Missing Links of High Energy Astrophysical Phenomena

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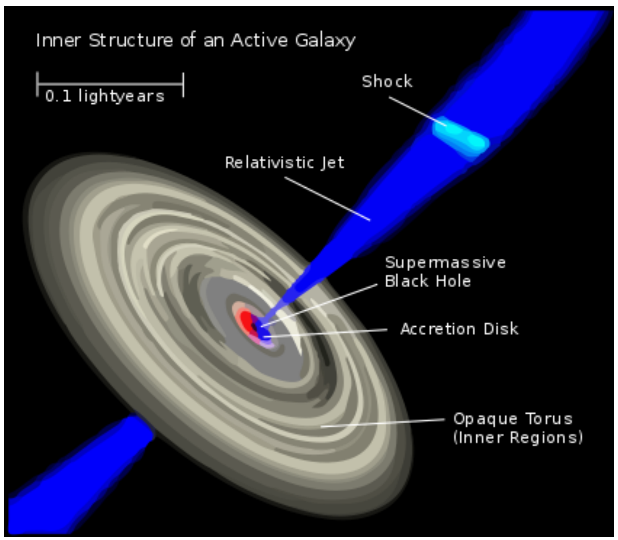
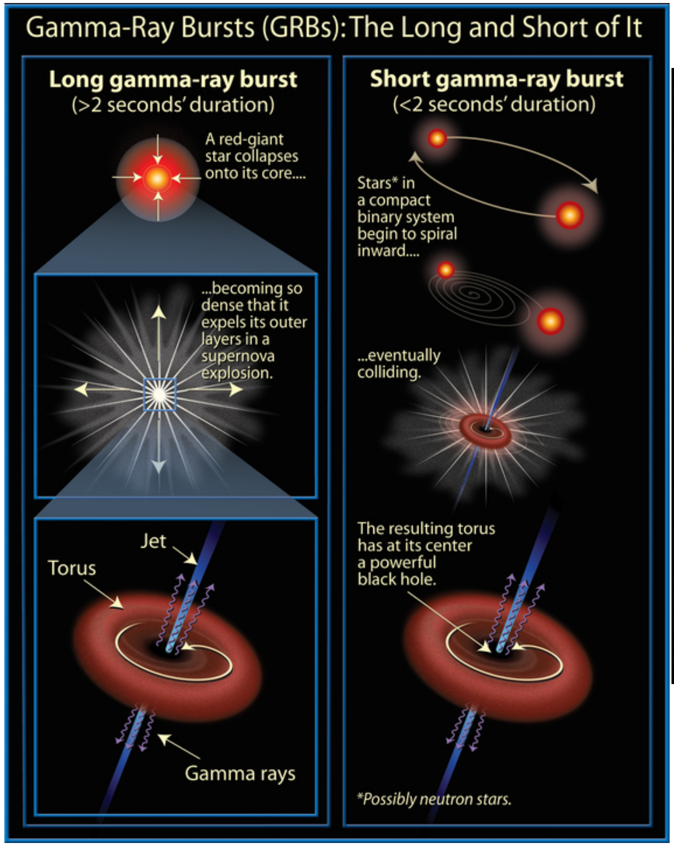
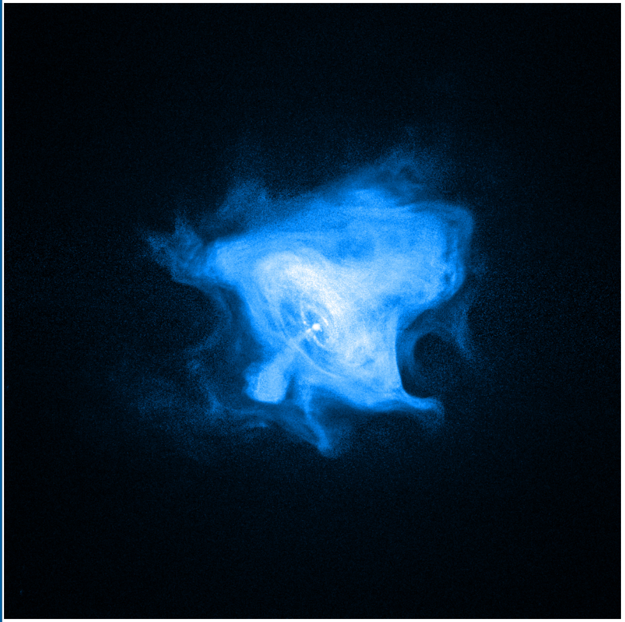
key questions of high energy astrophysics I

How (relativistic or non-relativistic) outflows are accelerated and how the energy is converted to thermal and non-thermal emission?

What is the central engine? → *mostly compact objects (BH, NS, WD)*

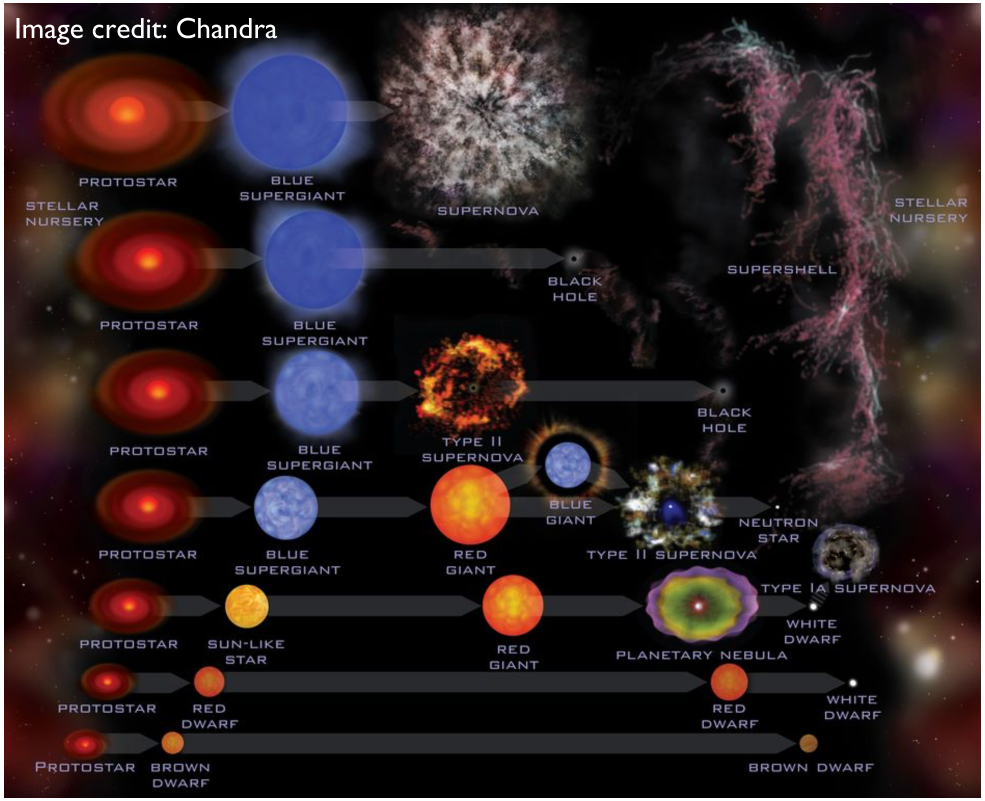






key questions of high energy astrophysics II

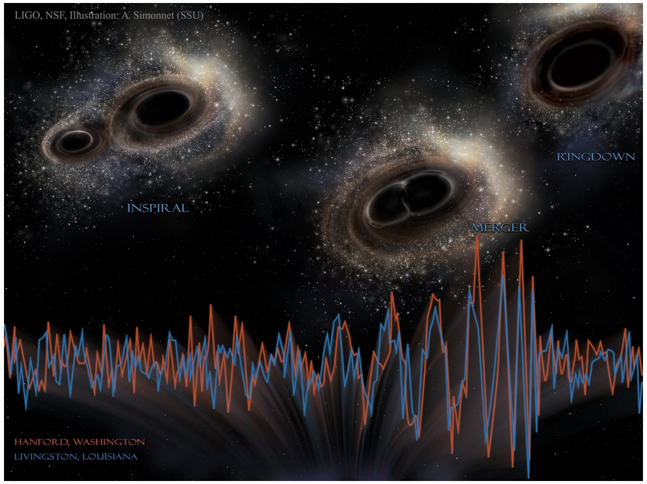
What kind of massive star (RSG, BSG, WR) produces
what kind of compact object (NS or BH? B field, rotation, disk?)
and what kind of explosive transient (SN, GRB or else) ?

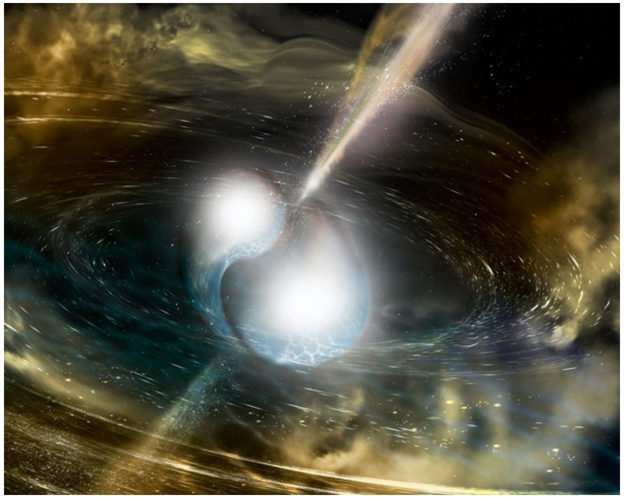


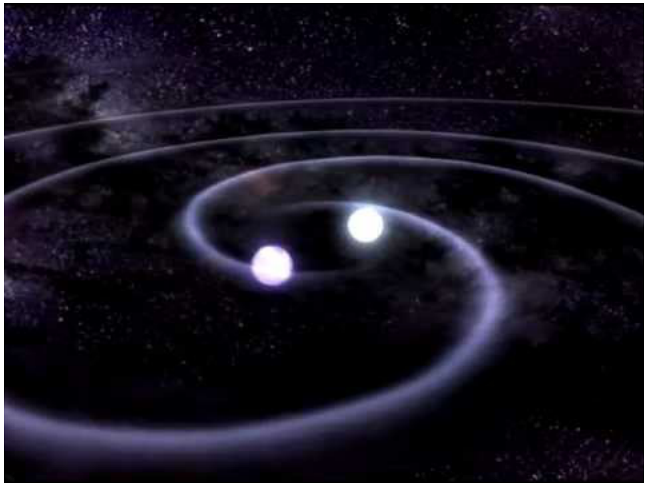
key questions of high energy astrophysics III

What kind of compact binaries (BBH, BNS, BHNS, …) produces what kind of compact object (NS or BH? B field, rotation, disk?) and what kind of explosive transient (GRB, FRB, or else) ?

How compact binaries are formed?







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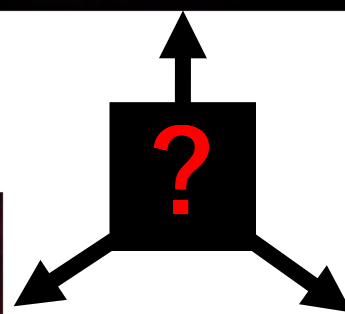
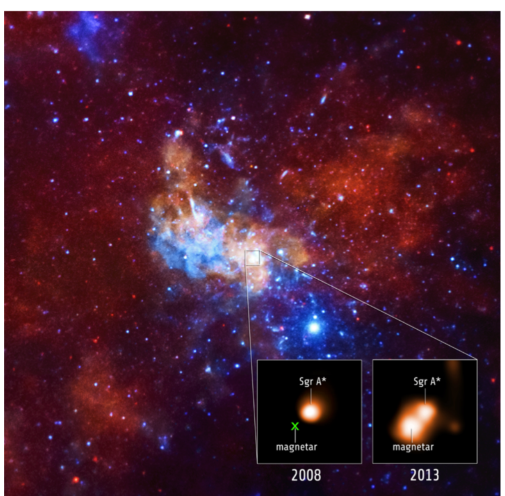
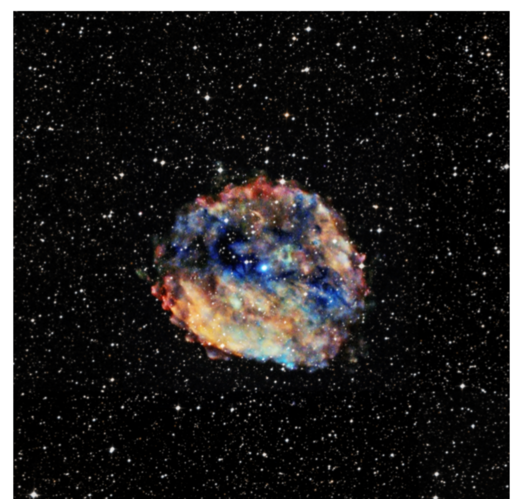
1. A missing link

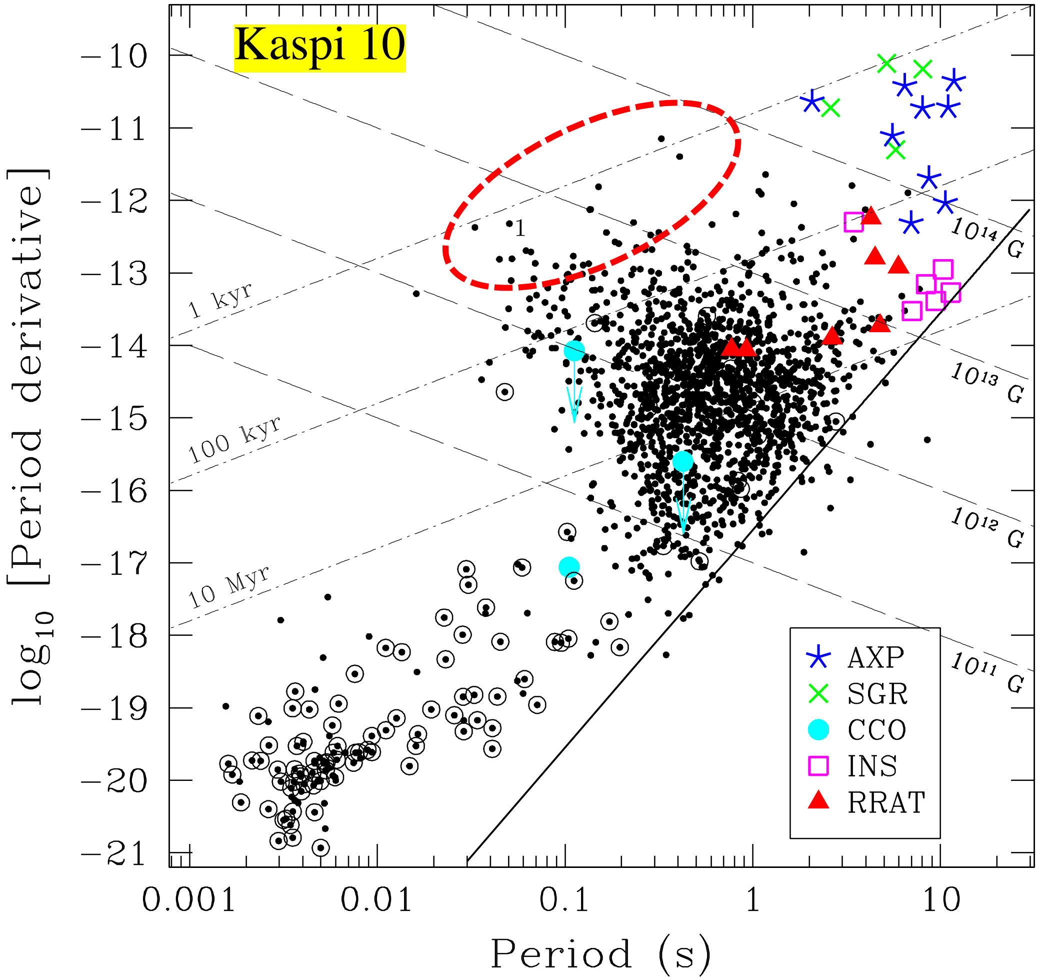
The diversity of young neutron stars

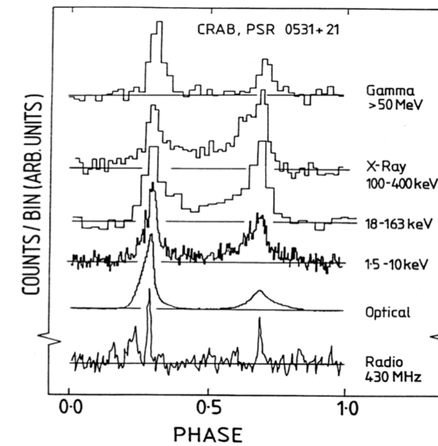


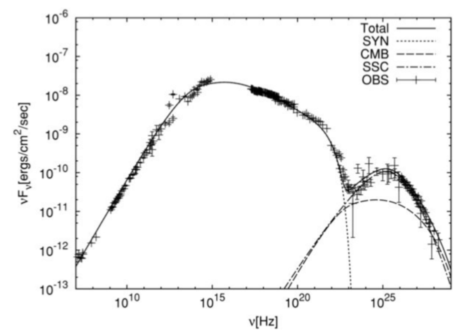




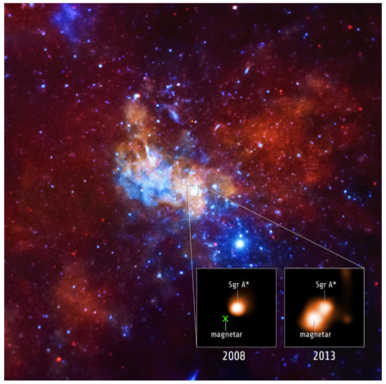
(Young) pulsars

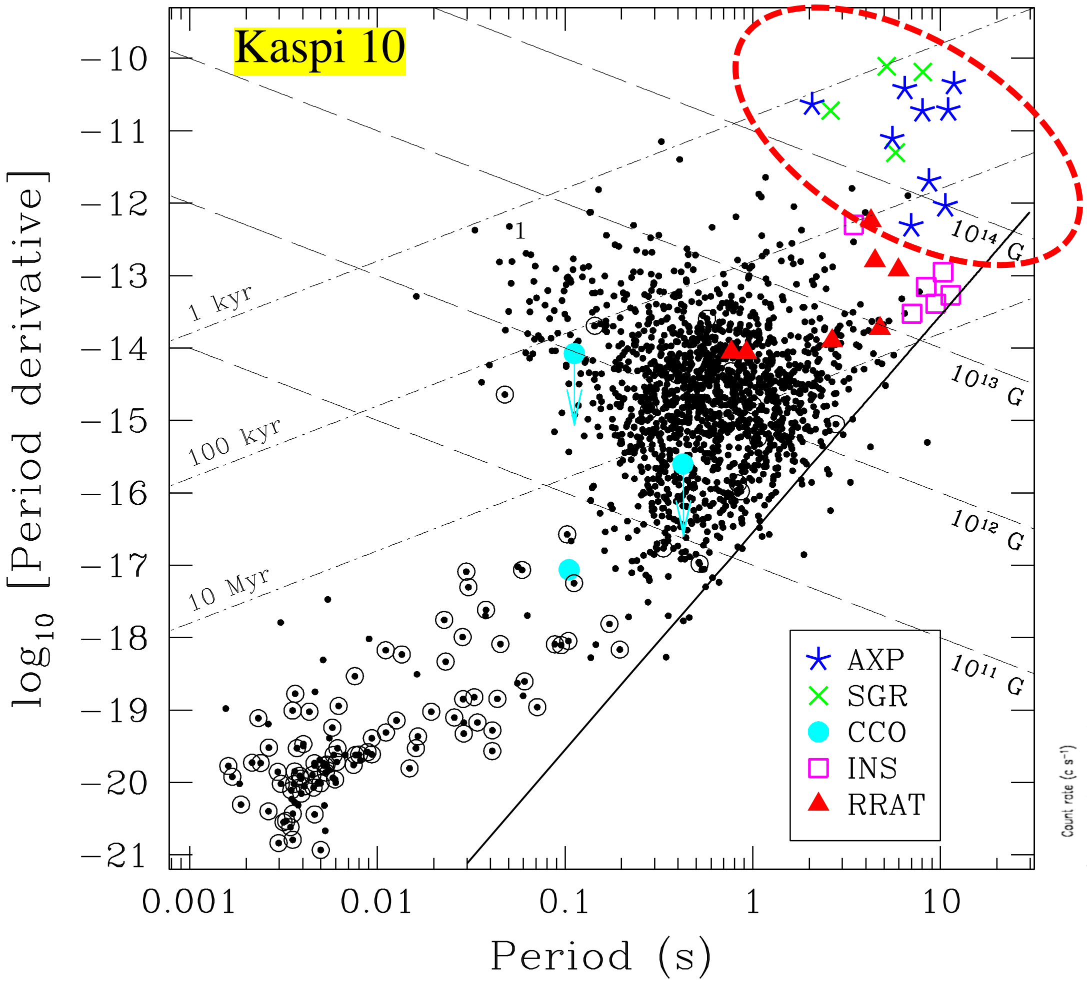


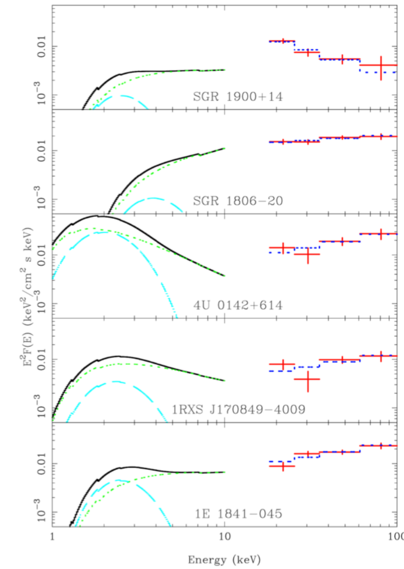


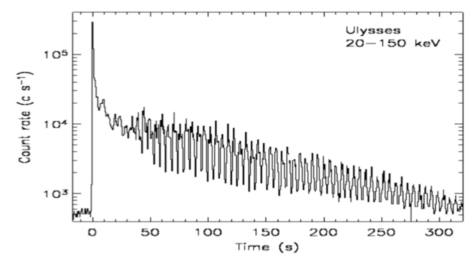


Magnetars

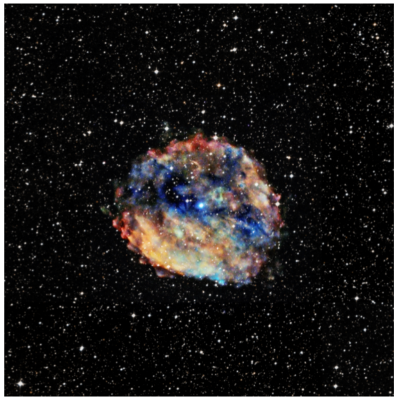

Sgr A*
magnetar
2008
Sgr A*
magnetar
2013

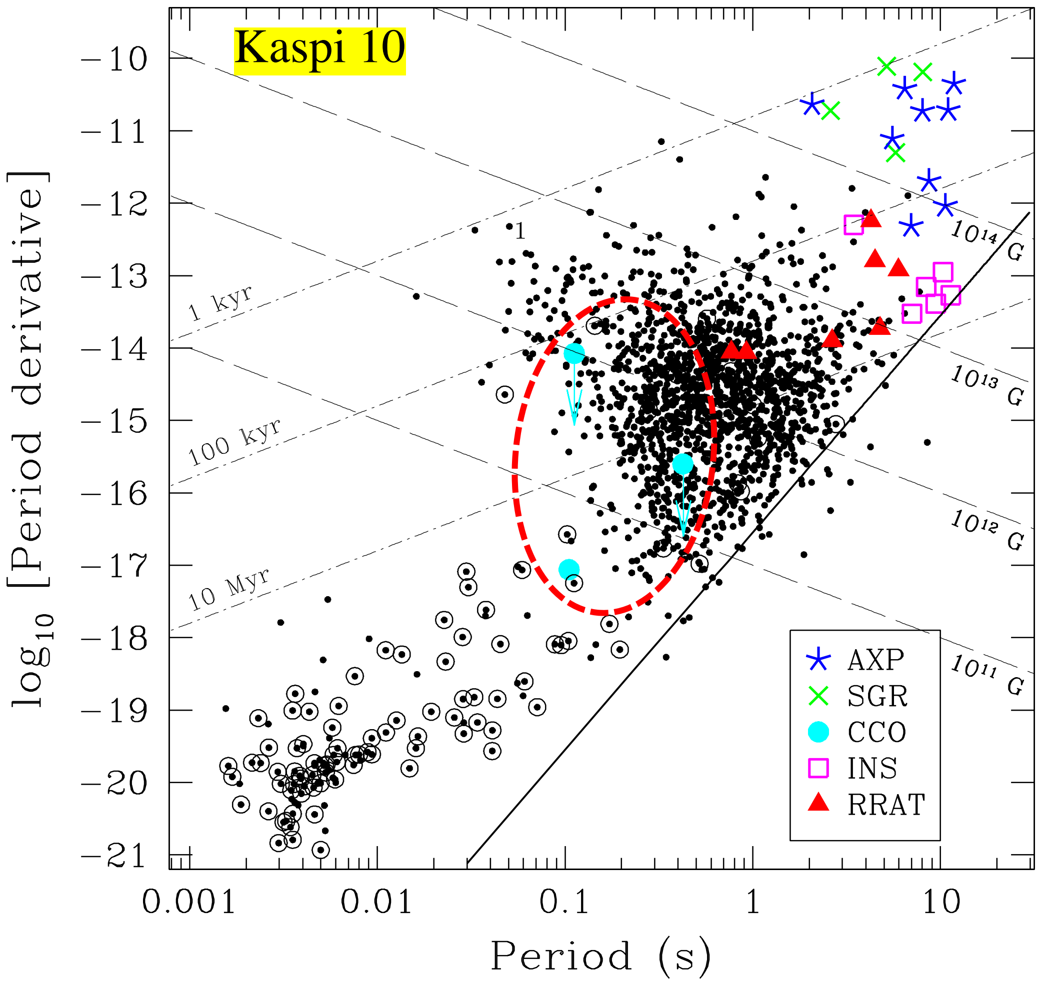

Kaspi 10
log10 [Period derivative]
Period (s)
1 kyr
100 kyr
10 Myr
10^14 G
10^13 G
10^12 G
10^11 G
AXP
SGR
CCO
INS
RRAT

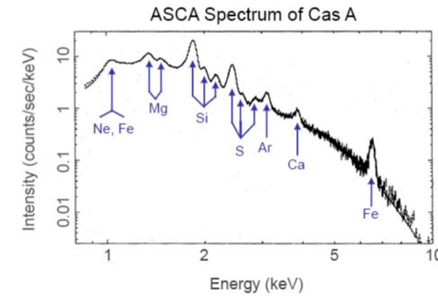

SGR 1900+14
SGR 1806−20
4U 0142+614
1RXS J170849−4009
1E 1841−045
E²F(E) (keV² /cm² s keV)
Energy (keV)


Ulysses
20−150 keV
Count rate (c s⁻¹)
Time (s)

Central Compact objects



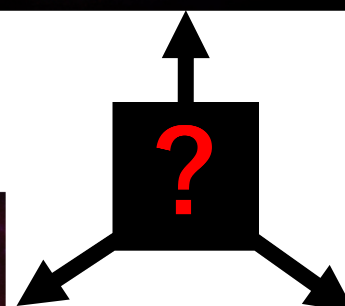


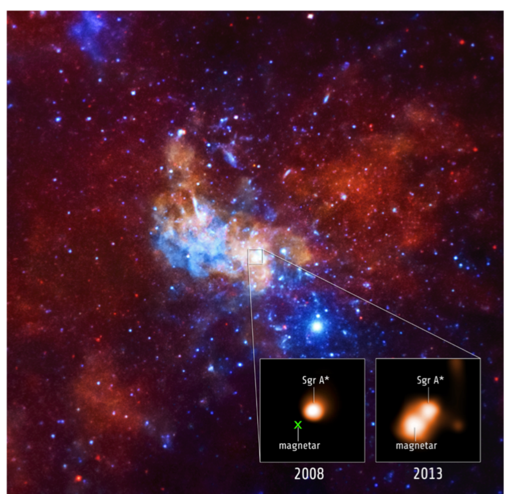


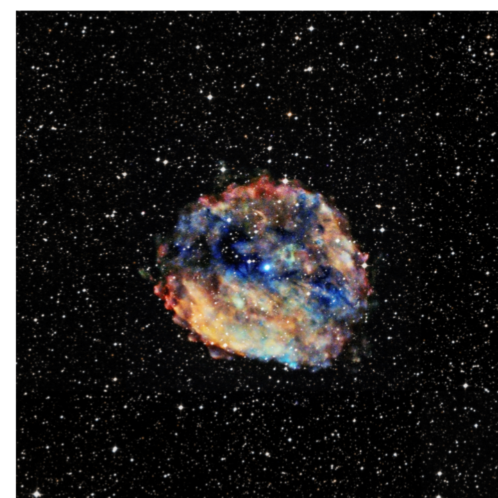
The diversity of young neutron stars

The formation rates are roughly comparable
~ 1/100-1000 yr.

What makes them different?







CCO formation -

Fallback accretion may be crucial!

e.g., Torres-Forne ´ et al.16

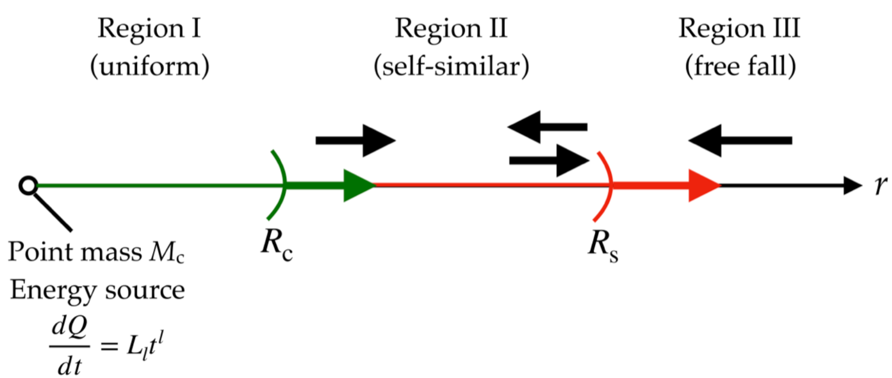
Fallback accretion can bury the B field if Mdot is smaller than

$$\dot{M}_{\mathrm{crit,bury}} \sim 10^{-5}\, M_\odot\, \mathrm{s}^{-1} \left(\frac{B_*}{10^{13}\,\mathrm{G}}\right)^{3/2}$$

OK, then how to make pulsars?

Pulsar wind vs fallback accretion

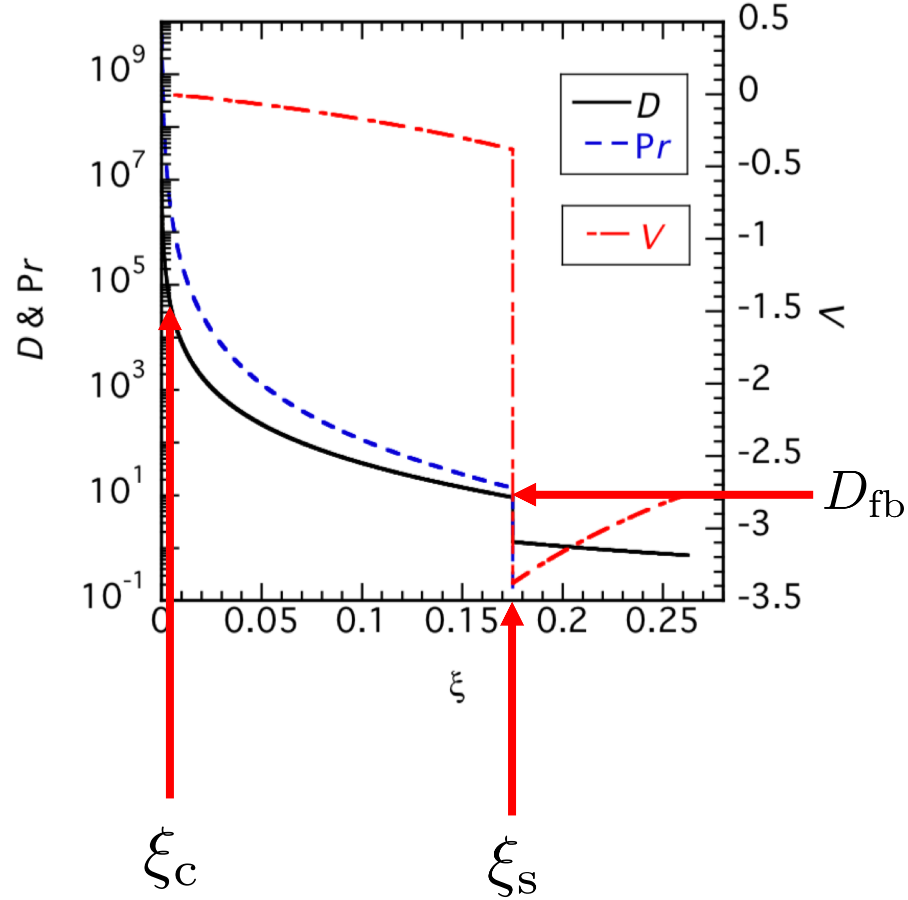
Constructing a new sequence of self-similar solutions Shigeyama & KK 18



$$\rho(\xi, t) = \frac{L_l t^{l-\frac{1}{3}} D(\xi)}{(GM_c)^{5/3}},$$

$$v(\xi, t) = \left(\frac{GM_c}{t}\right)^{1/3} V(\xi),$$

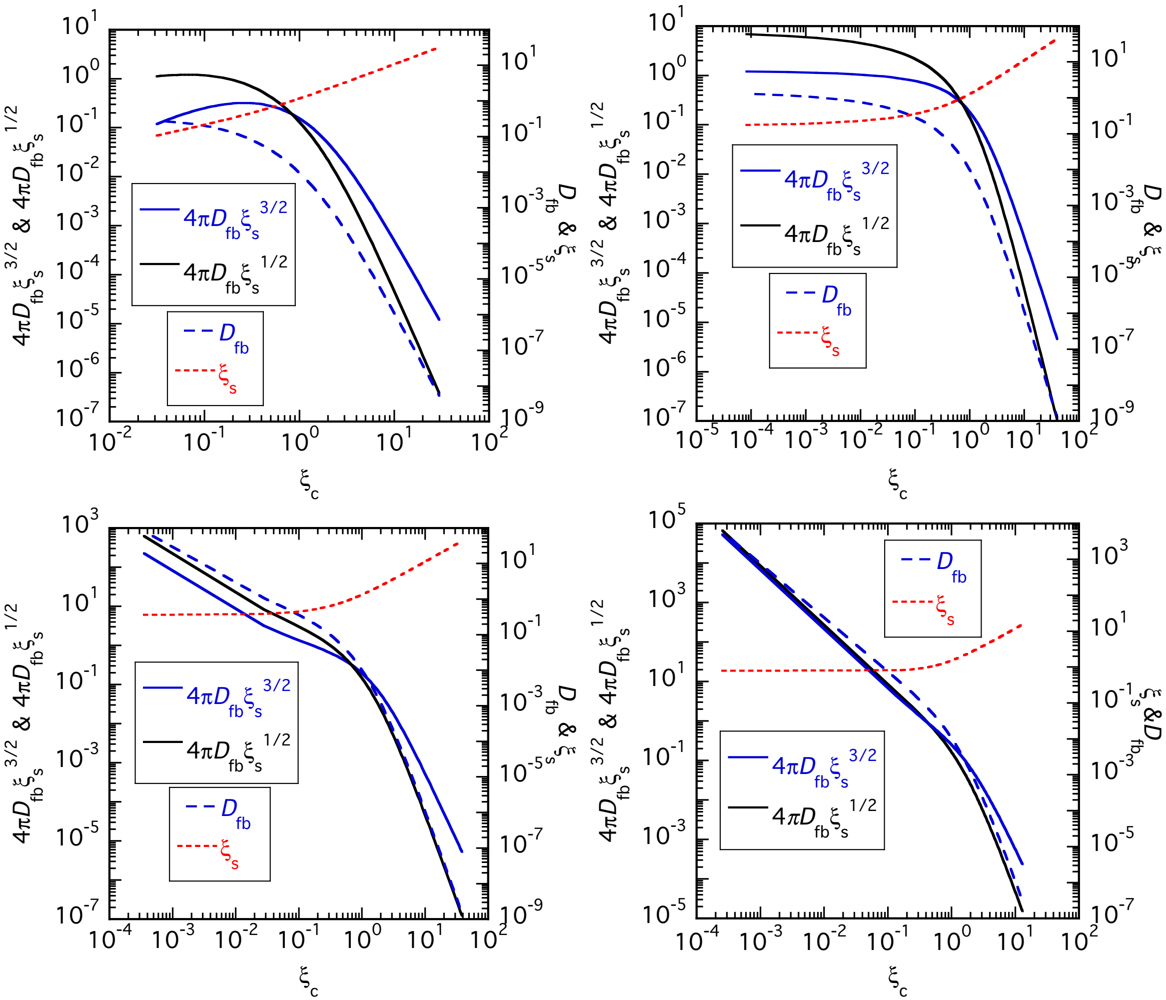
$$p(\xi, t) = \frac{L_l t^{l-1} \mathrm{Pr}(\xi)}{GM_c}, \quad \xi = \frac{r}{(GM_c t^2)^{1/3}}$$



Pulsar wind vs fallback accretion

Shigeyama & KK 18

$\gamma = 6/5$ $\gamma = 4/3$



$\gamma = 7/5$ $\gamma = 5/3$

For γ <= 4/3, there is no solution with accretion rate larger than $\dot{M}_{\rm crit} = \frac{r_{\rm s}\dot{Q}}{GM_{\rm c}} \times (4\pi D_{\rm fb}\sqrt{\xi_{\rm s}})_{\rm crit}.$

Pulsar wind vs fallback accretion

Shigeyama & KK 18

In the critical situation of NS with fallback,

$$r_{\rm s} \sim 4.2 \times 10^9 \,{\rm cm}\, \xi_{\rm s} \left(\frac{t_{\rm fb}}{20\,{\rm s}}\right)^{2/3}.$$ ← the shock surface at the fb time

$$\xi_{\rm c,crit} \sim 2.8 \times 10^{-4} \left(\frac{t_{\rm fb}}{20\,{\rm s}}\right)^{-2/3}.$$ ← the contact surface = the NS surface

$$\xi_{\rm s,crit} \sim 0.3 \text{ and } (4\pi D_{\rm fb}\sqrt{\xi_{\rm s}})_{\rm crit} \sim 10.$$ ← γ >~ 4/3

$$\dot{Q}_{\rm crit} \sim 2.7 \times 10^{45}\,{\rm erg\,s^{-1}} \left(\frac{B_*}{10^{13}\,{\rm G}}\right)^2 \left(\frac{P}{10\,{\rm ms}}\right)^{-2}$$ ← a split monopole like spindown

Parfrey et al. 16

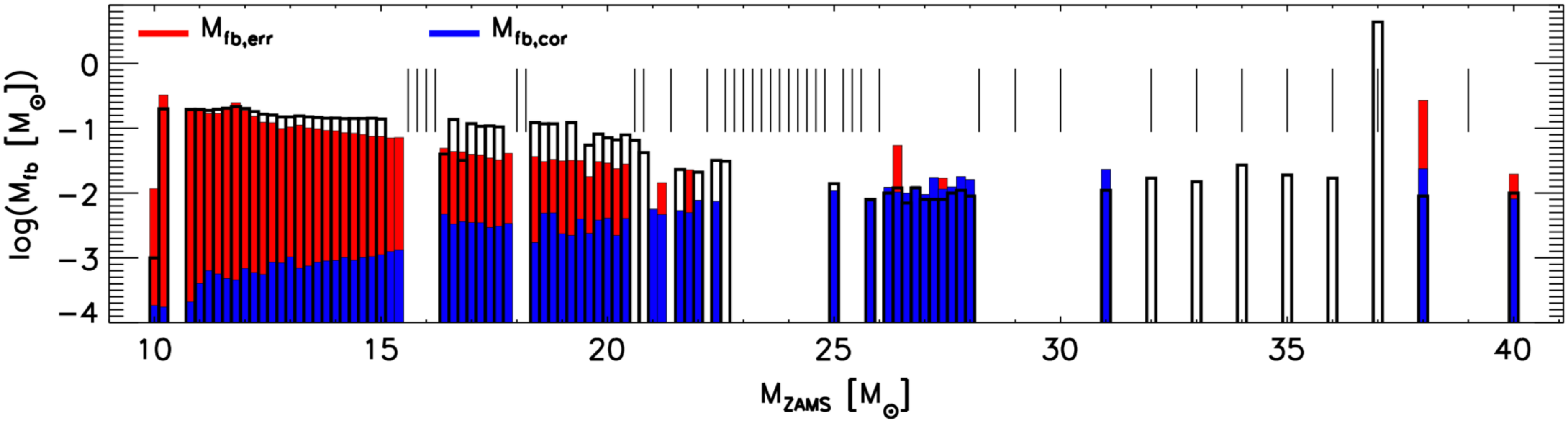
⇩

Fallback accretion can be repelled if Mdot is smaller than

$$\dot{M}_{\rm crit,repul} \sim 8 \times 10^{-5}\, M_\odot\, {\rm s^{-1}} \frac{\xi_{\rm s,crit}}{0.3} \frac{(4\pi D_{\rm fb}\sqrt{\xi_{\rm s}})_{\rm crit}}{10} \left(\frac{B_*}{10^{13}\,{\rm G}}\right)^2 \left(\frac{P}{10\,{\rm ms}}\right)^{-2} \left(\frac{t_{\rm fb}}{20\,{\rm s}}\right)^{2/3}$$

Fallback accretion onto NS

Should depend on the progenitor inner structure e.g., Ugliano et al. 12; Ertl et al.16

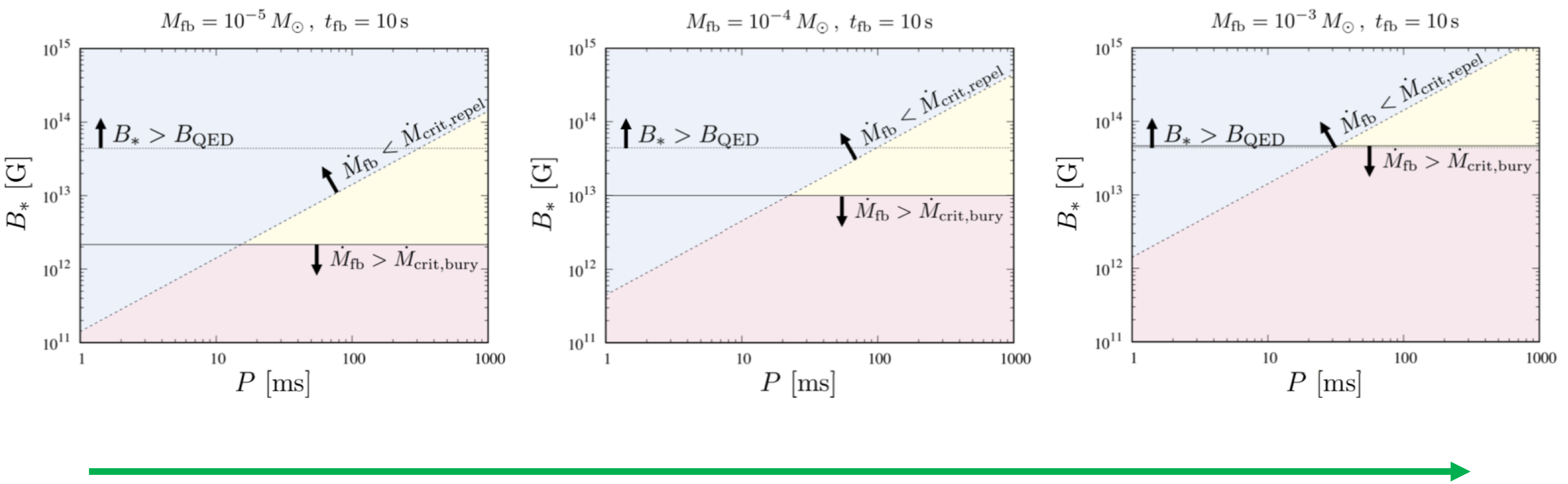


The fallback typically starts when the neutrino luminosity significantly decreases, i.e., ***t_{fb} ~ 10 s*** *after the core bounce, and the accretion rate subsequently decreases as $\propto (t/t_{fb})^{-5/3}$ for $t \gtrsim t_{fb}$.*

The total mass of the fallback matter increases for more massive stars, ranging from ***$M_{fb} \sim 10^{-(2\text{-}4)}\, M_\odot$*** *.*

Correspondingly, the peak mass accretion rate is estimated to be ***$\sim 10^{-(3\text{-}5)}\, M_\odot\, s^{-1}$*** *.*

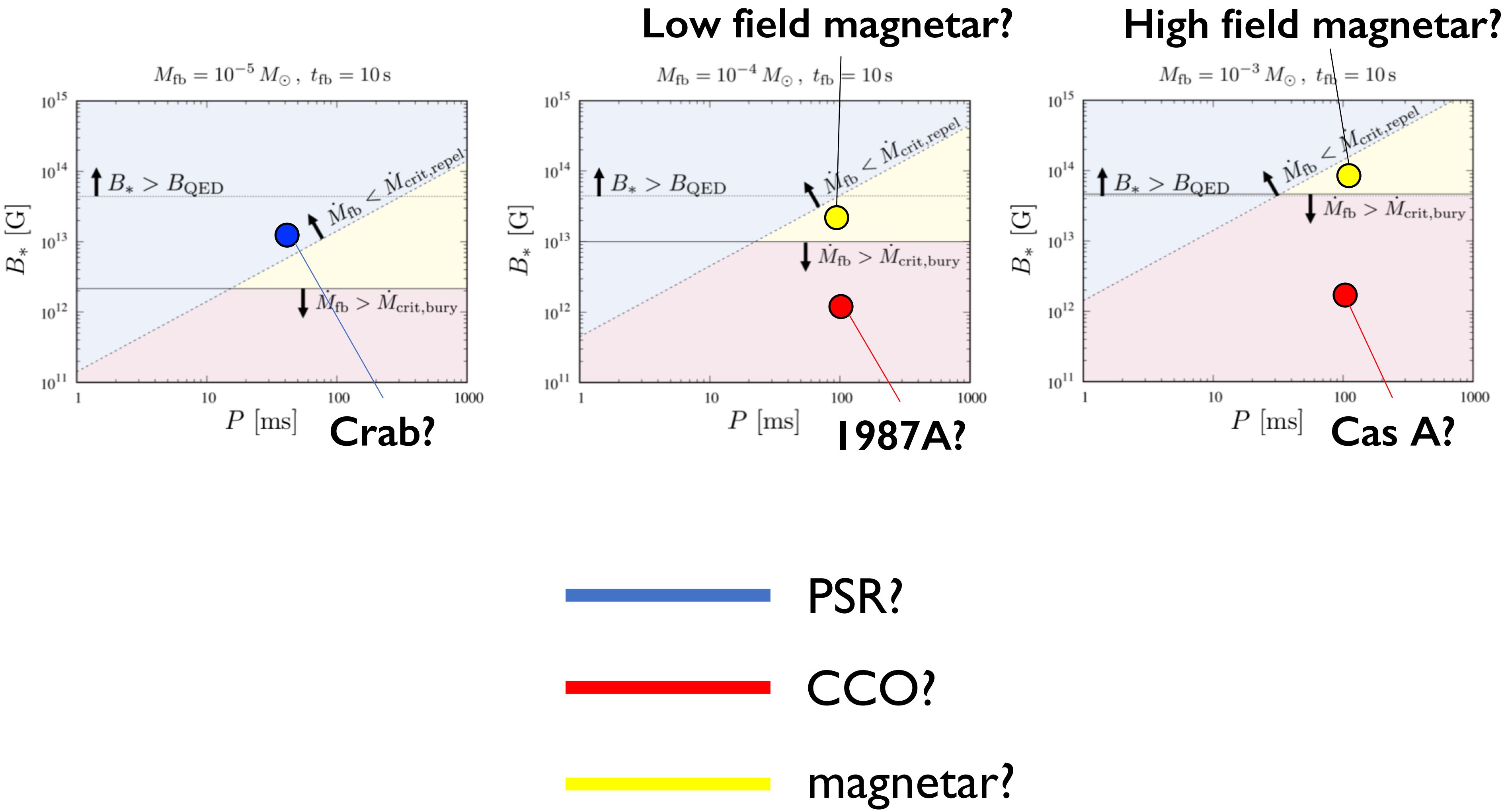
The fate of newborn neutron stars with fallback accretion



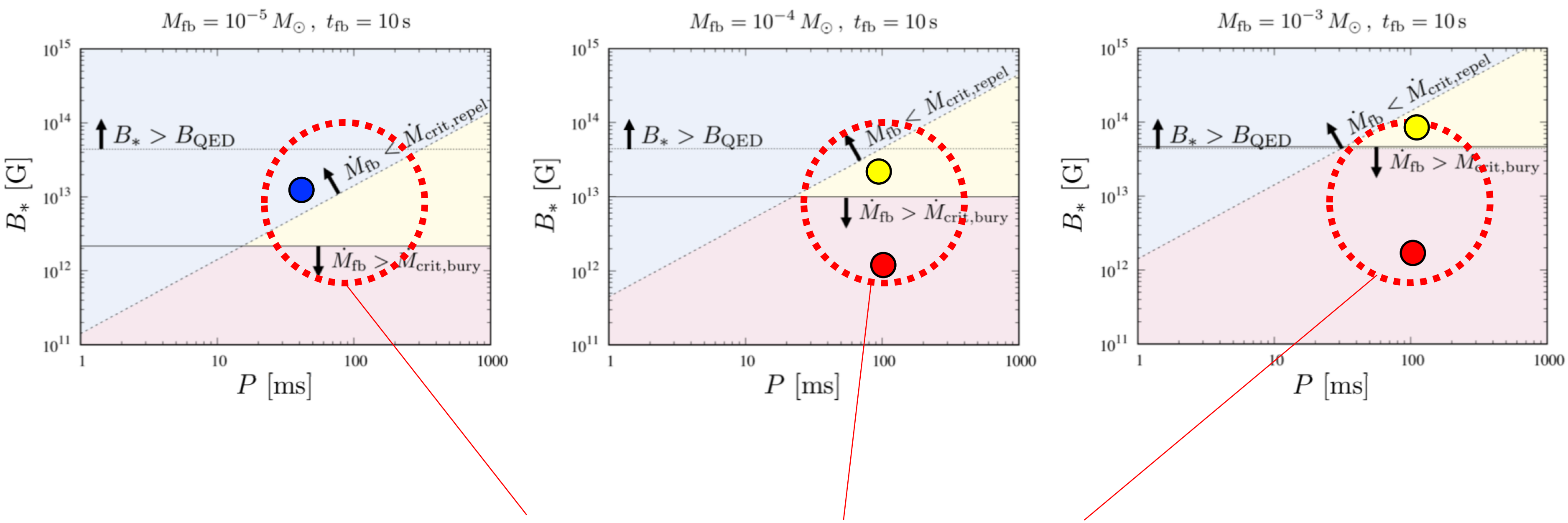
more abundant,
less massive progenitor

less abundant,
more massive progenitor

The fate of newborn neutron stars with fallback accretion



The fate of newborn neutron stars with fallback accretion



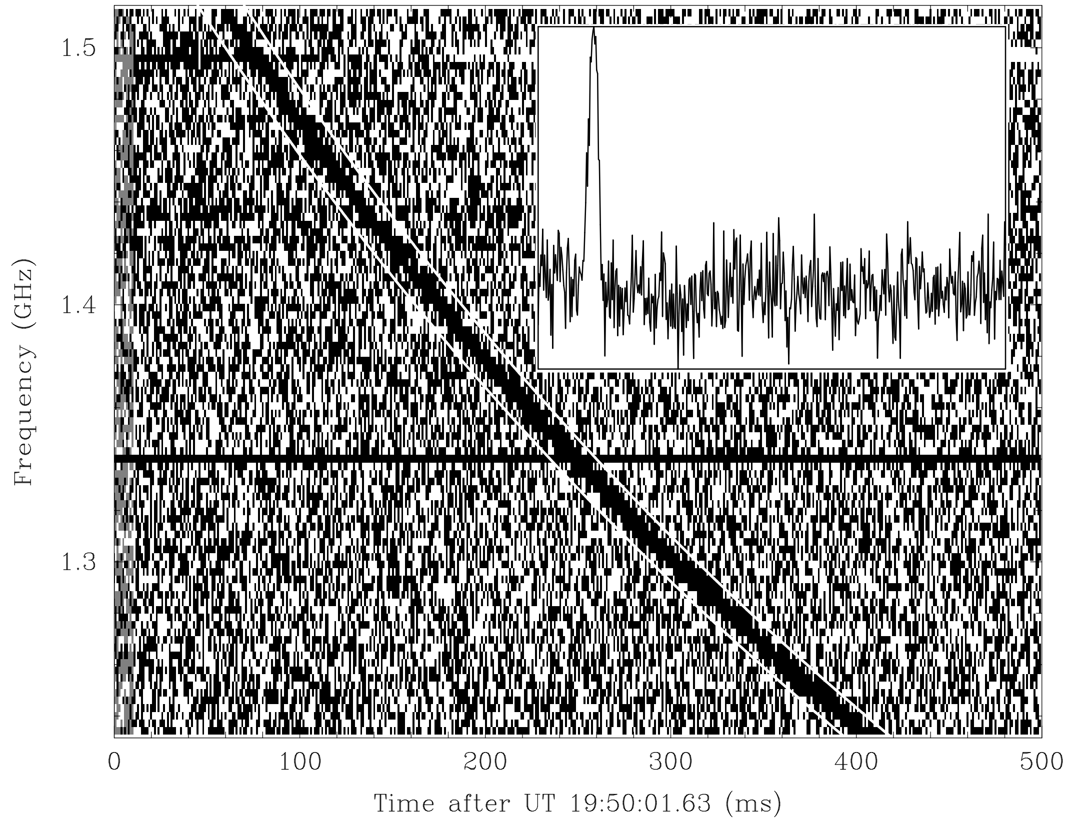
typical ranges of parameters for newborn NSs ~ the intersection of the boundaries

→ The fact that the three classes have a comparable population can be naturally explained?

2. *A Missing Central Engine*

Fast radio bursts

- τ ~1-10 ms
- S_ν ~ 0.1-1 Jy
- ν ~ GHz
- event rate ~ 10^3 day^{-1} sky^{-1}
- $\delta t_\nu \sim \nu^{-2}$
- DM ~ 500-1000 cm^{-3} pc
- ~50 events so far with Parkes, Arecibo, and GBT, UTMOST, ASKAP, (and CHIME?) but not with LOFAR
- One is repeating (FRB121102)!

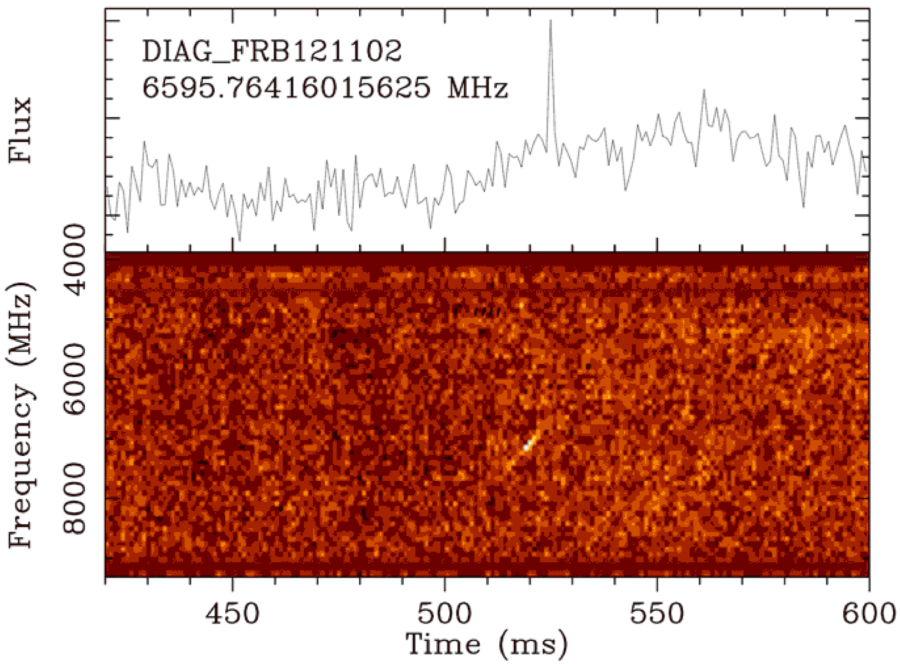


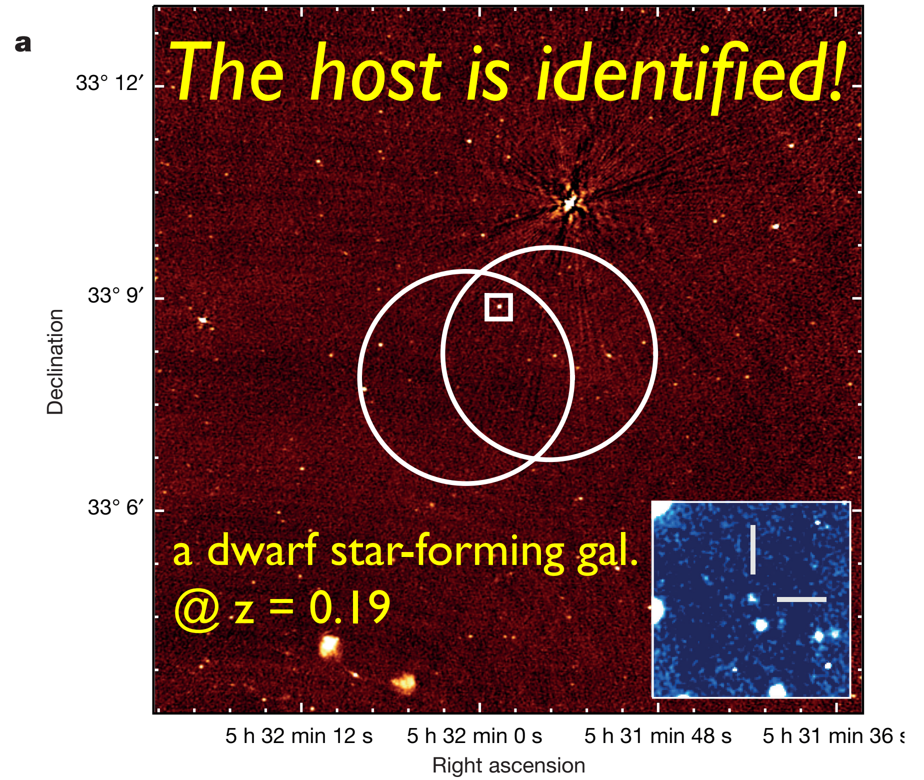
Lorimer et al. 2007; Keane et al. 2012; Thornton et al. 2013; Burke-Spolaor & Bannister 2014; Spitler et al. 2014; Ravi, Shannon & Jameson 2015; Petroff et al. 2015; Masui et al. 2015; Champion et al. 2015 …

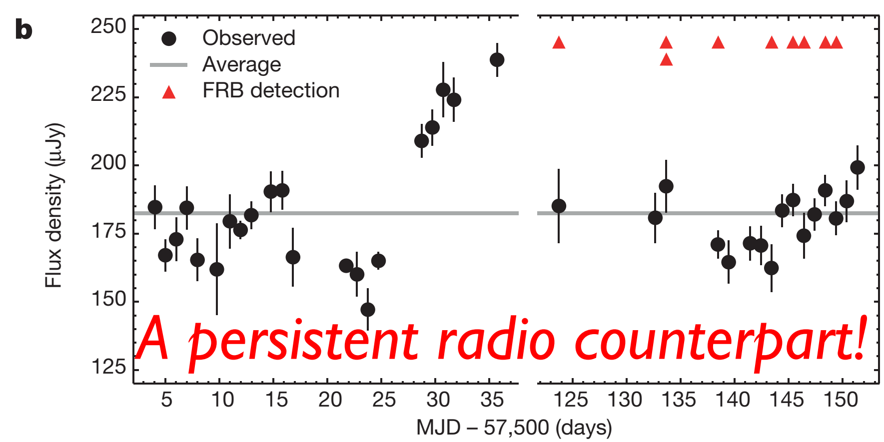
FRB 121102

Spitler+16, Chatterjee+17, Marcote+17, Tendulkar+17, …

It repeats! e.g., ~10 times in ~3 hrs

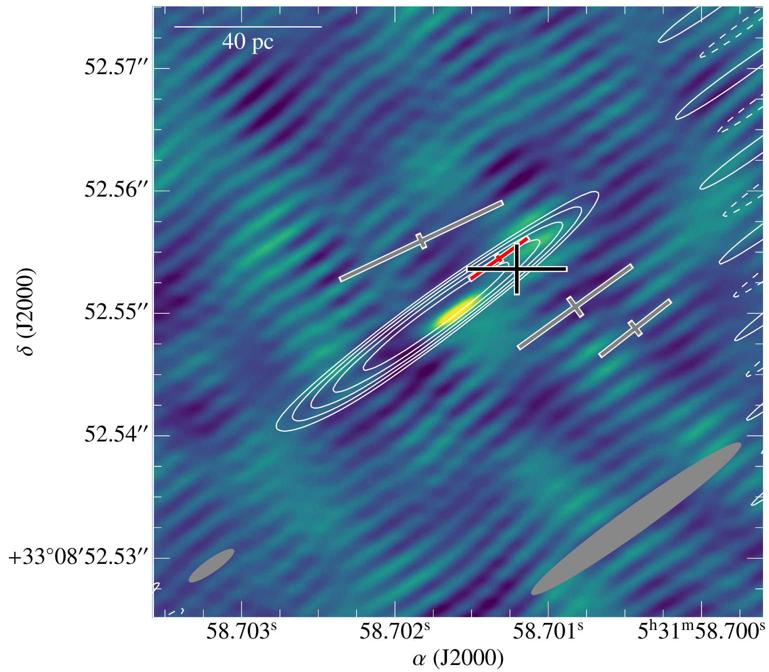


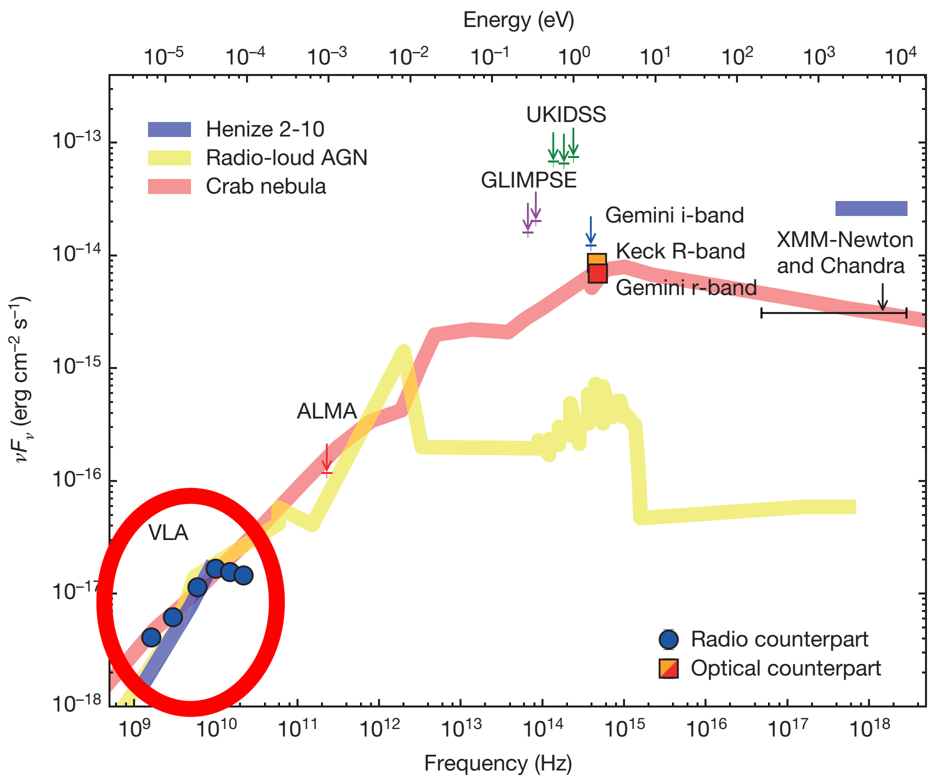




The Persistent Radio Counterpart

Spitler+16, Chatterjee+17, Marcote+17, Tendulkar+17, …





The source is localized within ~ 0.7 pc (!!) & associated with a star forming region …

The spectrum is compatible with the Crab pulsar-wind nebula …

Kokubo+17


An FRB in a bottle?
Or a bubble?
= pulsar wind nebula
& supernova remnant

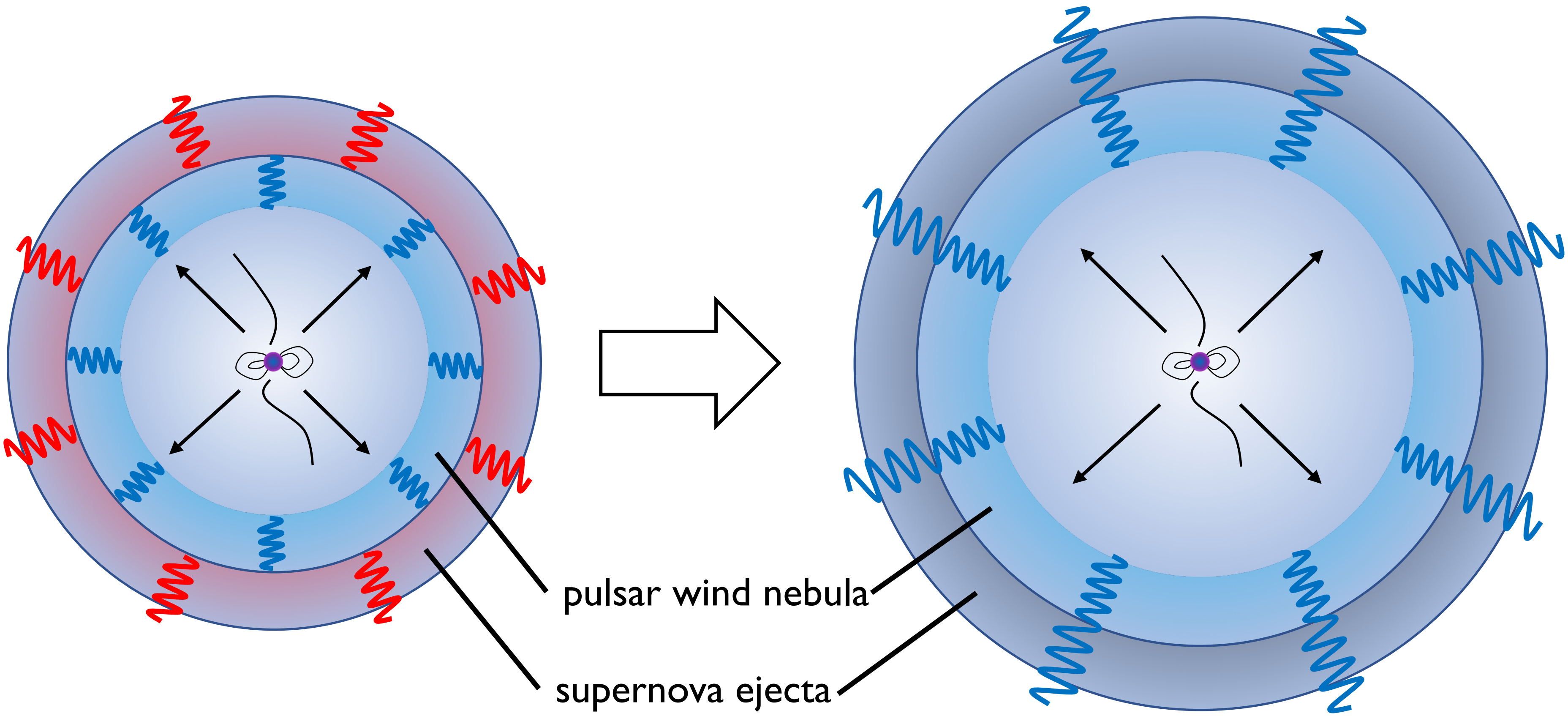
A Very Young NS in a Bubble

~ a few months after the explosion

The PWN emission is absorbed and thermalized in the supernova ejecta, powering a luminous supernova.

~ 1-100 yr after the explosion

The non-thermal pulsar wind nebula (PWN) emission in the radio bands starts to escape the supernova ejecta.
→ repeating FRBs and the persistent radio counterpart?



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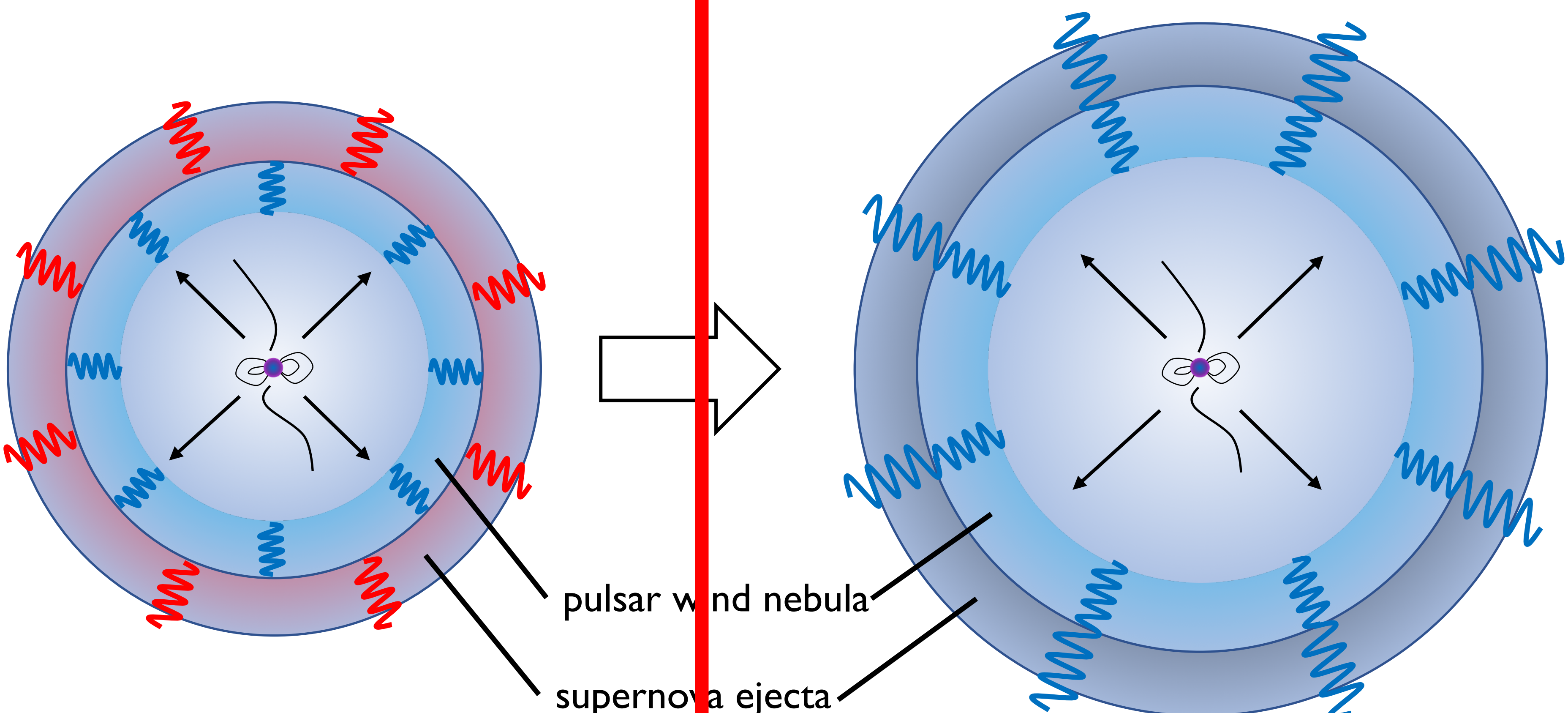
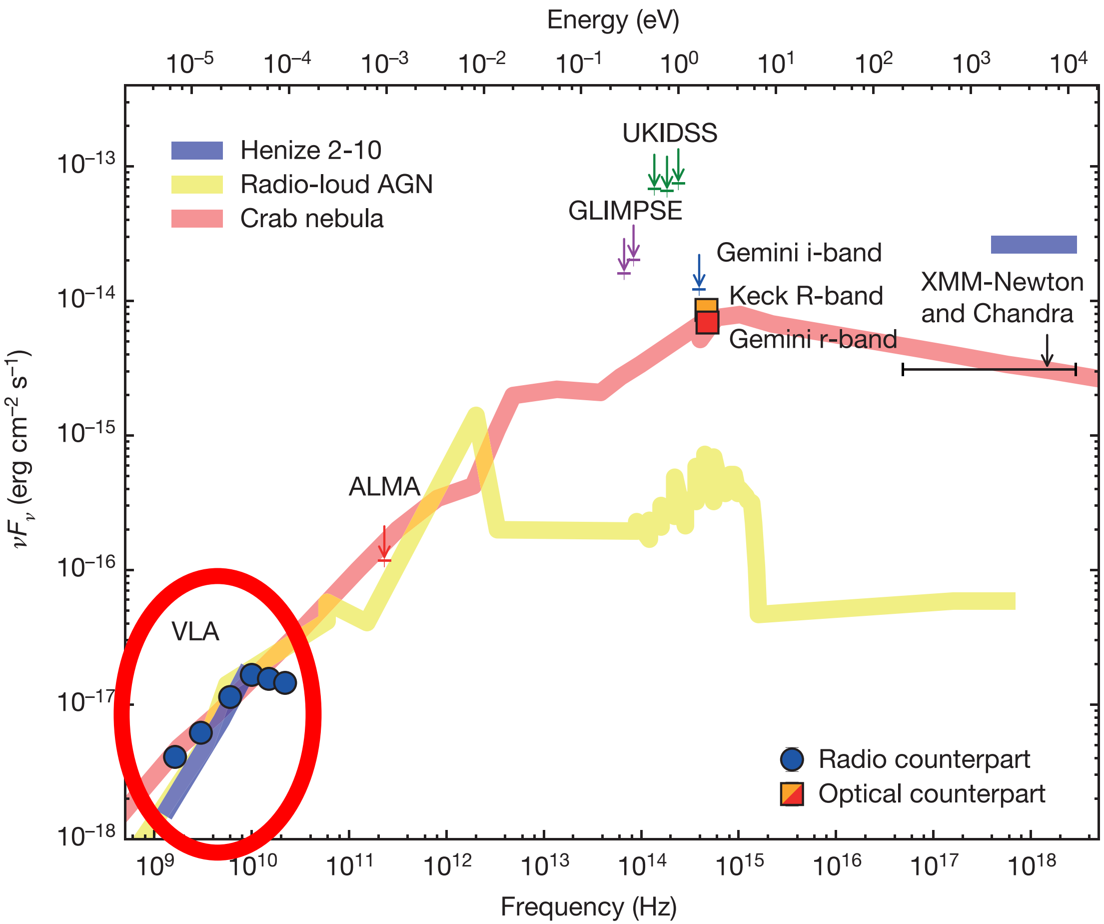


Very young, but not too young



The flux is much higher than the Crab

→ *Much younger and powerful than the Crab pulsar.*

In the early stage, radio waves cannot escape the nebula ...

→ *The NS is sufficiently old and/or the SN ejecta mass is small.*

Formation rate

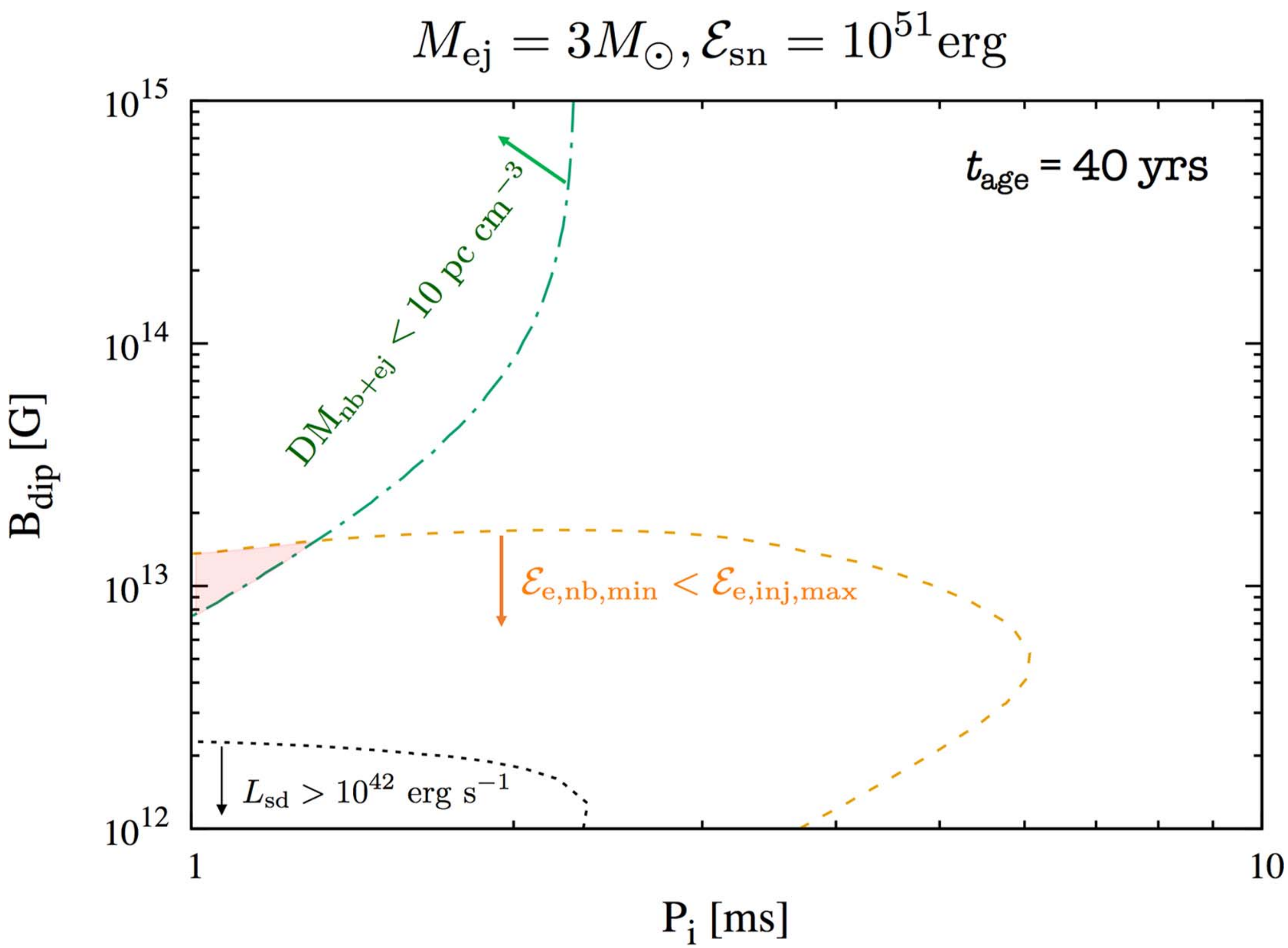
- The rate of repeating FRBs inferred from the survey
  $\sim\ 1.4 \cdot 10^{-5}\ \ \mathrm{sq.\,deg}^{-1}\,\mathrm{s}^{-1}$ (Scholz+16)
- which can be translated to the formation rate as

$$\sim 60 f_b^{-1}\,\mathrm{Gpc}^{-1}\,\mathrm{yr}^{-1}\,(\mathcal{T}_{\mathrm{FRB}}/10\,\mathrm{yr})^{-1}$$

for τ_{FRB} ~ 10 yr & f_b ~ 1 → ~ 0.1 % of CCSNe
for τ_{FRB} ~ 100 yr & f_b ~ 1 → ~ 0.01 % of CCSNe
(though the uncertainty is huge)

Constraints on NS & SN

KK & Murase 17



- ✓ *PWNe with M_{ej} ~ a few M_{sun}, P_0 ~ ms, B_{dip} ~ 10^{13} G, & t_{age} ~ a few 10-100 yrs can explain the repeating FRB.*
- ✓ *If t_{age} ~ 100 yrs, the formation rate is ~ 0.01 % of core-collapse SNe.*

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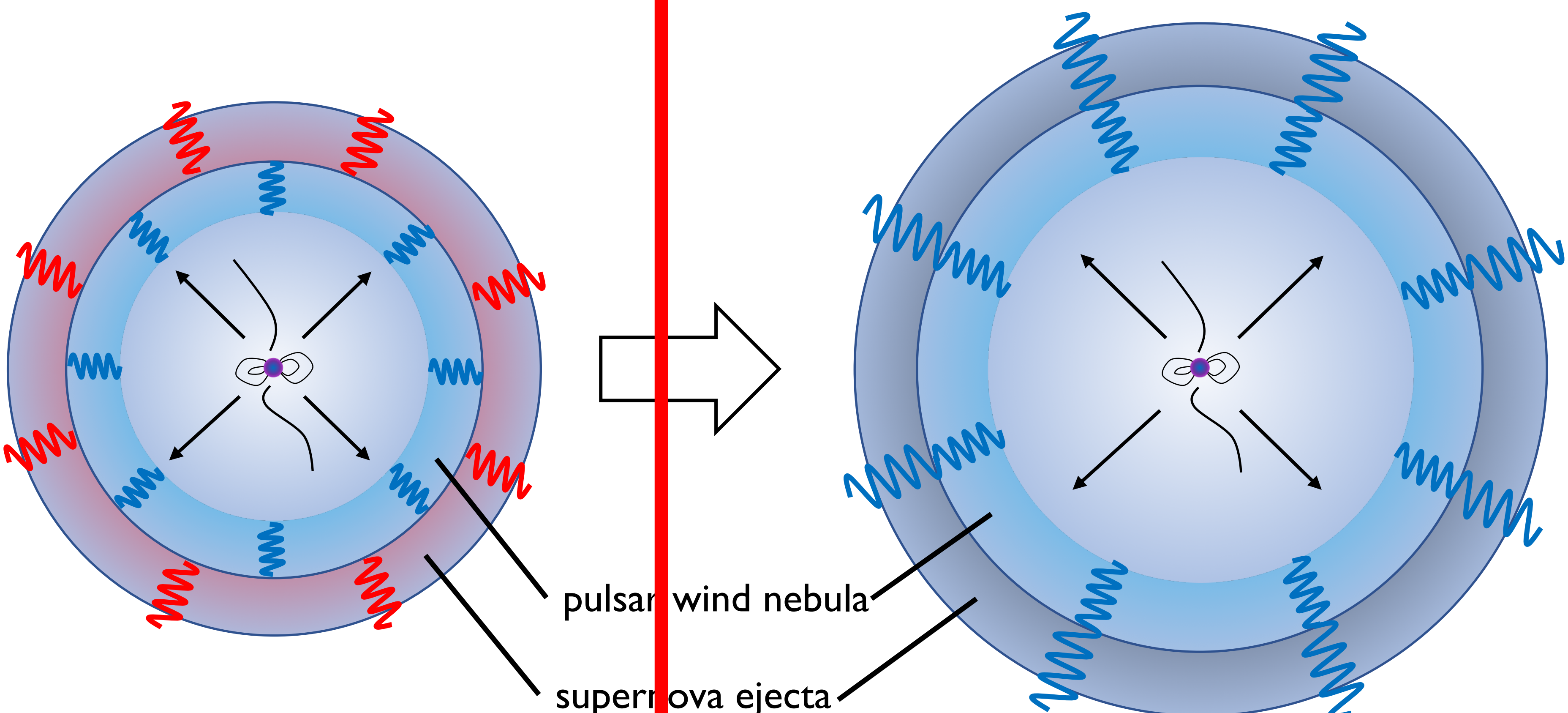
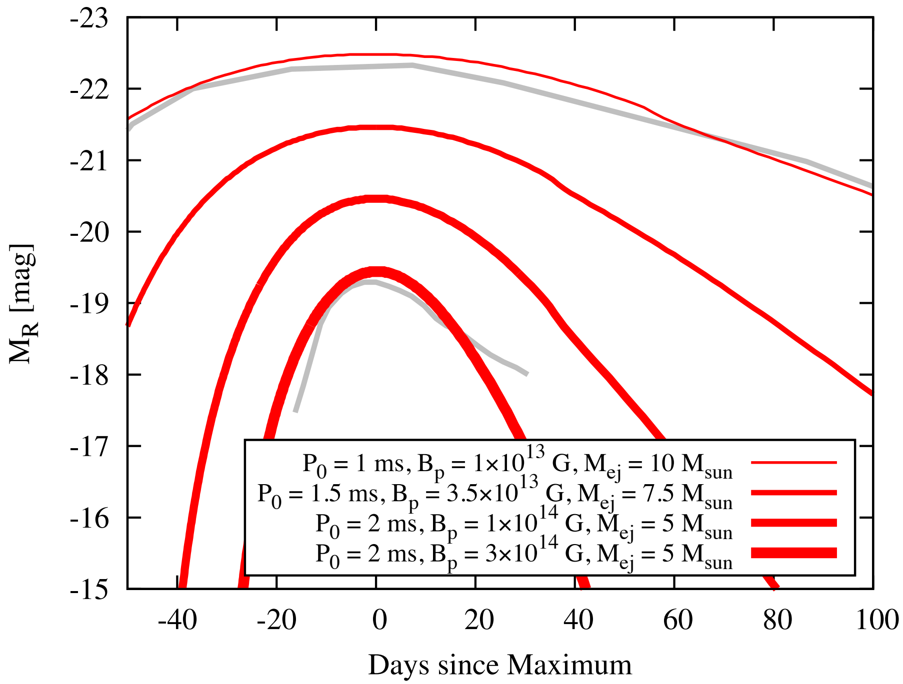


Diversity of pulsar-driven supernovae

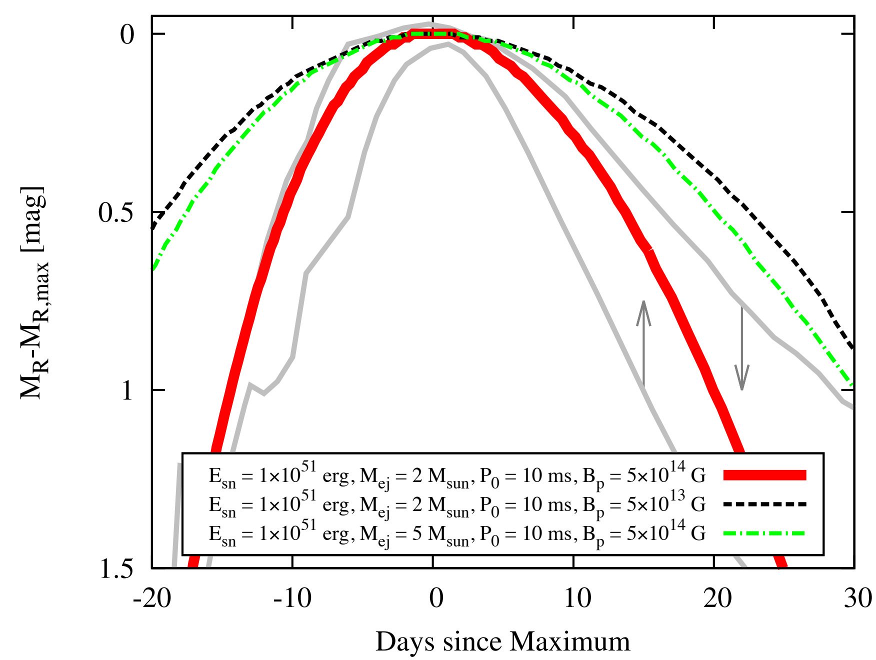
"Height"



For a given P_0 ,
SN becomes the brightest if

$$t_{\rm sd} \sim t_{\rm dif}$$

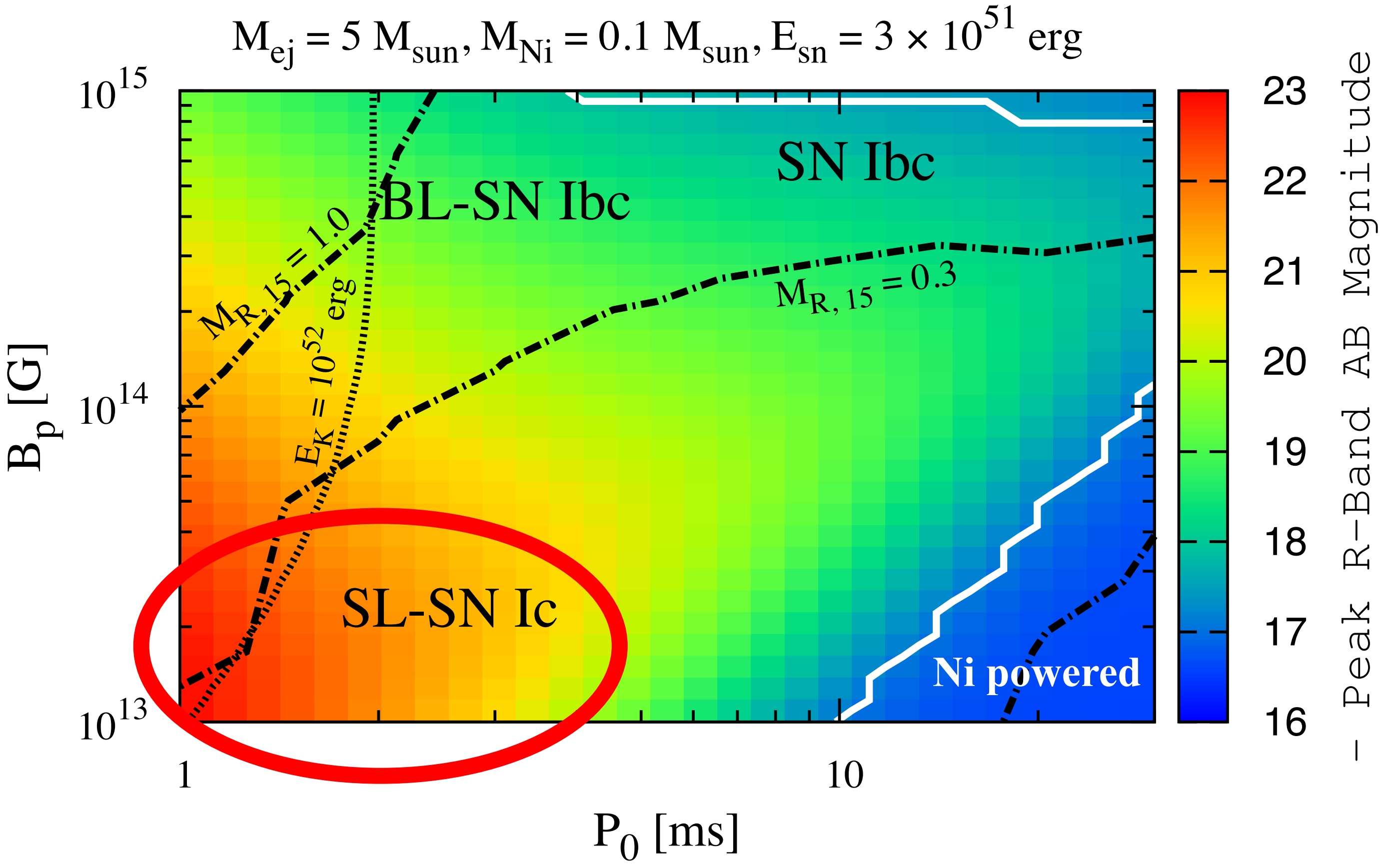
"Width"



For a given P_0 ,
SN becomes slower
for a smaller B_p

KK +16

Superluminous Supernovae – FRBs?



KK+16
Murase, KK, Meszaros 16

See also
Metzger+16, Margalit+17

- ✓ *Pulsar-driven superluminous SNe: M_{ej} ~ a few M_{sun}, P_0 ~ ms, B_{dip} ~ 10^{13} G*
  → consistent with the young NS model for FRB 121102
- ✓ *The event rate is consistent; ~ 0.01 % of core collapse SNe*
- ✓ *The host gal. type is also consistent*

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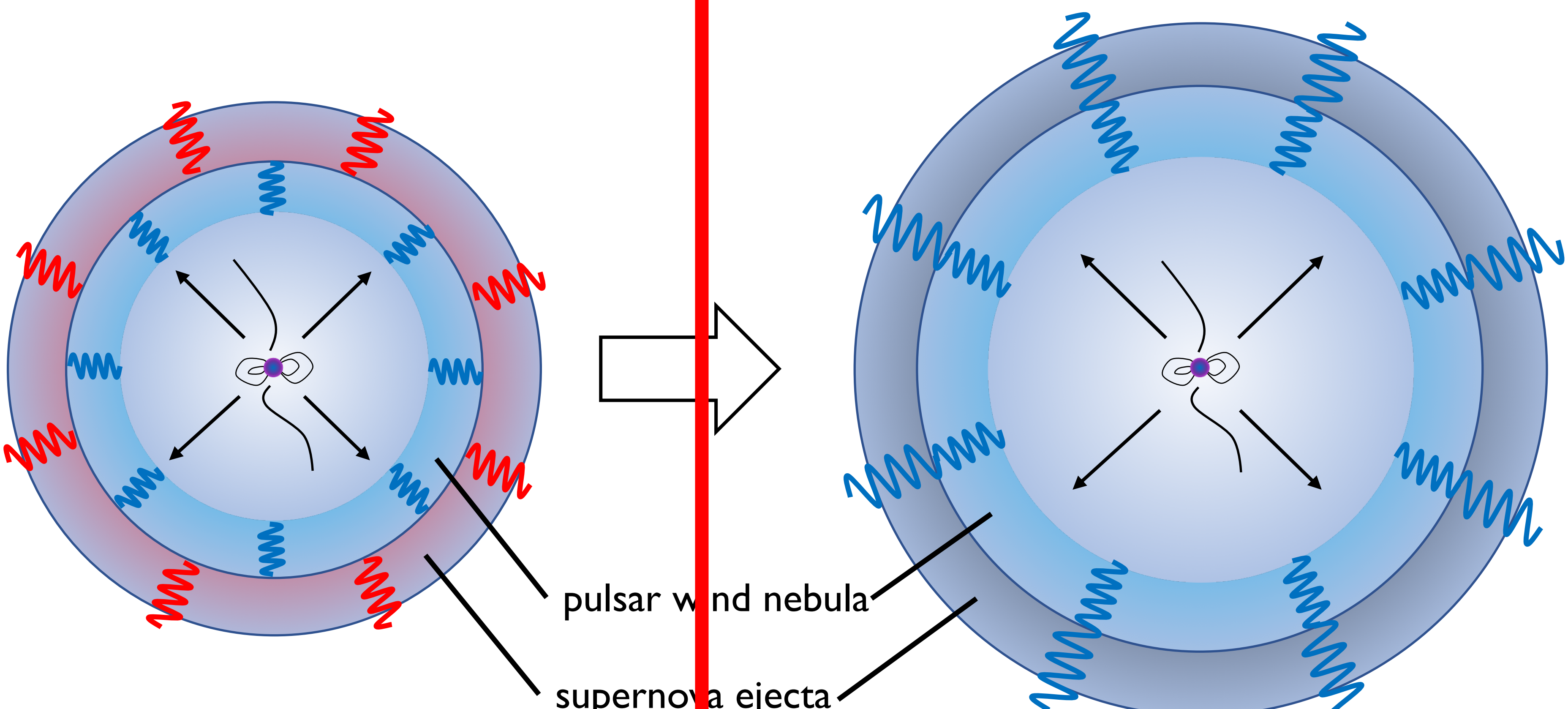
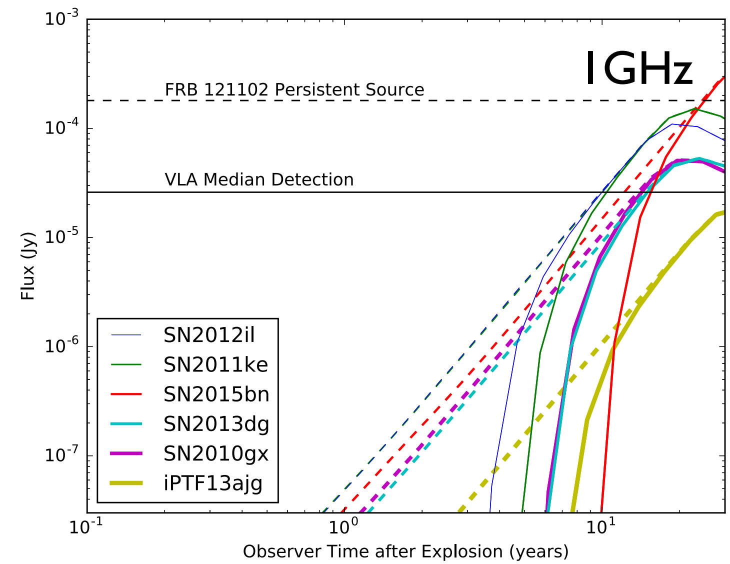


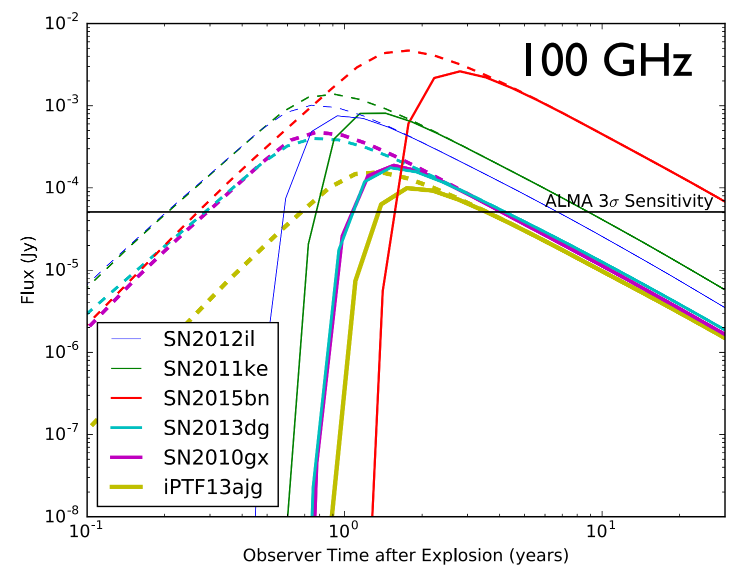
Radio PWNe of SLSN remnants

Omand,KK,Murase 17

0. fit SLSN light curves with the pulsar driven model
1. calculate the early PWN emission

✓ Detectable with ALMA from ~ 1 Gpc
<~ a few yrs after the explosion
✓ Detectable with VLA from ~ 1 Gpc
~ few 10 yrs after the explosion, and consistent with FRB121102

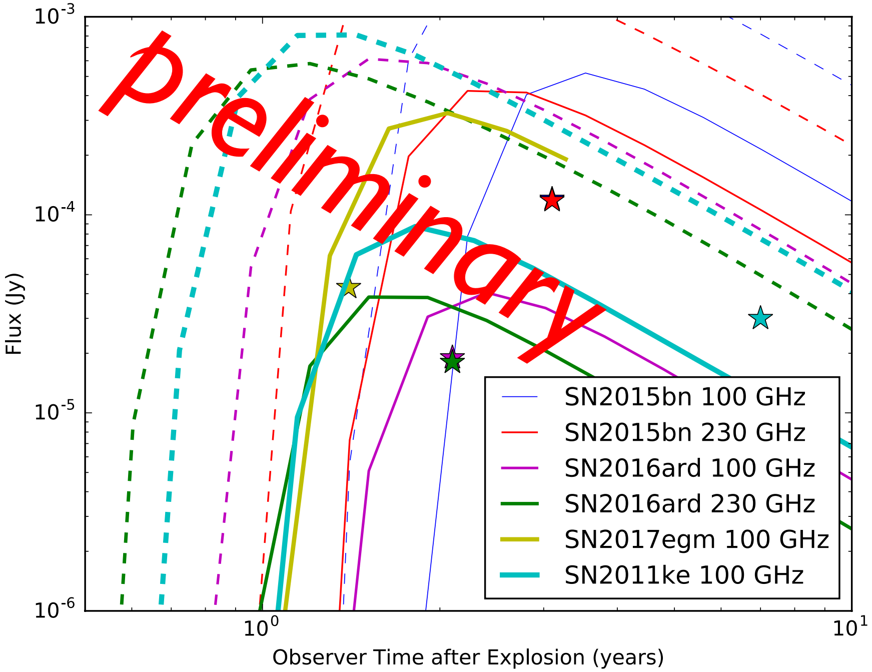




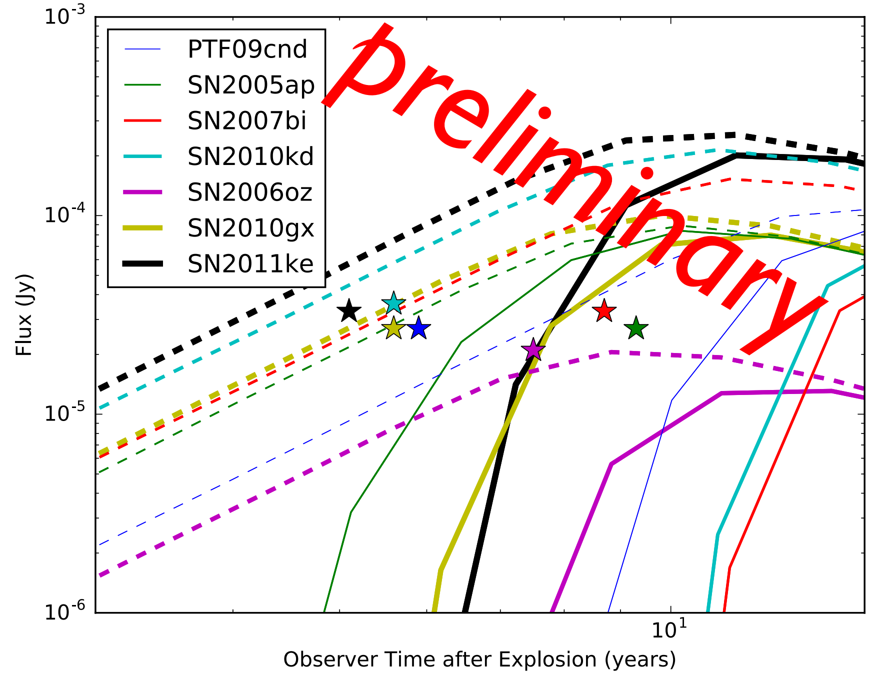
Still missing …

- The observed upper limits on the radio PWNe

by ALMA and NOEMA

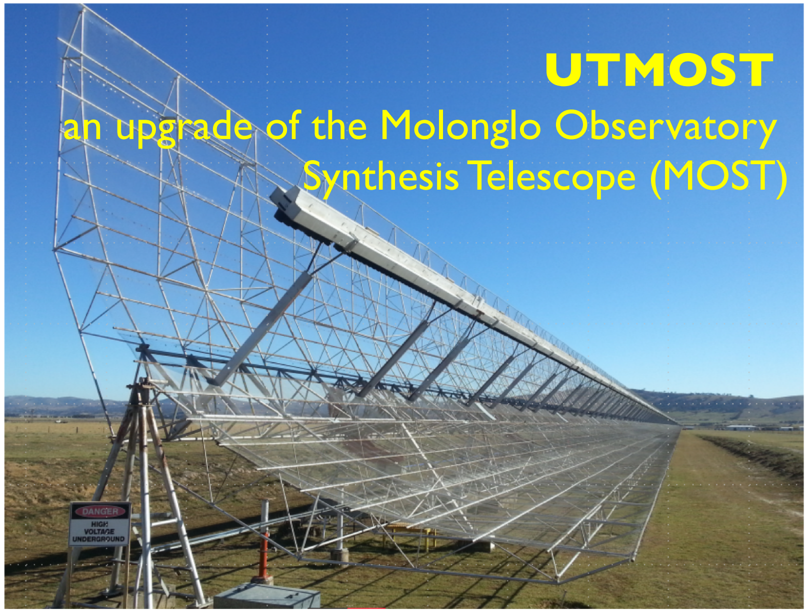


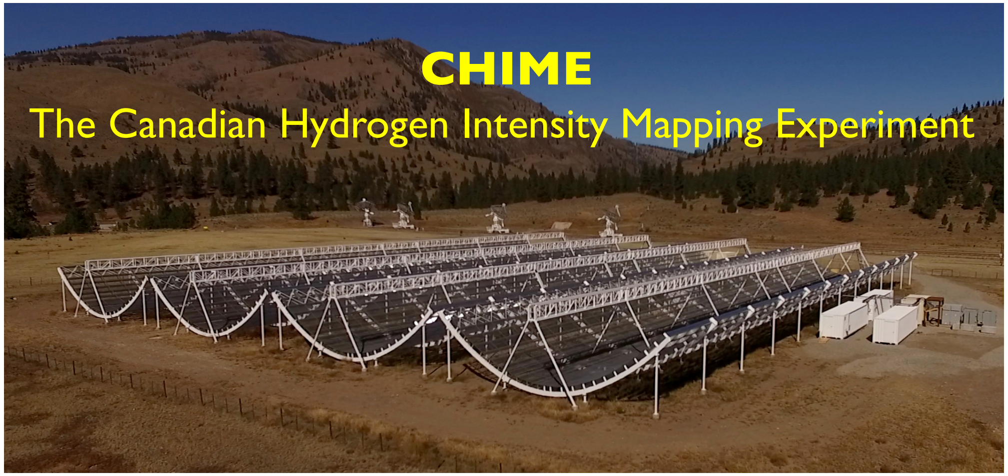
by VLA (including FRB search)



Omand et al. in prep
Law et al. in prep

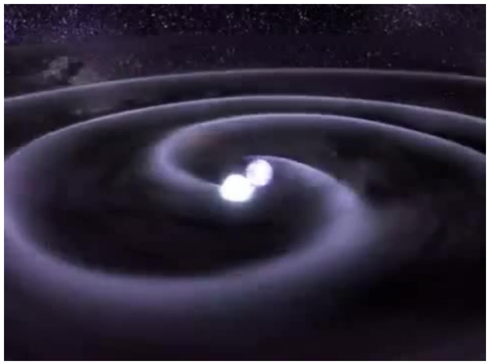
Powerful survey facilities online





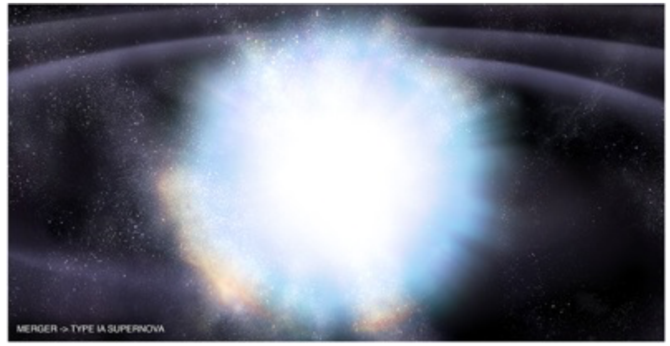
3. A Missing Energy

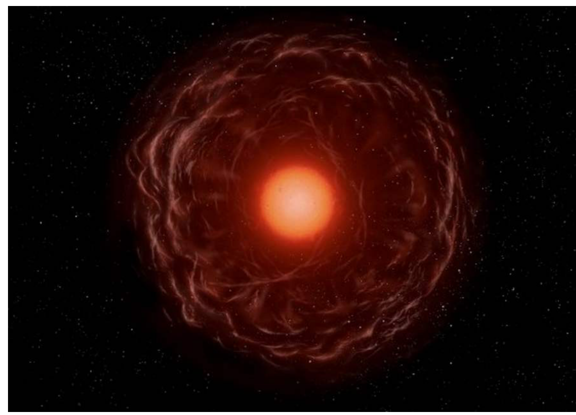
Double WD merger



~ 1 yr $^{-1}$gal^{-1}

Ia SNe?





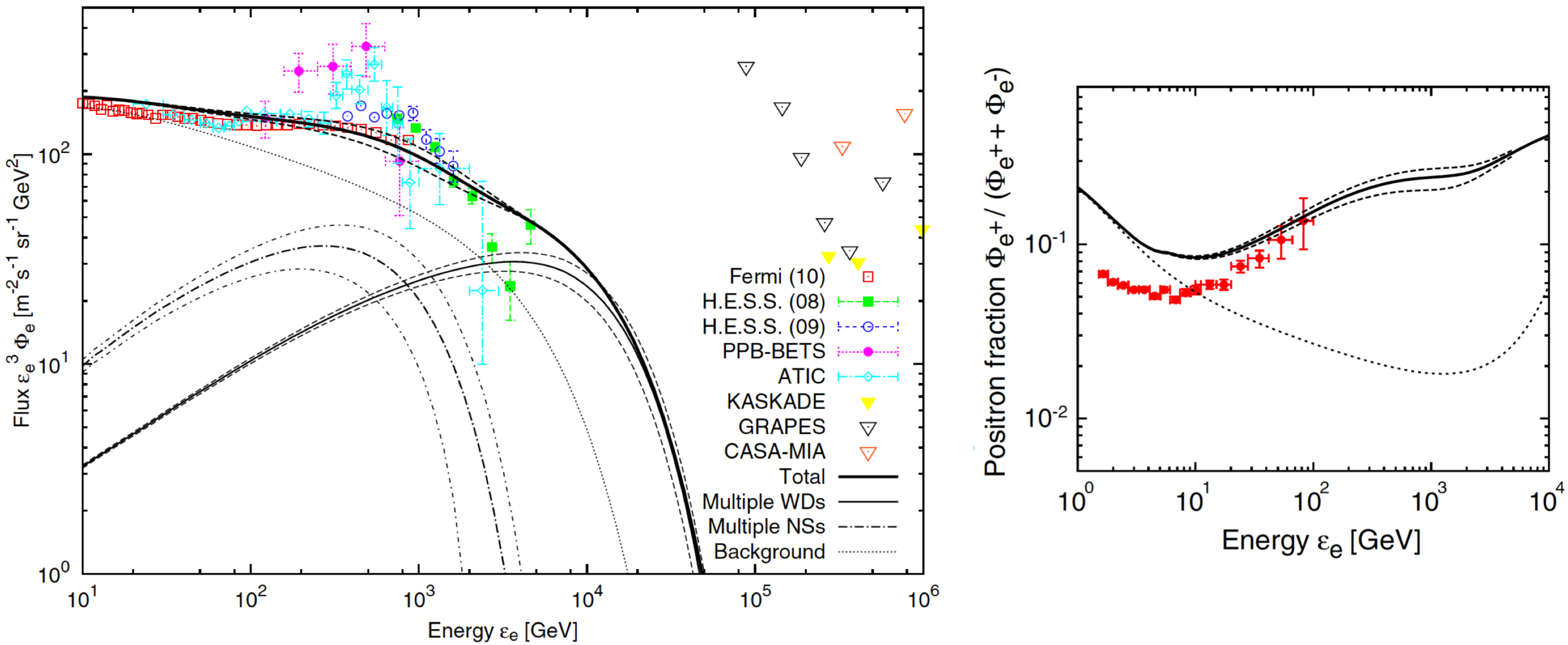
Debris expansion

Not found

Fast-spinning WD
@ mass shedding limit?
→ P_{rot} = 1-10 sec

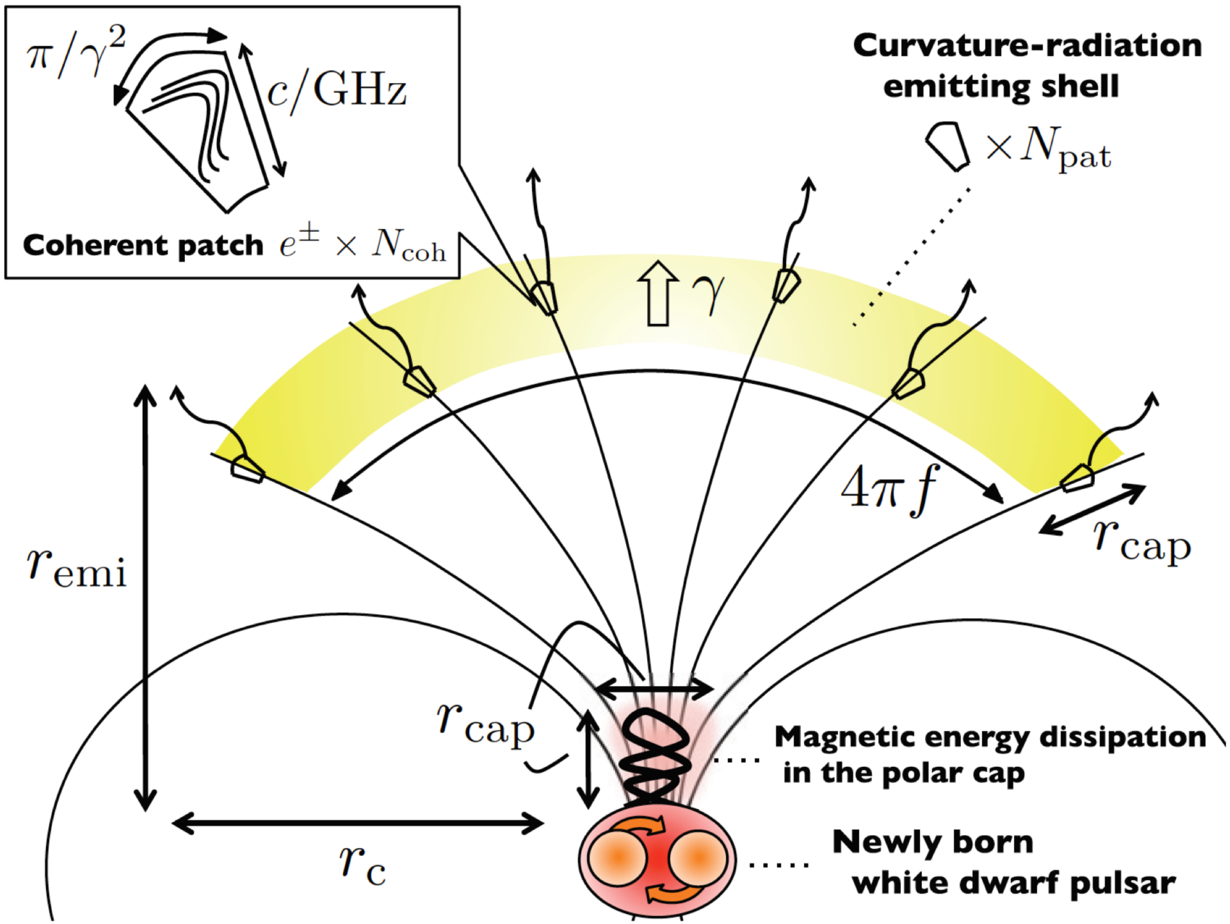
~ 10^{50}erg/100yr
~ 10 % of CCSN

Cosmic ray $e^{\pm}$ factories?



Kashiyama, Ioka, & Kawanaka 11

Origin of FRBs?



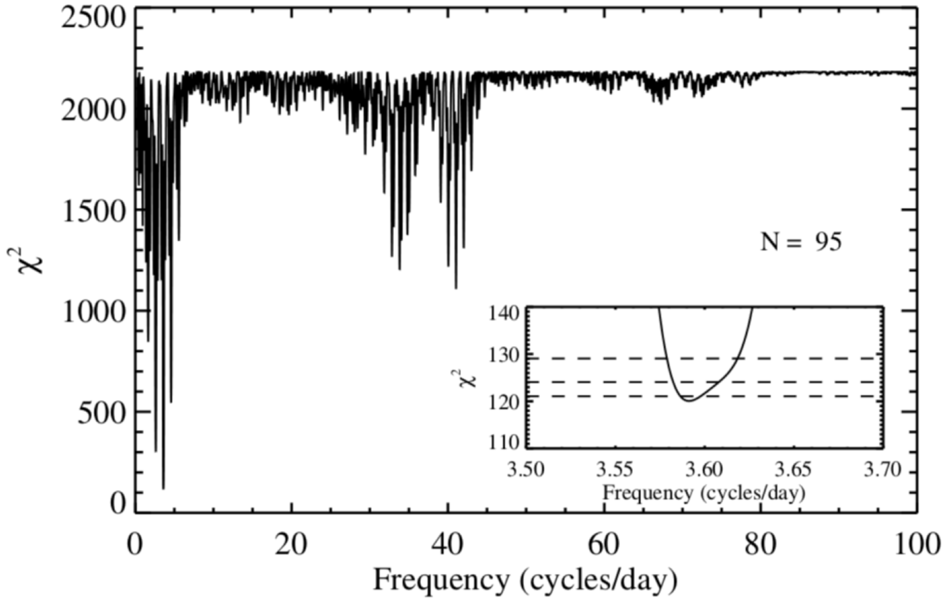
Kashiyama, Ioka & Mészáros 13

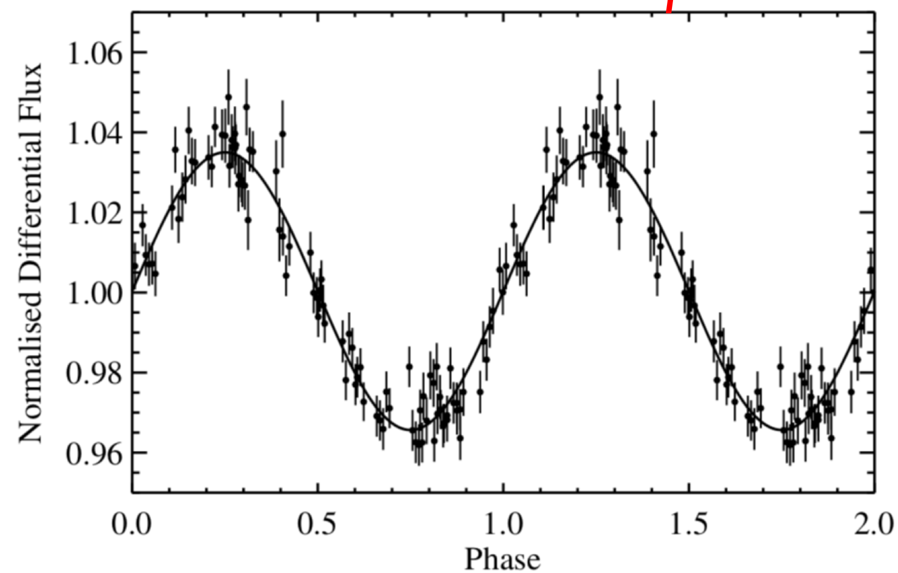

Let’s search for fast spinning single WDs!

The Target Signal

e.g., magnetized (3×10^8 G) WD G111−49

P = 6.68 hr
Amp. ~ 5%





See also

- DECam minute cadence survey Belardi+ (2016)
- Kepler/K2 observation of pulsating WD Hermes+ (2017)

But there is no sub-mimute cadence survey so far …

How many fssWDs?

WD birth rate: $\dot{N}_{\rm WD} \sim 1\,{\rm yr}^{-1}\,{\rm gal}^{-1}$ Badenes & Maoz (2012)

Double WD merger rate: $\dot{N}_{\rm merger} \sim 10^{-(2\text{-}3)}\,{\rm yr}^{-1}\,{\rm gal}^{-1}$

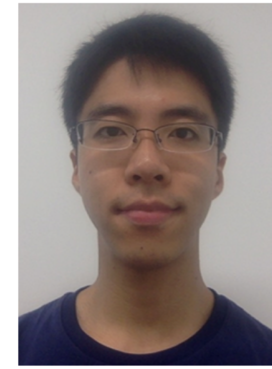
→ fraction of merger-origin WDs: $f_{\rm ffsWD} \sim 0.1\text{-}1\%$

Local number density of WDs from Gaia observations

$$n_{\rm WD} = 4.49 \times 10^{-3}\,{\rm pc}^{-3}$$ Hollands+ (2018)

$$\rightarrow \quad 4.49 \times 10^{-5}\,{\rm pc}^{-3} \left(\frac{f_{\rm fssWD}}{1\%}\right)\left(\frac{n_{\rm WD}}{4.49 \times 10^{-3}{\rm pc}}\right)$$

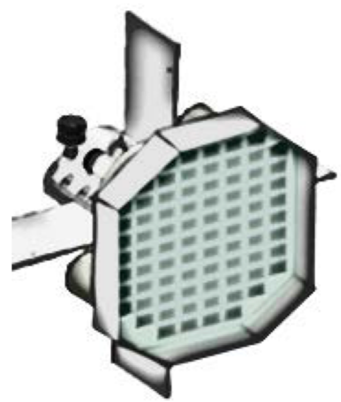
HeSO

The Hertz Spinning Object survey（仮名）

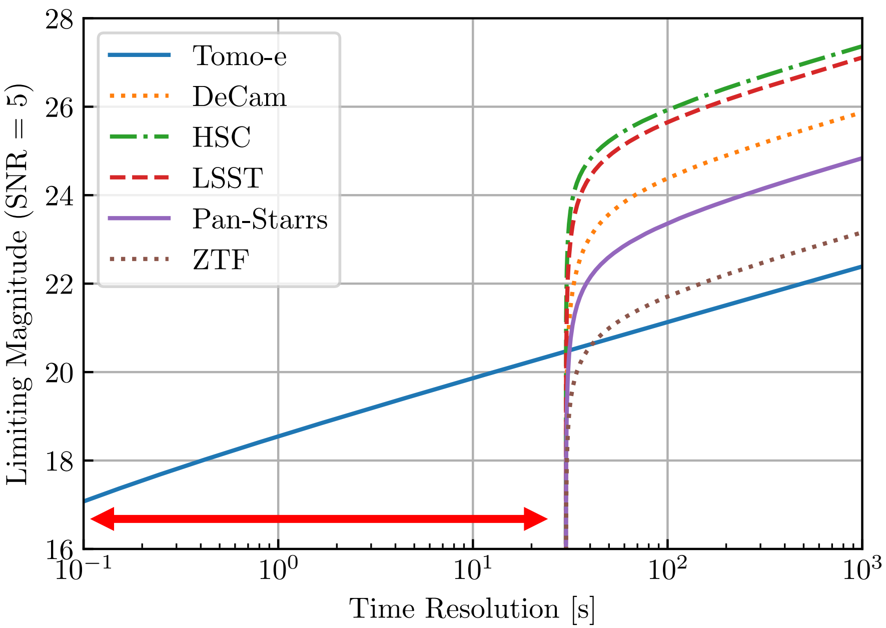
with the Tomo-e Gozen Camera; Tomo-e

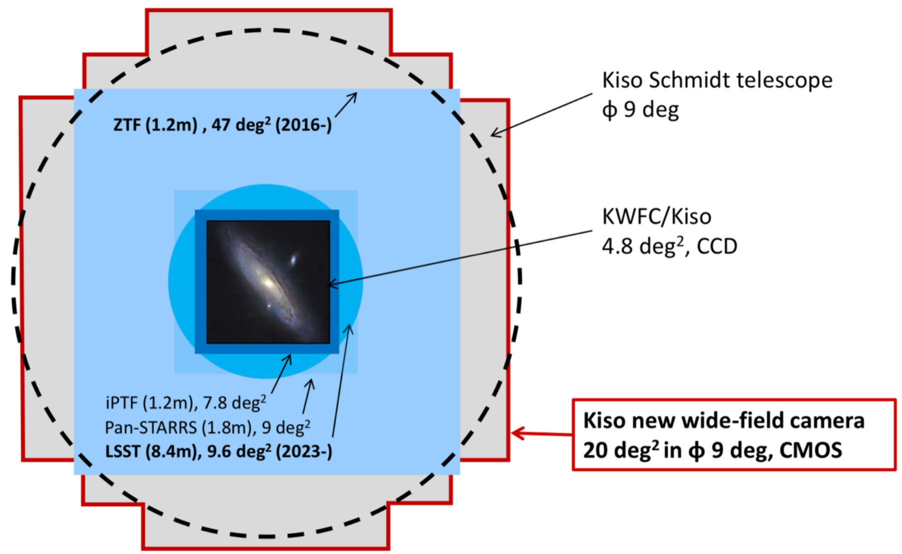
- Telescope: Kiso 105 cm Schmidt
- Field of view : 20 deg^2 in ϕ 9 deg
- Sensor: 1k x 2k CMOS sensor†
- Chips: 84
- Pixel scale : 1.2 arcsec/pix
- Frame rate : 2 frames/sec (max)
- Filter : SDSS-g+r, SDSS-g, SDSS-r ‡



† Driven at ordinary temperature and pressure
‡ Manually exchange between filters in the daytime

Why with Tomo-e?



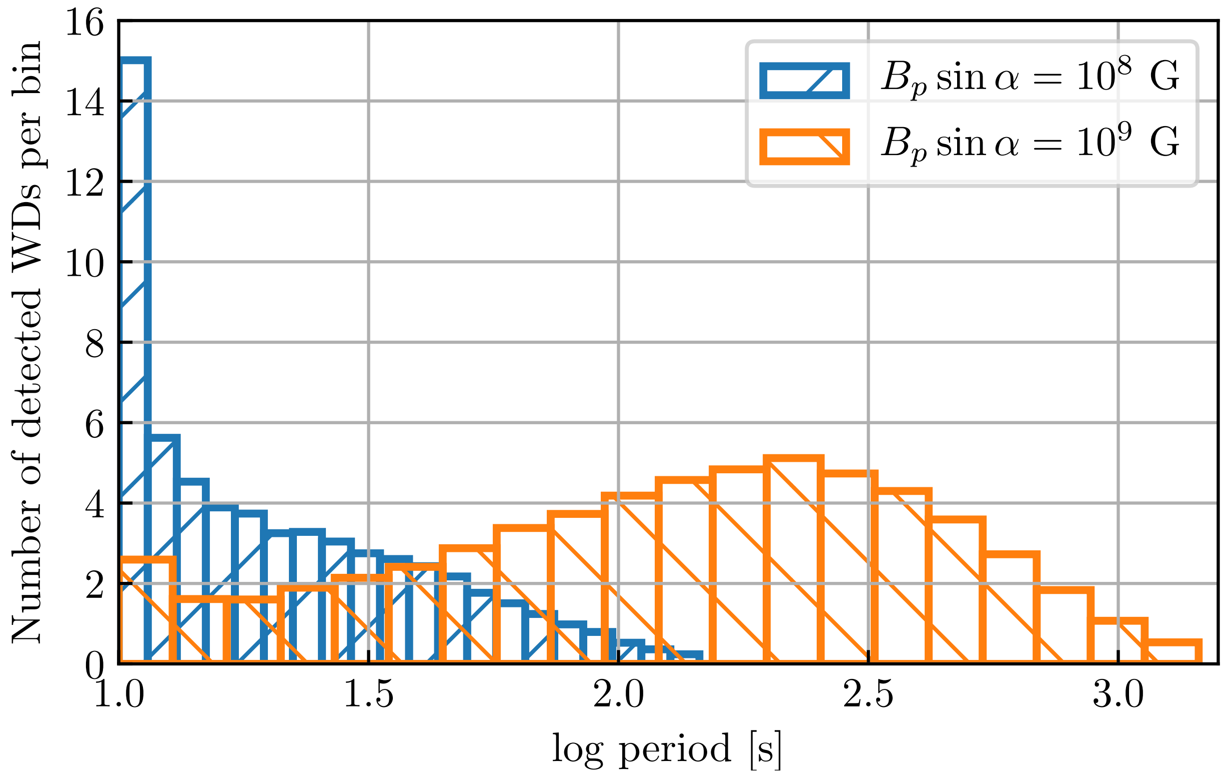


Because it's a CMOS camera capable of sub-minute cadence!

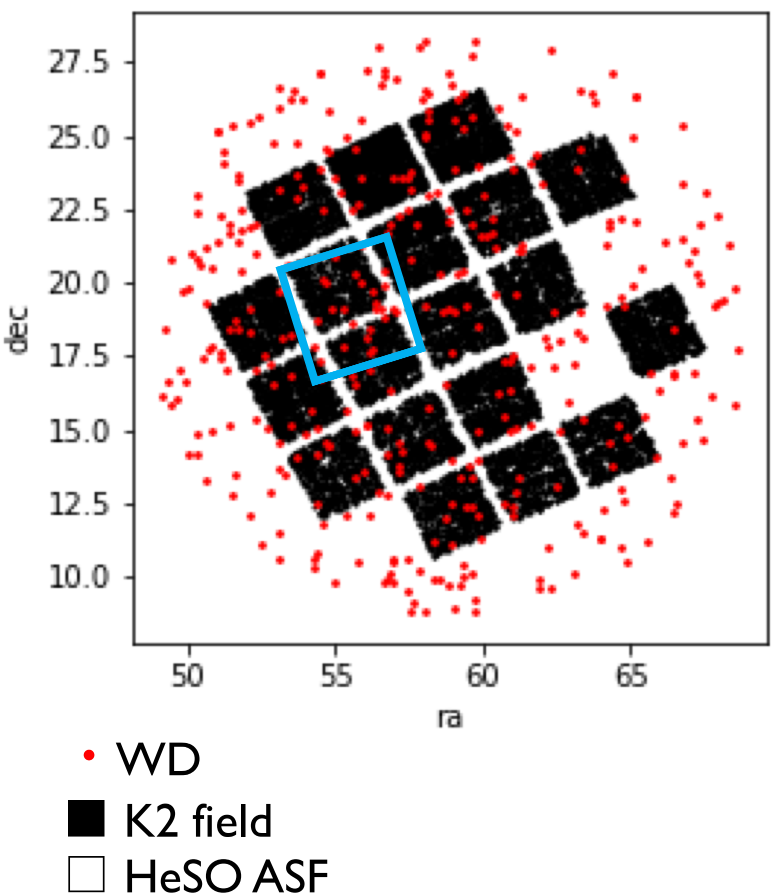
& because of its wide field of view!

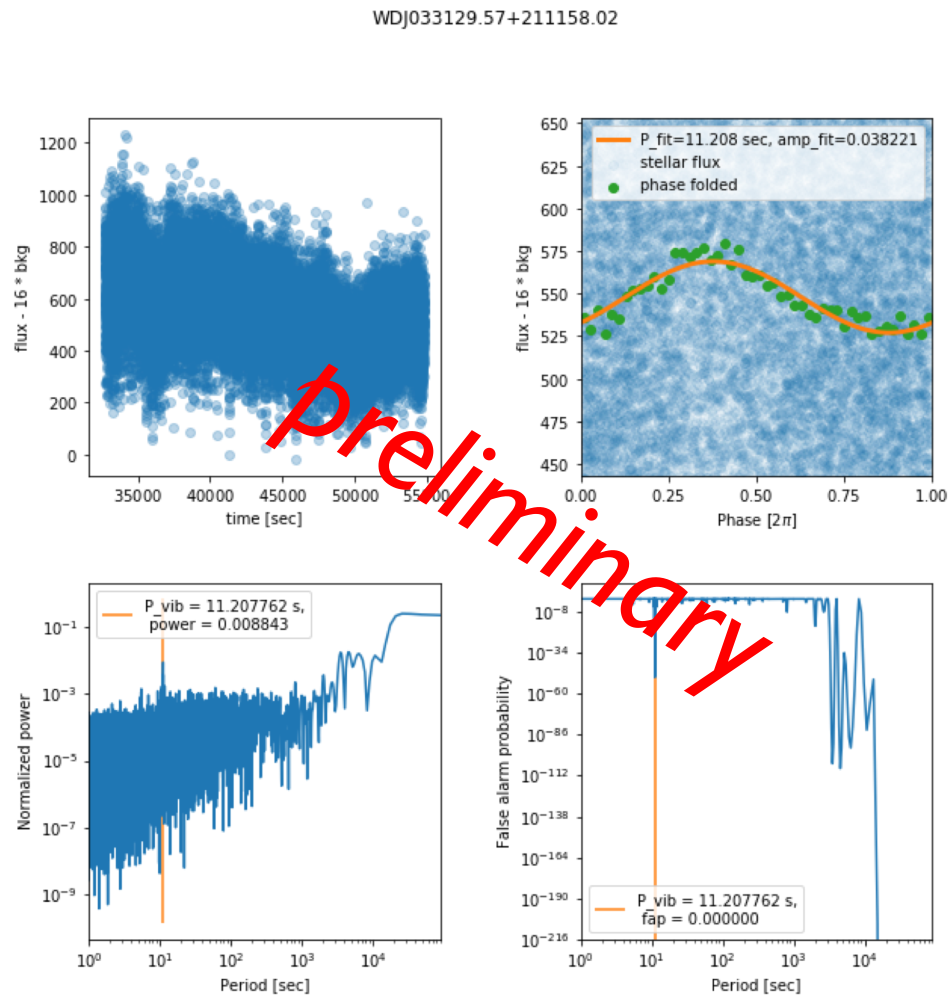
Prospects

- Limiting magnitude: g = 19, sky coverage 10,000 deg^2
- f_{fssWD} = 0.3%



Pipeline Construction, Test Observations Under Way





Summary

1. The diversity of young neutron stars is originated from the fallback accretion onto the newborns?

2. The central engine of (repeating) FRBs and superluminous SN is the same?

3. Let us search for the fastest spinning white dwarf!