Astrophysics shedding light on exotic light states.

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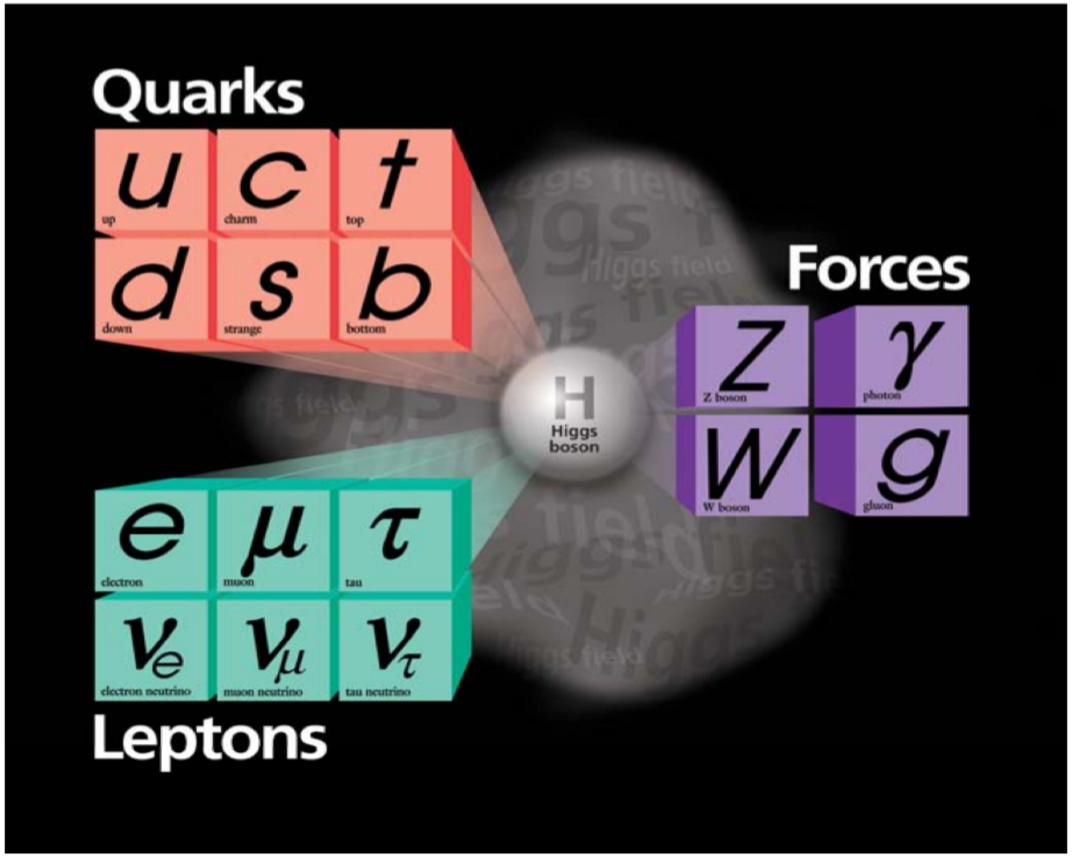
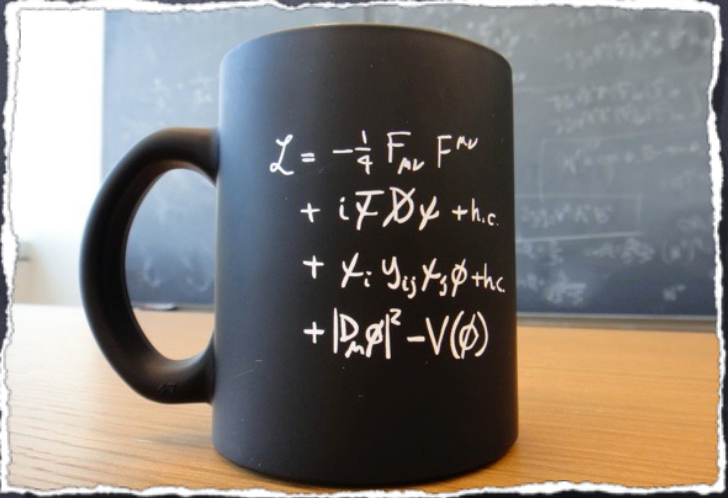
Based on works in collaboration with
P V S Pavan Chandra & Mrunal Korwar

[arxiv: 1709.07888, 1808.01295, 1909.12855]

The Standard Model





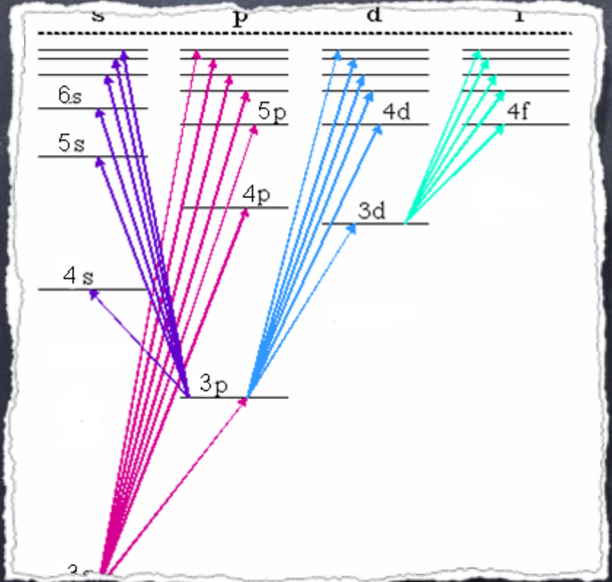
Unknowns !

[Quanta (2015)]

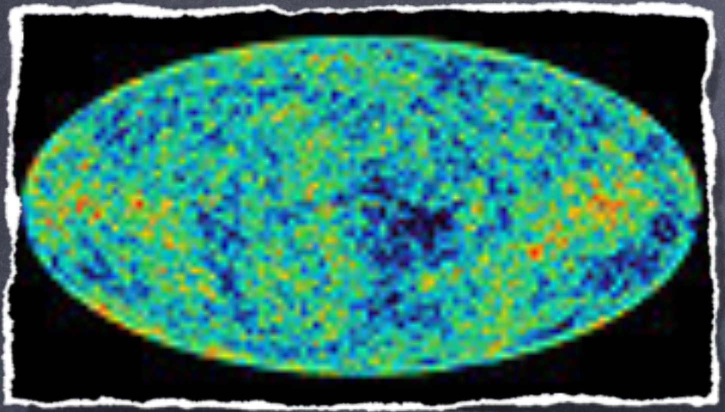
Collider searches

Direct detection

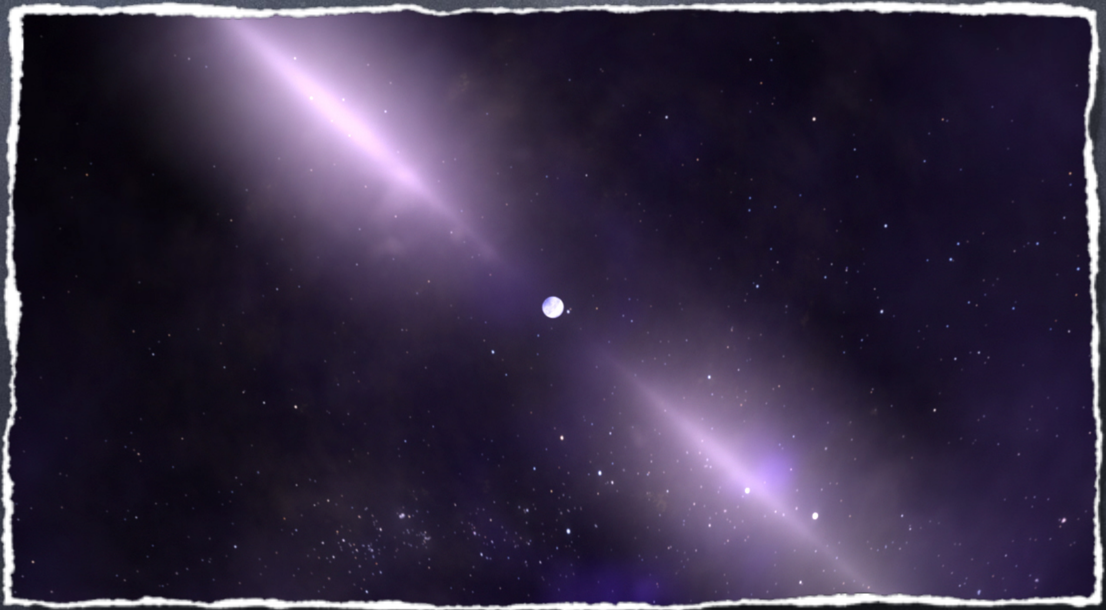
Low-energy probes



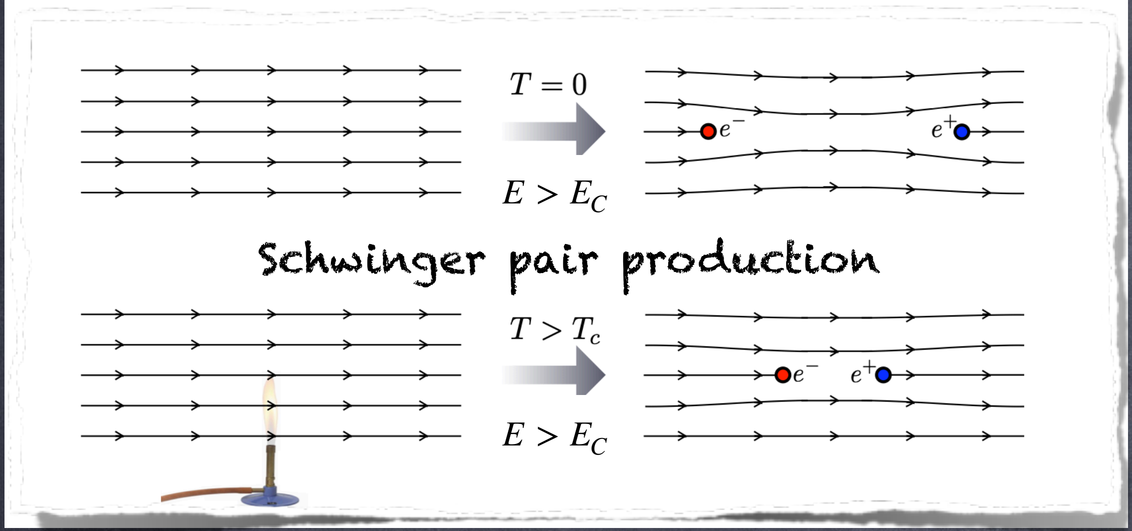
Cosmology



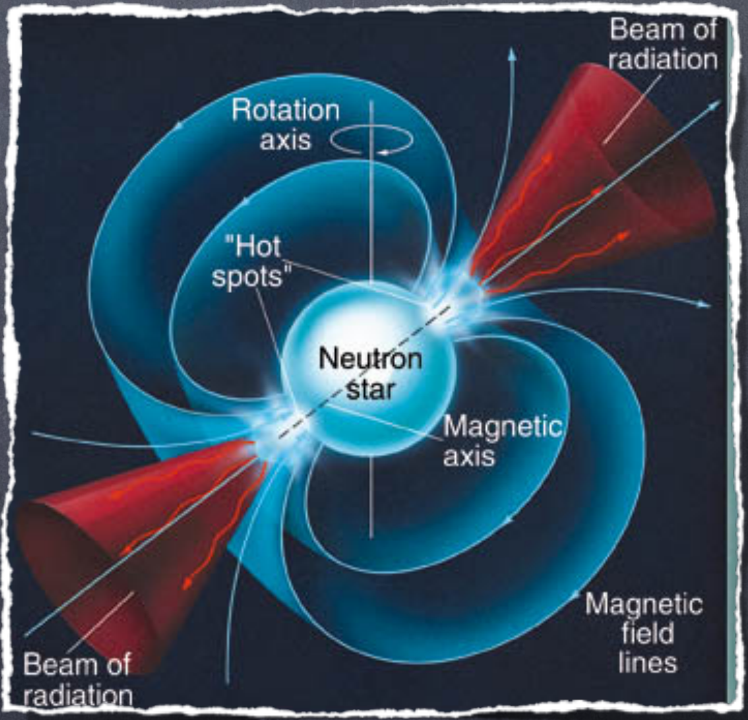
Astrophysics

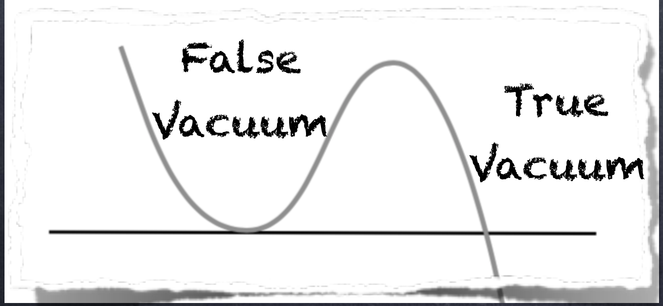


Light fractionally charged particles & their possible non-perturbative production in compact astrophysical objects...



[Brown (2015)]





Kinetic Mixing & Milli electrically charged Particles

Visible sector ↔ Dark sector

Kinetic mixing portal

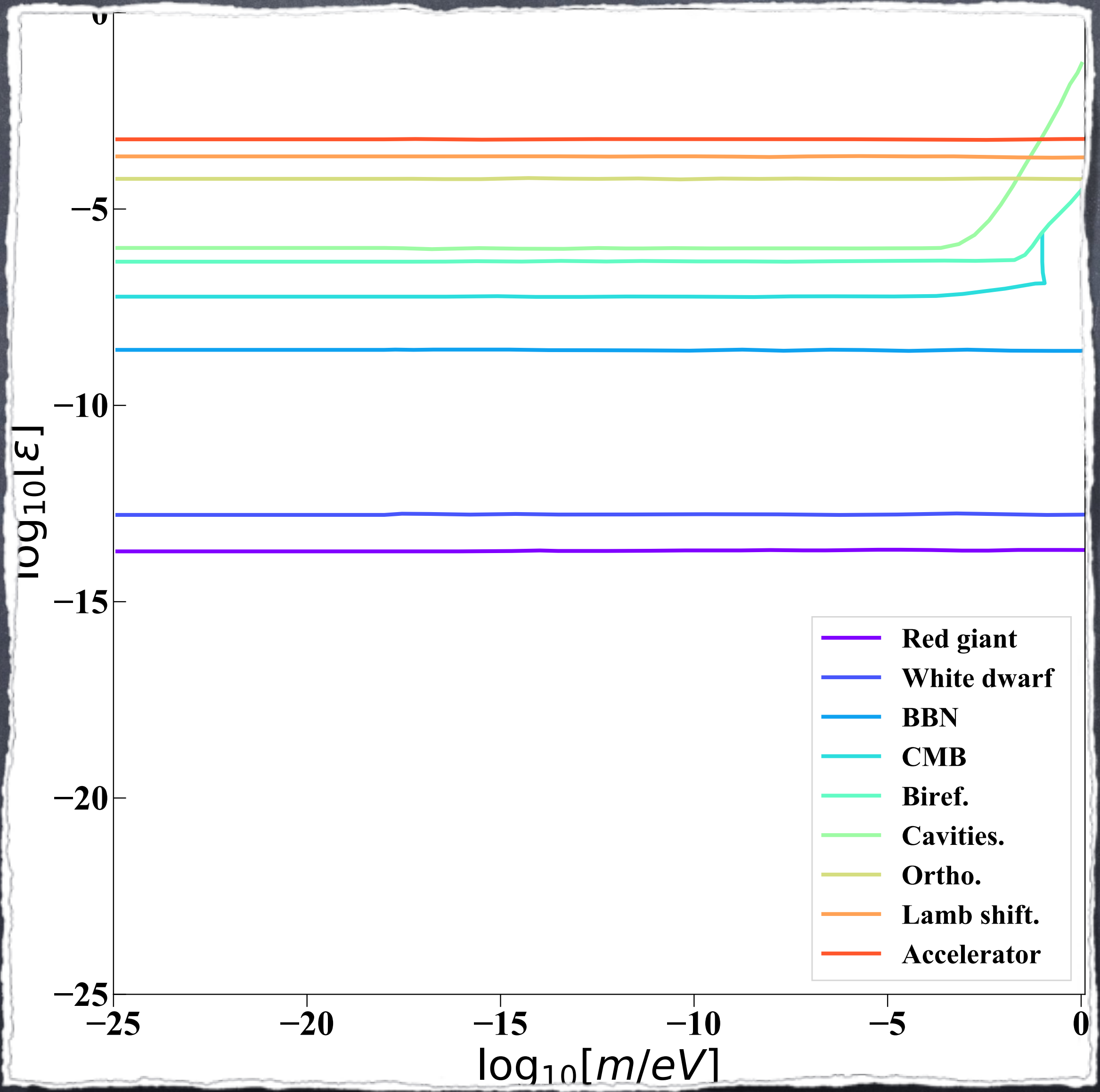
$$\mathcal{L} \supset \bar{\chi}_{\rm D}\left(i\not{\partial} - e_{\rm D}\not{A}^{\rm D} - m_\chi\right)\chi_{\rm D} - \frac{1}{4}A^{\rm D}_{\alpha\beta}A^{{\rm D}\,\alpha\beta} - \frac{\xi}{2}A^{\rm D}_{\alpha\beta}B^{\alpha\beta}$$

$$\epsilon \equiv \xi\,\frac{e_{\rm D}}{e}\cos\theta_{\rm W}$$

$$A^{\rm D}_\alpha \to A^{\rm D}_\alpha - \xi B_\alpha$$

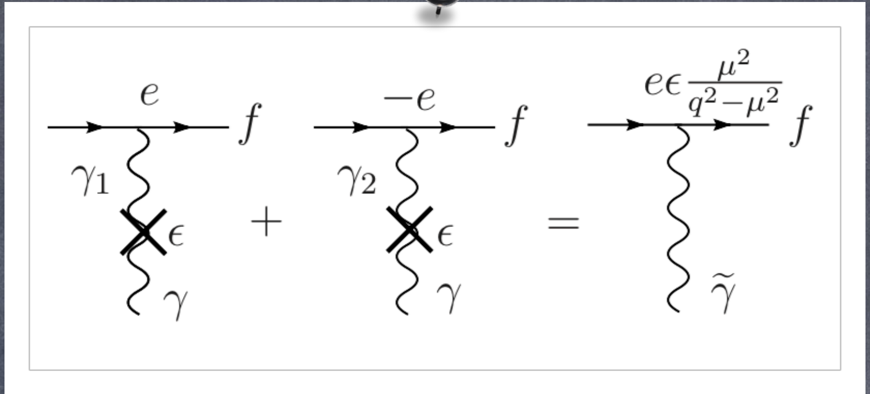
[Holdom (1986); L. J. Hall & Goldberg (1986),..]

Constraints



[Vogel, Redondo (2013); Fundamental Physics at the Intensity Frontier (2012)]

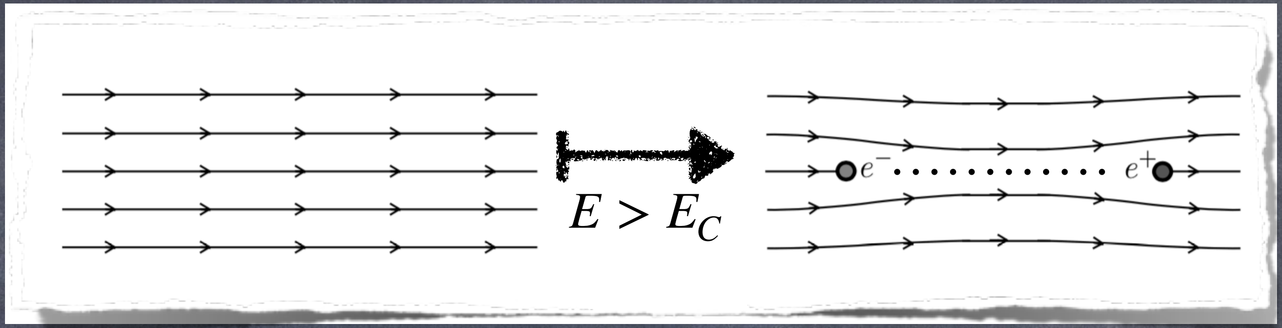
Loop holes ?



$$q_f(k^2 \simeq \omega_P^2) \simeq \frac{\mu^2}{\omega_P^2} \, q_f(k^2 \simeq 0)$$

[Masso, Redondo (2006); Melchiorri, Polosa & Strumia (2007); Abel, Jaeckel, Khoze & Ringwald (2008)...]

Non-perturbative Production



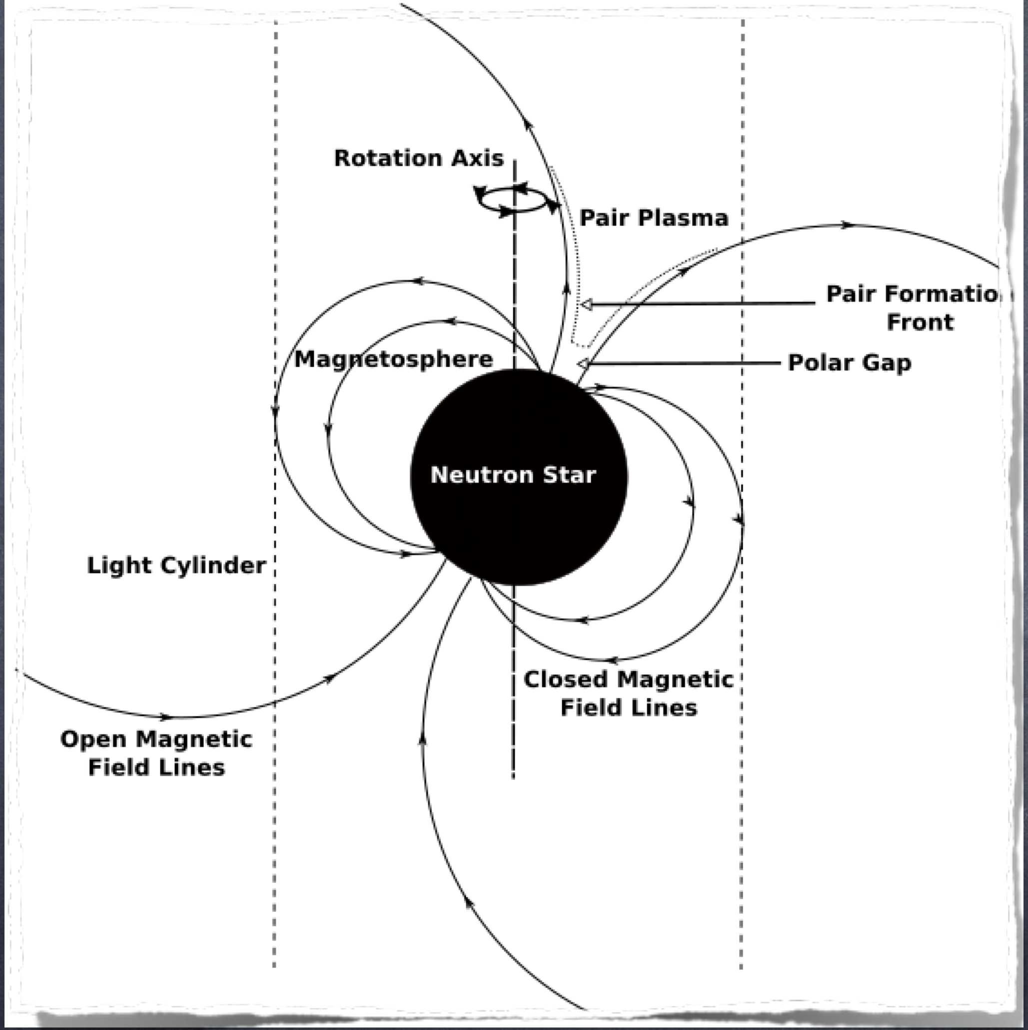
Schwinger Pair Production

$$\Gamma^{\mathrm{E}}_{0,sp} = \sum_{p=1}^{\infty} \frac{e^2 E^2}{4\pi^3 p^2} \exp\left[-\frac{m^2 p\pi}{eE}\right]$$

$$\boxed{T=0}$$

[Schwinger (1951),...]

Neutron Stars



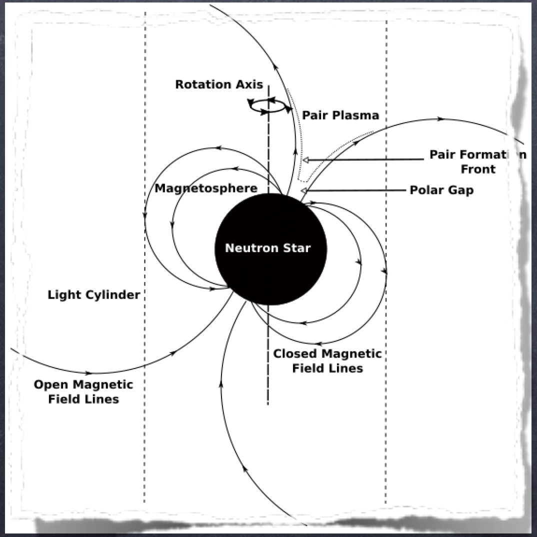
[Goldreich & Julian (1969),...]

Schwinger Pair Production
In
Electric & Magnetic Fields

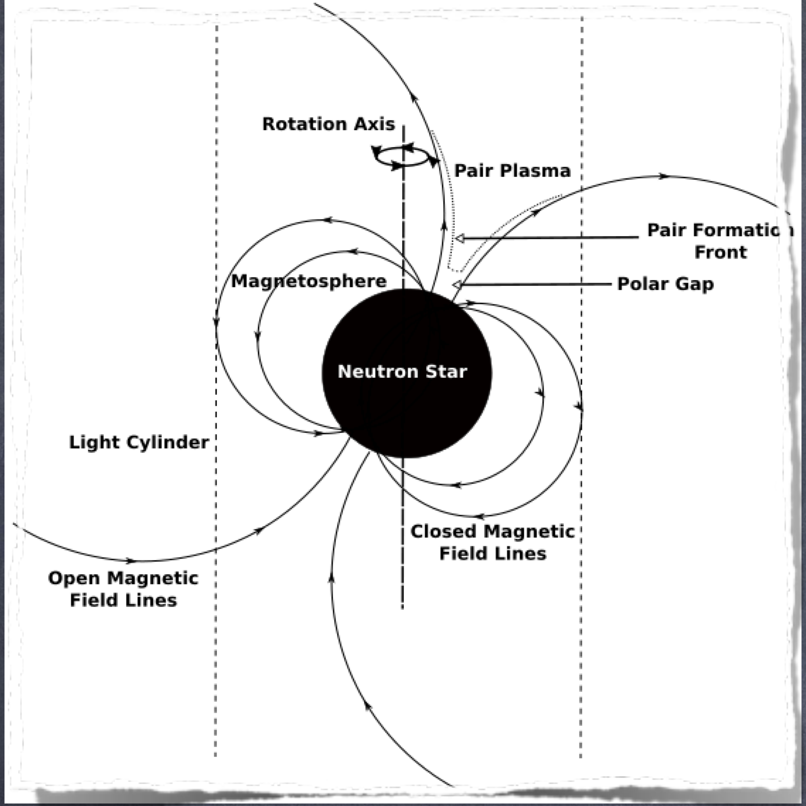
$$\Gamma^{\mathrm{EB}}_{\chi\bar{\chi}} = \frac{\epsilon^2 e^2 E B}{4\pi^2\hbar^2}\coth\left[\frac{\pi c B}{E}\right]\exp\left[-\frac{\pi m_\chi^2 c^3}{\hbar \epsilon e E}\right]$$

$\boxed{T=0}$

[Nikishov (1970), Korwar & AT (2018)...]



Neutron Star Vacuum Gaps & Electric Fields



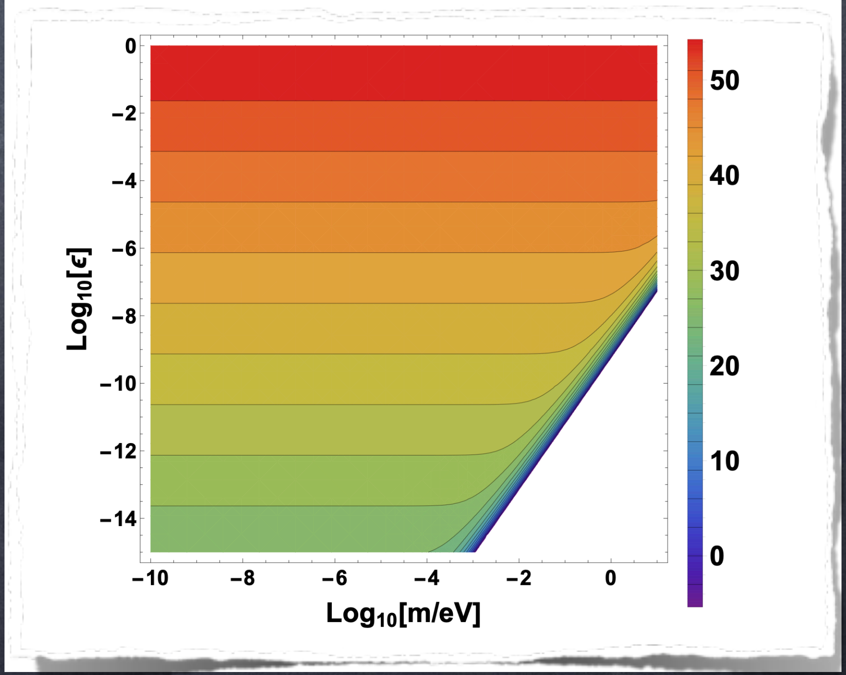
$$|\vec{E}_{\mathrm{NS,PG}}| = \frac{1}{2}\Omega_{\mathrm{NS}} B_{\mathrm{NS}} R_{\mathrm{NS}} \cos^3\theta$$

[Goldreich & Julian (1969); Handbook of Pulsar Astronomy (2005)]

$$B \sim 10^{15}\,\mathrm{G}$$

Magnetars !

$$|\vec{E}_{\mathrm{M}}| \sim 10^{14}\,\mathrm{Vm}^{-1}$$



[Korwar & AT (2017)]

Energetics

$$\int d\mathcal{V}\left[\frac{d^2\mathcal{E}_{\rm RL}}{dt\,d\mathcal{V}}+\frac{d^2\mathcal{E}^{\chi\bar{\chi}}_{\rm SPP}}{dt\,d\mathcal{V}}\right]\lesssim\int d\mathcal{V}\,\frac{1}{\mathcal{T}_{\rm M}}\left[\frac{\vec{B}^2_{\rm M}}{2\mu_0}+\frac{\epsilon_0\vec{E}^2_{\rm M,PG}}{2}\right]$$

$$\frac{d^2\mathcal{E}^{\chi\bar{\chi}}_{\rm SPP}}{dt\;dV}=\Gamma^{\rm EB}_{\chi\bar{\chi}}\,\epsilon e|\vec{E}_{\rm M,PG}|l_0+\Gamma^{\rm EB}_{\chi\bar{\chi}}\,\epsilon e|\vec{E}'_{\rm M,PG}|(l-l_0)$$

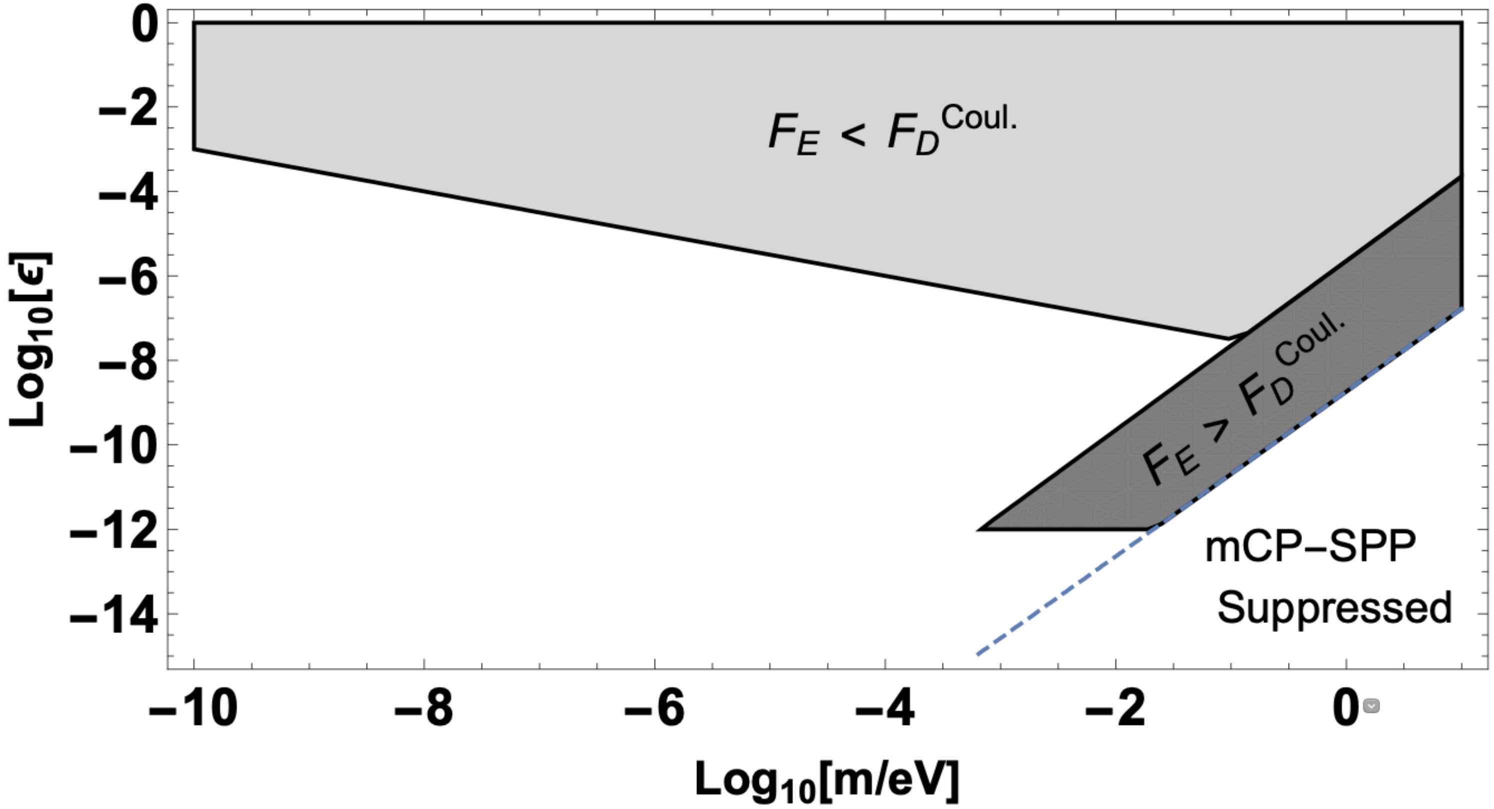
$$\left\langle\int d\mathcal{V}\frac{d^2\mathcal{E}_{\rm RL}}{dt\,d\mathcal{V}}\right\rangle^{\rm PQXR}_{\rm M}=4.3\times10^{34}\,{\rm ergs\,s^{-1}}$$

[McGill Magnetar Catalog (2016)]

$$\epsilon\;\lesssim\;10^{-12}$$

[Korwar & AT (2017)]

Limits



[Korwar & AT (2017)]

Magnetically charged Particles

$$\partial_\mu F^{\mu\nu} = -eJ^\nu \ , \quad \partial_\mu \tilde{F}^{\mu\nu} = -gK^\nu$$

$$\mathcal{L} = -\frac{n^\alpha n^\mu}{2n^2}\Big[\eta^{\beta\nu}\big(F^A_{\alpha\beta}F^A_{\mu\nu} + F^{\tilde{A}}_{\alpha\beta}F^{\tilde{A}}_{\mu\nu}\big) - \frac{1}{2}\epsilon_\mu{}^{\nu\gamma\delta}\big(F^{\tilde{A}}_{\alpha\nu}F^A_{\gamma\delta} - F^A_{\alpha\nu}F^{\tilde{A}}_{\gamma\delta}\big)\Big]$$
$$- eJ_\mu A^\mu - \frac{4\pi}{e}K_\mu \tilde{A}^\mu \ .$$

$$F_{\mu\nu} = \frac{n^\alpha}{n^2}\left(n_\mu F^A_{\alpha\nu} - n_\nu F^A_{\alpha\mu} - \varepsilon_{\mu\nu\alpha}{}^\beta n^\gamma F^{\tilde{A}}_{\gamma\beta}\right)$$

[Zwanziger (1971)]

Kinetic mixing & Milli magnetically charged particles

$$\begin{aligned}\mathcal{L}_{\rm MMM} \supset & -\frac{n^\alpha n^\mu}{2n^2}\Big[\eta^{\beta\nu}\big(F^A_{\alpha\beta}F^A_{\mu\nu}+F^{\tilde A}_{\alpha\beta}F^{\tilde A}_{\mu\nu}\big)-\frac{1}{2}\epsilon_\mu{}^{\nu\gamma\delta}\big(F^{\tilde A}_{\alpha\nu}F^A_{\gamma\delta}-F^A_{\alpha\nu}F^{\tilde A}_{\gamma\delta}\big)\Big]-eJ_\mu A^\mu-\frac{4\pi}{e}K_\mu\tilde A^\mu \\ & -\frac{n^\alpha n^\mu}{2n^2}\Big[\eta^{\beta\nu}\big(F^A_{{\rm D}\alpha\beta}F^A_{{\rm D}\mu\nu}+F^{\tilde A}_{{\rm D}\alpha\beta}F^{\tilde A}_{{\rm D}\mu\nu}\big)-\frac{1}{2}\epsilon_\mu{}^{\nu\gamma\delta}\big(F^{\tilde A}_{{\rm D}\alpha\nu}F^A_{{\rm D}\gamma\delta}-F^A_{{\rm D}\alpha\nu}F^{\tilde A}_{{\rm D}\gamma\delta}\big)\Big] \\ & -\frac{m^2_{\rm DA}}{2}A_{{\rm D}\mu}A^\mu_{\rm D}-e_{\rm D}J_{{\rm D}\mu}A^\mu_{\rm D}-\frac{4\pi}{e_{\rm D}}K_{{\rm D}\mu}\tilde A^\mu_{\rm D}+\chi\frac{n^\alpha n^\mu}{n^2}\eta^{\beta\nu}\big(F^A_{{\rm D}\alpha\beta}F^A_{\mu\nu}-F^{\tilde A}_{{\rm D}\alpha\beta}F^{\tilde A}_{\mu\nu}\big)\ .\end{aligned}$$

$$\begin{aligned}A_\mu \to A_\mu+\chi A_{{\rm D}\mu} \quad &, \quad \tilde A_\mu \to \tilde A_\mu \\ A_{{\rm D}\mu} \to A_{{\rm D}\mu} \quad &, \quad \tilde A_{{\rm D}\mu} \to \tilde A_{{\rm D}\mu}-\chi\tilde A_\mu\end{aligned}$$

$$\mathcal{L}_{\rm int.} \supset eJ_\mu A^\mu+e\chi J_\mu A^\mu_{\rm D}+e_{\rm D}J_{{\rm D}\mu}A^\mu_{\rm D}+\frac{4\pi}{e}K_\mu\tilde A^\mu+\frac{4\pi}{e_{\rm D}}K_{{\rm D}\mu}\tilde A^\mu_{\rm D}-\frac{4\pi\chi}{e_{\rm D}}K_{{\rm D}\mu}\tilde A^\mu$$

[Zwanziger (1971), Terning et. al. (2019)]

$$\xi \equiv \chi\left(\frac{g_{\rm D}}{g}\right)$$

Kinetic mixing & Milli magnetically charged particles

$$
\begin{aligned}
\mathcal{L}_{\text{MMM}} \supset & -\frac{n^\alpha n^\mu}{2n^2}\left[\eta^{\beta\nu}\left(F^A_{\alpha\beta}F^A_{\mu\nu} + F^{\tilde{A}}_{\alpha\beta}F^{\tilde{A}}_{\mu\nu}\right) - \frac{1}{2}\epsilon_\mu{}^{\nu\gamma\delta}\left(F^{\tilde{A}}_{\alpha\nu}F^A_{\gamma\delta} - F^A_{\alpha\nu}F^{\tilde{A}}_{\gamma\delta}\right)\right] - eJ_\mu A^\mu - \frac{4\pi}{e}K_\mu \tilde{A}^\mu \\
& - \frac{n^\alpha n^\mu}{2n^2}\left[\eta^{\beta\nu}\left(F^A_{\mathrm{D}\alpha\beta}F^A_{\mathrm{D}\mu\nu} + F^{\tilde{A}}_{\mathrm{D}\alpha\beta}F^{\tilde{A}}_{\mathrm{D}\mu\nu}\right) - \frac{1}{2}\epsilon_\mu{}^{\nu\gamma\delta}\left(F^{\tilde{A}}_{\mathrm{D}\alpha\nu}F^A_{\mathrm{D}\gamma\delta} - F^A_{\mathrm{D}\alpha\nu}F^{\tilde{A}}_{\mathrm{D}\gamma\delta}\right)\right] \\
& - \frac{m^2_{\mathrm{D}A}}{2}A_{\mathrm{D}\mu}A^\mu_{\mathrm{D}} - e_{\mathrm{D}}J_{\mathrm{D}\mu}A^\mu_{\mathrm{D}} - \frac{4\pi}{e_{\mathrm{D}}}K_{\mathrm{D}\mu}\tilde{A}^\mu_{\mathrm{D}} + \chi\frac{n^\alpha n^\mu}{n^2}\eta^{\beta\nu}\left(F^A_{\mathrm{D}\alpha\beta}F^A_{\mu\nu} - F^{\tilde{A}}_{\mathrm{D}\alpha\beta}F^{\tilde{A}}_{\mu\nu}\right) .
\end{aligned}
$$

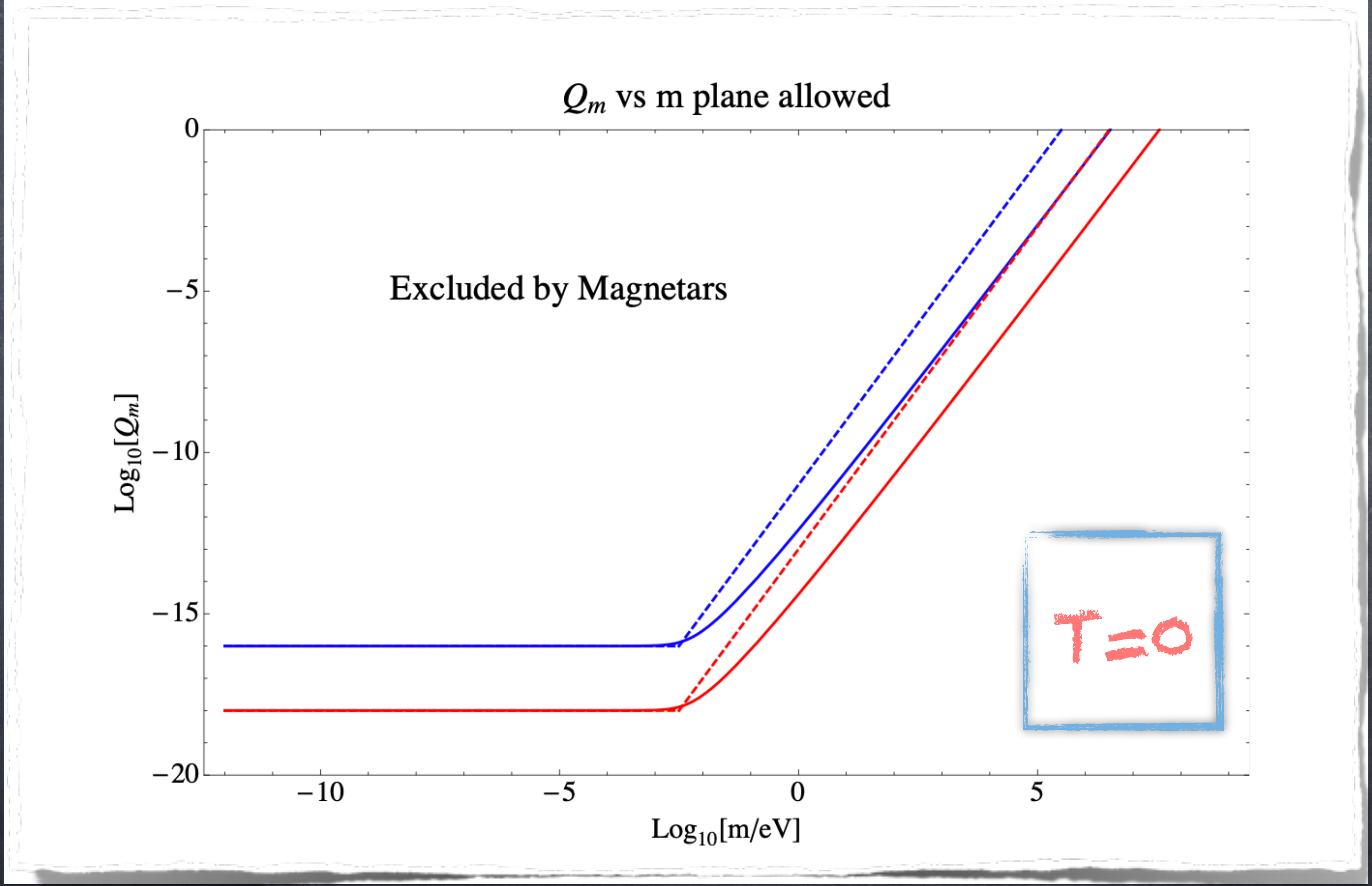
$$
\begin{aligned}
A_\mu \to A_\mu + \chi A_{\mathrm{D}\mu} \quad &, \quad \tilde{A}_\mu \to \tilde{A}_\mu \\
A_{\mathrm{D}\mu} \to A_{\mathrm{D}\mu} \quad &, \quad \tilde{A}_{\mathrm{D}\mu} \to \tilde{A}_{\mathrm{D}\mu} - \chi\tilde{A}_\mu
\end{aligned}
$$

$$
\mathcal{L}_{\text{int.}} \supset eJ_\mu A^\mu + e\chi J_\mu A^\mu_{\mathrm{D}} + e_{\mathrm{D}}J_{\mathrm{D}\mu}A^\mu_{\mathrm{D}} + \frac{4\pi}{e}K_\mu\tilde{A}^\mu + \frac{4\pi}{e_{\mathrm{D}}}K_{\mathrm{D}\mu}\tilde{A}^\mu_{\mathrm{D}} - \frac{4\pi\chi}{e_{\mathrm{D}}}K_{\mathrm{D}\mu}\tilde{A}^\mu
$$

[Zwanziger (1971), Terning et. al. (2019)]

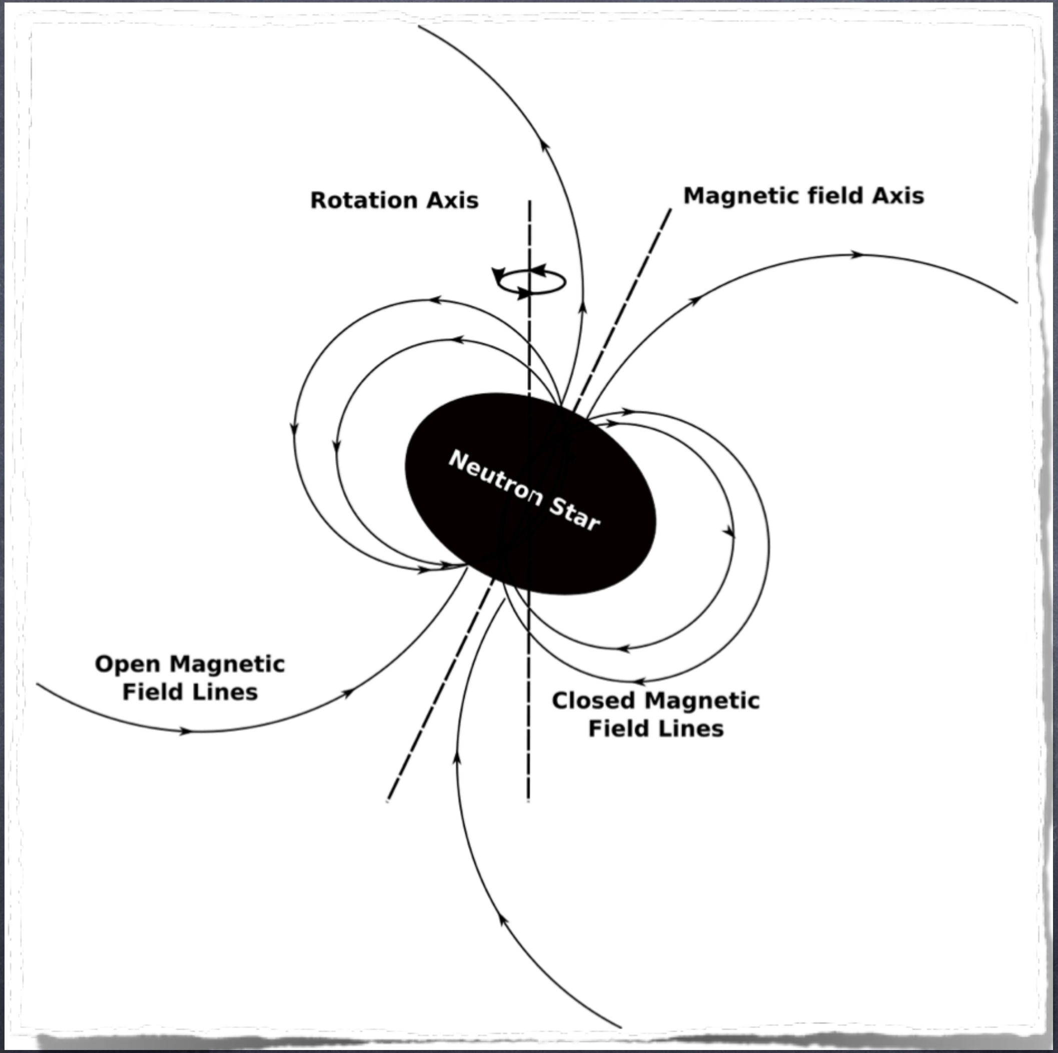
$$
\xi \equiv \chi\left(\frac{g_{\mathrm{D}}}{g}\right)
$$

Limits from Energetics



[Anson & Huang (2017)]

Magnetic-field-induced quadrupole moments

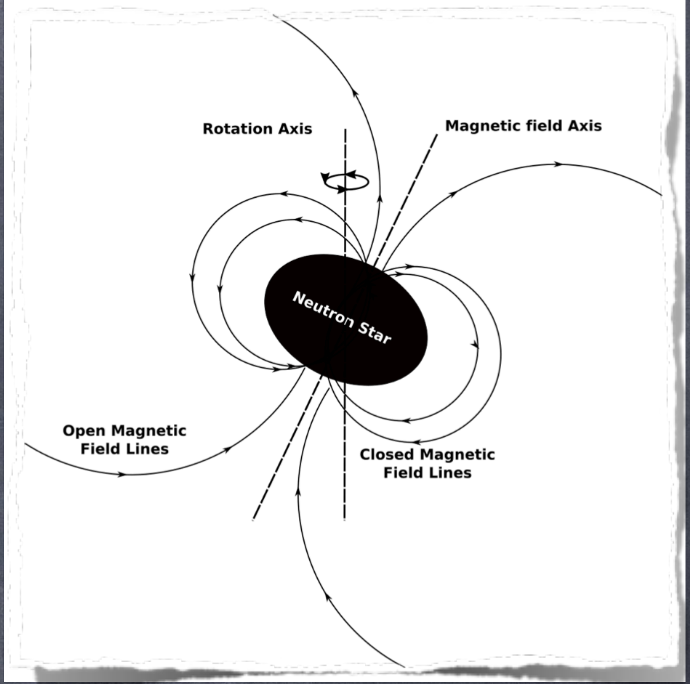


[Chandrasekhar & Fermi (1953),
Ferraro (1953),...]

$$\begin{aligned} B_r &= B_0 \cos\theta & B_\theta &= -B_0 \sin\theta & (r < R) \quad , \\ B_r &= B_0 \left(\frac{R}{r}\right)^3 \cos\theta & B_\theta &= \frac{1}{2} B_0 \left(\frac{R}{r}\right)^3 \sin\theta & (r > R) \quad . \end{aligned}$$

$$r(\cos\theta) = R + \zeta P_l(\cos\theta) \quad (\zeta \ll R)$$

$$\delta E = \frac{3}{25}\left(\frac{\zeta}{R}\right)^2 \frac{GM^2}{R} + \frac{9}{20}\zeta B_0^2 R^2$$



Magnetic fields generically lead to a quadrupole deformation

[Chandrasekhar & Fermi (1953), Ferraro (1953),...]

Quadrupole ellipticities

$$\tilde{\varepsilon}_{\rm Q} = -\frac{3}{2}\frac{\tilde{Q}_{33}}{I_3}$$

$$\tilde{\varepsilon}_{\rm Q}^{\rm const.} = \frac{2}{15}\frac{B^2}{B_*^2}$$

$$\tilde{\varepsilon}_{\rm Q}^{\rm 1\text{-}poly.} = \frac{36\pi^5(12-\pi^2)}{5(\pi^2-6)^3}\frac{B^2}{B_*^2}$$

[Haskell (2007),…]

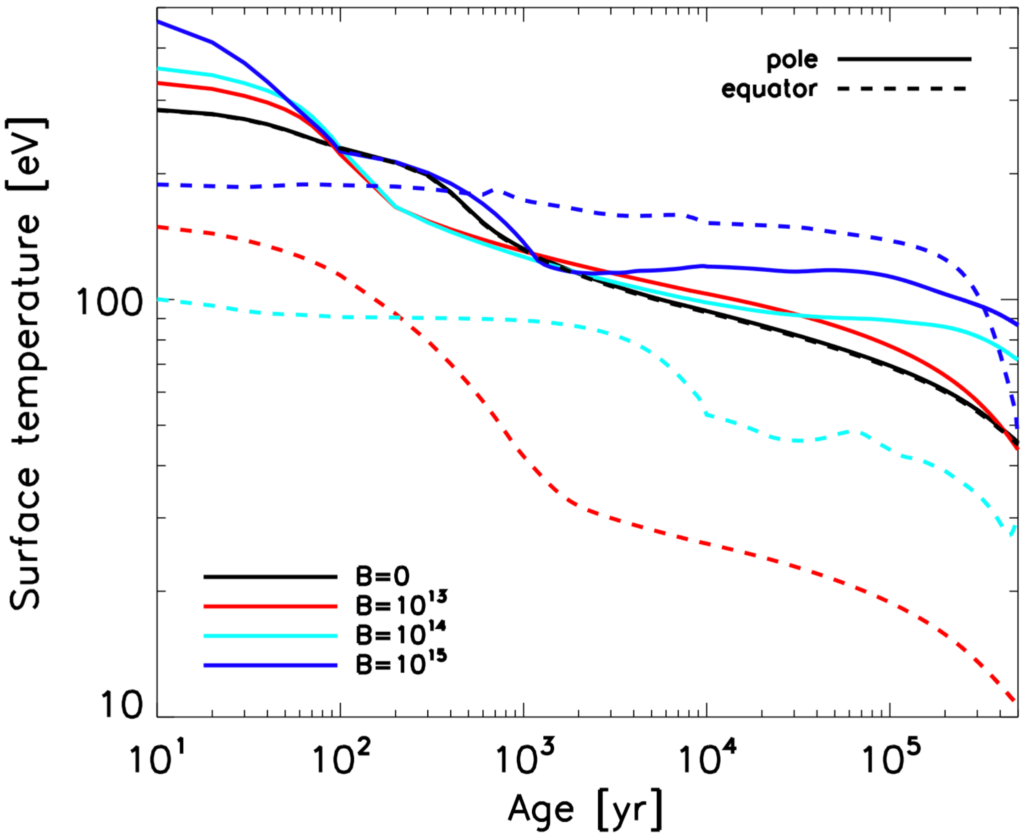
$$\tilde{\varepsilon}_{\rm Q}^{\rm Obs.\ \ GRB} \lesssim 10^{-2} - 10^{-1}$$

[Ushomirsky et. al. (2000), Owen et. al. (2005), Lasky et. al. (2015), LIGO/VIRGO (2019)…]

Neutron star thermal history

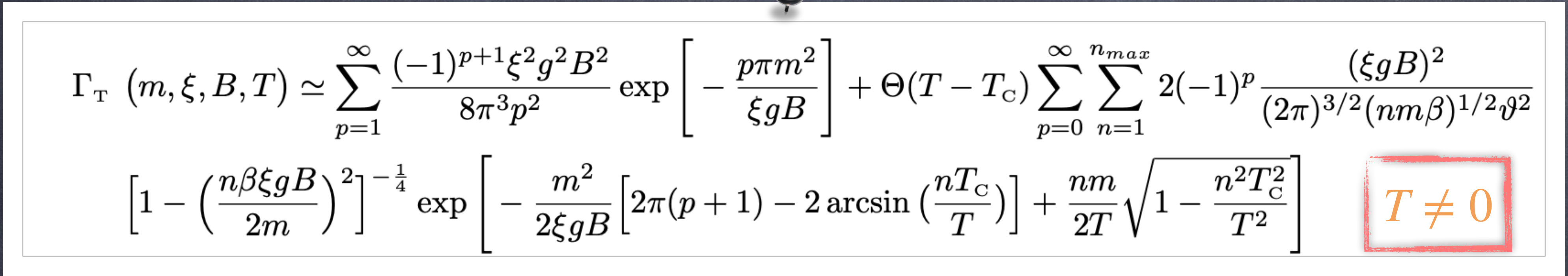
$\sim \quad 10^{11}\,\mathrm{K} \rightarrow 10^{6}\,\mathrm{K}$

over a few thousand years



[Shapiro & Teukolsky (1983), Vigano et. al. (2013),...]

Finite temperature Schwinger pair production



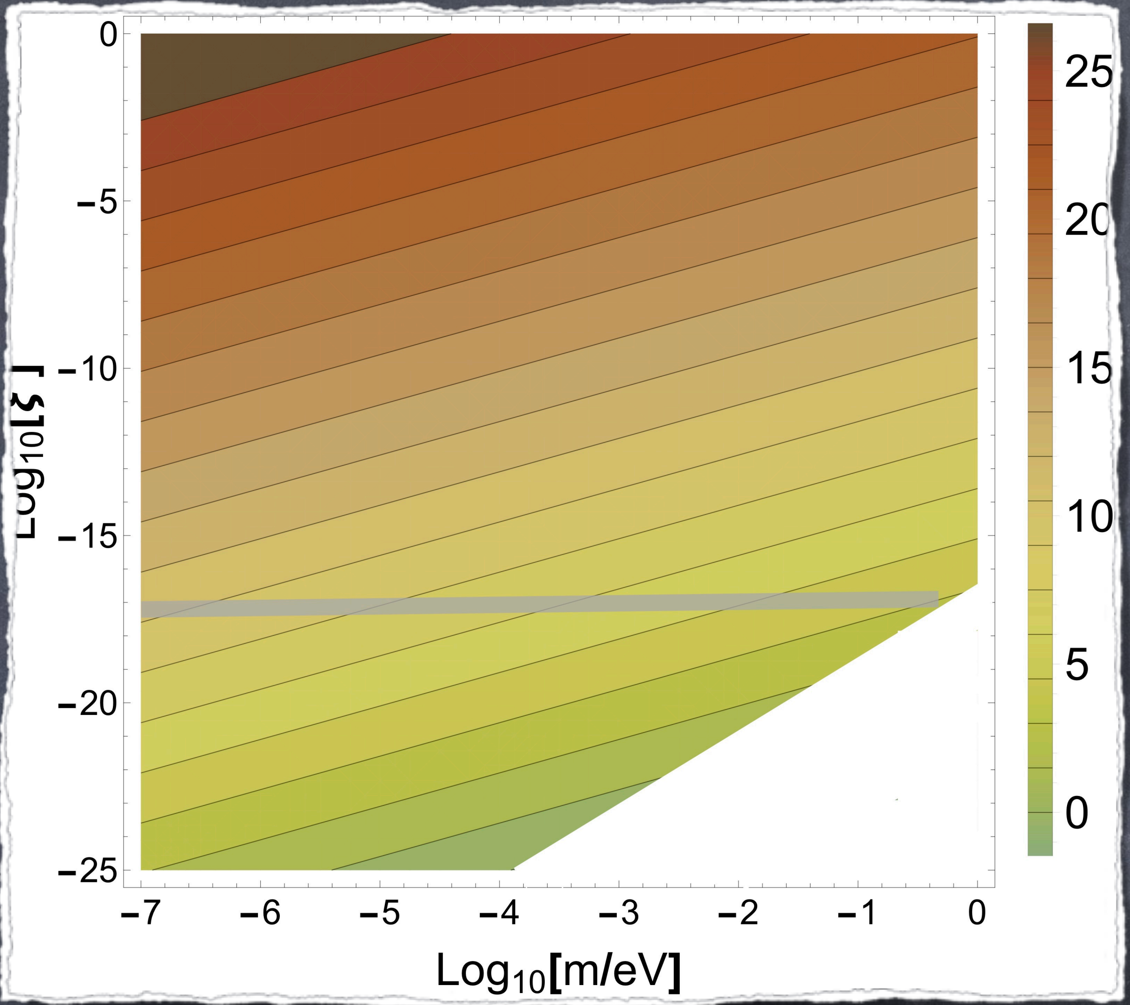
$$\Gamma_{\mathrm{T}}\,(m,\xi,B,T) \simeq \sum_{p=1}^{\infty} \frac{(-1)^{p+1}\xi^2 g^2 B^2}{8\pi^3 p^2} \exp\left[-\frac{p\pi m^2}{\xi g B}\right] + \Theta(T-T_{\mathrm{C}}) \sum_{p=0}^{\infty} \sum_{n=1}^{n_{max}} 2(-1)^p \frac{(\xi g B)^2}{(2\pi)^{3/2}(nm\beta)^{1/2}\vartheta^2}$$

$$\left[1-\left(\frac{n\beta\xi g B}{2m}\right)^2\right]^{-\frac{1}{4}} \exp\left[-\frac{m^2}{2\xi g B}\left[2\pi(p+1) - 2\arcsin\left(\frac{nT_{\mathrm{C}}}{T}\right)\right] + \frac{nm}{2T}\sqrt{1-\frac{n^2 T_{\mathrm{C}}^2}{T^2}}\right] \qquad \boxed{T \neq 0}$$

[Korwar & AT (2018)]

- Exponential enhancement compared to zero temperature
- Presence of a critical temperature below which thermal enhancements switch off.

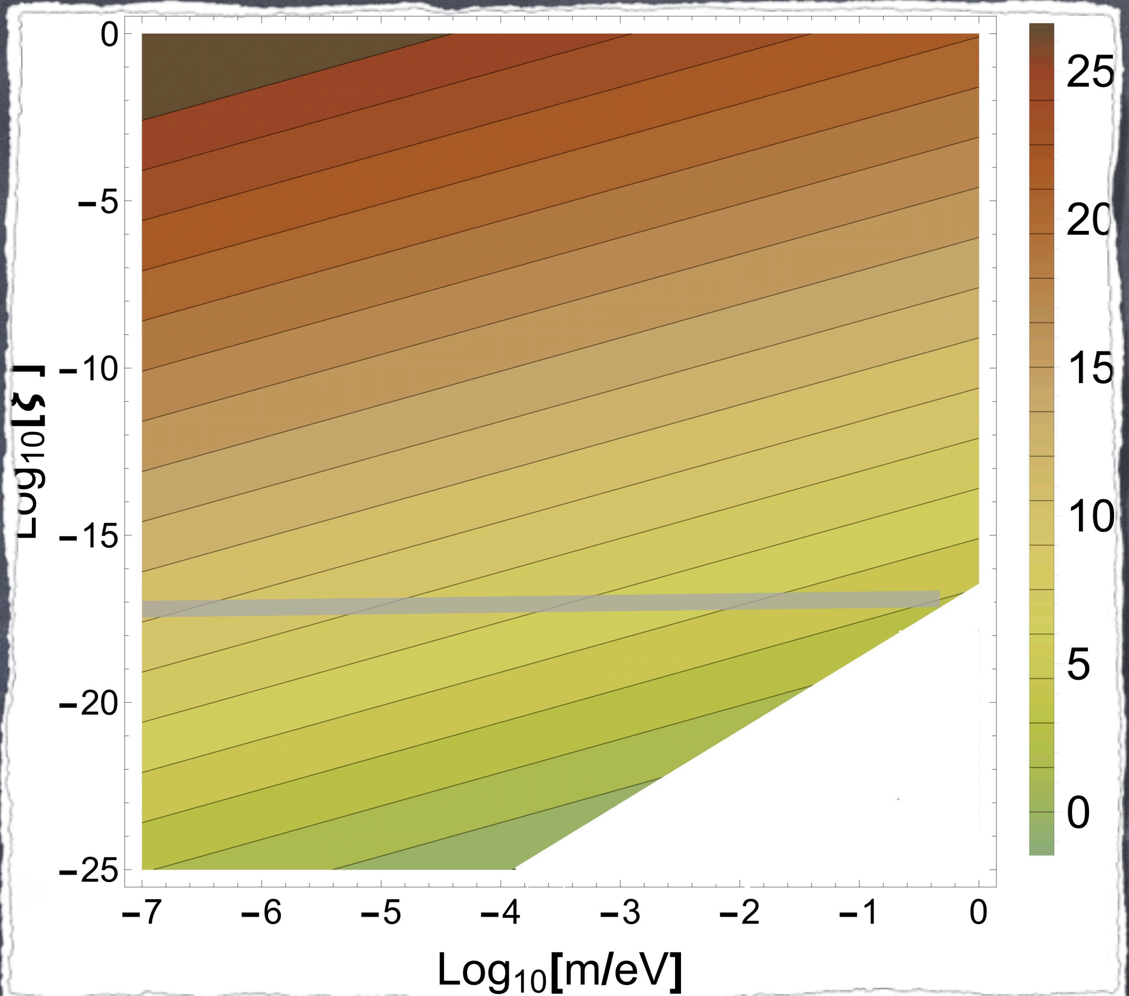
[Gies (1999), Brown (2015), Medina & Ogilvie (2017), Gould & Rajantie (2017), Korwar & AT (2018),...]



$$\boxed{T_C(m, \xi, B) \equiv \frac{\xi g B}{2m}}$$

[Chandra, Korwar & AT (2019)]

Possibility of abrupt changes as the neutron star cools in the early stages !



$$\boxed{T_C(m, \xi, B) \equiv \frac{\xi g B}{2m}}$$

[Chandra, Korwar & AT (2019)]

Continuous gravitational waves

$$h_{ij}^{TT} = \frac{1}{r}\hat{\Lambda}_{ij;kl}(\hat{n})\frac{2G}{c^4}\ddot{\mathcal{Q}}_{kl}\left(t - \frac{r}{c}\right)$$

$$\begin{aligned} h_+ &= h_0 \sin\alpha\left[\frac{1}{2}\cos\alpha\sin\theta\cos\theta\cos\Omega_{\rm NS}t_r - \sin\alpha\frac{1+\cos^2\theta}{2}\cos 2\Omega_{\rm NS}t_r\right] , \\ h_\times &= h_0 \sin\alpha\left[\frac{1}{2}\cos\alpha\sin\theta\sin\Omega_{\rm NS}t_r - \sin\alpha\cos\theta\sin 2\Omega_{\rm NS}t_r\right] . \end{aligned}$$

$$h_0 = -\frac{6G}{c^4}\tilde{\mathcal{Q}}_{33}\frac{\Omega_{\rm NS}^2}{r} .$$

[Ipser (1971), Thorne (1980),
Bonazzola & Gourgoulhon (1996)...]

Continuous gravitational waves

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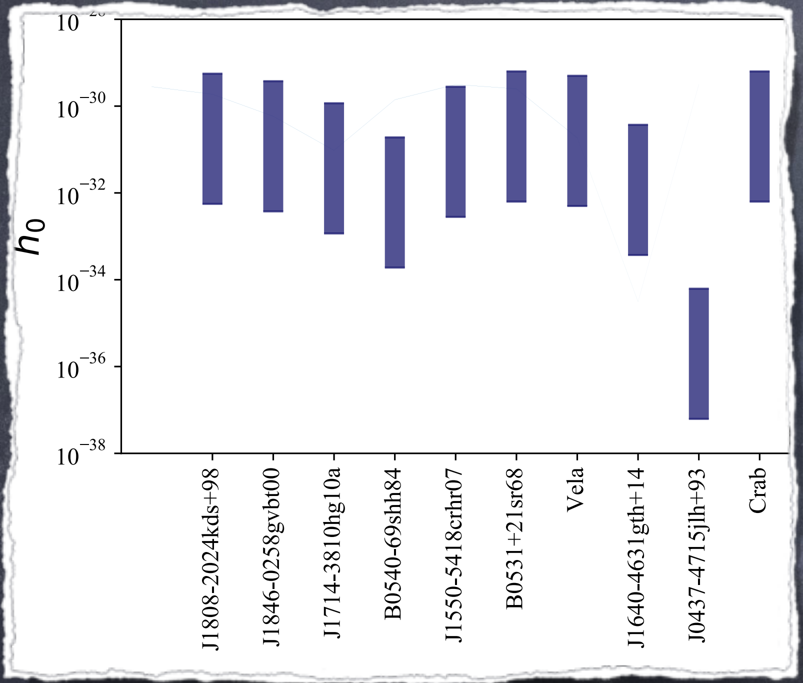
$$h_0 = -\frac{6G}{c^4}\tilde{\mathcal{Q}}_{33}\frac{\Omega_{\rm NS}^2}{r} .$$

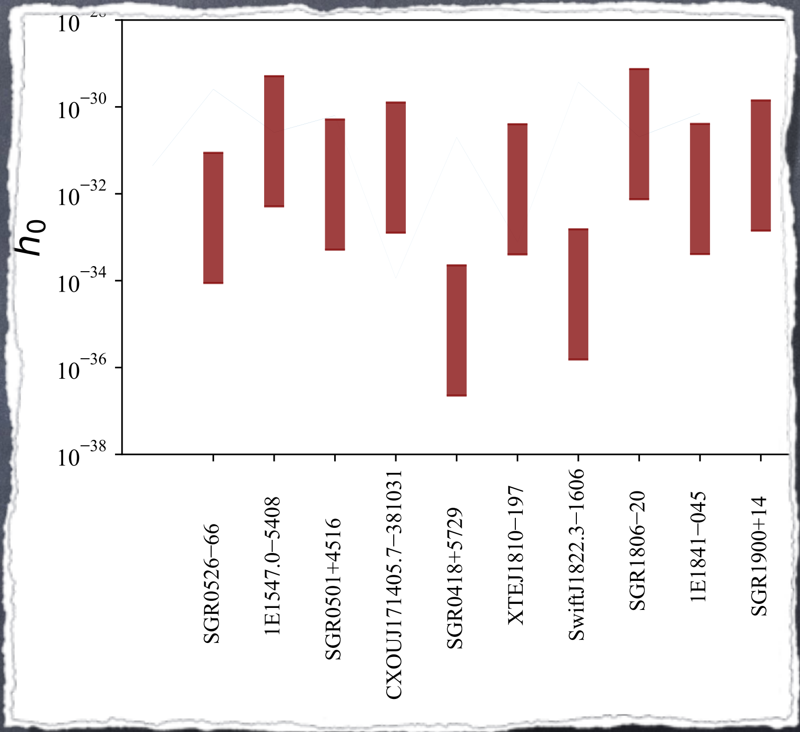
$$B^2 \propto \frac{P\dot{P}}{\sin^2\alpha}$$

[Ipser (1971), Thorne (1980),
Bonazzola & Gourgoulhon (1996)...]

$$h_0^{2\Omega_{\rm NS}} \simeq 10^{-31}\,\mathfrak{D}\left(\frac{R_{\rm NS}}{10\,{\rm km}}\right)^2\left(\frac{\rm kpc}{r}\right)\left(\frac{\rm s}{P}\right)\left(\frac{\dot P}{10^{-11}}\right)$$

[Chandra, Korwar & AT (2019)]





[ATNF pulsar Catalog (2005)]

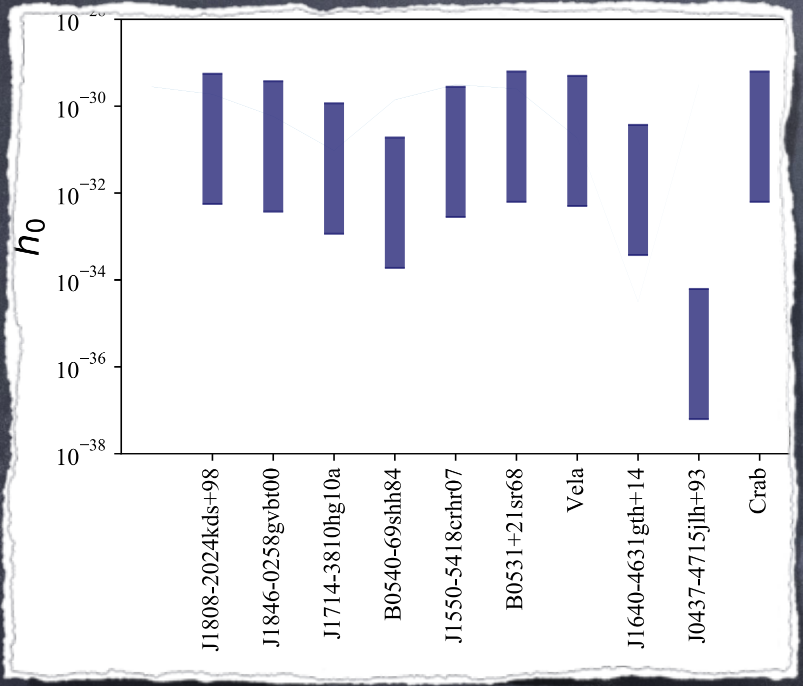
[McGill Magnetar Catalog (2016)]

$$h_0 \gtrsim 10^{-26} - 10^{-27}\,,\quad [10\,Hz,\ 100\,Hz] \qquad [LIGO/VIRGO]$$

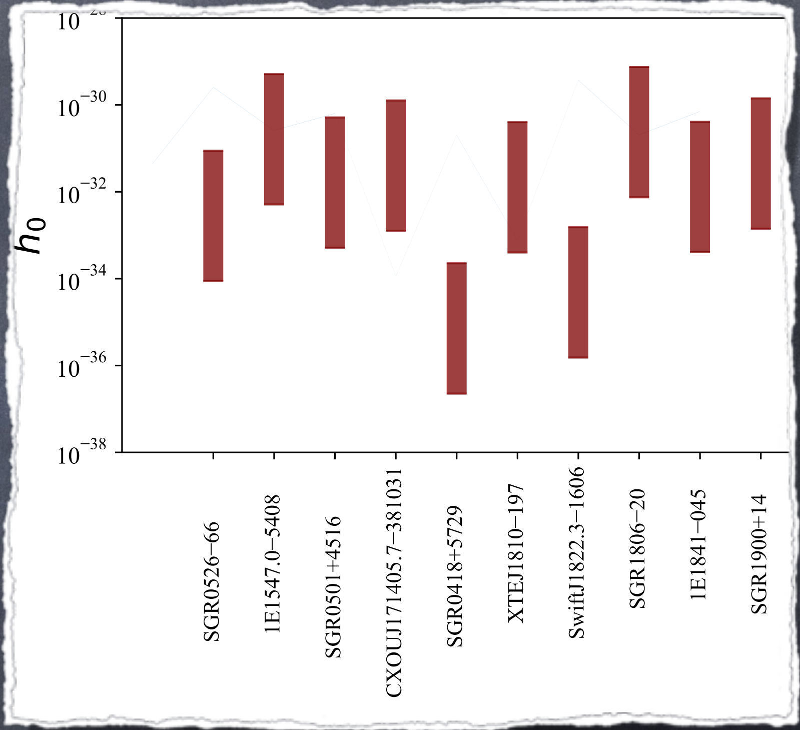
$$h_0 \gtrsim 10^{-24} - 10^{-26}\,,\quad [10\,Hz,\ 100\,Hz] \qquad [ET]$$

$$h_0^{2\Omega_{\rm NS}} \simeq 10^{-31}\,\mathfrak{D}\left(\frac{R_{\rm NS}}{10\,{\rm km}}\right)^2\left(\frac{\rm kpc}{r}\right)\left(\frac{\rm s}{P}\right)\left(\frac{\dot P}{10^{-11}}\right)$$

[Chandra, Korwar & AT (2019)]



[ATNF pulsar Catalog (2005)]



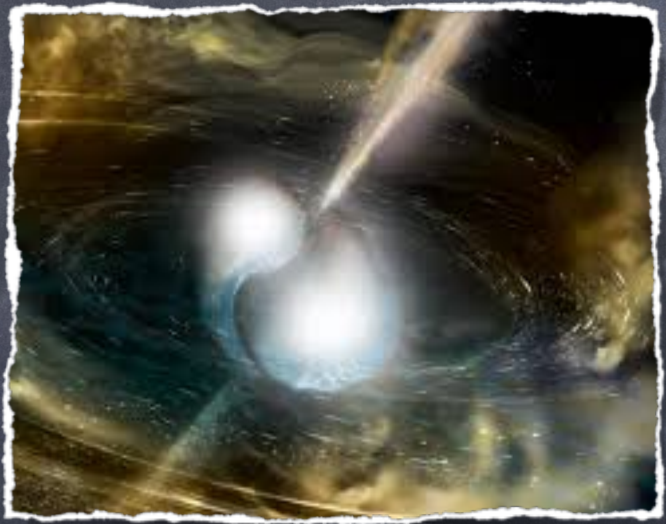
[McGill Magnetar Catalog (2016)]

Very low !

$h_0 \gtrsim 10^{-26} - 10^{-27}$, $[10\,Hz,\ 100\,Hz]$ [LIGO/VIRGO]

$h_0 \gtrsim 10^{-24} - 10^{-26}$, $[10\,Hz,\ 100\,Hz]$ [ET]

Millisecond Magnetars



Very small time periods

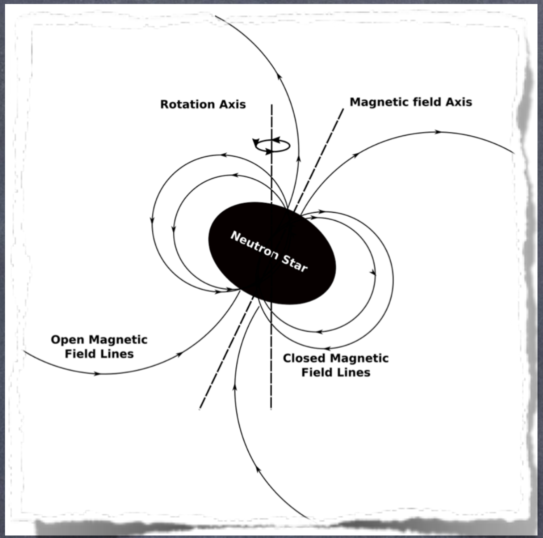
&

extremely large Magnetic fields

$P_0 \sim \mathcal{O}(1)\,\mathrm{ms}$ $B_0 \sim 10^{16}\,\mathrm{G}$

[Dai et. al. (1998), Metzger et. al. (2011) Rowlinson et. al. (2013),...]

Neutron star magnetic field and spin-down evolution

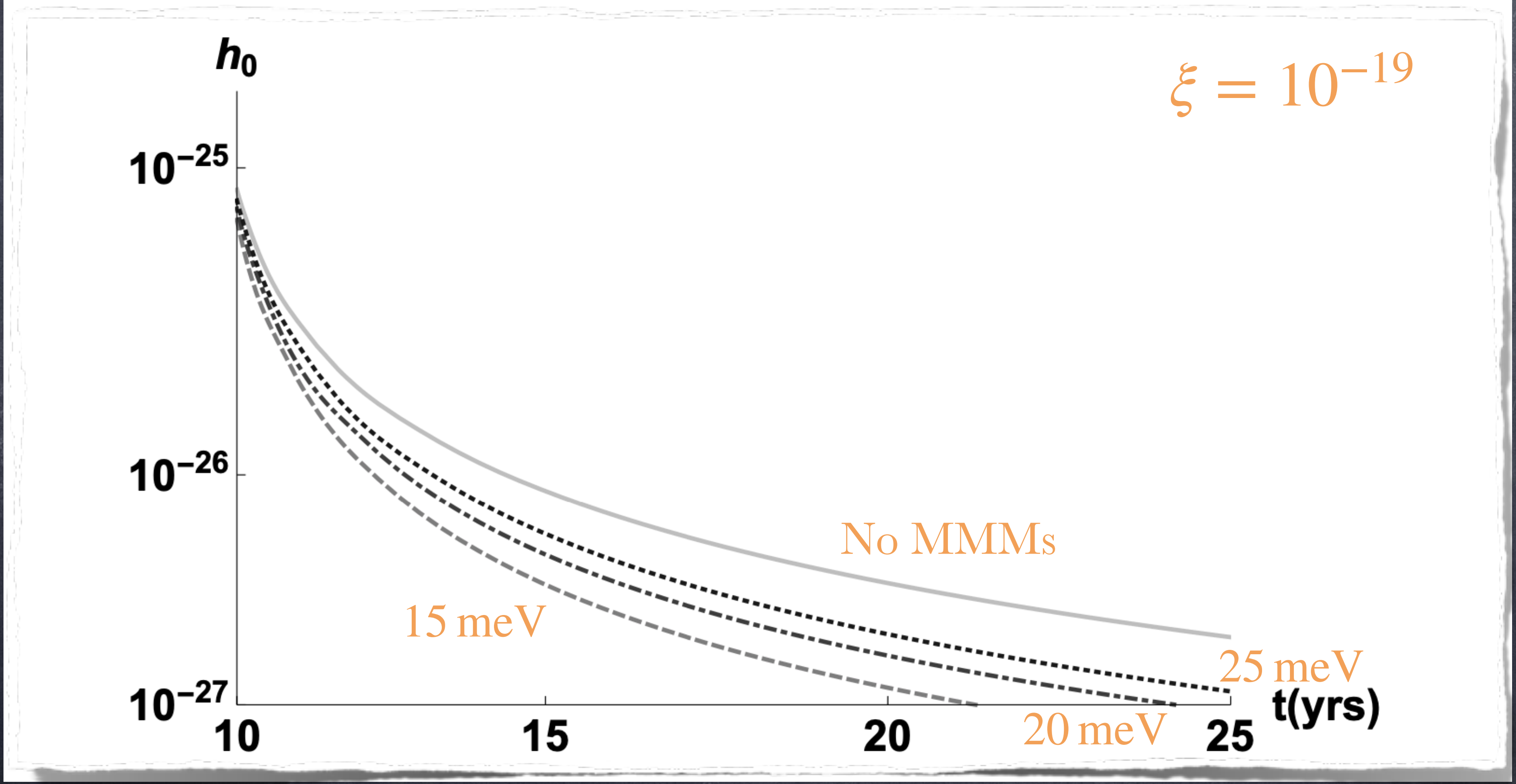


$$\frac{d\Omega_{\rm NS}(t)}{dt} \simeq -\frac{5}{12}\frac{R_{\rm NS}^4}{M_{\rm NS}} B_{\rm NS}^2(t)\Omega_{\rm NS}^3(t) - \frac{64}{25} G M_{\rm NS} R_{\rm NS}^2 \tilde{\varepsilon}_{\rm Q}^2(t)\Omega_{\rm NS}^5(t)$$

$$\frac{dB_{\rm NS}(t)}{dt} \simeq \frac{B_{\rm NS}(t)}{\tau_{\rm dyn.}} e^{-t/\tau_{\rm dyn.}} - \frac{B_{\rm NS}(t)}{\tau_{\rm ohm}} - \frac{B_{\rm NS}^2(t)}{B_{\rm NS}(0)\tau_{\rm hall}} - \frac{2\xi g\, l\, V_m}{R_{\rm NS}^3}\,\Gamma_{\rm T}\big(m, \xi, B_{\rm NS}(t), T(t)\big)$$

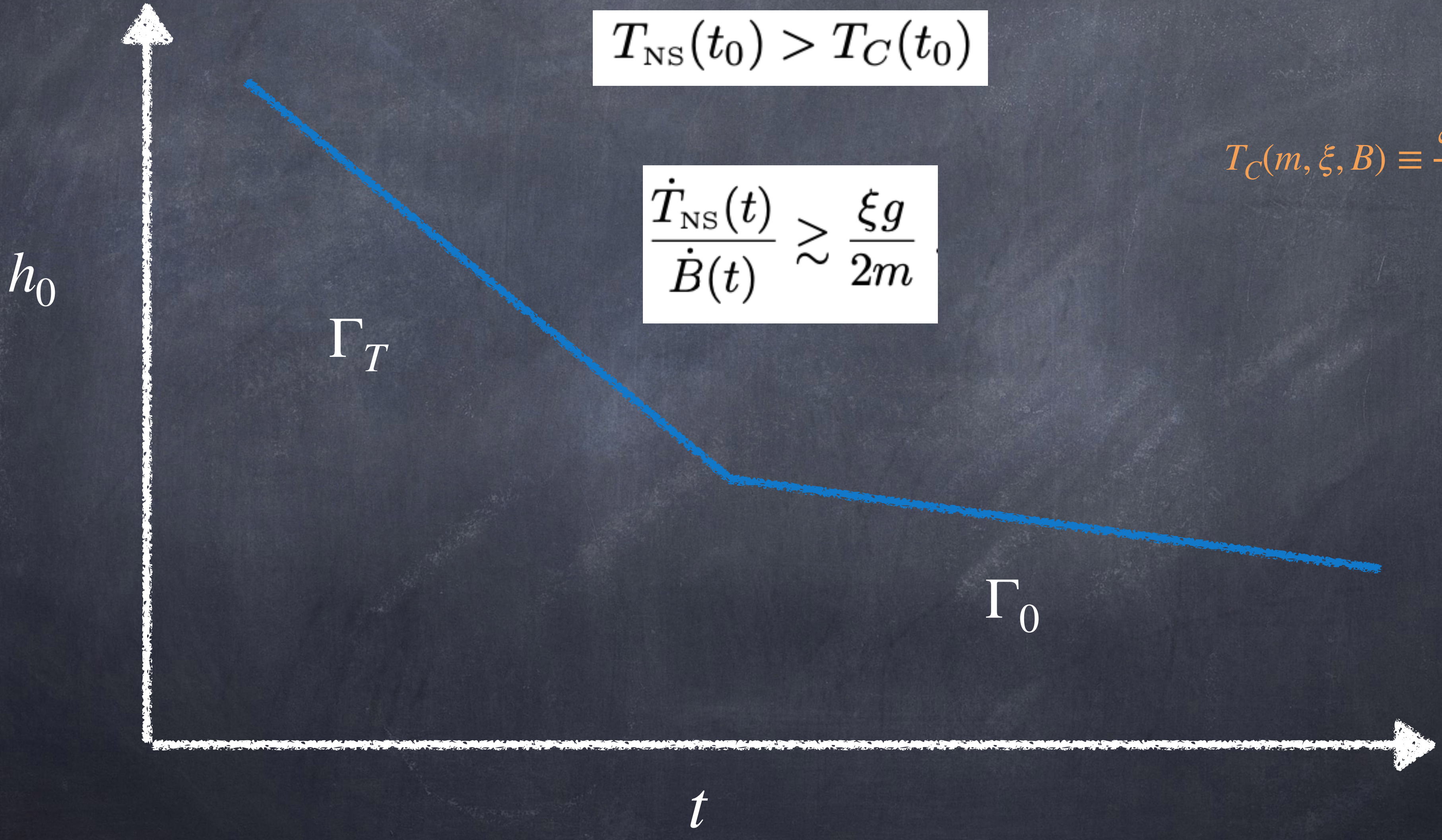
[Chandra, Korwar & AT (2019)]

Millisecond Magnetar early stage continuous GWs with MMMs



[Chandra, Korwar & AT (2019)]

Millisecond Magnetar early stage continuous GWs with MMMs



$$T_{\rm NS}(t_0) > T_C(t_0)$$

$$\frac{\dot{T}_{\rm NS}(t)}{\dot{B}(t)} \gtrsim \frac{\xi g}{2m}$$

$$T_C(m, \xi, B) \equiv \frac{\xi g B}{2m}$$

Summary

- The extreme environments in compact stellar objects, such as neutron stars, provide avenues for testing novel effects inaccessible to terrestrial experiments, as well as putting limits on new physics.

- Energetic, magnetic & spin-down evolution in Magnetars, for instance, may place novel, non-trivial constraints on milli electrically charged particles via their non-perturbative production.

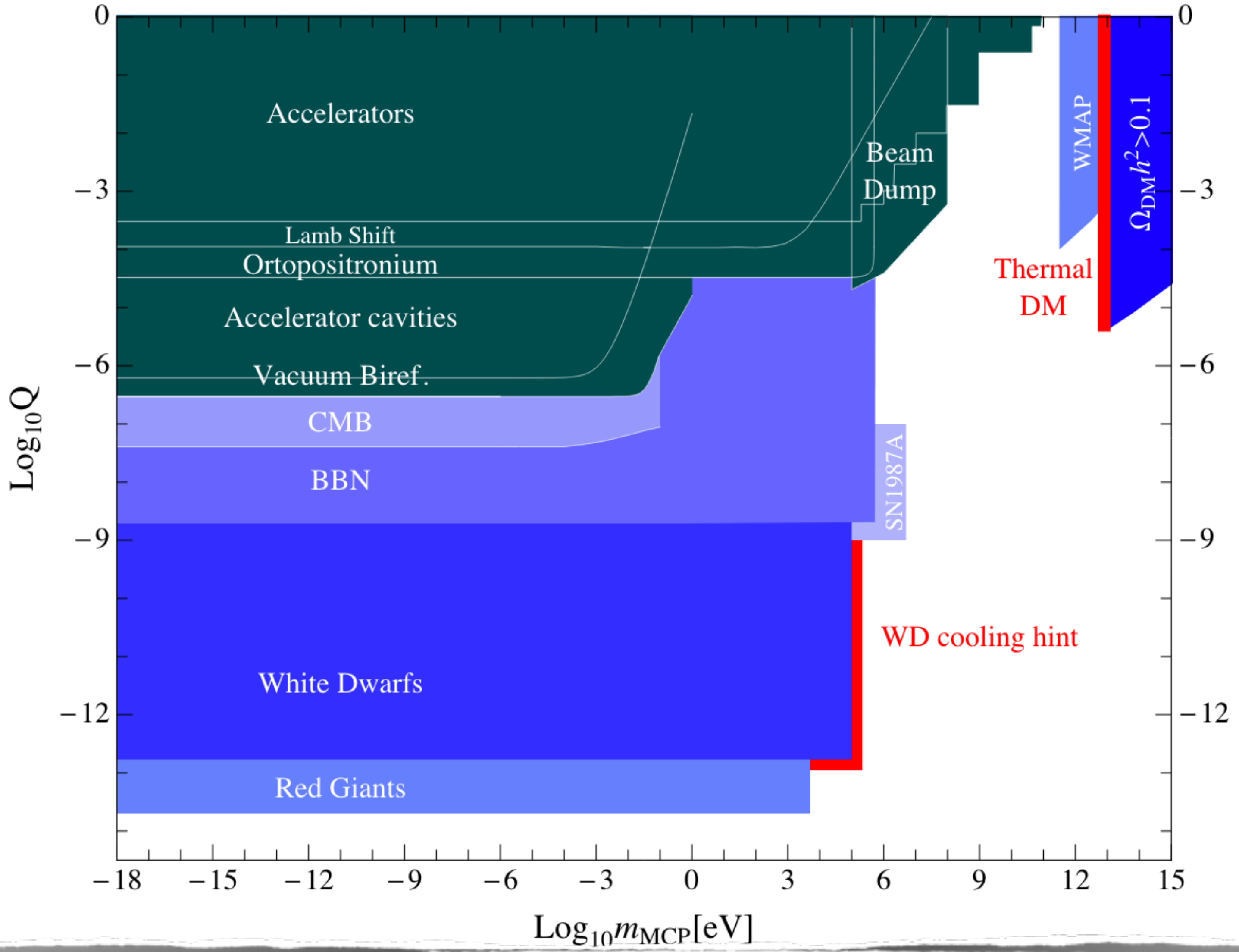
- Energetic arguments place stringent limits on milli magnetic monopoles, as well.

- Non perturbative production of milli magnetic monopoles in neutron stars could alter the evolution of the magnetic-field-induced quadrupole moments.

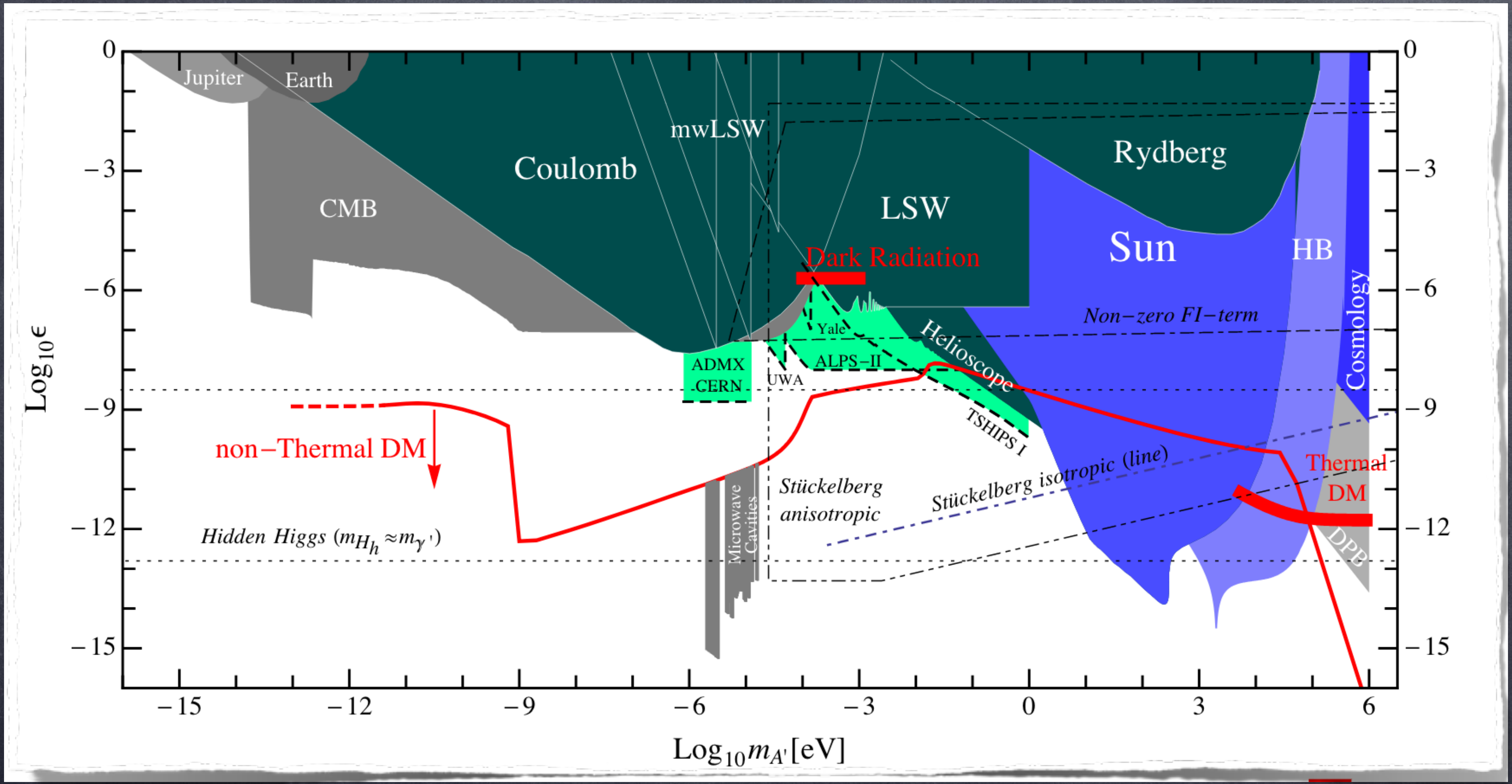
- Early stage continuous gravitational waves from millisecond Magnetars therefore may contain characteristic imprints, distinct from conventional astrophysical ones, that will be signatures for these exotic states.

Thank you.

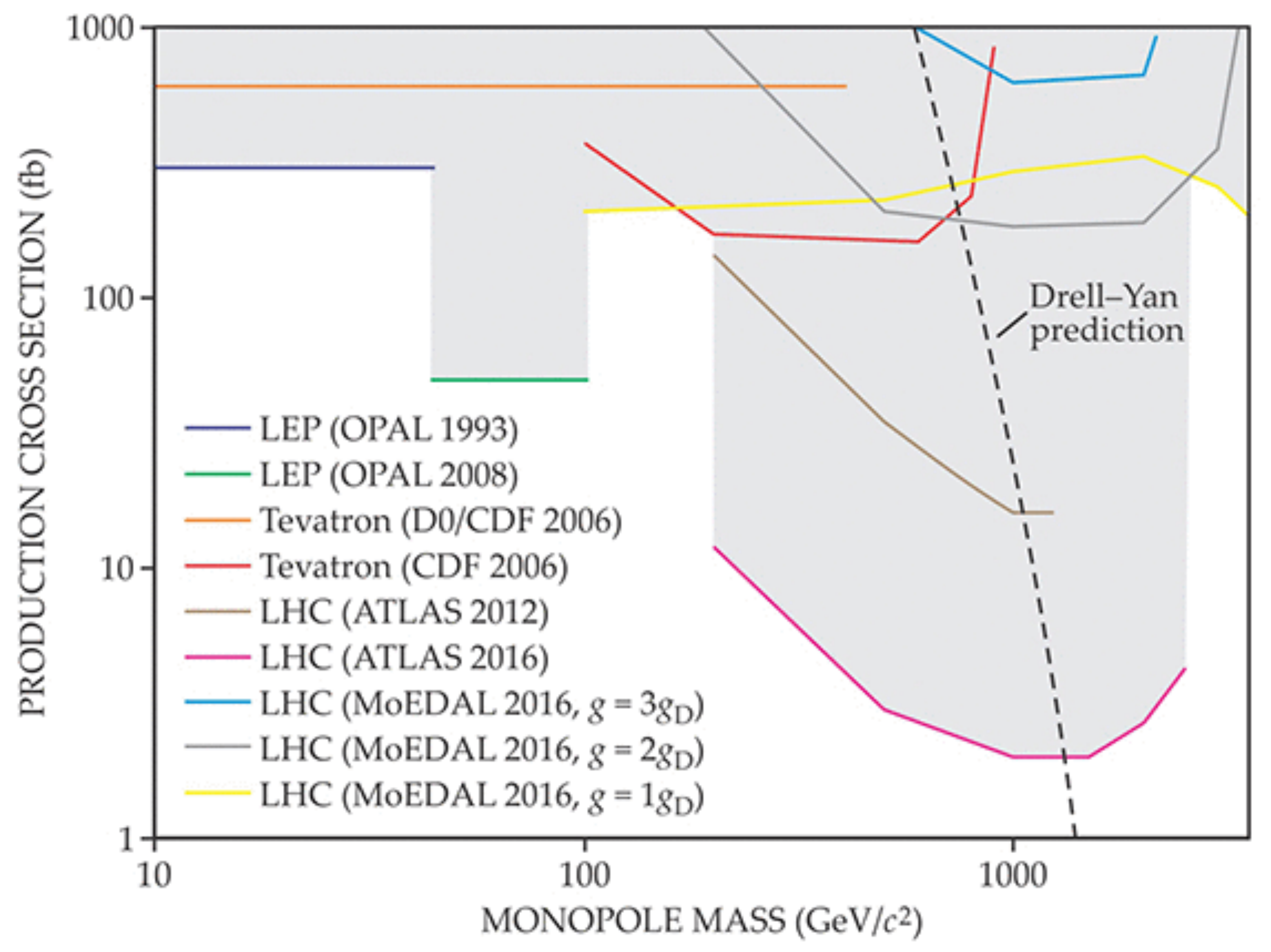
Backup slides



[Snowmass (2013)]



[Snowmass (2013)]


1000
100
10
1
PRODUCTION CROSS SECTION (fb)
10
100
1000
MONOPOLE MASS (GeV/c²)
Drell–Yan prediction
LEP (OPAL 1993)
LEP (OPAL 2008)
Tevatron (D0/CDF 2006)
Tevatron (CDF 2006)
LHC (ATLAS 2012)
LHC (ATLAS 2016)
LHC (MoEDAL 2016, g = 3g_D)
LHC (MoEDAL 2016, g = 2g_D)
LHC (MoEDAL 2016, g = 1g_D)