2015 GRB Workshop – RIKEN - Tokyo - Aug 31st – Sept. 2nd

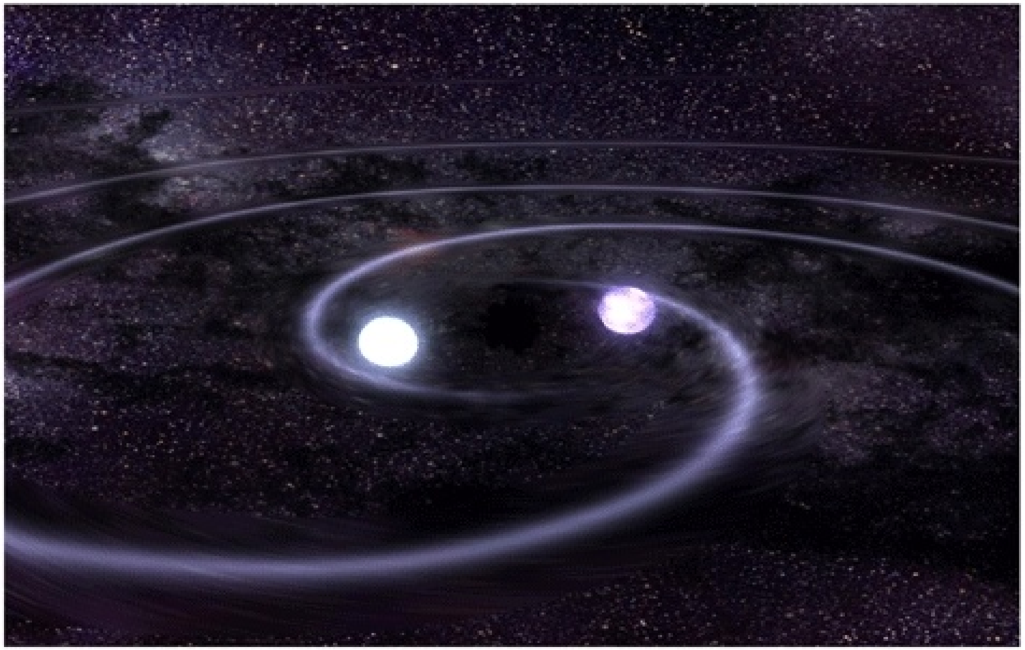
NS physics with GW observations: the importance of being magnetic

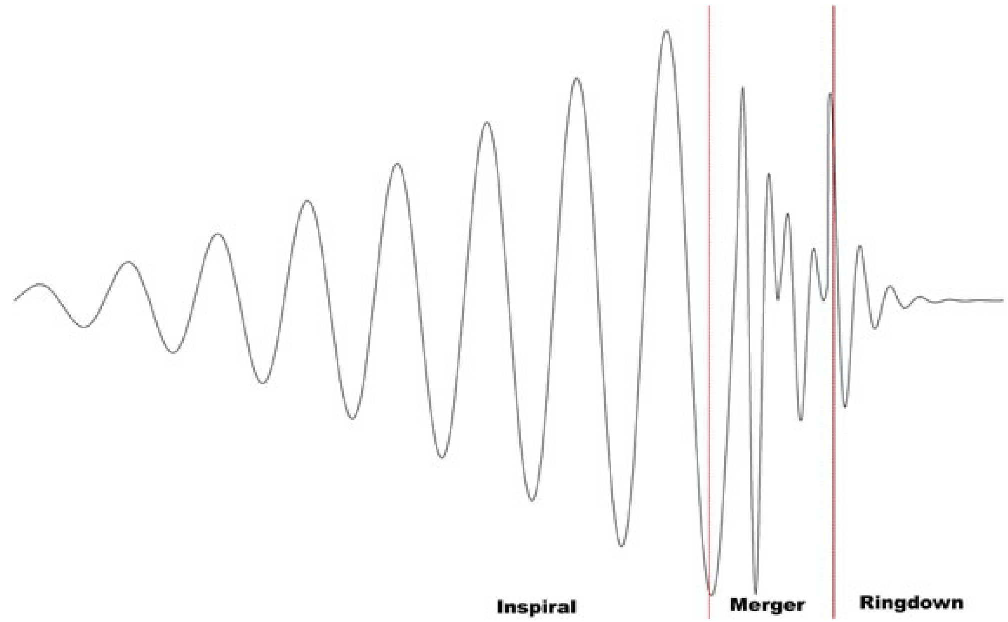
Simone Dall'Osso

TAT - University of Tübingen

in collaboration with
Bruno Giacomazzo (Trento University)
Rosalba Perna (Stony Brook University)
Luigi Stella (Astronomical Observatory of Rome)

Binary NS mergers





inspiral ⟶ GW-driven, ~ point-mass approx

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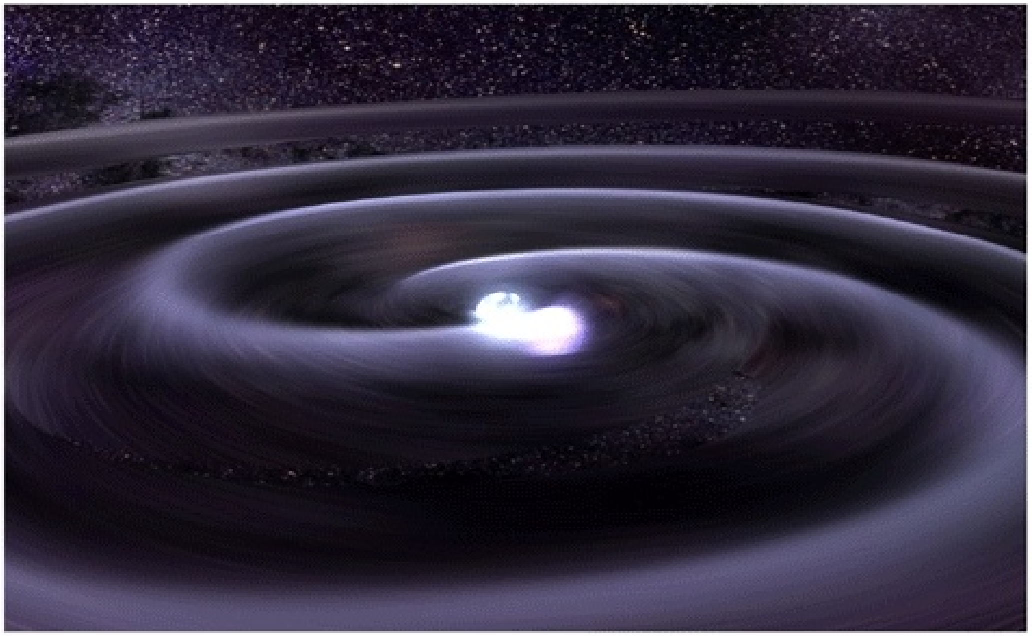

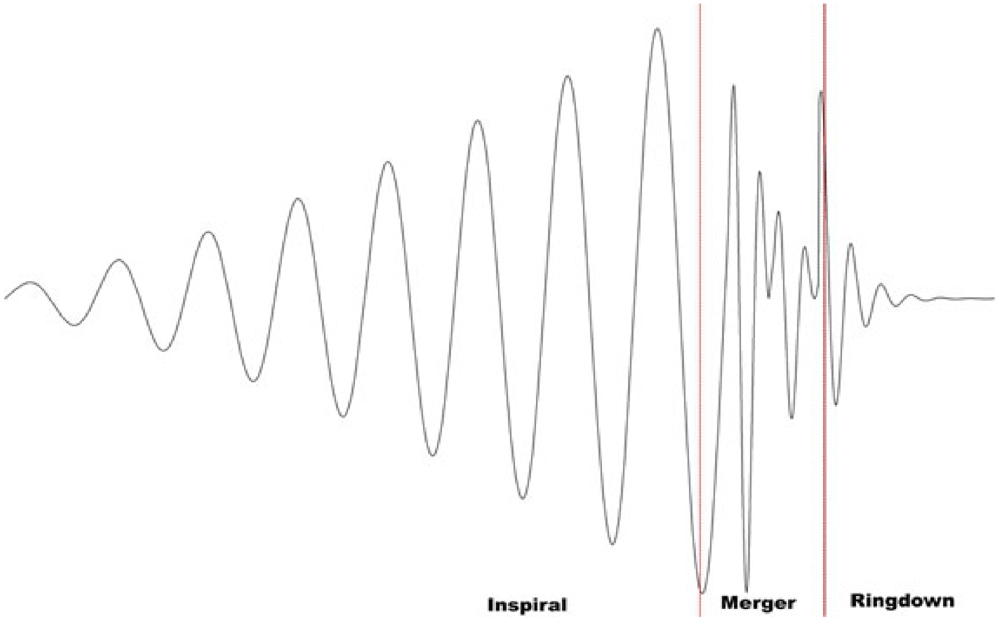

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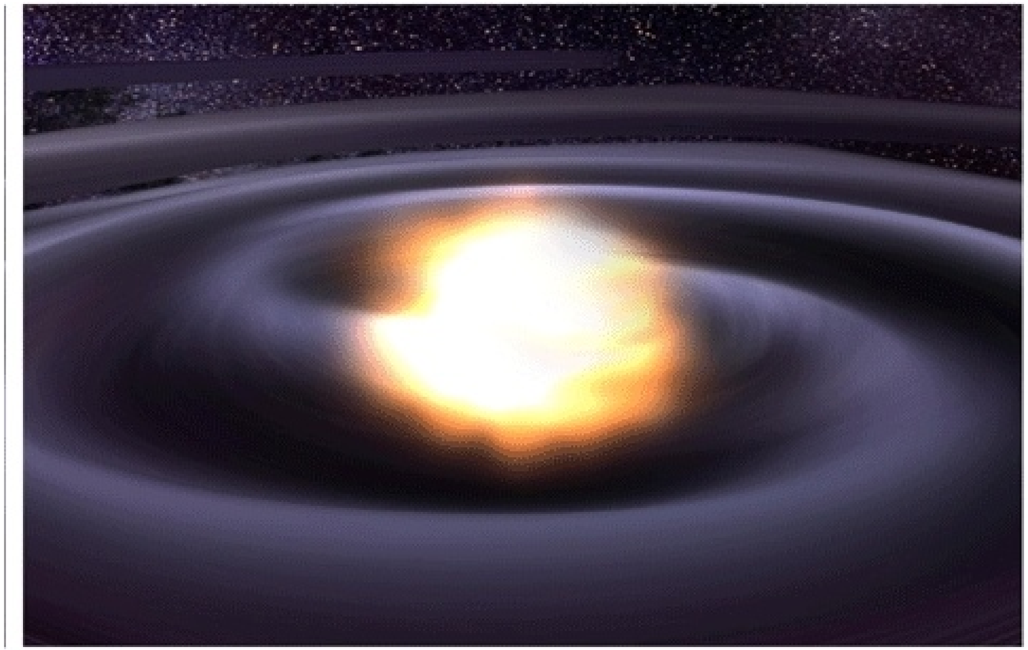

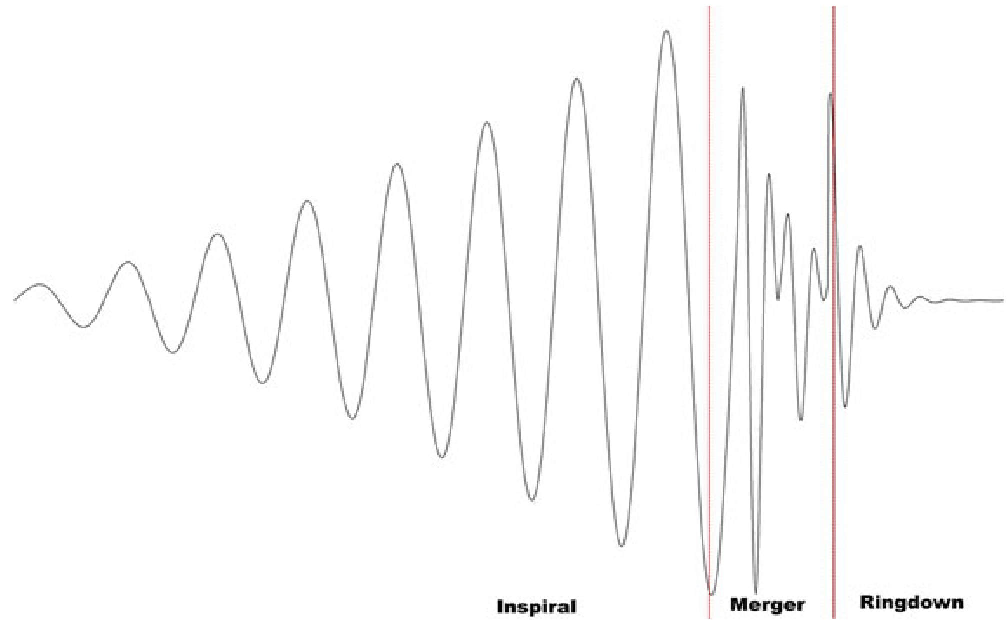

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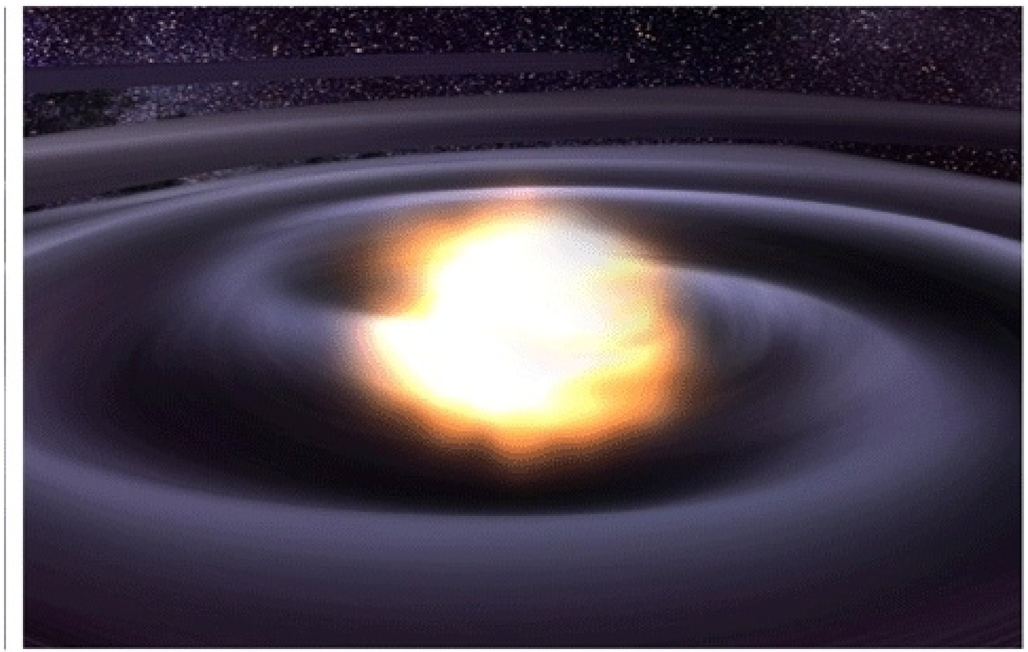

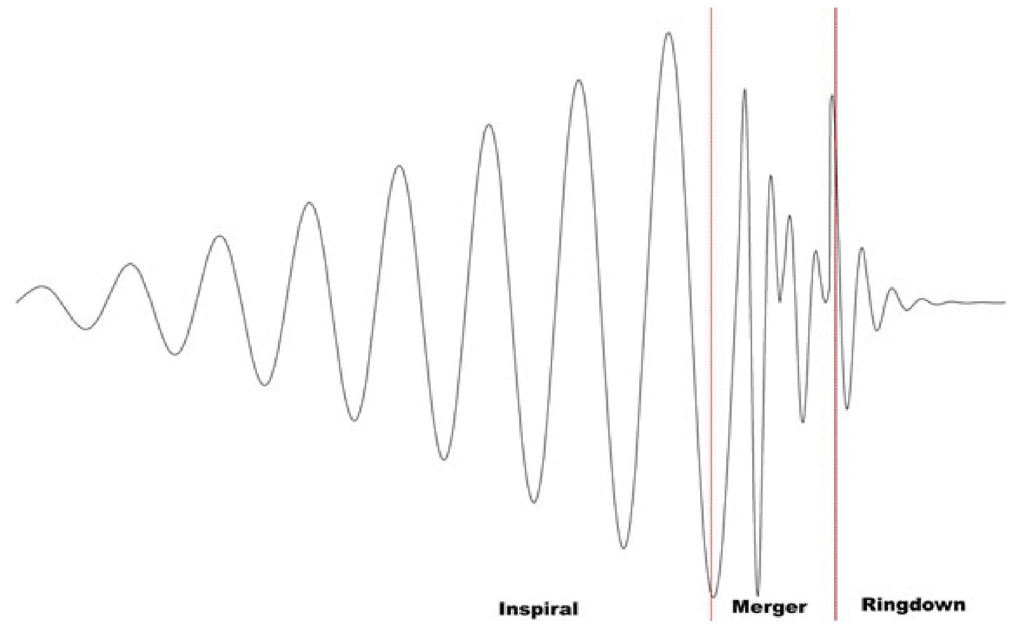

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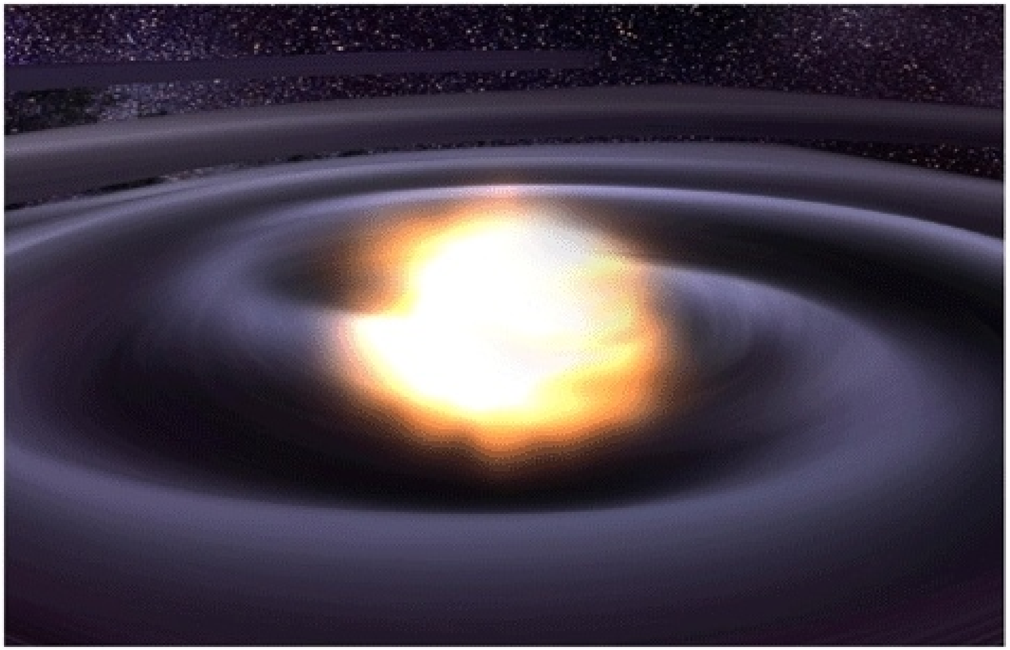

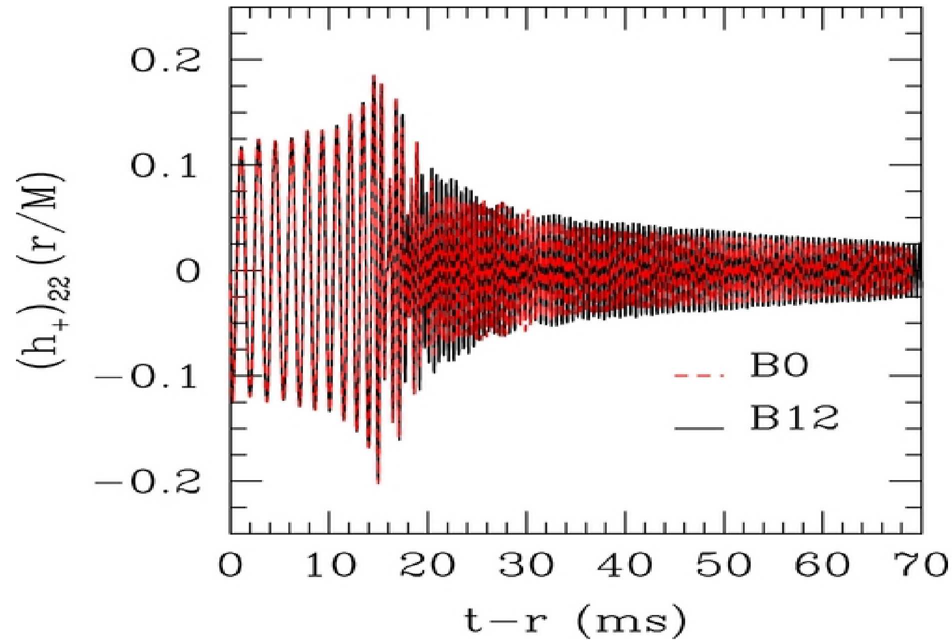

Giacomazzo & Perna (2013)

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Post-merger remnants

$$\begin{cases} \text{Direct collapse to BH} & \text{if} \quad M_{TOT} > M_{max}(\Omega) \\ \text{Formation of an unstable NS} & \text{if} \quad M_{max}(\Omega) > M_{TOT} > M_{max} \\ \text{Formation of an stable NS} & \text{if} \quad M_{TOT} < M_{max} \end{cases}$$

$$M_{max}(\Omega) = M_{max}(1 + \alpha\,\Omega^{\beta})$$

Post-merger remnants

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- Formation of an unstable NS if $M_{max}(\Omega) > M_{TOT} > M_{max}$
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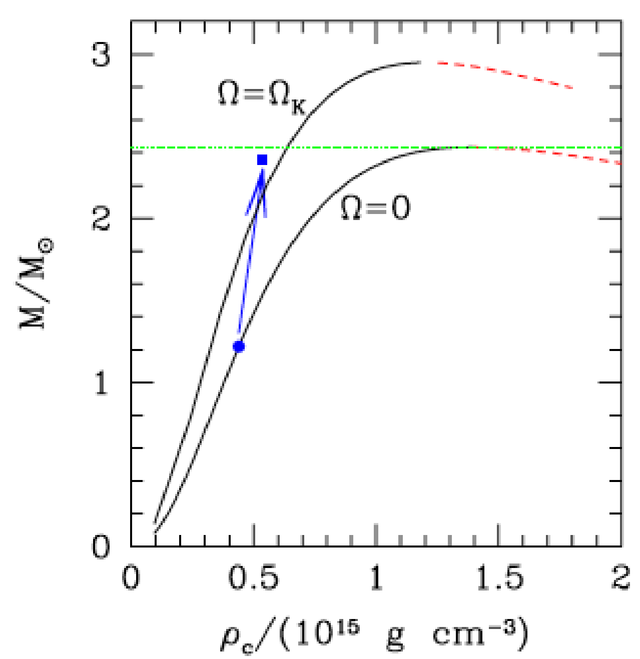

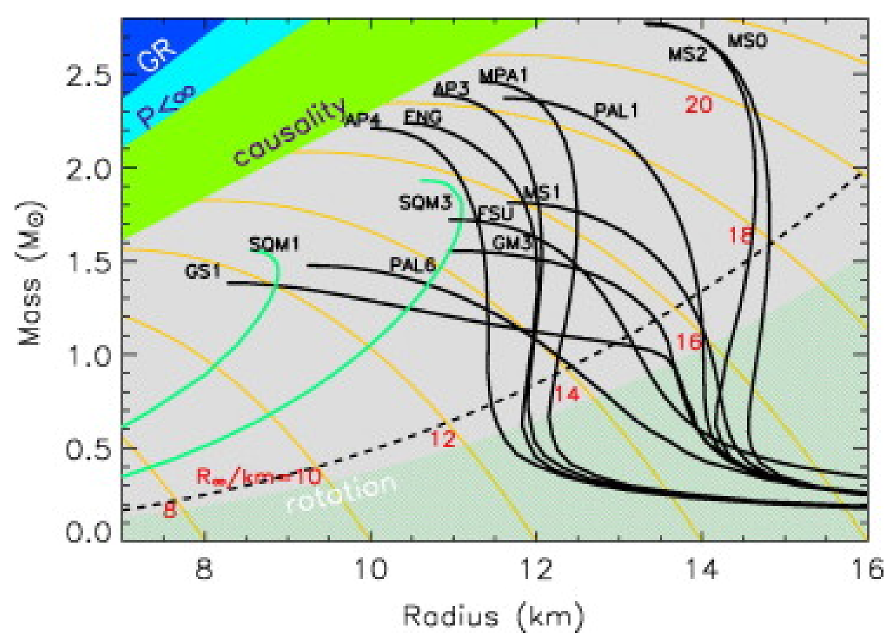

Post-merger remnants

Differential rotation/turbulence → strongly twisted internal field $E_B \geq 10^{50}$ erg

e.g., Rosswog et al. (2003), Rezzolla et al. (2011), Giacomazzo & Perna (2013), Giacomazzo et al. (2015), Kyotoku et al. (2015), ...

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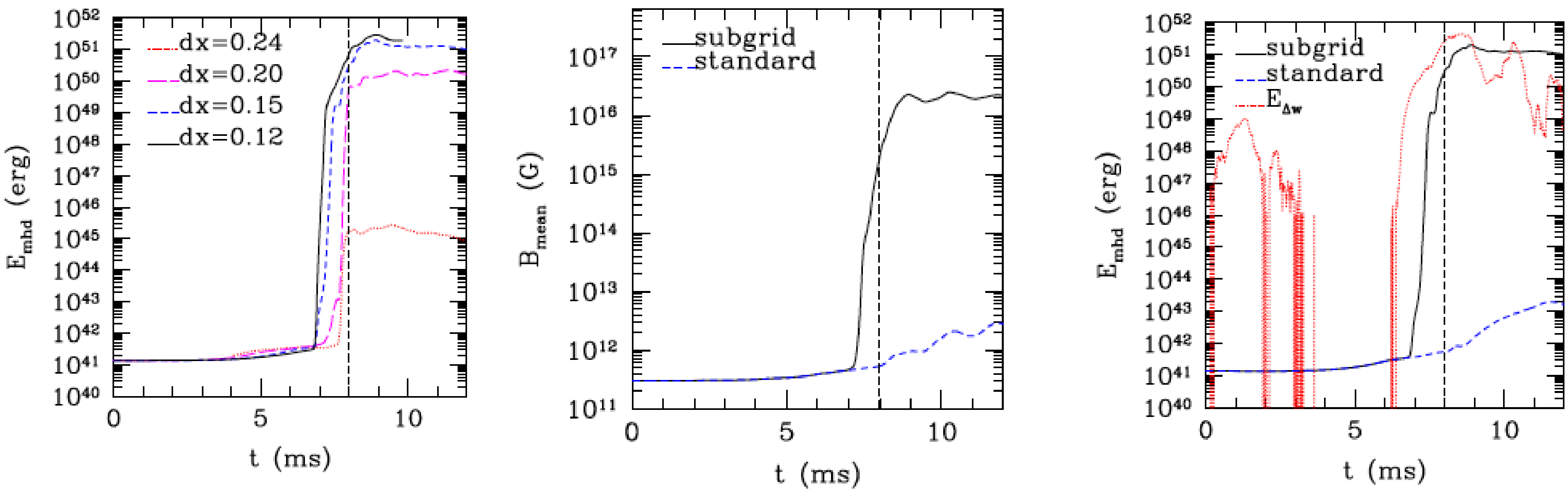
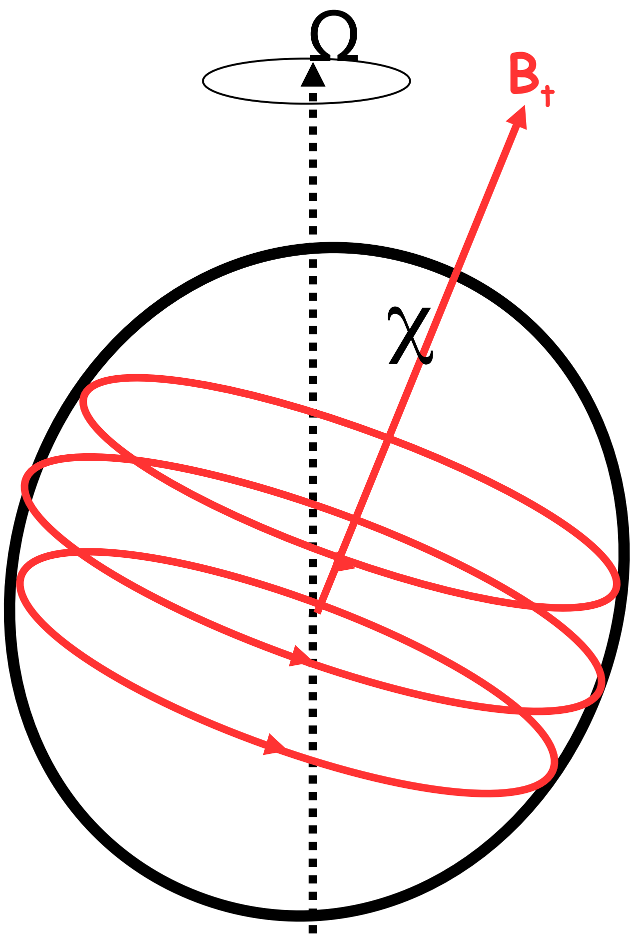


GW emission: a generic mechanism

TOROIDAL B **PROLATE DISTORTION**



$\chi \neq 0$ excites freebody precession

$\Omega_{pre} = \varepsilon_B \Omega \cos\chi$ (Mestel & Takhar72)

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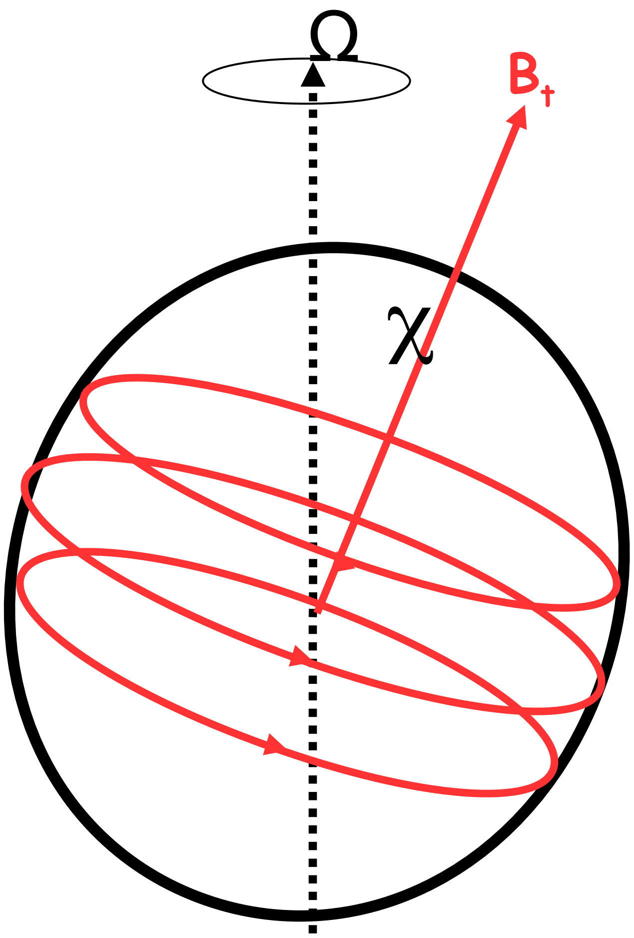

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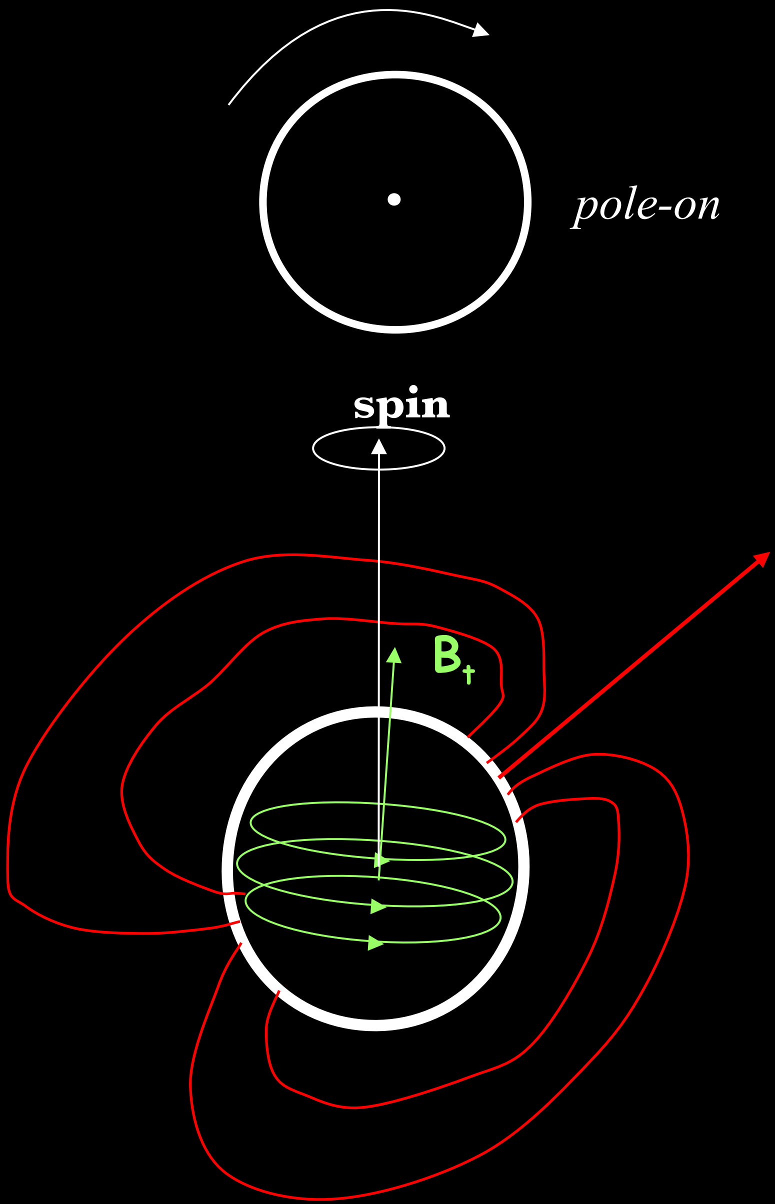
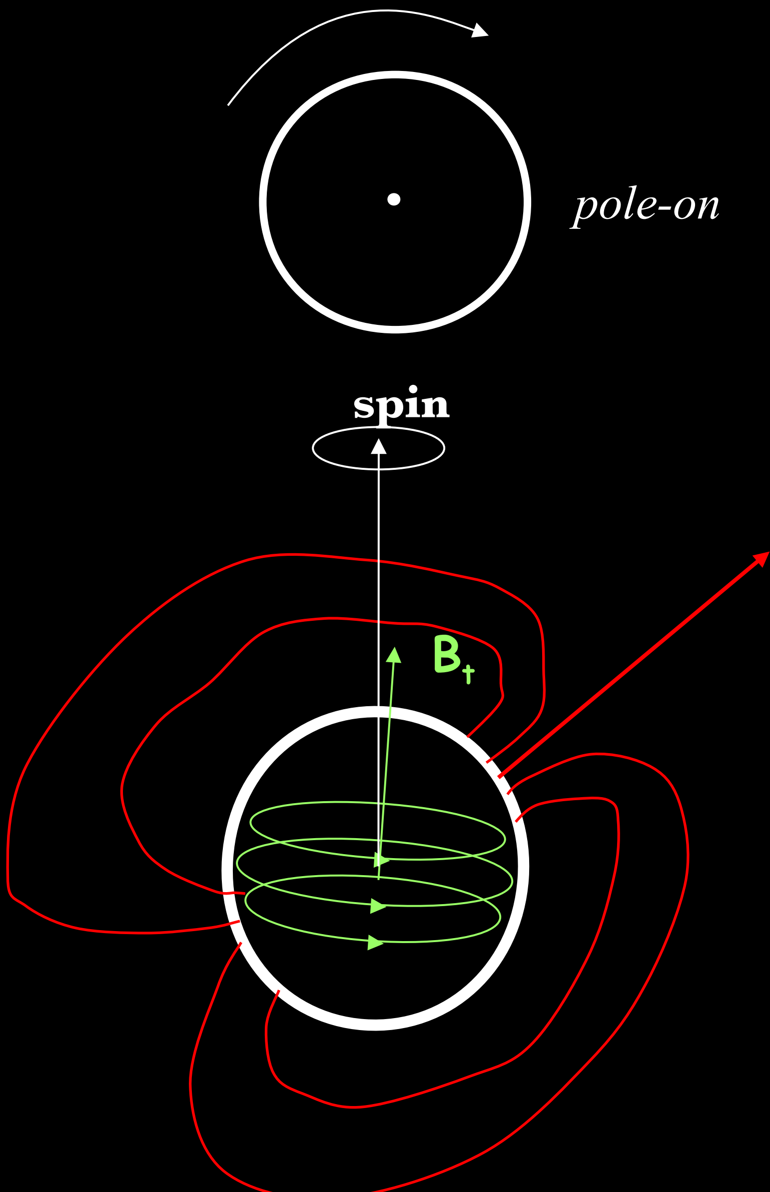


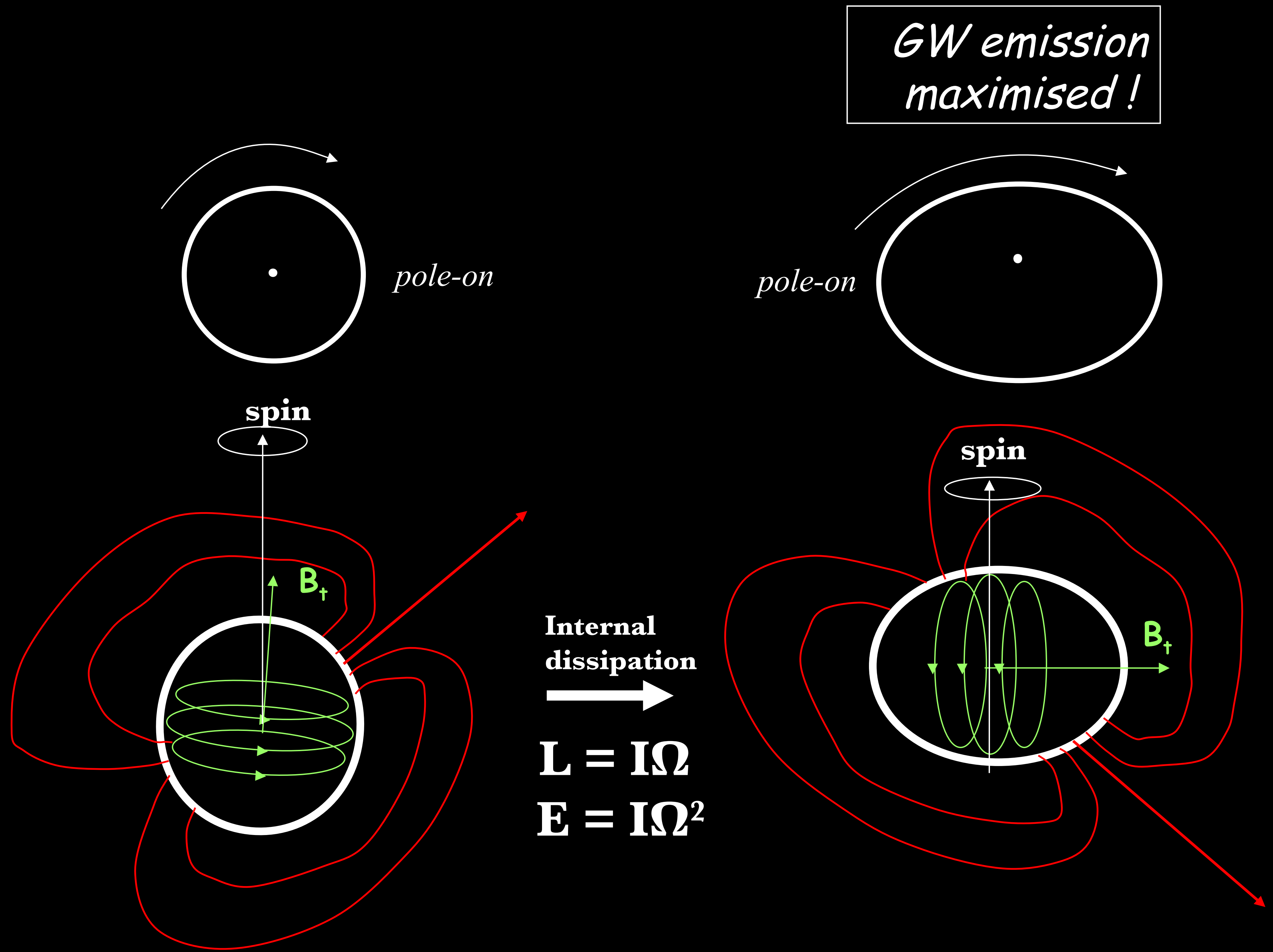
pole-on
spin
B_t



Internal dissipation →

$$L = I\Omega$$

$$E = I\Omega^2$$


GW emission maximised !
pole-on
pole-on
spin
spin
B_t
B_t
Internal dissipation
L = IΩ
E = IΩ²

GW emission: a generic mechanism

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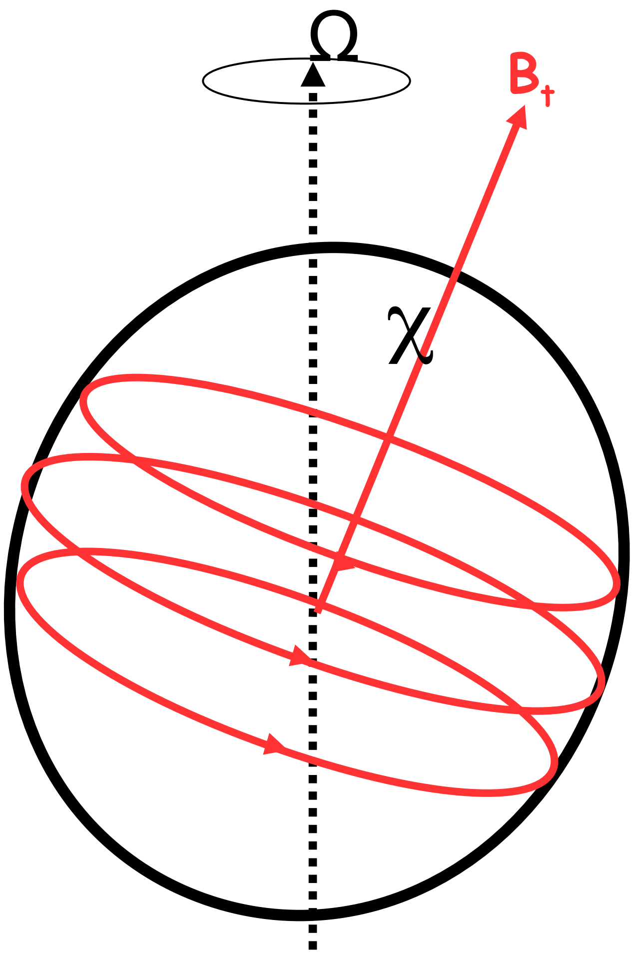

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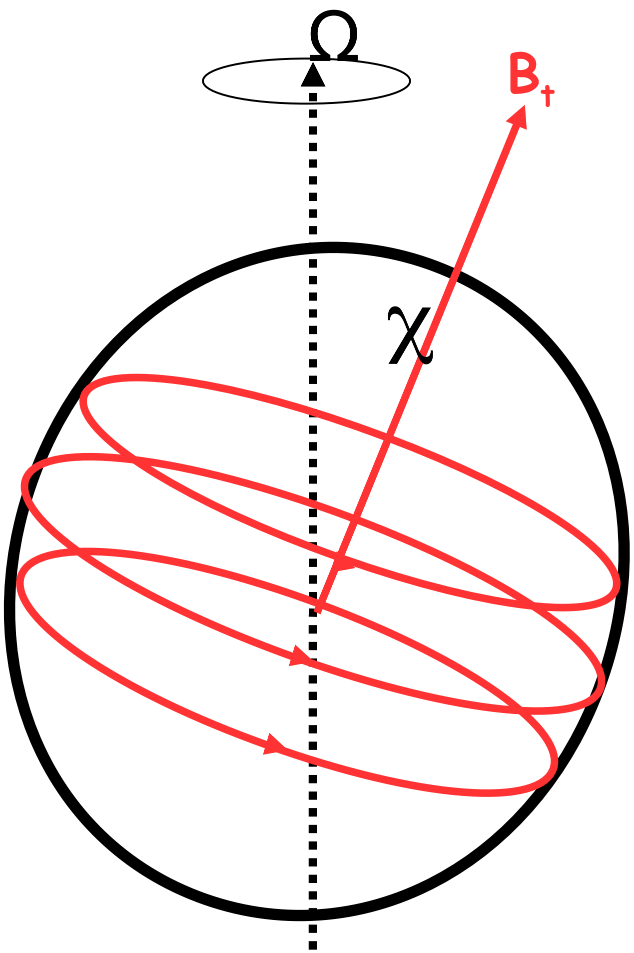

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Proposed application in different contexts where differential rotation plays a role

1. magnetar formation in core-collapse

Thompson & Duncan 1992,1993

Stella et al. 2005, Dall'Osso, Shore & Stella 2009

GW emission: a generic mechanism

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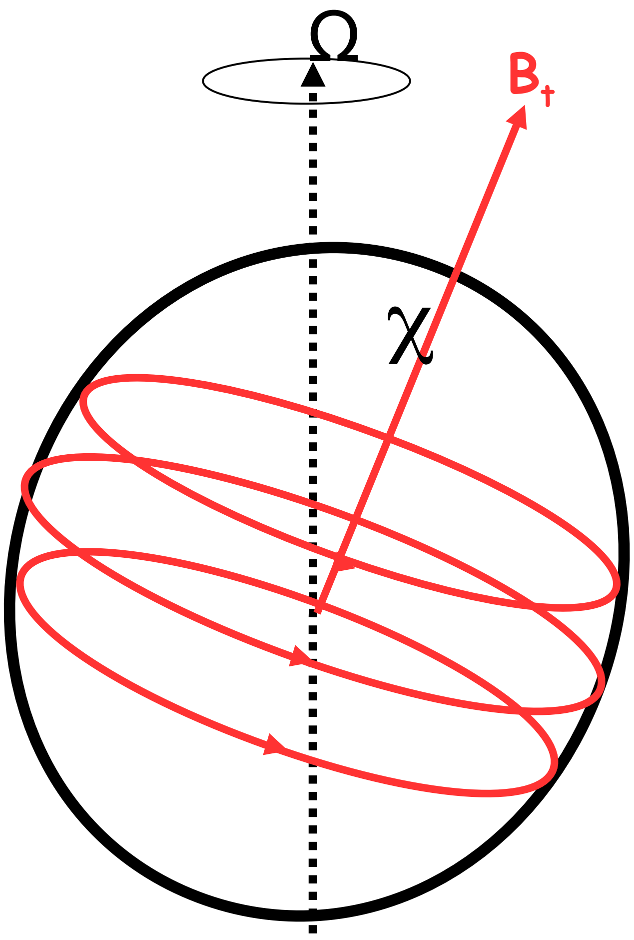

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Proposed application in different contexts where differential rotation plays a role

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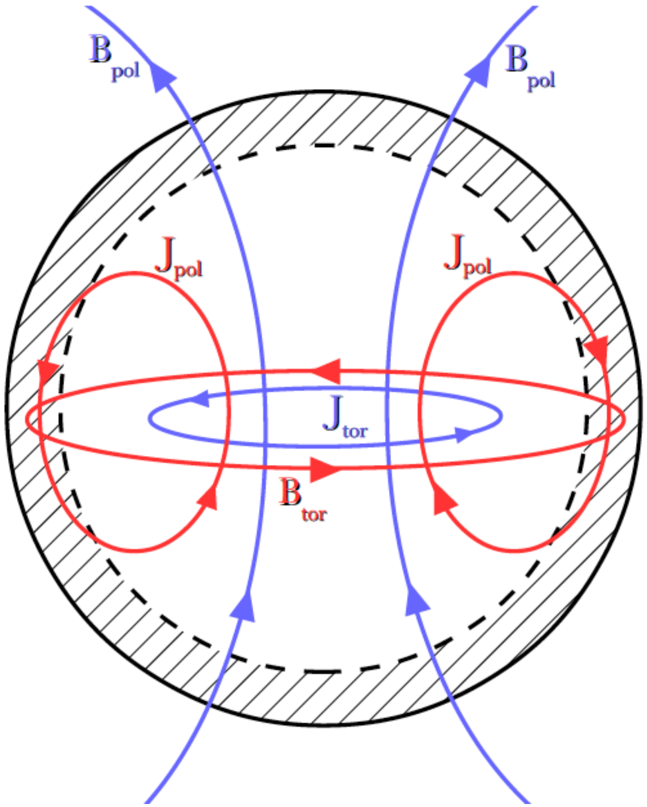
Thompson & Duncan 1992,1993
Stella et al. 2005, Dall'Osso, Shore & Stella 2009

2. *r*-modes in accreting NSs in LMXBs
Rezzolla et al. (2001)
Cuofano et al. (2012)

Interior vs. exterior field: stability

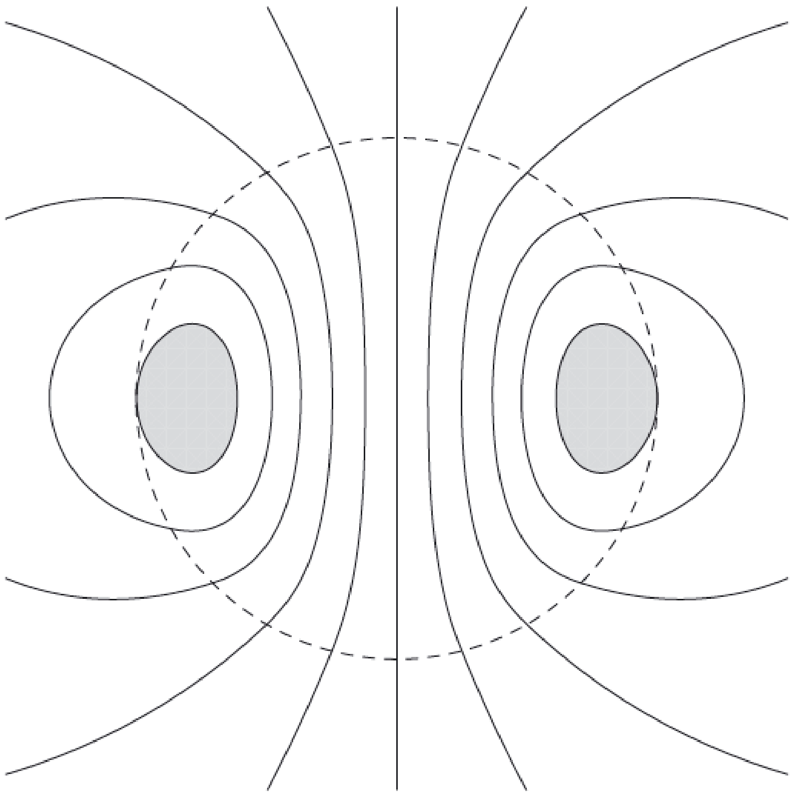


So-called twisted-torus is a generic relaxed state for NS global fields (Spruit & Braithwaite 2006)

Stability limit for such configurations depends critically on stable stratification of NS matter (Reisenegger 2009, Akgün et al. 2013)

Large toroidal-to-poloidal field ratios can be stable (Braithwaite 2009, Akgün et al. 2013)

Magnetically-induced ellipticity



$$\epsilon_B^0 \sim \frac{E_B}{E_{grav}} \simeq 3.5 \times 10^{-4} B_{16}^2 R_6^4 M_{1.4}^{-2}$$

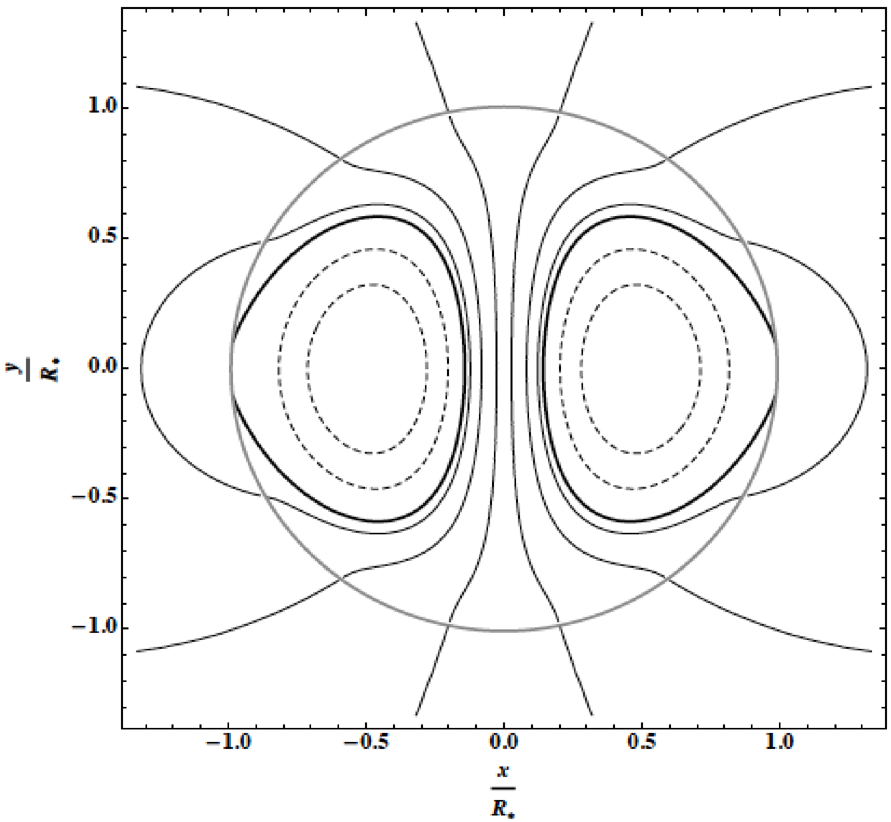
$$\epsilon_B \simeq 3.4 \times 10^{-7} B_{dip,14}^2 \frac{R_{12}^4}{M_{1.4}^2} \left(1 - 0.37 \frac{E_T}{E_{pol}}\right)$$

$$\frac{E_T}{E_{pol}} < \frac{80}{B_{pol,14}} \frac{M_{2.36}}{R_{12\mathrm{km}}^2}$$

Mastrano et al. 2011

Akgün et al. 2013

Magnetically-induced ellipticity



Dall'Osso et al. 2014

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$$\epsilon_B^{new} \simeq 3.2\times10^{-6} B_{dip,14}^2 \frac{R_{12}^4}{M_{1.4}^2} \left(1-0.73\frac{E_T}{E_{pol}}\right)$$

$$\frac{E_T}{E_{pol}} < \frac{500}{B_{pol,14}} \frac{M_{2.36}}{R_{12km}^2}$$

Damping Time

Orthogonalization of the newly formed magnetar caused by internal dissipation of free precession

Must be faster than *em* spindown

τ_{em} ◊ 1.1 $(P_{ms}/B_{d,14})^2$ days ~ 10^5 s

Fluid *npe* matter - **bulk viscosity** main mechanism

Small initial tilt angle ($\leq$1 deg)

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Small initial tilt angle (≤1 deg)

$$\boldsymbol{\tau_{diss} \sim 5\ (B_t/10^{16}G)^2\ (P/ms)^2\ (T/10^{10}K)^{-6}\ s}$$

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Short dissipation timescale ~ 10^{2-3} s

Signal properties

1) How strong are the expected signals?

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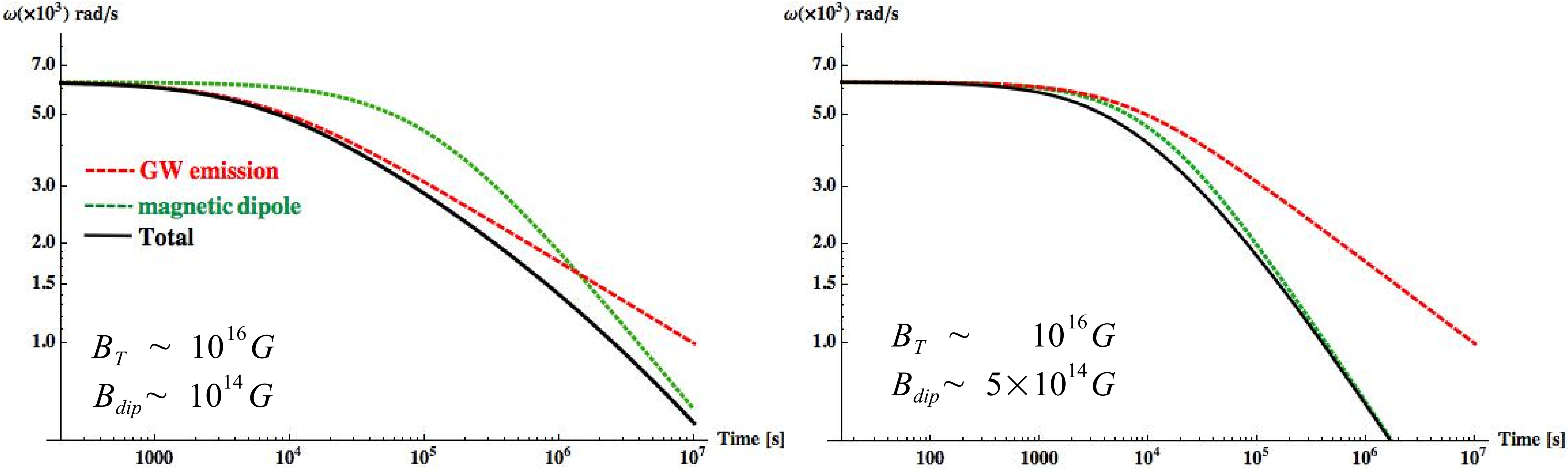
$$\dot{\Omega} = -\frac{2}{3}\frac{\mu_d^2}{I c^3}\Omega^3 - \frac{32}{5}\frac{G}{c^5} I \epsilon_B^2 \Omega^5$$



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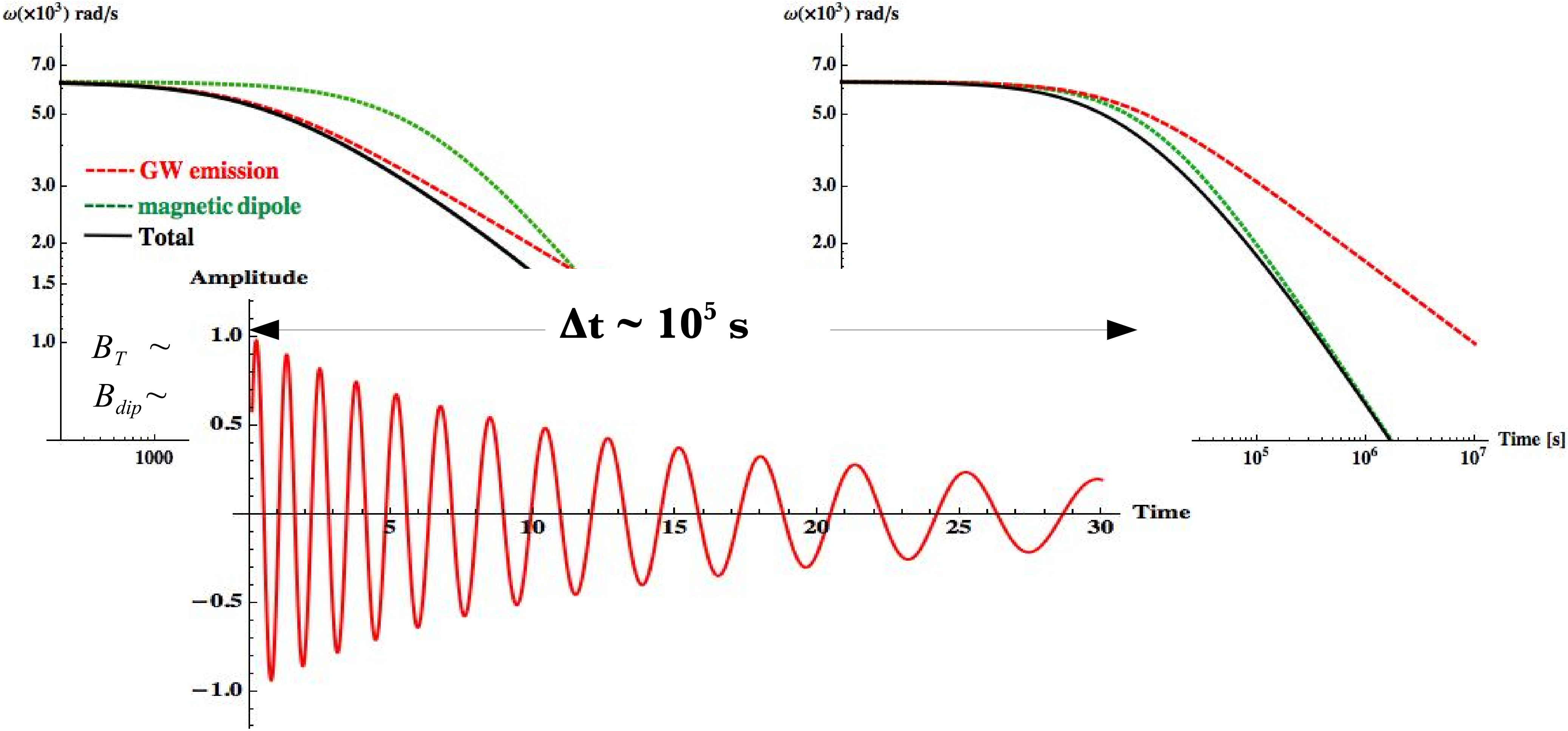

$B_T \sim$

$B_{dip} \sim$

$\Delta t \sim 10^5$ s

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$$\begin{cases} h[t(f)] = \dfrac{4 G I \epsilon_B}{c^4 D} \left(\dfrac{\Omega}{\pi}\right)^2 \\ \hat{h}(f) = \dfrac{1}{2} h[t(f)] \left(\dfrac{df}{dt}\right)^{-1/2} \exp\{-i\,\phi[t(f)]\} \\ t \text{ expressed in terms of } f \text{ using the spin-down model} \end{cases}$$

$$S/N = 2\left[\int \frac{|\tilde{h}(f)|^2}{S_h(f)}\,df\right]^{1/2}$$

D_{hor} ~ 35 Mpc

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D_{hor}~200 Mpc

for NS-NS inspirals

(Abadie et al. 2010)

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$$\left(\frac{\mathrm{S}}{\mathrm{N}}\right)_{\mathrm{GW}} \simeq 10 \left(\frac{\mathrm{D}}{33.5\mathrm{Mpc}}\right)^{-1} \left(\frac{\mathrm{R}}{15\mathrm{km}}\right) \left(\frac{\mathrm{M}}{2.36\mathrm{M}_\odot}\right)^{1/2} \times \left[\left(\frac{f_f}{\mathrm{kHz}}\right)^{-2} - \left(\frac{f_i}{\mathrm{kHz}}\right)^{-2}\right]^{1/2}$$

@35 Mpc

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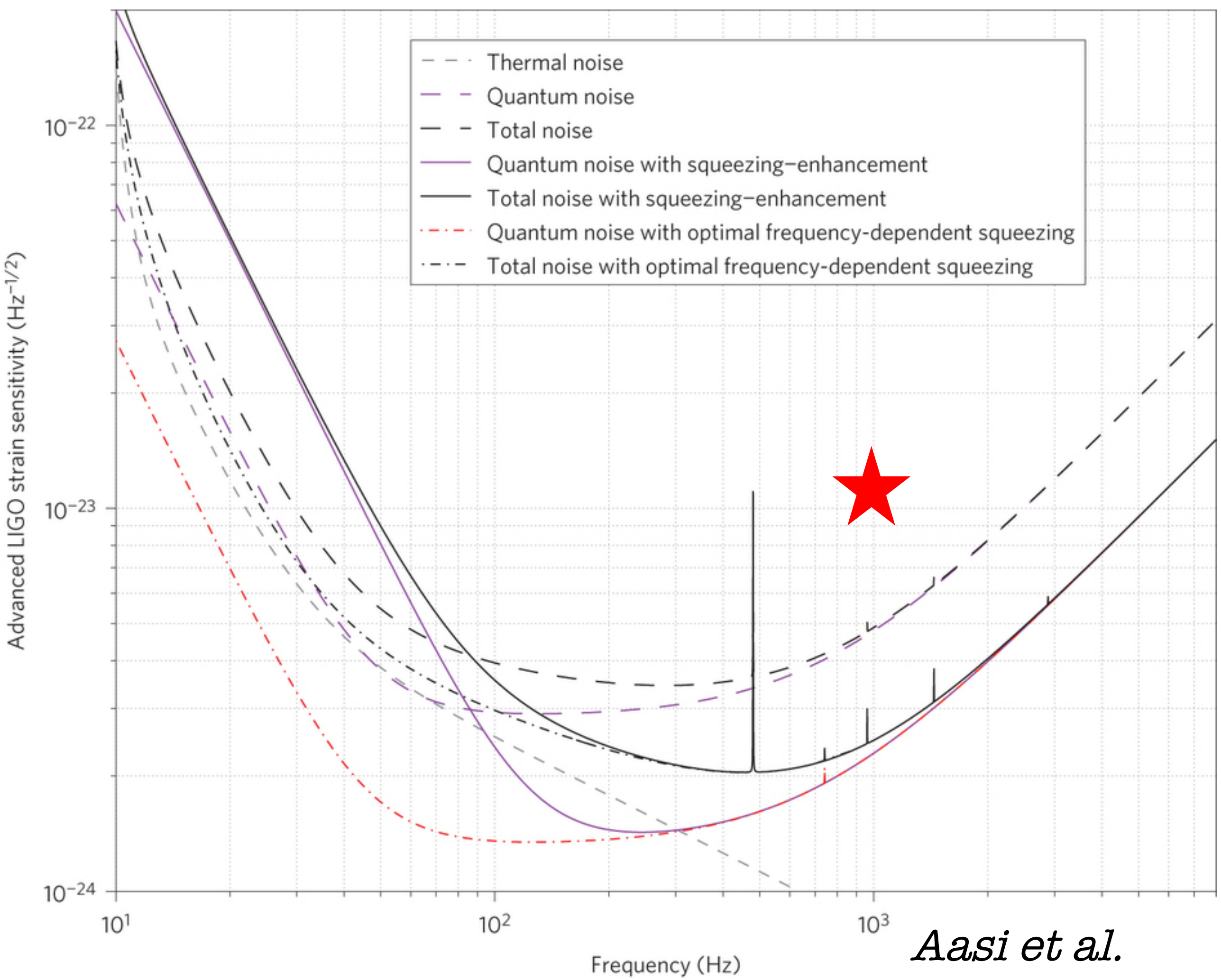

Aasi et al. (2013)

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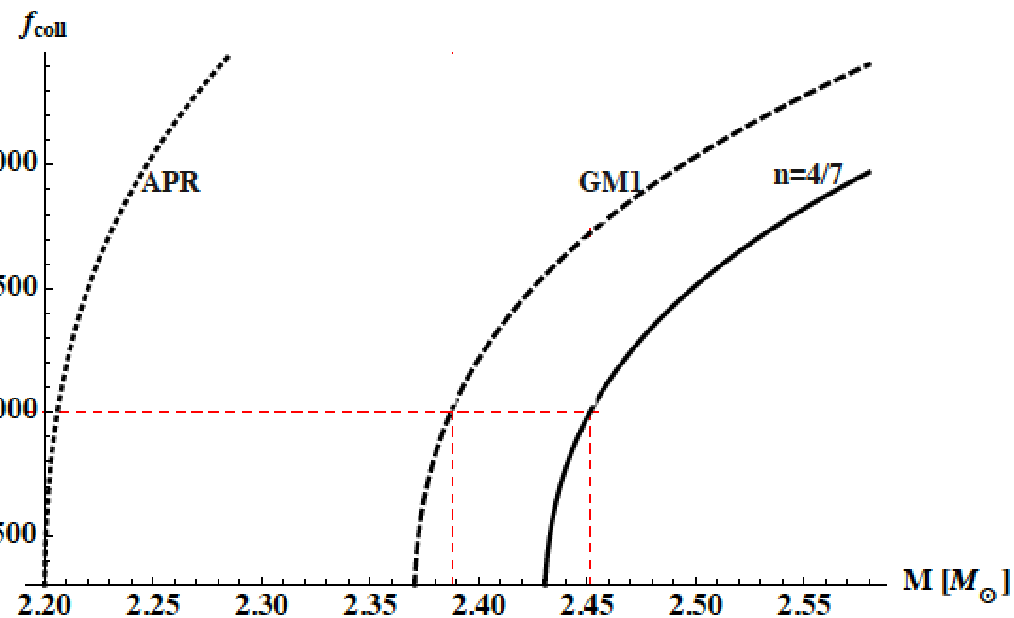
Fast (uniform) rotation → sustains supramassive PMNS against collapse

Falcke & Rezzolla (2014), Lasky et al. (2014)



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a) distance of expected signals ≤ 35 Mpc
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c) fraction of stable NSs depends on EOS

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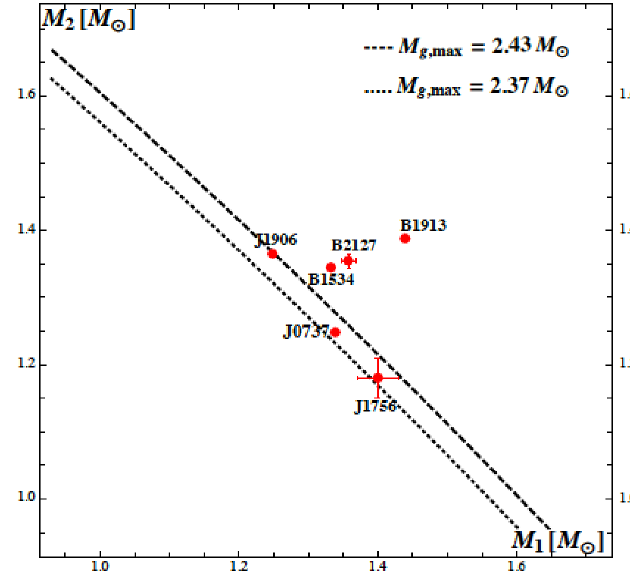
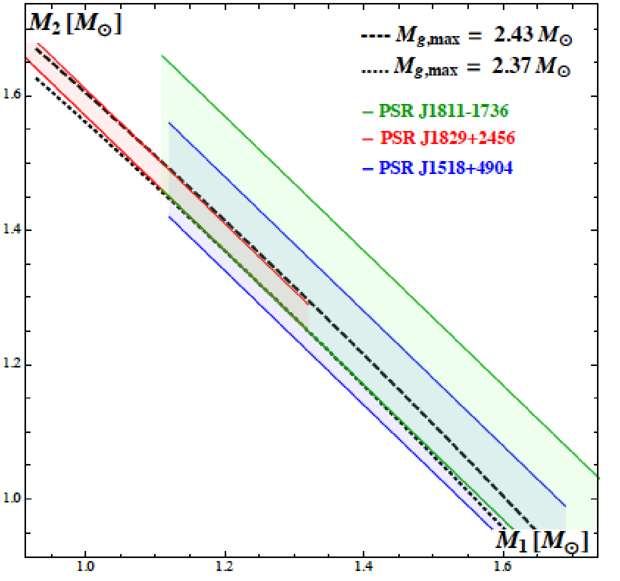


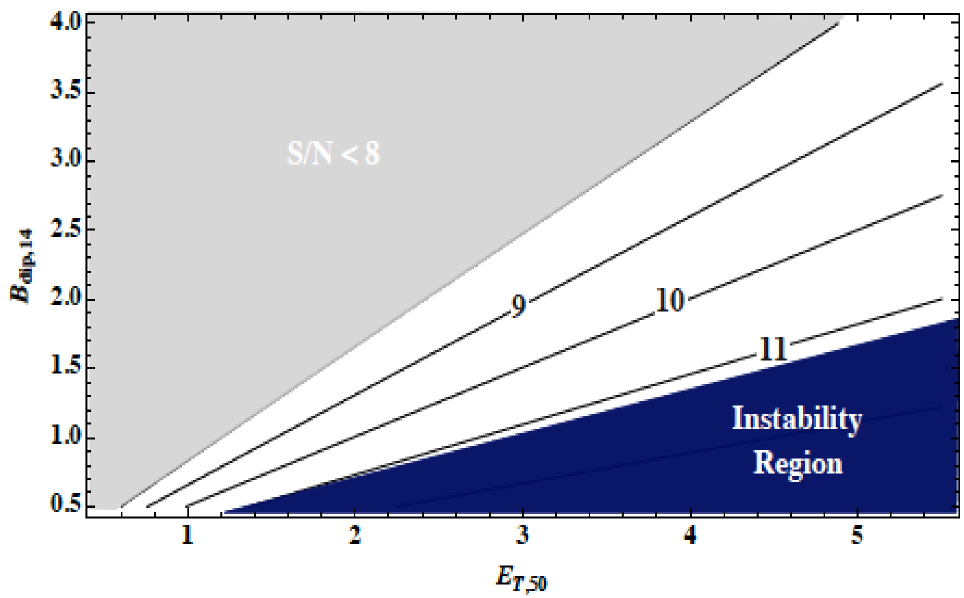


Dall'Osso et al. (2014)
data from Kiziltan et al. (2013)

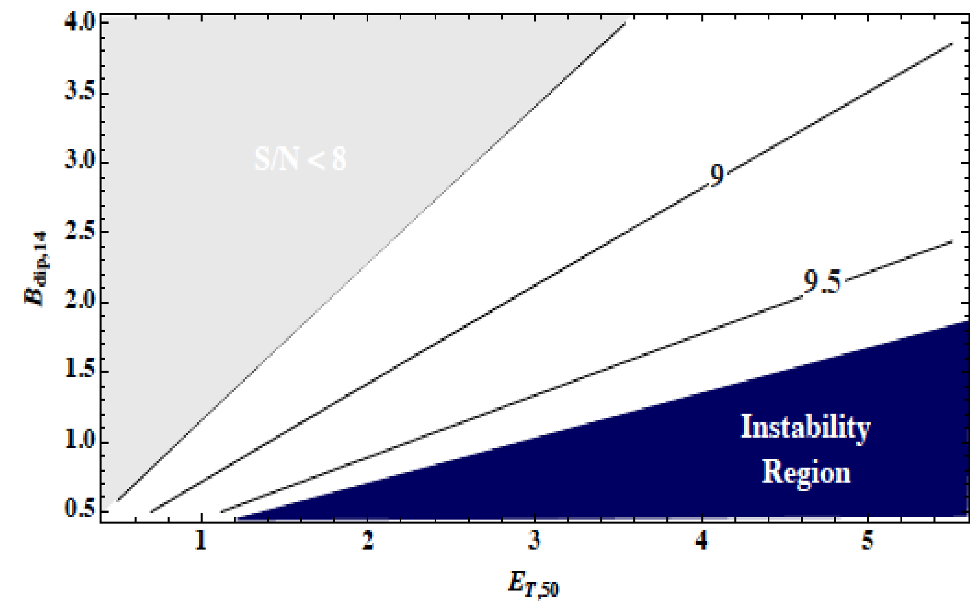
$$M_{rest} = M_g + 0.075\,M_g^2$$

Timmes et al. (1996)

Massive "Magnetars" from BNS mergers



Stable PMNS
D ~ 35 Mpc



Hypermassive PMNS
D ~ 16 Mpc

Dall'Osso et al. (2014)

Open questions

Dedicated observational strategies to reveal the putative signals (ongoing)

Generalization of results to interior field configuration of "arbitrary" shape and for different EOS's (next step)

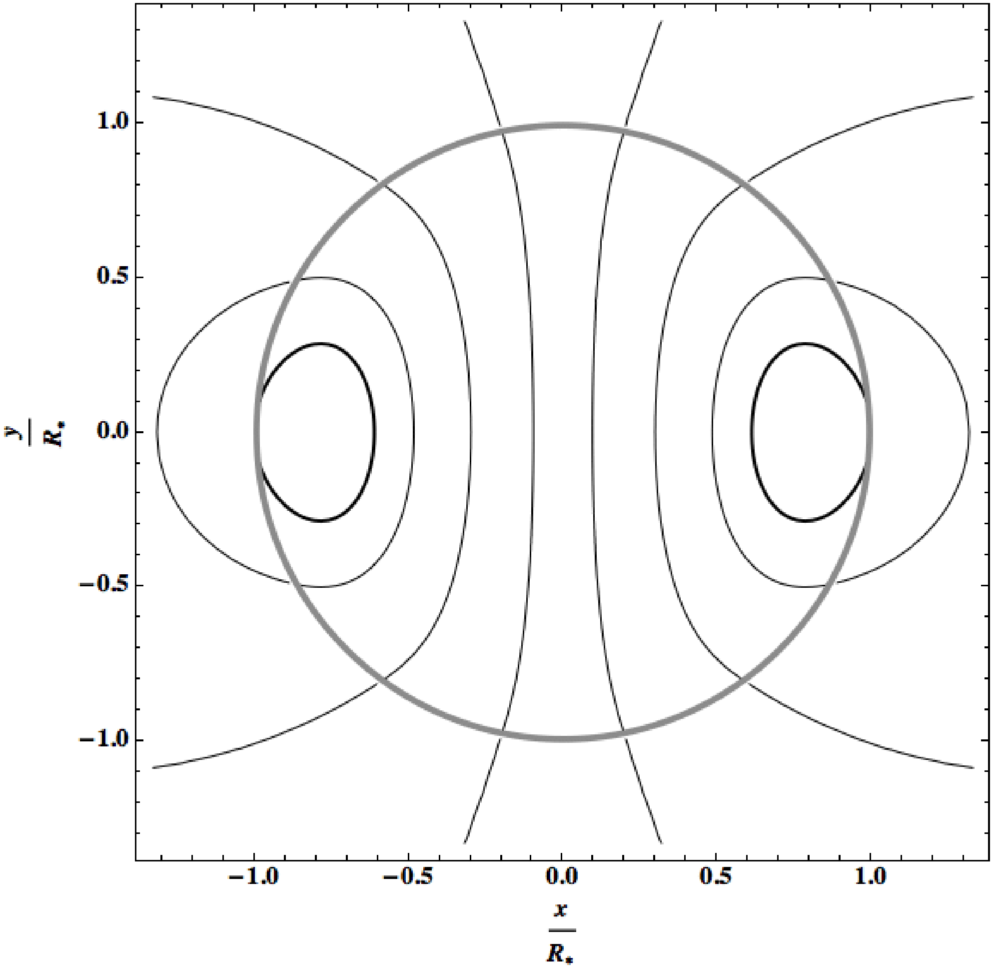
Calculation of microphysical effects beyond current approximation, e.g. stability of magnetic fields, the effect of internal viscosity, etc.

Understanding the fate of angular momentum and the initial spin rate of the PMNS, particularly important for "unstable" PMNS

...and of course determining the **actual event rates. GW signals!?**

Extra Slides

Twisted-Torus Configuration



$$(1/\mu_0)(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = \nabla \delta p + \delta\rho \nabla \Phi,$$

$$\boldsymbol{B} = B_0[\eta_{\rm p} \nabla \alpha(r, \theta) \times \nabla \phi + \eta_{\rm t} \beta(\alpha) \nabla \phi],$$

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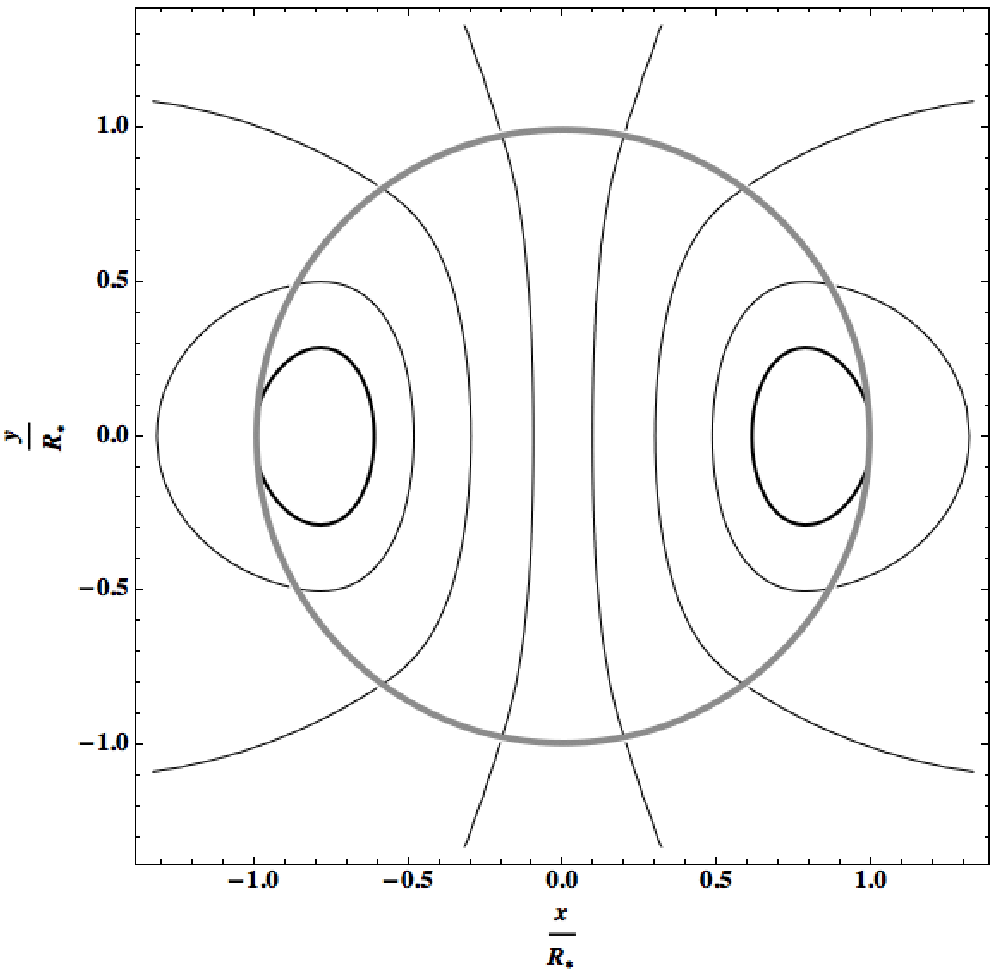

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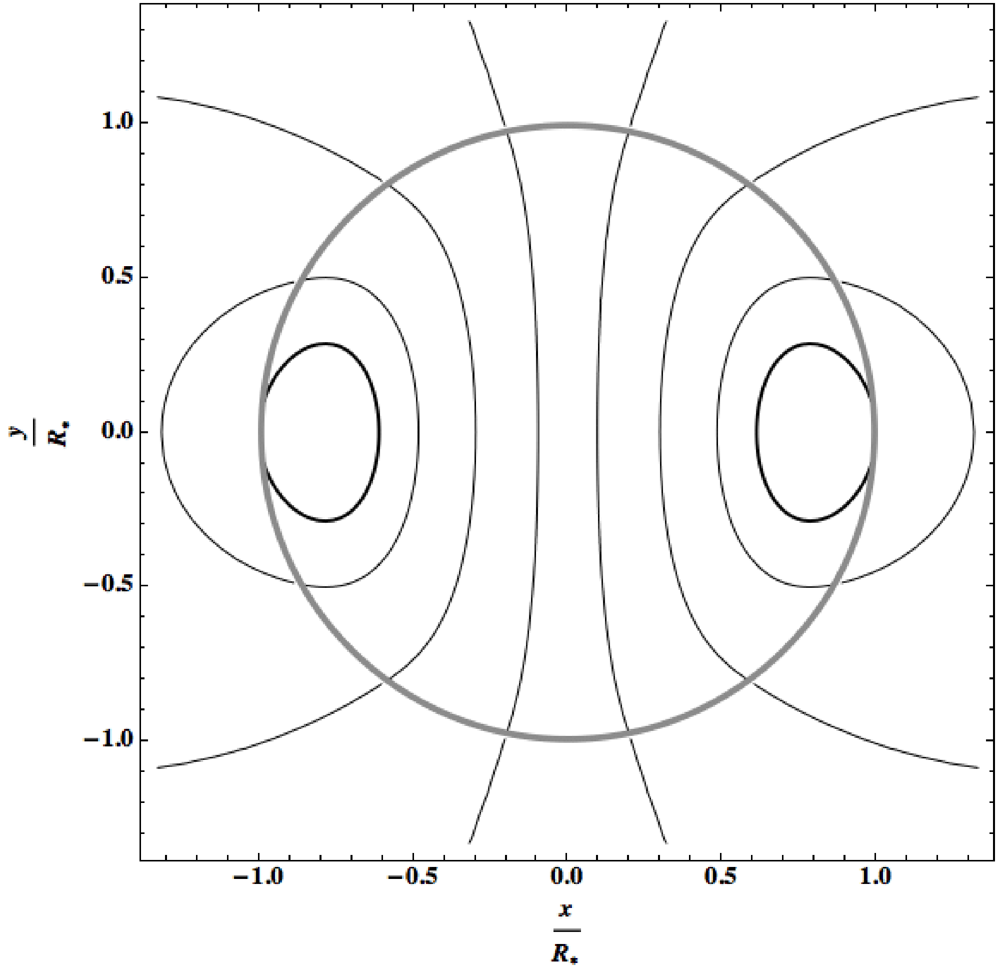

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$$-\frac{B_0^2}{\mu_0 r^2 \sin^2 \theta} \left(\eta_{\rm p}^2 \nabla \alpha \hat{\Delta} \alpha + \eta_{\rm t}^2 \beta \nabla \beta\right) = \nabla \delta p + \delta\rho \nabla \Phi,$$

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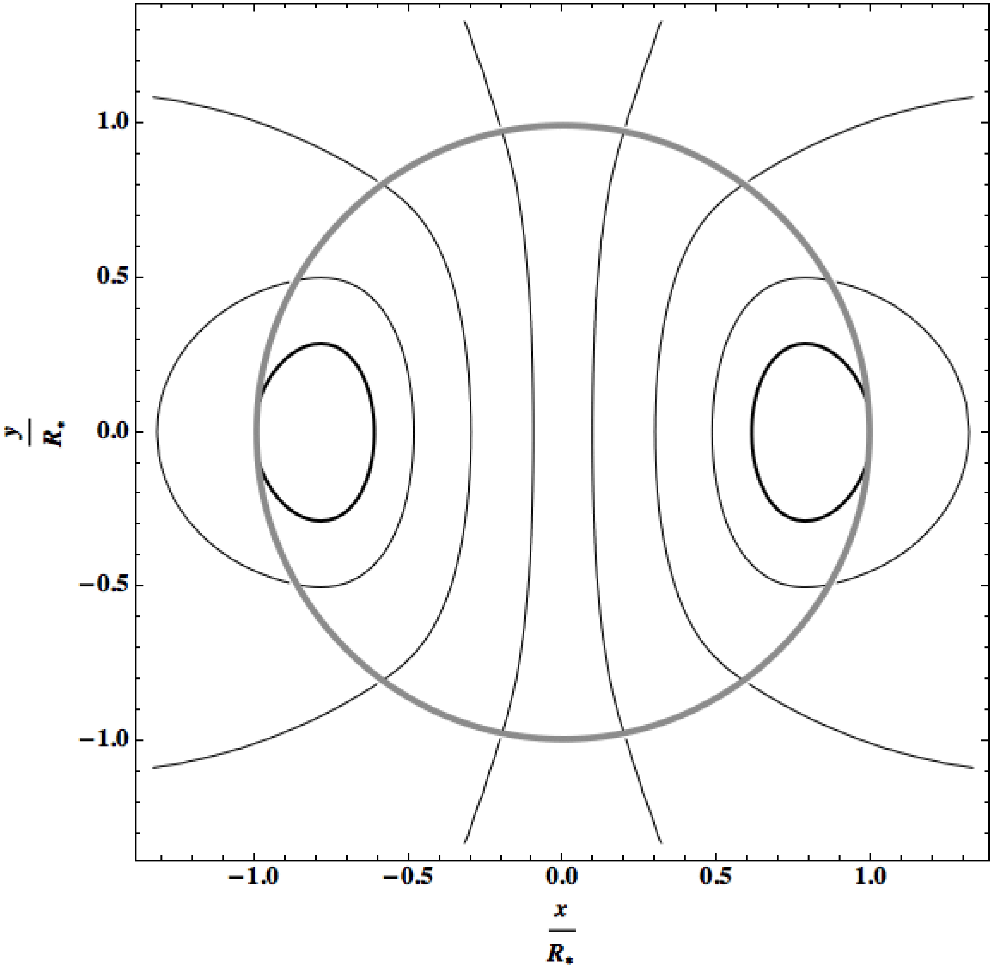

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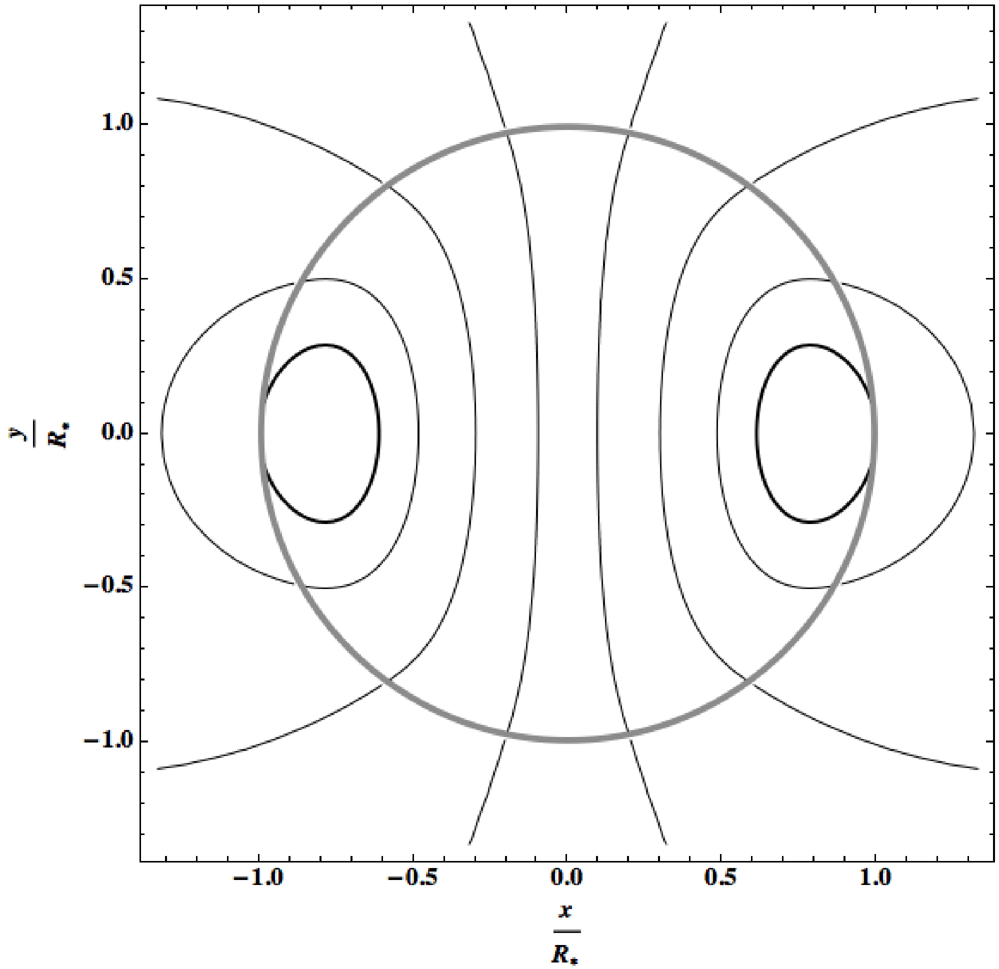
$$-\frac{B_0^2}{\mu_0 r^2 \sin^2\theta} \left(\eta_{\rm p}^2 \nabla \alpha \hat{\Delta} \alpha + \eta_{\rm t}^2 \beta \nabla \beta\right) = \nabla \delta p + \delta\rho \nabla \Phi,$$

$$\hat{\Delta} = \frac{\partial^2}{\partial r^2} + \frac{\sin\theta}{r^2} \frac{\partial}{\partial \theta} \left(\frac{1}{\sin\theta} \frac{\partial}{\partial \theta} \right)$$

Twisted-Torus Configuration



$$(1/\mu_0)(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = \nabla \delta p + \delta\rho \nabla \Phi,$$

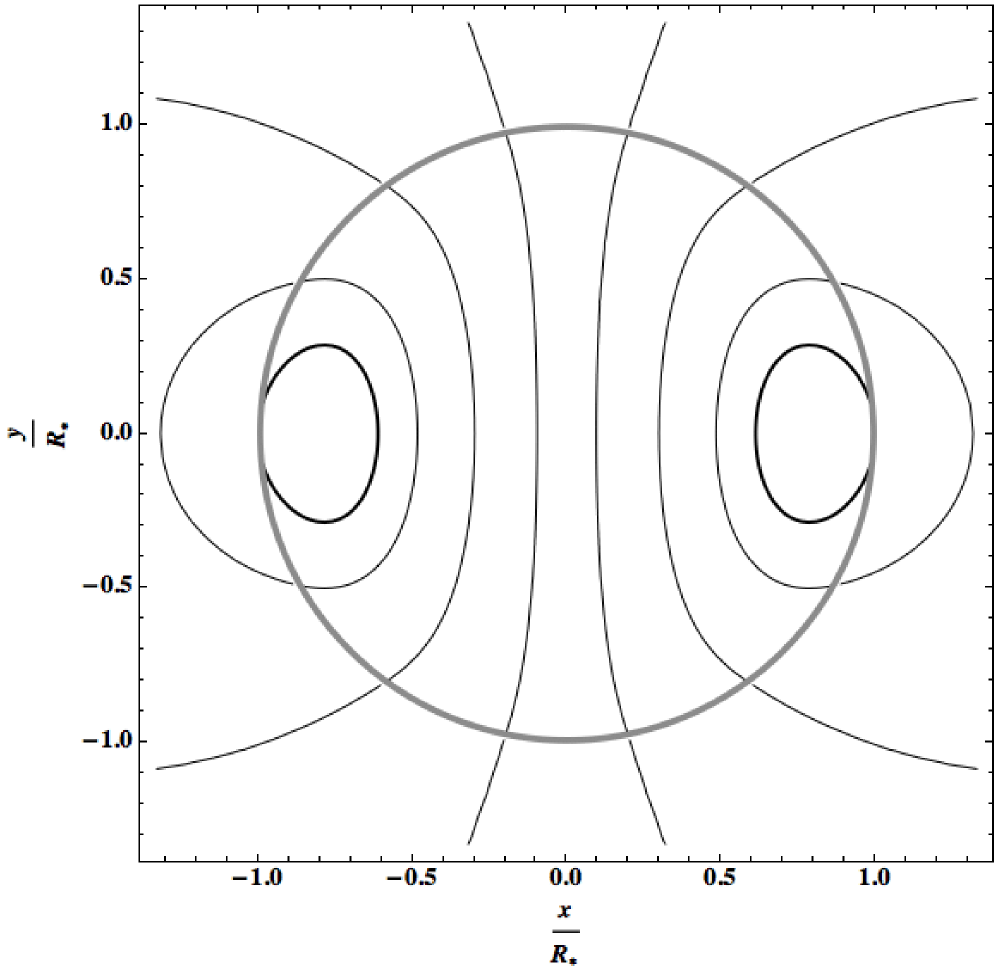
$$\boldsymbol{B} = B_0[\eta_p \nabla\alpha(r,\theta) \times \nabla\phi + \eta_t \beta(\alpha)\nabla\phi],$$

$$-\frac{B_0^2}{\mu_0 r^2 \sin^2\theta}\left(\eta_p^2 \nabla\alpha \hat{\Delta}\alpha + \eta_t^2 \beta \nabla\beta\right) = \nabla \delta p + \delta\rho \nabla \Phi,$$

$$\hat{\Delta} = \frac{\partial^2}{\partial r^2} + \frac{\sin\theta}{r^2}\frac{\partial}{\partial\theta}\left(\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\right)$$

$$\delta p = \frac{-B_0^2 \alpha}{\mu_0 r^2 \sin^2\theta}\left[\eta_p^2 \hat{\Delta}\alpha + 2\eta_t^2\left(\frac{\alpha^3}{3} - \frac{3\alpha^2}{2} + 3\alpha - \ln\alpha + C_0\right)\right]$$

Twisted-Torus Configuration



$$(1/\mu_0)(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = \nabla \delta p + \delta\rho \nabla \Phi,$$

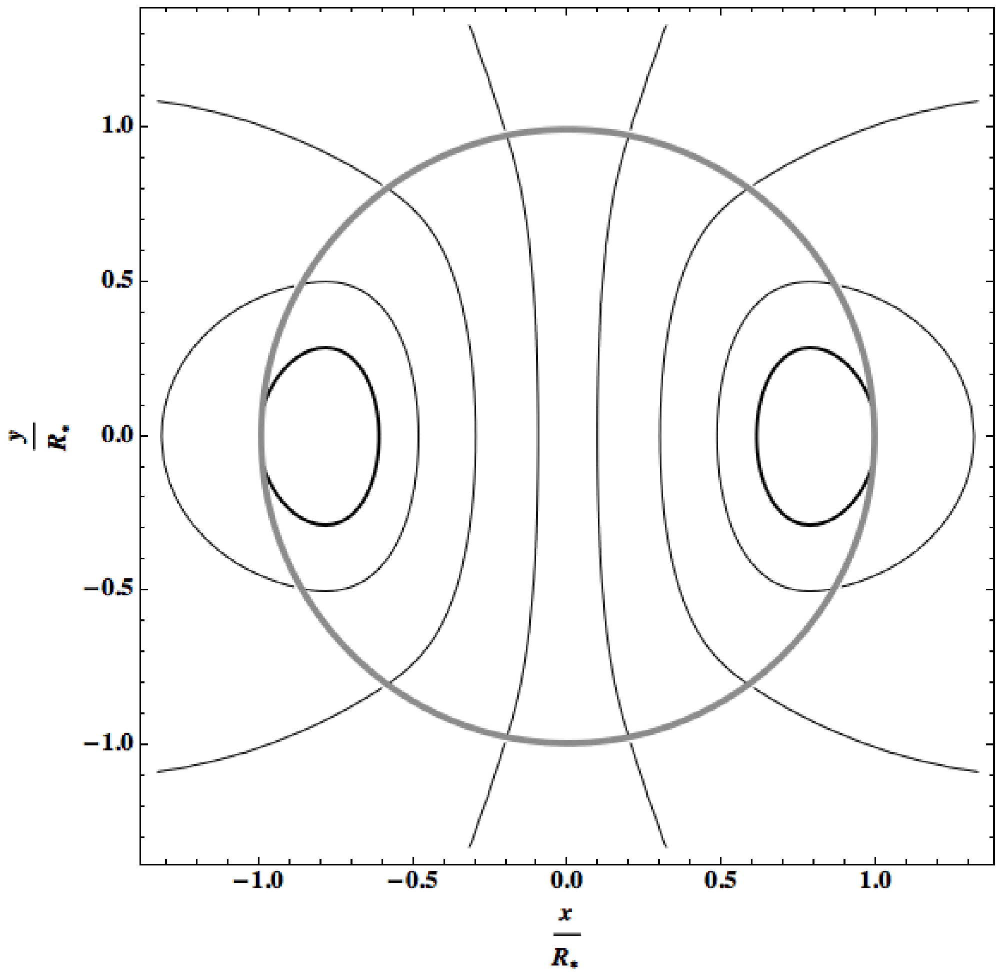
$$\boldsymbol{B} = B_0[\eta_{\mathrm{p}} \nabla \alpha(r,\theta) \times \nabla \phi + \eta_{\mathrm{t}} \beta(\alpha) \nabla \phi],$$

$$-\frac{B_0^2}{\mu_0 r^2 \sin^2\theta} \left(\eta_{\mathrm{p}}^2 \nabla \alpha \hat{\Delta} \alpha + \eta_{\mathrm{t}}^2 \beta \nabla \beta\right) = \nabla \delta p + \delta\rho \nabla \Phi,$$

$$\hat{\Delta} = \frac{\partial^2}{\partial r^2} + \frac{\sin\theta}{r^2} \frac{\partial}{\partial \theta} \left(\frac{1}{\sin\theta} \frac{\partial}{\partial \theta} \right)$$

$$\delta\rho \frac{\mathrm{d}\Phi}{\mathrm{d}r} = \frac{B_0^2}{\mu_0} \left[\eta_{\mathrm{p}}^2 \alpha \frac{\partial}{\partial r} \left(\frac{\hat{\Delta}\alpha}{r^2 \sin^2\theta} \right) + 2\eta_{\mathrm{t}}^2 \left(\frac{\alpha^3}{3} - \frac{3\alpha^2}{2} + 3\alpha - \ln\alpha + C_0 \right) \frac{\partial}{\partial r} \left(\frac{\alpha}{r^2 \sin^2\theta} \right) \right]$$

Twisted-Torus Configuration



$$(1/\mu_0)(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = \nabla \delta p + \delta\rho \nabla \Phi,$$

$$\boldsymbol{B} = B_0[\eta_\mathrm{p} \nabla \alpha(r, \theta) \times \nabla \phi + \eta_\mathrm{t} \beta(\alpha) \nabla \phi],$$

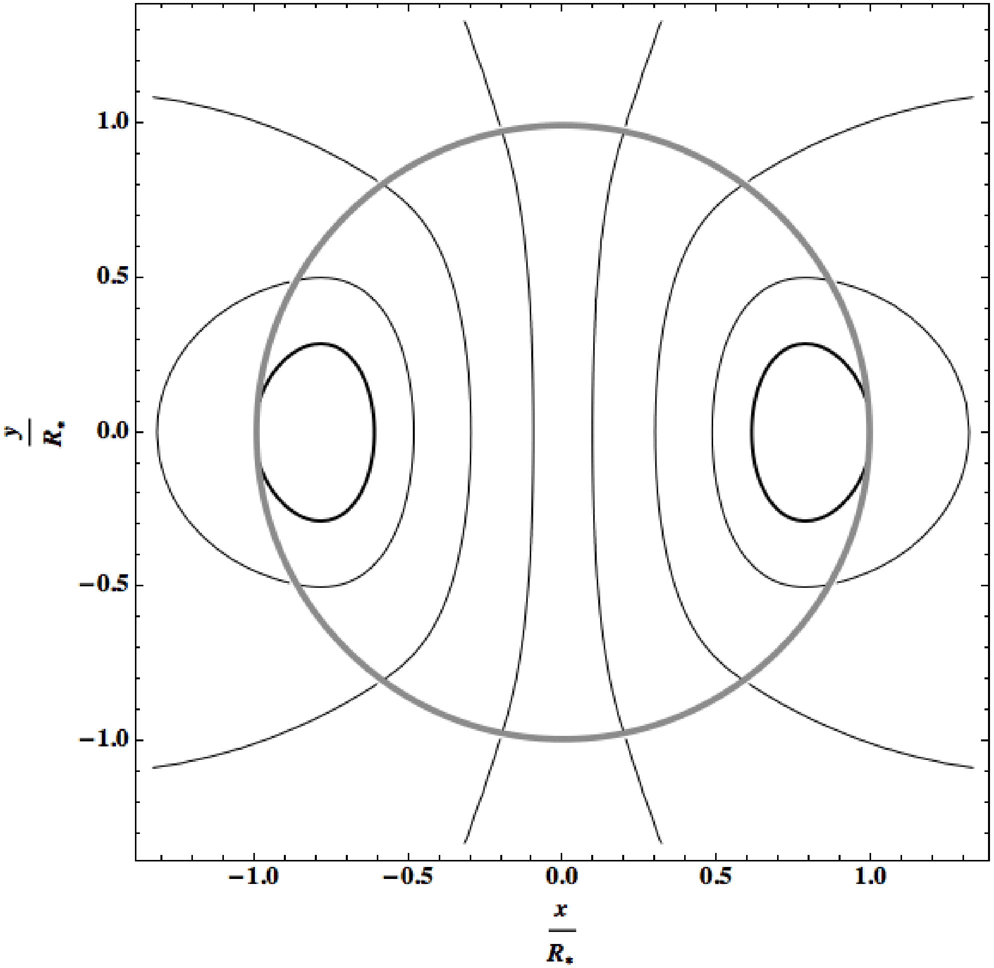
$$-\frac{B_0^2}{\mu_0 r^2 \sin^2\theta} \left(\eta_\mathrm{p}^2 \nabla \alpha \hat{\Delta} \alpha + \eta_\mathrm{t}^2 \beta \nabla \beta\right) = \nabla \delta p + \delta\rho \nabla \Phi,$$

$$I_{jk} = R_*^5 \int_V \mathrm{d}V [\rho(r) + \delta\rho(r, \theta)](r^2 \delta_{jk} - x_j x_k).$$

$$\epsilon = \frac{I_{zz} - I_{xx}}{I_0}$$

$$\delta\rho \frac{\mathrm{d}\Phi}{\mathrm{d}r} = \frac{B_0^2}{\mu_0} \left[\eta_\mathrm{p}^2 \alpha \frac{\partial}{\partial r} \left(\frac{\hat{\Delta}\alpha}{r^2 \sin^2\theta} \right) + 2\eta_\mathrm{t}^2 \left(\frac{\alpha^3}{3} - \frac{3\alpha^2}{2} + 3\alpha - \ln\alpha + C_0 \right) \frac{\partial}{\partial r} \left(\frac{\alpha}{r^2 \sin^2\theta} \right) \right]$$

Twisted-Torus Configuration



$$(1/\mu_0)(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = \nabla \delta p + \delta\rho \nabla \Phi,$$

$$\boldsymbol{B} = B_0[\eta_{\rm p} \nabla \alpha(r,\theta) \times \nabla \phi + \eta_{\rm t} \beta(\alpha) \nabla \phi],$$

$$-\frac{B_0^2}{\mu_0 r^2 \sin^2\theta}\left(\eta_{\rm p}^2 \nabla \alpha \hat{\Delta} \alpha + \eta_{\rm t}^2 \beta \nabla \beta\right) = \nabla \delta p + \delta\rho \nabla \Phi,$$

$$I_{jk} = R_*^5 \int_V \mathrm{d}V[\rho(r) + \delta\rho(r,\theta)](r^2 \delta_{jk} - x_j x_k).$$

$$\epsilon = \pi R_*^5 I_0^{-1} \int_V \mathrm{d}r\, \mathrm{d}\theta \delta\rho(r,\theta) r^4 \sin\theta (1 - 3\cos^2\theta)$$

$$\delta\rho \frac{\mathrm{d}\Phi}{\mathrm{d}r} = \frac{B_0^2}{\mu_0}\left[\eta_{\rm p}^2 \alpha \frac{\partial}{\partial r}\left(\frac{\hat{\Delta}\alpha}{r^2 \sin^2\theta}\right) + 2\eta_{\rm t}^2\left(\frac{\alpha^3}{3} - \frac{3\alpha^2}{2} + 3\alpha - \ln\alpha + C_0\right)\frac{\partial}{\partial r}\left(\frac{\alpha}{r^2 \sin^2\theta}\right)\right]$$