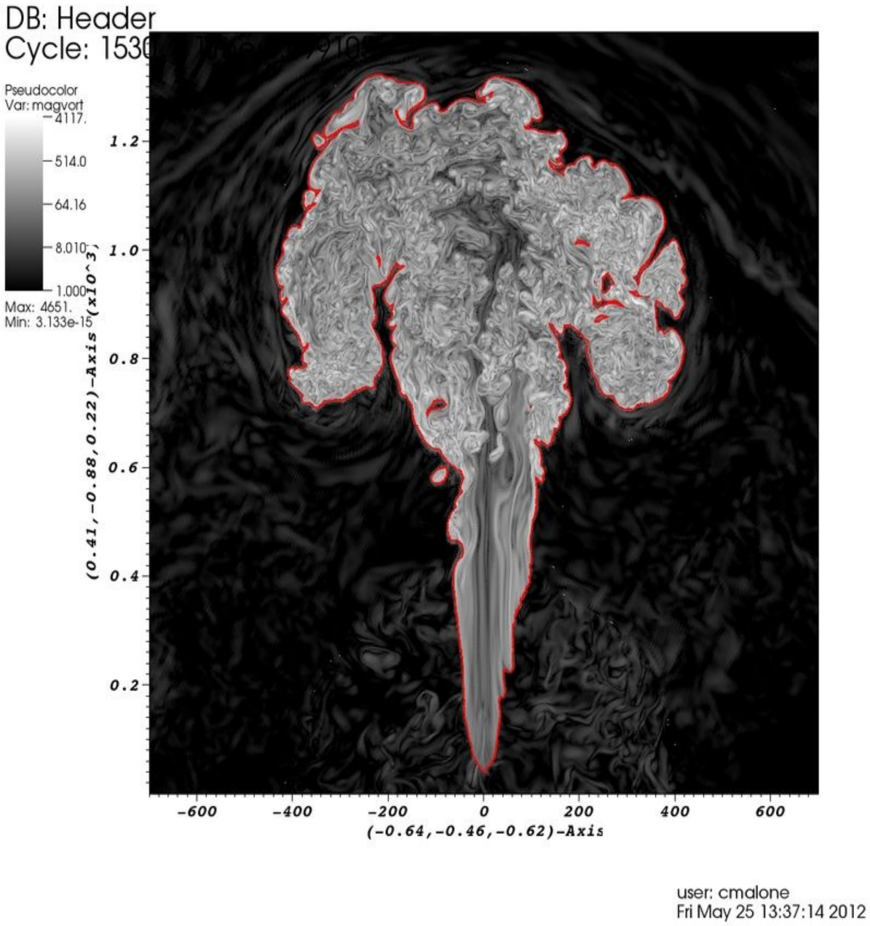
Mag. vorticity

EGR

Turbulence Only In Ash?

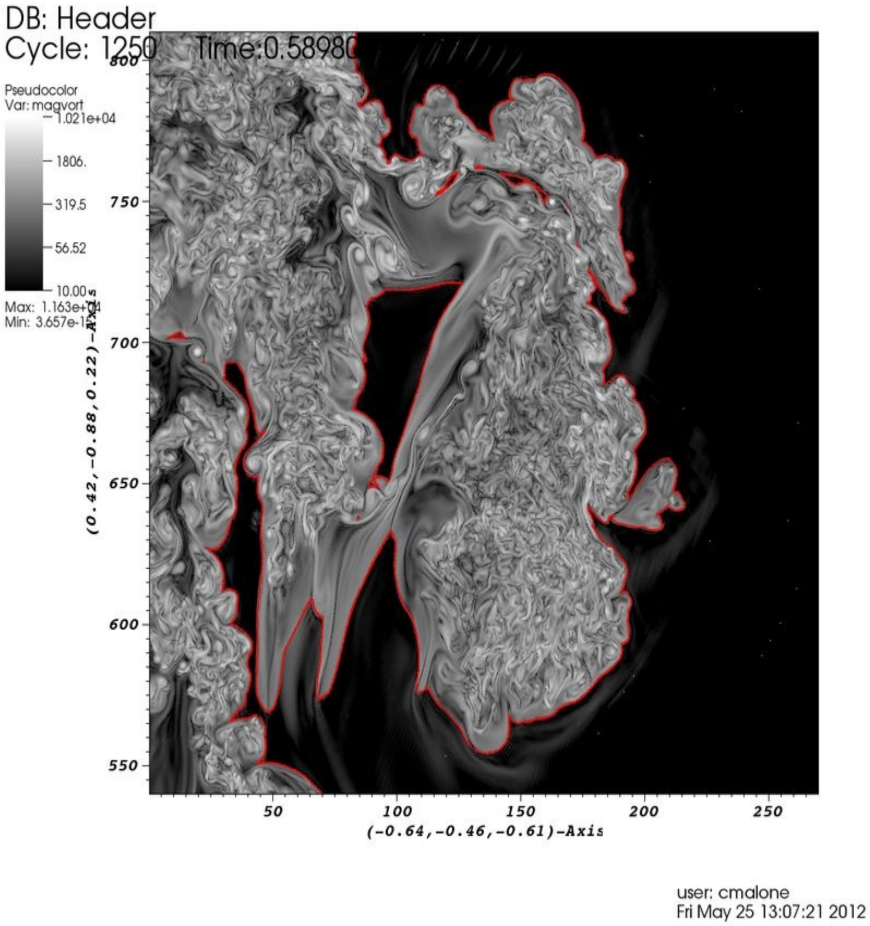
Malone+ 2013

Mag. vorticity



Plowing through convective field

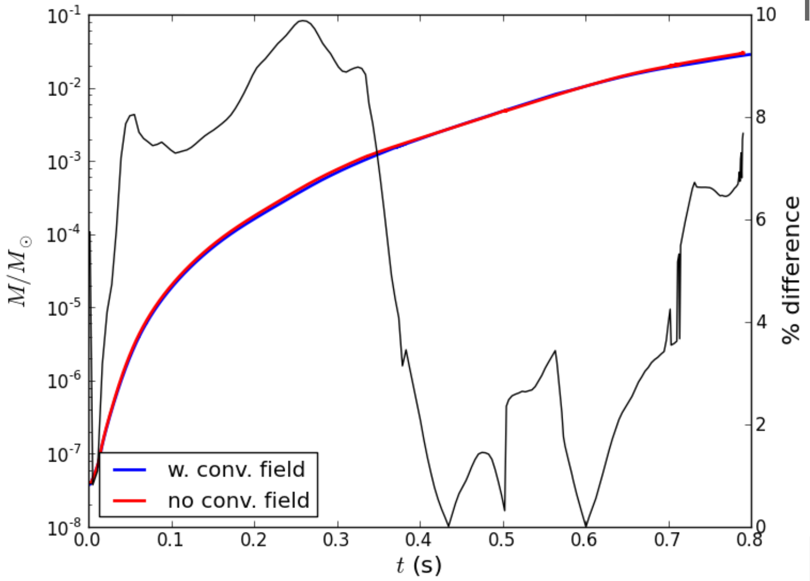
Mag. vorticity



Not much outside...

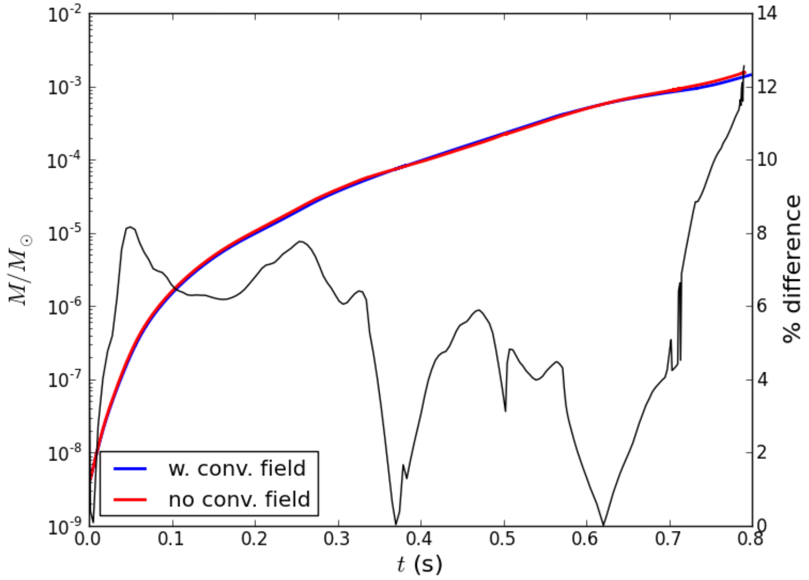
Effect of Convective Field

Total burned mass

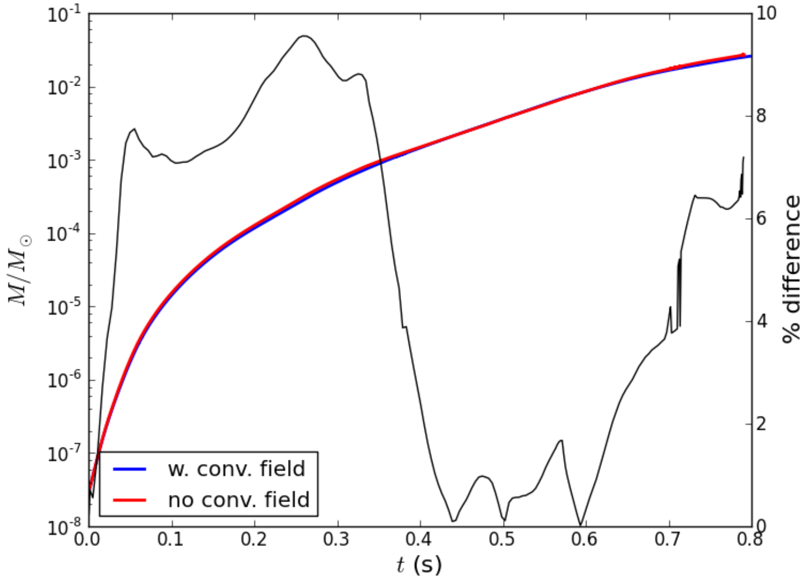


Malone+ 2013

Total IME mass

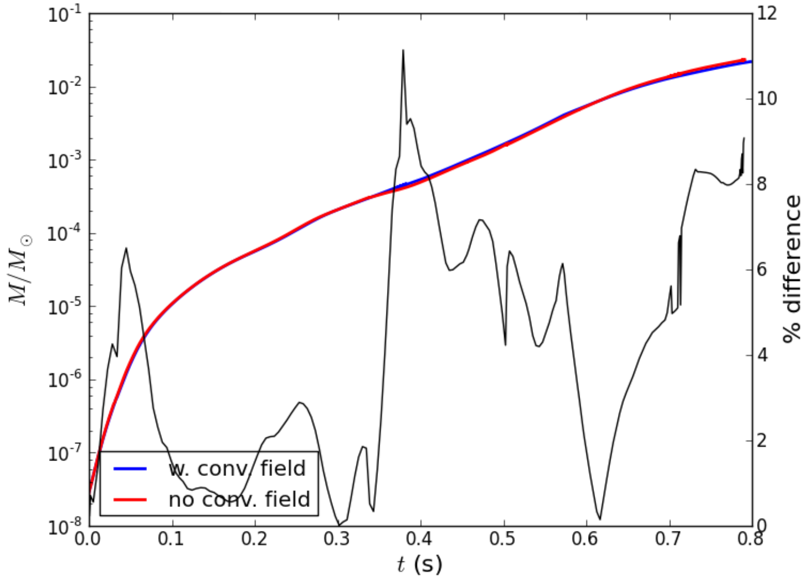


Total IGE mass



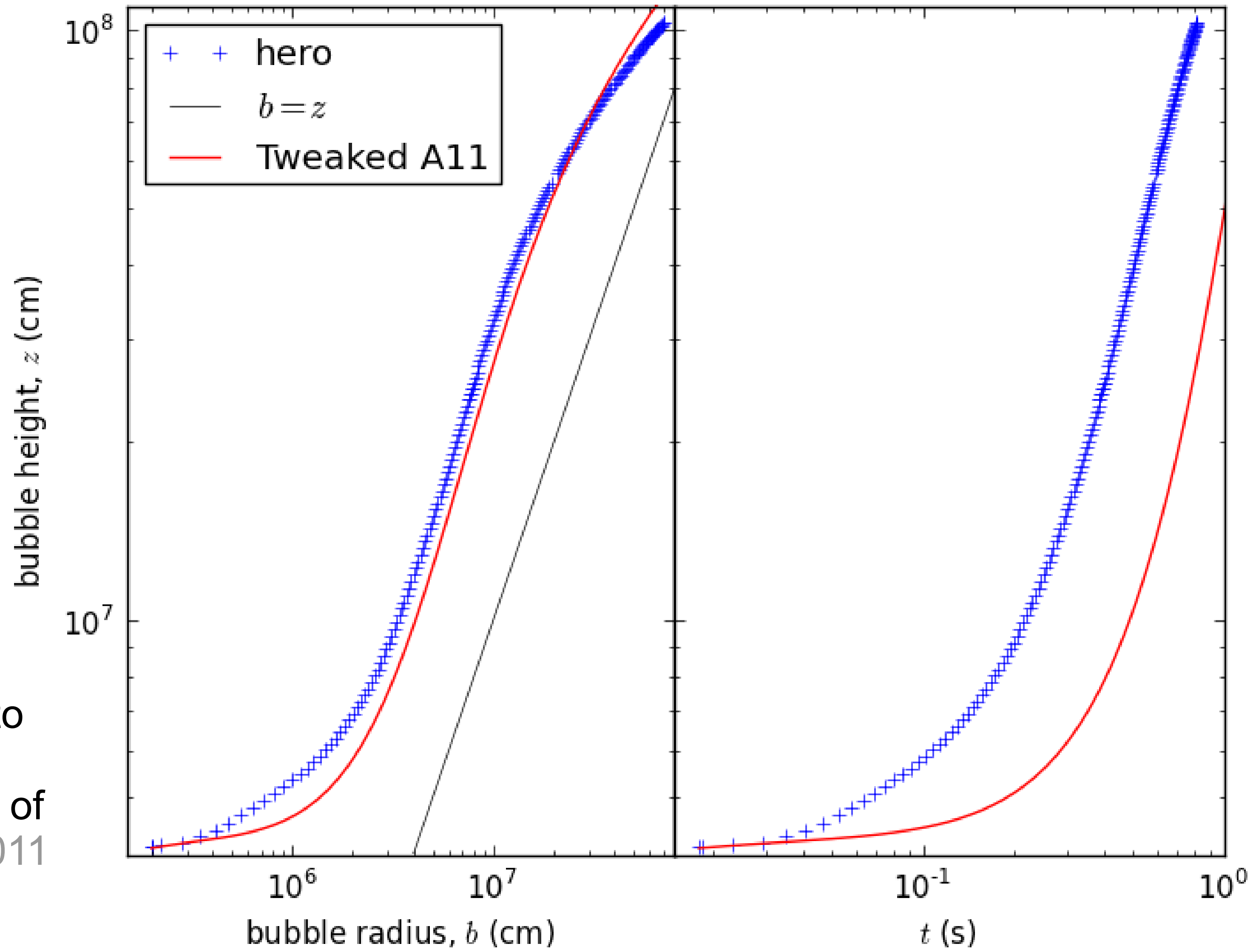
Differences on the 10% level!

Total ^{56}Ni mass



Comparison to Analytic Thermals

Malone+ 2013

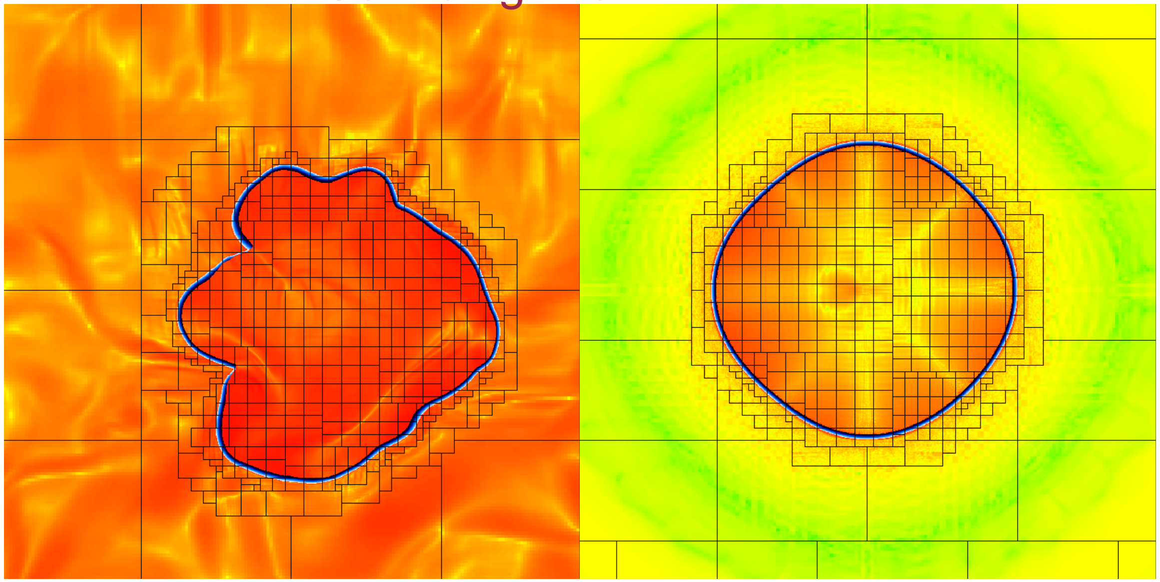


Compared to analytic prescription of Aspden+ 2011

Ignition Closer To the Center?

Malone+ 2013

Central ignition



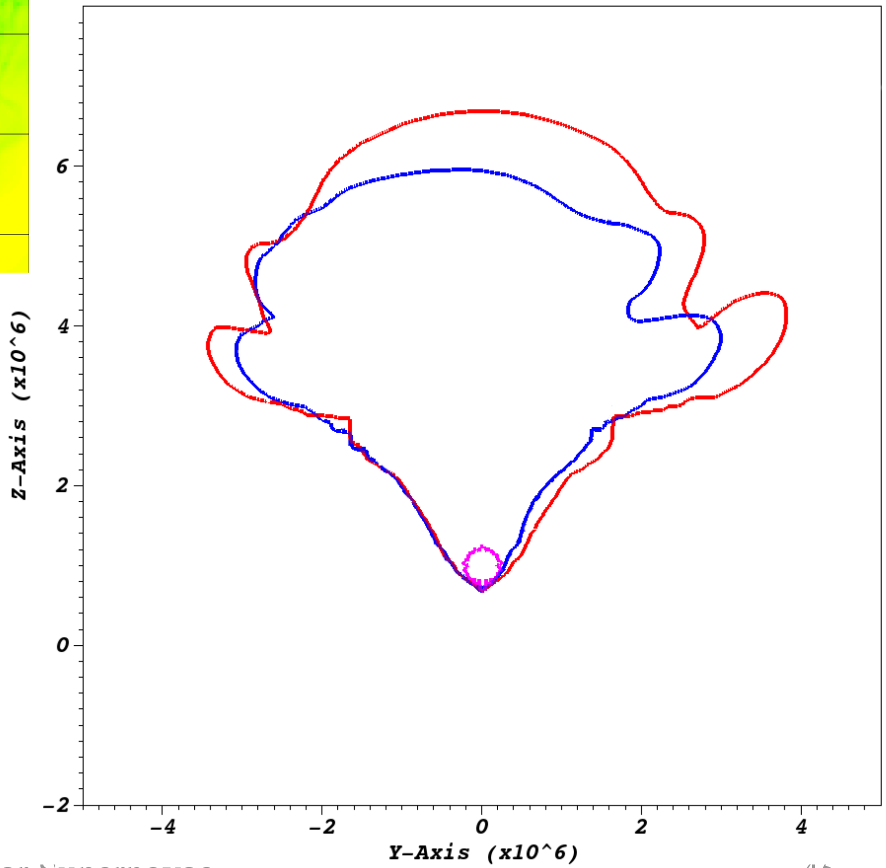
w. convection

no convection

Effect of turbulence on flame evolution stronger near center

Near central ignition tough to burn through to other side

10 km off-center



Conclusions

- Localized ignition likely off-center (~50 km)
- Ignition occurs in outflow region
- Background turbulence doesn't matter* unless you ignite near the center
- Most of the turbulence in the vicinity of the flame is within the ash
- A “burn through” seems quite difficult

Future Work

- More high-resolution simmering/ignition models
- Rotation (requires rework of Maestro algorithm)
- More realistic turbulent flame model (in progress, and see Ma+ 2013)
- Better characterization of turbulence
- Level sets?