An Overview of Current Research in Computer Modeling of Stellar Explosions

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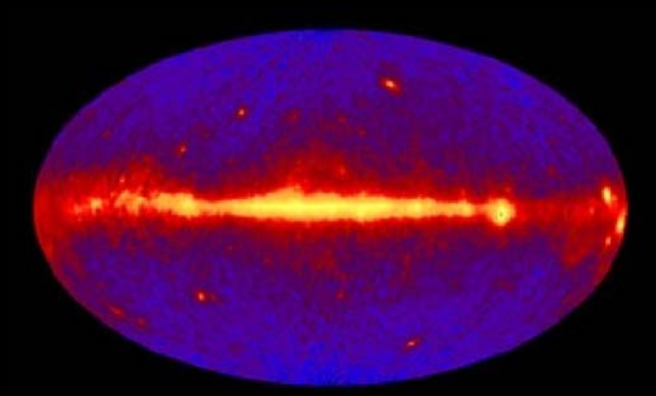
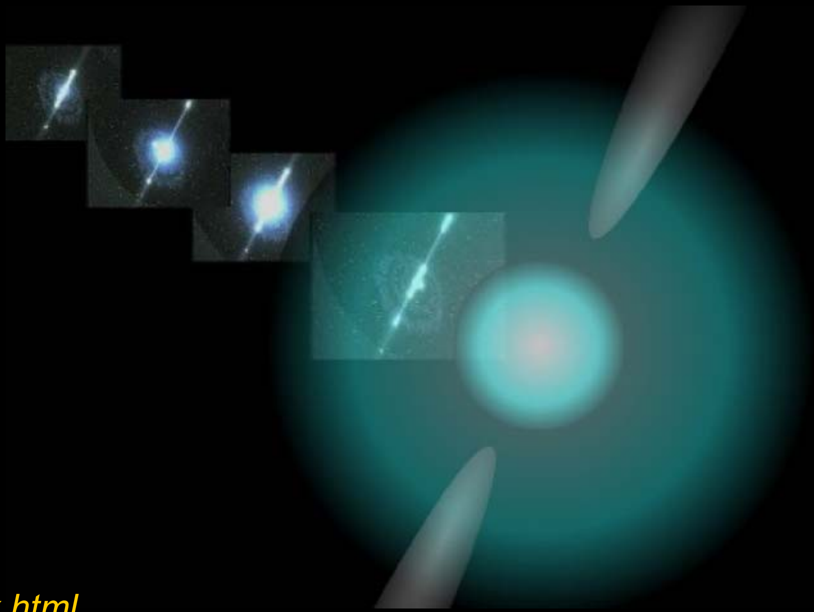




http://csep10.phys.utk.edu/guidry/stellarExplosions/index.html

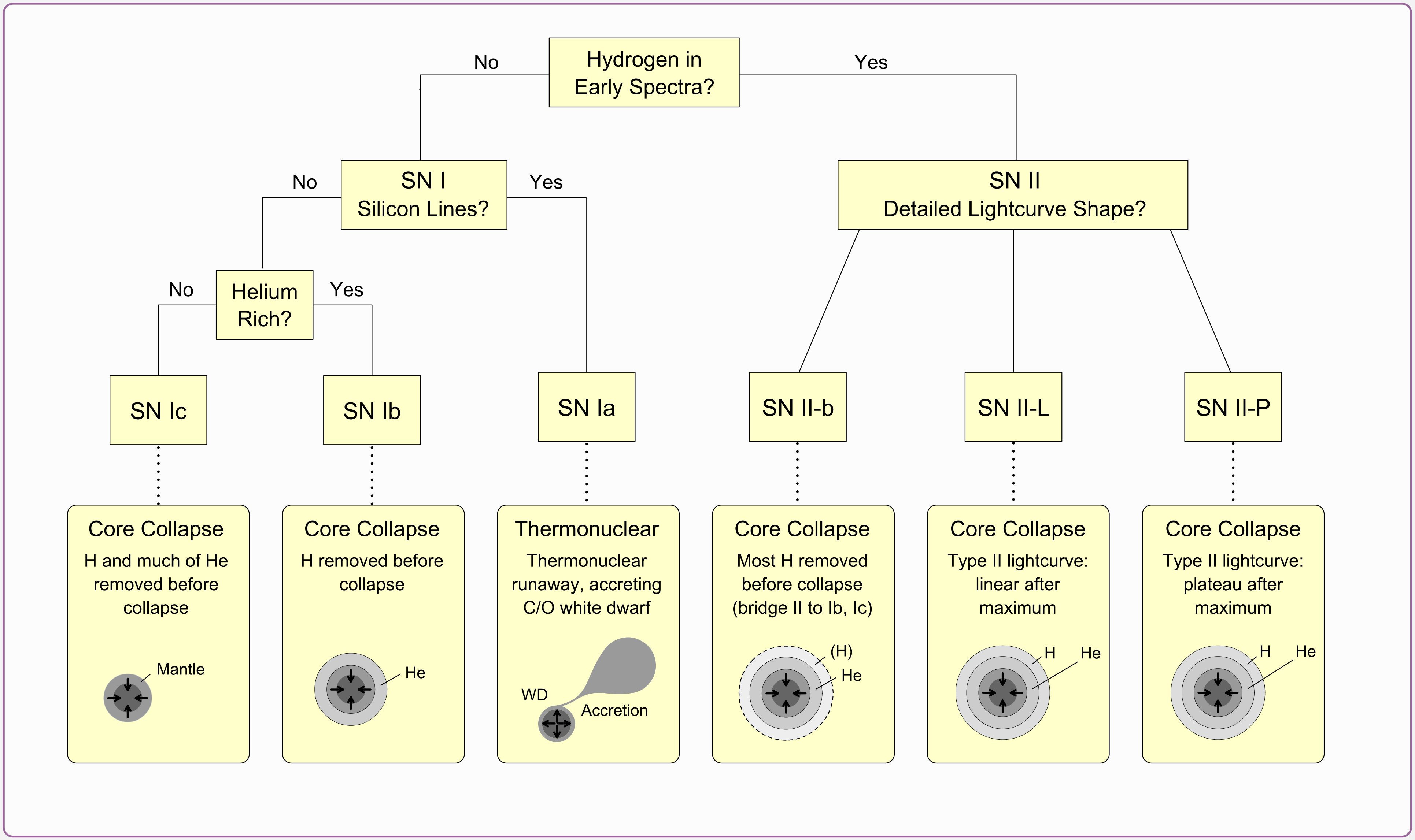
Large Stellar-Scale Energy Sources

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 $\sim 10^{50}$ - 10^{53} erg in a matter of seconds. For reference, the Sun 's luminosity is $\sim 10^{33}$ erg/second, so these events can outshine an entire large galaxy of say 100 billion normal stars for a short period of time.

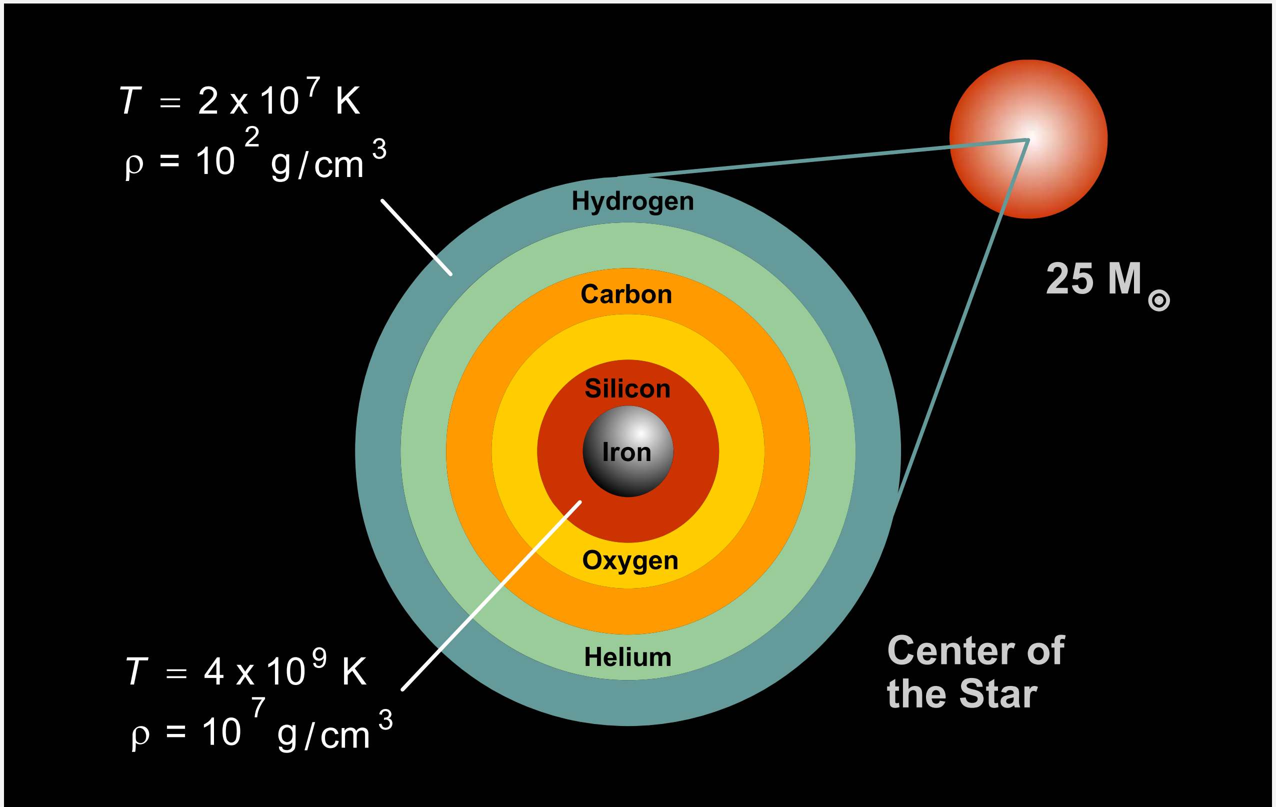
What could be the energy source for such events? We know of at least three possibilities:

- *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

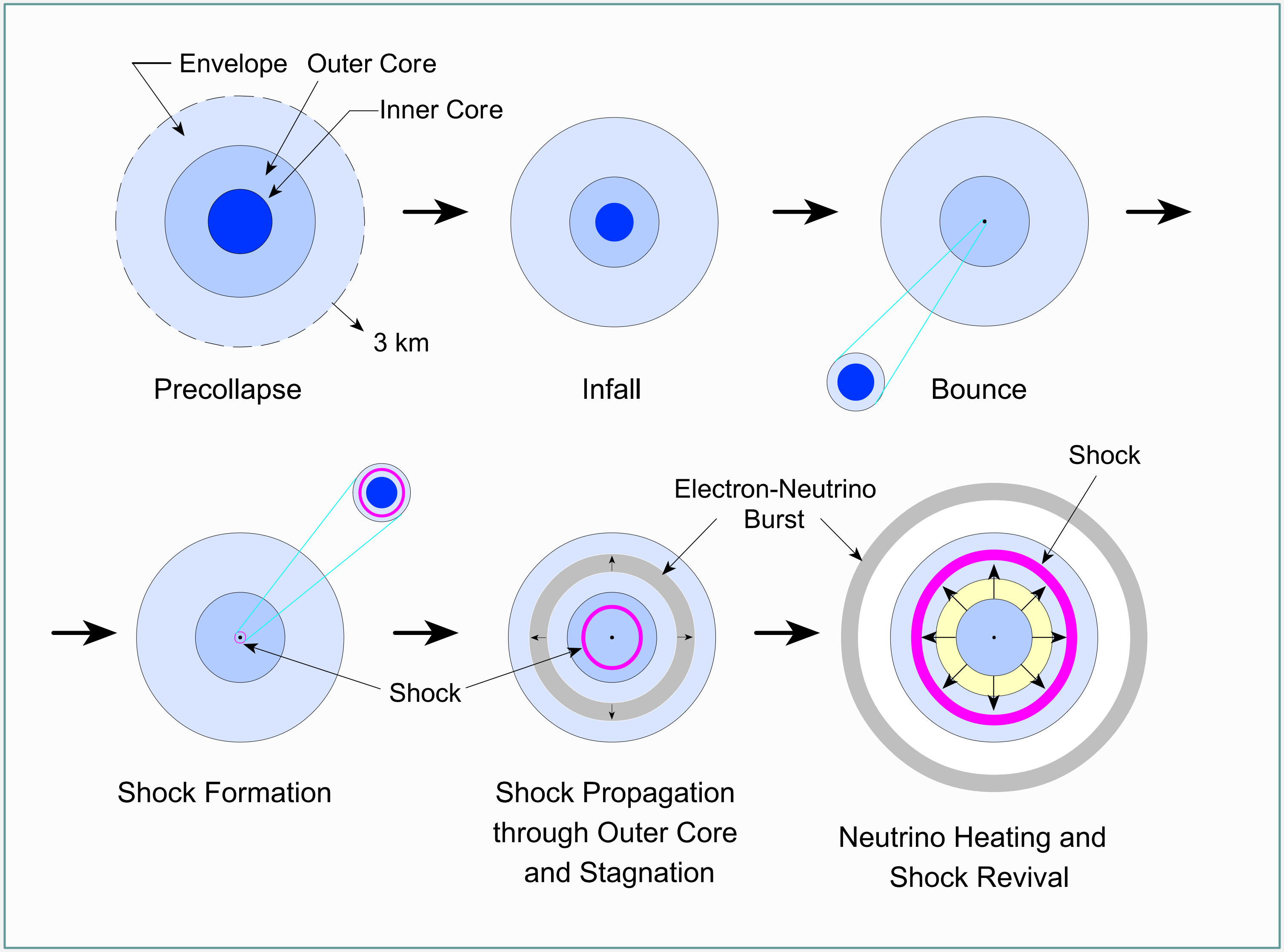


Core of Massive Star Late in Its Life

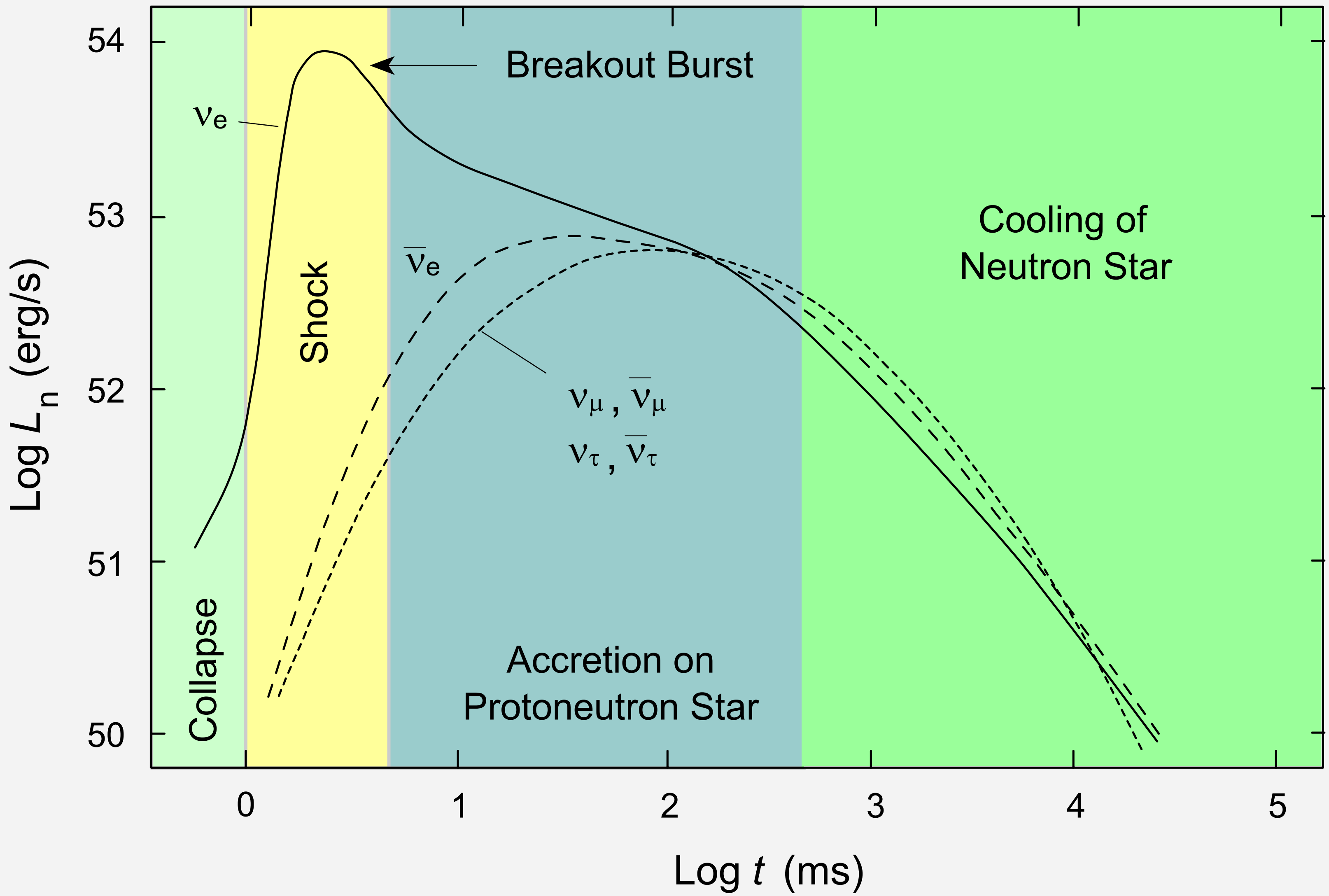


Center of 25 Solar Mass Star Late in its Life

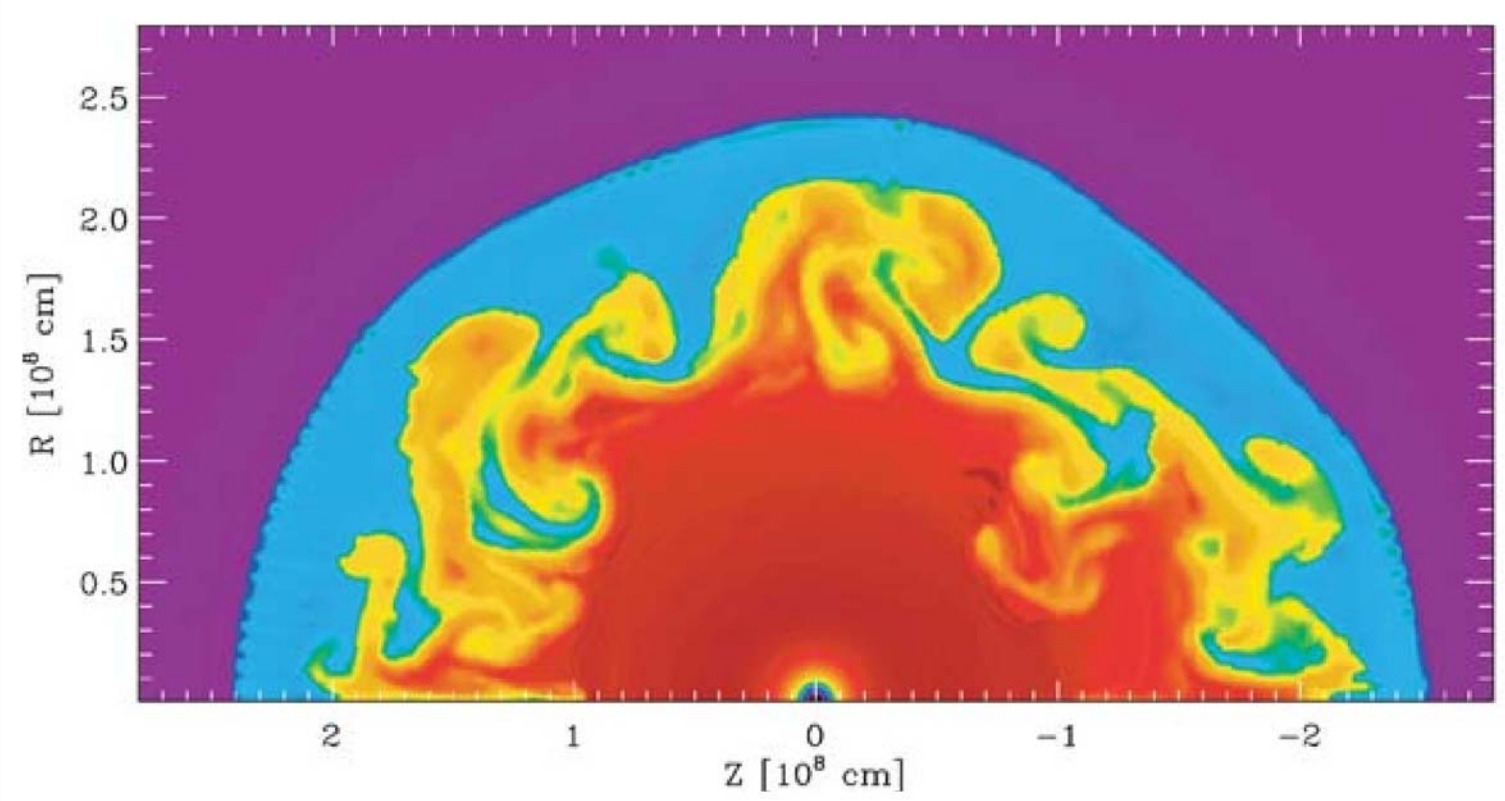
The Neutrino Reheating Mechanism



Neutrino Luminosity, Core-Collapse Supernova

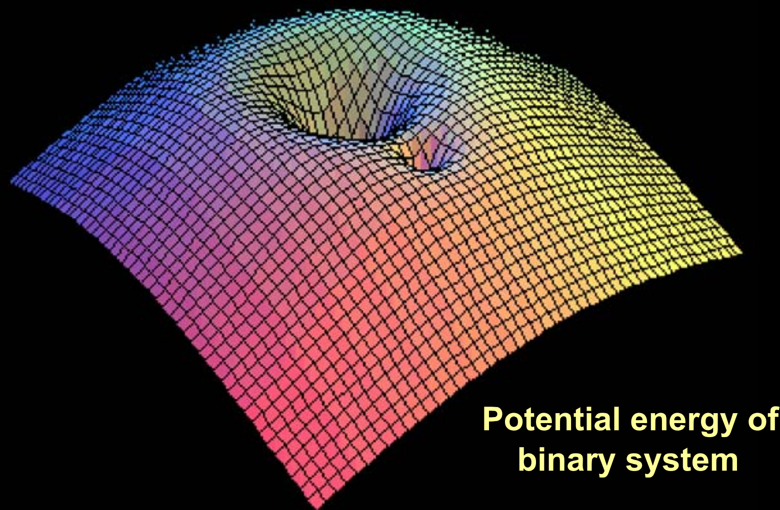


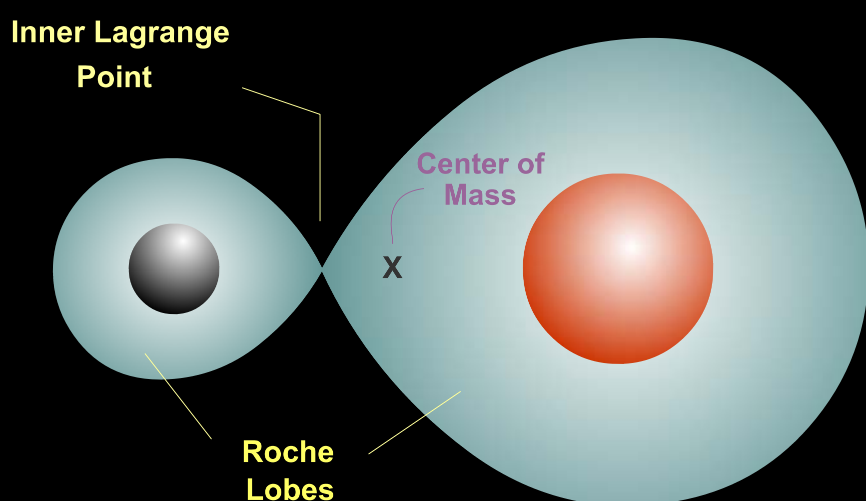
Convection below the Shock in Core-Collapse Supernova

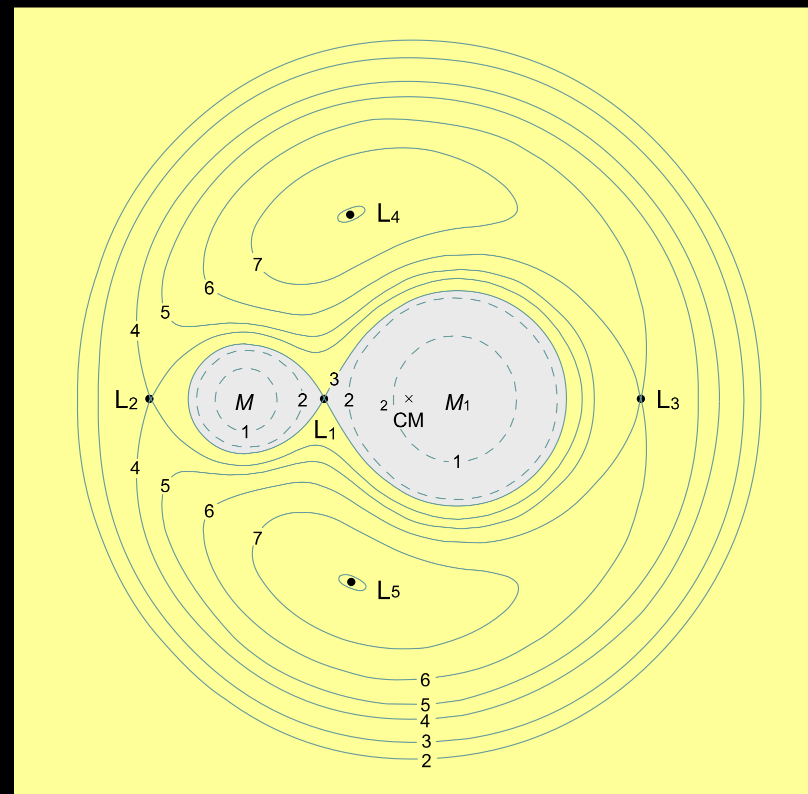


Core-Collapse Sim

Gravitational Potential Energy in Binary Systems: Roche Lobes

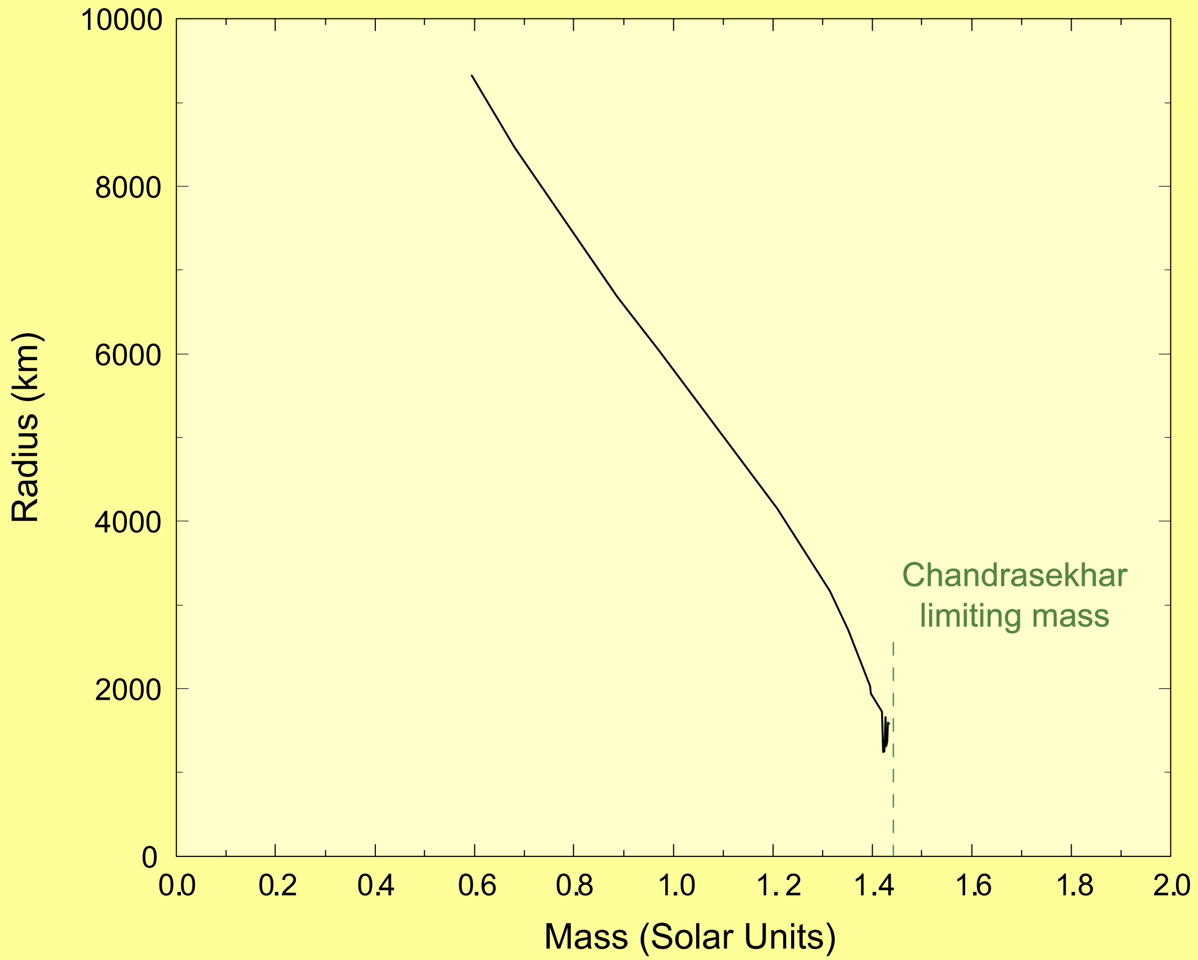




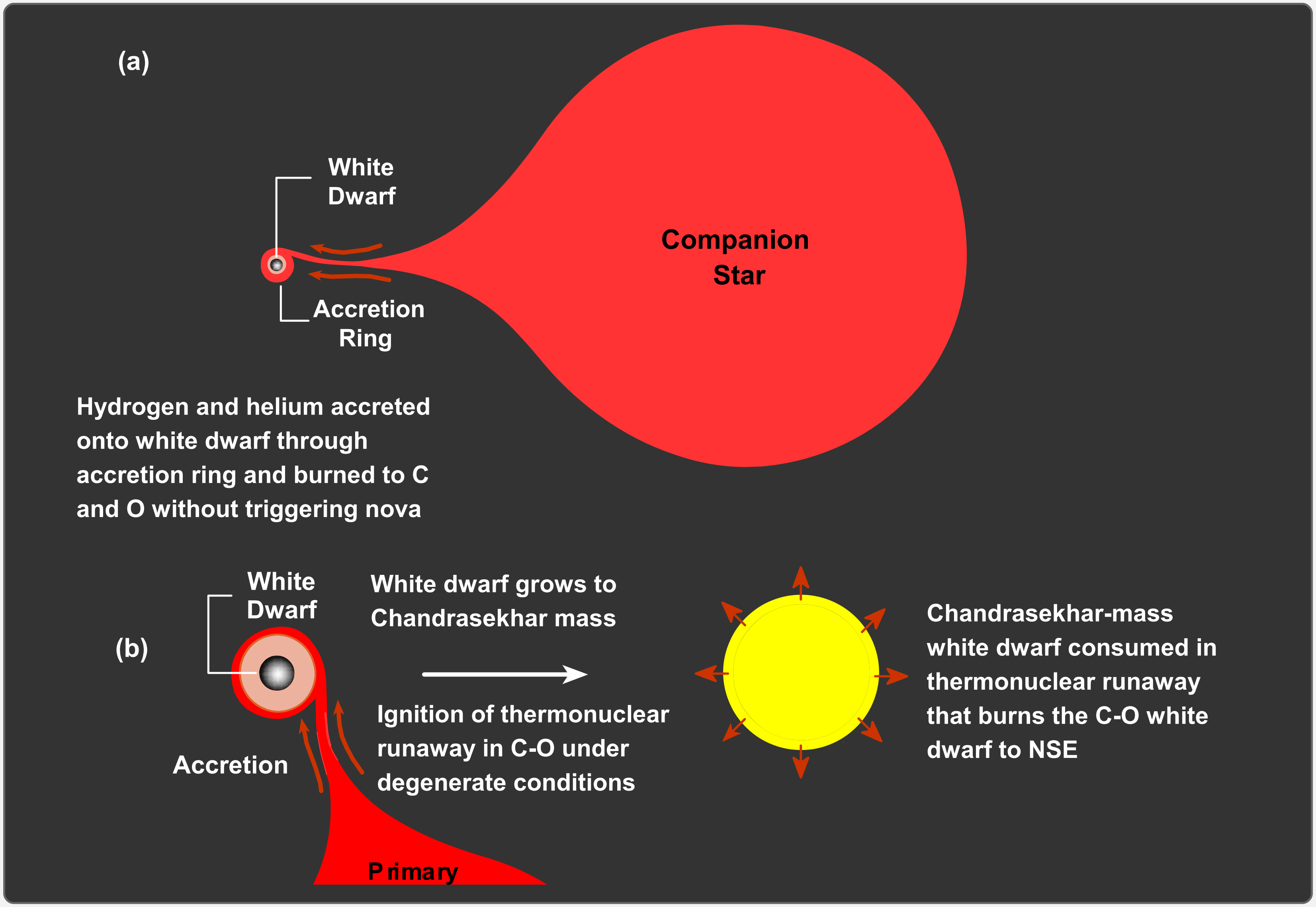


Roche Overflow

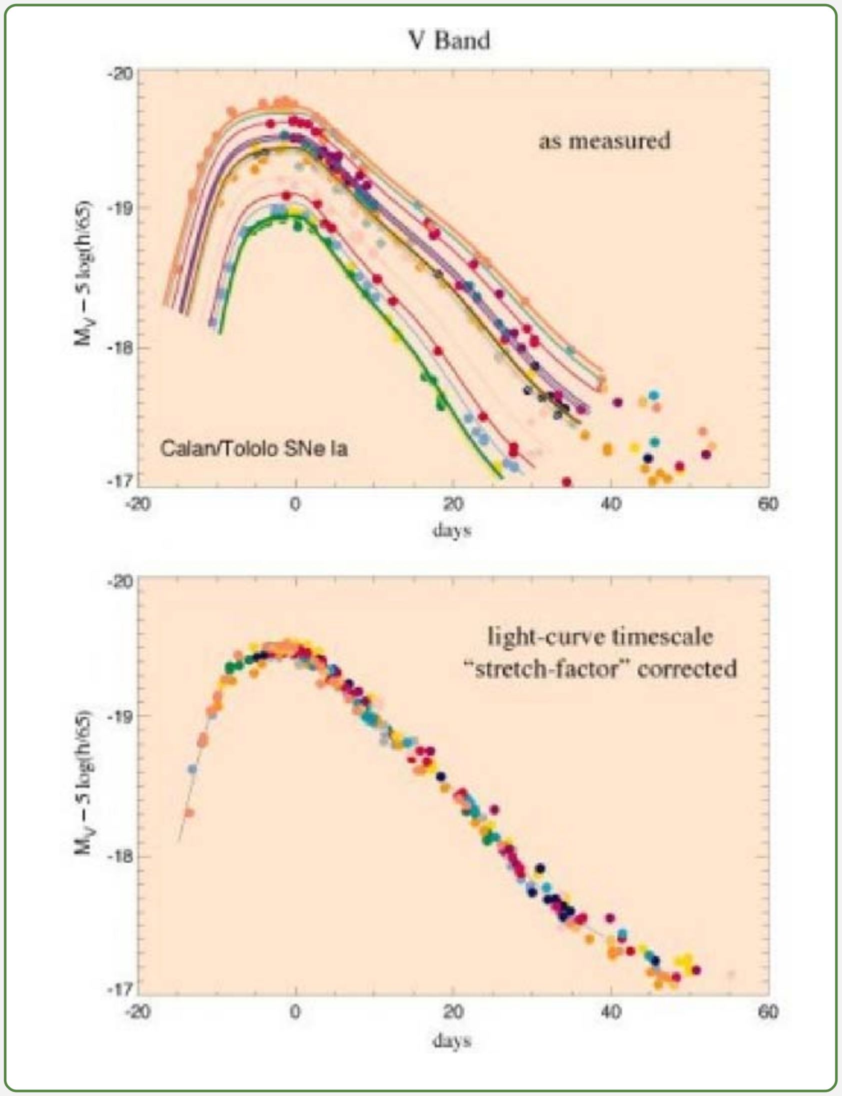
Chandrasekhar Limiting Mass



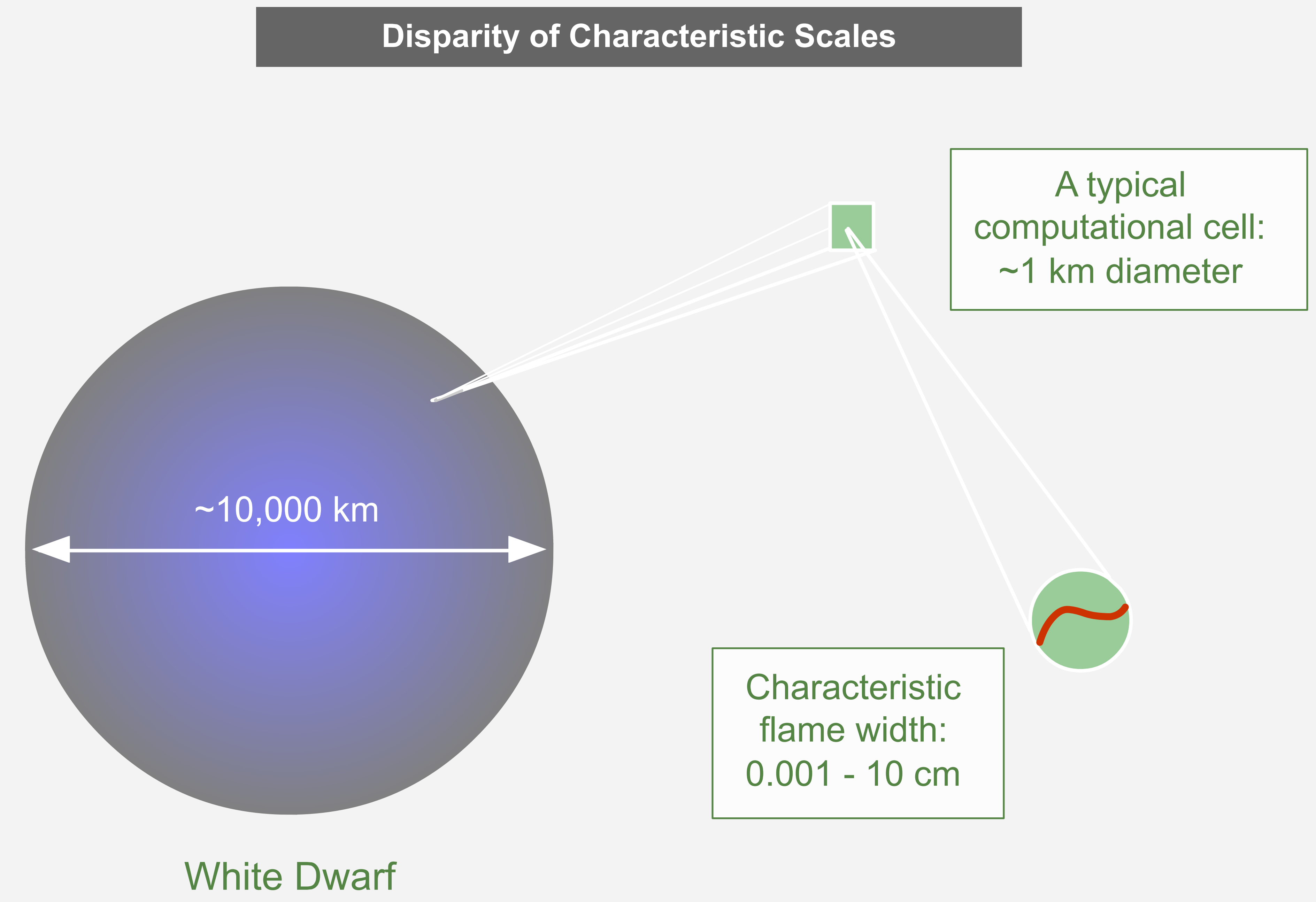
The Type Ia Supernova Mechanism



Standardizable Candles



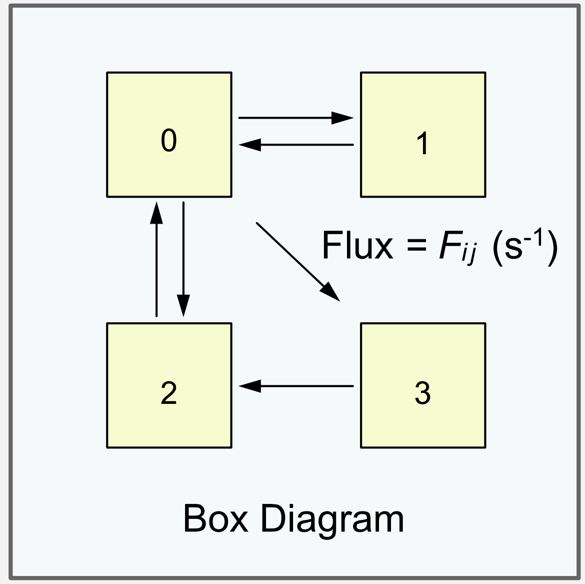
Friedmann Solver


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

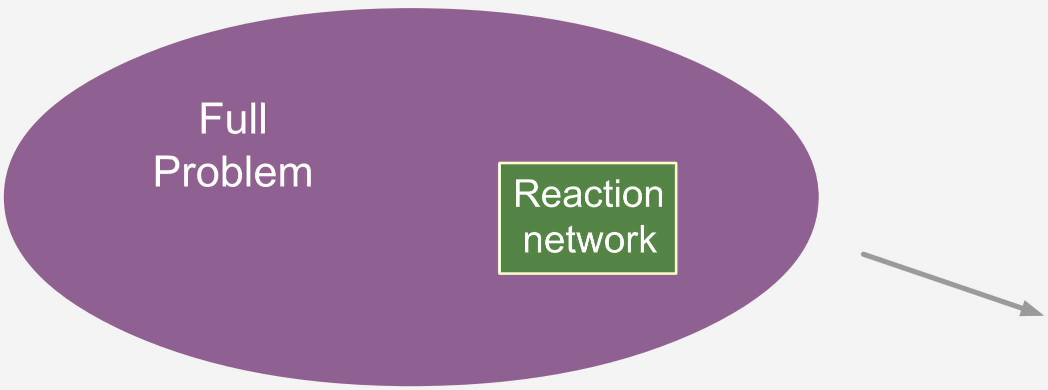
Reaction Networks: Sources, Sinks, and Fluxes

Coupled ordinary differential equations

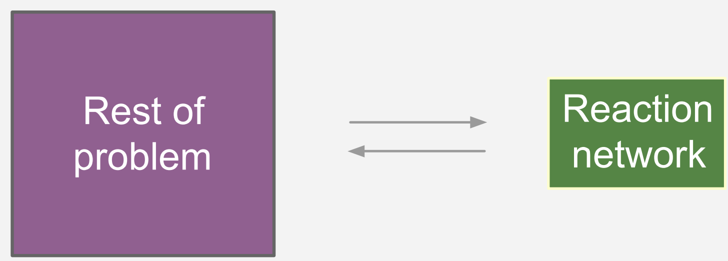
$$\frac{dY_i}{dt} = \sum_j F_{ij}$$



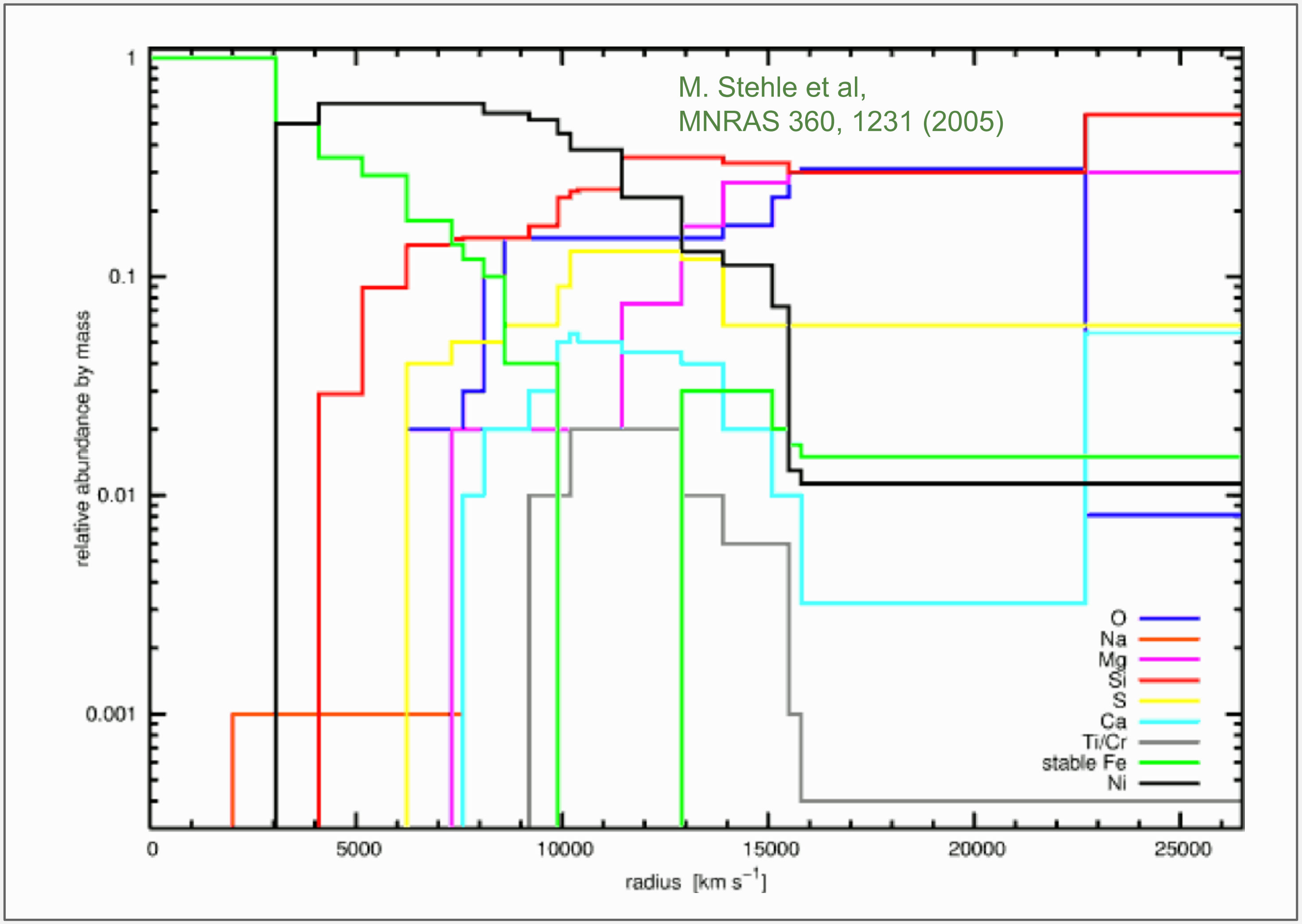
Often part of a larger problem:



A common approximation:
operator splitting

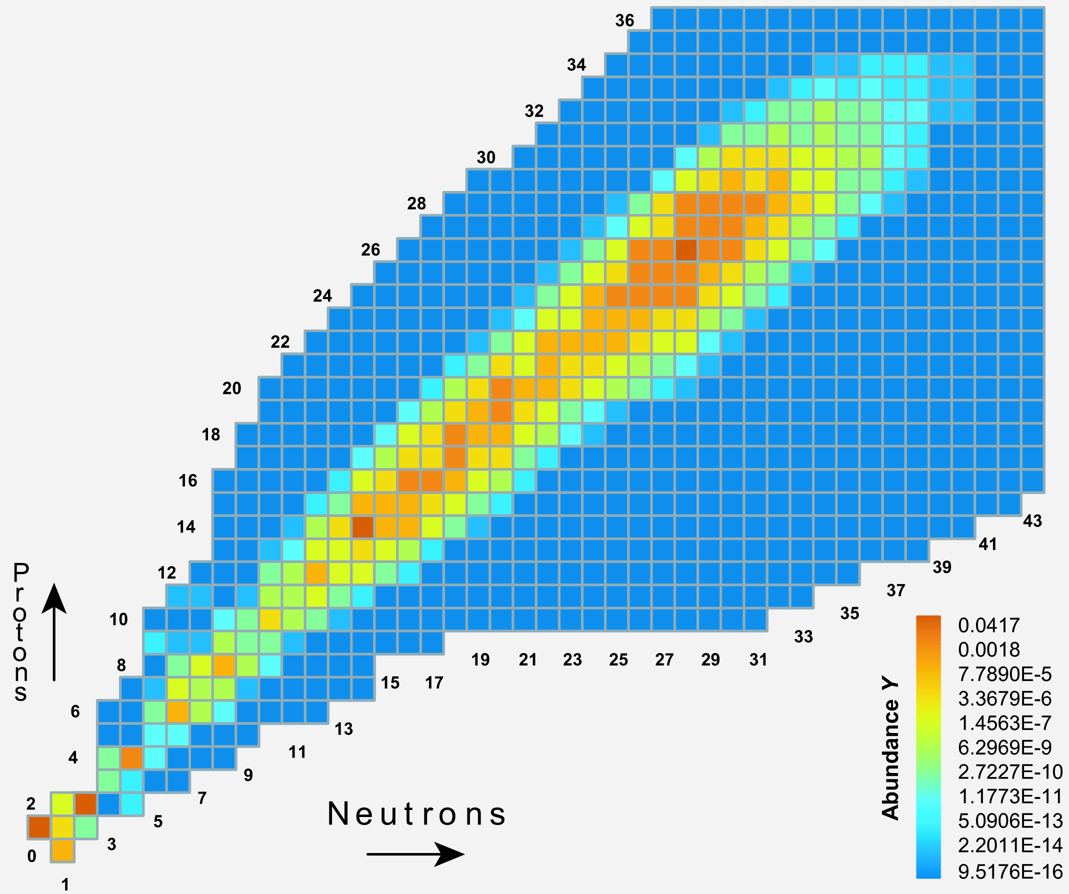


Abundance Tomography from SN2002bo



Note intermediate mass elements at high velocity

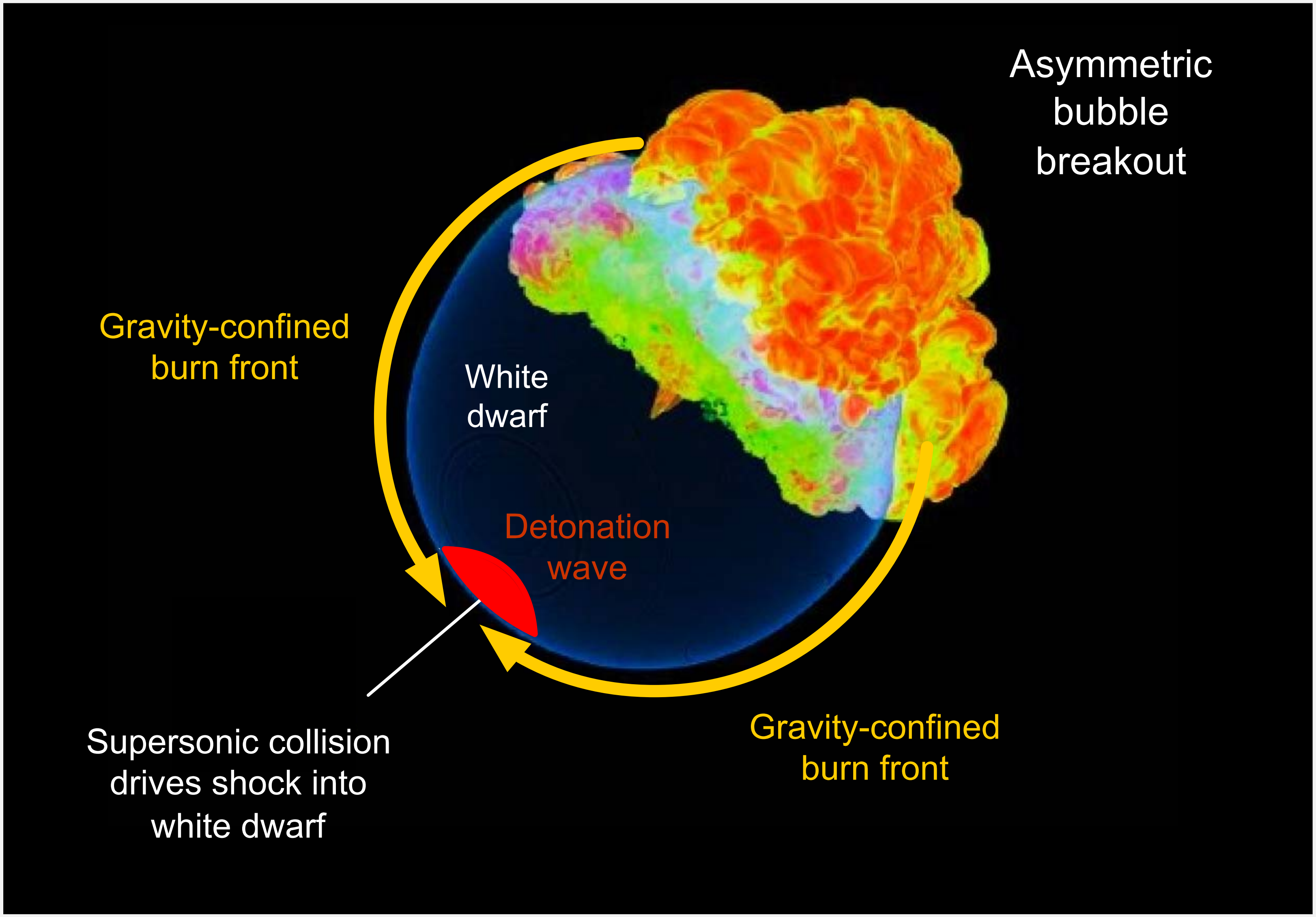
Solving Large Thermonuclear Networks



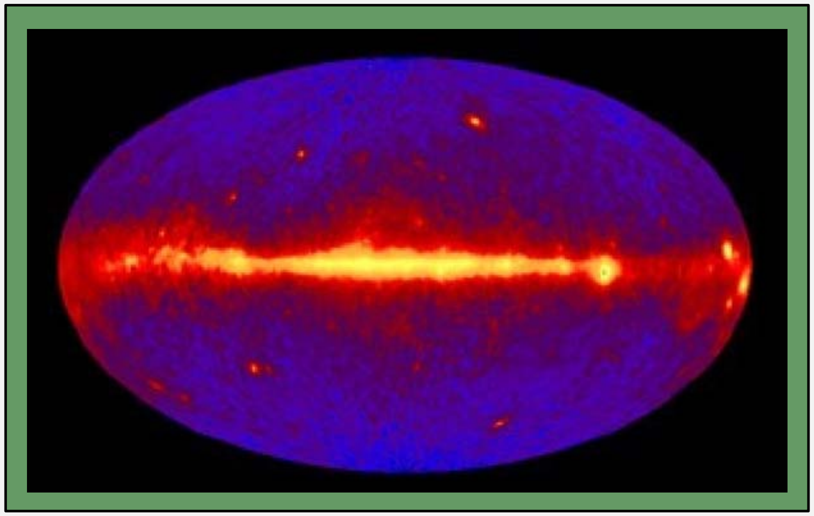
Compare Abundance

Compare NZ

Gravity-Confined Detonation



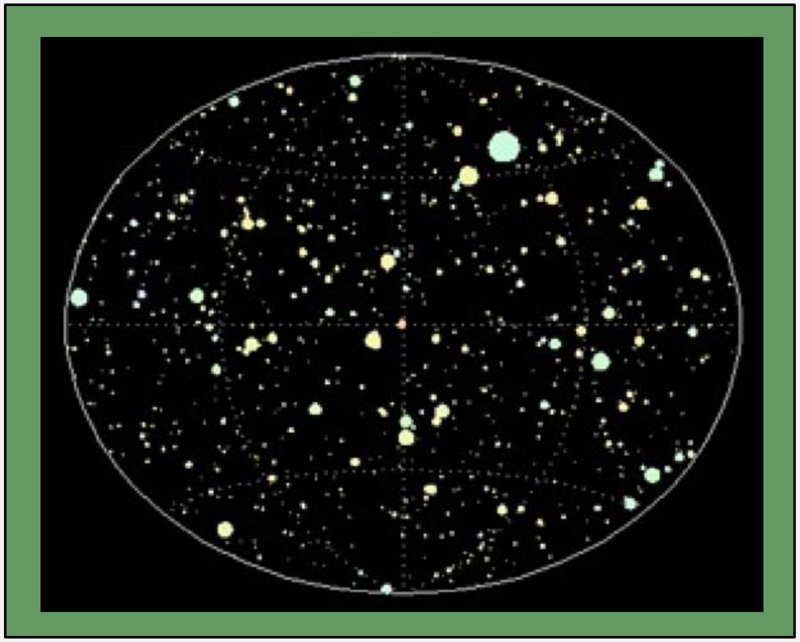
The Gamma-Ray Sky



Gamma-Ray Sky, Galactic Coordinates

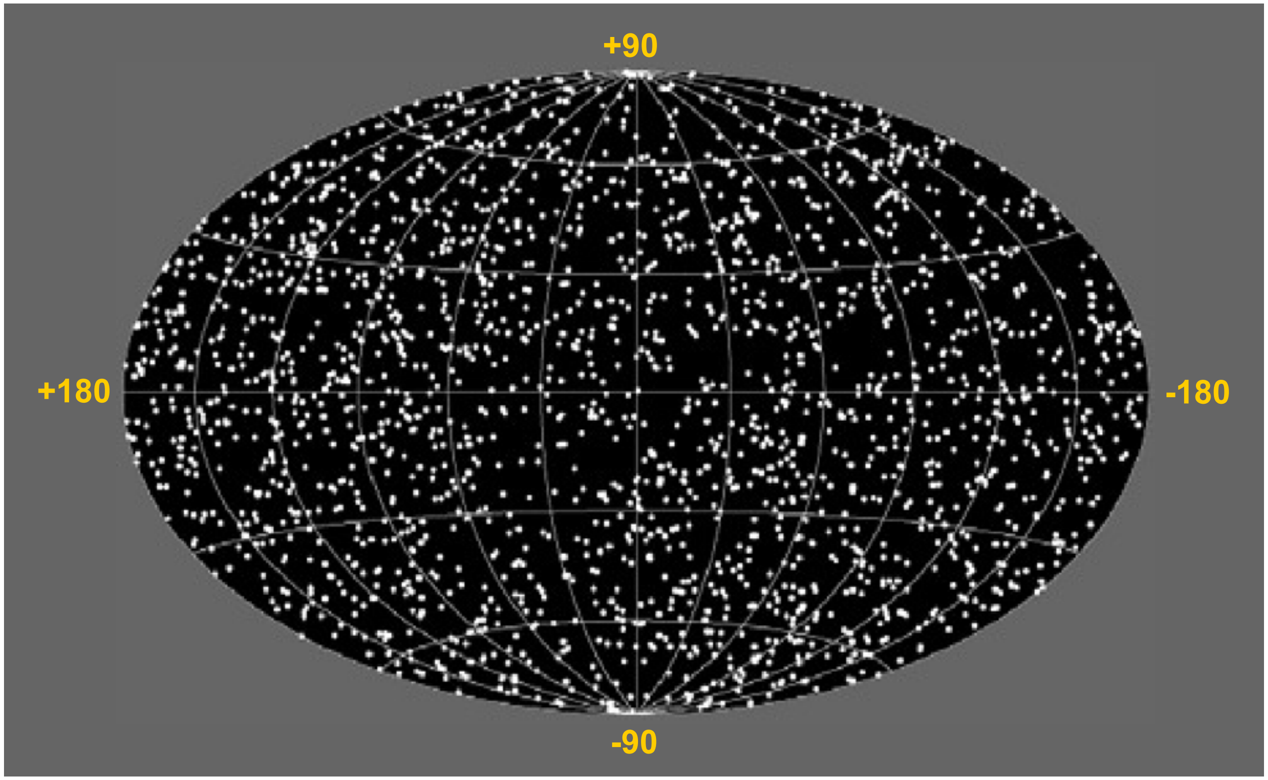
The diffuse glow running horizontally through the image is from gamma ray sources in the plane of our galaxy. Bright spots to the right in the galactic plane are pulsars. Brighter spots above and below the plane of the galaxy are distant quasars.

Gamma-Ray Bursts



Gamma ray bursts were discovered in the 1960s by U.S. Air Force Vela satellites (Spanish *velar:* "to watch"). Unclassified project designed to test detecting and monitoring nuclear explosions violating test ban treaties.

Gamma-Ray Bursts



Several Thousand Gamma-Ray Bursts in Galactic Coordinates (BATSE)

Gamma-Ray Burst

Properties of Gamma-Ray Bursts

- Isotropic distribution on the sky argues for cosmological distances. Confirmed by direct redshift measurements for afterglow lines

  Redshifts from $z =$ 0.0085 - 4.5 (average $z \sim 1$)

- Spectrum is non-thermal, typically peaking at ~ 200 keV and extending perhaps to GeV.

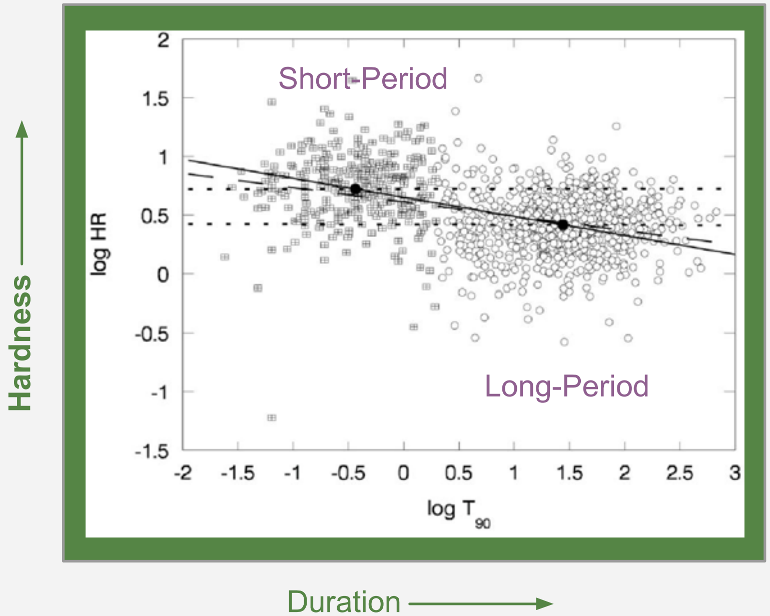
- Duration of bursts from 0.01 seconds to several hundred seconds

- Variety of time structure, from rather smooth to millisecond fluctuations (implying very compact source by causality).

- Two classes: long-period and short-period

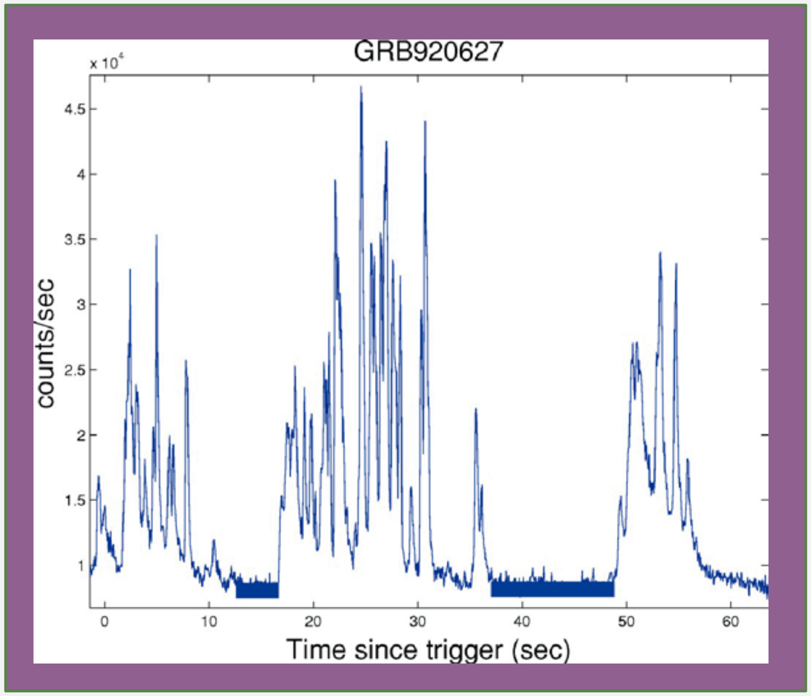
Gamma-Ray Bursts

Long-Period and Short-Period Bursts



Y. Qin et al, Publ. Astron. Soc. Jpn. **52**, 759 (2000)

A Long-Period Burst

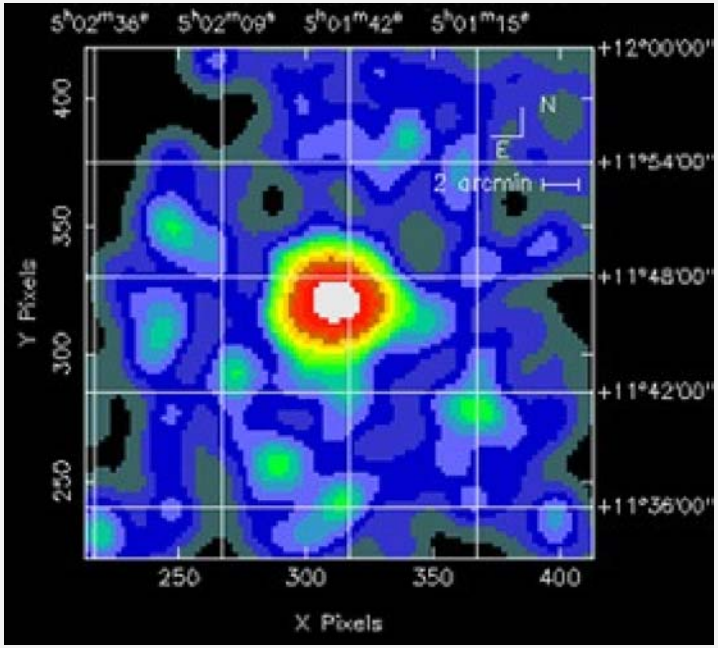


T. Piran, Rev. Mod. Phys. 76, 1143 (2005)

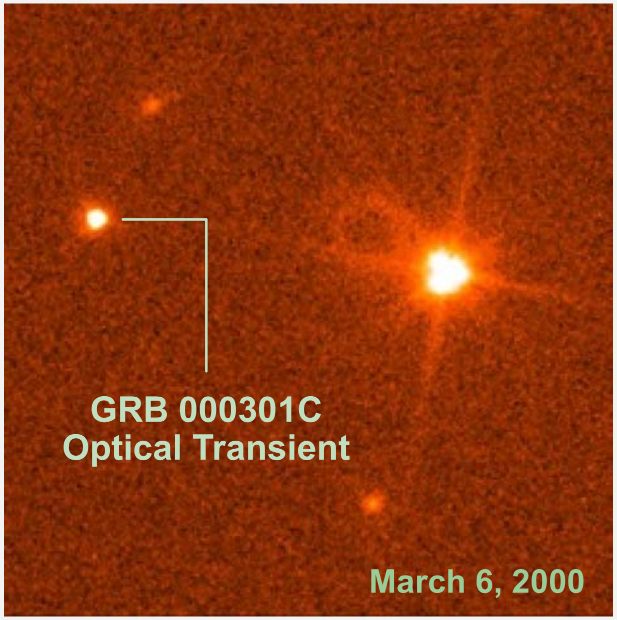
Localization and Afterglows

Required: (1) Arcminute or better resolution

(2) Response in seconds to minutes



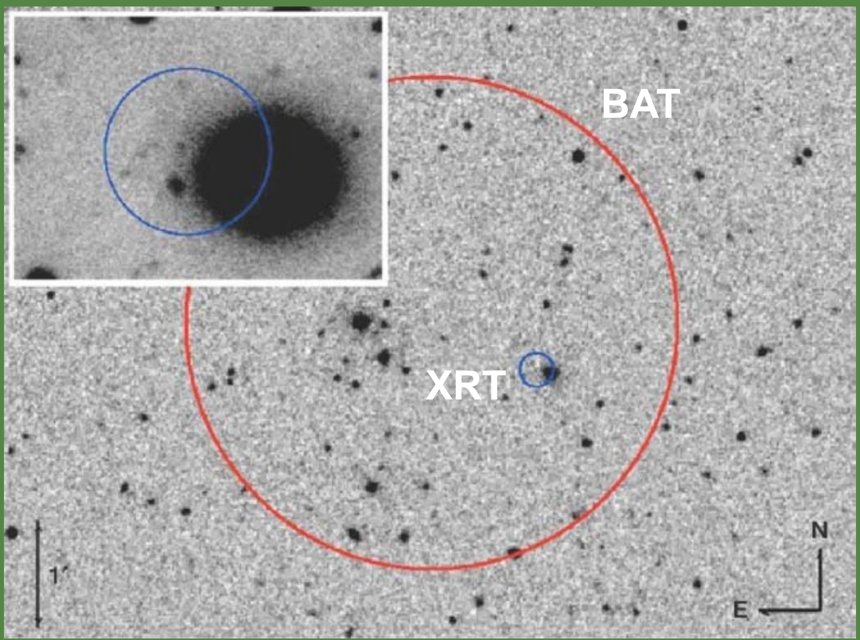
Beppo-SAX GRB Localization



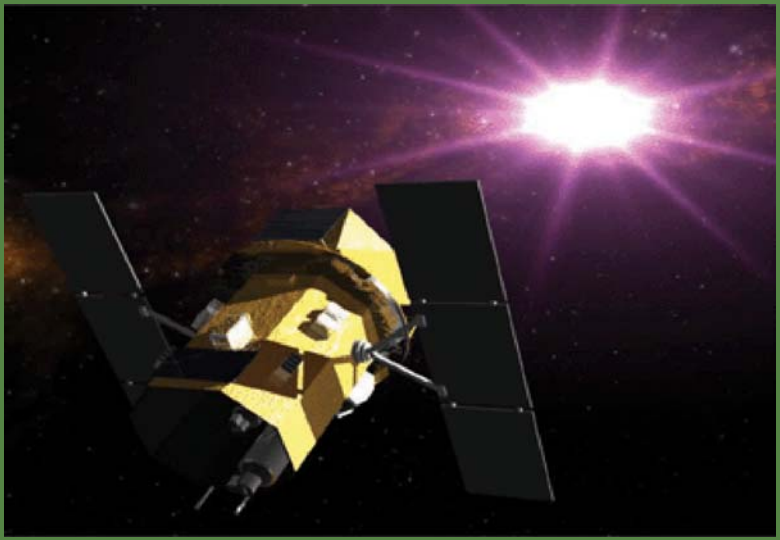
Gamma-Ray Burst Transient

Localization and Afterglows

Optical association of GRB 050509B (short-period GRB) with a large elliptical galaxy at z = 0.225



N. Gehrels, et al, Nature **437**, 851 (2005)



Science 311, 30 (2006)

SWIFT (artist's conception)

BAT: Burst Alert Telescope

XRT: X-Ray Telescope

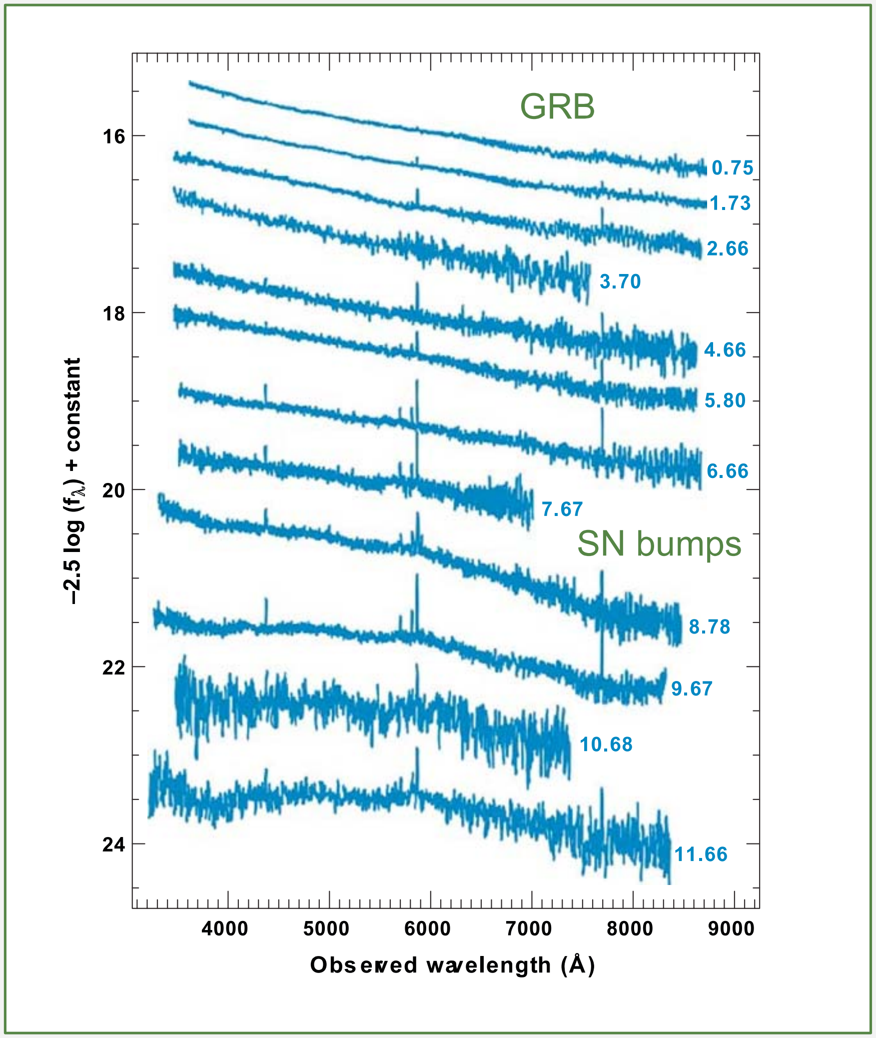
Association with Galaxies

- The identification of afterglows has permitted gamma-ray bursts to be associated with galaxies
- Long-period (soft) bursts appear to be strongly correlated with star-forming regions (strong correlation with blue light).
- Short-period (hard) bursts are generally fainter and sampled at smaller redshift than long-period bursts. Short-period bursts appear to not be correlated with star-forming regions.
- Long-period (soft) bursts appear to be associated with regions of low metallicity.

Long-Period Bursts and Supernovae

There is now strong evidence that many (perhaps all) long-period (soft) bursts are associated with supernova explosions.

Emergence of SN2003dh from GRB 030029 Afterglow

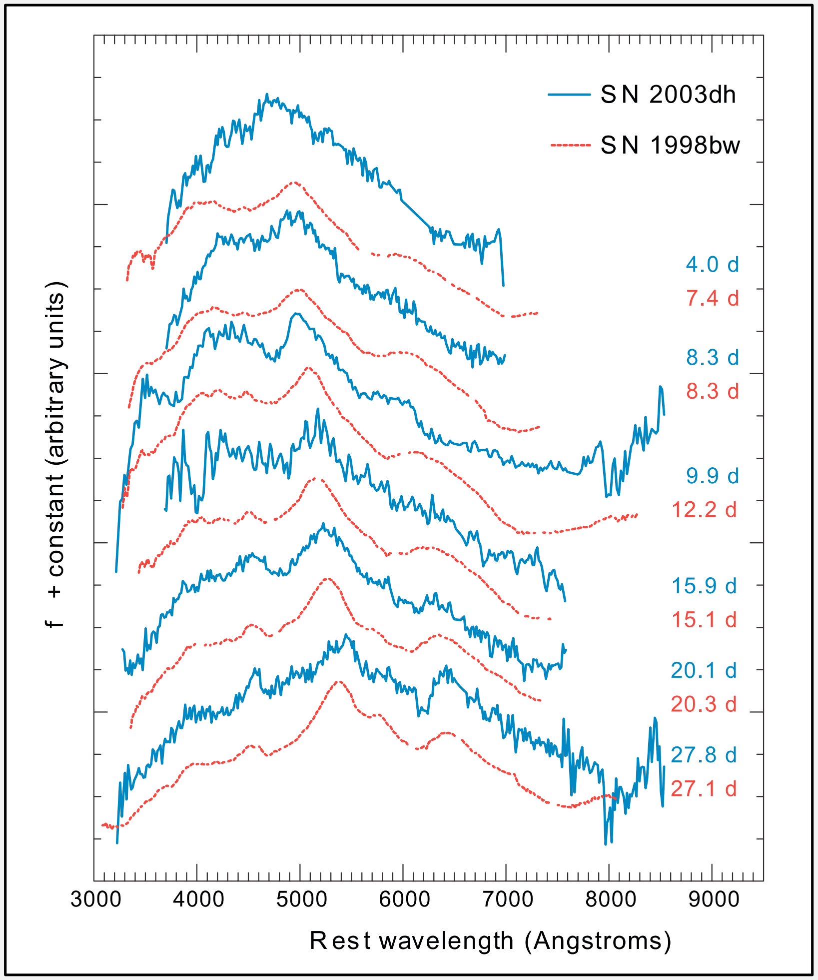


(Narrow emission lines are from host galaxy)

T. Matheson. *Cosmic Explosions in Three Dimensions: Asymmetries in Supernovae and Gamma-Ray Bursts* (P. Hoflich, P. Kumar, J. C. Wheeler, eds.), p. 351 (Cambridge, 2004).

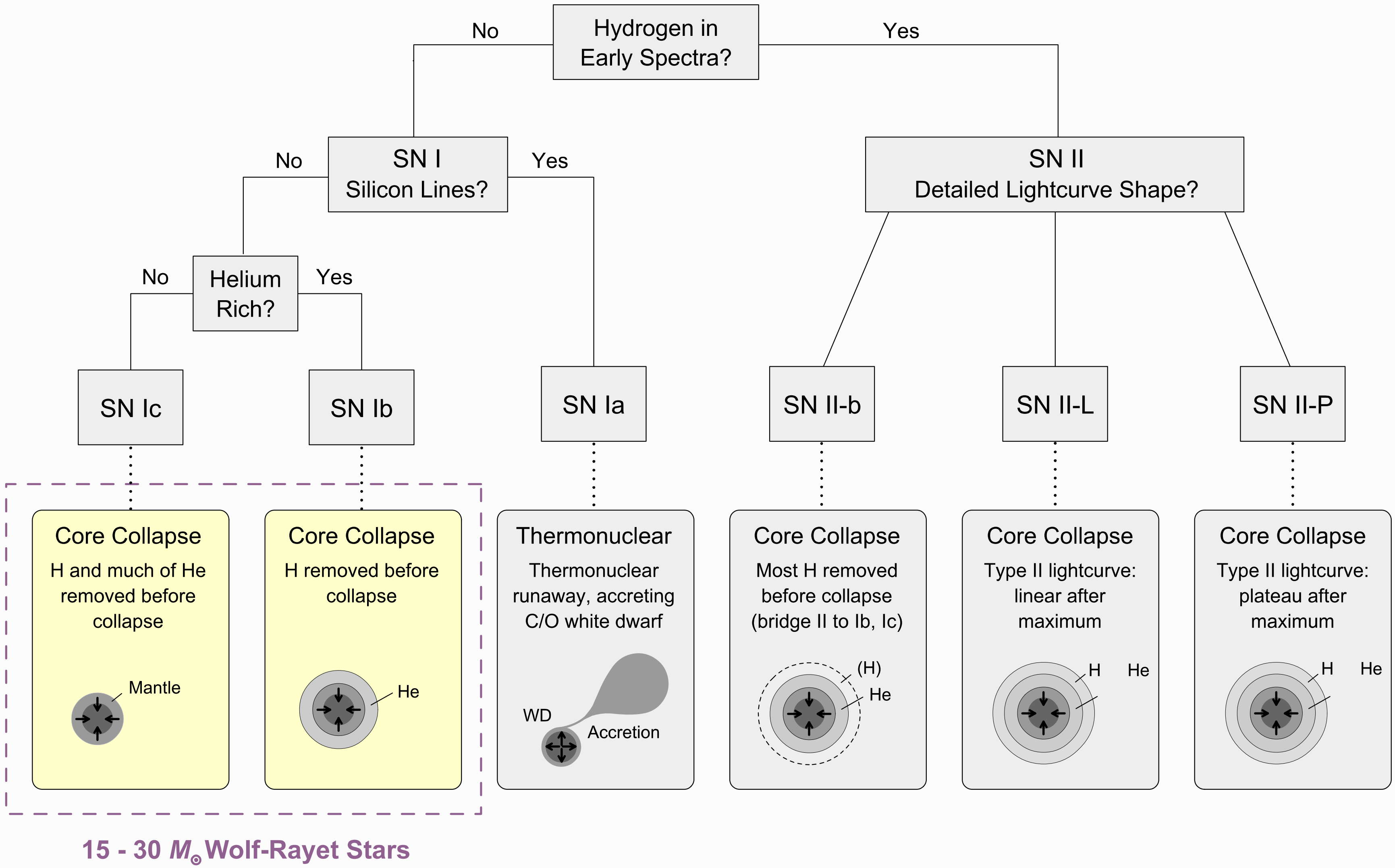
Long-Period Bursts and Supernovae

Comparison: Rest-Frame Optical spectrum
for SN2003dh (GRB 030329) and SN1998bw



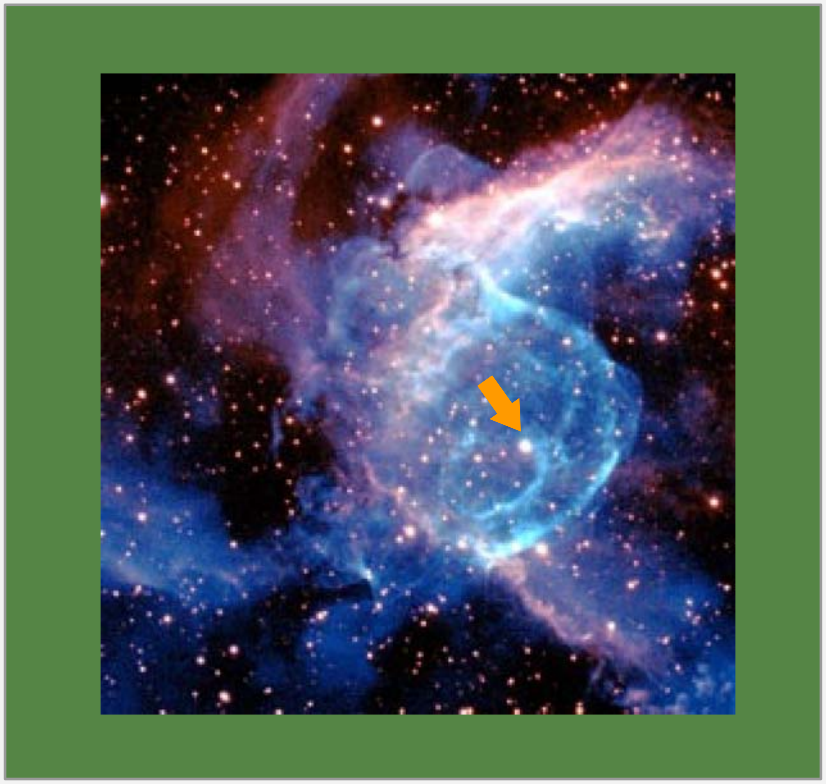
J. Hjorth et al, Nature **423**, 847 (2003).

Classification of Supernovae



Wolf-Rayet Stars, Supernovae, and GRB

Wolf-Rayet Star HD56925



Progenitors of Type Ib and Ic Supernovae
(massive, rapidly spinning, stripped of H and possibly He)

Models

- All models require highly relativistic jets to account for properties:
  - (1) Lorentz Γ factors of at least 200
  - (2) Focused with opening angle of ~0.1 rad and power ~ 10^{50} erg/s
  - (3) Long-period bursts must (at least sometimes) deliver ~ 10^{52} ergs to much larger solid angle (~1 rad) to produce supernova, and central engine must operate for 10 seconds or longer.
- Potential long power timescale implicates accretion onto compact object

The current working hypothesis:

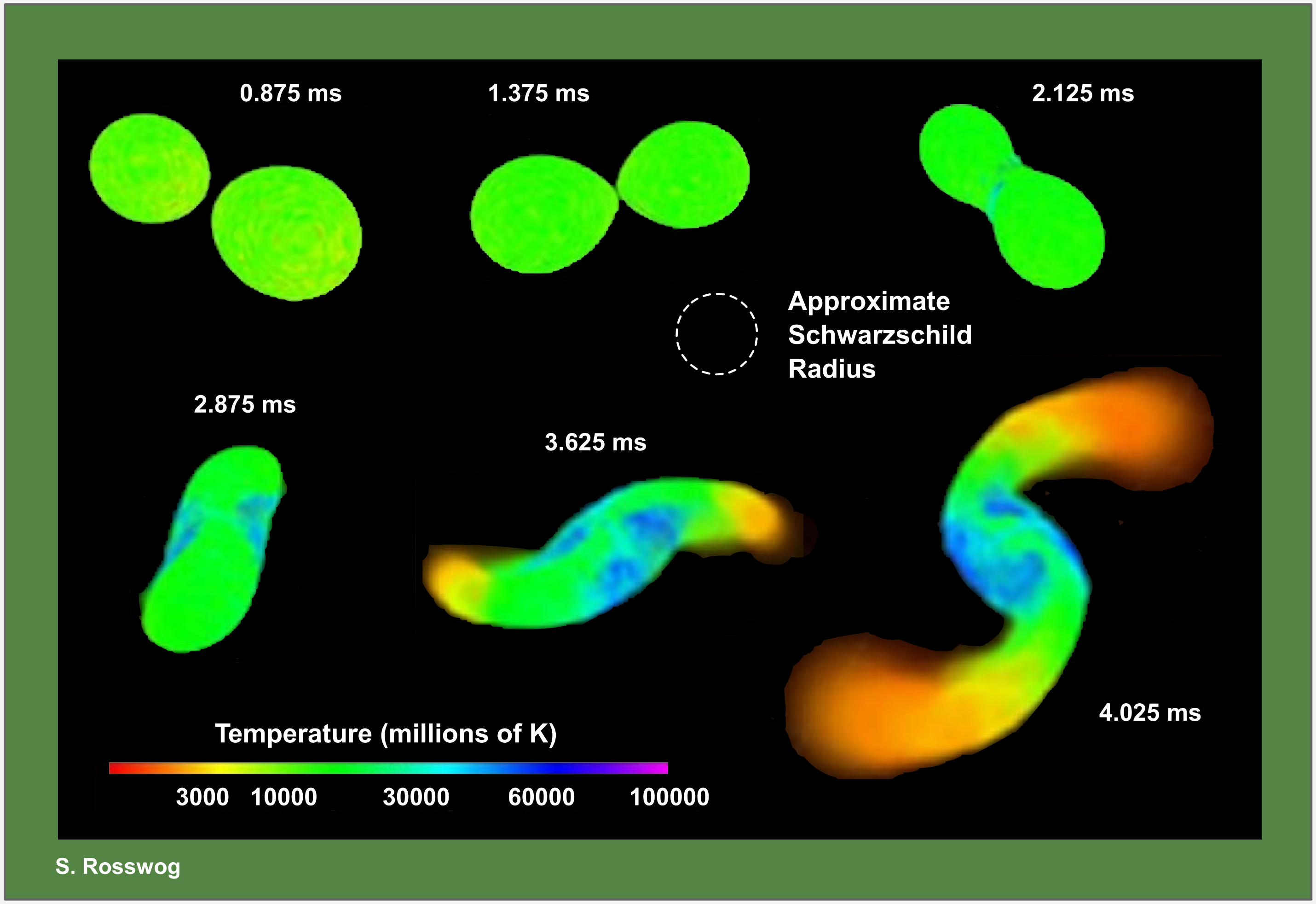
Long-period bursts result from the core collapse of massive rotating stars. They may often be accompanied by supernova events.

Short-period bursts result from the merger of neutron stars (or possibly a neutron star and black hole).

Both lead to the formation of a rapidly rotating Kerr black hole that emits relativistic jets on its polar axis

Models: Long-Period Bursts

Simulation of a Neutron-Star Merger



Merger

Merger2

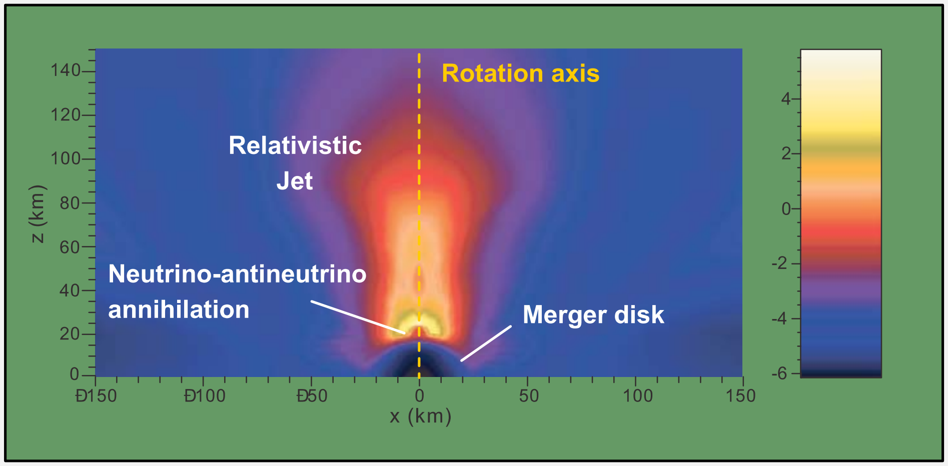
Merger Reuben

Models

Nature of jet:

- *Fireball:* hot baryons, thermally loaded with pairs and radiation greatly exceeding rest mass
- *Poynting Flux:* Large-scale magnetic field effects (baryons play little role; no internal shocks)
- *Baryon Contamination Problem:* Gamma-ray emission must be from relativistic plasma with low baryon contamination

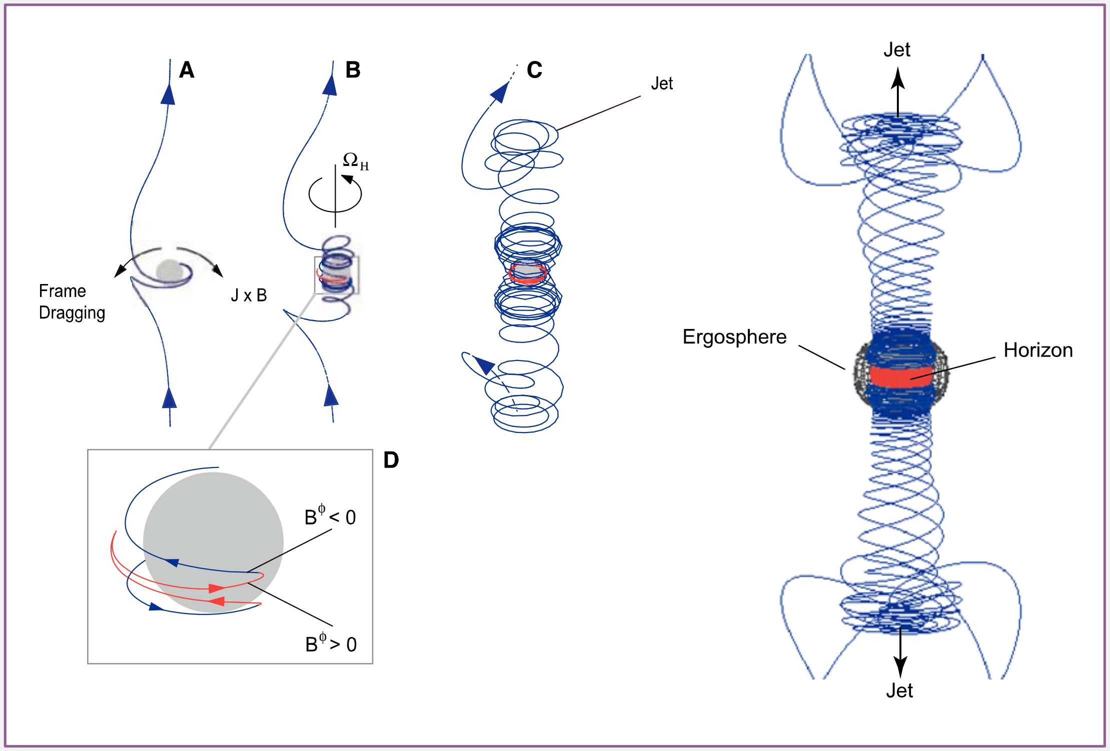
Annihilation of neutrino-antineutrino pairs above a neutron star merger disk driving relativistic jets along the rotation axis.



S. Rosswog, Science **303**, 46 (2004)

Models

Magnetic Extraction of Energy from a Kerr Black Hole



V. Semenov, S. Dyadechkin, B. Punsly, Science **305**, 978 (2004)

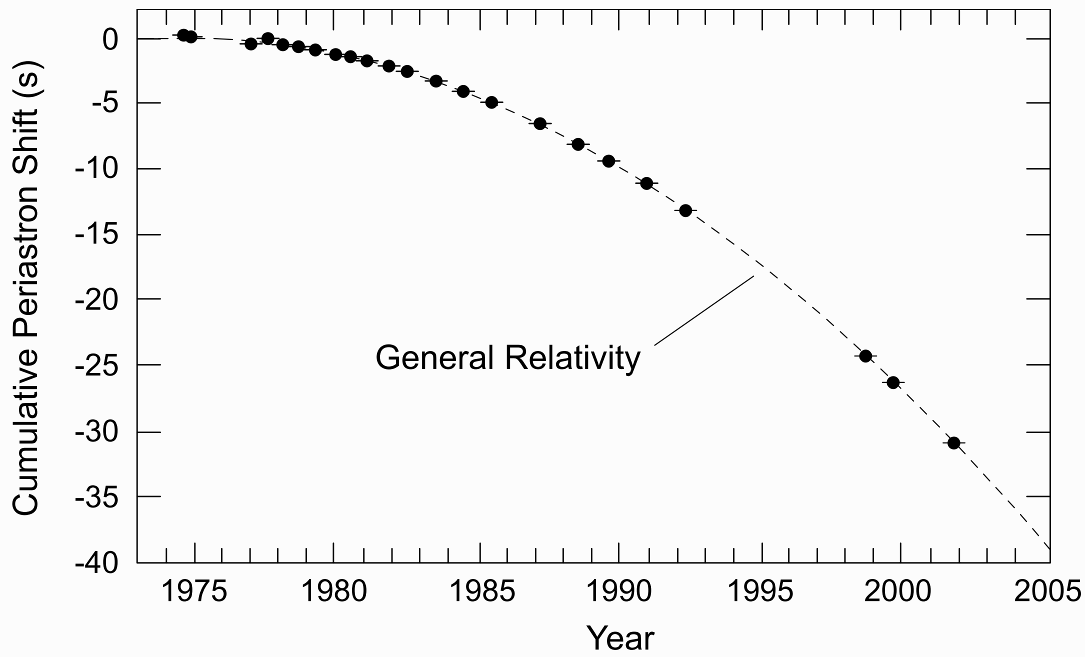
For movie files illustrating the magnetic extraction of energy from a Kerr black hole, click the button below (Note: 3-8 MB files)

Magnetic Examples

V. Semenov, S. Dyadechkin, B. Punsly, Science **305**, 978 (2004)

Gravitational Waves

- Gravitational waves represent the last prediction of general relativity not yet directly confirmed by observation. There is *indirect evidence* from the Binary Pulsar:



- Theoretically, the most likely events that will produce detectable gravitational waves are (1) *neutron star mergers* and (2) *core-collapse supernovae*.

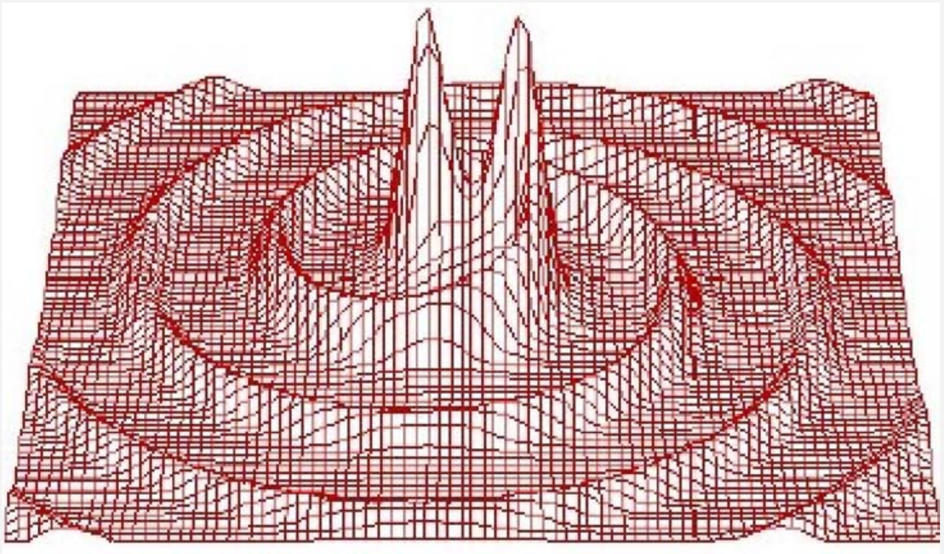
Gravitational Waves

Gravity Waves

Chirp 1

Chirp 2

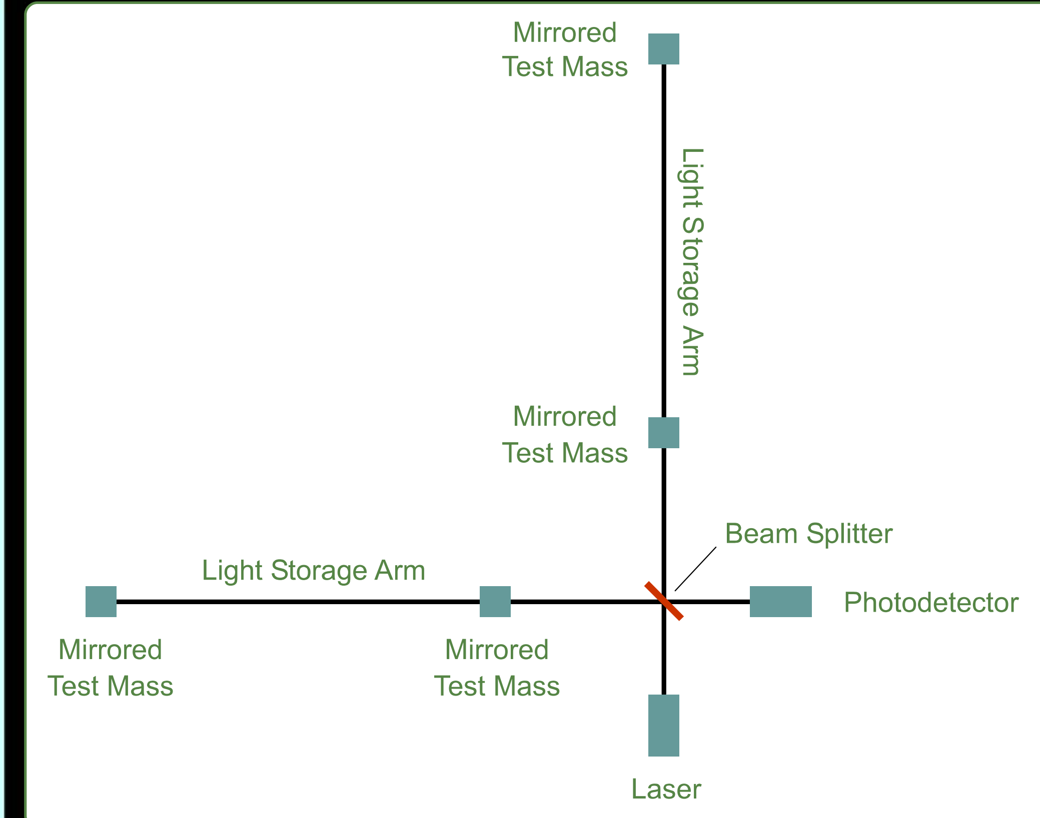
Chirp 3



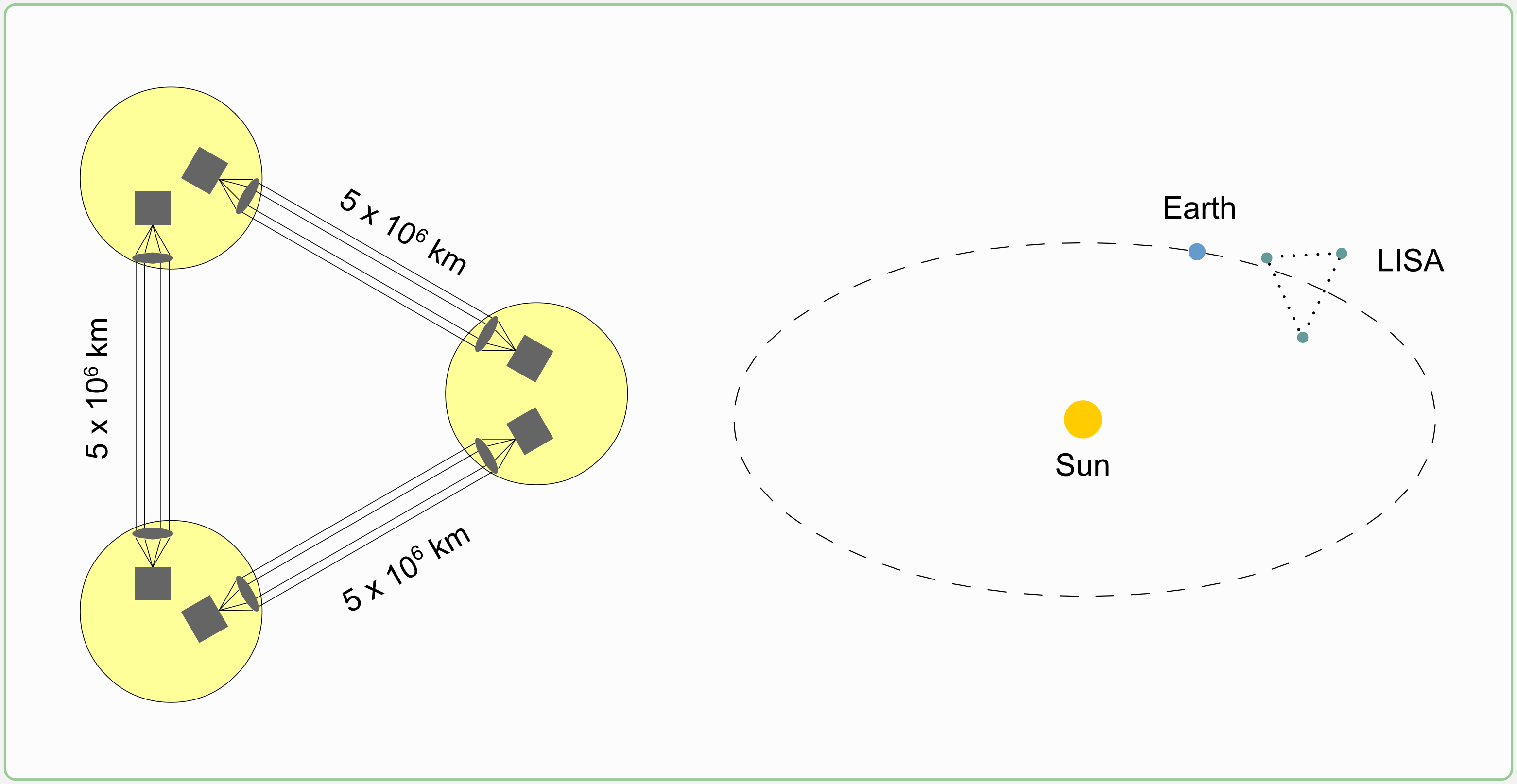
LIGO

Hanford, Washington

Livingston, Louisiana

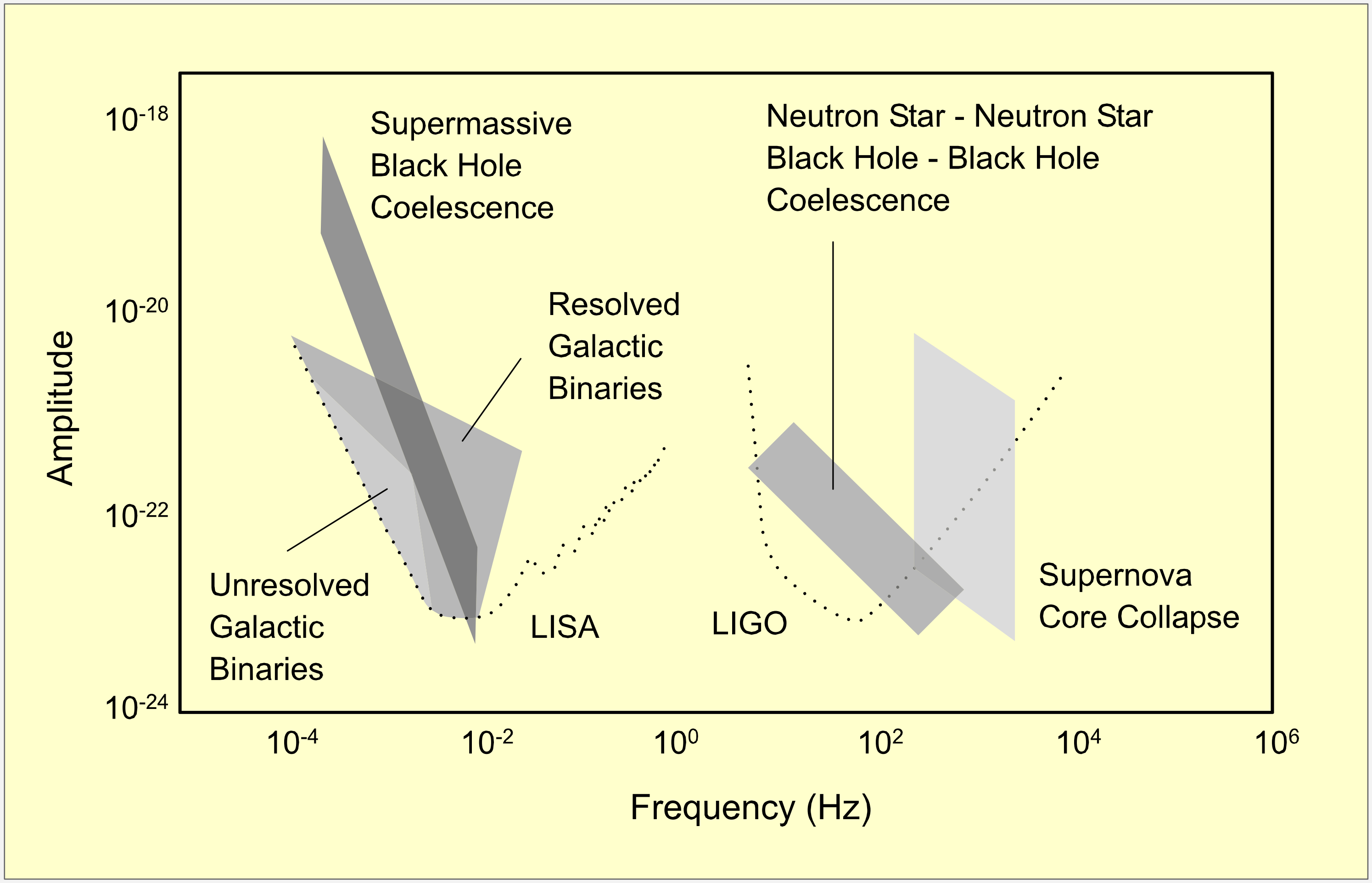


LISA (Proposed)

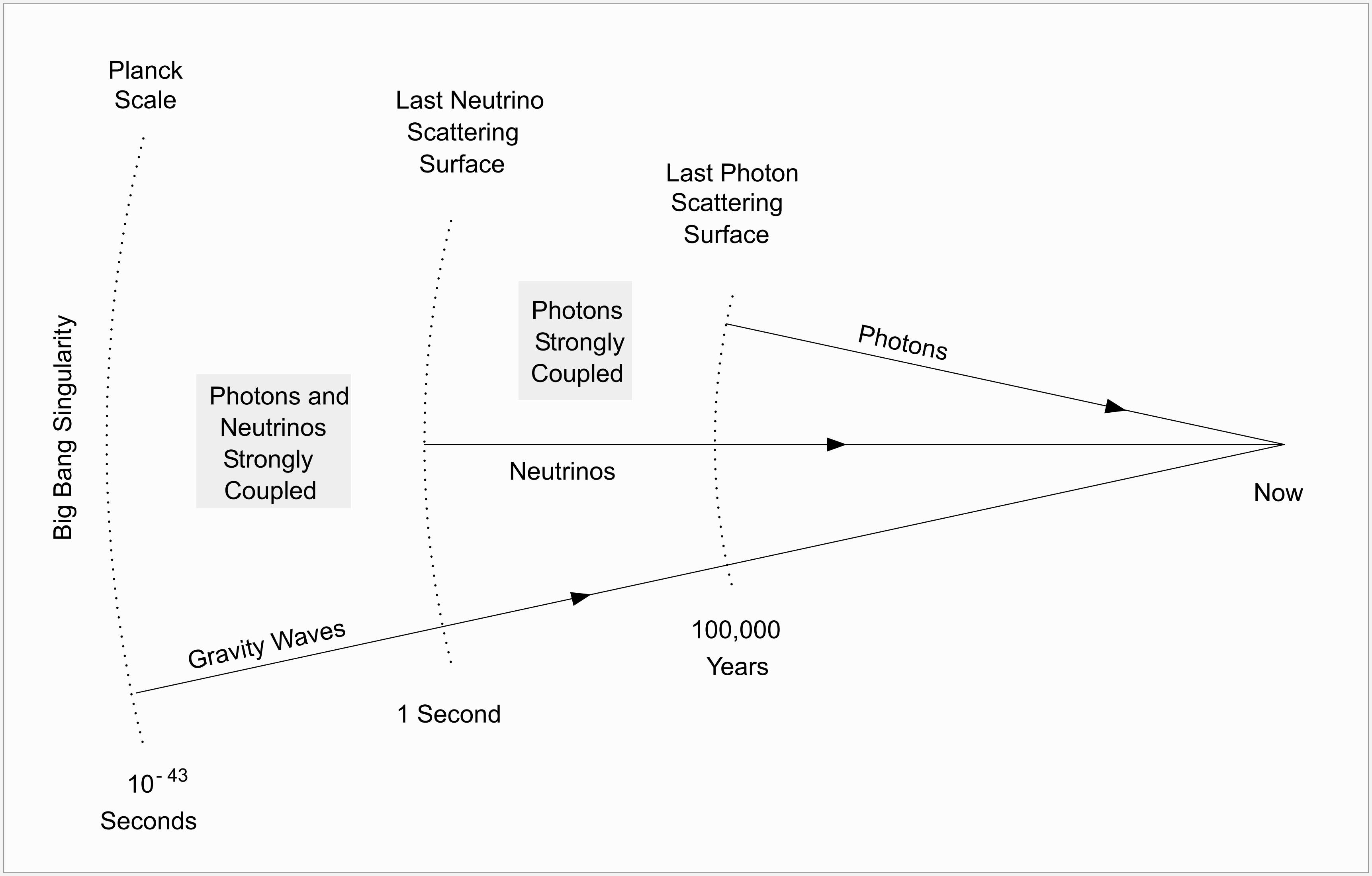


LISA Orbit

Detection Ranges for Gravitational Waves

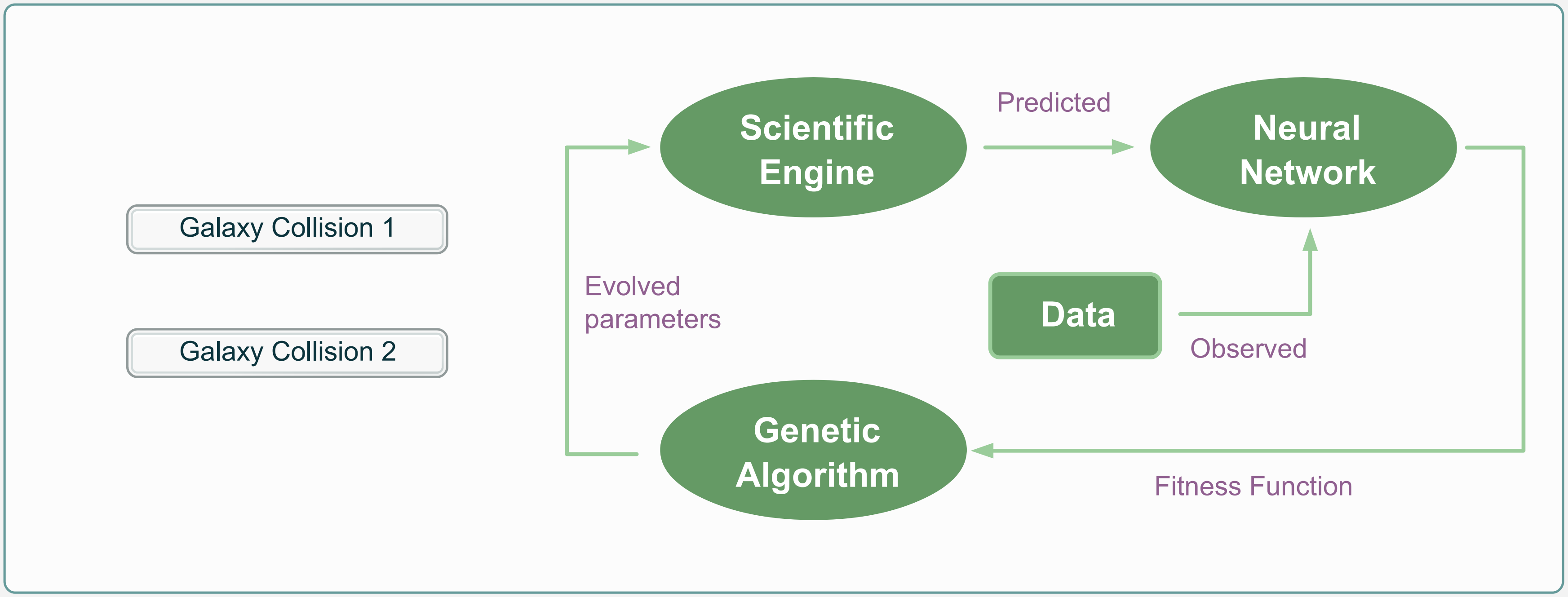


Gravitational Waves: the Deepest Probe

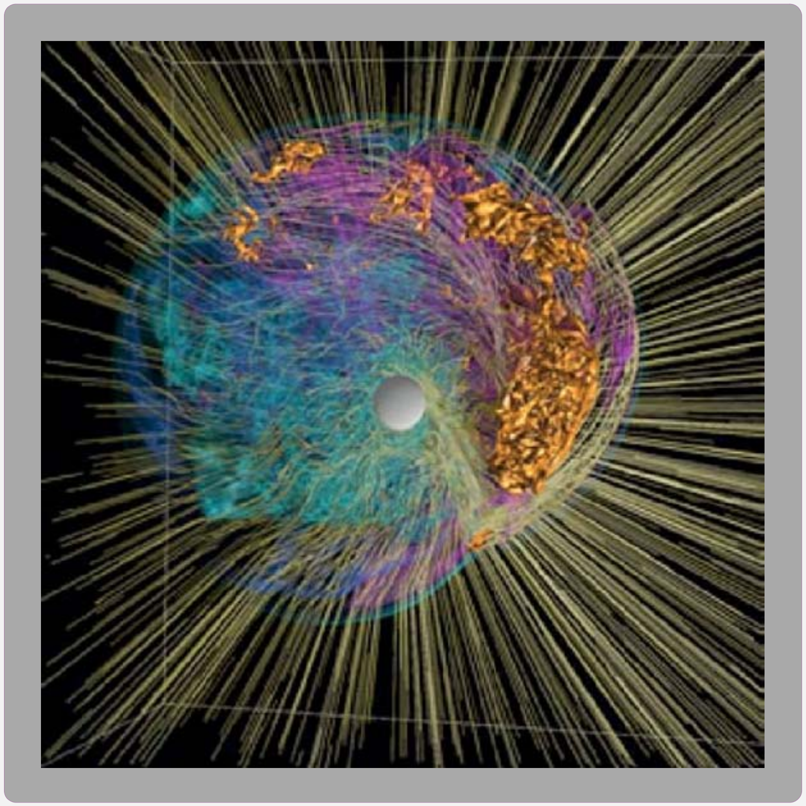


Artificial Intelligence and Galaxy Collisions

- *Neural Network* for pattern recognition
- *Genetic Algorithm* for global optimization in complex parameter space
- *Scientific Engine:* gravity tree plus SPH hydrodynamics to simulate galaxy collisions.

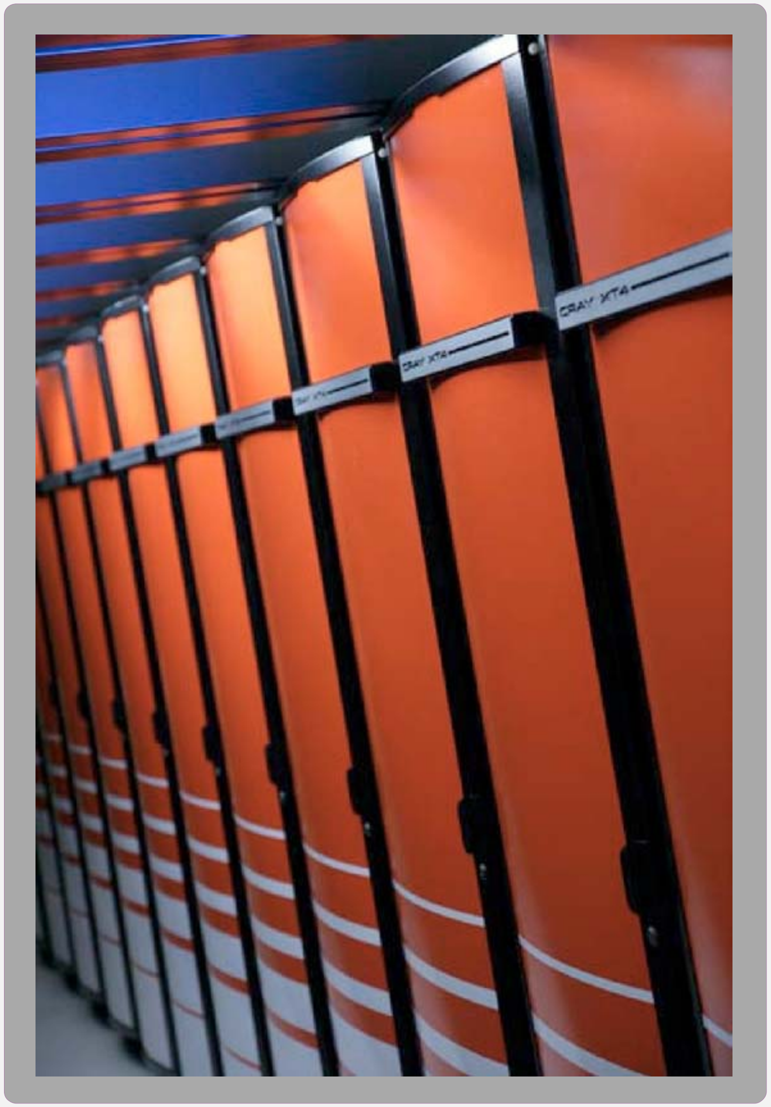


Computational and Visualization Power



Complex visualization of a core-collapse supernova simulation

Jaguar cabinets



Computational and Visualization Power

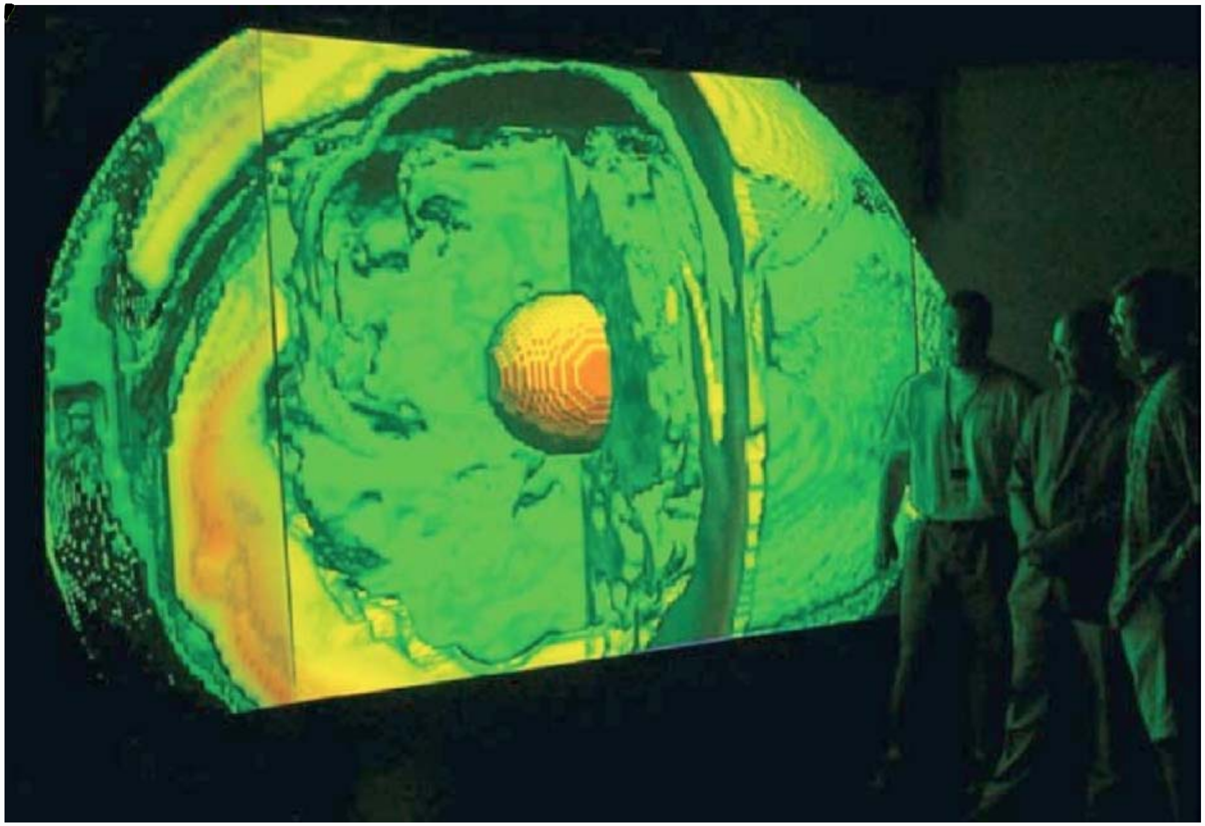
The Jaguar system, a Cray XT4 located at ORNL's National Center for Computational Sciences, now uses more than 31,000 processing cores to deliver up to 263 trillion calculations a second (or 263 teraflops).

↓

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