The Vigorous Afterlife of Massive Stars

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New Manifestations

→ DISCUSSED:

-- (Long) Gamma-Ray Burst: Afterglows and Central Engines

-- Accretion onto Black Holes

-- Strongly-Magnetized Neutron Stars: Magnetars

→ Omitted:

-- Accretion-Powered and nuclear-Powered ms X-ray Pulsars

-- White Dwarf Populations and X-ray Sources in Globular Clusters

-- X-ray Quasi-Periodic Oscillations (QPOs) in Accreting Sources

-- Ultra-luminous X-ray Sources and Intermediate-Mass Black Holes

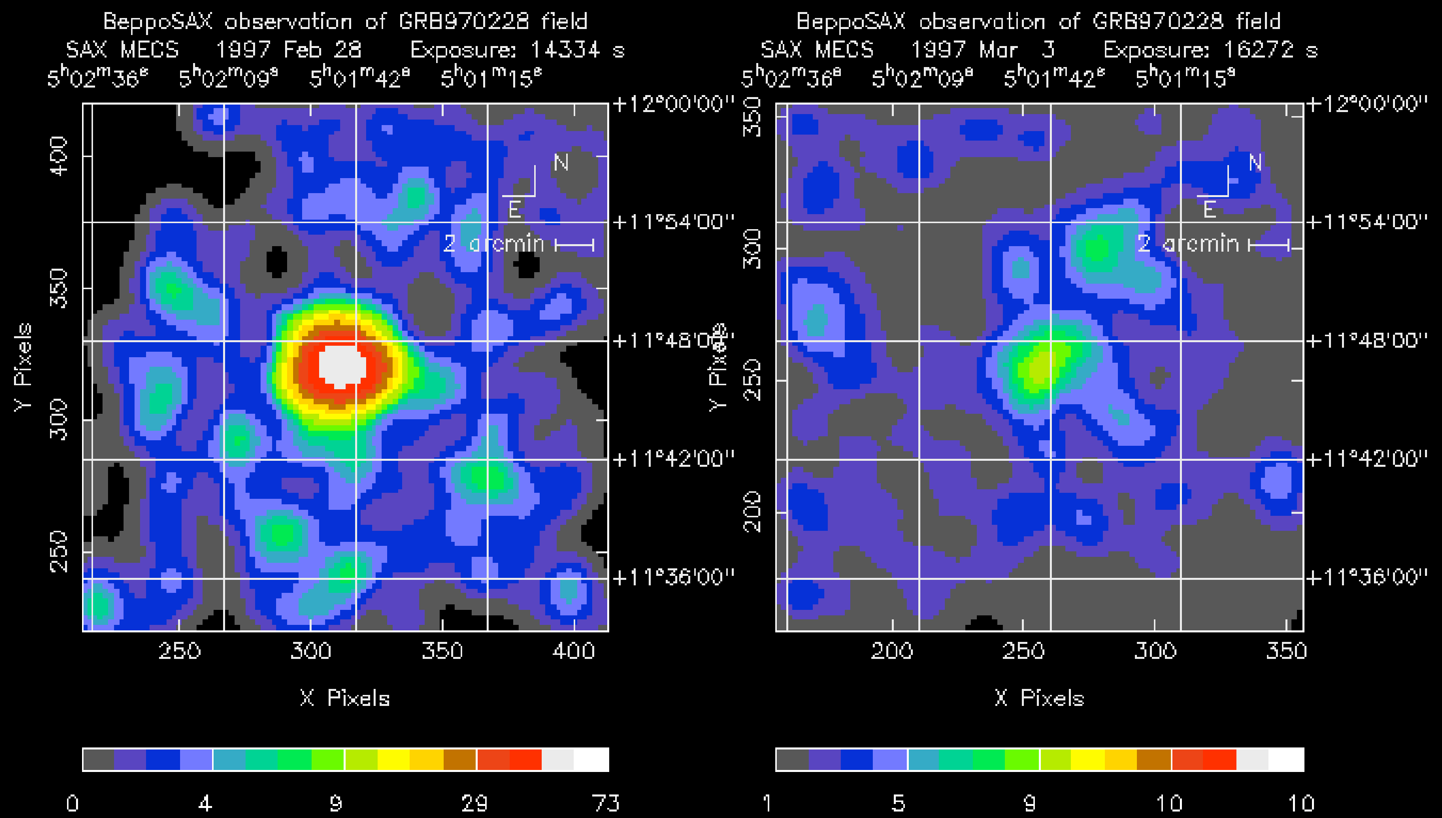
-- Supernova Remnants

GAMMA-RAY BURTS

Gamma-Ray Burst Afterglows

→ 30 years after GRB Discovery, detection of an X-ray afterglow

Costa et al. (1997)

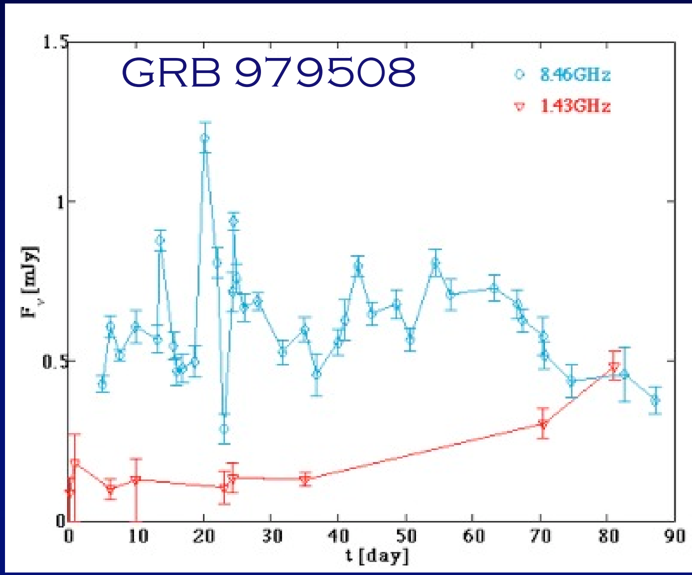


→ Discovery of Optical and Radio Afterglows followed quickly

Gamma-Ray Burst Afterglows

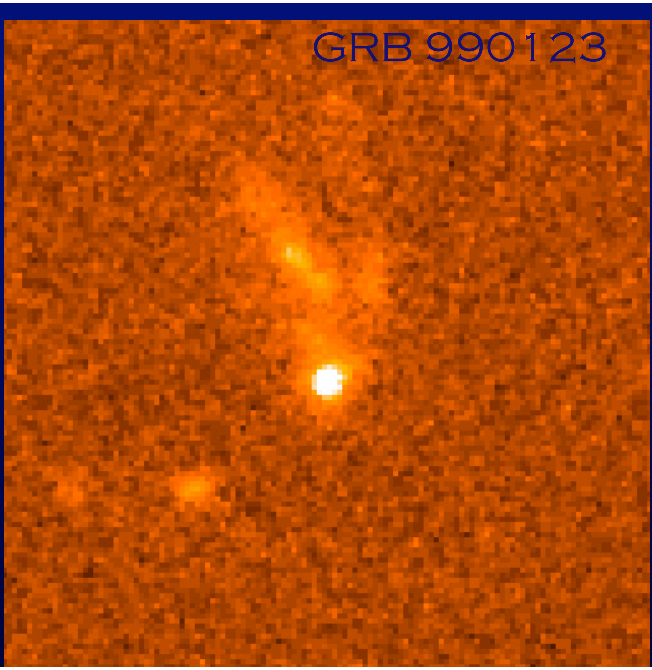
→ Disappearance of Scintillation confirms the Fireball Model (non-relativistic expansion)

Frail et al. (1997)



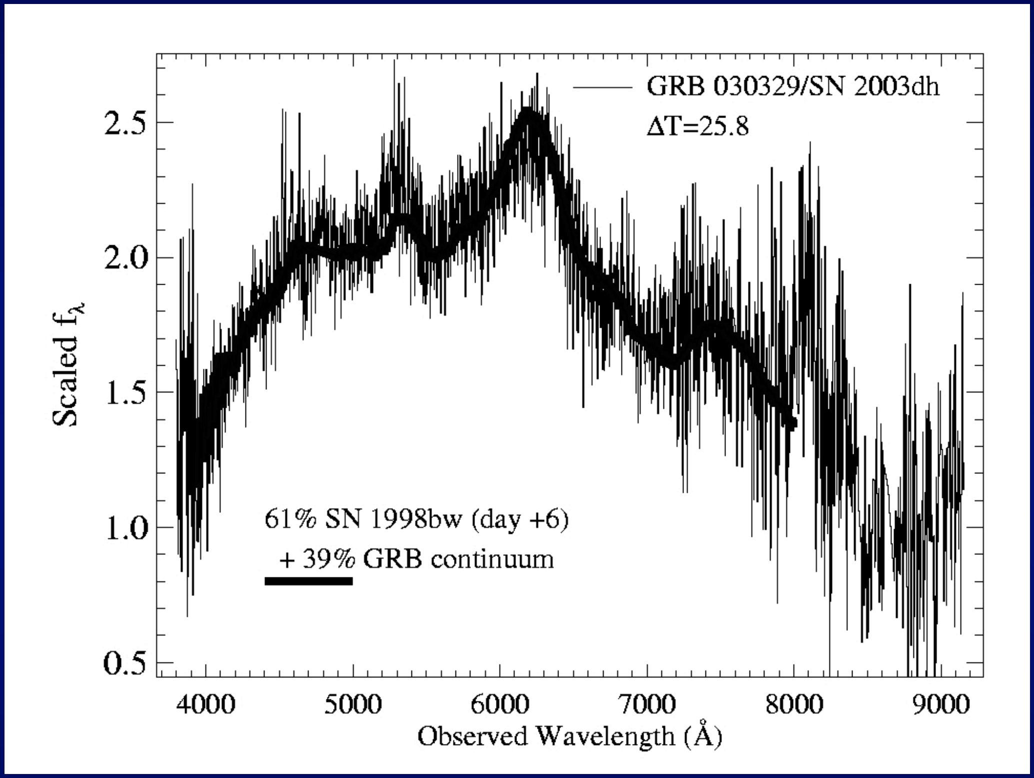
→ Identification of Host Galaxies at cosmological distances

van Paradijs et al. (1997)
Metzger et al. (1997)

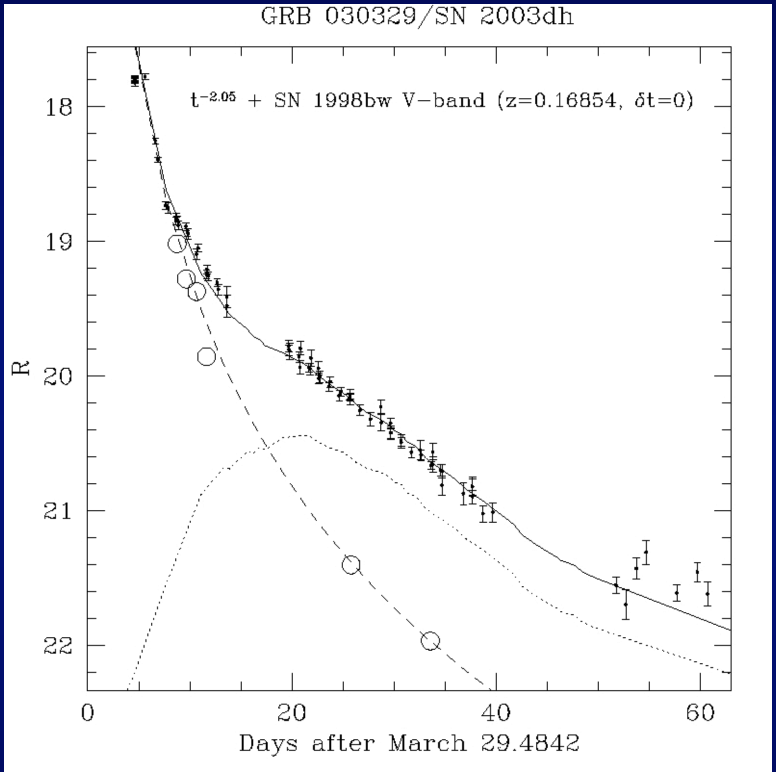


Long GRB / Supernova Association

Spectroscopy



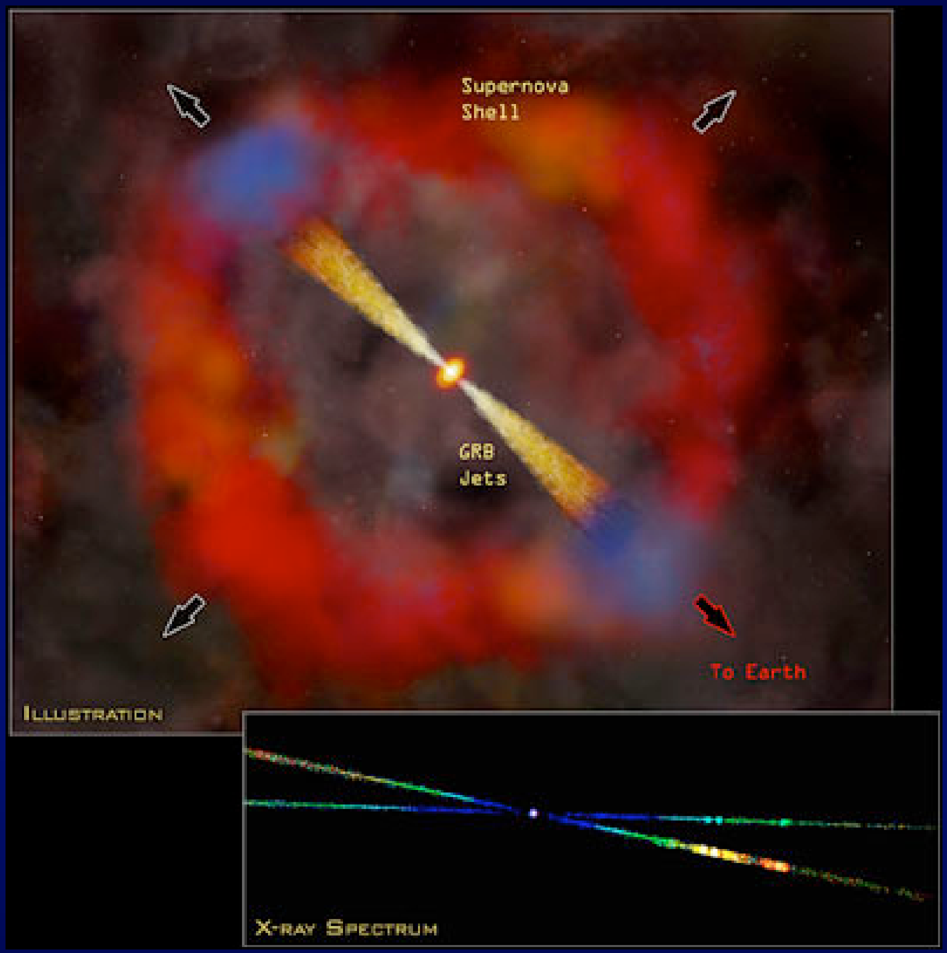
Photometry



Stanek, Matheson et al. (2003)

[Earlier tentative: GRB980425 + SN 1998bw (Galama et al. 1998)]
Strong supernova / Weak GRB

Gamma-Ray Bursts as Jetted Supernovae

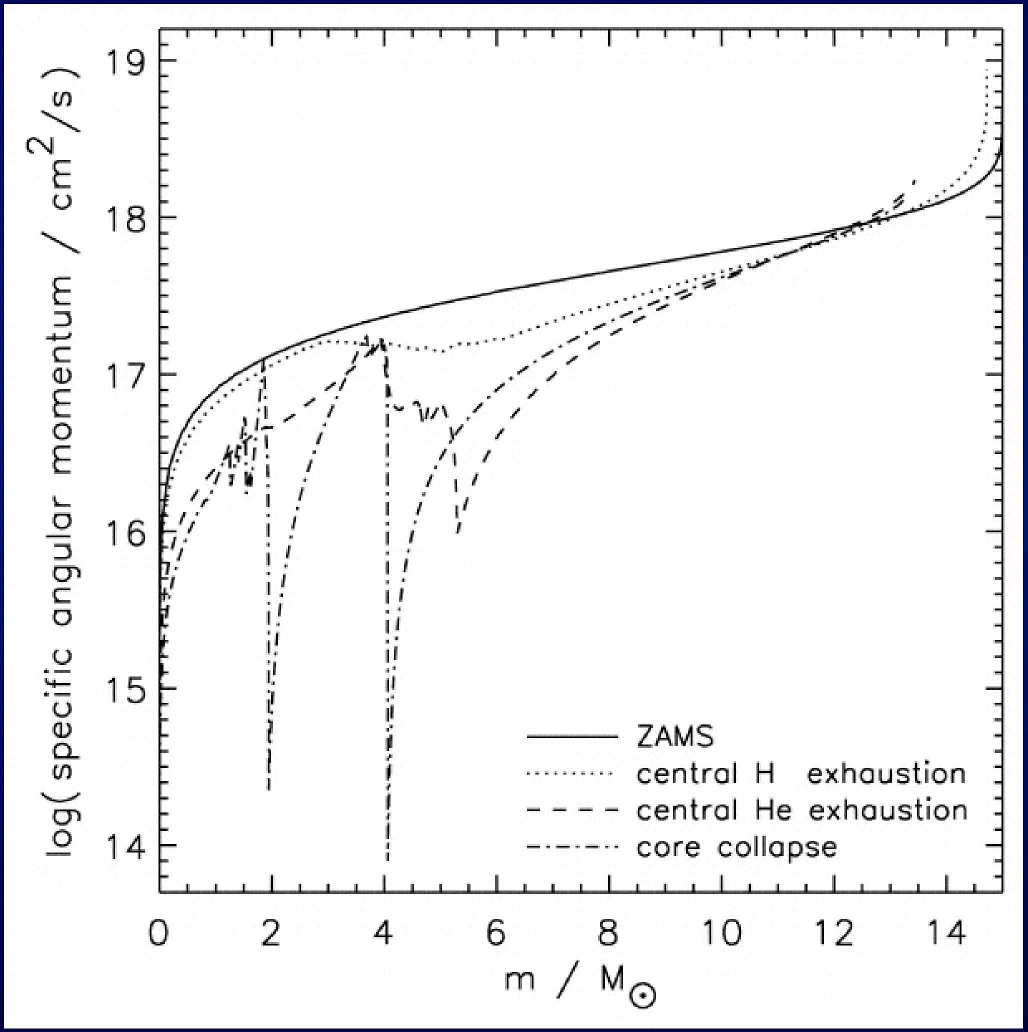


- Jet Models
  [UT:Panaitescu, Kumar]
- Environment
- X-ray Lines
- x-ray/ Optically Dark Cases
- Polarization
- new class of X-ray Flashes
- ...

→"Hypernova/Collapsar"
central engine Models

Massive Star Core-Collapse

Fryer & Heger (2000)

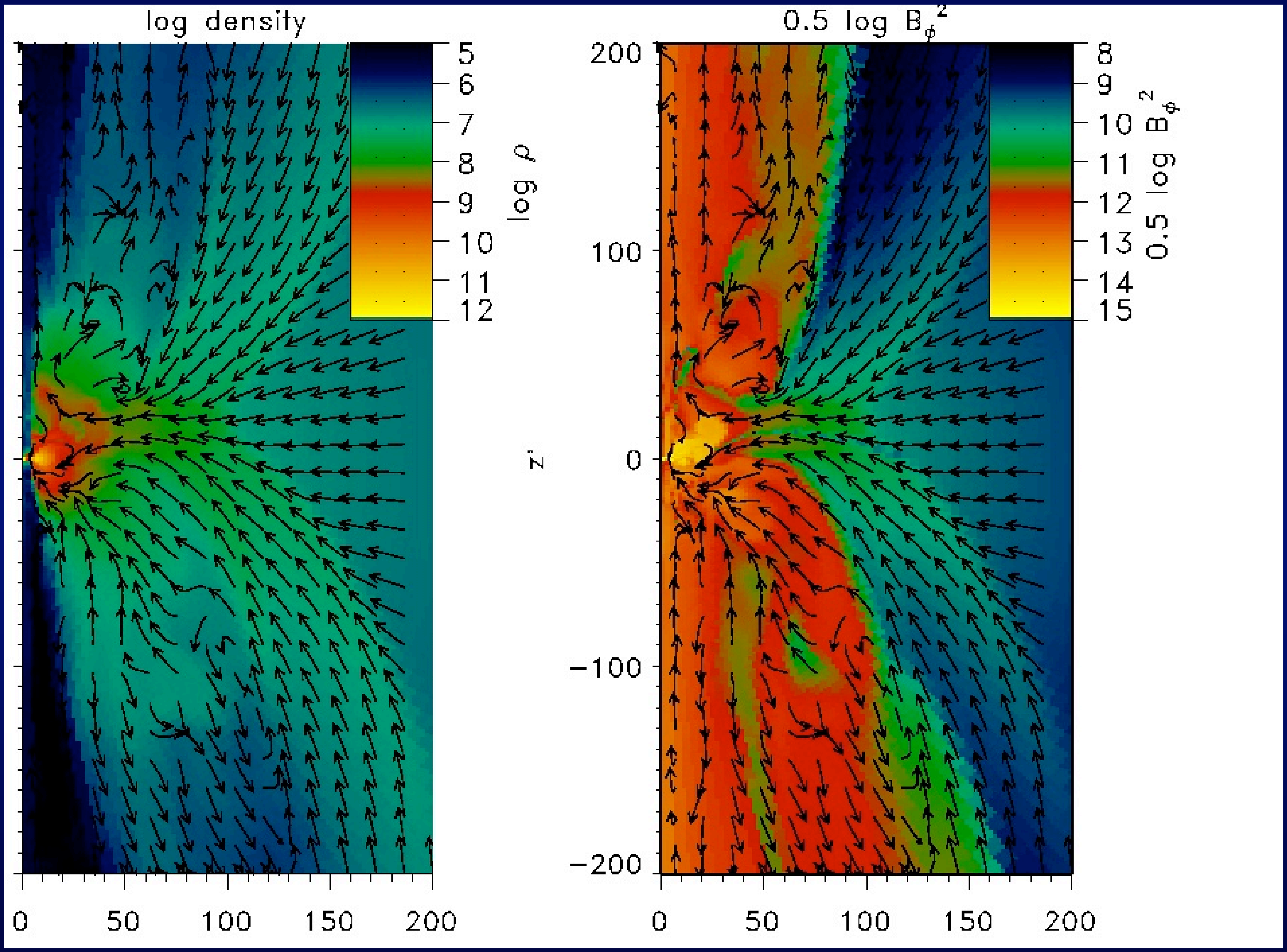


- Coupled stellar and Angular momentum Evolutions
- Initial condition for collapse simulations
- Core-collapse Outcome is sensitive

Collapsar: MHD Simulations (2D)

Proga et al. (2003)

- → Polar outflow
- → MHD transport
- → Heat Advection



[Earlier hydro: MacFadyen & Woosley (1999,2001)]

Selected Open Issues: GRBs

- different nature of short Gamma-ray Bursts?

- Global energetics, beaming, jet structure for long GRBs

- continuum between supernovae and GRBs (Amount of Rotation?)

- "explosion" mechanism: successful vs. delayed vs. failed supernovae
(shock, weak shock, no shock)

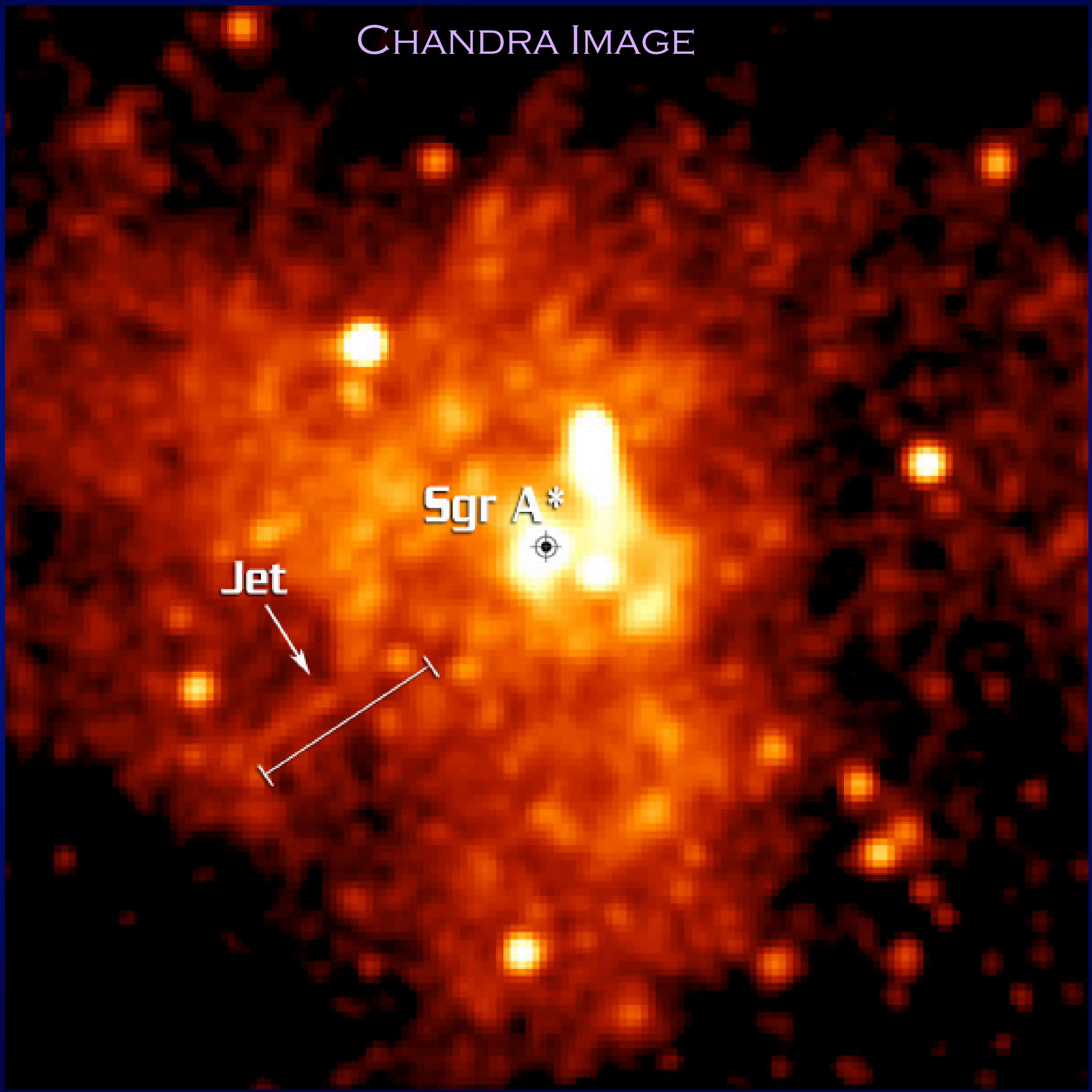
- energy "channel": BH accretion (wind?) vs. BH spin (jet?) vs. MHD+rotation

- Progenitor: stellar evolution, <u>angular momentum distribution</u> at collapse

→Observational Future: SWIFT (2004)

BLACK HOLE ACCRETION

Black Hole Accretion: Galactic Center



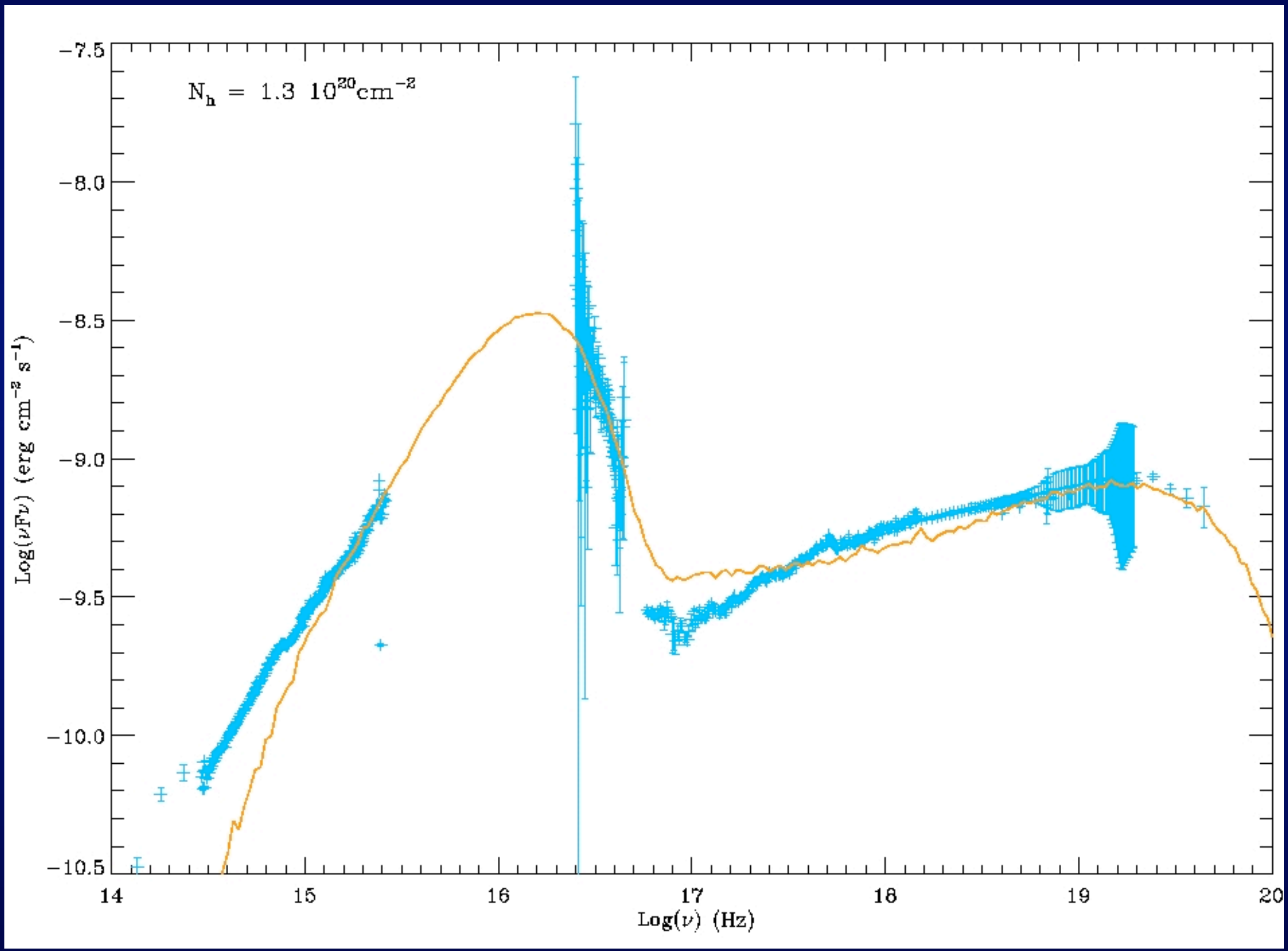
Chandra Image

Baganoff et al. (2003)
Narayan & Collaborators

- Massive Black Hole of 2.5×10^6 solar masses
- Bondi accretion rate Directly Estimated from X-ray Image
- Black Hole Accretion underluminous by several orders of magnitude
- Concept of heat advection In hot flow: "ADAF"

Black Hole Accretion: galactic Binaries

XTE J1118+480



Chaty et al. (2003)
[UT: Hynes]

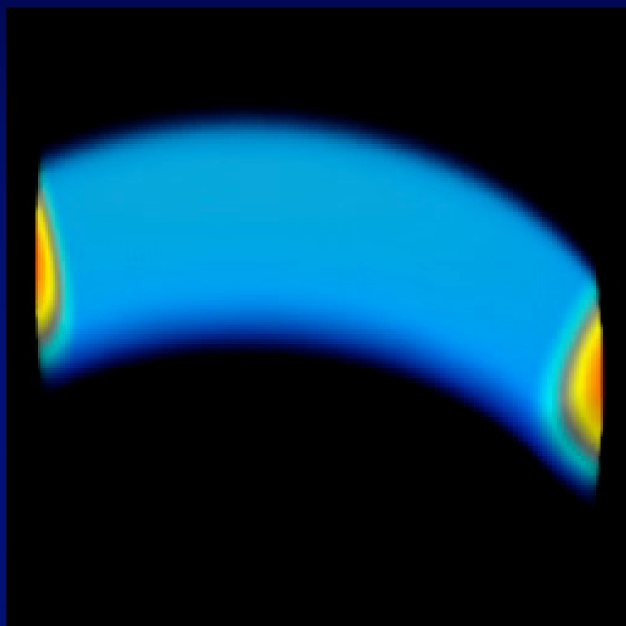
-- Stellar mass BH

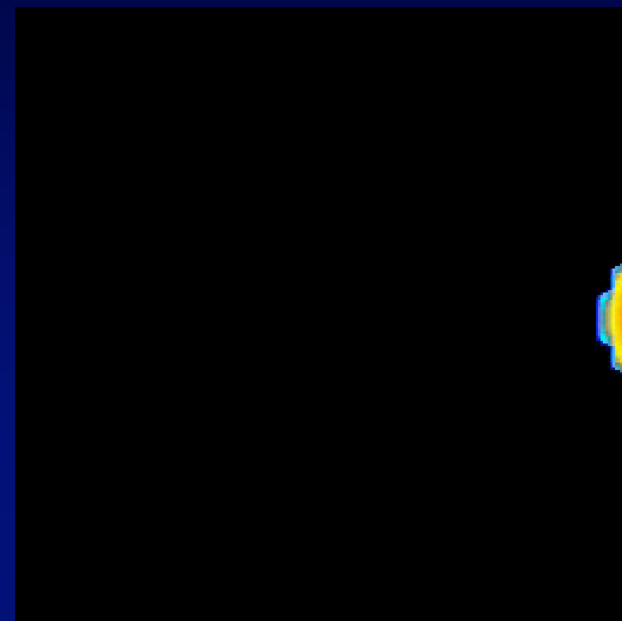
-- Soft Cutoff implies Thin disk truncated Far From BH

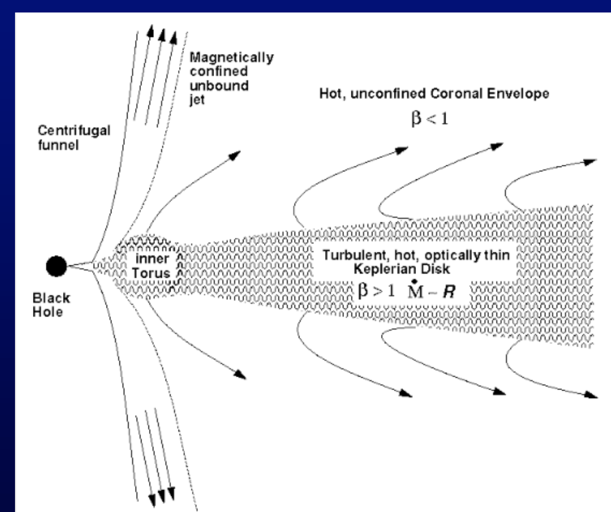
-- evidence for inner hot flow

Black Hole Accretion: MHD Simulations

Density evolution







Magneto-rotational Instability

Full (Static) GR MHD, Kerr BH,
Prograde Adiabatic torus

De Villiers & Hawley (2003)
Hawley & balbus (2002)

Selected Open Issues: BH Accretion

-- Global structure of flows with advection (wind?)

-- nature of flow near the black hole (marginally stable orbit, etc...)

-- feasibility of BH spin extraction, origin of Jets

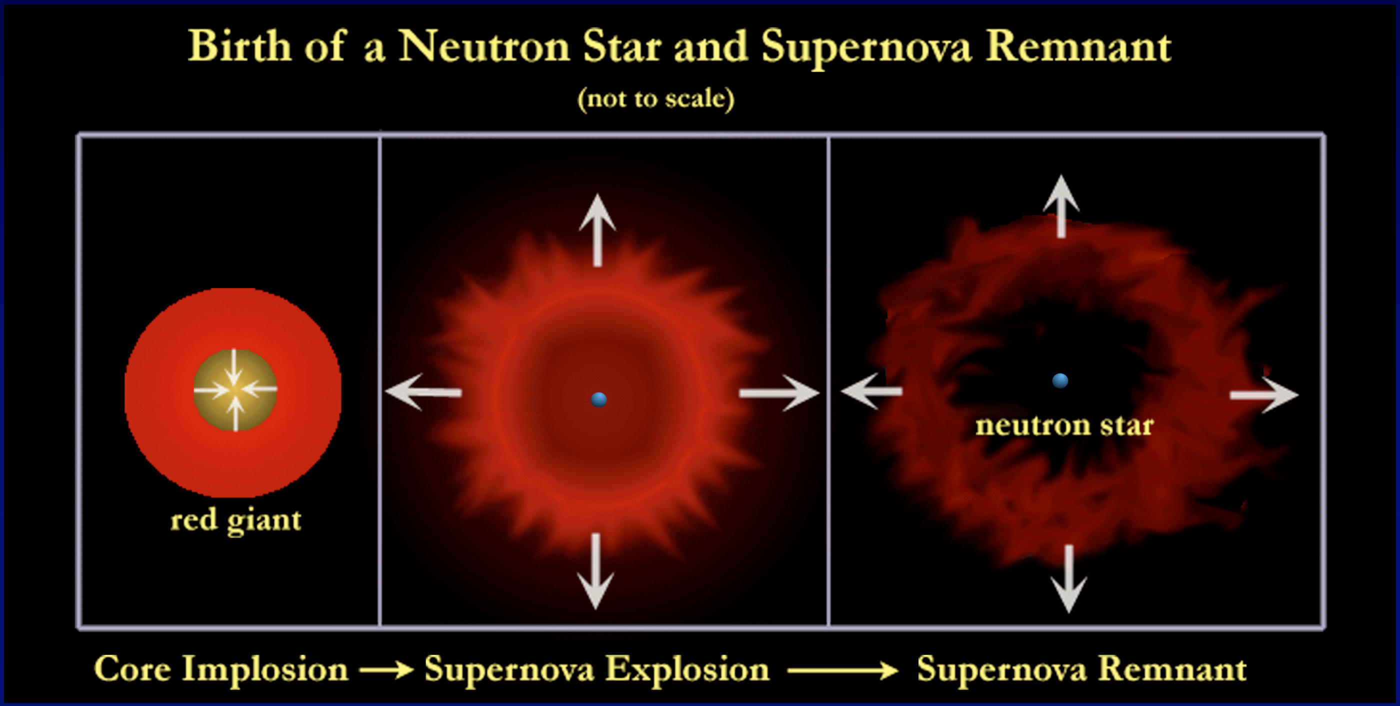
-- Collision-less nature of flow (turbulence, particle heating)

-- Measure of BH spin via broadened iron line?

→ Observational Future: Constellation-X (2011)
Black Hole Imager (?)

NEUTRON STARS

Less Massive Stars: Neutron Stars



Traditionally two flavors of pulsars:

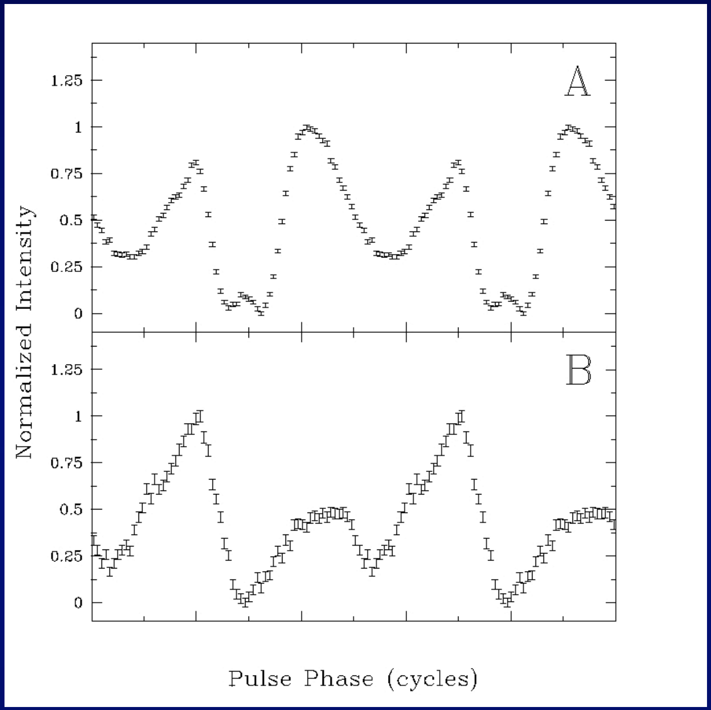
- Rotation-Powered (Radio) Pulsars
- Accretion-Powered (X-ray) Pulsars (with companion)
- Magnetic Field B~ 10^{12} G typically

New Flavors:

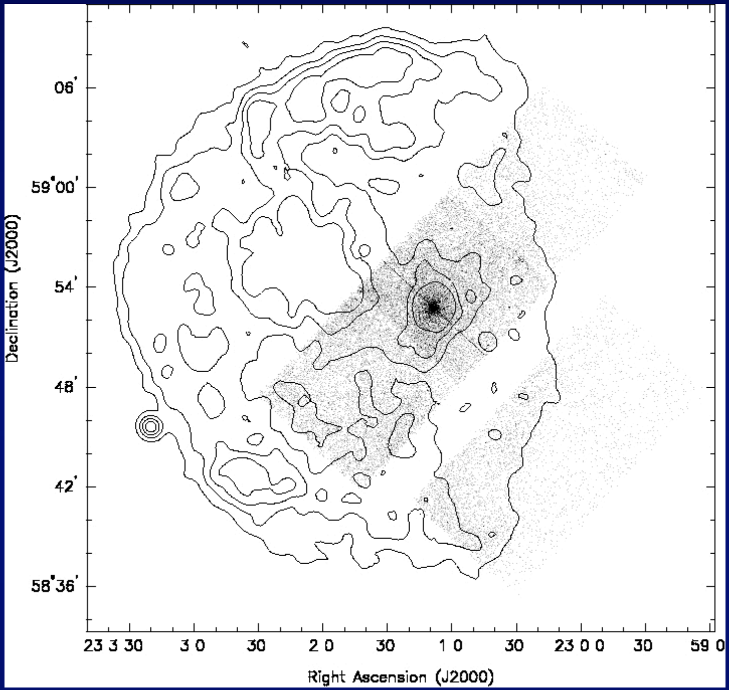
- Magnetars (strongly magnetized)
- Accretion- and Nuclear-Powered ms X-ray Pulsars

Anomalous X-ray Pulsars

V. Kaspi & Collaborators



X-ray light curve



Association with SN Remnants

Period and its derivative --> B ~ 10^{15} G

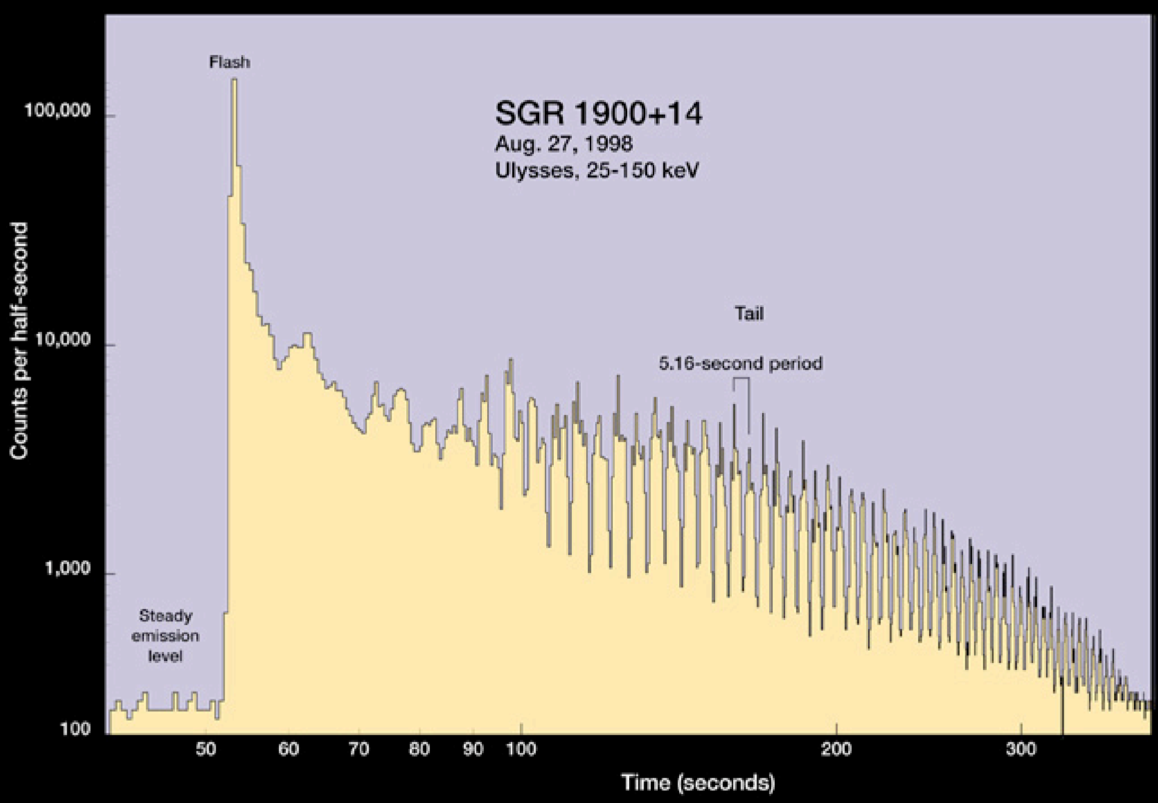
--> L_X ~ 10^{35} erg s^{-1} is not powered by rotation

Very faint in optical --> L_X is not powered by accretion

---> Luminosity powered by (strong) magnetic Field decay?

Soft Gamma Repeaters & Magnetars

Giant Flare of 1998: Light Curve



C. Kouveliotou
R. Duncan
C. Thompson
And Collaborators

- highly super-Eddington
- persistent L_X ~ AXPs
- Periodicity ~ AXPs
- Period and derivative
  --> B ~ 10^{15} G
- one AXP shows bursts
  -> Related objects

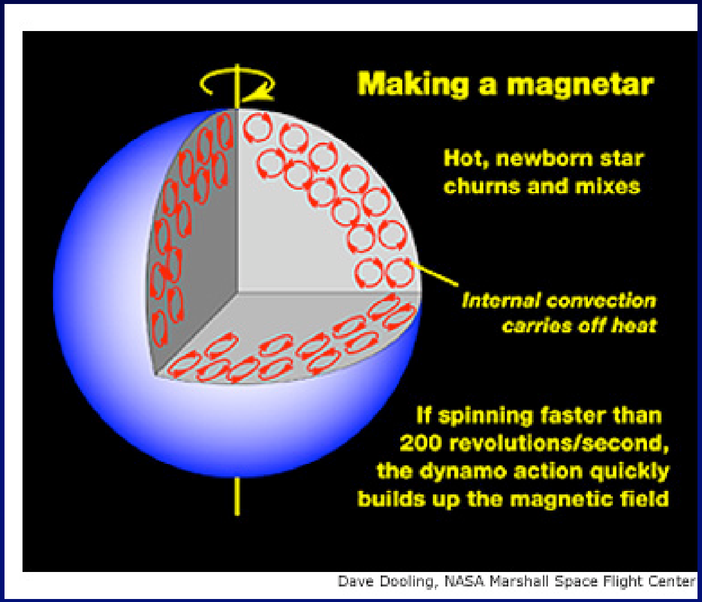
--> Magnetars, bursts powered by magnetic fields / starquakes

Neutron Star Magnetism and Magnetars

---- Proto-neutron star Dynamo ----

Fast Rotation at birth + convection
--> Efficient magnetic Field Dynamo

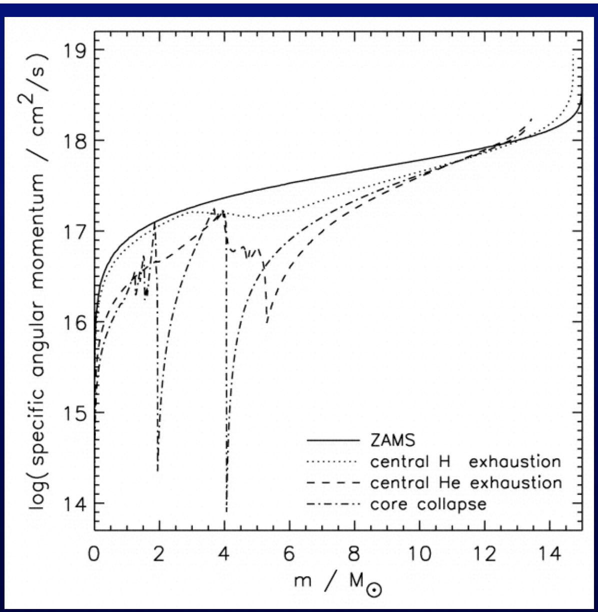
Duncan & Thompson (1992)
Thompson & Duncan (1993)



---- Magneto-rotational Instability ----

Differential Rotation during
core-collapse or in proto-neutron star
--> field amplification by analogy to
differentially-rotating accretion disks

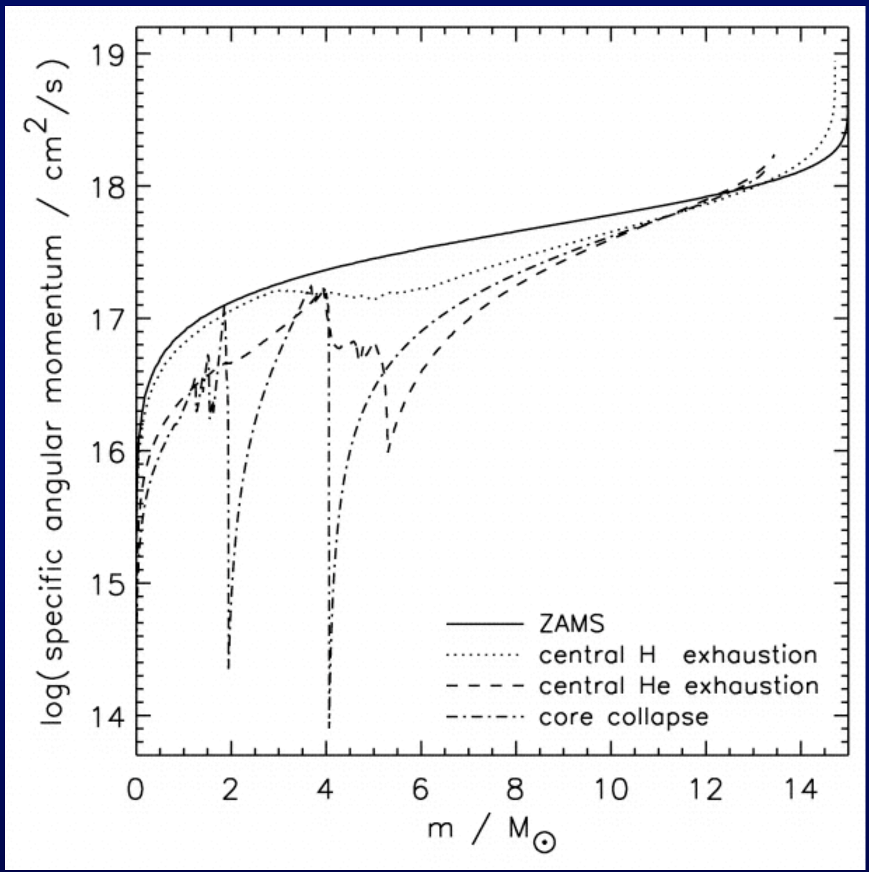
Akiyama & Wheeler (2003)



EPILOGUE

Common Physical Ingredient

Angular Momentum Transport



- Now better understood for Accretion disks: MHD turbulence from magnetic field + differential rotation (Balbus & Hawley 1991)

- Not understood for stars: solar interior --> solid body rotation

- crucial for GRB central engines, neutron star magnetism and perhaps burst oscillations

Differential Rotation in Stars

- Linear stability analysis
- hydrodynamics

- "Salt-finger" type modes
--> constant rotation on cylinders
--> non-constant rotation within spherical shell

The Astrophysical Journal, Vol. **150**, November 1967

DIFFERENTIAL ROTATION IN STARS

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Received April 4, 1967; revised June 16, 1967

ABSTRACT

The stability of differential rotation in the radiative zones of stars is investigated. For sufficiently large χ/ν (χ is the thermal diffusivity and ν the kinematic viscosity), it is shown that a necessary condition for stability in regions of homogeneous chemical composition is that the angular momentum per unit mass be an increasing function of distance from the rotation axis. In cylindrical coordinates (ϖ, φ, z), this condition is given by $\partial(\varpi^2\Omega)/\partial\varpi \geq 0$ and $\partial\Omega/\partial z = 0$, where Ω is the angular velocity. The condition is also a sufficient one when applied to axisymmetric perturbations. The stable thermal stratification which exists in the radiative zone cannot prevent the instability since, in stars, the thermal diffusivity is much greater than the kinematic viscosity. The turbulent diffusion of angular momentum, which arises when the stability condition is violated, is so rapid that it would appear to preclude the fast rotation of the Sun's interior which has been proposed by Dicke * In the absence of the instability associated with thermal diffusion, i.e , if $\chi = 0$, Dicke's solar model is found to be stable.

Another means whereby angular momentum might be brought up from the solar interior is by the mechanism of spin-down associated with the formation of an Ekman boundary layer just below the solar convective envelope. The transport of angular momentum, either by spin-down or by turbulent diffusion, would result in the mixing of material below the convective zone of solar type stars if an external torque were applied to the stellar surface. Thus, the depletion of lithium and beryllium would be an inevitable consequence of the loss of a significant fraction of the star's initial angular momentum.

I. INTRODUCTION

Differential Rotation + magnetic Field

Menou, Balbus & Spruit (2003)

- New ingredients:
  - weak magnetic field
  - Resistivity (+viscosity+heat conduction)

- New result:
  - in inviscid or perfect-conductor limits
  - --> constant rotation on cylinders
  - --> constant rotation within shell

Menou (2003)

  => solid body rotation!

- Amenable to numerical simulations (transport and mixing in stars)?

  → could help explain the diversity of afterlife manifestations