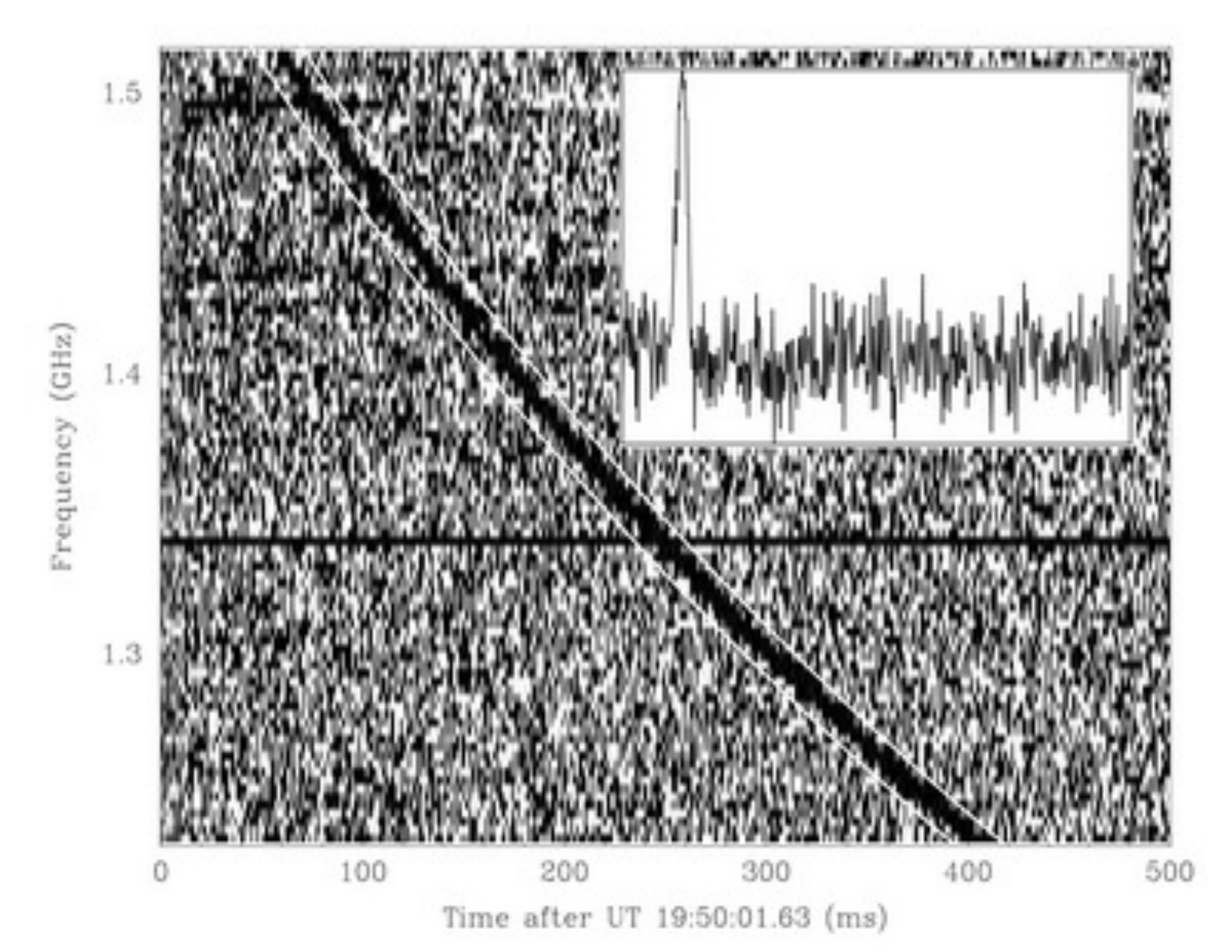
ARTHUR SUVOROV, KOSTAS KOKKOTAS, SEPTEMBER 20, YEREVAN

YOUNG MAGNETARS WITH FRACTURING CRUSTS AS FAST RADIO BURST REPEATERS

FRB REPEATERS: A COSMIC MYSTERY

- Fast Radio Bursts (FRBs) are ~ms duration, bright (~Jy flux) extragalactic bursts of unknown origin. These observations suggests compact object progenitor

$$\left(\frac{E_{\rm FRB}}{1.2\times10^{39}\ {\rm erg}}\right)\approx\left(\frac{F}{\rm Jy\ ms}\right)\left(\frac{\nu}{\rm GHz}\right)\left(\frac{D}{\rm Gpc}\right)^2(1+z)^{-1}$$



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- Neutron stars collapsing to black holes, ejecting “magnetic hair” (Falcke & Rezzolla ‘14
- Merger of charged black holes (Zhang ‘16; Liu et al. ’16; Liebling & Panenzuela ‘16)
- Magnetospheric activity during neutron star mergers (Totani ‘13)
- Unipolar inductor in neutron star mergers (Hansen & Lyutikov ‘01; Piro ‘12; Wang et al.
- White dwarf mergers (Kashiyama et al. ‘13)
- Pulses from young neutron stars (Cordes & Wasserman ’15; Connor et al. ‘15; Lyutikov & Pshirkov ’16; Kashiyama & Murase ‘17)
- (Young) Magnetars (Popov et al. ’07; Kulkarni et al. ‘14; Lyubarsky ‘14; Katz ‘15; Pen & Kumar ‘16; Metger et al. ’ 17; Beloborodov ‘17; Margarlit & Metzger ‘18)
- Schwinger instability in young magnetars (Lieu ‘17)
- Sparks from cosmic strings (Vachaspati ‘08; Yu et al. ‘14)
- Evaporating primordial black holes (Rees ’77; Keane et al. ‘12)
- White holes (Barrau et al. ’14)
- Flaring stars (Loeb et al. ‘13; Maoz et al. ‘15)
- Axion stars (Tkachev ‘15; Iwazaki ‘15)
- Asteroids/comets falling onto neutron stars (Geng & Huang ’ 15; Dai et al. ‘16)
- Quark novae (Chand et al. ‘15)
- Dark matter-induced collapse of neutron stars (Fuller & Ott ‘15)
- Higgs portals to pulsar collapse (Bramante & Elahi ’15)
- Planets interacting with a pulsar wind (Mottez & Zarka ’15)
- Black hole superradiance (Conlon & Herdeiro ‘17)
- Extragalactic light sails (Lingam & Loeb ‘17)
- Neutron star-white dwarf binaries (Gu et al. ’16)
- Clumpy jets from accreting black holes (Yi et al. ’19)
- Black hole interacting with an AGN (Das Gupta & Saini ‘17; Waxman ‘17)
- Wandering AGN beam (Katz ’17)
- Black hole laser powered by axion superradiant instabilities(Rosa & Kephart ‘18)

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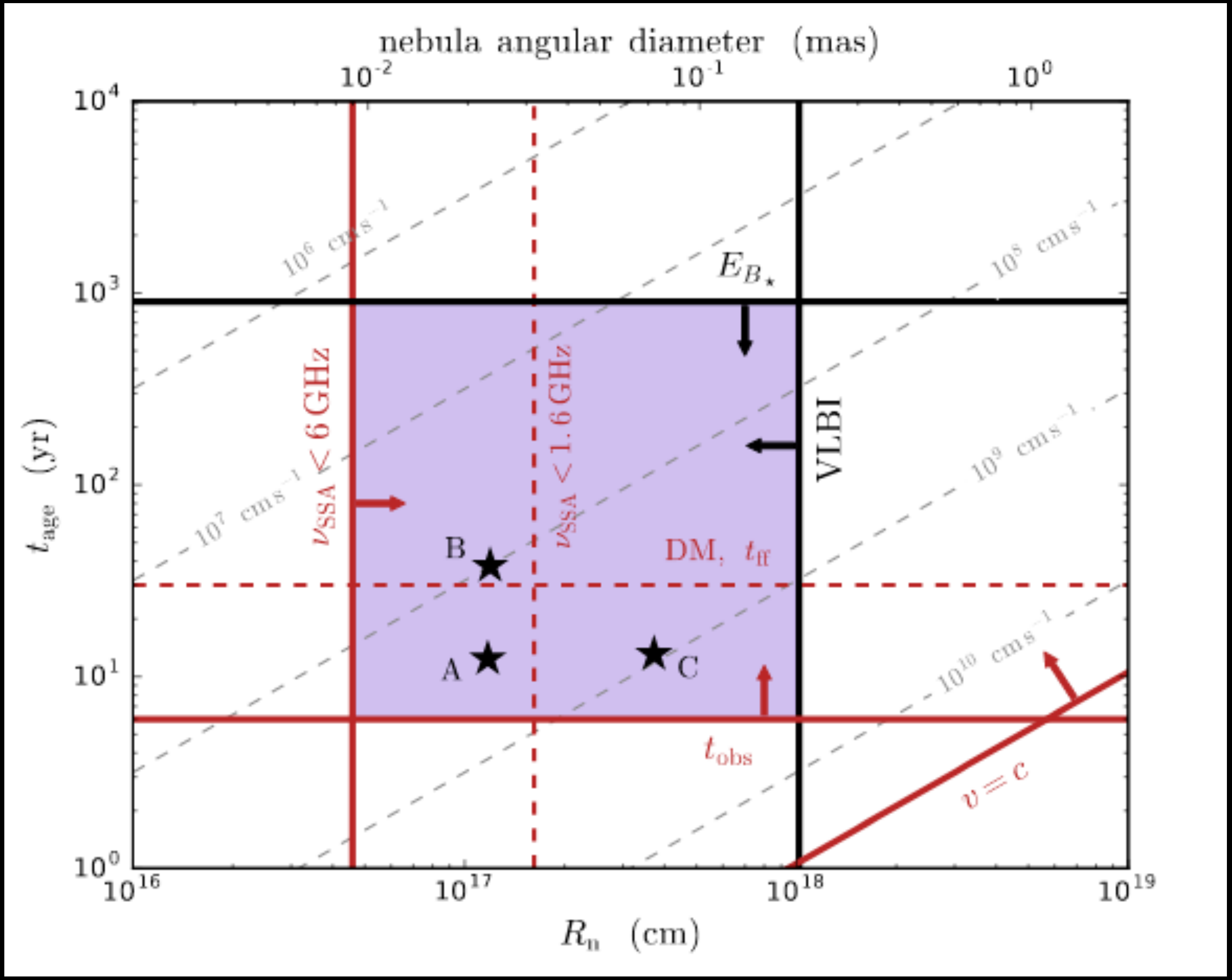
- For FRB 121102, upper limit set by the ability for the source to power the persistent emission; ~30–100 yrs old (Margalit & Metzger 2018)

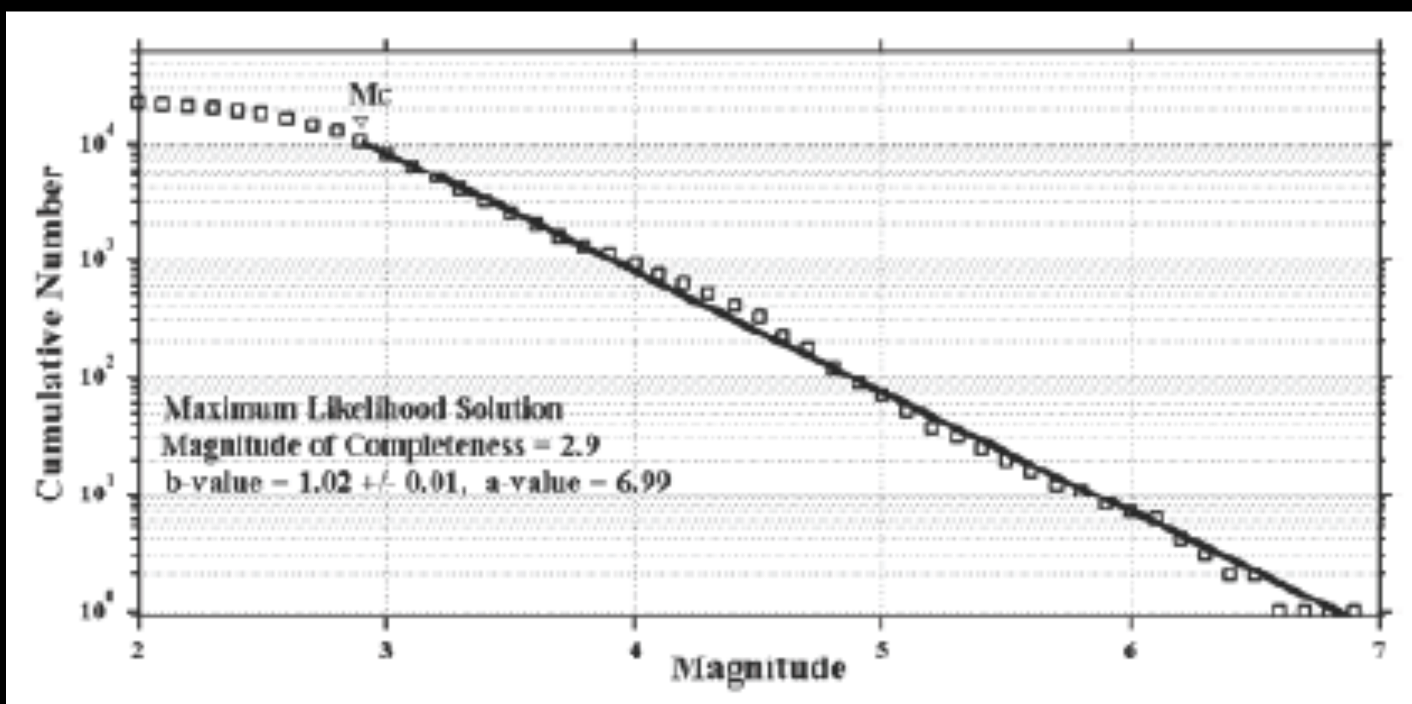
$$t_{\rm age}\lesssim\frac{E_{\rm B_\star}}{\nu L_\nu}\approx900\,B_{16}^2\ {\rm yr}$$

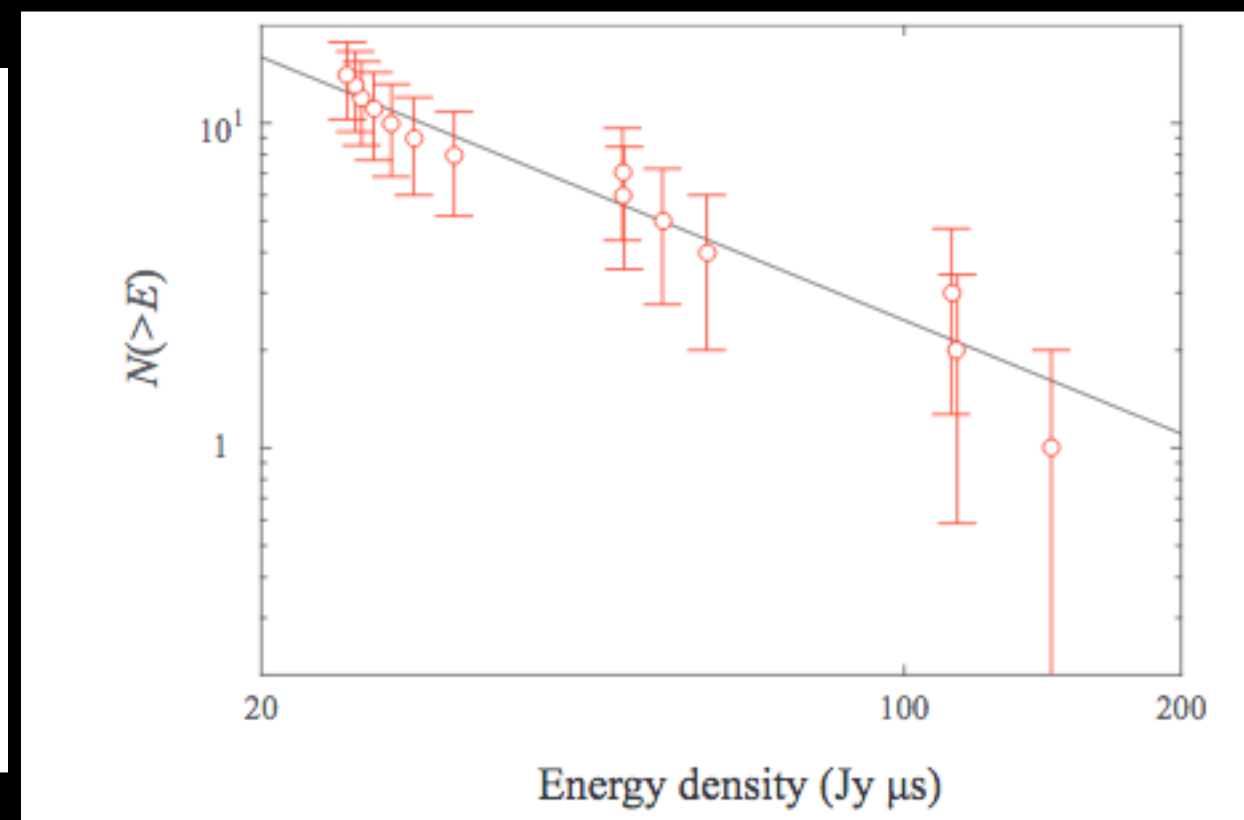


Age and size of persistent source (radius of synchrotron nebula) constraints; Margalit & Metzger 2018

ENERGETICS OF FRB 121102

Energetics seem to follow power-laws (Wang et al. 2018), with exponent matching the Gutenberg-Richter (1956) law for earthquakes; tectonic neutron star progenitor?





Earthquakes
(Öztürk 2017)

$$N(>E) \propto \int_E^{\infty} E^{-\alpha} dE \propto E^{-\alpha+1}$$

FRB 121102
(Wang et al. 2018)

CRUST FRACTURING LEADING TO FRBS

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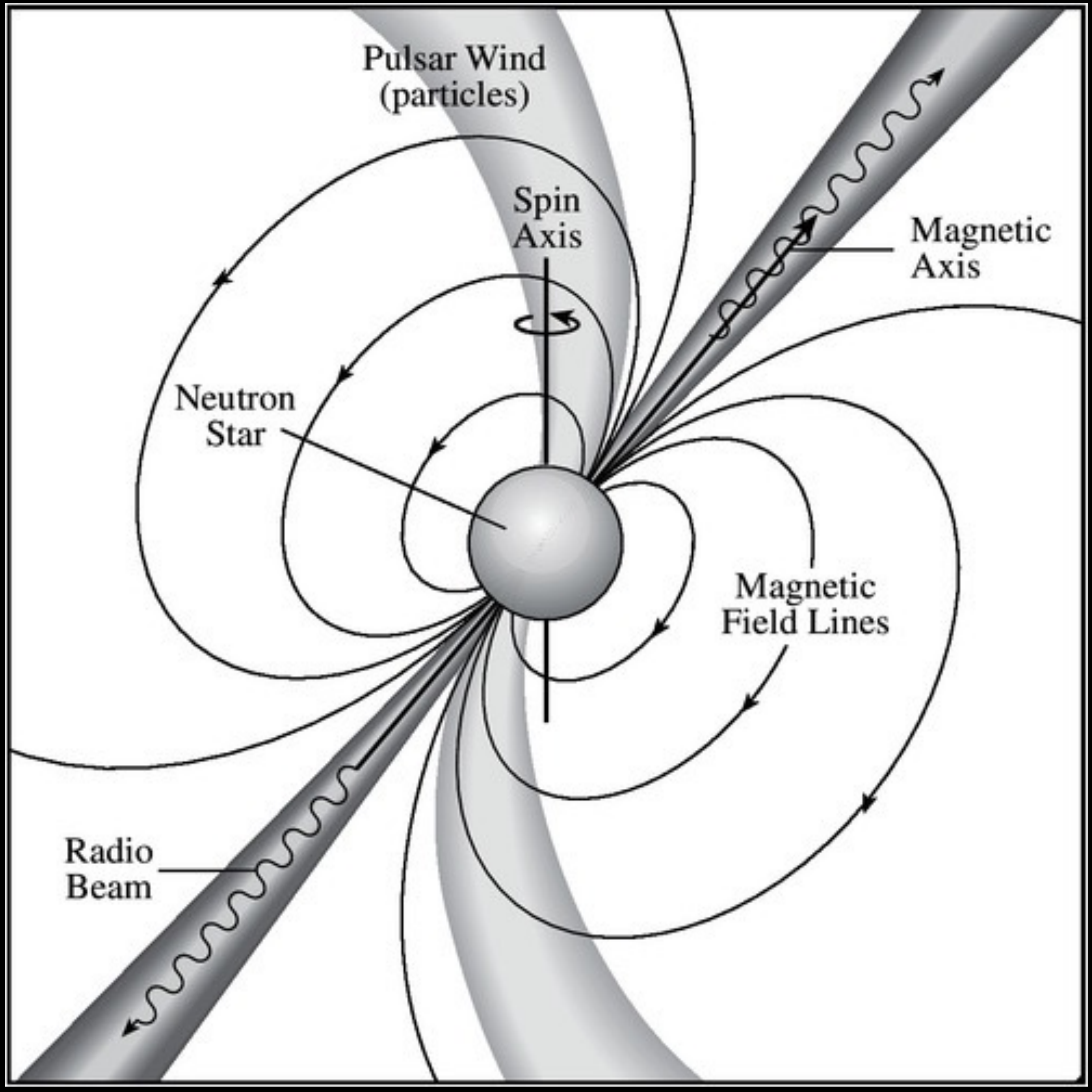


- Crustal slippage events dislocate field line `anchor points', injecting magnetic twist into the magnetosphere in ~milliseconds (Lyutikov 2015; Wadiasingh & Timokhin 2019)
- Electrons in the magnetosphere are then accelerated with large Lorentz factor due to magnetic reconnection, and move along magnetic field lines, producing curvature radiation with ~GHz frequencies.

$$\nu_c = \frac{3c\gamma^3}{4\pi R_c} = 7.16 \times (\frac{\gamma}{100})^3 (\frac{10\,\mathrm{km}}{R_c})\,\mathrm{GHz}$$

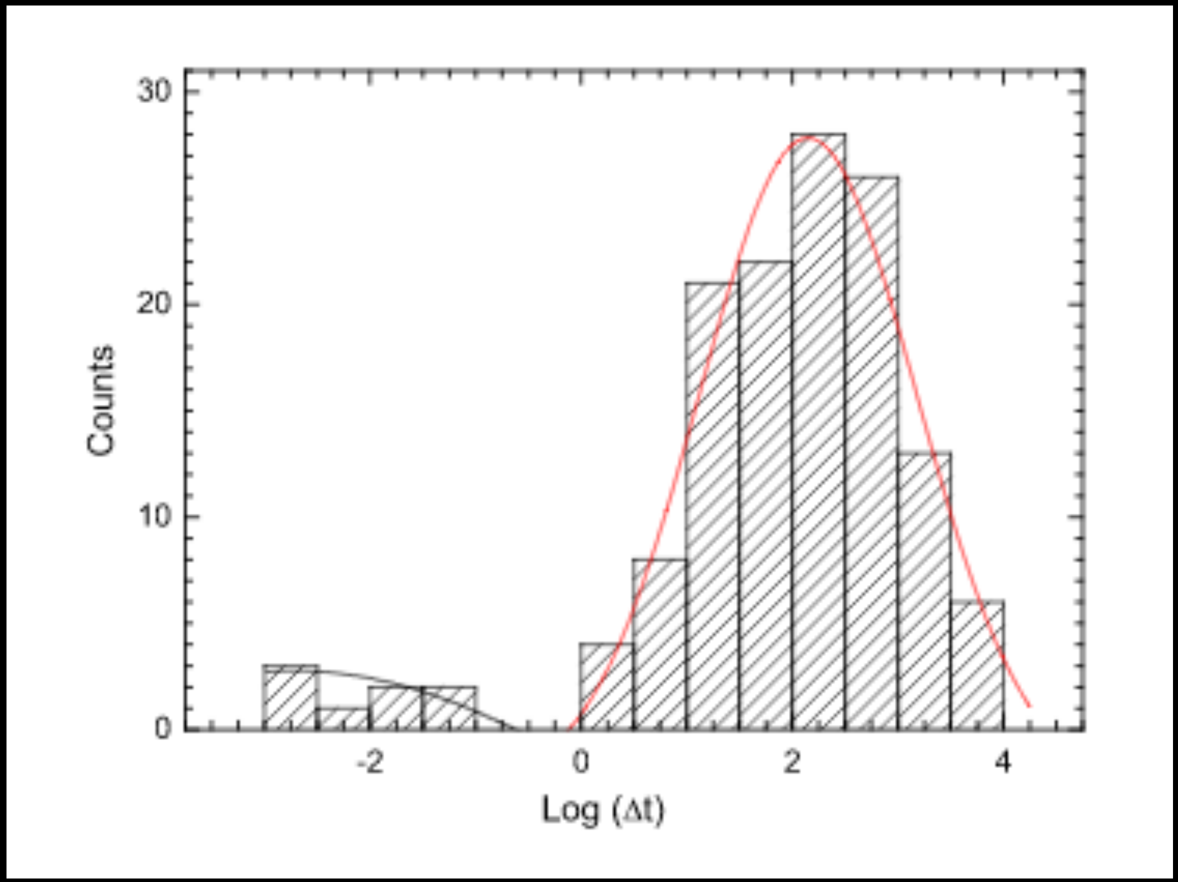
- Several other possibilities have been considered (e.g. Beloborodov 2017 — relativistic internal shocks in the magnetar wind, launched by magnetospheric flares)

WAITING TIMES OF FRB 121102

Li et al. (2019) found that the waiting times appear to be bimodal, clustering around ~10^{-3} s (possibly Alfvén) and at separately ~10^{2} s (possibly global elastic mode instability; Thompson et al. 2017; i.e. something related to mechanical processes in the crust)

$$t_A \sim 10^{-3} \left(\frac{\rho}{10^{13}\ \mathrm{g\ cm^{-3}}}\right)^{1/2} \left(\frac{L}{10^{5}\ \mathrm{cm}}\right) \left(\frac{B}{10^{15}\ \mathrm{G}}\right)^{-1} \mathrm{s},$$

Also found little-to-no correlation between energetics and waiting times; strange if the mechanism is expected to be intrinsic (i.e. longer wait usually means more energy)



(Li et al. 2019)

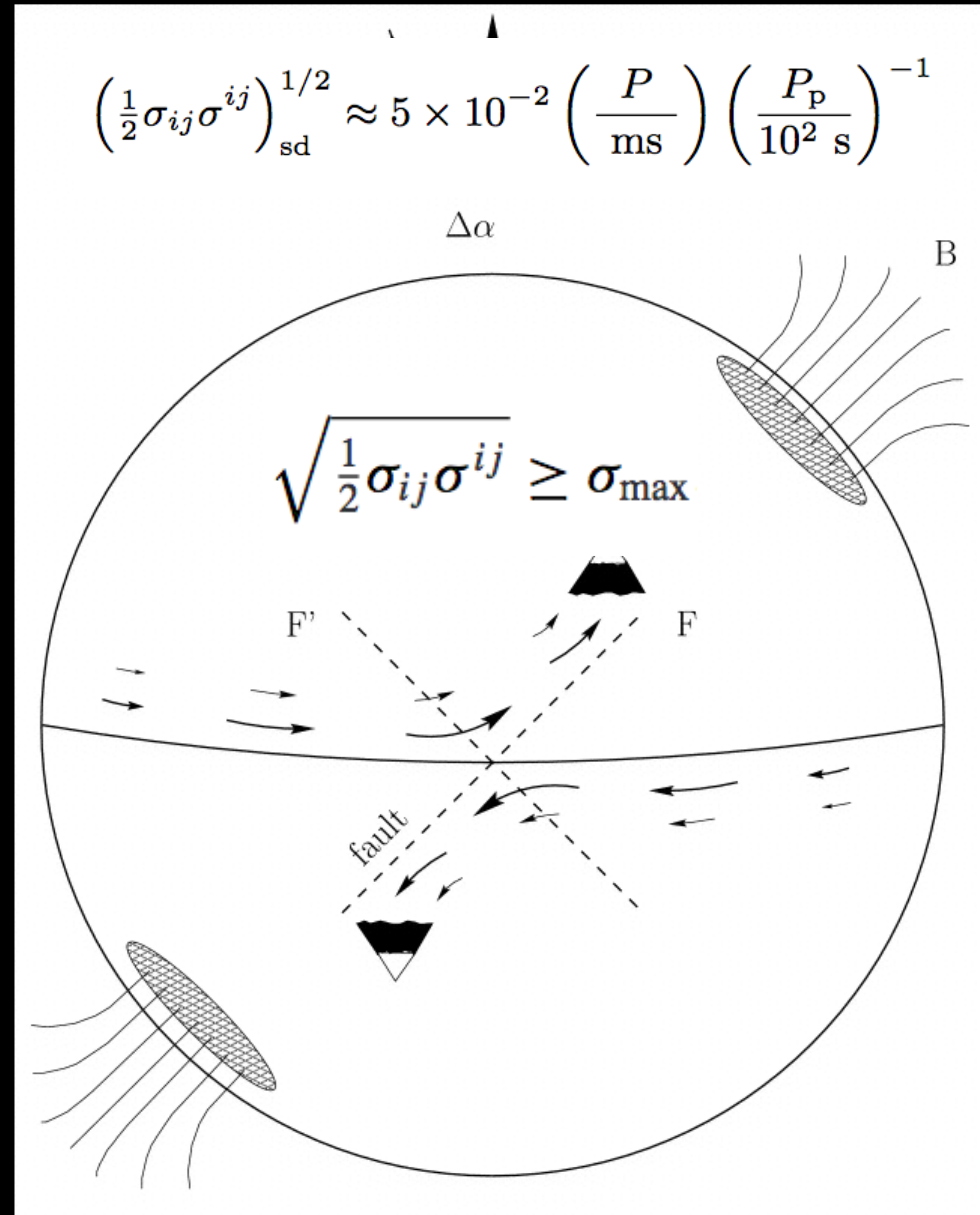
STATISTICAL CURIOSITY

- The bursts seem to admit properties in line with those seen in earthquakes; so perhaps tectonic activity on young neutron stars is responsible for the FRBs?

- Assuming a quake scenario, what mechanism can force crust failures within neutron stars, with ages <100 years (as for FRB 121102) which also allows for this non-correlation? Magnetic stress? Spin-down?

$$\mu\sigma_{ij} = \mathcal{M}^0_{ij} - \mathcal{M}_{ij}$$

$$\mathcal{M}_{ij} = \frac{1}{4\pi}\left(B_i B_j - \frac{1}{2}B^2\delta_{ij}\right)$$



(Franco et al. 2000)

HALL DRIFT

- Magnetars with very strong magnetic fields, >~ 10^15 G; when they are young, and rapidly rotating, magnetic field can evolve rapidly through Hall drift.

- The process of field line advection due to the generation of an electric current from magnetic flux transport by mobile electrons

$$t_{\rm H} \sim 640 \left(\frac{n_e}{10^{34}\ {\rm cm}^{-3}}\right)\left(\frac{L}{10^5\ {\rm cm}}\right)^2\left(\frac{B}{10^{15}\ {\rm G}}\right)^{-1} {\rm yr},$$

- If the field is also strongly multipolar, then the differing L-fields will reconfigure at seemingly stochastic intervals

- Gourgouliatos et al. (2016) showed that Hall drift can induce significant magnetic field rearrangements within ~100 years for stars with `turbulent' fields.

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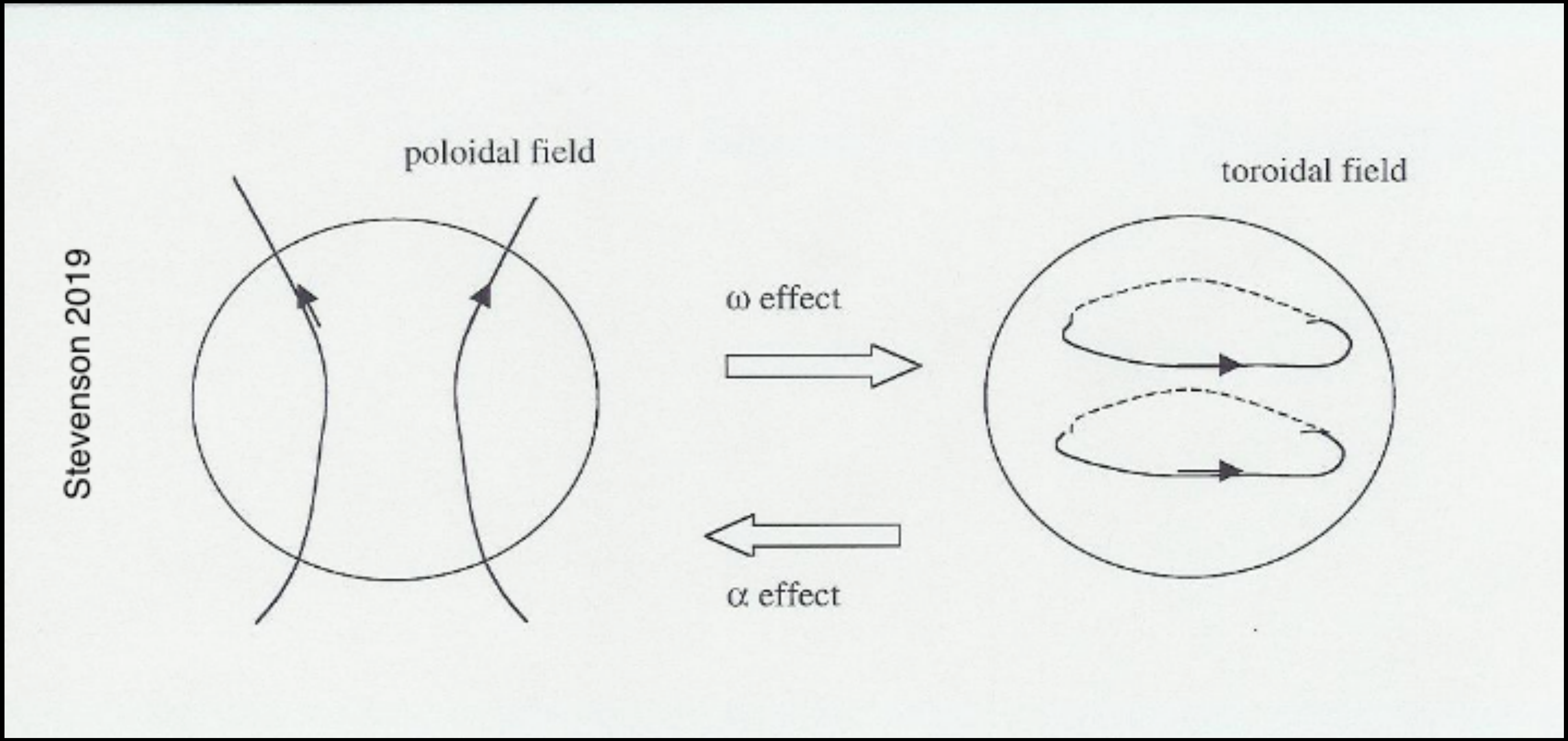
- Following a collapse, the magnetic field can be amplified or tangled due to:
- Core-Surface differential rotation and turbulent convection dynamo (Thompson & Duncan 1992);



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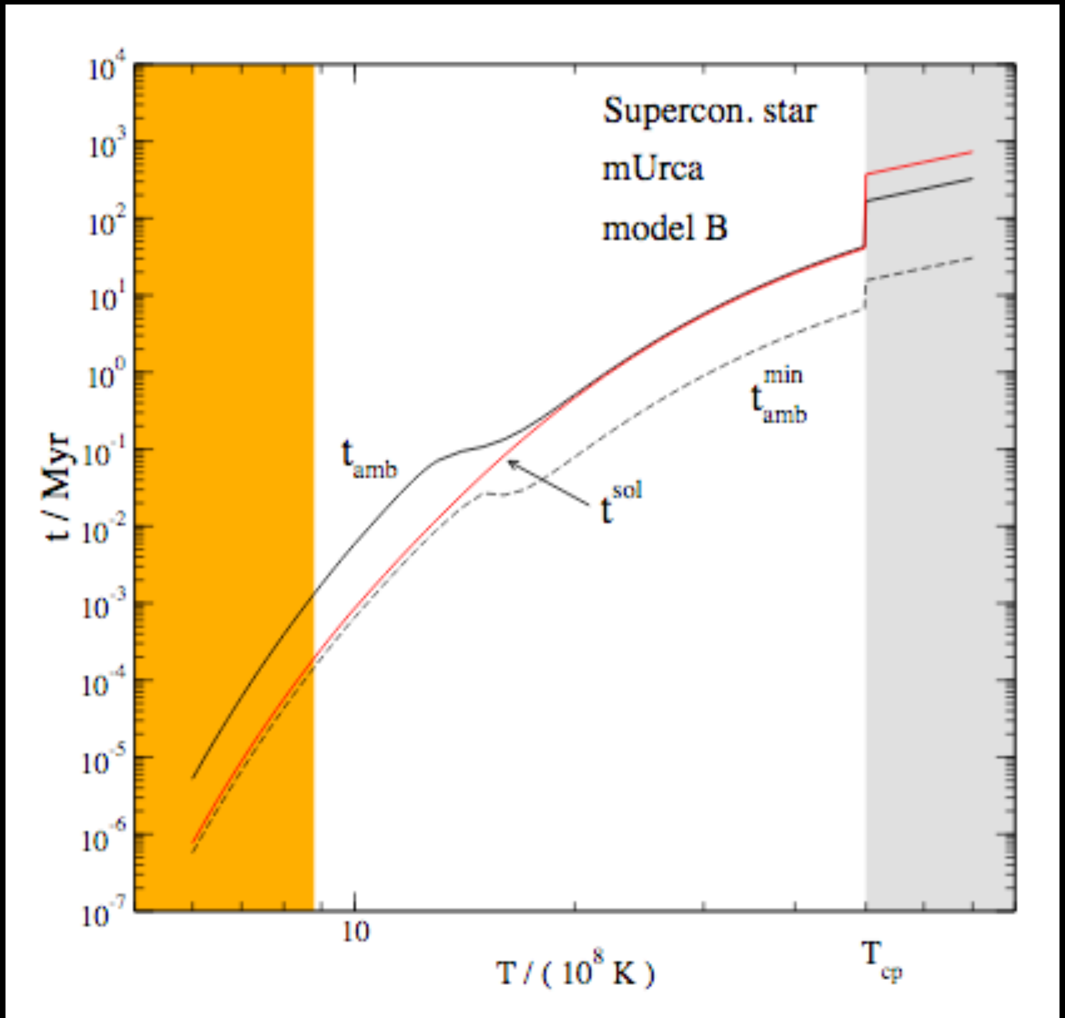

(Passamonti et al. 2017)

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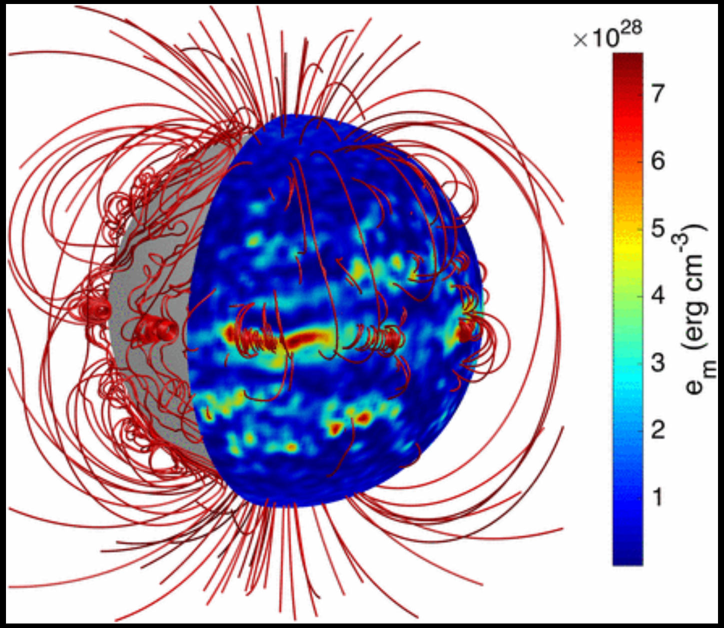
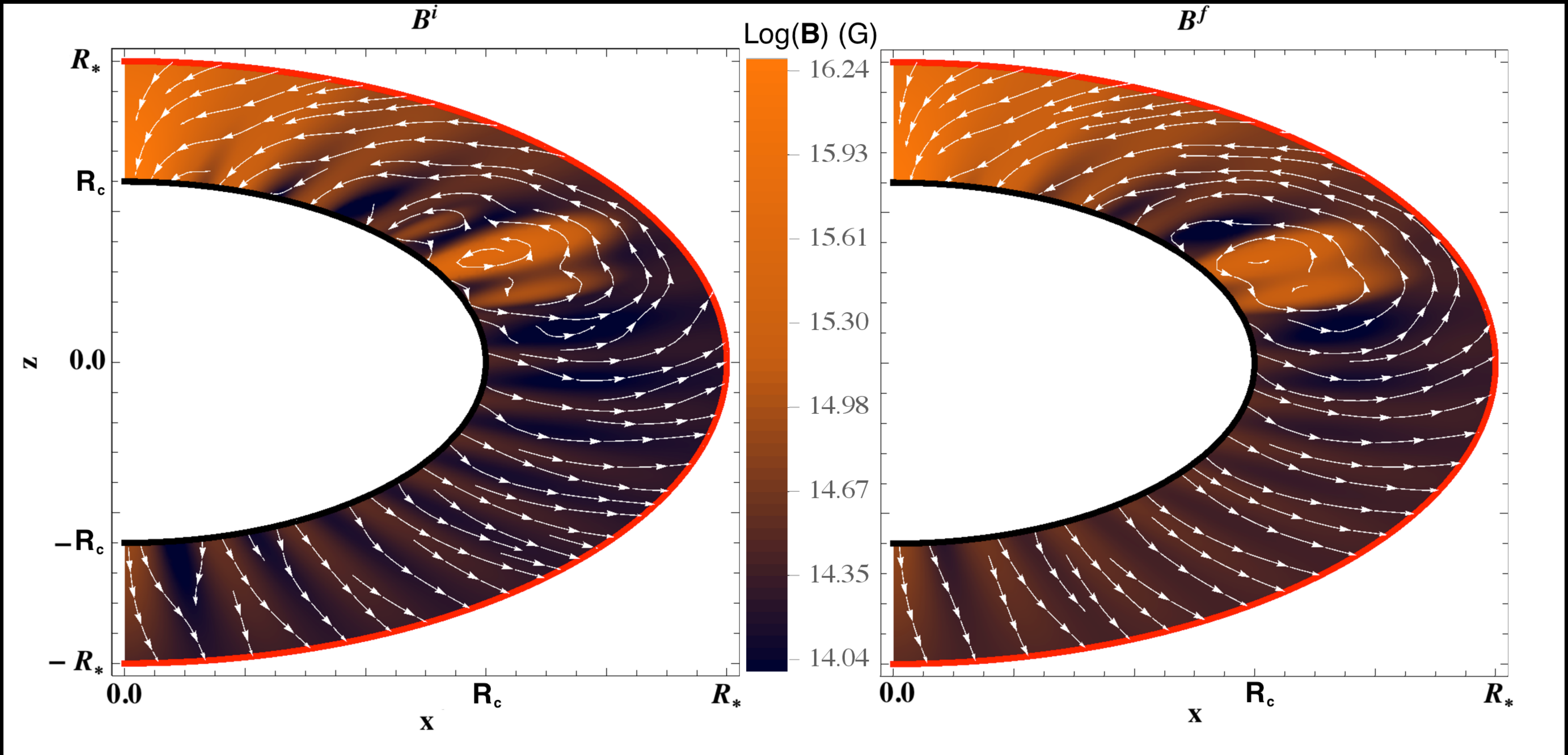
- Shockwave instabilites from the core bounce (Endeve et al. 2012);
- Superfluid turbulence (Peralta et al. 2005; Ferrario et al. 2015);
- Magnetorotational instability (Shibata et al. 2006; Sawai et al. 2013);
- Thermoelectric instabilites (Geppert 2017);
- Kelvin-Helmholtz instability at the shear layers (Price & Rosswog 2006);
- Fermionic Chiral imbalances (Del Zanna & Bucciianti 2018);



Gourgouliatos et al. (2016)

MAGNETIC FIELD EVOLUTION

- Star is born with a `turbulent' magnetic field, which then evolves rapidly through Hall drift (and later Ohmic diffusion) — gradually `unwinding'

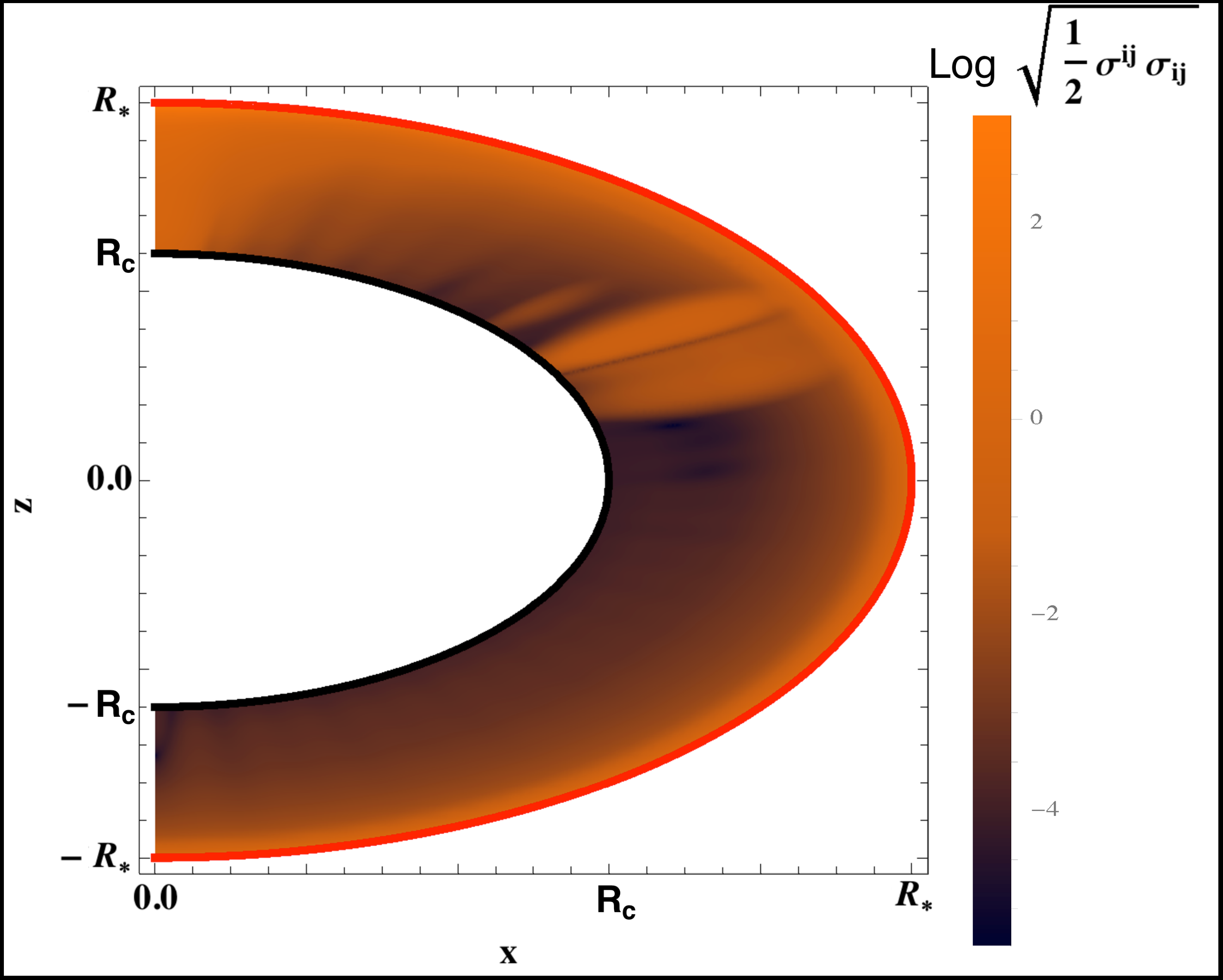


(Suvorov & Kokkotas 2019)

CRUST YIELDING DUE TO MAGNETIC STRESS

$$\left(\frac{E_{\rm quake}}{4\times10^{39}\ {\rm erg}}\right)\approx\left(\frac{\sigma_{\rm max}}{10^{-2}}\right)\left(\frac{d}{10^{-1}R_c}\right)^2\left(\frac{l}{10^{3}\ {\rm cm}}\right)$$

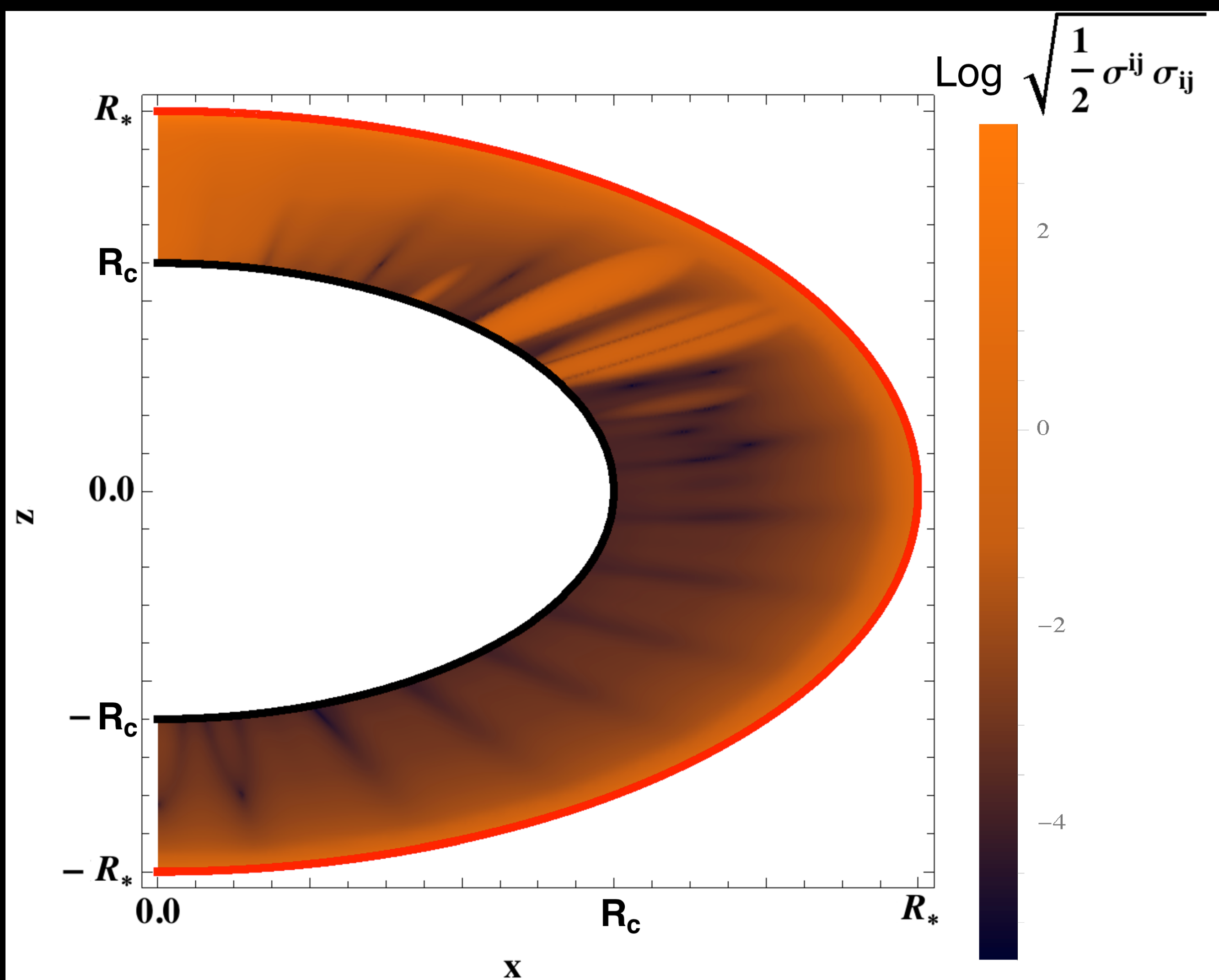
- The ions in the crustal layers interact via Coulomb potentials which are screened by the mobile, degenerate electrons, and form a crystal, the particulars of which determine the elastic properties of the crust.
- The maximum stress the crust can sustain ~ 0.04 - 0.1 (e.g. Baiko & Chugunov 2018)
- Fractures are complicated due to multipolar magnetic field evolution, and timescales are tied to multipole order.

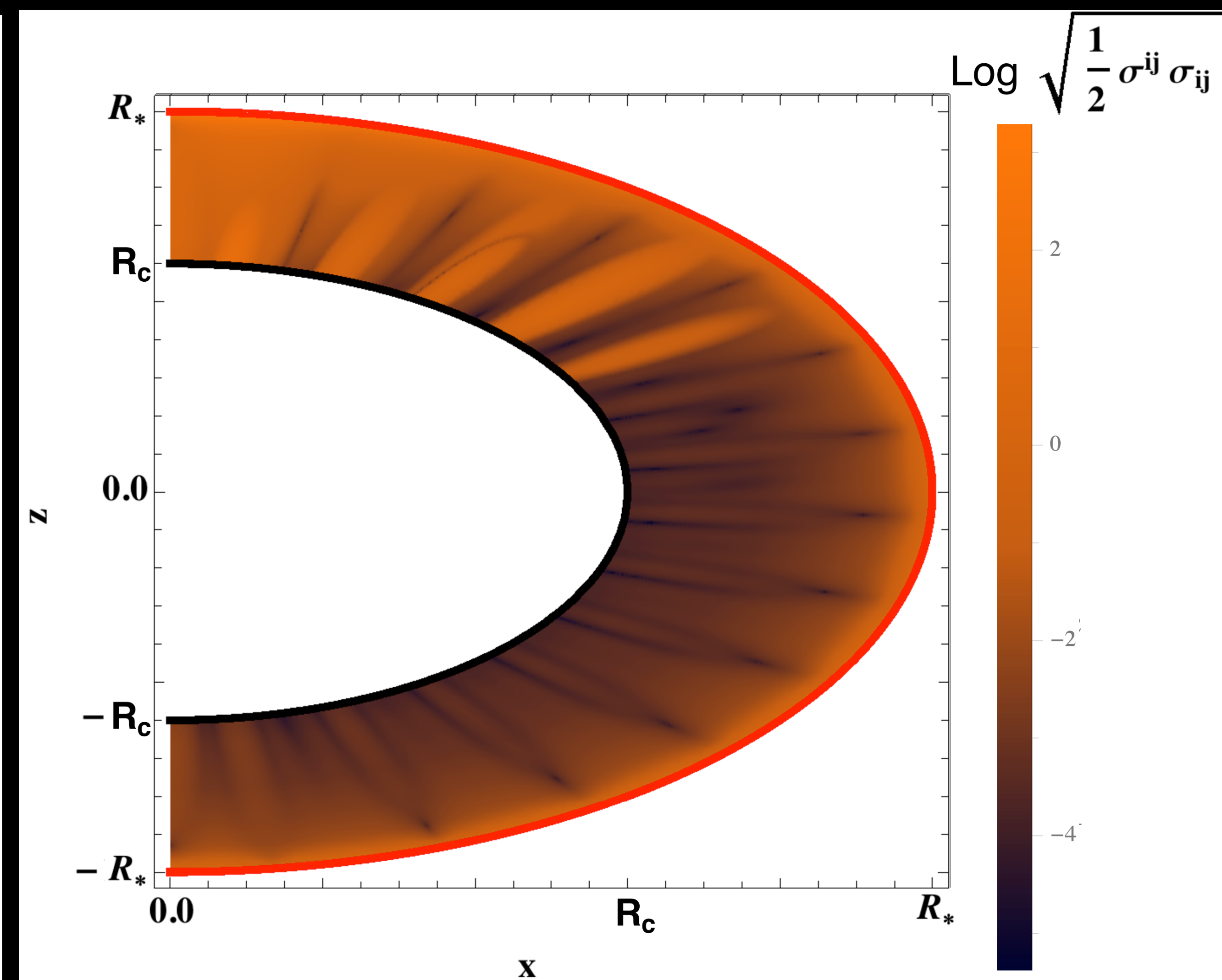


(Suvorov & Kokkotas 2019)

CRUST YIELDING DUE TO MAGNETIC STRESS

As the field evolves, the fracture geometry is tied to the multipolar structure, and can be complicated





Crtical stresses reached at different times, initiating FRB behaviour at seemingly uncorrelated intervals

SUMMARY

- Young magnetars can be born with particularly `tangled' magnetic field structures because of the complications of core-collapse supernovae and merger events.

- As shown by Gourgouliatos et al. (2016) using sophisticated, 3D numerical simulations, stars in such initial states can have significant field evolution within ~ 100 yr.

- This rapid evolution, consistent in time with the age of FRB 121102, suggests that FRBs might originate due to rapid field evolution, which we showed can generate strongly anisotropic stresses and initiate radio emission.

- Population synthesis models of Popov et al. 2010 suggest that magnetars, with strong enough to produce the flares, should be rare => possibly why we have only seen two repeaters to date

POPULATION STATISTICS? GWS?

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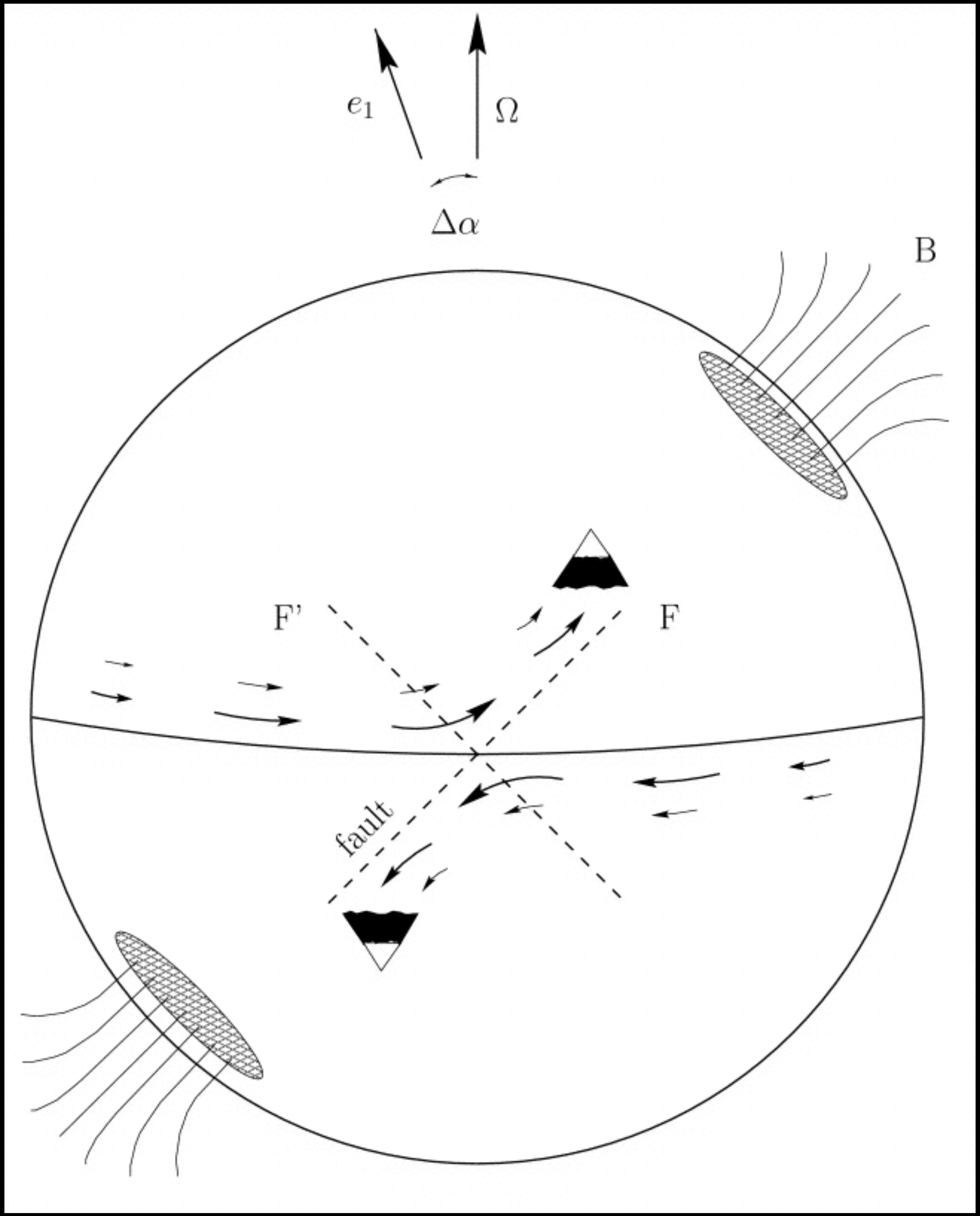

(Franco et al. 2000)