Modeling Type Ia Supernova Explosions

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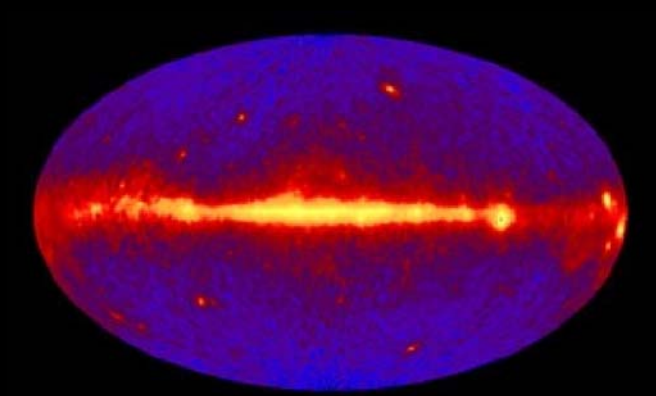
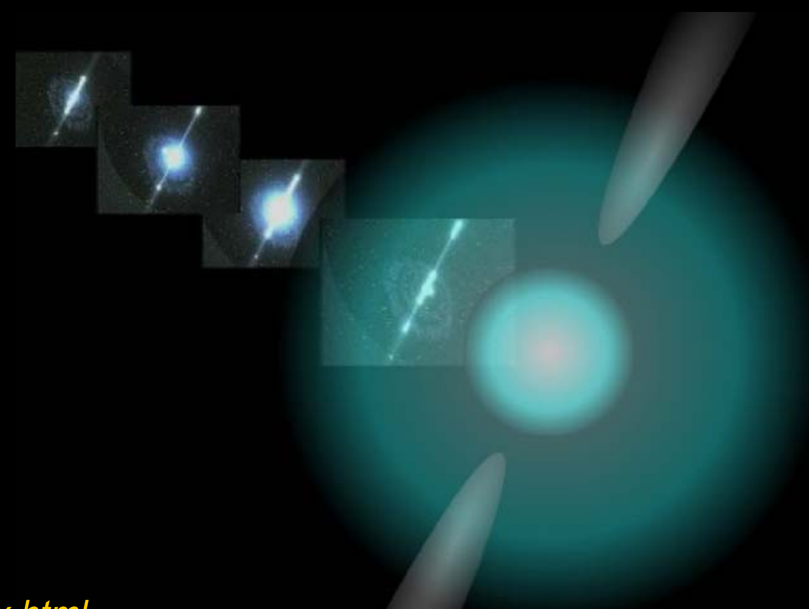




http://csep10.phys.utk.edu/guidry/stellarExplosions/index.html

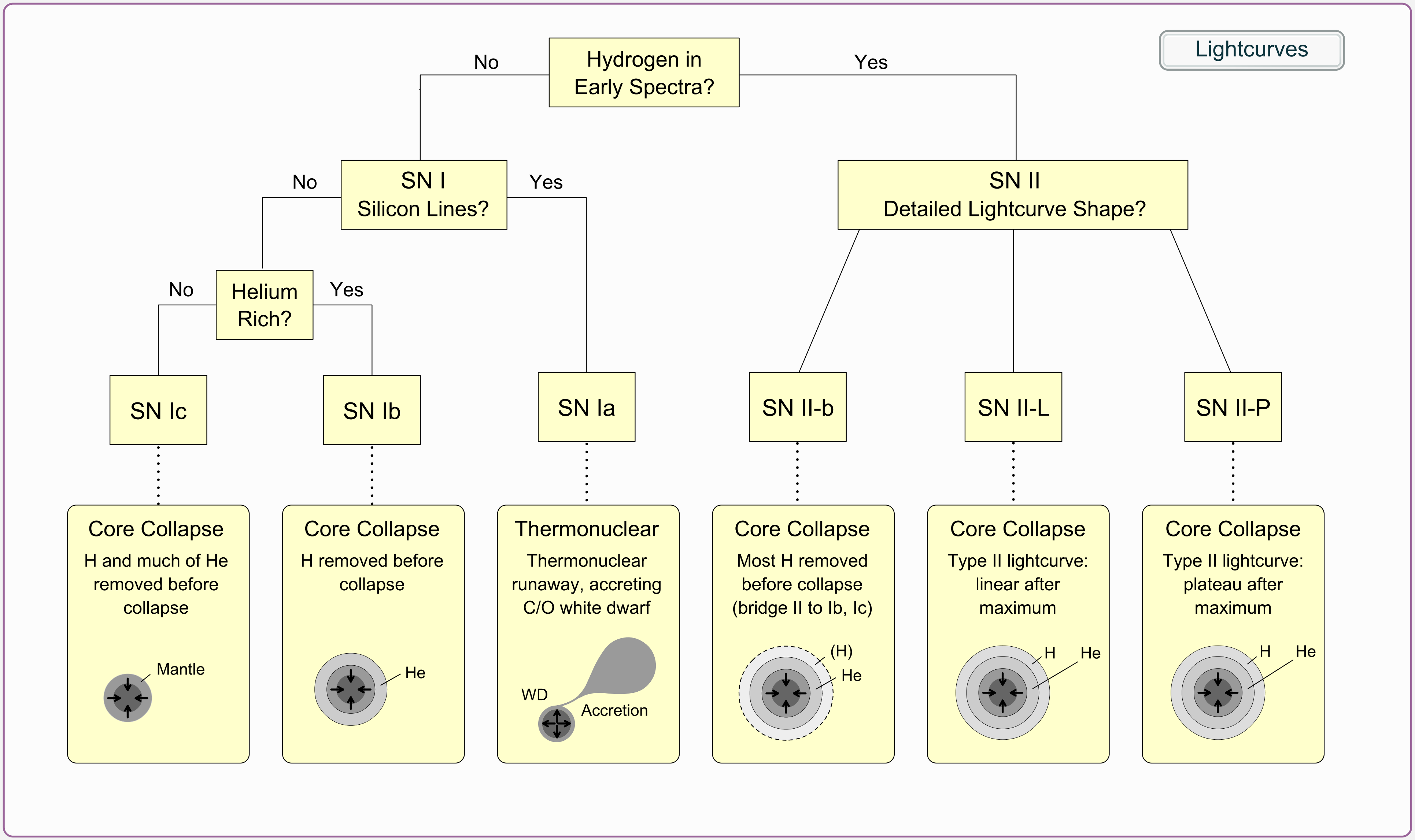
Large Stellar-Scale Energy Sources

Modern observational astronomy has revealed the existence of various extremely violent events (different classes of supernovae and gamma-ray bursts) that originate in objects the size of stars or smaller, but that can release ~10^{50} - 10^{53} erg in a matter of seconds. For reference, the Sun 's luminosity is ~10^{33} erg/second, so these events can outshine an entire large galaxy of say 100 billion normal stars for a short period of time.

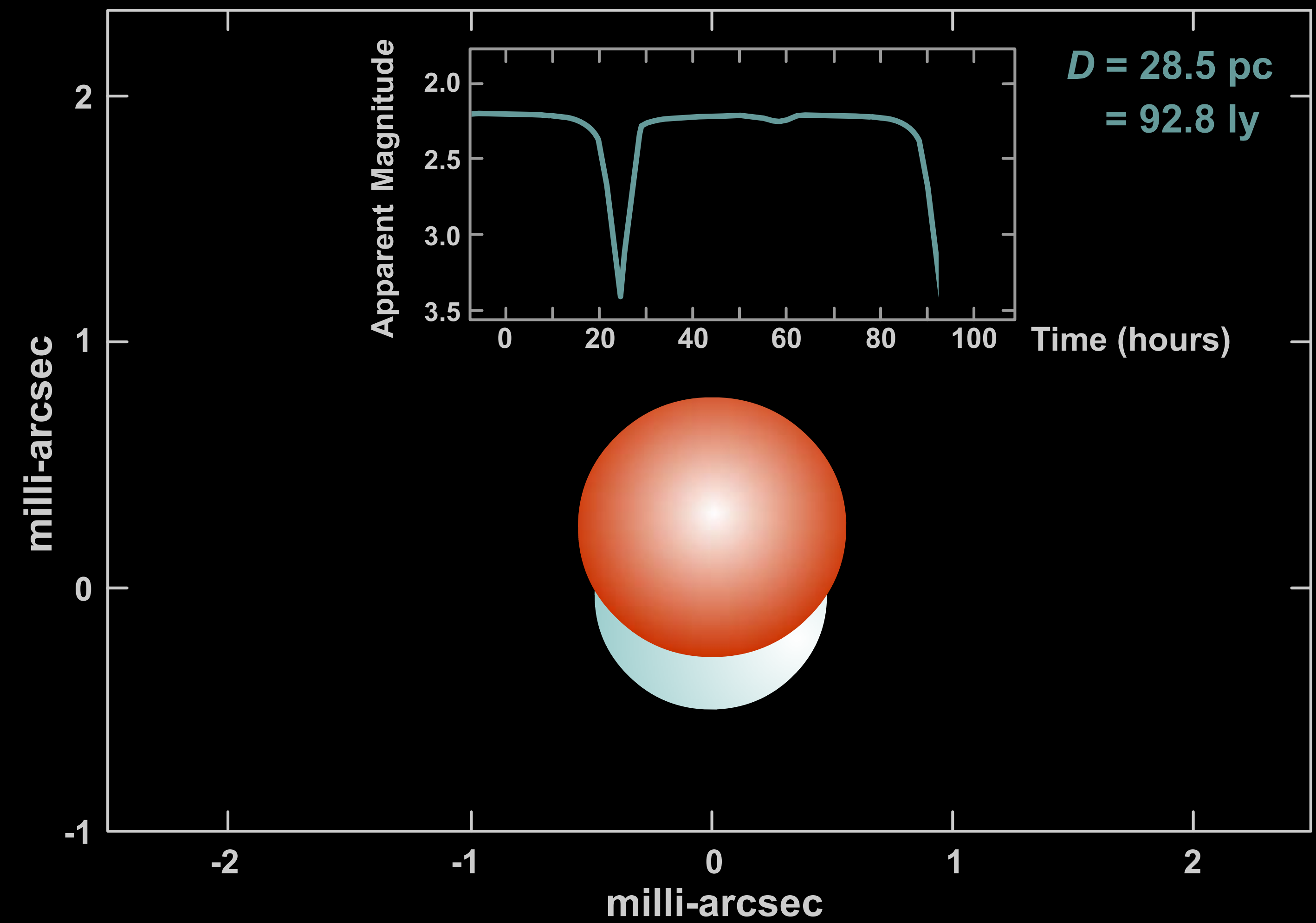
What could be the energy source for such events? We know of at least three possibilities:

- *GRAVITATIONAL:* Coherent collapse of a dense stellar core down to neutron star or black hole radii, and/or incoherent accretion of mass onto a neutron star or black hole, can release energy in this range.
- *THERMONUCLEAR:* Runaway nuclear burning of about 1 solar mass of carbon or oxygen to iron-group nuclei releases energy on this scale.
- *ROTATIONAL and MAGNETIC:* Extraction of energy stored in angular momentum and magnetic fields of compact stellar remnants could release energy on this scale.

Classification of Supernovae

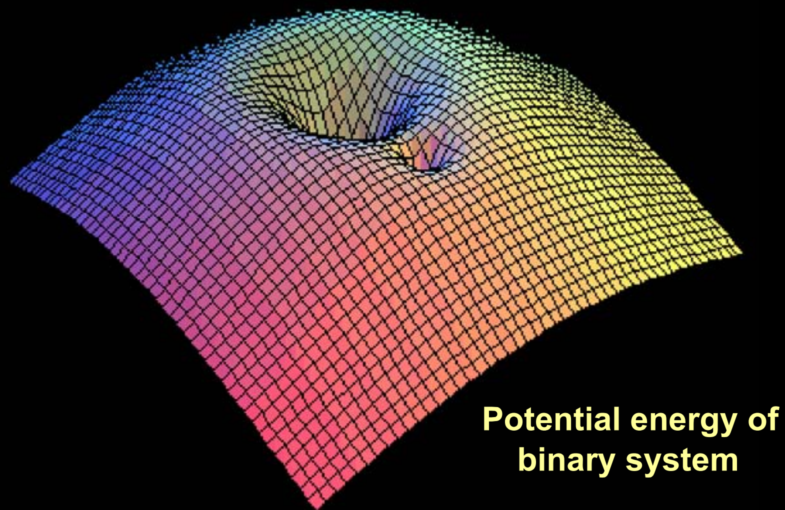


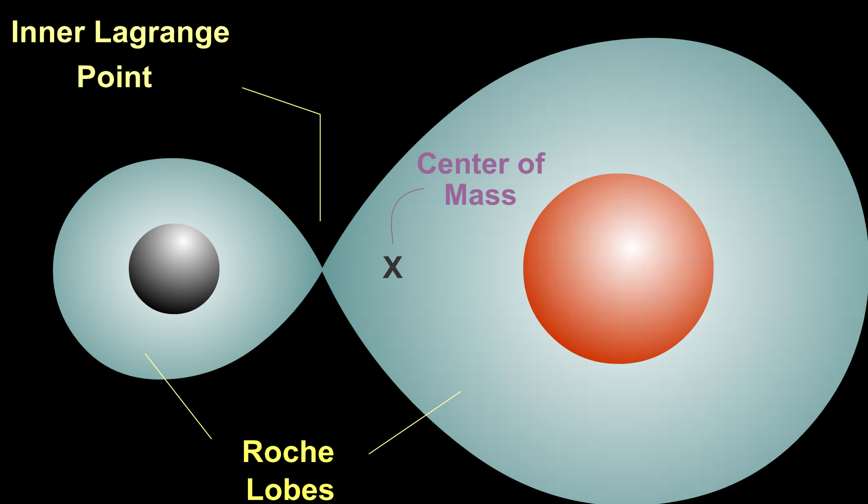
Binary Star Systems

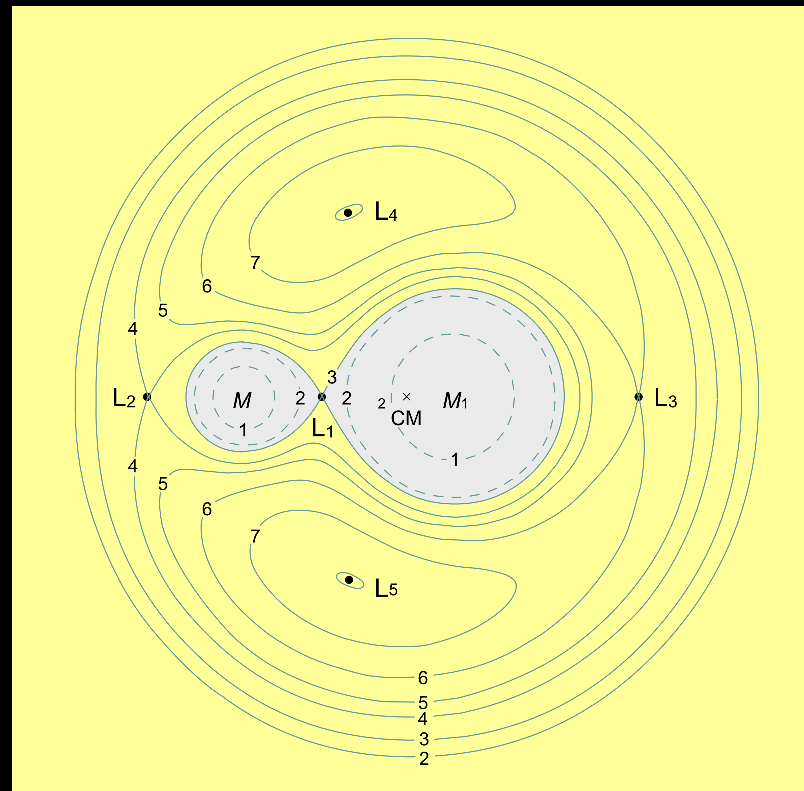


Revolution of the Algol System Play Stop Back Step Home

Gravitational Potential Energy in Binary Systems: Roche Lobes

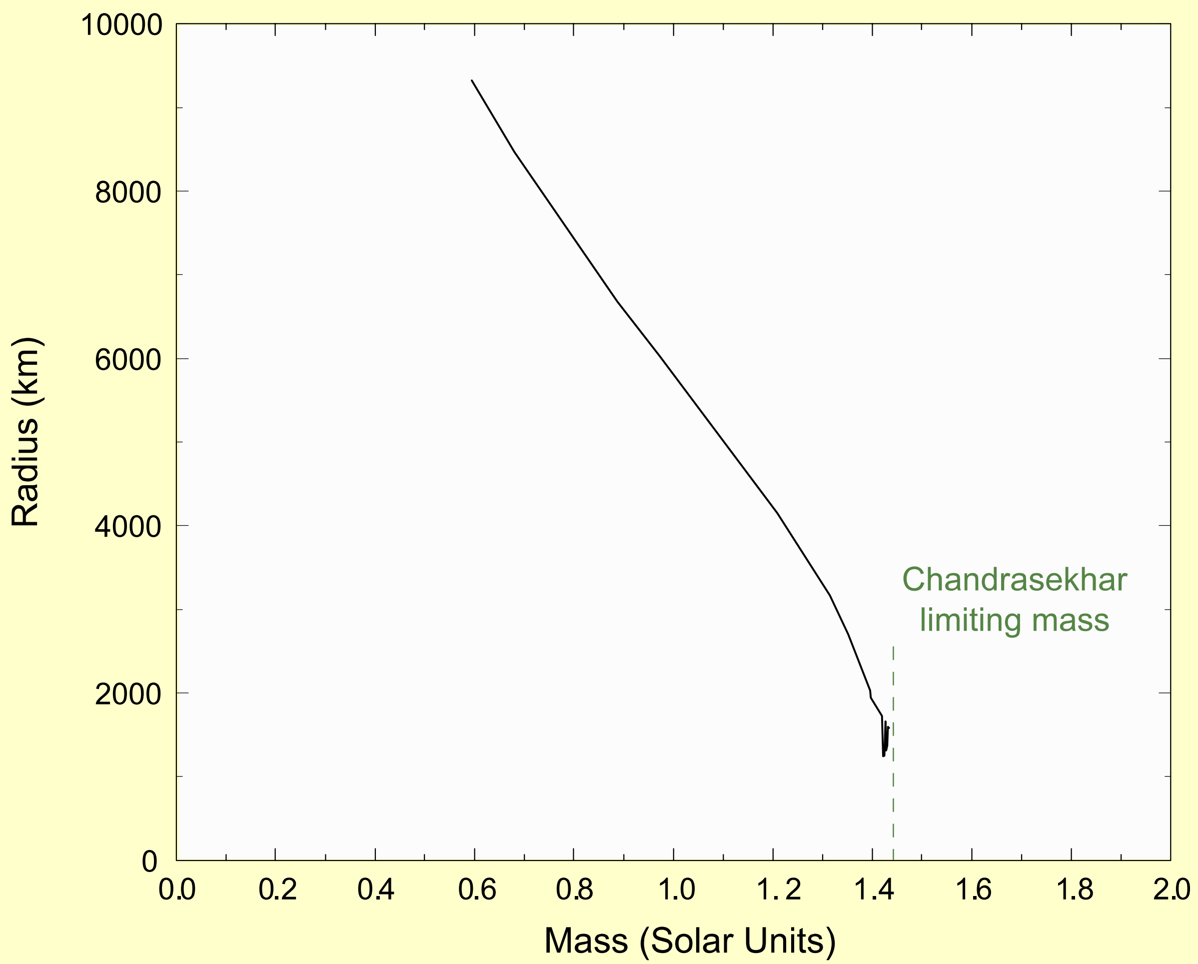




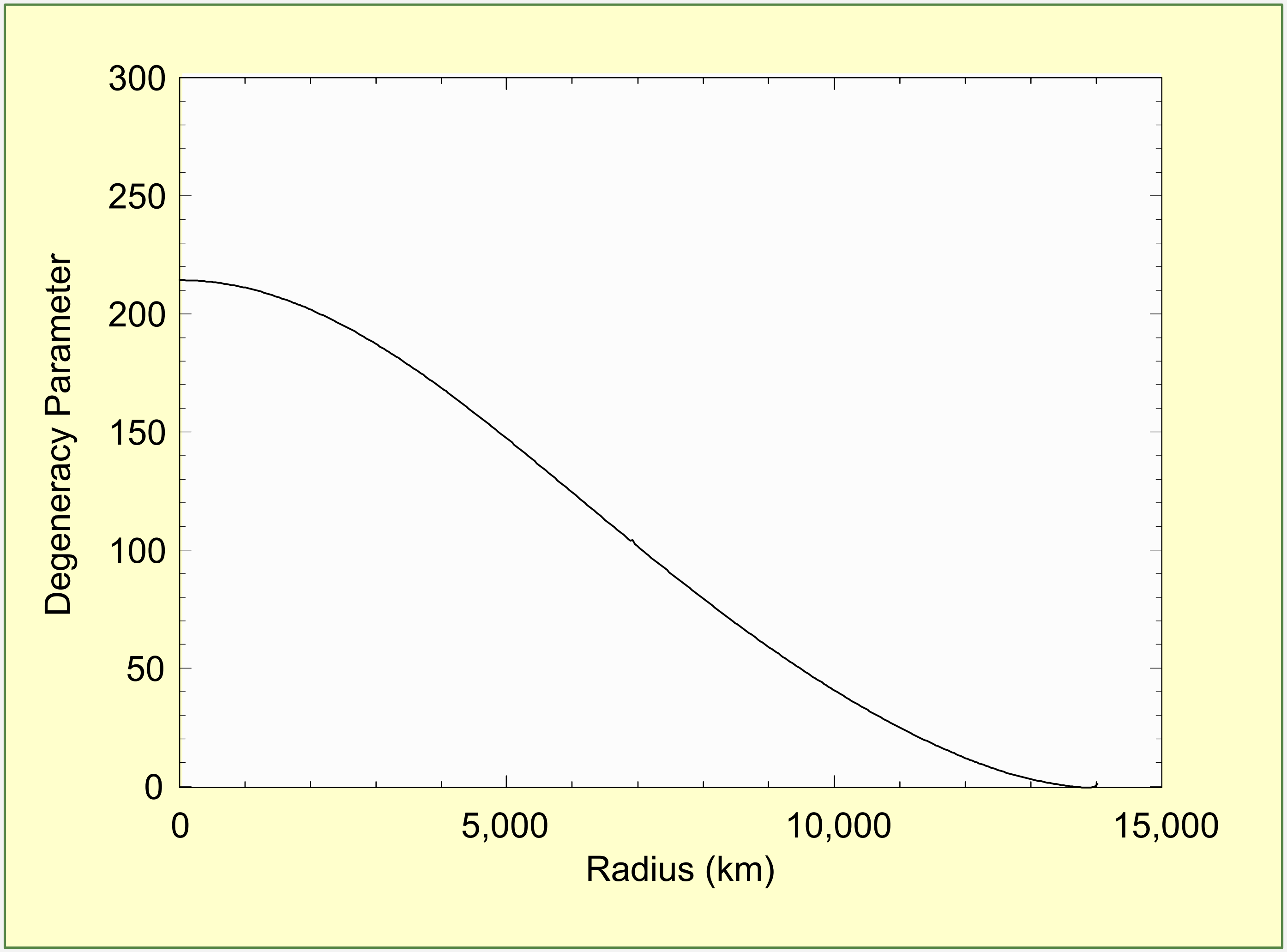


Roche Overflow

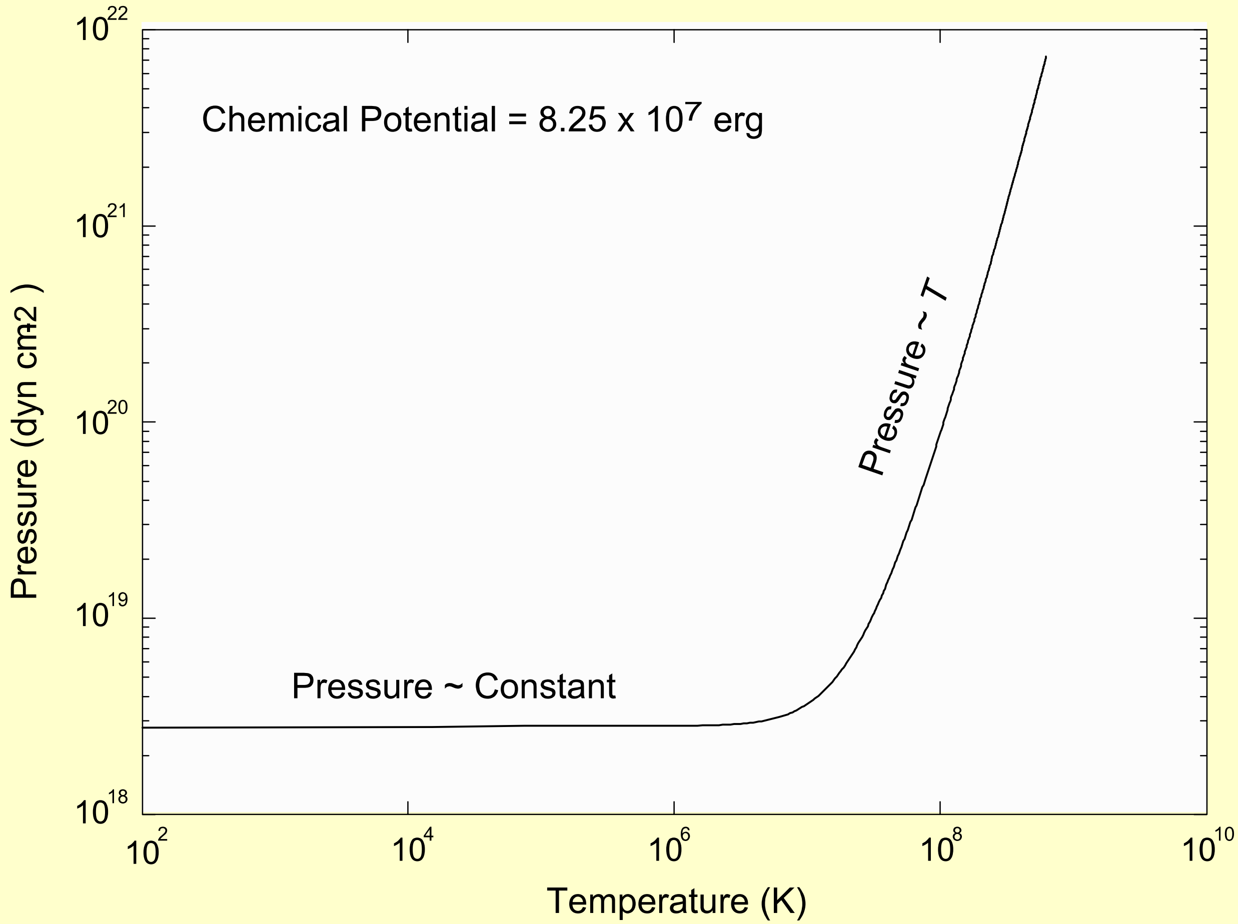
Chandrasekhar Limiting Mass



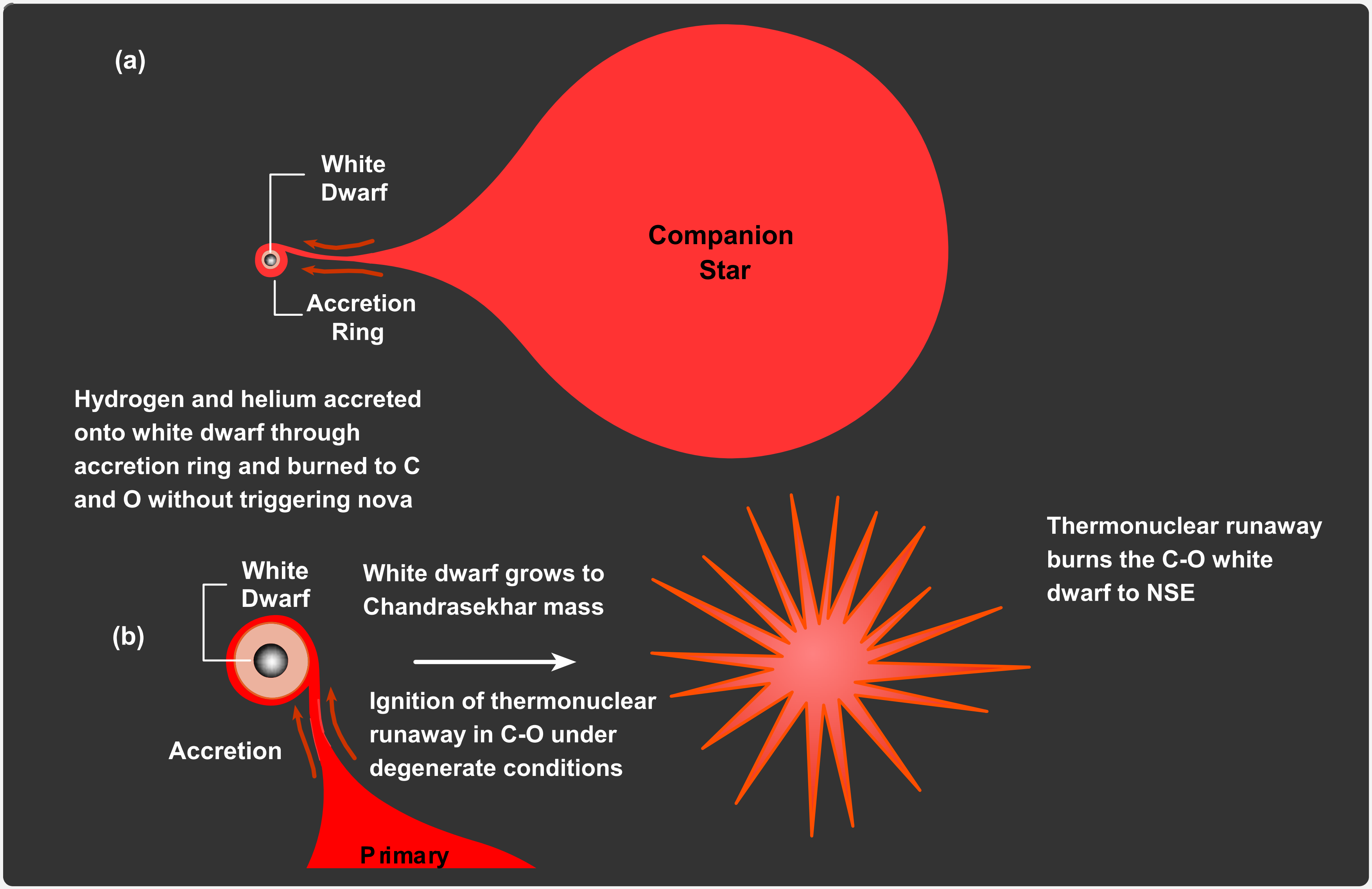
White Dwarfs Dominated by Degenerate Electron Gas



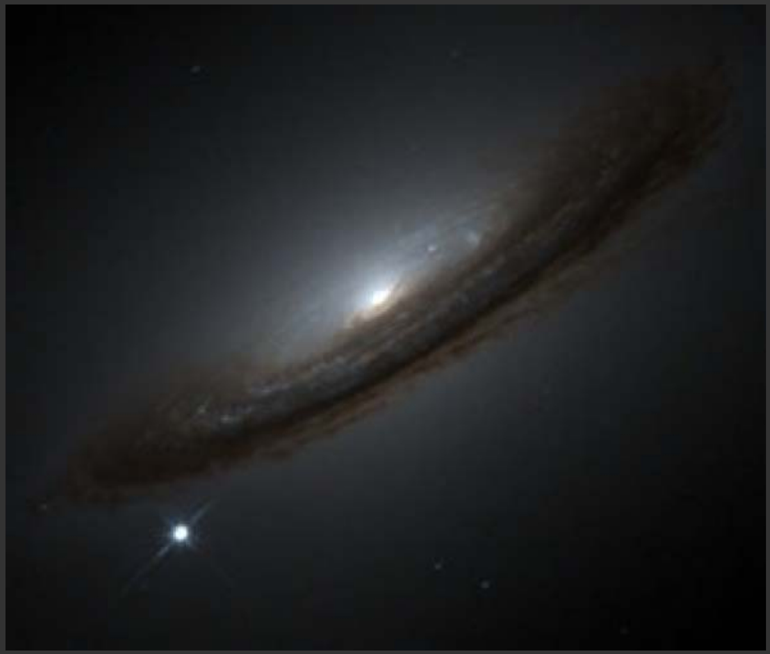
Temperature, Pressure, and Degeneracy



The Type Ia Supernova Mechanism



Example: Supernova 1994d

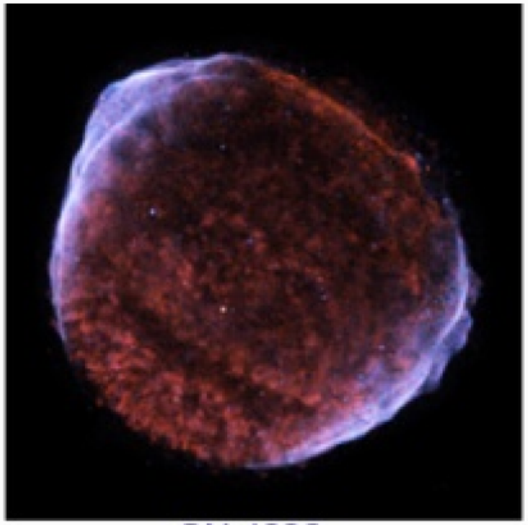


Supernova 1994D

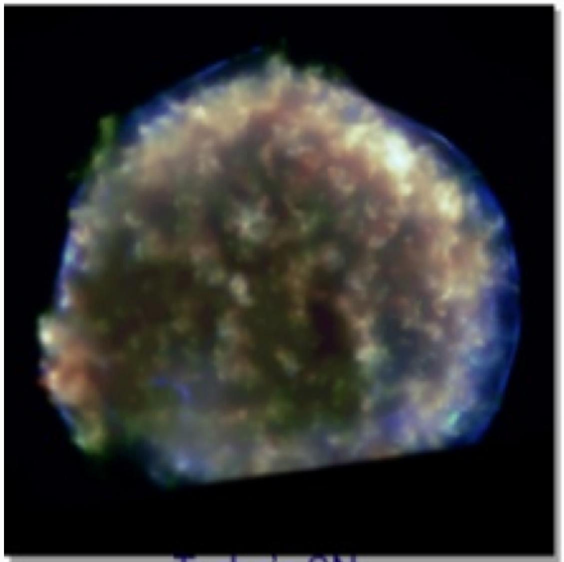
Show Labels

Light Curve

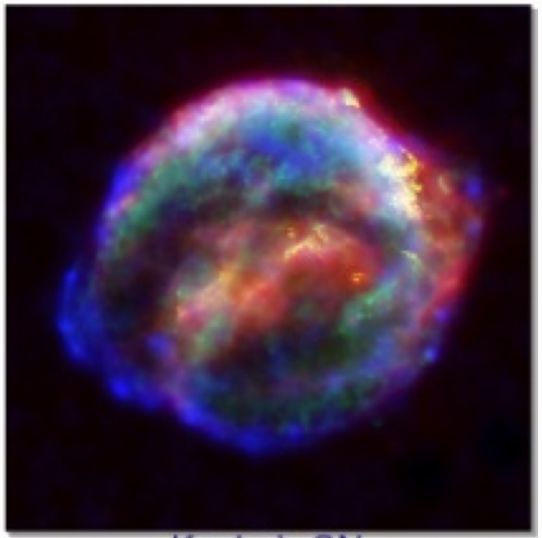
Historical Type Ia Supernovae



SN 1006



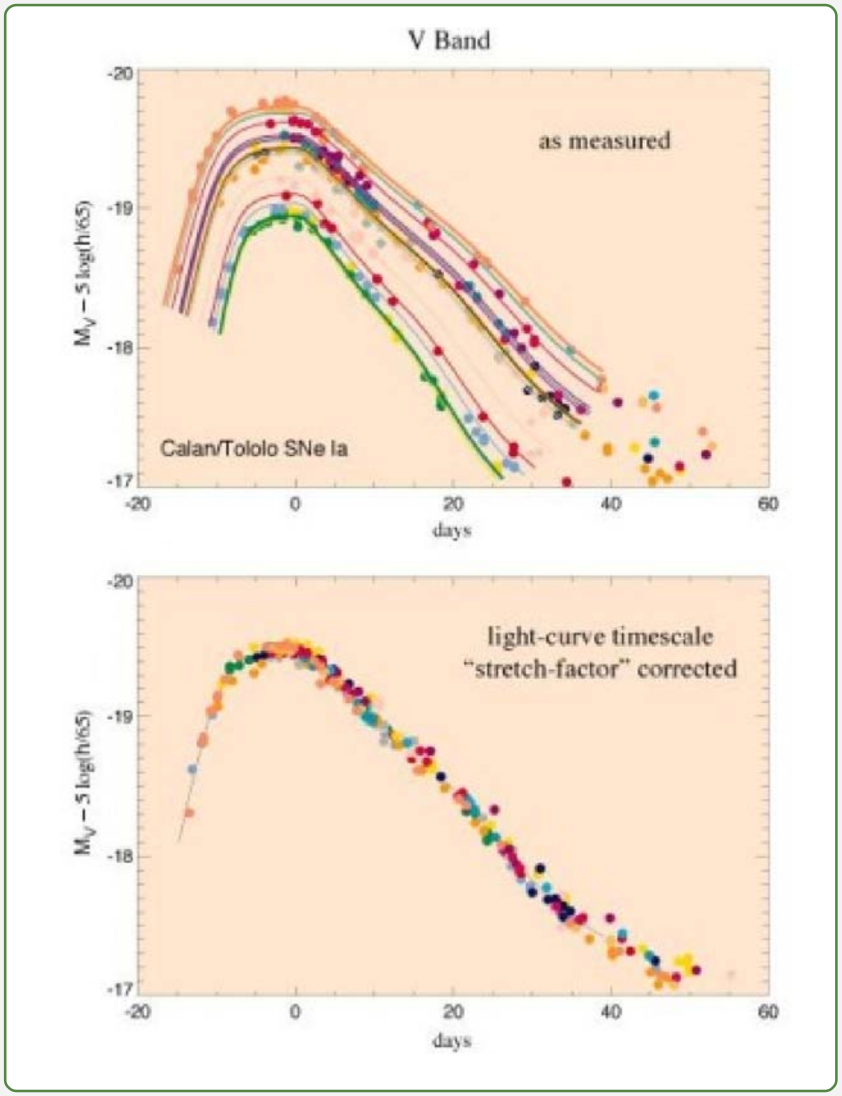
Tycho's SN



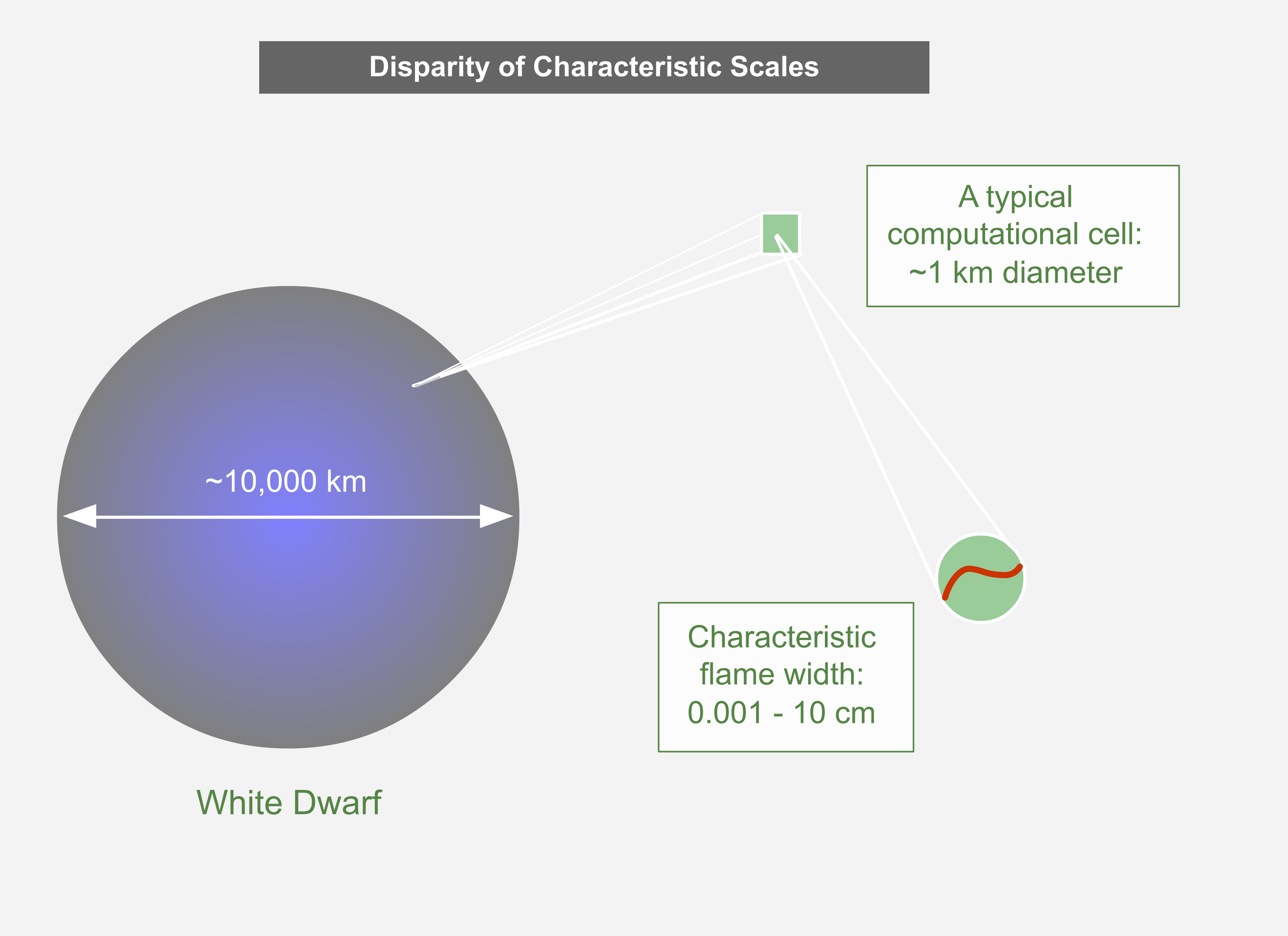
Kepler's SN

All images: Chandra Observatory

Standardizable Candles



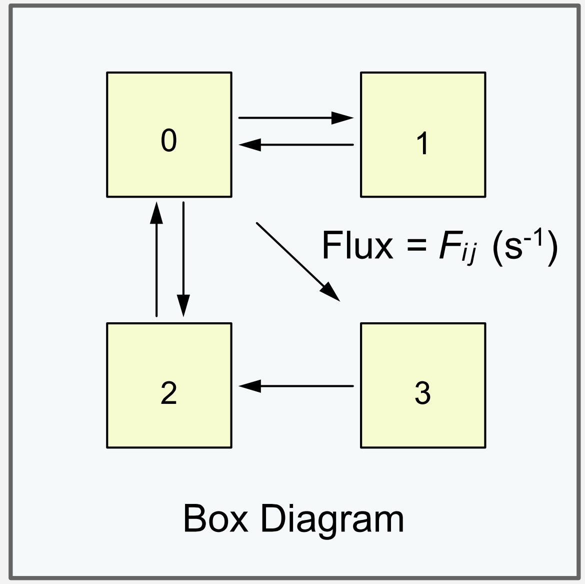
Friedmann Solver


Disparity of Characteristic Scales
A typical computational cell: ~1 km diameter
~10,000 km
Characteristic flame width: 0.001 - 10 cm
White Dwarf

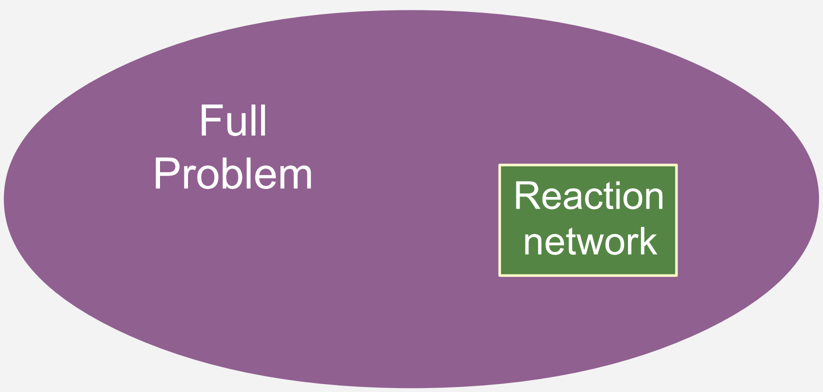
Reaction Networks: Sources, Sinks, and Fluxes

Coupled ordinary differential equations

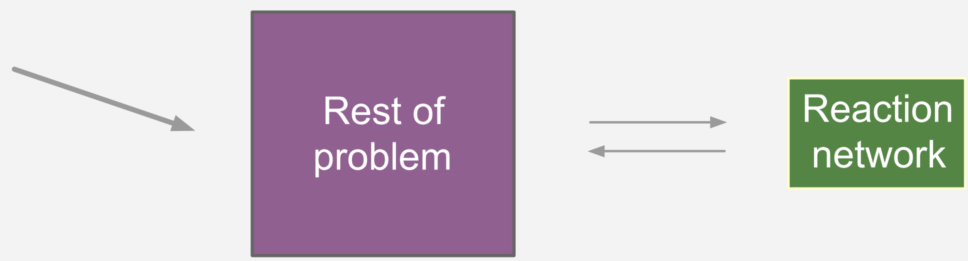
$$\frac{dY_i}{dt} = \sum_j F_{ij}$$



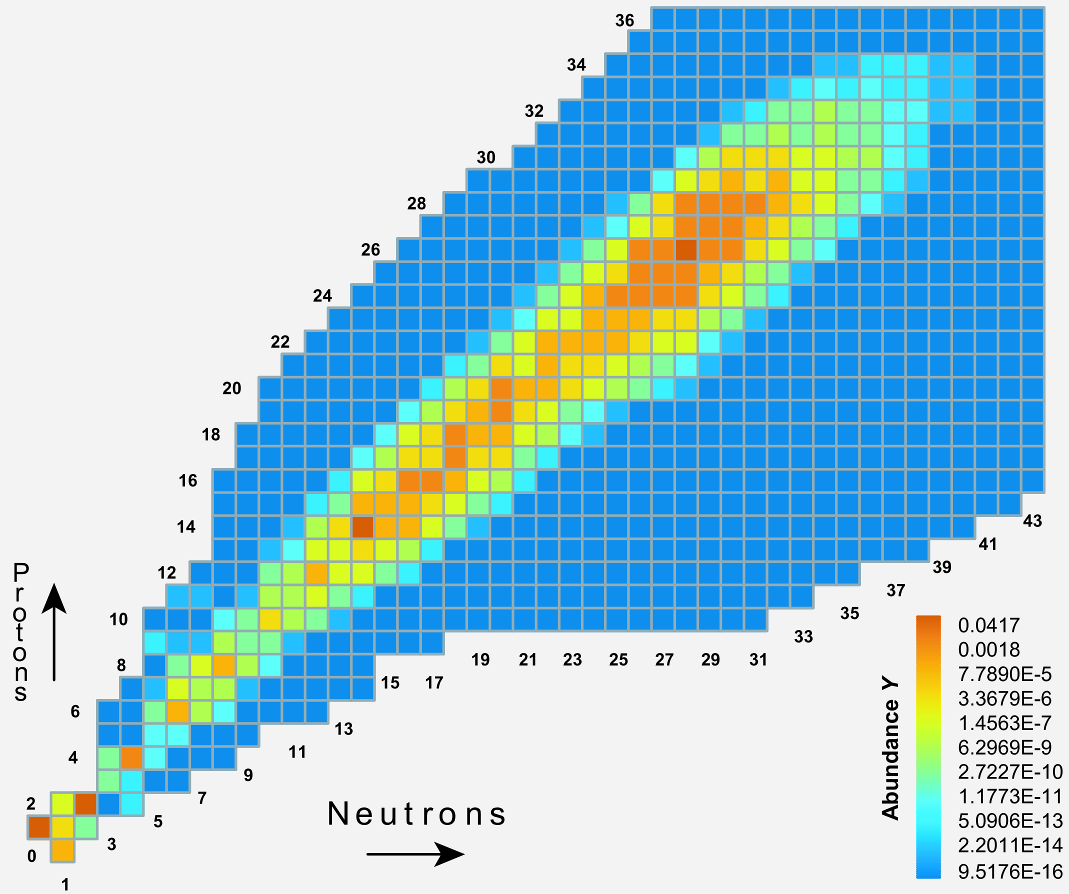
Often part of a larger problem:



A common approximation:
operator splitting



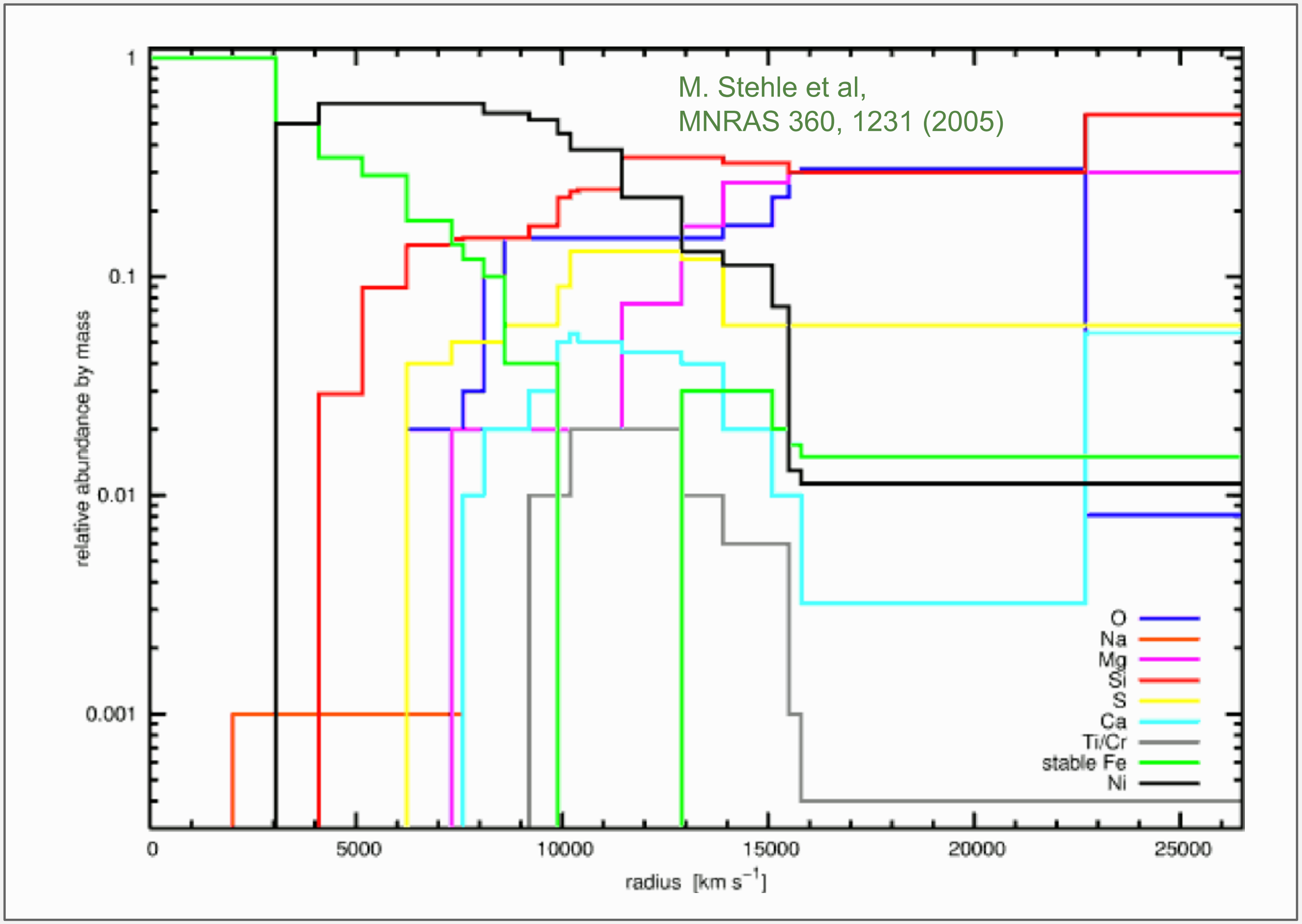
Solving Large Thermonuclear Networks



Compare Abundance

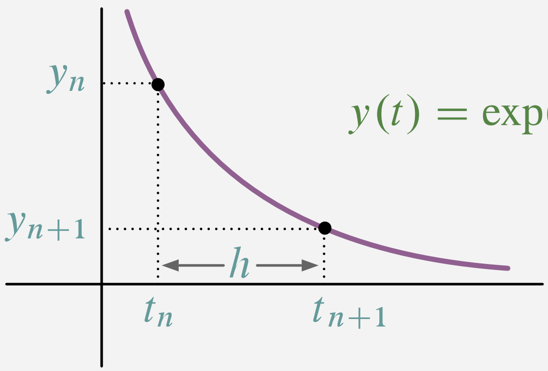
Compare NZ

Abundance Tomography from SN2002bo



Note intermediate mass elements at high velocity

Finite-Difference Approximations



$$\frac{dy}{dt} = -ky$$

Explicit Finite Difference (forward Euler)

$$y_{n+1} \simeq y_n + h \left.\frac{dy}{dt}\right|_{t_n}$$
$$= (1 - hk)\, y_n$$

Explicit finite difference methods require only the derivatives already known to advance the solution by one timestep

Implicit Finite Difference (backward Euler)

$$y_{n+1} \simeq y_n + h \left.\frac{dy}{dt}\right|_{t_{n+1}}$$
$$= y_n - hk\, y_{n+1}$$
$$\rightarrow \quad y_{n+1} = \frac{1}{1 + hk}\, y_n$$

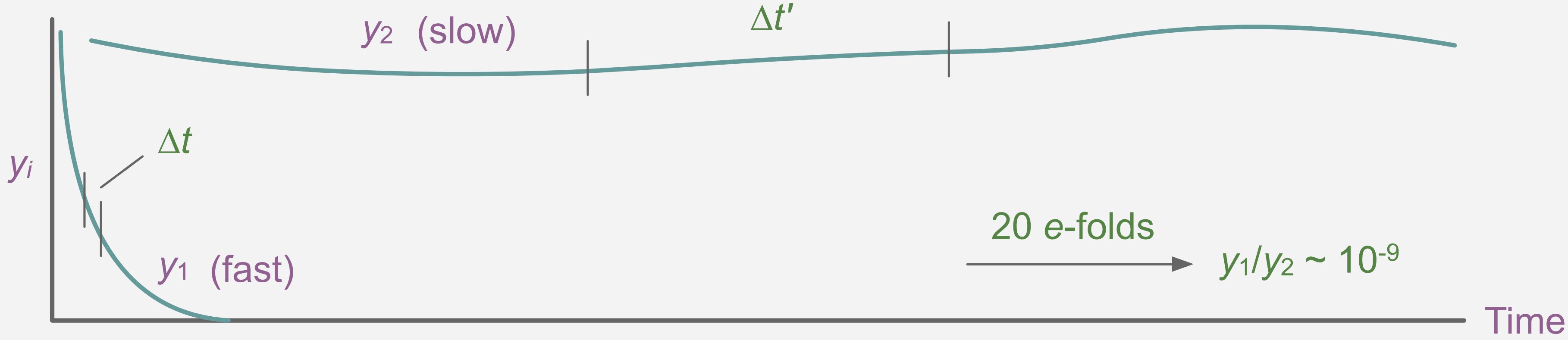
Implicit finite difference methods require derivatives at future timesteps to advance the solution by one timestep

Stiff Differential Equations

It is difficult to give a precise definition of stiffness. A reasonable one for our purposes is

A system of equations is stiff when the maximum stepsize for an acceptable finite-difference solution is limited by stability, not accuracy. Roughly, physical systems are stiff when there are characteristic rates in the system ranging over many orders of magnitude.

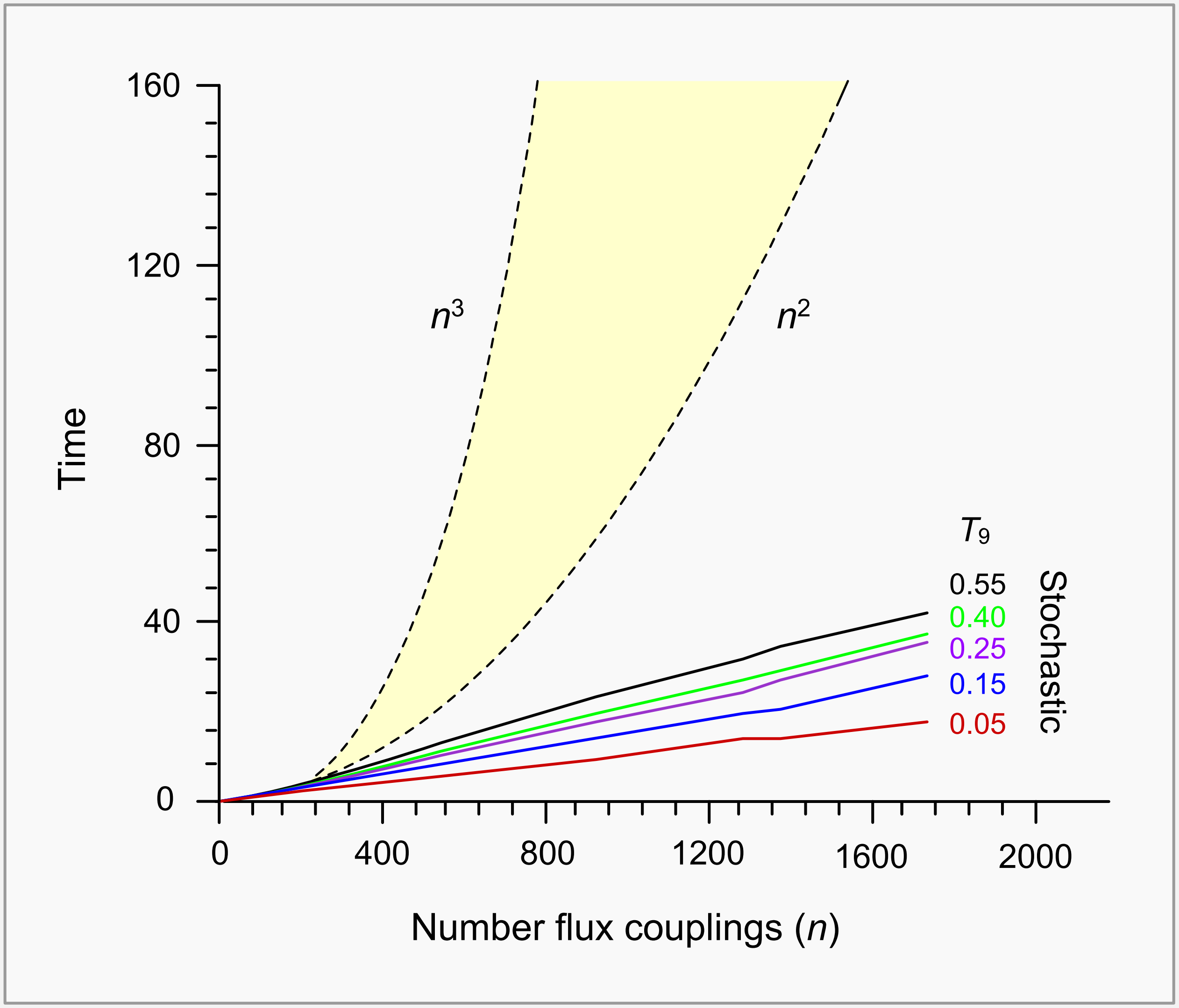
Example:



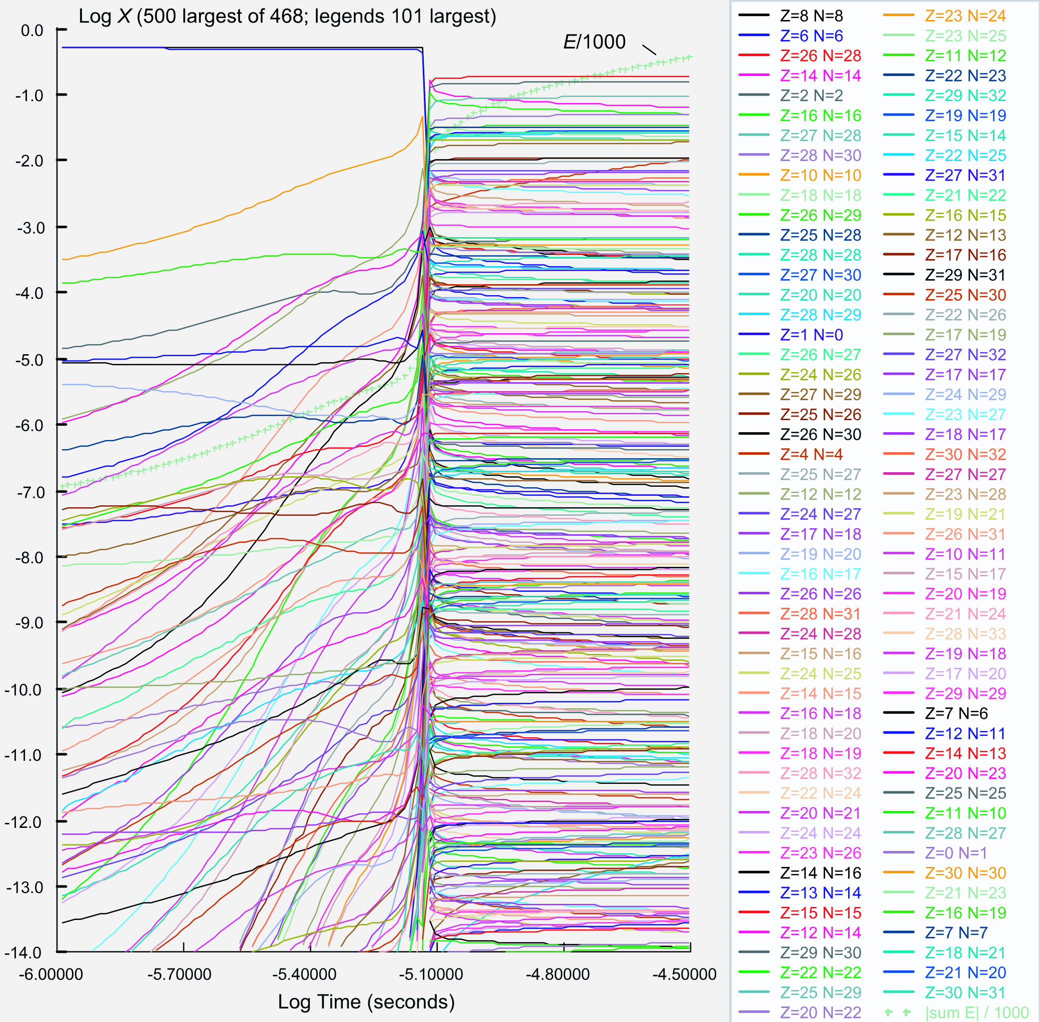
For an *explicit method:* The maximum stable timestep Δt is set by *fast component, y_1*. Typically it is of order $1/k$, where k is the fastest rate.

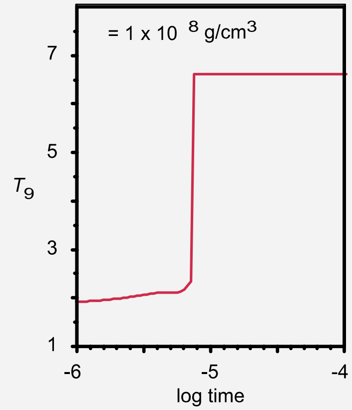
For an *implicit method:* *Any* positive timestep is stable, though not necessarily accurate.

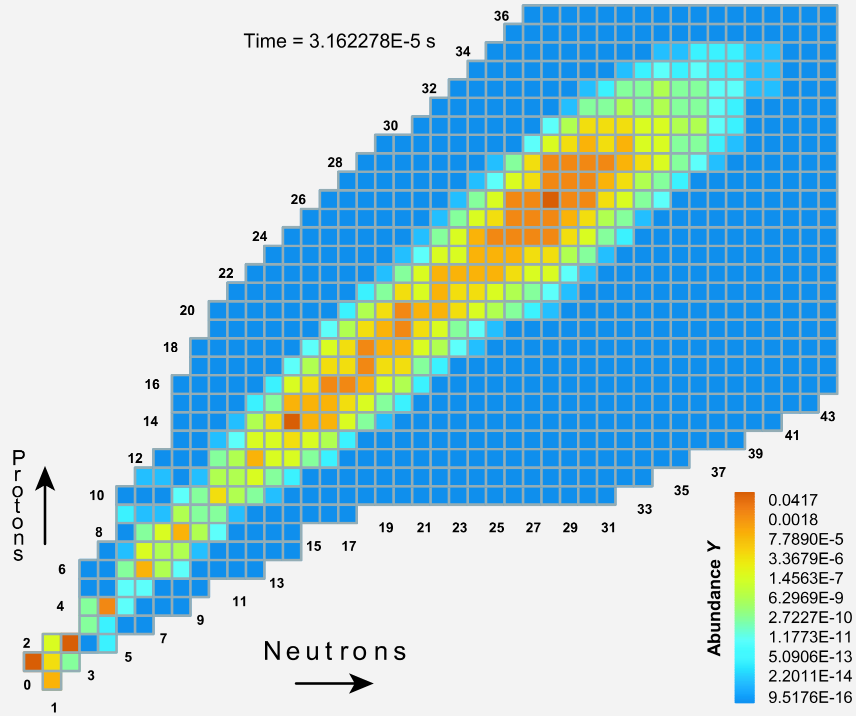
Scaling Properties



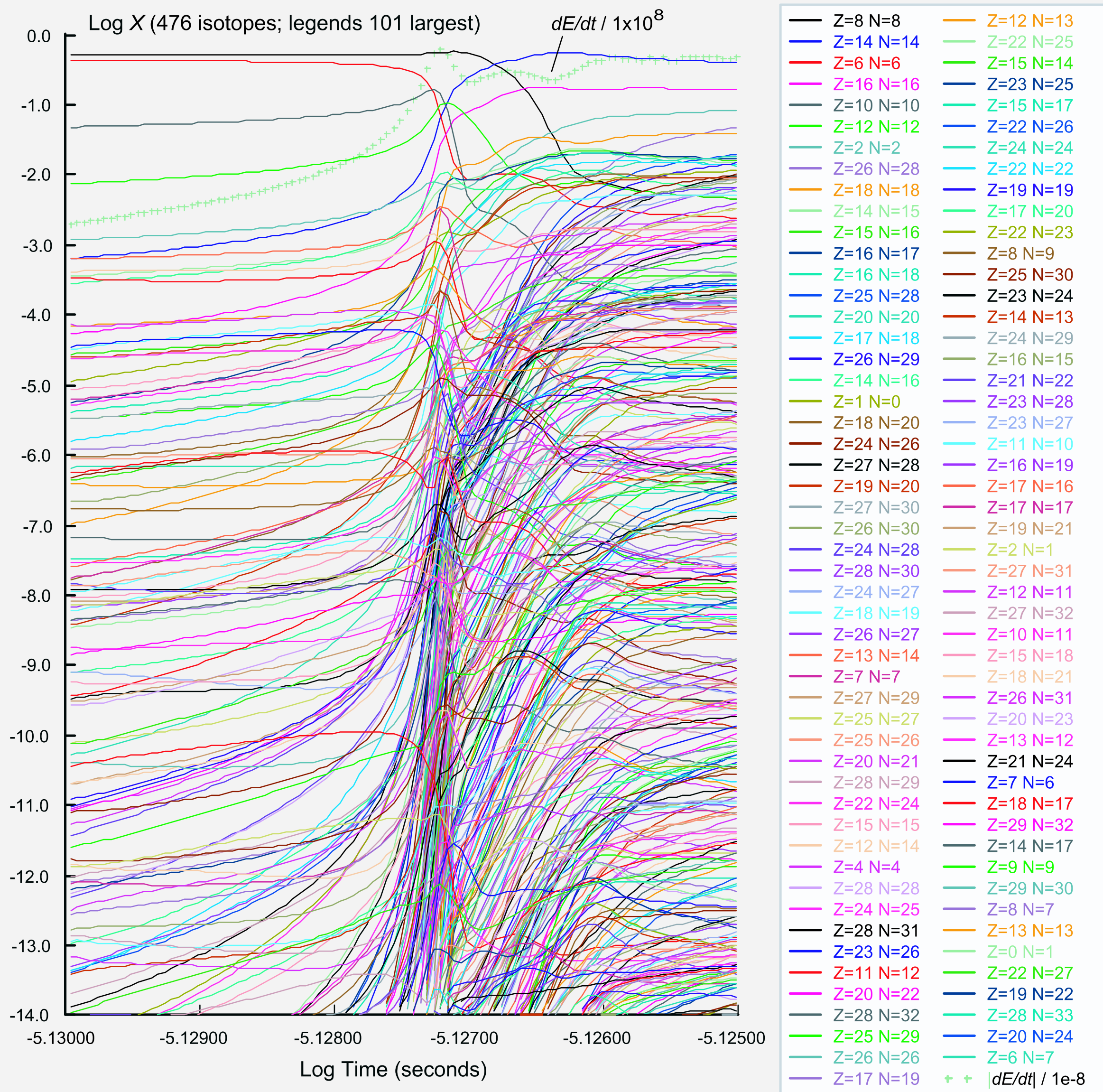
Thermonuclear Network, Type Ia Supernova



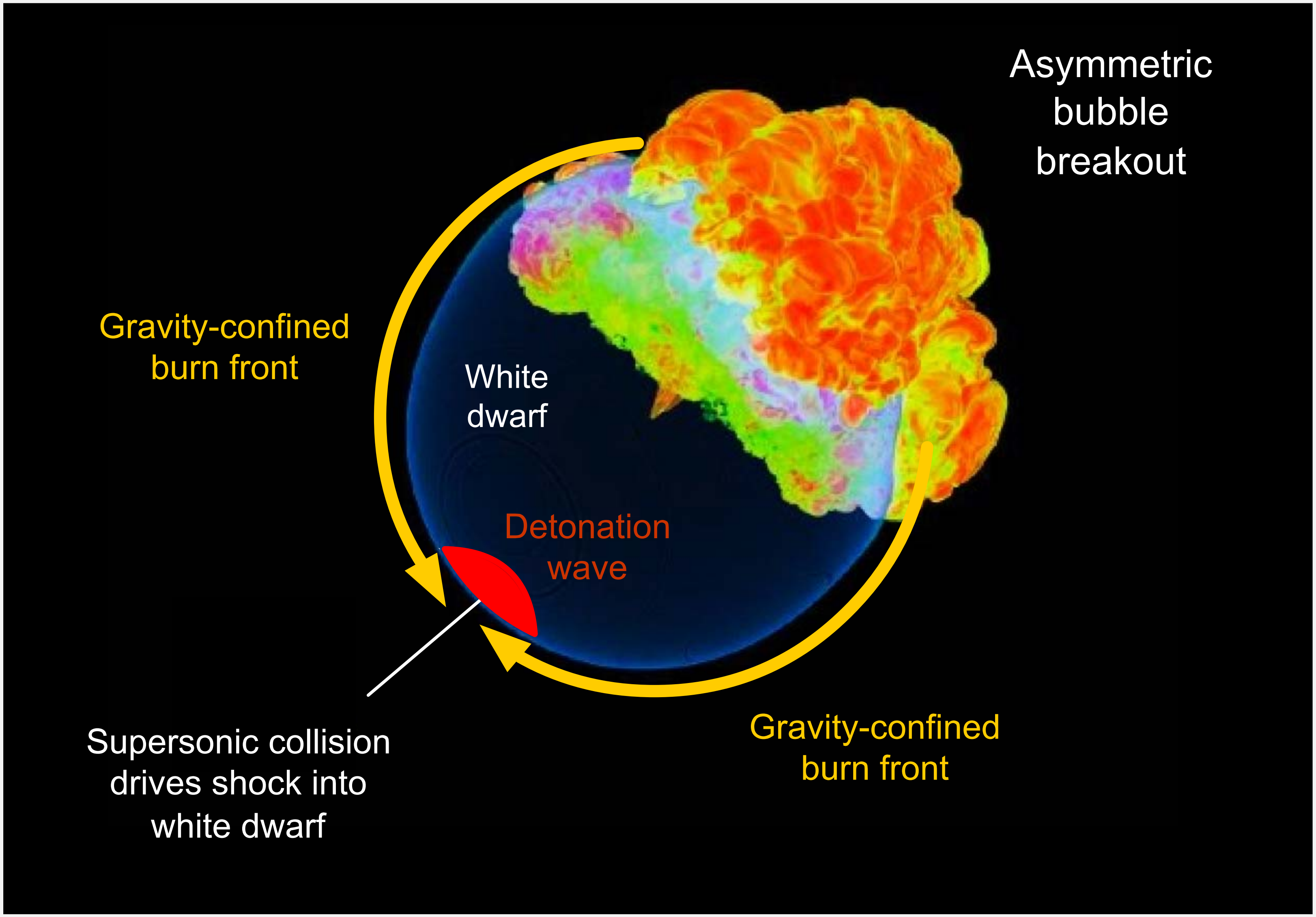




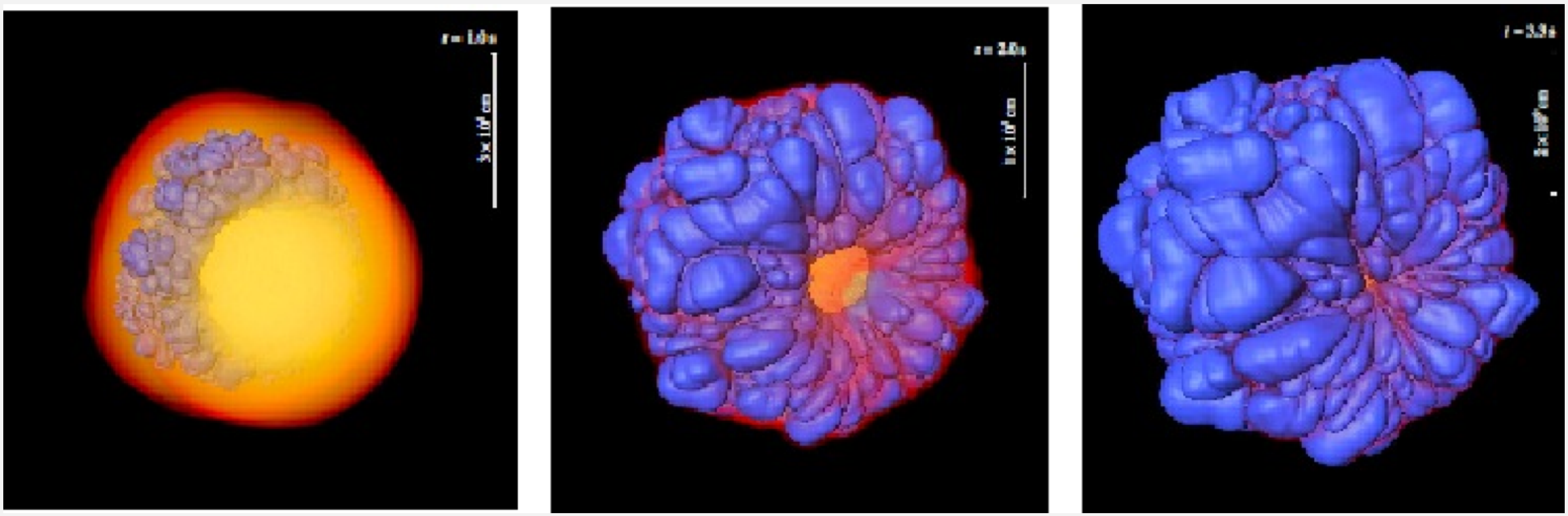
Thermonuclear Network, Type Ia Supernova



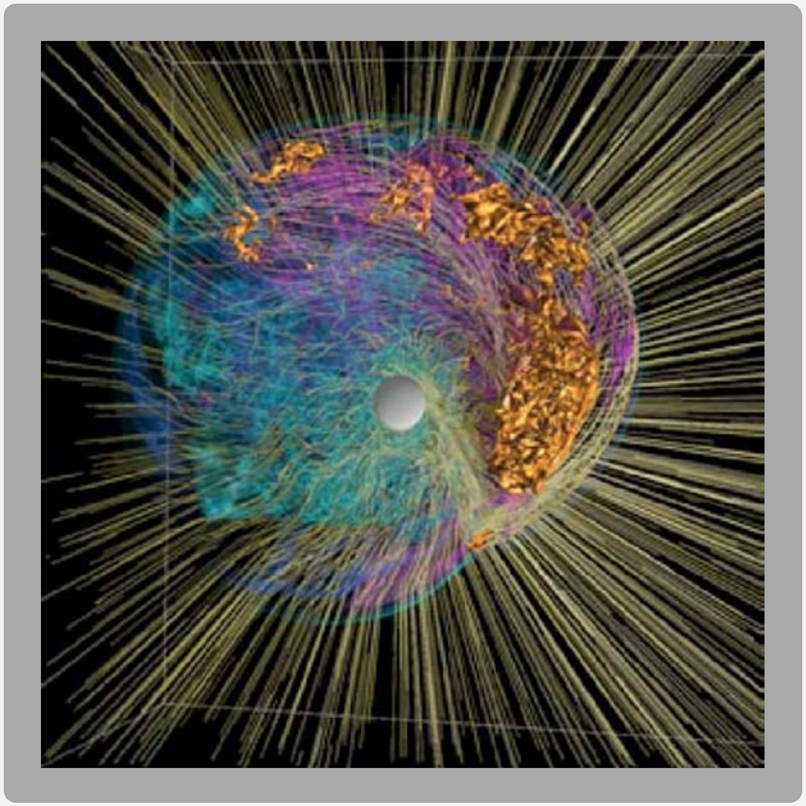
Gravity-Confined Detonation



Gravity-Confined Detonation

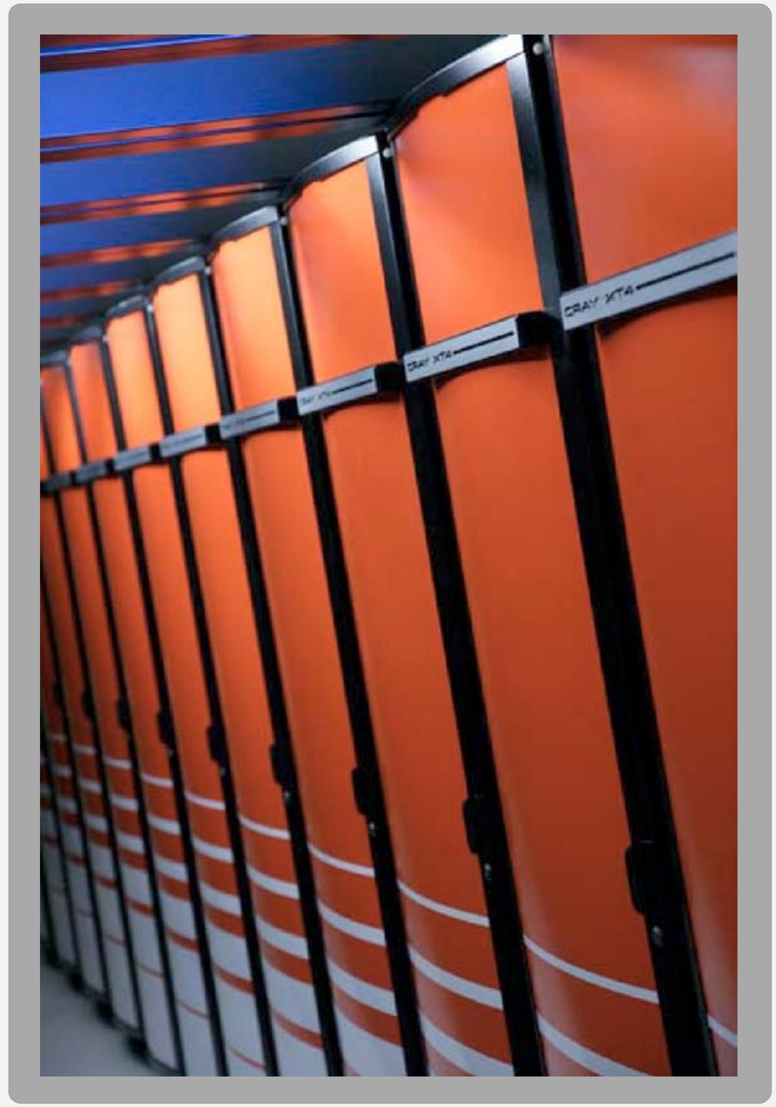


Computational and Visualization Power



Complex visualization of a core-collapse supernova simulation

Jaguar cabinets



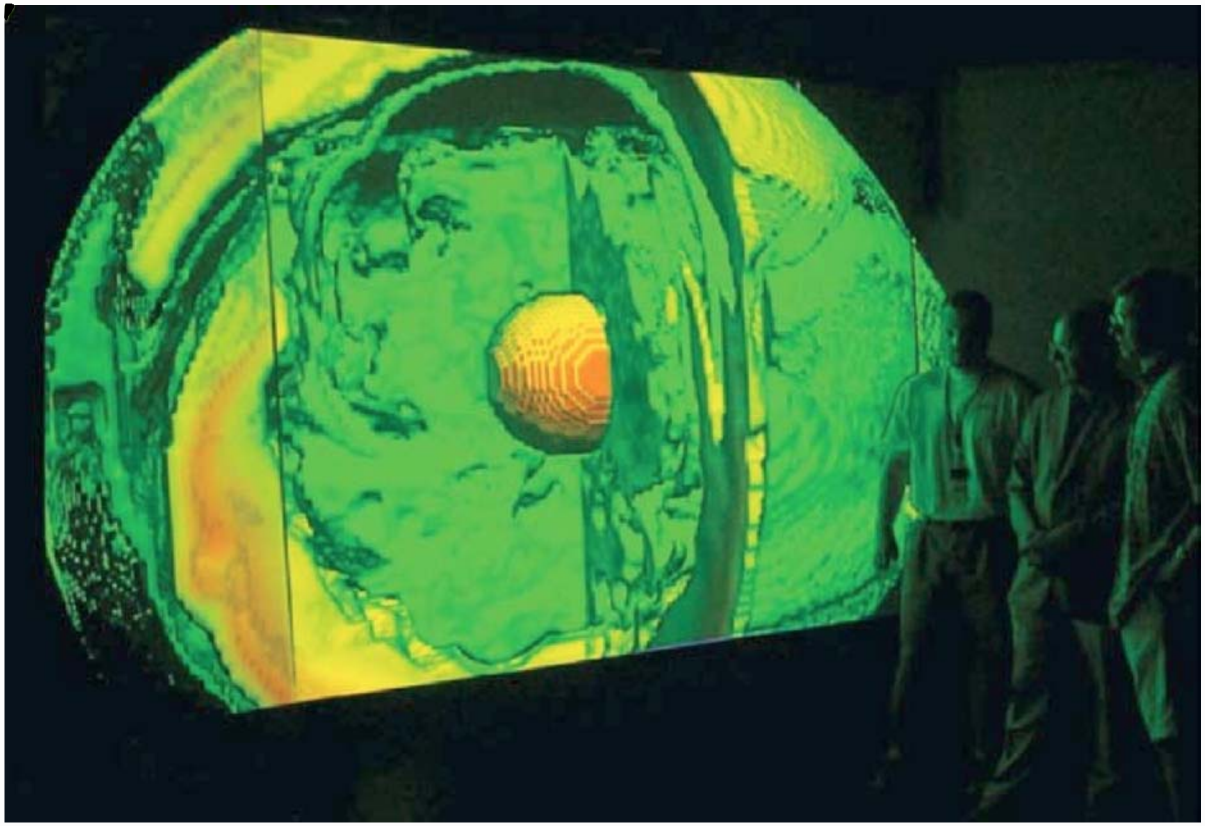
Computational and Visualization Power

The Jaguar system, a Cray XT4 located at ORNL's National Center for Computational Sciences, now uses more than 31,000 processing cores to deliver up to 263 trillion calculations a second (or 263 teraflops).

1 petaflop (10^{15} floating point operations per second) by 2009.

Computational and Visualization Power

Everest Visualization Facility



- 27 1280 x 1024 high-end projectors
- Approximately 9 meter by 2.5 meter spatial extent
- Greater than 35 million pixels
- Driven by its own parallel computing cluster