# マグネター磁場の長期時間変動
# Long term evolution of magnetar field


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広島大学 極限宇宙研究拠点
CORE-U
Core of Research for the Energetic Universe
HIROSHIMA UNIVERSITY

# Magnetic field evolution of an isolated NS ?

Weak fields in an accreting binary system

⇒ MS pulsars

Evolution of order 10^6-10^8 years

One of unsolved issues for a single NS

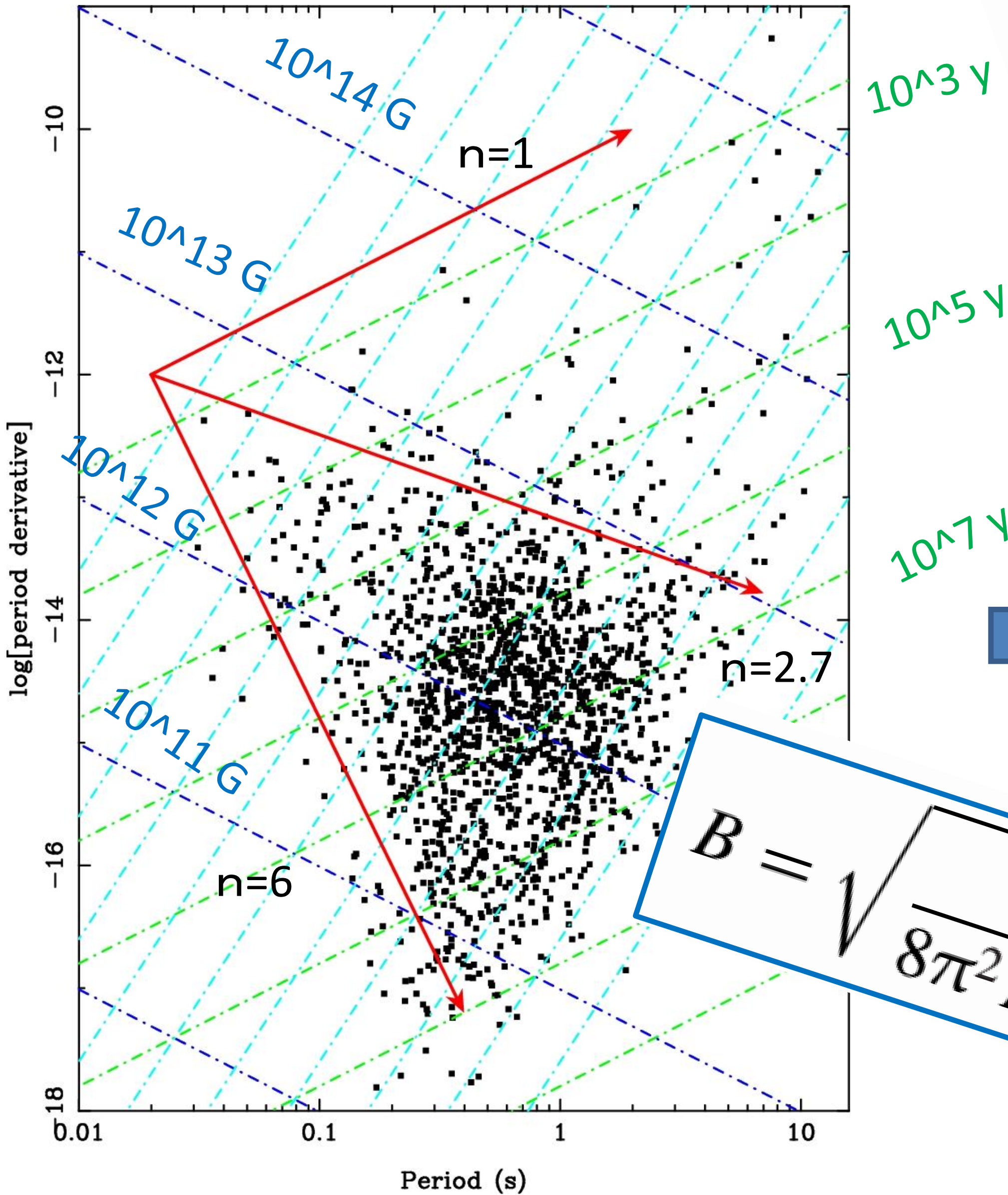
No definite observation

Statistical argument/ model simulation

-> yes/no : No consensus

# Pulsar braking and the *P*–Pdot diagram
# Johnston+ MNRAS, Volume 467, 1 2017

$$\tau_c = \frac{P}{2\dot{P}}.$$




$$\dot{\nu} = -K\nu^n$$

magnetic field decay?

→ decay of
the inclination angle
**(Johnston+2017MN)**

$$B = \sqrt{\frac{3c^3 I}{8\pi^2 R^6 \sin^2\alpha} P\dot{P}},$$

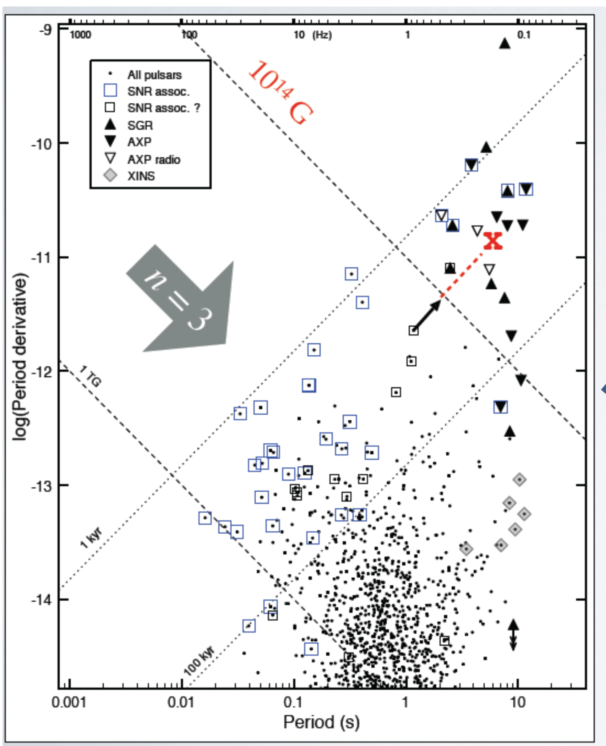
# braking indices (second derivative)

# magnetic dipole radiation $n = 3$

**Exceptions?**

Only for 8 PSRs

PSRJ1734-3333 $B_d = 5E13$




Espinoza+ 2011

$$n = 0.9 \pm 0.2$$

Magnetar in $\tau = 2.9 \times 10^4\, yrs$

PSR J1846-0258 $B_d = 5E13$

Index change after outburst

$$n = 2.65 \rightarrow 2.19$$

Archibald+ 2015

# Evolution of magnetar field

Magnetars only

(Strong B > $10^{14}$ G

Young< $10^4 - 10^5$ yrs)

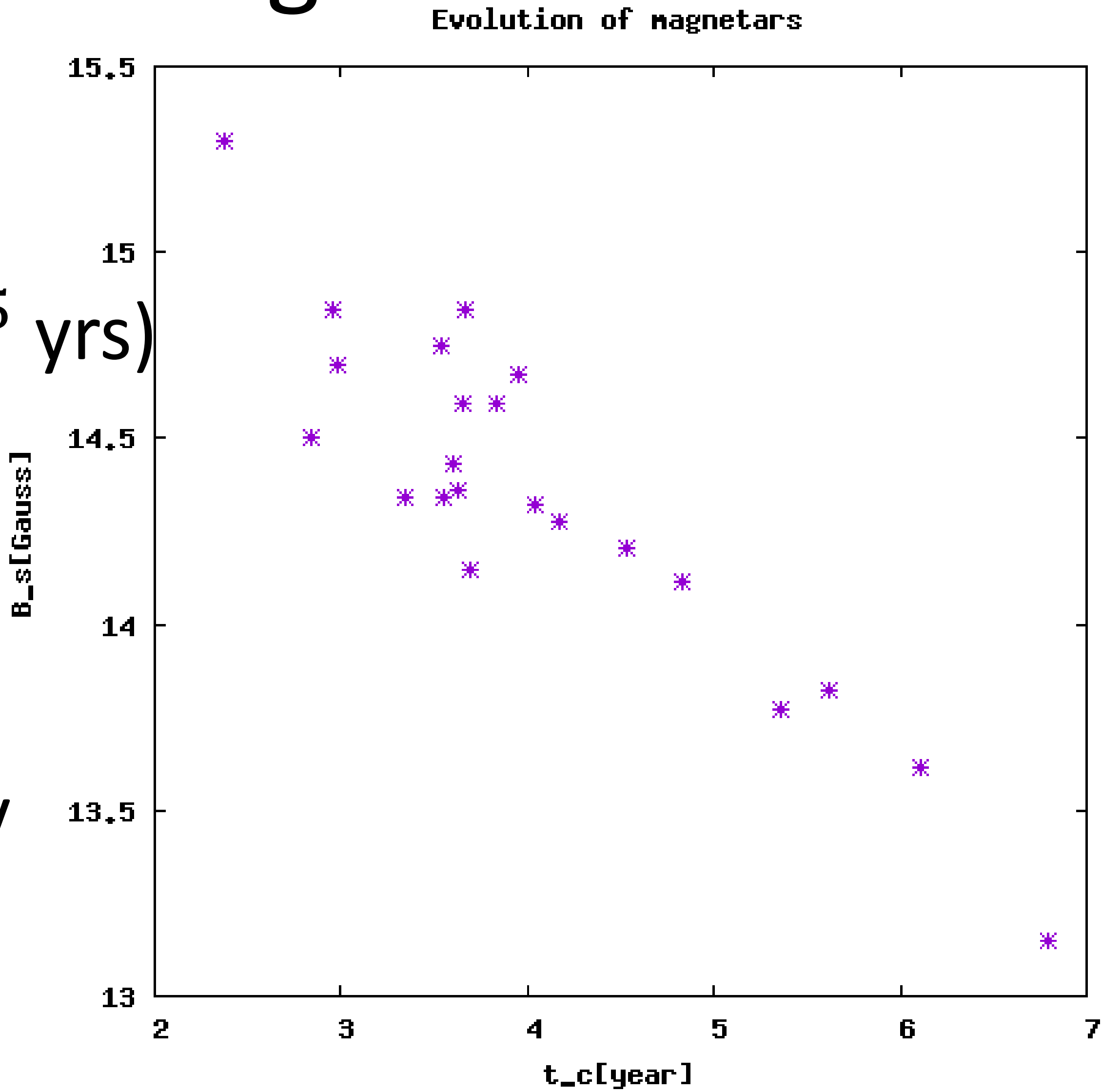
Energy supply

B= $10^{14}$ in $10^4$ ys

L= $10^{47} erg \ /10^4$ y

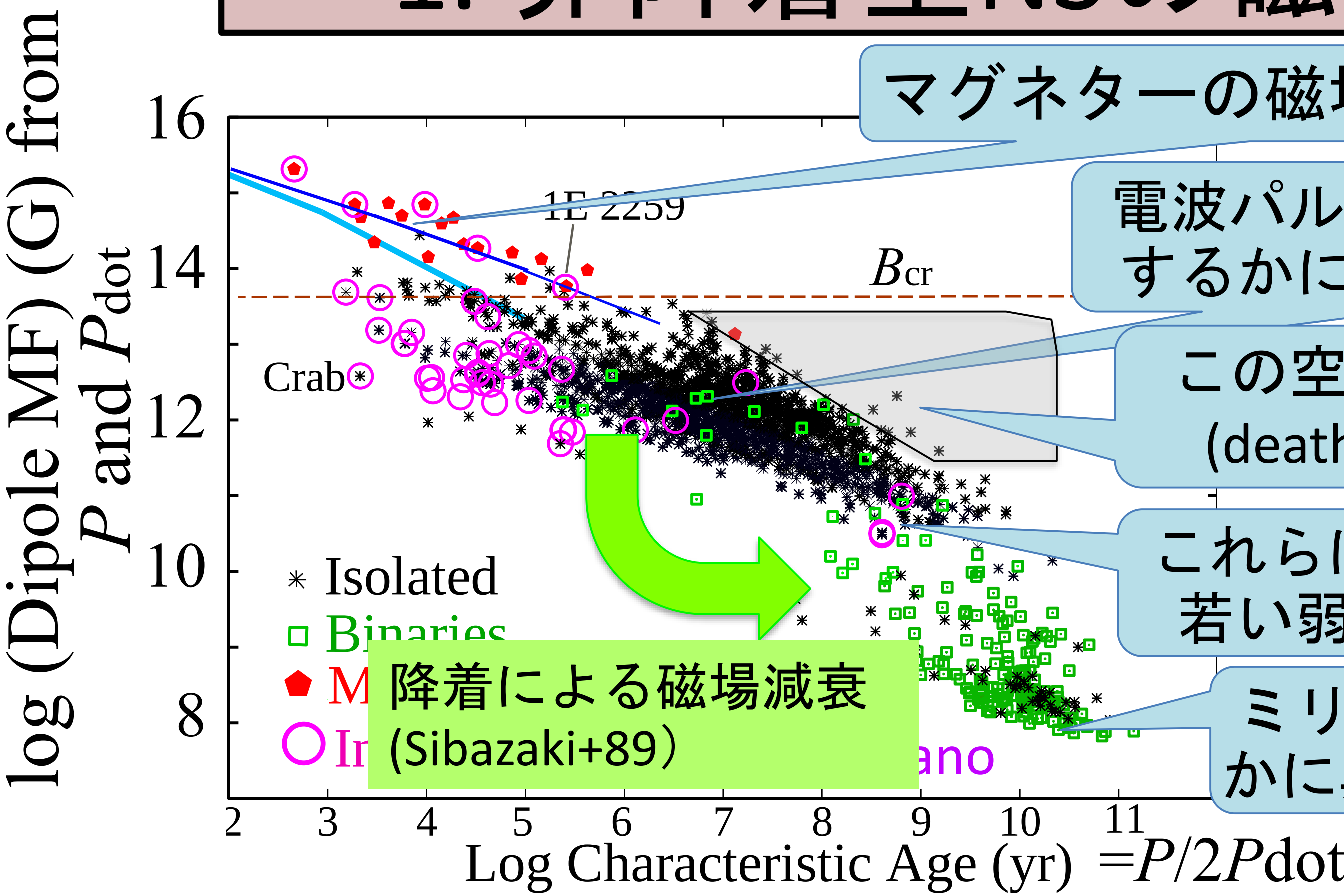
= $10^{36} erg$ /s

$> L_{Rot}$




See also Beloborodov & Li (2016) ApJ for heating mechanism

# 1. 非降着型NSの磁場




マグネターの磁場は減衰する。

電波パルサーの磁場も減衰するかに見える、しかし…

この空隙は、選択効果 (death line) のため。

これらは実は極めて若い弱磁場のNS。

ミリ秒パルサーは明らかに異なる集団を形成。

降着による磁場減衰 (Sibazaki+89）

NSの磁場は、永久電流が担うのではなく、中性子のスピン整列による核物質強磁性の結果か。誕生時の微小な質量差などで強磁性と常磁性が分かれ、強磁性相もある時点で常磁性に相転移するのでは (Makishima+99, Makishima 03,16)。

# Evolution of magnetar field

Working hypothesis

Evolution only for strong field (>$10^{14}$ G )

& young (< 10 thousand years) regimes

I think two important keys, strong B & short T

Strong B

-> Nonlinear effect of B

ambipolar diffusion in core/Hall drift in crust

Only for young age

-> Thermal history/cooling NS

Magnetic field is fixed, when dominated

# Energetics for a magnetar

Order-of-magnitude estimate $B = 10^{15}G \propto (P\dot{P})^{1/2}$

$$\vec{j} \times \vec{B} - \nabla p - \rho \nabla \Phi = f_s + \rho v \nabla v$$

$E_{mag} \approx 10^{47} (B_{15})^2, E_{gr} \approx 10^{53}, E_{rot} \approx 10^{45}$ ergs

$E_T \approx 10^{47} \ (T_{c\,9})^2$(@t=kyrs) ergs

Stellar structure determined by gravity and degenerate pressure

$$\varepsilon \approx E_{mag} / E_{gr} \approx 5 \times 10^{-6} (B_{15})^2$$

Small (non-spherical) irregularity

Barotrope $p = p(\rho)$ is good approximation, but is not exact

Initial magnetic field structure is never 'ground state'

# Some recent works

- Core

Beloborodov & Li (2016) ApJ

Passamonti + (2017)MNRAS

Gusakov+ (2017,18) MNRAS,PRD

- Crust

-> coupling to magnetosphere

Akgun + (2017,18) MNRAS

- Magnetosphere

Glampedakis+(2014) Fujisawa&Kisaka(2014),Pili+(2015-), …

YK+(2017,2018) MNRAS

# n-p-e system in core

- Creation/dissipation of current by non-equilibrium beta-process

$$n \rightarrow p + e + v$$
$$p + e \rightarrow n + v$$

$$\nabla(n_k v_k) = 0 \quad \rightarrow \quad \nabla(n_k v_k v) = \gamma_k$$

$$\nabla(\sum e_k n_k v_k) = 0 \quad \rightarrow \nabla(\sum e_k n_k v_k) \neq 0$$

Evolution

$$\partial_t B = -\nabla \times E$$

$$E = -v \times B + j \times B/en_e + \sigma^{-1} j + \mathrm{k}\underline{\nabla \delta \mu_n} \times B - \nabla \delta \mu_e /e$$

$\propto v\_n - v\_p$

Multi-components + multi-dimensions are important

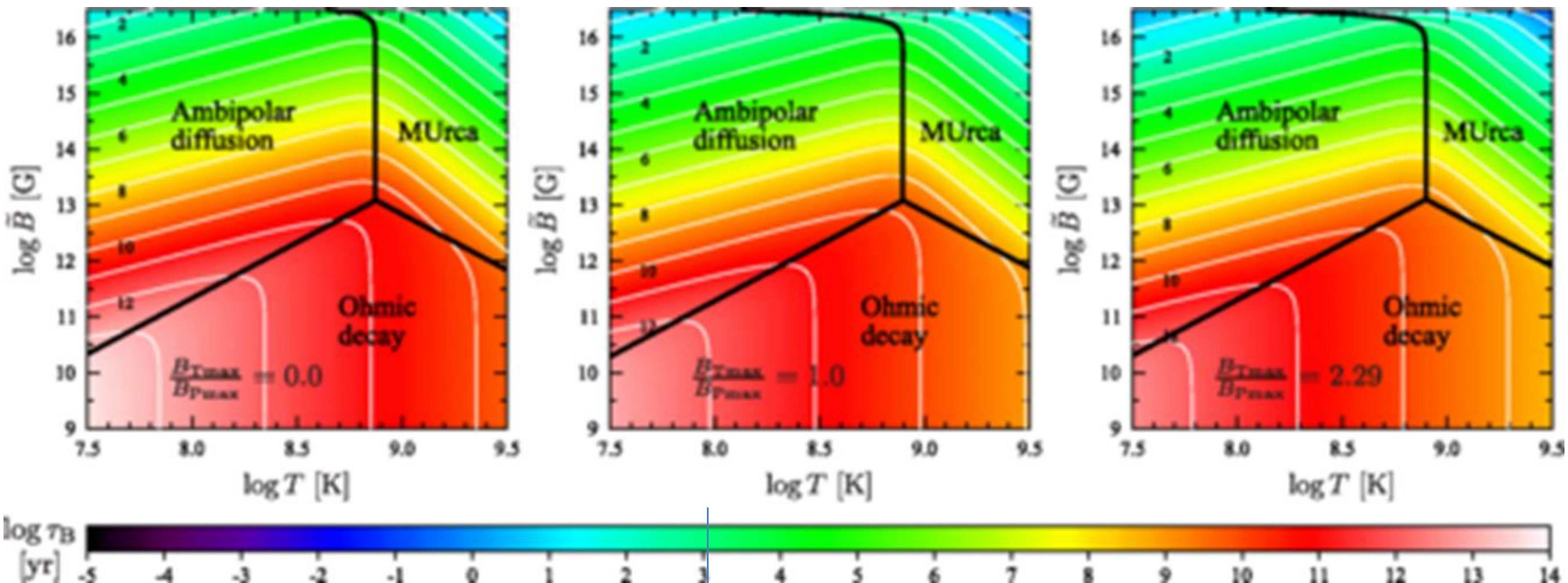
not 'grad' but 'rot (cur)' fields

+ super-fluid

# Decay time scale of magnetic fields in core　I

M. E. Gusakov, E. M. Kantor, and D. D. Ofengeim

Phys. Rev. D **96**, 103012




T<1kys

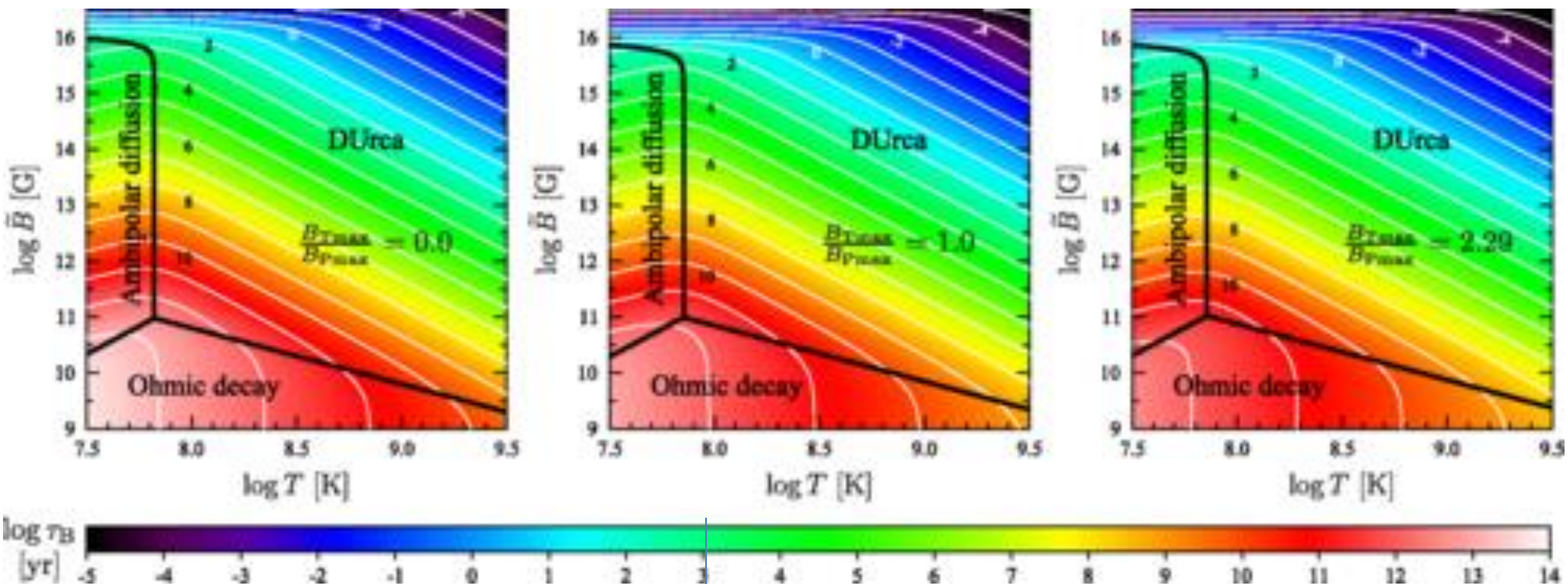
Modified URCA

$$n + n \rightarrow n + p + e + v$$
$$n + p + e \rightarrow n + n + v$$

# Decay time scale of magnetic fields in core II

M. E. Gusakov, E. M. Kantor, and D. D. Ofengeim

Phys. Rev. D **96**, 103012




T<1kys

Direct URCA

$$n \to p + e + \nu$$
$$p + e \to n + \nu$$

# Comment

- Timescale of B field evolution estimated

  1-10 kyr

?Hopefully  mass of magnetar by evolution

✓Depending on initial configuration(irregularity)

-> ambiguity

✓Long-term simulation for multi-components in 2 or 3D space

# Magnetic field evolution in crust by Hall effect

In dynamical timescale

=>MHD equilibrium (n,p)

$$\vec{j} \times \vec{B} - \nabla p - \rho \nabla \Phi = 0$$

Not Hall equilibrium (e)

$$\varepsilon \approx 10^{-6} B_{15}^2$$
$$\approx B^2 / p \approx (t_{dyn} / t_{Alf})^2$$

$$\vec{v}_e = -\vec{j} / (en_e), \partial_t \vec{B} = \nabla \times (\vec{v}_e \times \vec{B})$$

$$\partial_t \vec{B} = -\nabla (en_e)^{-1} \times \nabla p - \nabla (\rho / en_e) \times \nabla \Phi \underline{\neq 0}$$

Evolution of magnetic field in a longer timescale

$$\tau_H = 4\pi en_e L^2 / cB_0 \approx 10^3 (L_{0.1km})^2 (B_{15})^{-1} yrs$$

Important for strong B and in small scale

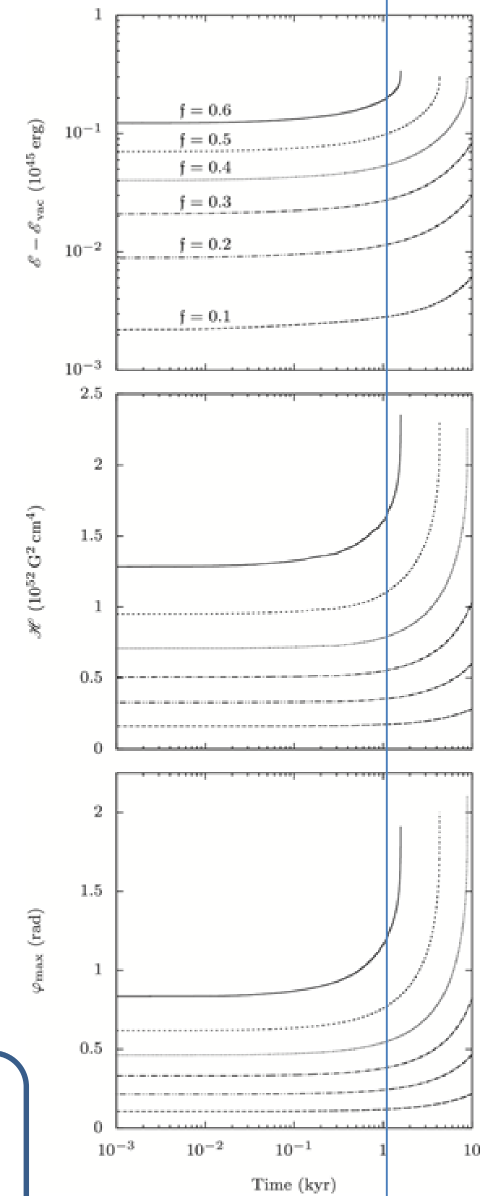
Models Virgono + 2012,Gourgouliatos + 2014, Y.K.+2012,...

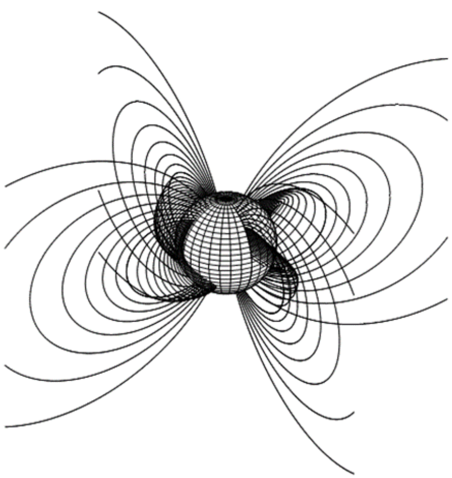
# Coupling between crust and magnetosphere

Long-term evolution of the force-free twisted magnetosphere of a magnetar

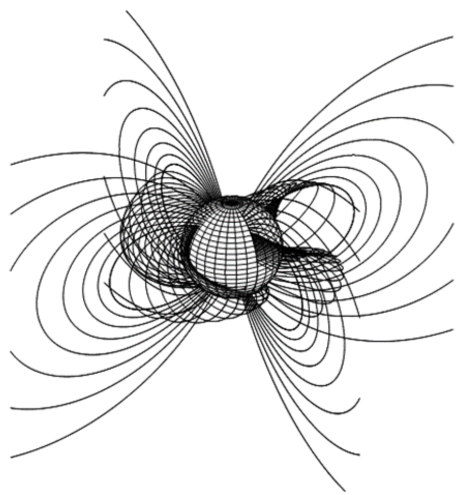
Akgun + Mon Not R Astron Soc. 2017;472

1 k yrs

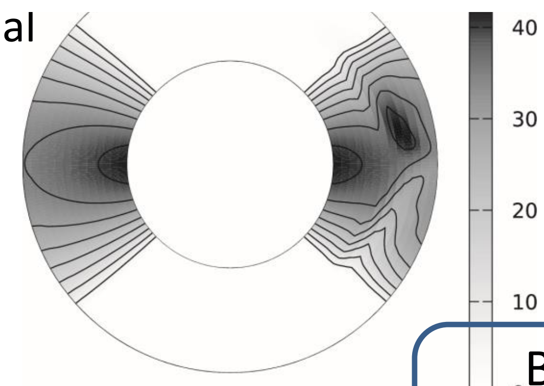


Initial



10^3 yrs




Crust enlarged for display

Burst/Flare

$\Delta E \approx 0.4 \times E_{ms,14}$

$\approx 10^{44} erg$

# Comment

- ? Explosion at 1kyrs

  E=10^44 ergs @Bs=10^14G

- Or breakdown of the model

Burst/Flare

$\Delta E \approx 0.4\times E_{ms,14}$

$\approx 10^{44} erg$

?BC at interface

?Initial model

?...

Wrong estimate

Theoretically Impossible

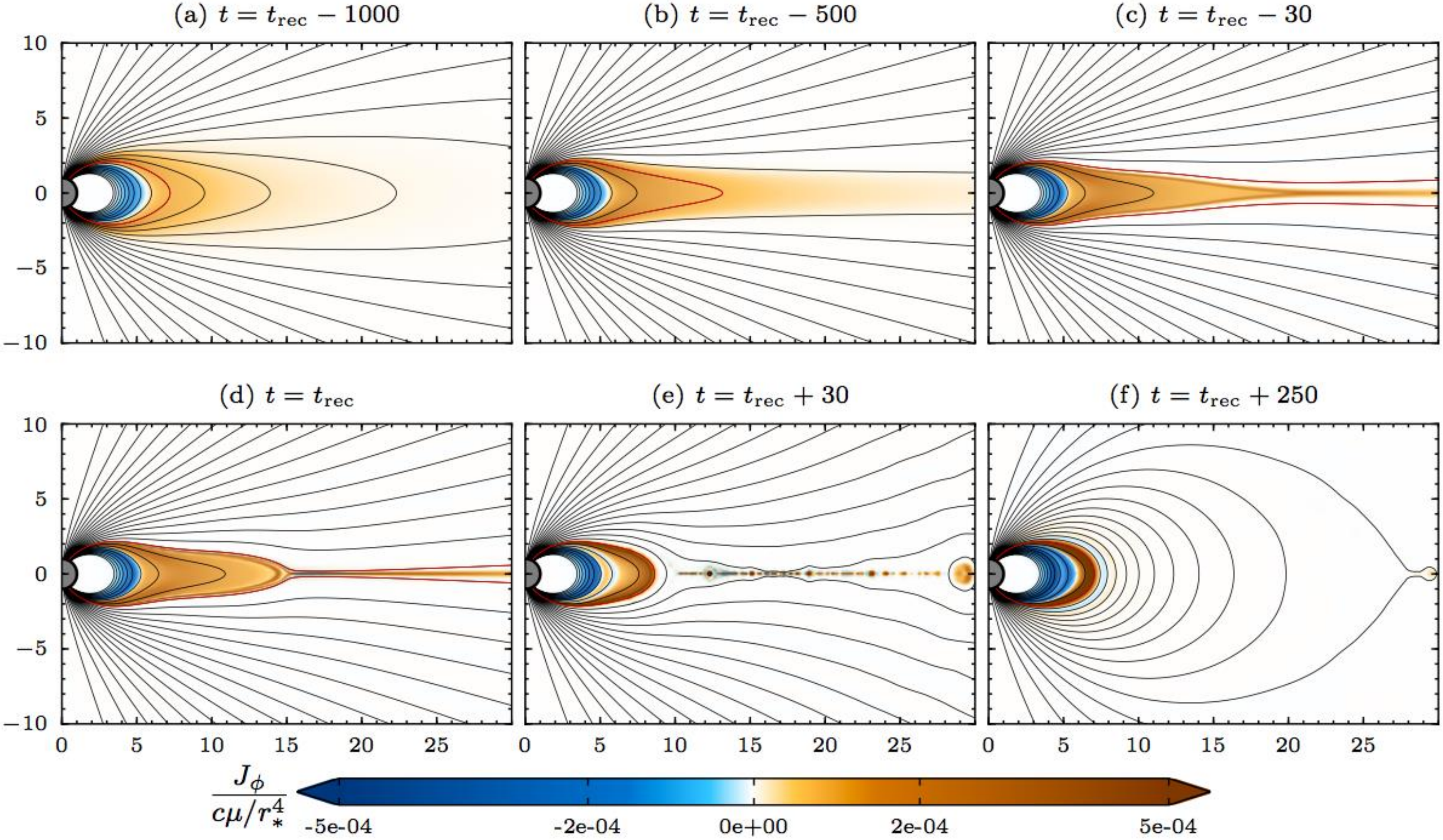
$$\Delta E = E_{max} - E_{vac}$$

Open field for $\frac{\Delta E}{E_{vac}}$ >0.66

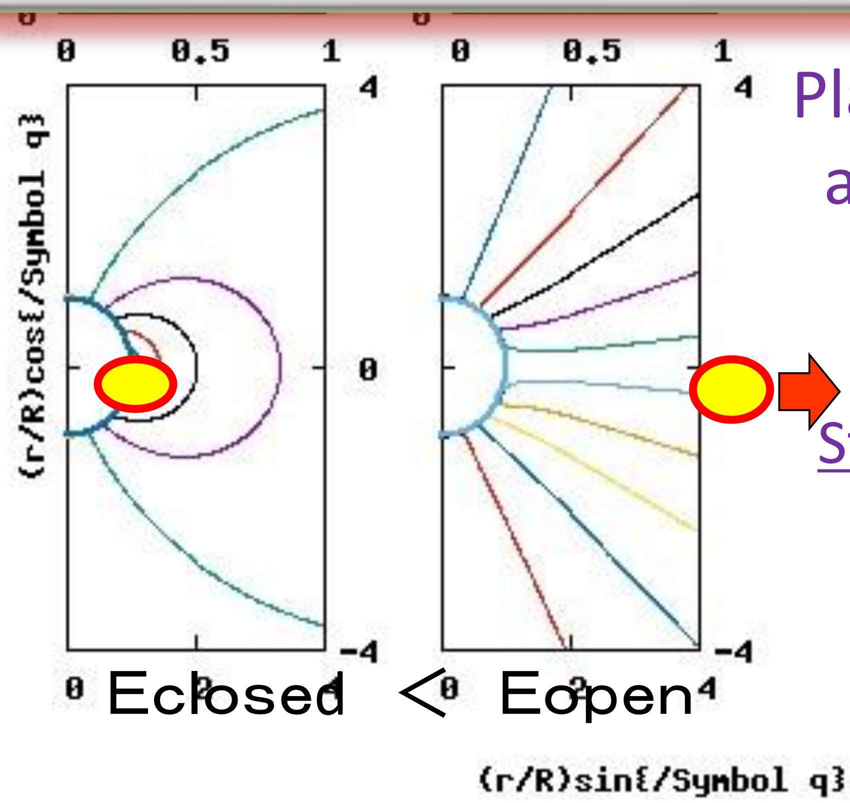
$$\Delta E_{Burst} \approx E - E_{open}$$

Magnetosphere

# TWISTING, RECONNECTING MAGNETOSPHERES
# Parfrey+(2012,2103) ApJ



# Magnetic energy for open field

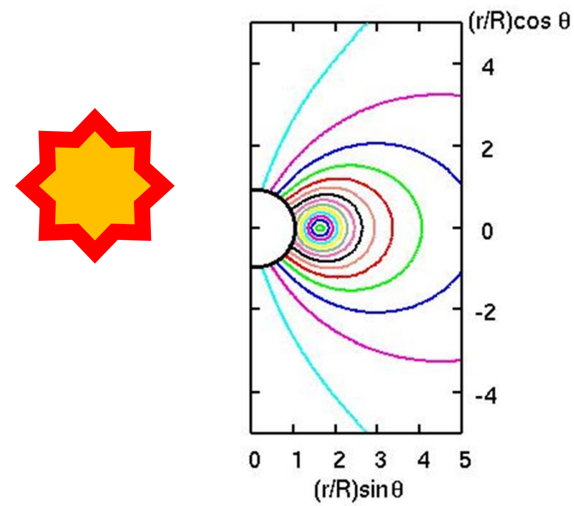



$E_{closed} < E_{open}$

Plasma ejection
at explosion

Structure with a rope

Maximum energy of magnetar flare?
Possible transition through opening field?



# Force-Free Magnetosphere

## Low-beta-plasma in magnetosphere

$$(B_{15})^2 \approx 10^8 g/cm^3 > \rho >> p$$

Force-free cond. $\vec{j} \times \vec{B} = 0 \Rightarrow \vec{j} \,//\, \vec{B}$

## Nonlinear partial diff eqn. (GS eqn.)

$$\Rightarrow \quad D(G) = -SS' \qquad (= -\gamma G^n)$$

Lüst & Schlüter 1954; Chandrasekhar 1956;
Chandrasekhar & Prendergast 1956;
Prendergast 1956; Shafranov 1957;
Grad & Rubin 1958

Present model

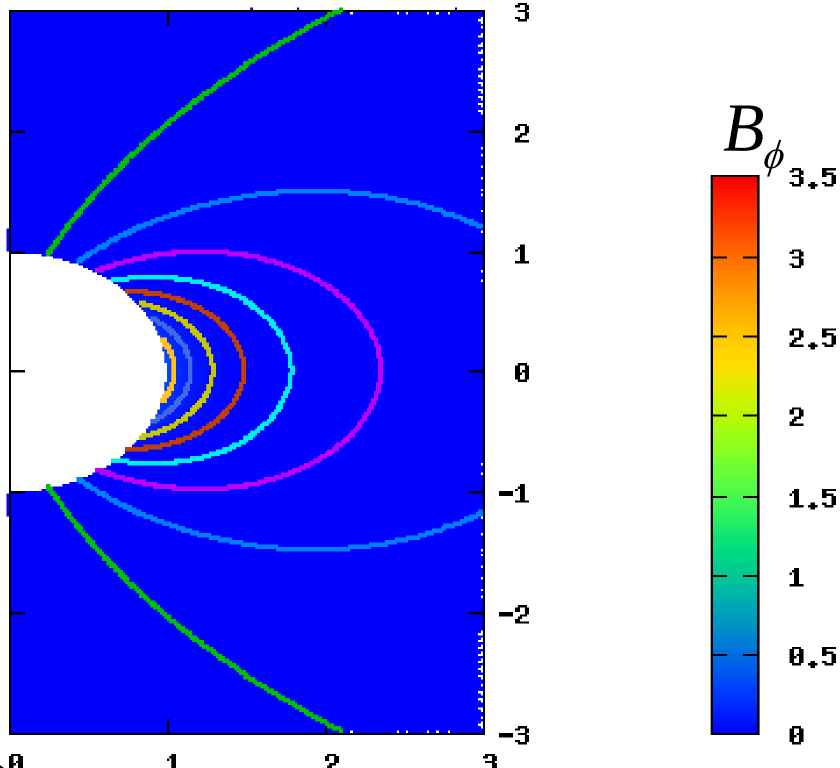
G: Magnetic flux/Poloidal comp.

S: Current stream/Toroidal comp.

$$A_\phi \Leftrightarrow (B_r, B_\theta)$$

$$B_\phi \Leftrightarrow (j_r, j_\theta)$$

# Quasi-static evolution
# A sequence of equilibrium solutions




$(r, \theta)$ plain

G Magnetic field lines

Model of n=7 and M/R=0.25

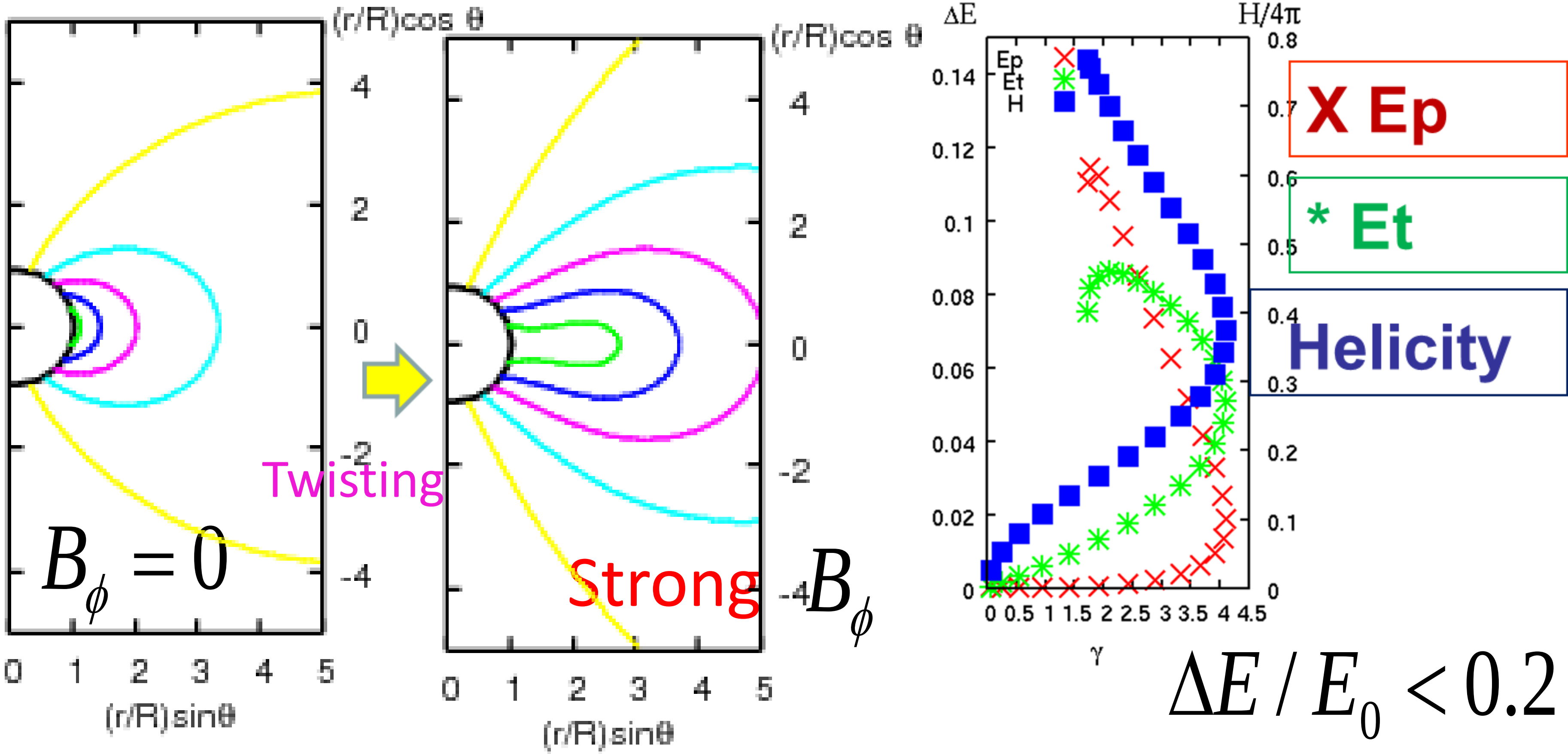
Axisymmetric model

Increasing twist
in a long timescale
>> dynamical one

A flux rope
detached

Kojima 17 MN / 1703.02273

# Results in flat spacetime



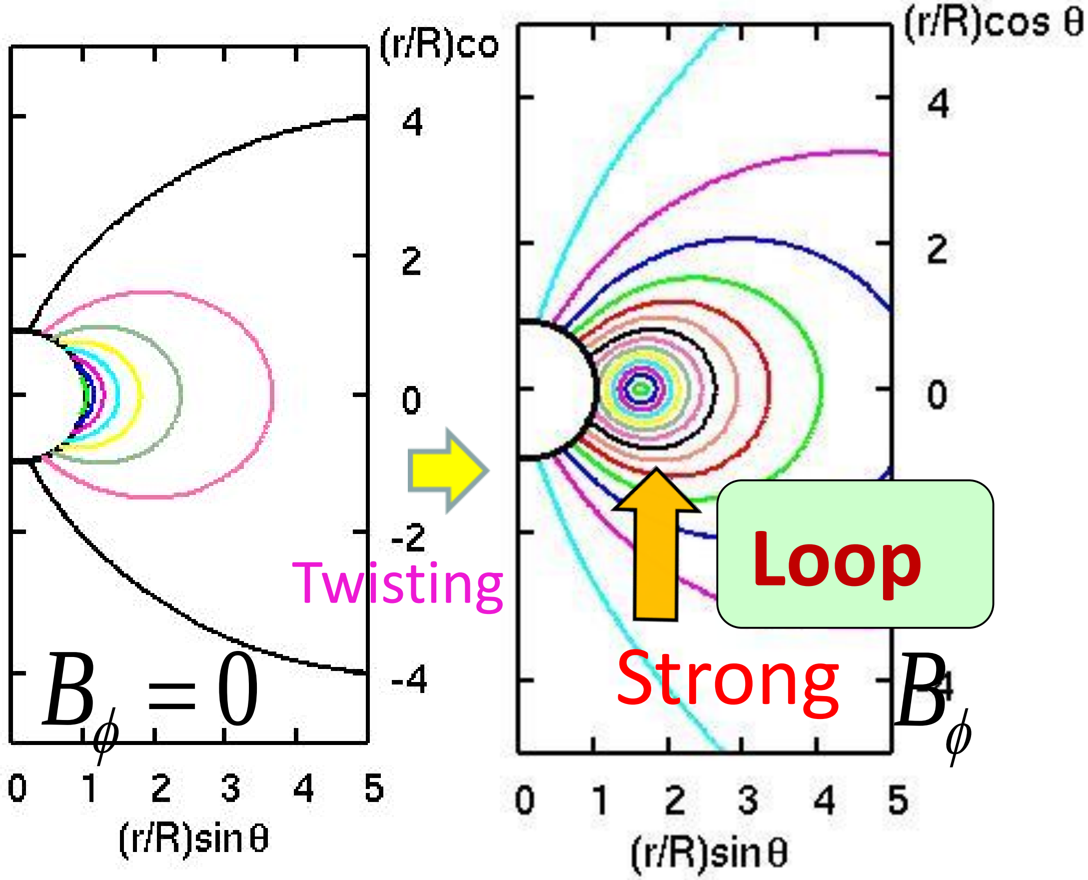

Pure dipole

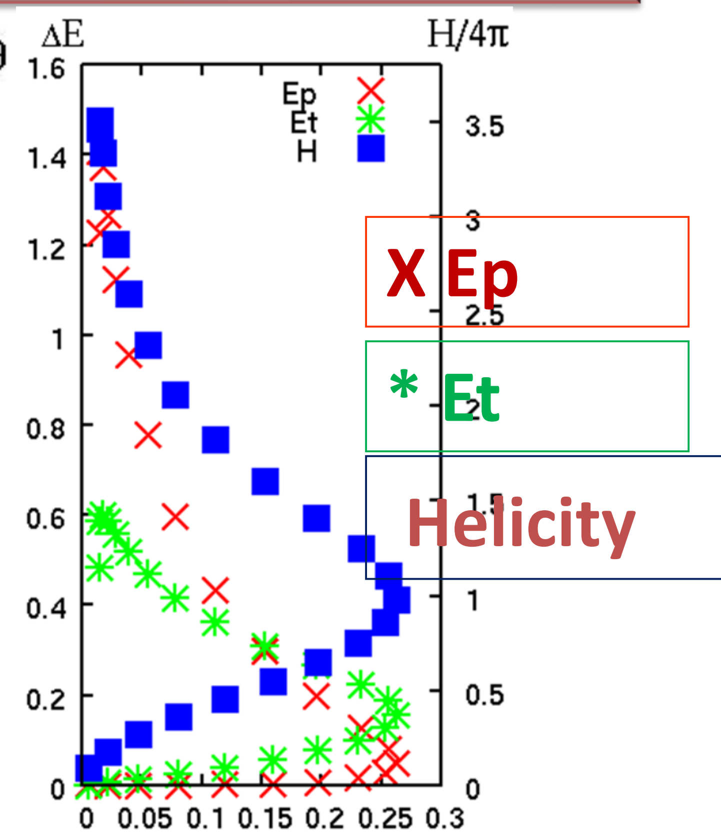
Highly twisted structure with n=7

Flat spacetime

Kojima 17 MN / 1703.02273

# Magnetosphere in relativistic model



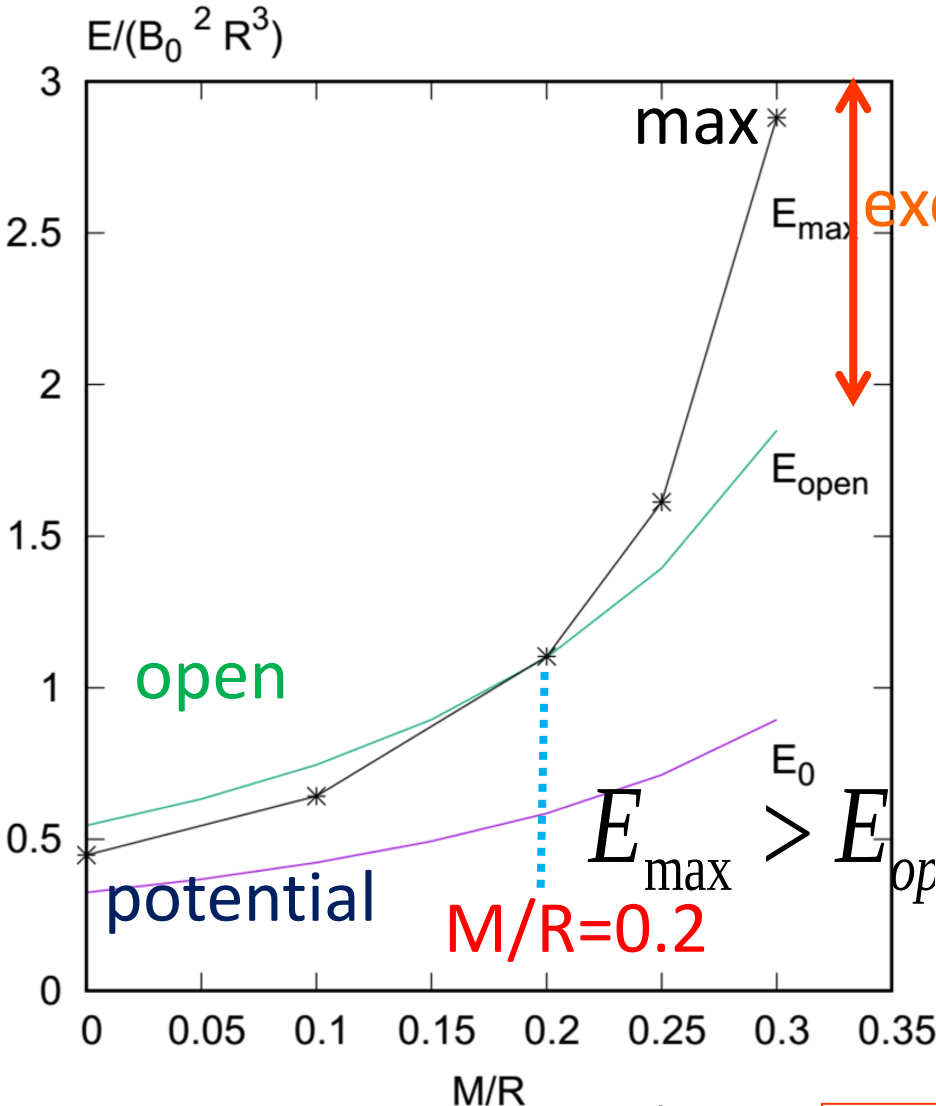

$$(\Delta E / E_0)_{\max} \approx 2$$

Pure dipole

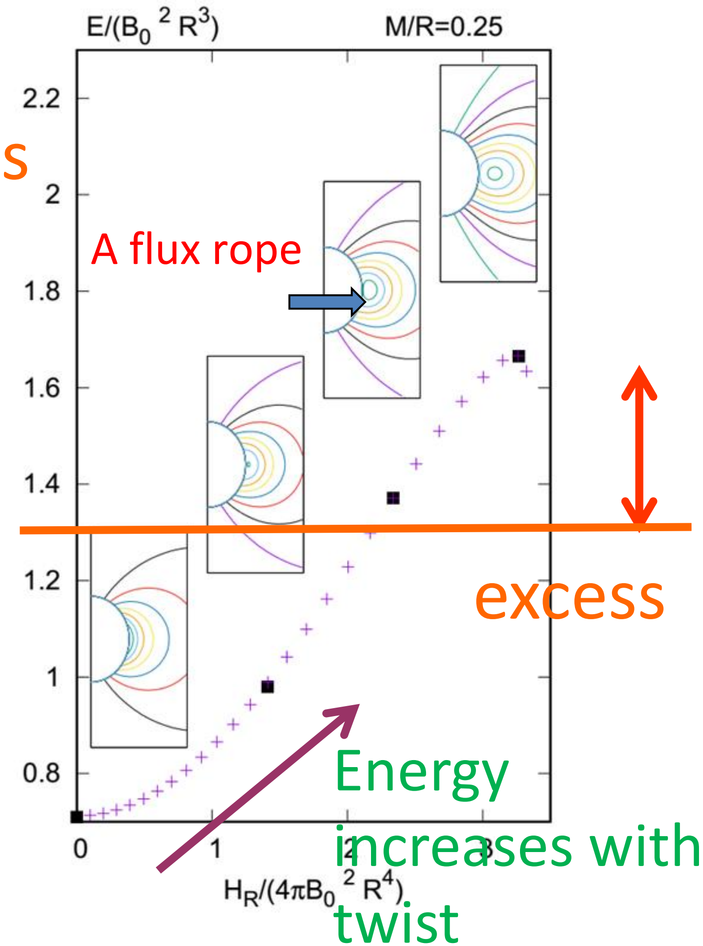
Highly twisted structure with n=7

In curved spacetime M/R=1/4

# Results




Relativistic factor M/R.




M/R=0.25.

Kojima+18 1801.06292 / MN

# Summary and Discussion

- Formation of flux rope in a relativistic system
- Larger energy stored in Magnetosphere

| Flat | curved |
|---|---|
| $\Delta E/E_0$<0.2 | $\Delta E/E_0$<2 |
| $\Delta E_{max} \approx 2 \times 10^{46}\ (B_{15})^2$ | $\Delta E_{max} \approx 2 \times 10^{47}\ (B_{15})^2$ |
| | Enough energy and possibly opening |

- Maximum helicity (or twisted) state
- Transition between two states => Flare?

Relativity is important in magnetars, and the expulsion of magnetized flux rope is related to their activity.

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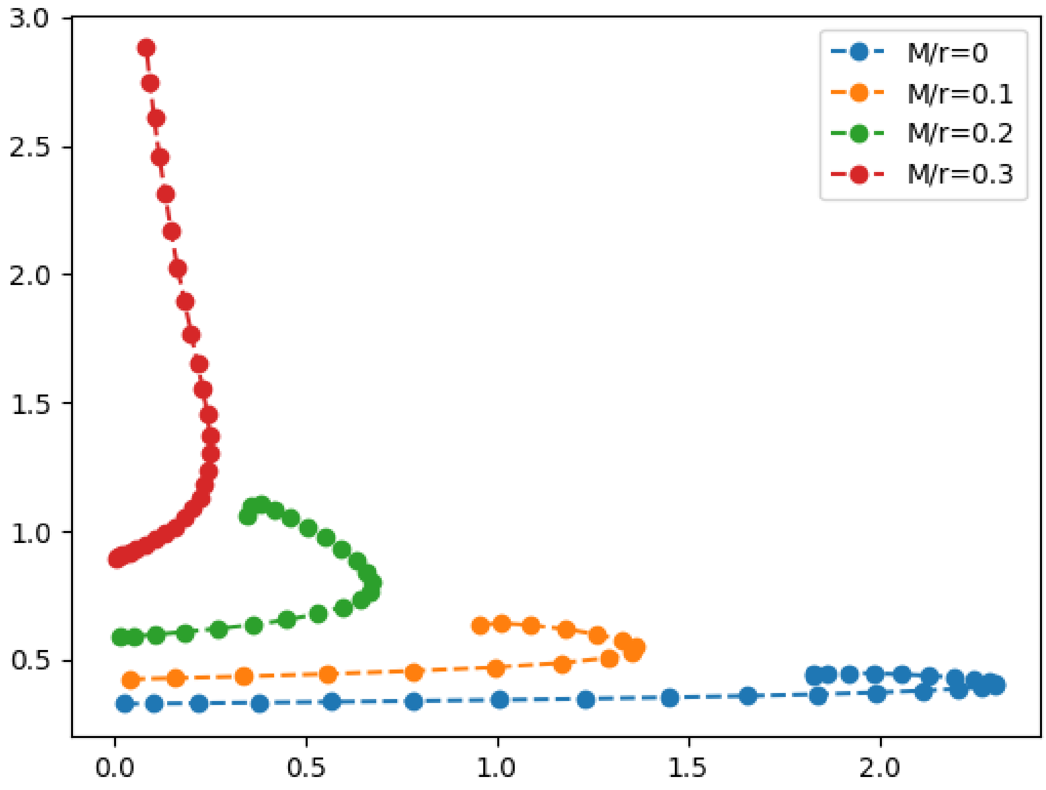
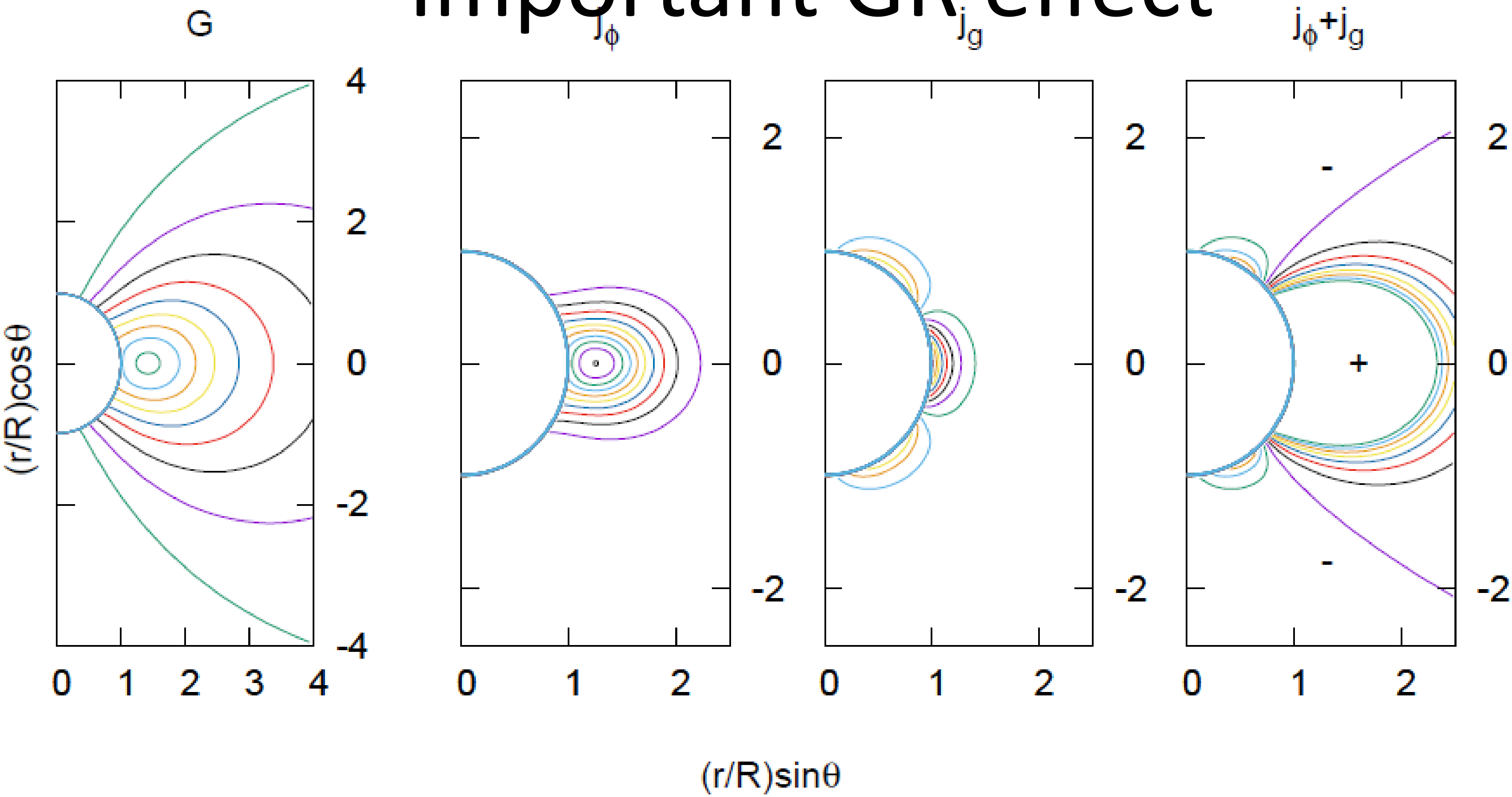
Other mechanism for rope formation

Confinement of current / large n or external vacuum models

# Effect of GR



# Important GR effect




Magnetic function, current, ‘GR-induced current’, sum

Covered by negative current

# Fate of magnetic flux rope and GW?

Huge energy $\Delta E_{max} \approx 2 \times 10^{47}\ (B_{15})^2$ stored in magnetosphere

GW radiation with $10^{47}$ ergs ?

Important to judge total energy by GW astro.

REF

Internal mag. reconfiguration

Ioka (2001) $\approx 10^{49}\, ergs$

Corsi &Owen (2011) $< 10^{48} - 10^{49}\, ergs$

Kashiyama & Ioka (2011)

Ciolfi+(2012),Zink+(2012) MHD simulation

.....

$$E_{GW} < 10^{40} (B_{15})^2$$

# Fate of magnetic flux rope and GW?

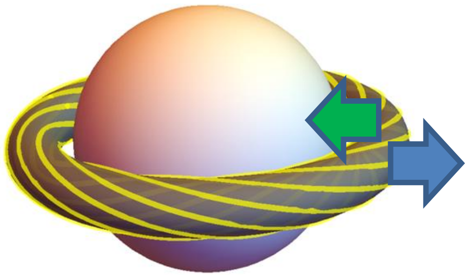
Preliminary

GW for an external origin

$\Delta E_{GW} \approx \Delta E_{EM}/E_{GR} \times \Delta E_{EM}$ , $(E_{GR}{=}M^2/R \sim M)$

✓ Ejection of ring, GW burst

$$\Delta E_{GW} \approx 2 \times 10^{38}\,(B_{15})^4$$



✓ Bombard, Excitation of f-mode

$$\Delta E_{GW} \approx 8 \times 10^{38}\,(B_{15})^4$$

$$h_c \sim 3 \times 10^{-24}\ @10kpc$$

-> 3rd generation of GW observatory

# Final remarks

Magnetar as unique object to exhibit magnetic field variation.

Big challenge to understand phenomena there.