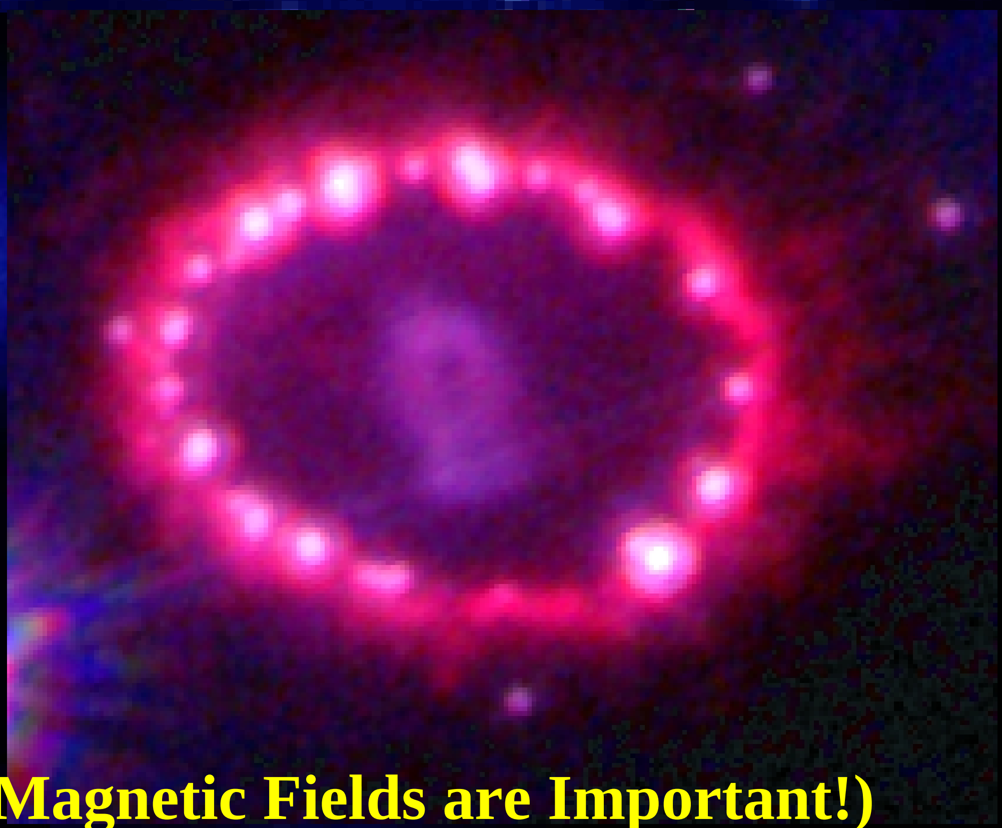
Gamma-ray Bursts: Supermassive or Hypermassive Neutron Star formation in Binary Mergers and Asymmetric Supernovae Core Collapses?



(Conclusion: Rotation and Magnetic Fields are Important!)

References

Paul Shapiro and Peter Sutherland, “The Polarization of Supernovae Light: A Measure of Deviation from Spherical Symmetry”, *Ap. J.*, **263** (1982)

S. Chandrasekhar, *Radiative Transfer*, Dover, New York (1960)

Lifan Wang, D. Howell, P. Hoflach, and J.C. Wheeler, “Bipolar Supernova Explosions”, *Ap. J.* **550** ,1030 (2001)

Lifan Wang, et al., “Broadband Polarimetry of Supernovae..”, *Ap.J.* **467**, 435 (1996).

S. Akiyama, J.C. Wheeler, D. Meier, I. Lichtenstadt, “The MRI Instability in Core-collapse Supernova Explosions”, Ap.J. 584, 954 (2003)

M. Duez, Y. Liu, S. Shapiro, M. Shibate, B. Stephens, “Collapse of magnetized hypermassive neutron stars in general relativity”, astro-ph/0510653 (1995)

Outline

I. Background: supranovae model of GRBs.

II. Evidence of asymmetry in supernovae core collapses
- spectropolarimetry

III. Dynamical models: ultimate problem is 3-D with rotation, magnetic fields, and neutrino transport
- jet-induced supernovae?
- magnetorotational instability in core collapse: inevitable production of large magnetic fields.

IV. Can rotation and magnetic fields lead to sufficiently strong jets to explode the supernova?

VII. Implications for supernovae, hypernovae, and gamma-ray bursts.

I. BACKGROUND

Some supernovae leave behind pulsars - rotating, magnetic neutron stars. Are the rotation and magnetic field important for the supernova explosion?

A Crab-like field of 10^{12} Gauss and a Crab-like rotation of 33 ms are dynamically unimportant.

BUT

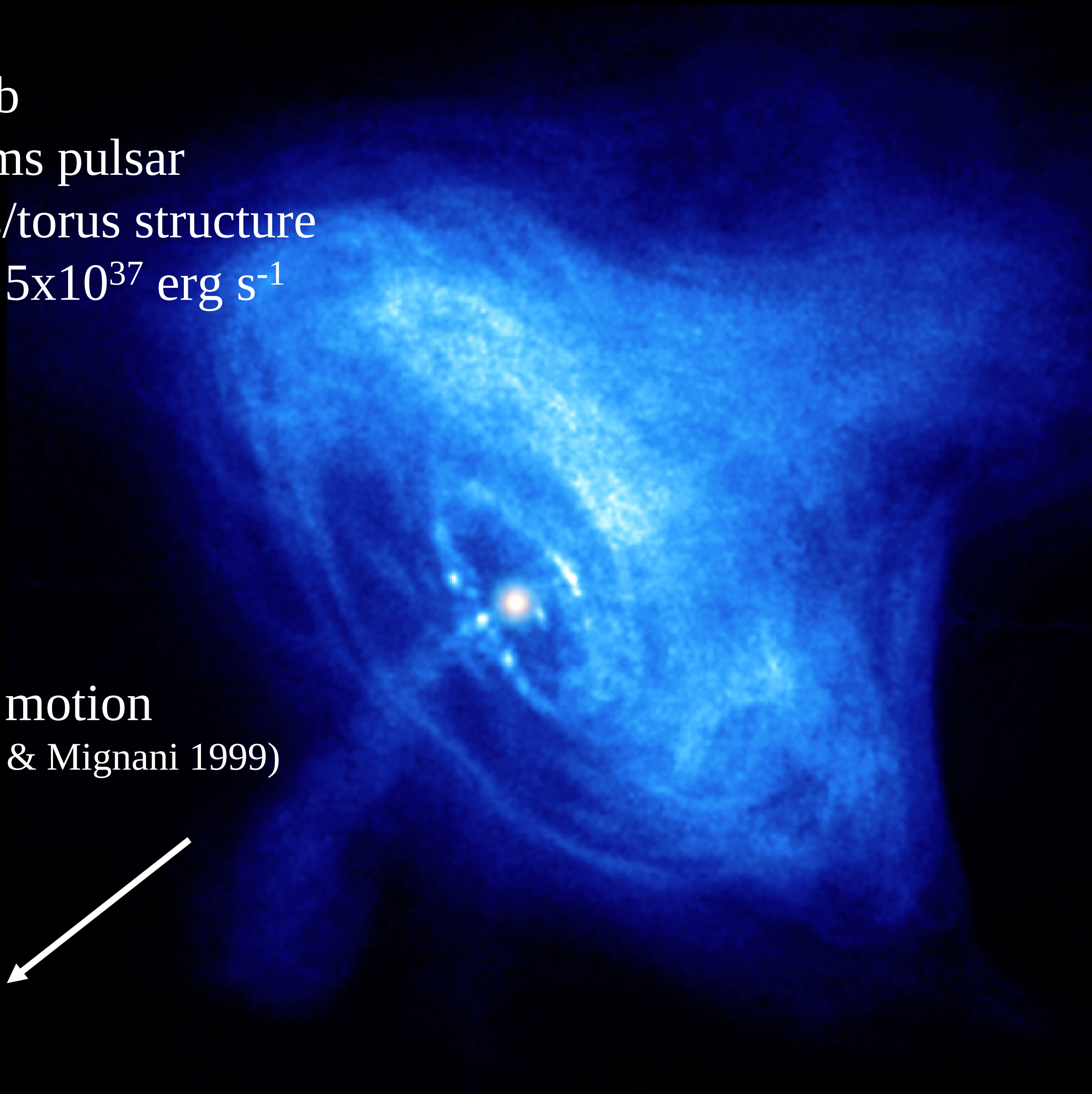
QUESTION: What were the field and rotation during collapse and were they dynamically important?

references: see many publications on this subject by the University of Texas (Austin) group: Wheeler, Hoflich, et al, Crab

33 ms pulsar

axis/torus structure

L ~ 5×10^{37} erg s^{-1}



Proper motion

(Caraveo & Mignani 1999)

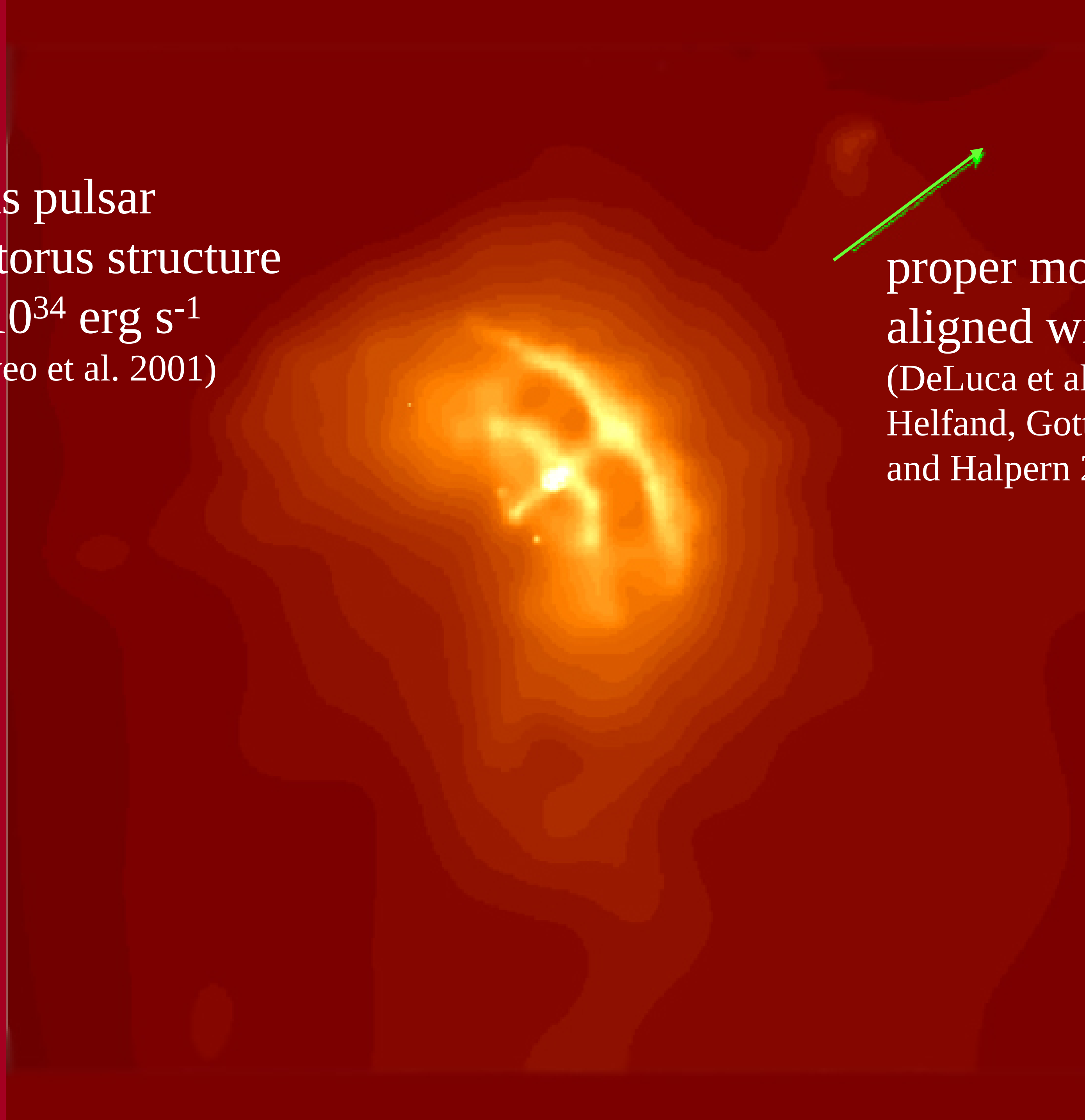
Vela

89 ms pulsar

axis/torus structure

L ~ 10^{34} erg s^{-1}

(Caraveo et al. 2001)



proper motion

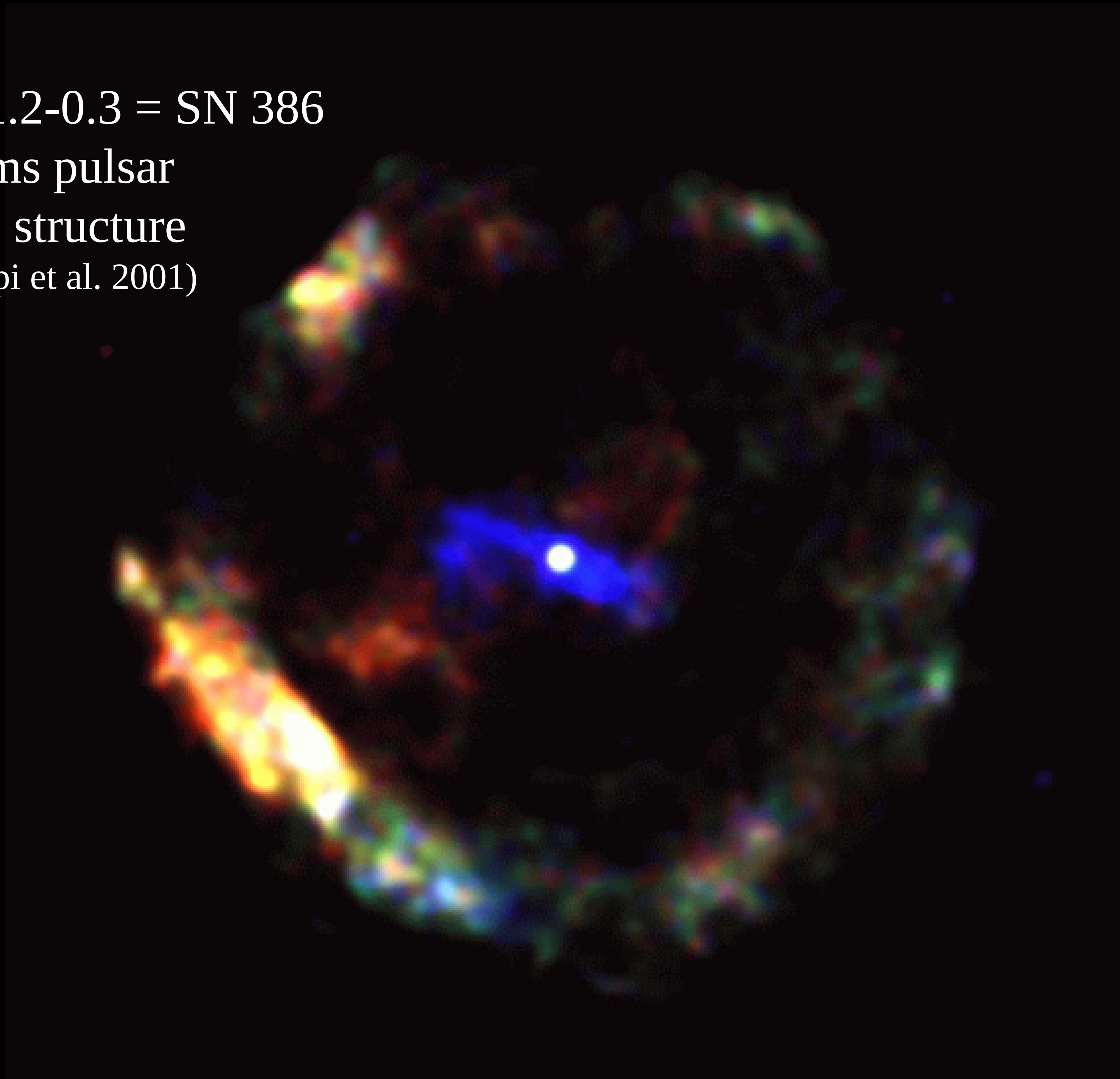
aligned with axis

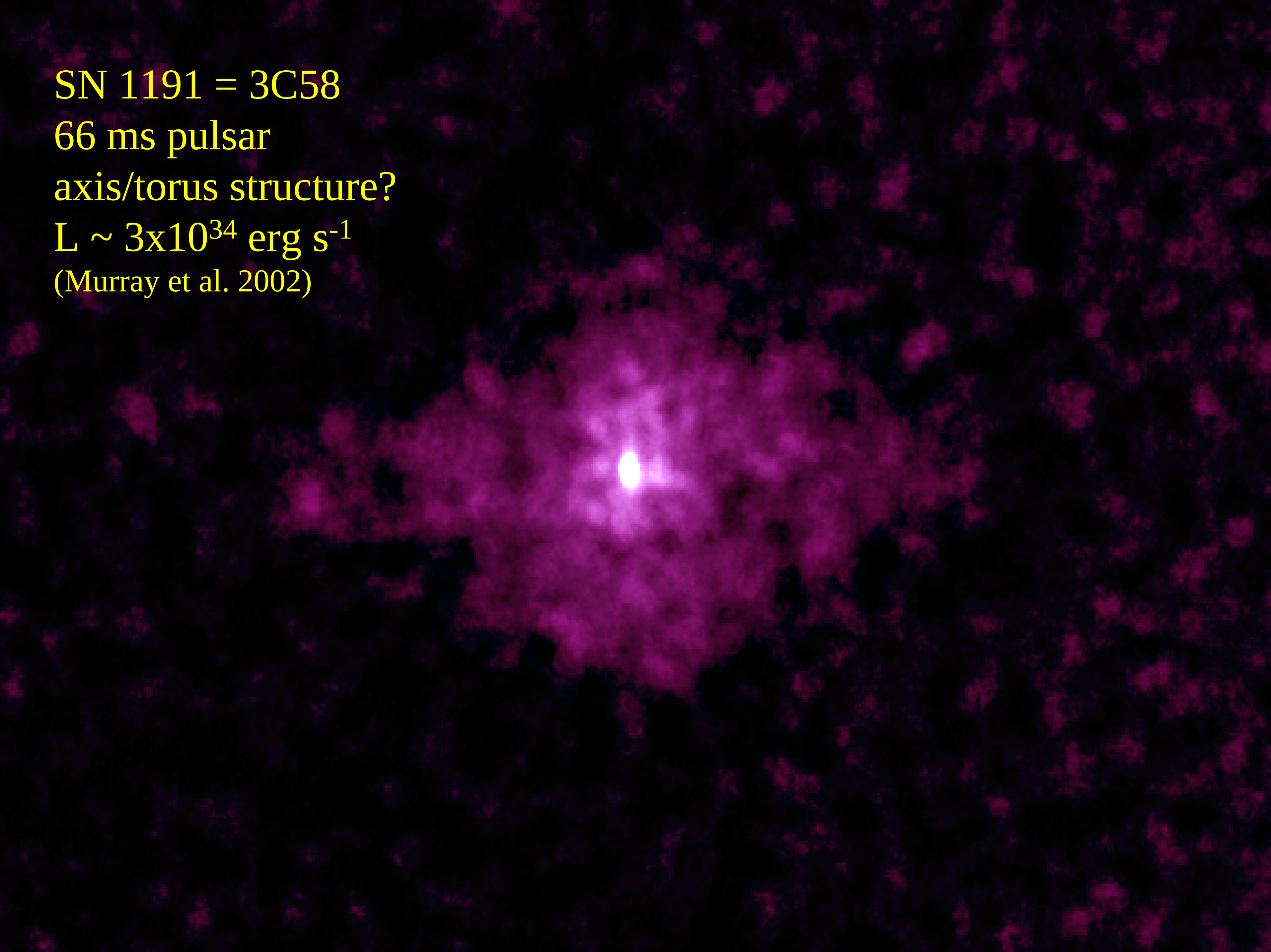
(DeLuca et al. 2000;

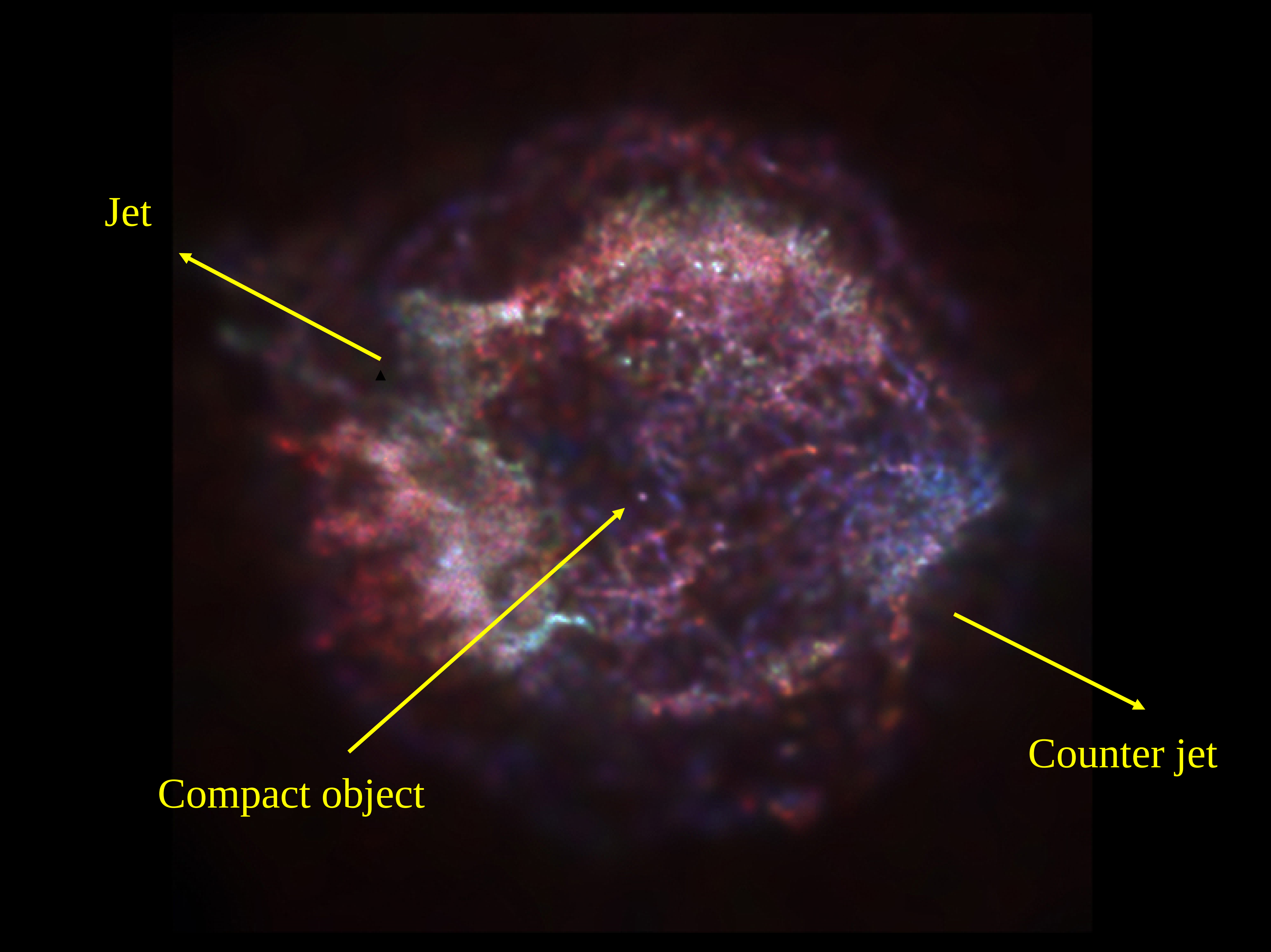
Helfand, Gotthelf

and Halpern 2001)

G11.2-0.3 = SN 386
65 ms pulsar
axis structure
(Kaspi et al. 2001)




SN 1191 = 3C58
66 ms pulsar
axis/torus structure?
L ~ 3×10^{34} erg s^{-1}
(Murray et al. 2002)


Jet
Compact object
Counter jet


SN 1987A
SINS
Kirshner, et al.

II. Spectropolarimetry: A tool for exploring asymmetries in SN explosions

Cannot "see" shape of distant supernova
Spectropolarimetry yields wavelength-dependent information on the shape of the photosphere and line-forming regions

$I \propto E^2$, polarization is a "quasivector," $0^o = 180^o$ (not 360^o)

Measure Stokes Vectors:

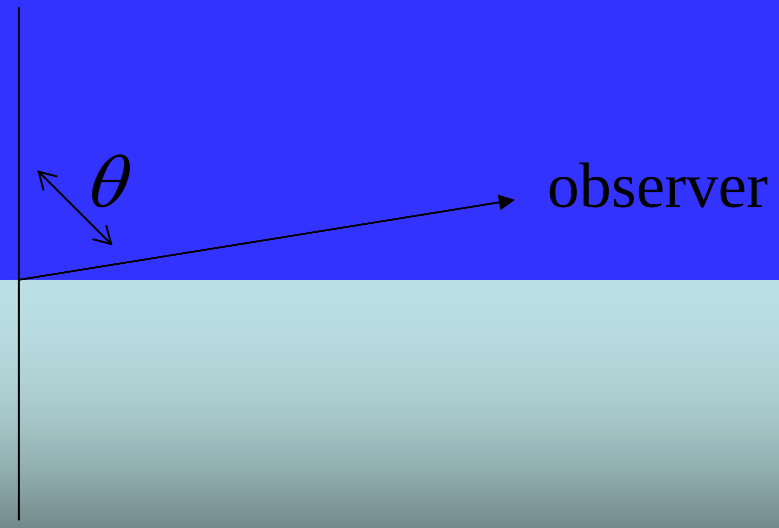
$I = I_0 + I_{90}$
$Q = I_0 - I_{90}$
$U = I_{45} - I_{-45}$

$P = (Q^2/I^2 + U^2/I^2)^{1/2} = (q^2 + u^2)^{1/2}$; $\chi = 1/2 \tan^{-1}(u/q)$

Origin of Polarization

Chandraskehar (1949, 1960) solved the problem of polarization of radiation from a plane-parallel stellar photosphere

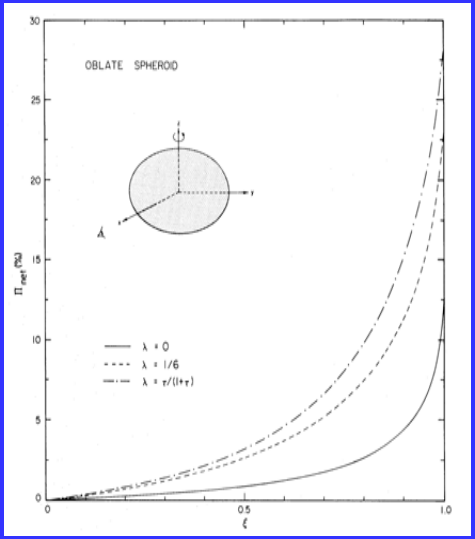
- assumes that pure electron scattering occurs at the photosphere; (problem similar to Rayleigh scattering of sunlight)

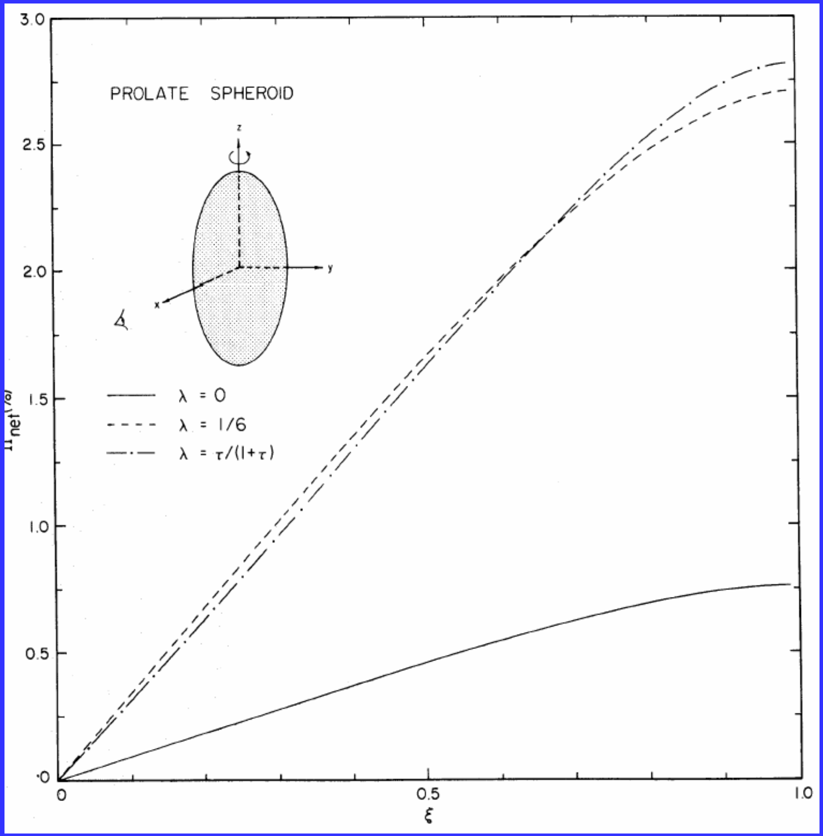


- linear polarization
- maximum at $\theta = 90^o$
  $\Pi = Q/I = 11.7\%$

Apply this to Supernovae: Basic theory
Shapiro and Sutherland (1982)

SN has asymmetric, scattering atmosphere → gives net linear polarization





III. Observations of polarization from Supernovae

Systematic differences between Type Ia thermonuclear explosions and core collapse supernovae (Wang et al. 1996)

Type Ia tend to show low polarization, especially at and after maximum light (but growing evidence for polarization pre-max)

All core collapse supernovae show significant polarization, ~ 1%, requires distortion axis ratios of ~ 2 to 1

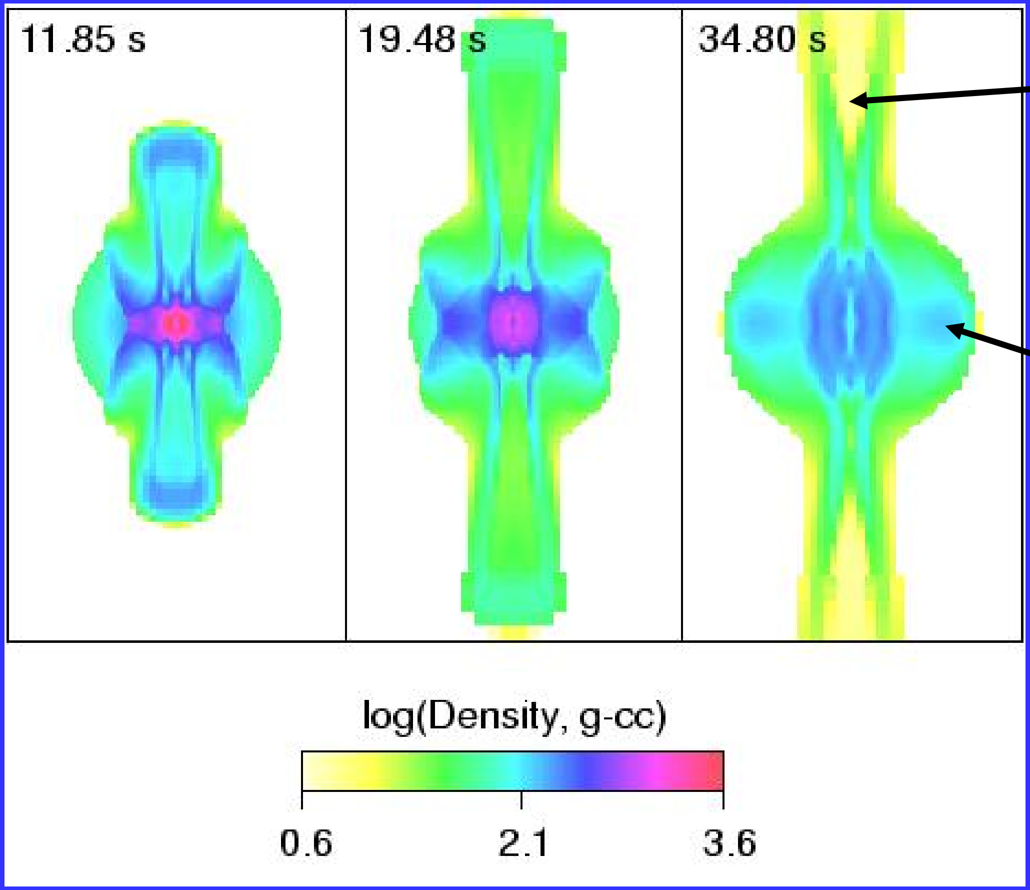
Polarization tends to be larger at later times when see deeper in and larger when outer hydrogen envelope is less when see deeper in, both imply ***it is the machinery, the core collapse mechanism itself that is strongly asymmetric*** (Wang et al. 1996, 2001)

Inference: The explosion is often (but not always) substantially bi-polar (Wang et al. 2001)

IV. Jet-induced Supernovae ???

3D hydrodynamical calculation of jet-induced supernova (Khokhlov et al. 1999). Sufficiently strong jets can explode the supernova (without neutrinos, in principle) and impart large asymmetries.

Axis/torus structure



jet
“nickel”
prolate

torus,
O, Ca,
oblate

slide from
J.C. Wheeler

Asymmetric Core Collapse

Core collapse events are polarized

Jets work

Role of rotation/magnetic fields

Magneto-rotational instability (Akiyama et al. 2003)

Ultimate problem is 3-D with rotation, magnetic fields and neutrino transport – polarization observations appear to demand asymmetry

V. Magneto-Rotational Instability - MRI

Akiyama, Wheeler, Meier & Lichtenstadt (2003):
proof-of-principal calculations using spherical collapse code.

Works on timescale of Ω^{-1} but field grows exponentially!!

Saturation B field is independent of small seed field;

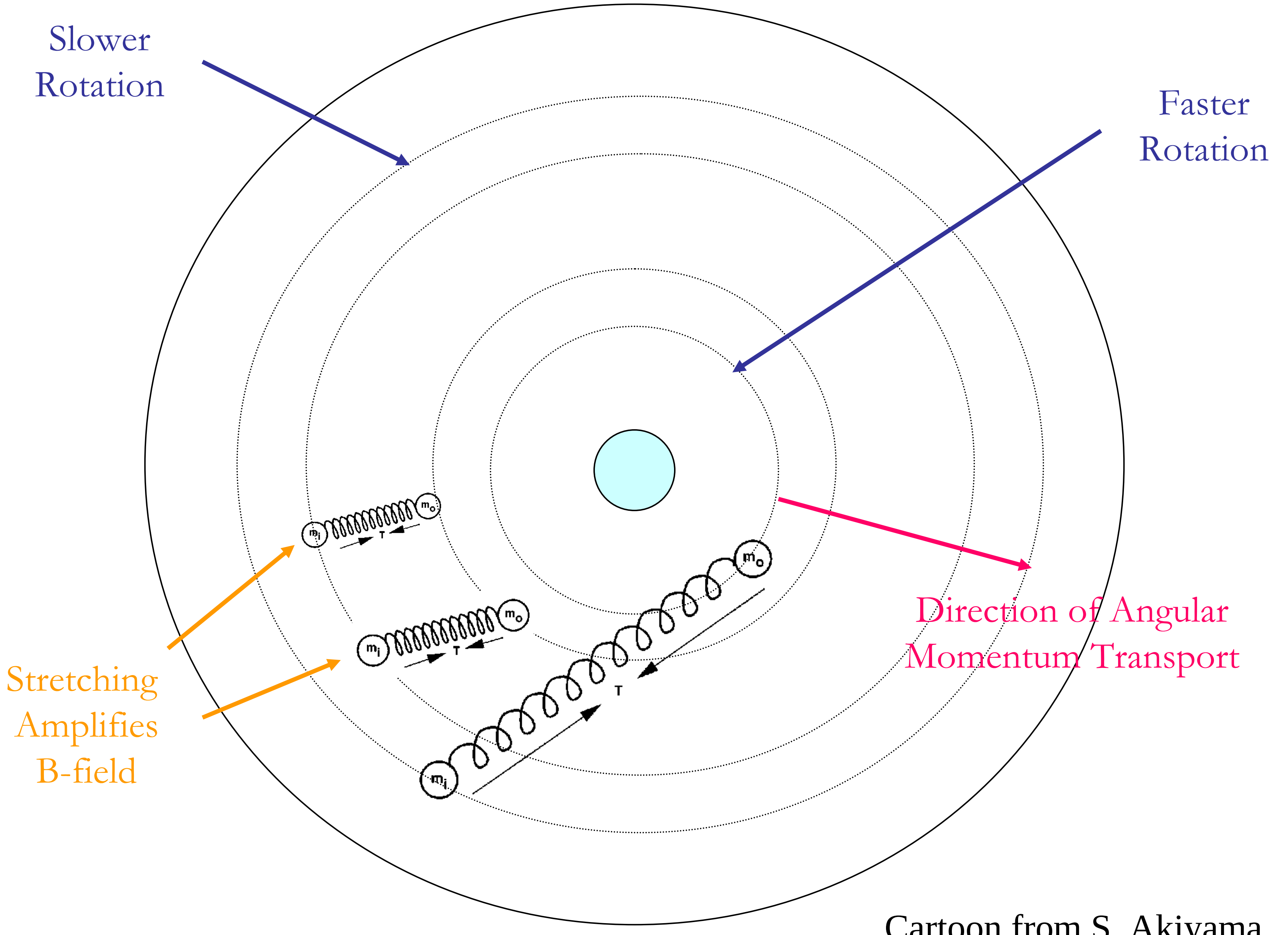
Should occur in supernovae collapse conditions.

Find fields ~ 10^{15} - 10^{16} Gauss in a *few tens of milliseconds*

Characteristic luminosit:y

$L = B^2 R^3\, \Omega/2 \sim 3\text{x}10^{52}$ erg s^{-1} $B_{16}^{\ 2}\, R_{NS,6}^{\ 3}\, (P_{NS}/10 \text{ msec})^{-1} \sim 10^{51} - 10^{52}$ erg/s

$E_{rot} = 1/2\ I_{NS}\, \Omega_{NS}^{\ 2} \sim 1.6\text{x}10^{50}$ erg $M_{NS}\, R_{NS,6}^{\ 2}\, (P_{NS}/10 \text{ msec})^{-2}$



Cartoon from S. Akiyama

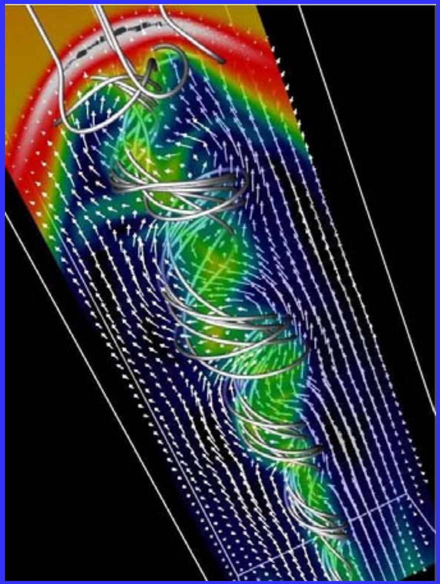
IMPLICATIONS

The MRI appears unavoidable in the collapse (supernova or GRB).

Collapse calculations that omit this (i.e. essentailly all of them to date) are likely to be incorrect at some level.

The magnetic field generated by the MRI must be included in any self-consistent collapse calculation.

The MRI may lead to strong jets.



M. Nakamura (From Meier et al. 2001)

Relevant dynamics - large magnetic fields generated internally