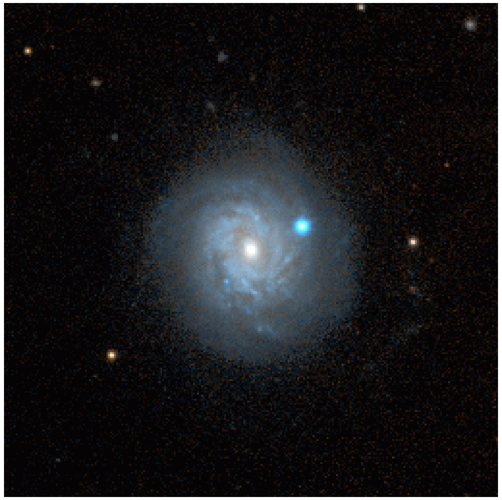
Lecture 7. Thermonuclear (type Ia) supernovae. Models (deflagration and detonation). Role in modern cosmology.

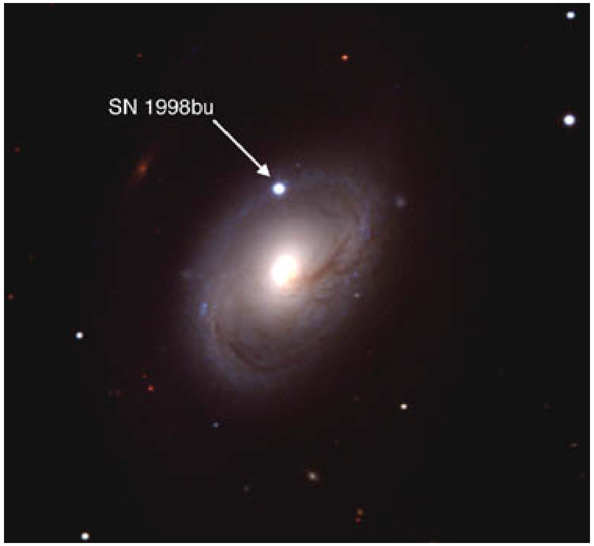
- discovery by Tycho de Brahe (Nov 11, 1572)

"Stella Nova" (1573), discovery chart



SN 1998aq

SN 1998dh



SN 1998bu

SN 1994D

HST

Type Ia supernovae are the biggest thermonuclear explosions in the universe.

Twenty billion, billion, billion megatons.

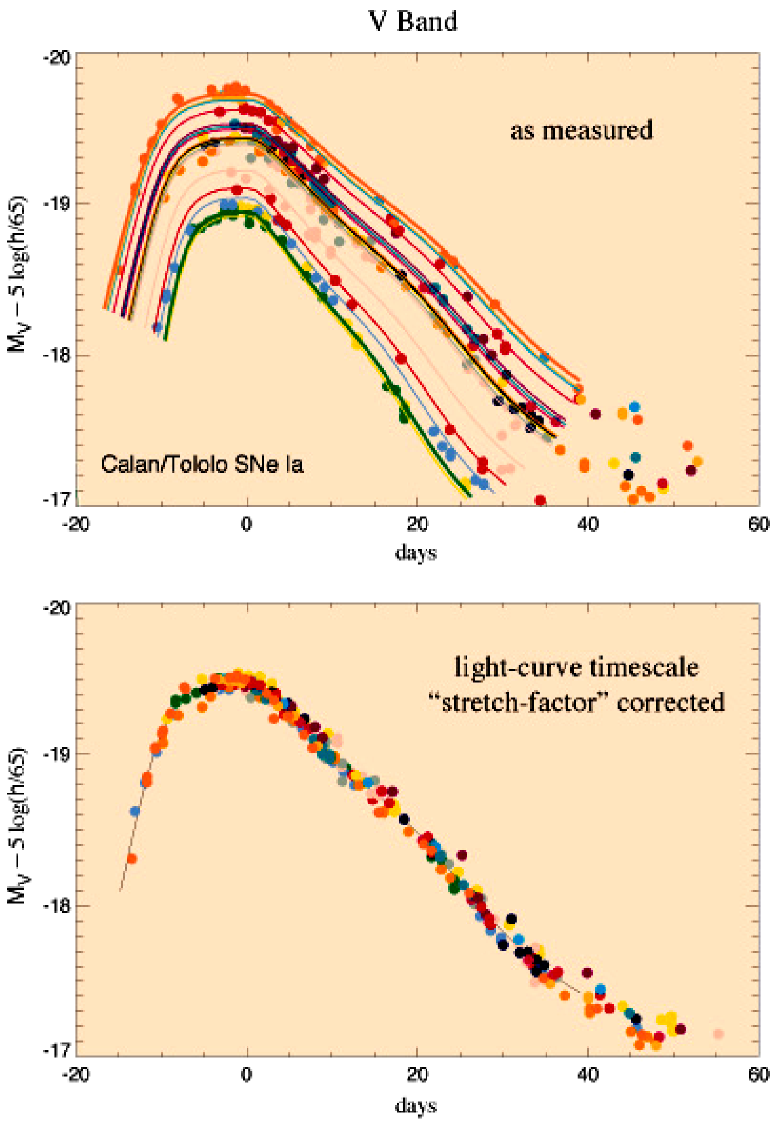
For several weeks their luminosity rivals that of a large galaxy.

Observational facts

SN 1994D

- Very bright, regular events, peak L ~ 10^{43} erg s^{-1}
- Associated with an old stellar population (found in ellipticals, no clear association with spiral arms)
- No hydrogen in spectra; strong lines of Si, Ca, Fe
- Not strong radio sources
- Total kinetic energy ~10^{51} erg (no compact remnant)
- Higher speed, less frequent than Type II

Low Redshift Type Ia Template Lightcurves

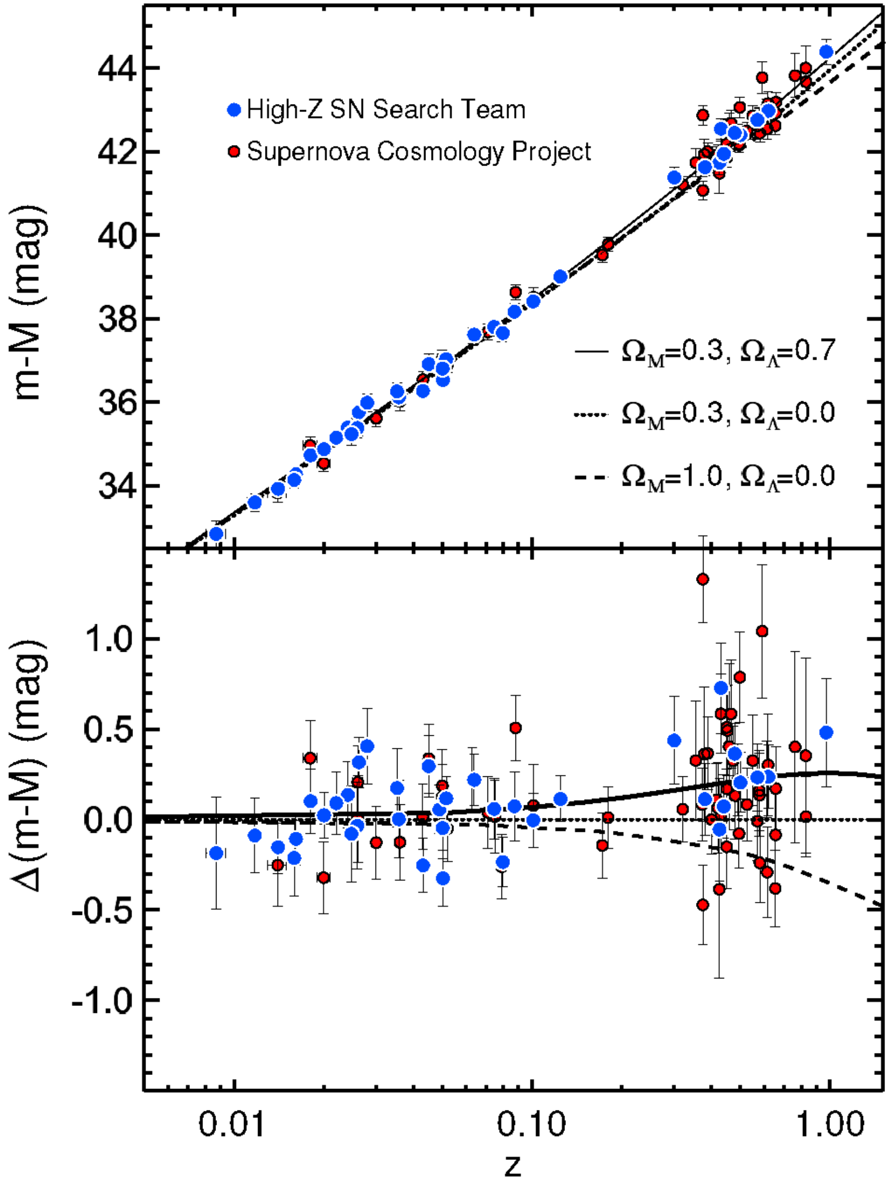


The Pskowski - Phillips Relation

Broader = Brighter

Can be used to compensate for the variation in observed SN Ia light curves to give a "calibrated standard candle".

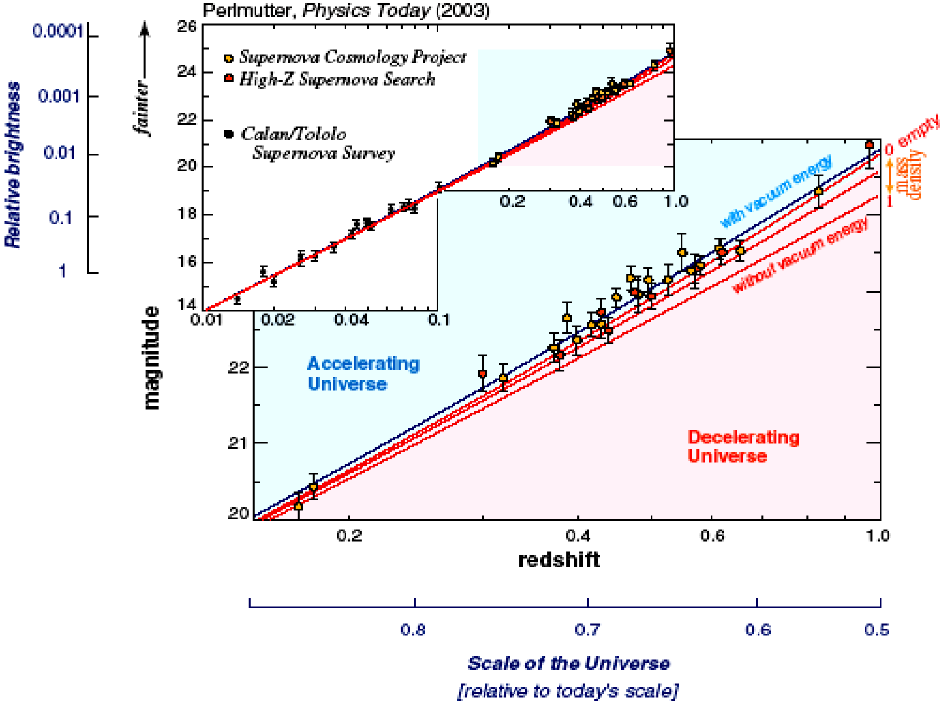
Note that this makes the supernova luminosity at peak a function of a single parameter – e.g., the width.

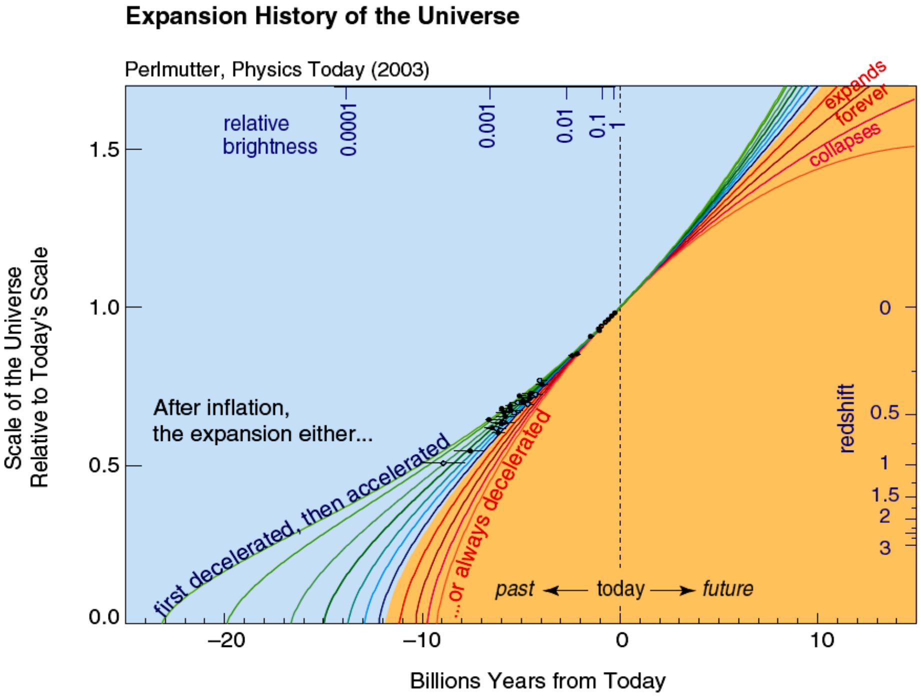


The greatest astronomical discovery in the end of XX century:

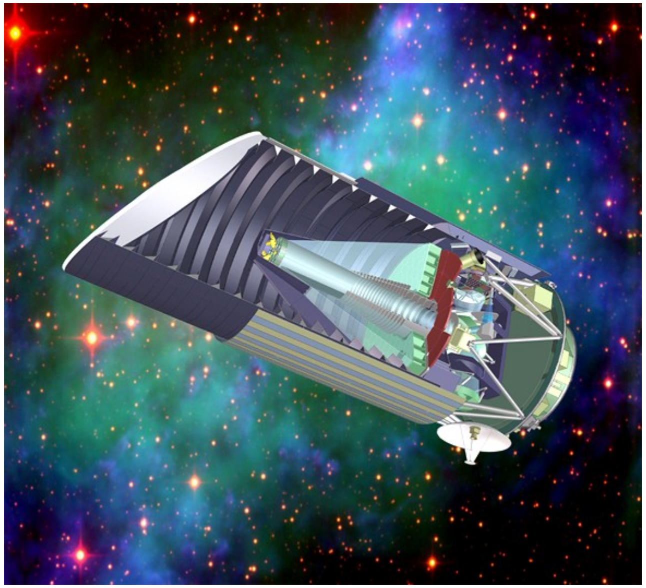
Type Ia supernovae at large distances seem to be fainter, for their observed red shift, than what would be expected in any cosmology without a cosmological constant.

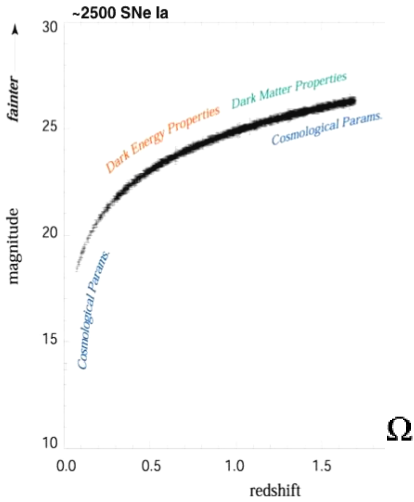
Measuring the Universe with SNe

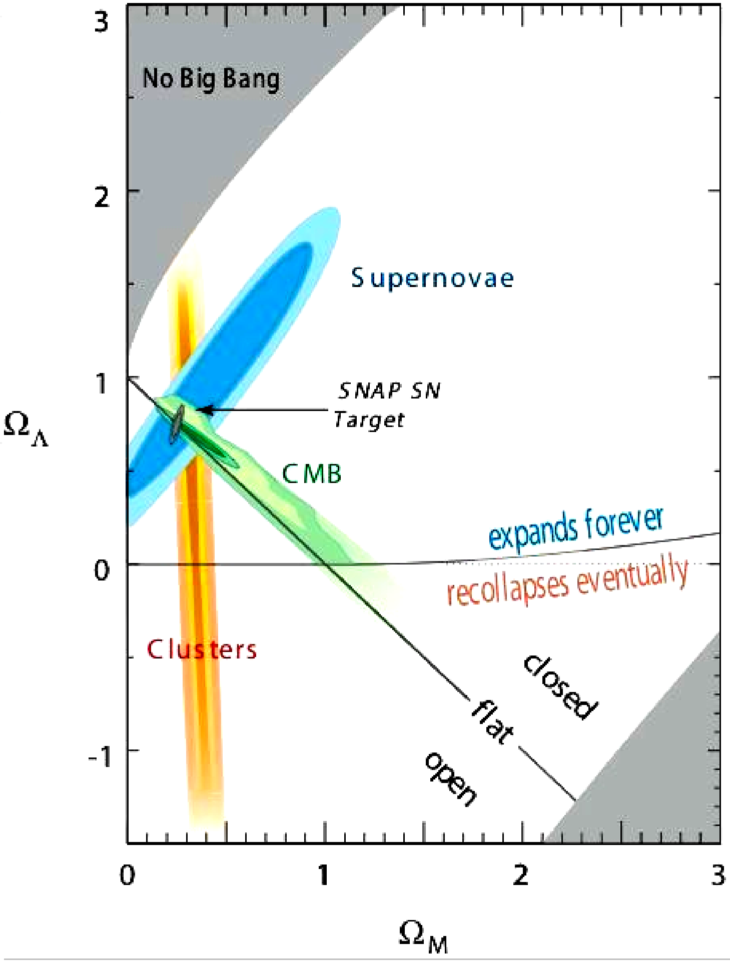




SNAP project: ~2500 type 1 SNe up to z=1.7







See snap.lbl.gov for more detail

Models that have been suggested

- *All based upon accreting white dwarfs – to explain association with old population, absence of hydrogen, regularity, etc.*

- *Merging white dwarfs*

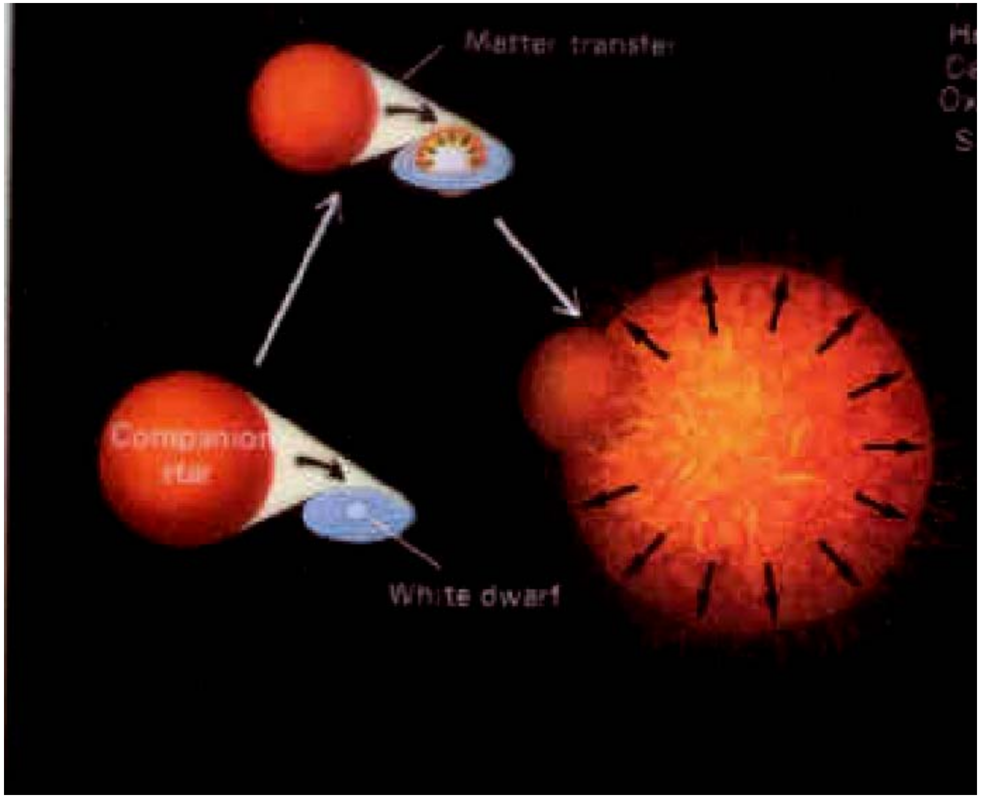
  High accretion rate leads to ignition at the edge
  Flame burns stably to center, converts dwarf to NeO
  Collapse to a neutron star

- *``Sub-Chandrasekhar" mass models*

  Accretion at about 3 x 10^{-8} solar masses/yr
  Build a thick He layer of about 0.15 to 0.20 solar masses on top of a carbon-oxygen white dwarf of 0.7 – 0.9 solar masses
  He detonation induces a detonation of the CO core
  Problems with spectrum and difficulty detonating CO
  Does produce some missing isotopes.

Leading Model

Accretion and growth to the Chandrasekhar Mass (1.38 solar masses)
Degenerate thermonuclear explosion. **(Hoyle and Fowler, 1960).**



In order to avoid the nova instability must accrete at a rate ~10^{-7} solar masses per year.

This must be maintained for millions of years.

Possible observational counterpart – supersoft x-ray sources, SSS (controversial)

Progenitor

Arnett (1968, 1969)
Nomoto, Sugimoto, & Neo (1976)

Ignition occurs as the *highly screened* carbon fusion reaction $^{12}C + ^{12}C \rightarrow ^{24}Mg^{*}$
begins to generate energy faster than (plasma) neutrino losses can carry it away.

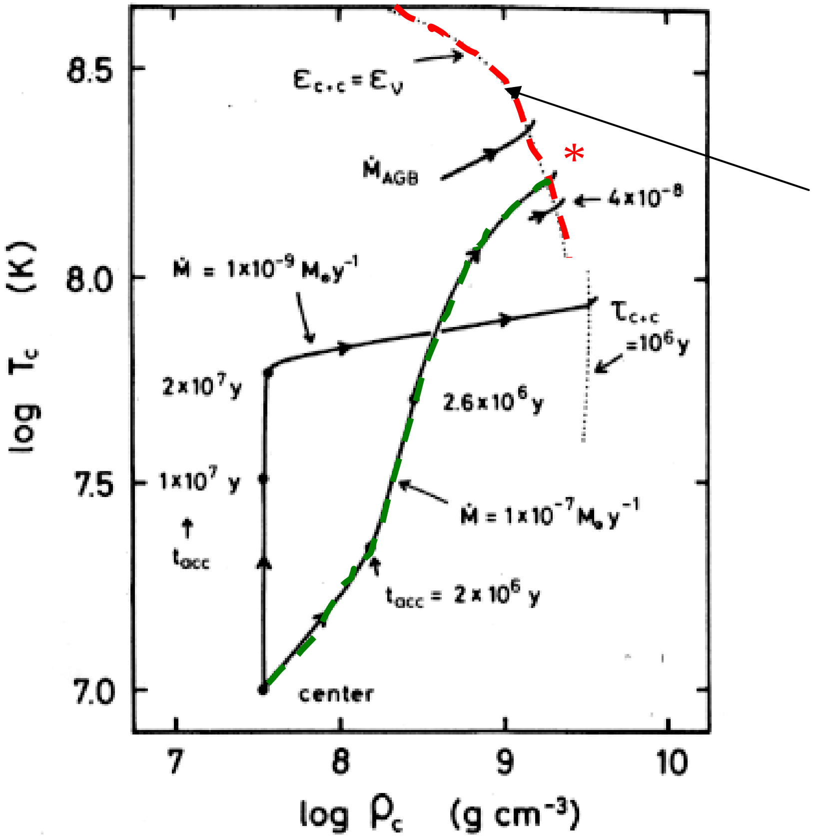
At a given temperature, the plasma neutrino losses first rise with density and then decline when

$$\hbar\omega_p > kT.$$

$$\text{As } \rho \rightarrow 3\times10^{9} \text{ gm cm}^{-3}\text{; T} \approx 3 \times 10^{8} \text{ K}$$

$$S_{\text{nuc}}\,(^{12}\text{C} + ^{12}\text{C}) \geq S_{\nu}\,(\text{plasma}); \qquad \text{M} \approx 1.38\ \text{M}_{\text{sun}}$$

The ignition conditions depend weakly on the accretion rate. For lower accretion rates the ignition density is higher. Because of the difficulty with neutron-rich nucleosynthesis, lower ignition densities (high accretion rates) are favored.



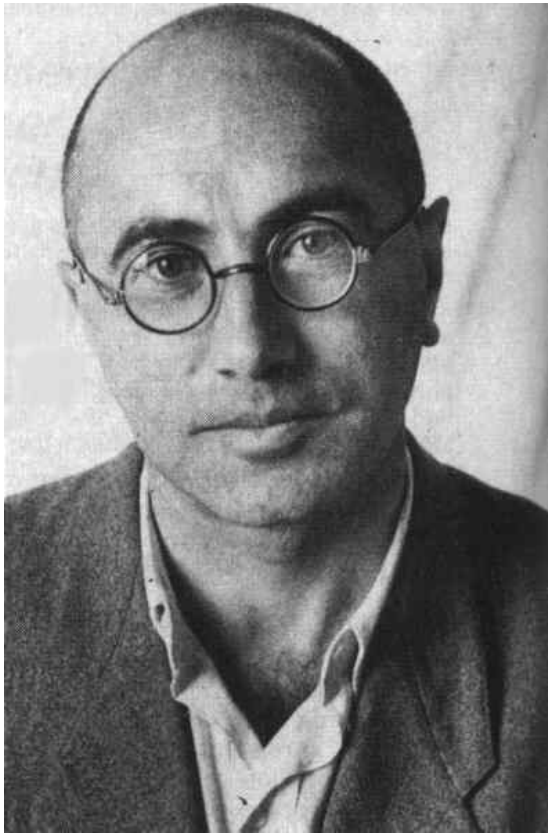
Ignition when nuclear energy generation by (highly screened) carbon fusion balances cooling by neutrino emission.

Ignition conditions and formation of deflagration wave (flame)

- ***Supernova preceded by 100 years of convection throughout most of its interior (Woosley). Energy goes into raising the temperature of the white dwarf (not expansion, not radiation).***
- ***"good convective model" is when the central temperature has risen to 7 x 10^8 K. Density ~ 2.5x10^9 g/cm^3 Timescales: for convection ~ 100 s, for nuclear burning ~ 100 s***
- ***As energy generation in CC burning ~T^{26}, burning time for T~7x10^8 K becomes < convection time scale, sound contact on the pressure gradient scale (~400 km) is also lost. Burning gets localized in a thin layer.***
- ***Burning starts (maybe in many points) and results in a deflagration wave (velocity of burning front < velocity of sound) when the ignition of fresh fuel is governed by heat and active reactant transport, i.e. by thermal conduction and diffusion***

Convection for 100 years, then formation of a thin flame sheet.

Flame, or deflagration wave. Theory: 1D: Zeldovich & Frank-Kamenetsky 1938 for chemical flames



Ya.B. Zeldovich (1914-1987)

Deflagration (flame) = laminar combustion front propagating with a subsonic velocity due to thermal conduction and diffusion

Detonation (explosion) = explosive burning of a fuel with burning front propagating supersonically

$$\tau_{diffusion} \approx \tau_{nuc}$$

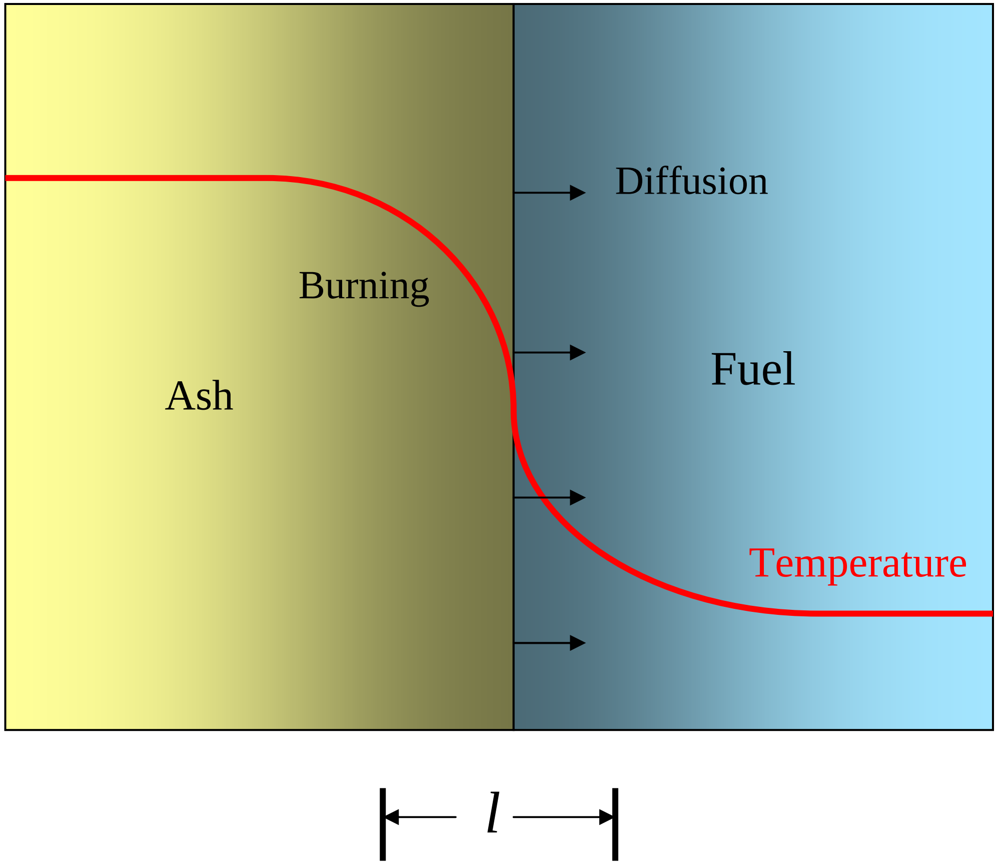
$$\left(\frac{l^2 \kappa \rho}{c}\right) \approx \left(\frac{\varepsilon}{S_{nuc}}\right)$$

ε = internal energy (erg/g)

κ = opacity (cm^2 / g)

S_{nuc} = energy generation (erg/g/s)

ρ = density ($\mathrm{g/cm}^3$)



$$l = \left(\frac{\varepsilon c}{\kappa \rho S_{nuc}}\right)^{1/2}$$

$$v_{cond} = l / \tau$$

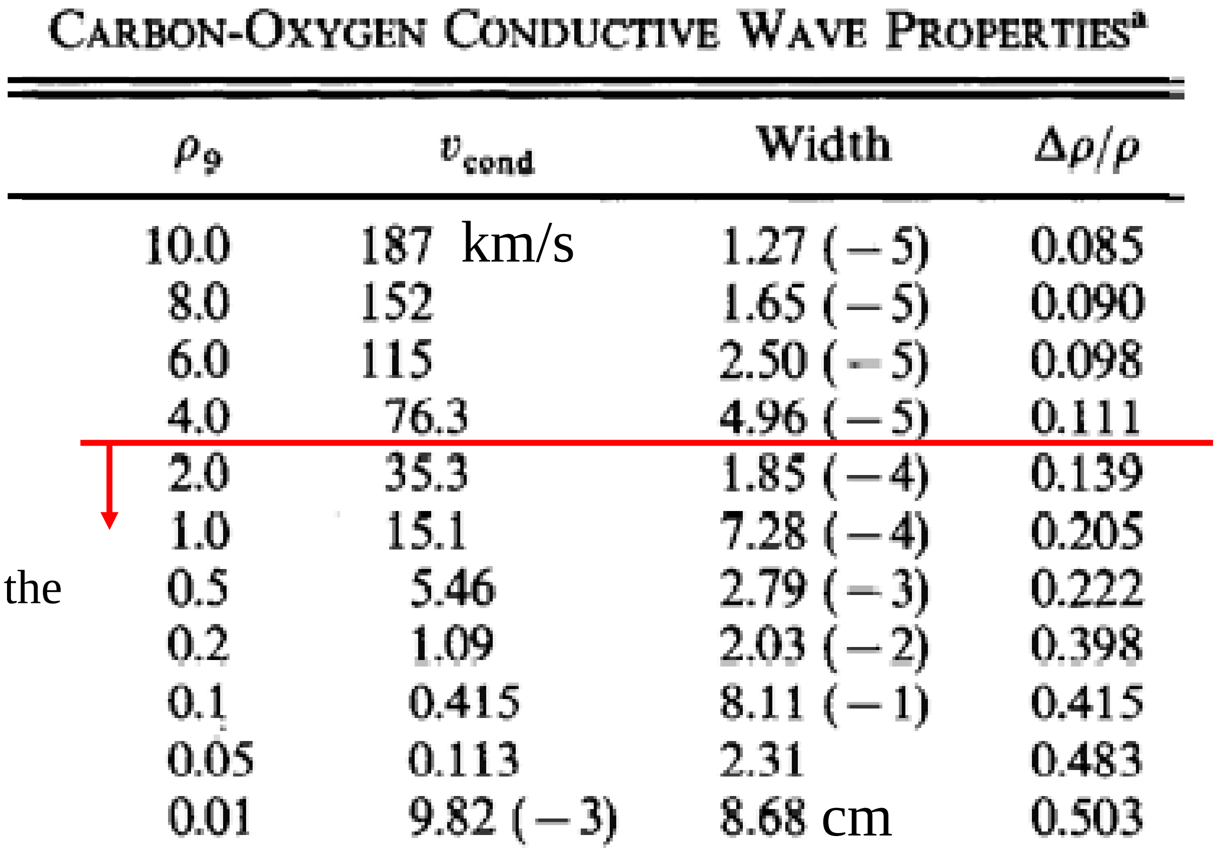
This is the conductive
- or sometimes “laminar”
- flame speed.

Laminar Flame Speed

(Timmes and Woosley, (1992), *ApJ*, **396**, 649)

$$v_{\text{cond}} \approx \left(\frac{c\, S_{nuc}}{\varepsilon\, \kappa\, \rho} \right)^{1/2}$$

$$c_{\text{sound}} \approx 10{,}000 \text{ km/s}$$



CARBON-OXYGEN CONDUCTIVE WAVE PROPERTIES[a]

ρ_9	v_{cond}	Width	$\Delta\rho/\rho$
10.0	187 km/s	1.27 (−5)	0.085
8.0	152	1.65 (−5)	0.090
6.0	115	2.50 (−5)	0.098
4.0	76.3	4.96 (−5)	0.111
2.0	35.3	1.85 (−4)	0.139
1.0	15.1	7.28 (−4)	0.205
0.5	5.46	2.79 (−3)	0.222
0.2	1.09	2.03 (−2)	0.398
0.1	0.415	8.11 (−1)	0.415
0.05	0.113	2.31	0.483
0.01	9.82 (−3)	8.68 cm	0.503

nb. these speeds are comparable to the convective speeds prior to runaway

Pure deflagration: fail to reproduce SN Ia (?)

- *At 10 billion K burning always goes to completion and makes iron. Only below four billion K (few x 10^7gm cm-3) does one begin to make Si, S, Ar, Ca, Mg, etc. Almost all the initial white dwarf is more dense than that.*

- *So, naive physics gives us a flame that burns the star slowly to iron, experiences a lot of electron capture, and barely unbinds the star – maybe after several pulses. The star has enough time to expand, temperature drops and burning dies out completely….*

But actually…
A Successful Model Must:

(Starting from 1.38 solar masses of carbon and oxygen)

- Explode violently
- Produce approximately 0.6 solar masses of ^{56}Ni (0.1 to 1 M_{sun}) *For the light*
- Produce at least 0.2 solar masses of SiSArCa *For the spectrum*
- Not make more than about 0.1 solar masses of ^{54}Fe and ^{58}Ni combined *For the nucleosynthesis*
- Allow for some diversity

It has been known empirically for some time that the way to get around these problems and agree with observations is with a flame that starts slowly, pre-expands the star (so as to avoid too much electron capture) then moves very rapidly when the density is around $10^7 - 10^8$ gm cm^{-3}.

Unfortunately the laminar flame has just the opposite behavior and a prompt explosion (detonation) would turn the whole star to iron (in conflict with the spectrum).

But how to get a flame that moves at greater than about 30% the sound speed?

- ***Landau-Darrieus instability (1944).*** *Operates in the limit of small accelerations w.r.t. gravity. Leads to wrinkling of the flame front and acceleration of burning*
- ***Rayleigh-Taylor Instability.*** *Operates if gravity acceleration is important. The ashes are from 20% to100% lighter than the fuel.* $g_{eff} \sim 10^9$ *cm* s^{-2}.
- ***Turbulence***

  The RT instability leads to Kelvin-Helmholtz instability and turbulence
- ***Delayed Detonation***

  At late times the flame may accelerate to supernonic speeds and become a self-sustaining detonation wave

NO SELF-CONSISTENT MODEL HAS BEEN FOUND SO FAR

Some semi-empirical models with deflagration-detonation transition at the appropriate radius do work.

Intermezzo: Hydrodynamic Instabilities of the flame front

Landau and Lifschitz (Fluid Mechanics, 2nd Edition, § 128), describe conditions for stability of a planar flame front under taking into account the influences and gravity and capillary forces. The conditions for instability under small deviations of the planar interface are given by an dispersion relation in horizontal wave number $k=2\pi/\lambda$ and decay rate Ω are given by a dispersion relation obtained implicitly by

$$\Omega^2 (v_1+v_2) + 2\Omega k v_1 v_2 + k^2 (v_1 - v_2) v_1 v_2 - gk(v_1 - v_2) = 0$$

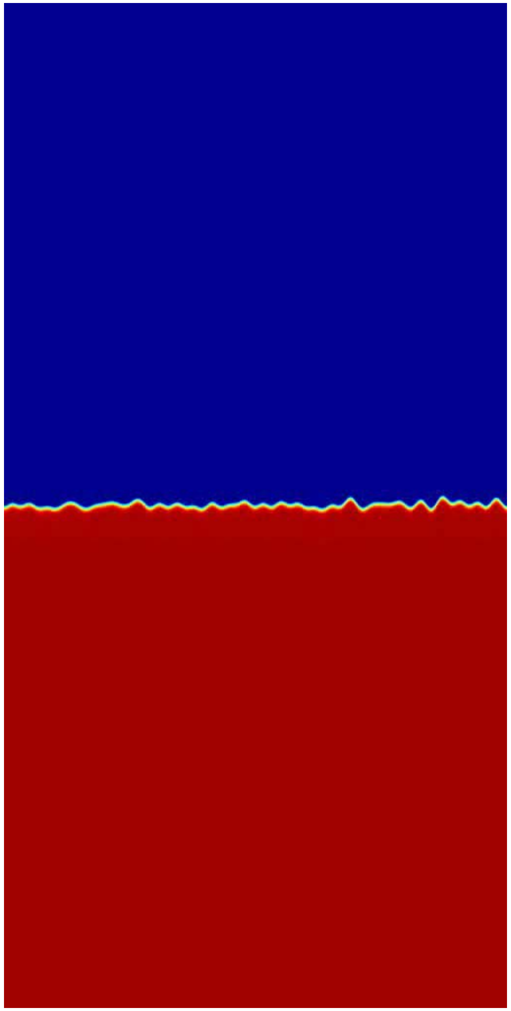
where g is the acceleration of the interface due to gravity, $v_{1/2}$ is vertical flow speed in the (fuel/ash), and we have ignored the influence of capillary pressure.

In the limit g→0 we recover the Landau-Darrieus instability (for any k)
In the limit of large g we recover classical RT instability:

$$\Omega^2 = kg\Delta\rho/(\rho_1+\rho_2)$$

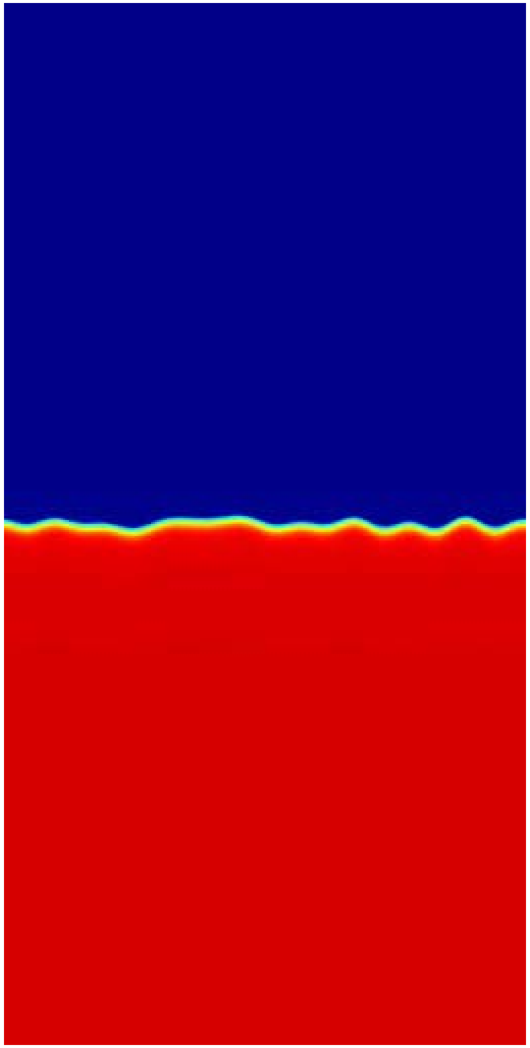
(here we took into account that $\rho v=\mathrm{const}$ due to mass conservation)

Temperature profile in ^{12}C- ^{24}Mg burning. LD-instability. $P=5\times10^{7}$ g/cm^{3}. No gravity acceleration



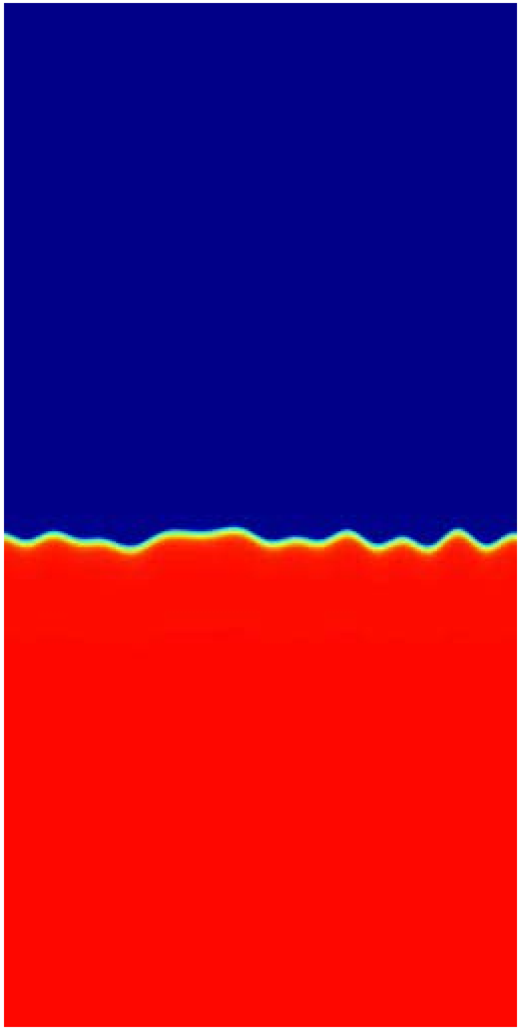
LD instability leads to wrinkling of the flame front

Temperature profile in ^{12}C- ^{24}Mg burning. RT-instability. P=5×10^7 g/cm^3, g=10^9cm/s^2

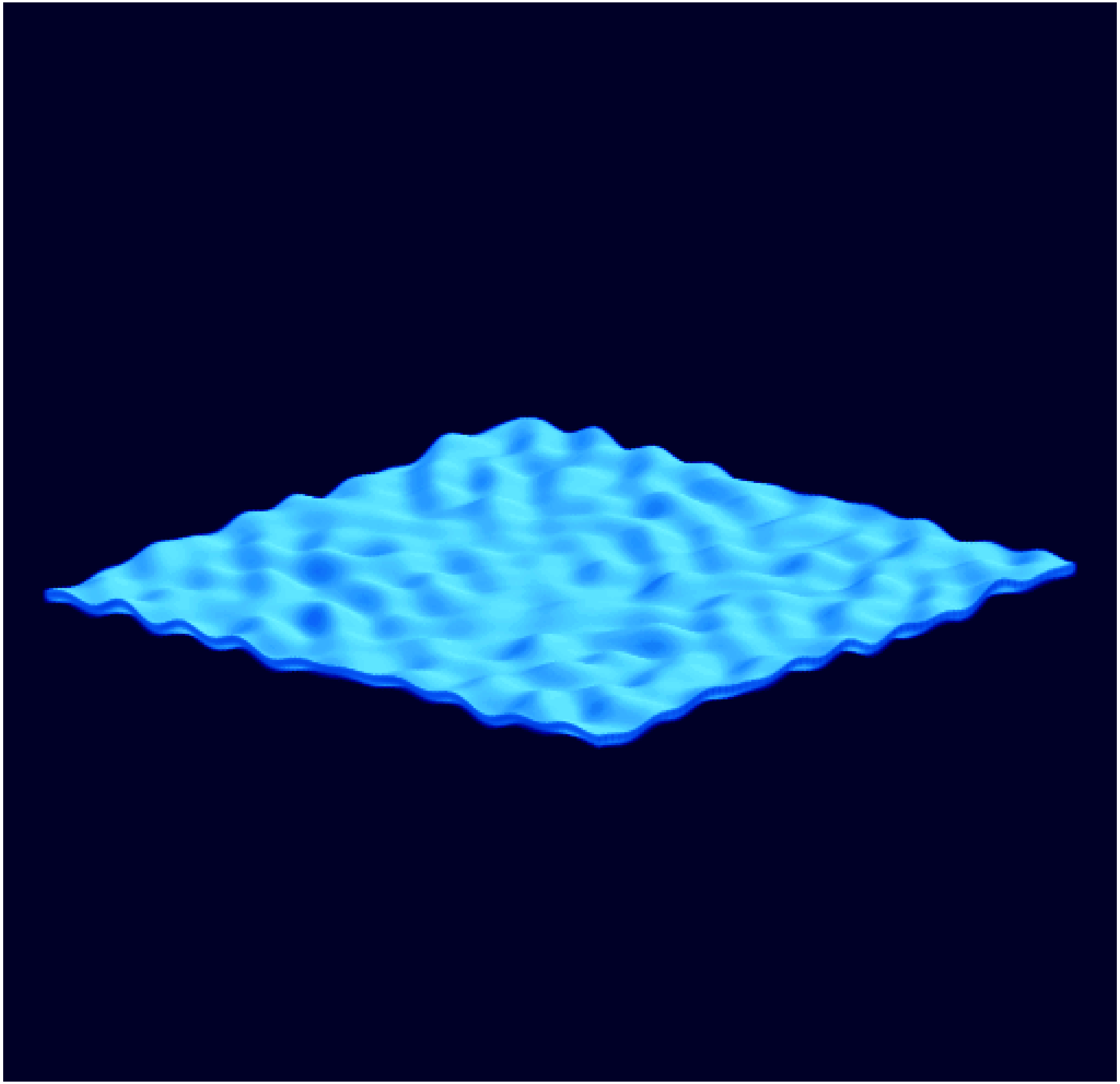


RT instability leads to turbulence

Temperature profile in ^{12}C- ^{24}Mg burning. LD+RT instability. $P=1.5\times10^7$ g/cm^3. $g=10^9$cm/s^2



RT mushrooms burnt away before strong turbulence developes

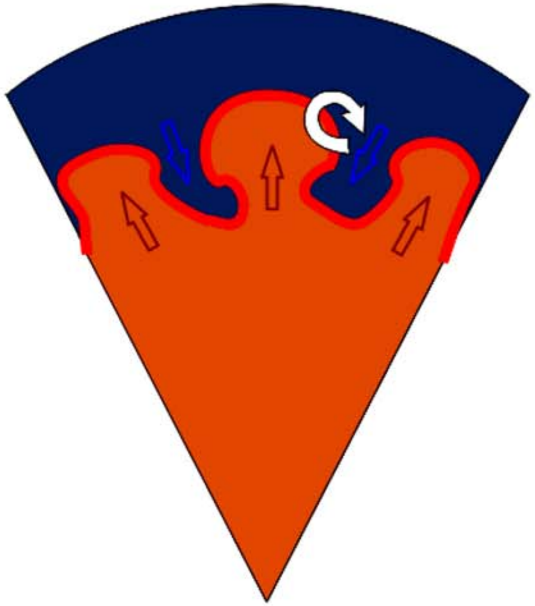


ZIngale and Woosley, 2005, 3D

No transition to detonation has been found

SNe Ia as problem of turbulent combustion

- interaction of flame with turbulence → turbulent combustion
- generic instabilities:

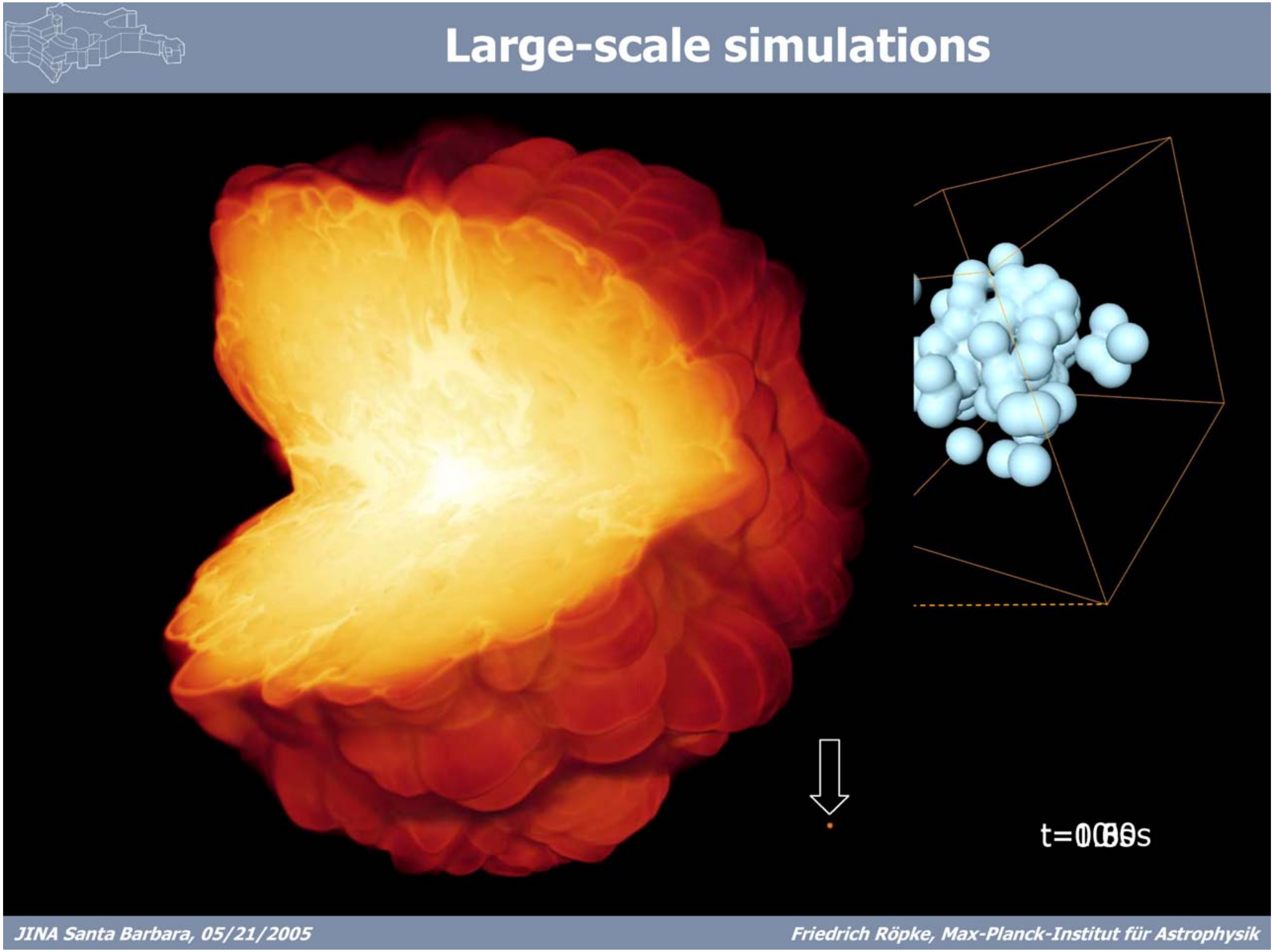


estimate Re around RT-bubble:
$L \sim 10^7$ cm, $v_{\text{shear}} \sim 10^7$ cm s^{-1}
$\rho \sim 10^9$ g cm^{-3}, $\eta \sim 10^9$ g cm^{-1} s^{-1}

→ Re $\sim 10^{14}$

formation of turbulent energy cascade

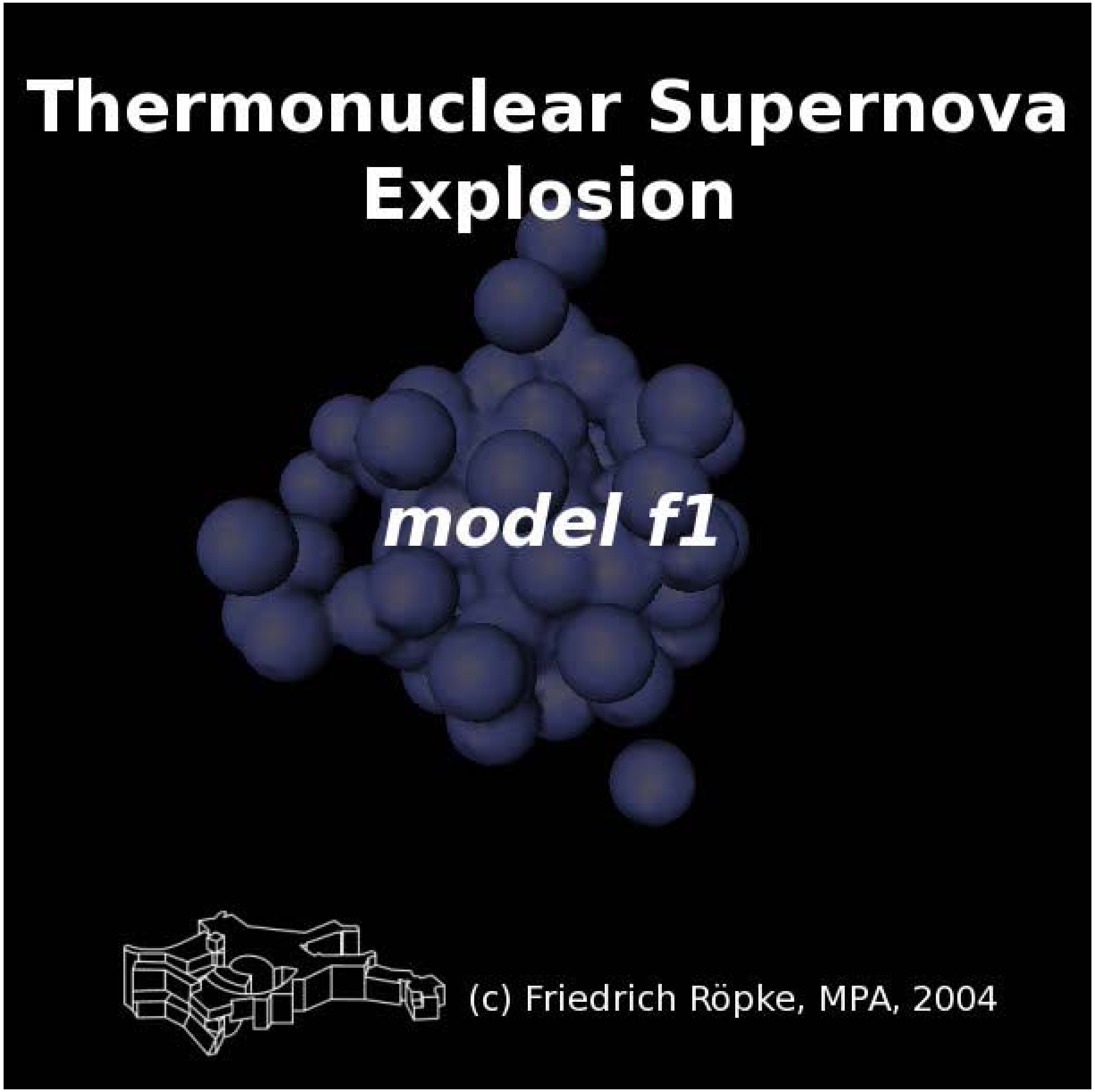
- wrinkling of the flame front → flame surface ↑ → net burning rate ↑ → flame propagation strongly accelerated
- later transition to (supersonic) detonation?



Large-scale simulations

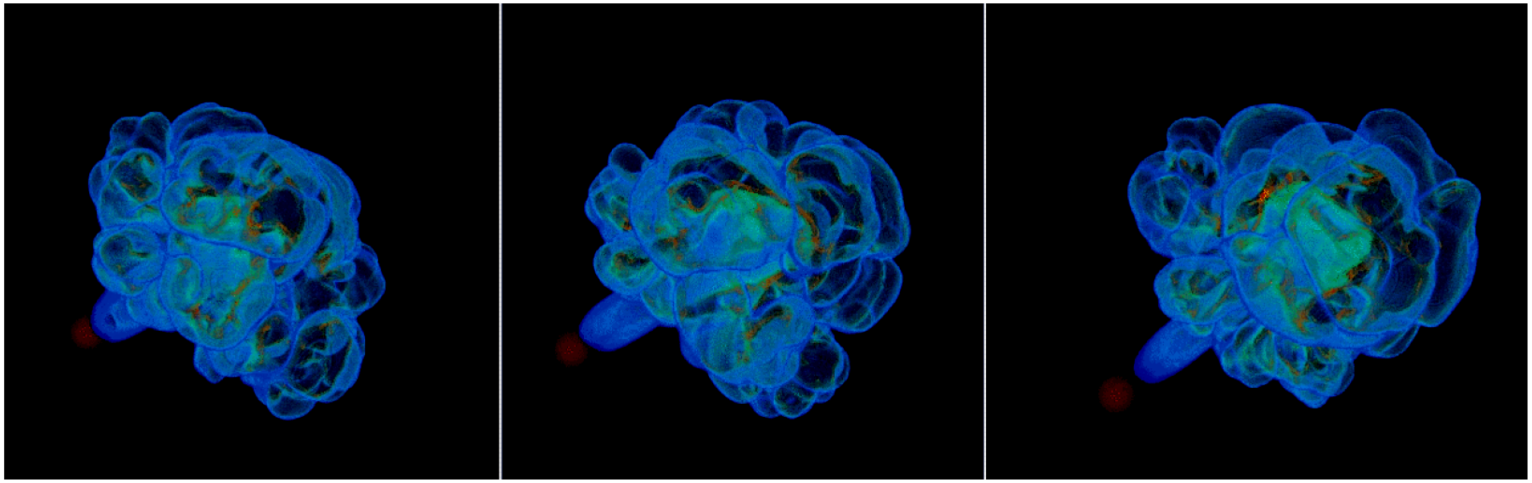
JINA Santa Barbara, 05/21/2005

Friedrich Röpke, Max-Planck-Institut für Astrophysik


Thermonuclear Supernova Explosion
model f1
(c) Friedrich Röpke, MPA, 2004

Memory Loss of The Initial Conditions

Off-center ignition models at 12, 20, and 35 km at 2 km resolution.



Variations in the offset (and initial bubble size) are unlikely to affect early evolutionary phases in any significant way.

SN Ia light curves.

After the white dwarf has expanded a few times its initial radius its internal energy (and entropy) will be chiefly due to radiation, that is -

$$S_r \sim T^3/\rho \;\approx\; \text{constant}$$

$$\rho \propto 1/r^3, \text{ so}$$

$$\mathrm{T} \;\propto\; 1/r$$

$$\varepsilon = aT^4/\rho \propto 1/r$$

Before the radiation can diffuse out, the supernova has expanded from a few times 10^8 to 10^{15} cm. During that time, the internal energy goes down from ~10^{51} erg to ~10^{44} erg. The internal energy is totally inadequate to power the light curve.

Energy from explosion:

E ~ 10^{51} erg

T ~ 10^{10} K   R ~ few x 10^8 cm

Light can escape when:

$\tau_{\text{diff}} \approx t$

$$\frac{R^2 \kappa \rho}{c} \sim t$$

$$\kappa = \kappa_{es} + \kappa_{line} \sim 0.1\,\mathrm{cm^2\,g^{-1}}$$

$$\rho \sim \frac{3M}{4\pi R^3}$$

$$M \sim M_\odot = 2\times 10^{33}\,\mathrm{gm}$$

$$R = v t$$

$$v \sim 5000\,\mathrm{km\,s^{-1}}$$

$$\Rightarrow t_{peak} = \sqrt{\frac{3\kappa M}{4\pi v c}} = 1.8 \times 10^6\,\mathrm{s}$$

$$\Rightarrow R \sim 10^{15}\,\mathrm{cm}$$

Adiabatic expansion implies that the interior temperature has dropped by 10^6 and the interior energy is negligible.

Radioactivity is essential to keep the supernova hot and shining!

Radioactivity

$${}^{56}\mathrm{Ni} + \mathrm{e}^{-} \rightarrow {}^{56}\mathrm{Co} + \nu \qquad \tau_{1/2} = 6.1\,\mathrm{days}$$

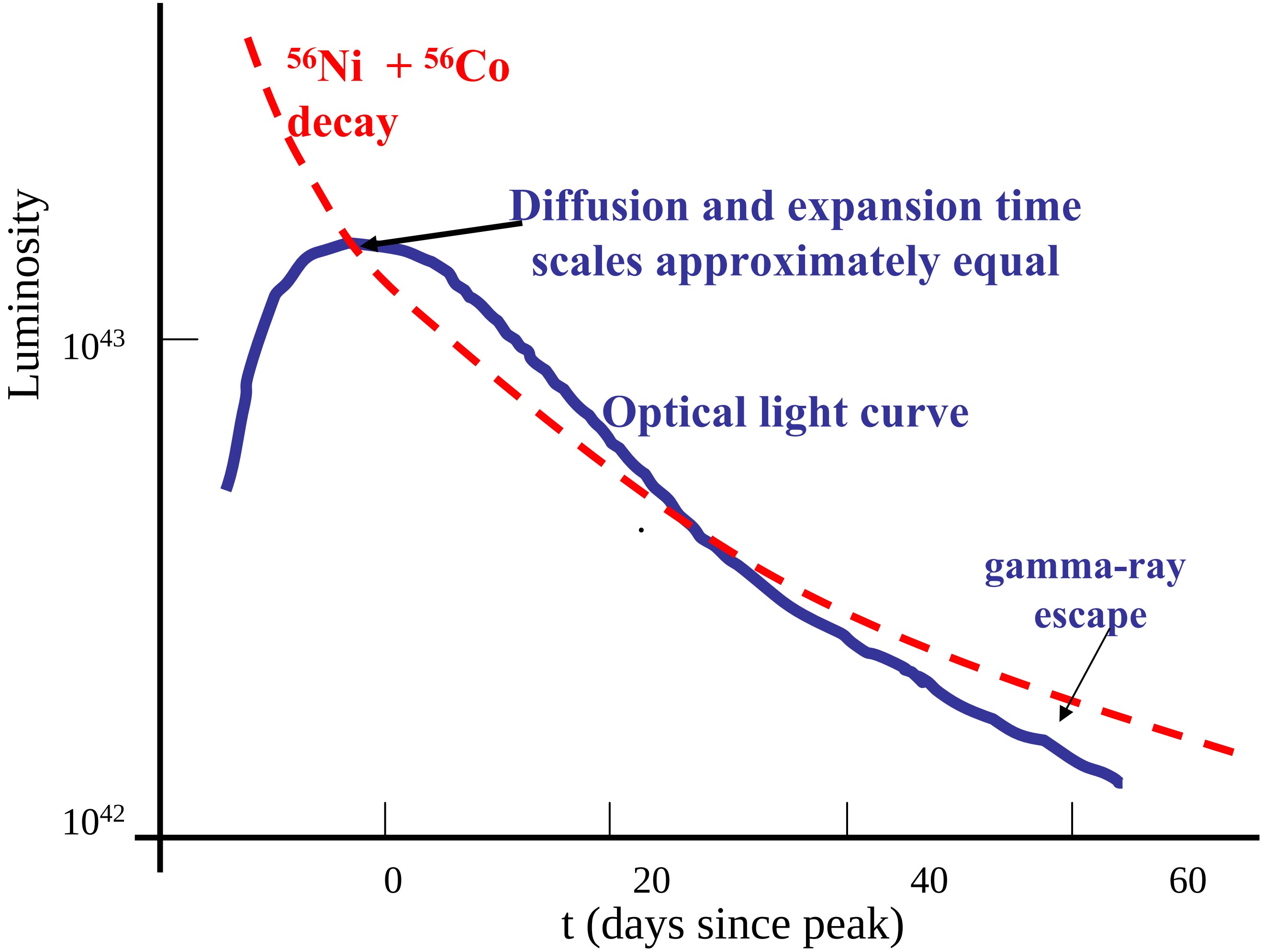
$q = 3.0 \text{ x } 10^{16}$ erg/g

$${}^{56}\mathrm{Co} + \mathrm{e}^{-} \rightarrow {}^{56}\mathrm{Fe} + \nu \qquad \tau_{1/2} = 77.1\ \mathrm{days}$$

$q = 6.4 \text{ x } 10^{16}$ erg/g

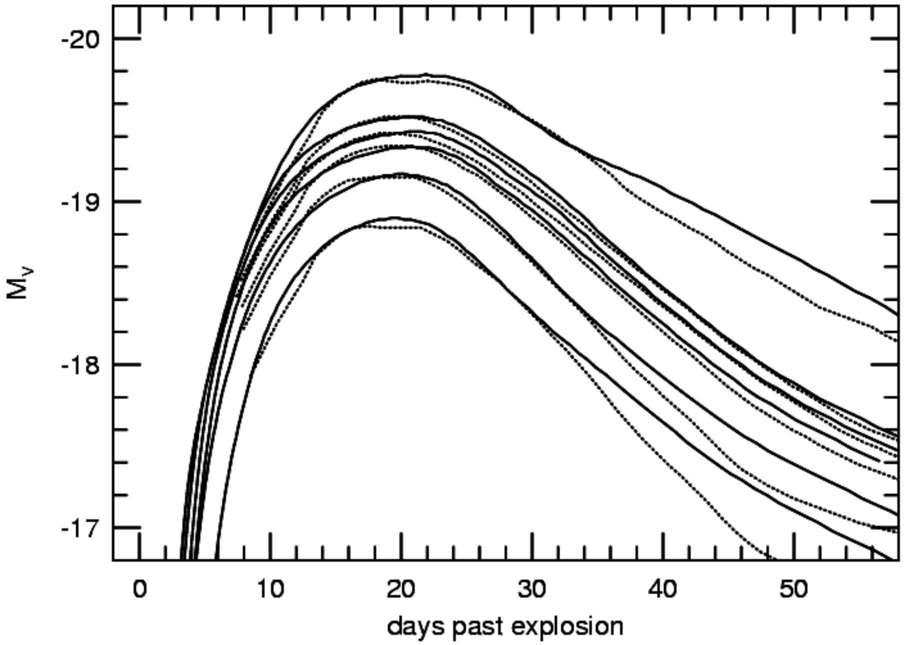
0.6 solar masses of radioactive Ni and Co can thus provide 1.1 x 10^{50} erg at late times after adiabatic expansion is essentially over.

Qualitative Type Ia Supernova Light Curve



More ^{56}Ni implies a larger luminosity at peak. ***(Arnett's rule)***

Universality of SNIa light curves and Pskowskij-Philips relation



Pinto & Eastman, (2001), *New Astron,*

A single supernova model (energy, density structure, etc) in which only the mass of ^{56}Ni has been varied. Also shown are the standard template of light curves displaying the width-luminosity relation.

What matters?

- The mass of ^{56}Ni -- contributes explosion energy, radioactive energy, and opacity.
- The mass of ^{54}Fe, ^{58}Ni, and other stable members of the iron group -- contribute opacity and explosion energy,
  but no radioactive energy.
- The mass of SiSArCa -- contribute to the explosion energy, but not the opacity or radioactive energy.
- The explosion energy -- depends on the ignition density (hence accretion rate) and C/O ratio as well as all the above masses.
- Mixing

Conclusions

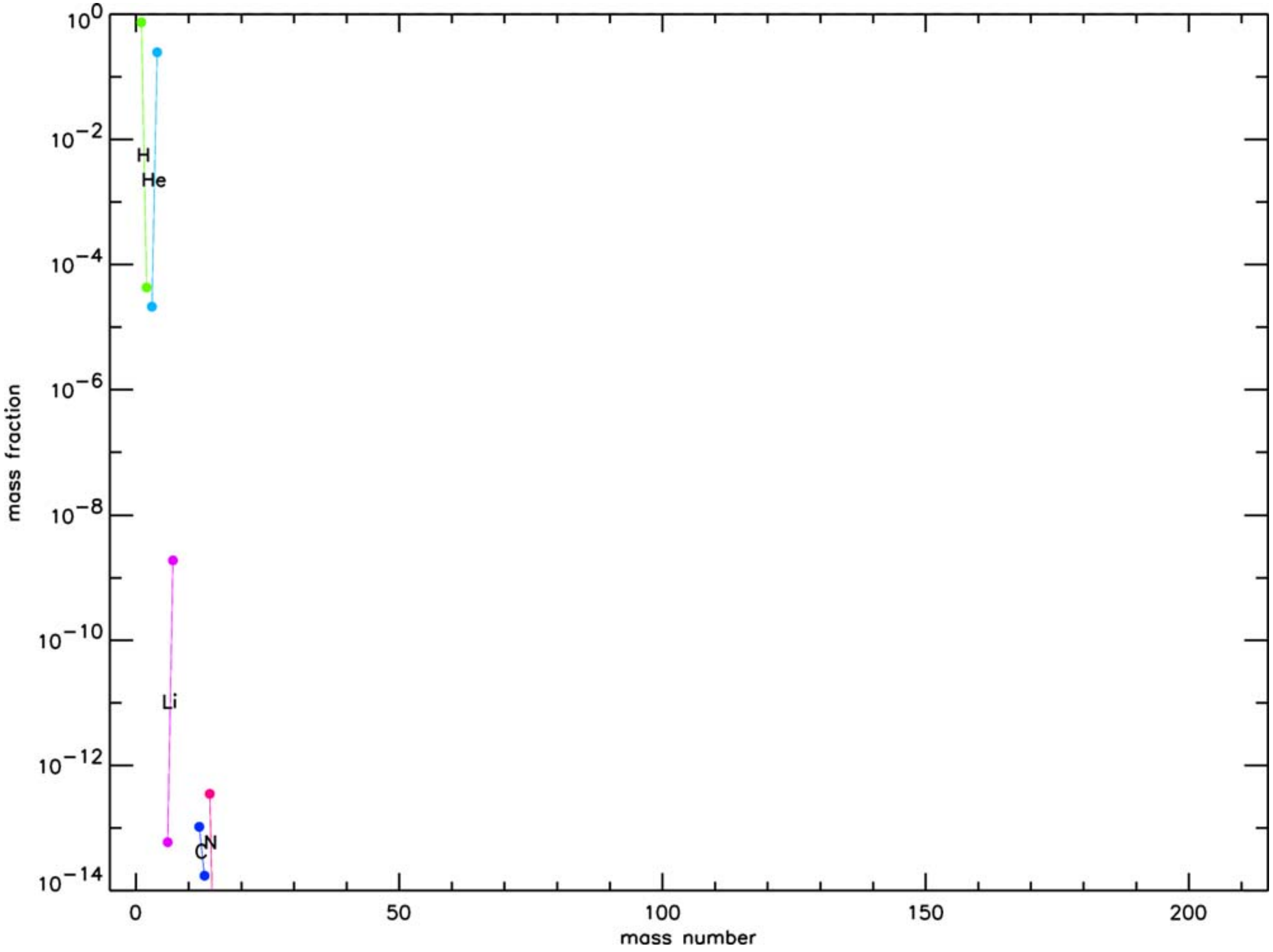
- A first principles understanding of how Type Ia supernovae explode is still lacking, but progress is being made

- Recent achievements: Detonation may plays no role in the explosion – though this issue is not conclusively resolved. SN Ia explode by a carbon deflagration in which instabilities and turbulence play a key role.

- The width-luminosity relation is a consequence of the *atomic physics* of the explosion, in particular a temperature-dependent escape probability of photons. The most important parameter is the mass of ^{56}Ni.

- Just how (how often and where) the white dwarf ignites is a crucial piece of uncertain physics.

Primordial nucleosynthesis (B.Fields)



Today (Solar abundance pattern)