RETIREMENT CELEBRATION

In Honor Of:

Dr. David Berley

PROGRAM MANAGER

Laser Interferometer Gravitational Wave Observatory (LIGO)

Directorate for Mathematical and Physical Sciences

Division of Physics

FRIDAY, MARCH 24, 2000

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Supernovae and Multimessenger Astronomy

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Barry Barish

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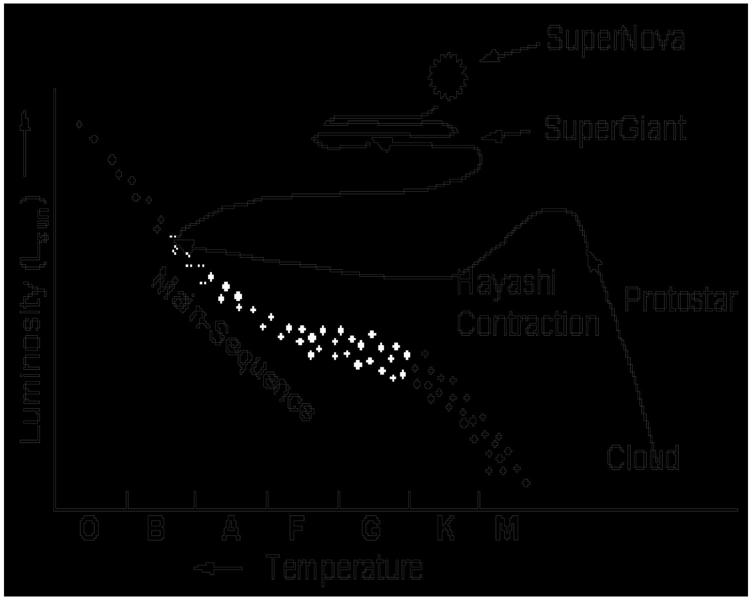
Supernovae

- **<u>Helium Burning Main Sequence</u> in massive stars, a series of nuclear burning stages transforms the star into an onion-like shell structure, until Silicon and Sulfur burning create a core of iron (and other iron-peak elements.**

- **During this phase the star will criss-cross the upper regions of the H-R diagram from Red Supergiant to Blue Supergiant and back as different core and shell burning stages ignite.**

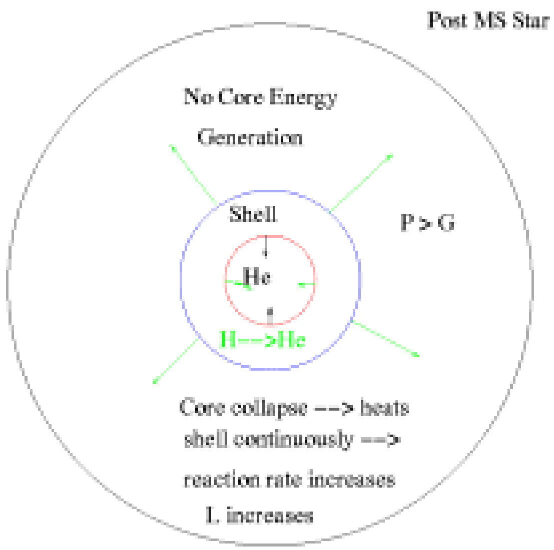
- **Each successive nuclear burning stage releases less energy than the previous stage, so the lifetime in each stage becomes progressively shorter.**



For a 20 $M_{\odot}$ star:

Main sequence lifetime ~ 10 million years
Helium burning (3-) ~ 1 million years
Carbon burning ~ 300 years
Oxygen burning ~ 2/3 year
Silicon burning ~ 2 days

Nuclear Burning Stages



Triple-Alpha Process

4He + 4He + 4He --> 12C

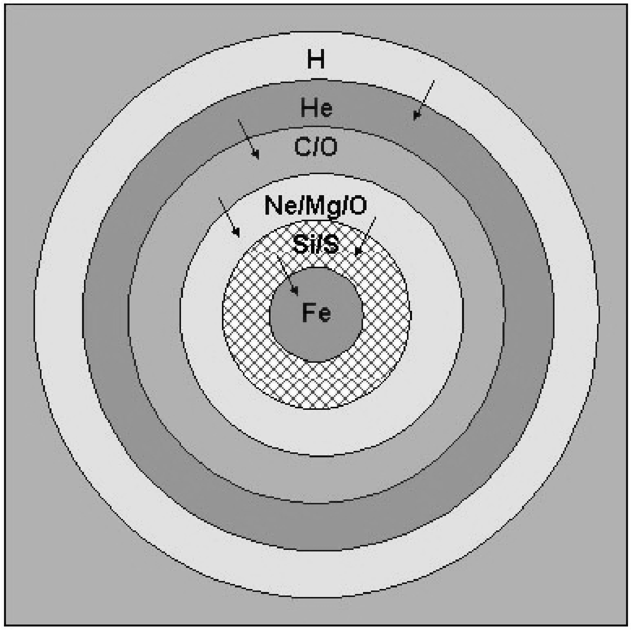
Only stars with masses greater than about $0.4M_{\odot}$ will reach temperatures high enough to ignite the Triple-alpha process

Advanced Nuclear Burning Stages

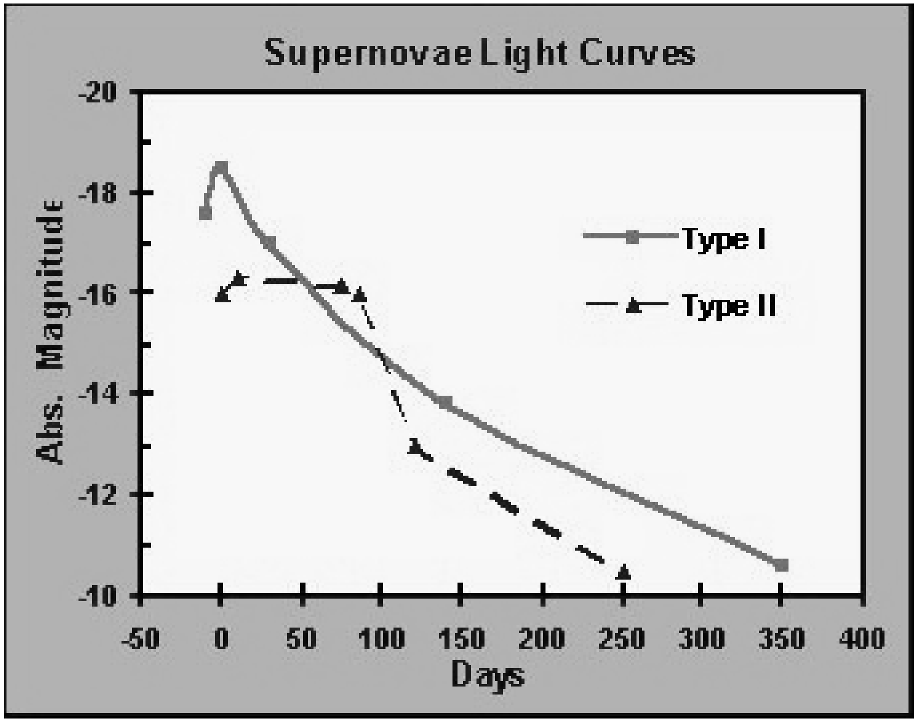
Following the Triple-alpha process there are a variety of reactions which may occur depending on the mass of the star.

Supernovae

gravitational stellar collapse



The Collapse



Optical Light Curve

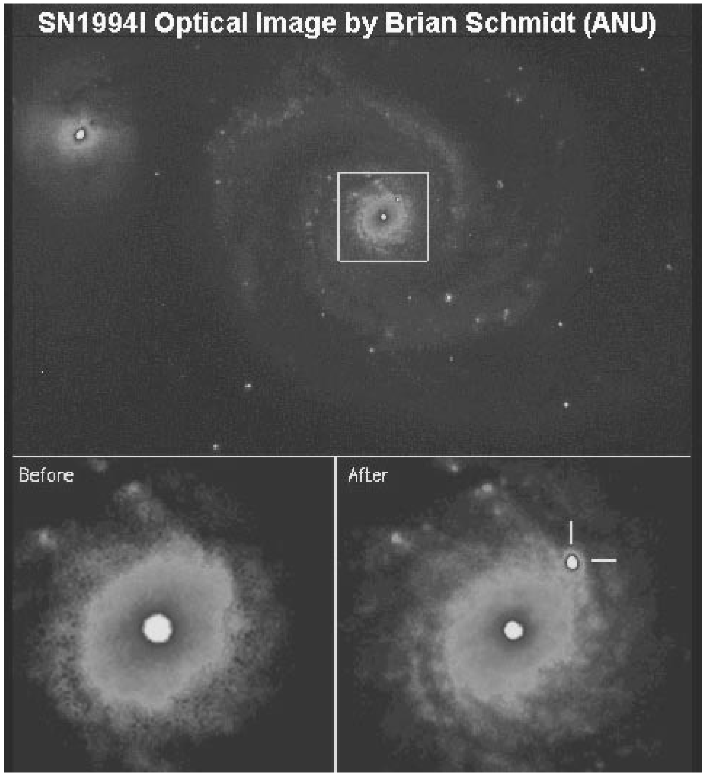
Supernovae

optical observations

SN remnant

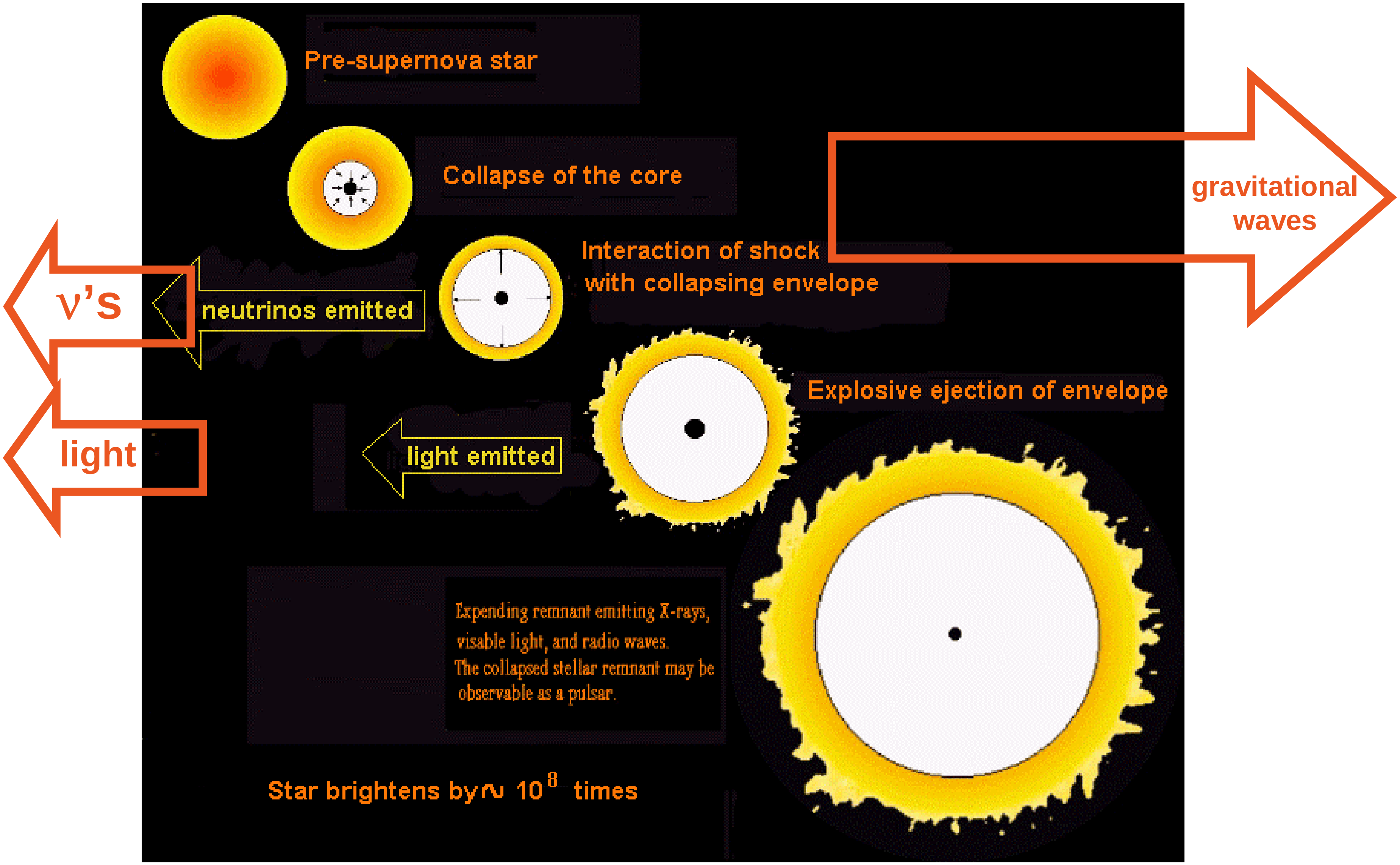
Crab Nebula 1054 AD

SN explosion



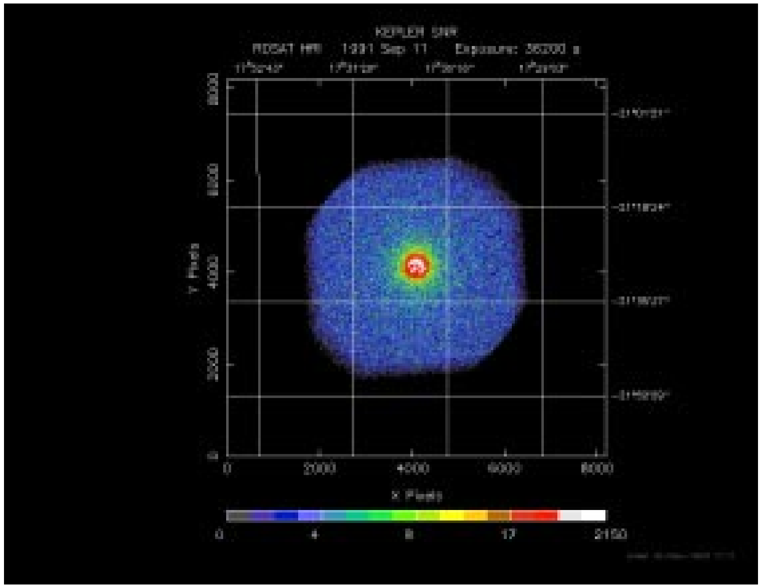
Supernovae - SN1994I

Supernova Sequence

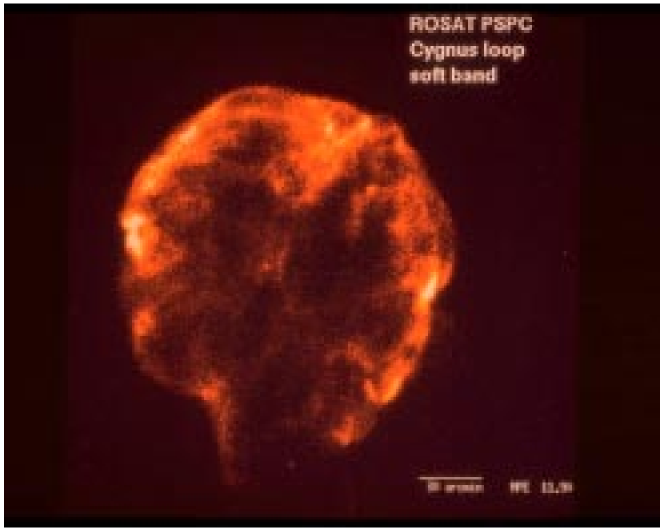


Supernova Sequence

- Within about 0.1 second, the core collapses and gravitational waves are emitted.
- After about 0.5 second, the collapsing envelope interacts with the outward shock. Neutrinos are emitted.
- Within 2 hours, the envelope of the star is explosively ejected. When the photons reach the surface of the star, it brightens by a factor of 100 million.
- Over a period of months, the expanding remnant emits X-rays, visible light and radio waves in a decreasing fashion.



Kepler SNR



Cygnus Loop Remnant

Historical Supernovae (our galaxy)

- **SN1006** in Centaurus in the southern sky
- **SN1054** - The Crab Supernava in Taurus recorded by Chinese and Native American astronomers
- **SN 1572** -Tycho's Supernova, studied in detail by Tycho Brahe
- **SN 1604** Kepler's Supernava

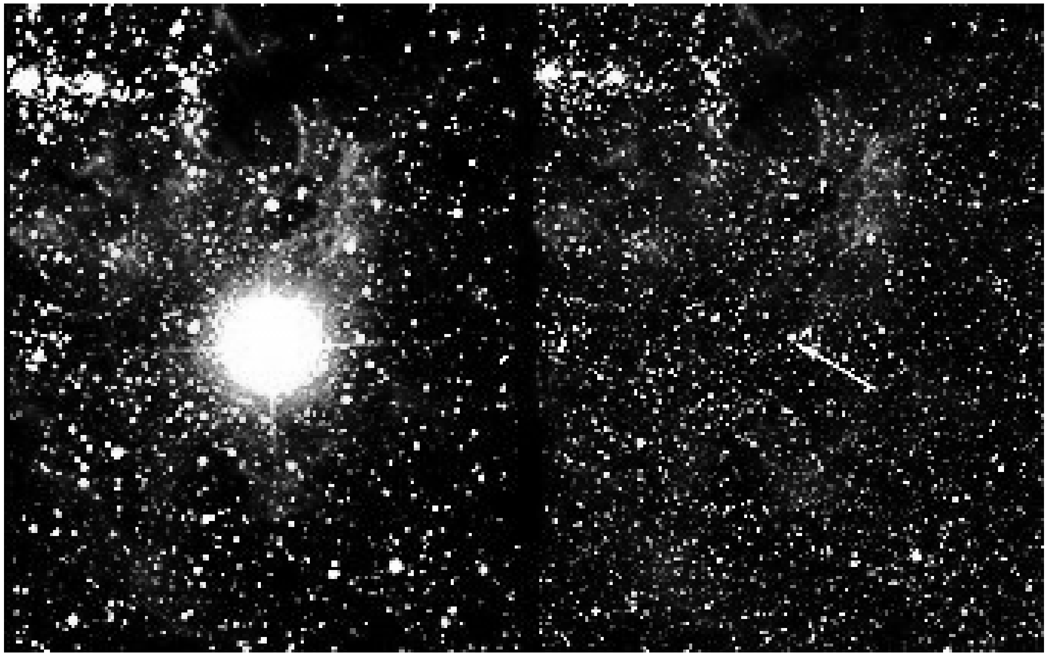
+other possible Milky Way supernovae

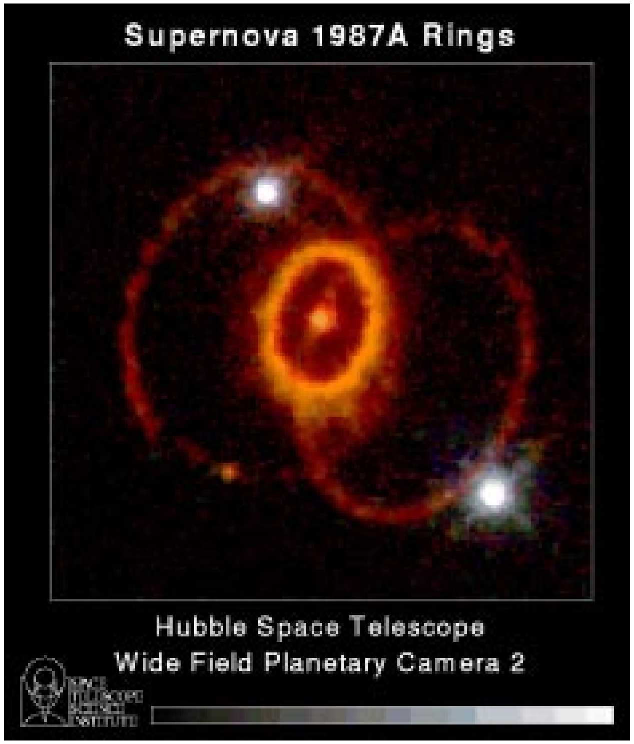
Rate

	Rate
our galaxy	1/50 years
within Virgo Cluster	~ 1 year

SN 1987A

Large Magellanic Cloud (LMC)





First SN with observations of star that exploded - Sk -69 202

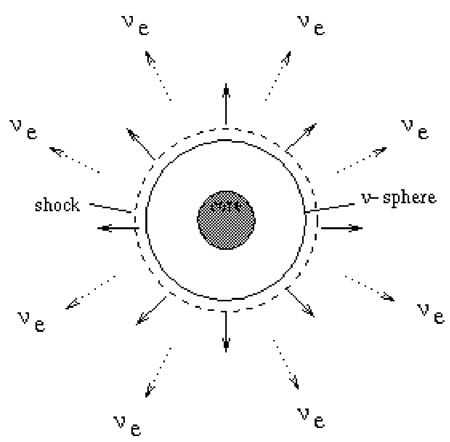
Supergiant with

T = 16000K

Luminosity = 100,000$L_\odot$

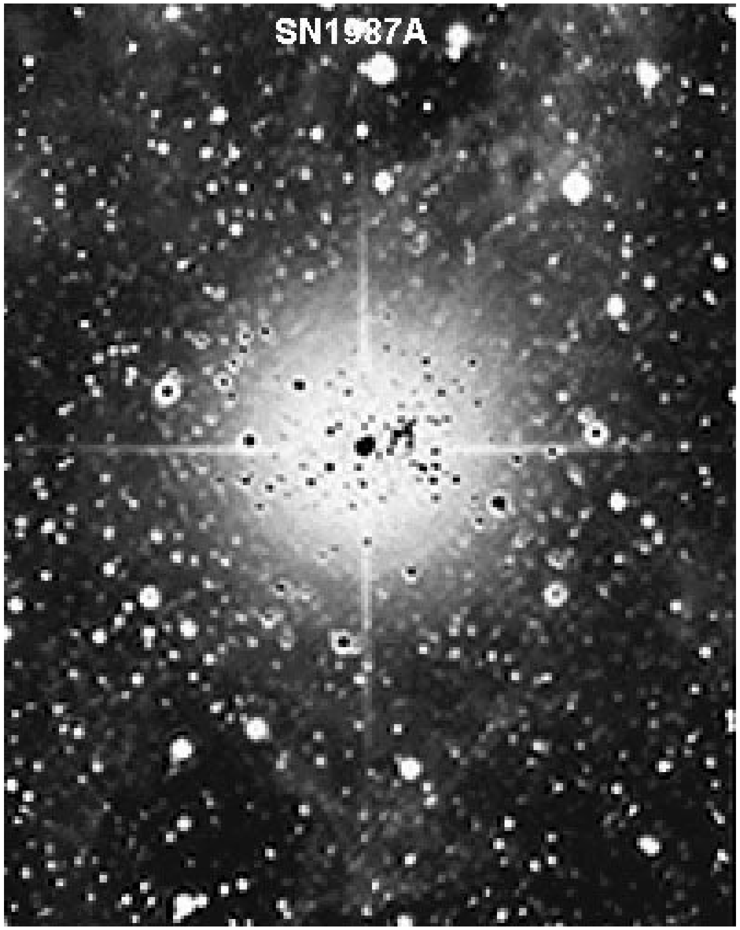
Mass ~ 20$M_\odot$

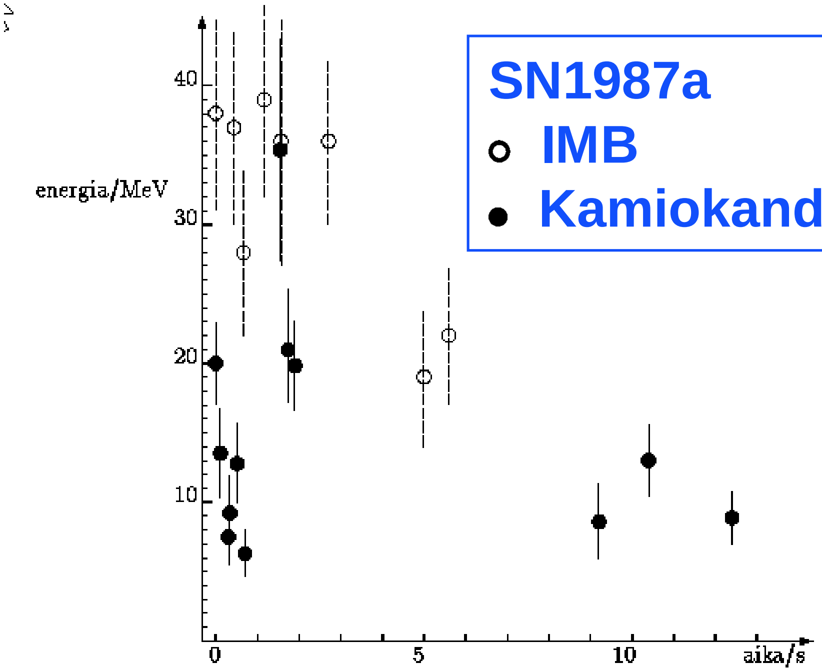
Neutrinos from SN1987A



- Neutrino Emission from massive star gravitational collapse
- Precedes photon signal by hours
- Neutrino luminosity typically 100x optical luminosity

Neutrinos from Gravitational Stellar Collapse

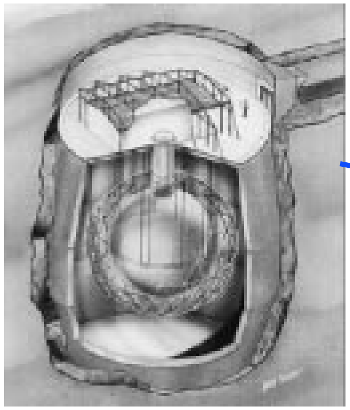




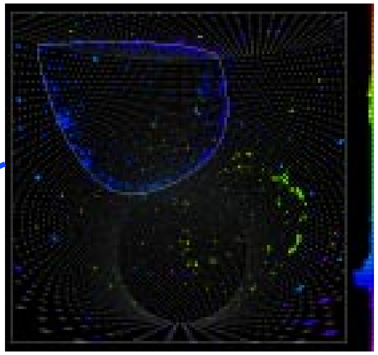
SN1987a
○ IMB
● Kamiokande

Energy emitted in ν's ~ $2\ 10^{46}$J

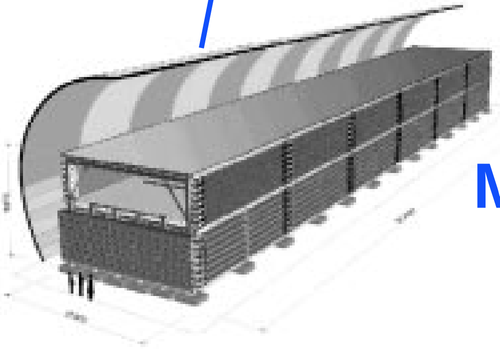
Neutrino Supernovae Network



SNO



SuperK



MACRO

Techniques

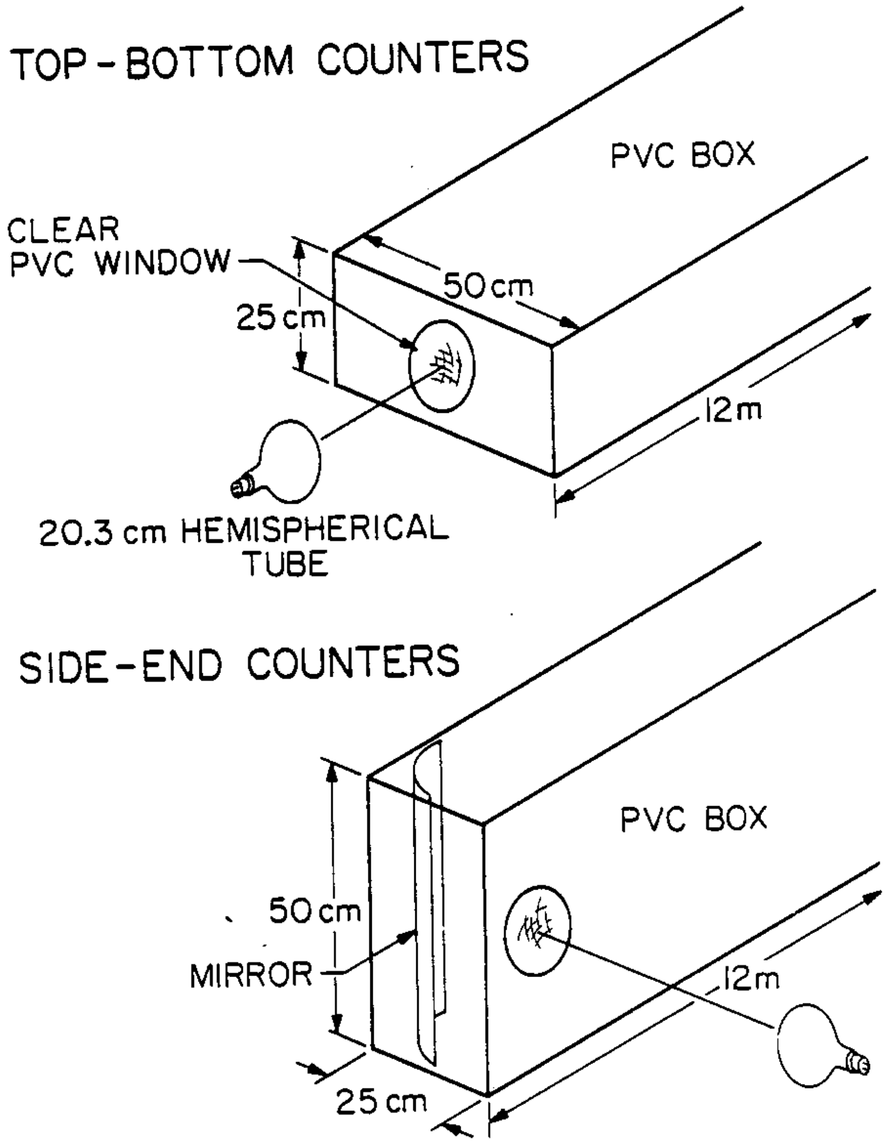


Fig. (4)4 A view of the PVC scintillator containers showing the optics and viewing window for externally mounted 8″ hemispherical phototubes.

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- H_20 Cerenkov – SuperK
- D_20 Cerenkov – SNO
- Scintillator – MACRO, LVD

MACRO Search for Galactic Supernovae

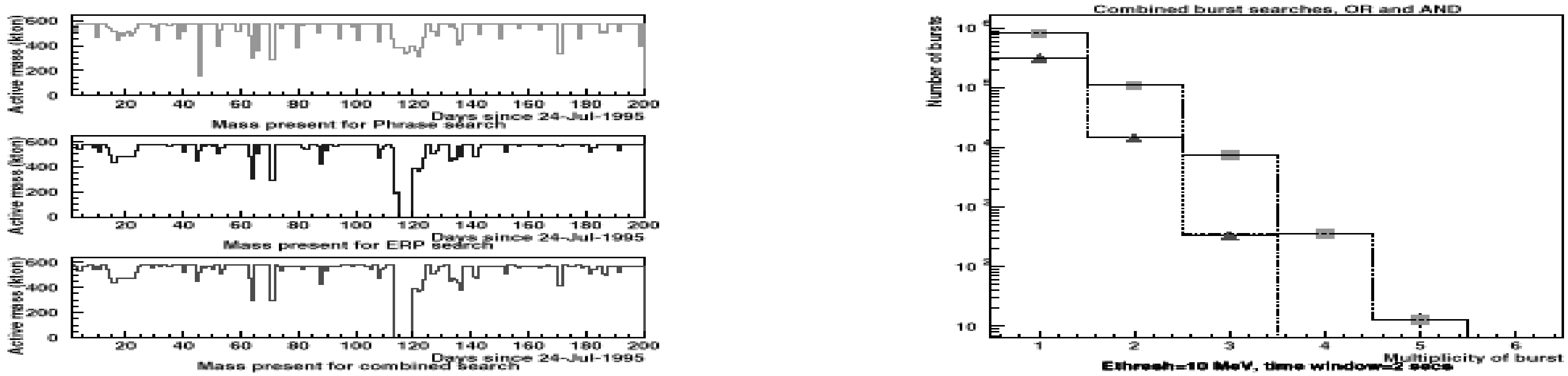


Figure 1.12: (a) Active mass present for the PHRASE, ERP and combined searches as a function of time (for each day, the active mass is an average over runs, weighted by relative livetime.) (b) Multiplicity distributions for a 2 second time window, plus Poissonian predictions, for both an AND (triangles) and an OR (squares) of ERP and PHRASE hits ($E>$ 10 MeV) for the full time period.

MACRO results: <u>NO events</u>
600 tons, ~ 8 years
low background rate
sensitive to entire galaxy

SNEWS

A Neutrino Early Warning System for Galactic SNII

- provide an early warning for galactic SNII

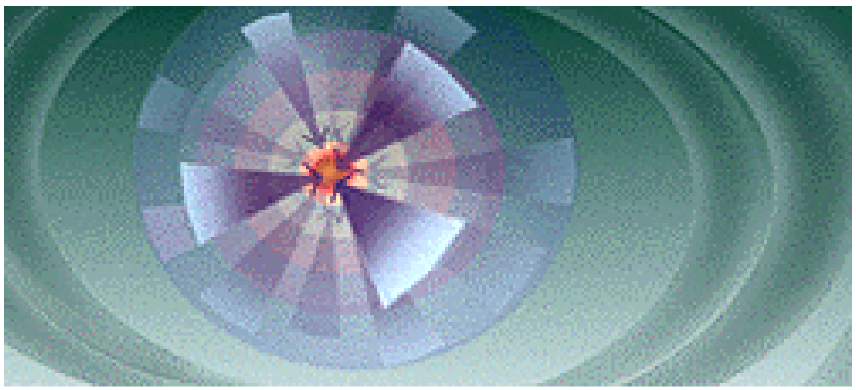
- coincidence network to establish minimum response time, eliminate false alarms and provide pointing information.

Detector	Type	Mass (kton)	Location	# events @10 kpc	Status
Super-K	water Cherenkov	32	Japan	4400	**signaling SNEWS since May 1998**
MACRO	scint.	0.6	Italy	150	**signaling SNEWS since March 1998**
LVD	scint.	0.7	Italy	170	**signaling SNEWS since Feb. 1999**
SNO	H_2O, D_2O	1.7 1	Canada	350 430	running signaling
AMANDA	long string	$M_{eff} \sim 2$/pmt	Antarctica	N/A	running
Baksan	scint.	0.33	Russia	70	running
Borexino	scint.	1.3	Italy	~200	2000
Kamland	scint.	1	Japan	300	2001
OMNIS	high Z	10 kT Fe, 4 kT-Pb	USA	2000	2000+
LAND	high Z	1	Canada	450	2000+
Icanoe	liquid argon	9	Italy		2000+

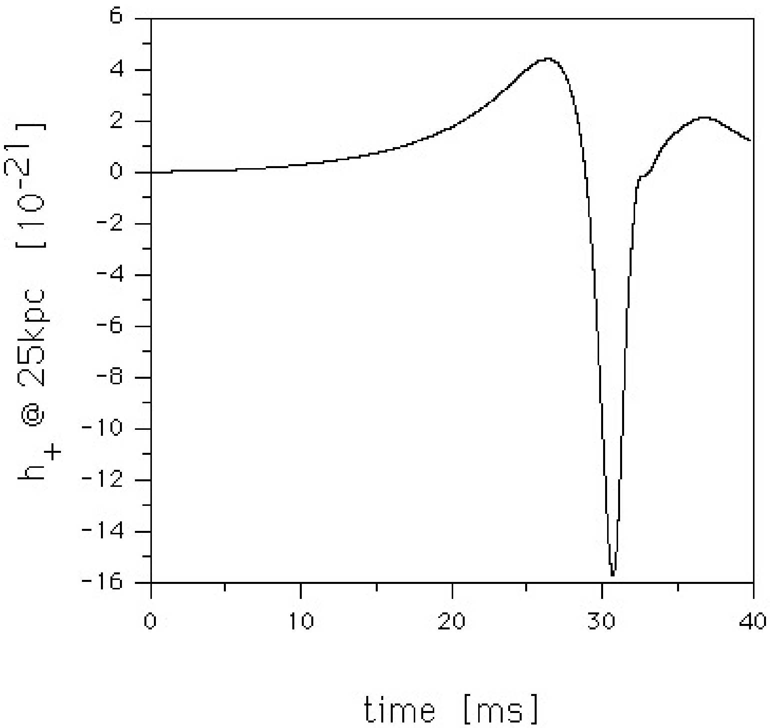
1) disperse to skilled astronomers
2) disperse to amateur astronomers thru Sky and Telescope magazine
3) approved experiment to point the Hubble Space Telescope

Supernovae *Gravitational Waves*

Non axisymmetric collapse



'burst' signal

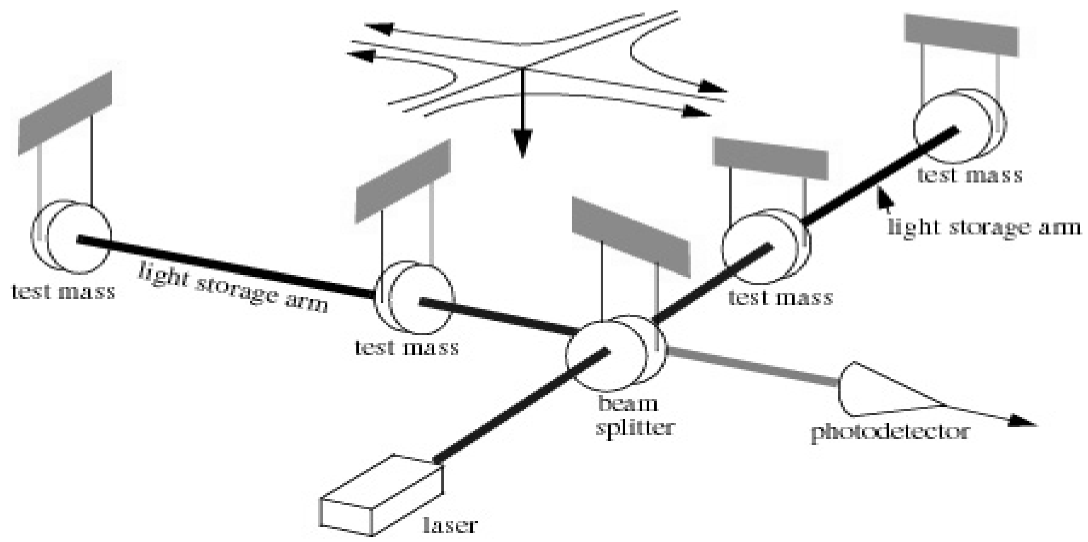


Rate

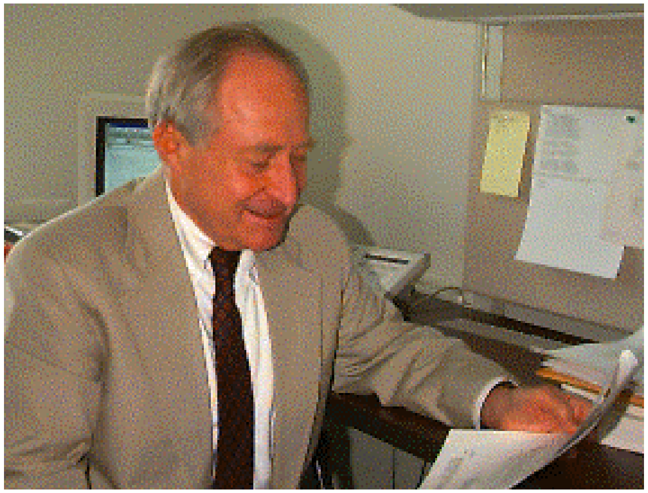
1/50 yr - our galaxy

3/yr - Virgo cluster

Detector concept



- The concept is to compare the time it takes light to travel in two orthogonal directions transverse to the gravitational waves.
- The gravitational wave causes the time difference to vary by stretching one arm and compressing the other.
- The interference pattern is measured (or the fringe is split) to one part in 10^{10}, in order to obtain the required sensitivity.



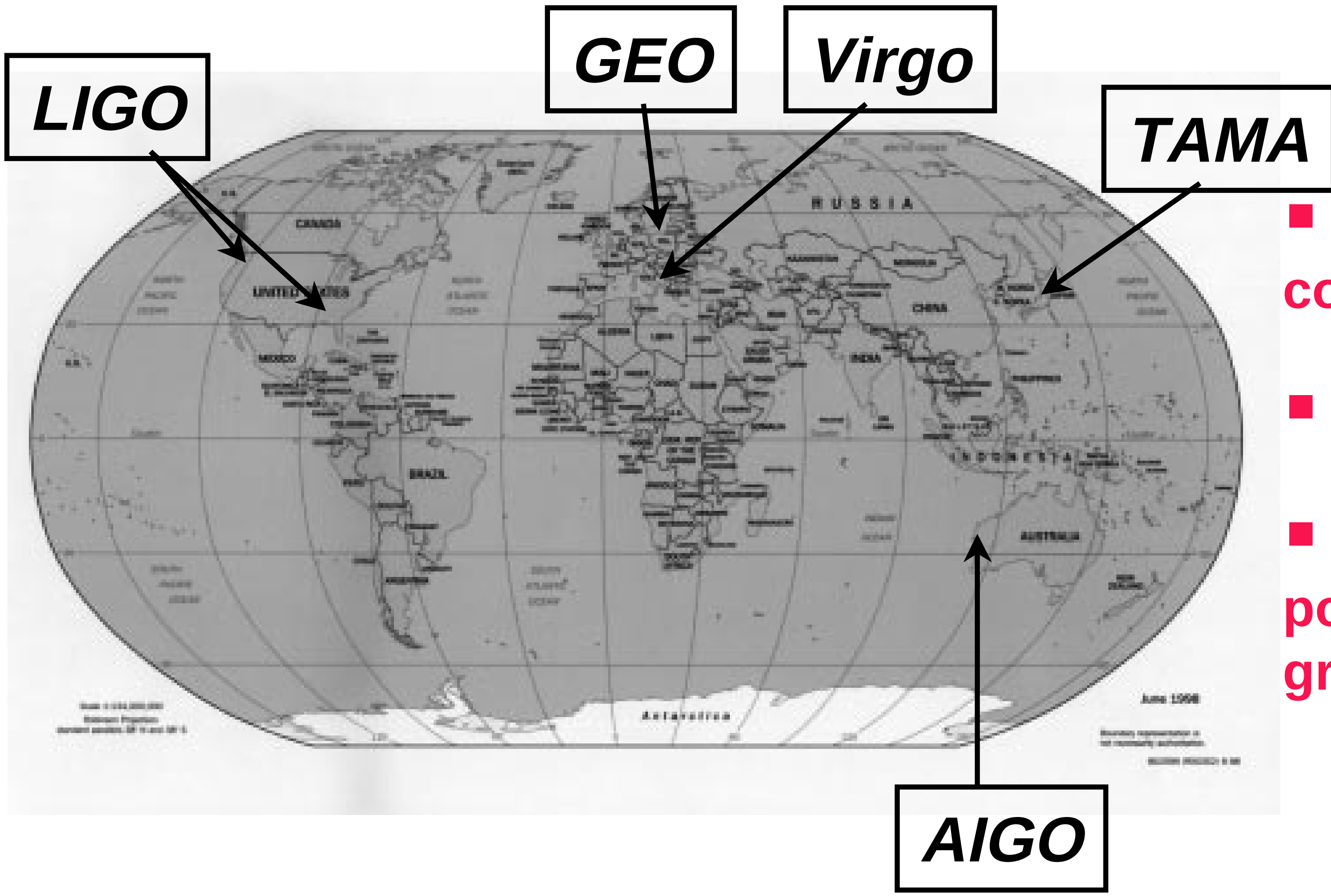
LIGO sites

Hanford Observatory

Livingston Observatory

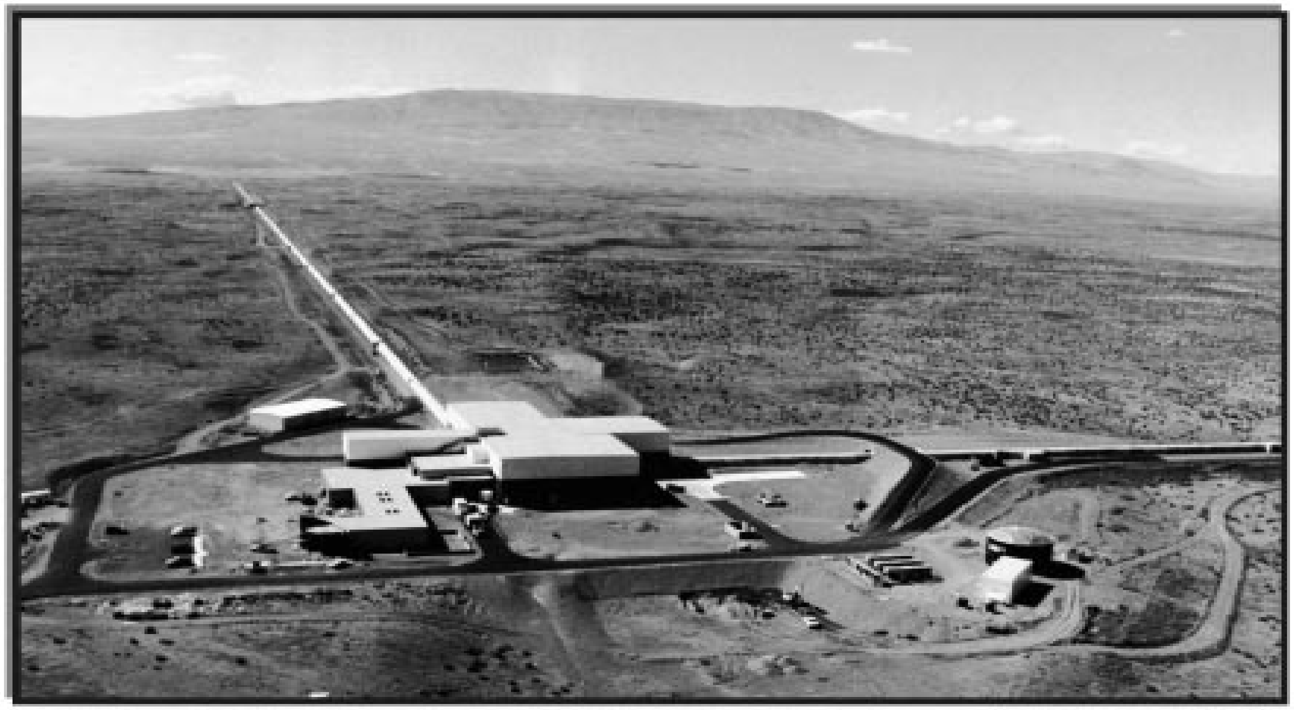
International Network

Simultaneously detect signal (within msec)



- detection confidence
- locate the sources
- decompose the polarization of gravitational waves

LIGO Hanford



LIGO Livingston

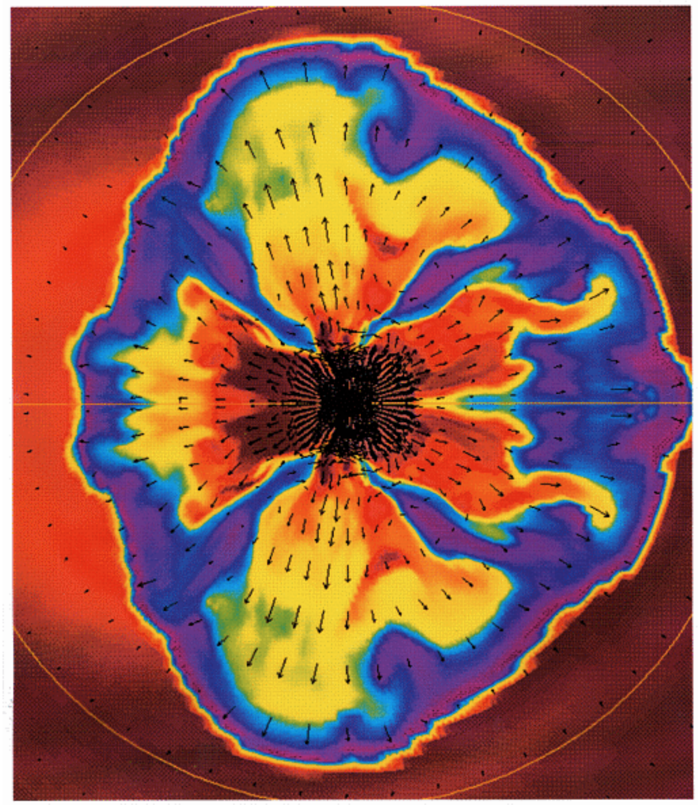
Model of Core Collapse

A. Burrows et al

Fig. 3.—Kick Sequence: Initial and Final States

Burrows

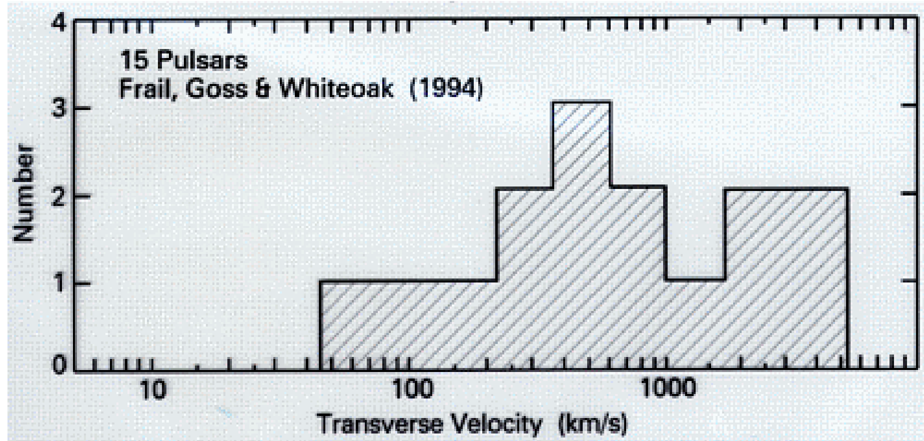
kick sequence



gravitational core collapse

Asymmetric Collapse?

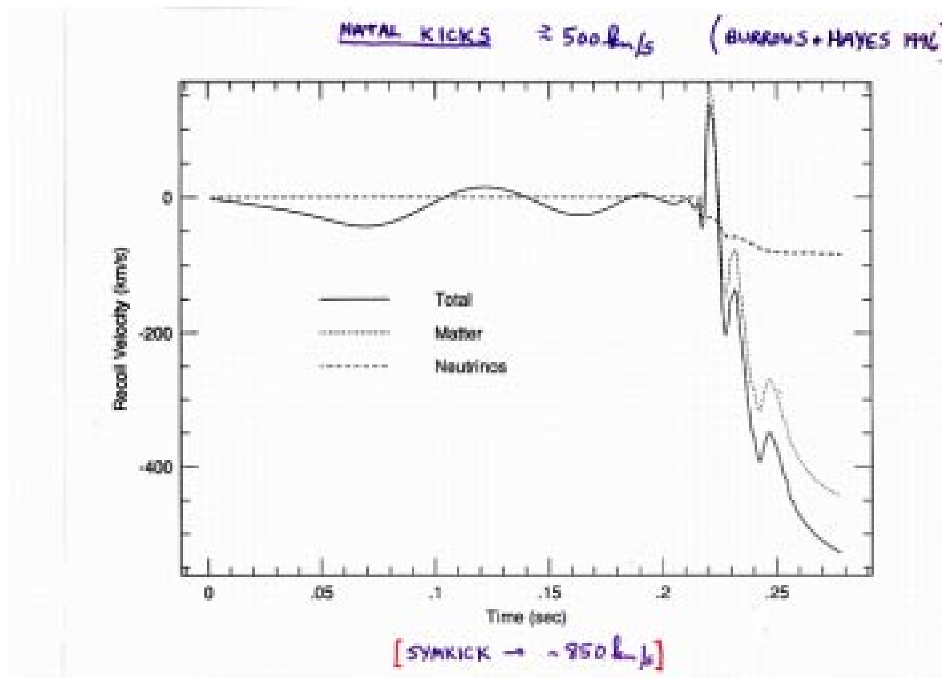
pulsar proper motions



Velocities -
- young SNR(pulsars?)
- > 500 km/sec

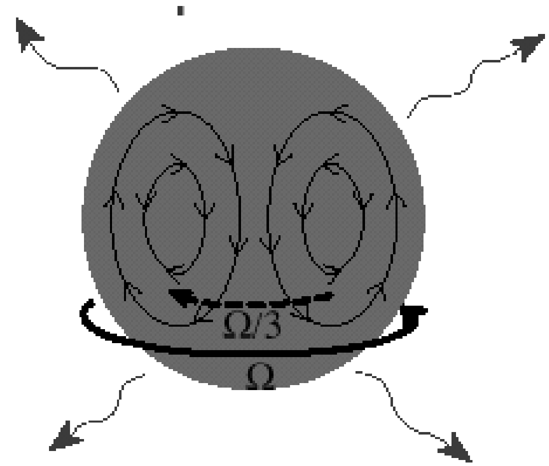
Burrows et al

- recoil velocity of matter and neutrinos



LIGO Sources
neutron star births

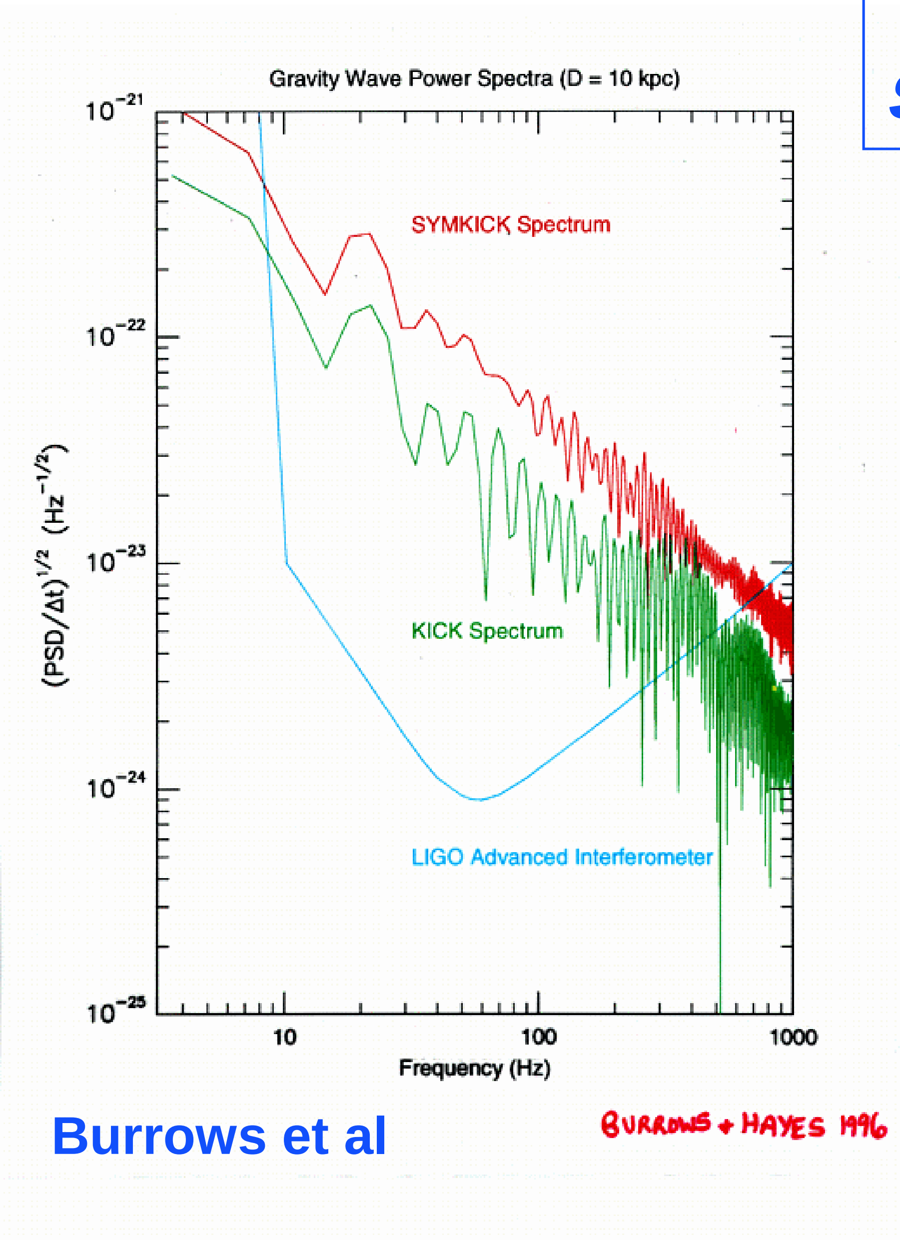
- **Supernovae: stellar core collapse -> NS**
  - » ***If* NS born with P_{spin} < 10 msec:** *R-Mode instability.*
    - Observations -> Spin evolution, viscosity, mode-mode coupling
    - LIGO-II: detectable to 20Mpc (VIRGO cluster)
  - » ***If* in our galaxy (~1/50 yr):**
    - Boiling -> Neutrinos and Gravitational Waves.
    - Cross correlate -> dynamics of 1st one sec of NS life



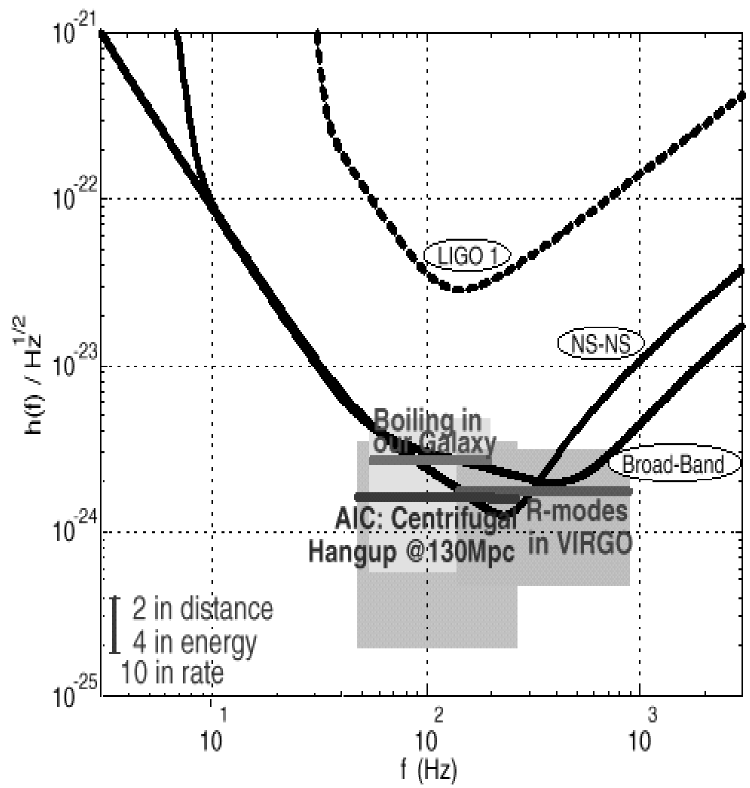
- **Accretion-Induced Collapse of White Dwarfs**
  - » **Only O/Ne/Mg Dwarfs likely to produce NS's (~1/yr at 130Mpc)**
  - » **Centrifugal hangup at ~ 60 km -> bar-mode instability -> Gravitational Waves [but hydrodynamic losses?]**
  - » **When shrunk to ~10km -> R-mode instability**

LIGO

supernovae sensitivity



Burrows et al



neutron star births

Conclusions

- **Multimessenger astronomy has great promise for the future**

- **All we need is the next galactic supernovae … (or some other multimessenger source)**

Best of luck from those of us on LIGO

We will miss you!!!