Physics in Strong Magnetic Fields

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ISSI Workshop on “Strongest Magnetic Fields In the Universe”
Bern, Switzerland, Feb.2-7, 2014

How Strong is "Strong"?

Depends on

Objects,
Questions/Issues…
Who you talk to…

For atomic physicists

Critical Field:

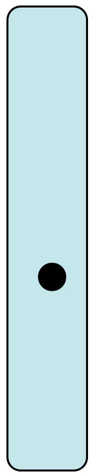
$$\hbar\omega_{ce} = \hbar\frac{eB}{m_e c} = \frac{e^2}{a_0} \quad \Longrightarrow \quad B = B_0 = 2.35 \times 10^9 \text{ G}$$

Strong field: $B \gg B_0$

Property of atoms/molecules is very different from zero-field

Atoms and Molecules

Strong B field significantly increases the binding energy of atoms



For $b = \frac{B}{B_0} \gg 1, \quad B_0 = 2.35 \times 10^9 \text{ G}$

$$|E| \propto (\ln b)^2$$

E.g. $|E| = 160 \text{ eV}$ at 10^{12}G

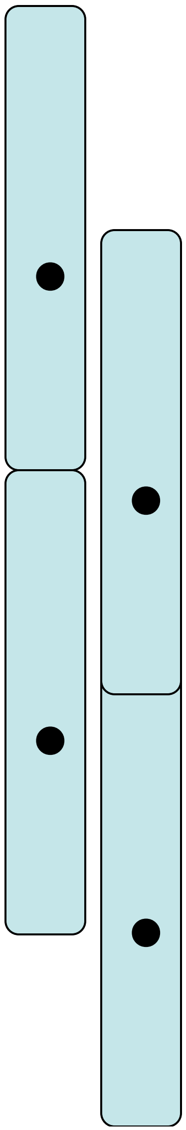
$|E| = 540 \text{ eV}$ at 10^{14}G

Atoms combine to form molecular chains:

E.g. $H_2, H_3, H_4, \ldots$

Condensed Matter

Chain-chain interactions lead to formation of 3D condensed matter



Binding energy per cell $|E| \propto Z^{9/5} B^{2/5}$

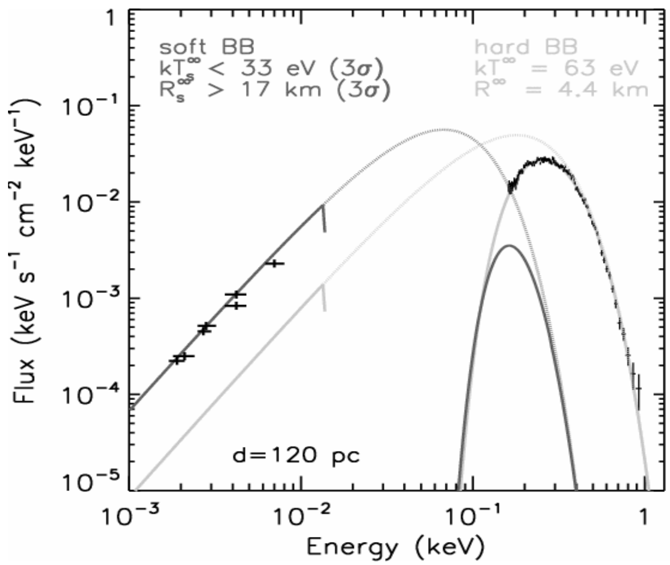
Zero-pressure density

$$\simeq 10^3 A Z^{3/5} B_{12}^{6/5} \text{ g cm}^{-3}$$

Thermally Emitting Isolated NSs

"Perfect" X-ray blackbody:

RX J1856.5-3754



Burwitz et al. (2003)

Spectral lines detected:

(e.g., van Kerkwijk & Kaplan 06; Haberl 06)

RXJ1308+2127 (0.2-0.3 keV)
RXJ1605+3249 (~0.45 keV)
RXJ0720-3125 (~0.3 keV)
RXJ0420-5022 (~0.3 keV)?
RXJ0806-4123 (~0.5 keV)?
RBS 1774 (~0.7 keV)?

Atmosphere is cool for atoms to exists

$\Longrightarrow B \sim 10^{13-14}$G? magnetar descendant & off-beam radio pulsar?

Spectral line for 10^9G WD…

For Condensed Matter Physicists

B fields affect the transport properties

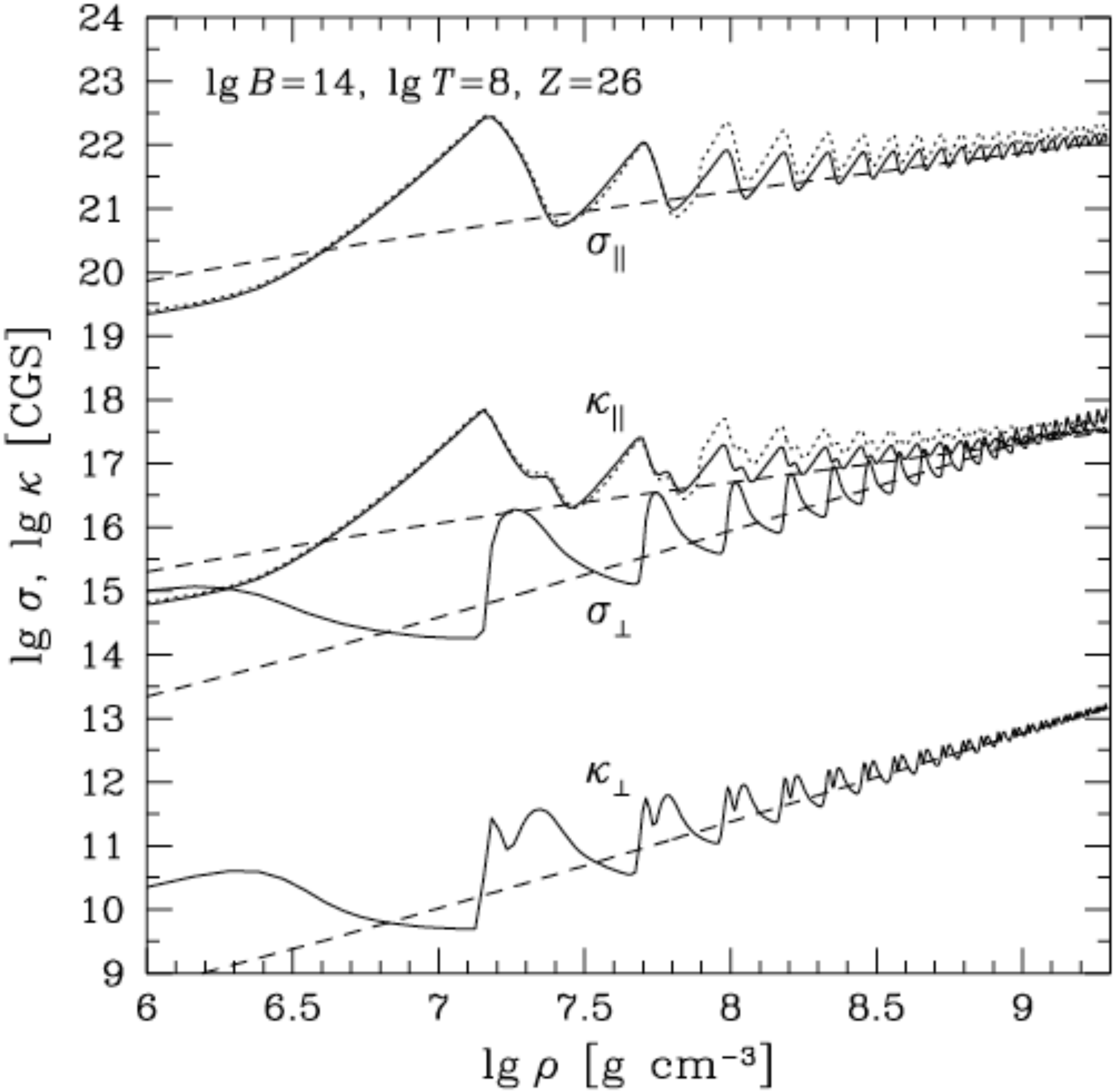
$$\text{gyrofrequency } \omega_c^* = \frac{eB}{m_e^* c} \gg \text{elecron collision frequency } \tau_0^{-1}$$

$\Rightarrow$ $\text{transverse conductivity suppressed by a factor of } (\omega_c^* \tau_0)^{-2}$

Affect thermal structure of NS envelope and cooling

(e.g. Hernquist, van Riper, Page, Heyl & Hernquist, Potekhin & Yakovlev etc.)

Heat and electric conductivities

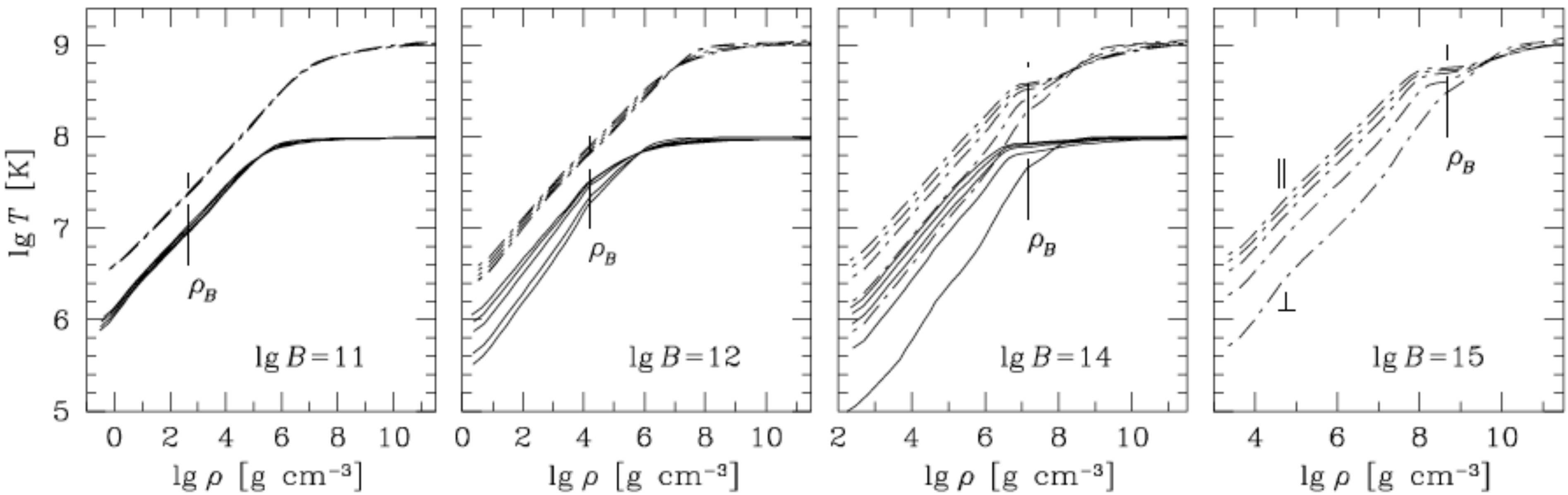


de Haas-van Alphen oscillations

Potekhin 1999

Nonuniform surface T due to anisotropic heat transport

- Region where B perpendicular to r: heat flux is reduced
- Region where B parallel to r: heat flux remains or increases (due to quantization)



Potekhin & Yakovlev 2001

For Particle Physicists

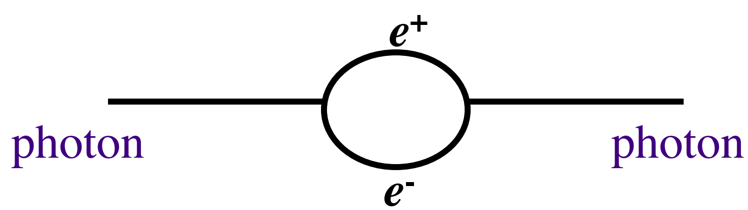
QED Processes in Superstrong B Fields

- **Photon splitting:**

$$\gamma \longrightarrow \gamma \quad + \quad \gamma$$

- **Vacuum birefringence:**

(photon propagation affected by B field)

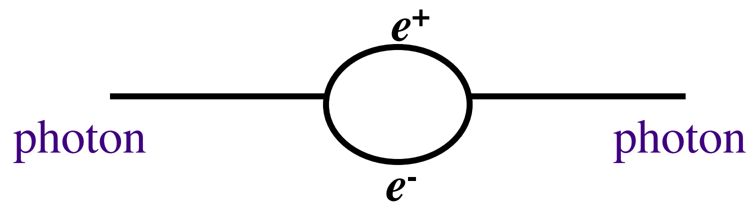


Critical Field:

$$\hbar\omega_{ce} = \hbar\frac{eB}{m_e c} = m_e c^2$$

➔ $$B_Q = 4.4 \times 10^{13}\ \mathrm{G}$$

Vacuum Polarization in Strong B



Heisenberg & Euler,
Weisskopf, Schwinger,
Adler…

Dielectric tensor: $$\boldsymbol{\varepsilon} = \mathbf{I} + \Delta\boldsymbol{\varepsilon}_{\mathbf{vac}}$$

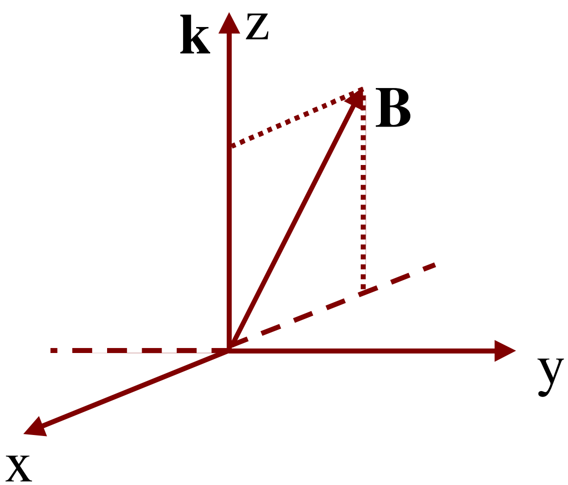
$$|\Delta\varepsilon_{\rm vac}| \sim 10^{-4}(B/B_Q)^2, \text{ with } B_Q = 4.4\times10^{13}\ \mathrm{G}$$

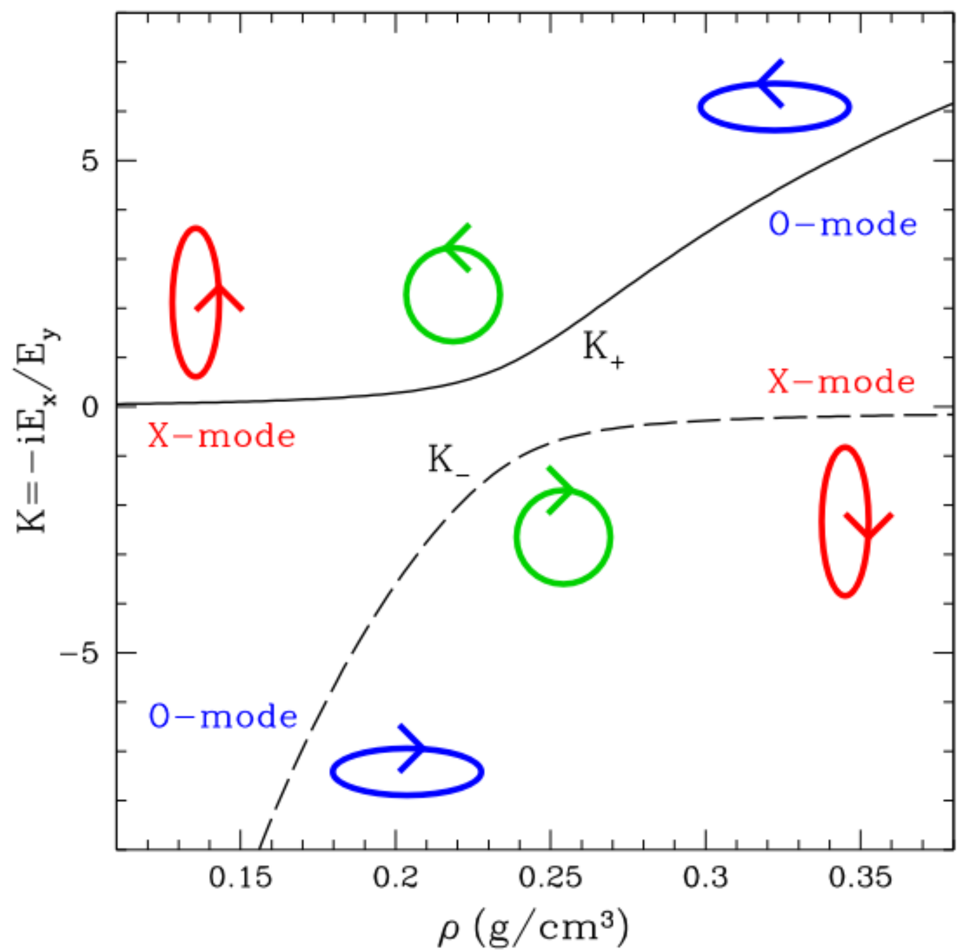
Two photon modes:

Ordinary mode (//)

Extraordinary mode (⊥)

"Plasma+Vacuum" ==> Vacuum resonance



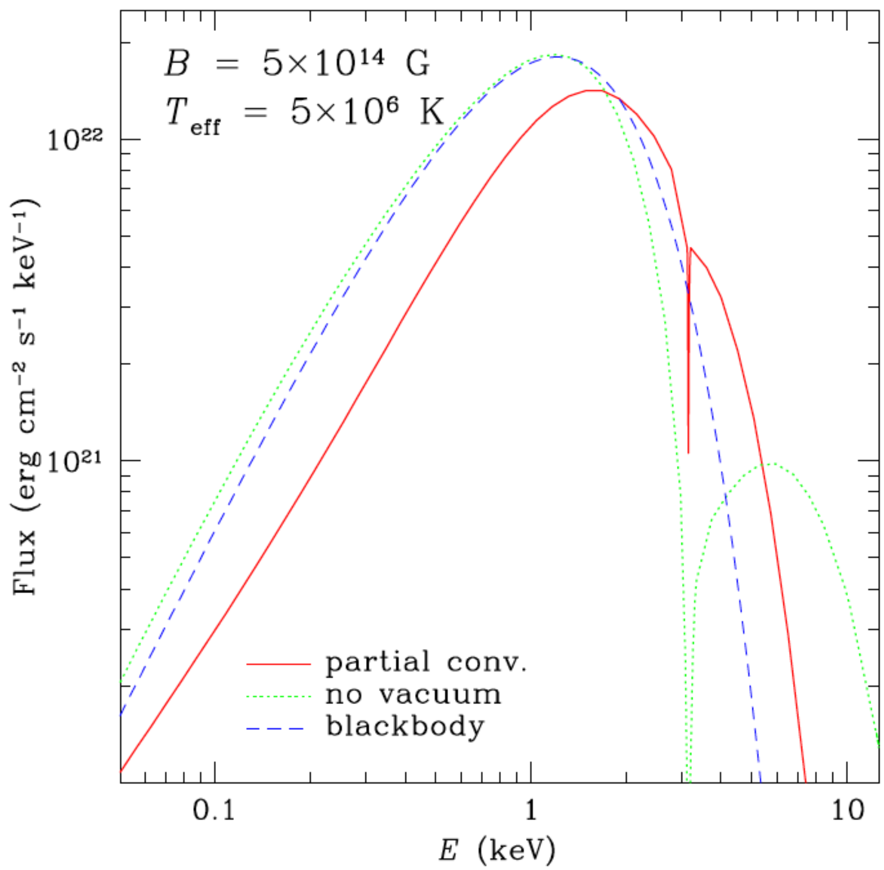


Astrophysical Consequence:

The two photon modes have very different opacities

=> Vacuum polarization can affect radiative transfer significantly

=> **Spectrum and polarization signal from the NS**



Van Adelsberg & DL 2006

For (Most) Astrophysicists

"Classical" B-fields can be "strong"

Their effects are important, interesting, rich…

“Clouds” and Stars/Compact Objects

“Clouds” and Stars/Compact Objects

Static equilibrium requires:

$$\frac{E_{\rm mag}}{E_{\rm grav}} \sim \frac{B_{\rm in}^2 R^3/6}{GM^2/R} \sim \frac{1}{6\pi^2 G}\left(\frac{\Phi}{M}\right)^2 < 1$$

If only large-scale poloidal fields

“Clouds” and Stars/Compact Objects

Static equilibrium requires:

$$\frac{E_{\rm mag}}{E_{\rm grav}} \sim \frac{B_{\rm in}^2 R^3/6}{GM^2/R} \sim \frac{1}{6\pi^2 G}\left(\frac{\Phi}{M}\right)^2 < 1$$

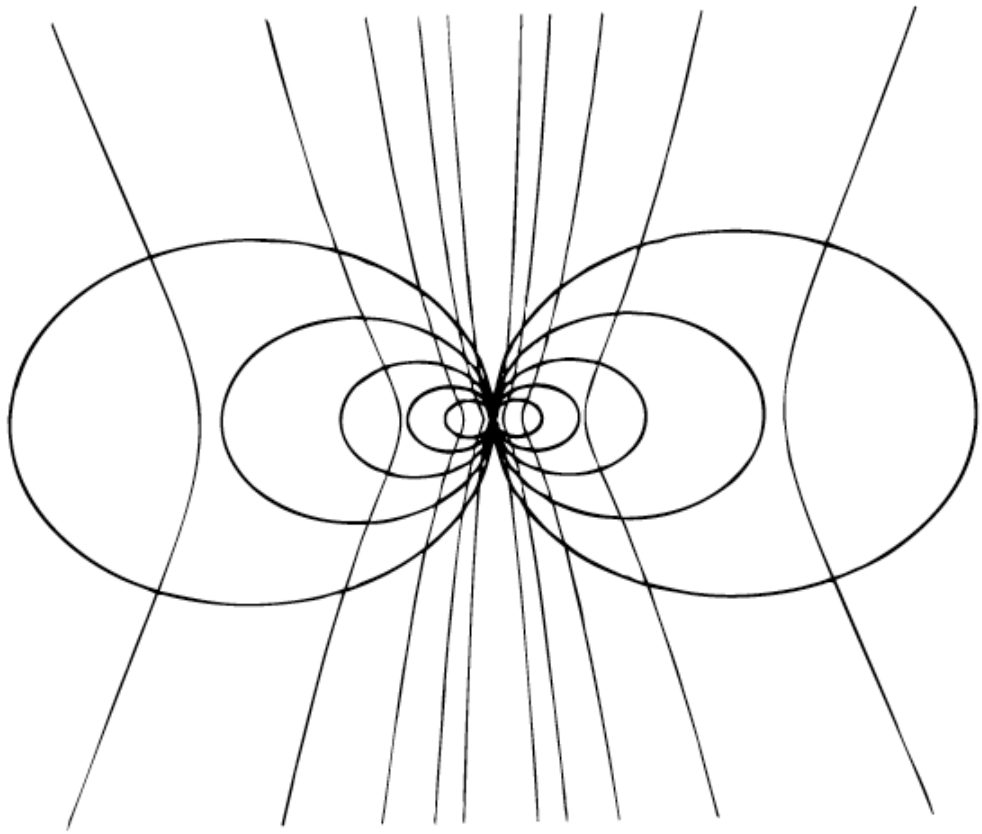
If only large-scale poloidal fields

Star formation:

Clouds with $E_{\rm mag}/E_{\rm grav} > 1$

Need ambipolar diffusion (low-mass star formation?)

Cloud Contraction via Ambipolar Diffusion



F. Shu, Li… 1996

“Clouds” and Stars/Compact Objects

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“Clouds” and Stars/Compact Objects

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If only large-scale poloidal fields

E.g. For Neutron stars: $B_{\rm in} < 10^{18}\,{\rm G}$

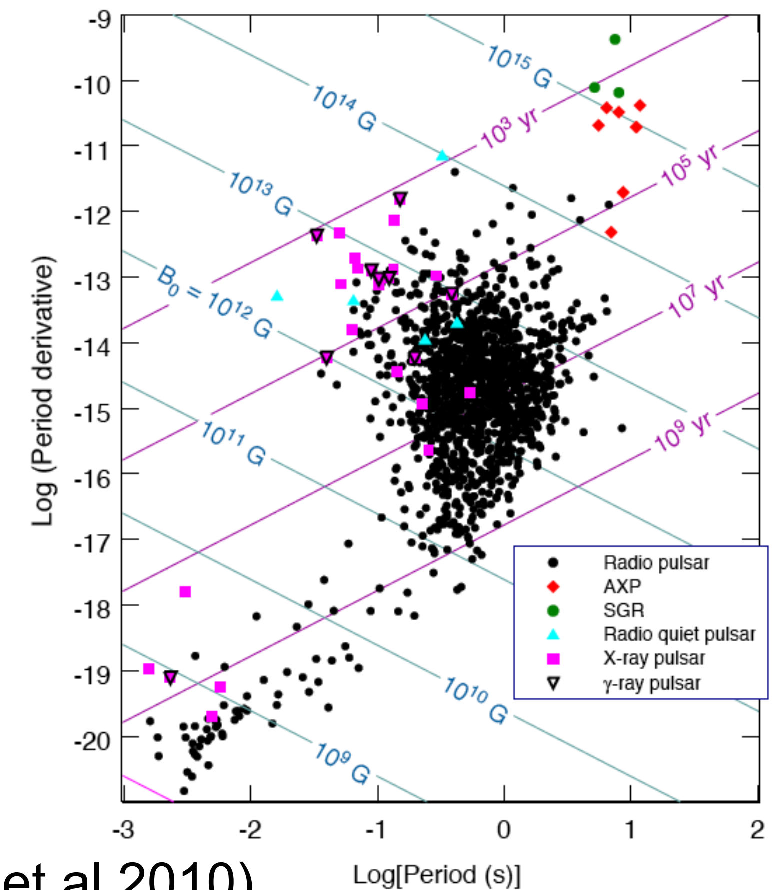
Magnetic Fields of Isolated Neutron Stars

Radio pulsars: $P, \dot{P} \Rightarrow$

$$\text{Most pulsars}: \ B \sim 10^{12-13} \text{ G}$$

$$\text{Millisecond pulsars}: \ B \sim 10^{8-9} \text{ G}$$

$$\text{High}-\text{B radio pulsars}: \ B \sim 10^{14} \text{ G}$$



Magnetars:

Neutron stars powered by B-Fields

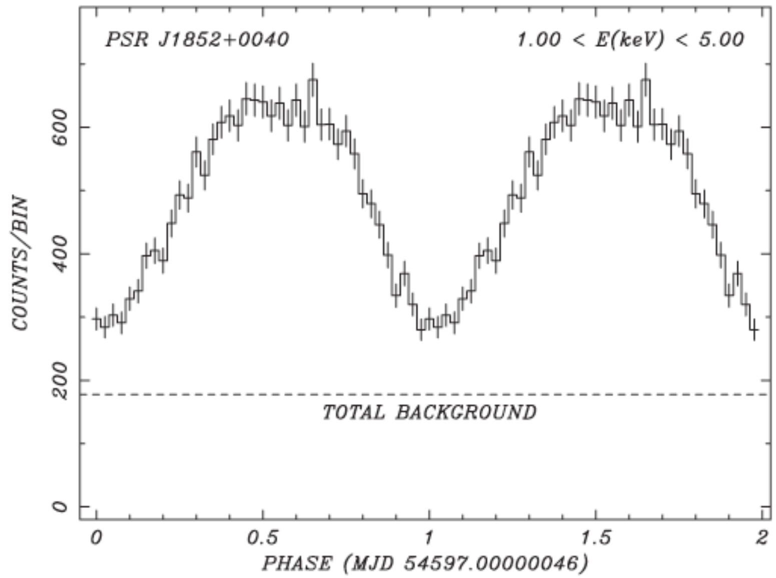
--- Usually $>10^{14}$G

--- Low-field ($\sim 10^{13}$G) magnetars (Rea et al 2010)

But internal fields could be higher

Hidden Magnetic Fields of Neutron Stars

- NS in Kes 79 SNR has $B_{\rm dipole} \simeq 3 \times 10^{10}$ G, but large pulse fraction 60%



(Halpern & Gotthelf 2010)

=> $B_{\rm crust} \sim$ a few $\times\, 10^{14}$ G

(Shabaltas & DL 2011)

- SGR 0418+5729, with $B_{\rm dipole} \simeq 4 \times 10^{12}$ G (Rea et al. 2010)

==> Internal field is much larger (Turolla et al 2011)

B Fields: How Strong is “Strong”?

Energetics

Magnetars:

Even in quiescence, $L \sim 10^{34-36} \mathrm{erg\ s}^{-1} \gg I\Omega\dot{\Omega}$

Giant flares in 3 SGRs

12/2004 flare of SGR1806-20 has E>10^{46}erg

➔ B > a few 10^{14} G

Observed (nonconvective) Stars

Star type	Upper main sequence	White dwarf	Neutron star
Radius R [km]	$10^{6.5}$	10^4	10^1
Maximum magnetic field B_{max} [G]	$10^{4.5}$	10^9	10^{15}
Maximum magnetic flux $\Phi_{max} \equiv \pi R^2 B_{max}$ [G km^2]	10^{18}	$10^{17.5}$	$10^{17.5}$

Reisenegger

$$\Phi_{\max} \sim 10^{17.5-18}\,\mathrm{G\,km^2}$$

$$\frac{E_{\rm mag}}{E_{\rm grav}} < 10^{-6}$$

If no hidden interior field

➔ **No effect on global static equilibrium of stars**

Local "Static" Equilibrium

Neutron star crusts:

Crust breaking occurs when

$$B > 2 \times 10^{14} \left(\frac{\theta_{\rm max}}{10^{-3}} \right)^{1/2} \, {\rm G}$$

Magnetic field evolution (e.g. Ohmic and Hall) cause crust breaking

(A. Cumming, J. Pons)

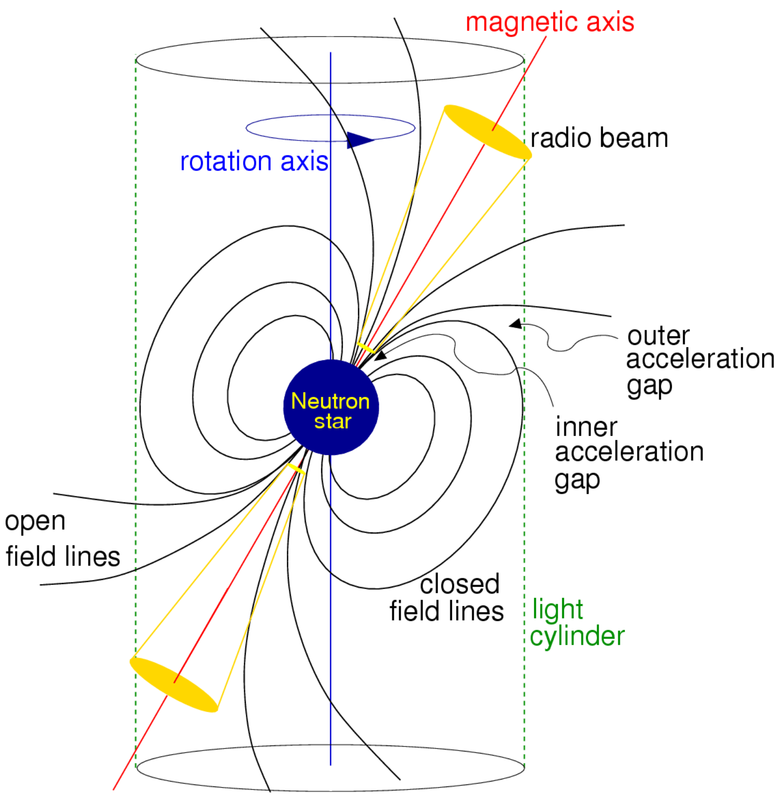
Consequences of breaking:

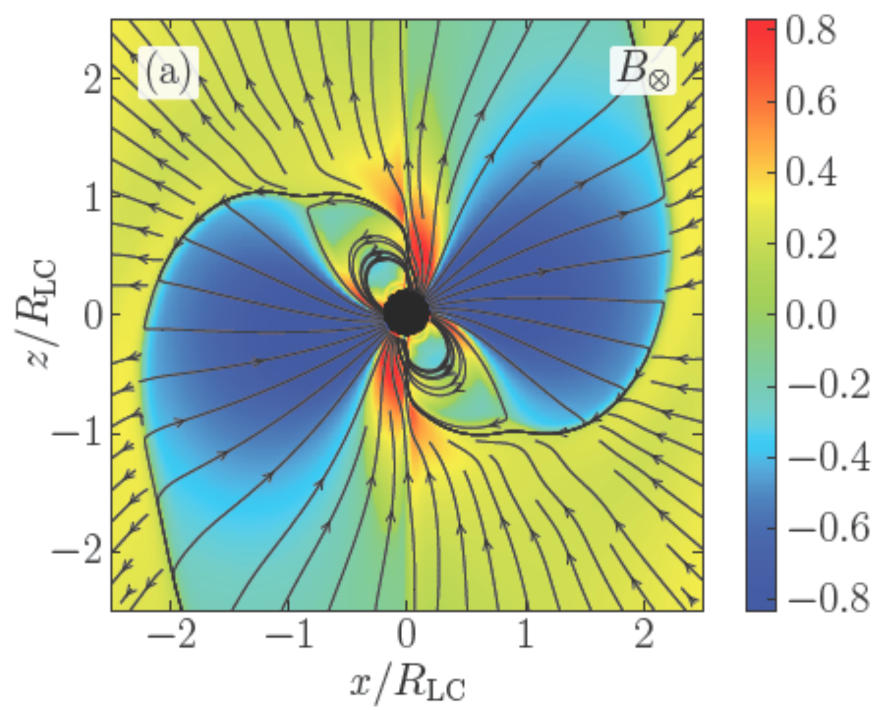
-- Fast or slow? (Y. Levin)
-- Energy release?
-- Can energy get out? (B. Link 2014; Blaes et al. 1989)
-- Magnetar flares?

Even weak field can be "Strong" outside the star…

(e.g. magnetic braking of stars…)

Magnetospheres: Radio Pulsars

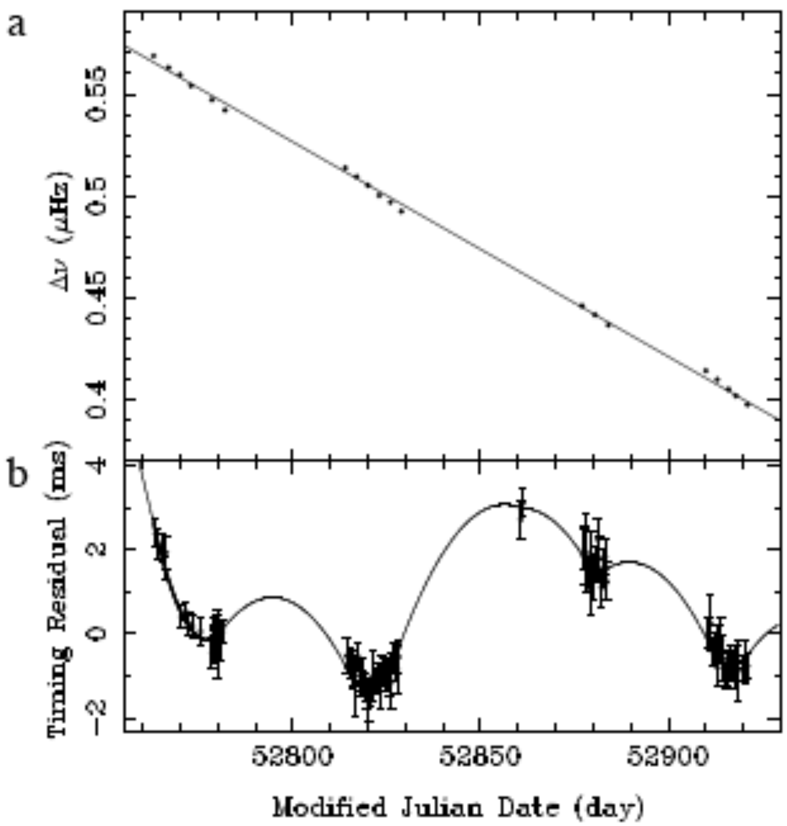




Tchekovskoy, Spitkovsky…

Magnetospheres: Radio Pulsars

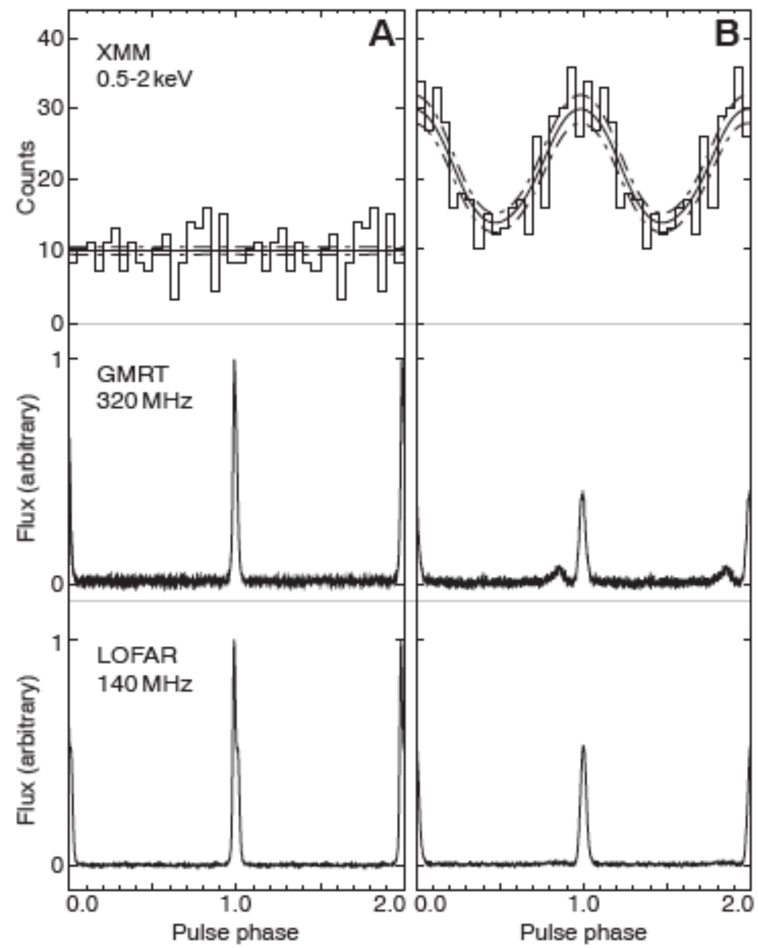
Mode-switching pulsars



Kramer et al. 2006

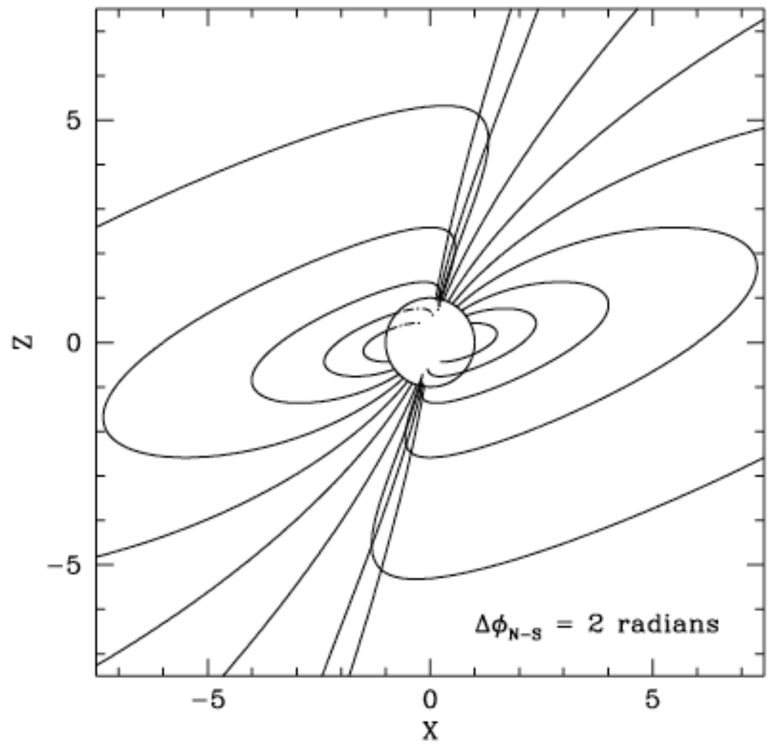
Radio B mode

Radio Q mode

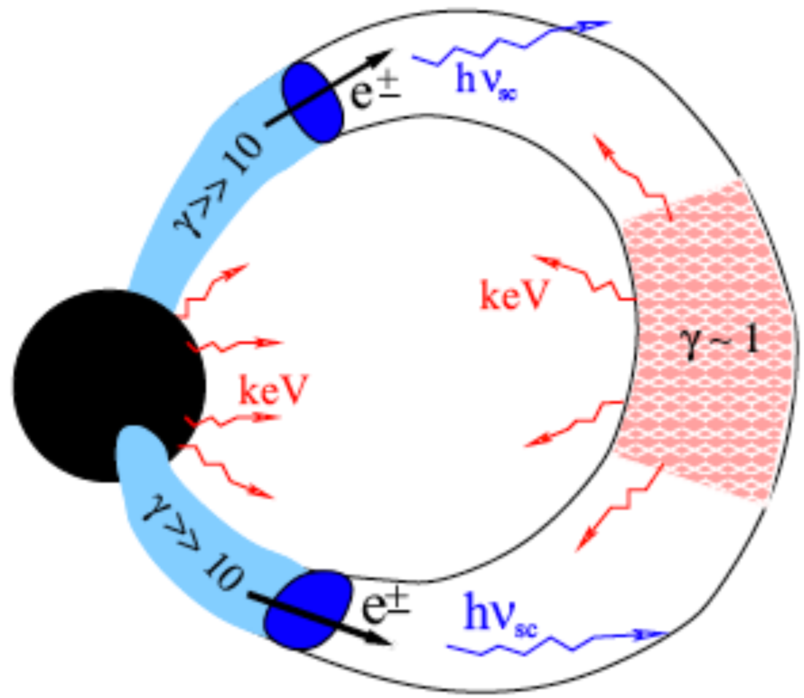


Hermsen et al 2013

Magnetospheres: Magnetars

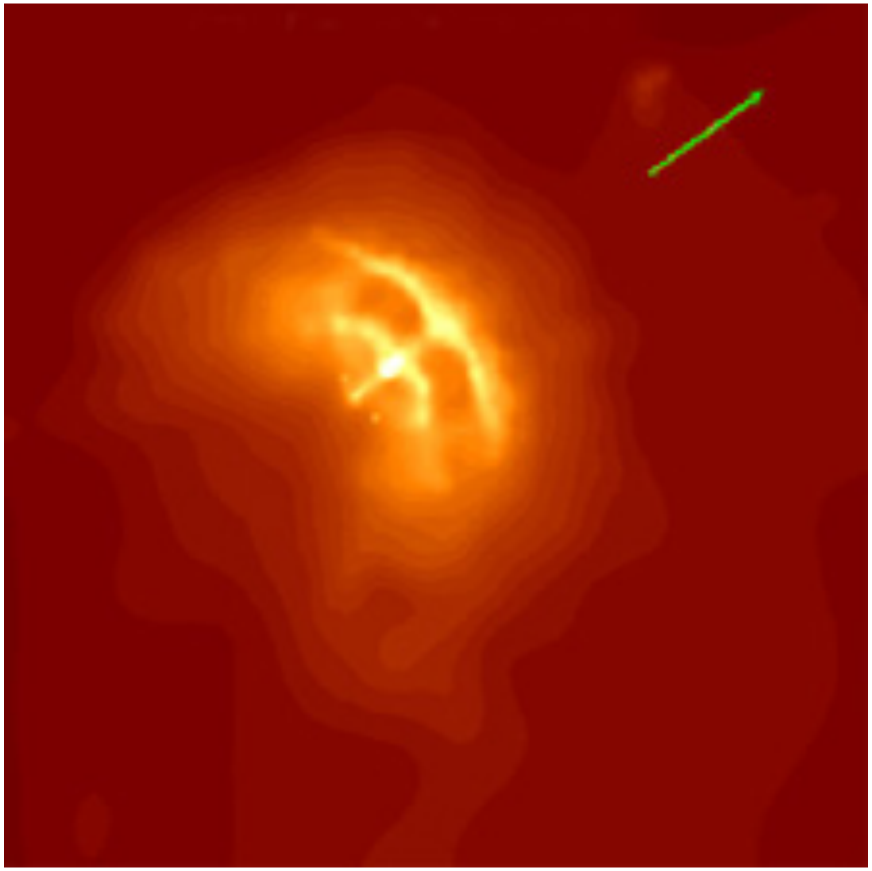


Thompson, Lyutikov & Kulkarni 2002



Beloborodov 2013

Pulsar Wind Nebulae

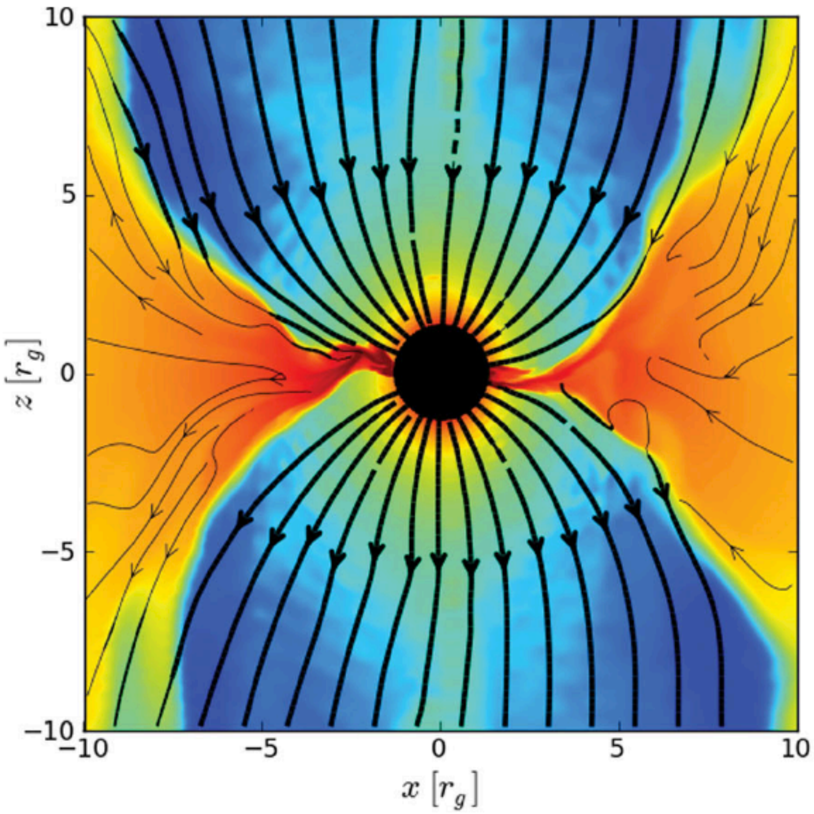


Accretion Disks

Accretion Disks

Magnetically Dominated Disks

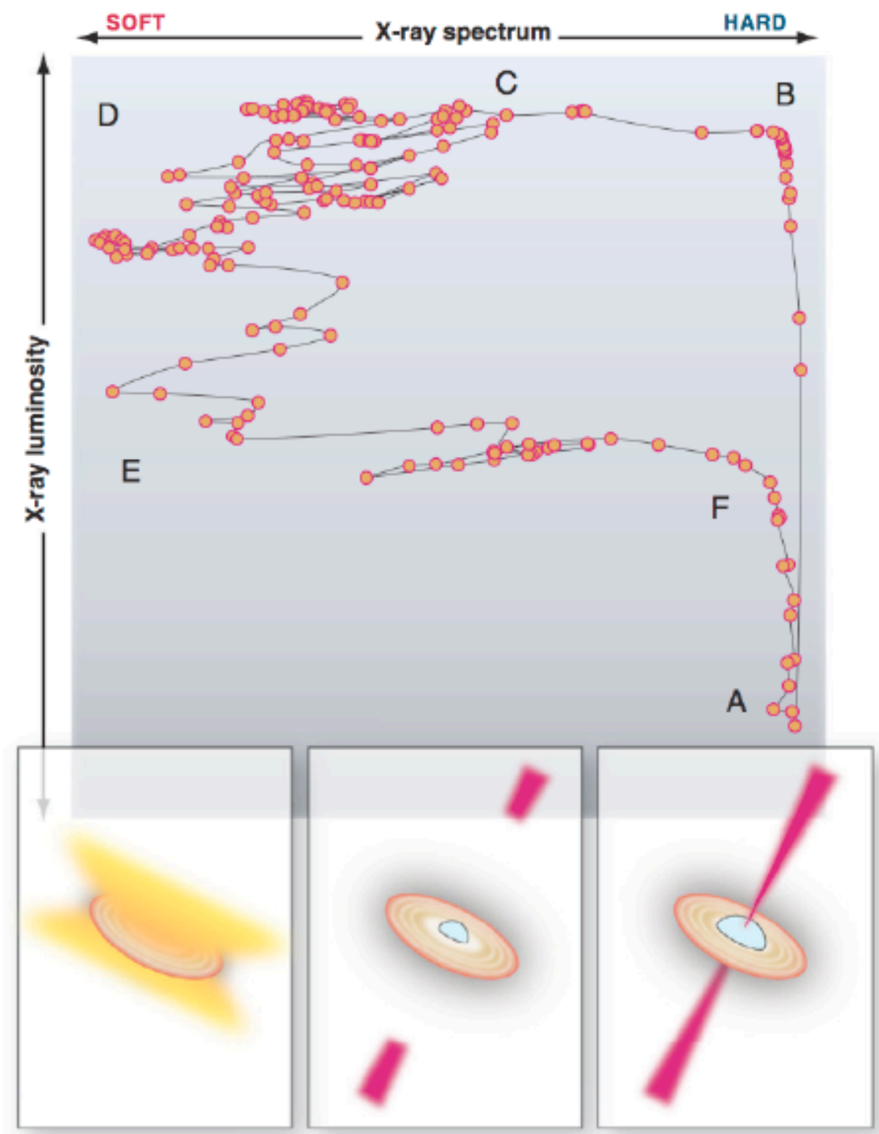
$$\frac{B^2}{8\pi} > \frac{1}{2}\rho v_K^2$$



Relativisic jets in
BH x-ray binaries/AGNs:

McKinney et al.2012

State Transition and Jets from BH x-ray Binaries



Jets:
episodic vs steady

Fender & Belloni 2012

Accretion Disks

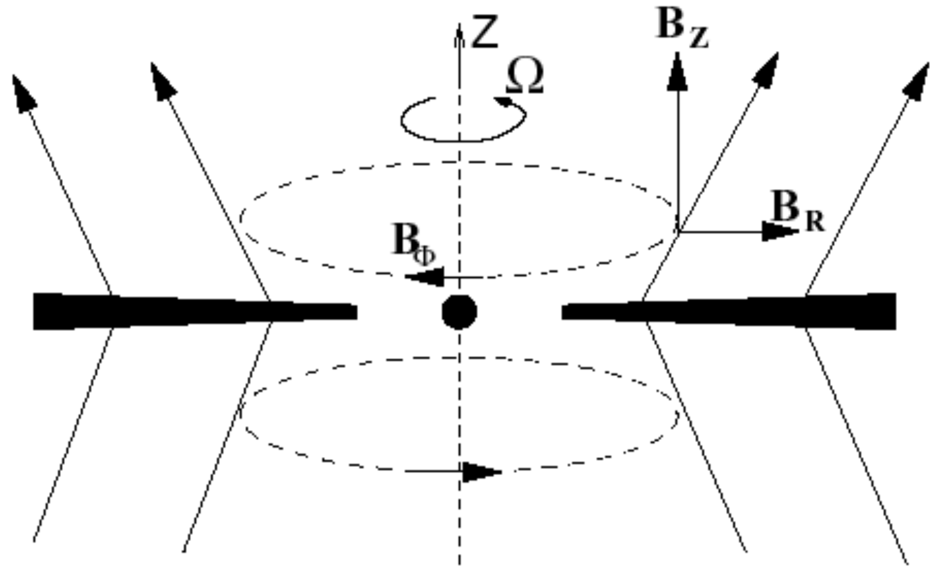
Super-thermal B Fields

$$\frac{B^2}{8\pi} > \frac{1}{2}\rho c_s^2$$

Magnetocentrifugal winds/outflows (e.g., Blandford-Payne)

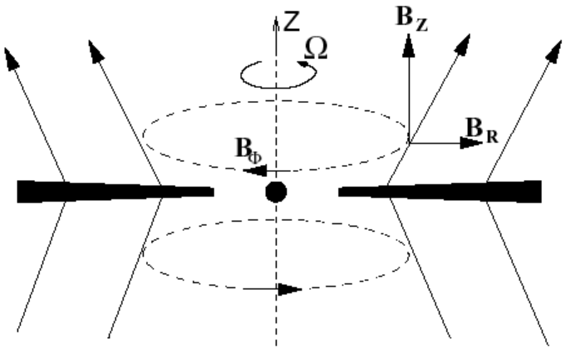
X-ray binaries (thermal state)

Protostars



Magnetic Field Advection in Accretion Disks

Such large-scale strong field cannot be produced in disks (?)…
Need to be advected from outside



Radial advection inward: $|u_r| \sim \dfrac{\nu}{r}$

Diffusion outward: $|u_{\rm diff}| \sim \dfrac{\eta}{H}\dfrac{B_r}{B_z}$

Depend on magnetic Prandtl number $P_r = \dfrac{\nu}{\eta}$

~ 1 from MRI simulations

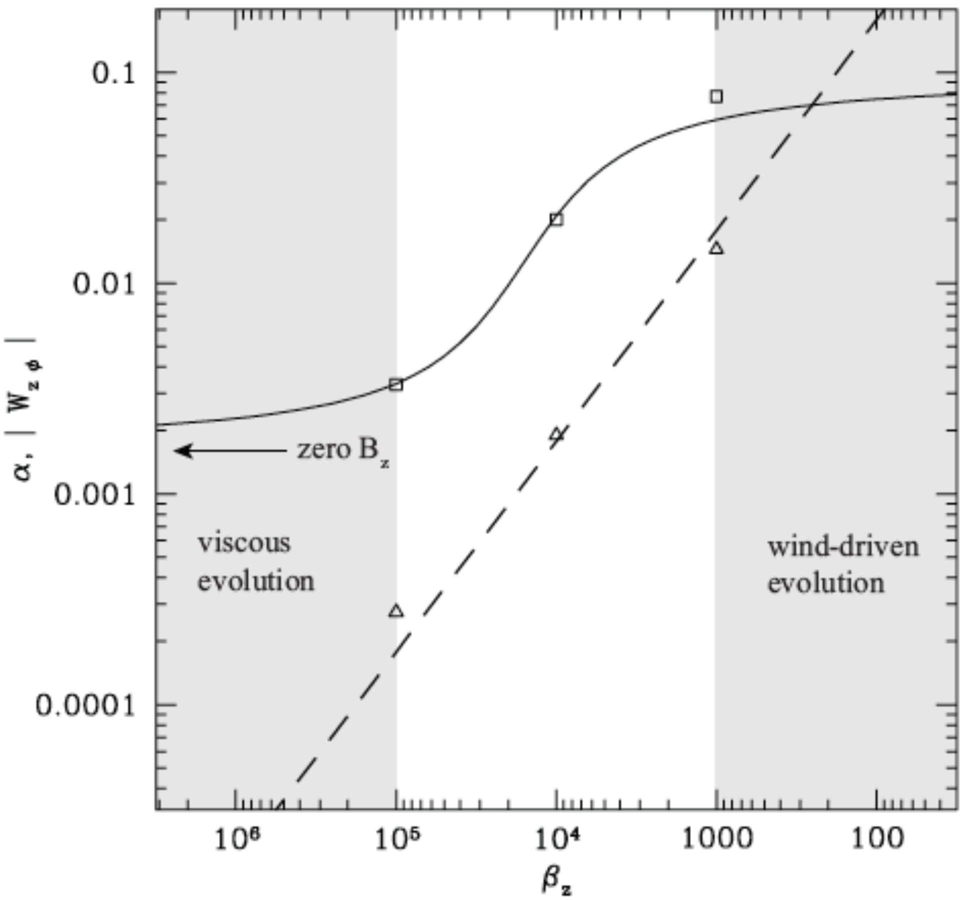
Vertical structure important (e.g. Guilet & Ogilvie 2013)

e.g., conductivity higher at disk surface → field advection faster than mass
H_B is larger than H

Sub-Thermal Magnetic Fields in Disks

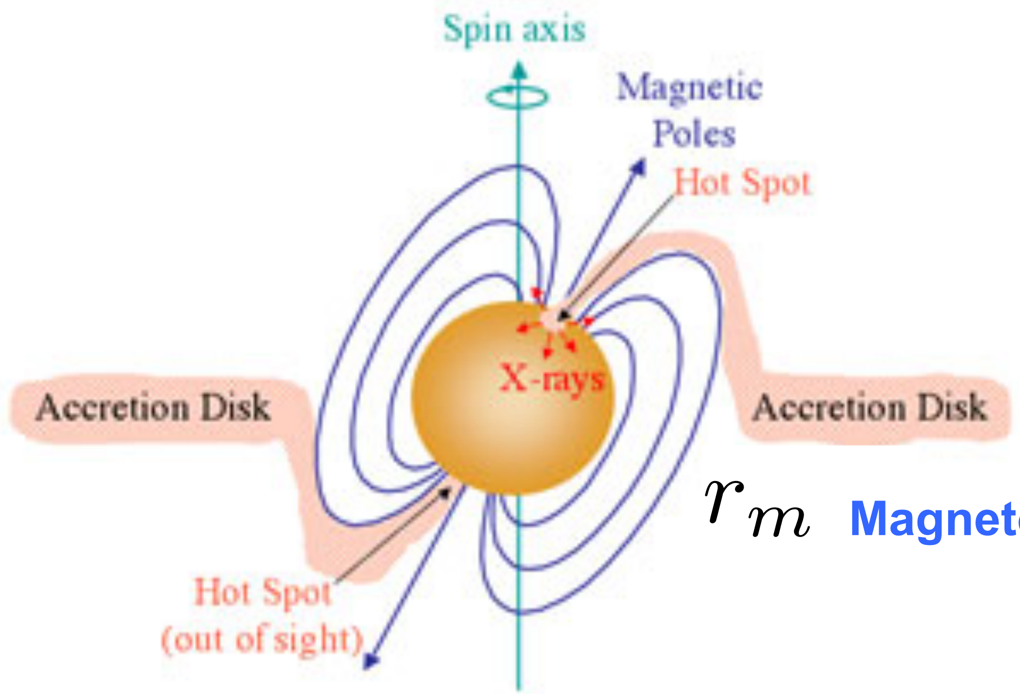
➔ MRI → turbulence

Strength of turbulence depends on net vertical field (Hawley et al. 1995)



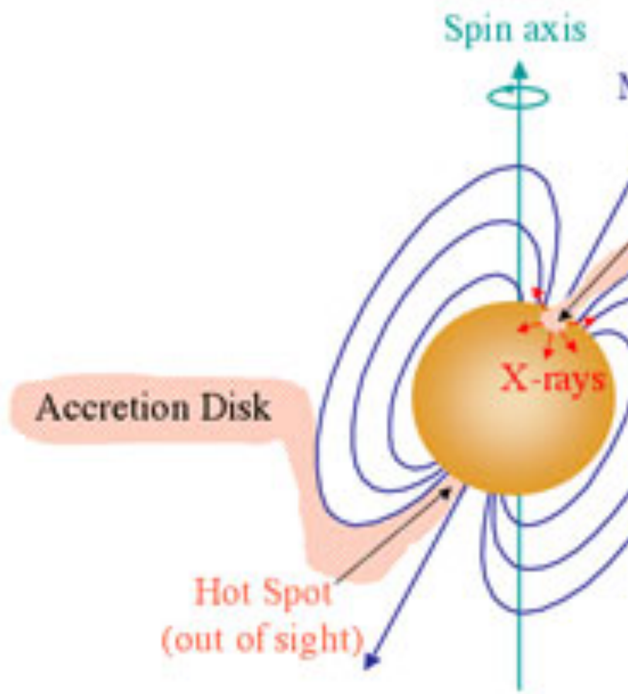
Simon et al. 2013
Armitage et al. 2013

Disk Accretion onto Magnetic Stars



r_m **Magnetosphere radius**

Disk Accretion onto Magnetic Stars



$$r_m \sim \left(\frac{\mu^4}{GM\dot{M}^2}\right)^{1/7}$$

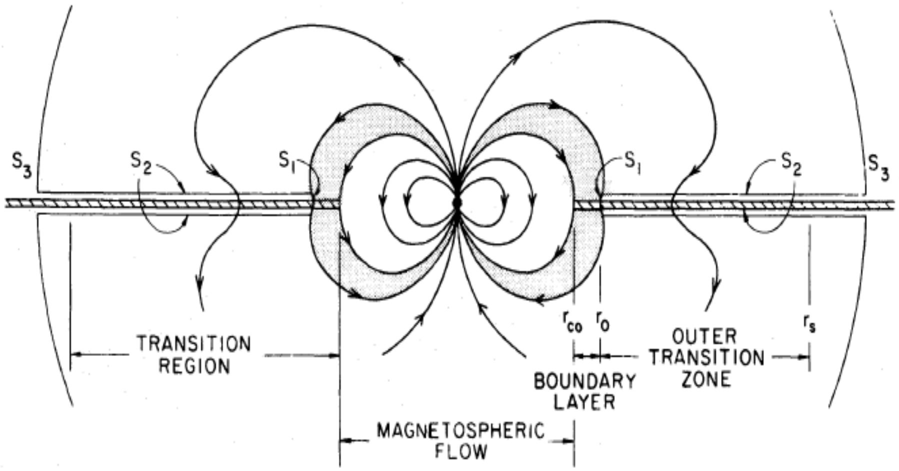
$$\frac{B(r)^2}{8\pi} \sim \frac{1}{2}\rho V_r V_\phi$$

Accreting x-ray pulsars: $B_\star \sim 10^{12}\mathrm{G}, \quad r_m \sim 10^2 R_\star$

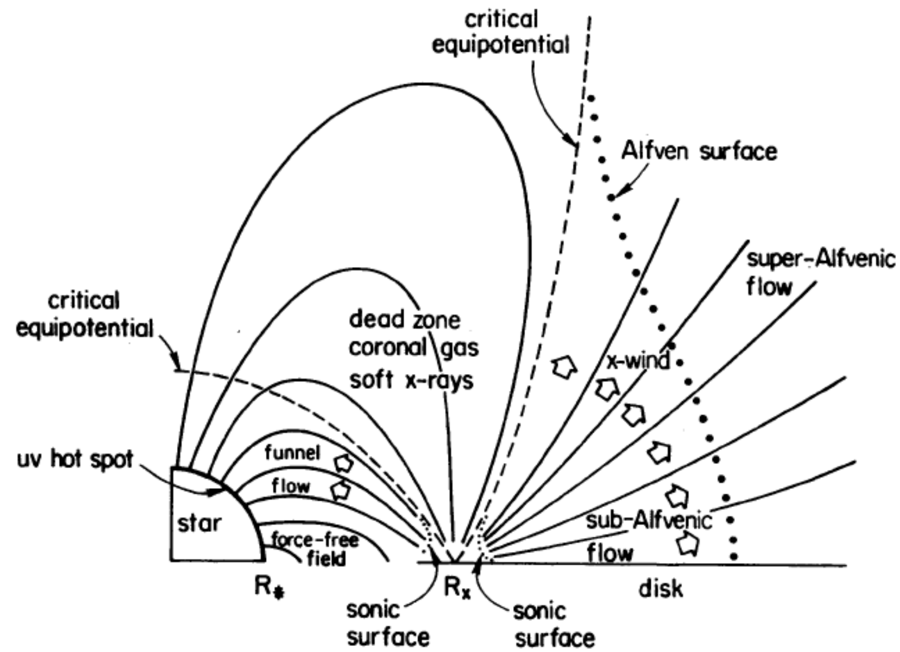
Accreting ms pulsars: $B_\star \sim 10^{8}\mathrm{G}, \quad r_m \sim (\text{a few}) R_\star$

Accreting WDs (Intermediate polars): $B_\star \sim 10^{7}\mathrm{G}, \quad r_m \sim 10 R_\star$

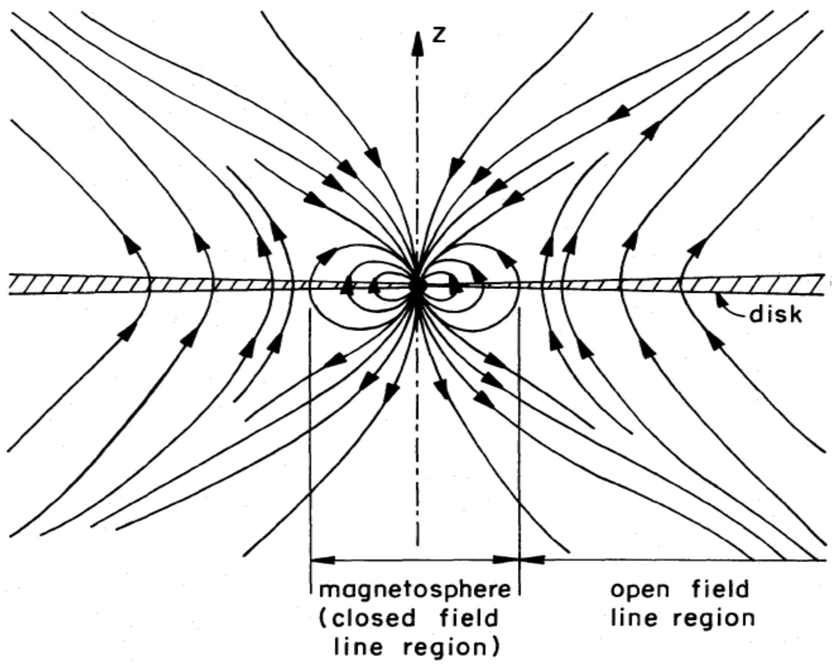
Protostars (Classical T Tauri stars): $B_\star \sim 10^{3}\mathrm{G}, \quad r_m \sim (\text{a few}) R_\star$



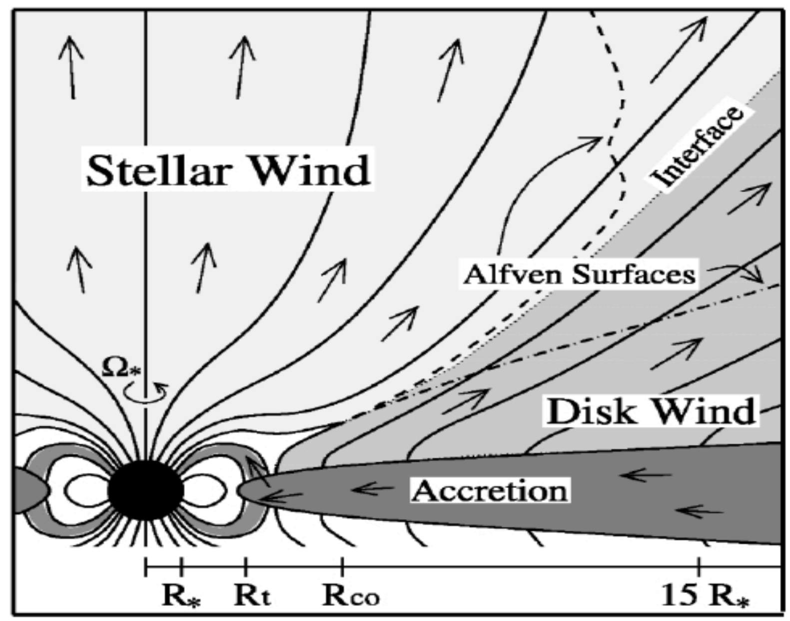
Ghosh & Lamb 1979



Shu et al. 1994



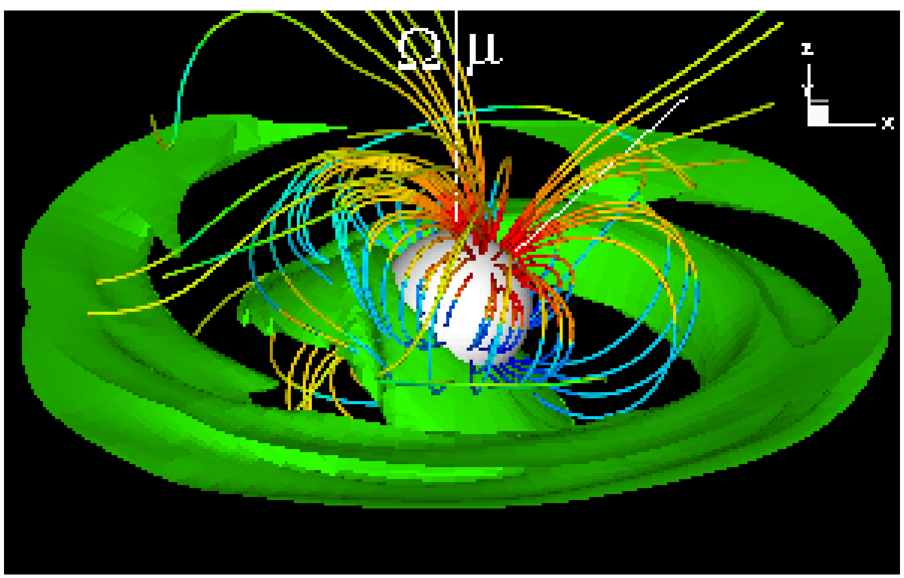
Lovelace et al. 1995



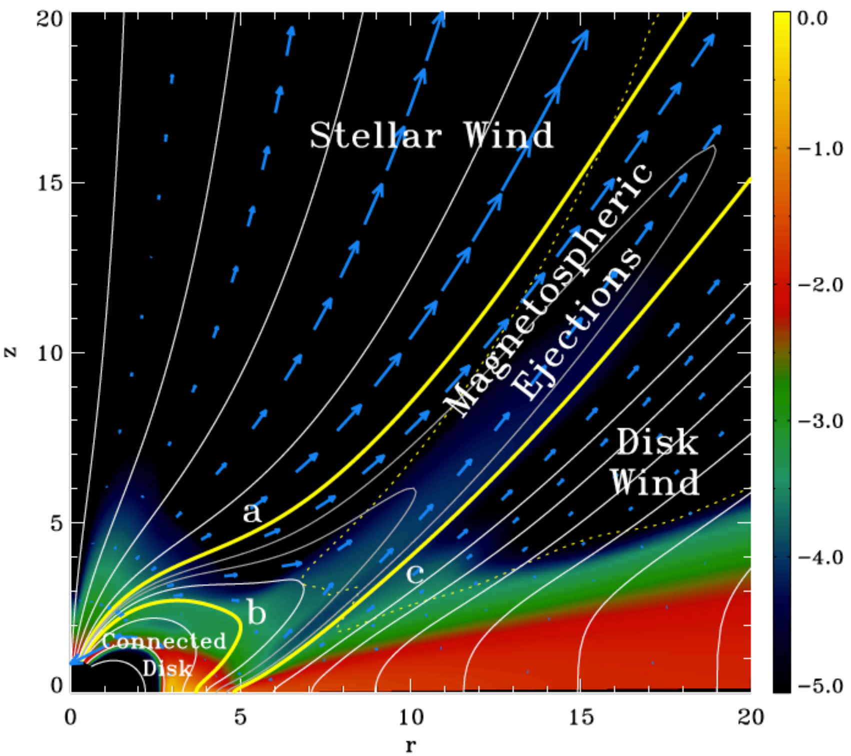
Matt & Pudritz 2005

Simulations…

Hayashi, Shibata & Matsumoto, Miller & Stone, Goodson, Winglee & Bohm, Fendt & Elastner, Matt et al, Romanova, Lovelace, Kulkarni, Long, Lii et al, Zanni & Ferreira, ……

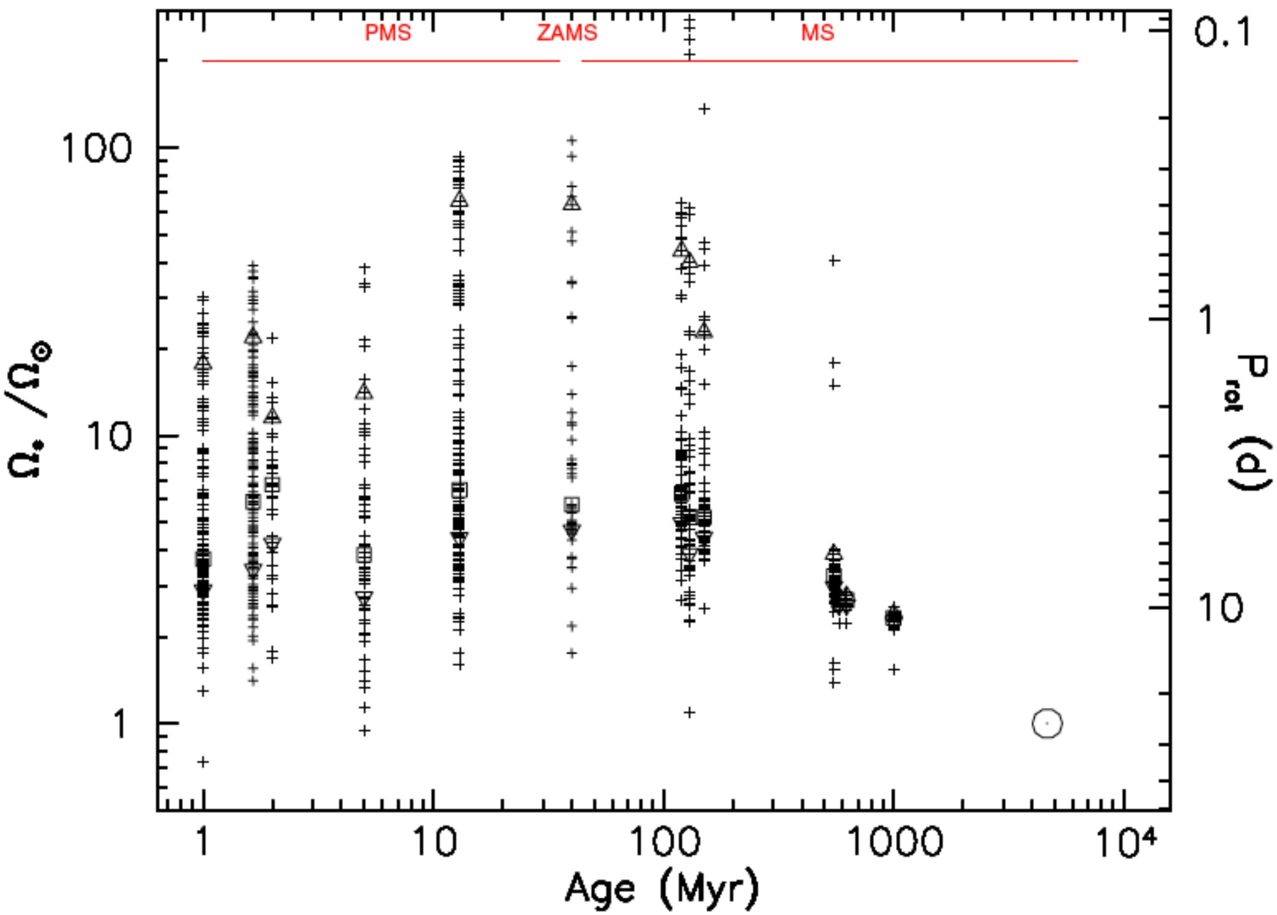


Romanova et al. 12



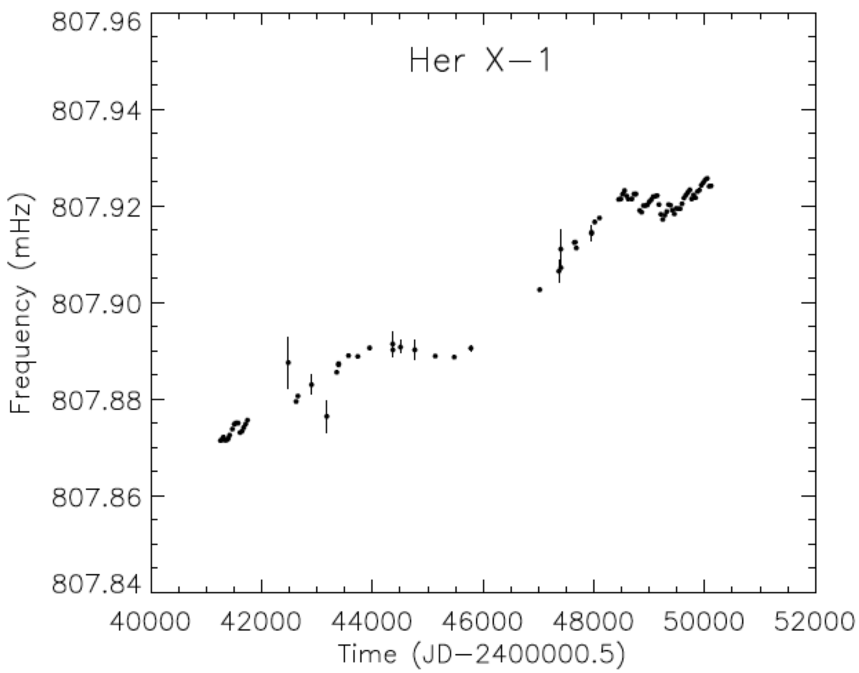
Zanni & Ferreira '13

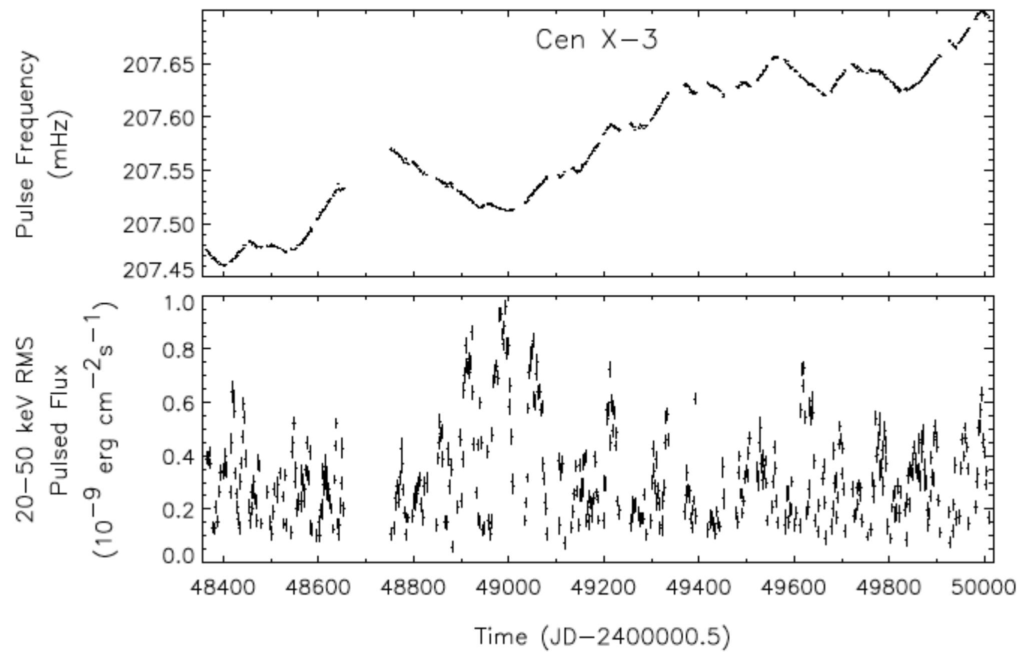
Application:
Rotation of Protostars: why 10% of breakup?



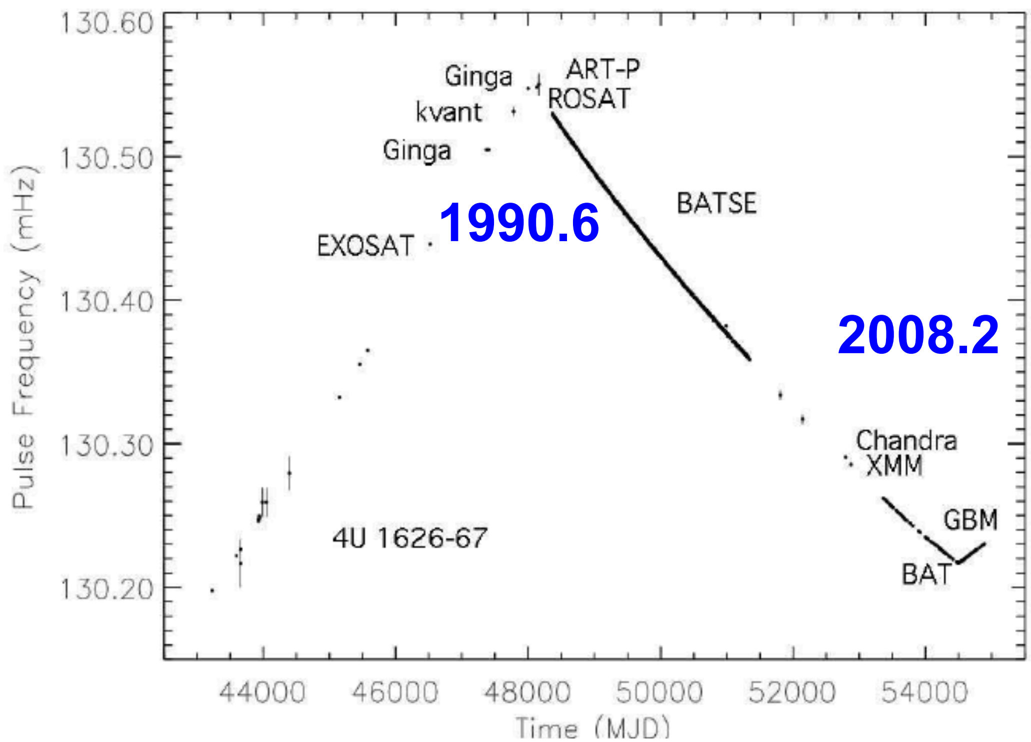
Gallet & Bouvier 2013

Application:
Spinup/Spindown of Accreting X-ray pulsars





Bildsten et al. 1997

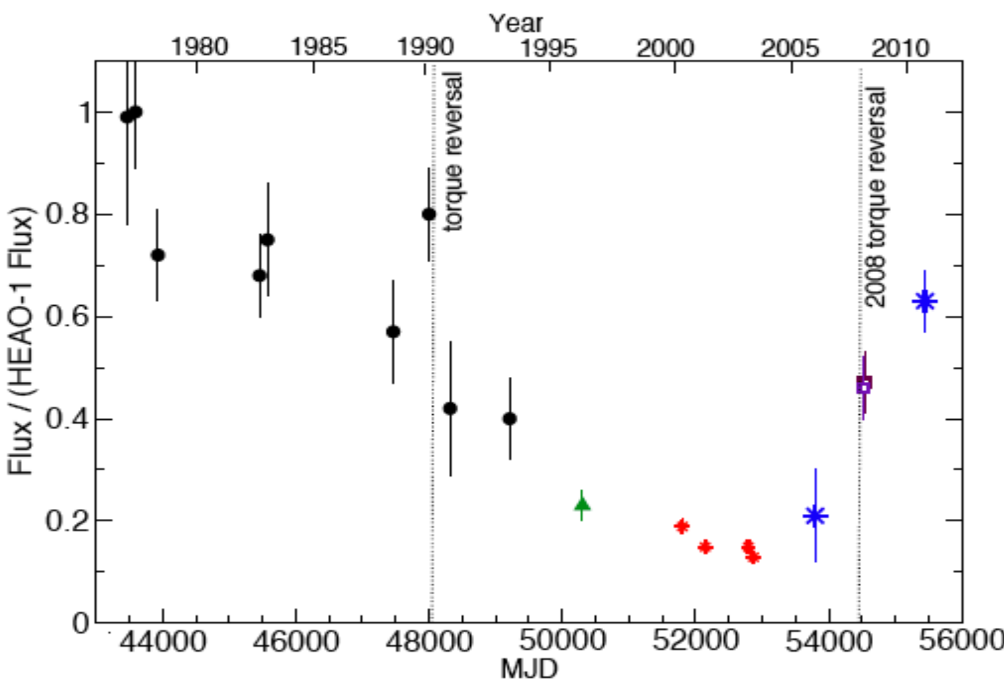


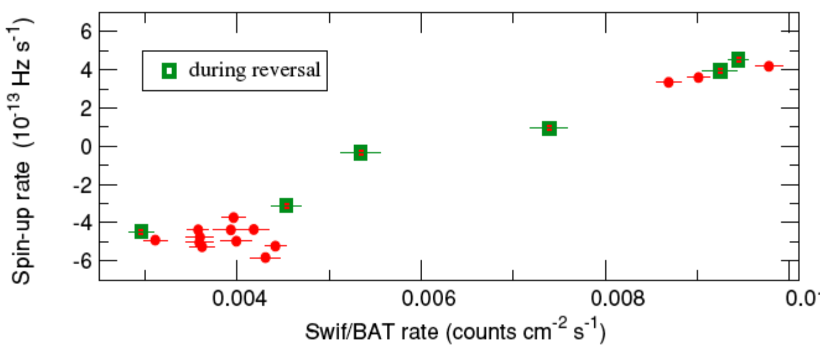
4U1626-67

7.66s

Transition lasted 150 days

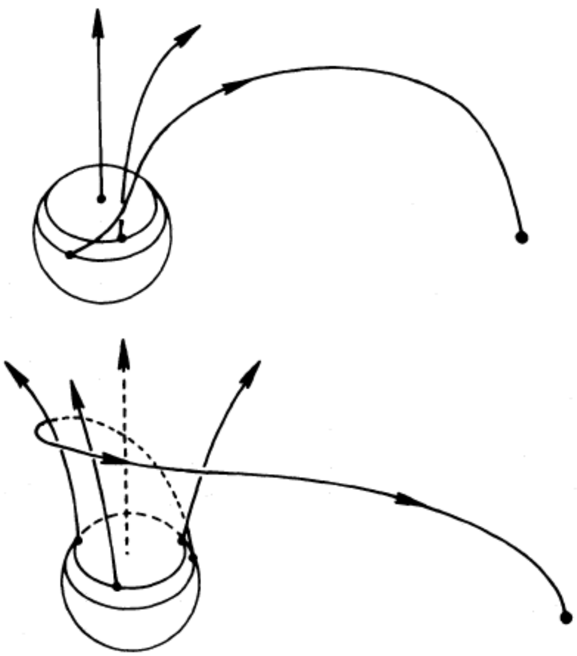
Camero-Arranz et al. 2010,2012

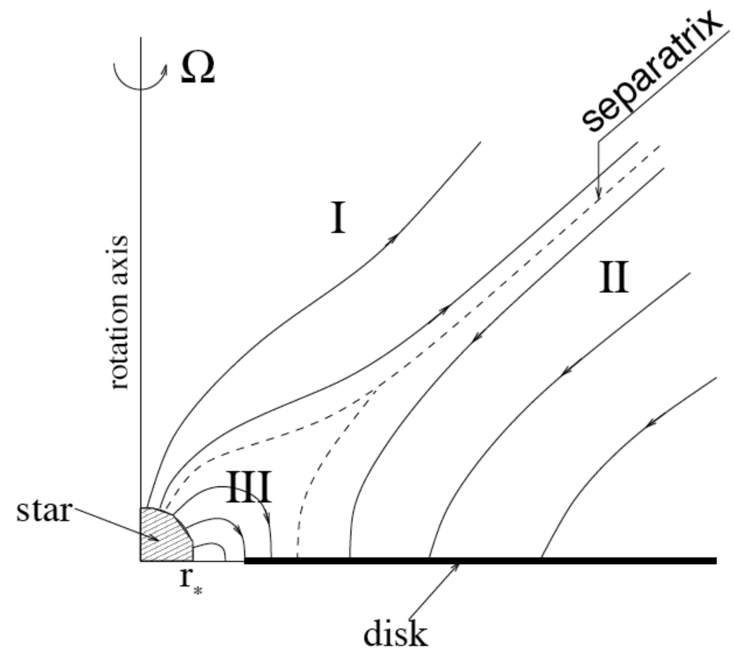




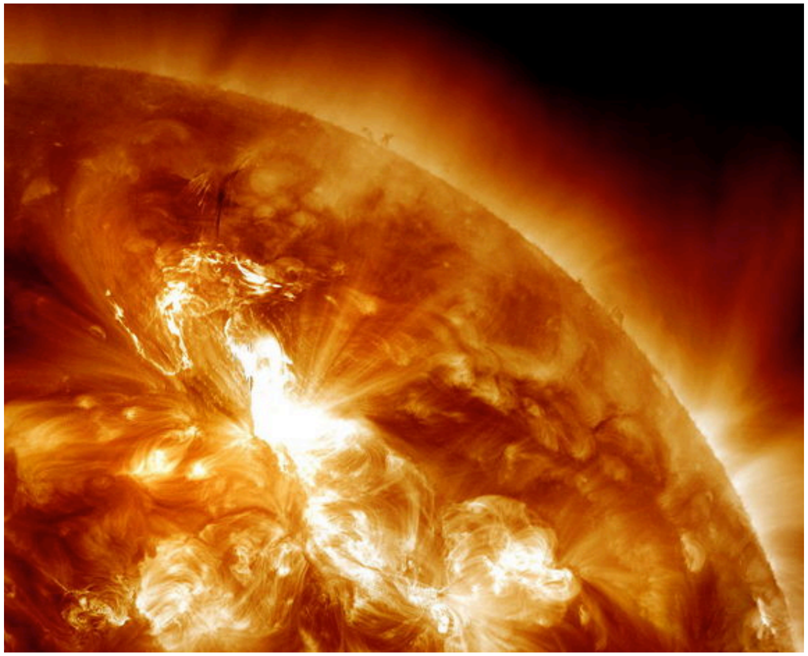
Key Physics: Star-Disk Linkage

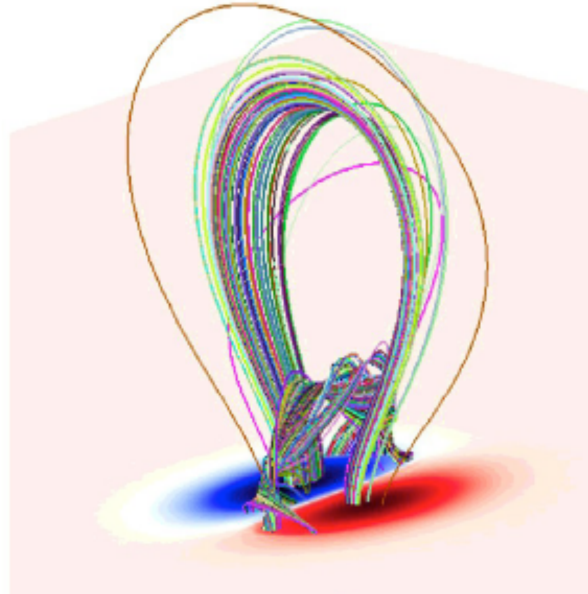
Linked fields are twisted by differential rotation…



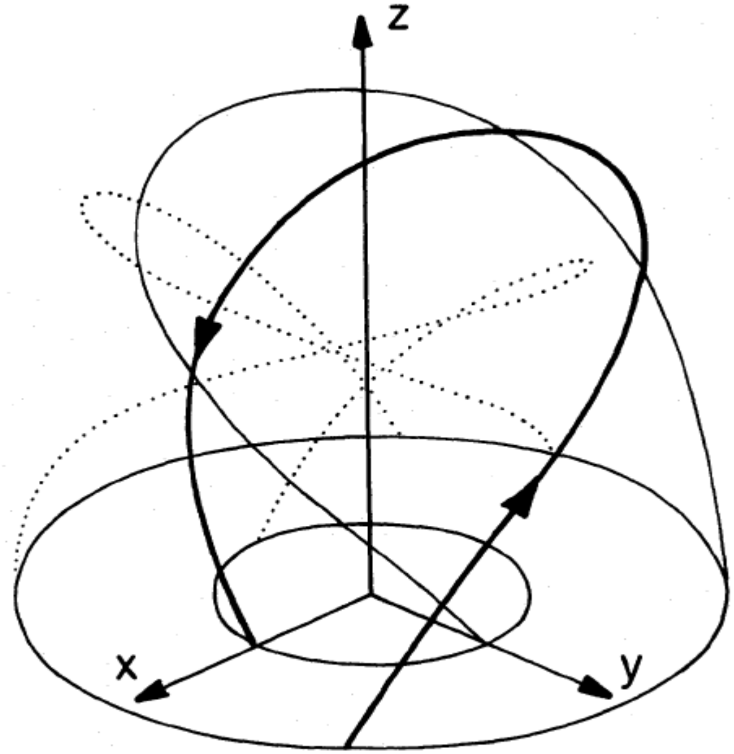


Aly; Lovelace et al.; Uzdensky,…



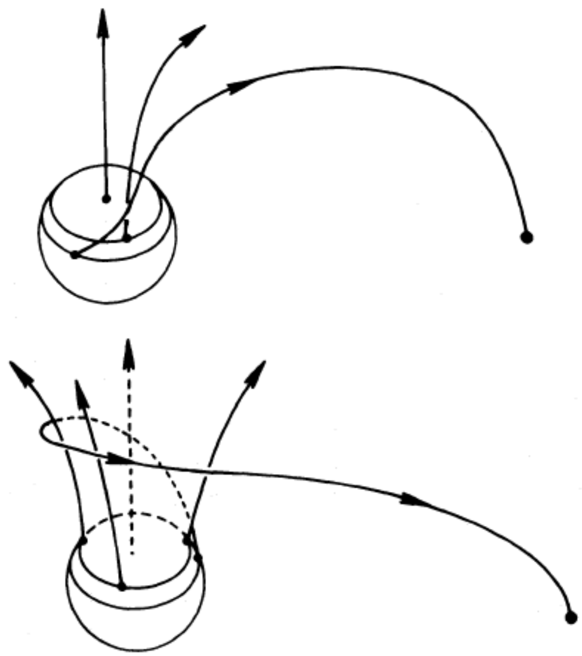


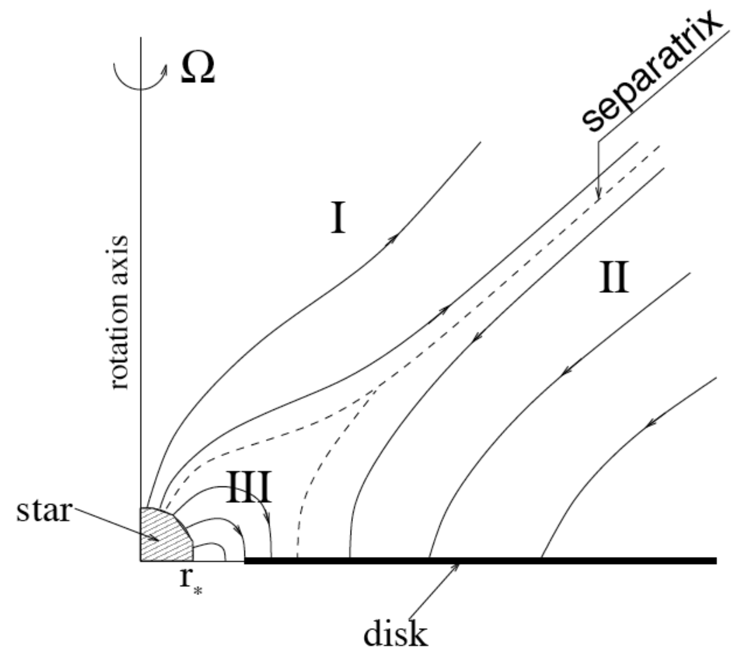
(b)



Star-Disk Linkage

Linked fields are twisted by differential rotation…
➔Field inflates, breaks the linkage





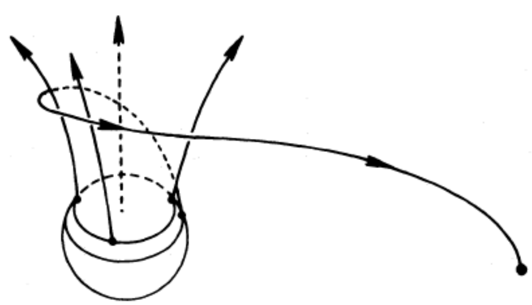
Maximum twist: $\left|\frac{B_{\phi+}}{B_z}\right|_{\max} \sim 1$

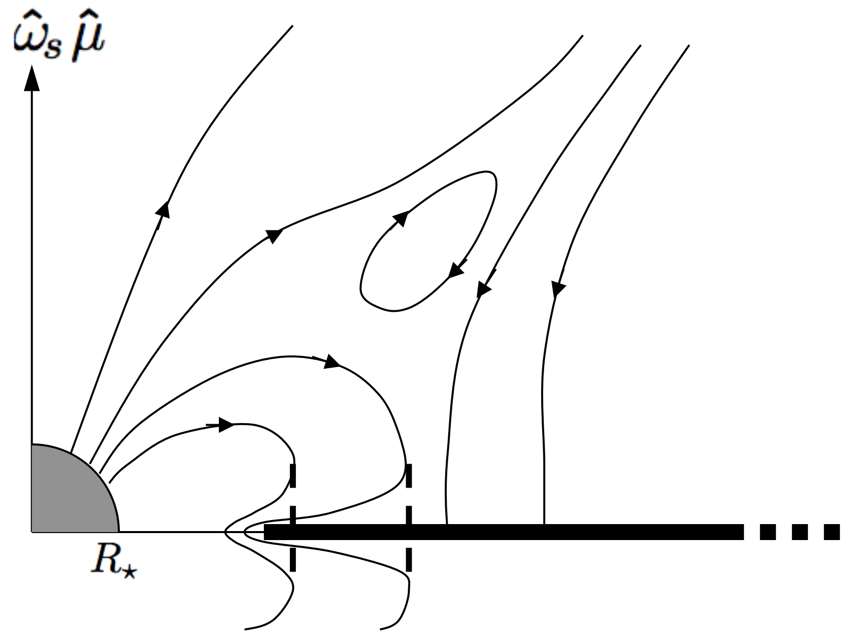
Aly; Lovelace et al.; Uzdensky,…

Star-Disk Linkage: Quasi-cyclic behavior

(Width, Time-dependence…)

Stellar field penetrates the inner region of disk;
Field lines linking star and disk are twisted --> toroidal field --> field inflation
Reconnection of inflated fields restore linkage





Inevitable…

Star-Disk Linkage: Quasi-cyclic behavior
(Width, Time-dependence…)

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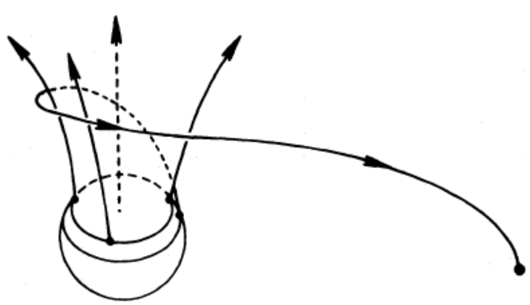
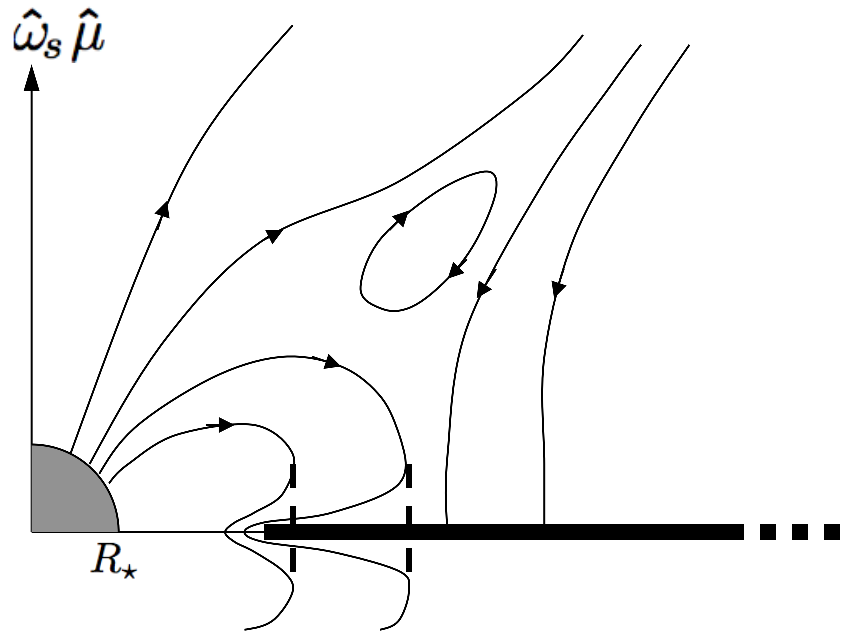
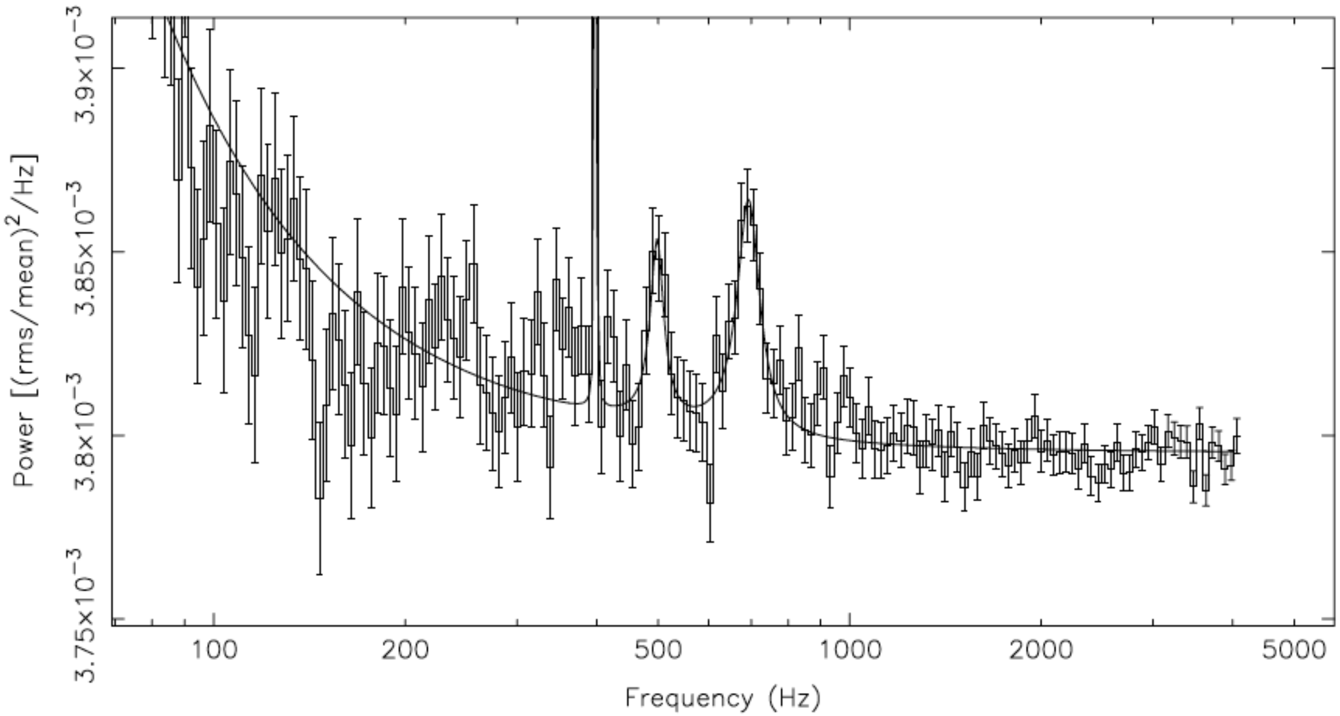




Application: Connection with QPOs in LMXBs (and other systems) ?

kHz QPOs in Accreting Millisecond Pulsars



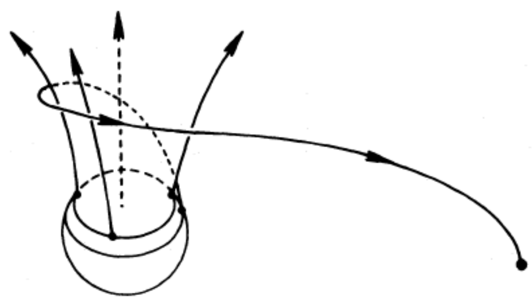
Van der Klis 2005

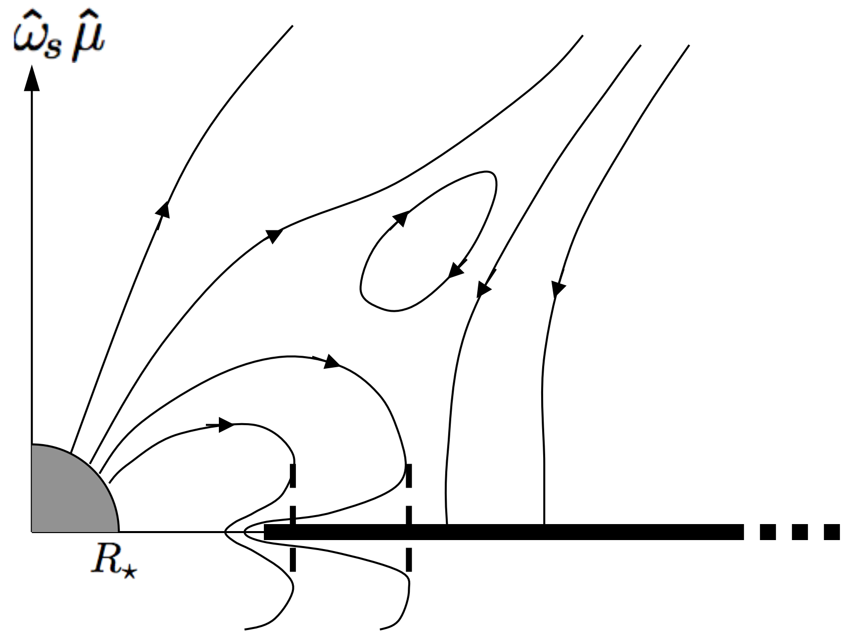
SAX J1808.4-3658: $\nu_s = 401\ \mathrm{Hz},\ \nu_h - \nu_l \simeq \nu_s/2\ (\pm\mathrm{a\ few\ Hz})$

XTE J1807.4-294: $\nu_s = 191\ \mathrm{Hz},\ \ \nu_h - \nu_l \simeq \nu_s$

Star-Disk Linkage: Quasi-cyclic behavior
(Width, Time-dependence…)

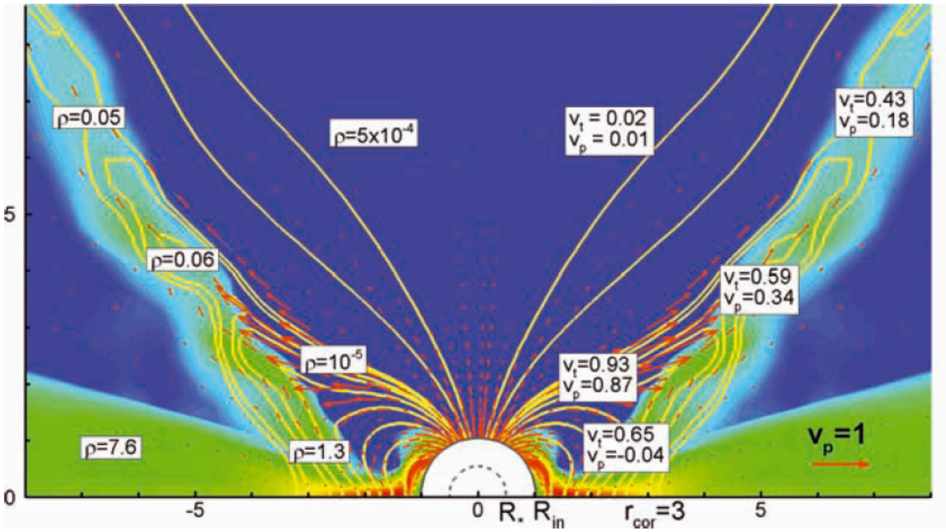
Stellar field penetrates the inner region of disk;
Field lines linking star and disk are twisted --> toroidal field --> field inflation
Reconnection of inflated fields restore linkage



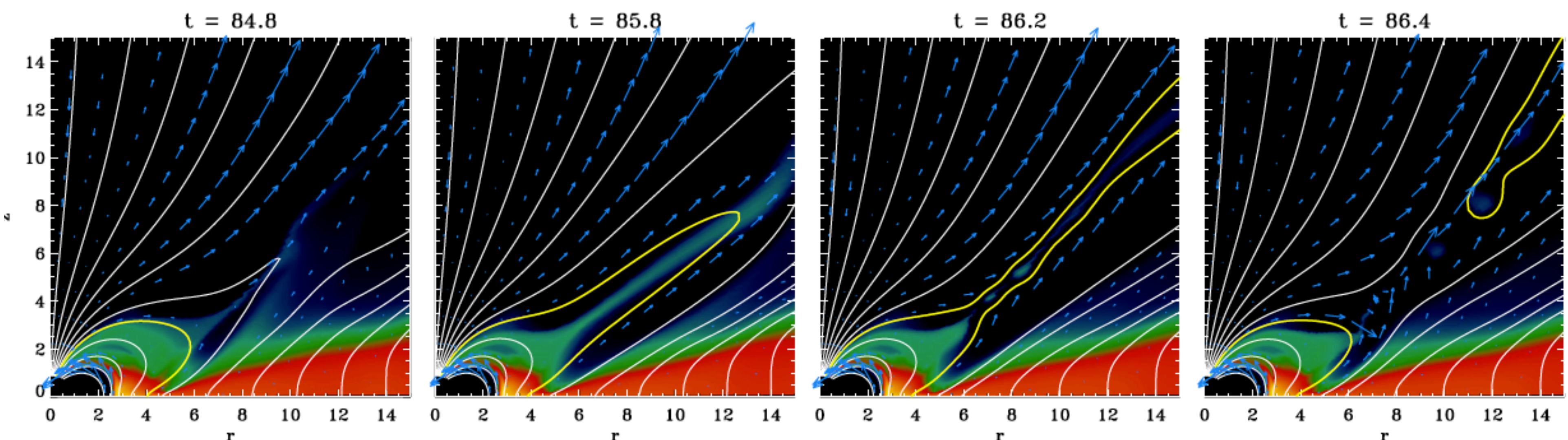


Application: Episodic outflow …

Ejection from Magnetospheric Boundary

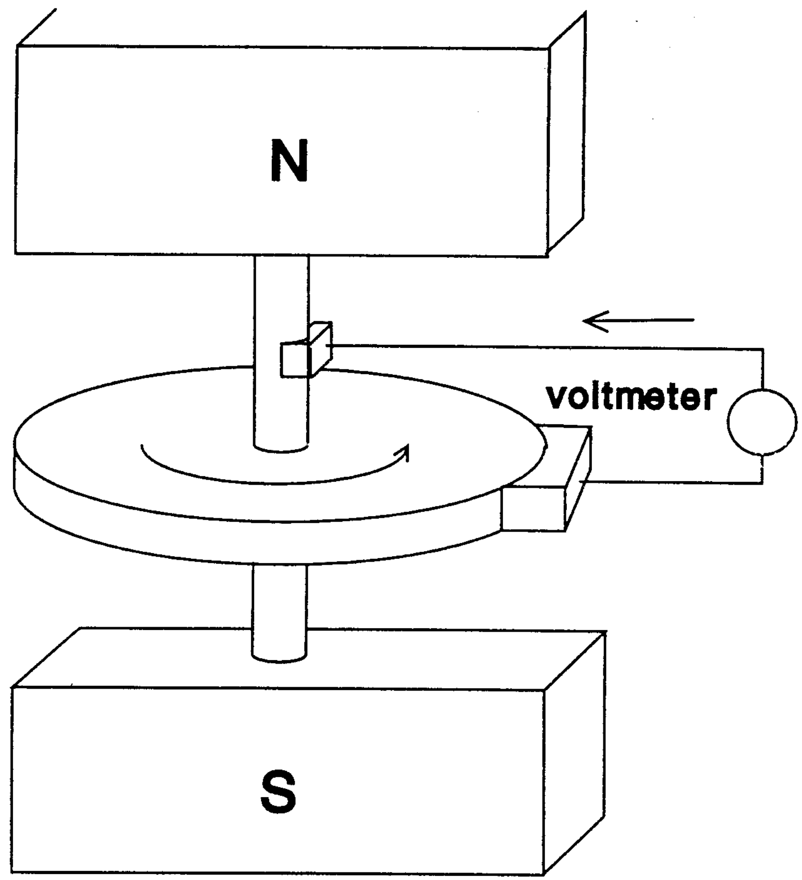


Romanova et al. 2009

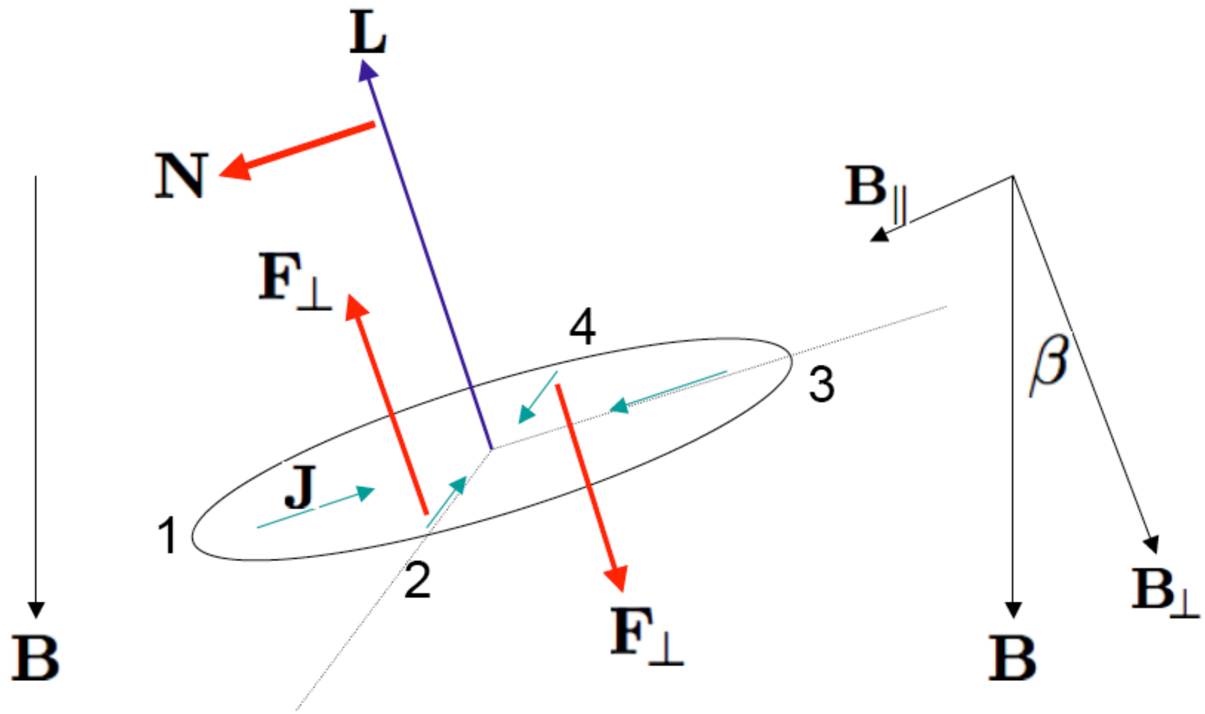


Zanni & Ferreira 2013

Star-Disk Linkage ➔ Spin-Disk Misalignment (?)



Star-Disk Linkage ➔ Spin-Disk Misalignment (?)

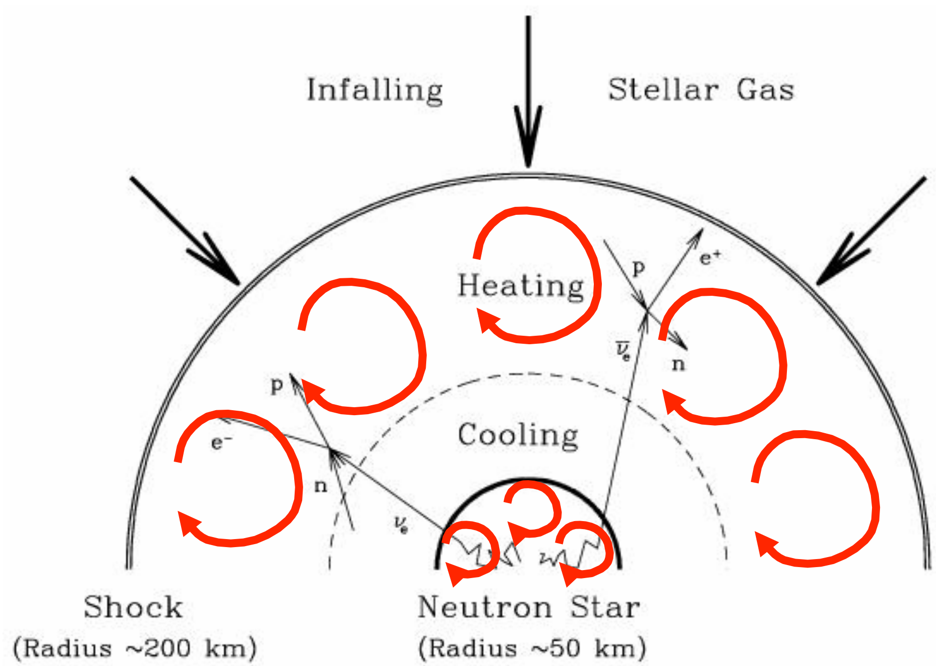


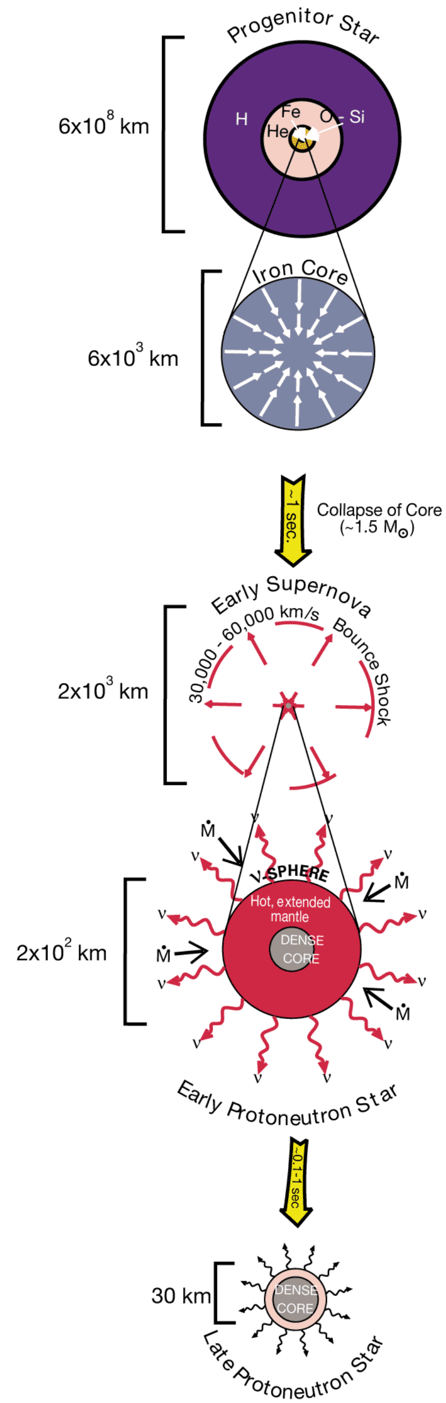
Lai et al 2011

7 degree misalignment in solar system…; exoplanetary systems…

Magnetic Fields in Formation of Compact Objects

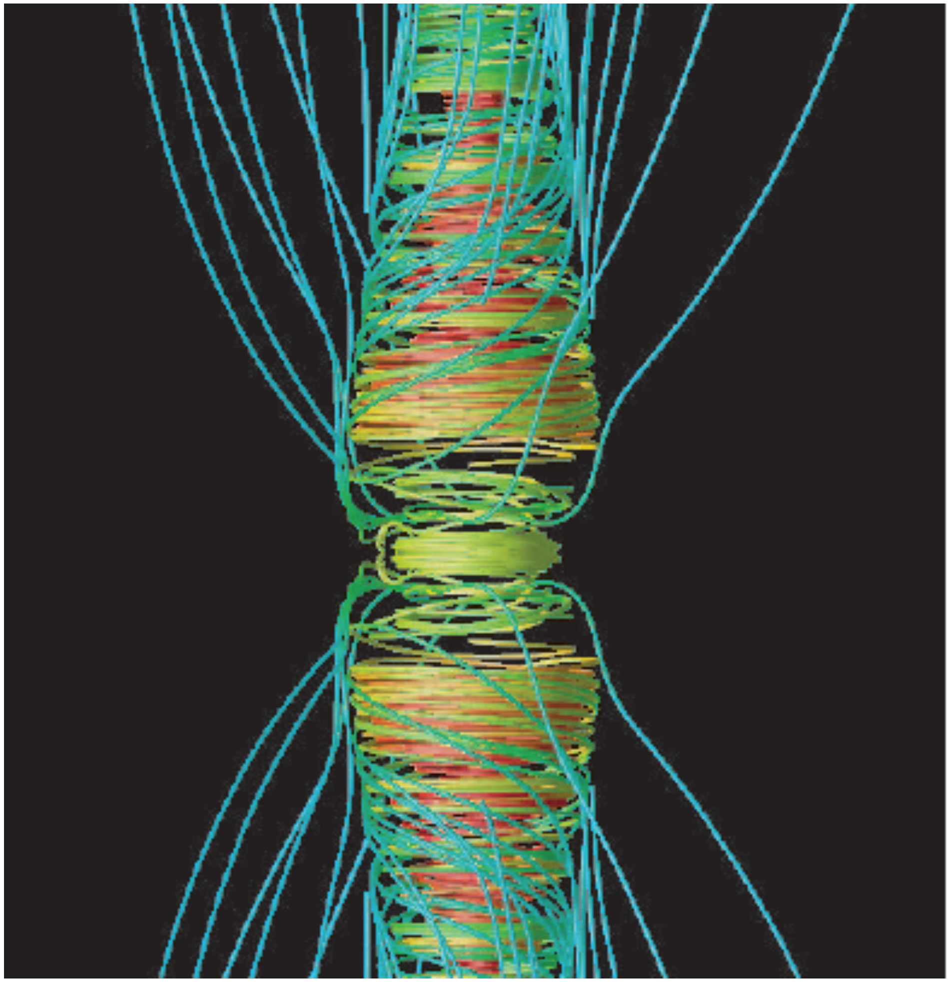
Core-Collapse Supernova → NS





Magnetically Driven Supernova/Hypernova

LeBlanc & Wilson 1970; Bisnovatyi-Kogan et al. 1976;….
Wheeler, Yamada, Thompson, Shibata, Moiseenko, Burrows,…



-- Require rapid rotation
(uncertain preSN rotation)

-- MRI scale usually not
resolved unless put in $>10^{15}$G

Burrows et al. 2007

Roles of Magnetars in Supernovae

-- Power explosion: 1-3 ms, ~10^{15}G

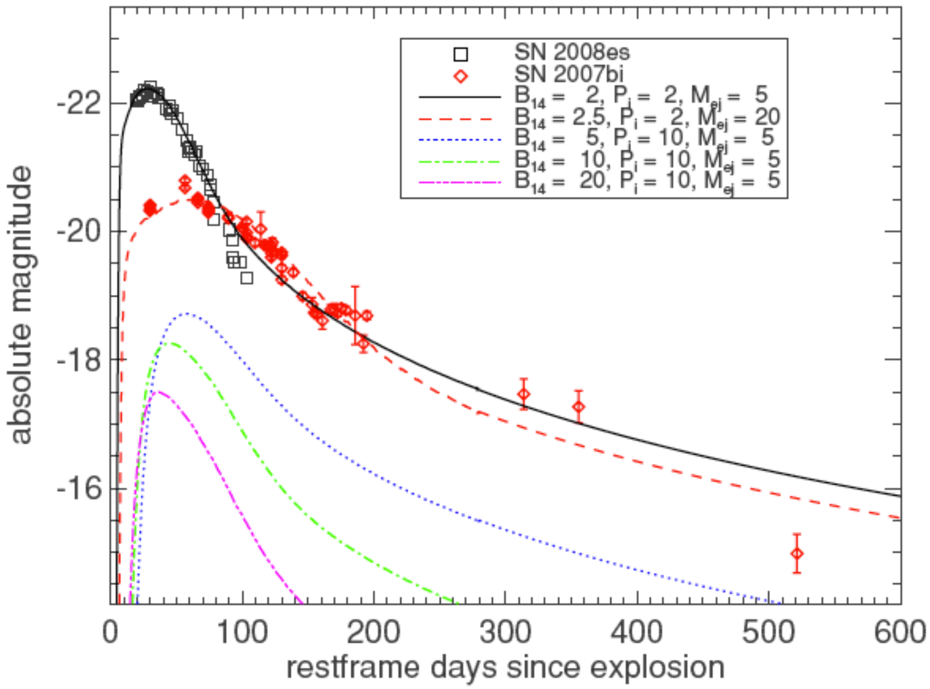
(Bodenheimer & Ostriker 1974; Wheeler et al. 2000; T. Thompson et al. 2004….)

-- For ~10 ms, not affect explosion, but still impact lightcurves:

Spindown time ~days-weeks (~photon diffusion through remnant)

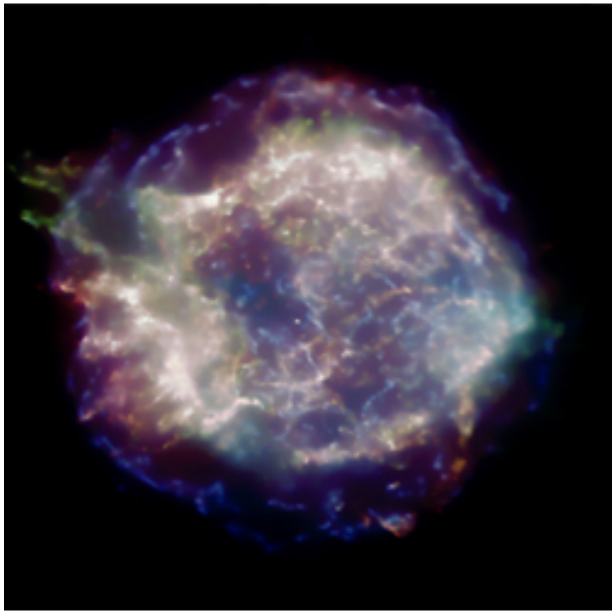
May explain SLSNe with L>10^{44}erg/s (Kasen & Bilsten 2010; Woosley 2010);

But Dado & Dar 2014



Kasen & Bildsten 2010

Central Compact Objects (CCOs) in SNRs



CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p[a] (%)	B_s (10^{11} G)
RX J0822.0 − 4300	Puppis A	3.7	2.2	0.112	11	<9.8
CXOU J085201.4 − 461753	G266.1 − 1.2	1	1	...	<7	...
1E 1207.4 − 5209	PKS 1209 − 51/52	7	2.2	0.424	9	<3.3
CXOU J160103.1 − 513353	G330.2 + 1.0	$\gtrsim$3	5	...	<40	...
1WGA J1713.4 − 3949	G347.3 − 0.5	1.6	1.3	...	<7	...
CXOU J185238.6 + 004020	Kes 79	7	7	0.105	64	0.31
CXOU J232327.9 + 584842	Cas A	0.33	3.4	...	<12	...

Halpern & Gotthelf

➔ **Small surface dipole field** (although internal field could be higher)

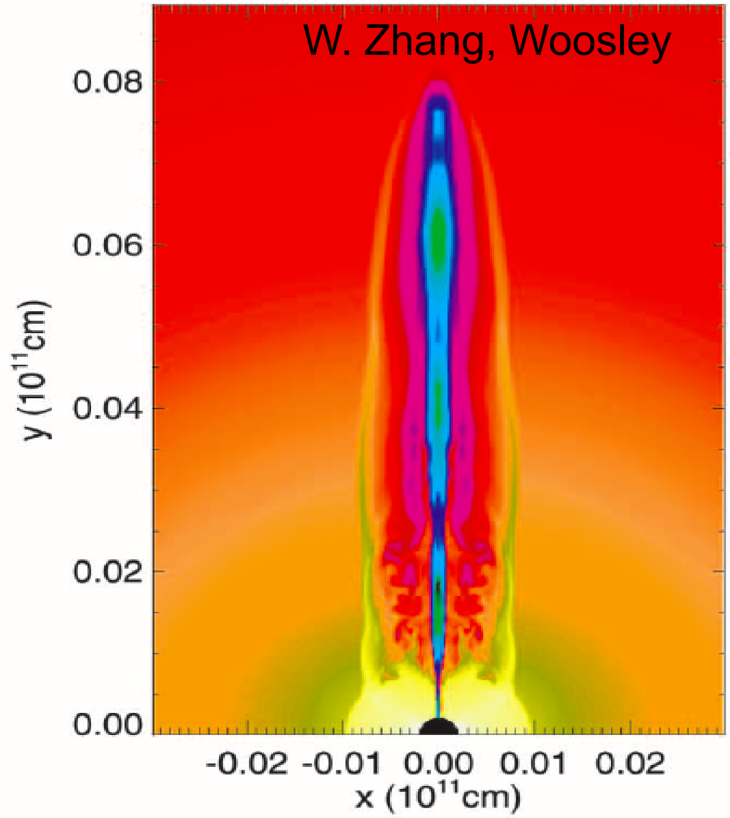
Central Engine of (Long) GRBs

1. Hyper-accreting black hole

Neutrino annihilation, BZ ➔ jets

2. Millisecond Magnetars

Rotational energy



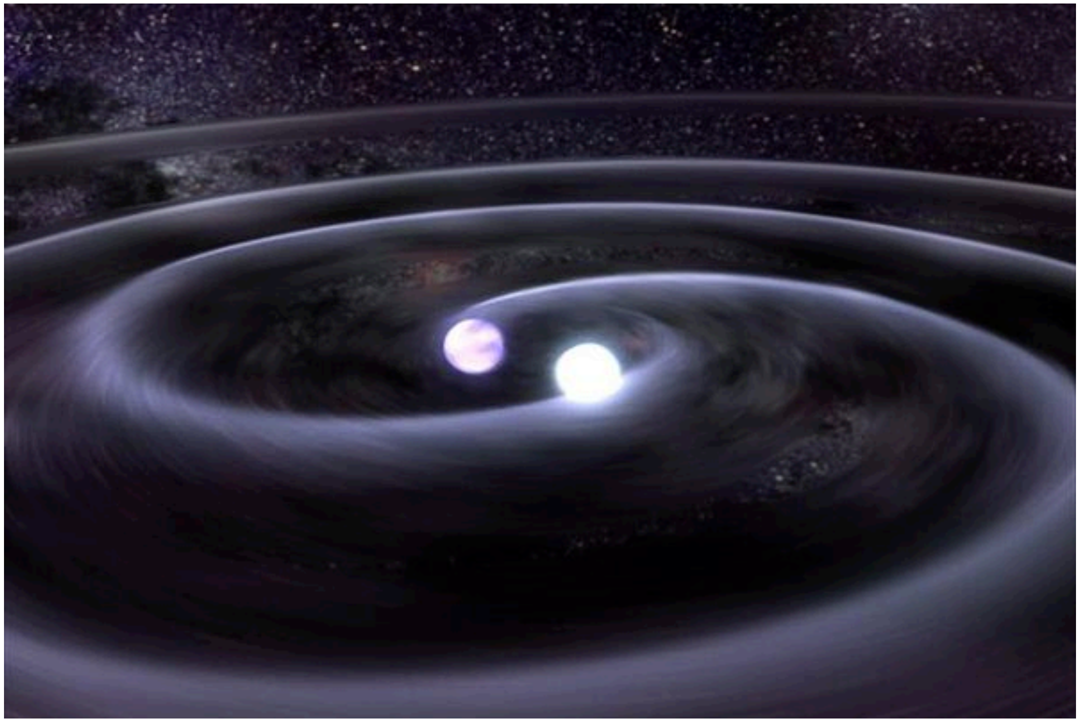
Observational constraints:

-- long-lasting (10^4s) x-ray emission/flares

-- high polarization in reverse-shock emission

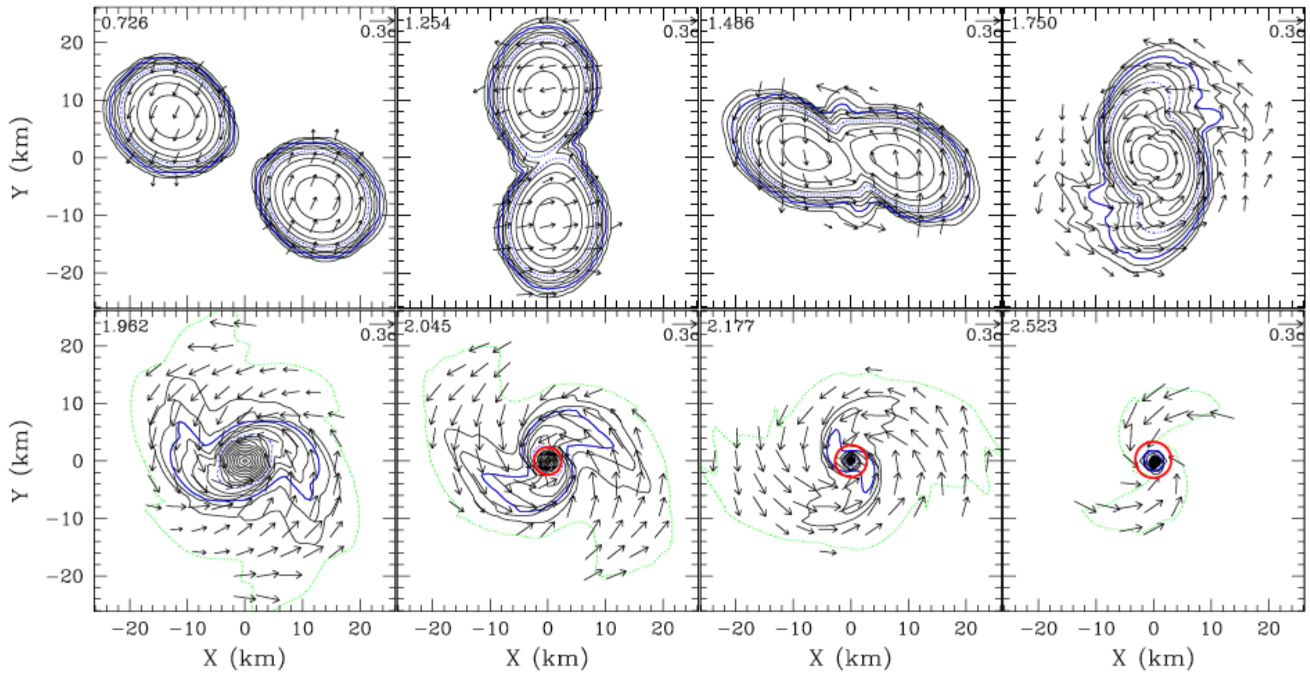
➔ large-scale B field in GRB jets (Mundell et al. 2013)

Magnetic Fields in Merging Compact Binaries

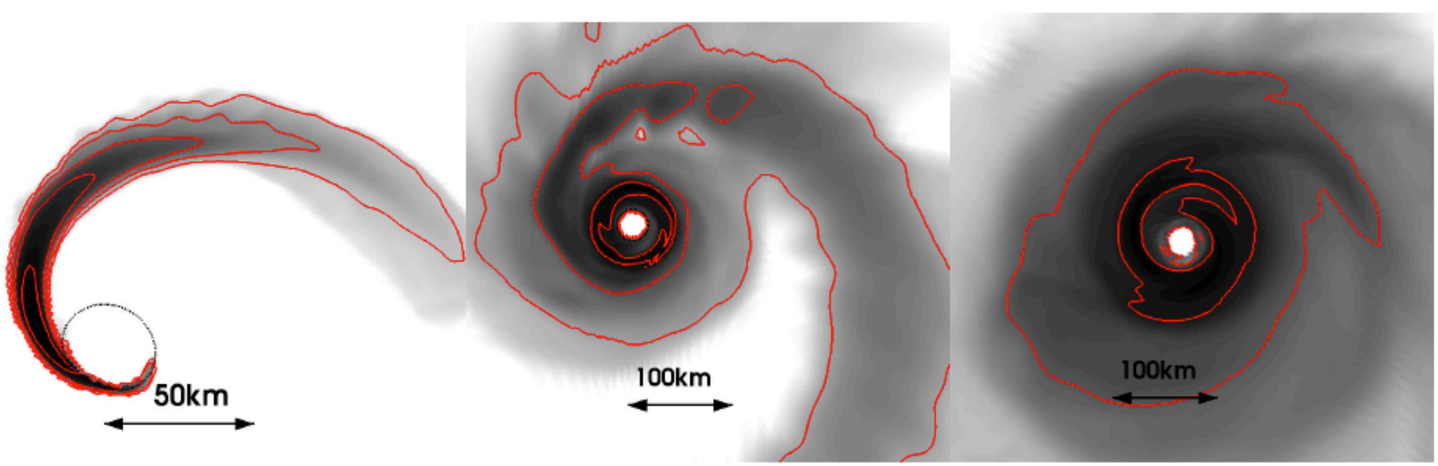


NS/NS and NS/BH binaries: GWs for LIGO/VIRGO
EM counterparts (short GRBs, kiloNova)

Compact WD/WD Binaries: GWs for eLISA/NGO, R CrB stars,
AM CVn binaries, transients, AIC, SN Ia



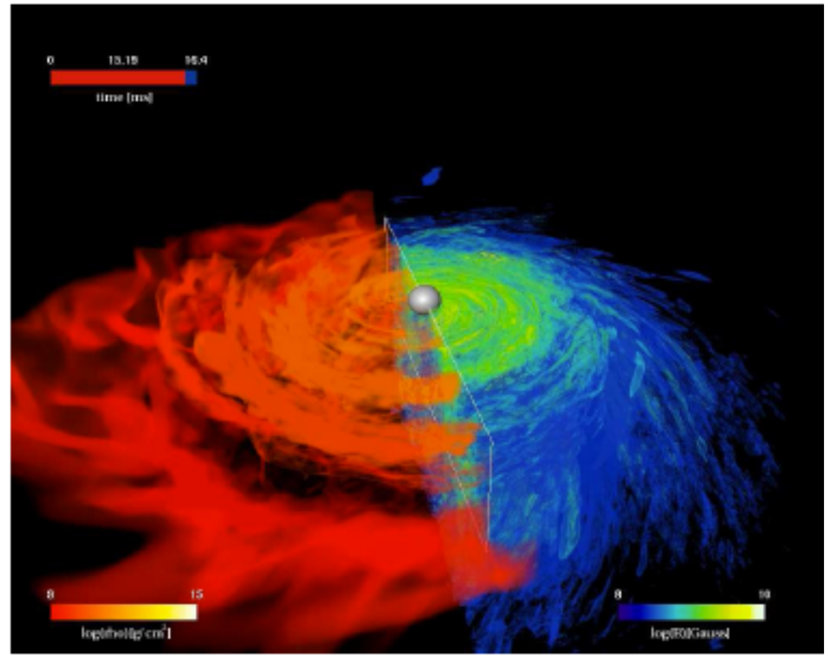
Shibata et al. 2006



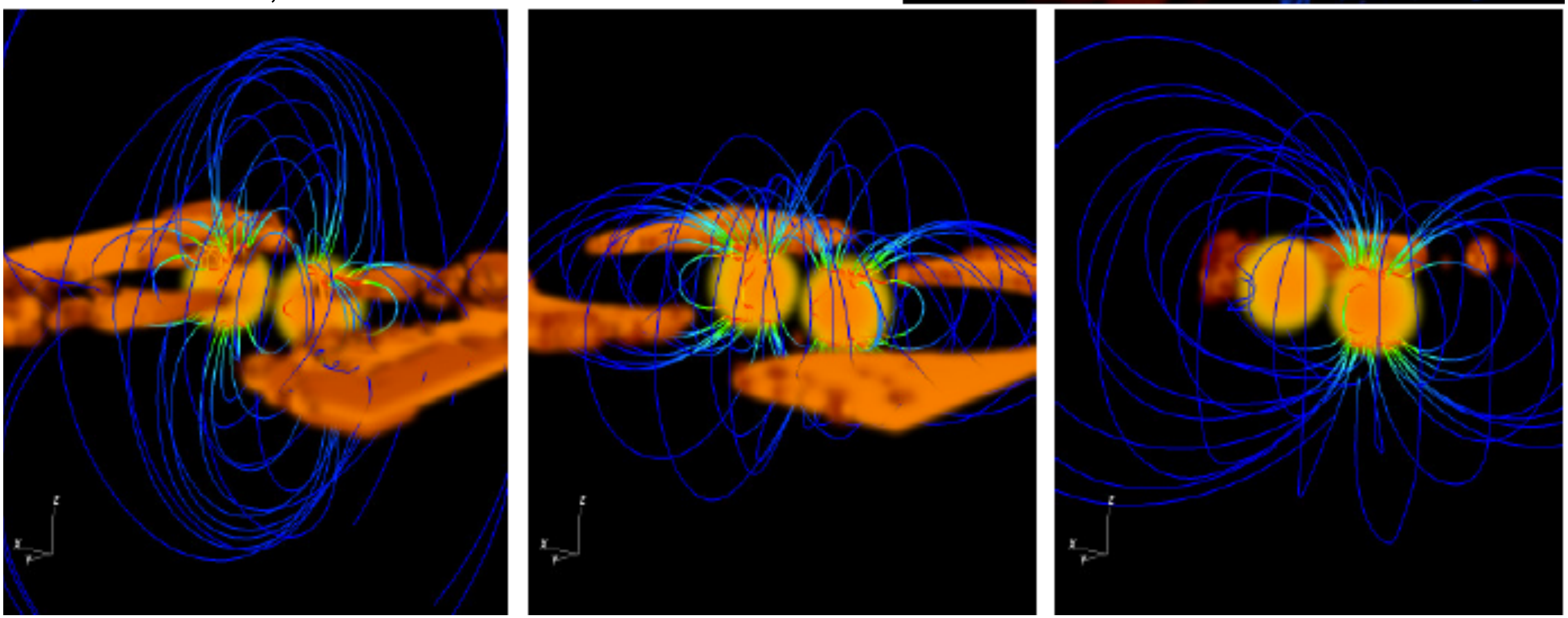
Foucart et al. (Cornell) 2011,13

Merger Simulation with B Fields

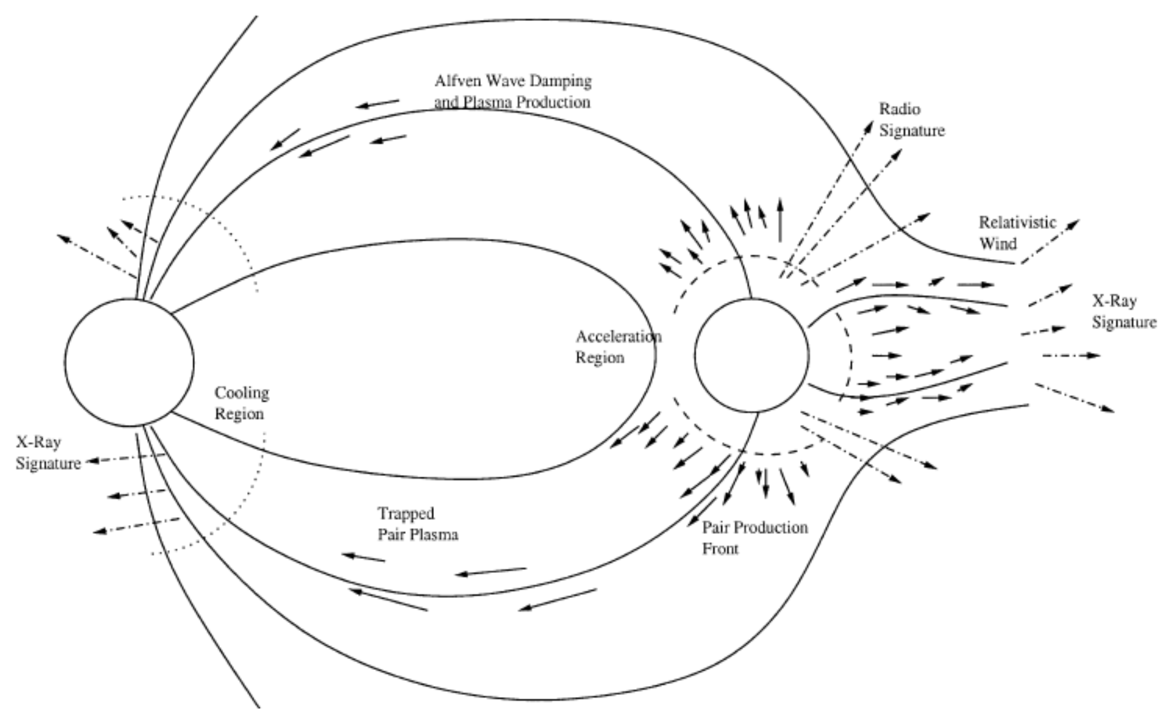
Giacomazzo,
Rezzolla et al 2011



Palenzuela, Lehner et al. 2013



Merger of Magnetospheres



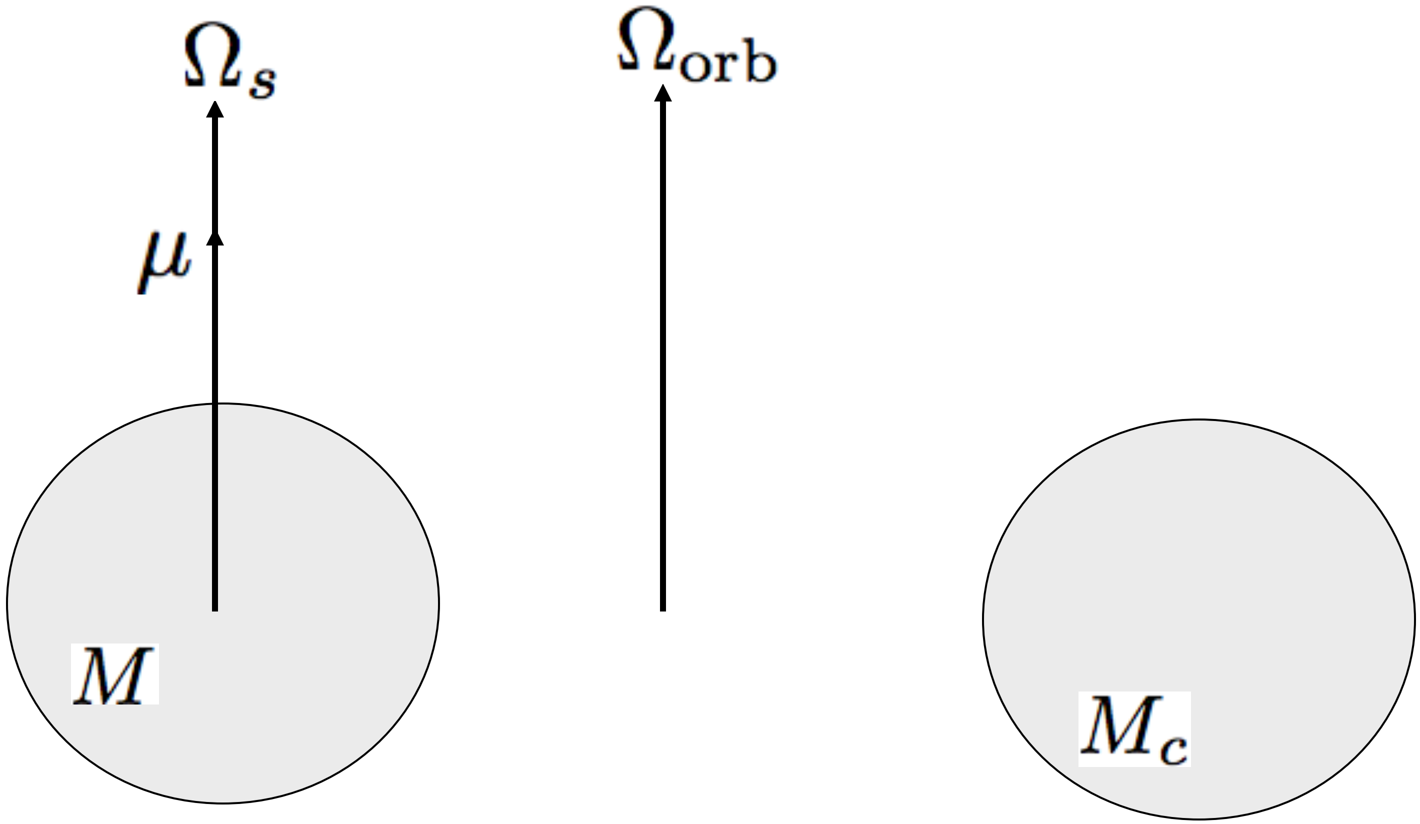
Hansen & Lyutikov 2001

Pre-Merger Phase: Magnetic NSs

Cf. Double Pulsars: PSR J0737-3039

pulsar A: $\sim 10^{10}$G

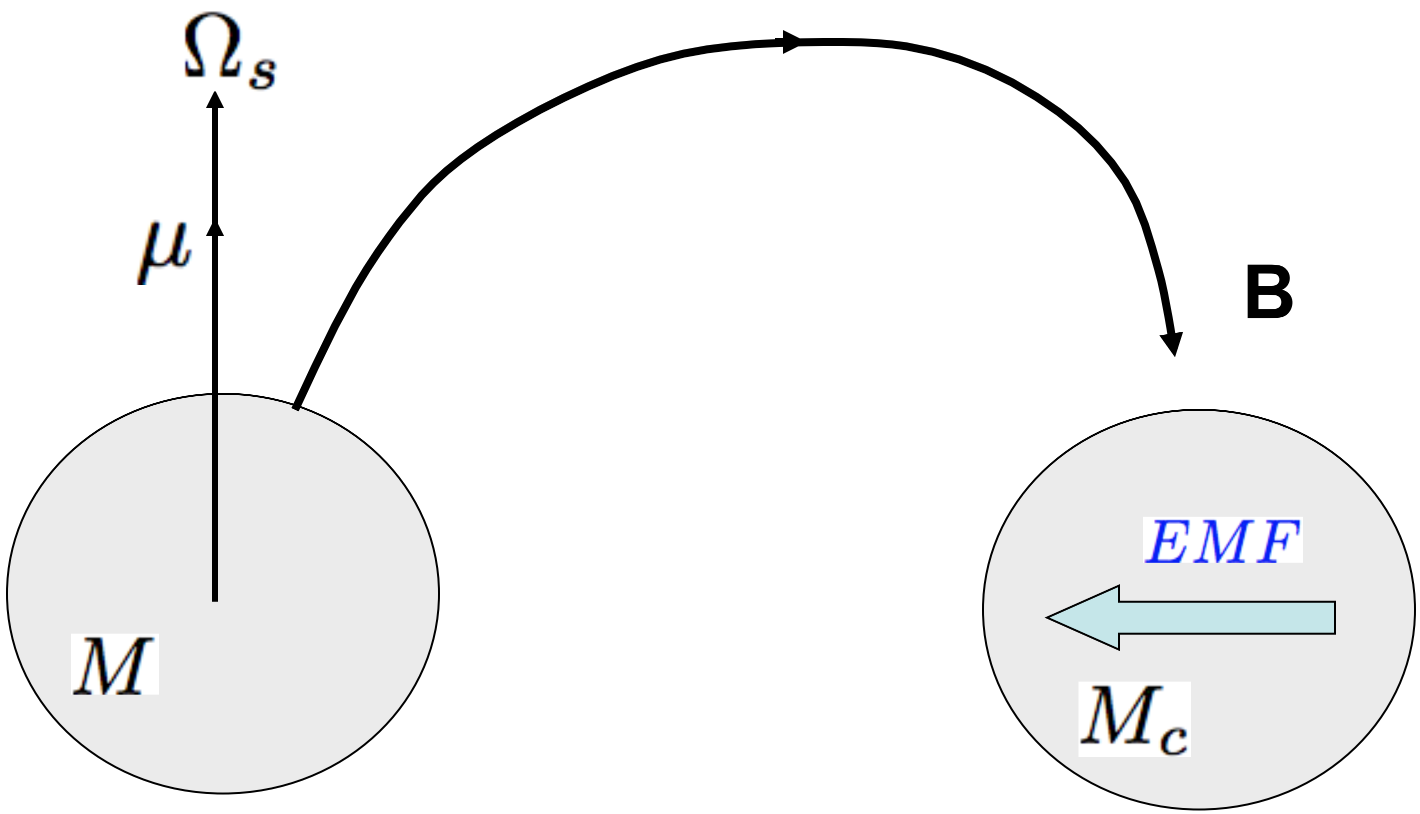
pulsar B: $\sim$a few $\times 10^{12}$G



Consider a binary with

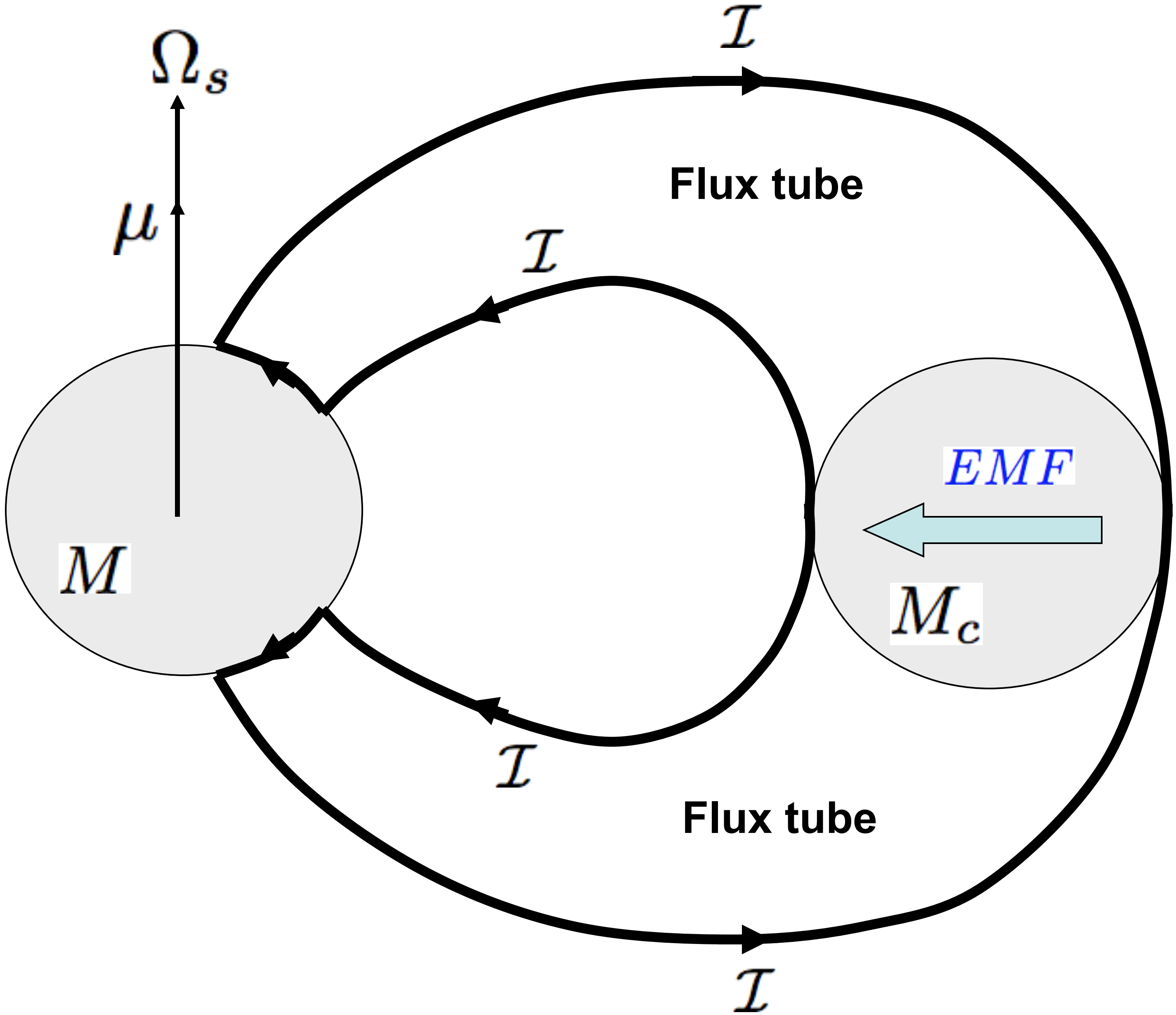
-- magnetic NS (>10^{12}G) + non-magnetic NS

-- embedded in a tenuous plasma (magnetosphere)



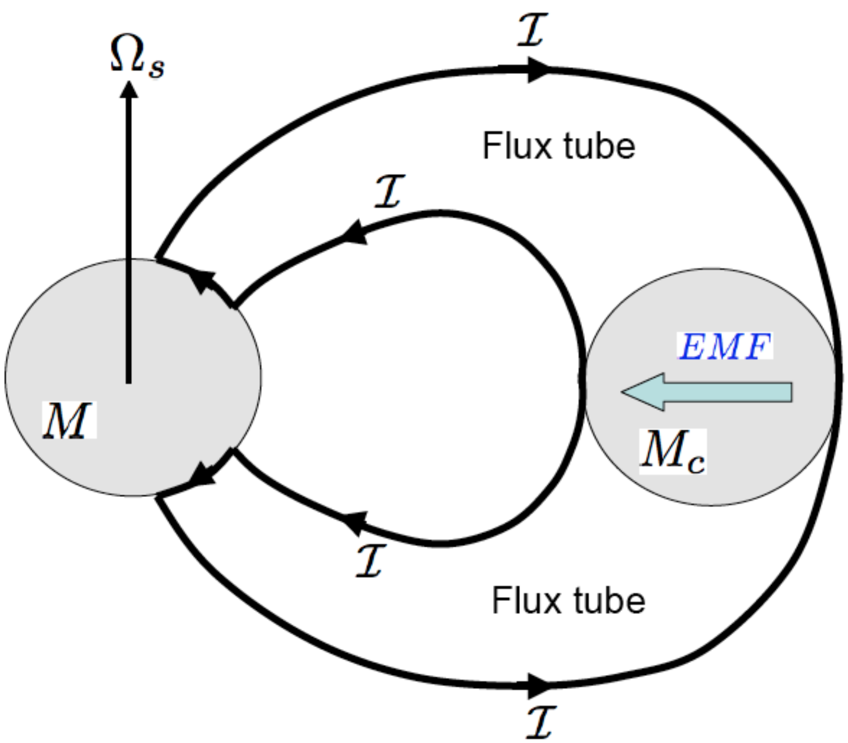
$$\text{EMF}: \quad \Phi = 2R_c \left| \frac{\mathbf{v}}{c} \times \mathbf{B} \right|$$

$$\text{e.g.} \quad \Phi \sim 10^{13}\ \text{Volt} \quad \text{at} \quad f_{\text{orb}} = 20\ \text{Hz}$$



Ω_s
μ
$\mathcal{I}$
Flux tube
$\mathcal{I}$
EMF
M
M_c
$\mathcal{I}$
Flux tube
$\mathcal{I}$

DC Circuit Powered by Orbital Motion



$$\mathrm{EMF}: \quad \Phi = \frac{2\mu R_c}{ca^2}(\Omega_{\mathrm{orb}} - \Omega_s)$$

$$\mathrm{Current}: \quad \mathcal{I} = \frac{\Phi}{\mathcal{R}}$$

$$\mathrm{Dissipation}: \quad \dot{E}_{\mathrm{diss}} = \frac{\Phi^2}{\mathcal{R}}$$

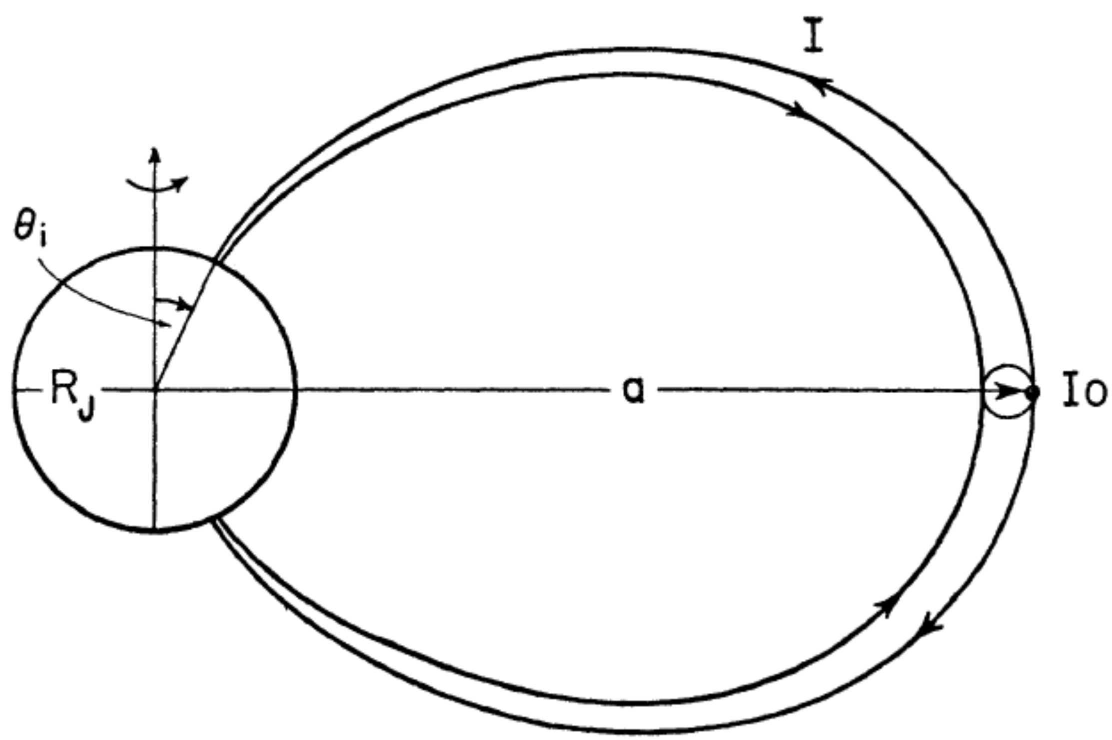
THE ASTROPHYSICAL JOURNAL, Vol. 156, April 1969

IO, A JOVIAN UNIPOLAR INDUCTOR

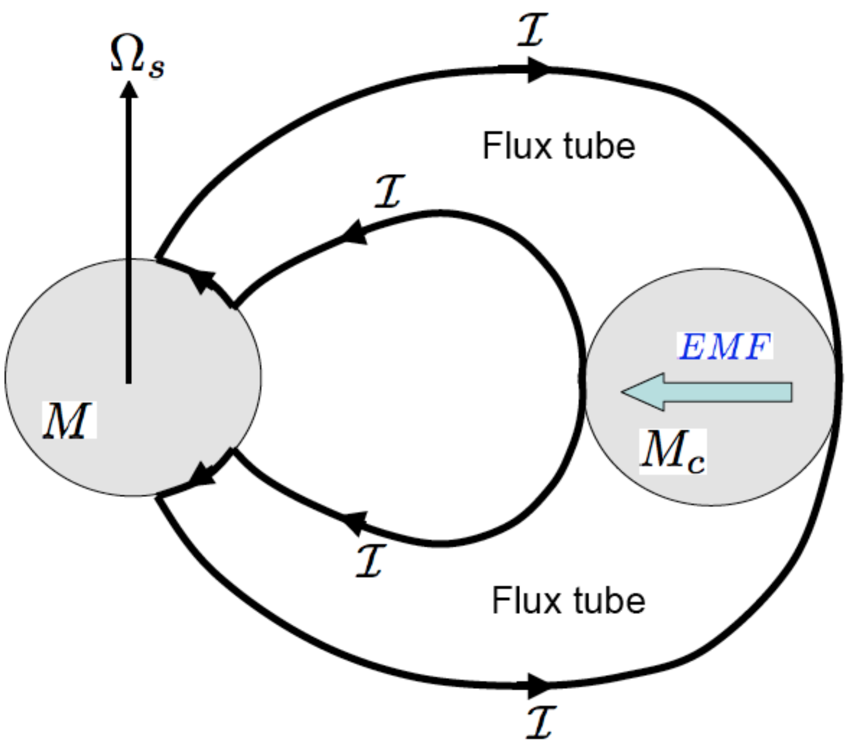
PETER GOLDREICH*
California Institute of Technology

AND

DONALD LYNDEN-BELL
Royal Greenwich Observatory



DC Circuit Powered by Orbital Motion



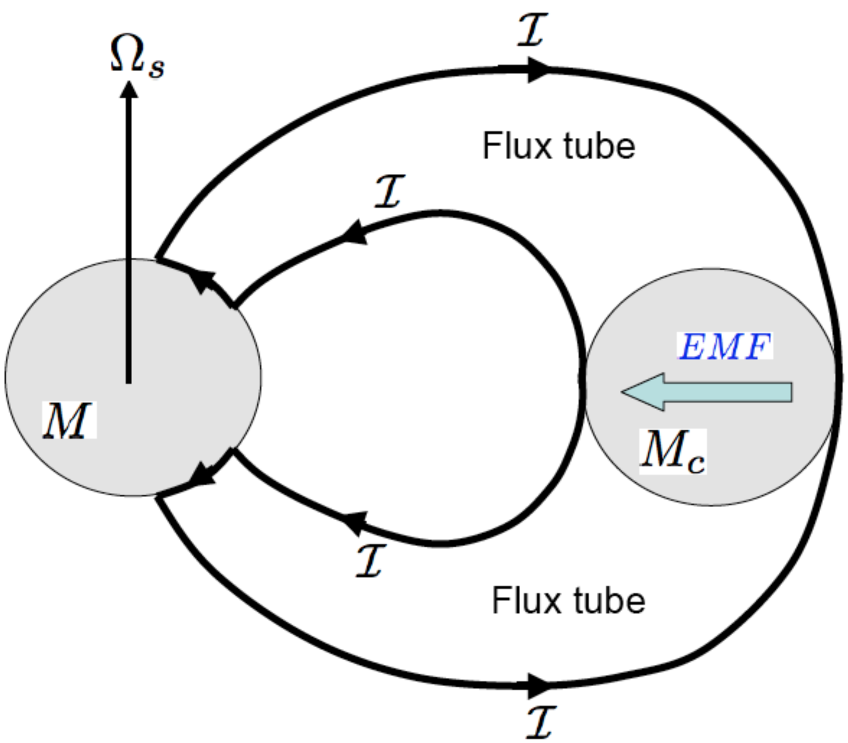
$$\text{EMF}: \quad \Phi = \frac{2\mu R_c}{ca^2}(\Omega_{\rm orb} - \Omega_s)$$

$$\text{Current}: \quad \mathcal{I} = \frac{\Phi}{\mathcal{R}}$$

$$\text{Dissipation}: \quad \dot{E}_{\rm diss} = \frac{\Phi^2}{\mathcal{R}}$$

Results depend on the resistance: $\mathcal{R}$

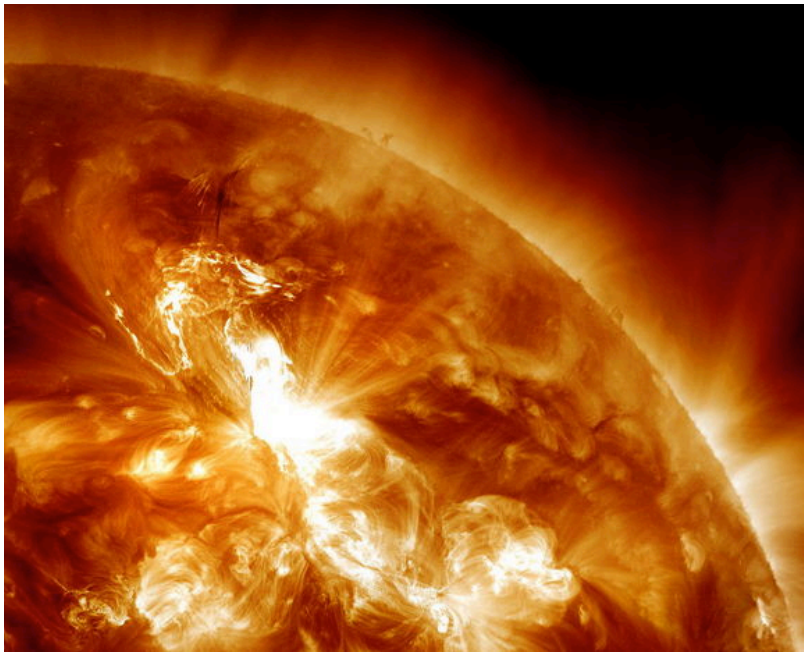
DC Circuit Powered by Orbital Motion

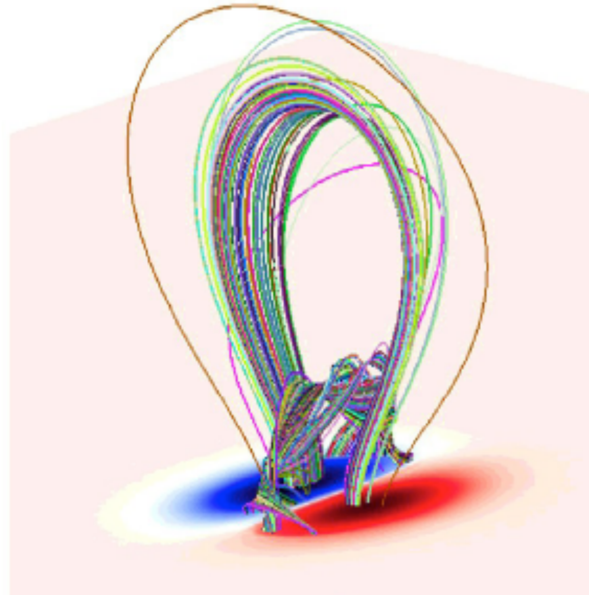


Problems with small $\mathcal{R}$ (➔large $\mathcal{I}$):

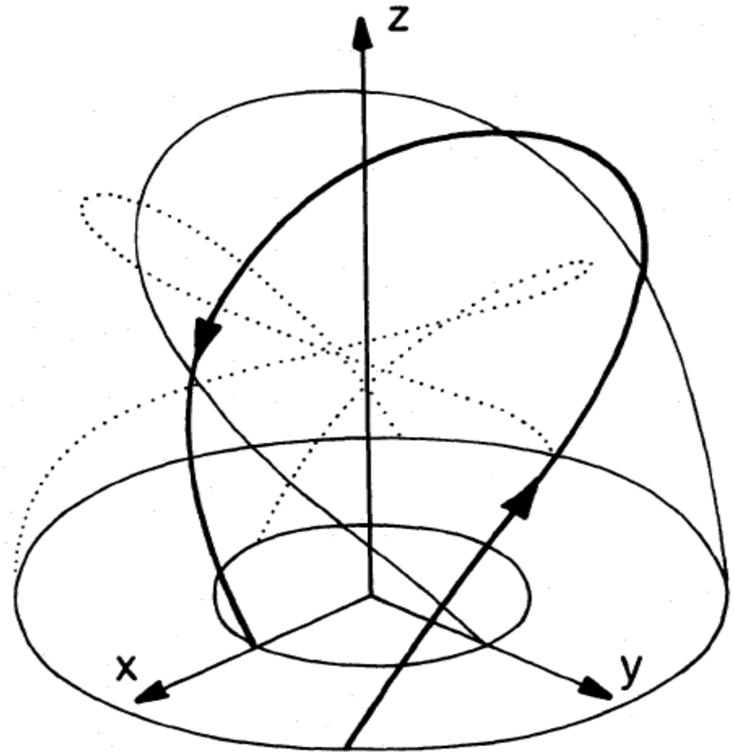
Flux tube is twisted

$$\frac{|B_\phi|}{|B_z|} \sim \frac{16\, v/c^2}{\mathcal{R}}, \quad v = (\Omega_{\rm orb} - \Omega_s)a$$

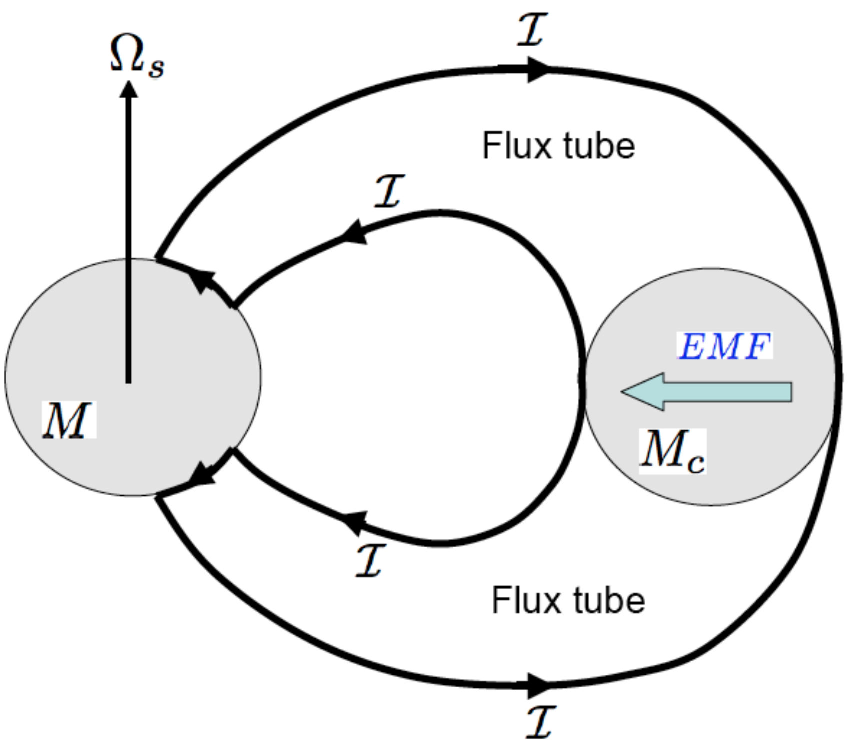




(b)



DC Circuit Powered by Orbital Motion



$$\frac{|B_\phi|}{|B_z|} \sim \frac{16\, v/c^2}{\mathcal{R}}, \quad v = (\Omega_{\rm orb} - \Omega_s)a$$

Circuit will break when $|B_\phi|/|B_z| \gtrsim 1$

Energy Dissipation in the Magnetosphere of Pre-merging NS Binary

DL 2012

$$\dot{E}_{\rm max} \simeq 7 \times 10^{44} \left(\frac{B_{\rm NS}}{10^{13}\,{\rm G}}\right)^2 \left(\frac{a}{30\,{\rm km}}\right)^{-13/2} {\rm erg~s^{-1}}$$

Actual dissipation rate:

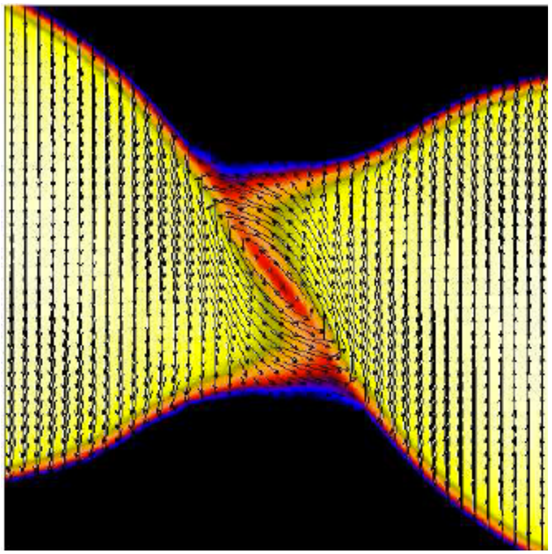
$$\dot{E} \sim 2 \times 10^{44} \left(\frac{B_{\rm NS}}{10^{13}\,{\rm G}}\right)^2 \left(\frac{a}{30\,{\rm km}}\right)^{-7} {\rm erg~s^{-1}}$$

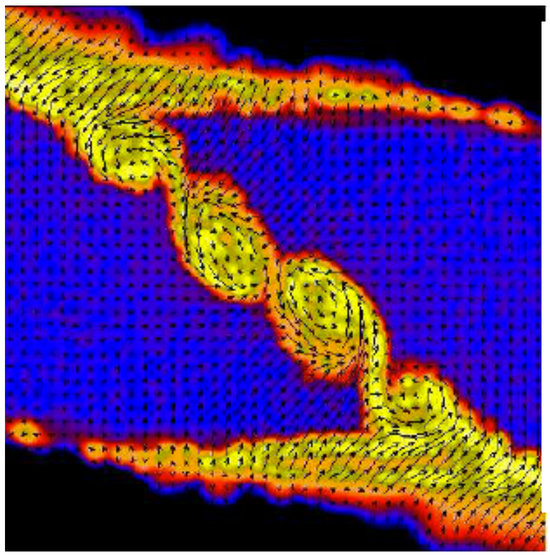
- **This Edot will not affect orbital decay rate (GW signal)**
- **Radio emission prior to binary merger (?)** cf. Vietri 96; Hansen & Lyutikov 01

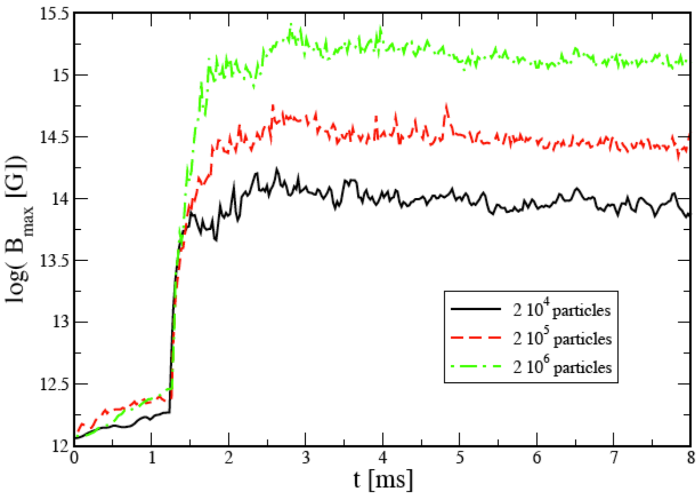
cf. isolated pulsars: $\dot{E} \simeq 10^{33} \left(\frac{B_{\rm NS}}{10^{13}\,{\rm G}}\right)^2 \left(\frac{P}{1\,{\rm s}}\right)^{-4} {\rm erg~s^{-1}}$

During the NS/NS Binary Merger

KH instability at interface ➔ Generate strong B field?



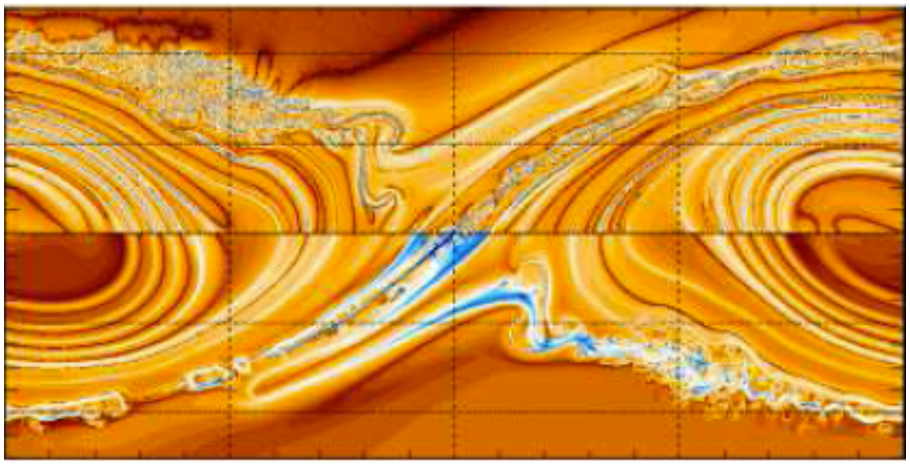


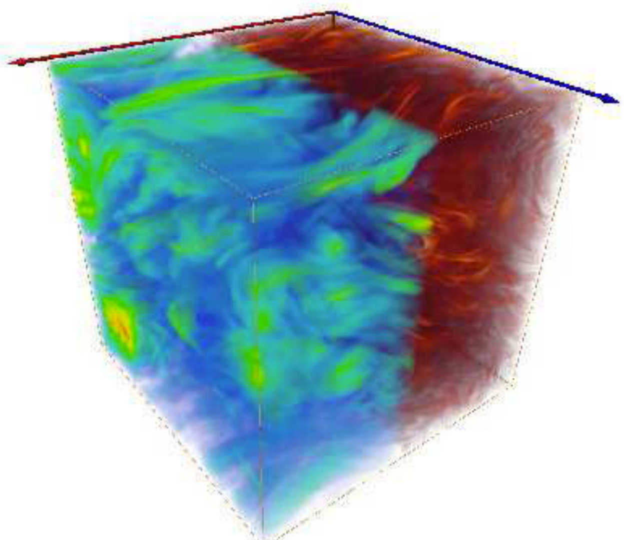


Price & Rosswog 2006

During the NS/NS Binary Merger

KH instability at interface ➔ Generate strong B field?

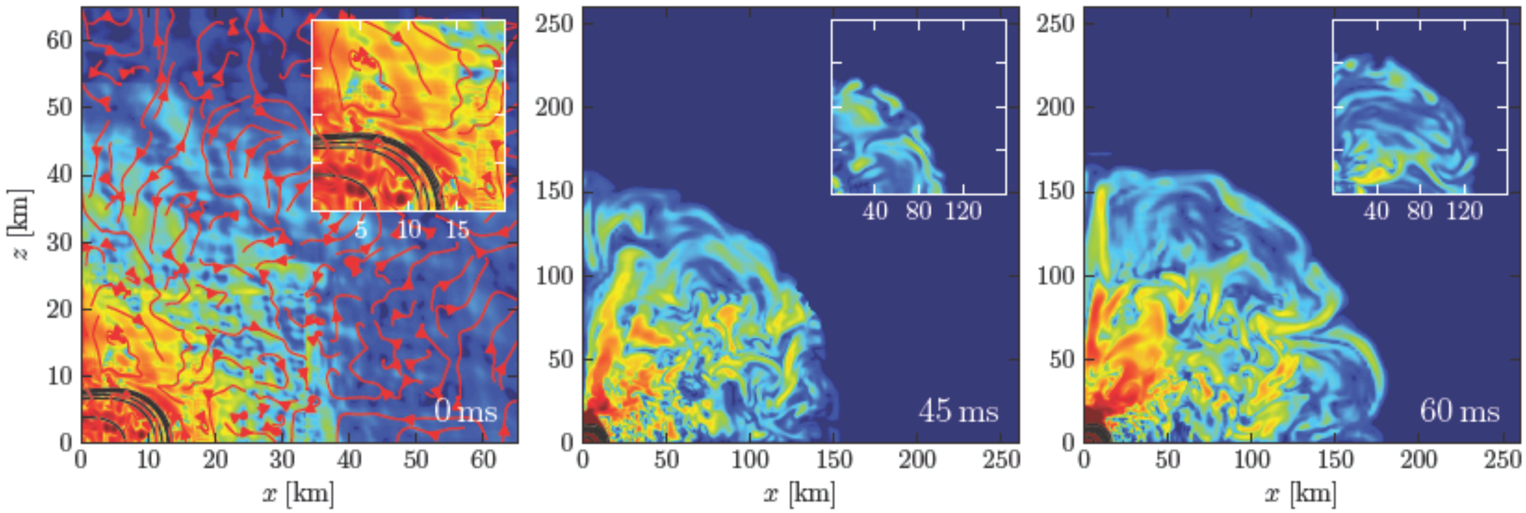




Obergaulinger, Aloy & Muller 2010

➔ Yes, but dynamical impact of the field is limited to shear layer

Magnetic Fields in the Merger Remnant



Siegel, Ciolfi & Rezzolla 2014

-- Field amplification by differential rotation (MRI resolved?)

-- Wind/outflow

-- Formation of ms magnetar?

Summary

Physicists' strong magnetic fields:

-- Atomic physics
-- Condensed matter: Transport property
-- Particle physics: QED effects, radiative transfer

Astrophysicists' strong fields:

mostly "classical", but effects important, interesting and rich

-- **Stars & Compact Objects**: Static equilibrium, local equilibrium (crusts), Field evolution, Magnetospheres.
-- **Disks**: MAD disks, Jets/outflows, field advection, turbulence
-- **Disk accretion onto magnetic stars**: star-disk linkage, QPOs, outflows, misalignments
-- **Core collapse and Formation:** MHD supernova, ms magnetars, GRBs
-- **Binary Mergers**: pre-merger interaction, interface B-field generation, GRBs