



Magnetar Evolution and the Associated Stochastic Gravitational Wave Background

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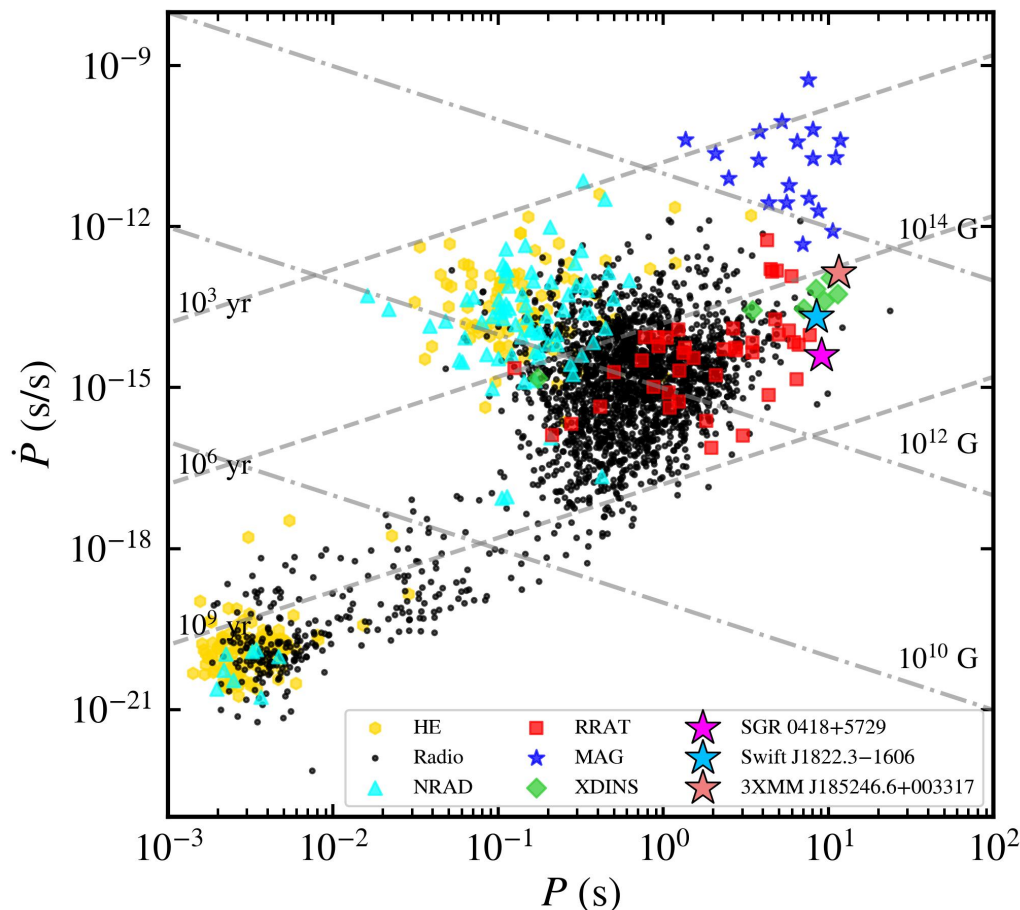
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2026.07 @FPS15, 贵阳

- I. 低磁场磁星形成
- II. 磁形变随机引力波背景
- III. 巨耀发激发的 f 模背景

一、低磁场磁星的形成

Source	P (s)	$\dot{P}$ ($10^{-15} \text{ s s}^{-1}$)	B_d (10^{12} G)	τ_c (Myr)
SGR 0418+5729	9.08	4	6.1	36
Swift J1822.3-1606	8.43	21	14	6.3
3XMM J185246.6+003317	11.56	< 140	< 41	> 1.3



低磁场磁星特点

- 表面偶极场较弱: $B_d \leq 10^{13} \text{ G}$
- 自转周期长, 特征年龄大
- 仍表现出磁星爆发与反常 X 射线辐射
- 指向强内部场或局部多极场

一、低磁场磁星的形成

磁层半径:

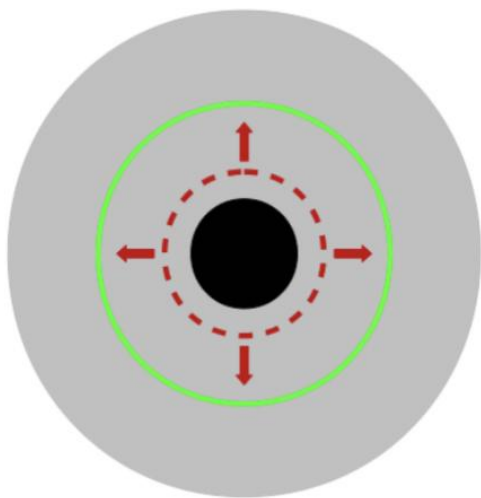
$$R_m = \xi \left(\frac{\mu^4}{2GM \dot{M}^2} \right)^{1/7}$$

共转半径:

$$R_c = \left(\frac{GM}{\Omega^2} \right)^{1/3}$$

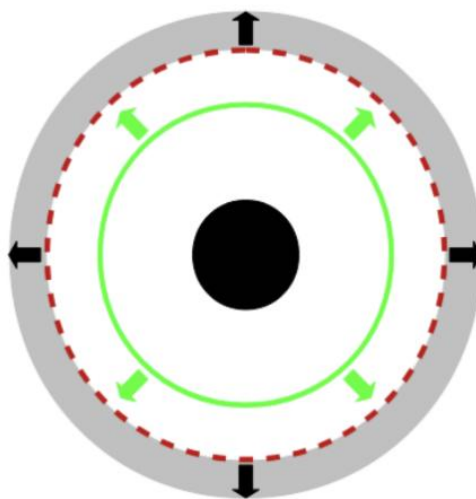
光速圆柱半径:

$$R_l = c/\Omega.$$



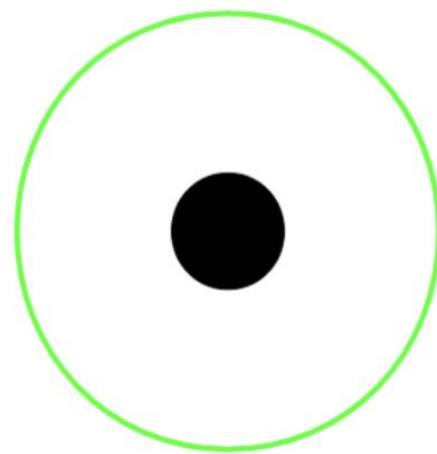
$$R_m < R_c$$

吸积相



$$R_m > R_c$$

螺旋桨相



$$R_m > R_l$$

抛射相

一、低磁场磁星的形成

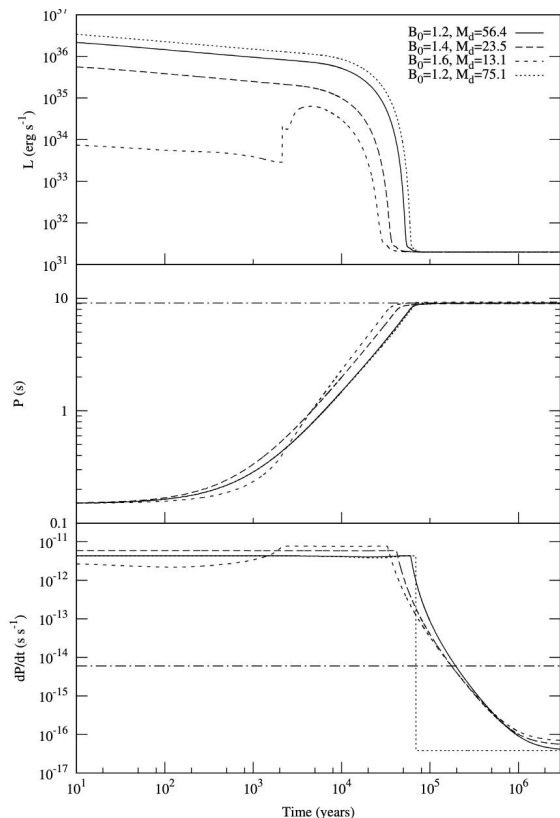


Figure 1. Luminosity, period, and period-derivative evolution of model sources for an initial period $P_0 = 150$ ms. Values of the initial disk mass (in units of $10^{-6} M_\odot$) and the magnetic field (in 10^{12} G) at the poles of the neutron star are given in the figure. The horizontal lines correspond to the period (9.1 s) and the present upper limit on the period-derivative of SGR 0418+5729 ($6 \times 10^{-15} \text{ s s}^{-1}$). We also present the minimal torque case (dotted curve) where the disk torque is assumed to vanish when $r_A \geq r_{LC}$.

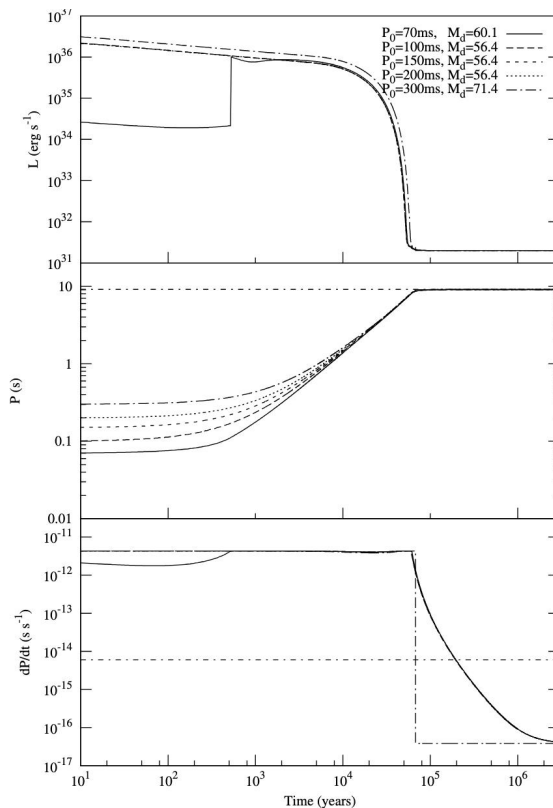


Figure 2. Luminosity, period, and period-derivative evolution of model sources for a polar magnetic field of $B_0 = 1.2 \times 10^{12}$ G on the surface of the neutron star. Values of the initial disk mass (in units of $10^{-6} M_\odot$) and initial period are given in the figure. The horizontal lines show the present period and upper limit on $\dot{P}$. The period derivative curves converge to a final value of $\sim 4 \times 10^{-17} \text{ s s}^{-1}$, a lower limit given by the dipole spin-down torque when the disk becomes inactive. The dipole spin-down case is given by the dot-dashed curve.

回落盘模型

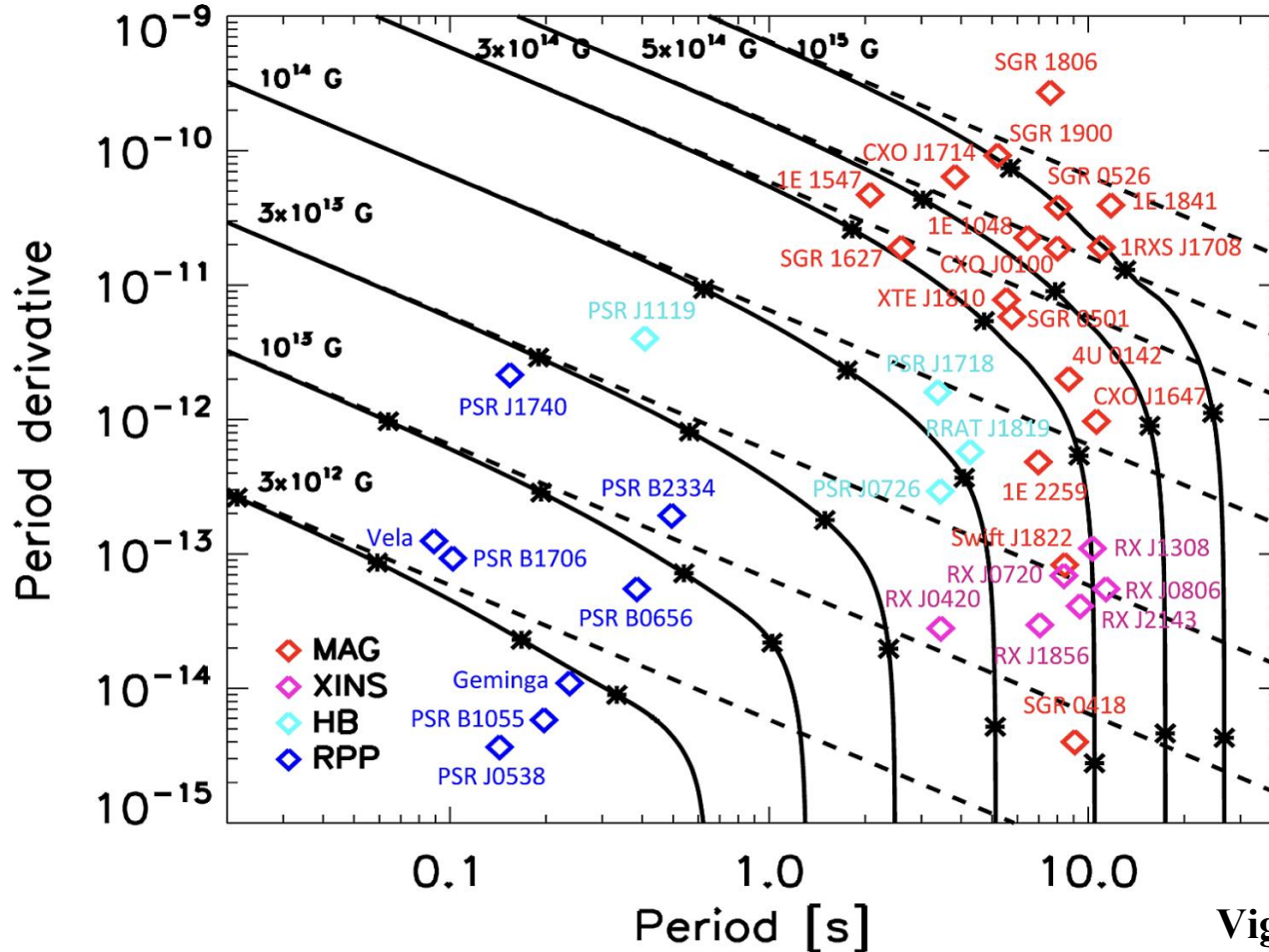
- 正常脉冲星 + 小质量回落盘
- 盘制动可解释 P 与 Pdot
- 爆发依赖近表面多极场释放
- 难点：会预言更多普通脉冲星爆发

结论：低磁场磁星更可能源于磁星演化

Alpar et al. 2011

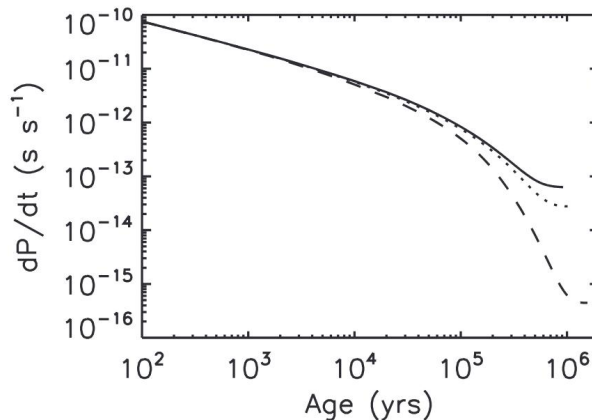
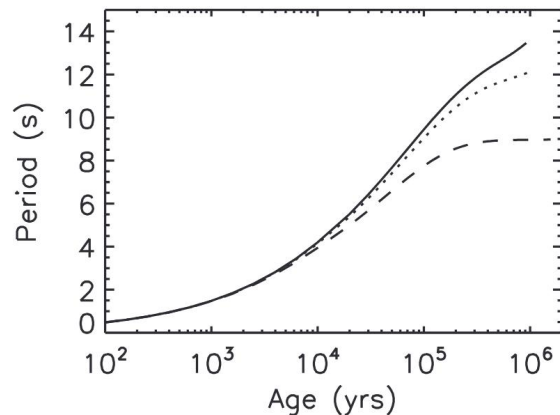
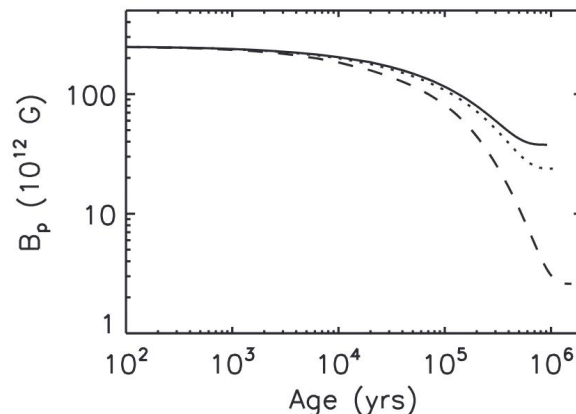
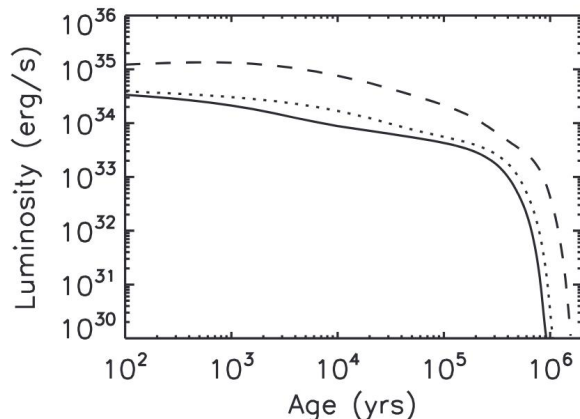
一、低磁场磁星的形成

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left[\frac{c^2}{4\pi\sigma} \nabla \times (\mathbf{e}^\nu \mathbf{B}) + \frac{c}{4\pi en_e} [\nabla \times (\mathbf{e}^\nu \mathbf{B})] \times \mathbf{B} \right]$$



Vigano et al. 2013

一、低磁场磁星的形成



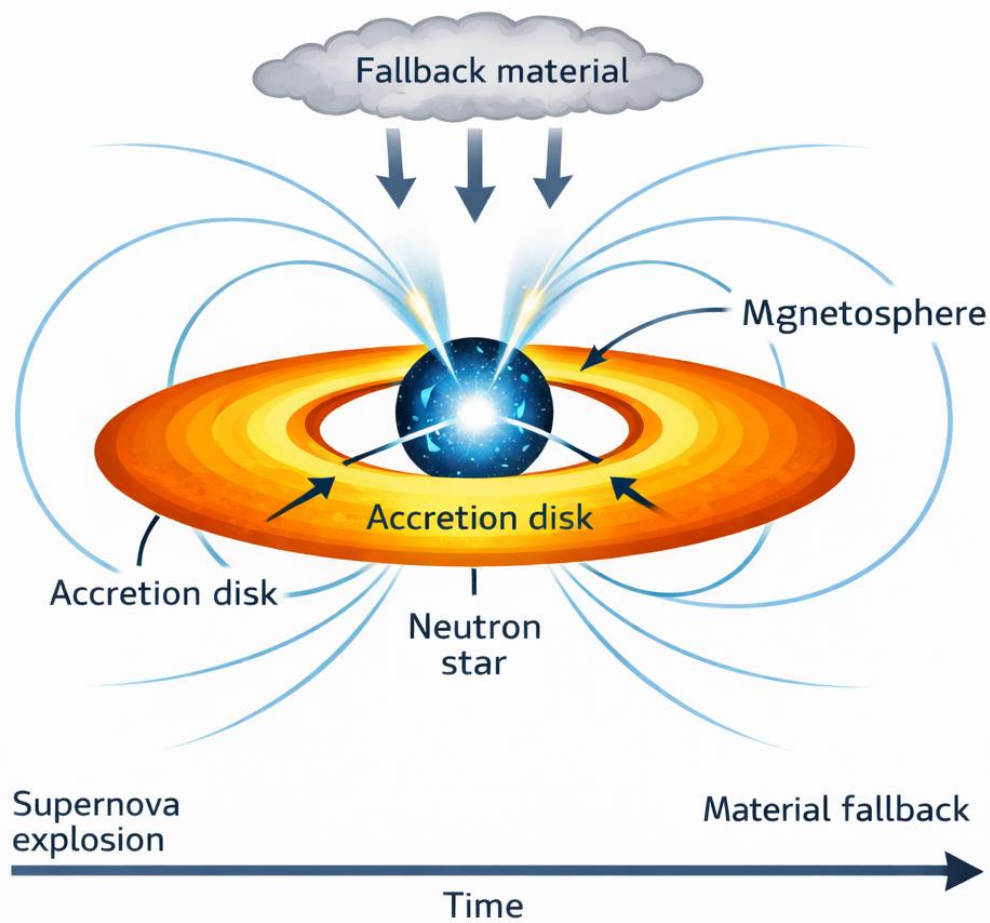
磁热演化模型

- 磁热演化可以解释观测P与Pdot, 但要求其初始表面磁场 $< 2 \times 10^{14}$ G;
- 爆发依赖内部强大的环向磁场;
- 难点: 初始偶极场与内部环向场强度差异太大, 可能危及磁场构型的稳定性。

Turolla et al. 2013

一、低磁场磁星的形成

Neutron Star Fallback Accretion Schematic



回落吸积率:

$$\dot{M} = \frac{2M_{\text{fb}}}{3t_{\text{fb}}(1 + t/t_{\text{fb}})^{5/3}},$$

吸积时表面磁场掩埋:

$$B = \frac{B_0}{1 + \Delta M / 10^{-5} M_{\odot}}$$

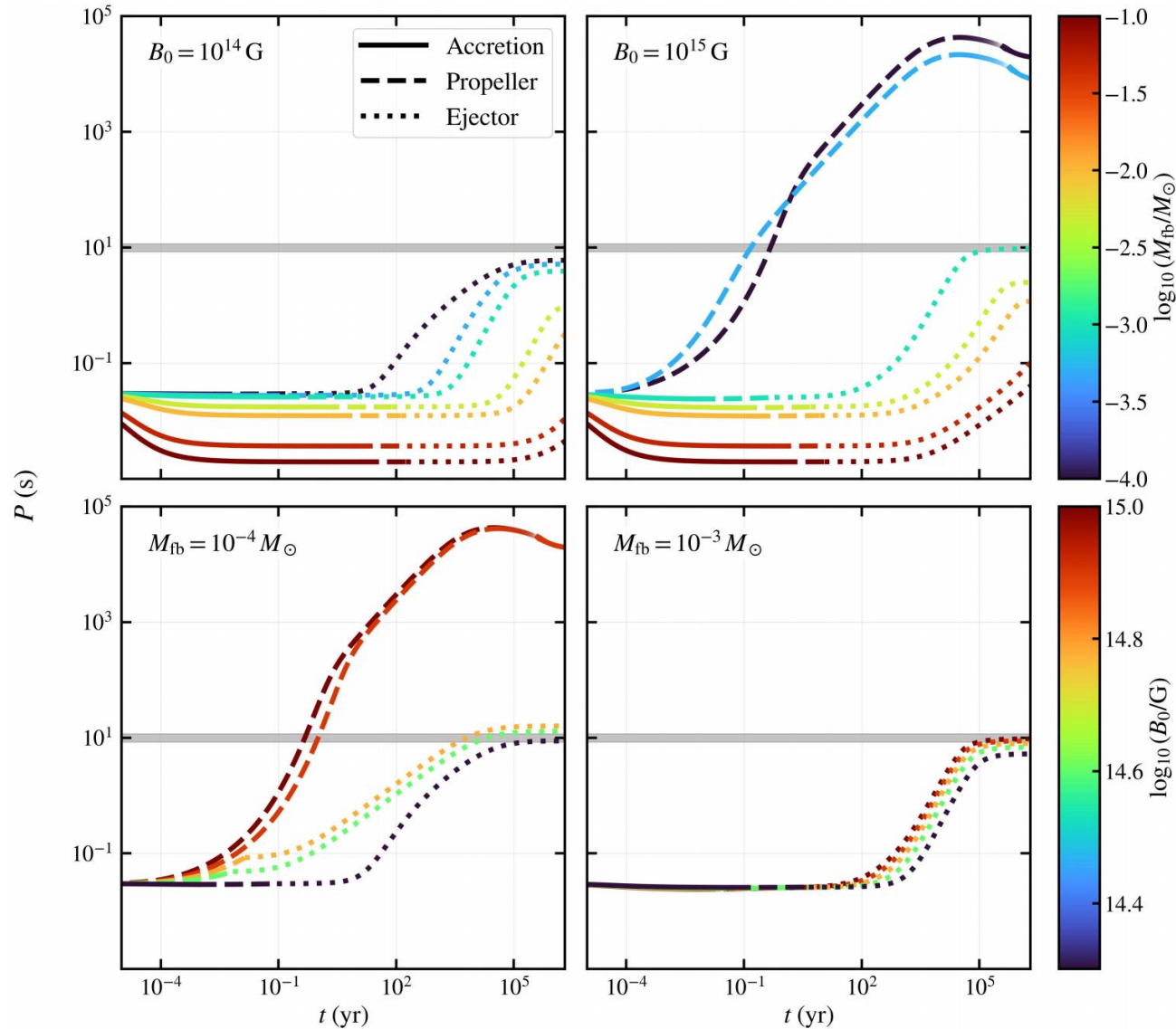
吸积结束后磁场浮出:

$$\dot{B}_d = 10^{-2} \left(\frac{\Delta M}{M_{\odot}} \right)^{-3} \left(1 - \frac{B_d}{B_0} \right)^2 \left(\frac{B_0}{10^{12} \text{ G}} \right) \text{ G yr}^{-1}$$

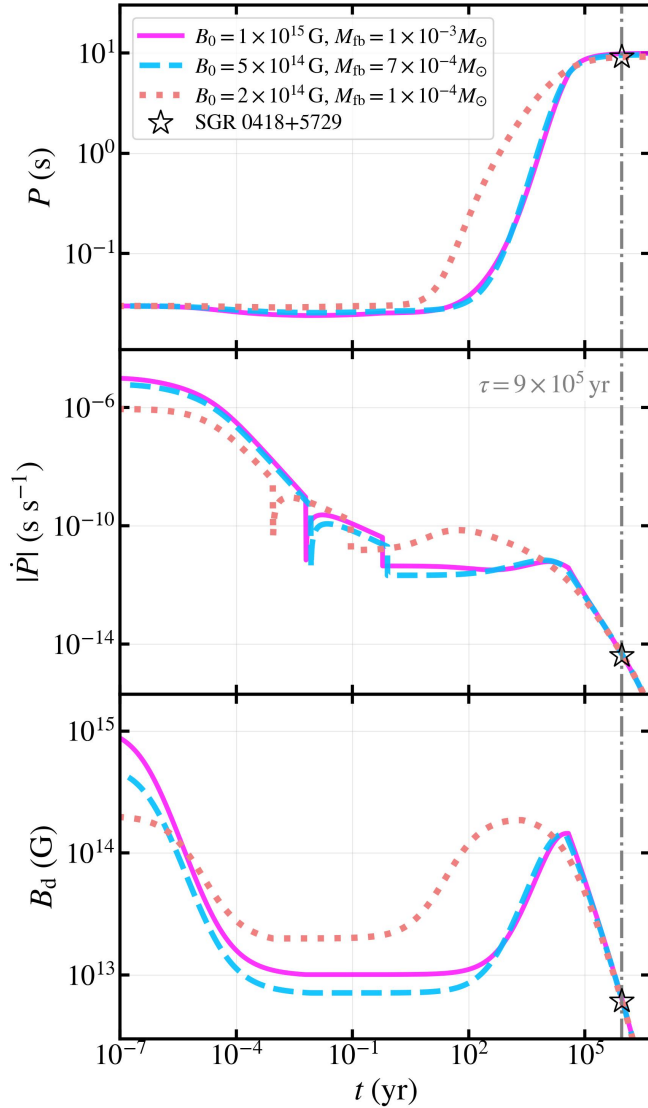
长时标下磁场衰减:

$$B_{\text{bur}}(t) = B_0 \frac{\exp(-t/\tau_O)}{1 + (\tau_O/\tau_H) [1 - \exp(-t/\tau_O)]}$$

一、低磁场磁星的形成

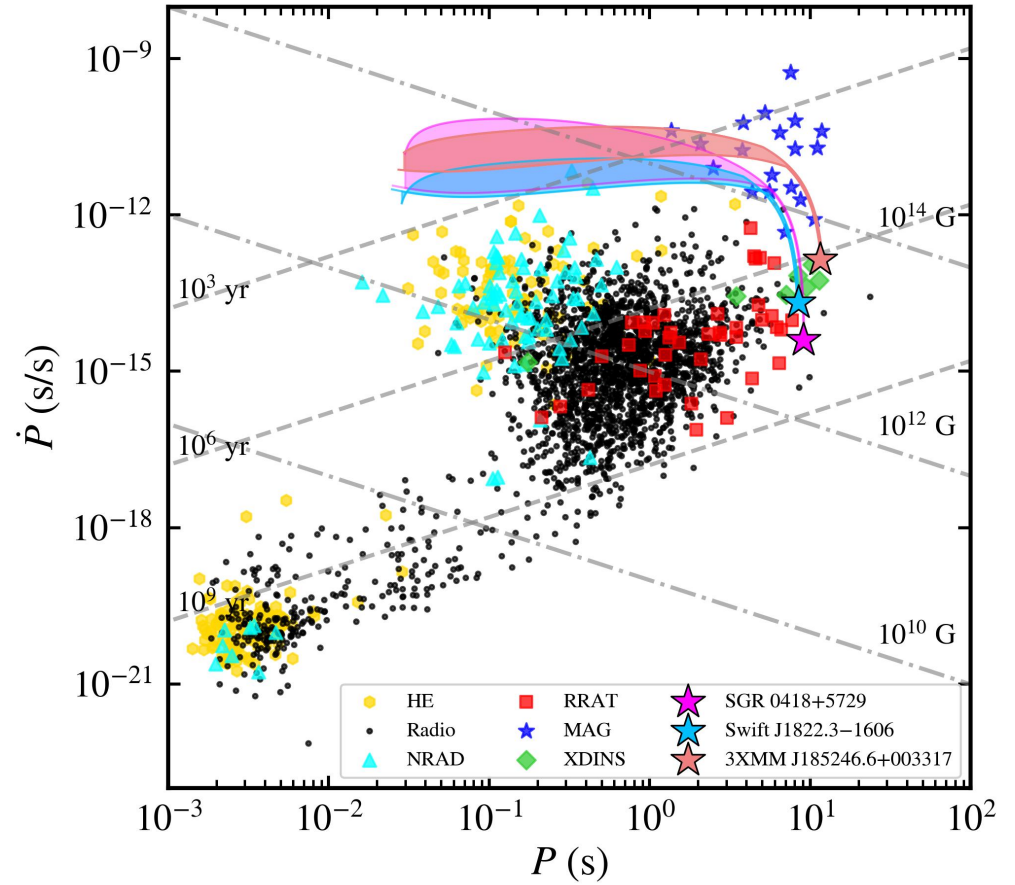


一、低磁场磁星的形成

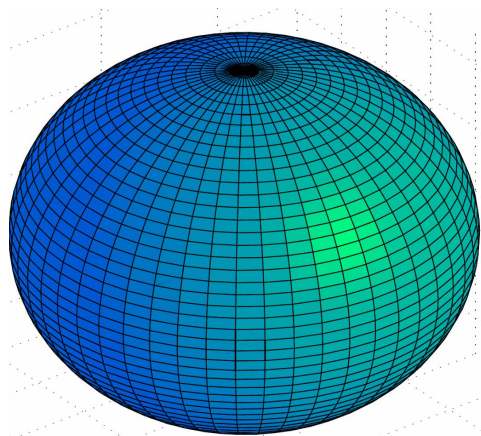


Source	P (s)	$\dot{P}$ (10^{-15} s s ⁻¹)	B_d (10^{12} G)	τ_c (Myr)	B_0 (10^{14} G)	M_{fb} ($10^{-4} M_\odot$)	τ (10^5 yr)
SGR 0418+5729	9.08	4	6.1	36	2–10	1–10	9
Swift J1822.3–1606	8.43	21	14	6.3	2–10	3–12	4
3XMM J185246.6+003317	11.56	< 140	< 41	> 1.3	4–8	2–6	1.5

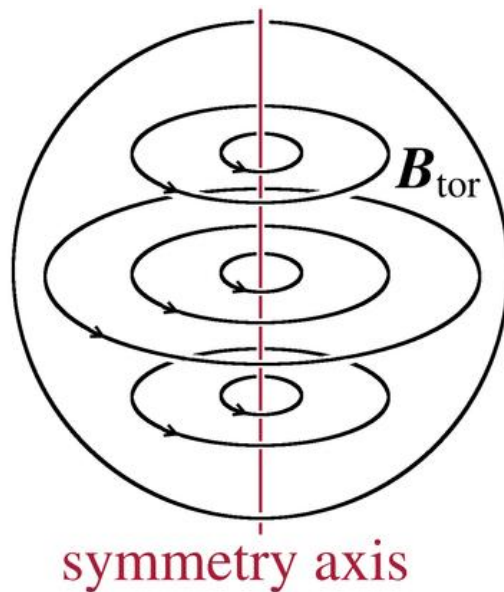
Notes. References: Rea et al. (2010, 2013); Scholz et al. (2013, 2014); Rea et al. (2014); Zhou et al. (2014)



二、磁形变随机引力波背景



南瓜型

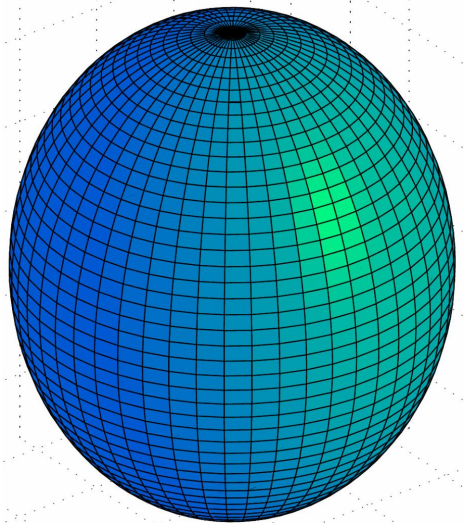
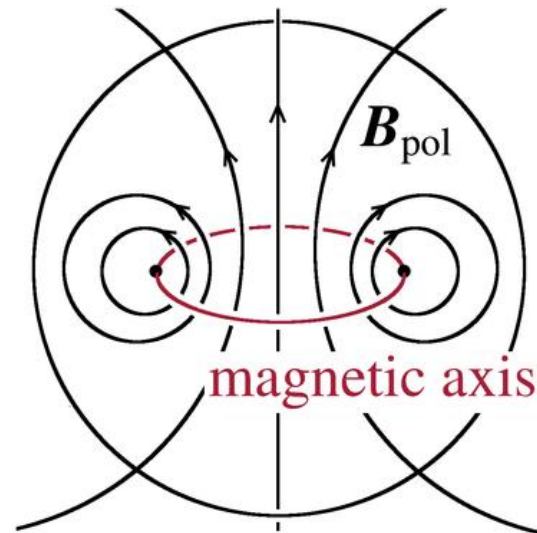


内部极向磁场主导:

$$\epsilon = 3.4 \times 10^{-7} \left(\frac{B}{10^{13} \text{G}} \right) \left(\frac{H_{c1}(0)}{10^{16} \text{G}} \right)$$

内部环向磁场主导:

$$\epsilon \approx -10^{-8} \left(\frac{H}{10^{15} \text{G}} \right) \left(\frac{\bar{B}_{in}}{10^{13} \text{G}} \right)$$



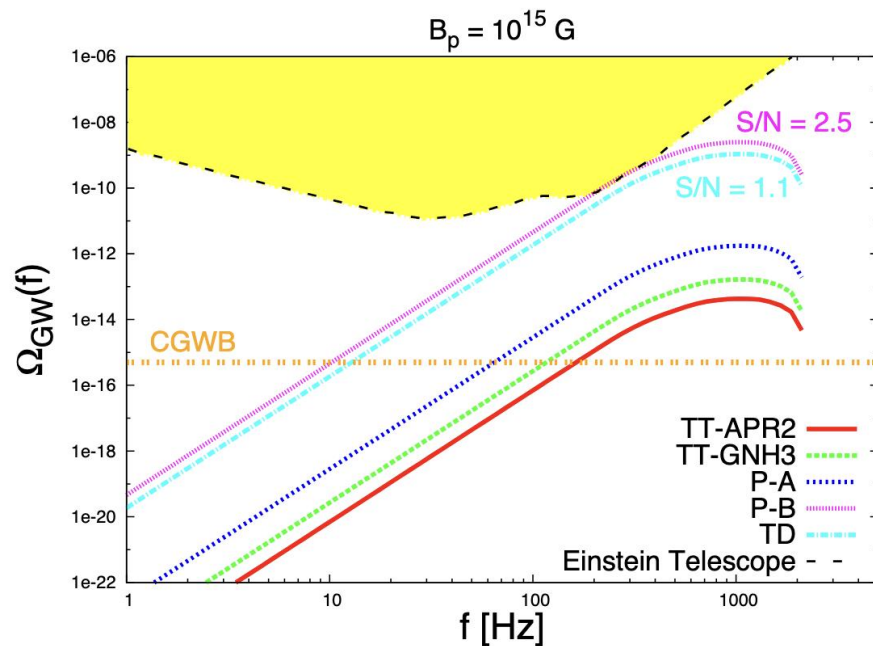
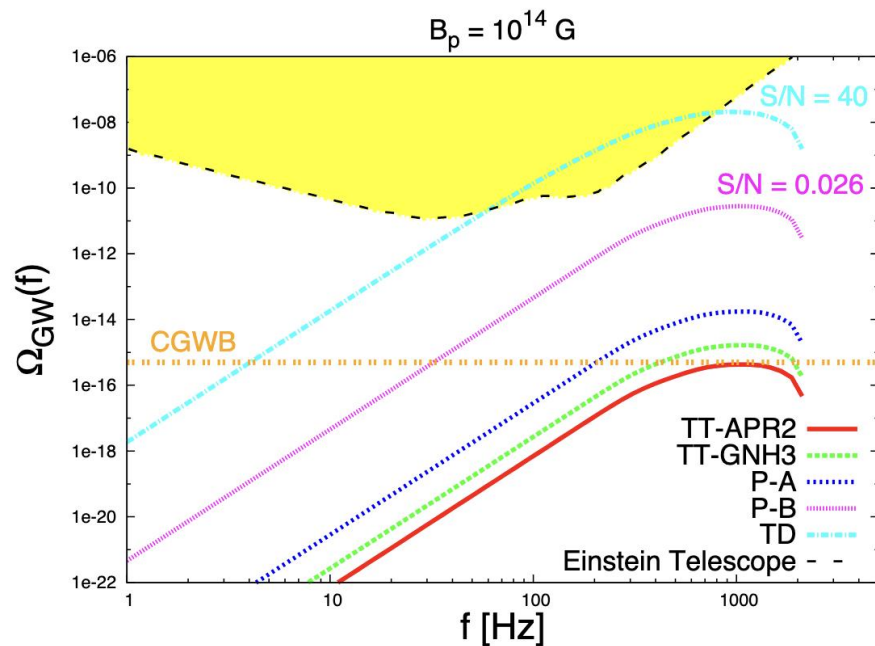
橄榄球型

二、磁形变随机引力波背景



无量纲能量密度背景谱:

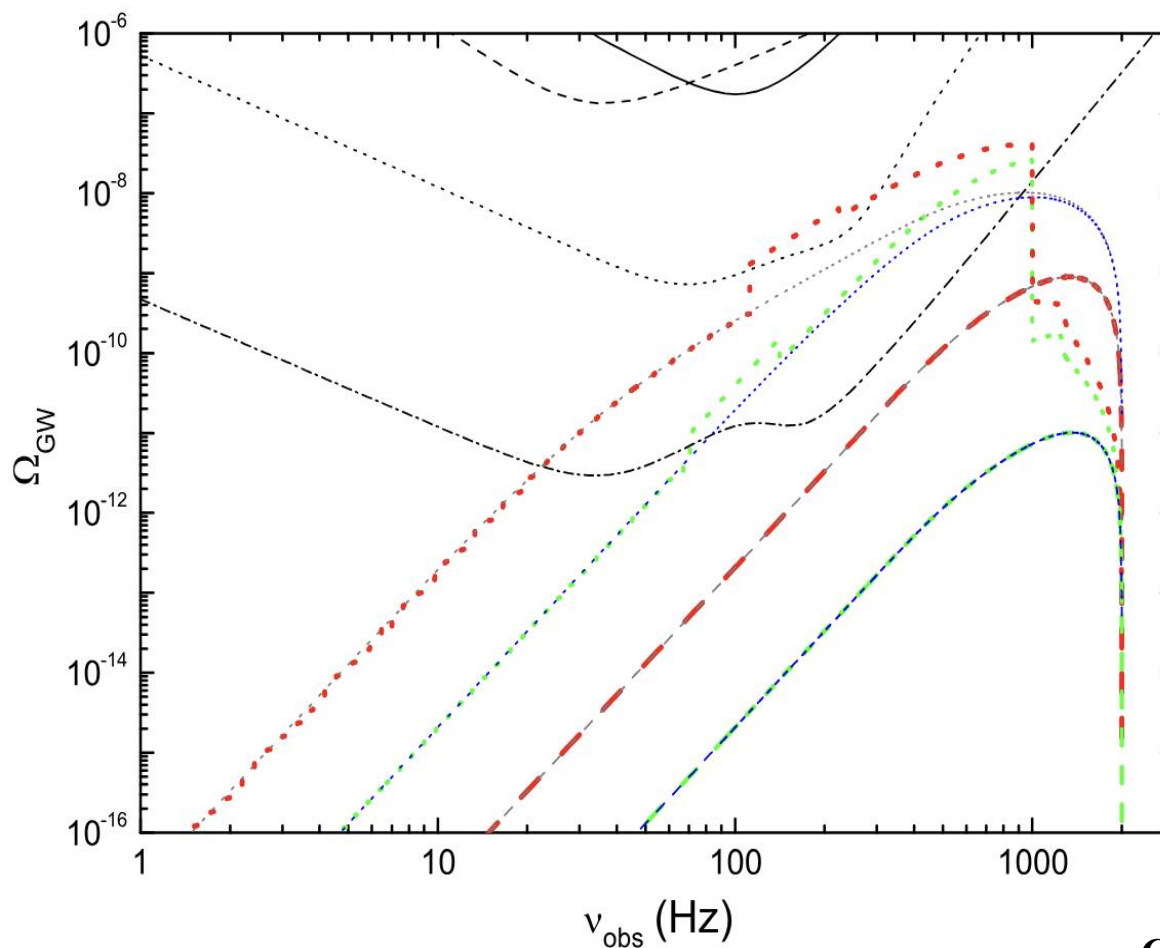
$$\Omega_{\text{GW}}(\nu_{\text{obs}}) = \frac{8\pi G \nu_{\text{obs}}}{3H_0^3 c^2} \int_0^{z_{\text{upp}}} \frac{R_s(z)}{(1+z)E(\Omega, z)} \frac{dE_{\text{gw}}}{d\nu_e} dz$$



Marassi et al. 2010

二、磁形变随机引力波背景

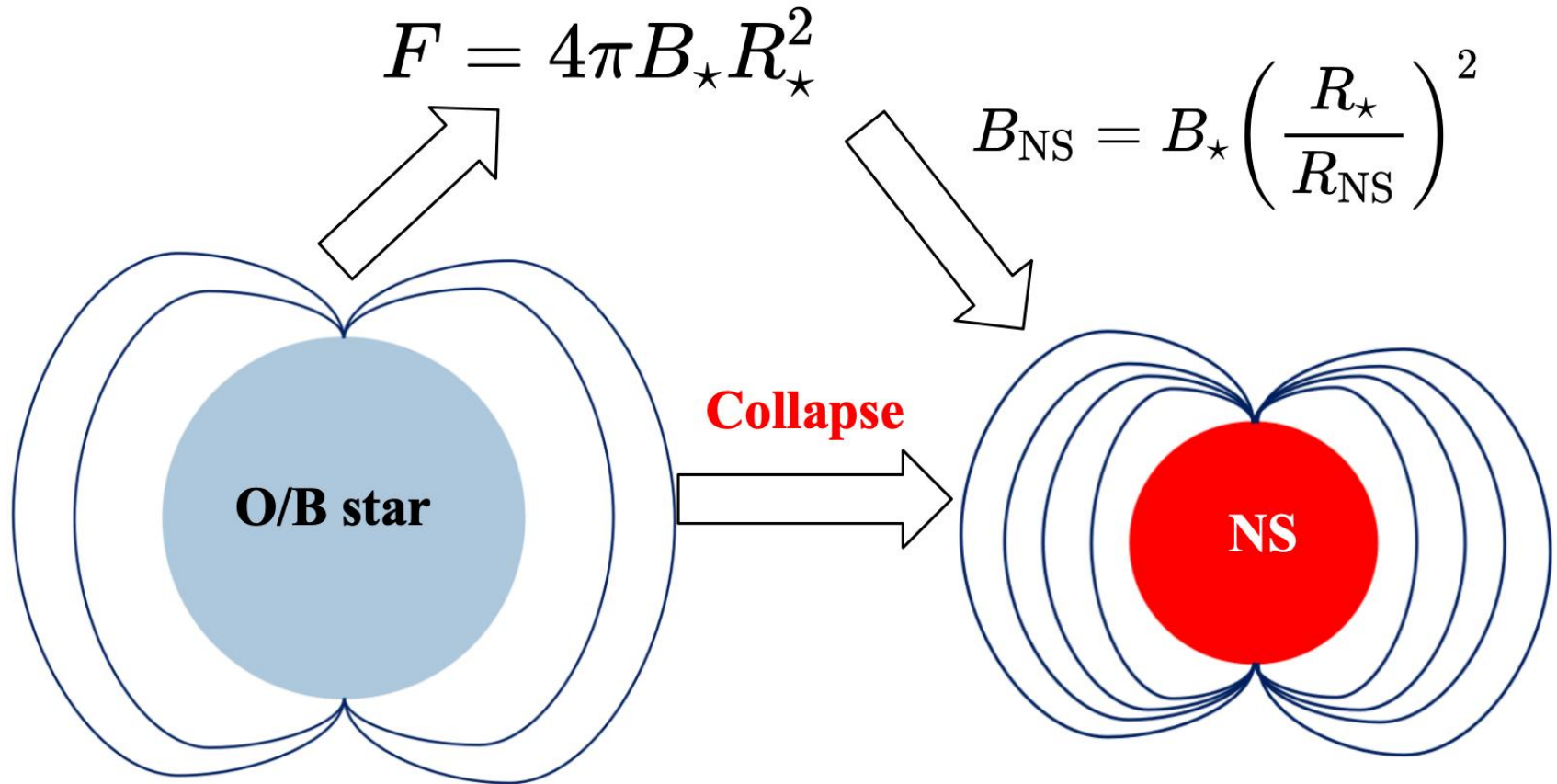
磁倾角演化:
$$\frac{d \sin \chi}{dt} = \frac{\cos^2 \chi}{\sin^2 \chi} \frac{\sin \chi}{\tau_d} - \frac{2G}{5c^5} \epsilon_B^2 I \omega^4 \sin \chi.$$



Cheng et al. 2015

二、磁形变随机引力波背景

化石场理论:



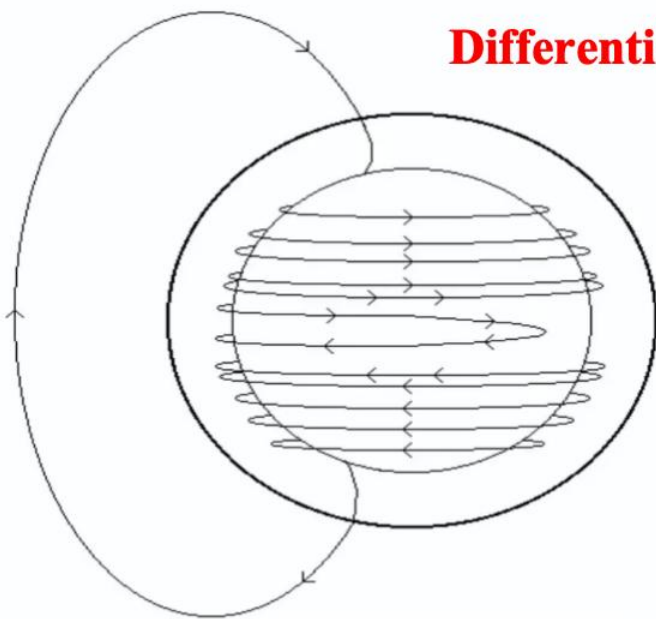
Ferrario & Wickramasinghe (2006); Makarenko et al. (2021)

二、磁形变随机引力波背景

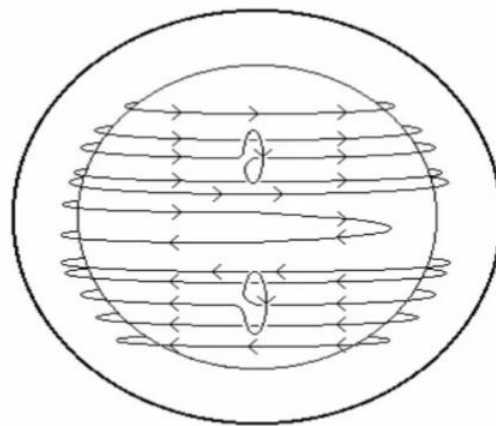


发电机机制:
$$\frac{\partial \vec{B}}{\partial t} \rightarrow \nabla \times (\alpha \langle \vec{B} \rangle) + \vec{r} \times (\langle \vec{B} \rangle \cdot \nabla) \vec{\Omega}$$

Differential rotation & Convection



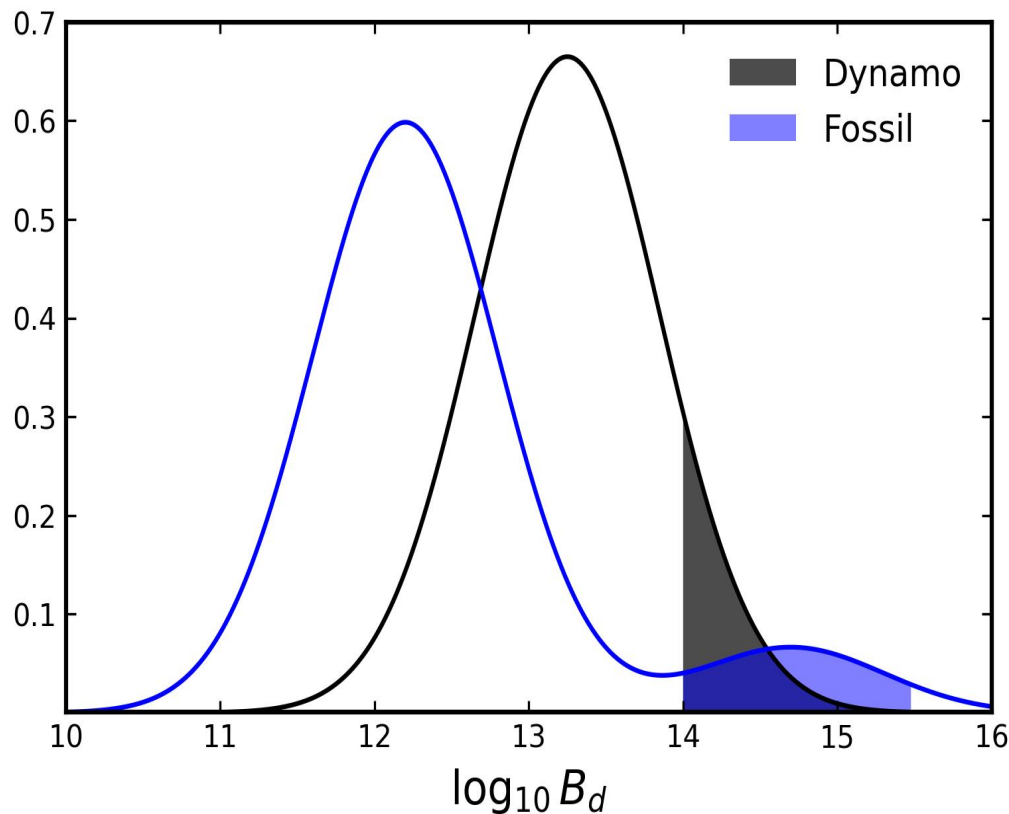
The Ω effect



The α effect

Parker (1955); Thompson & Duncan (1993)

二、磁形变随机引力波背景



发电机模型:

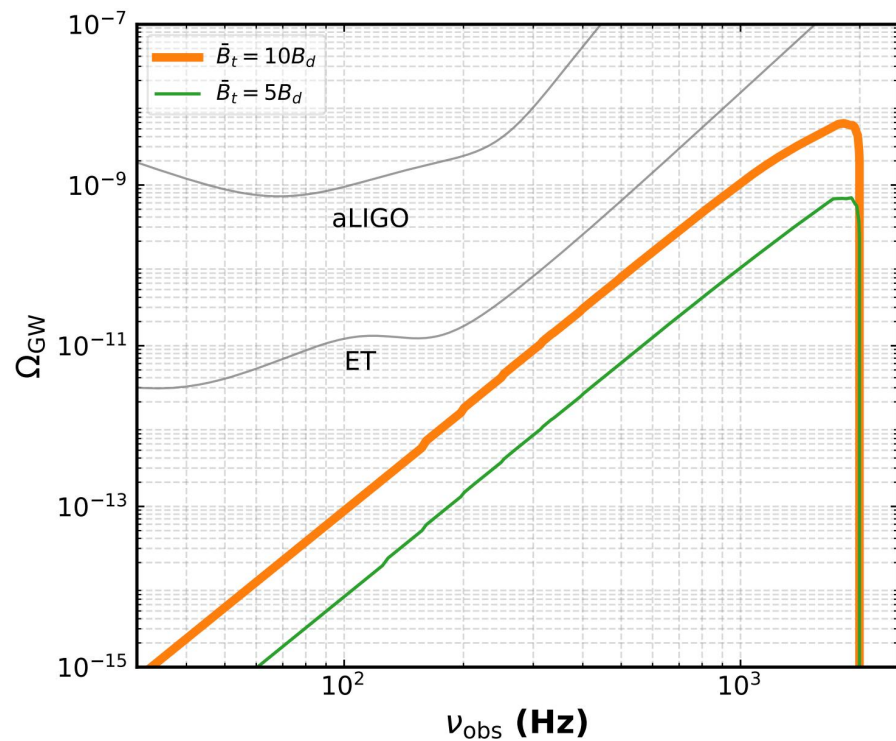
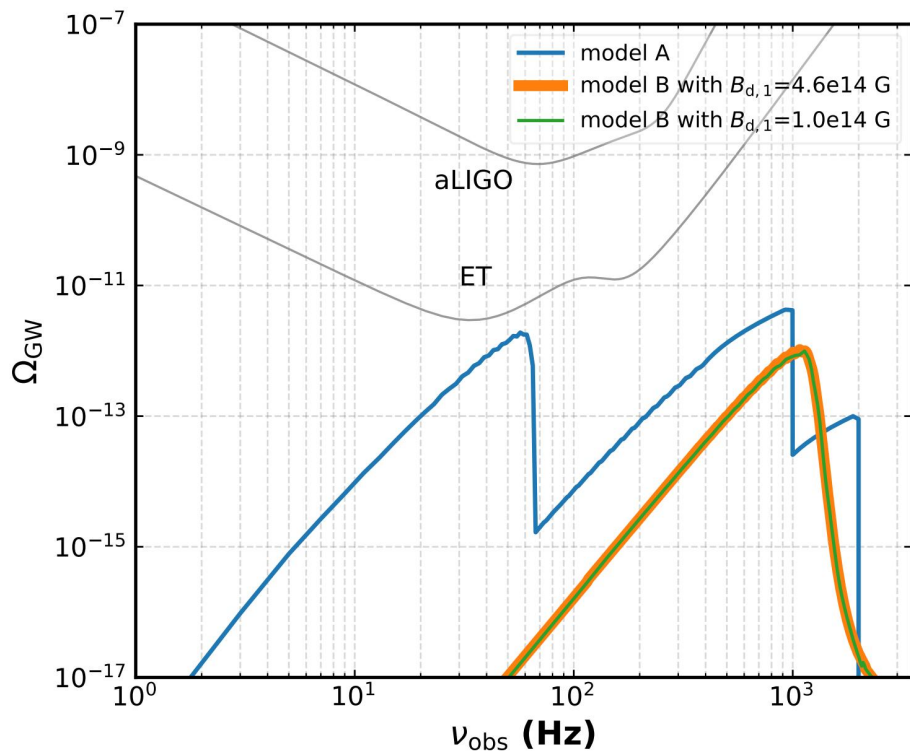
$$P_B(B_d; \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp \left\{ -\frac{(\log B_d - \mu)^2}{2\sigma^2} \right\}$$

化石场理论:

$$P_B(B_d; \mu, \sigma) = \frac{0.9}{\sqrt{2\pi}\sigma_1} \exp \left\{ -\frac{(\log B_d - \mu_1)^2}{2\sigma_1^2} \right\} + \frac{0.1}{\sqrt{2\pi}\sigma_2} \exp \left\{ -\frac{(\log B_d - \mu_2)^2}{2\sigma_2^2} \right\}$$

Popov et al. (2009); Makarenko et al. (2021)

二、磁形变随机引力波背景

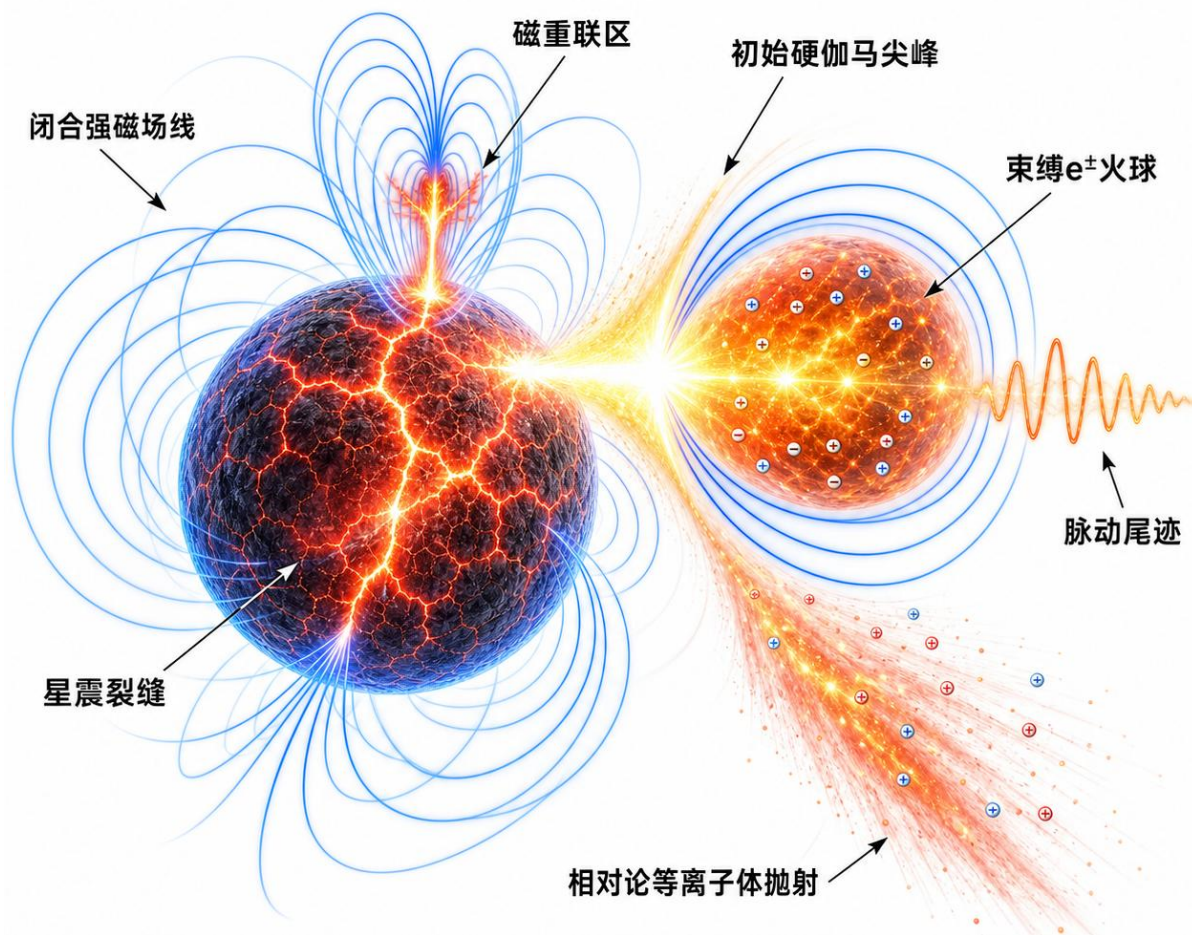


Yan et al. 2025

三、巨耀发激发的 f 模背景



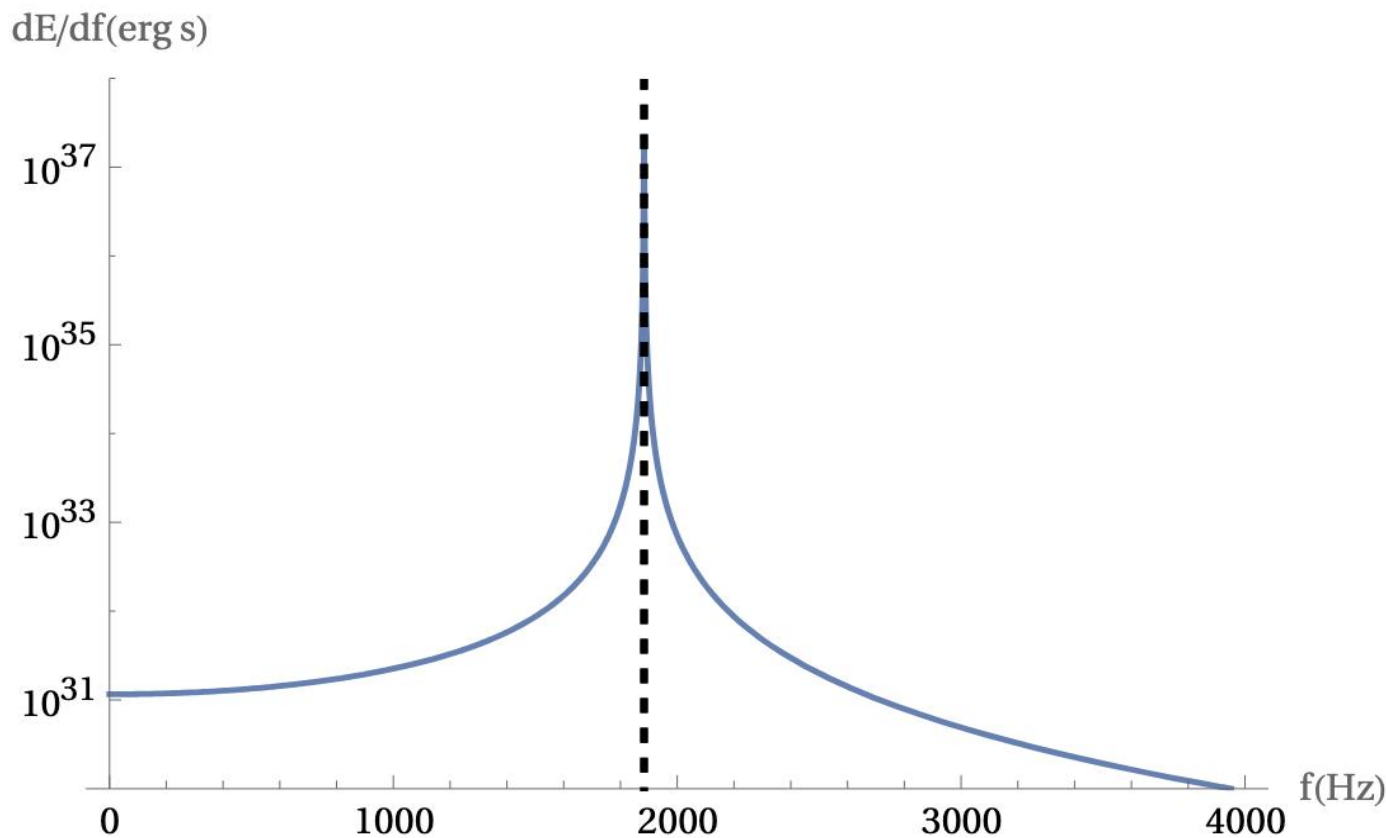
磁星巨耀发



三、巨耀发激发的 f 模背景

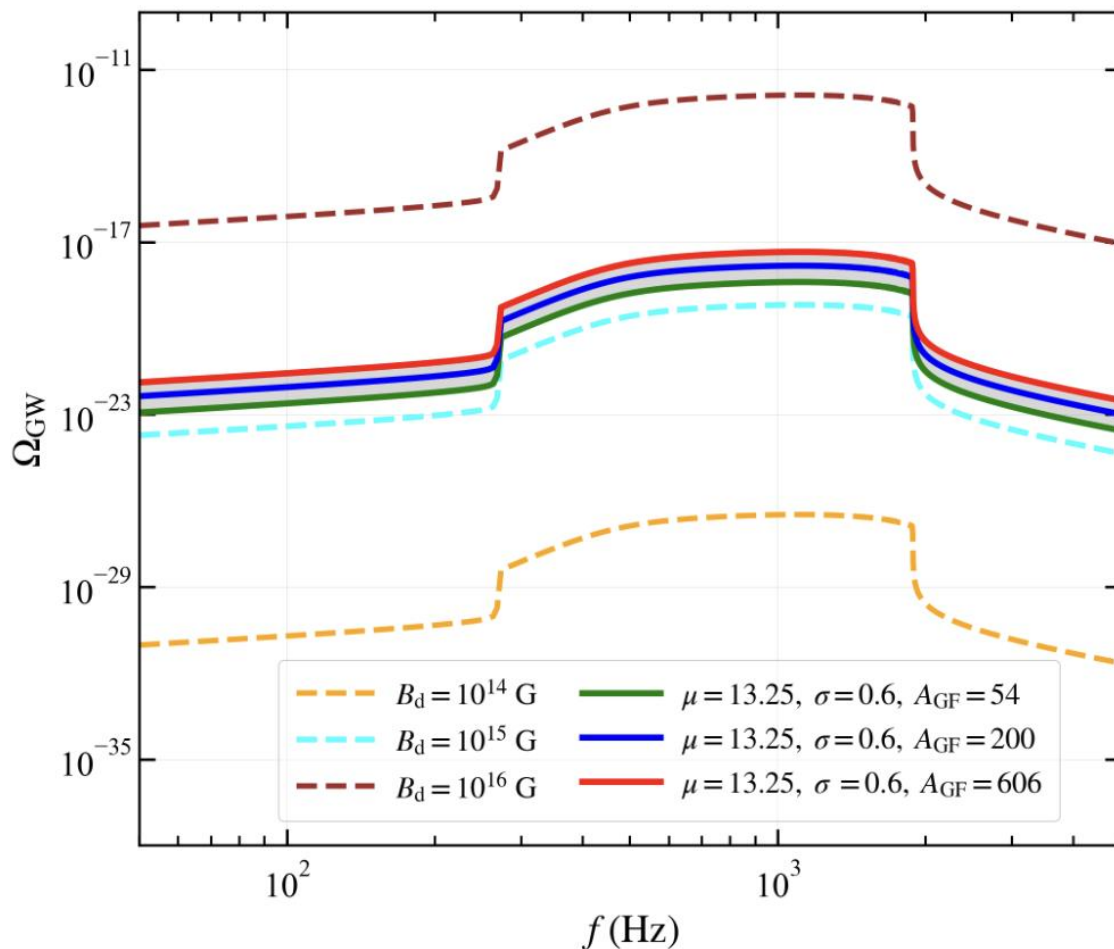


引力波能谱:
$$\frac{dE_{\text{GW}}}{df} = \frac{2\pi^2 d^2 f_{\text{fmode}}^2 c^3}{G} \frac{h_{\text{max}}^2 (2\pi f_{\text{fmode}})^2}{[\tau^{-2} + 4\pi^2 (f - f_{\text{fmode}})^2] [\tau^{-2} + 4\pi^2 (f + f_{\text{fmode}})^2]}$$



Kouvatsos et al. 2025

三、巨耀发激发的 f 模背景



磁场分布:

$$P_x(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left[-\frac{(x - \mu)^2}{2\sigma^2} \right]$$

巨耀发爆发平均次数:

$$N_{\text{GF}}(B_d) = A_{\text{GF}} \left(\frac{B_d}{10^{15} \text{ G}} \right)^\alpha$$

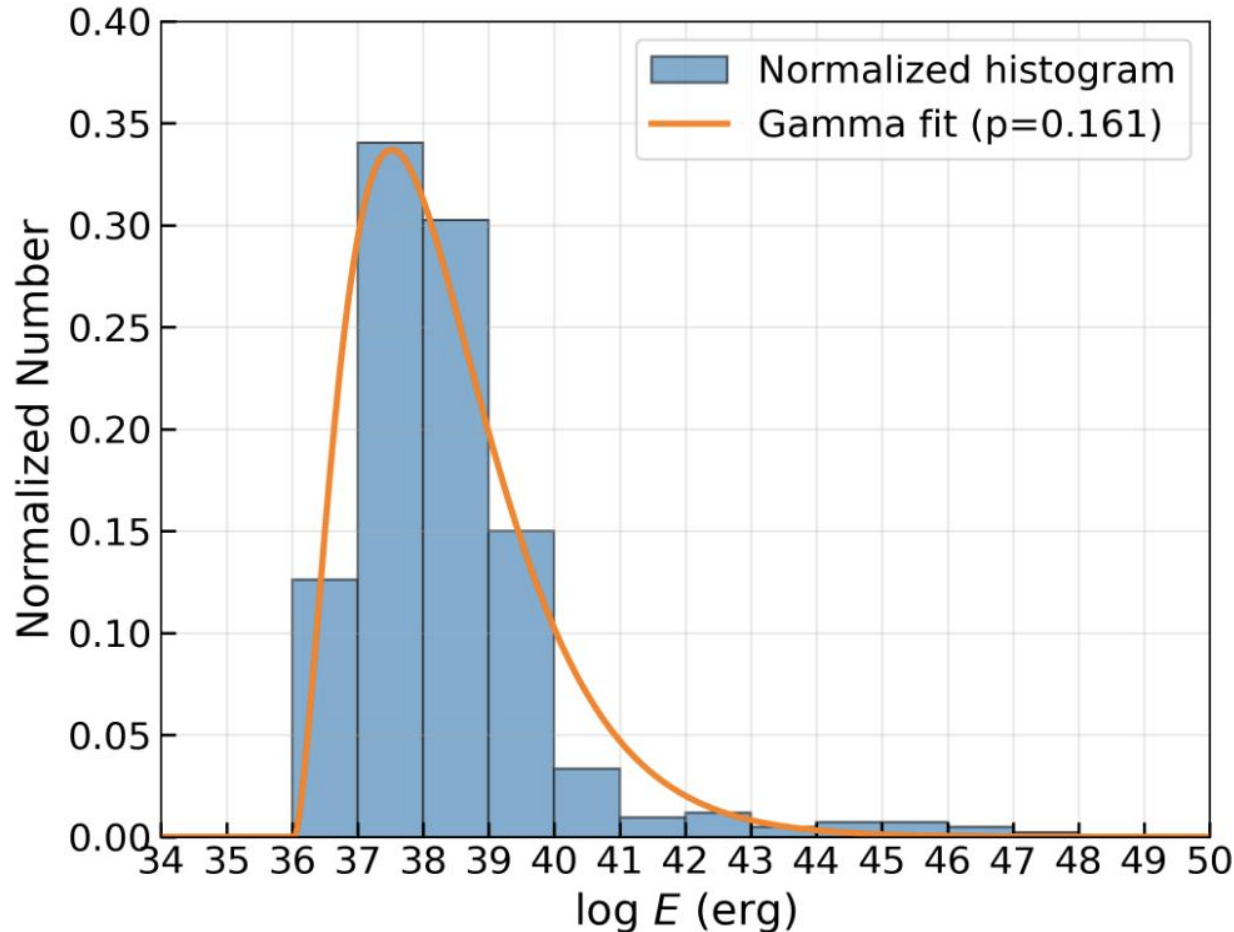
巨耀发局部事件率:

$$R_{\text{GF}}^{(V)}(0) = 3.8_{-3.1}^{+4.0} \times 10^5 \text{ Gpc}^{-3} \text{ yr}^{-1}$$

Burns et al. 2021

三、巨耀发激发的 f 模背景

伽马分布: $P_B(X; \gamma, \beta, \ell) = \frac{1}{\beta^\gamma \Gamma(\gamma)} (X - \ell)^{\gamma-1} \exp \left[-\frac{X - \ell}{\beta} \right]$

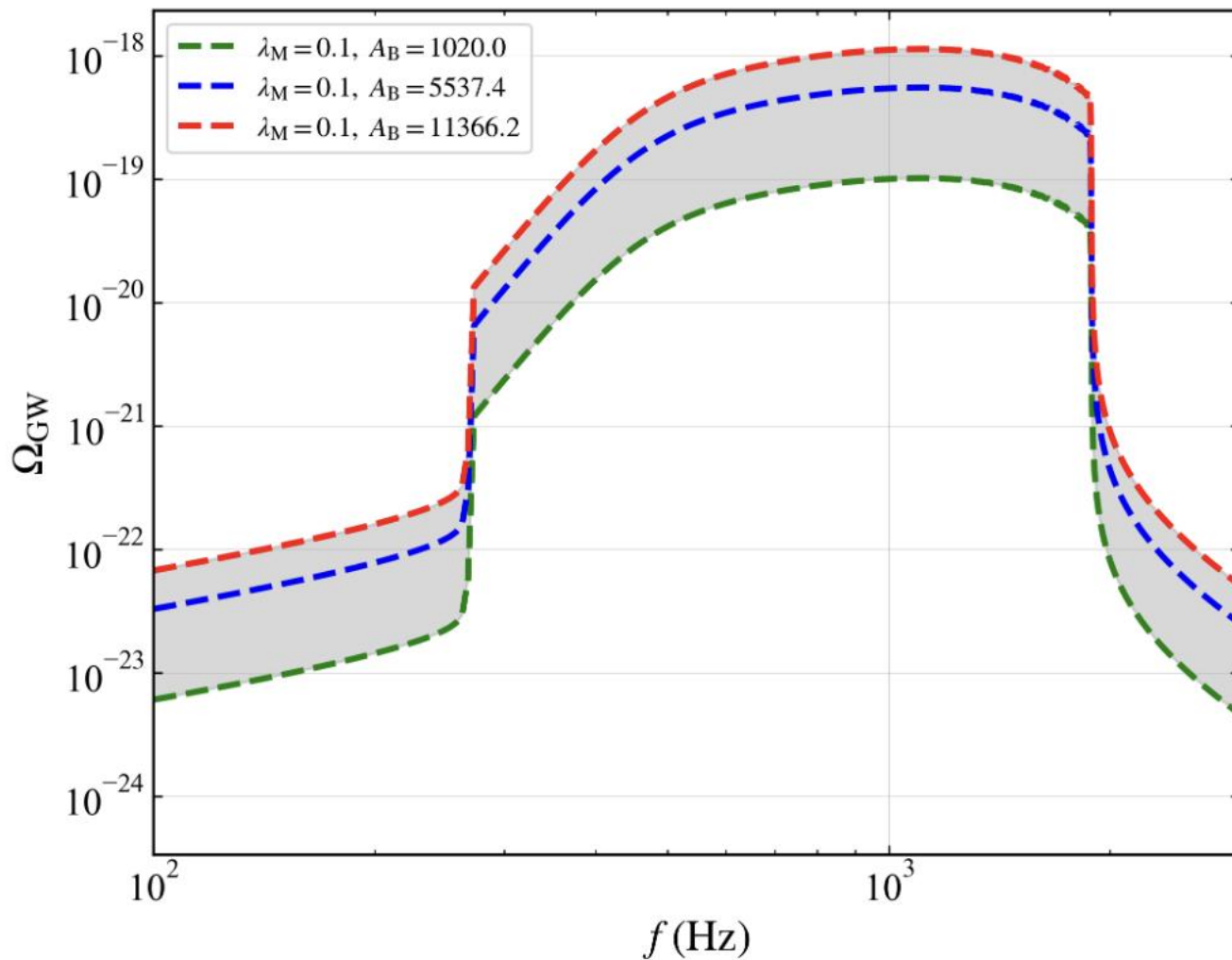


$$\gamma = 2.73$$

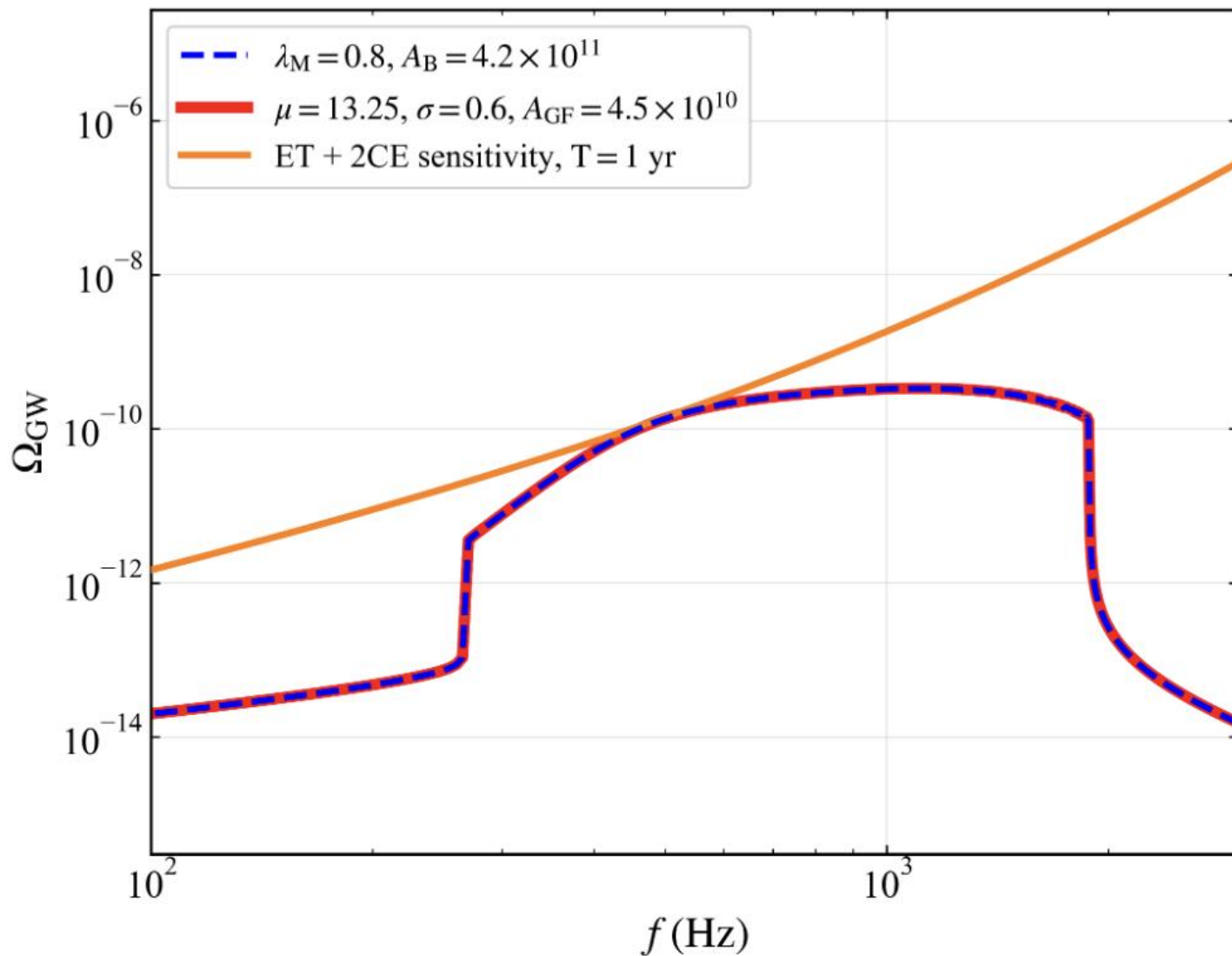
$$\beta = 0.86$$

$$\ell = 36.03$$

三、巨耀发激发的 f 模背景



三、巨耀发激发的 f 模背景



低磁场磁星形成

- 1、模型成功的在 $(1.5-9) \times 10^5$ 年之间复现出了低磁场磁星的观测**P**和**Pdot**值，这与经典磁热演化模型结果基本一致；
- 2、模型限制低磁场磁星初始磁场**B₀**在 $(2-10) \times 10^{14}$ G之间，且存在一个中等质量的回落盘，回落盘质量约为 $10^{-4}-10^{-3}$ Msun。

磁形变随机引力波背景

- 1、发电机模型下，如果磁星内部具有强的环向磁场，其无量纲引力波背景谱呈现一个多峰结构；
- 2、引入磁场分布后，整体背景会被显著压低，即使对ET进行一年的观测积分，起信噪比也远低于预期。

巨耀发激发 f 模背景

- 1、引入磁场分布主要降低最大背景增幅，不改变谱形，即使使用ET+2CE、观测 1 年，现实参数下背景仍远低于灵敏度曲线；
- 2、需要把磁星爆发次数提高到 $A_{GF} \approx 4.5 \times 10^{10}$ 或 $A_B \approx 4.2 \times 10^{11}$ ，远超观测校准值，其背景信号才有可能被探测器所捕获。

Thanks!