Cosmic Jets: A Universal Phenomenon

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Talk Outline

- Taxonomy and Unification of Cosmic Jets
  - Jets from Dead Stars
    - Supermassive black holes (active galactic nuclei)
    - Stellar mass white dwarfs, neutron stars, and black holes
  - Jets from Stars Being Born
  - Jets from Dying Stars
    - Planetary nebulae
    - Supernovae
    - Black hole formation

- Production of Cosmic Jets by Rotating Magnetic Fields
  - Launching
  - Acceleration and Collimation
  - Attaining, and Maintaining, Relativistic Speeds (stability)
  - Special Applications: Supernovae & Gamma-ray Bursts

- Summary and Conclusions

Acknowledgements

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  - Y. Uchida* (Science Univ. of Tokyo)
  - R. Krasnopolsky (Caltech)

*1934-2002

Taxonomy and Unification of Cosmic Jets

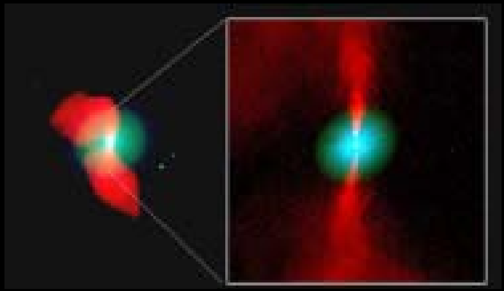
Cosmic Jets from Dead Stars: Supermassive Black Holes

- 1918: First observed jet: optical jet in M87, by Heber Curtis (Lick Observatory)

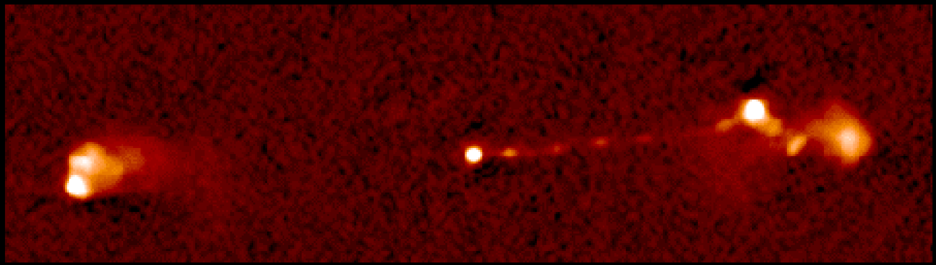
Virgo A=M87

- 1943: Carl Seyfert's active galactic nuclei
- 1950s: Cosmic radio sources (radio galaxies): Vir A, Cen A, Cyg A, *etc*.

3C 272.1=M84



- 1959, 1962: 3rd Cambridge (3C) Radio Survey – radio galaxies and quasars



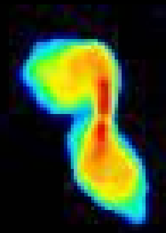
3C 204 (quasar)

Cosmic Jets from Dead Stars: Supermassive Black Holes (cont.)

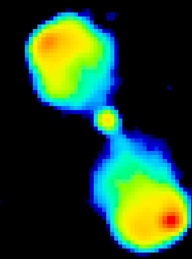
- 1968: BL Lacertae objects and “blazars” – radio galaxy and quasar jets seen end-on

BL Lac

- 1970: “Radio quiet” quasars (w/o jets?)
- 1974: Fanaroff & Riley Classes I & II; <u>all radio quasars seemed to be FR II objects</u>

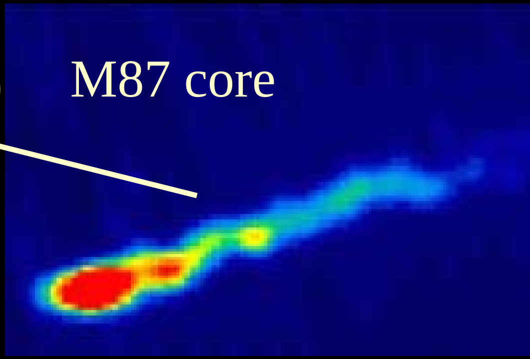


Type I



Type II

- 1981: “Superluminal” motion and relativistic jets ($1.005 < \gamma_{jet} < 25$; $0.1c < v_{jet} < 0.999c$); 3C 273, 3C 279
- 1993: Helical, “wiggled” jets deep in the radio galaxy core (Conway & Murphy 1993; Reid 1998)



- 2001: Some “radio quiet” quasars are FR I radio sources (Blundell & Rawlings 2001); <u>even RQQs have jets!</u>

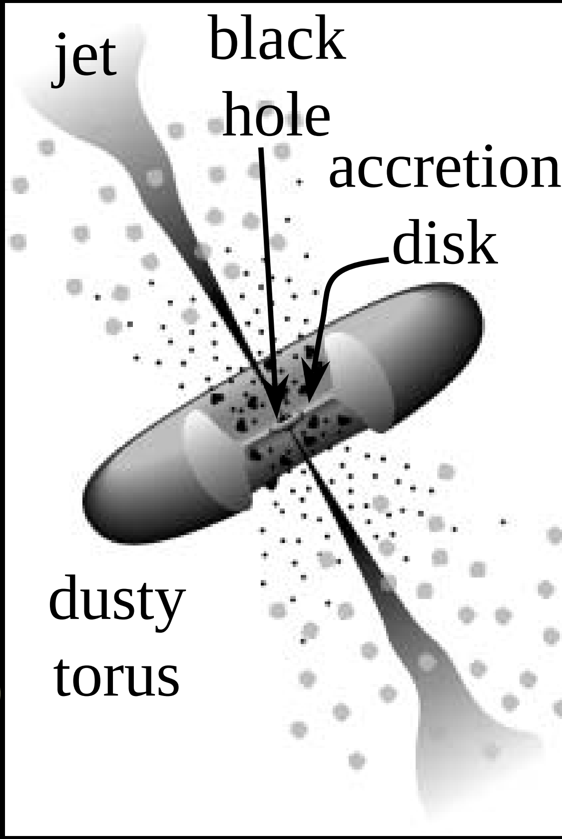
Current Grand Unified Model For All Active Galactic Nuclei

- Unification by viewing angle:
  FR I radio galaxy ⇒ BL Lac;
  FR II radio galaxy ⇒ radio QSR;
  Seyfert 2 ⇒ Seyfert 1

- Unification by black hole mass:
  Seyfert (10^7 $M_\odot$) ⇒ QSO (10^9 $M_\odot$)

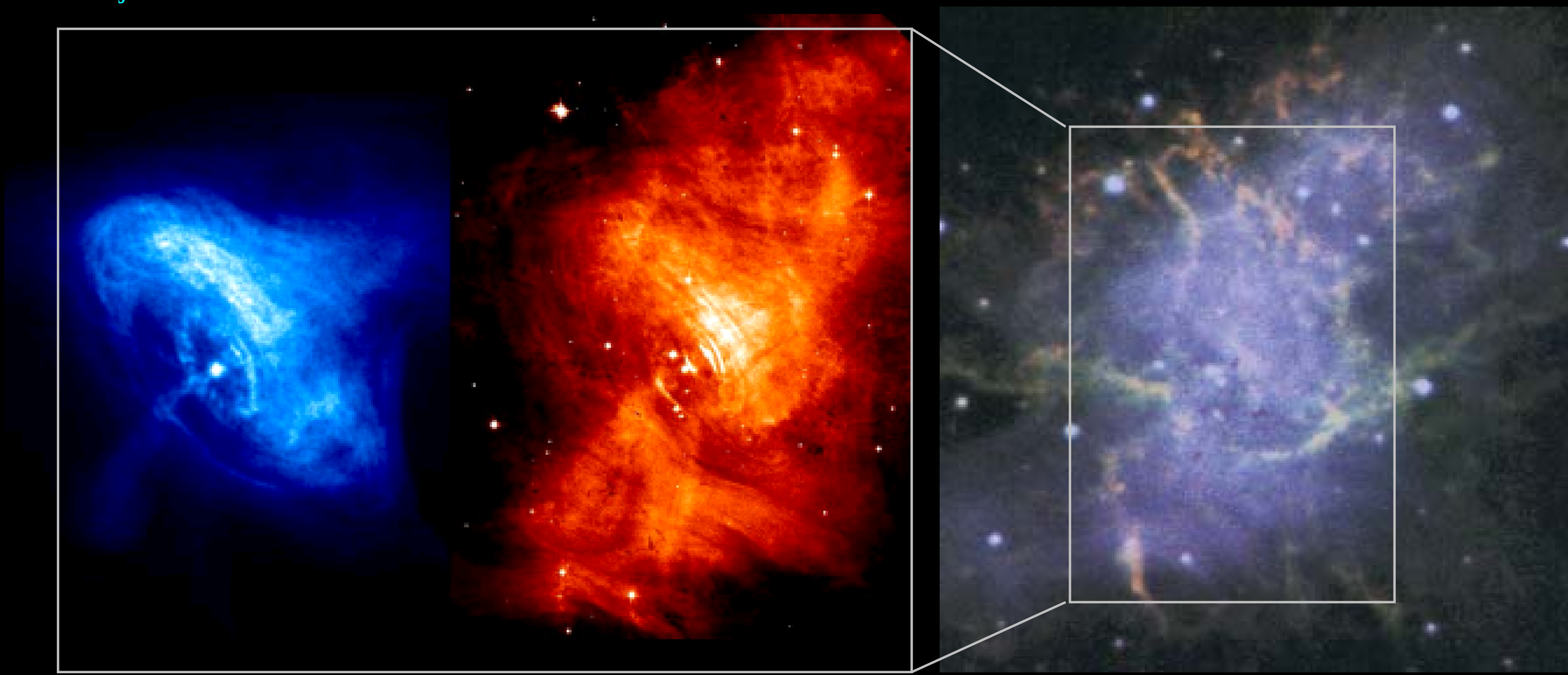
- Unification by accretion rate:
  LLAGN ($dm/dt << 1$) ⇒ Sy/QSO ($dm/dt \sim 1$)

- Unification by black hole spin:
  Radio quiet QSO ⇒ Radio loud QSR



Cosmic Jets from Dead Stars:
Isolated Neutron Stars

- 1968: Radio pulsar discovered in Crab Nebula (M1)
- 1969: Magnetic pulsar winds suggested as explanation for Crab Nebula energy source (Michel; Goldreich & Julian; Gunn & Ostriker)
- 1970: Pulsars must be born with large "kick" velocities (150 km s^{-1})
- 2002: HST/Chandra optical/X-ray movies of Crab Nebula **(**Hester et al.**);** $v_{jet} \sim 0.5c$; pulsar moves in the direction of this jet at ~ 150 km s^{-1}



Cosmic Jets from Dead Stars:
Neutron Stars, White Dwarfs, and Black Holes
In Binary Star Systems

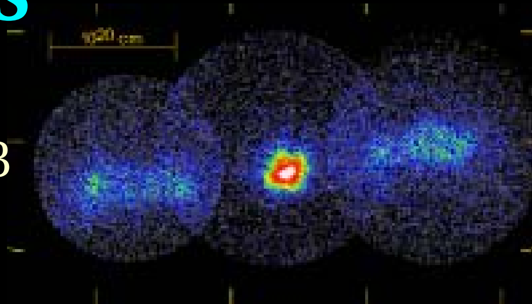
Some Examples:

- 1979: Discovery of SS 433 jets (Margon *et al*. 1979); v_{jet} = 0.26 c; possible rapidly-accreting neutron star

- 1980: Discovery of jets in Symbiotic stars — accreting white dwarf binaries (Herbig 1980; Kafatos & Michalitsianos 1982); v_{jet} <= 0.02 c

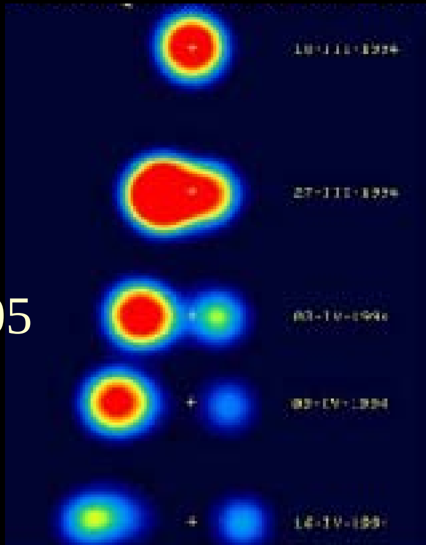
- 1992-4: Discovery of jet in black hole X-ray binary GRS 1915+105 (Castro-Tirado *et al*. 1992); v_{jet} ~ 0.87–0.98 c

SS 433



R Aquarii

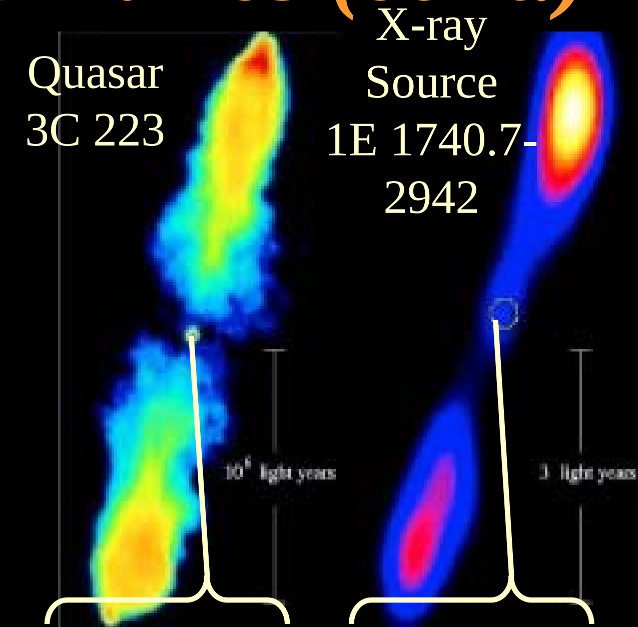
GRS 1915+105

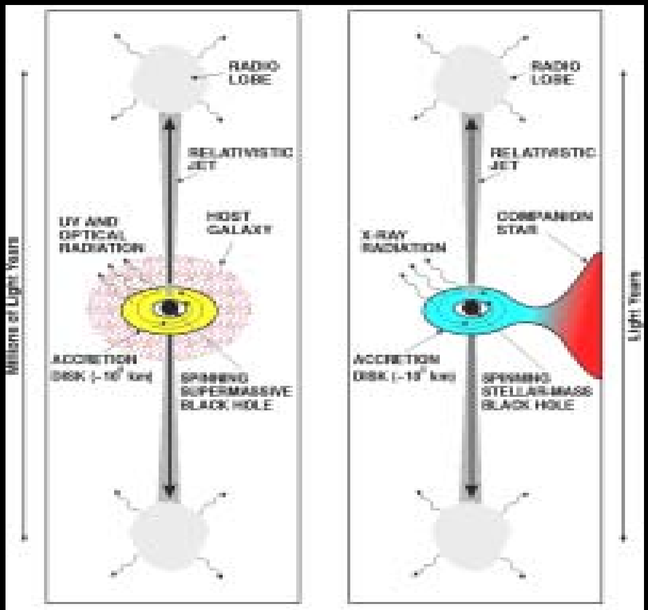


Cosmic Jets from Dead Stars:
Stellar-Mass Black Holes in Binaries (cont.)

- 1992-4: Discovery of Microquasars (Mirabel & Rodriguez) and superluminal motion ($1.005 < \gamma_{jet} < 25$; $0.1c < v_{jet} < 0.999c$)
- 1998: X-ray 'dips' (loss of inner accretion disk) associated with radio jet ejection
- 2002: 3C 120 Seyfert galaxy shows a similar X-ray dip when radio jet blobs ejected (Marscher *et al*. 2002)

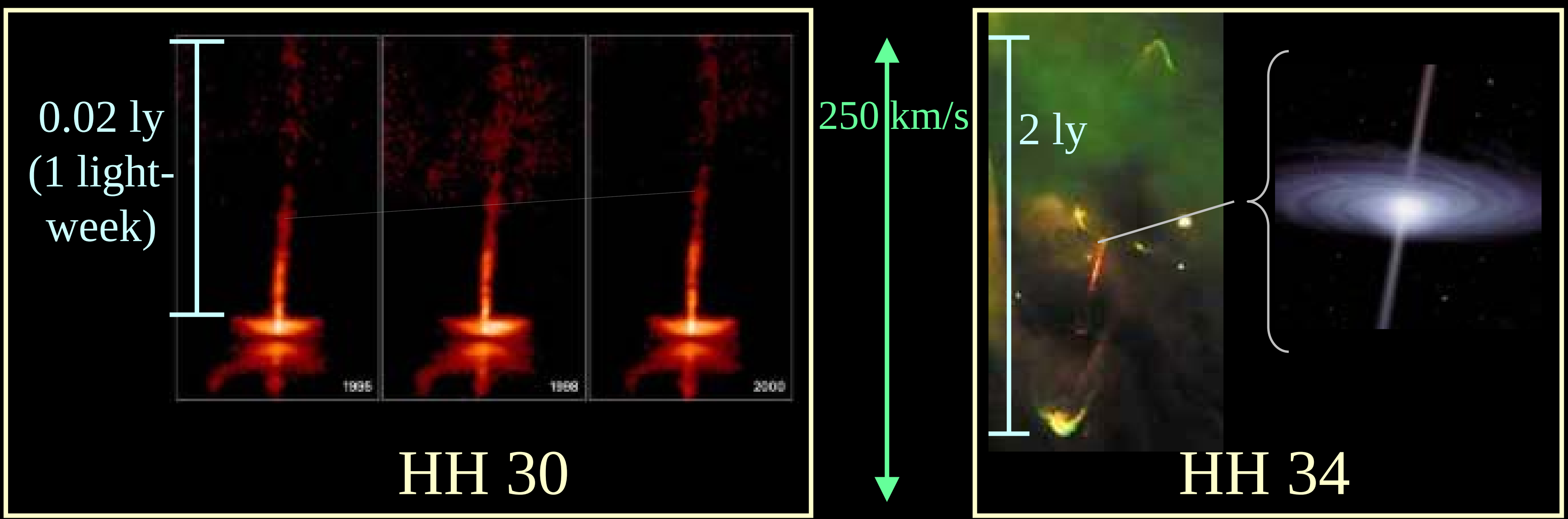
⇒ Jets from supermassive black holes and from stellar-mass black holes are very, very similar





Cosmic Jets from Stars Being Born: Proto-planetary Systems

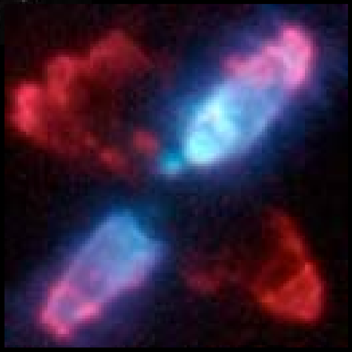
- 1981: First star-formation bipolar outflows discovered
- 1995: Jets associated with proto-planetary accretion disks (HST)



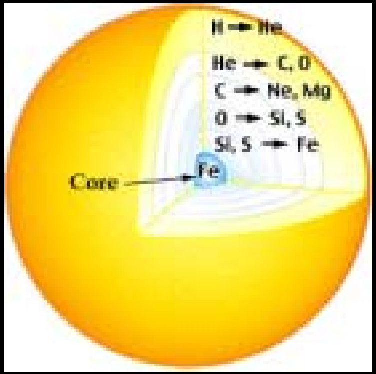
⇒ Jets appear to be ejected at roughly the escape velocity of the central star ($v_{jet} \sim v_{esc} \sim 0.0005c$)

Cosmic Jets from Dying Stars: "Planetary" Nebula Systems

- Death of a star < 10 $M_{\odot}$ in mass
  - Enters the red giant/supergiant phase near end of its life
  - Benignly ejects a "planetary" nebula
  - Leaves behind a white dwarf (< 1 $M_{\odot}$; < 10^9 cm in size)
- 1996-7: First planetary nebula jets discovered (velocities up to v_{jet} ~1000 km s^{-1})

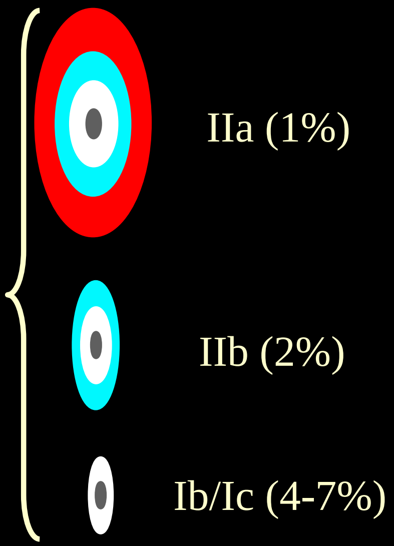



Cosmic Jets from Dying Stars: Supernovae



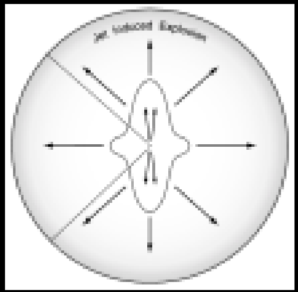
- Death of a star 10 - 30 $M_\odot$ in mass
  - Enters the red supergiant phase near end of its life
  - Iron core collapses to **neutron star**
  - Outer envelope violently ejected: luminosity ~ 10^{44} erg s^{-1} for few months (total ~10^{51} erg of energy)
- 1991: First evidence for jets in SN explosions: polarization of core-collapse supernova ejecta

  (Wang *et al.* 1996, 2001; Leonard *et al.* 2000, 2001)
  - Probably electron scattering from an asymmetric explosion
  - *Π* increases the deeper we see into the into the SN core
  - *Π* increases with time (becomes more asymmetric)
  - *Π* direction remains constant in time and wavelength



- Conclusions:
  - Core-collapse supernovae have a global prolate shape that appears to be associated with the central engine
  - A jet is producing energy comparable to the explosion itself and significantly altering the shape of the envelope

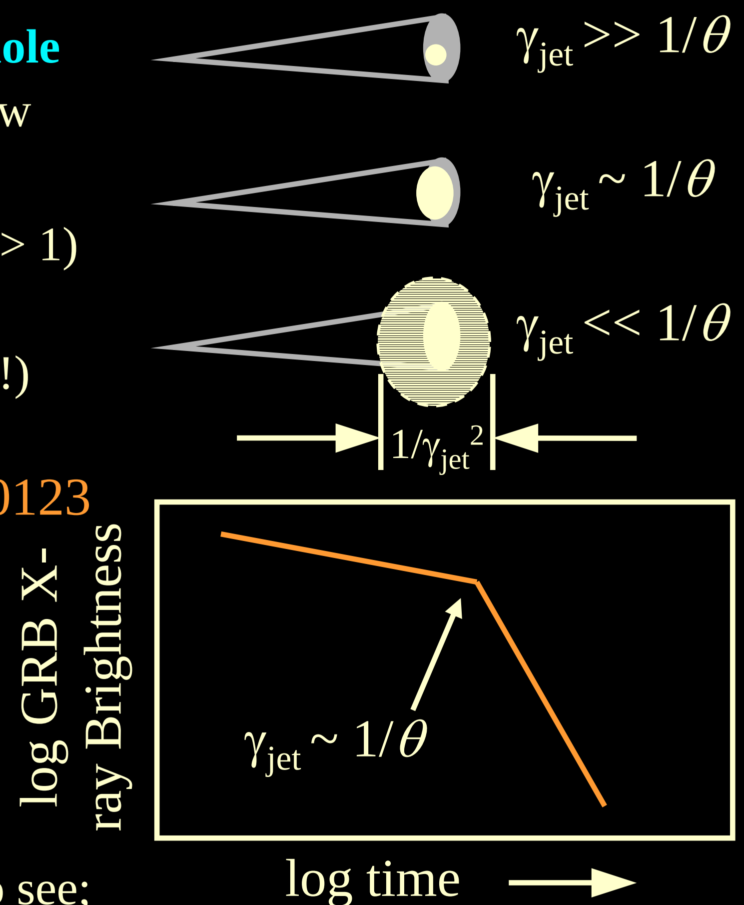
    ⇒ The explosion itself may be powered by a jet



Cosmic Jets from Dying Stars: Gamma-ray Bursts

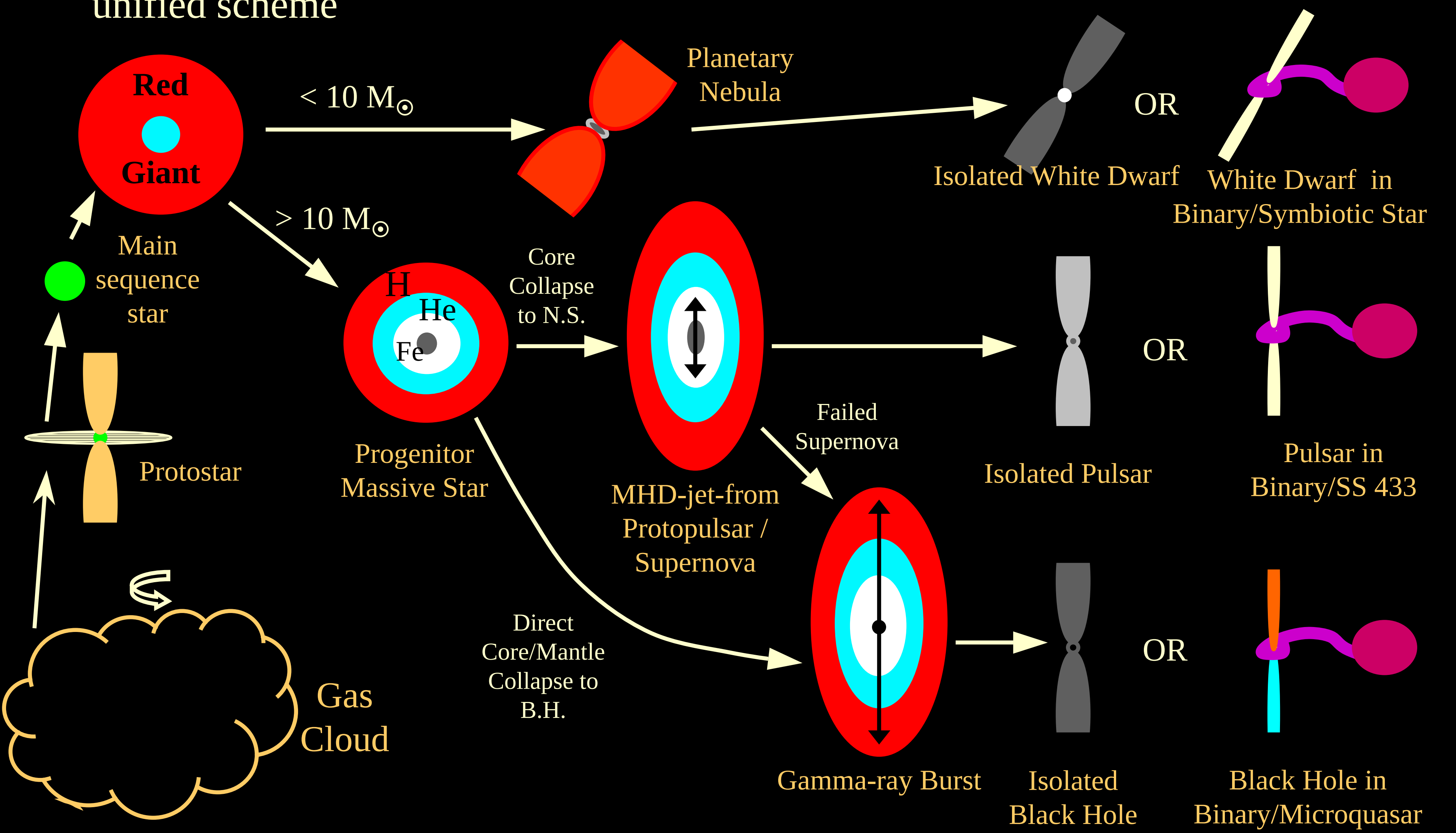
- Death of a star > 30 $M_\odot$ in mass
  - Red supergiant core expected to collapse to **black hole**
  - Observational consequences of this unclear until now
- "Long-duration" Gamma-ray Burst (1 – 2 per day)
  - Bright flash of gamma-rays, usually at very high z (> 1)
  - Lasts only of order seconds (2 - 300 seconds)
  - Apparent luminosity up to ~ 10^{52} erg s^{-1} ($10^8 \times$ SN!)
- 1999: First conclusive evidence for GRB jet: the "beaming break" in the light curve of GRB 990123

  (Rhoads 1998; Castro-Tirado et al. 1999)
  - GRBs have relativistic outflow (γ ~ 300 initially)
  - Can only see solid angle $\delta\Omega \sim 1/\gamma^2$ of outflow
  - As flow decelerates, we see more of outflow
  - If flow is a jet with opening angle θ, when $\gamma_{jet} \sim 1/\theta$, we have seen all of the jet there is to see; GRB X-ray light curve begins to decay faster
- Conclusions:
  - GRBs are, indeed, jets with θ ~ few degrees
  - Typical GRB jet energy ~10^{51} erg > ~ energy of SN



Proposed Grand Unified Model For All Stellar Jet Sources

- Supernova, GRB, and isolated pulsar jets provide missing links in a grand unified scheme



Characteristics of ALL Jet Sources

- Occur when there is accretion, shrinkage, or collapse of plasma in a gravitational field
- Occur in systems that are probably in a rapid rotation state
  - Conservation of angular momentum implies that <u>even a slight amount of rotation would be amplified greatly by collapse</u>
- Are associated with magnetic fields
  - Radio jets emit via the magnetic synchrotron mechanism
  - Jets are produced by stars that we believe have a strong magnetic field (pulsars, protostars, accretion disks)

⇒ The occurrence of jets appears to be a result of excess angular momentum produced in accretion or collapse

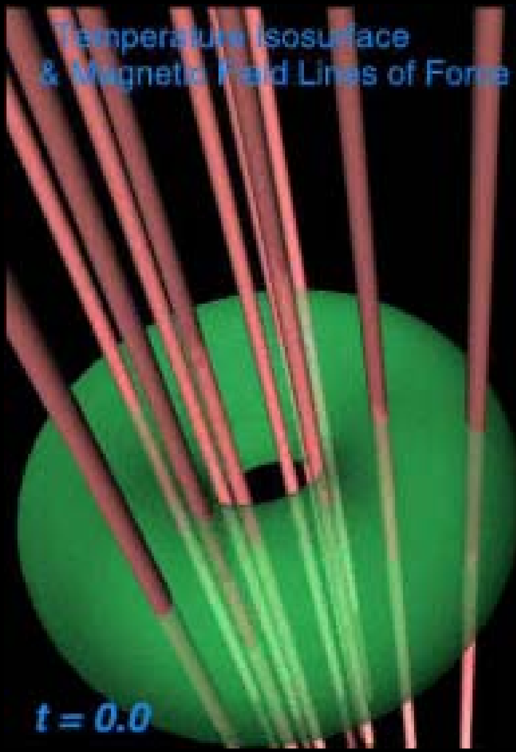
<u>A jet represents the expulsion of that excess angular momentum by magnetic processes</u>

Production of Cosmic Jets By Rotating Magnetized Systems

1. Jet Launching

Basic Principles of Magnetohydrodynamic Jet Production

- Basic MHD mechanism: Blandford (1976); Lovelace (1976)
  - Acceleration by rotating black holes (Blandford & Znajek [1977])
  - Acceleration by rotating [thin] accretion disks (Blandford & Payne [1982])



- First numerical simulations: Uchida & Shibata (1985)

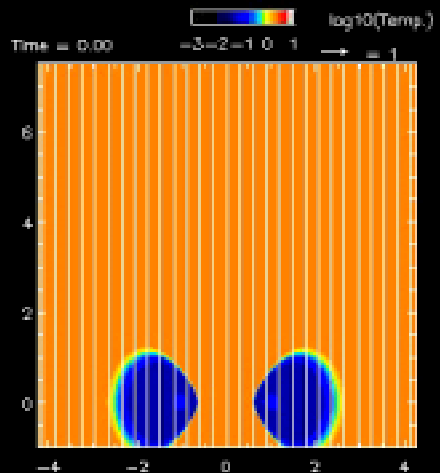
- Key ingredients in their “Sweeping Pinch” mechanism
  - Thick accretion disk or torus
  - Keplerian differential rotation ($\Omega \propto R^{-3/2}$)
  - Initial strong vertical magnetic field (strong enough to slow disk rotation)
  - $\mathbf{J} \times B$ force splits up into magnetic pressure and tension:

$$-\nabla \, (B^2 / 8\pi) \; + \; (\mathbf{B} \bullet \nabla \mathbf{B}) \, / \, 4\pi$$

Basic Principles of Magnetohydrodynamic Jet Production (continued)

- Typical results (e.g., Kudoh et al [1998]; Uchida et al. [1999])
  - Differential rotation twists up field into toroidal component, slowing rotation
  - Disk accretes inward, further enhancing differential rotation and B_φ
  - Greatest field enhancement is at torus inner edge

Uchida et al. (1999)



Kudoh, Matsumoto, & Shibata (1998)

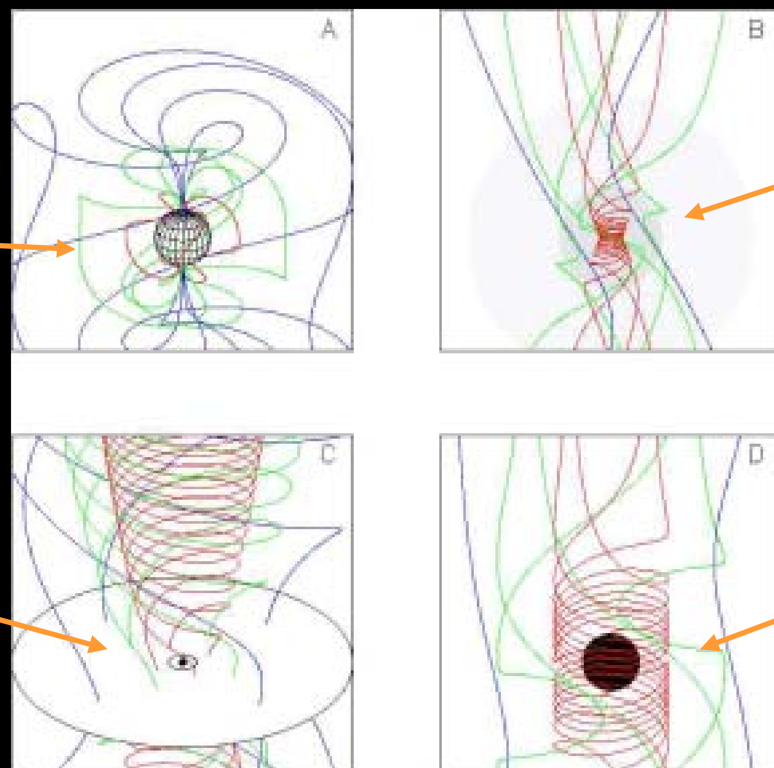
  - Magnetic pressure gradient (dB_φ^2 / dZ) accelerates plasma out of system
  - Magnetic tension [hoop stress] ($-B_\varphi^2/R$) pinches and collimates the outflow into a jet
  - Outflow jet speed is of order the escape velocity from the inner edge of the torus ($V_{jet} \sim V_{Alfven} \sim V_{esc}$)
  - Jet direction is along the rotation axis

Basic Principles of Magnetohydrodynamic Jet Production (continued)

- This basic configuration of differential rotation and twisted magnetic field accelerating a collimated wind can be achieved in all these micro- and macro-quasar-like objects

Pulsar magnetosphere, beyond the light cylinder

Collapsing, magnetized supernova core



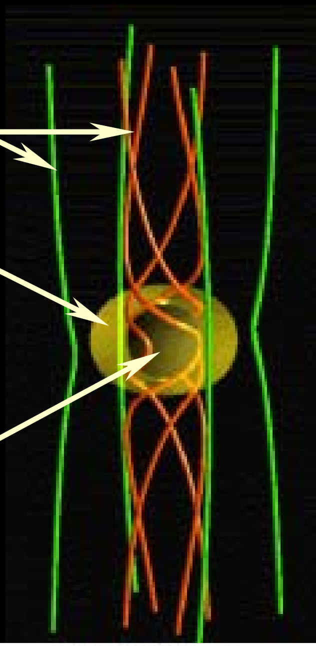
Magnetized accretion disks around white dwarfs, neutron stars, and black holes

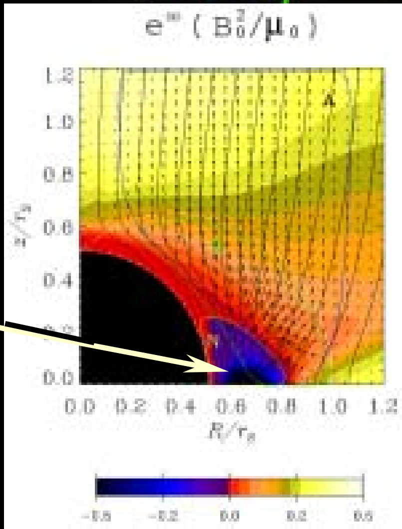
Magnetospheres of Kerr black holes, with differentially-rotating metric

- A good working hypothesis, therefore, is that all jets are created by similar MHD/electrodynamic processes

The Special Case of Kerr Black Holes: Indirect Magnetic Coupling

- Kerr hole (*a/M*=0.99995) accreting magnetized plasma:
  Koide, Shibata, Kudoh, & Meier (2002)
  - Electromagnetic power is ejected along the rotation axis by electromagnetic processes alone
  - This Poynting Flux power should eventually be turned into particles and a very fast jet
- Similar, but not identical, to Blandford-Znajek process
  - Magnetic field is tied to infalling plasma, *not horizon*
  - Frame dragging in the ergosphere twists up the field lines just as in the non-relativistic accretion disk case
  - Back-reaction of the magnetic field accelerates the ergospheric plasma to relativistic speeds *counter to the hole's rotation*: *negative energy plasma*
  - *Accretion of this negative energy plasma spins down the hole*
- More closely-related to the Punsly-Coroniti (1990) process ("ergospheric winds")





Important Point on Black Hole Spin

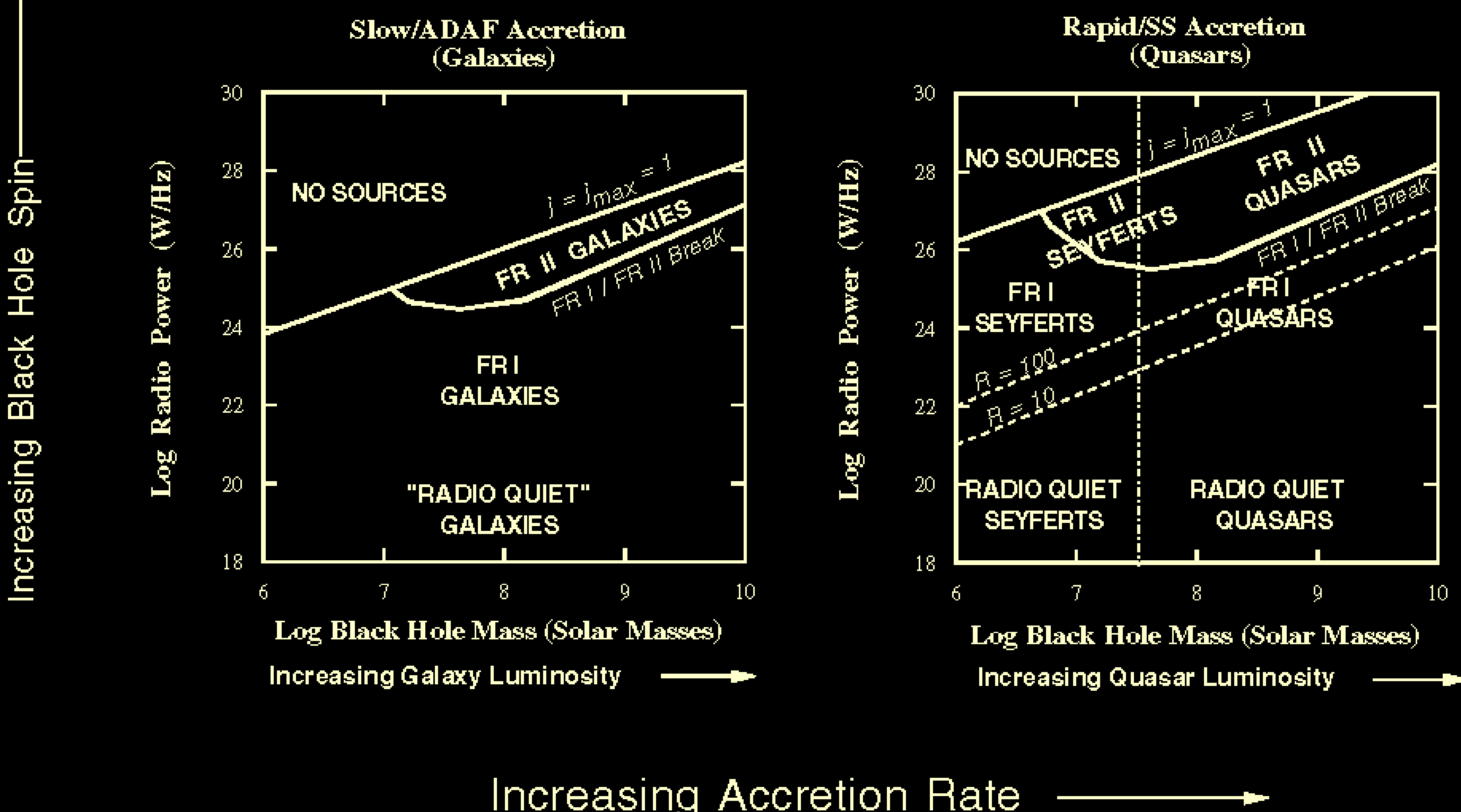
- Because these mechanisms extract black hole rotational energy, B.H. spin can provide a third unifying parameter for AGN (in addition to M, dM/dt) to throttle the jet power
  - **Quasars with the same**
    - **Mass M**
    - **Accretion rate dM/dt**
    - **Can differ in radio power by several orders of magnitude**
    - **There must be an important third parameter**
  - **In jet production models that launch via B.H. spin**

$$P_{jet} \sim L_{Edd} \, (dm/dt) \, (a / M)^2$$

Proposed Grand Unified Model for Extragalactic Relativistic Jet Sources

(Beyond Viewing Angle Effects)

Theoretical Owen-Ledlow Diagrams



Geometrically Thick Accretion Flows Are More Efficient at Launching Jets

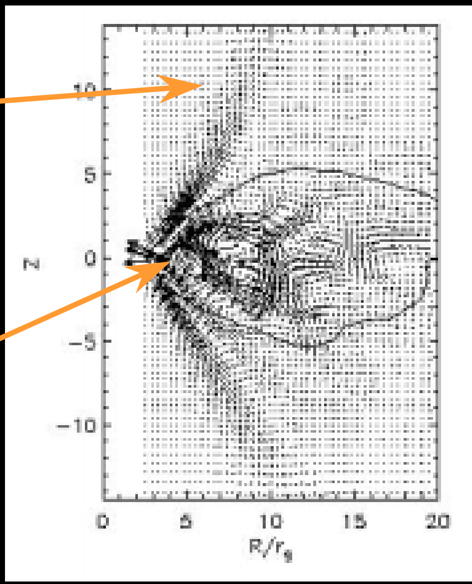
- Thicker disks have stronger MHD power (Meier 2001): $H \sim R \Rightarrow$ stronger poloidal magnetic field $B_p \sim (H/R)\, B_\phi$

$$L_{jet} = B_\phi^2 H^2 R^2 \Omega^2 / 4c$$

- Thermal pressure can assist jet production: Thicker, hotter disk lifts plasma out of deep potential well, making jets easier to launch
- One or both of these effects may be at work in recent 3-D MRI simulations by Hawley & Balbus (2002):
- These theoretical arguments are consistent with Fender (1999) <u>jets are suppressed in geometrically thin disks</u> by a factor > 35
- **<u>But very little accretion-jet work is being done</u>**

Magnetically-confined jet ONLY from geometrically thick portion

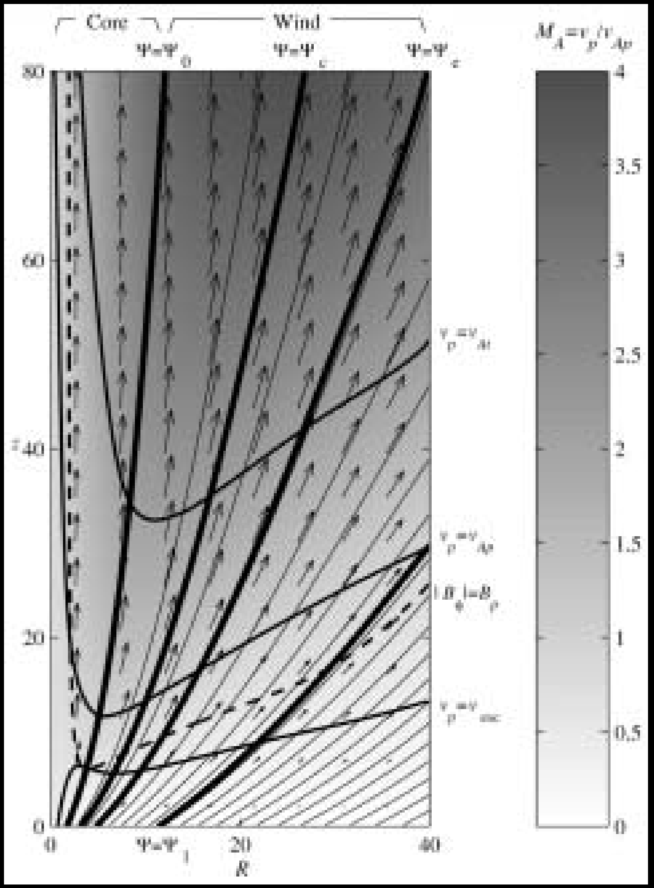
Thick, turbulent disk



2. Acceleration and Collimation

Slow Acceleration and Collimation Probably is the Norm for A.D. Winds

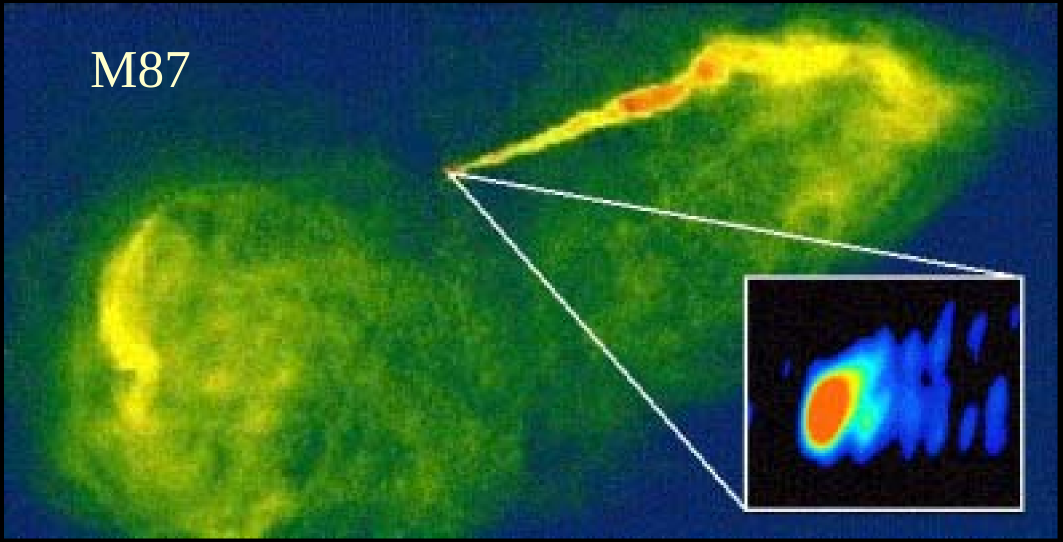
- Example: simulations of magnetized accretion disk winds (see, e.g., Krasnopolsky, Li, & Blandford 1999)
- After several dynamical times, the system reaches a steady state
  - Flow accelerates smoothly, reaching escape velocity and then the local Alfvén speed(s)
  - Collimation is slow but steady, reaching a jet-like state far away from the disk
  - Outflow speed is of order the escape velocity at the base of the flow
- Conclusion: Jet outflow is initially broad, slowly-collimating and slowly-accelerating



Krasnopolsky, Li, & Blandford (1999)

Slow Acceleration and Collimation (continued)

- NOTE: There is some observational evidence for slow collimation and broad outflow at the base of extragalactic jets
  - Junor, Biretta, & Livio (1999):
    VLBA image of M87 shows wide outflow at the base
  - Sikora & Madejski (2001):
    The base of *most* quasar jets *must* be broad, because they lack soft X-ray emission



- For binary black holes, slow collimation would occur over 100 $r_S \approx 10^8$ cm or 2 nas at 3 kpc

3. Attaining, and Maintaining, Relativistic Speeds

Highly-Relativistic Flow Probably Produced By Strong Magnetic Fields

- By definition, $\gamma >> 1$ implies $E_{kinetic} >> \rho c^2$

  $\Rightarrow$ low "mass loading" of the jet flow

- For a magnetic jet $v_{jet} \rightarrow V_{Alfven}$, so relativistic $\gamma_{jet} >> 1$ flow can be produced by having a very strong rotating magnetic field such that

  $\gamma_{Alfven} \approx V_{Alfven}/c = B/\sqrt{4 \pi \rho c^2} >> 1$

  $\Rightarrow$ low "mass loading" of the field lines (Poynting-Flux-Dominated)

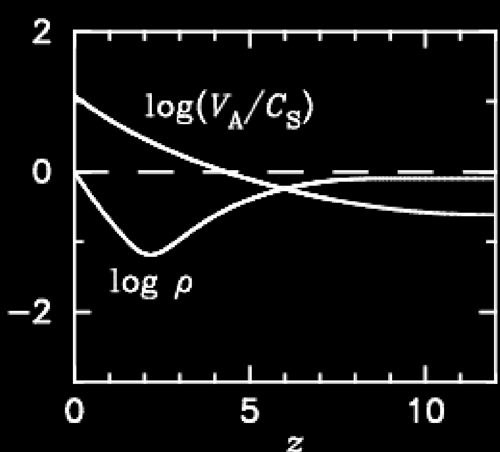
- The jet remains Poynting flux-dominated (PFD) if its speed remains <u>supersonic but sub-Alfvenic</u> ($c_s < v_{jet} < V_A$)

$$\frac{\dot{E}_{Poynting}}{\dot{E}_{kinetic}} = \frac{\frac{c}{8\pi}\left|\mathbf{E}\times\mathbf{B}\right|}{v_{jet}\,\frac{1}{2}\rho v_{jet}^2} = \frac{B^2}{4\pi\rho v_{jet}^2} = \left(\frac{V_A}{v_{jet}}\right)^2 > 1 \qquad \frac{\dot{E}_{fields}}{\dot{E}_{particles}} = \frac{v_{jet}\, B^2/4\pi}{v_{jet}\,\rho c_S^2} \approx \left(\frac{V_A}{c_S}\right)^2 >> 1$$

3D Numerical Simulations of Poynting-Flux-Dominated Jets

- Models of PFD jets have been built (*e.g.*: Li *et al.* 1992; Lovelace *et al.* 2001; Li *et al.* 2002; Vlahakis & Konigl 2002), but
  no full numerical simulations have produced highly *relativistic* jets yet

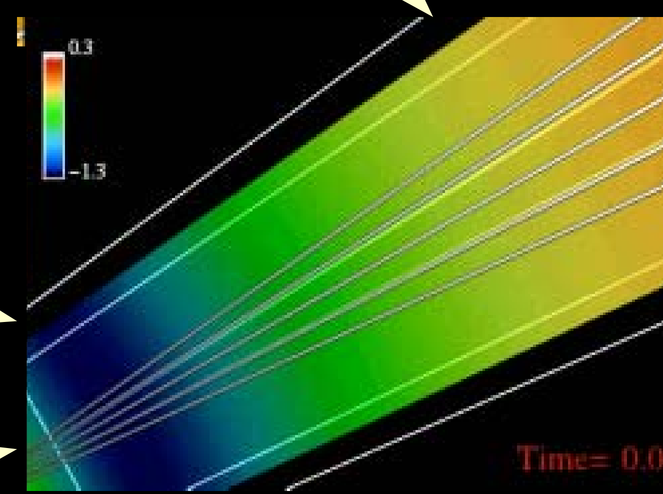
- Best results to date are from 3-D *non-relativistic* simulations (Nakamura et al. 2001, Nakamura & Meier 2003)



Field buckles when density gets too high

Flow is stable in decreasing density region

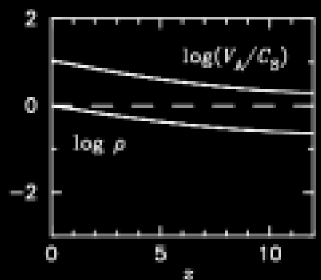
Twisting magnetic field at base

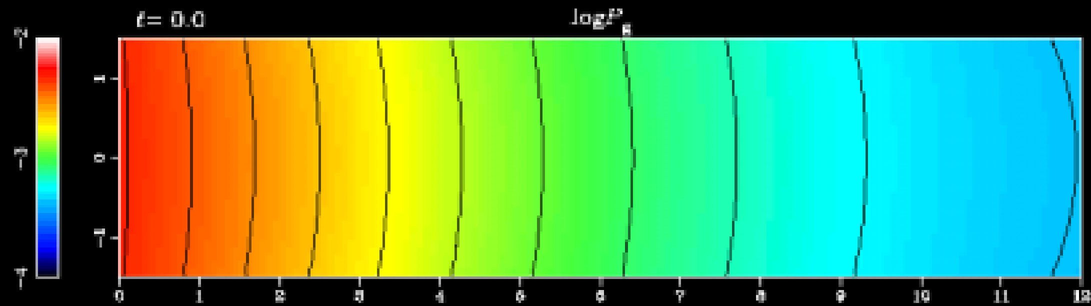


3D Numerical Simulations of Poynting-Flux-Dominated Jets

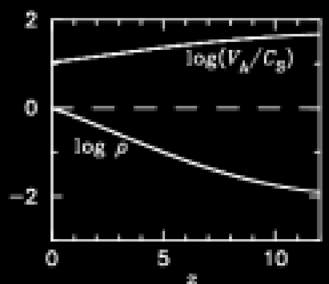
(Nakamura & Meier 2003)

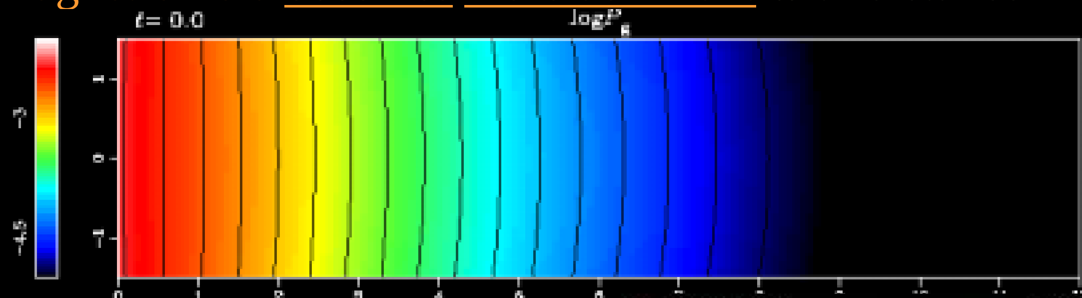
- Stability of PFD jets in decreasing density galactic atmospheres
  - For stability, a strong magnetic field ($V_A/c_S > 1$) is certainly necessary, but not sufficient



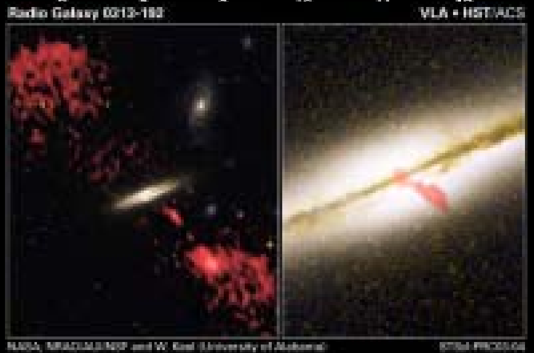


  - Jet is usually stable if the magnetic field becomes more dominant with distance





  - Process may be related to why spiral galaxies (with relatively large amounts of gas) generally do not produce large FR I / FR II radio sources except in rare cases when jet $\perp$ disk plane (Keel et al 2003)



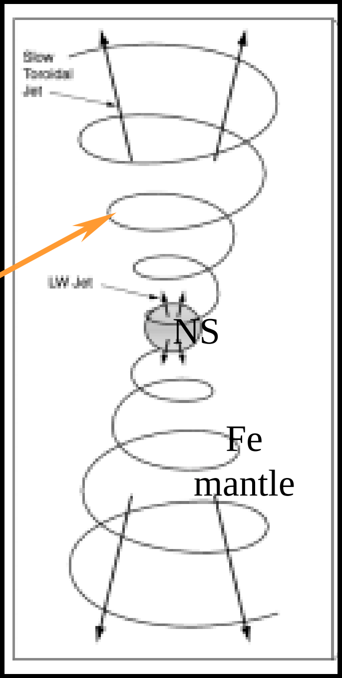
4. Special Applications:
Supernovae & Gamma-ray Bursts

MHD Jet-Powered Supernovae
(Wheeler, Meier, Wilson 2002)

- Many authors have proposed powering both classical and GRB supernovae by jets and/or MHD processes
  - Classical SN: LeBlanc & Wilson 1970; Bisnovatyi-Kogan 1971; Meier *et al*. 1976; Khokholov *et al*. 1999; Wheeler *et al*. 2000;
  - GRB SN: Woosley 1999; MacFadyen *et al*. 2001; Aloy *et al*. 1999; Ramirez-Ruiz *et al*. 2002
- New MHD jet-powered supernova model (Wheeler, Meier, Wilson 2002)
  - Jet *produced in iron mantle, above/outside proto-N.S., not inside*
  - Basic model
    - Proto-pulsar twists up magnetic field; proto-pulsar spins down
    - Produces slow, broad MHD wind/jet outflow for ~ 10 sec:

      $L_{MHD} = B^2 R^3 \Omega_{NS}/2 = 3 \times 10^{51}$ erg s^{-1} $B_{15}^2 R_{NS,6} (P_{NS}/1\text{ ms})^{-1}$

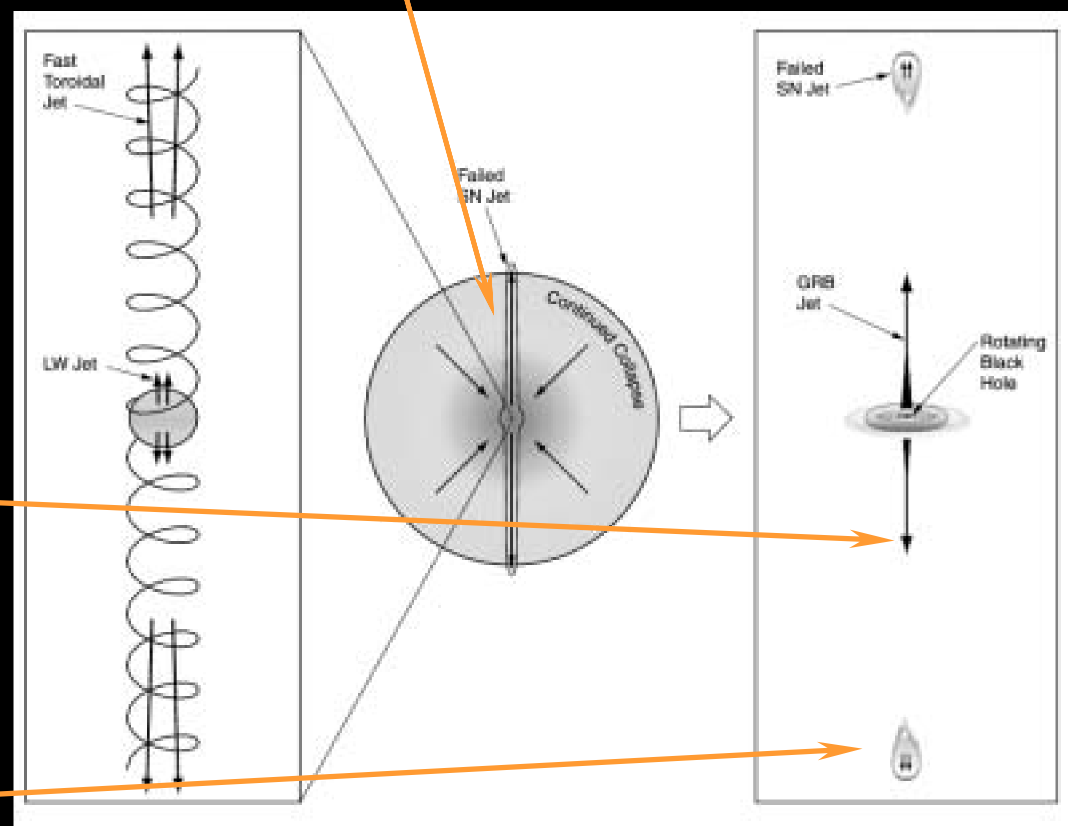
      $E_{rot,NS} = I_{NS} \Omega_{NS}^2/2 = 2 \times 10^{52}$ erg $(M_{NS}/1.5M_\odot)(P_{NS}/1\text{ ms})^{-2}(R_{NS,6})^2$
  - MHD outflow couples strongly to ionized iron mantle, ejecting it
  - Model is similar to Ostriker & Gunn (1971) idea except 10^{12} G pulsar fields are replaced by 10^{15} G *proto*-pulsar fields
  - Outflow is composed of iron-rich material



MHD Jet-Powered Supernovae (cont.)

- Model includes a γ-ray burst trigger in the magnetic switch
  - In rare instances, when $L_{MHD} > L_{crit}$ ($B > \sim 10^{16}$ G), jet becomes narrow and fast
  - Jet punches through mantle rather than coupling to it (Khokholov & Höflich 2001)
  - Explosion fails
  - Outer envelope may be ejected, but mantle falls back
- Failed supernova model for GRBs (Woosley 1999; MacFadyen *et al.* 2001) now may apply
  - Iron-rich jet produced by NS for ≤ 10 sec ($v_{jet} \sim 0.05\text{-}0.3$ c)
  - Mantle falls back over minutes to hours
  - NS crushed to rotating black hole
  - New $\gamma >> 1$ jet produced by BZ/PC mechanism
  - Relativistic jet catches up with slow iron-rich jet lobe at

    $R \sim v_{jet}\, \tau_{fallback} \sim 10^{12\text{-}13}$ cm
  - Interaction of fast and slow jets produces beamed gamma-rays



MHD Jet-Powered Supernovae (cont.)

- Questions & potential problems :
  - Can a 1 ms proto-pulsar be spun down to 10-100 ms in a few seconds by these jet-producing processes?
  - The 10^{14-15} G fields postulated are typical of magnetars, but whence the 10^{12-13} G fields of normal pulsars?
  - Are there other competing jet mechanisms (*e.g.*, neutrino jets, asymmetric bounce shock) that are viable?
  - The iron mantle is still neutron rich. Are *r*-process heavy elements still overproduced if mantle ejected? (problem for all SN models)
  - What causes some supernovae to fail and produce black holes? MHD/jet effects (*e.g.*, magnetic switch)? Explosion details (neutrinos, bounce shock)?

Summary and Conclusions

- Jets are produced whenever there is accretion, shrinkage, or collapse in a gravitational field
- The “purpose” of jets is to
  - Spin down the central object (remove excess angular momentum), even a central supermassive black hole
  - Impart energy to the interstellar and intergalactic media
  - Produce thrust to accelerate pulsars
  - Possibly explode supernovae
- Jets appear to be produced
  - By magnetic or electromagnetic processes near the central object
  - With approximately the escape velocity of the central object ($v_{jet} \sim v_{esc}$)
  - With initially a broad outflow, slowly accelerating and collimating via magnetic pressure and hoop stress (pinching)
- To remain stable, jets need
  - Strong magnetic fields (Poynting-flux-dominated; $V_A >> v_{jet} >> c_S$)
  - Steep external plasma gradients
- Even magnetically-dominated jets can be unstable to helical kinks and disruption