Type Ia Supernova Simulations: The Deflagration Model and Beyond

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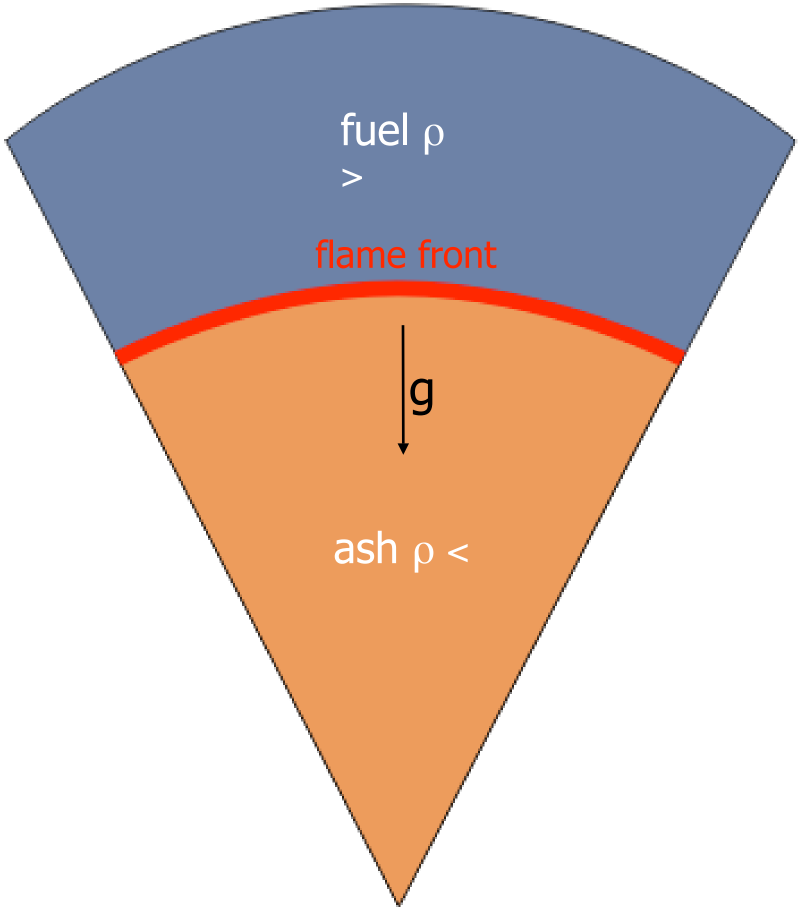
Turbulent combustion in SNe Ia

- Turbulent flame propagation in deflagration mode (consistent treatment)



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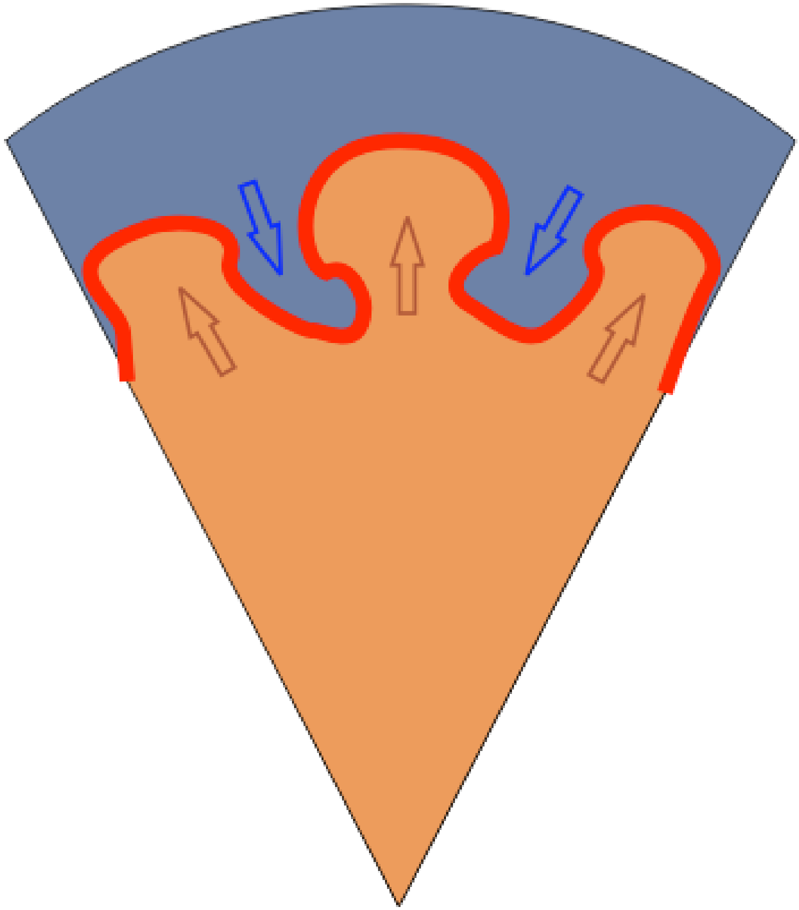

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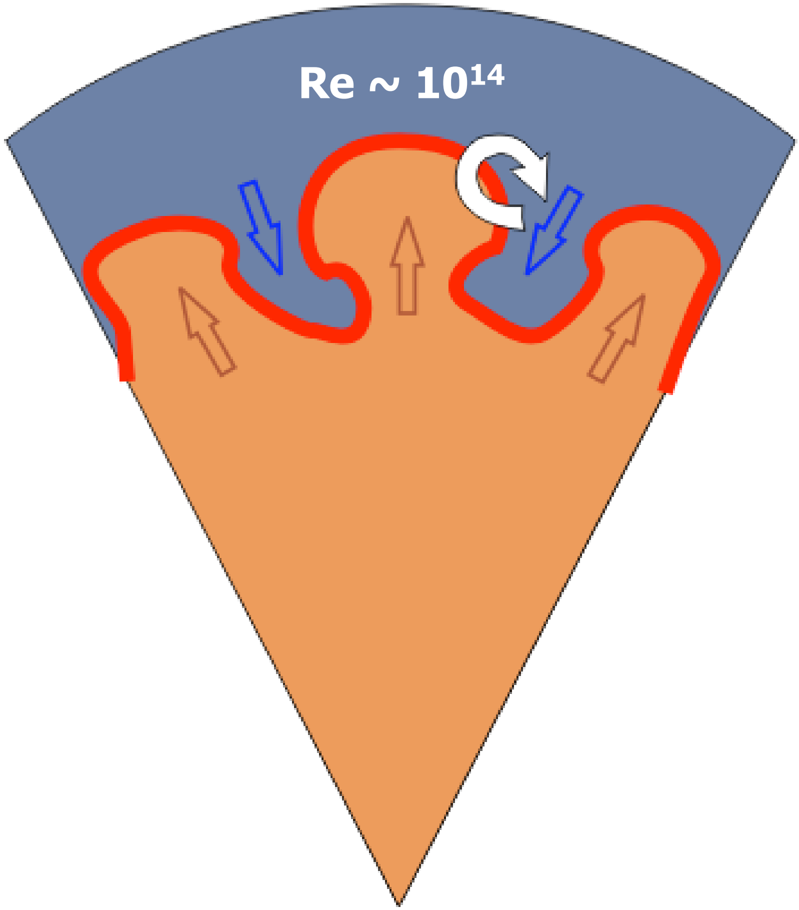
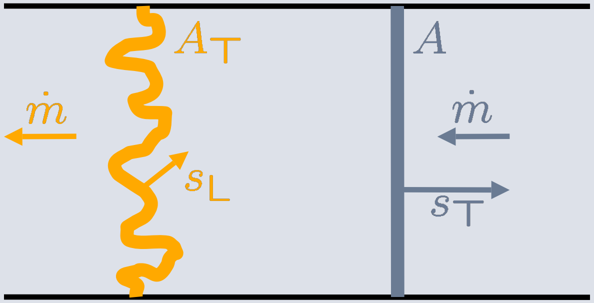


Turbulent deflagration

Turbulent deflagration

- most parts of the SN Ia explosion: turbulence does not penetrate internal flame structure: flamelet regime of turbulent combustion

Burning in the flamelet regime:

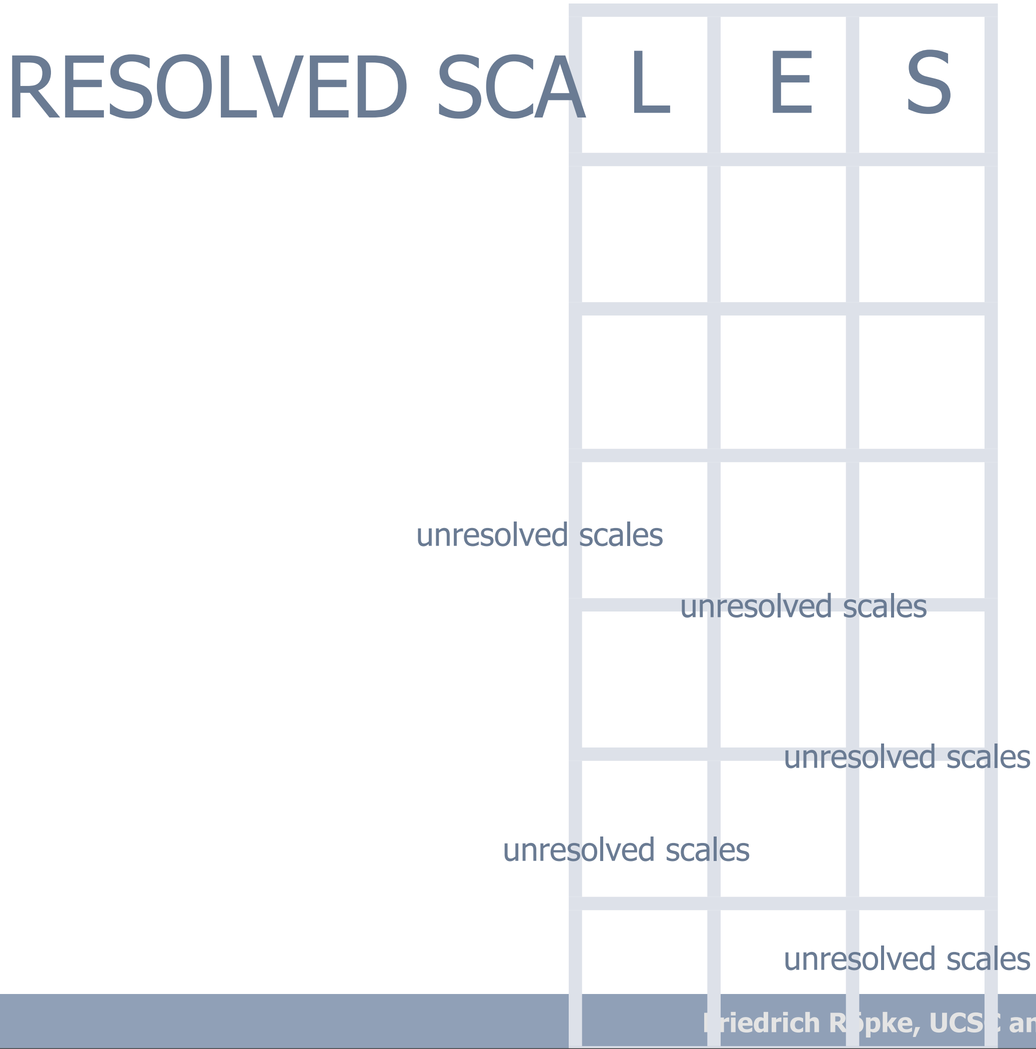


$\boxed{s_\mathrm{T} \propto v'}$ (Damköhler 1940)

- in very late stages: turbulence may affect burning microphysics → onset of distributed burning regime

Numerical Implementation I

- Large Eddy Simulation (LES) approach
- Subgrid-scale turbulence model (Niemeyer et al., 1995; Schmidt et al., 2005)



RESOLVED SCA L E S

unresolved scales

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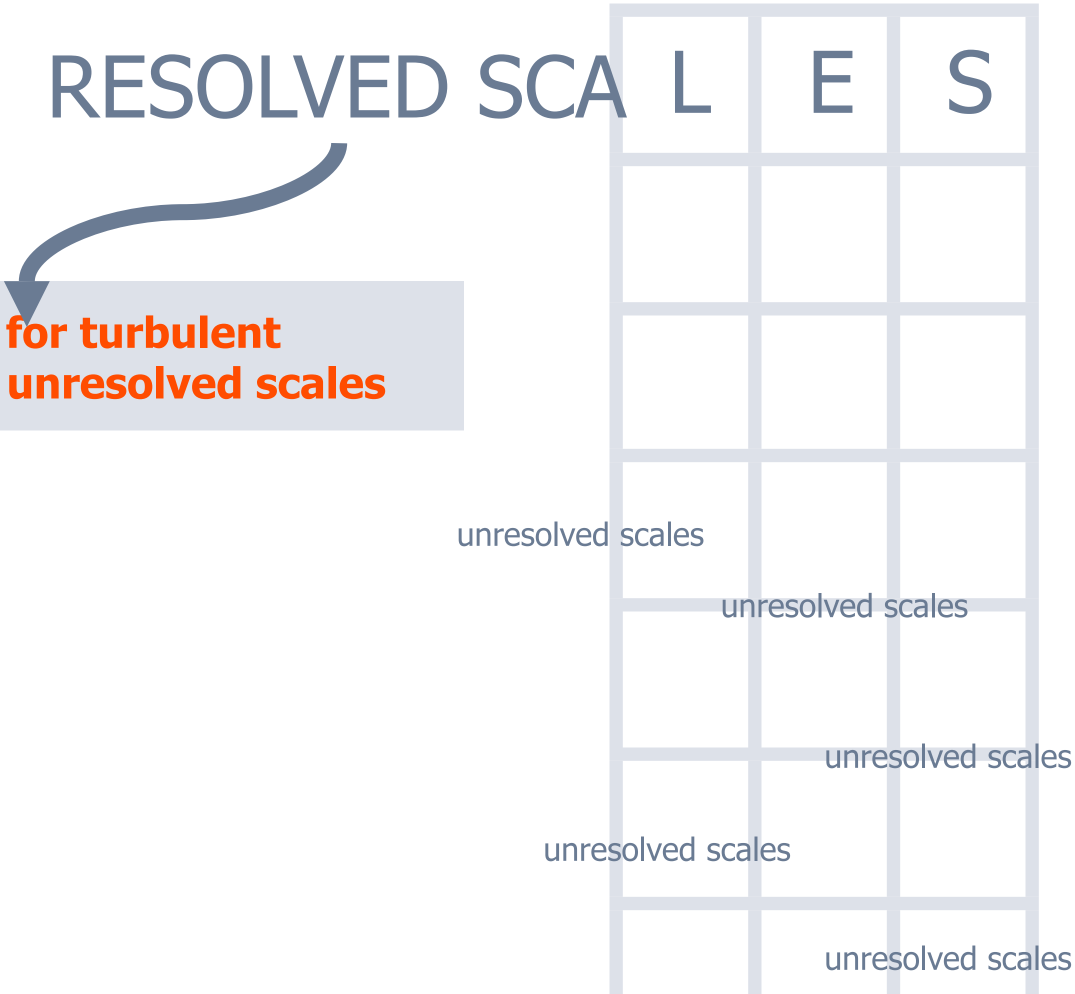

Balance equation for turbulent kinetic energy on unresolved scales

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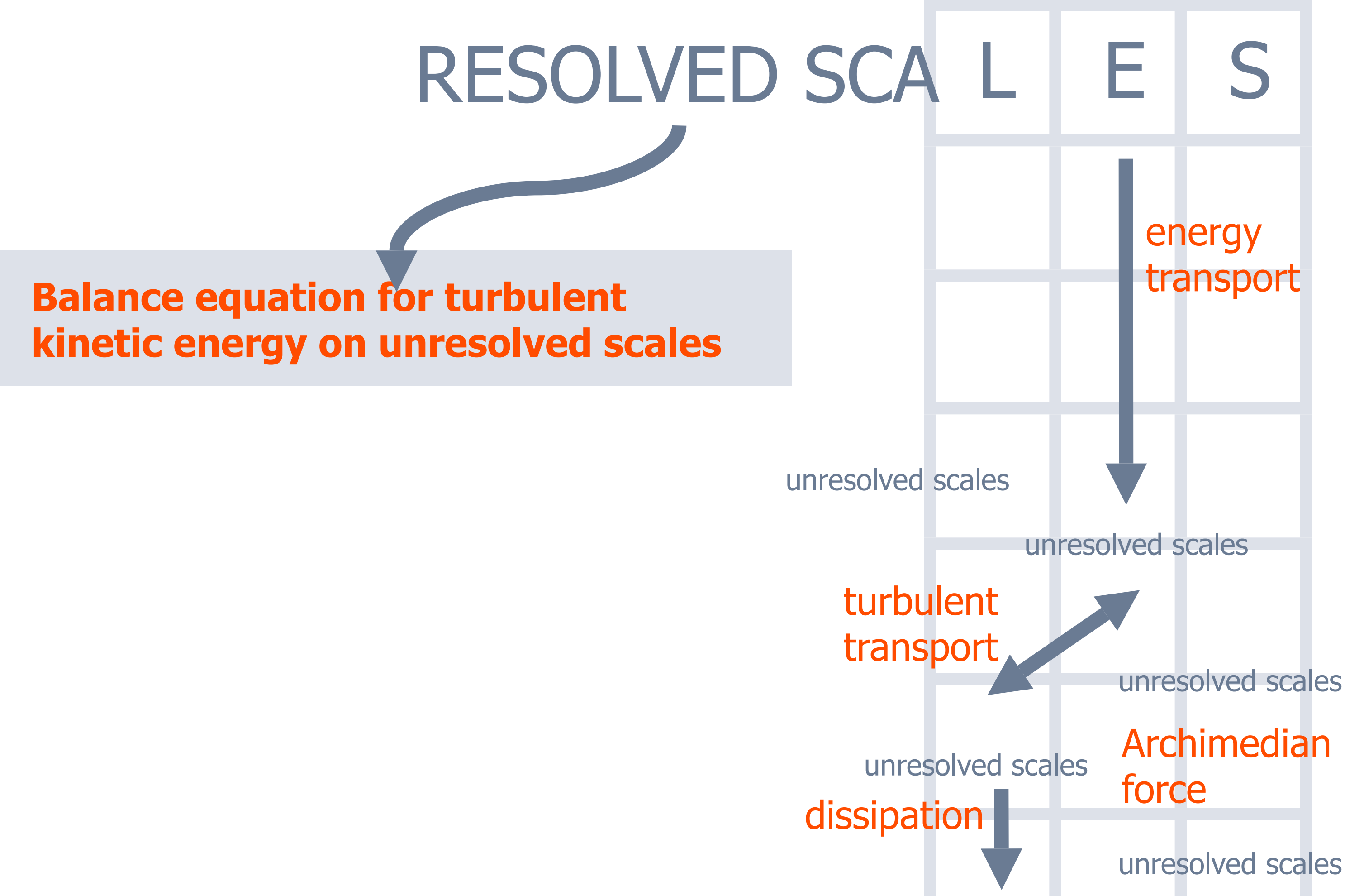

RESOLVED SCA L E S

Balance equation for turbulent kinetic energy on unresolved scales

energy transport

unresolved scales

unresolved scales

turbulent transport

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Archimedian force

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dissipation

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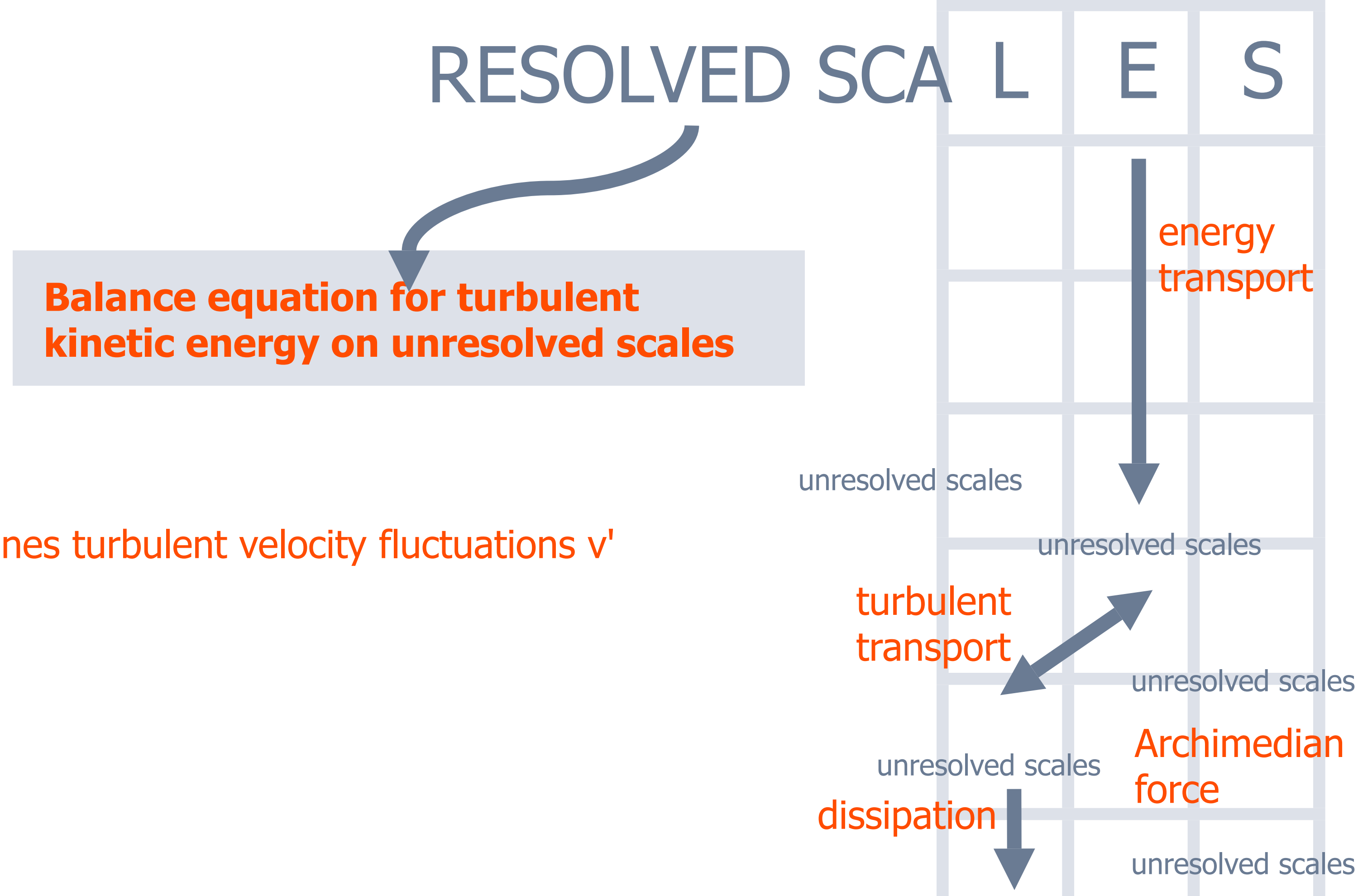


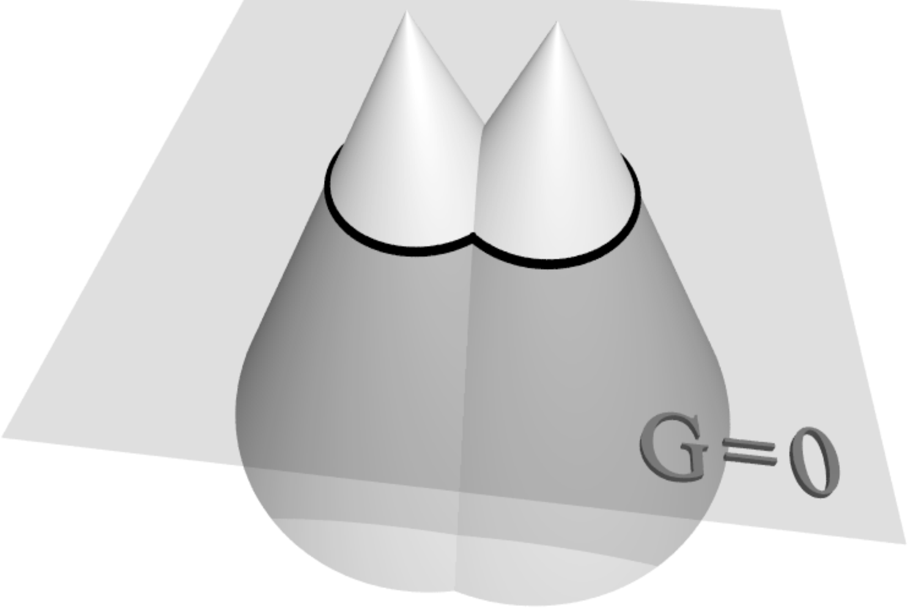
Balance equation for turbulent kinetic energy on unresolved scales

! determines turbulent velocity fluctuations v'

Numerical Implementation II

$$G \quad = \quad \{\vec{r} \mid G(\vec{r},t) = 0\}$$

$$\frac{\partial G}{\partial t} = (\mathbf{v}_{\mathrm{u}}\mathbf{n} + s_{\mathrm{u}}) \, |\nabla G|$$



M. Reinecke

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- seen from scales of WD: flame is discontinuity between fuel and ashes

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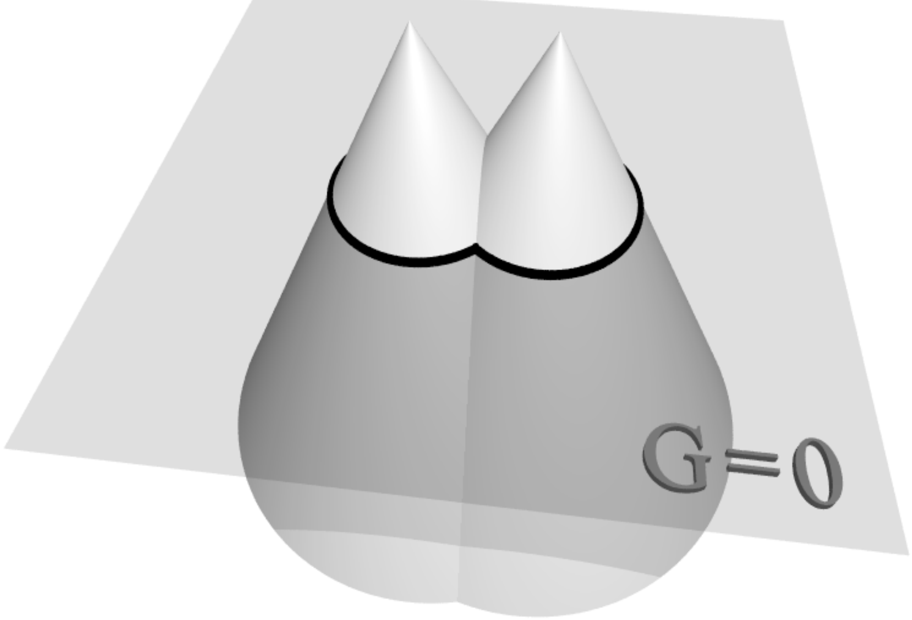

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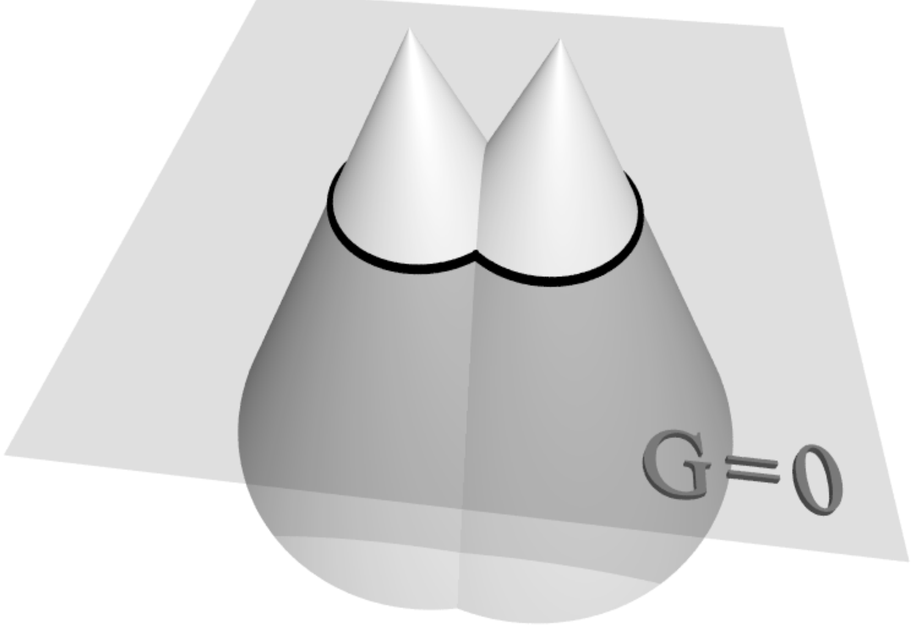

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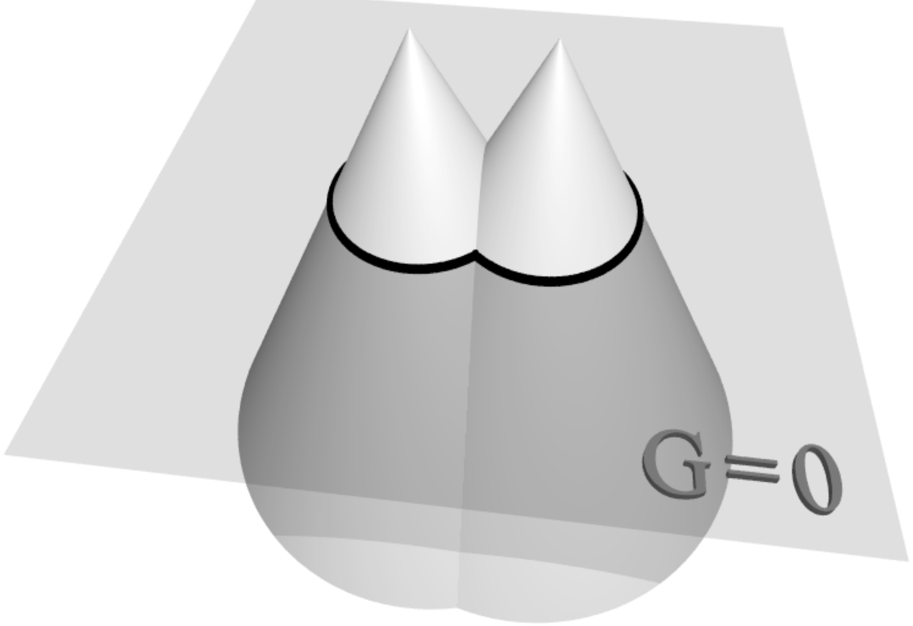

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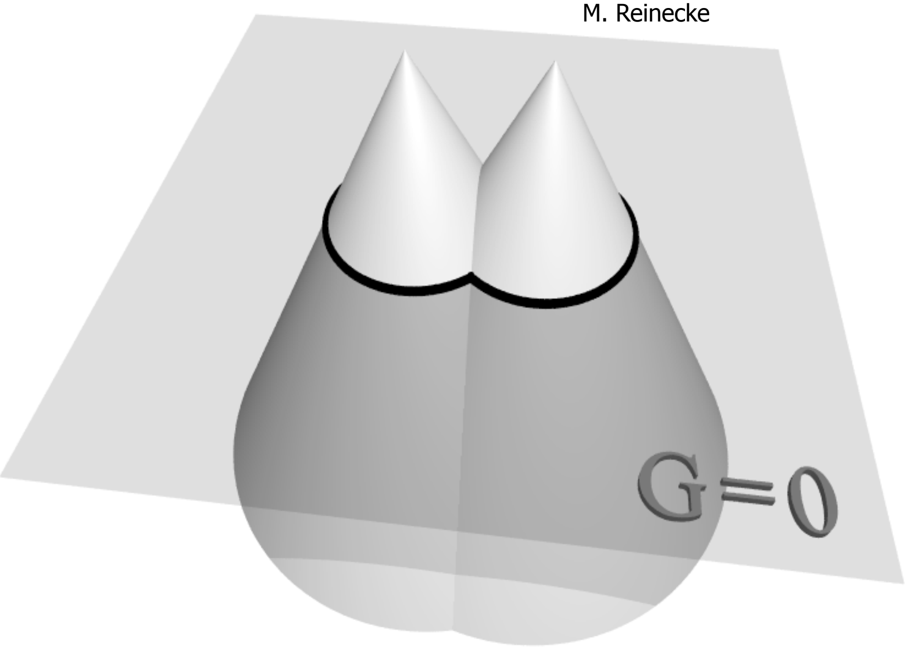
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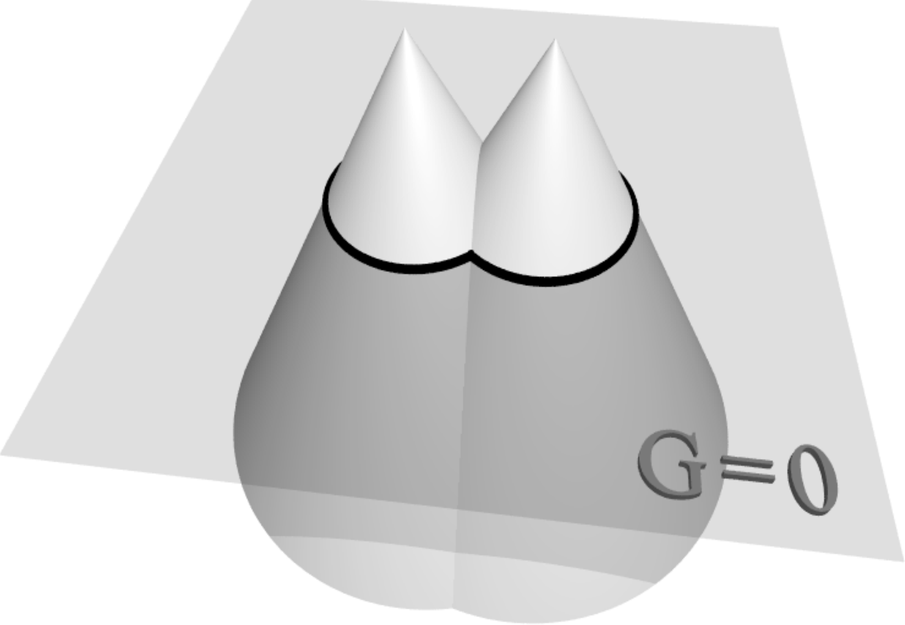

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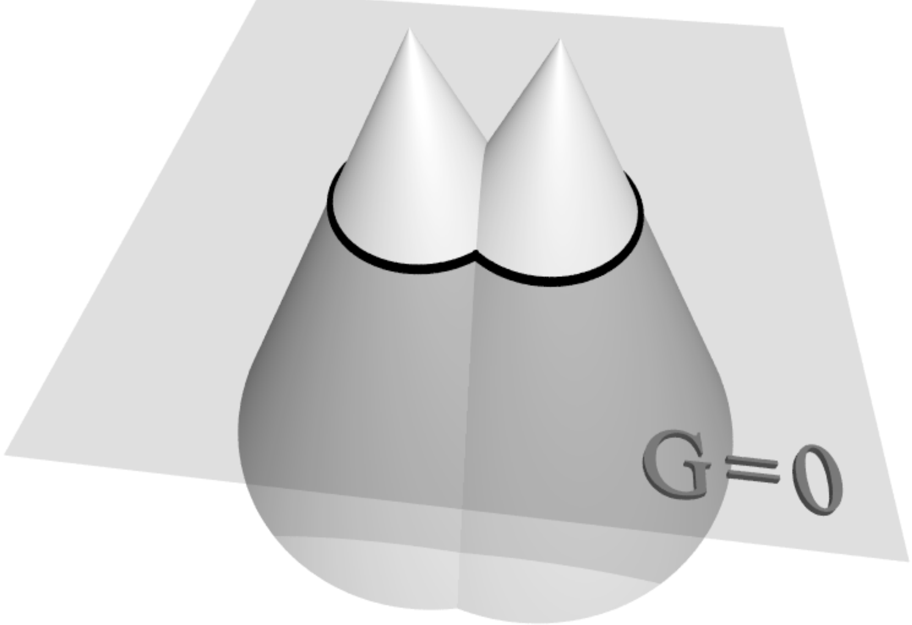
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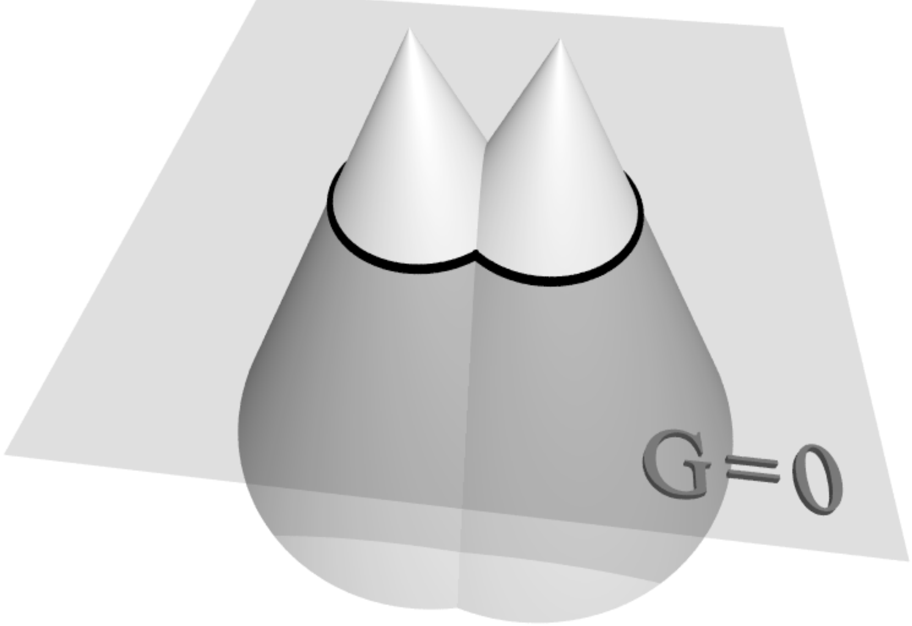

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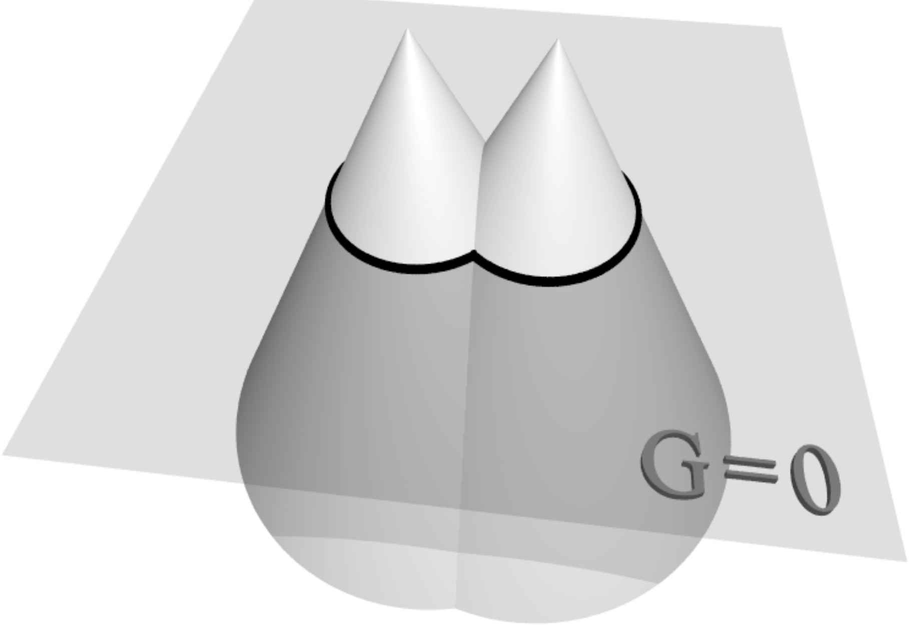

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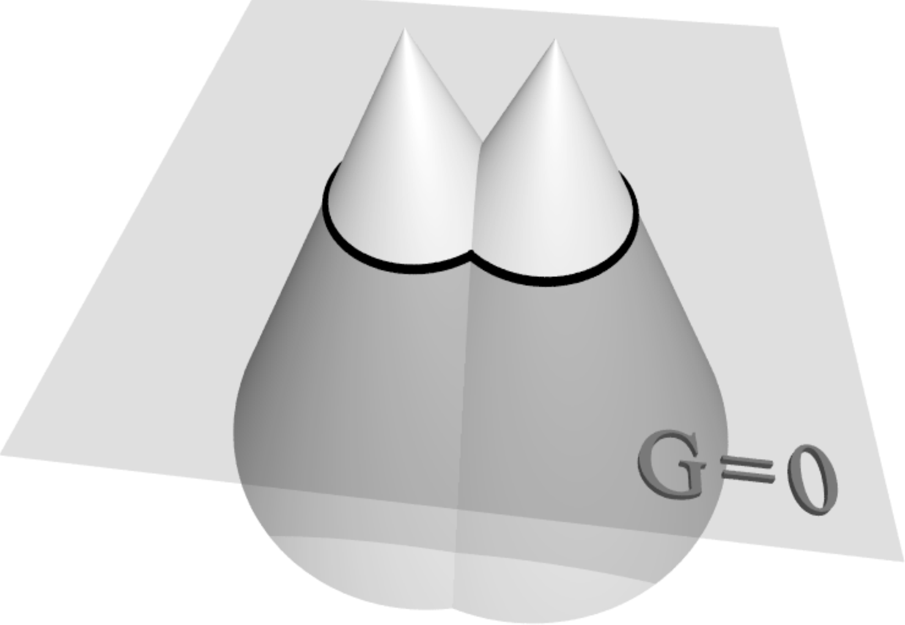

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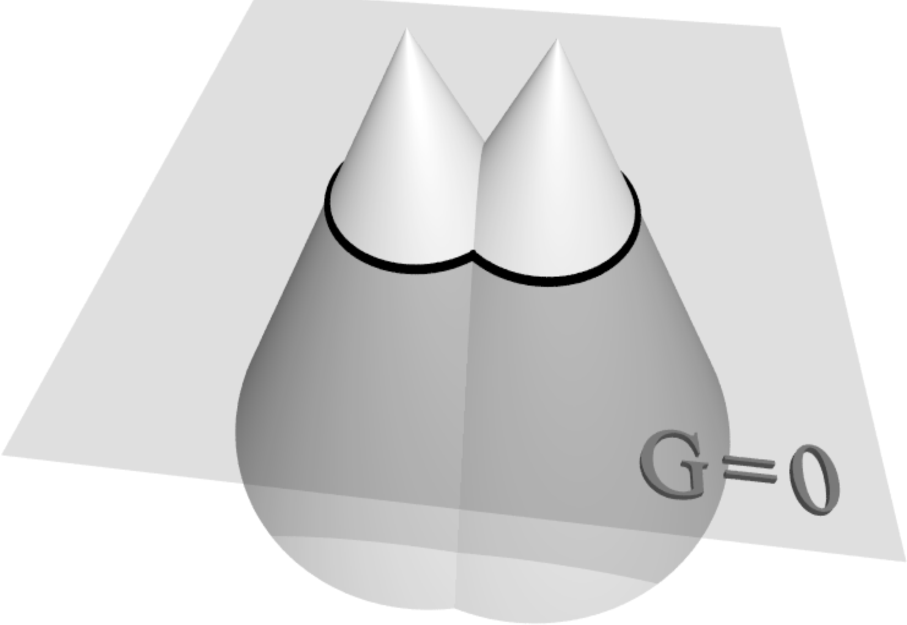

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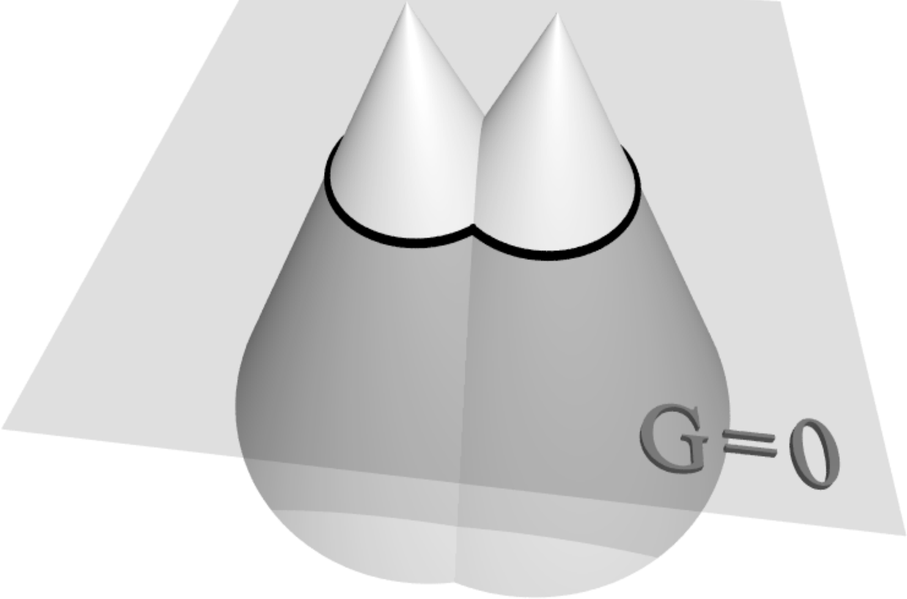

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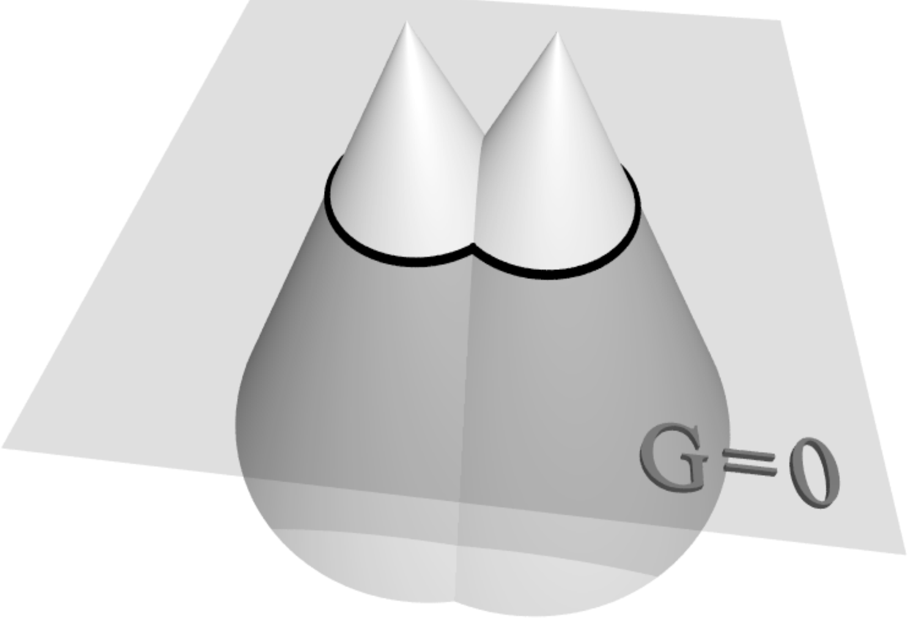

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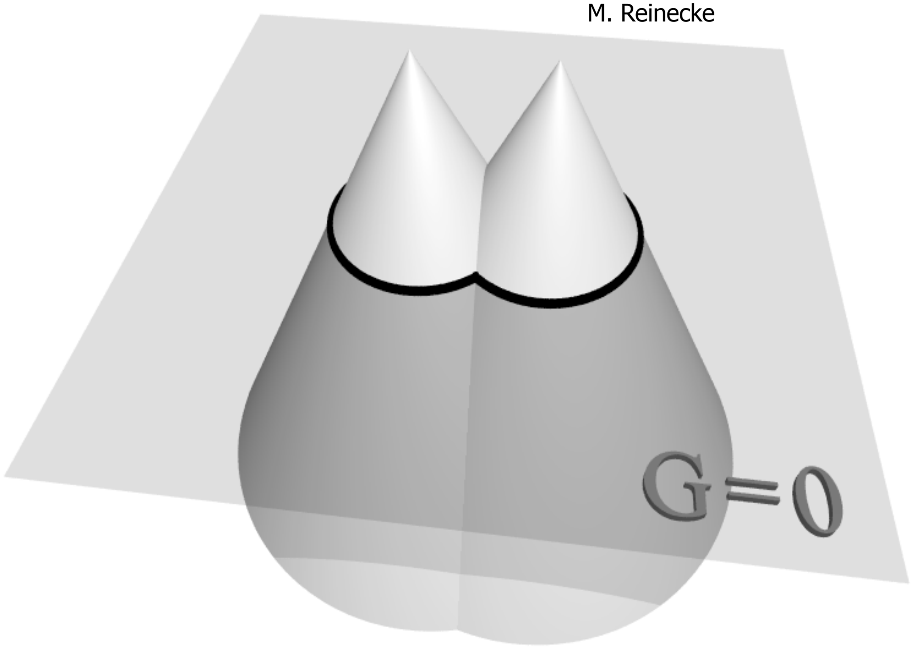

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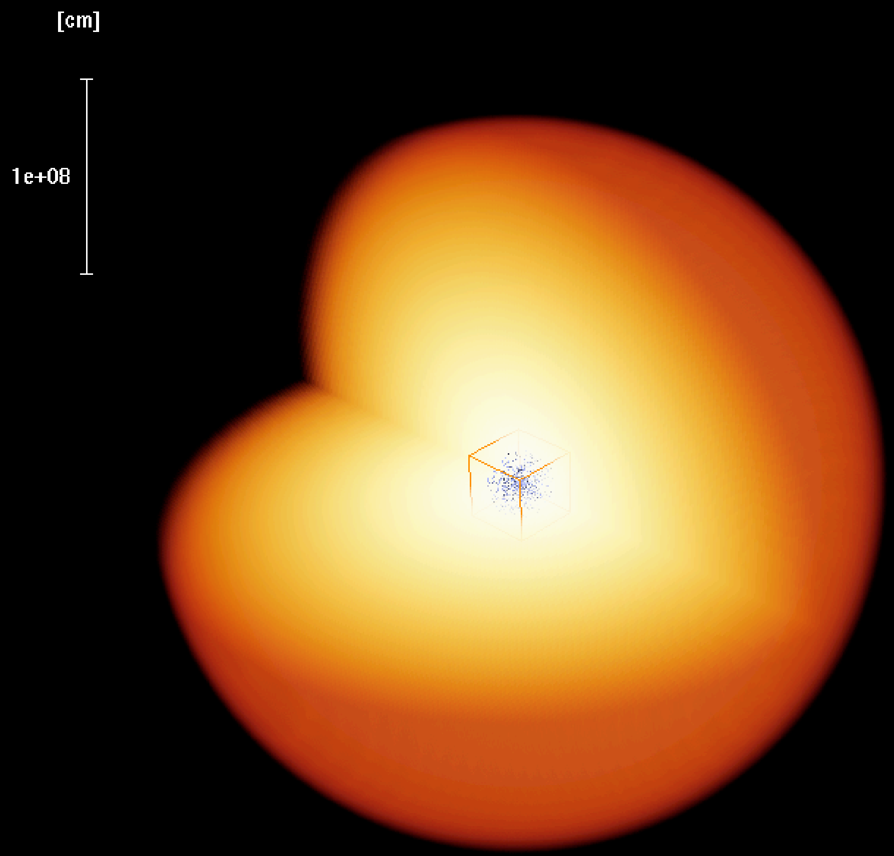
- simplified description of burning: everything behind G=0 isosurface is nuclear ash; depending on fuel density at burning: intermediate mass elements (“Mg”) or NSE (mixture of “Ni” and ^{4}He)

Pushing simulations to the limit

high-resolution model, improved subgrid-scale turbulence model, new burning law, multi-spot ignition:

- 1024^3 computational cells, 500.000 CPU hours on IBM regatta

Pushing simulations to the limit



t=0.0 s

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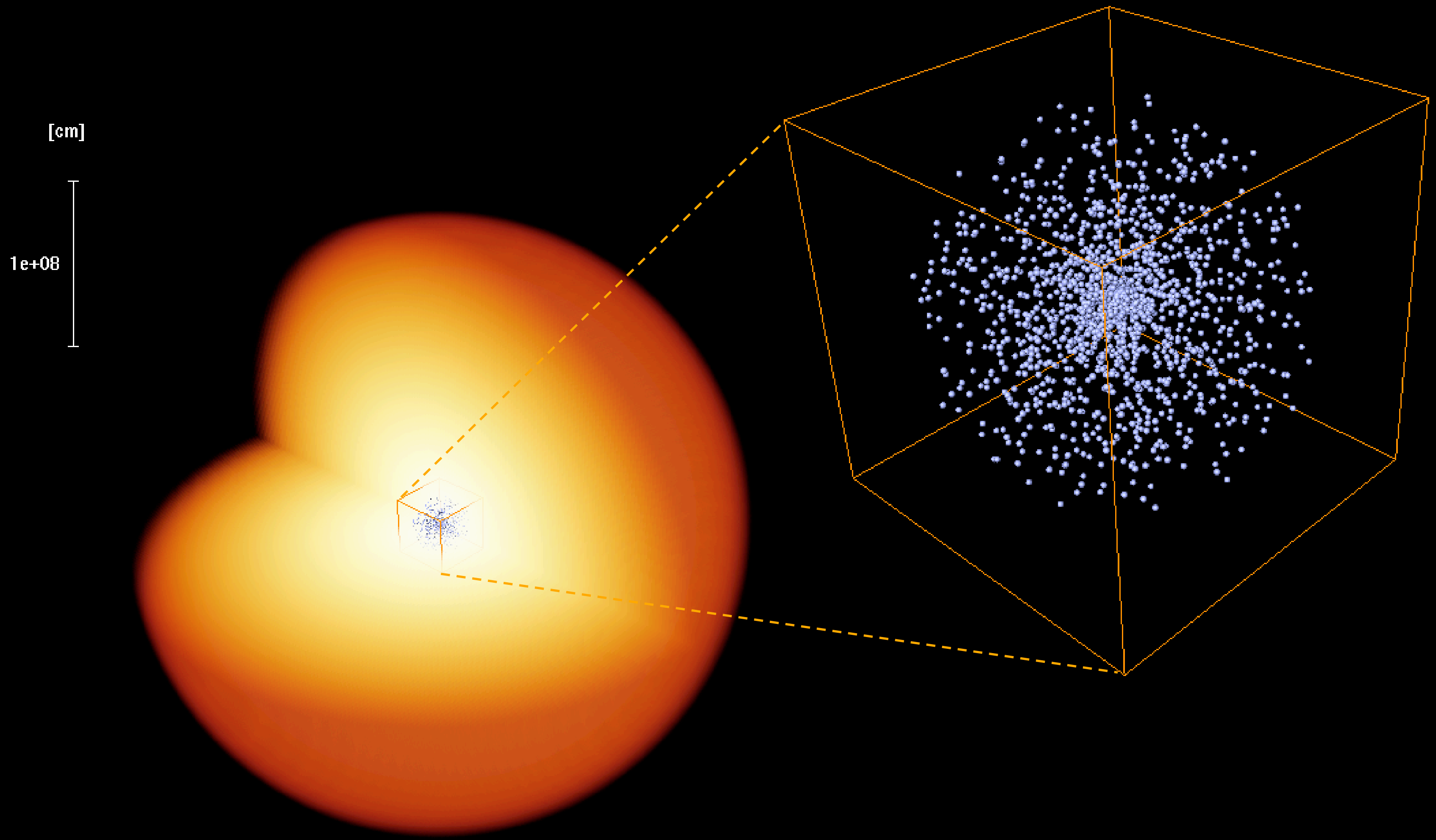

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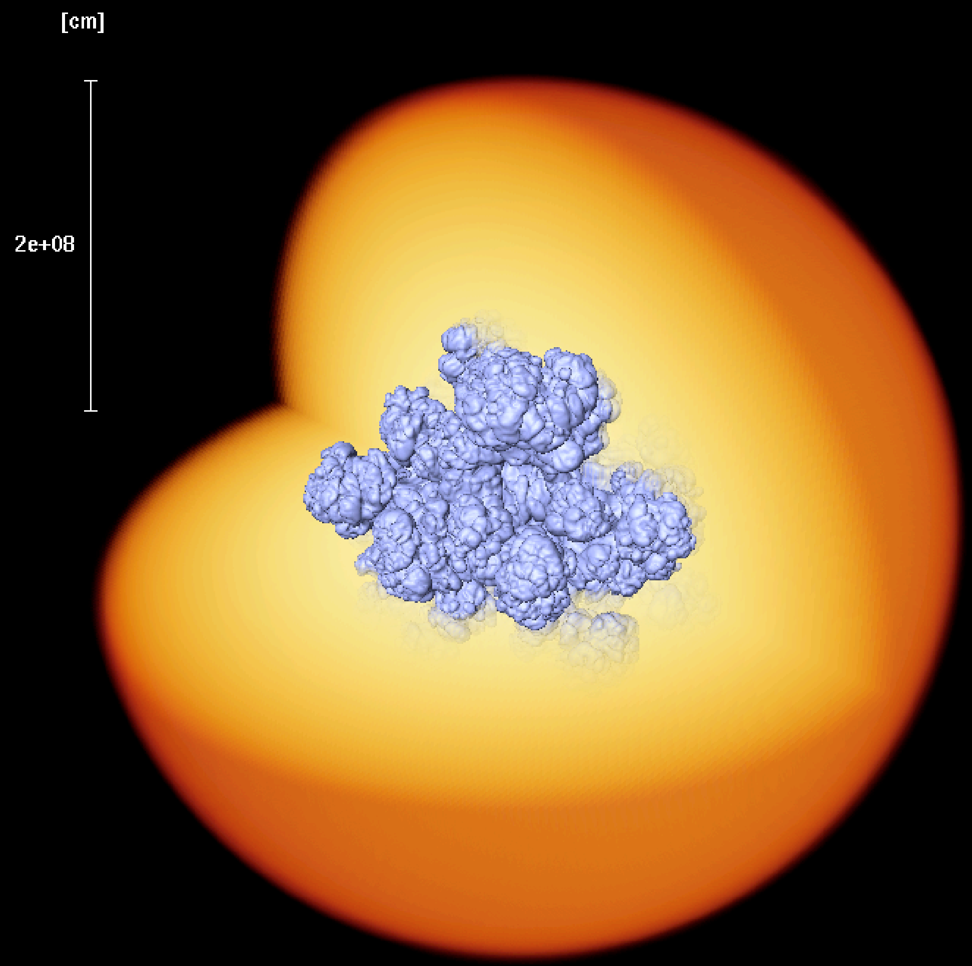
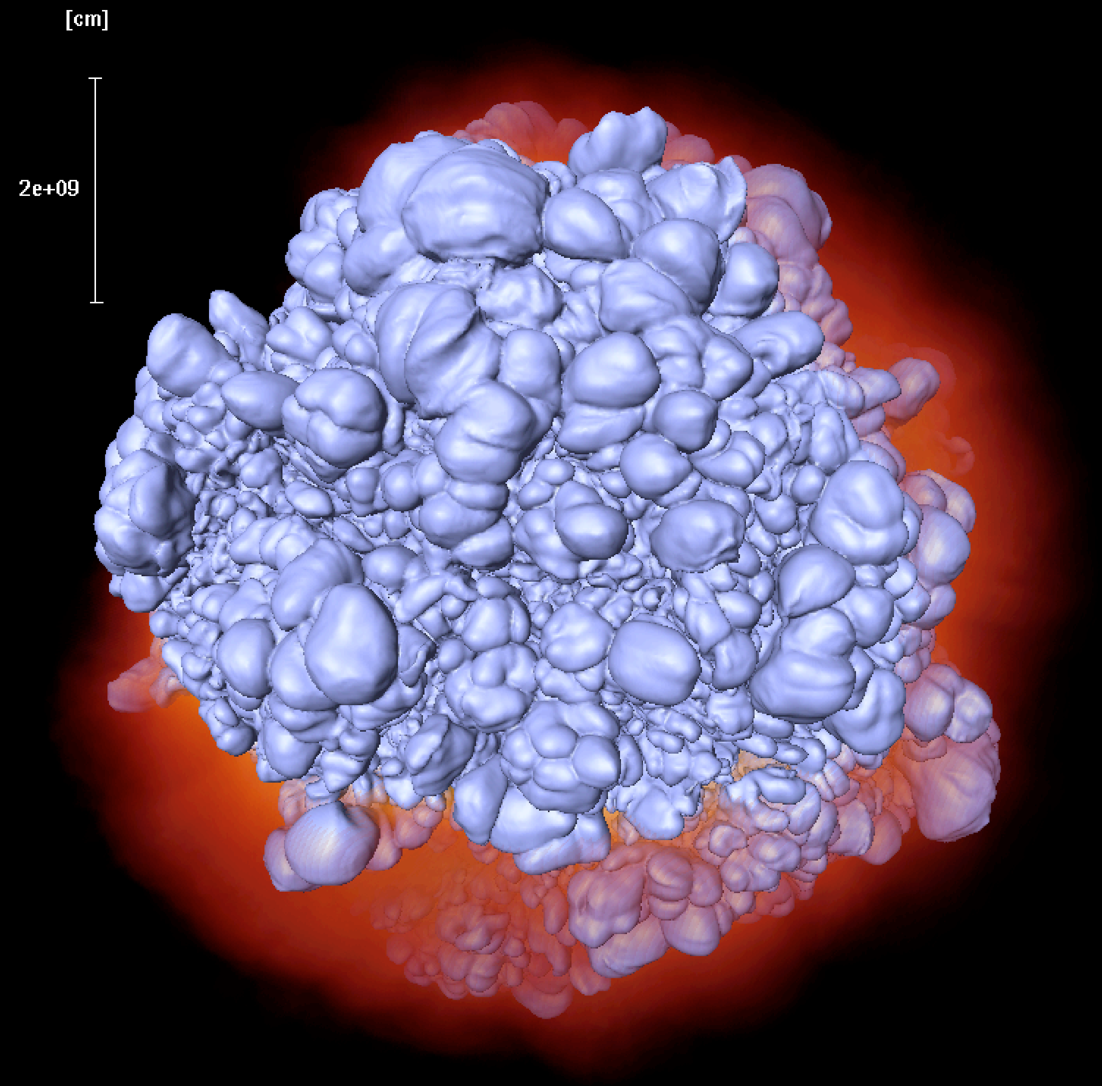


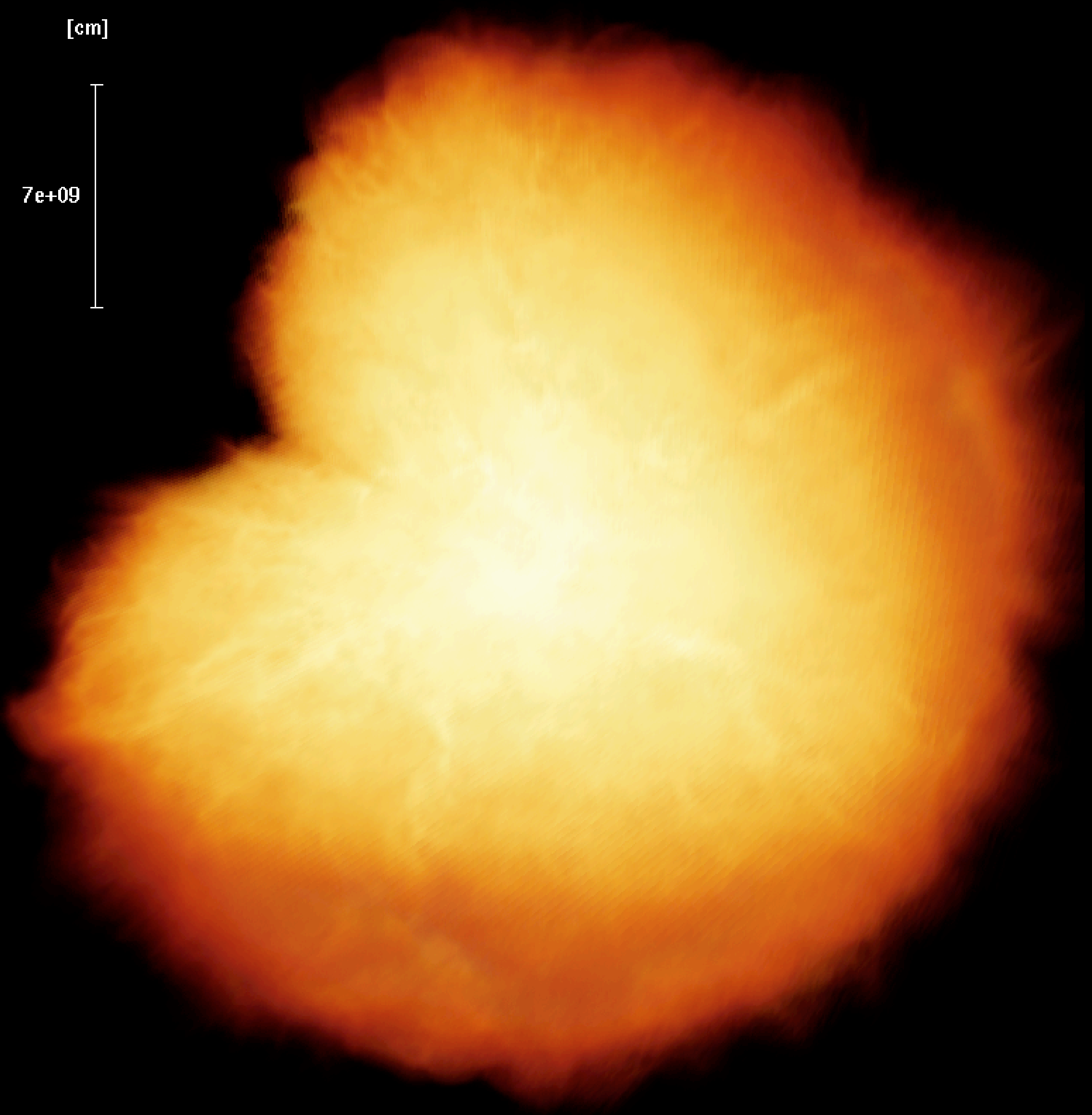
t=0.6 s

Pushing simulations to the limit



t=3.0 s

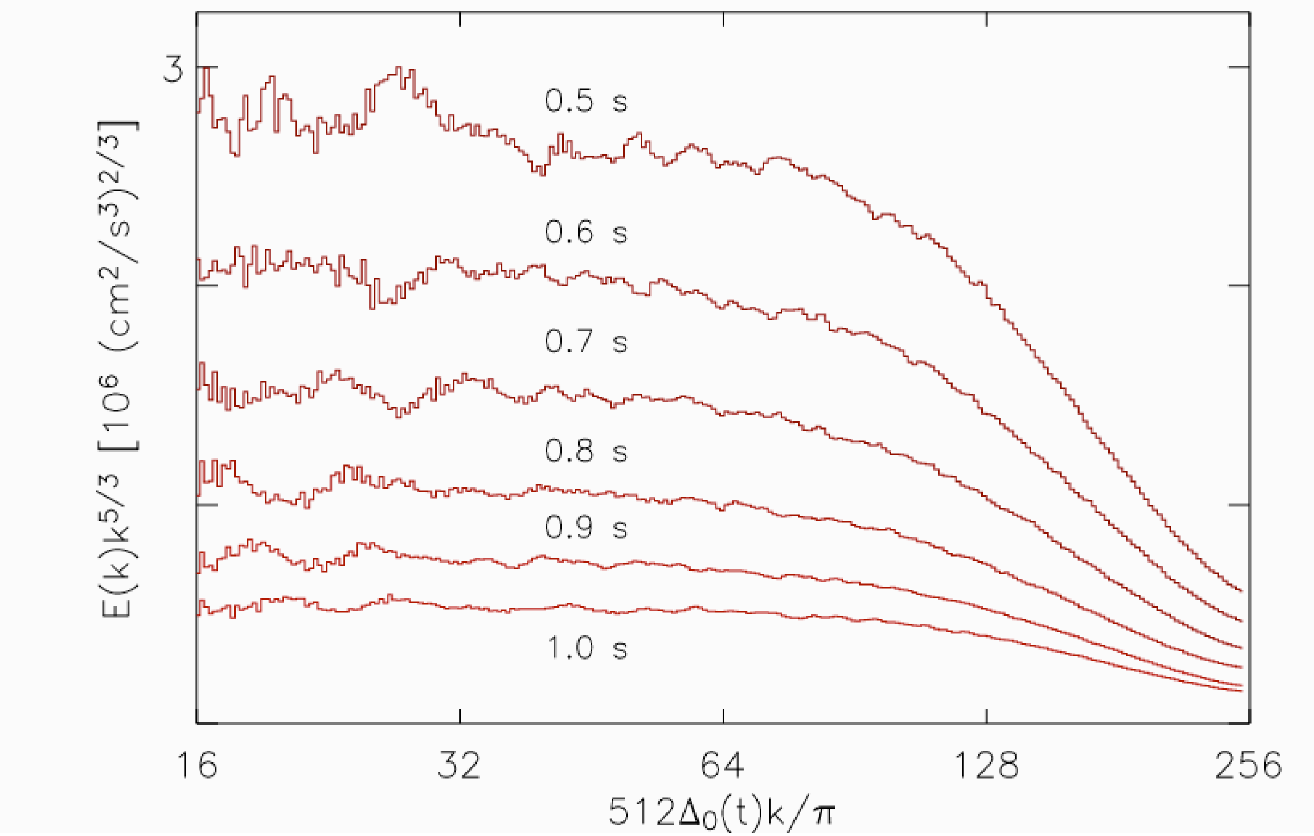
Pushing simulations to the limit



t=10.0s

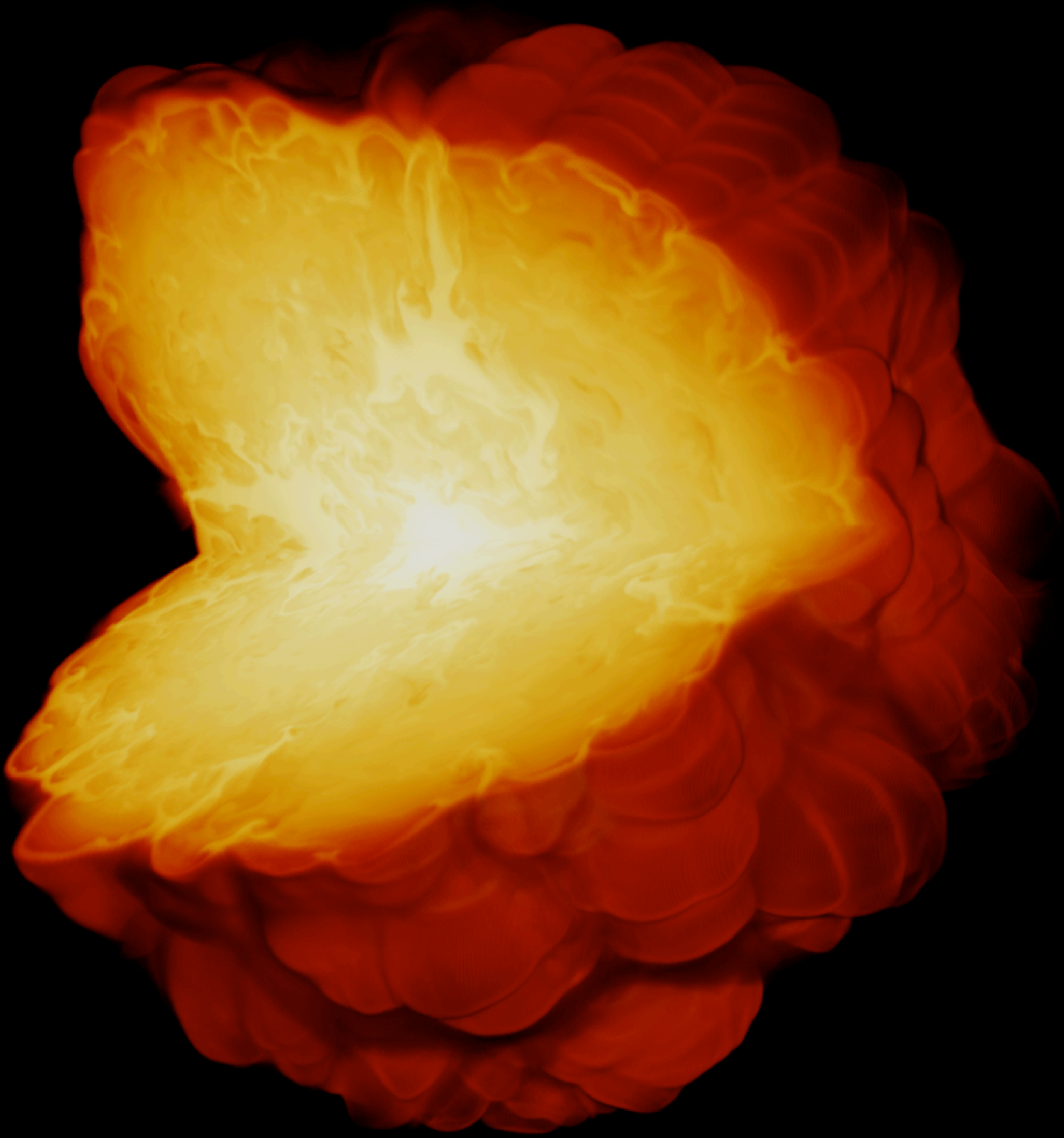
Turbulence on resolved scales

- Spectrum normalized to Kolmogorov scaling (Schmidt et al. in prep., Röpke et al., subm.)



- Turbulence following Kolmogorov scaling found on resolved scales ! LES ansatz justified

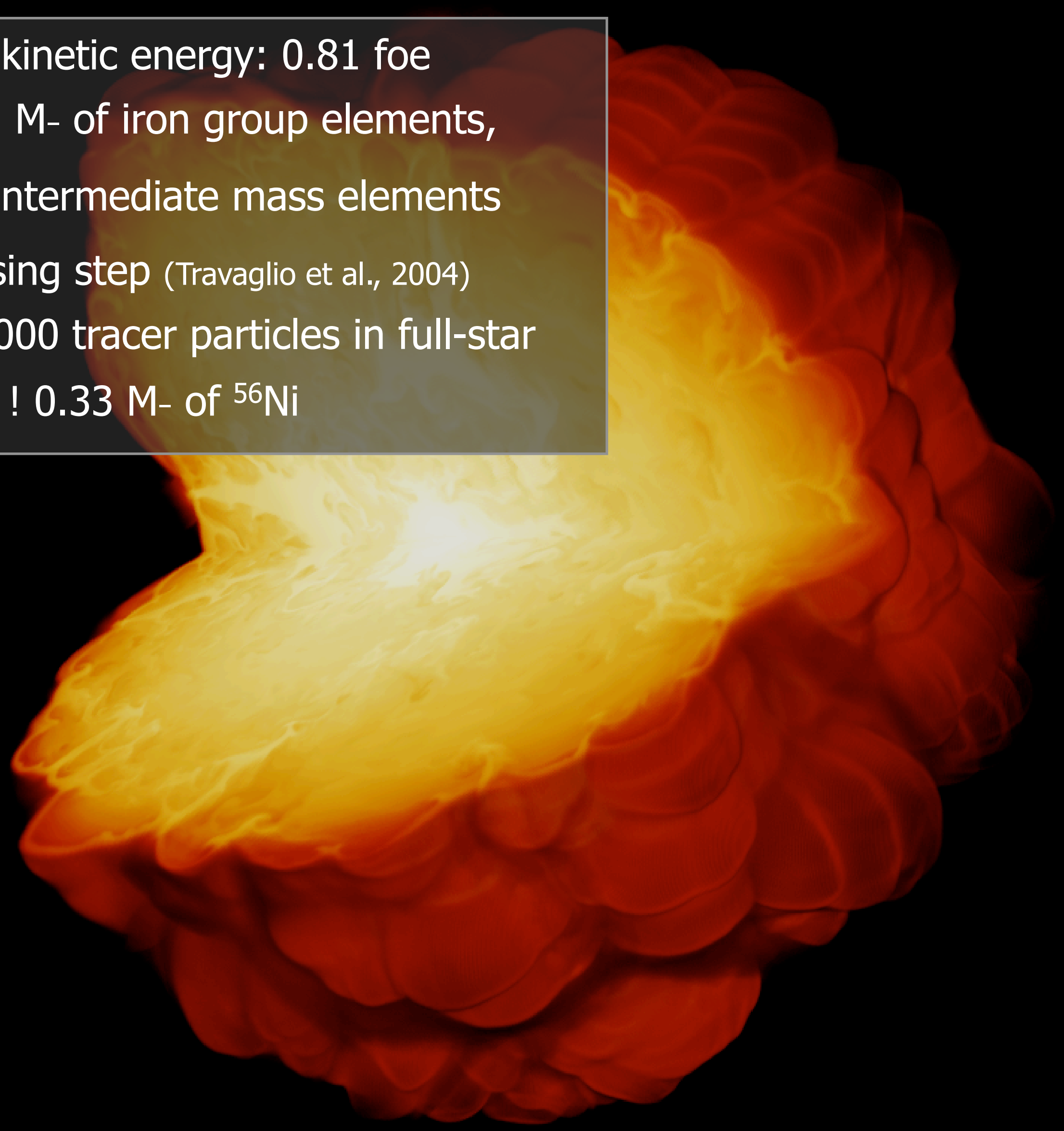
Results



Results

- asymptotic kinetic energy: 0.81 foe
- hydro: 0.61 M- of iron group elements,

  0.43 M- of intermediate mass elements
- postprocessing step (Travaglio et al., 2004) with ~150 000 tracer particles in full-star simulations ! 0.33 M- of ^{56}Ni



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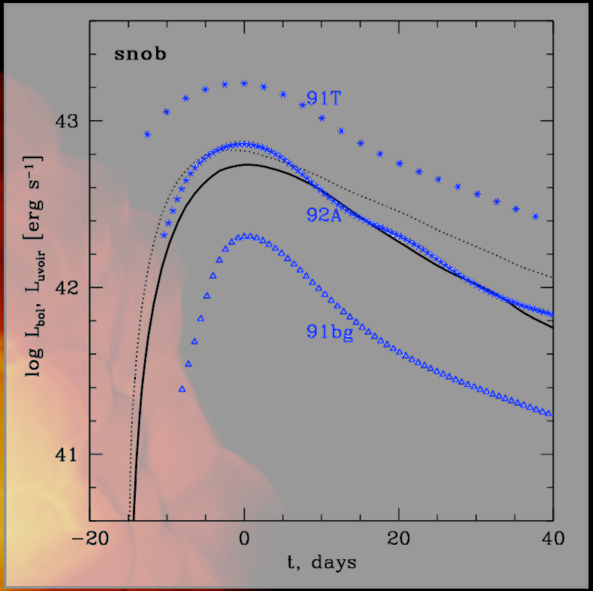
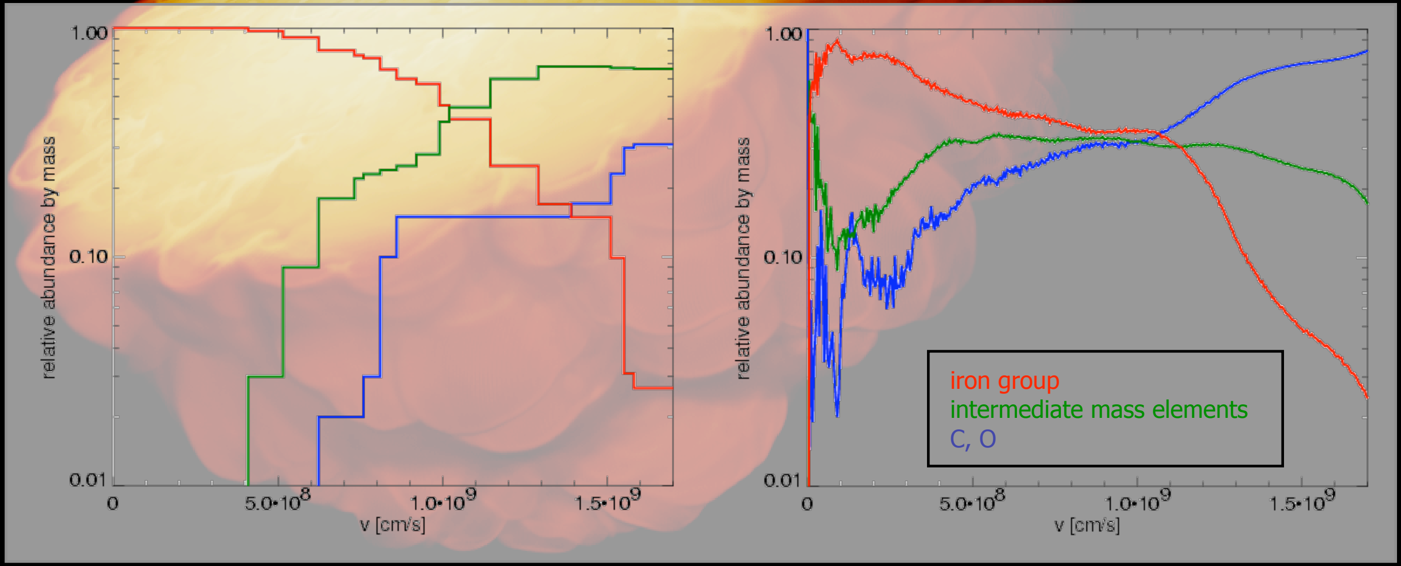
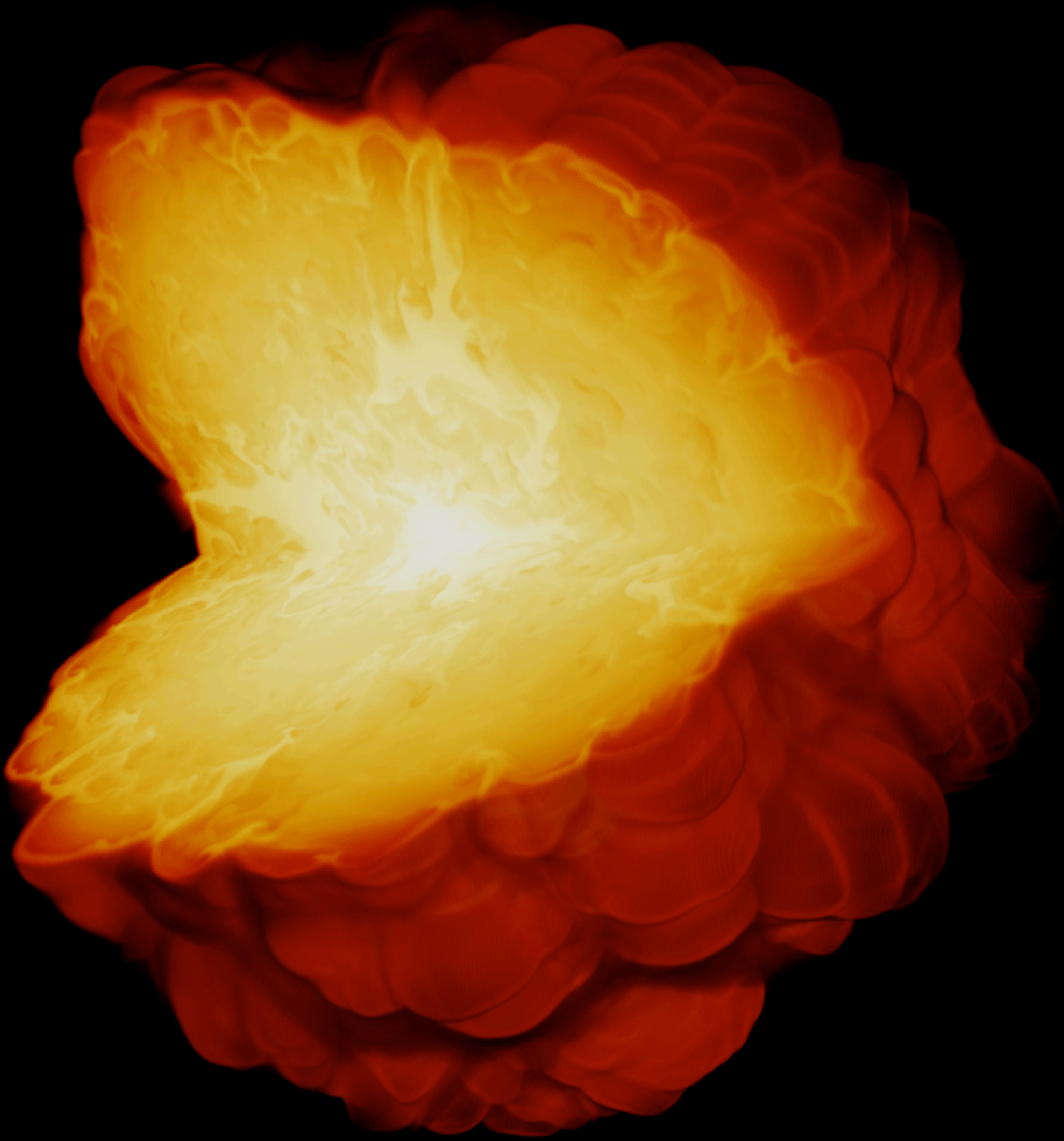




Deflagration model



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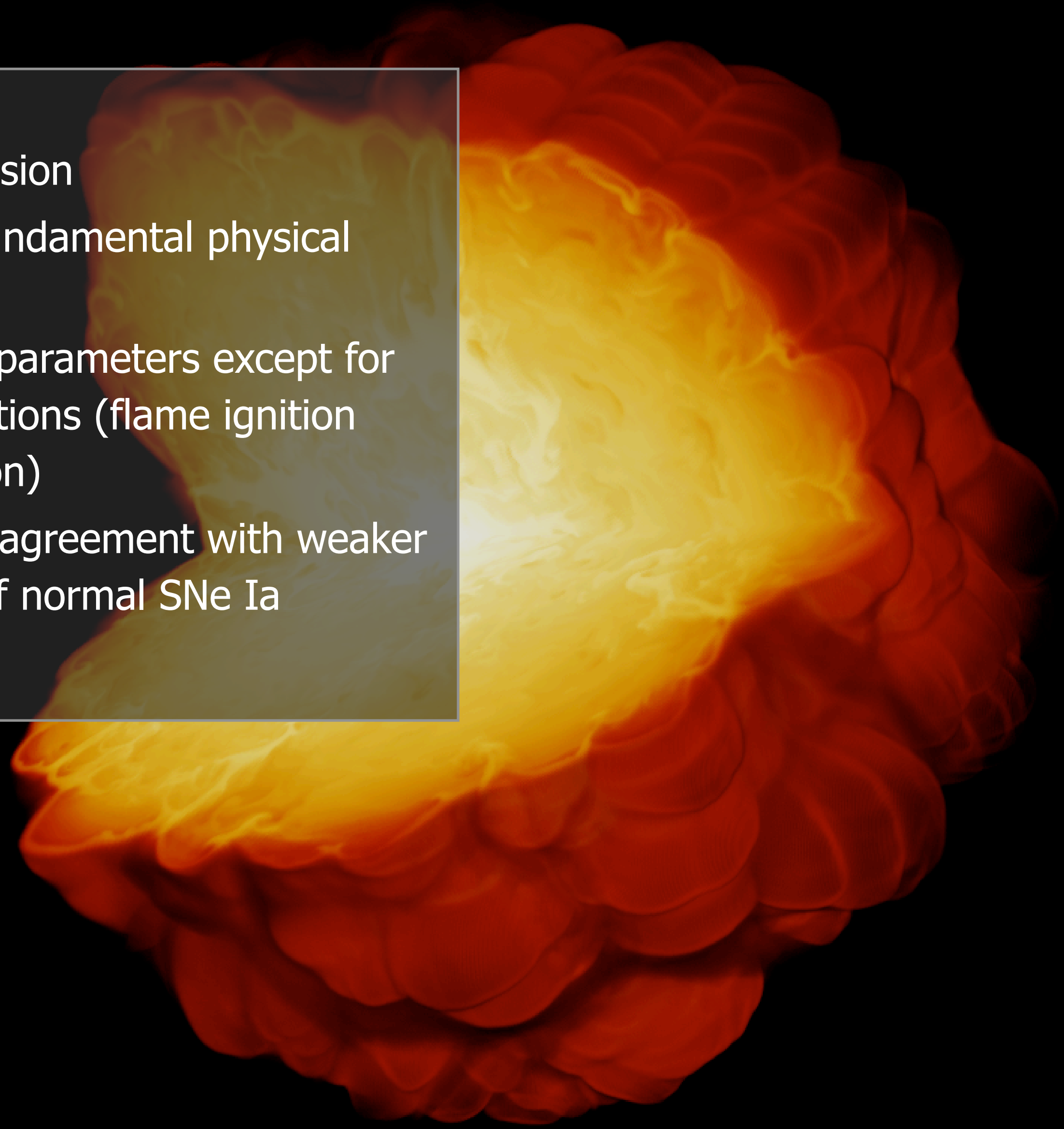

Successes

- yields explosion
- based on fundamental physical principles
- no tunable parameters except for initial conditions (flame ignition configuration)
- reasonable agreement with weaker examples of normal SNe Ia

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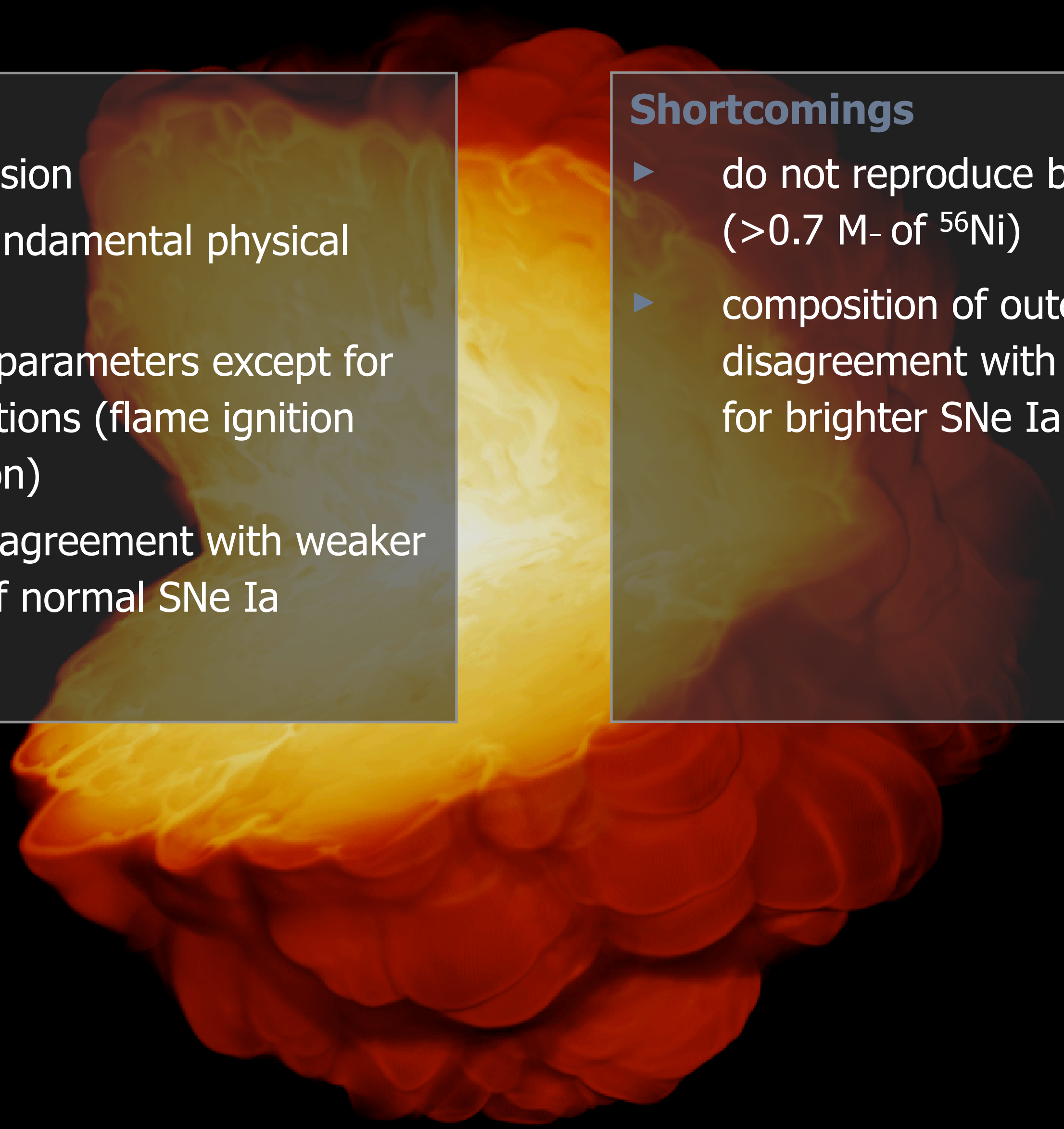

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- do not reproduce brighter SNe Ia (>0.7 M- of ^{56}Ni)
- composition of outer layers in disagreement with those expected for brighter SNe Ia

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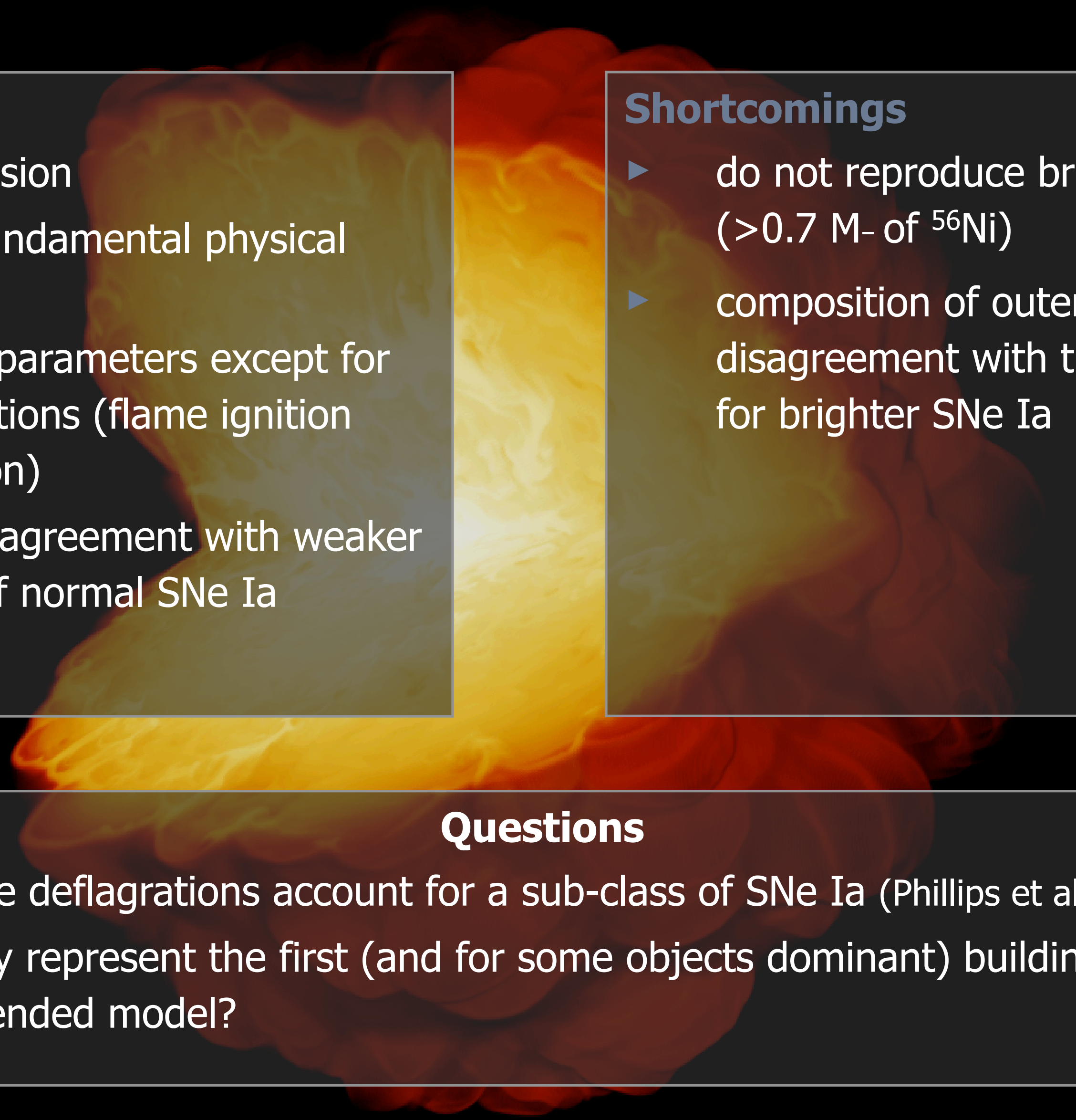

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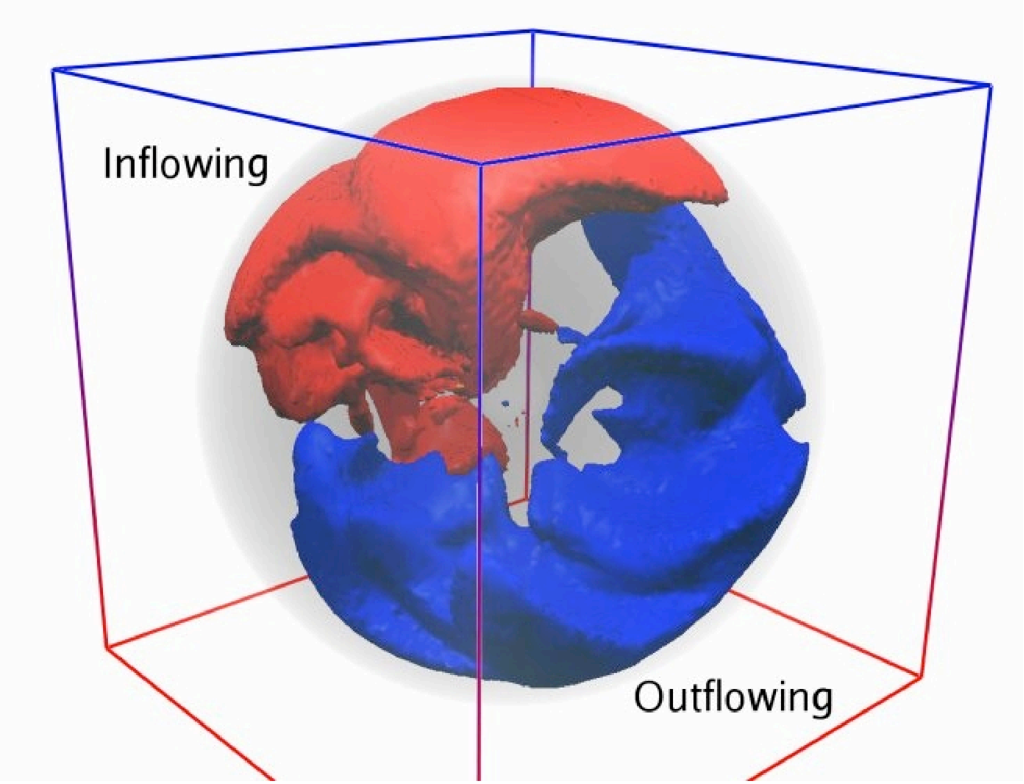
Questions

- Do pure deflagrations account for a sub-class of SNe Ia (Phillips et al., 2006)?
- Do they represent the first (and for some objects dominant) building block of an extended model?

Off-center ignition model

Motivation:

- pre-igntion convection may cause dipole flow (Kuhlen et al. 2006) ! lop-sided ignition?

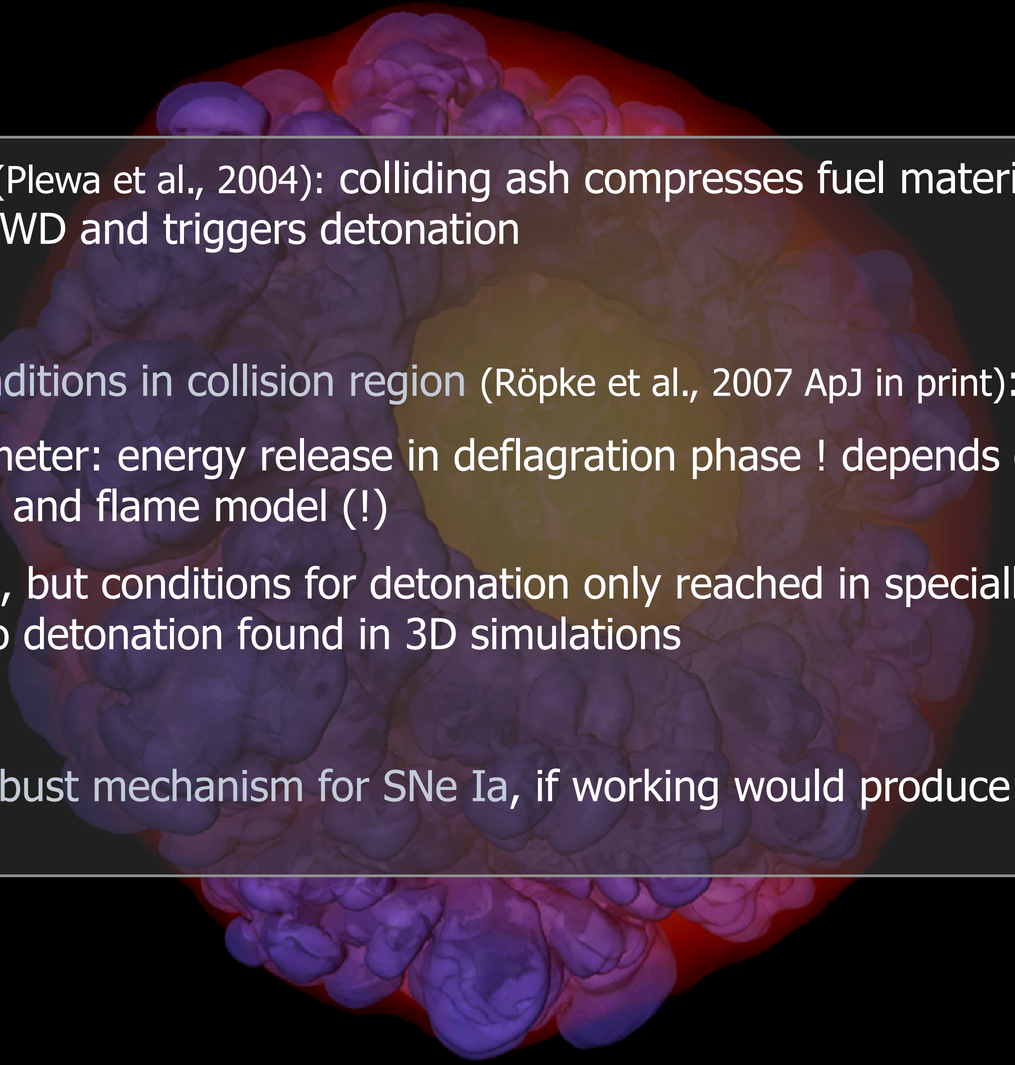


Kuhlen et al. 2006

- conceivable initial flame configurations: sphere (Calder et al., 2004), perturbed sphere, perturbed teardrop-like shape, two-sided configurations (Röpke et al. 2007, ApJ in print: ~20 2D simulations, 6 3D simulations testing the parameter space)

Off-center ignition model: example

Gravitationally Confined Detonations?



GCD scenario (Plewa et al., 2004): colliding ash compresses fuel material at the surface of the WD and triggers detonation

analysis of conditions in collision region (Röpke et al., 2007 ApJ in print):

deciding parameter: energy release in deflagration phase ! depends on ignition location/shape and flame model (!)

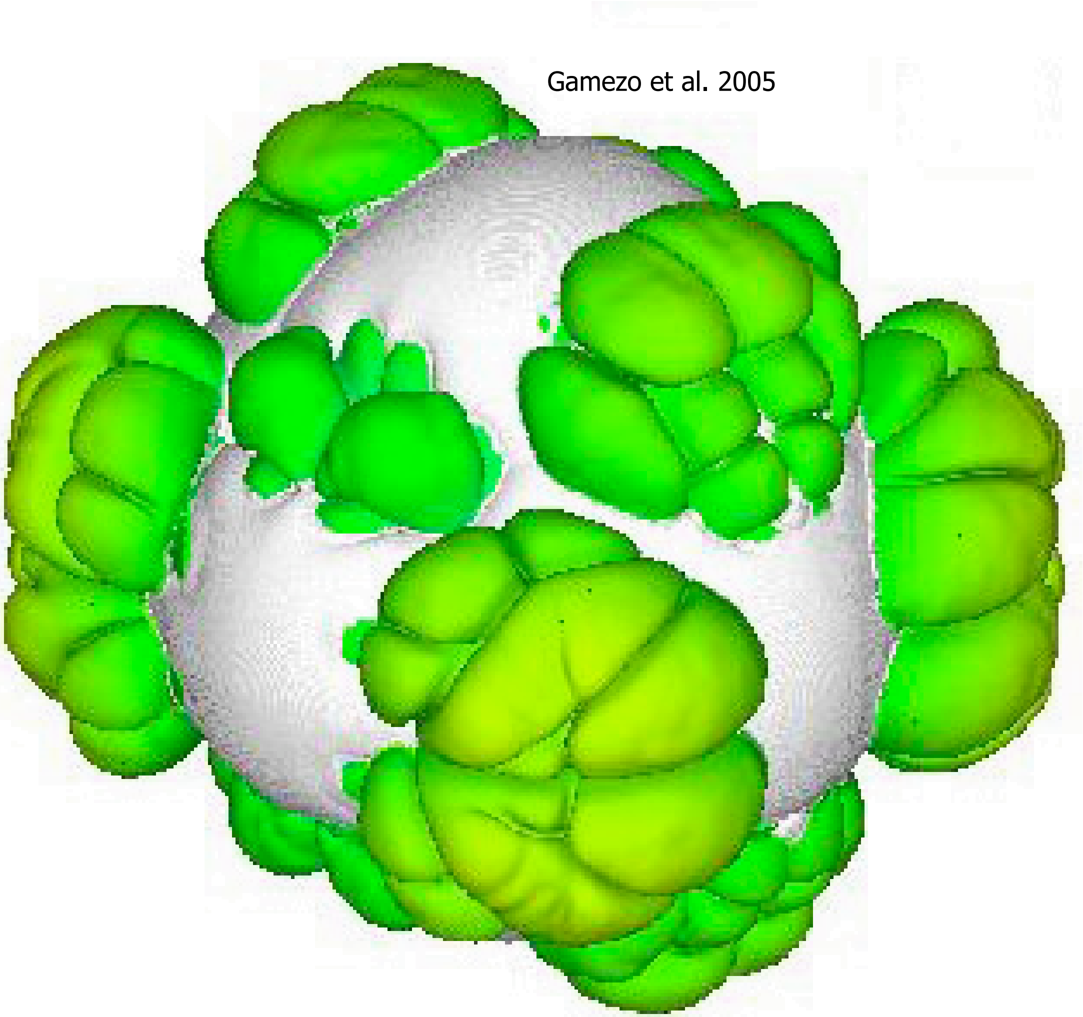
! GCD possible, but conditions for detonation only reached in specially tuned 2D simulations, no detonation found in 3D simulations

! GCD not a robust mechanism for SNe Ia, if working would produce very bright events

Delayed detonation model

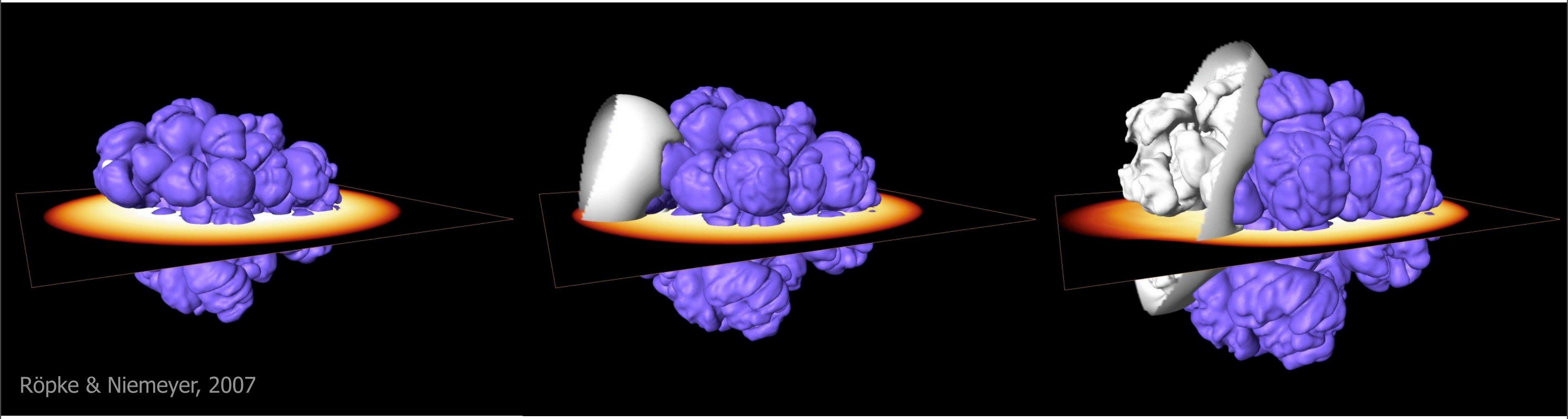
Idea:

- transition (DDT) to detonation after deflagration phase (Khokhlov, 1991)
- supersonic detonation front burns parts of remaining fuel



Gamezo et al. 2005

Problems of Delayed Detonations



Röpke & Niemeyer, 2007

Problems of Delayed Detonations

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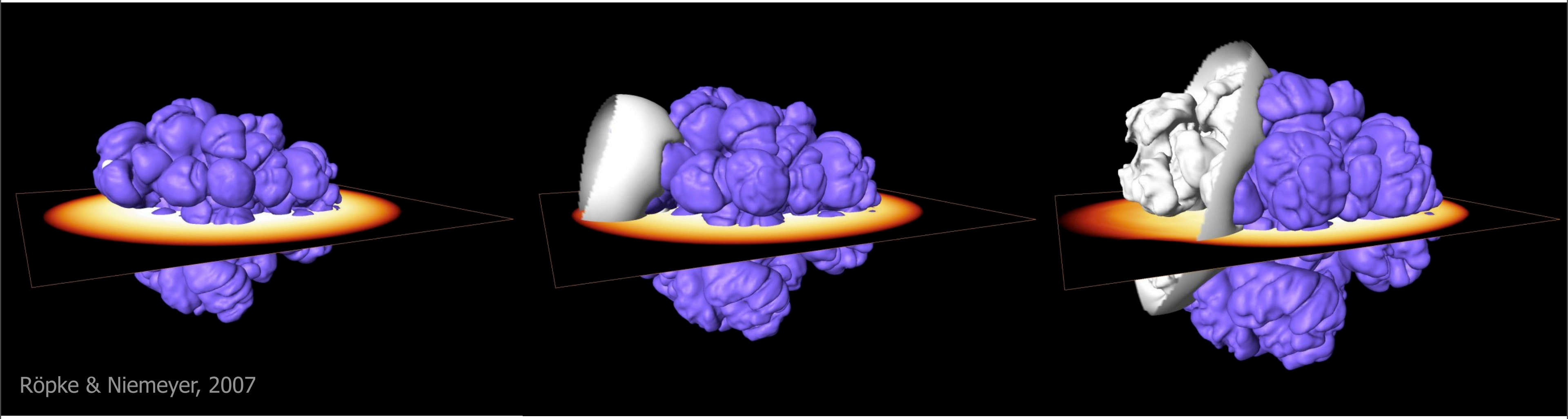

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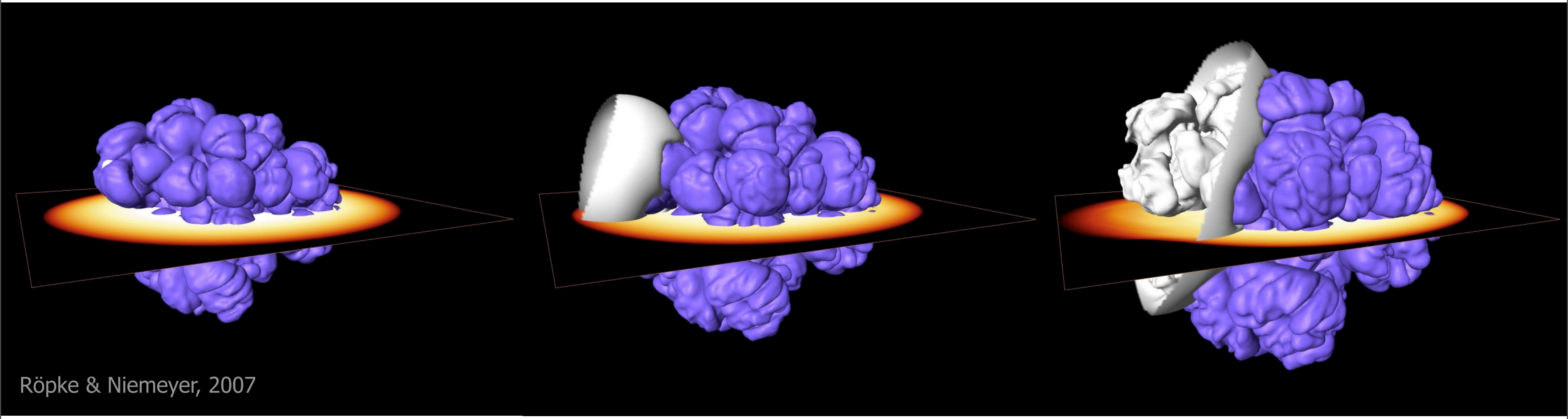

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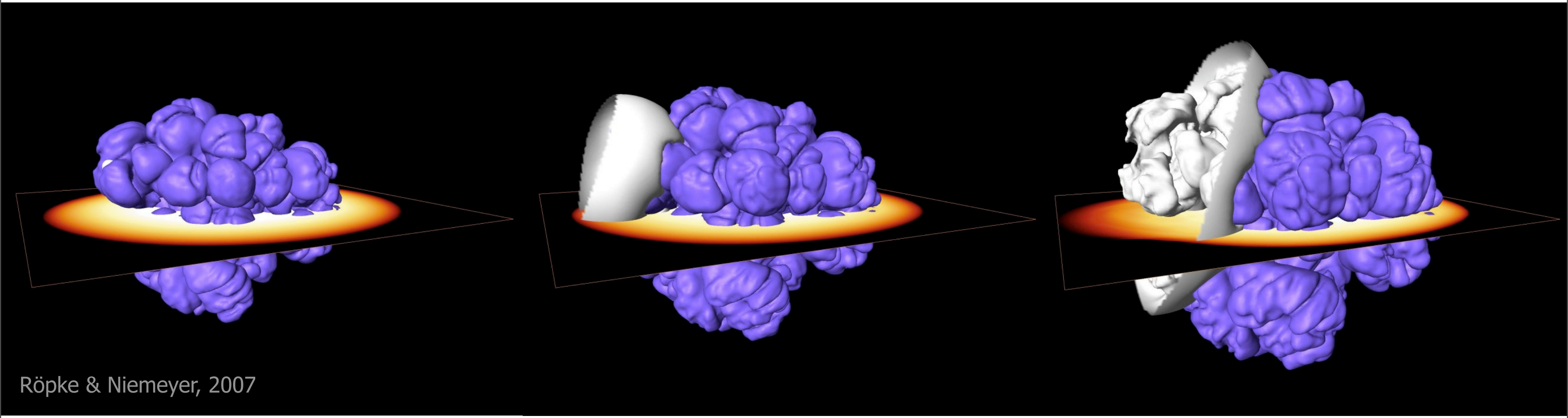
- competition with expansion: does it reach far side when triggered off-center?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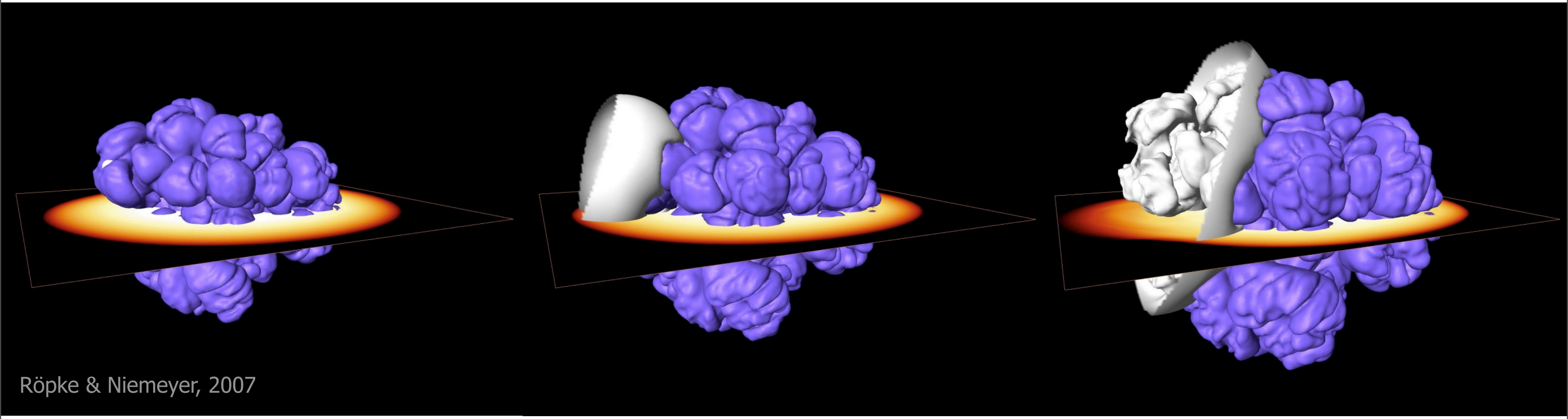

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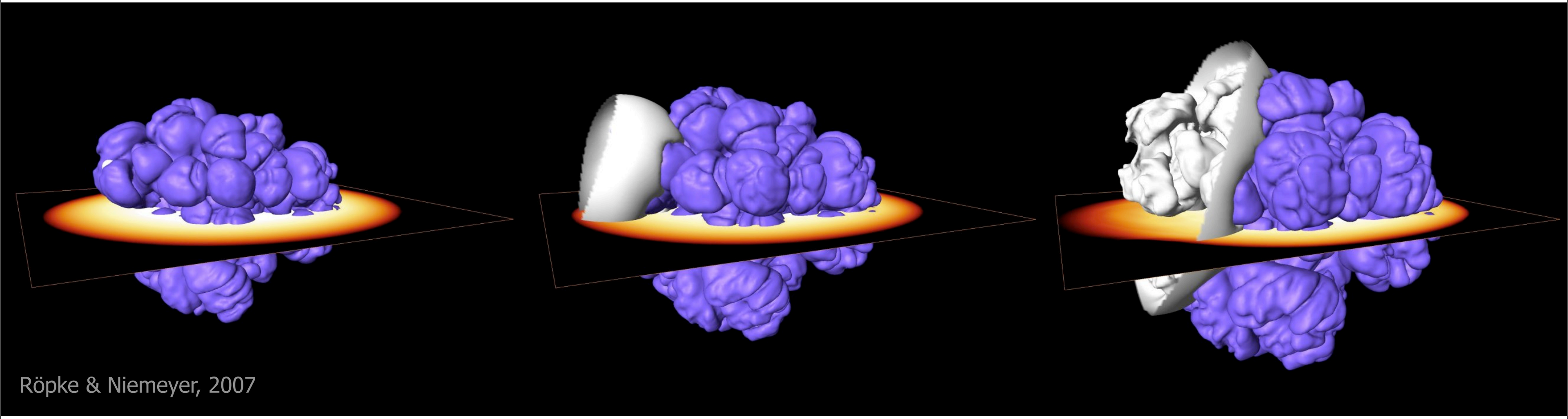

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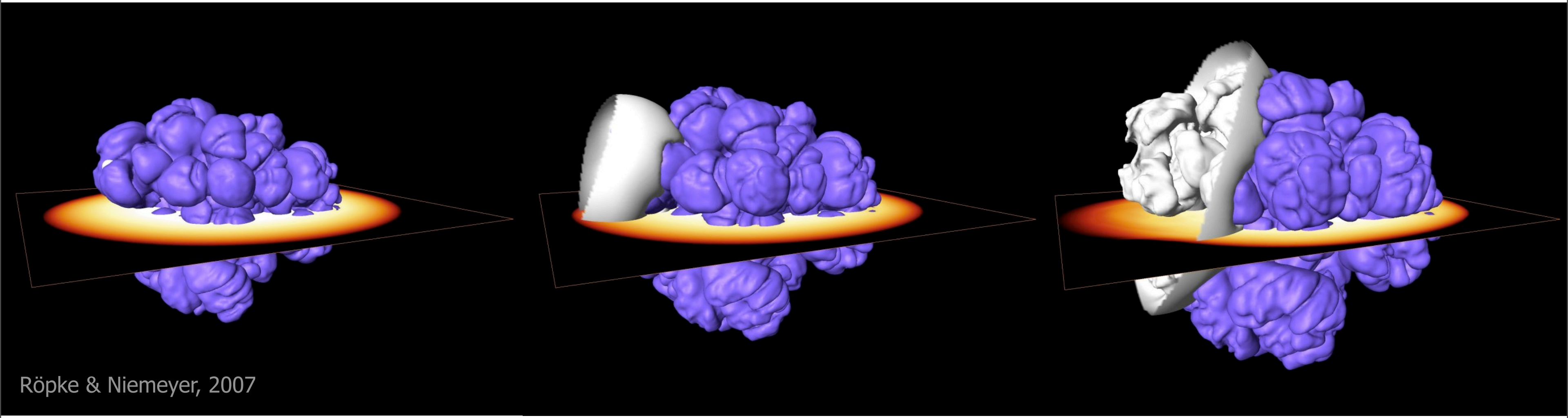

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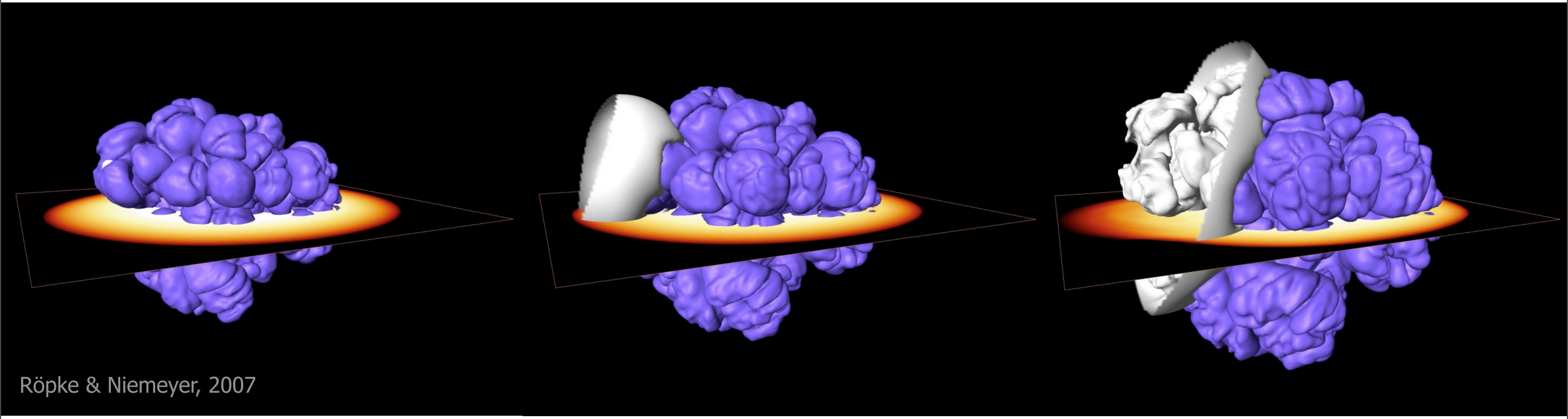

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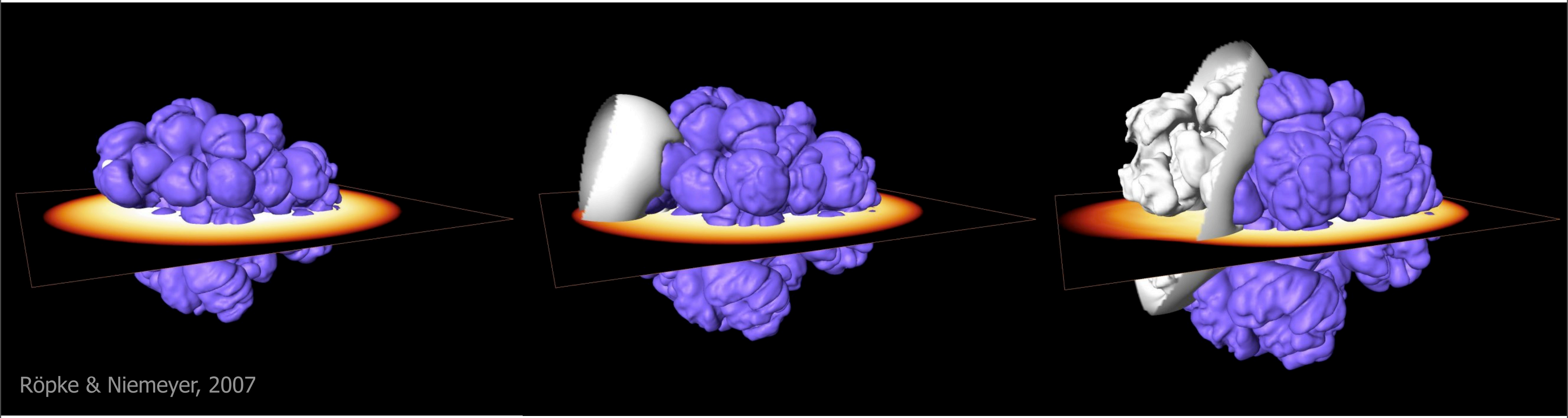

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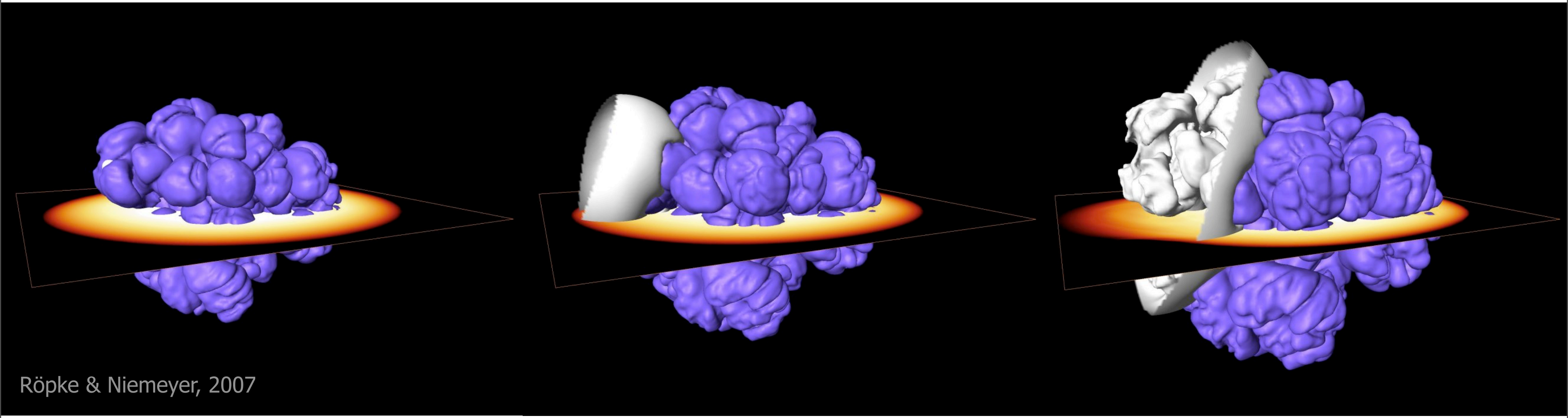

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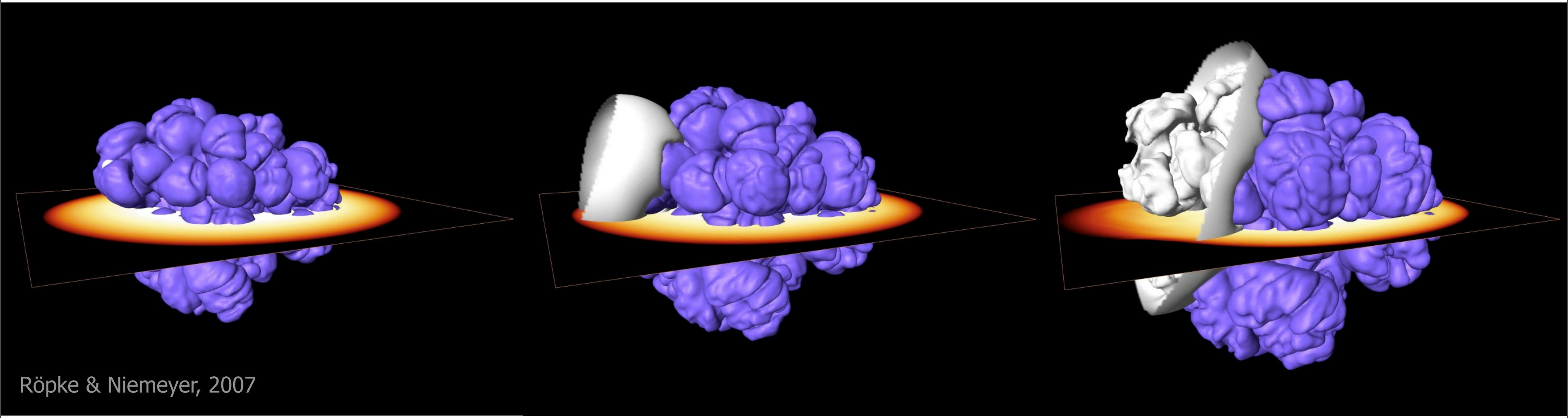

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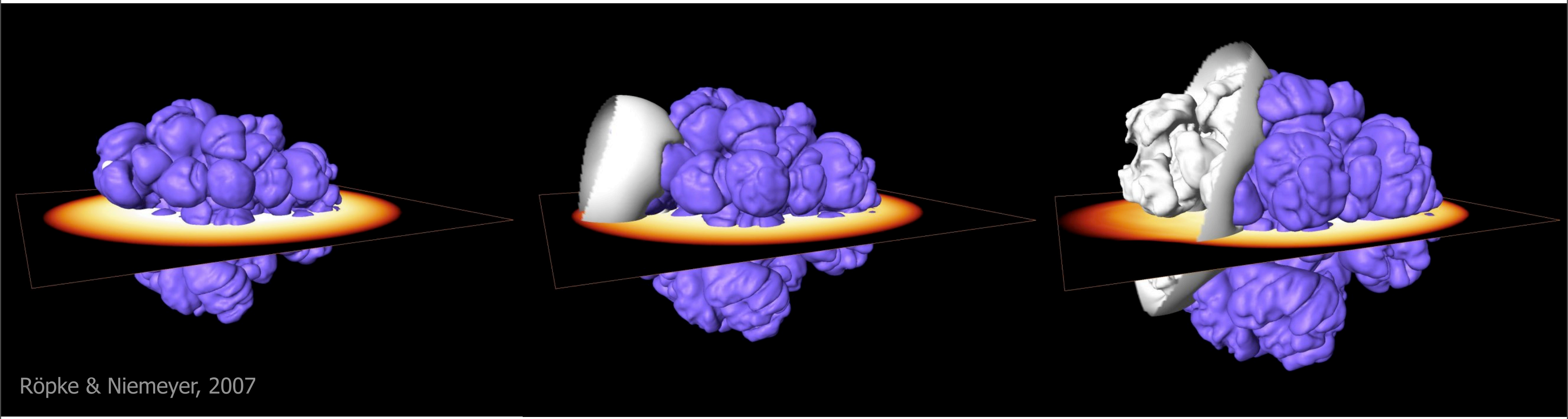

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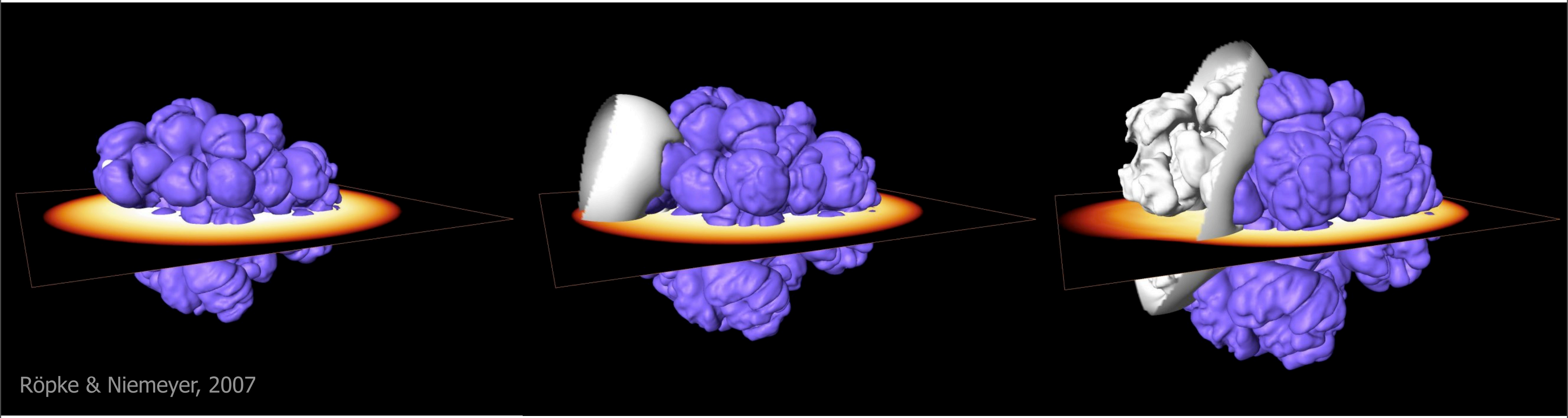
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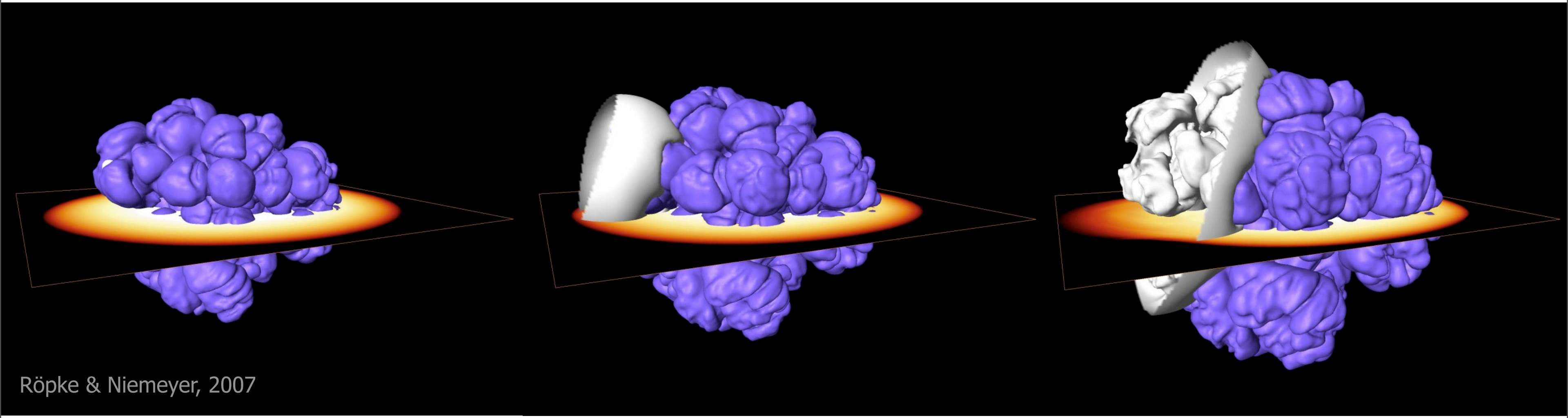

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- arbitrarily prescribe position and time for DDT (Gamezo et al. 2005)
- DDT once deflagration flame enters distributed burning regime (Golombeck & Niemeyer 2005)

Delayed detonation model: example

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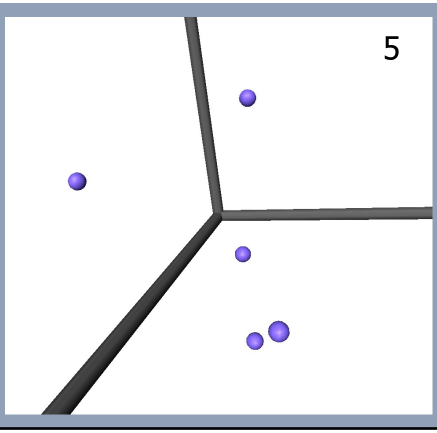
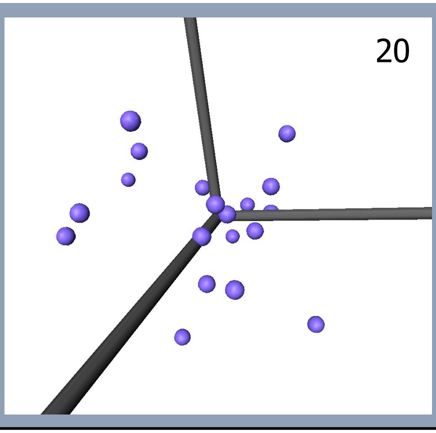
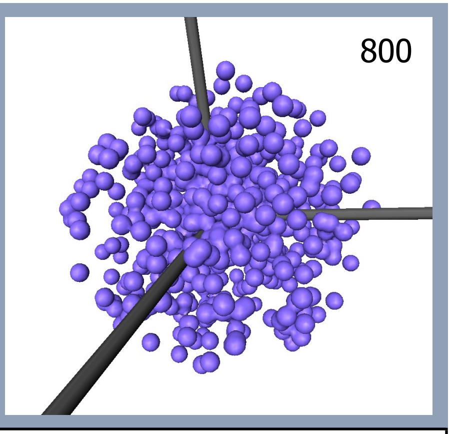
- varying the number of ignition kernels of the deflagration flame shifts emphasis from deflagration to detonation phase
- elegant way to reproduce range of observations of SNe Ia (Röpke & Niemeyer, 2007)

ignition configuration			
$E_{kin,asympt}$ [foe]	1.5	1.2	1.0
M(NSE) [M-]	1.14	0.83	0.64
M(IME) [M-]	0.22	0.44	0.55

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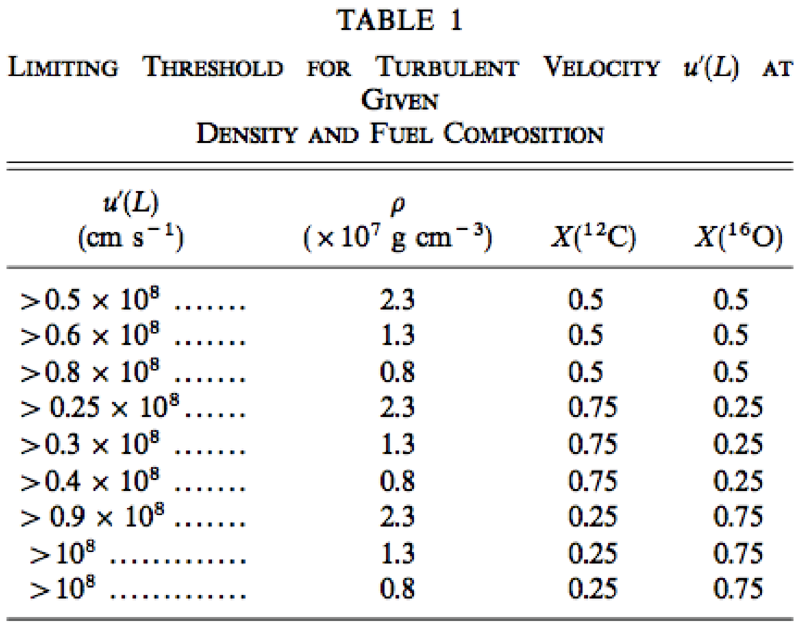

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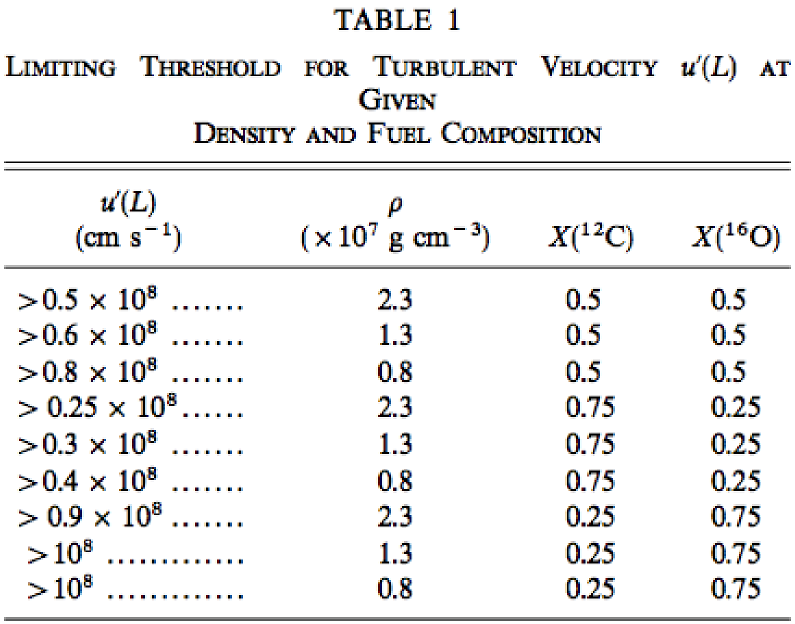

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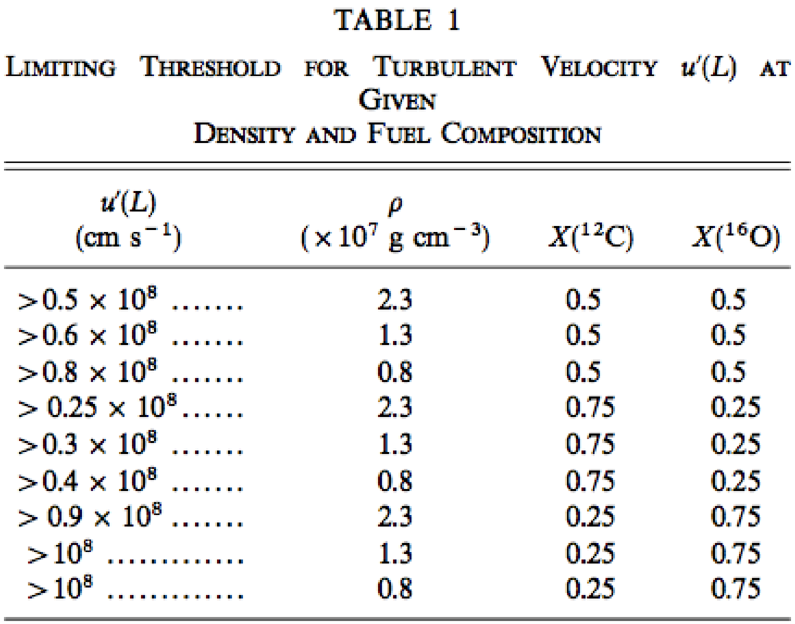

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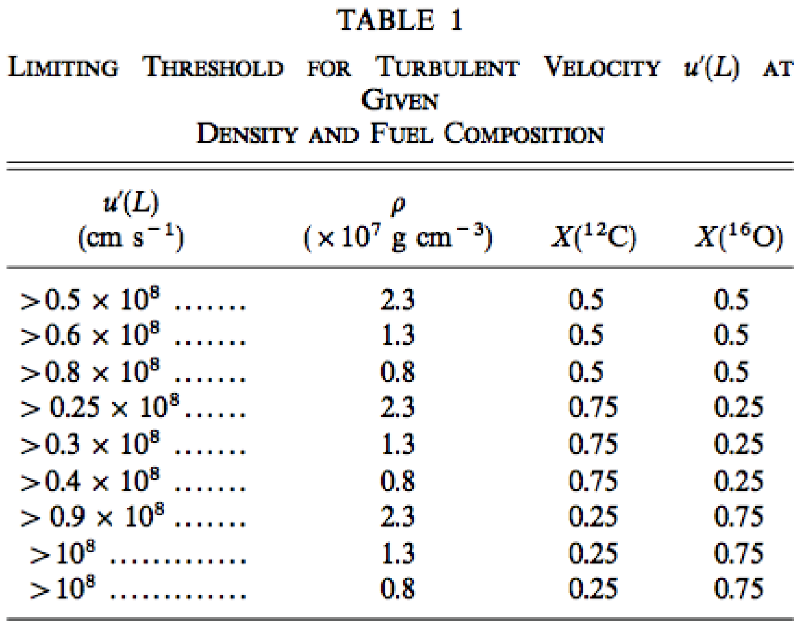

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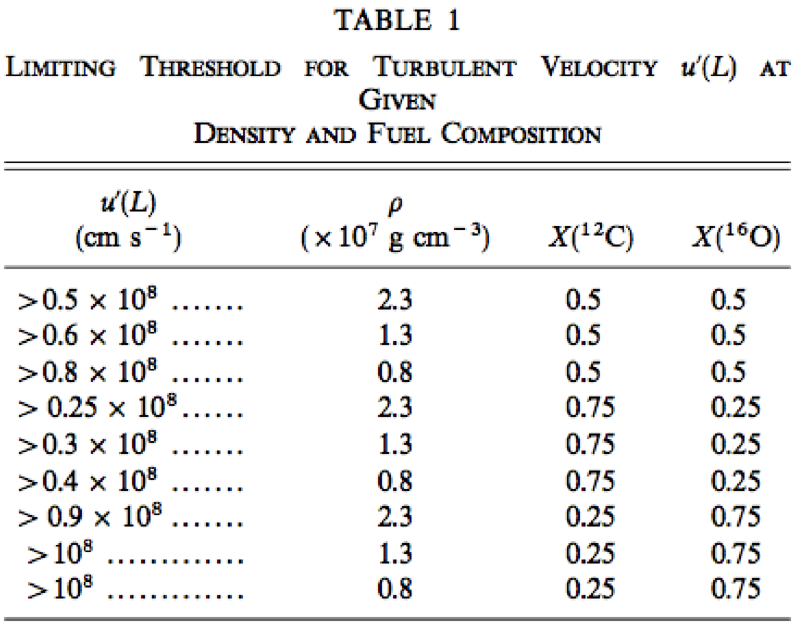

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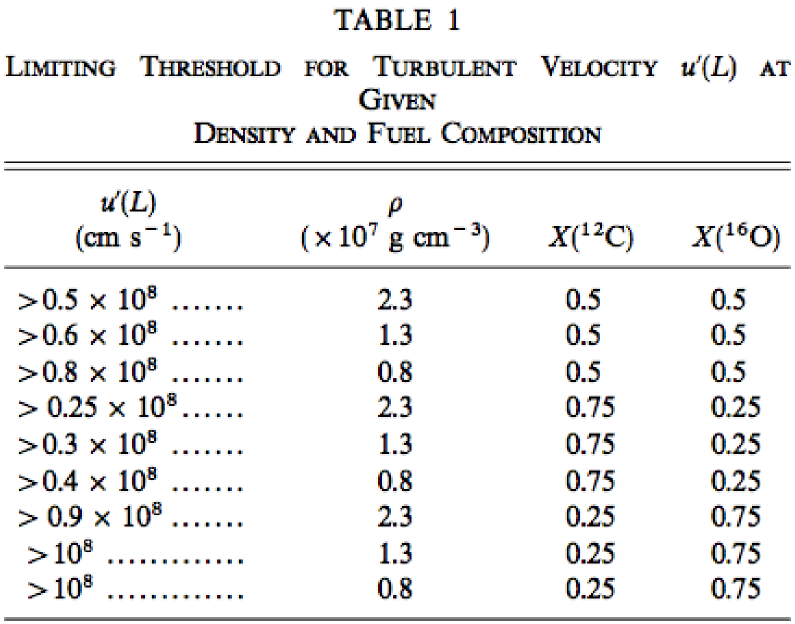

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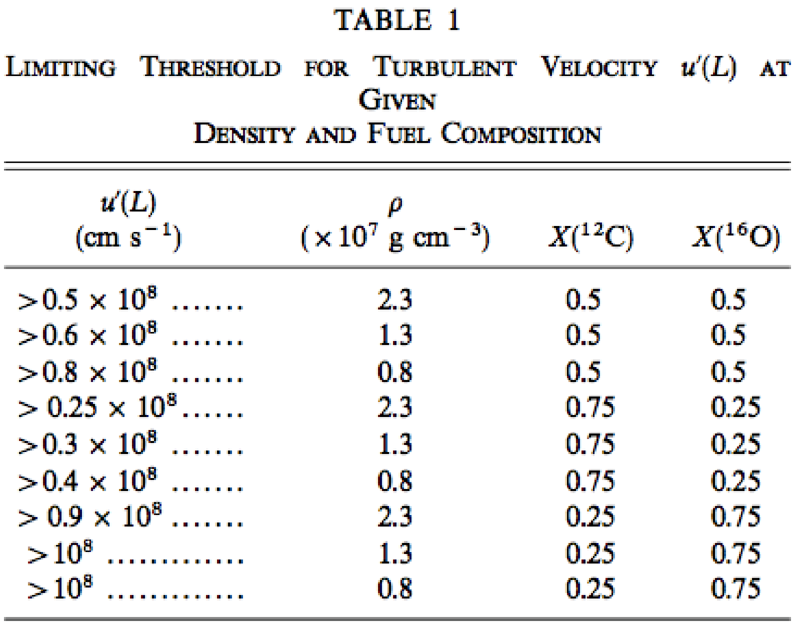

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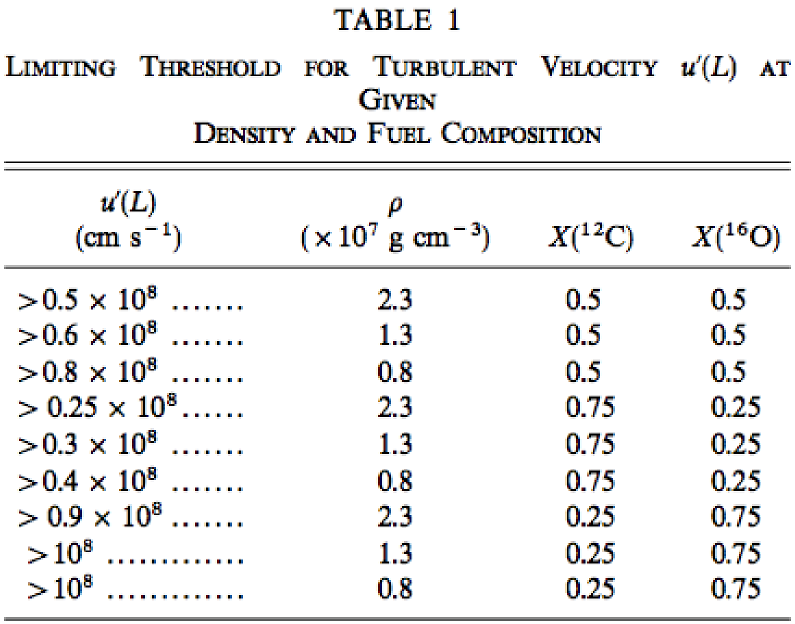

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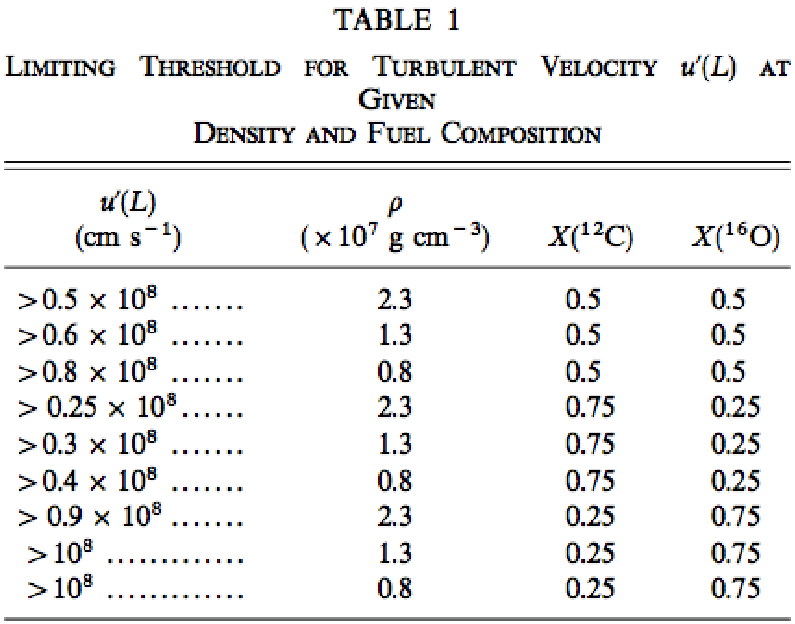

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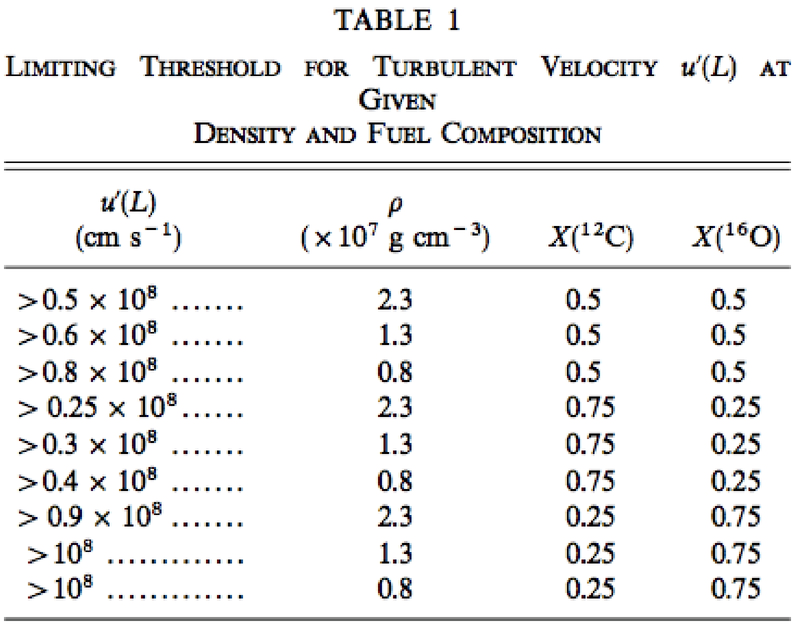

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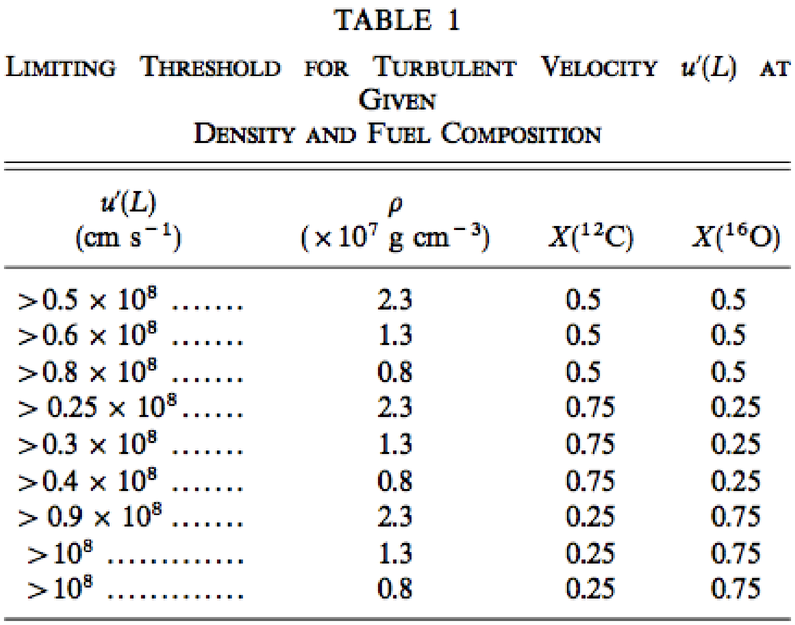

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$>0.4 \times 10^8$	0.8	0.75	0.25
$>0.9 \times 10^8$	2.3	0.25	0.75
$>10^8$	1.3	0.25	0.75
$>10^8$	0.8	0.25	0.75

Deflagration-to-Detonation Transitions?

- Niemeyer & Woosley (1997) hypothesis: DDT at onset of distributed burning regime
- only instance of drastic change in flame properties
- occurs at $\rho_{\mathrm{fuel}} \sim 10^7$ g cm^{-3} ! for this transition density best fits obtained in one-dimensional delayed detonation models
- analysis by Lisewski et al.(2000): claim
- needs updated analysis

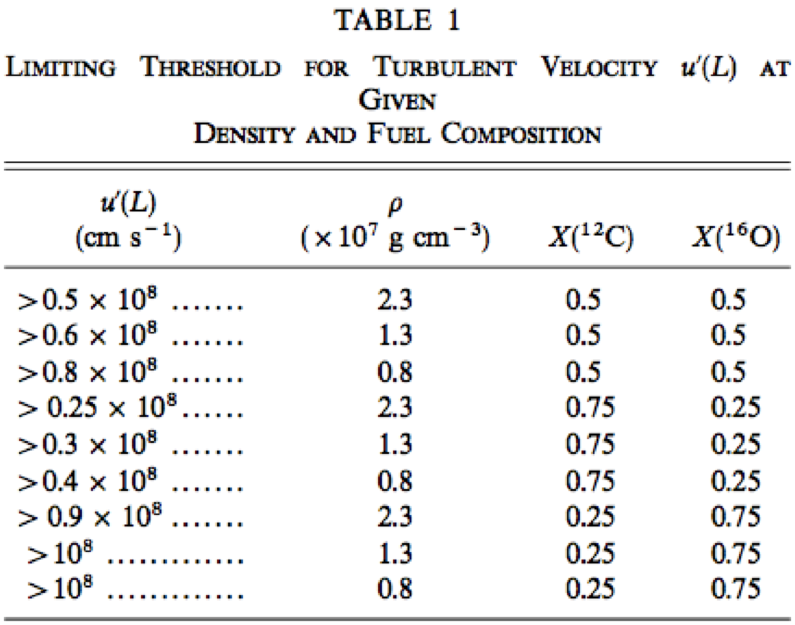

TABLE 1

LIMITING THRESHOLD FOR TURBULENT VELOCITY $u'(L)$ AT GIVEN DENSITY AND FUEL COMPOSITION

$u'(L)$ (cm s^{-1})	ρ ($\times 10^7$ g cm^{-3})	$X(^{12}\mathrm{C})$	$X(^{16}\mathrm{O})$
$>0.5 \times 10^8$	2.3	0.5	0.5
$>0.6 \times 10^8$	1.3	0.5	0.5
$>0.8 \times 10^8$	0.8	0.5	0.5
$>0.25 \times 10^8$	2.3	0.75	0.25
$>0.3 \times 10^8$	1.3	0.75	0.25
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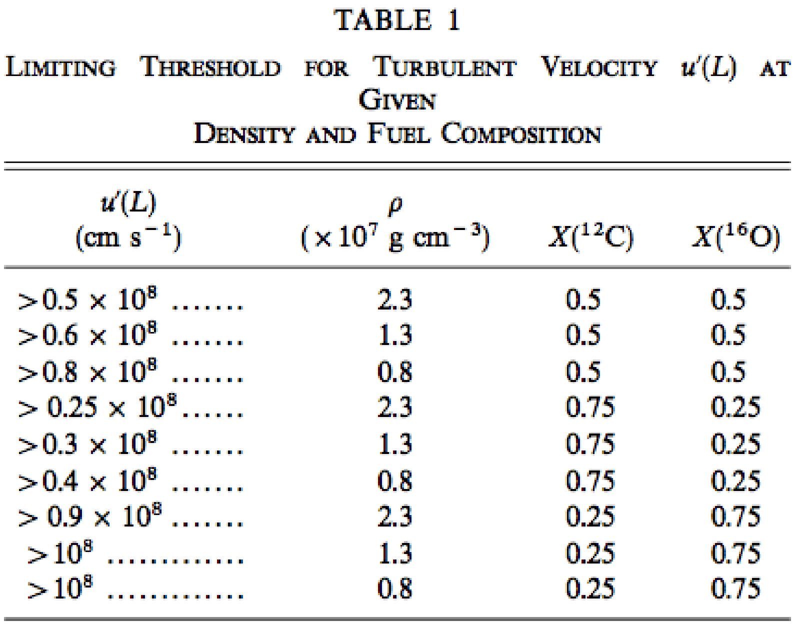

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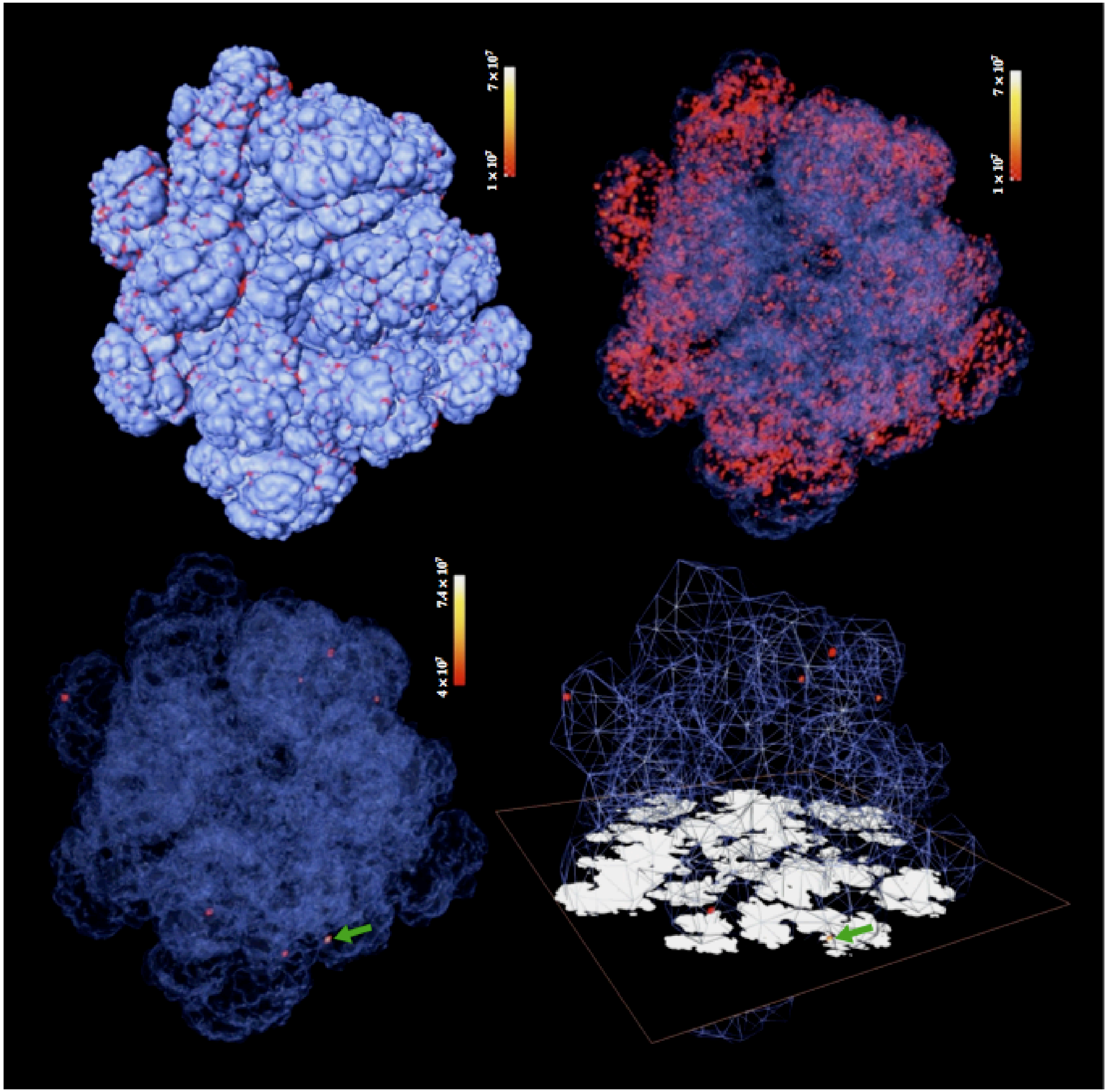
- needs updated analysis
- necessary but not sufficient conditions for DDT ! met in SN Ia models?

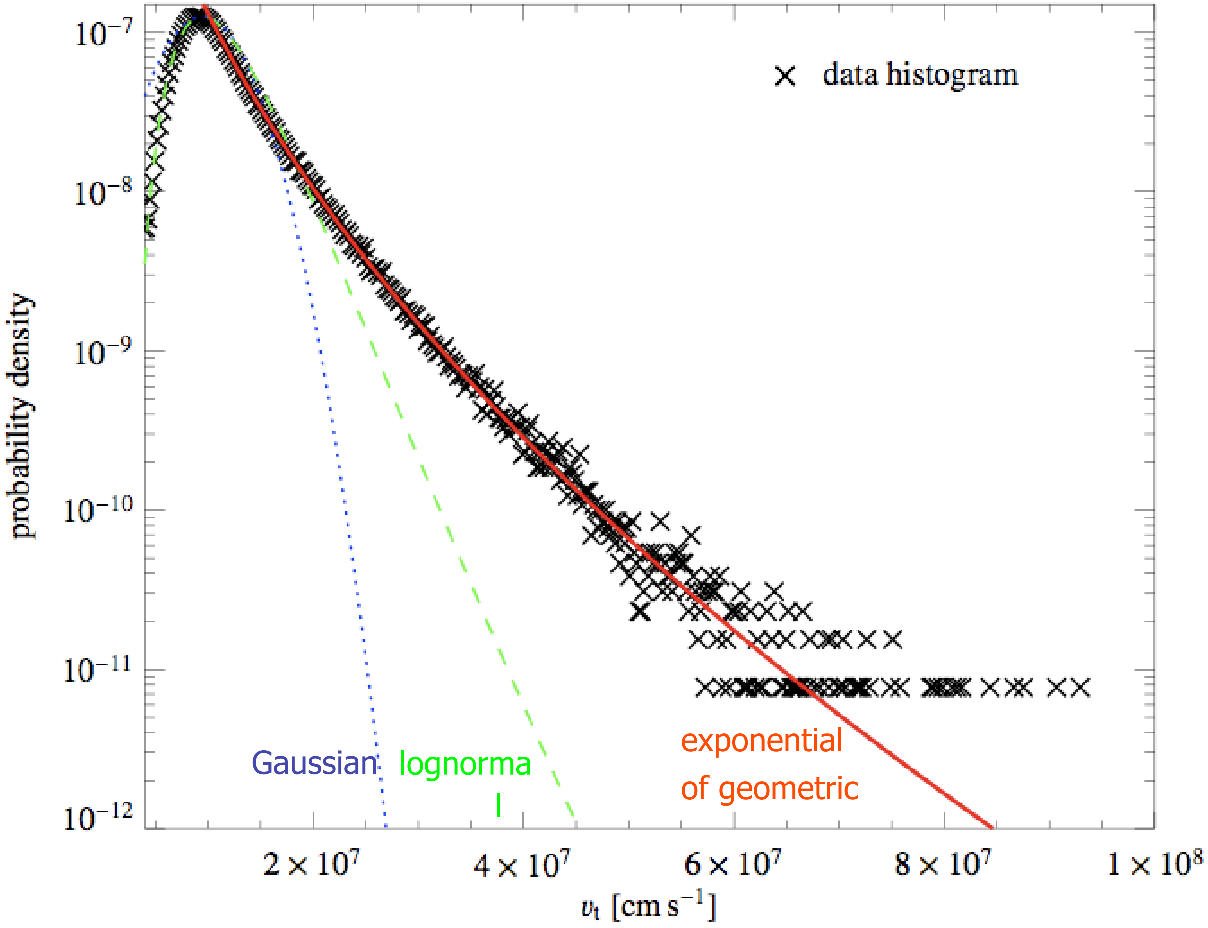
Deflagration-to-Detonation Transitions?

- Analysis of turbulent velocity flucutations as predicted by sub-grid scale model at the flame front for densities $1\ldots3$ £ 10^7 g cm^{-3} (Röpke, in prep.)



Deflagration-to-Detonation Transitions?

- High-amplitude turbulent velocity fluctuarions (~10^8 cm s^{-1}) occur at the onset of distributed burning regime on sufficiently large area of flame (~10^{12} cm^2)



Gaussian

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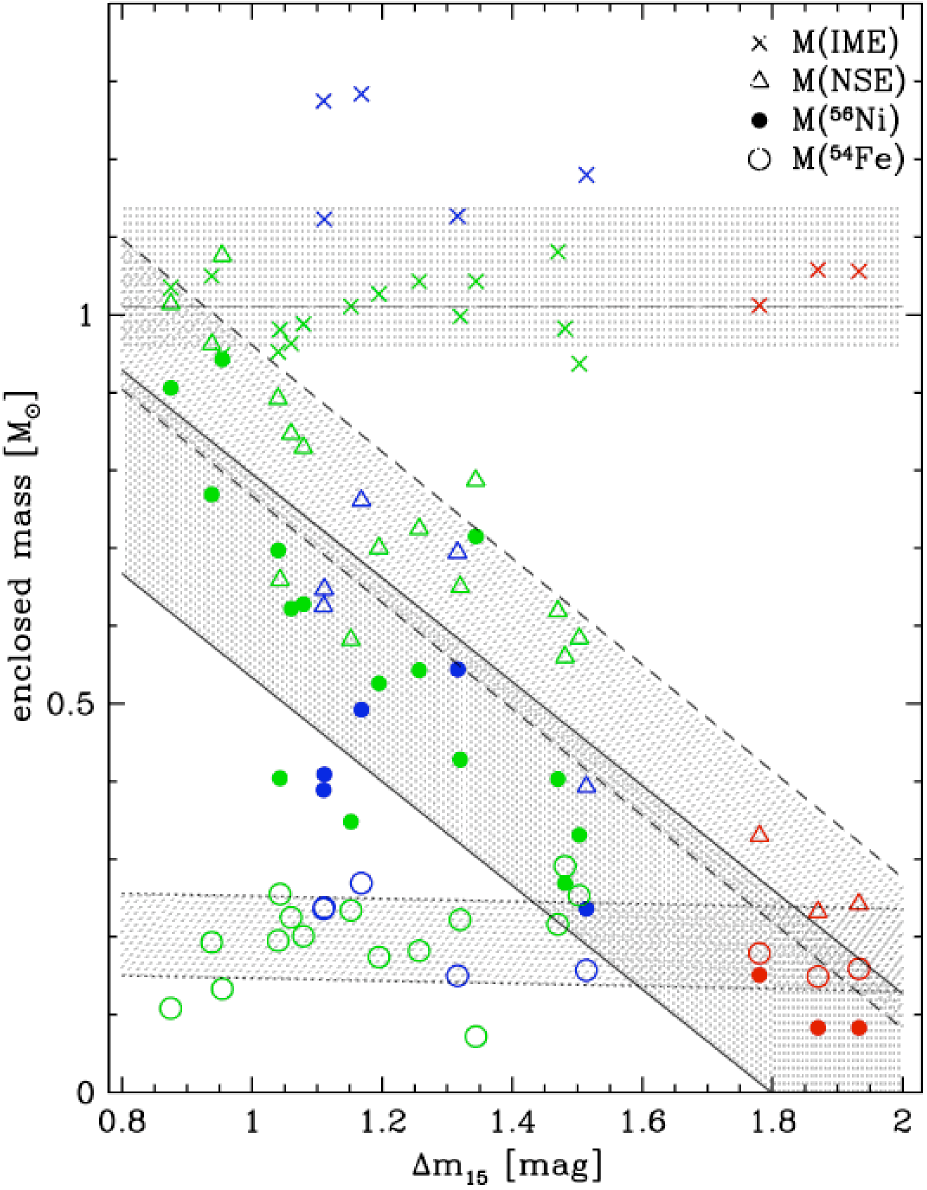
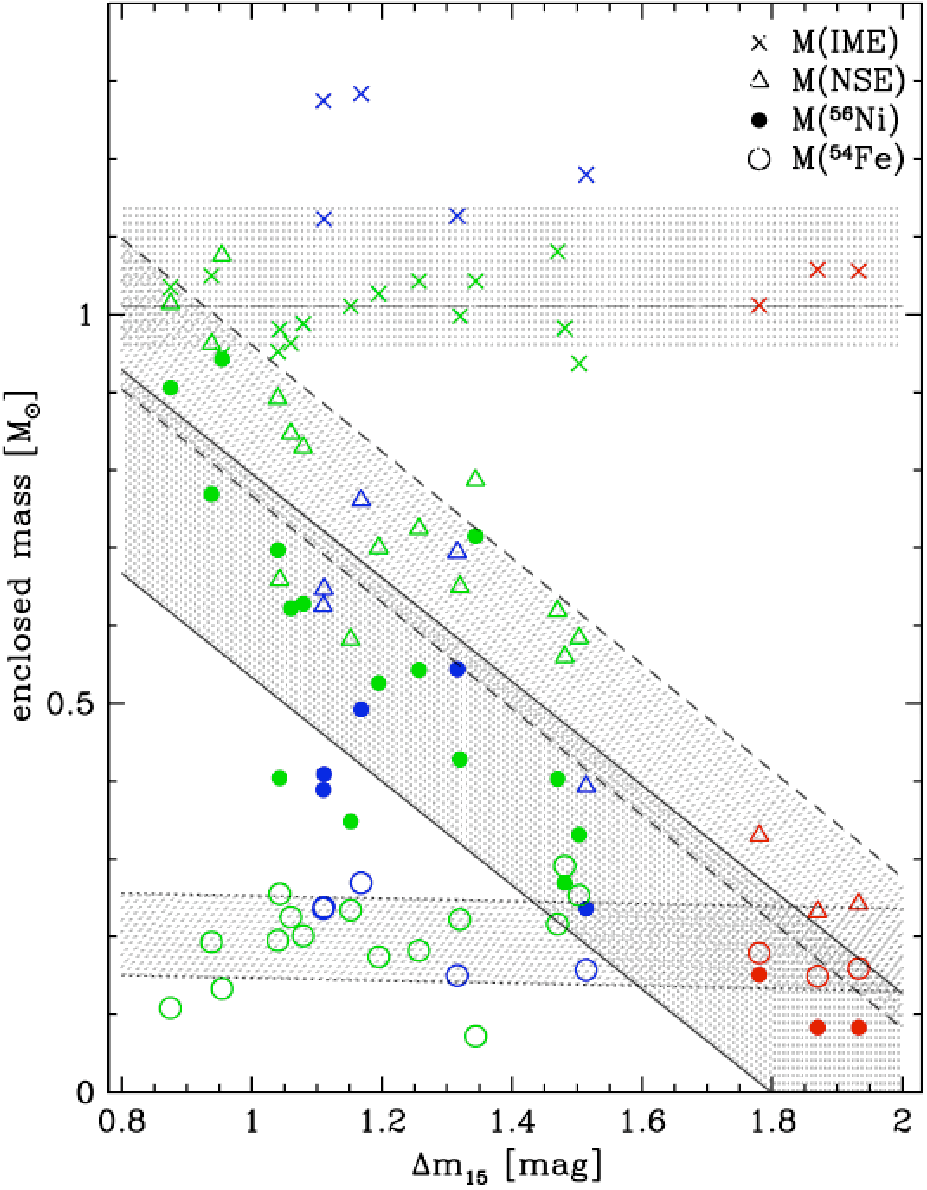
Speculation on the overall picture



Speculation on the overall picture

"Zorro diagram"



Speculation on the overall picture

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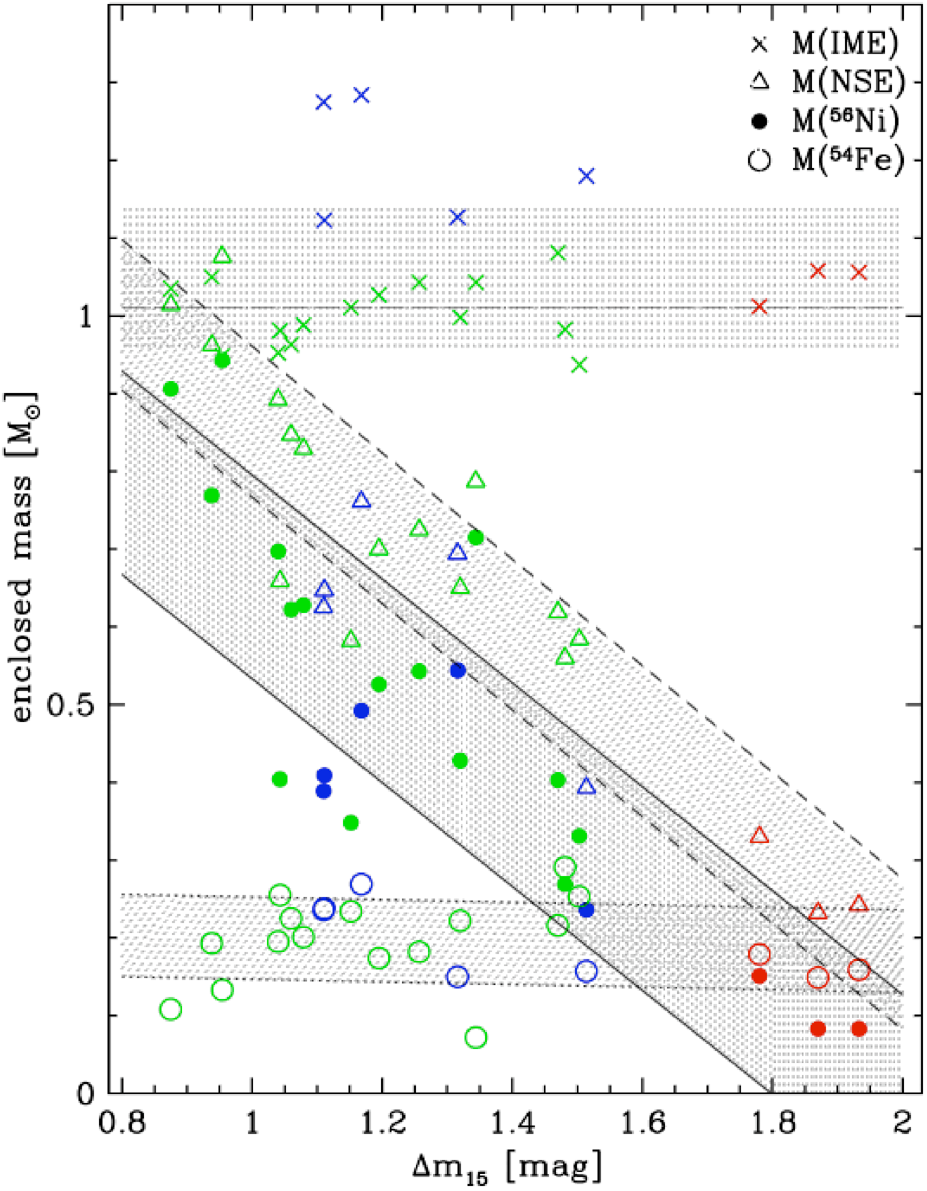
(Mazzali et al., 2007)



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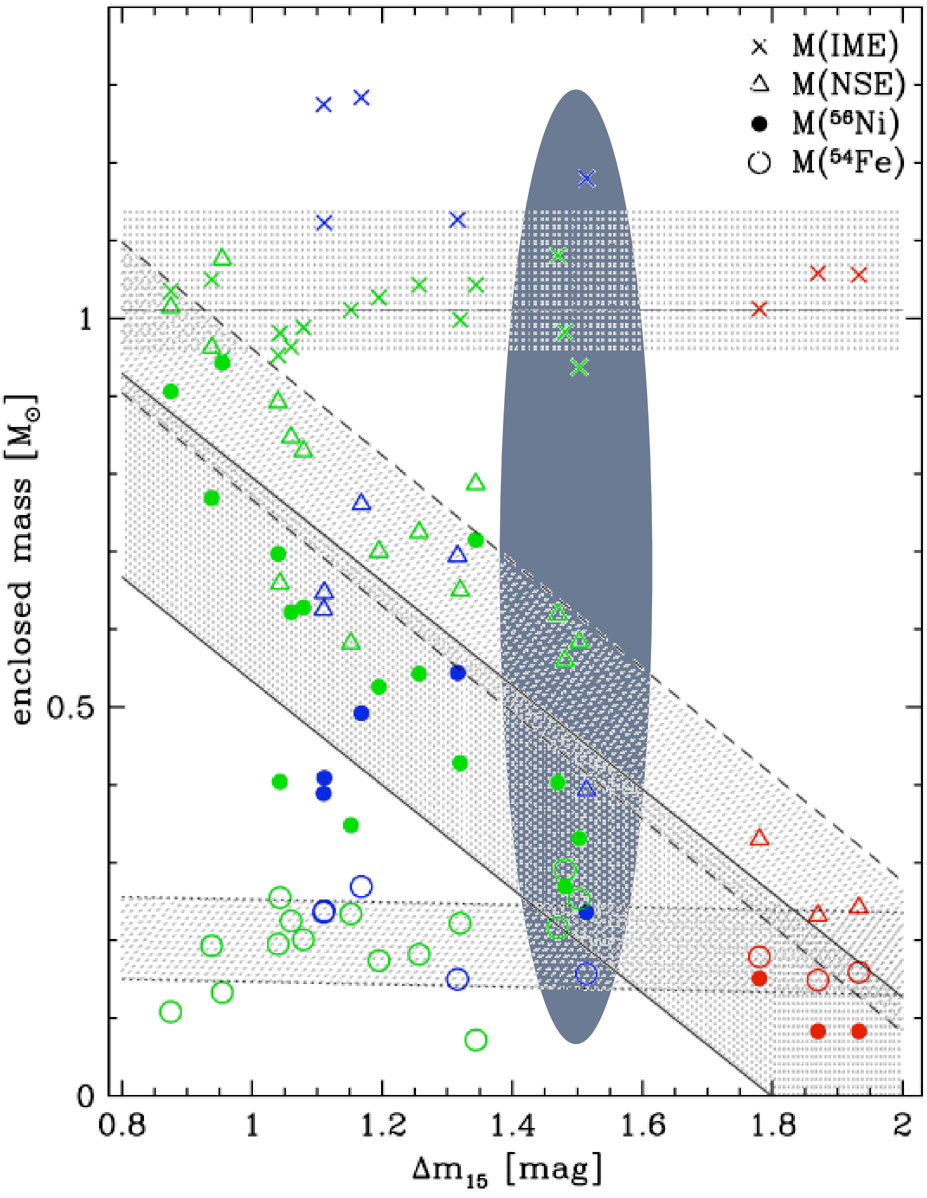
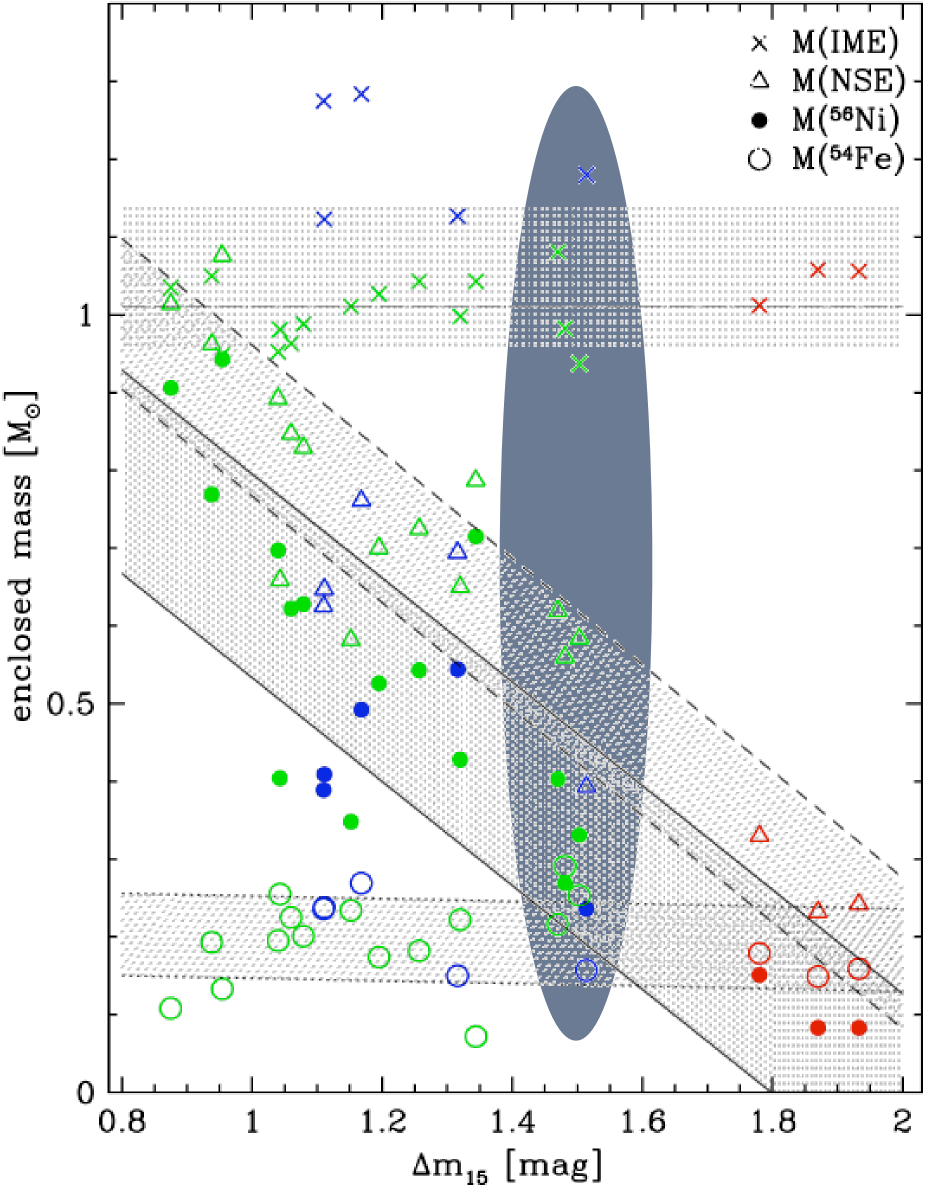


Speculation on the overall picture

"Zorro diagram"

(Mazzali et al., 2007)

- weak normal SNe Ia



Speculation on the overall picture

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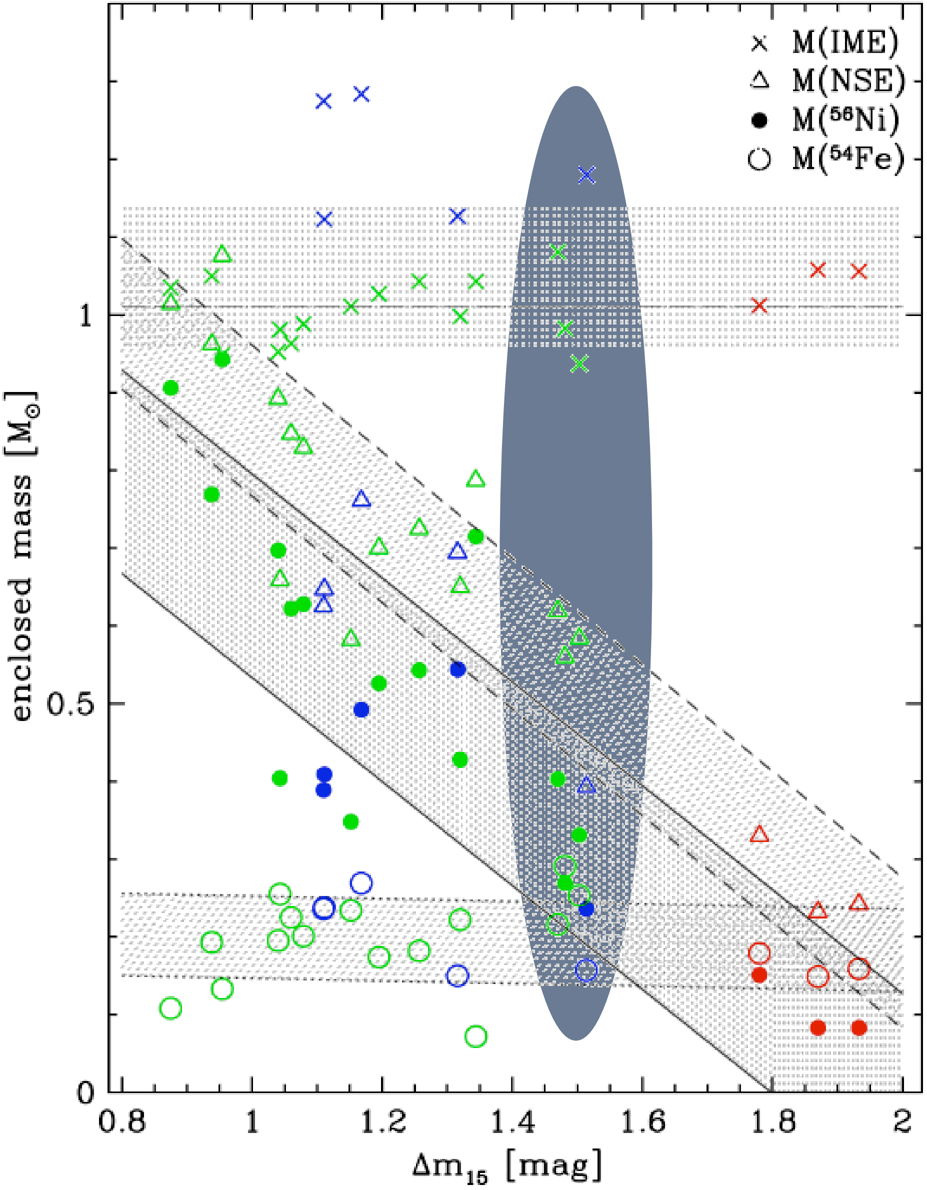

Speculation on the overall picture

"Zorro diagram"

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- weak normal SNe Ia
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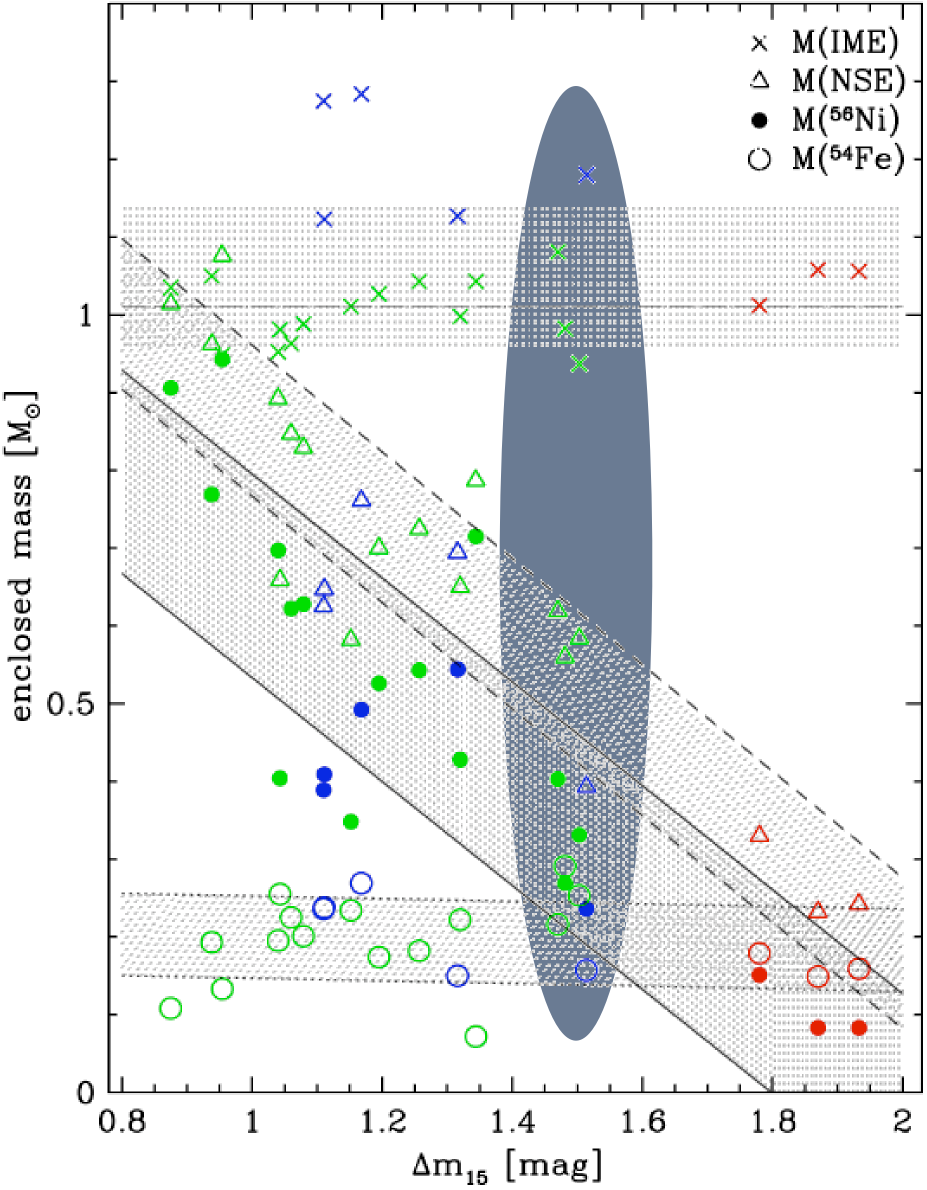

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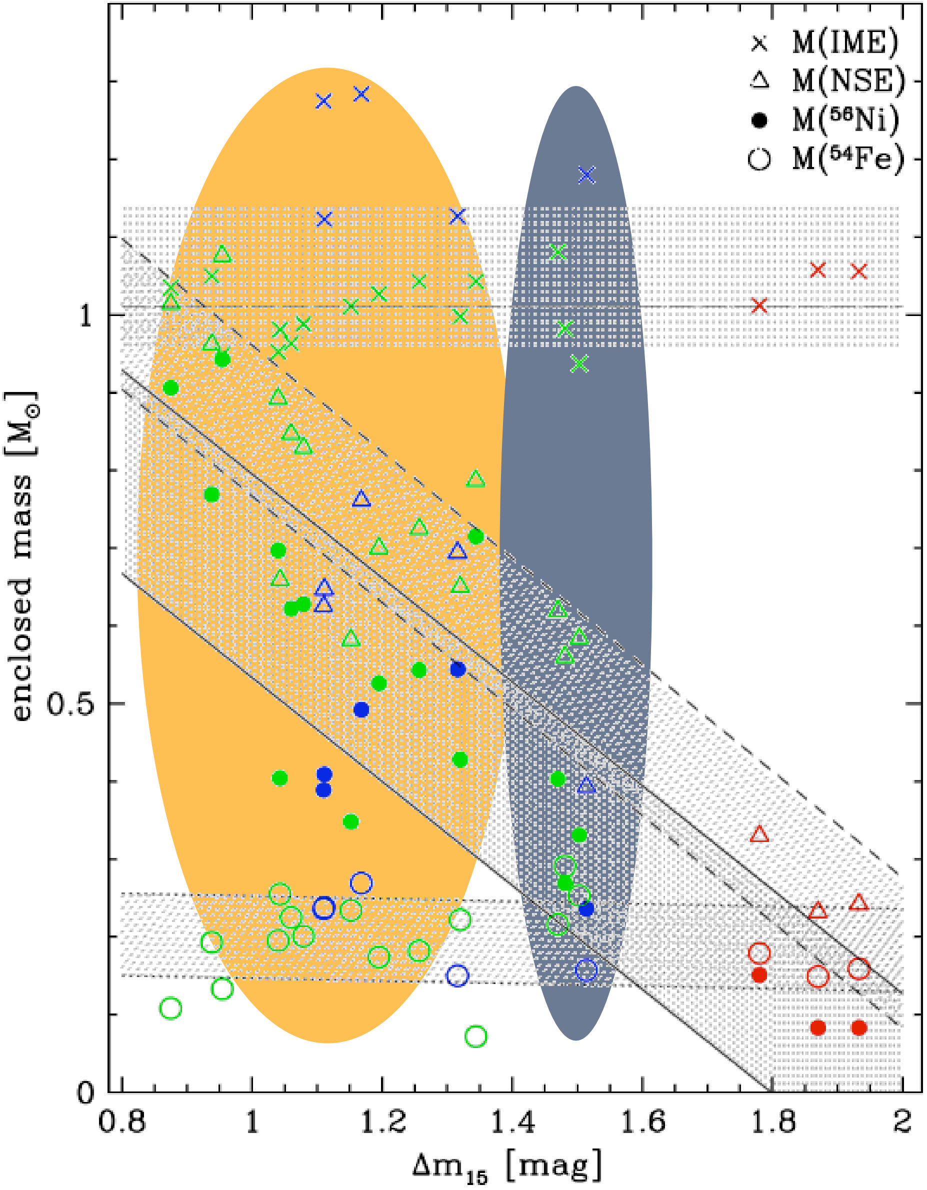

Speculation on the overall picture

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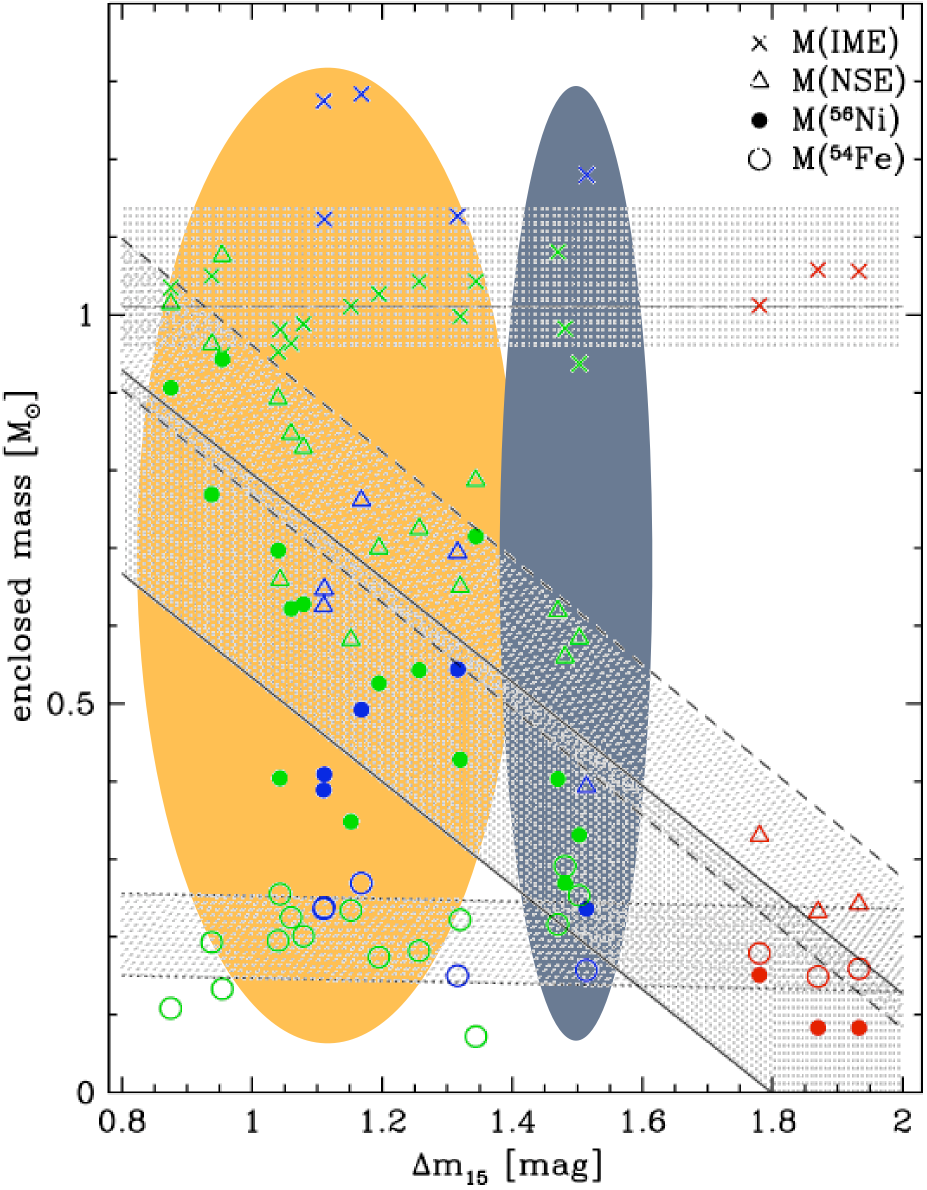
- bright SNe Ia



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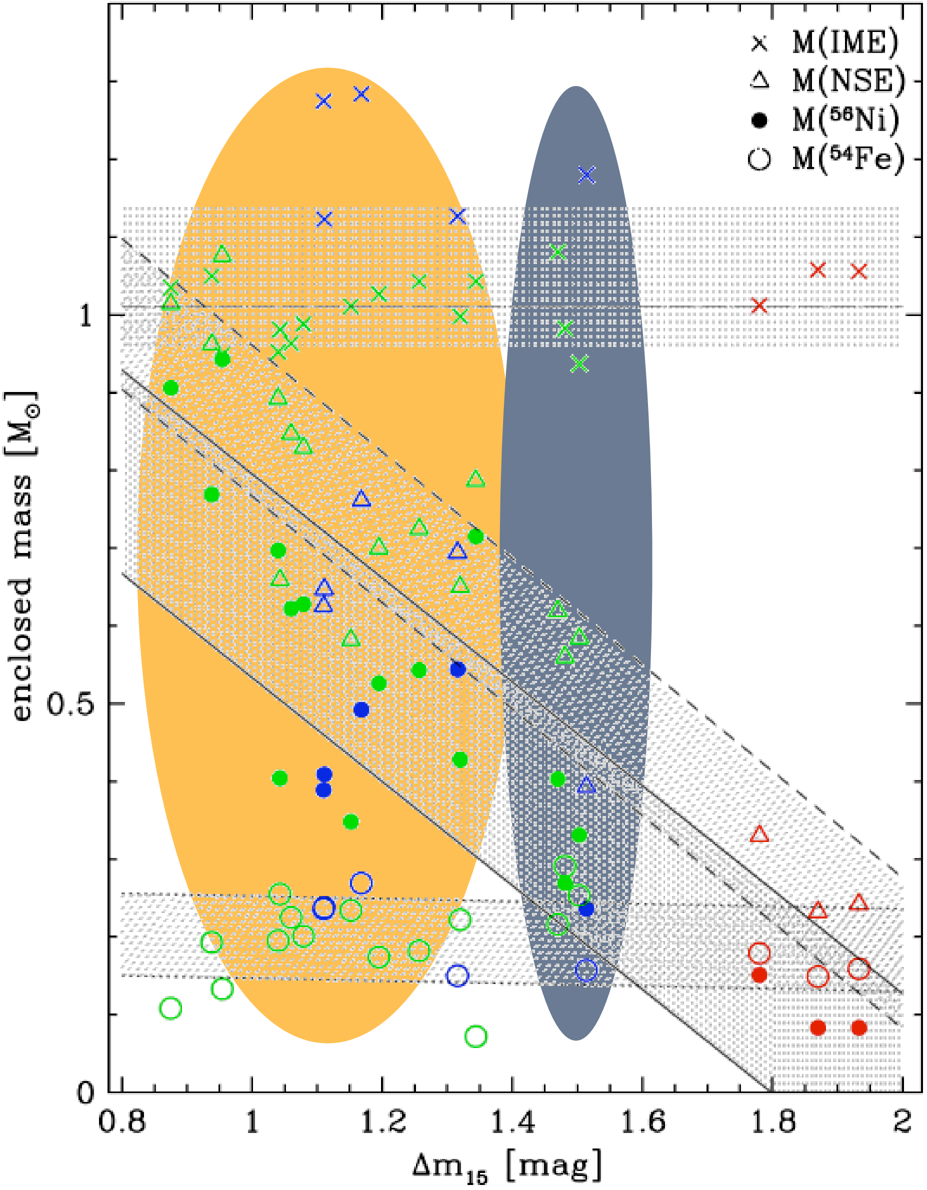

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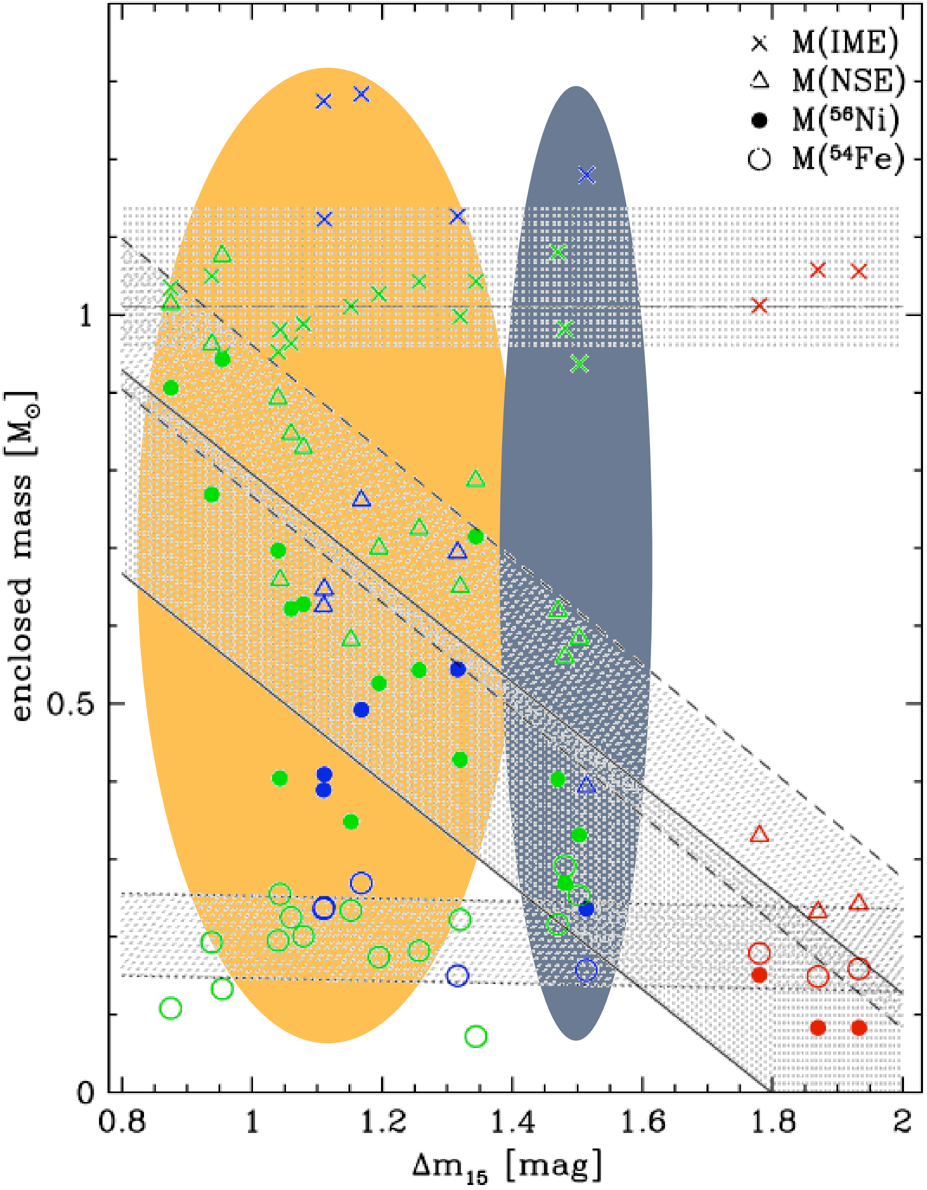
  for brightes examples:



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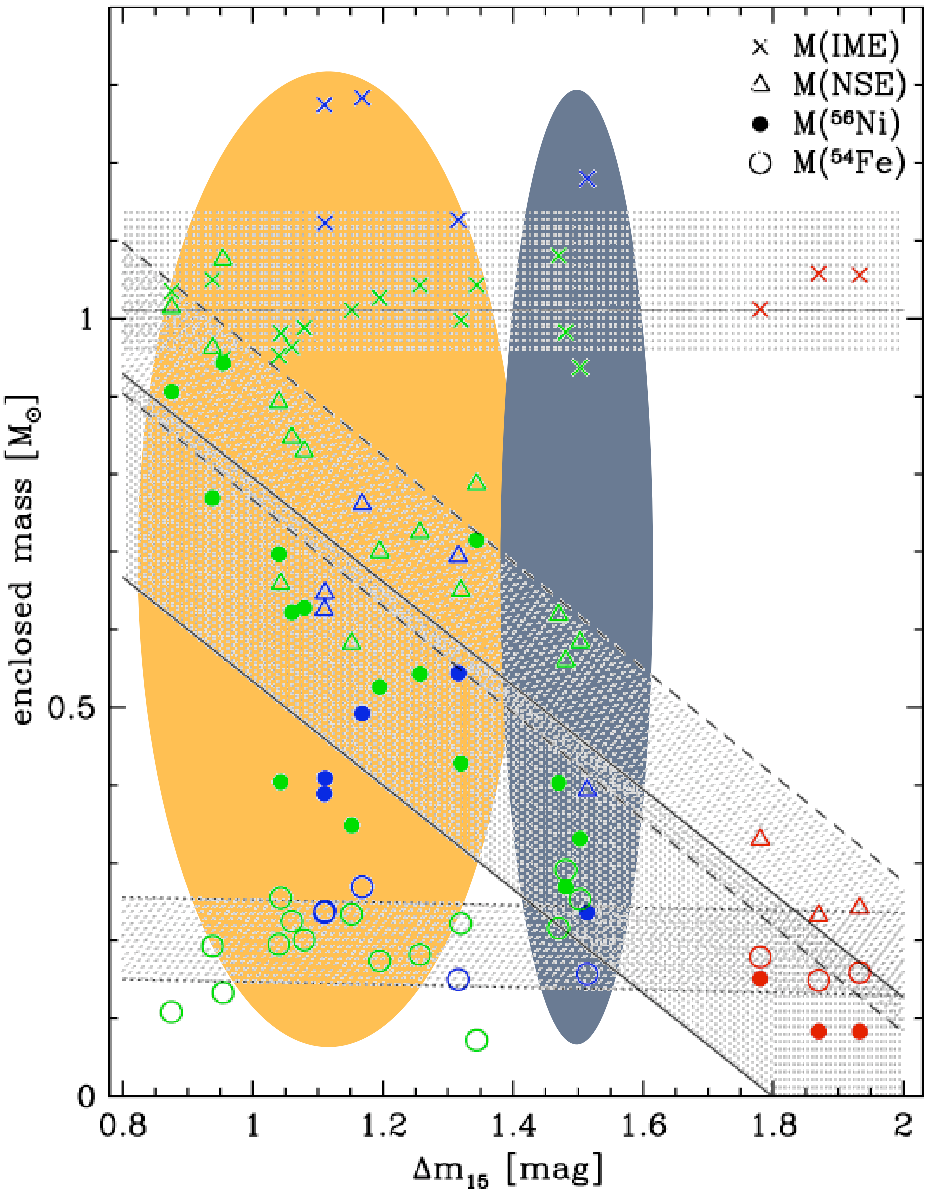

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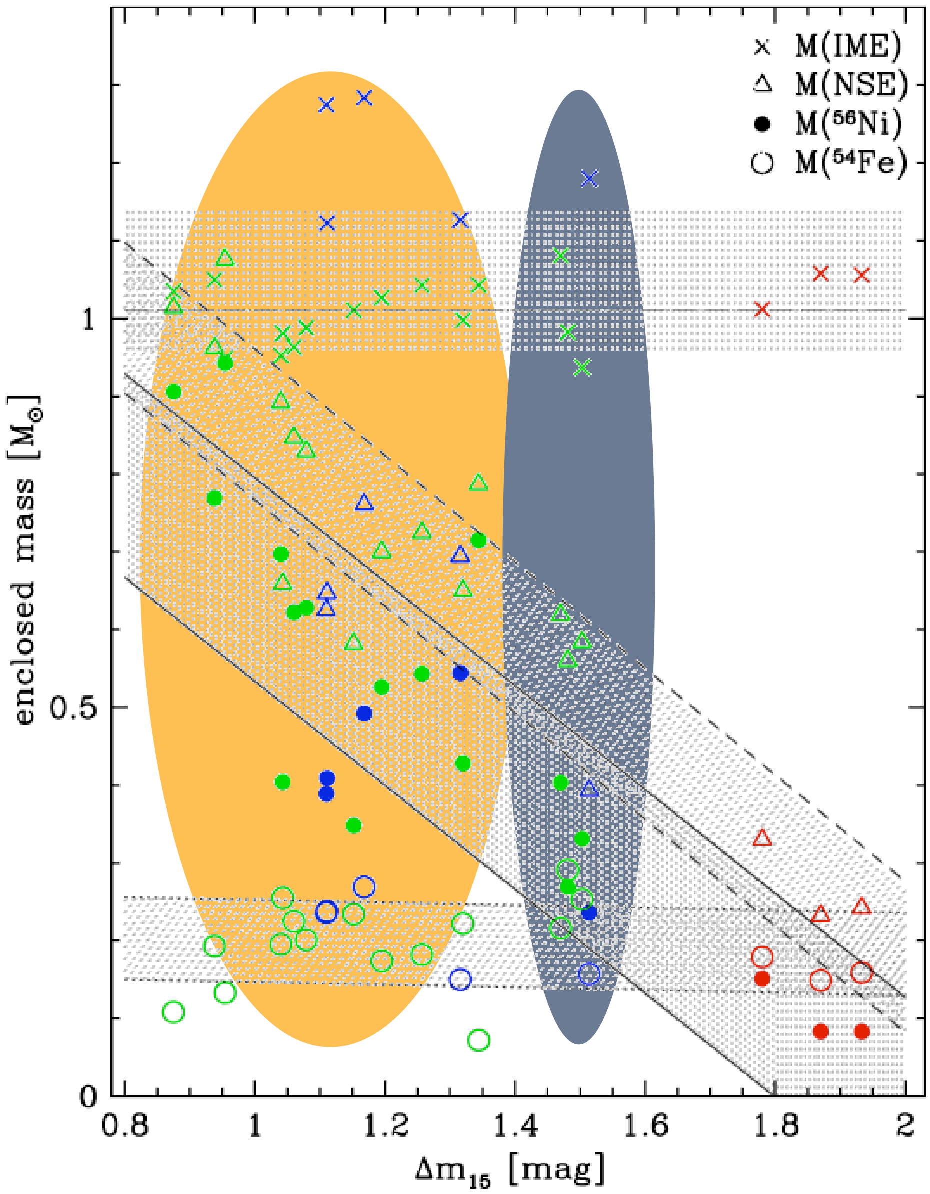

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  for brightes examples:
  detonation phase dominant
- sub-luminous: ???