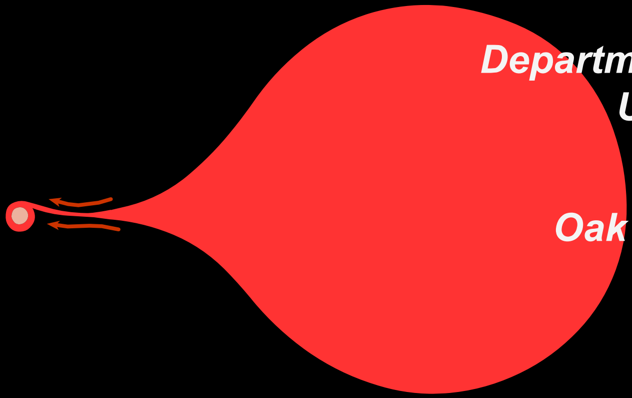
Bright Lights, Dark Energy, and a Quite Curious Coefficient

Thermonuclear Supernovae and the Equation of State for the Universe



Mike Guidry

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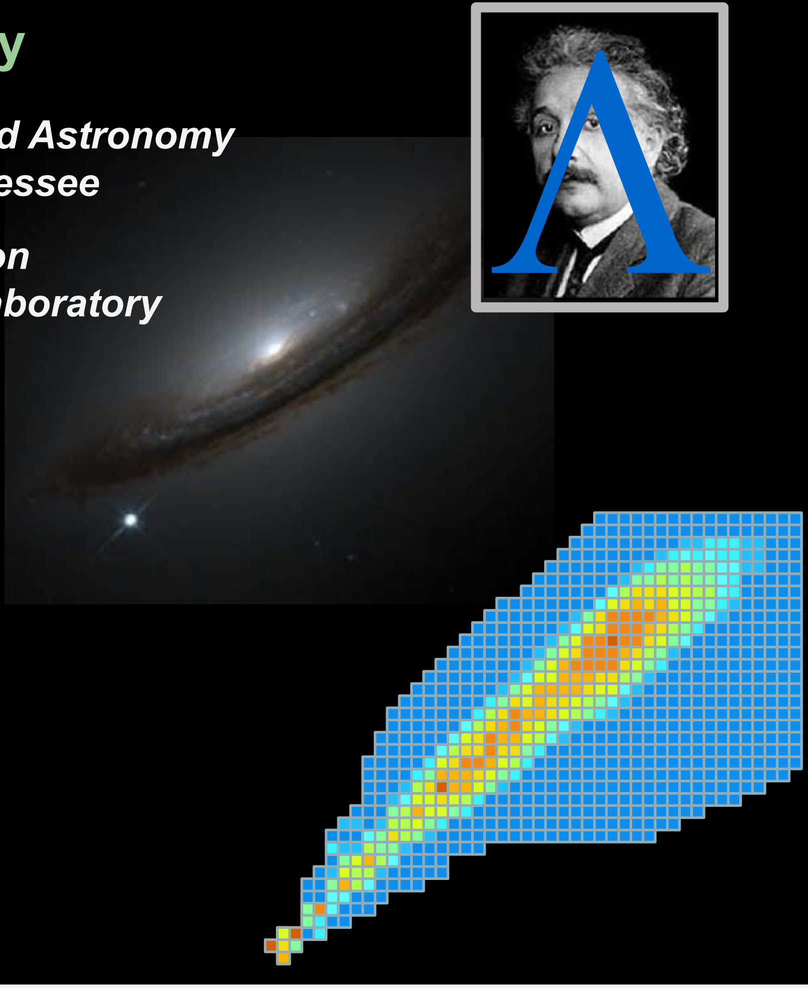
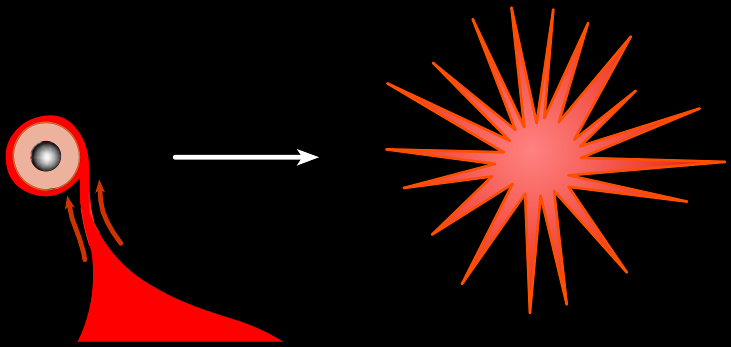
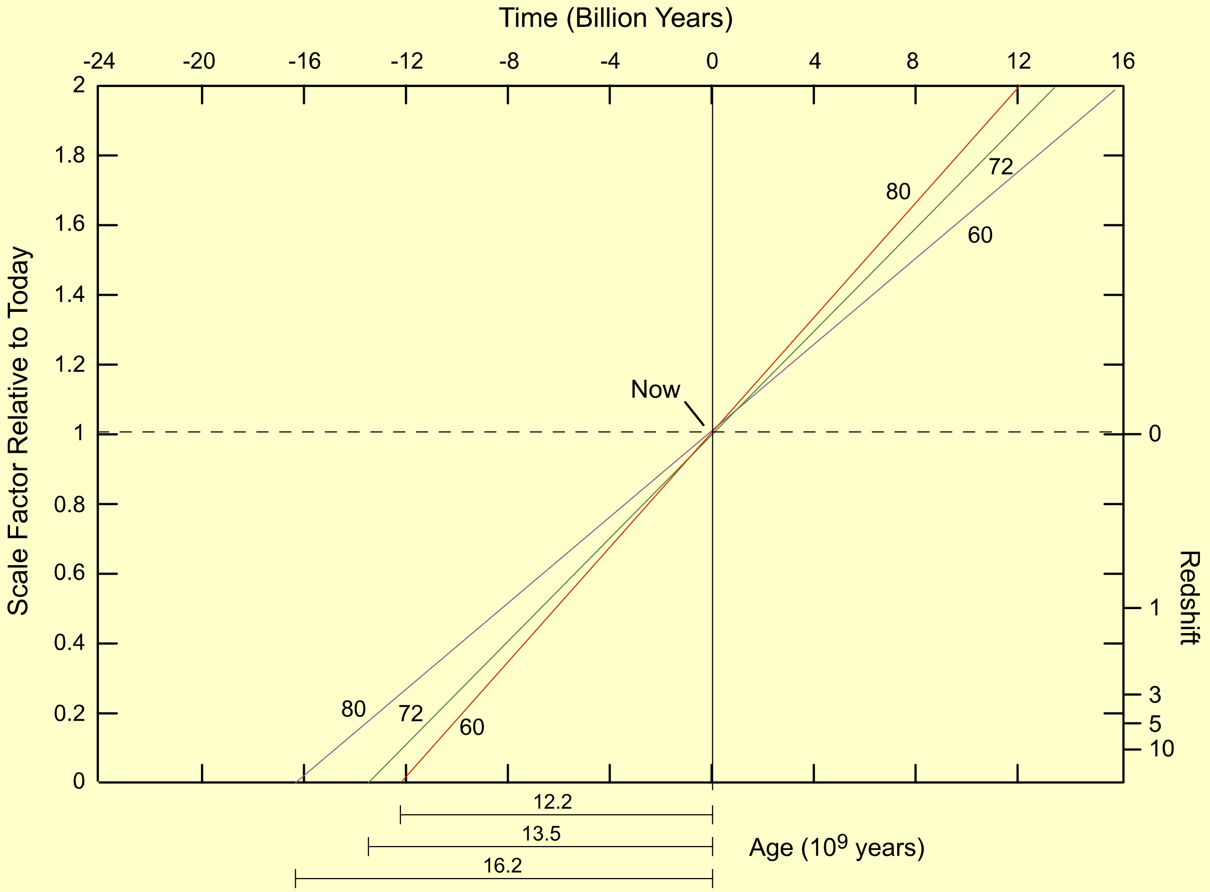




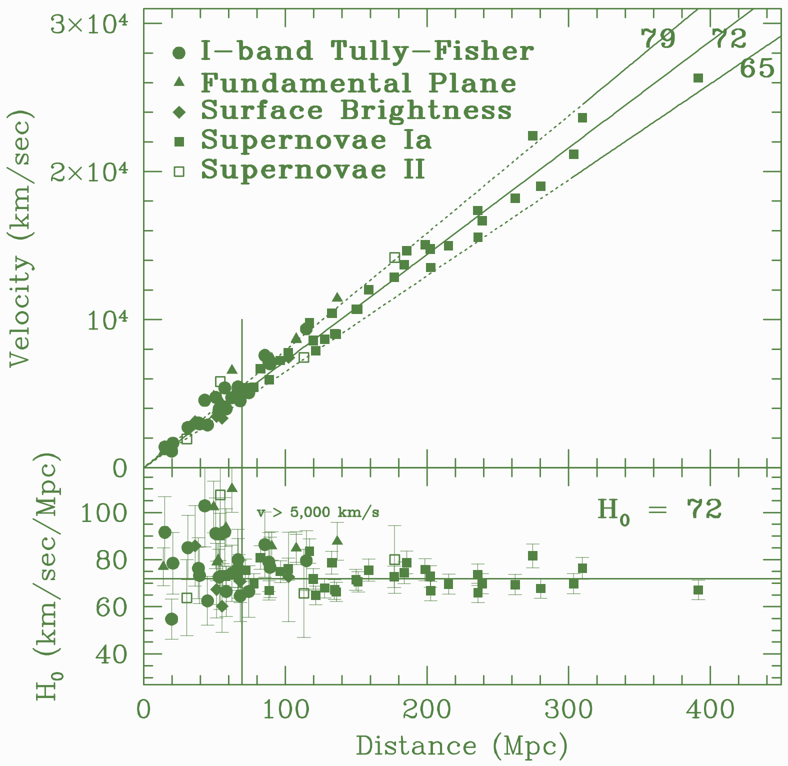
http://csep10.phys.utk.edu/guidry/stellarExplosions/index.html

The Expanding Universe and the Hubble Law



Hubble Expander

The Expanding Universe and the Hubble Law



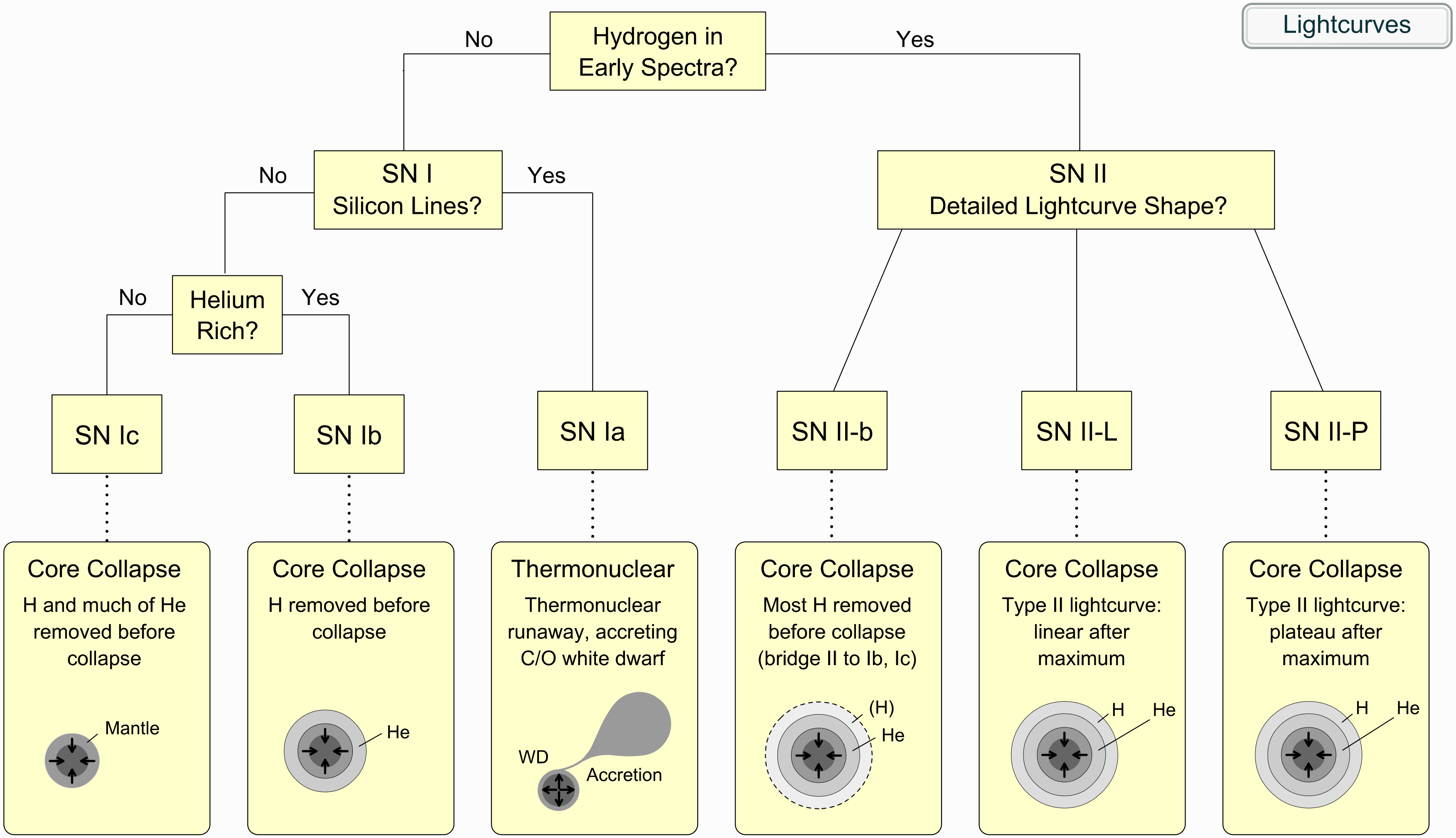
W. Freedman et al, ApJ 553, 47 (2001)

So detailed observations of more nearby galaxies (out to 30-40 Mpc) indicate that the Hubble law is obeyed fairly well.

What about for more distant galaxies? To answer that question, let's consider a seemingly completely different issue: the exploding stars that we call *supernovae.*

Classification of Supernovae

Lightcurves



Hydrogen in Early Spectra?

No

Yes

SN I
Silicon Lines?

SN II
Detailed Lightcurve Shape?

No

Yes

Helium Rich?

No

Yes

SN Ic

SN Ib

SN Ia

SN II-b

SN II-L

SN II-P

Core Collapse
H and much of He removed before collapse

Core Collapse
H removed before collapse

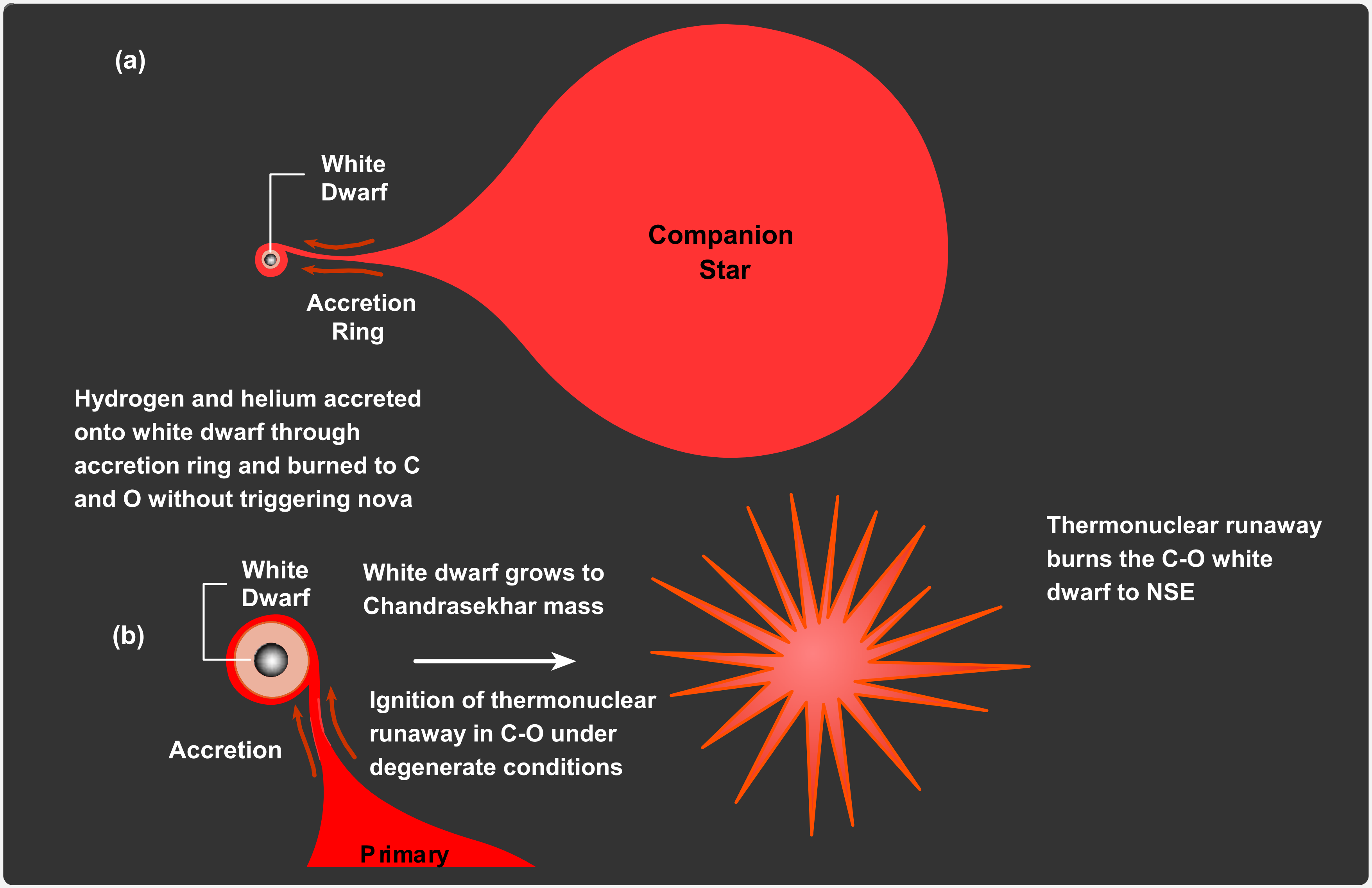
Thermonuclear
Thermonuclear runaway, accreting C/O white dwarf

Core Collapse
Most H removed before collapse (bridge II to Ib, Ic)

Core Collapse
Type II lightcurve: linear after maximum

Core Collapse
Type II lightcurve: plateau after maximum

The Type Ia Supernova Mechanism



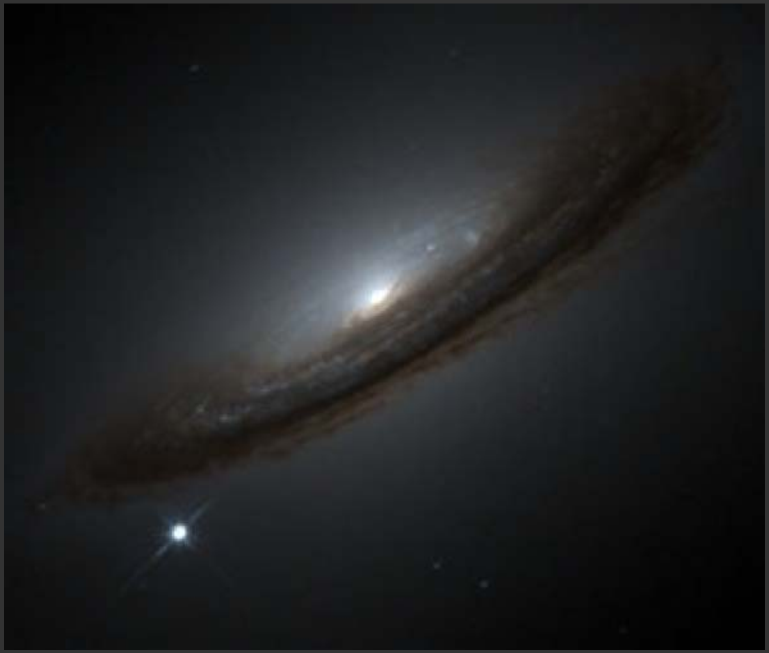
Hydrogen and helium accreted onto white dwarf through accretion ring and burned to C and O without triggering nova

White dwarf grows to Chandrasekhar mass

Ignition of thermonuclear runaway in C-O under degenerate conditions

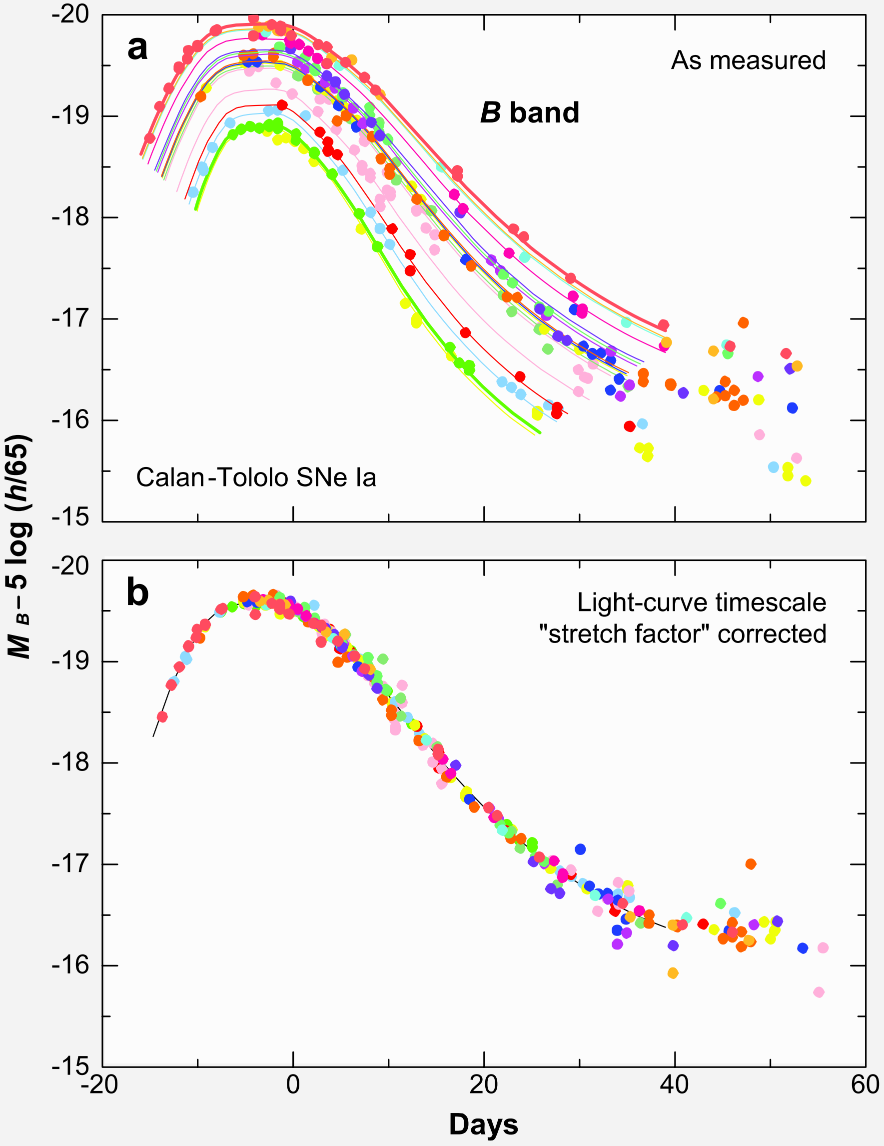
Thermonuclear runaway burns the C-O white dwarf to NSE

Example: Supernova 1994d



Supernova 1994D

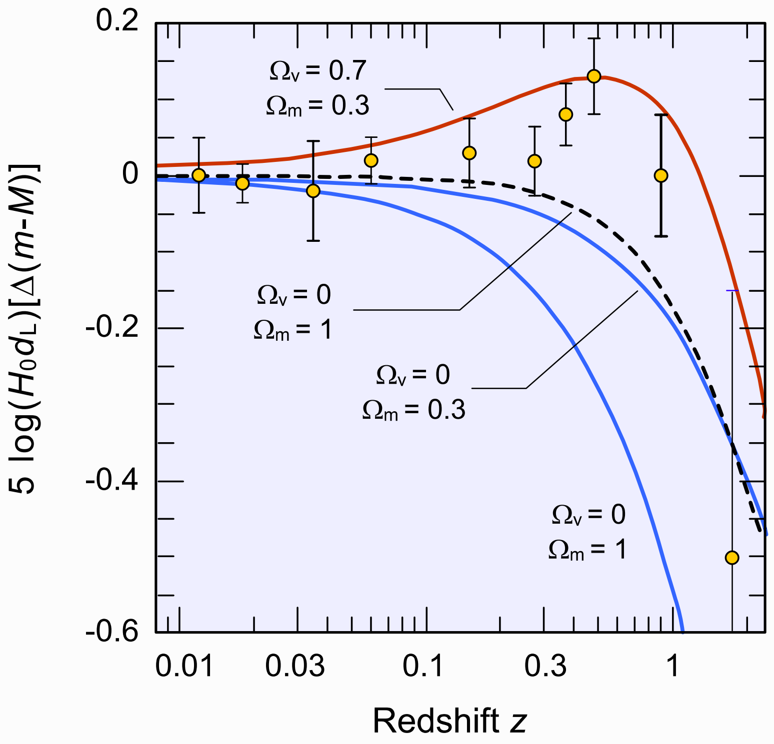
Standardizable Candles



B-band lightcurves for low-redshift Type Ia supernovae (Calan-Tololo survey; Hamuy, et al, 1996). As measured, the intrinsic scatter is 0.3 mag in peak luminosity. After 1-parameter correction the dispersion is 0.15 mag.

From *Ann. Rev. Astronomy and Astrophysics*, 46, 385 (2008)

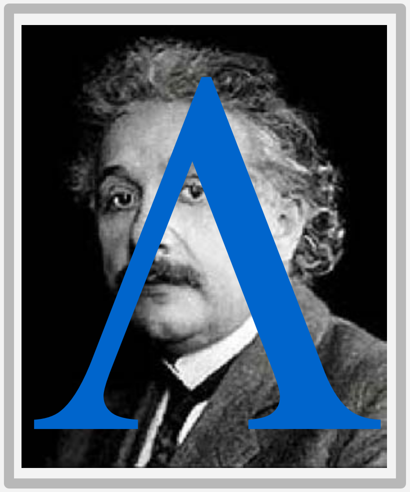
The Expanding Universe and the Hubble Law



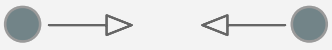
W. Freedman, et al, ApJ **553**, 47 (2001)

J. L.Tonry, et al, ApJ **594**, 1 (2003)

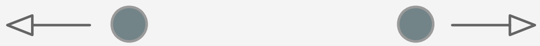
Friedmann Solver



Gravity

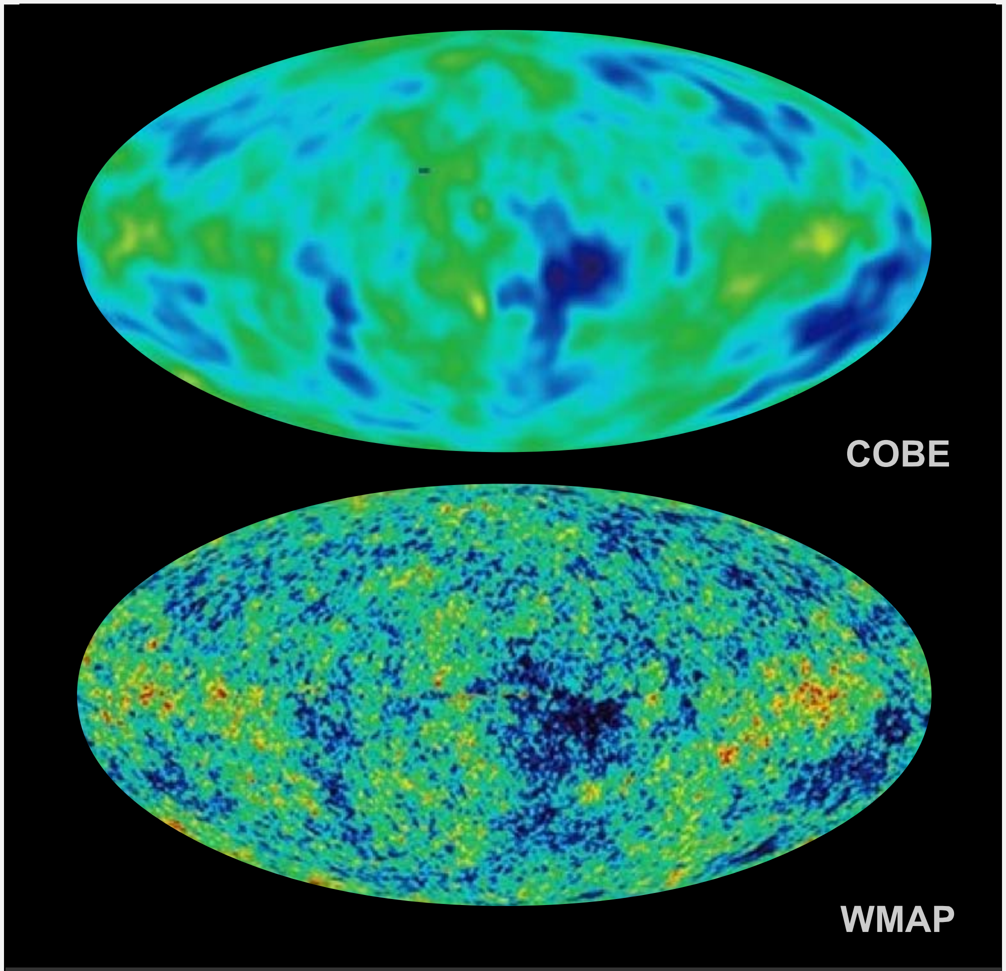


Antigravity



(Background of dark energy)

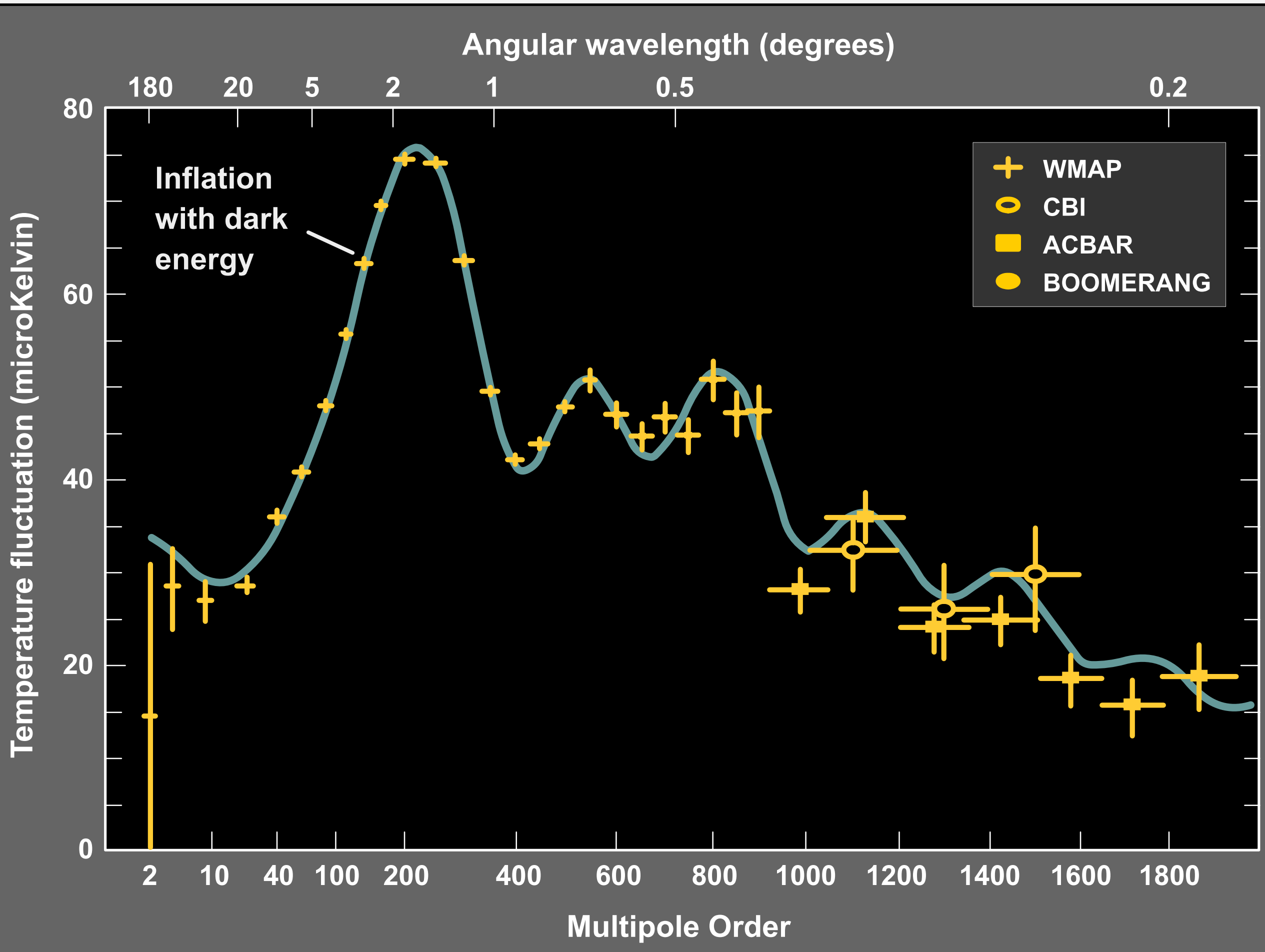
The Expanding Universe and the Hubble Law



COBE and WMAP Cosmic Microwave Maps

Remarkably uniform but fluctuations at the one part in 100,000 level

The Expanding Universe and the Hubble Law



☒ Data

☒ Inflation + dark energy

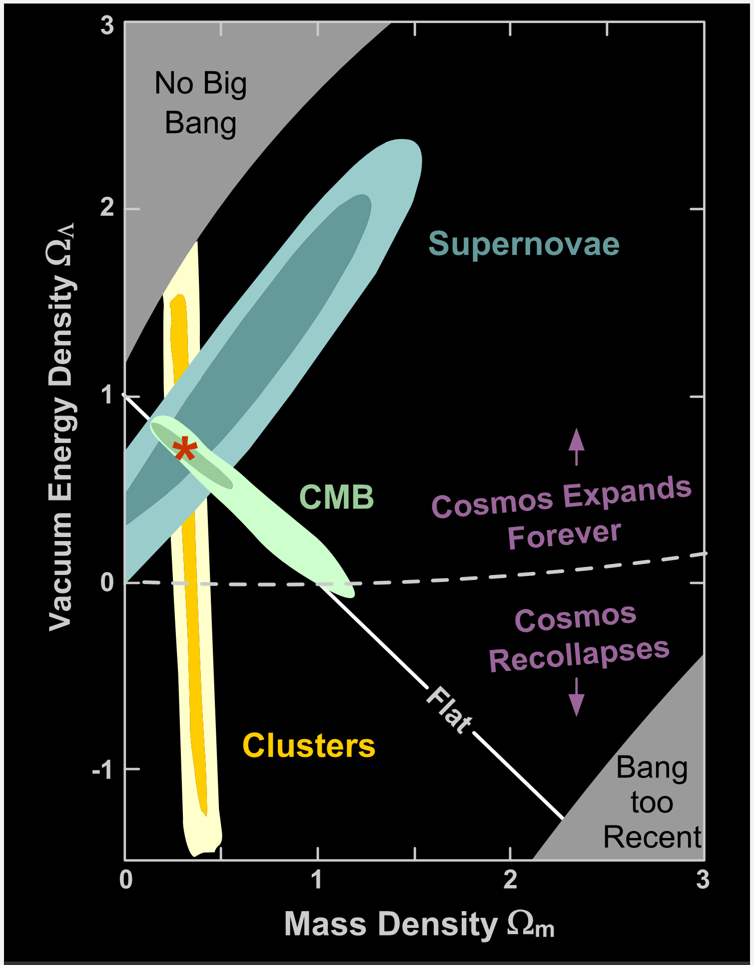
☐ Inflation, no dark energy

☐ No inflation, no dark energy

☐ Cosmic strings

A. H. Guth and D. I. Kalser, Science, 307, 884 (2005)

The Expanding Universe and the Hubble Law



Vacuum Energy and Mass Density

- The Universe is flat (Euclidean), with $\Omega = \Omega_r + \Omega_m + \Omega_\Lambda = 1$.
- Hubble constant $H_0 \sim 72$ km/s/Mpc.
- The energy density of the Universe now in radiation is negligible ($\Omega_r \sim 0$). Earlier it was more important.
- The energy density of the Universe now in matter is about 30% of closure density ($\Omega_m \sim 0.3$). Only a few percent of that matter is normal (baryonic) matter. The rest is dark matter.
- The energy density of the Universe presently in dark energy is about 70% of closure density ($\Omega_\Lambda \sim 0.7$).
- The Universe is flat but will expand forever because of dark energy.

The Einstein (Friedmann) Equations

$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$ (Einstein equations)

$R^{\sigma}_{\mu\nu\lambda}$ = *Riemann curvature tensor* (covariant measure of 4D curvature in locally Minkowski space; generalizes Gaussian curvature in 2D)

$R_{\mu\nu} = g^{\lambda\sigma} R_{\lambda\mu\sigma\nu}$ (Ricci tensor)

$R = g^{\mu\nu} R_{\mu\nu}$ (Ricci scalar)

Λ = scalar (Cosmological constant)

$T_{\mu\nu} = (\varepsilon + P) u_{\mu} u_{\nu} - P g_{\mu\nu}$ (Stress-Energy tensor: general form)

The Friedmann-Robertson-Walker Metric

$$ds^2 = -\,dt^2 + a(t)^2\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2\sin^2\theta\, d\phi^2\right) \qquad \text{(Line element)}$$

$$k = \begin{cases} +1 & \text{(positive curvature)} \\ \ \ 0 & \text{(flat)} \\ -1 & \text{(negative curvature)} \end{cases}$$

$$ds^2 = g_{\mu\nu}\, dx^{\mu} dx^{\nu}$$

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \longrightarrow g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & \frac{a^2}{1-kr^2} & 0 & 0 \\ 0 & 0 & a^2r^2 & 0 \\ 0 & 0 & 0 & a^2r^2\sin^2\theta \end{pmatrix}$$

(Minkowski metric)

(FRW metric)

$$T_{\mu\nu} = T_{\mu\mu} = (P + \rho)u_{\mu}u_{\mu} - Pg_{\mu\mu} \qquad \text{(FRW metric)}$$

The Equation of State for the Universe

Neglecting the cosmological constant, the Friedmann equations may be rewritten as

$$\left.\begin{aligned} \left(\frac{\dot{a}}{a}\right)^2 &= \frac{8\pi G}{3}\rho - \frac{k}{a^2} \\ \frac{\dot{\rho}}{\rho} + 3\left(1 + \frac{P}{\rho}\right)\frac{\dot{a}}{a} &= 0 \end{aligned}\right] \quad \text{Two equations in three unknowns}$$

$$P = P(\rho) = P(\varepsilon) \qquad \text{(Equation of state)}$$

Since the cosmic fluid is low density, assume equation of state

$$P = w\varepsilon$$

The adiabatic sound speed c_s is given by

$$c_s^2 = \frac{dP}{d\varepsilon}c^2$$

Thus, requiring that $c_s < c$ implies that $w < 1$

The Equation of State for the Universe

Pressure

Energy density

$$P = w\varepsilon$$

???

- $w < 1$ or causality violated: if $w > 1$, the speed of sound can exceed the speed of light.

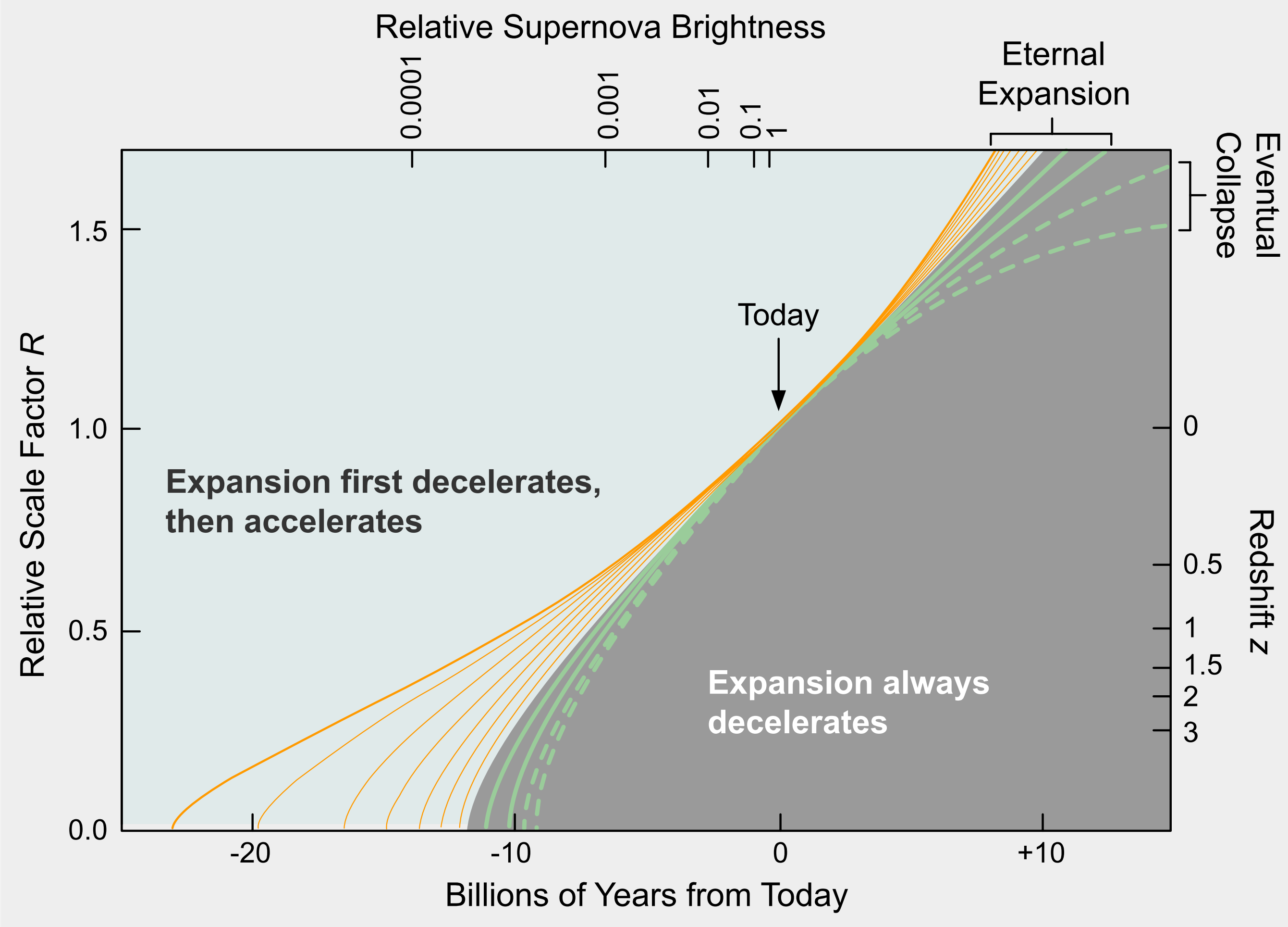
$$c_s^2 = \frac{dP}{d\varepsilon} c^2$$

- For non-relativistic matter, $w = 0$ $\qquad P = 0$
- For relativistic matter, $w = +1/3$ $\qquad P = \varepsilon/3$
- Accelerated expansion requires dominant component with $w < -1/3$
- Cosmological constant gives $w = -1$

$$\ddot{a} = -\frac{4\pi G}{3} a(\varepsilon + 3P)$$

$$= -\frac{4\pi G}{3} a\varepsilon(1 + 3w)$$

The Expanding Universe and the Hubble Law



History of Cosmic Expansion from High-Redshift Supernovae

Friedmann Solver

Constraining the Equation of State

- Observationally, the cosmic fluid seems to have 3 components:

  - Massive particles ("matter"): $w = 0$ ($\Omega_m = 0.30$)

  - Massless particles ("radiation"): $w = +1/3$ ($\Omega_m \sim 0$)

  - "Dark energy": $w < -1/3 = ?$ ($\Omega_m \sim 0.70$)

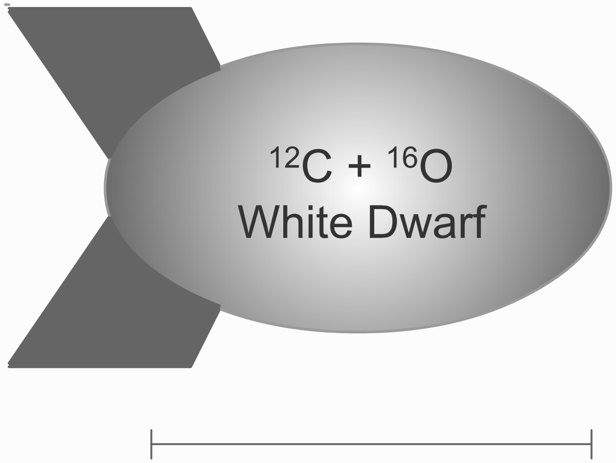
- The value of *w* for the dark energy could be constrained further if we could improve the precision of the Type Ia standardizable candle methodology:

  - Greater observational precision at deeper redshifts

  - A deeper theoretical understanding of the mechanism for Type Ia supernovae and what governs their (relatively small) differences in luminosity.

Improved Understanding of the Type Ia Mechanism

- The Type Ia precursor is a 1.5 solar mass thermonuclear bomb



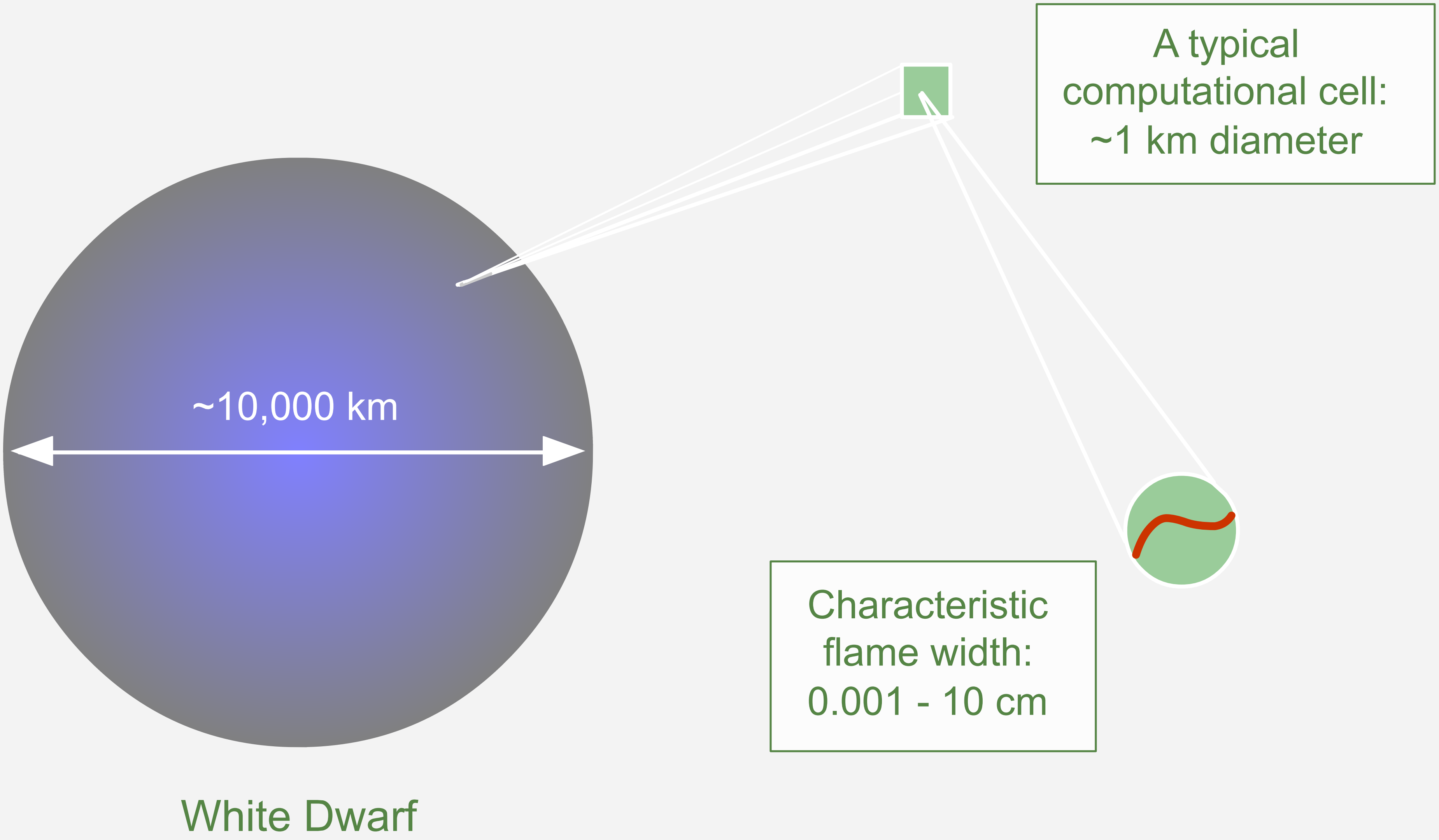
$^{12}C + ^{16}O$
White Dwarf

$M \sim 5 \times 10^5$ Earth masses
~ 1.4 Solar masses

~ 1 Earth Radius

- Three fundamental issues for an improved understanding of mechanism
  - What triggers the bomb (merger or accretion)?
  - How does one deal computationally with the huge range of scales?
  - How does the fuel burn and what ashes does it leave behind?

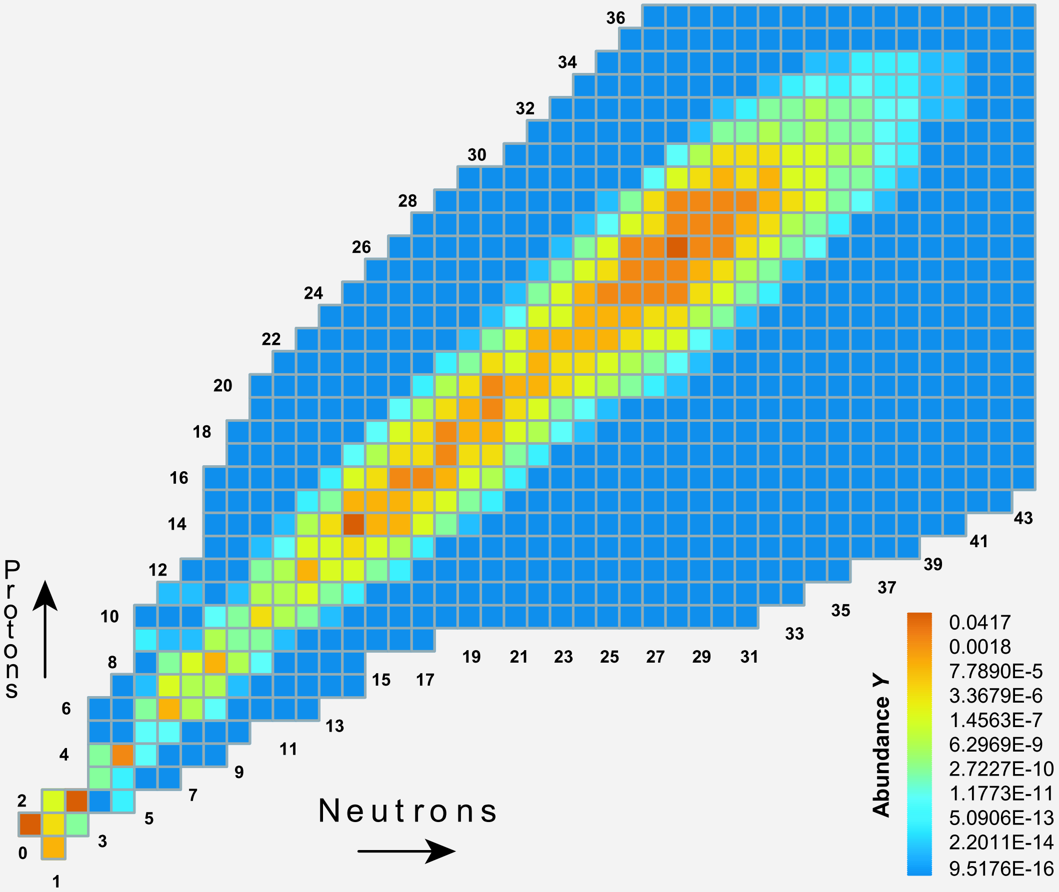
Disparity of Characteristic Spatial Scales



A typical computational cell: ~1 km diameter

Characteristic flame width: 0.001 - 10 cm

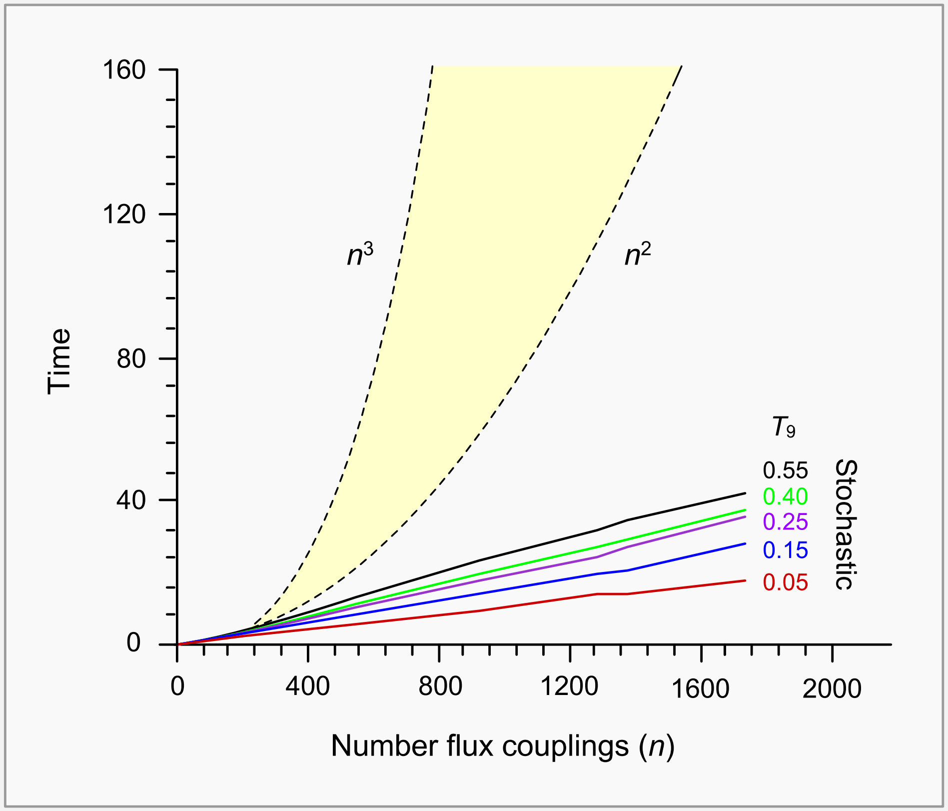
Solving Large Thermonuclear Networks



Compare Abund

Compare NZ

Scaling Properties



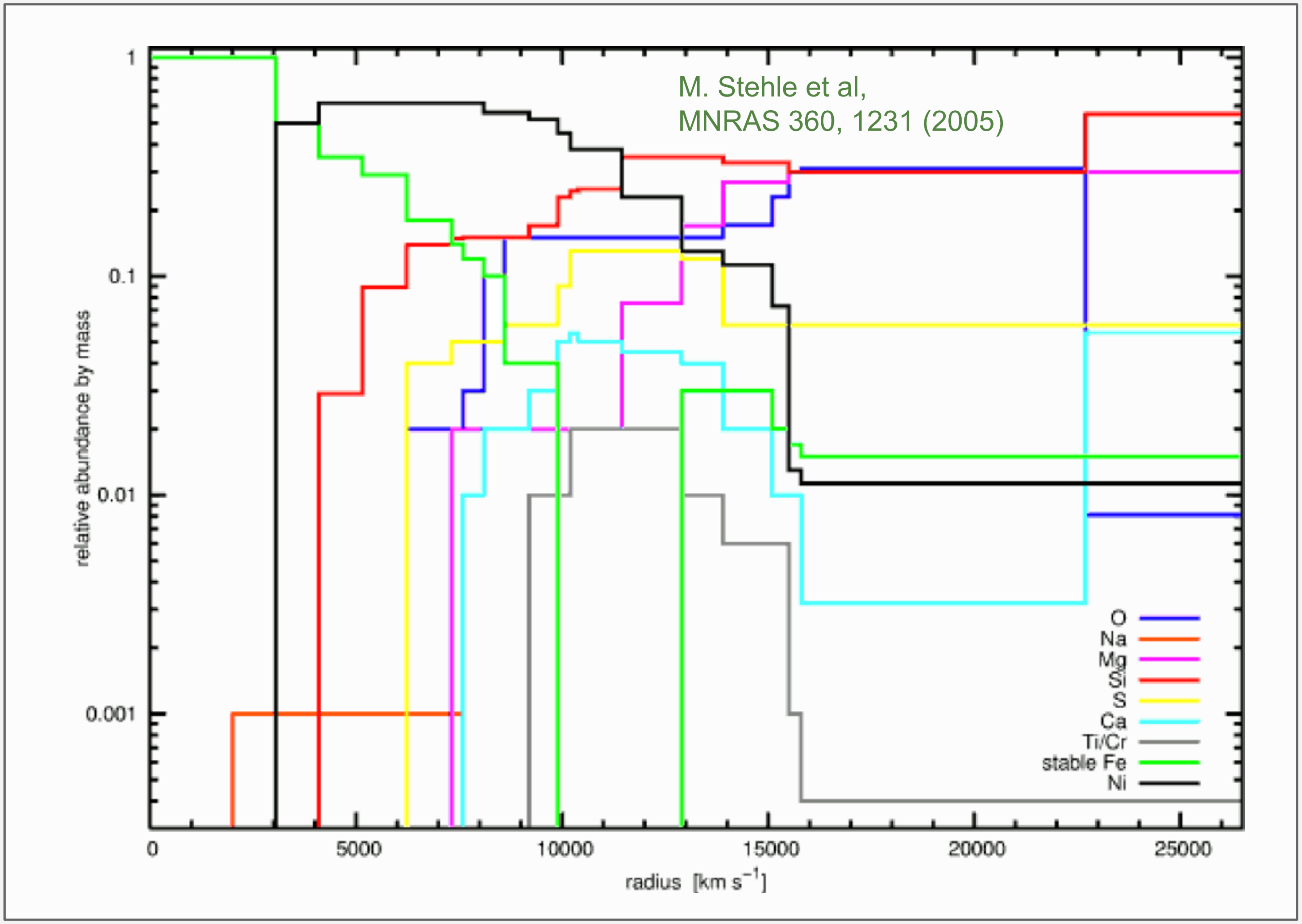
Options:

1. Reduce size of network by combining multiple boxes into single effective boxes. Valid for implicit or explicit methods, but biggest gain for implicit methods.

2. Identify the most stiff components and use approximate analytic solutions to approximate them by stable explicit step.

3. Combine (1) and (2).

Abundance Tomography from SN2002bo

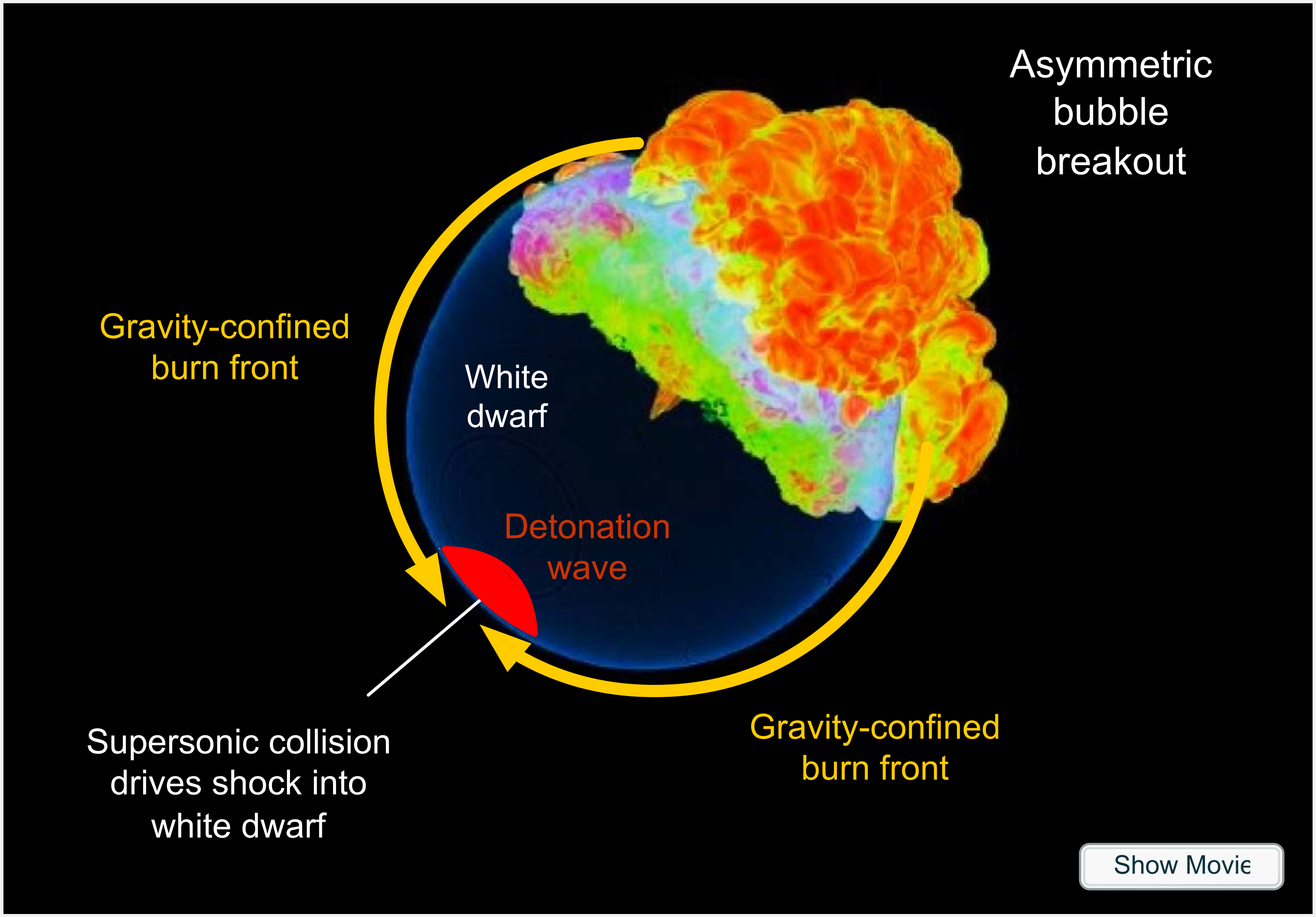


Note intermediate mass elements at high velocity

Data Require Deflagration Transitioning to Detonation

Observed light curves and elemental abundances in the expanding debris require a thermonuclear burn of the white dwarf that is partially deflagration (subsonic burn front) and partially detonation (supersonic burn front). Not easy to achieve.

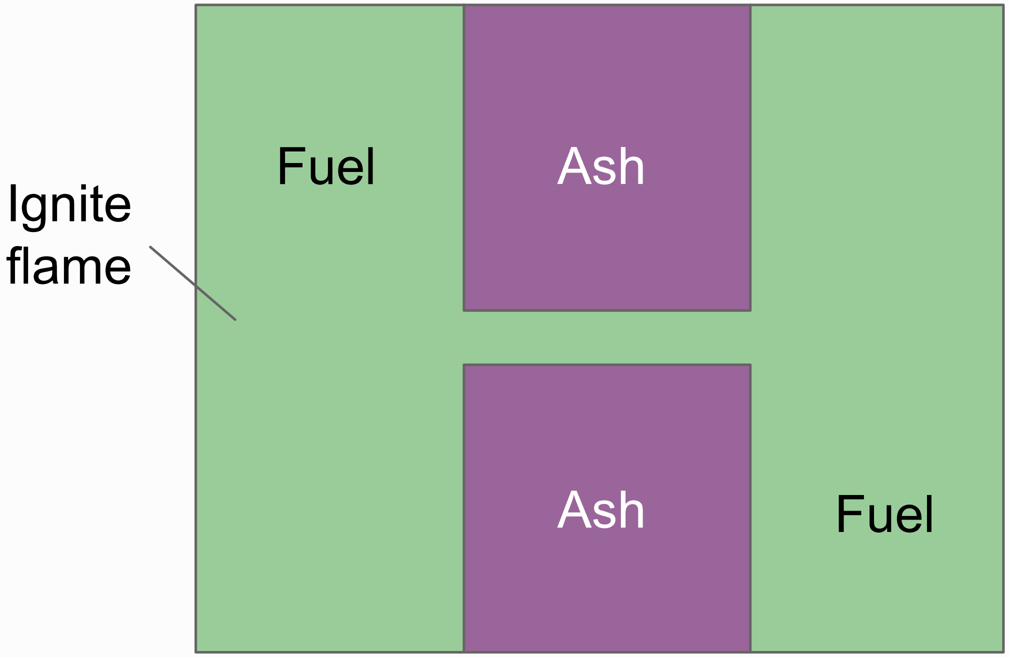
Gravity-Confined Detonation



Three-Dimensional Simulations of the Deflagration Phase of the Gravitationally Confined Detonation Model of Type Ia Supernovae, G. C. Jordan IV, R. T. Fisher, D. M. Townsley, A. C. Calder, C. Graziani, S. Asida, D. Q. Lamb, J. W. Truran.ApJ, 681:1448 131457 (2008)

Data Require Deflagration Transitioning to Detonation

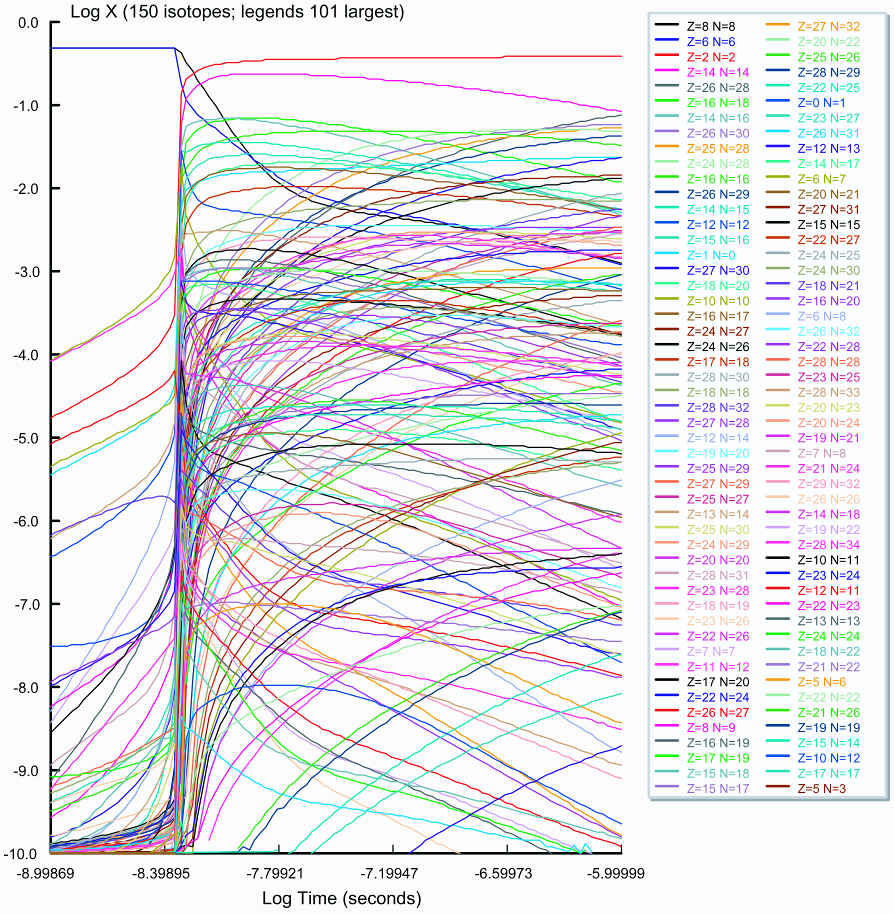
Chris Smith Thesis

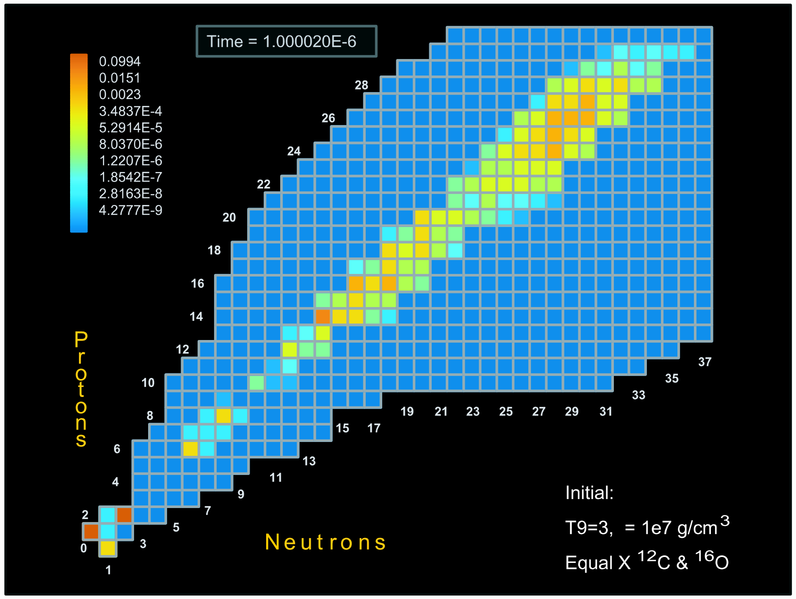


Simulate constriction caused by collision of rising and sinking plumes in burning bubbles

Multi-D Hydrodynamics Coupled to Realistic Network

Viktor Chypryna thesis: simulate GCD conditions with realistic network





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Summary

- For the first time it may be possible to couple realistic thermonuclear networks to multi-dimensional hydrodynamics in Type Ia supernova simulations.
- In addition to its intrinsic interest, an improved understanding the Type Ia mechanism has the practical implication of improving the standardizable candle properties that are critical to cosmology.
- One implication of improving the standardizable candle properties could be to precisely constrain the equation of state for the Universe.
- If the equation of state is known precisely for dark energy, this will place strong constraints on acceptable theories for the source of dark energy.