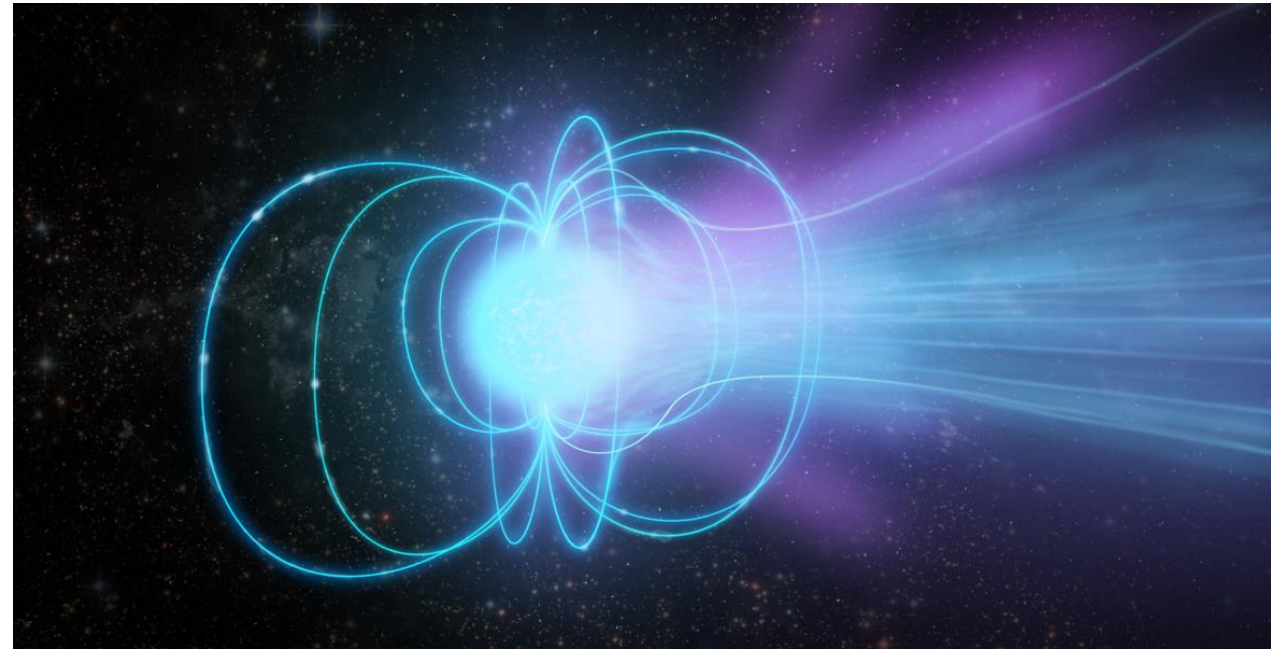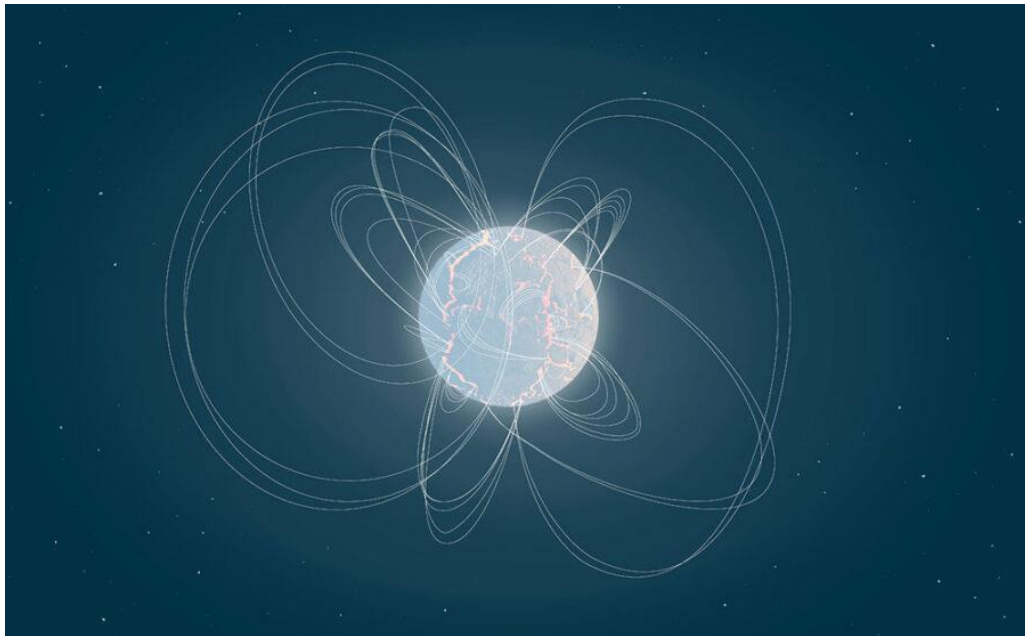2201.07507

HIGH MAGNETIC fiELD NSS IN BINARY SYSTEMS

Sergei Popov

WHAT DO WE CALL "A MAGNETAR"?

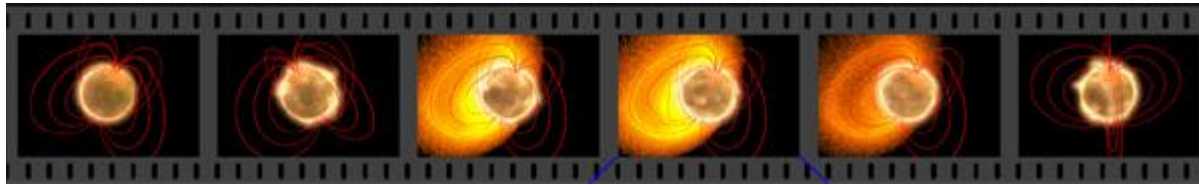Is it just a neutron star with a strong magnetic field?

Or it is necessary to have dominance of magnetic energy release in the total energy budget of the source?

Or, we are speaking about the same object, but at different stages of evolution?

DO WE EXPECT MAGNETARS IN BINARIES?

All know Galactic SGRs/AXPs are single sources

McGill on-line catalogue lists ~30 magnetars.
All of them are isolated objects.
However, an existence of a binary companion
(except cases of accretion on a compact object)
hardly can prevent detection of an SGR flare,
and the expected number of NSs in binaries
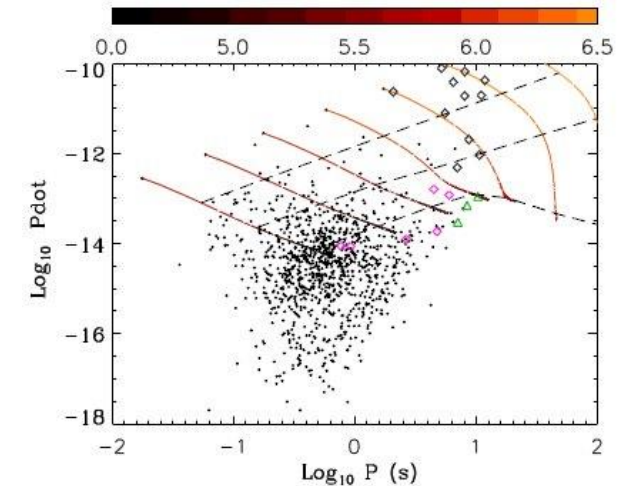is not as small as ~3%.

See, however,
2204.09701
2203.14947

Field decay might result in absence of older magnetars

Observations and theoretical
models favour magnetic field
decay.
Evolution is faster for higher
fields due to Hall cascade.

$$t_{\text{Hall}} = \frac{n_e e L}{J} = \frac{4\pi n_e e L^2}{cB},$$

Characteristic time scale for decay of magnetars' field
is at least less than ~few thousand years.
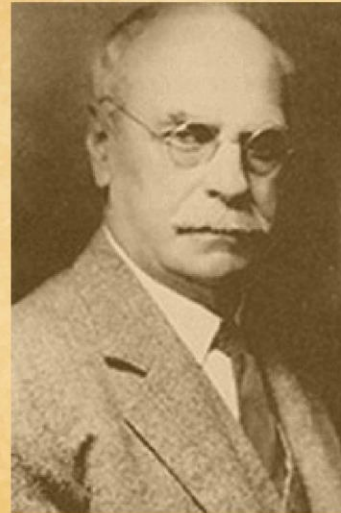
WHO IS KILLING MAGNETARS?

WANTED
FOR KILLING MAGNETARS
GEORG OHM
WRITE TO ARXIV.ORG

$1,000,000 REWARD

WANTED
FOR KILLING MAGNETARS
EDWIN HALL
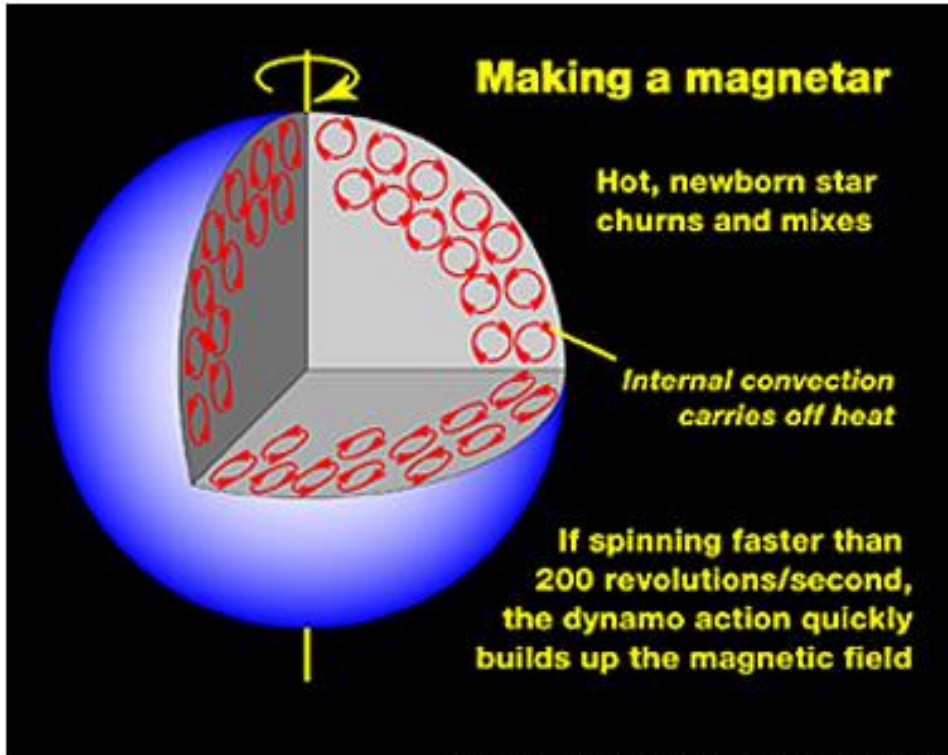WRITE TO ARXIV.ORG

$1,000,000 REWARD

To have reasonable number of magnetars in e.g. X-ray binaries we need to terminated field decay while fields are relatively high, as typical ages of binaries are large in comparison with the decay time scale.

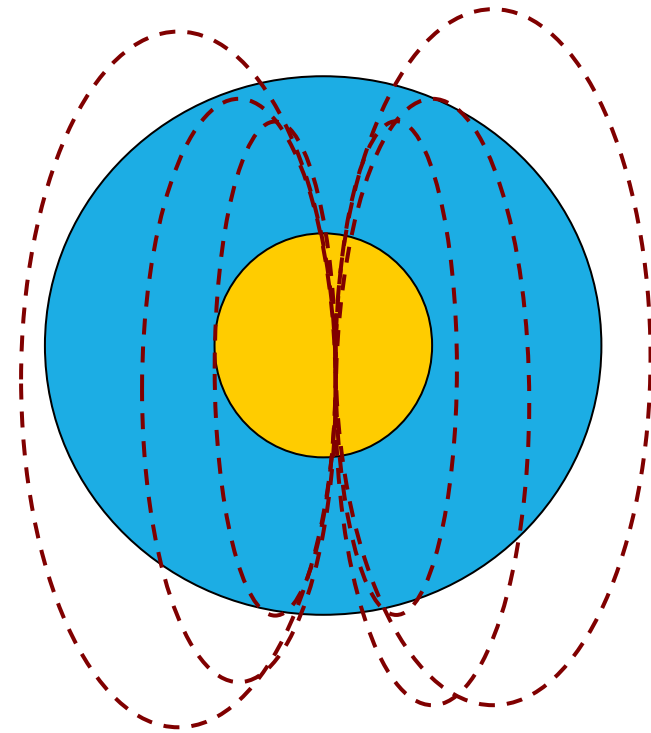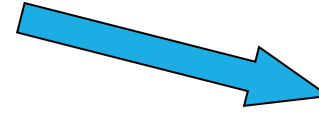**STOP HALL AND SLOW DOWN OHM!**

ORIGIN OF MAGNETARS FIELD

Generated

Fossil

Classical dynamo scenario starting from DT in 90s

Critisized by Spruit (2008)

DYNAMO MECHANISM CONDITIONS

Rapid initial rotation is necessary to produce large dipolar fields!

$P_0 \sim$ few msec
This is difficult to achieve due to slowdown of
a stellar core rotation (Heger et al. 2004, Meynet, Maeder 2005).
The same problem appear in GRB scenario.
In several recent studies fallback is used to spin-up the compact object.

Stellar rotation can be enhanced only in binaries.

In binaries there are different possibilities
to gain additional angular momentum
due to mass transfer or tidal interaction.

We need to perform population
synthesis calculations.

A QUESTION:

Why do all magnetars are isolated?

- 5-10 % of NSs are expected to be binary (for moderate and small kicks)

- All known magnetars (or candidates) are single objects.

- At the moment from the statistical point of view it is not a miracle, however, it's time to ask this question.

Two possible explanations

- Large kick velocities

- Particular evolutionary path

BINARY EVOLUTION CHANNELS.

Among all possible evolutionary paths that result in formation of NSs we select those that lead to angular momentum increase of progenitors.

- Coalescence prior to a NS formation.
- Roche lobe overflow by a primary without a common envelope.
- Roche lobe overflow by a primary with a common envelope.
- Roche lobe overflow by a secondary without a common envelope.

- Roche lobe overflow by a secondary with a common envelope.

This is an optimistic scenario, as it is assumed that angular momentum is not lost in significant amount after it has been gained (astro-ph/0505406)

OBSERVATIONAL EVIDENCE

There are several cases where observations favour magnetar birth in binary systems

THE PROGENITOR MASS OF THE MAGNETAR SGR1900+14

Ben Davies[1,2], Don F. Figer[2], Rolf-Peter Kudritzki[3], Christine Trombley[2], Chryssa Kouveliotou[4], Stefanie Wachter[5]

[1]School of Physics & Astronomy, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK.
[2]Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, 54 Lomb Memorial Drive, Rochester NY, 14623, USA
[3]Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI, 96822, USA
[4]Space Science Office, VP62, NASA/Marshall Space Flight Center, Huntsville AL 35812, USA and
[5]Spitzer Science Center, 1200 E California Blvd, California Institute of Technology, Pasadena, California 91125, USA

Draft version October 26, 2009

ABSTRACT

Magnetars are young neutron stars with extreme magnetic fields ($B \gtrsim 10^{14}$-10^{15} G). How these fields relate to the properties of their progenitor stars is not yet clearly established. However, from the few objects associated with young clusters it has been possible to estimate the initial masses of the progenitors, with results indicating that a very massive progenitor star ($M_{\mathrm{prog}} > 40 M_\odot$) is required to produce a magnetar. Here we present adaptive-optics assisted Keck/NIRC2 imaging and Keck/NIRSPEC spectroscopy of the cluster associated with the magnetar SGR 1900+14, and report that the initial progenitor star mass of the magnetar was a factor of two lower than this limit, $M_{\mathrm{prog}} = 17 \pm 2 M_\odot$. Our result presents a strong challenge to the concept that magnetars can only result from very massive progenitors. Instead, we favour a mechanism which is dependent on more than just initial stellar mass for the production of these extreme magnetic fields, such as the "fossil-field" model or a process involving close binary evolution.

Subject headings: open clusters & associations: individual (Cl 1900+14), stars: evolution, stars: neutron, stars: individual (SGR1900+14)

0910.4859

ANOTHER CASE

1405.3109

A VLT/FLAMES survey for massive binaries in Westerlund 1. IV. Wd1-5 - binary product and a pre-supernova companion for the magnetar CXOU J1647-45? [*]

J. S. Clark[1], B. W. Ritchie[1,2], F. Najarro[3], N. Langer[4], and I. Negueruela[5]

[1]Department of Physics and Astronomy, The Open University, Walton Hall, Milton Keynes, MK7 6AA, United Kingdom
[2]Lockheed Martin Integrated Systems, Building 1500, Langstone, Hampshire, PO9 1SA, UK
[3]Departamento de Astrofísica, Centro de Astrobiología, (CSIC-INTA), Ctra. Torrejón a Ajalvir, km 4, 28850 Torrejón de Ardoz, Madrid, Spain
[4]Argelander Institut für Astronomie, Auf den Hügel 71, Bonn, 53121, Germany
[5]Departamento de Física, Ingeniería de Sistemas y Teoría de la Señal, Universidad de Alicante, Apdo. 99, E03080 Alicante, Spain

ABSTRACT

Context. The first soft gamma-ray repeater was discovered over three decades ago, and subsequently identified as a magnetar, a class of highly magnetised neutron star. It has been hypothesised that these stars power some of the brightest supernovae known, and that they may form the central engines of some long duration gamma-ray bursts. However there is currently no consensus on the formation channel(s) of these objects.
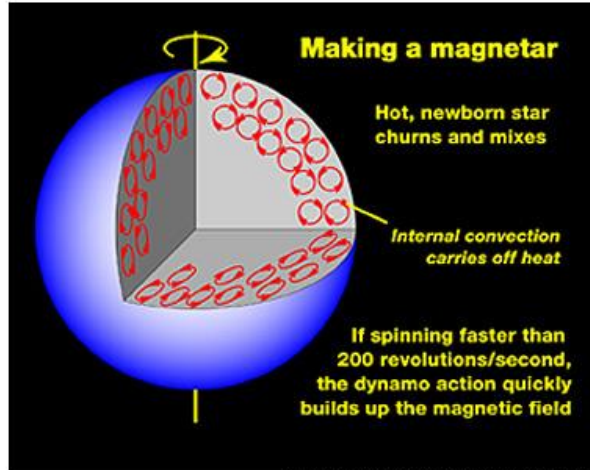
Aims. The presence of a magnetar in the starburst cluster Westerlund 1 implies a progenitor with a mass $\geq 40 M_\odot$, which favours its formation in a binary that was disrupted at supernova. To test this hypothesis we conducted a search for the putative pre-SN companion.

Methods. This was accomplished via a radial velocity survey to identify high-velocity runaways, with subsequent non-LTE model atmosphere analysis of the resultant candidate, Wd1-5.

Results. Wd1-5 closely resembles the primaries in the short-period binaries, Wd1-13 and 44, suggesting a similar evolutionary history, although it currently appears single. It is overluminous for its spectroscopic mass and we find evidence of He- and N-enrichement, O-depletion, and critically C-enrichment, a combination of properties that is difficult to explain under single star evolutionary paradigms. We infer a pre-SN history for Wd1-5 which supposes an initial close binary comprising two stars of comparable ($\sim 41 M_\odot + 35 M_\odot$) masses. Efficient mass transfer from the initially more massive component leads to the mass-gainer evolving more rapidly, initiating luminous blue variable/common envelope evolution. Reverse, wind-driven mass transfer during its subsequent WC Wolf-Rayet phase leads to the carbon pollution of Wd1-5, before a type Ibc supernova disrupts the binary system. Under the assumption of a physical association between Wd1-5 and J1647-45, the secondary is identified as the magnetar progenitor; its common envelope evolutionary phase prevents spin-down of its core prior to SN and the seed magnetic field for the magnetar forms either in this phase or during the earlier episode of mass transfer in which it was spun-up.

Conclusions. Our results suggest that binarity is a key ingredient in the formation of at least a subset of magnetars by preventing spin-down via core-coupling and potentially generating a seed magnetic field. The apparent formation of a magnetar in a Type Ibc supernova is consistent with recent suggestions that superluminous Type Ibc supernovae are powered by the rapid spin-down of these objects.

ORIGIN OF MAGNETARS IN BINARIES

Making a magnetar

Hot, newborn star churns and mixes

Internal convection carries off heat

If spinning faster than 200 revolutions/second, the dynamo action quickly builds up the magnetic field

Dave Dooling, NASA Marshall Space Flight Center

The mechanism of the magnetic field generation is still unknown.

α-Ω dynamo (Duncan,Thompson)
$α^2$ dynamo (Bonanno et al.)
or their combination

If a dynamo mechanism is operating then it is necessary to have rapid rotation to produce large dipolar field.

Three possibilities to spin-up a star during evolution in a binary:
1) Spin-up of a progenitor star in a binary by accretion;
3) Spin-up of a progenitor star via synchronization;
2) Coalescence of binary companions prior to a compact object formation.

Detalied results of calculations for the bimodal kick and moderate mass loss

Track	$\alpha_q = 0$		$\alpha_q = 2$	
	all	binary magnetars	all	binary magnetars
Merge	60.1%	—	35.7%	—
Primary RLO with CE+Sync.	1.6%	0.2%	0.02%	0.01%
Secondary RLO with CE+Sync.	1.4%	0.3%	2.5%	0.8%
Two RLO w/o CE on Primary	9.4%	0%	19.9%	0%
Two RLO w/o CE on Secondary	0.005%	0%	0.04%	0%
Single RLO w/o CE on Primary	26.1%	0.07%	39.3%	0.08%
Single RLO w/o CE on Secondary	0.7%	0.08%	1.4%	0.06%

We obtained ~10% of magnetars (i.e., NSs from spun-up progenitors), but among these NSs only ~1% are in survived binaries.

And, of course, all magnetars formed in NS+NS or NS+WD coalescence are isolated.

Popov, Prokhorov 2006

MAGNETIC FIELD AMPLIFICATION IN BINARIES
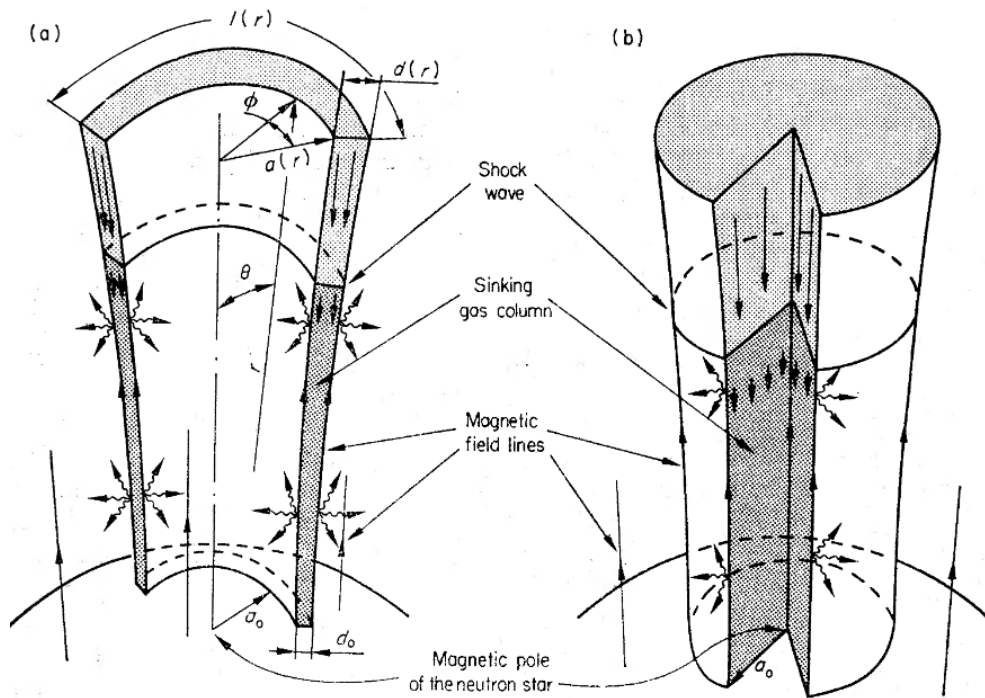
magnetic star τ Sco – result of coalescence
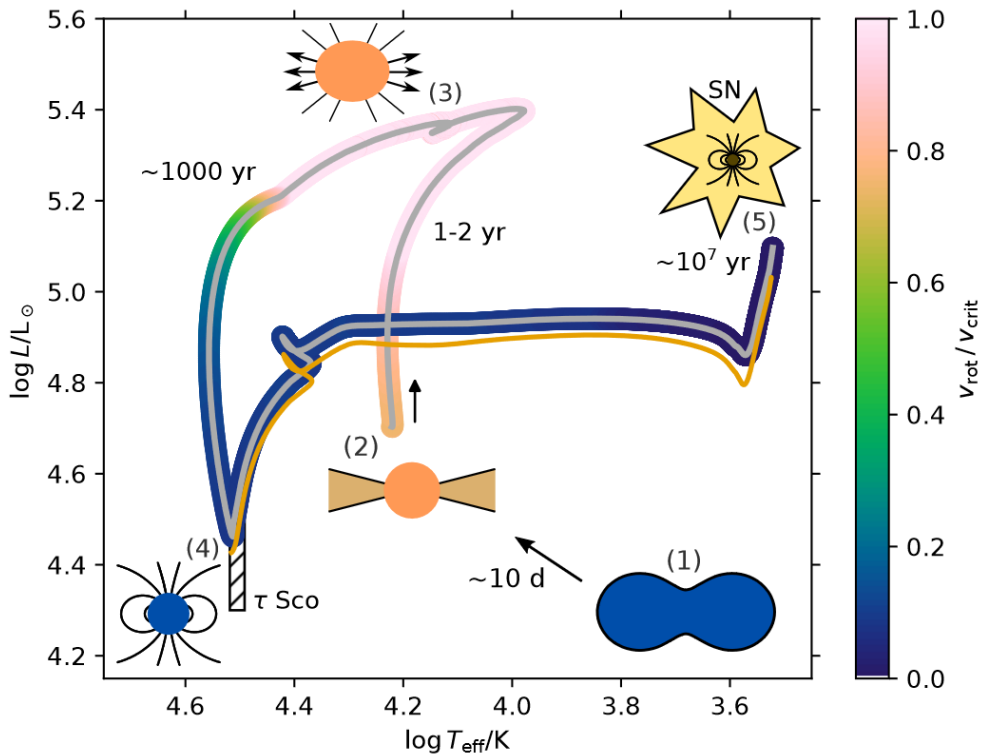
9 Msun +8 Msun
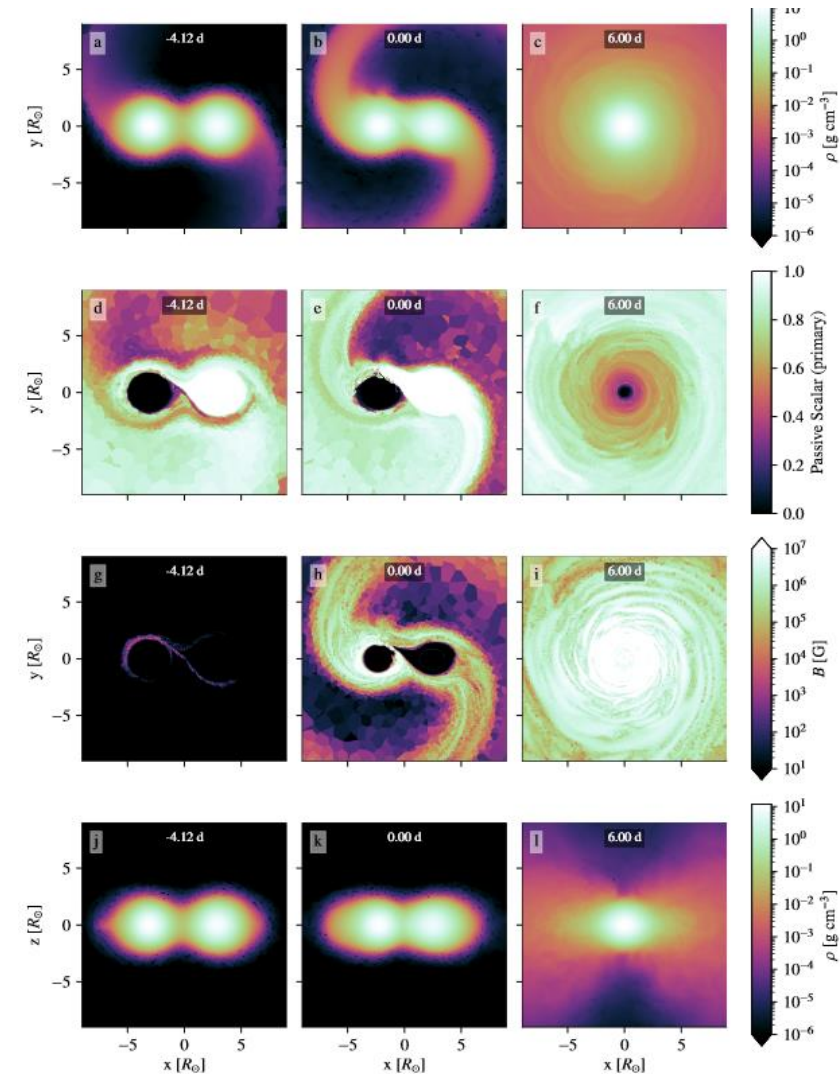
If all of the magnetic flux is conserved
until core collapse of the merger product,
a resulting neutron star of 10 km radius would have
a surface magnetic field strength of about 10^{16} G.
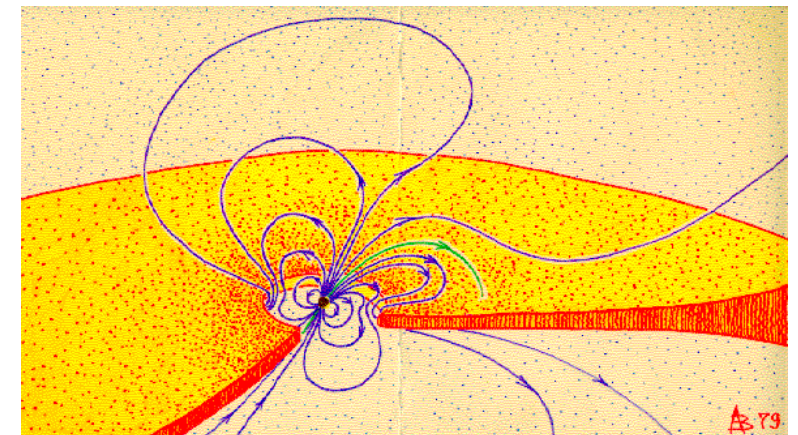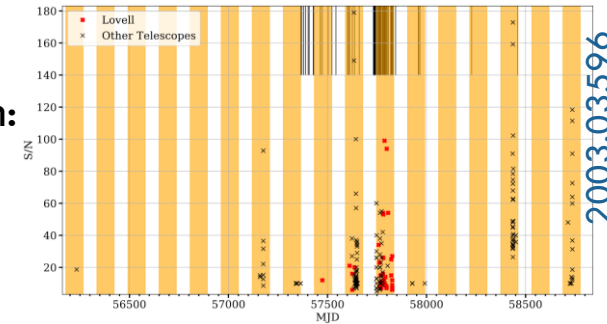
WHY DO WE NEED MAGNETARS, SOMETIMES?

+ FRBs with long periodicity?

Large luminosity

(a) (b)

$l(r)$

$d(r)$

ϕ

$a(r)$

θ

Shock wave

Sinking gas column

Magnetic field lines

a_0 d_0

Magnetic pole of the neutron star

a_0

If an accretion column is formed than the luminosity can exceed the Eddington (Basko, Sunyaev 1975, 1976).

Spin properties

Large magnetic fields can result in:

- Long spin periods;
- Rapid spin-down;
- Rapid spin-up;
- Accretor/Propeller transitions
  even for relatively large accretion rates.

2003.03596

Lipunov

ULTRALUMINOUS X-RAY PULSARS

Object	$L_{X,max}$, erg s^{-1}	P, s	$\dot{P}_{max}$, s^{-1}
M 82 X-2	1.8×10^{40}	~1.37	-2.7×10^{-10}
NGC 7793 P13	~10^{40}	~0.43	-3×10^{-11}
NGC 5907 ULX-1	~10^{41}	~1.1	-8×10^{-10}
NGC 300 ULX-1	4.7×10^{39}	~31.5	-5.6×10^{-7}
M 51 ULX-7	7×10^{39}	~2.8	-10^{-9}
M 81 X-6	3.6×10^{39}	2681	–
NGC 1313 X-2	2×10^{40}	~1.5	-3.3×10^{-8}
M 51 ULX-8	4.8×10^{39}	–	–
CXOU J073709.1+653544	~10^{39}	~18	-1.1×10^{-7}
SMCX-3	2.5×10^{39}	~7.8	-7.4×10^{-10}
RXJ0209.6-7427	~2×10^{39}	~9.3	-1.75×10^{-8}
SwiftJ0243.6+61241	~2×10^{39}	~9.8	~2.2×10^{-8}
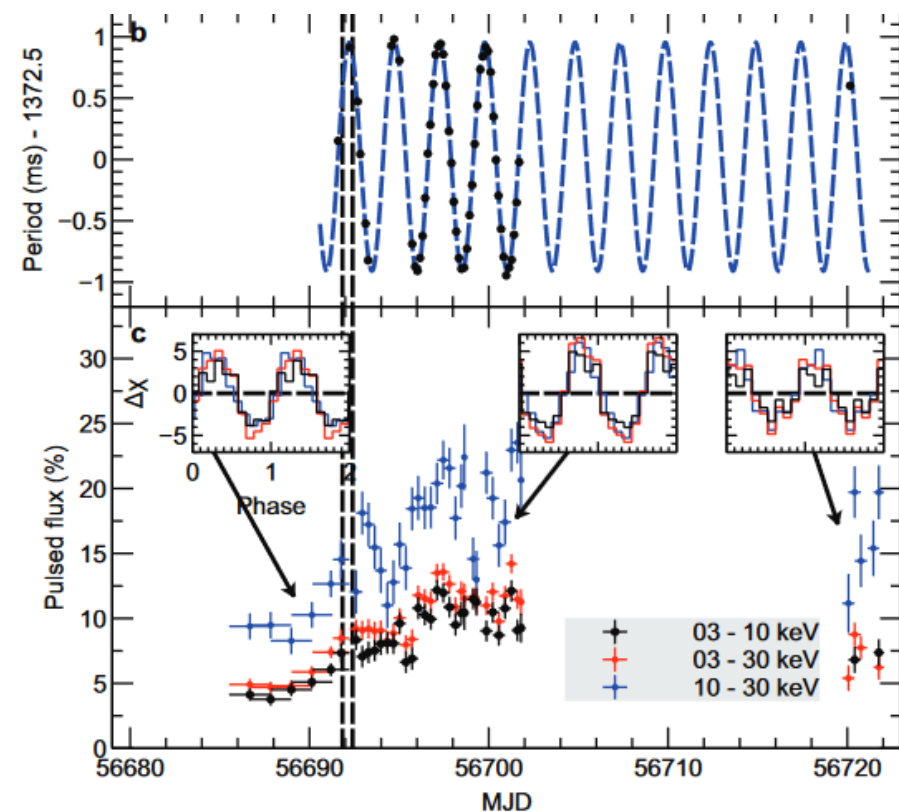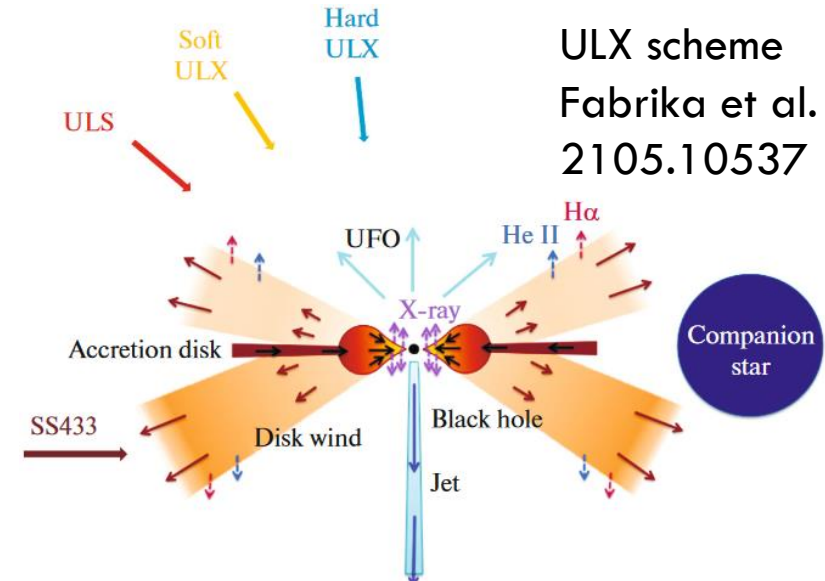
ACCRETING MAGNETARS

Typically magnetic fields of neutron stars in accreting X-ray binaries are estimated with indirect methods.
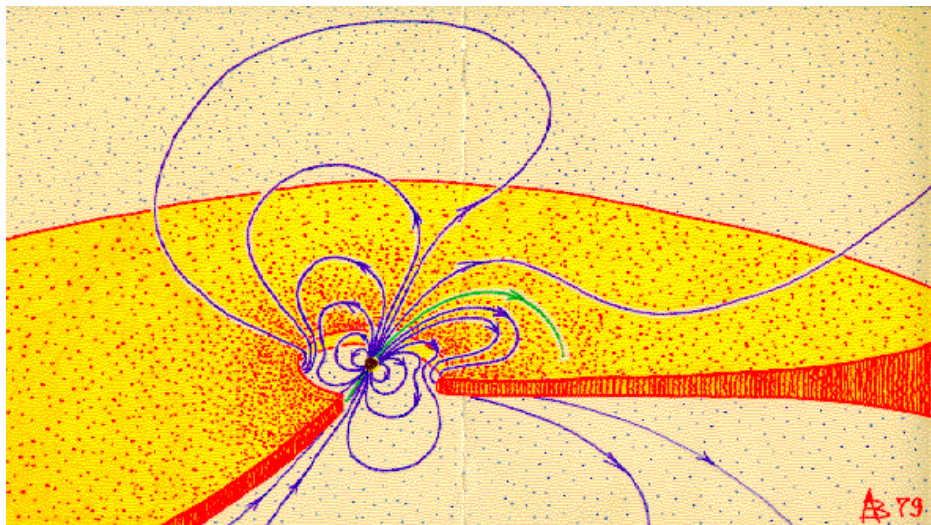
- Spin-up
- Spin-down
- Equilibrium period
- Accretion model
- …….
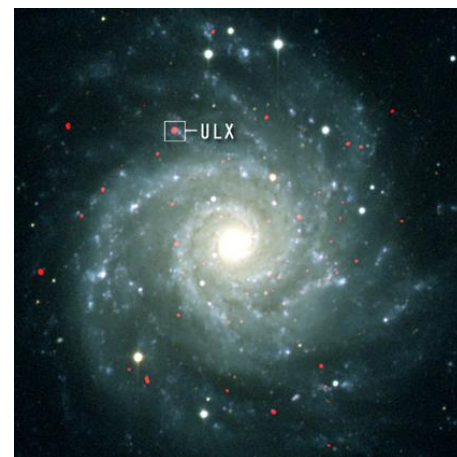
- ULX. NuSTAR J095551+6940.8 (M82 X-2). Ekşi et al. (2015).
- ULX. NGC 5907. Israel et al. (2017a)
- ULX. NGC 7793 P13. Israel et al. (2017b).
- 4U0114+65. Sanjurjo et al. (2017).
- 4U 2206+54. Ikhsanov & Beskrovnaya (2010).
- SXP1062. Fu & Li (2012)
- Swift J045106.8-694803. Klus et al. (2013).
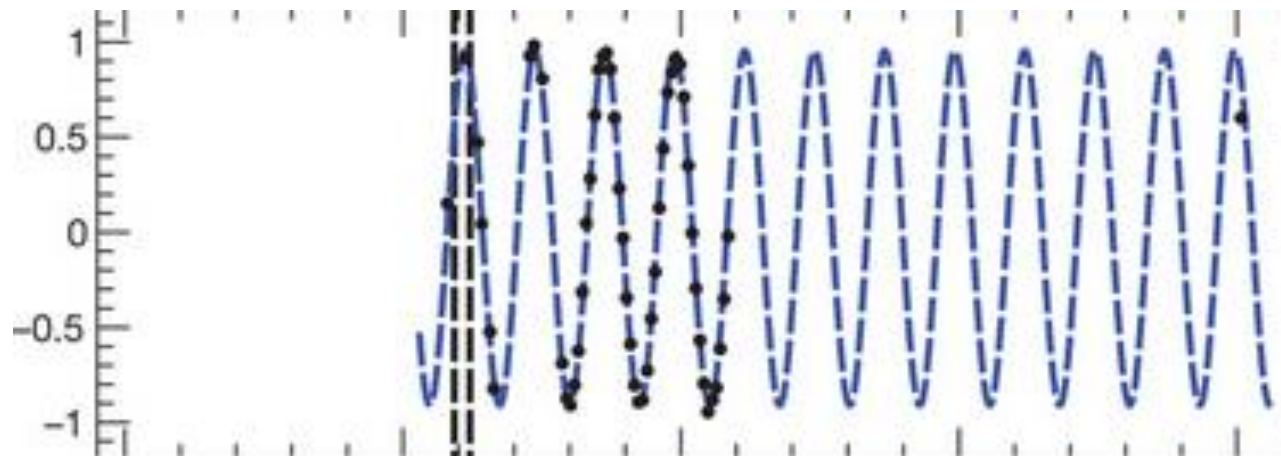
FIELD ESTIMATES BASED ON SPIN PROPERTIES

There are many classical and modern approaches to estimate NS's magnetic field from spin properties.

[See, eg. Chashkina&Popov 2012, Klus et al. 2014, Ho et al. 2014, Shi et al. 2015, Igoshev&Popov2018 and references to classical papers by Ghosh&Lamb, Davidson&Ostriker and many others therein.]

1. Equilibrium.

   A) disc accretion

   $$B = 2^{-1/4}\pi^{-7/6}k_t^{-7/12}\epsilon^{7/24}p^{7/6}\dot{M}^{1/2}(GM)^{5/6}R^{-3}.$$

   B) wind accretion

   $$B = 2\sqrt{\frac{2\eta}{k_t\pi}}p_{\mathrm{orb}}^{-1/2}v^{-2}(GM)^{3/2}\dot{M}^{1/2}pR^{-3}.$$

2. Spin-up.

   $$B = \frac{2^4\pi^{7/2}}{\epsilon^{7/4}}\frac{(I\dot{p})^{7/2}}{R^3p^7\dot{M}^3(GM)^{3/2}};$$

3. Spin-down.

   $$B = \frac{2}{R^3}\left(\frac{I\dot{p}GM}{2\pi k_t}\right)^{1/2}$$

Many more equations exist to estimate magnetic fields using spin and its derivatives (e.g. Shi et al. 2015). Typically, only dipolar component can be estimated.

E.g., 4U 0114+65, 4U 2206+54, SXP 1062, Swift J0451 were proposed as accreting magnetars.

SETTLING ACCRETION HELPS AGAINST MAGNETARS

	SXP1062	4U2206 + 54
$P^*(\mathrm{s})$	1062	5560
$P_B(\mathrm{d})$	$\sim 300^\dagger$	19(?)
$v_w(\mathrm{km/s})$	$\sim 300^\ddagger$	350
μ_{30}	~ 10	1.7
$\dot{M}_{16}$	0.6	0.2
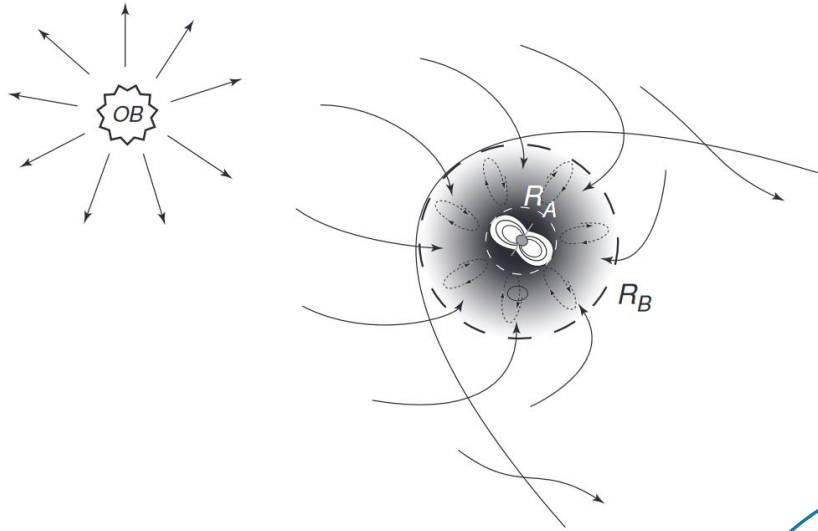
Typically, for wind-accreting systems long spin periods lead to high magnetic field estimates (e.g., Klus et al. 2014):

$$B \approx 1 \times 10^{14}\,\mathrm{G} \left(\frac{\eta}{\kappa_t}\right)^{1/2} R_{\mathrm{NS6}}^{-3} \left(\frac{M}{M_\odot}\right)^{3/2} \dot{M}_{16}^{1/2}$$
$$\times \left(\frac{V_{\mathrm{rel}}}{100\,\mathrm{km\,s^{-1}}}\right)^{-2} \left[\frac{P/100\,\mathrm{s}}{(P_{\mathrm{orb}}/10\,\mathrm{d})^{1/2}}\right].$$

However, for the settling accretion model which is valid for low accretions rates the field estimate is much lower:

$$B = 0.24 \times 10^{12}\,\mathrm{G}\,\eta_s \left(\frac{p/100\mathrm{s}}{p_{\mathrm{orb}}/10\mathrm{days}}\right)^{11/12} \dot{M}_{16}^{1/3} \left(v/(10^8\,\mathrm{cm/s})\right)^{-11/3}$$

FIELD DECAY IN HMXBS

CENTAURUS X-3: A HIGH MASS X-RAY BINARY
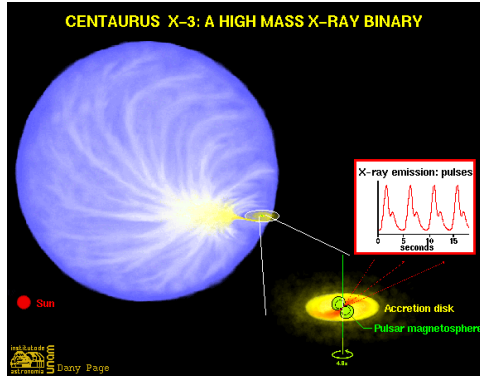
It is possible to use HMXBs to test models of field decay
on time scale >1 Myr (Chashkina, Popov 2012).
We use observations of Be/X-ray binaries in SMC
to derive magnetic field estimates,
and compare them with prediction of the Pons et al. model.
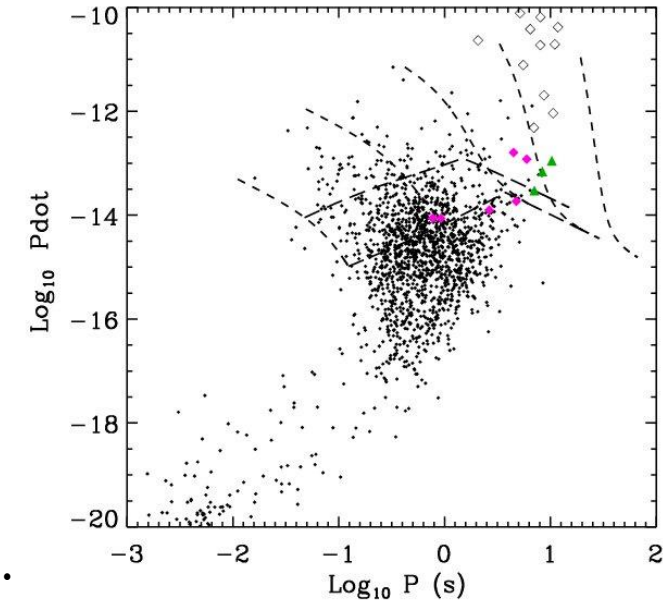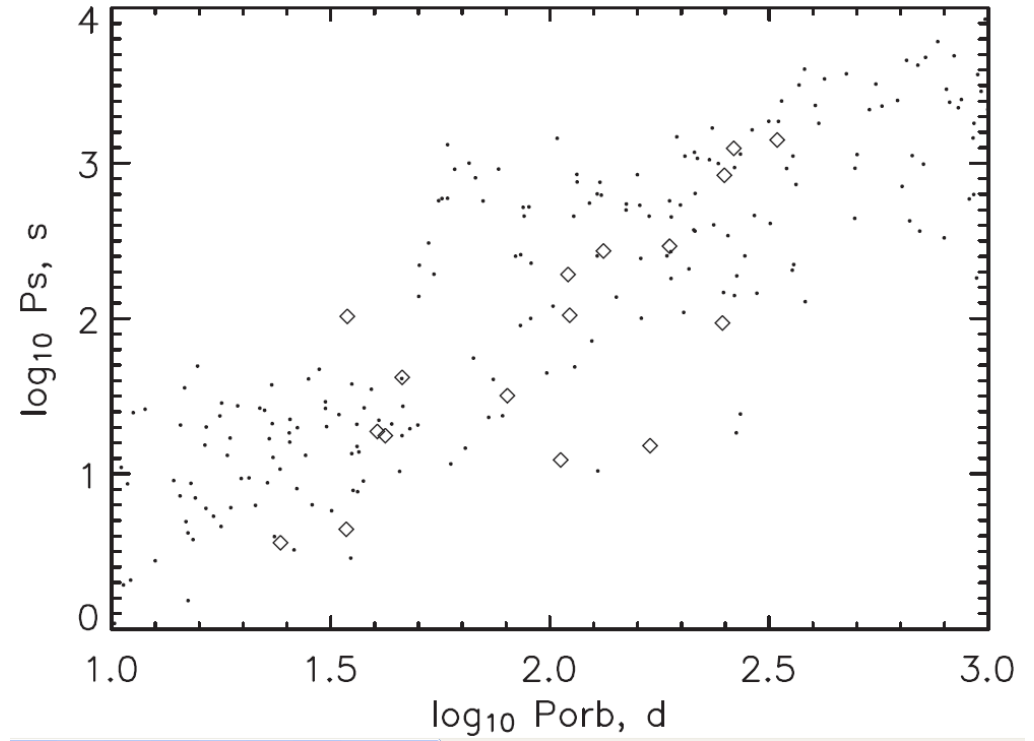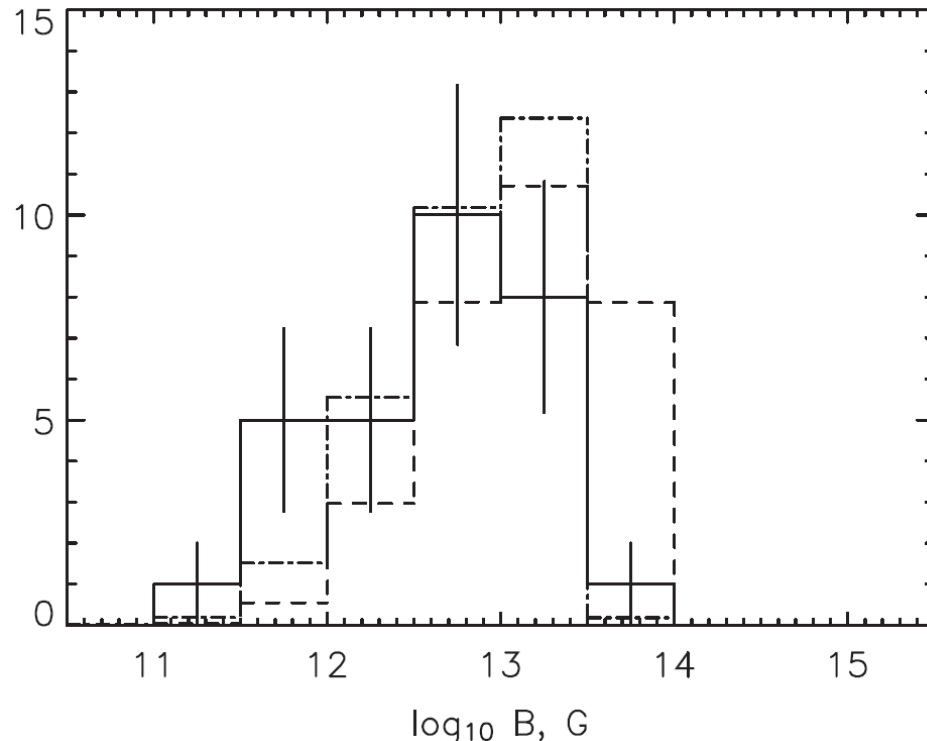
SXP 1062

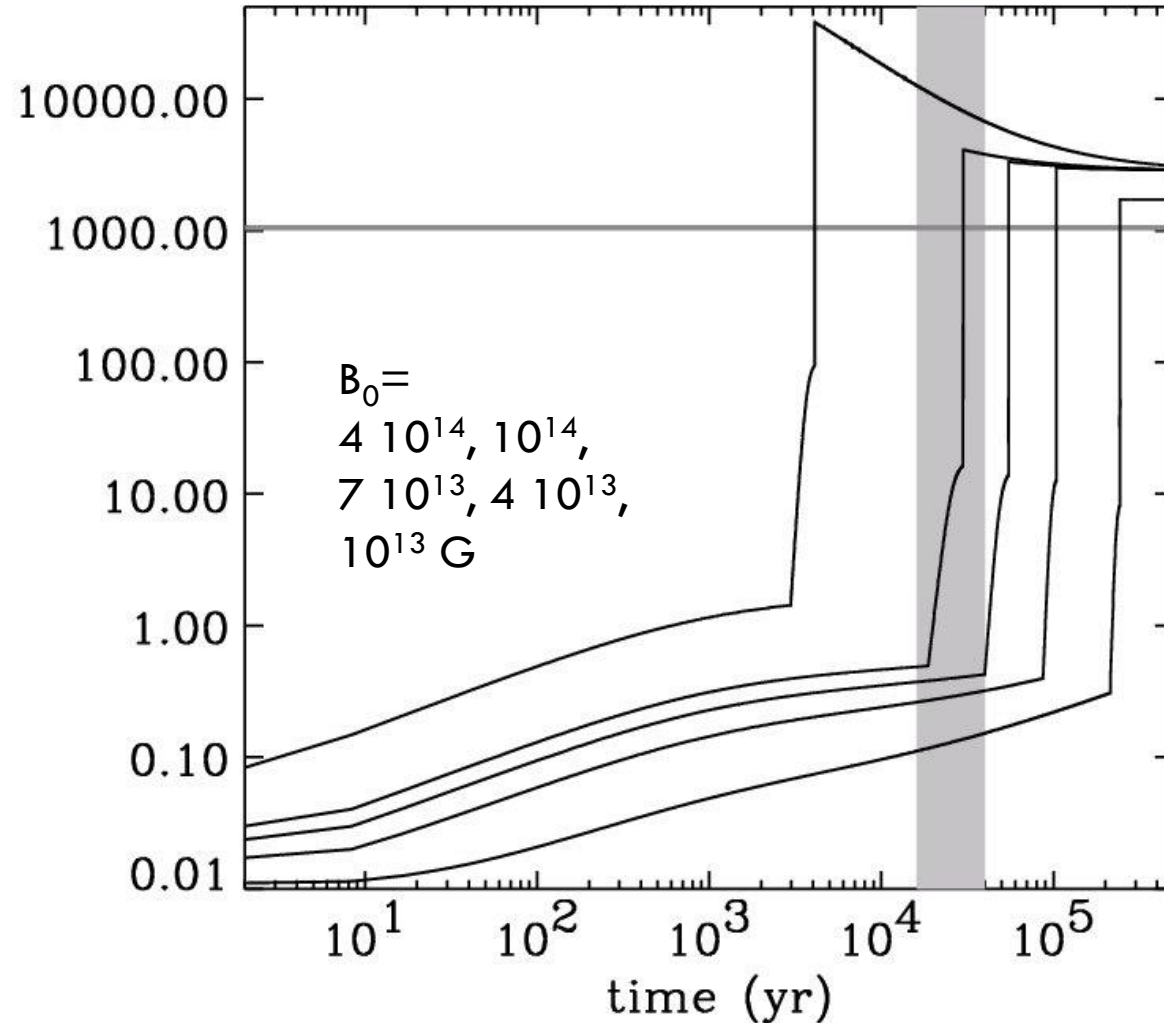A peculiar source was discovered in SMC.
Be/Xray binary, P=1062 sec.
A SNR is found. Age ~10^4 yrs.
(1110.6404; 1112.0491)

Typically, it can take ~1 Myr for a NS
with B~10^{12} G to start accretion.

SXP 1062

$B_0=$
$4 \cdot 10^{14}$, 10^{14},
$7 \cdot 10^{13}$, $4 \cdot 10^{13}$,
10^{13} G

time (yr)
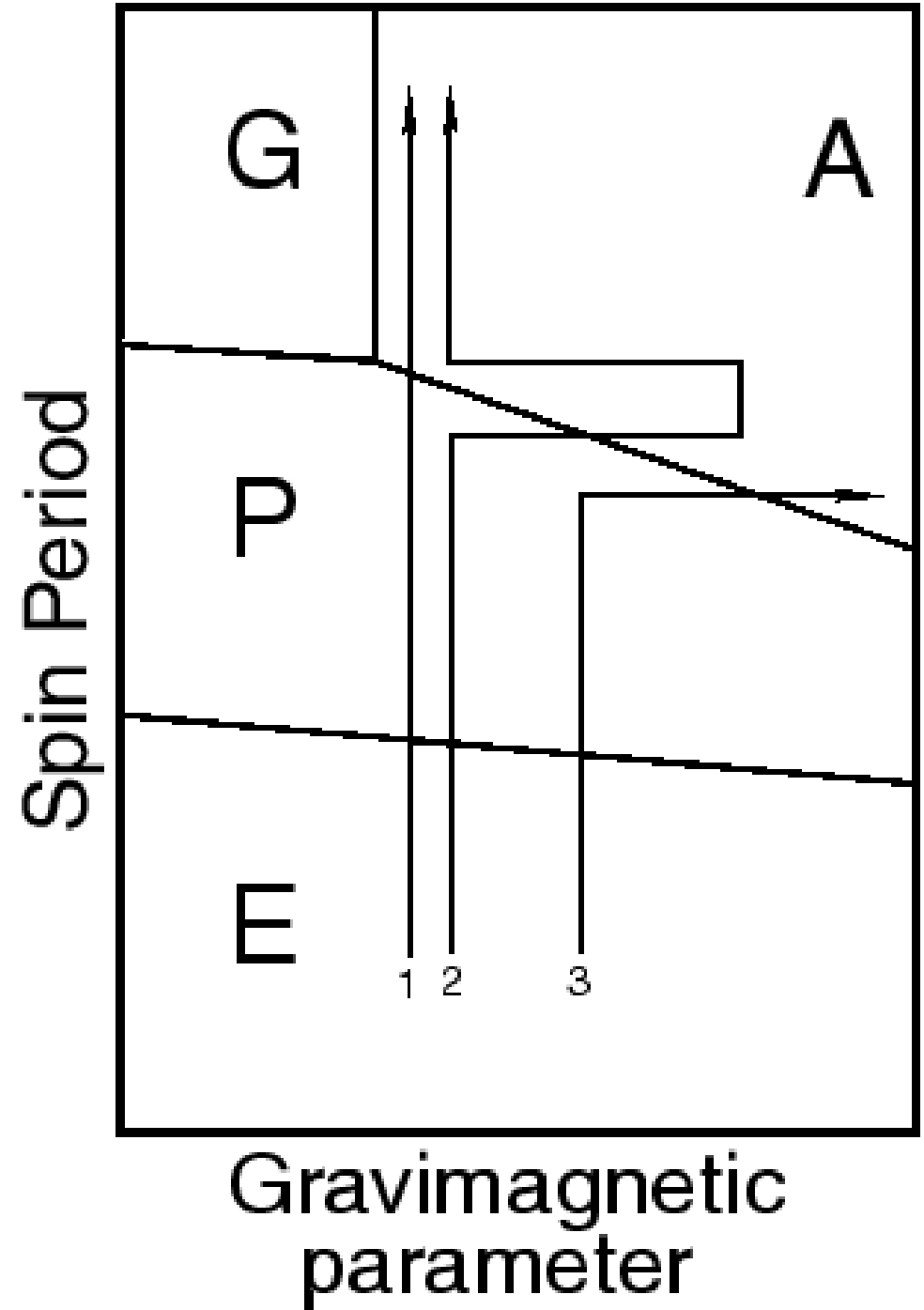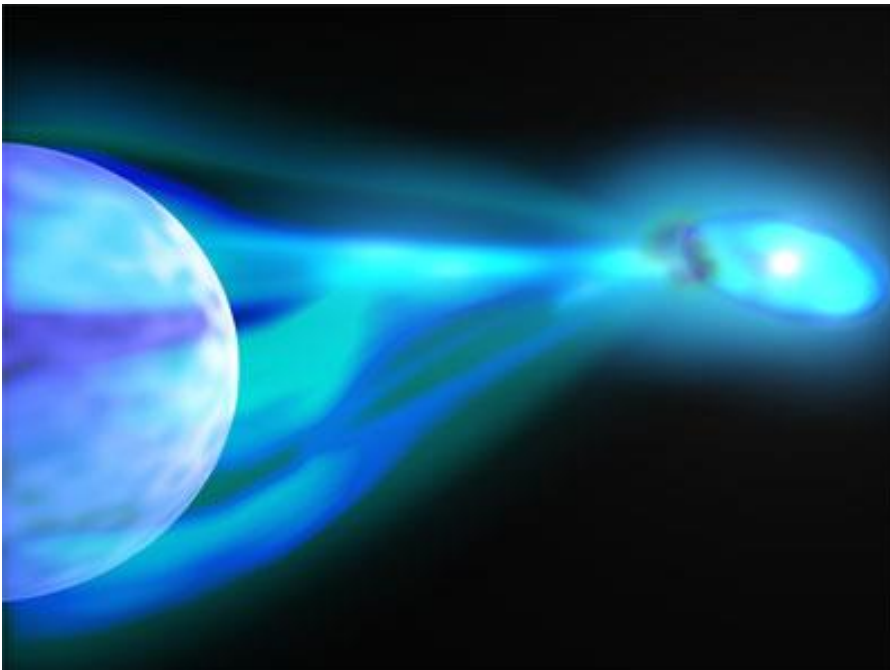
A crucial thing for studying
magneto-rotational evolution
is to have an independent age estimate.
In the case of HMXBs an interesting source
with known age is SXP1062
(H´enault-Brunet et al. 2012, Haberl et al. 2012).

We were able to reproduce
properties of SXP 1062 assuming
a magnetic field decay.

I.e., initially the NS was a magnetar
but now it has s standard
magnetic field.
The crucial element of this model is
the new accretion model by
Shakura et al. (2013).

BURSTS FROM LS I +61 303
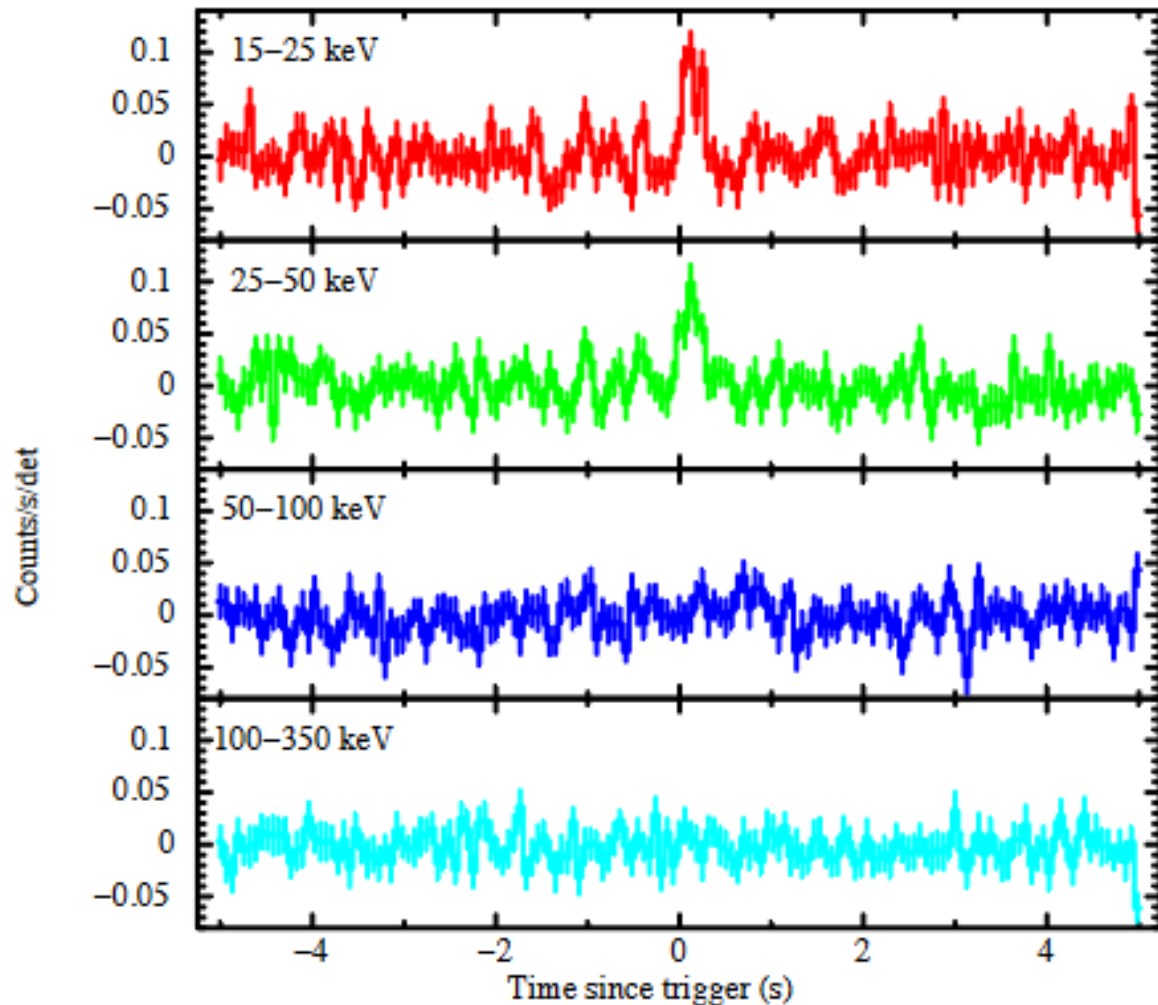
LS I 62 303 - the only example of
a magnetar-like activity in a binary system.
Low luminosity (2 10^{37} erg/s) can point
towards relative low field ($<10^{14}$G)

Another burst was detected by Swift
in 2012 (Burrows et al. 2012).

Spin period 0.27 s (2203.09423)

LS 5039 can be another magnetar
in a gamma-ray binary
if pulsations and the Pdot value
are confirmed (Yoneda et al. 2009.02075).
No bursts, but system similar to LS I +61 303.

HOW TO MAKE AN ACCRETING MAGNETAR?

Igoshev, Popov 1709.10385
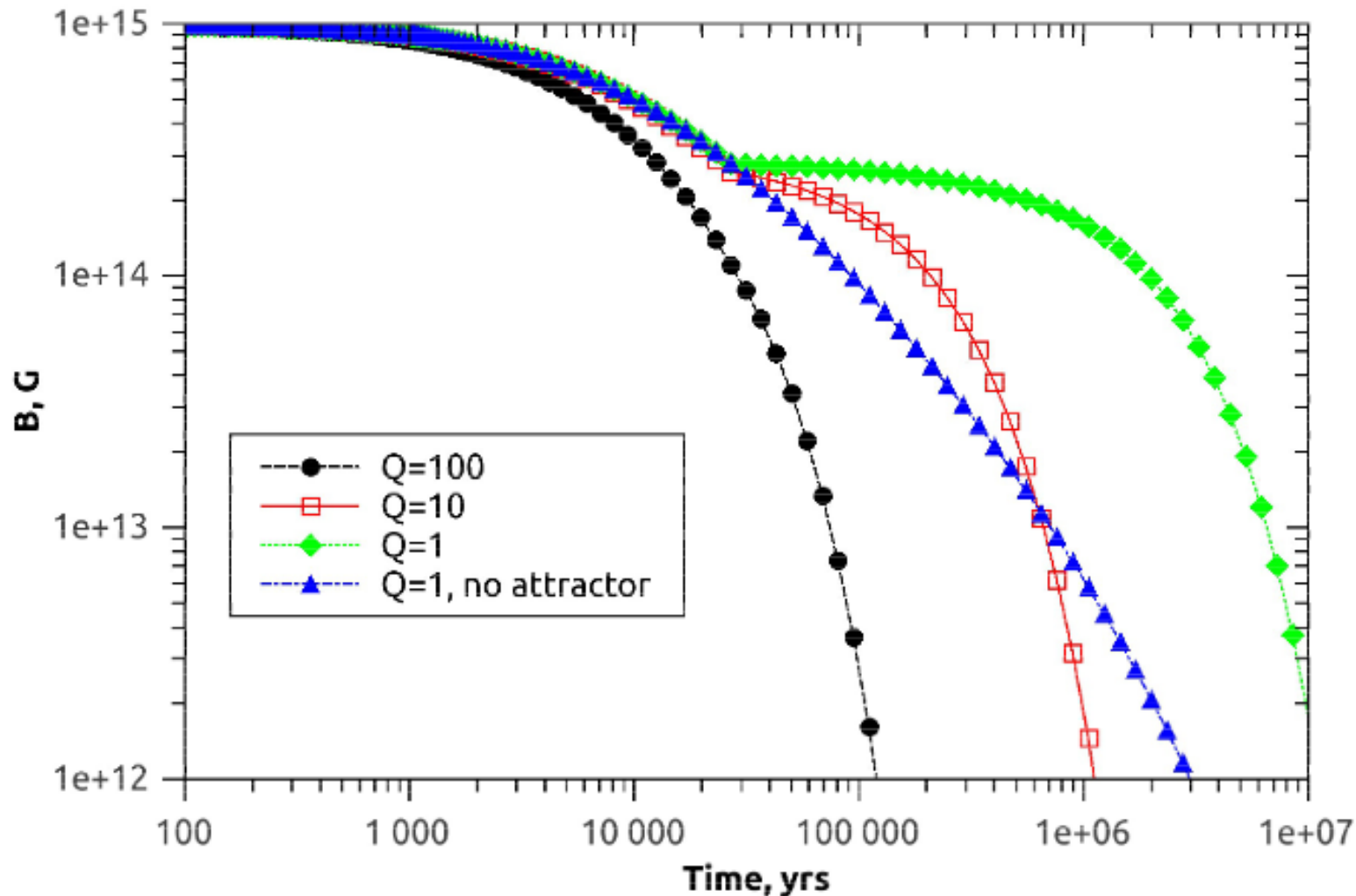
Three conditions are necessary:

1. Hall attractor;
2. Rapid cooling of the crust;
3. Low values of Q.

Hall attractor:
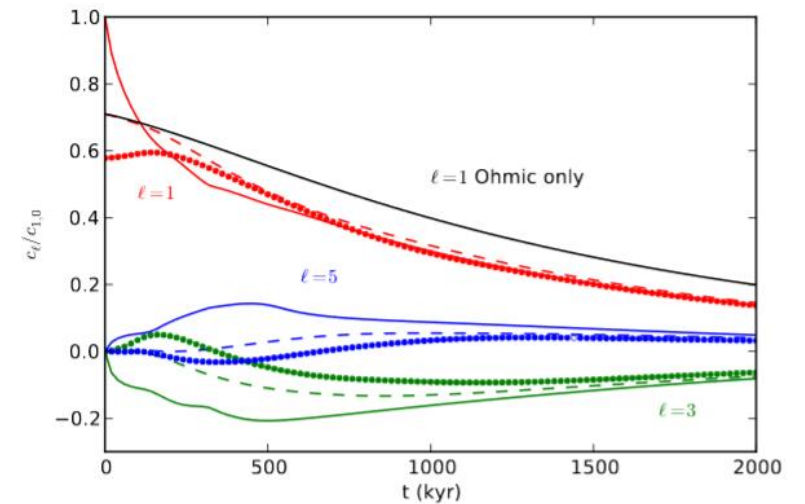
Gourgouliatos, Cumming 1311.7004

HALL CASCADE AND ATTRACTOR

The system is trying to relax towards a state of isorotation, with the electron fluid having the same angular velocity on a poloidal field line.
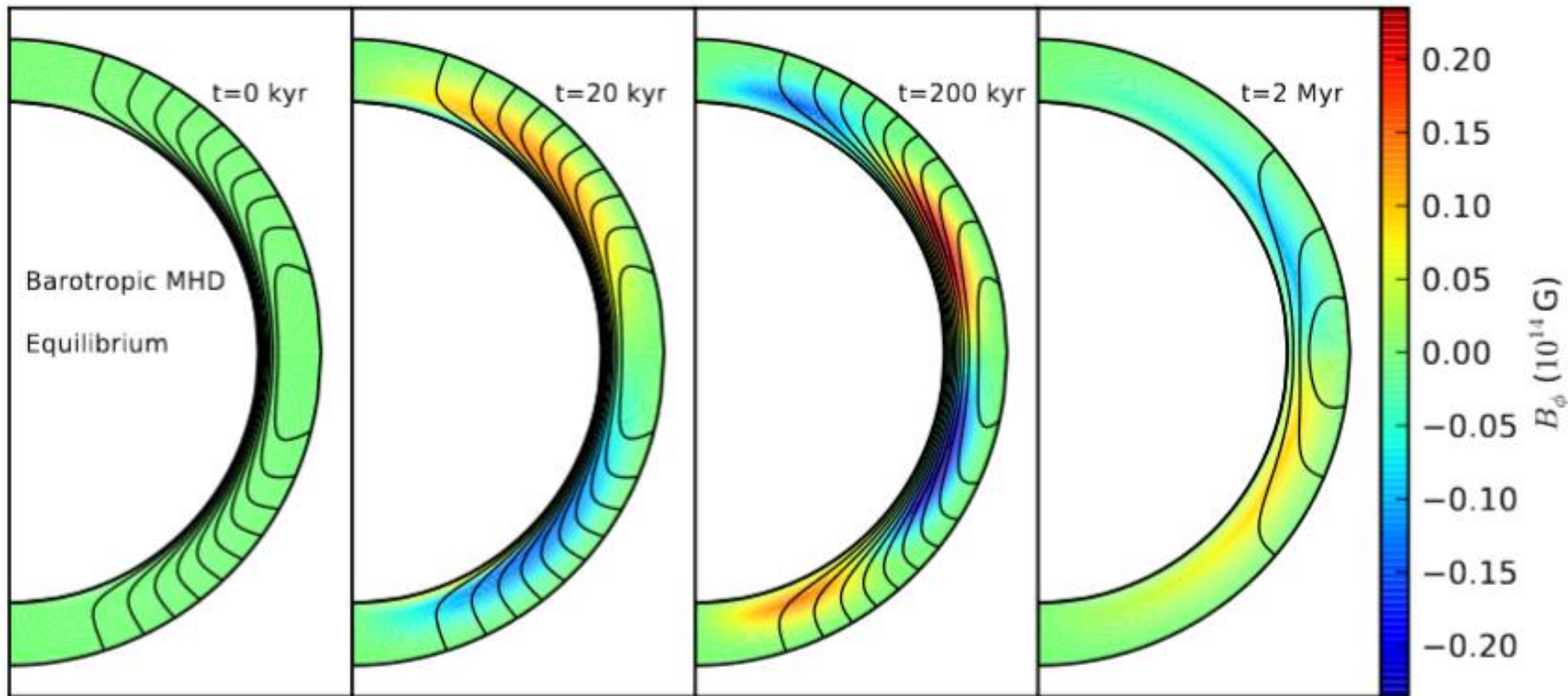
Hall cascade can reach the stage of so-called Hall attractor,
where the field decay stalls for some time (Gourgouliatos, Cumming).

EVOLUTION OF DIFFERENT COMPONENTS

1311.7004
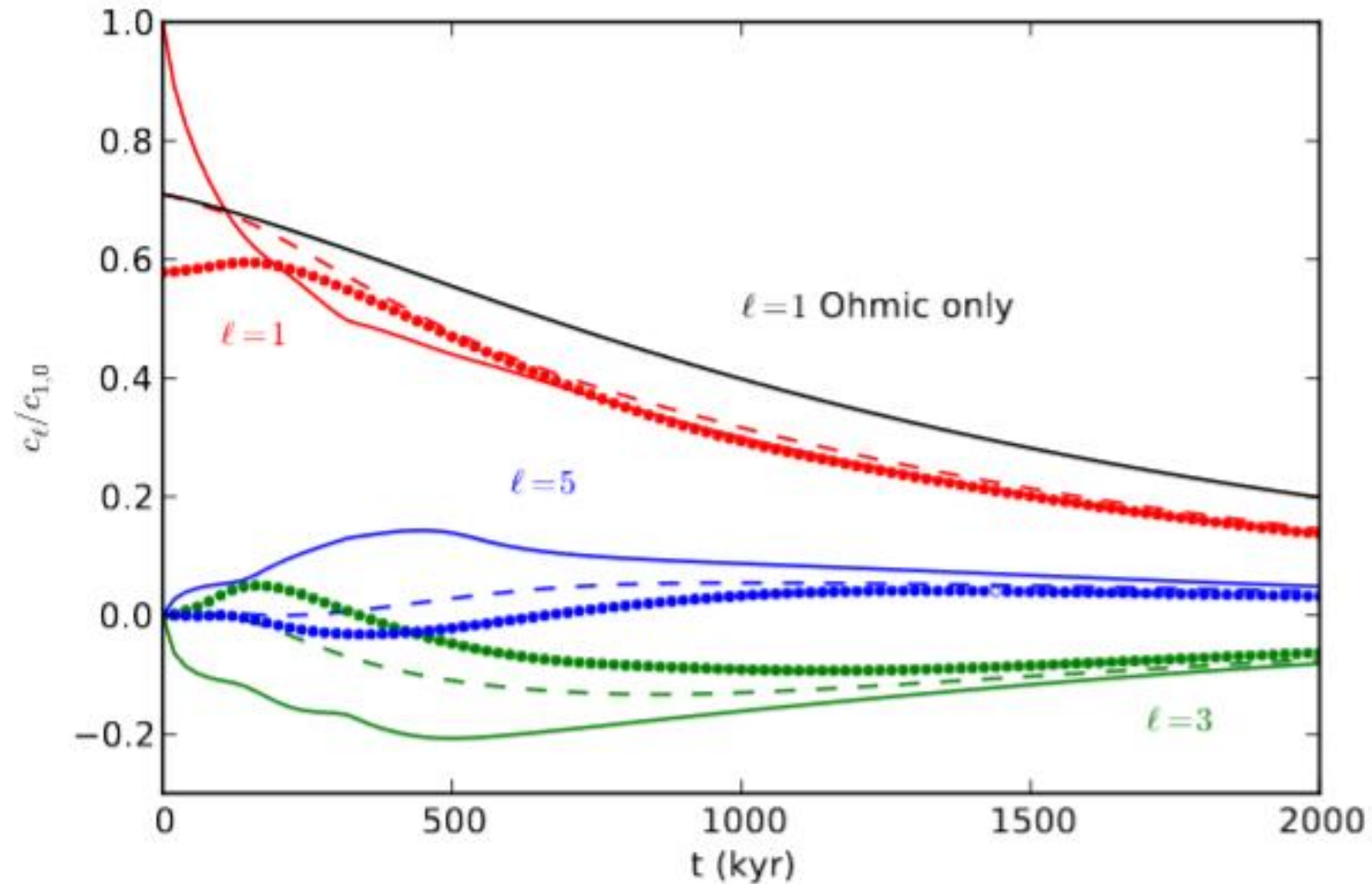
Hall attractor mainly consists of dipole and octupole

INDEPENDENT STUDIES OF THE HALL CASCADE
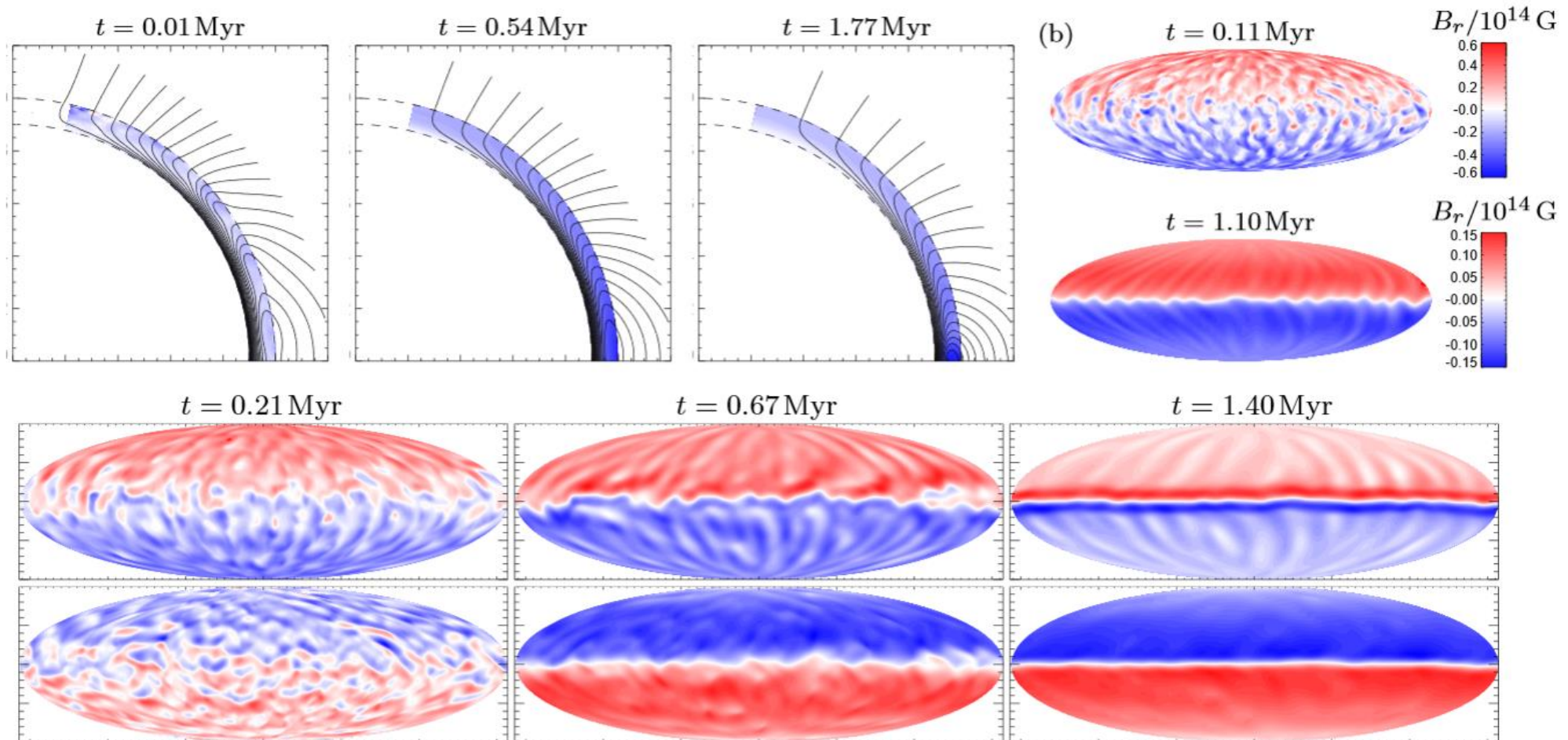
New calculations support the idea of a kind of stable configuration.

See also 1604.01399

CORE AND CRUST FIELD EVOLUTION
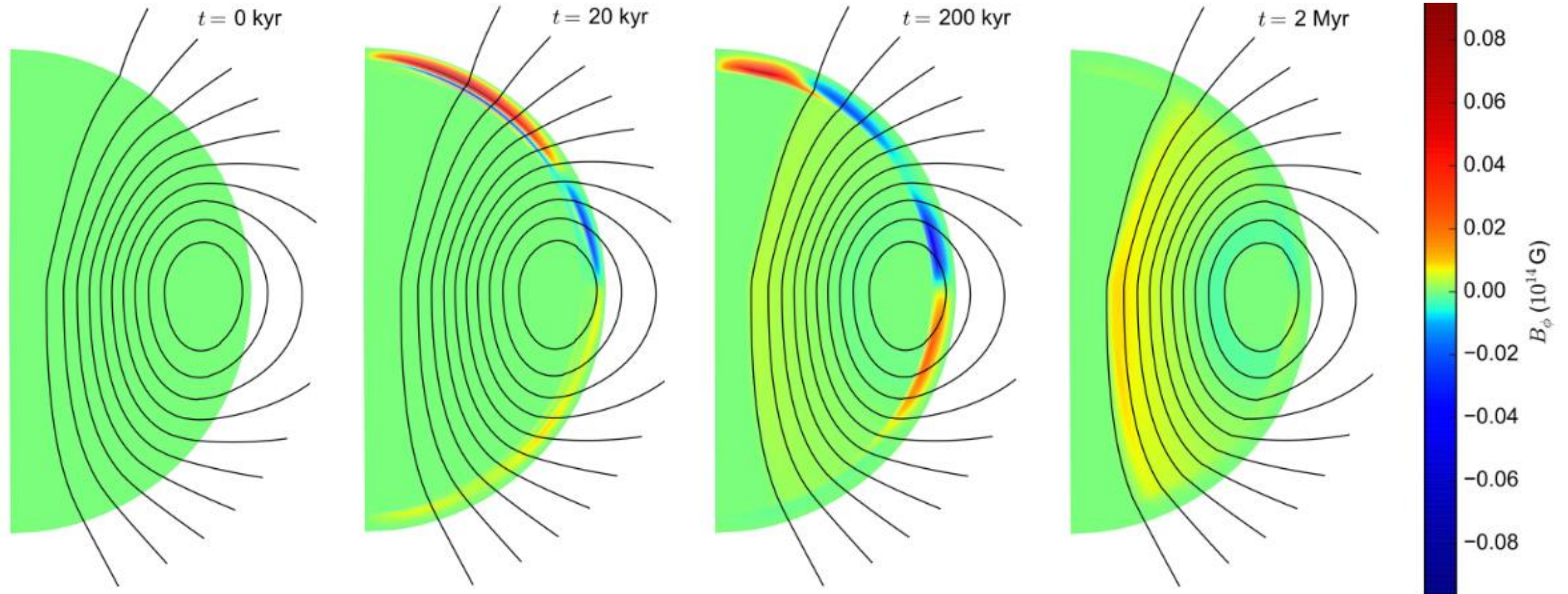
Hall attractor is confirmed.

Q=10

$\tau_{Hall}=10^4$yrs (10^{15} G/B)

$\tau_{Ohm}=2\ 10^6$ yrs/Q
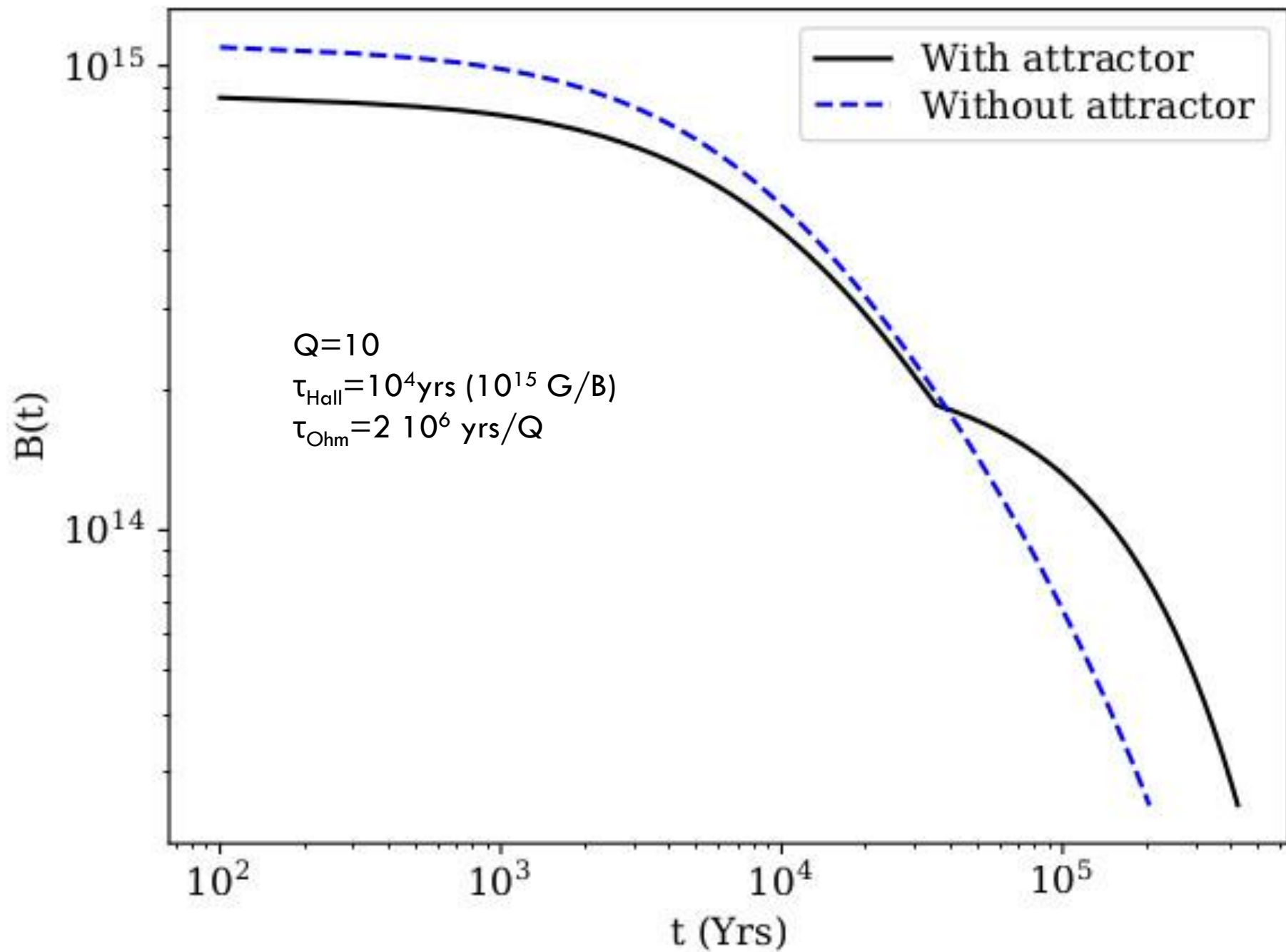
PARAMETERS OF ULX M82 X-2
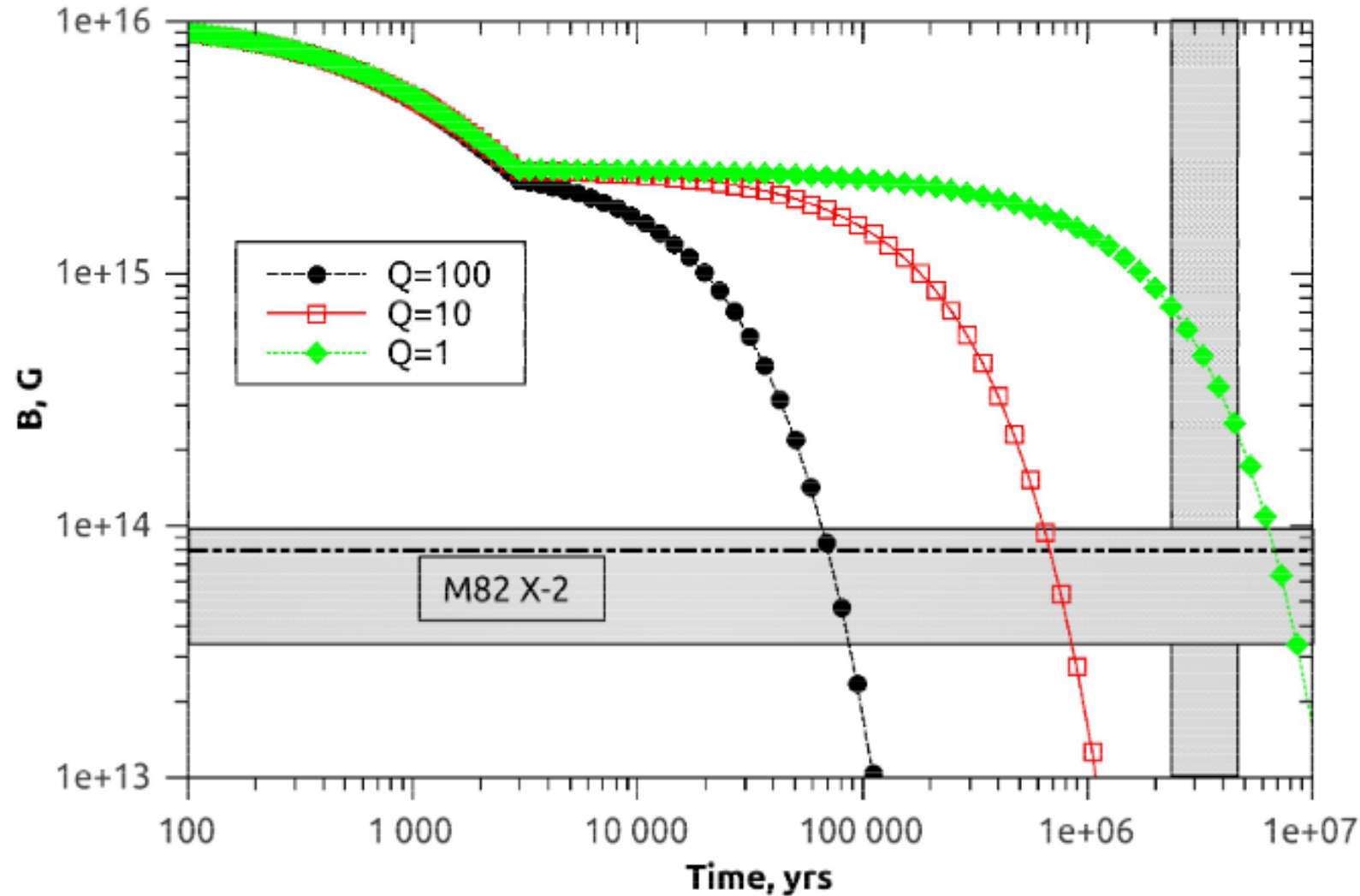
SEARCHING FOR EVIDENCE. I. CYCLOTRON LINES

ULX in M51

If electrons cyclotron – then B~ $6 \cdot 10^{11}$ G.

But the line is too narrow.

If proton cyclotron – then B~ $7 \cdot 10^{14}$ G.

NGC 300 ULX
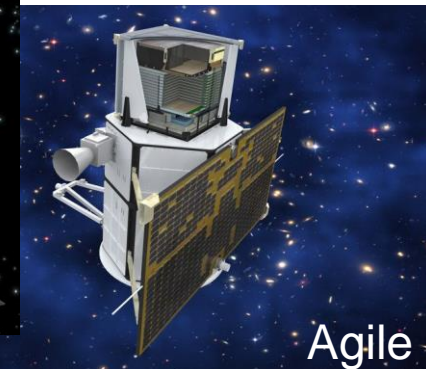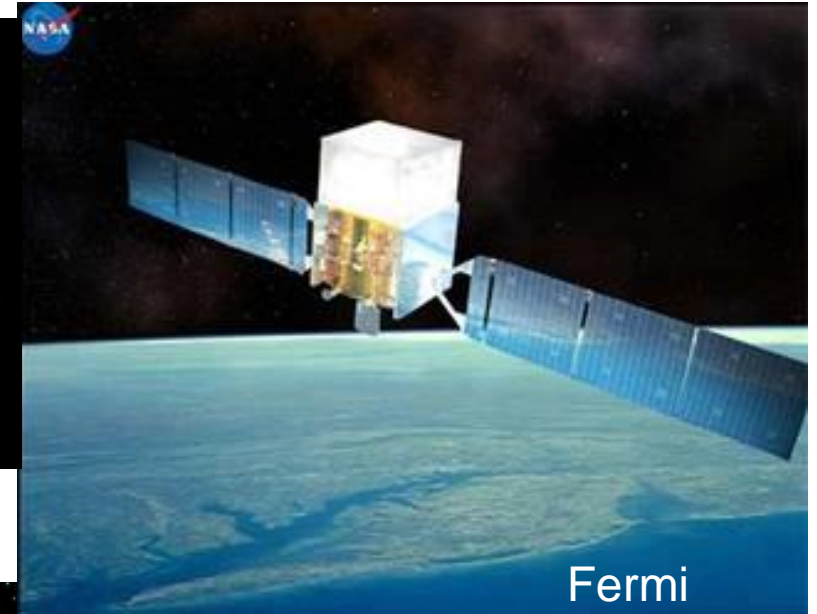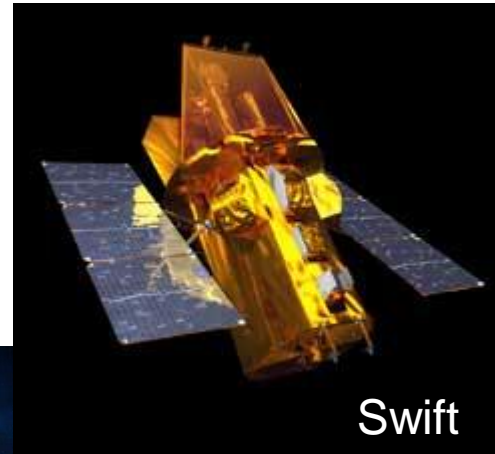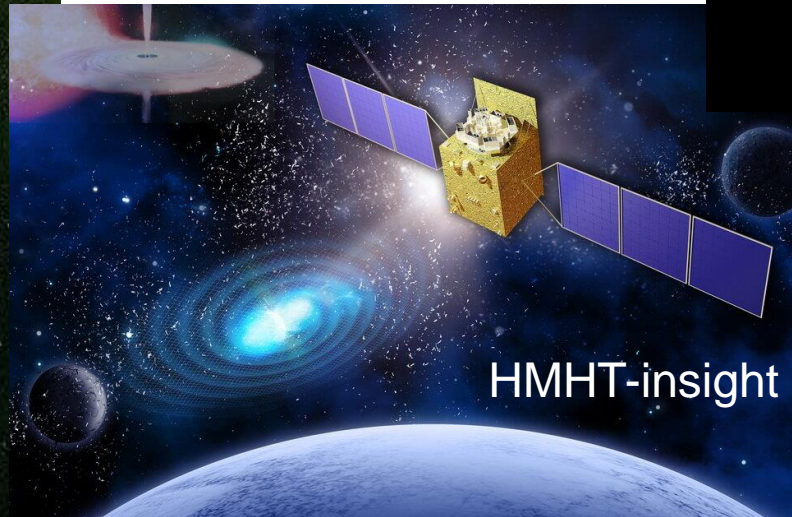
Electron cyclotron lime: B~10^{12} G.
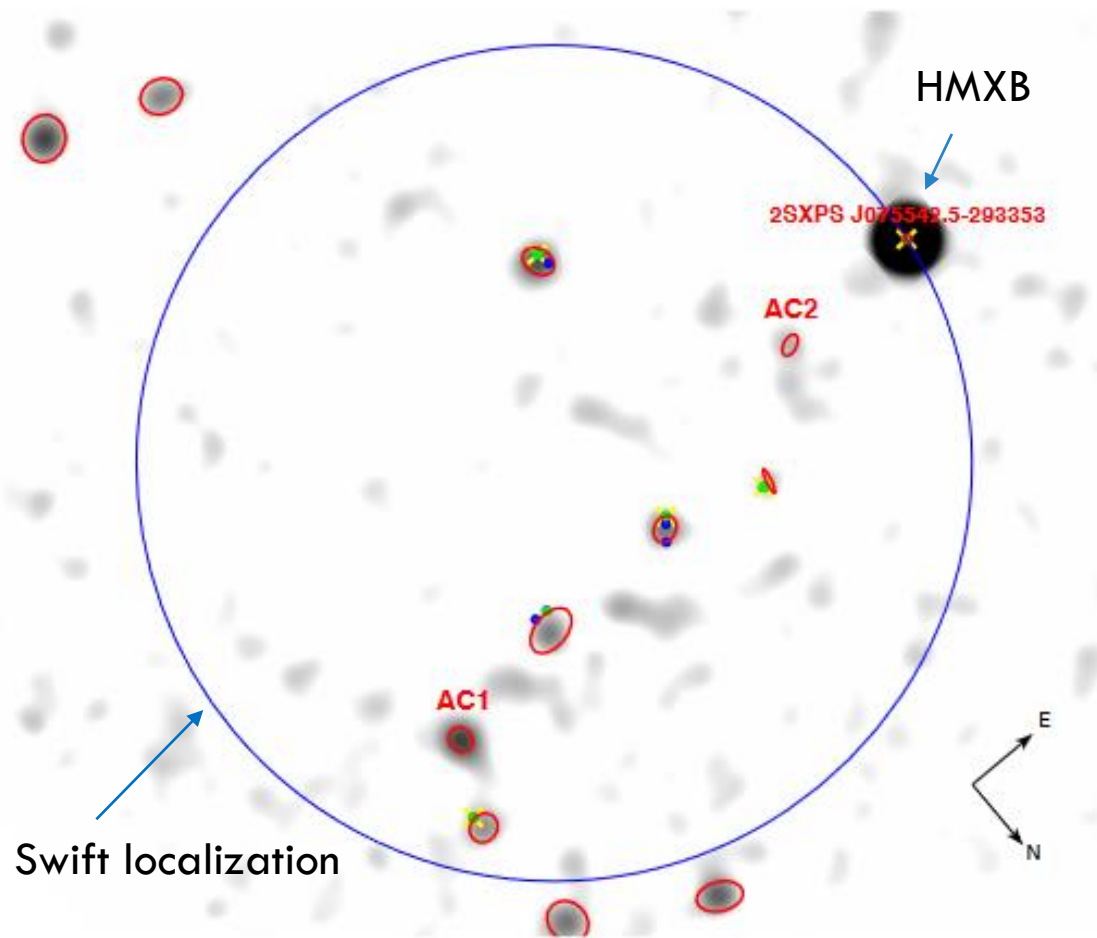
Brightman et al. 1803.02376

Walton et al. 1803.07571
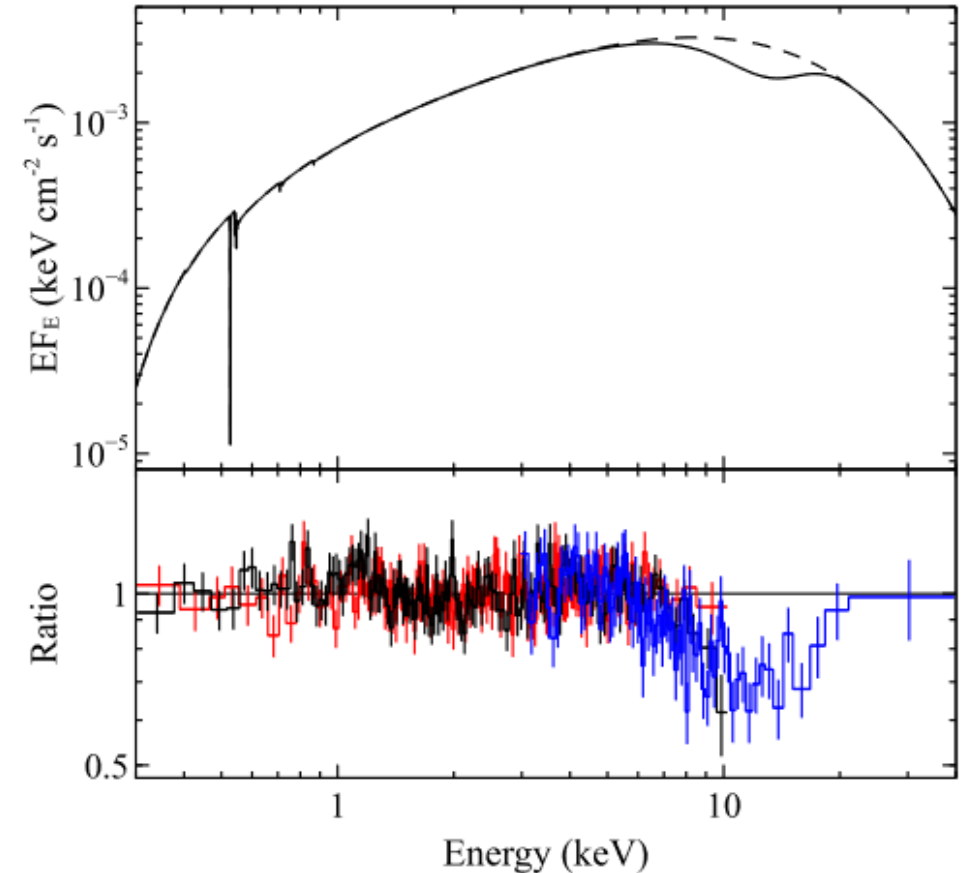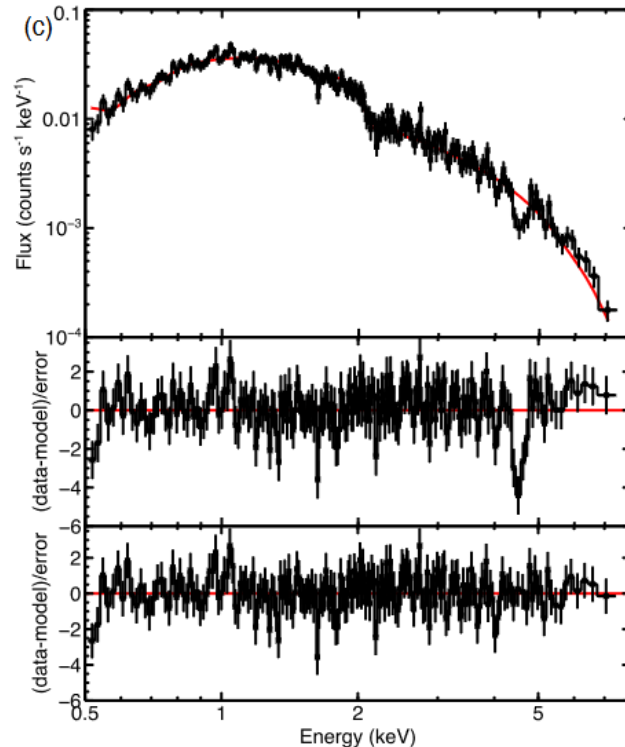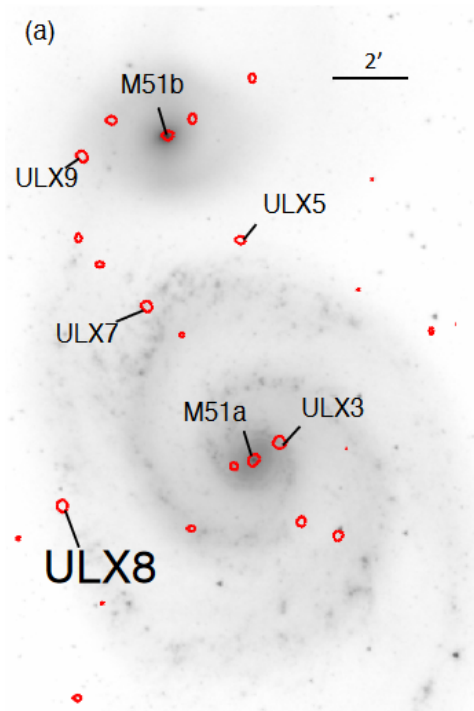
SEARCHING FOR EVIDENCE. II. MAGNETAR ACTIVITY

Continuous monitoring of high energy flares is going on thanks to many space detectors.

Swift

Fermi

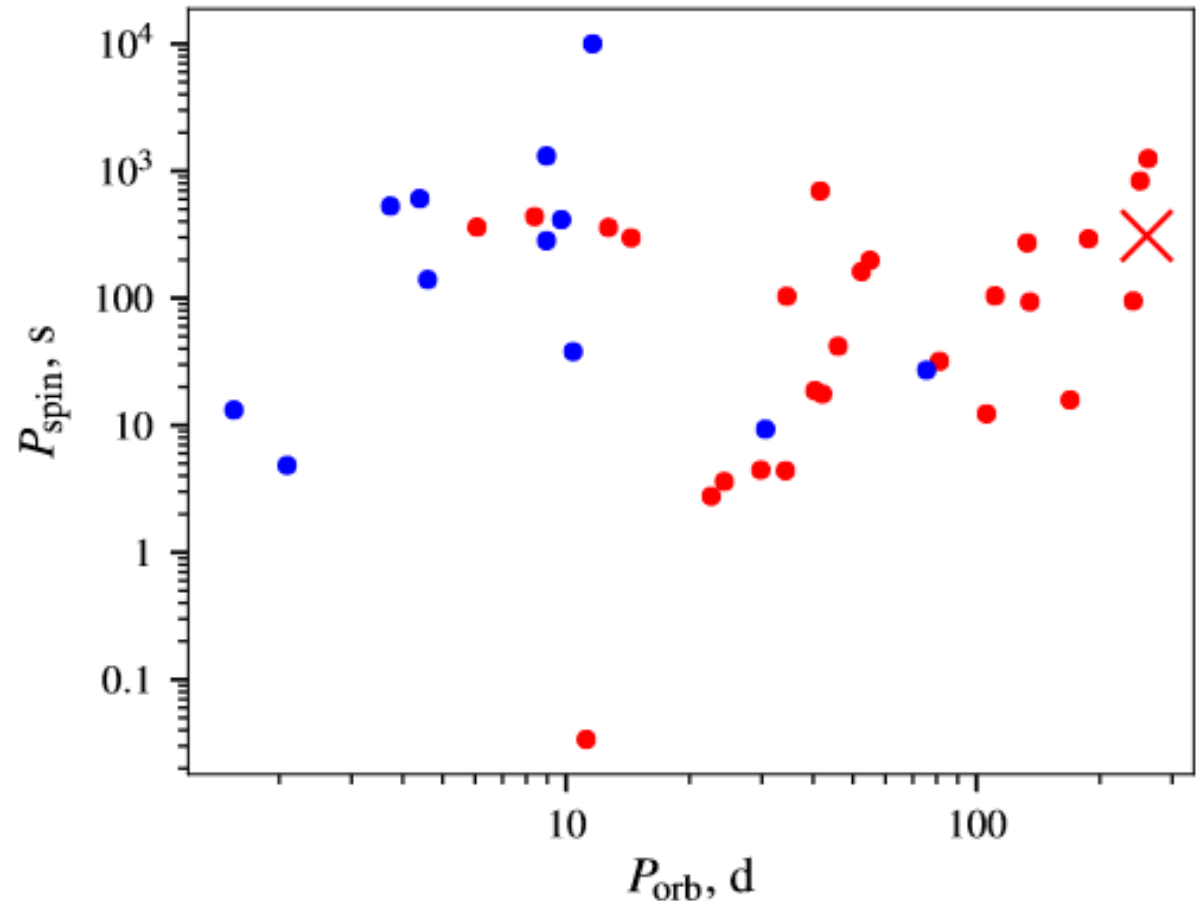HMHT-insight

Konus-Wind

Integral

Agile

THE FIRST EXAMPLE?

SGR 0755–2933

One 30 msec burst detected by Swift in 2016
Coincident with a HMXB.

See 2302.00027 about the evolution of this system

Doroshenko et al. 2101.10834

(UNCERTAIN) CONCLUSIONS

Still, we are not sure
if there are magnetars
in binary systems.

Some evidence exists,
but definite proof is lacking.
Also, formation mechanism and
evolution are uncertain.

Important for:

- origin of magnetars;
- field evolution;
- accretion physics;
- FRBs.

Perspectives:

Detection of activity — ultimate proof
for REAL magnetars in binaries.

Are there relatively old (few Myrs) NSs
with large fields, but no magnetar-like activity?

2201.07507