Fast radio burst research with FAST

4.7 FRBs searching stories and perspective

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NAOC, CAS

@

I am the speaker, but work is done by many others

Students, PKU-XAO-YNAO FRB searching team

many others

FAST FRB collaboration and …

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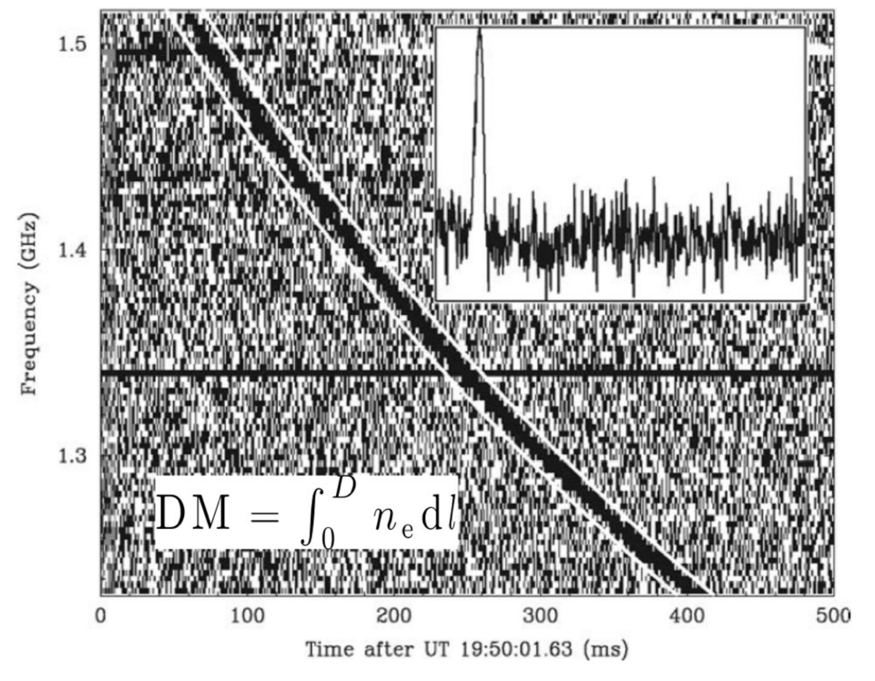
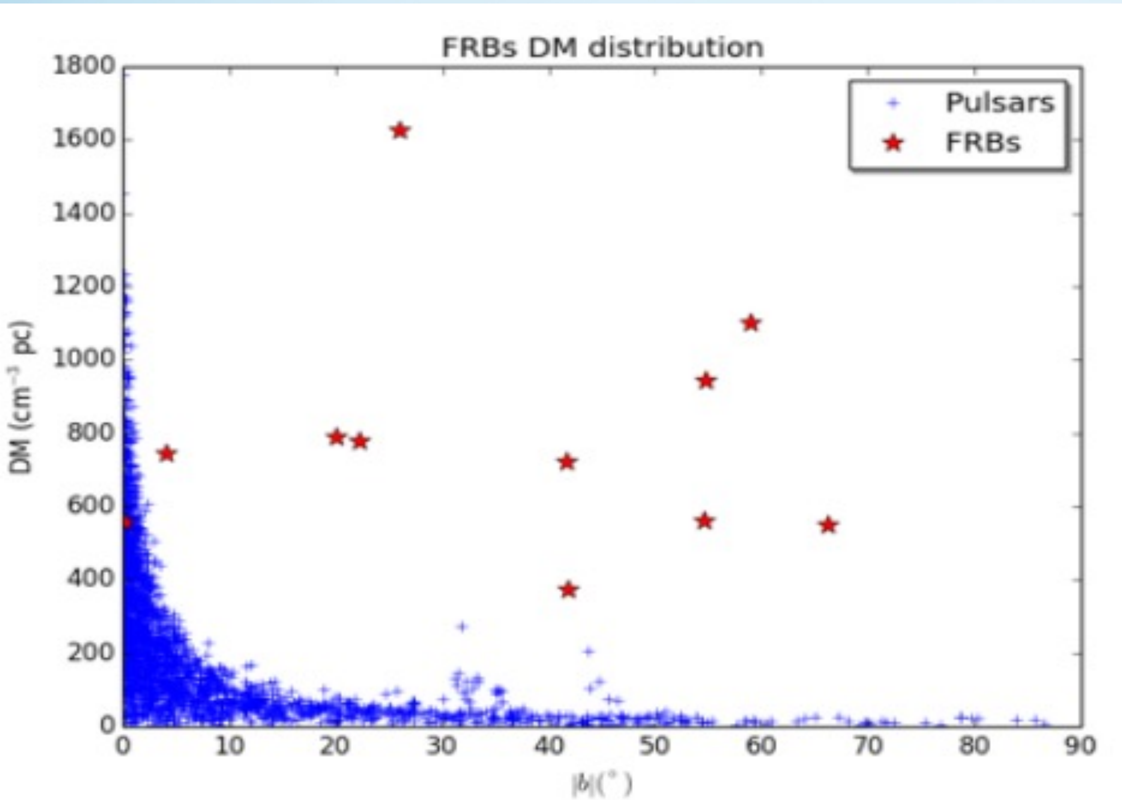
FRBs

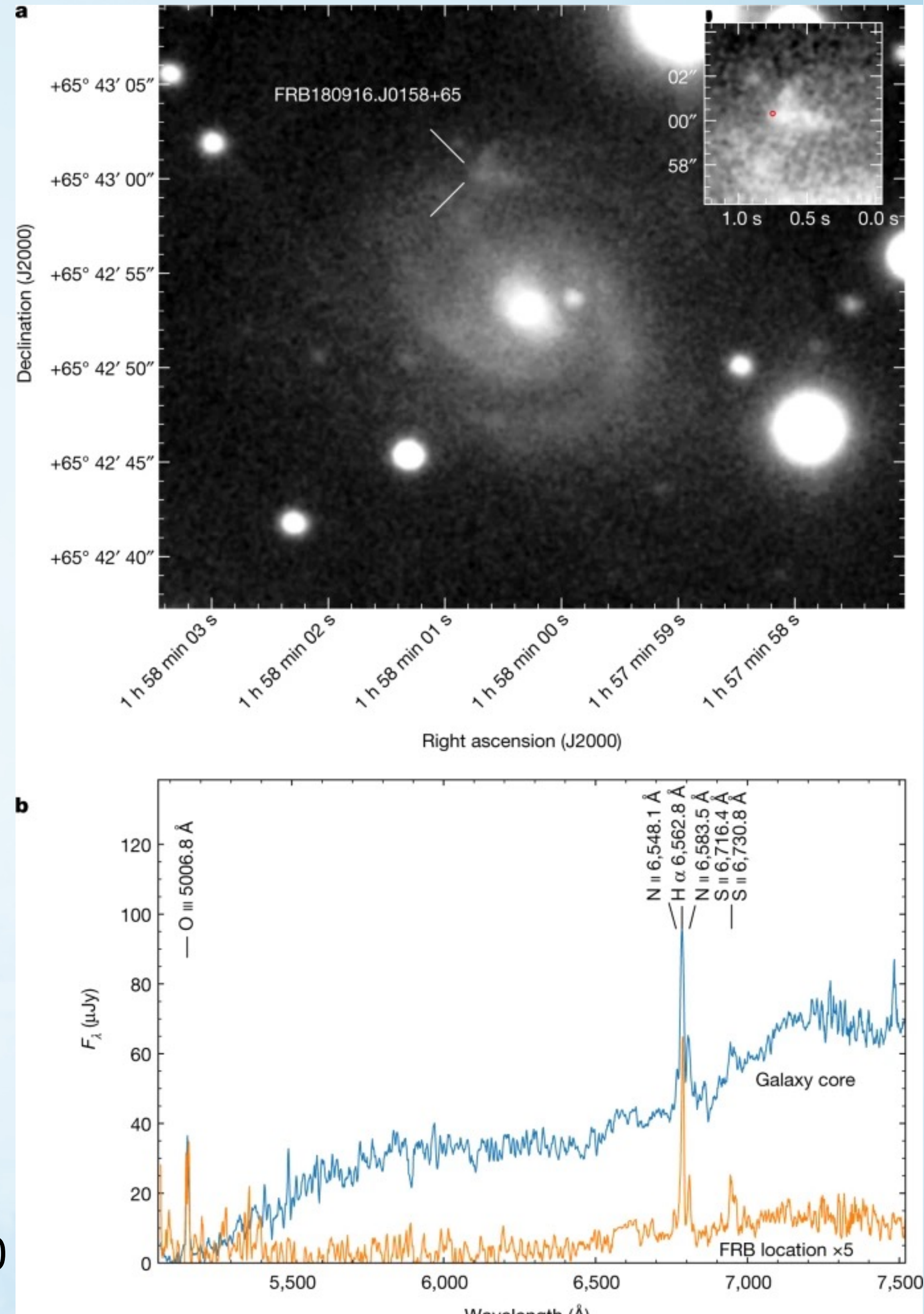
- High DM (Greater than local Galaxy values)
- Short duration (ms) --> must be compact
- Bright --> 1E38 erg
- Mostly found around 1GHz (recently detected around 100MHz)
- Spectrum now known
- Maybe two types
  - repetitive vs non repetitive
- **Unknown** origins
- Totally 119 are known.



Lorimer et al. 2007

Observational facts





FRB is extragalactic

Marcote et al., 2020

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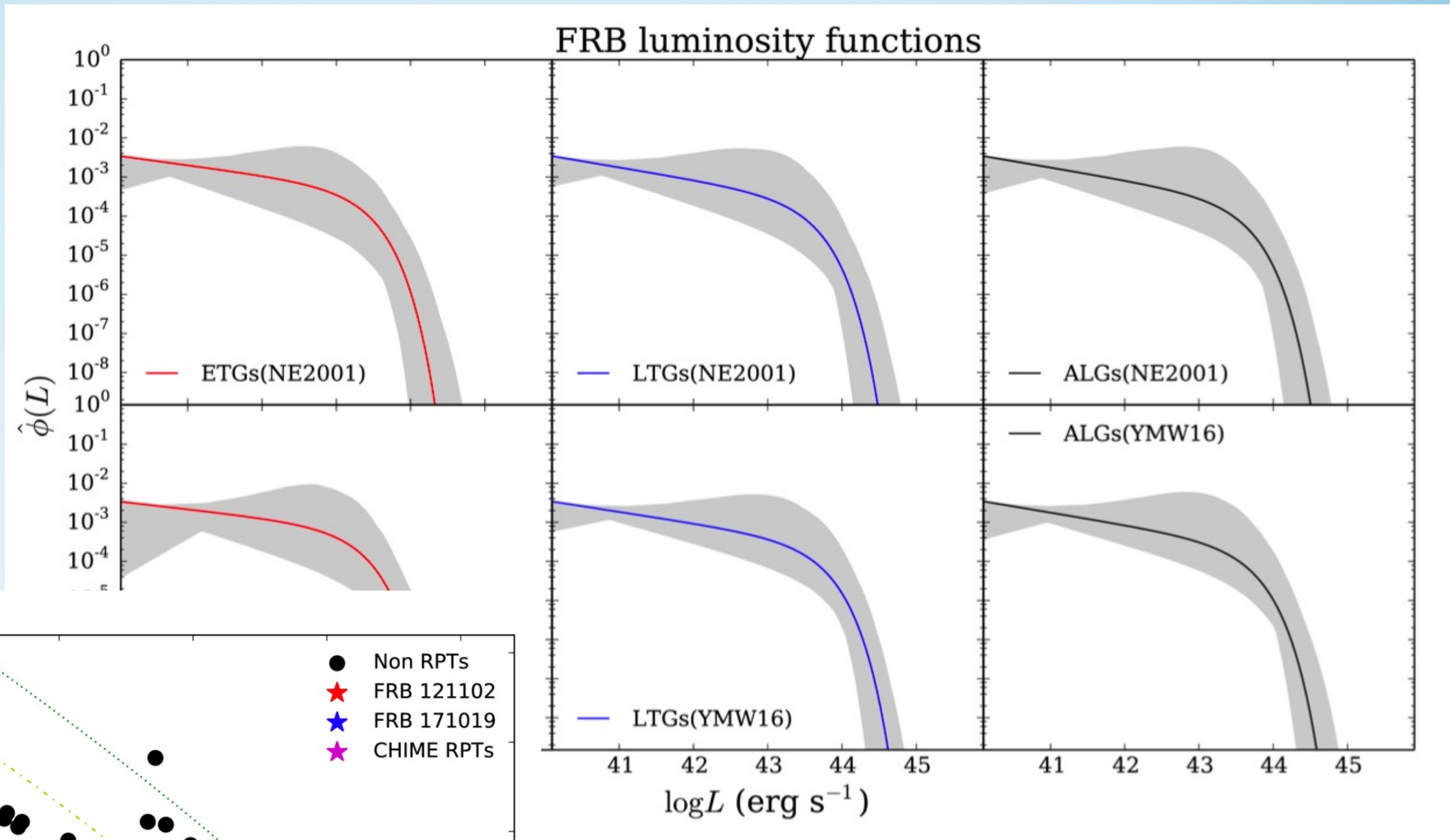
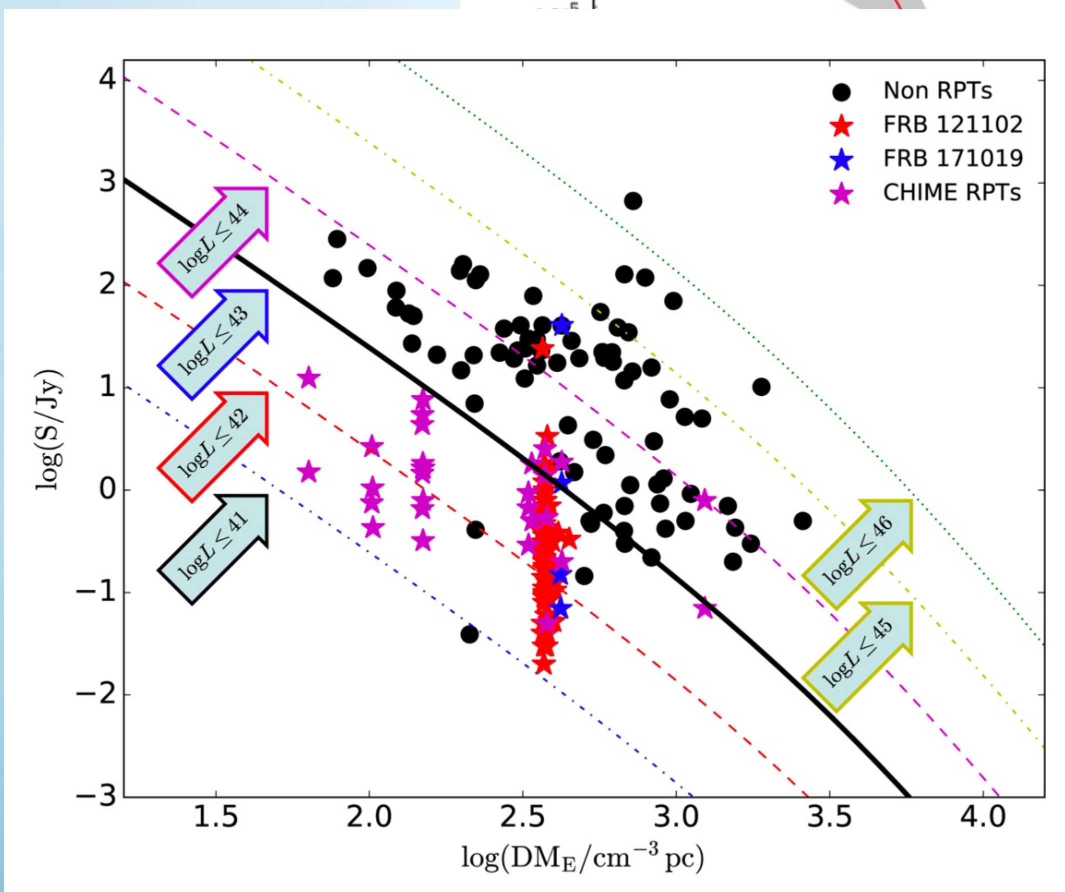


Luo et al., 2018

Peak flux of 1E42 erg/s
Cut-off around 1E44 erg/s

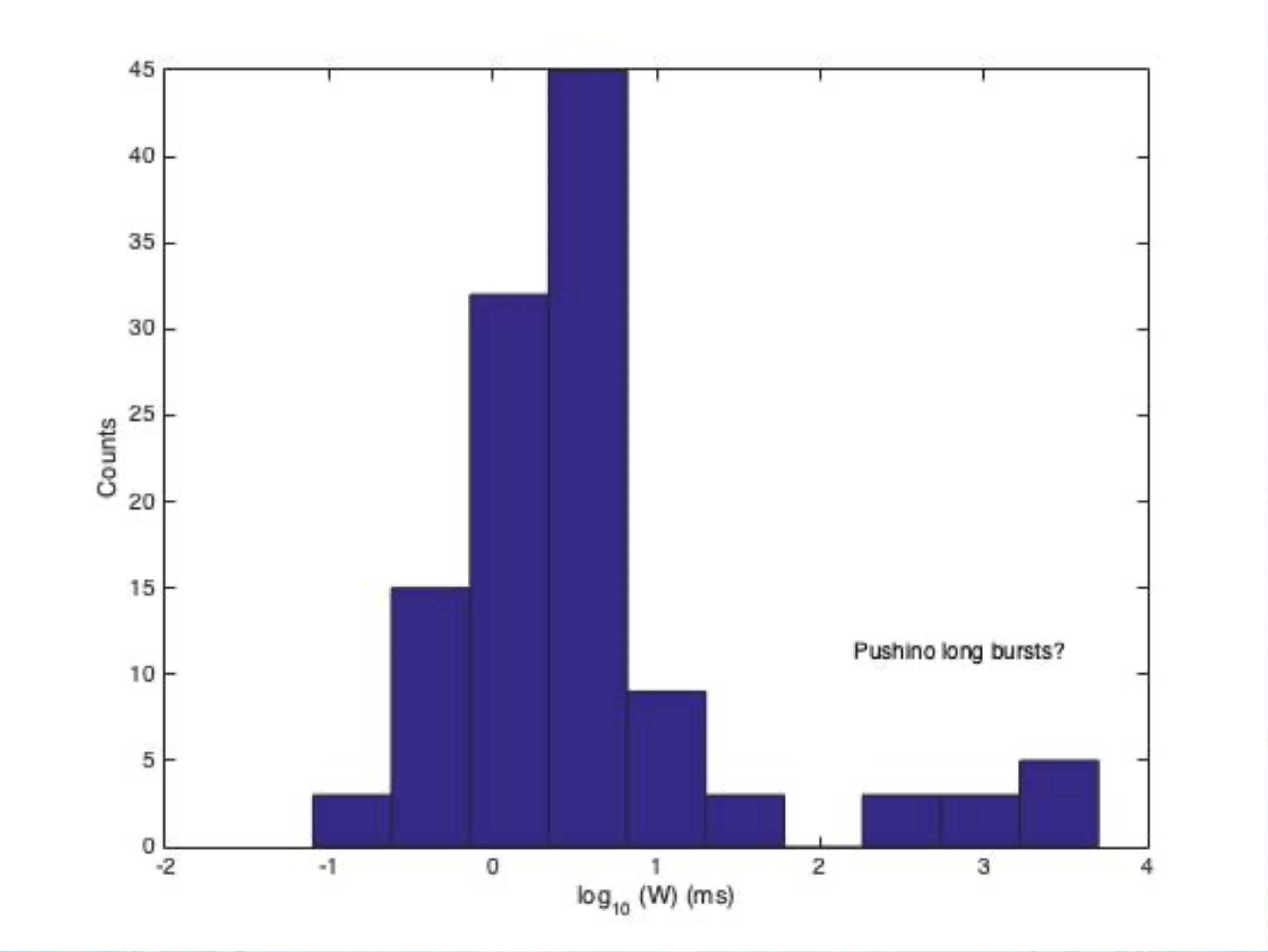


Luo et al., 2019

http://frbcat.org/

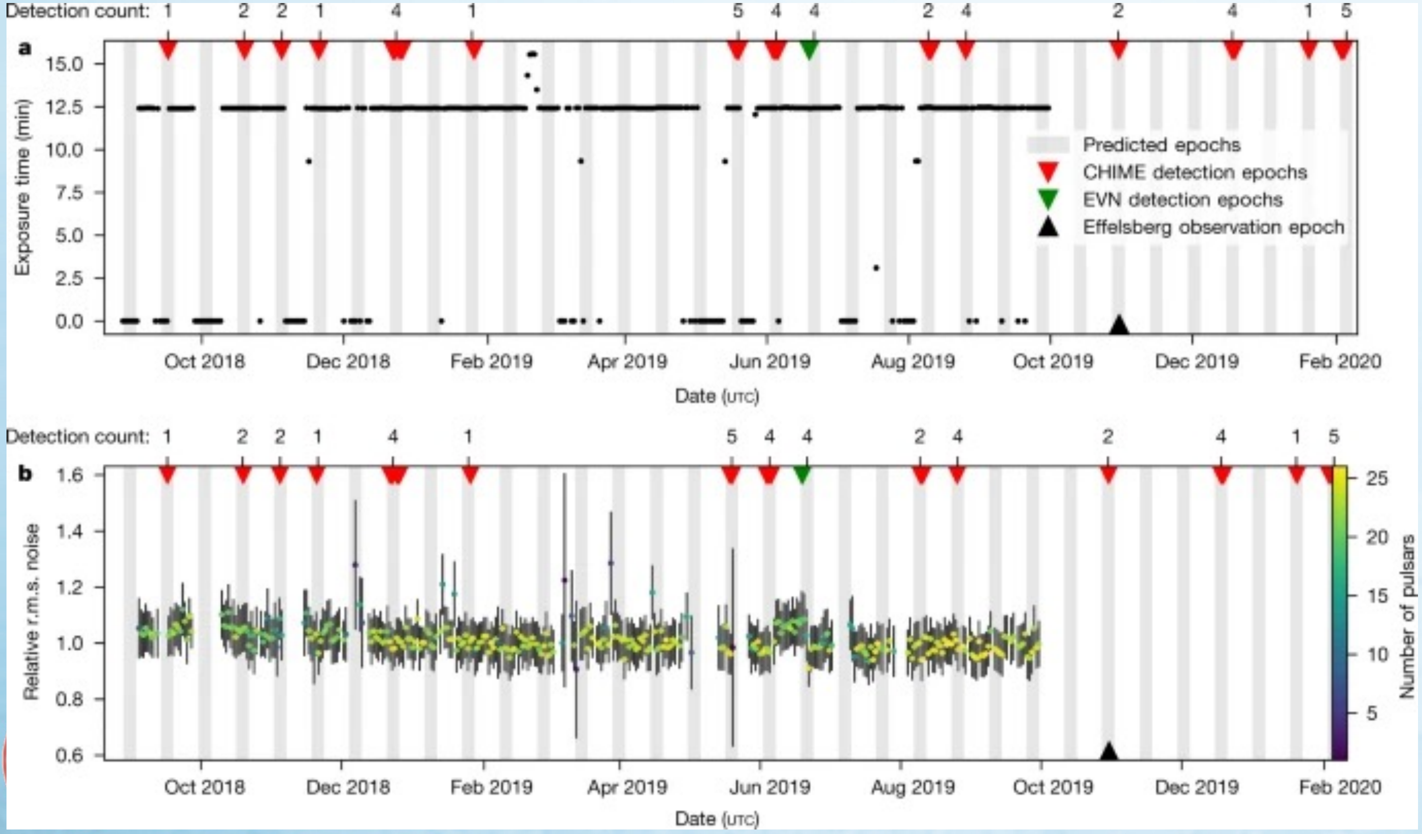
FRB pulse width

119 in total, 23 repeating ones.



Possible period

CHIME 2020



Key breakthrough in the past

- Discovery 2007
- Repeater 2012
- Host galaxy identification 2017
- High magnetic field 2018
- 16-day period 2019

One sentence conclusion

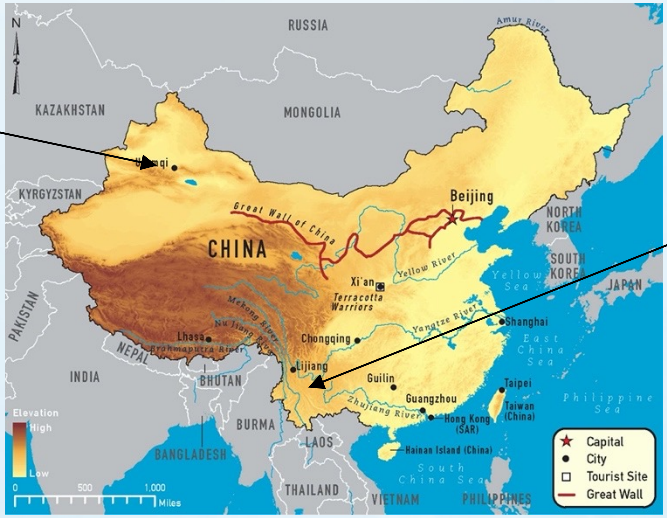
- FRB, repeating or not, is a ms-duration radio burst with about 1E42 erg/s peak flux.
- No spin-like period detected yet, but longer period may be discovered.

Outline

- Story 1: Searching strategy and a strange peryton
- Story 2: Burst in M82?
- Story 3: FRB from magnetosphere?
- Story 4:Not all monster are doing monster things
- Story 4.5: Monster turns vanilla

Story 1 Searching FRB with NS26m and KM 40m, Peryton detection

26 m in Xinjing



40 m in Yunnan

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2015, we decide to try to search for FRBs

Peking University

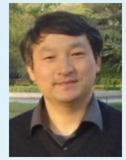
K. J. Lee (PI)

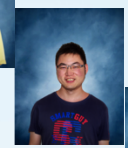
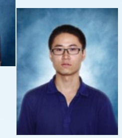
R. X. Xu (theory)

R. Luo (theory)

Y. P. Men (data processing, instrumentation)

C. F. Zhang (AI, data reduction)



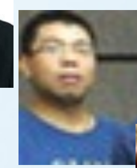
Xinjiang Observatory

X. Pei (data processing, instrumentation, observation)
Z. Y. Liu (instrumentation)

Z. G. Wen (data processing, observation)

J. P. Yuan (Data, observation)






Yunnan Observatory

L.F. Hao (observation, data processing)

Y.H. Xu (observation, data processing)

Z.X. LI (Observation, data processing)



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Supported by U1531243

Get proposal funded since 2015

- Discovery 2007
- Repeater 2012
- Host galaxy identification 2017
- High magnetic field 2018
- 16-day period 2019

1. We want to get KM40m working and observe pulsars
2. Use 26m and 40m to do localisation
3. Pulsar magnetosphere, profile, and polarisation
4. FRB searching
5. timing
6. AXP and SGR monitering

项目批准号	U1531243
申请代码	A03
归口管理部门	
依托单位代码	10087108A0031-0054

U1531243100815 1

国家自然科学基金委员会

资助项目计划书

资助类别： 联合基金项目

亚类说明： 重点支持项目

附注说明： 天文联合基金

项目名称： 云南台40米和新疆台25米脉冲星和快速射电暴观测研究

直接费用： 210万元　　**间接费用：** 29.6万元

项目资金： 239.6万元　　**执行年限：** 2016.01-2019.12

1，**建立和完善云南 40 米脉冲星观测系统以获取可靠的科学数据。**
工程”任务的同时，云南 40 米（S、X 波段）每年可以保证 2000

2，**脉冲轮廓多波段观测研究以检验脉冲星磁层辐射模型。**这一研究不仅能够检验脉冲星射电辐射模型（Lee et al., 2009），而且有助于国内新建望远镜的良好运行、获取可靠

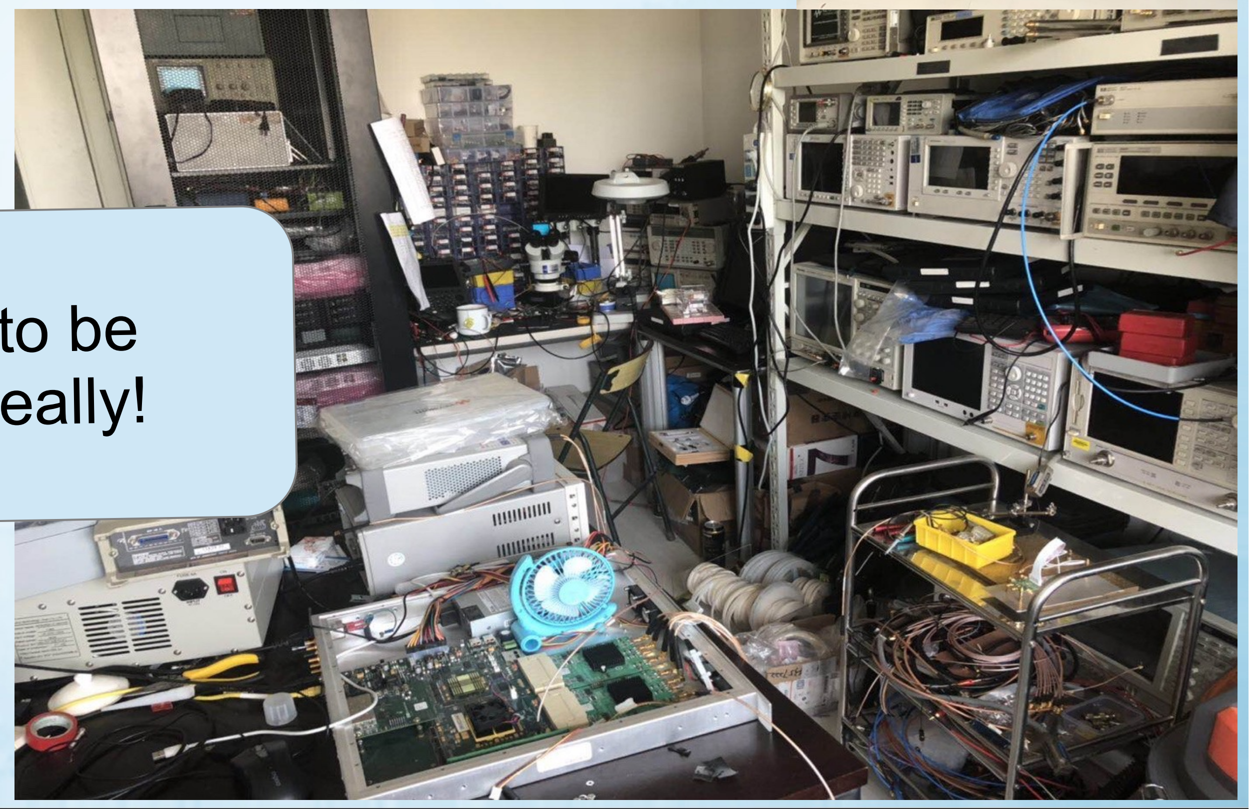
3，**发展国内脉冲星和爆发类射电天体的搜寻技术。** 过去 20 年中， 脉冲星相关科学的前沿无不与发现新类型的脉冲星息息相关。 发现新的脉冲星不仅仅为脉冲星测时阵列提

4，**常规计时监测若干脉冲星以获取自转、轮廓演变、消零等方面的信息。**脉冲星自转行为的变化以及脉冲缺失现象反映了磁层的动力学过程和星体内部结构；近期的研究还发现

5，**反常 X 射线脉冲星和软伽玛射线重复暴（AXP/SGR）的射电监测。**目前在约 30 颗 AXP/SGR 中发现几颗是射电暂现源；这对于人们了解 AXP/SGR 的本质是关键的。根据云台 40 米

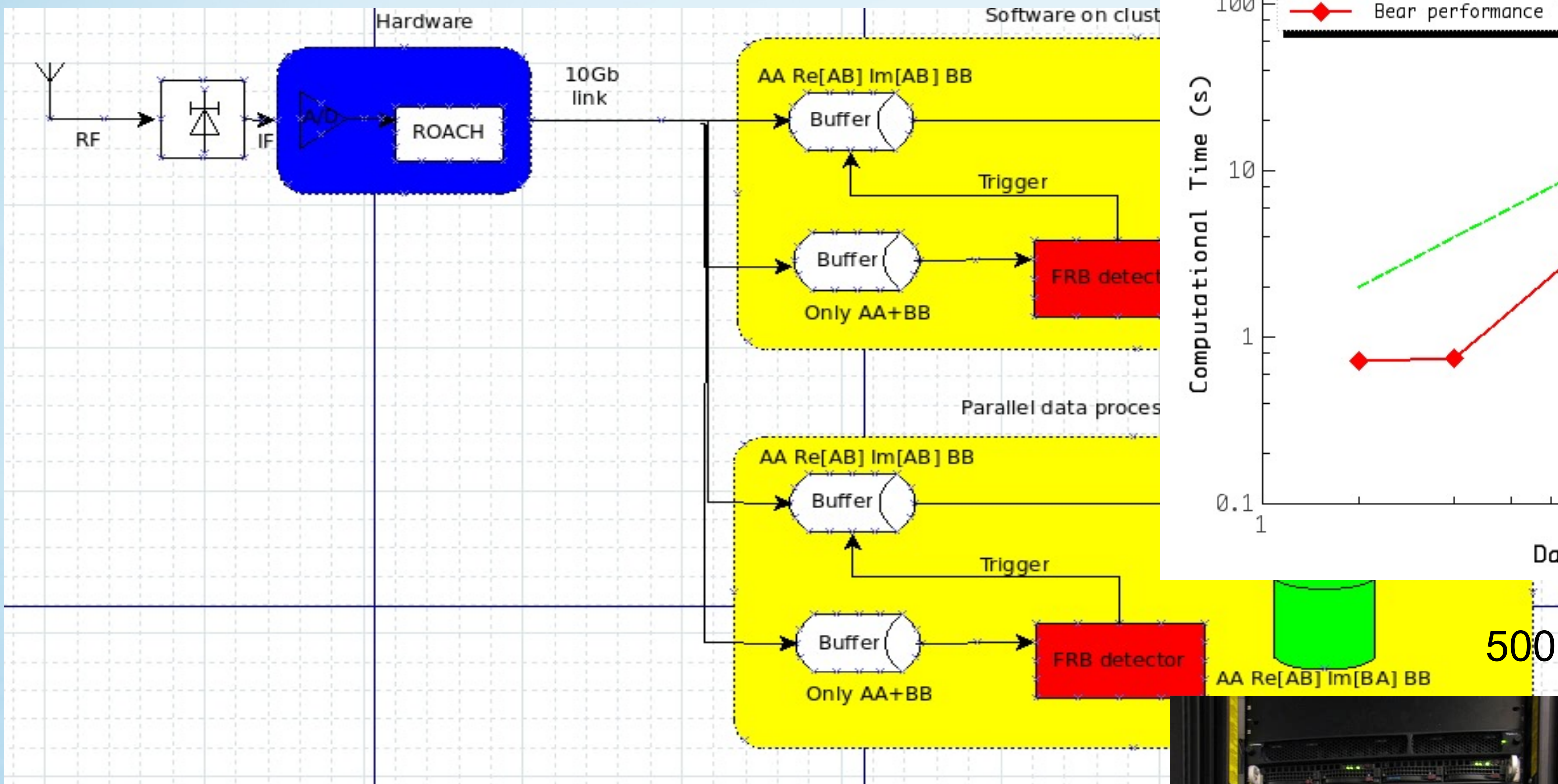
First, let there be a lab

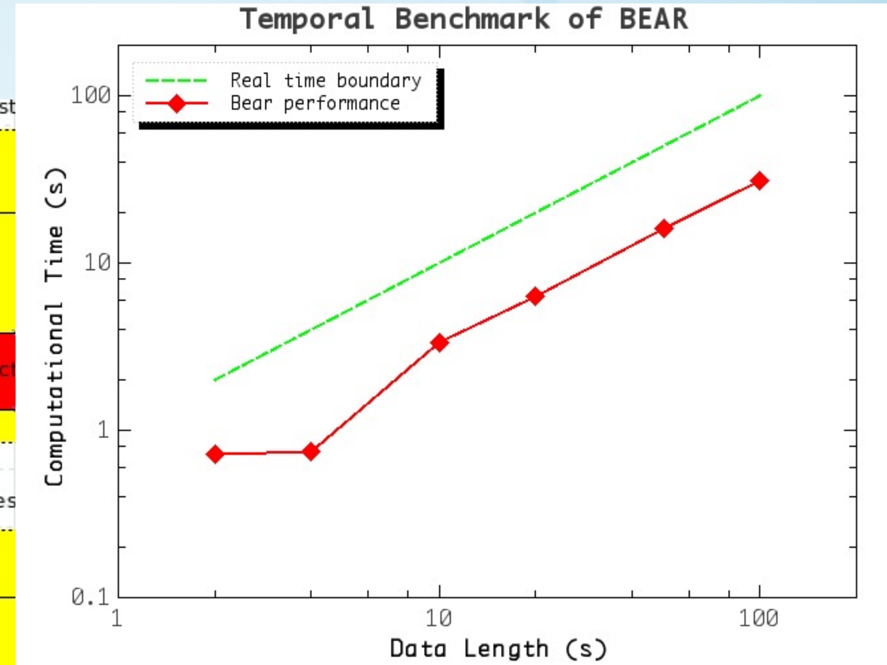
- We spend three minutes to convince Prof. Xu to convert his office to be a lab for 6 month. We then spend a few months to do so, and then we sneakily and gradually installed those noisy things such as miller and driller there.



That used to be my office really!

While waiting for the things to arrive, we code the software





500MHz BW, 3000 DM tries

Developed Software BEAR. Optimize the memory-cache access that we can real time processing with one cpu core. Also we get the match filter runs with O(N+m) complexity instead of Nlog(m) .

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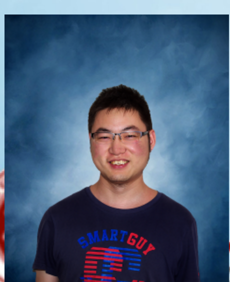
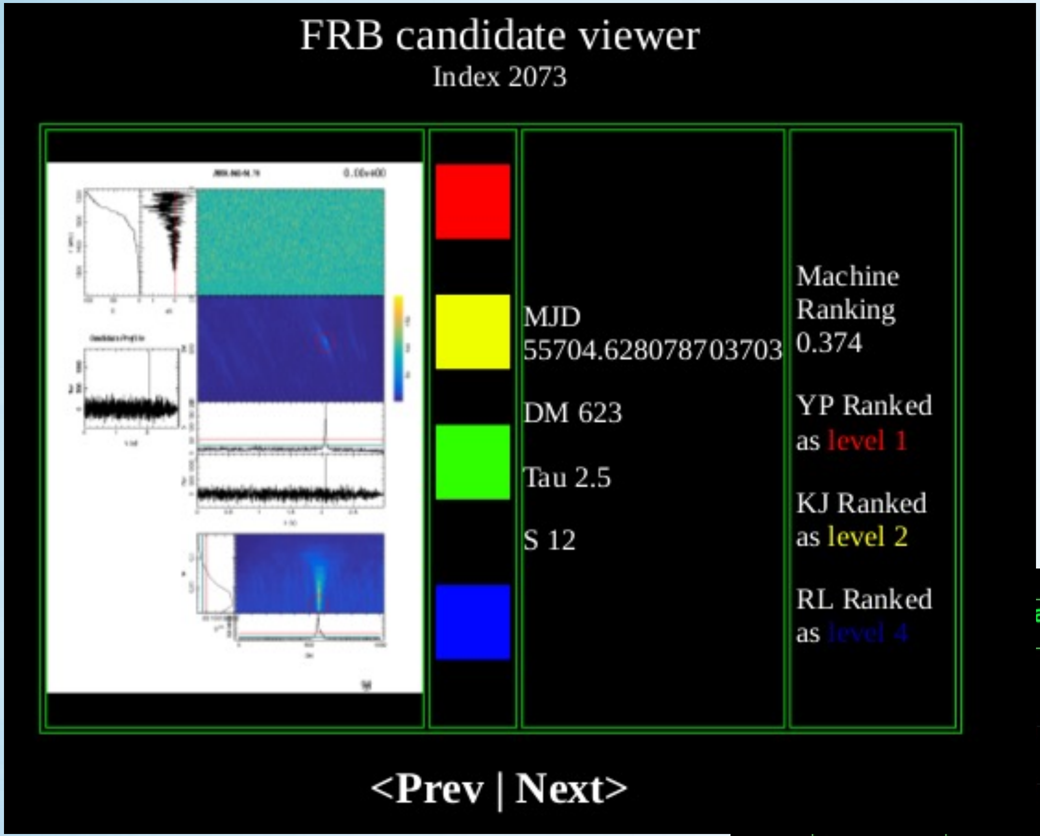
After we have the lab, Hardware developing

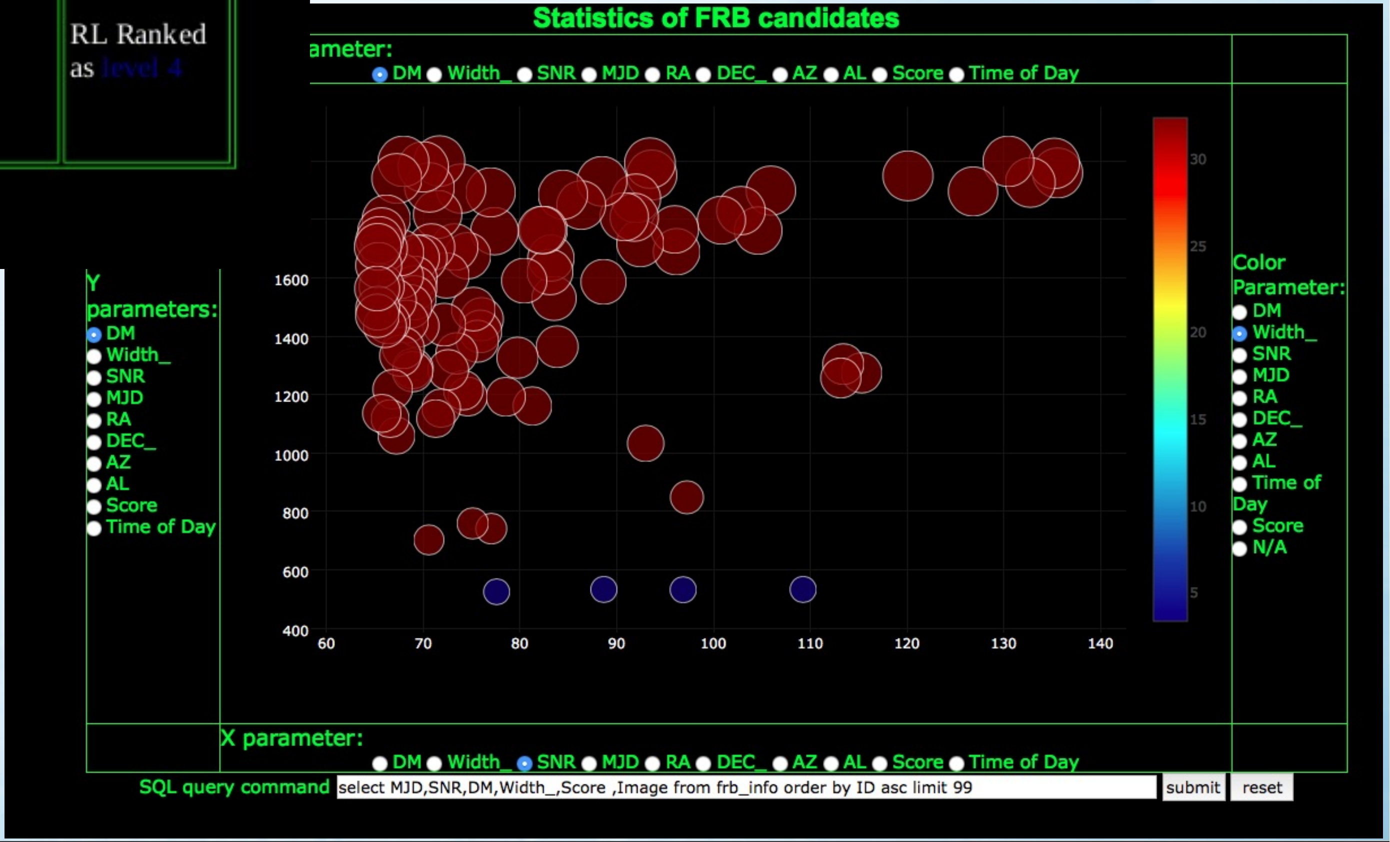
Roach 2 system

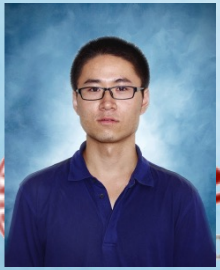


Web framework for sifting



We are trying to put the data online even before we saw the results. In this way, everyone can help and contribute.





Search scheme

To understand how to search for them efficiently, we need **luminosity function**. Distance is key uncertainties here. For most of FRBs, the only related information is DM

$$\mathrm{DM} = \mathrm{DM}_{\mathrm{MW}} + \mathrm{DM}_{\mathrm{halo}} + \mathrm{DM}_{\mathrm{IGM}}(z) + \frac{\mathrm{DM}_{\mathrm{host}} + \mathrm{DM}_{\mathrm{src}}}{1+z}. \quad +\mathrm{DMX}$$

Things we more or less know
Things we know a little
Things we know in general
Things we know we do not know
Things we don't know that we don't know

A simple subtraction of fixed value is OK for estimation, but the systematics is not traceble.

Bayesian approach

We pull out the Bayesian machinery not to measure the luminosity function but to evaluate how trustful the measurement is. The uncerstainty is folded into the likelihood, so we can see the impact to the final results.

$$P(\mathbf{\Theta}|\mathbf{X}) = \frac{P(\mathbf{\Theta})P(\mathbf{X}|\mathbf{\Theta})}{P(\mathbf{X})}$$

$$f(\log L, r, \mathrm{DM_{host}}, \mathrm{DM_{src}}, \log \epsilon) = \phi(\log L)\, f_r(r)\, f_{\mathcal{D}}(\mathrm{DM_{host}}|z) \times f_{\mathrm{S}}(\mathrm{DM_{src}})\, f_{\epsilon}(\log \epsilon)$$

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The host galaxy DM distribution, however, is not well understood.

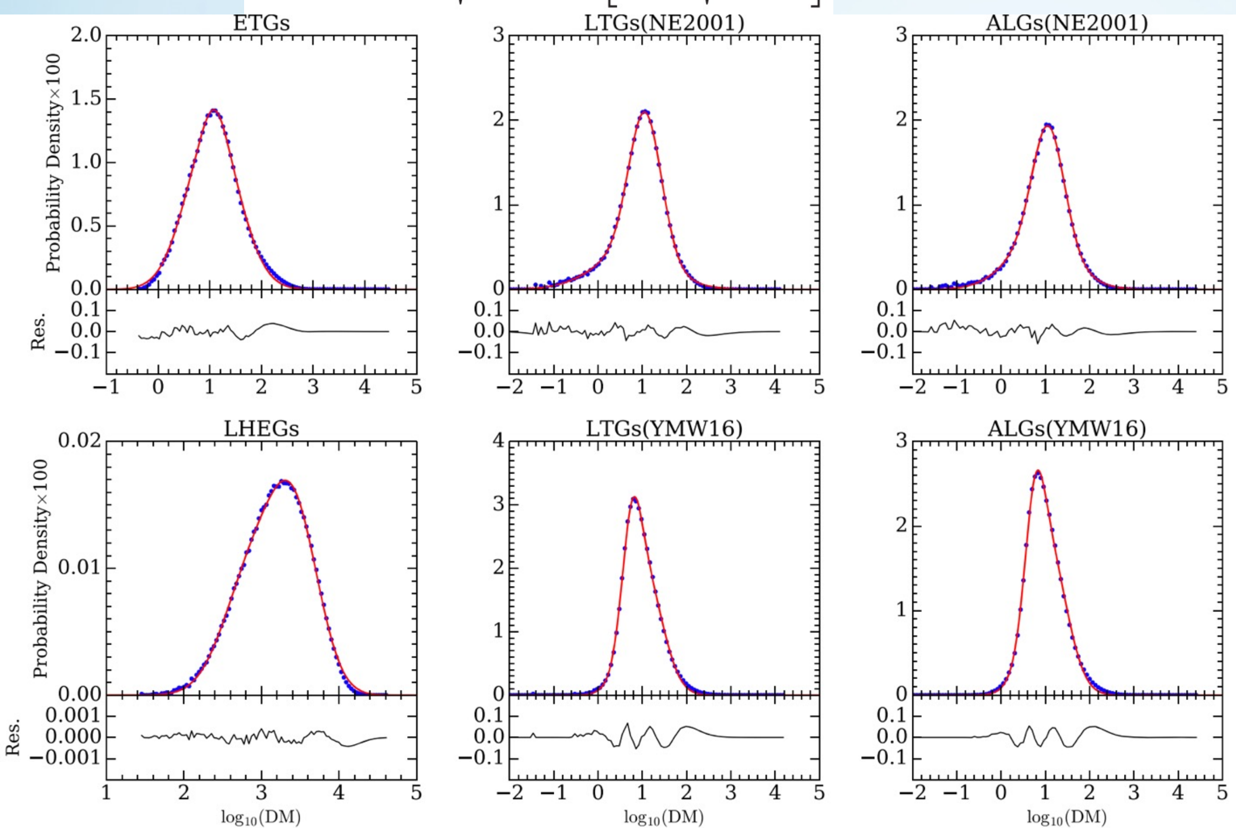
$$\langle n_e \rangle = 1.0\,\eta^{2/3}\left(\frac{T}{10^4\ \mathrm{K}}\right)^{0.45}\left(\frac{L_{\mathrm{H}\alpha}}{10^{40}\ \mathrm{erg\ s^{-1}}}\right)^{1/2}\left(\frac{R}{1\ \mathrm{kpc}}\right)^{-3/2}\ \mathrm{cm^{-3}},$$

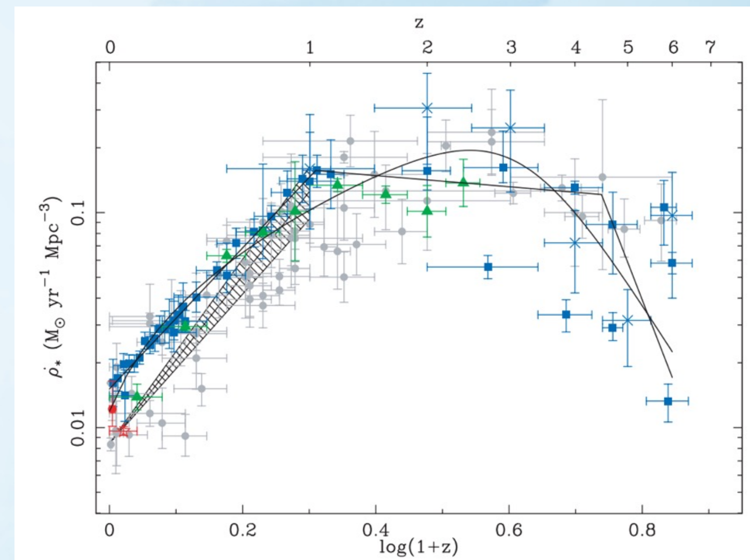
$$\frac{\mathrm{DM_{host,1}}}{\mathrm{DM_{host,2}}} = \frac{\langle n_e\rangle_1 R_{e,1}}{\langle n_e\rangle_2 R_{e,2}} = \sqrt{\frac{L_{\mathrm{H}\alpha,1}R_{e,2}}{L_{\mathrm{H}\alpha,2}R_{e,1}}}$$

We connect DM distribution function with Ha luminosity function. But Ha luminosity function is only known for near-by galaxies.

The thing must evolve a lot in the distance of FRB

$$f_{\mathcal{D}}(\mathrm{DM_{host}}|z) = \sqrt{\frac{\mathrm{SFR}(0)}{\mathrm{SFR}(z)}}\,f_{\mathcal{D}}\left[\mathrm{DM_{host}}\sqrt{\frac{\mathrm{SFR}(0)}{\mathrm{SFR}(z)}}\right]$$

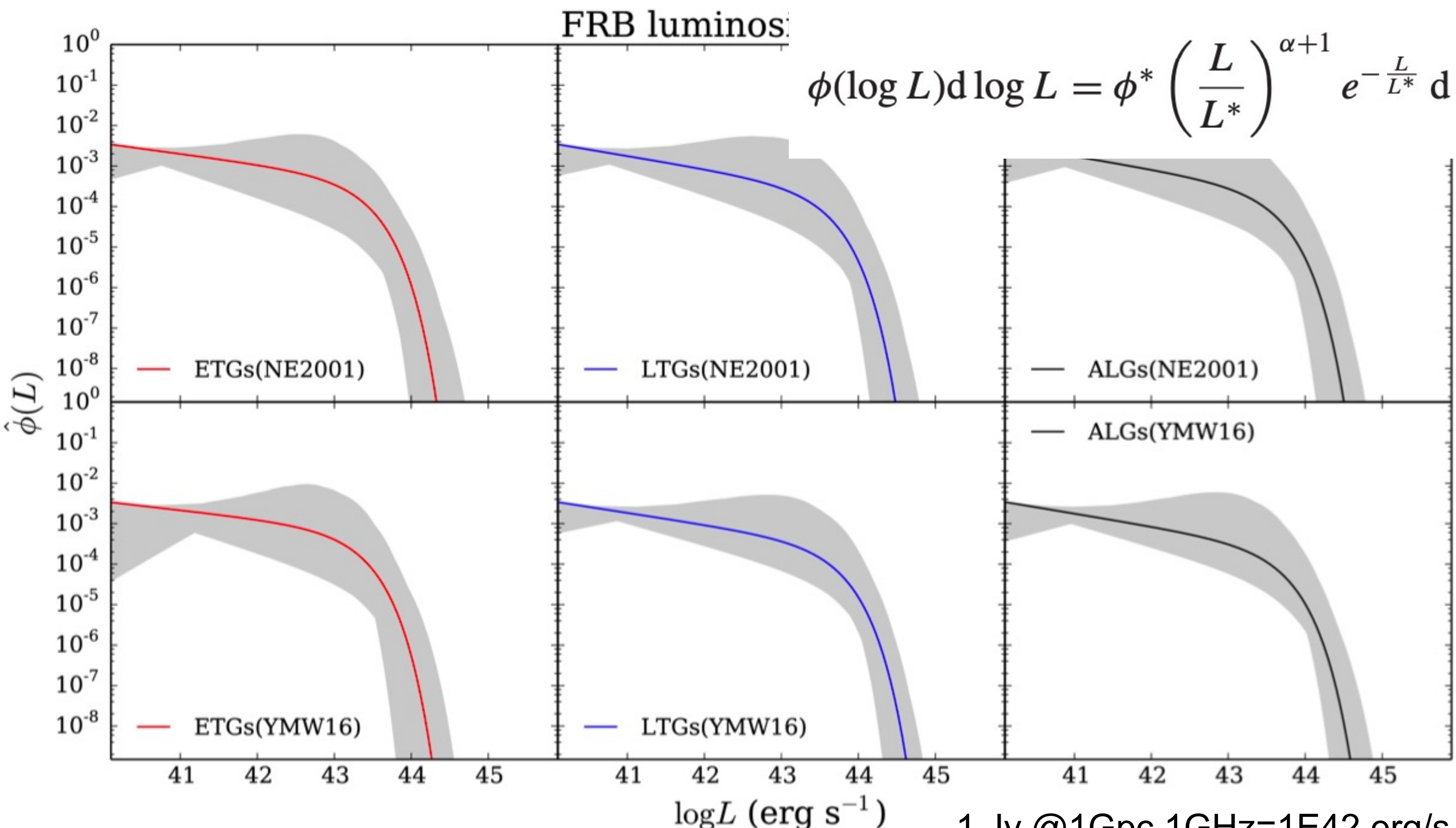




Hopkins and Beacom 2006

Luo et al., 2019

Galaxy type	No modelling for Galactic halo			Removed Galactic halo		
	α (1σ)	$\log L^*$ (1σ)	$\log L_0$ (95% C.L.)	α (1σ)	$\log L^*$ (1σ)	$\log L_0$ (95% C.L.)
ETGs (NE2001)	$-1.52^{+0.24}_{-0.23}$	$44.14^{+0.23}_{-0.33}$	$\leq$41.75	$-1.57^{+0.19}_{-0.26}$	$44.10^{+0.23}_{-0.33}$	$\leq$41.56
ETGs (YMW16)	$-1.62^{+0.29}_{-0.21}$	$44.18^{+0.26}_{-0.38}$	$\leq$41.96	$-1.67^{+0.21}_{-0.25}$	$44.23^{+0.27}_{-0.38}$	$\leq$41.82
LTGs (NE2001)	$-1.45^{+0.31}_{-0.28}$	$43.94^{+0.22}_{-0.35}$	$\leq$41.74	$-1.50^{+0.25}_{-0.26}$	$43.87^{+0.27}_{-0.30}$	$\leq$41.56
LTGs (YMW16)	$-1.57^{+0.17}_{-0.22}$	$44.32^{+0.22}_{-0.24}$	$\leq$41.96	$-1.60^{+0.15}_{-0.19}$	$44.29^{+0.33}_{-0.20}$	$\leq$41.82
ALGs (NE2001)	$-1.42^{+0.27}_{-0.27}$	$43.90^{+0.30}_{-0.29}$	$\leq$41.74	$-1.51^{+0.26}_{-0.25}$	$43.89^{+0.26}_{-0.28}$	$\leq$41.56
ALGs (YMW16)	$-1.57^{+0.19}_{-0.21}$	$44.31^{+0.22}_{-0.27}$	$\leq$41.96	$-1.63^{+0.16}_{-0.19}$	$44.34^{+0.21}_{-0.29}$	$\leq$41.82

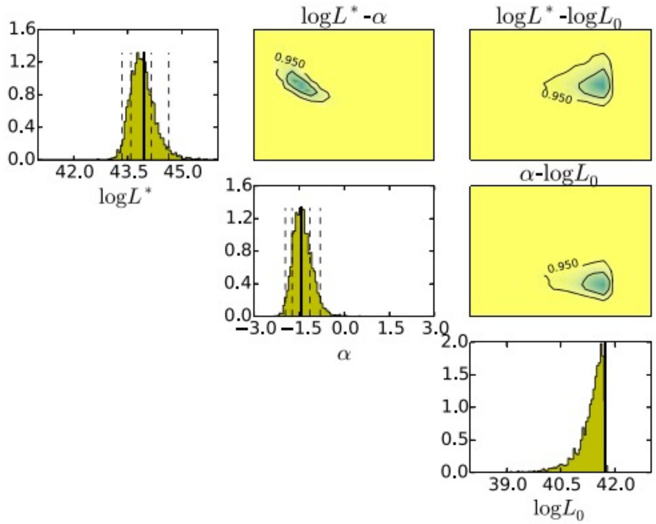


$$\phi(\log L)\mathrm{d}\log L = \phi^* \left(\frac{L}{L^*}\right)^{\alpha+1} e^{-\frac{L}{L^*}}\,\mathrm{d}\log L,$$

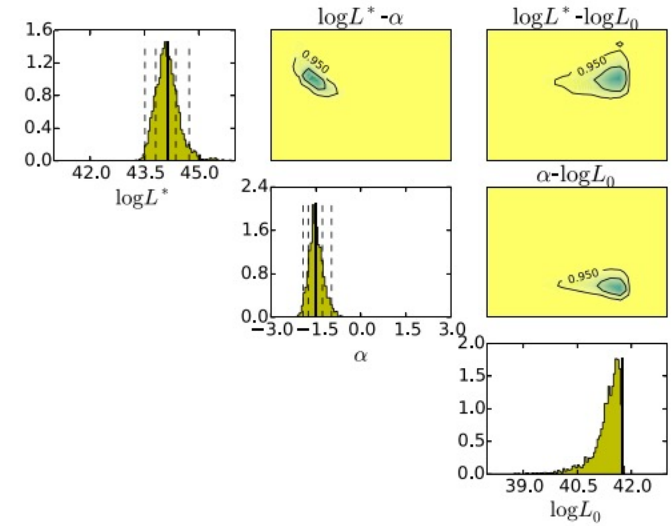
1 Jy @1Gpc 1GHz=1E42 erg/s

L* is real

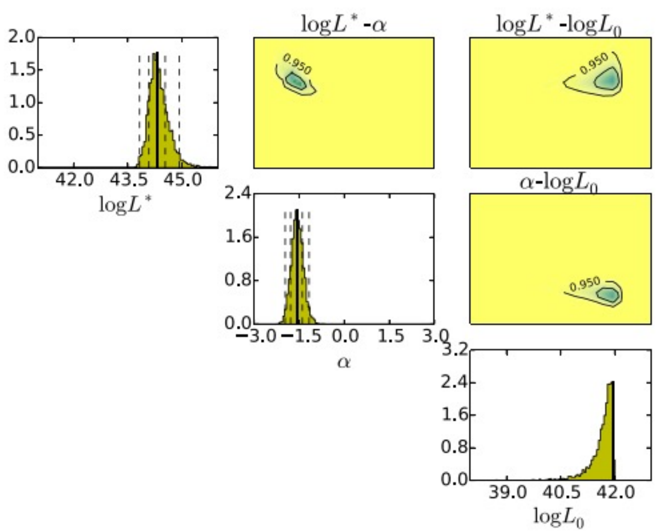
$$\phi(\log L)\mathrm{d}\log L = \phi^* \left(\frac{L}{L^*}\right)^{\alpha+1} e^{-\frac{L}{L^*}}\,\mathrm{d}\log L,$$



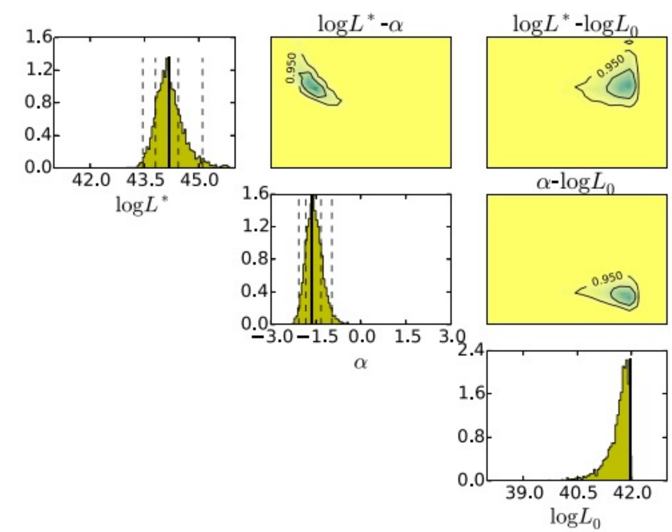
(a) LTGs (NE2001)



(a) ETGs (NE2001)



(b) LTGs (YMW16)



(b) ETGs (YMW16)

Real luminosity function

Normalised lumonisoty function is good, but event rate density is better.

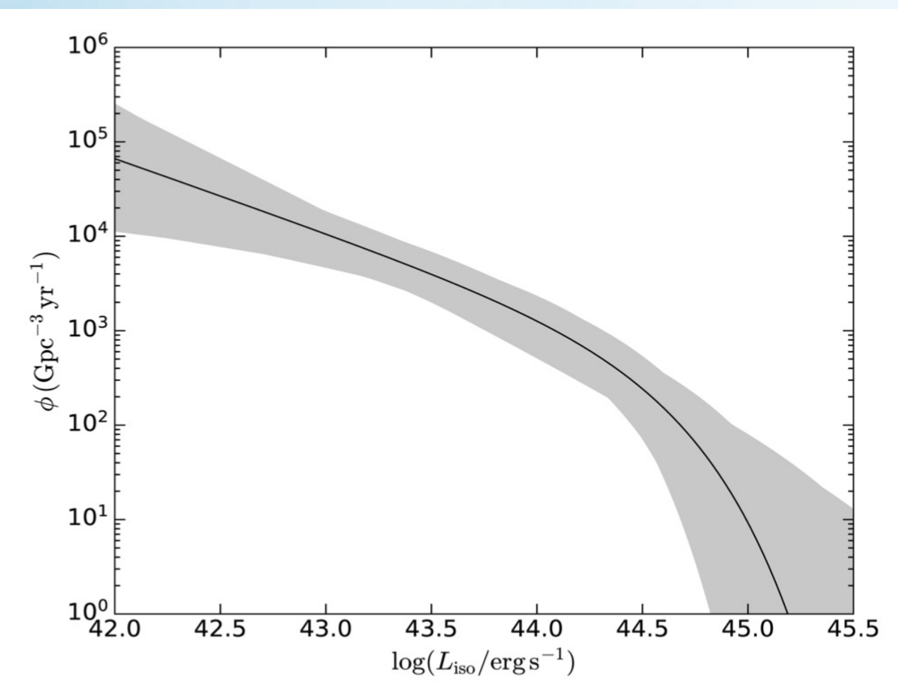
$$\mathcal{L}(\log S, w_o, N, \mathrm{DM_E}) = \prod_{j=1}^{M} \mathcal{L}_j(N_j) \cdot \prod_{k=1}^{N} f(\log S_k,\ \log w_{o,k},\ \mathrm{DM}_{\mathrm{E},k})$$

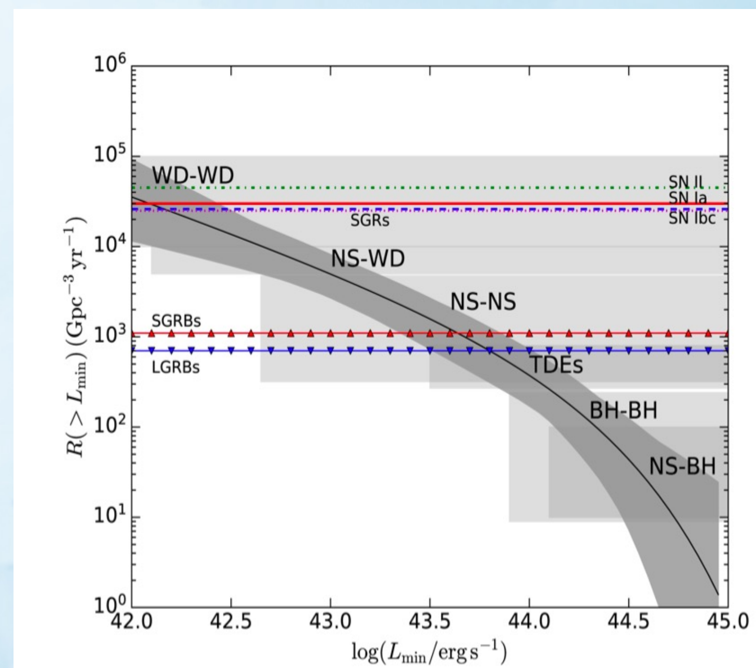
$$= \frac{\prod_{j=1}^{M} (\rho_j \Omega_j t_j)^{N_j} \cdot \exp\left(-\sum_{j=1}^{M} \rho_j \Omega_j t_j\right)}{\prod_{j=1}^{M} N_j!}$$

$$\cdot \prod_{k=1}^{N} f(\log S_k,\ \log w_{o,k},\ \mathrm{DM}_{\mathrm{E},k}), \qquad (5)$$

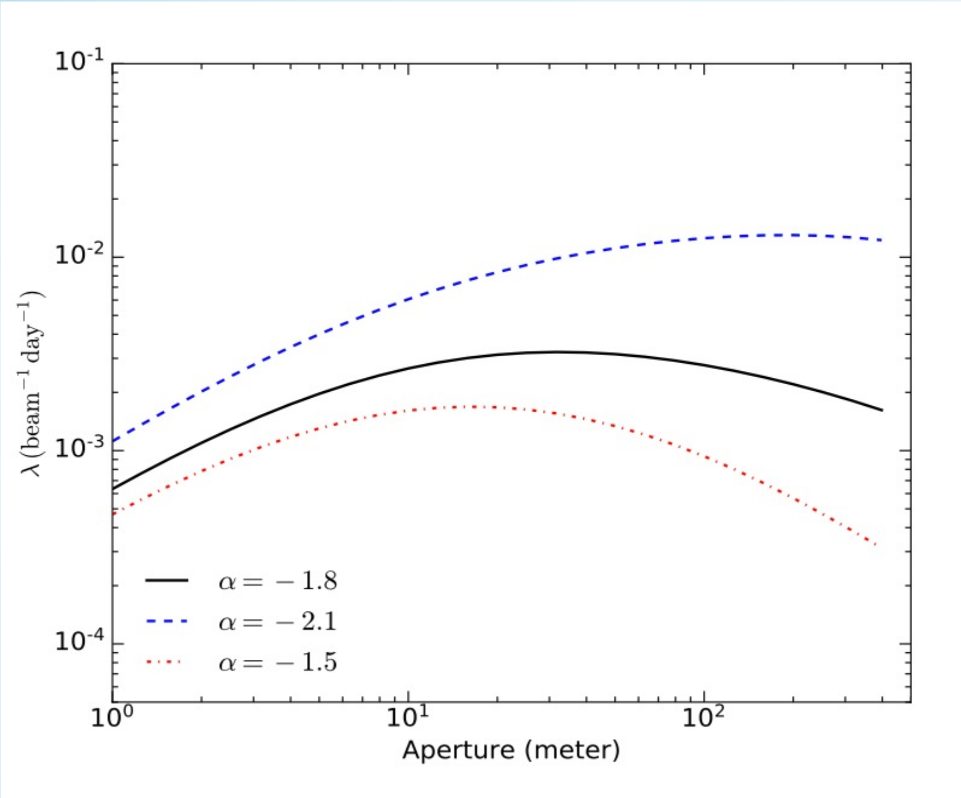
$$\alpha = -1.79^{+0.31}_{-0.35} \text{ and } \log L^* = 44.46^{+0.71}_{-0.38}$$

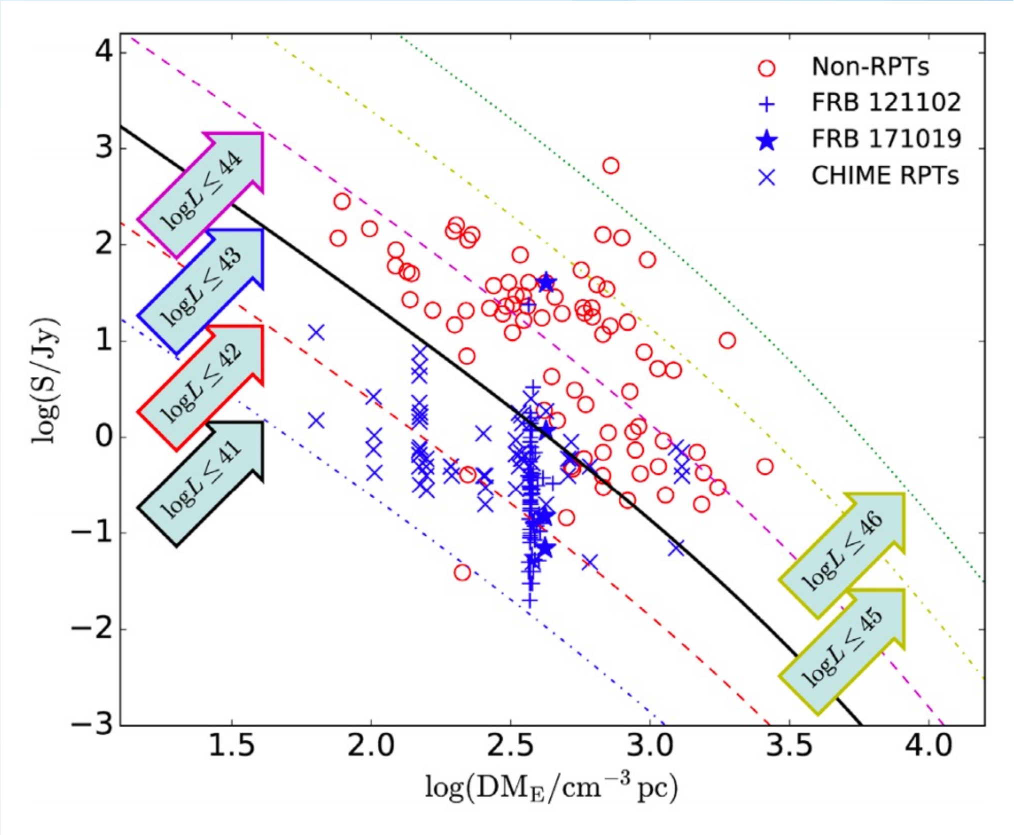
Luo et al., 2020





Inference from the model





This is why we though in 2017 “Hey! 26 meter is the best!”

Luo et al., 2020

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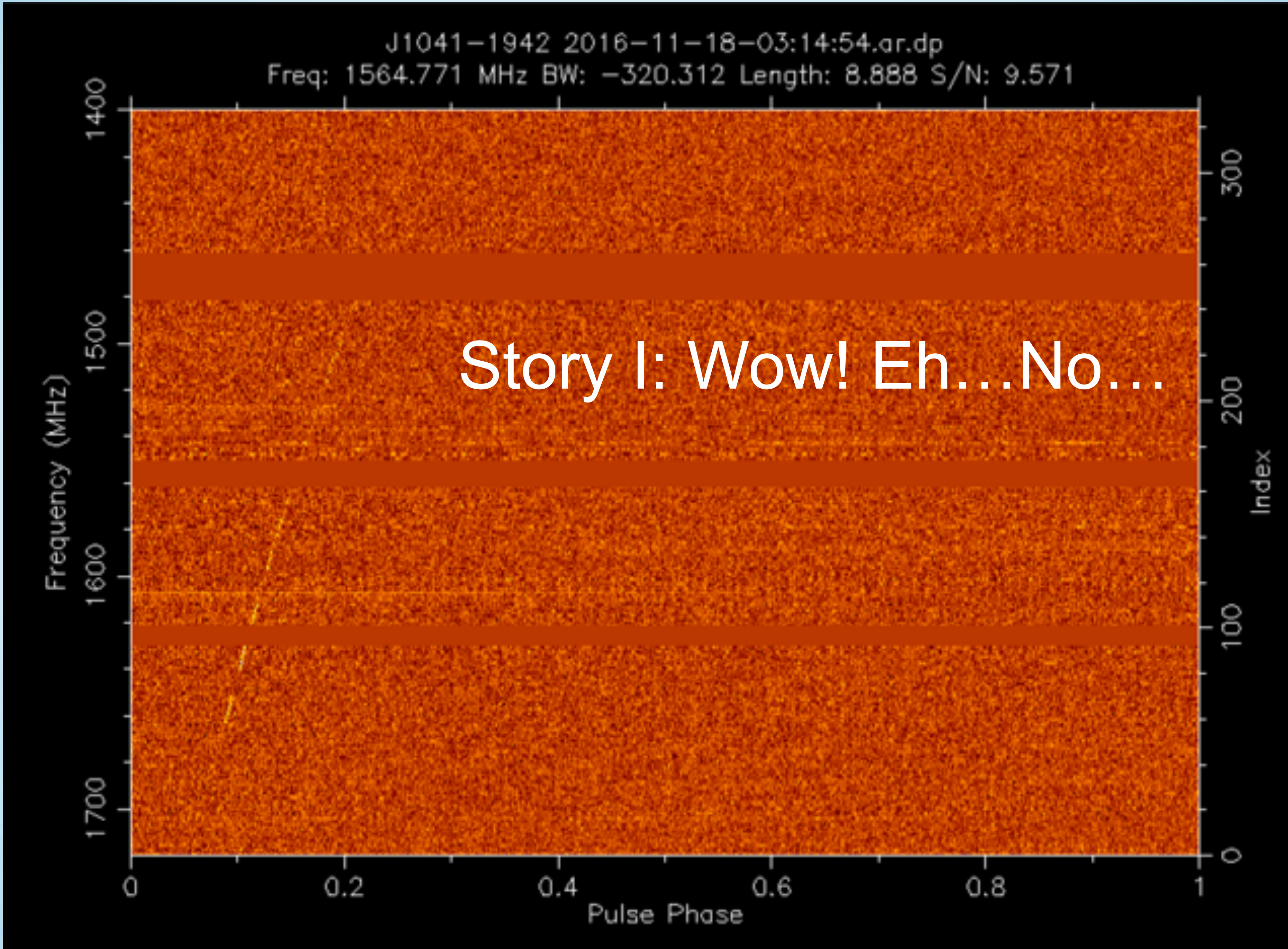
Story I: Wow! Eh…No…



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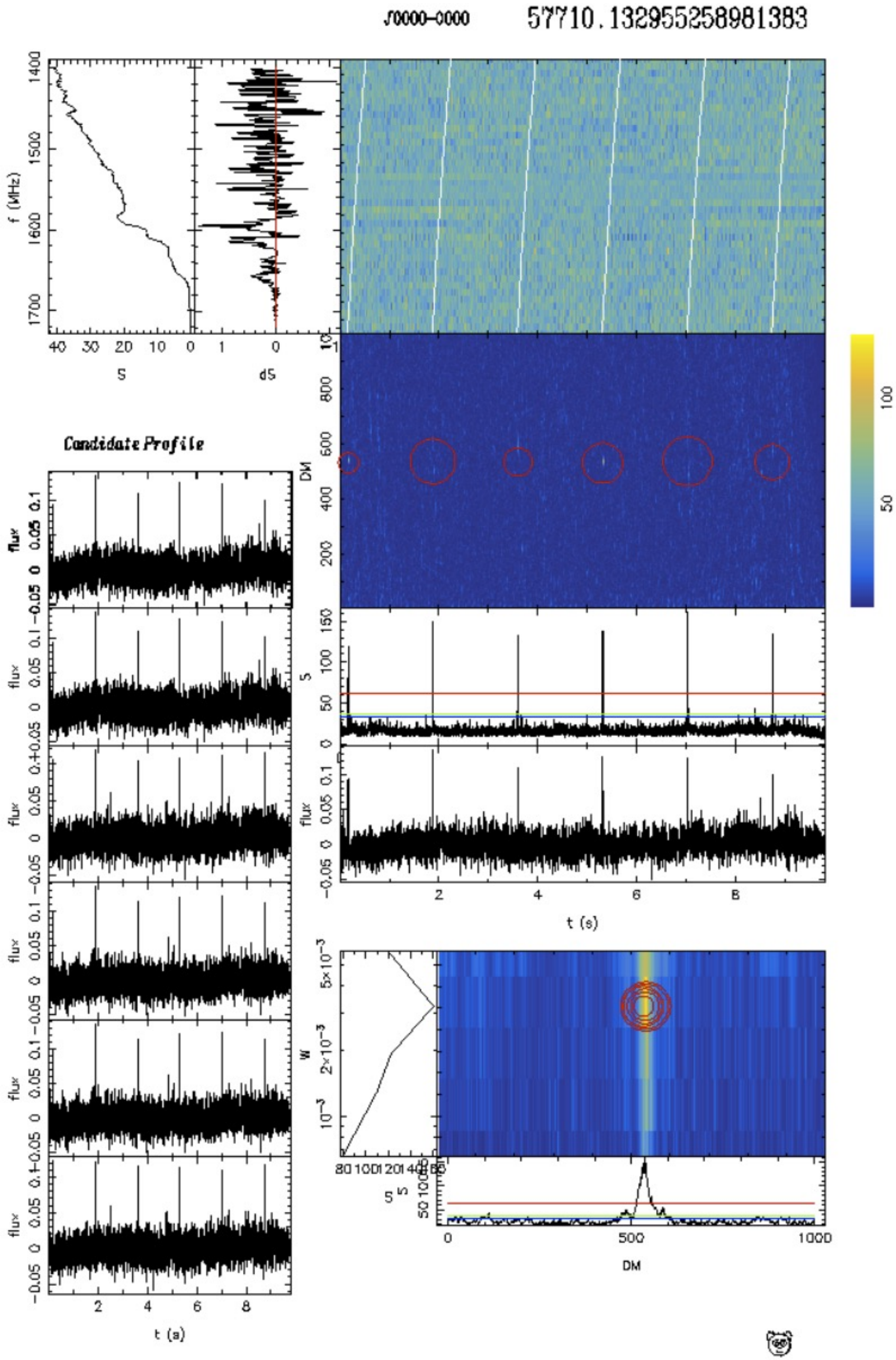
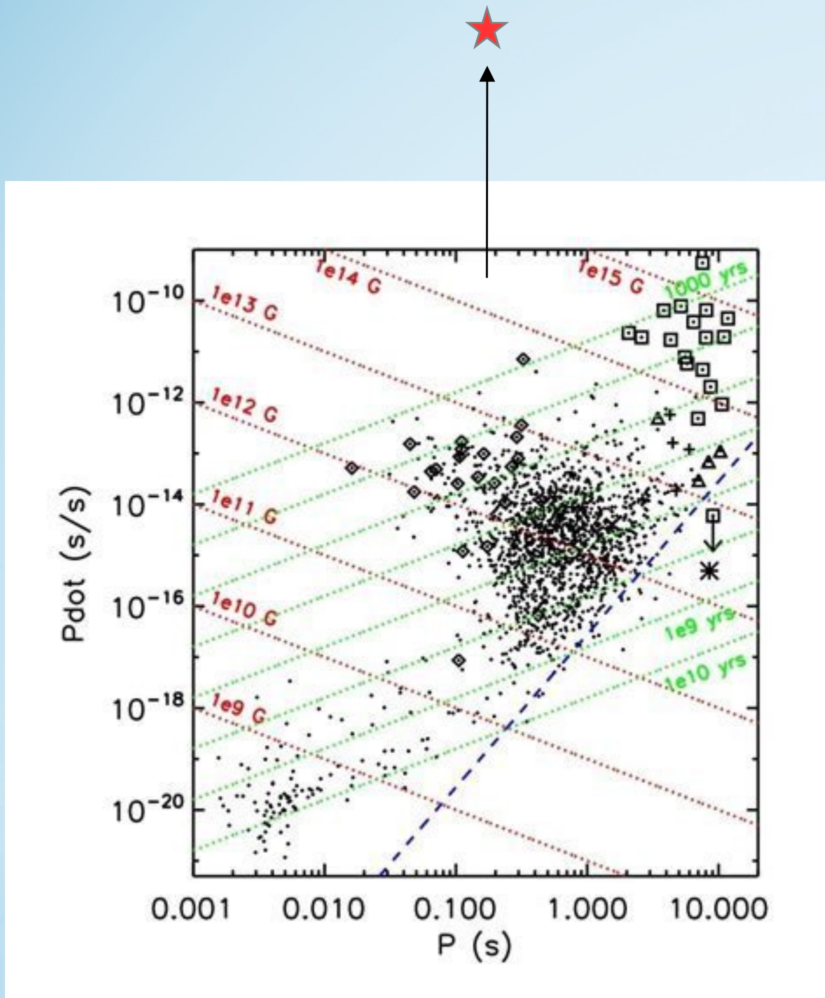
Men et al., 2018



DM ~ 530 pc cm^-3

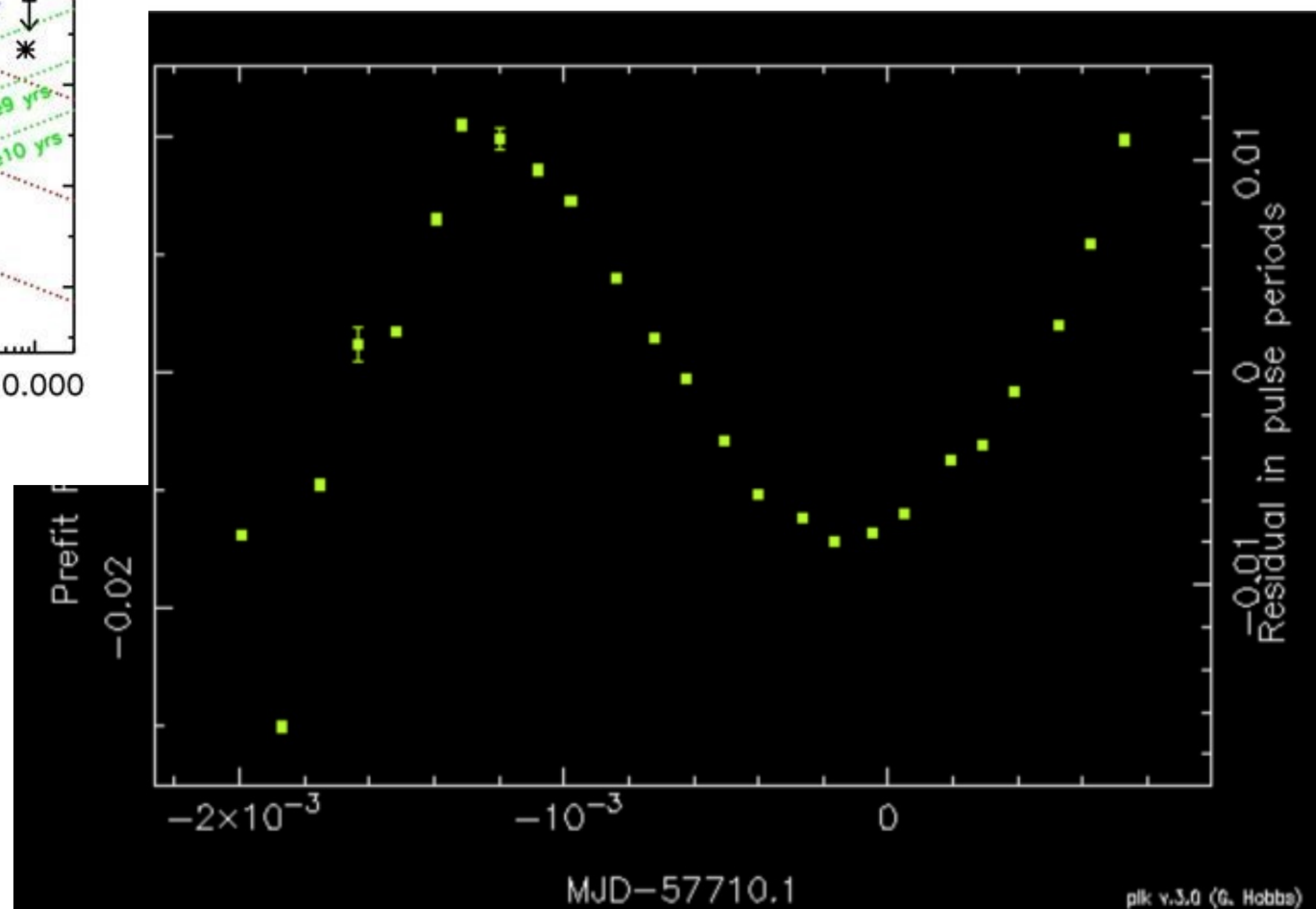
P0 ~ 1.7s

Not found in ATNF Pulsar Catalog!



$F0 \sim 0.58\ \mathrm{Hz} \quad F1 \sim 1e^{-6}\ \mathrm{s}^{-2}$

Normal pulsars: $F1 \sim 1e^{-15}\ \mathrm{s}^{-2}$



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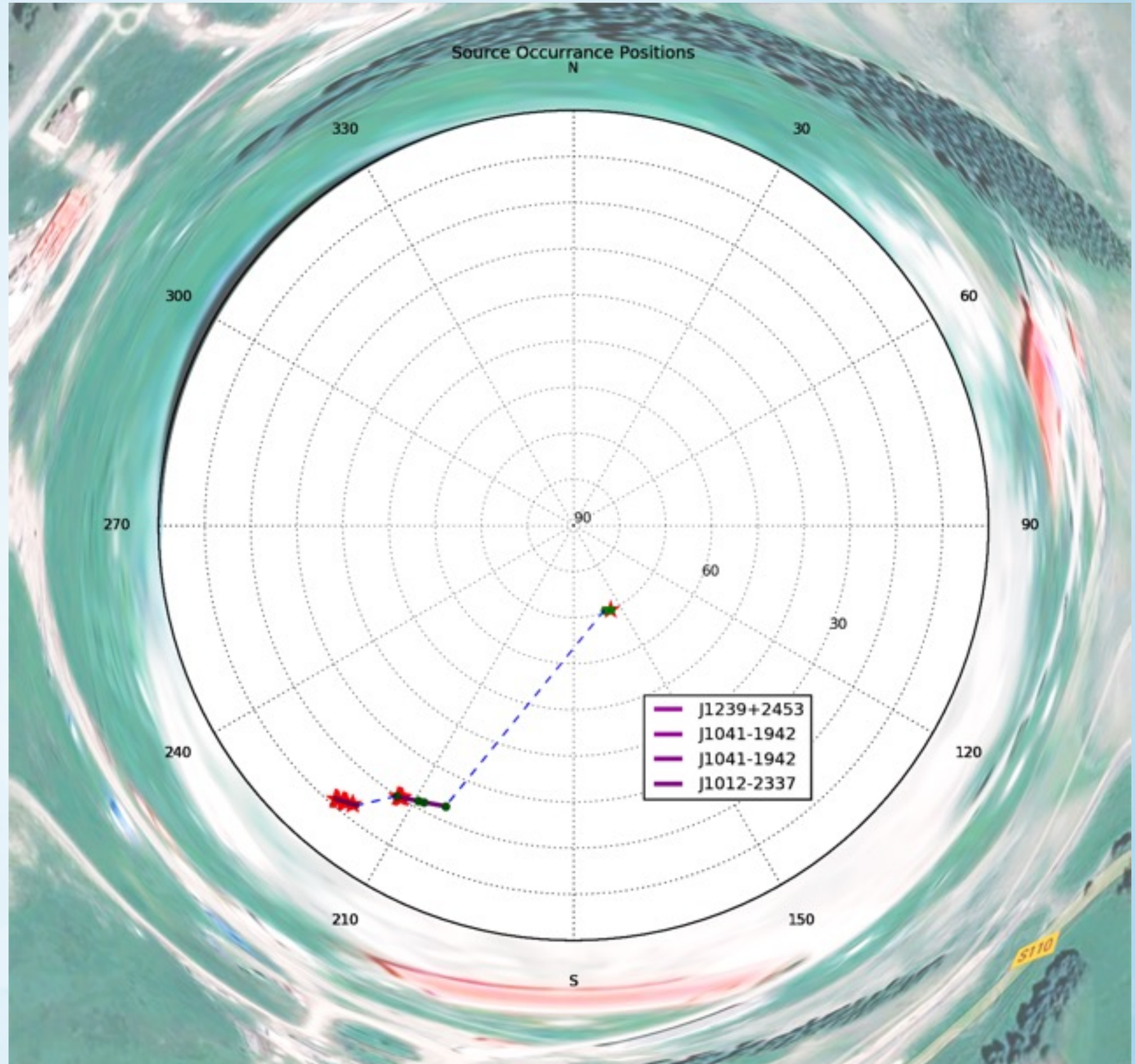
However…

- EM simulation using the telescope structure does not support reflection
- No record of airplane
- Not seen before and afterwards
- No record of car activities on site
- No record of new electronics installation.



	Pros	Cons
Communication	• Narrow channel	• No information flow • One detection only • Wideband
Radar	• Structured spectrum • Wideband	• One detection only
Microwave oven	• Wideband • DM-like dispersion	• **Timing precision**
Airplane/sat.	• One detection only	• **Will not see over one hour** • Wideband • DM-like dispersion
Local natural processes	• One detection only	• **Narrow channel feature** • DM-like dispersion
astronomical	• Event rate agree with FRBs • Dispersed curve	• **Narrow channel** • **Multiple sky position**

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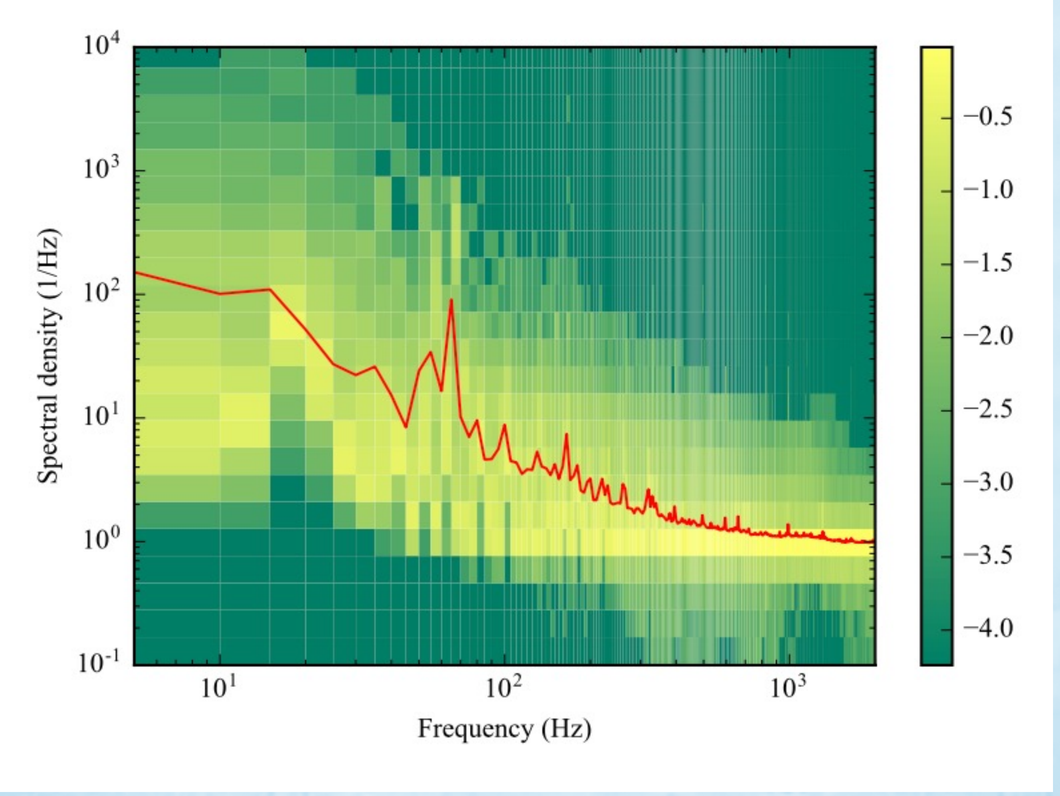
Lesson learnt:

1. It is very hard for single telescope without miultibeam system to confirm FRB detection.
2. Really need to understand RFIs.

Story 2: M82 FRB candidates



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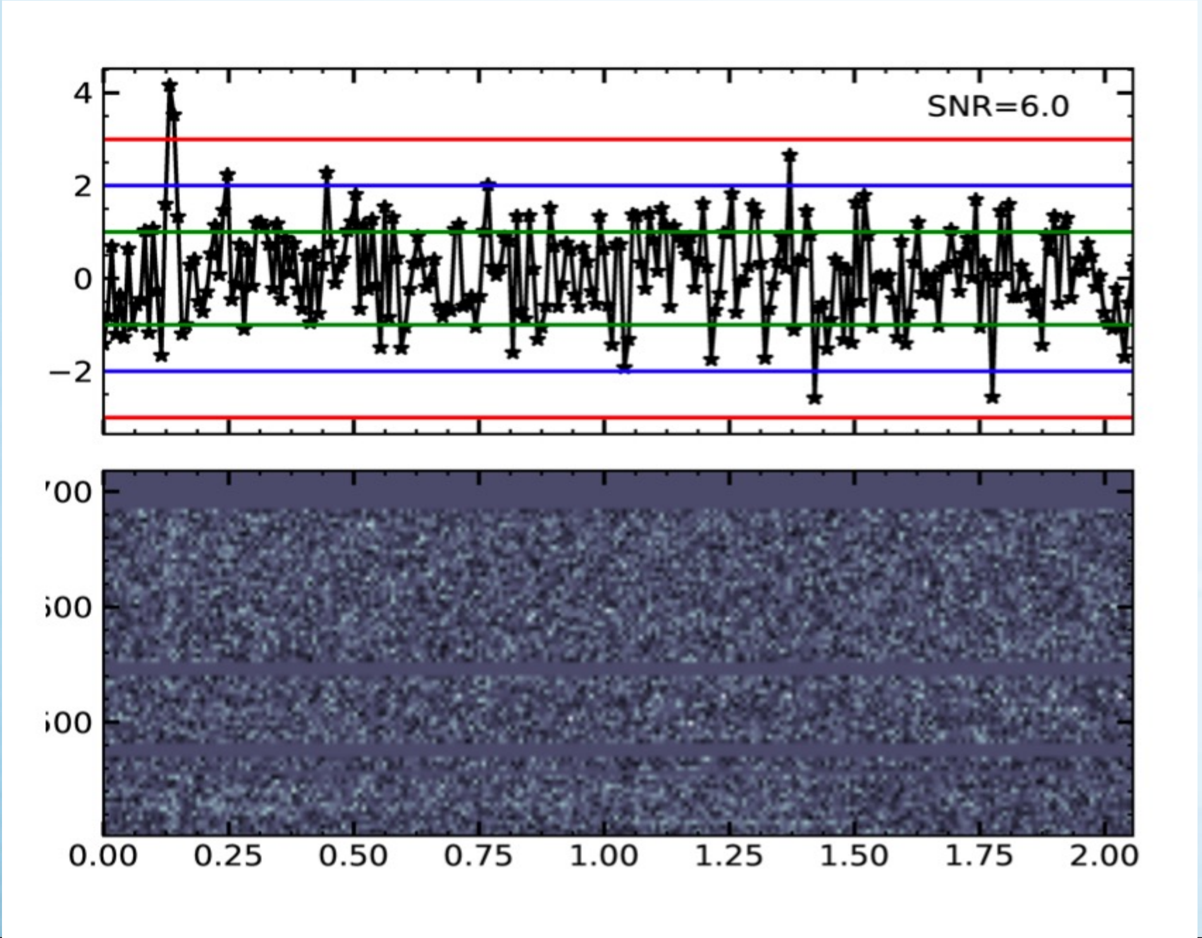
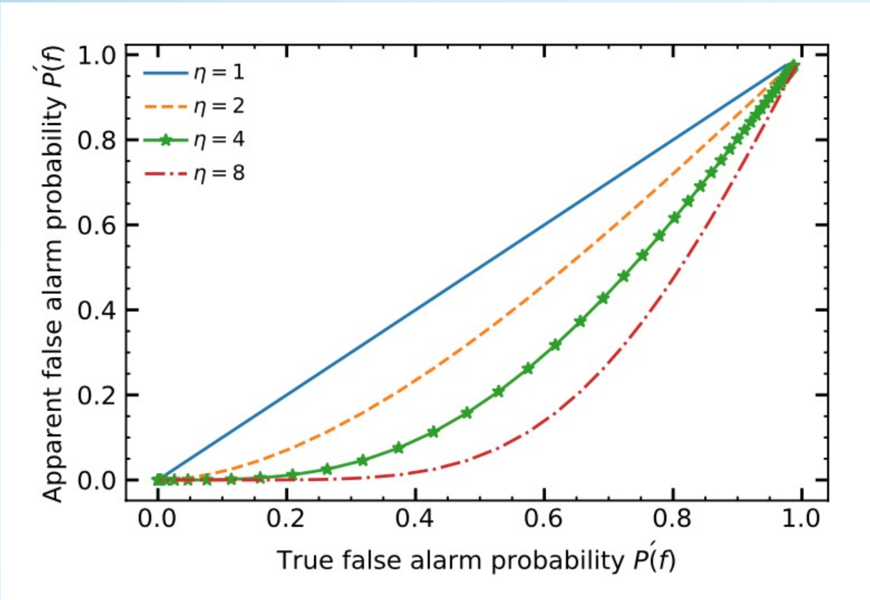
Observe M82 for 55 hours with NS26m. We get one event with low SNR. We performed follow ups with KM40m and HRT, but get no further bursts.

DM 1523
F=0.6 Jy
Fluence 7Jy ms
Both super giant pulse in M82 or cosmological FRB are compatible with observation

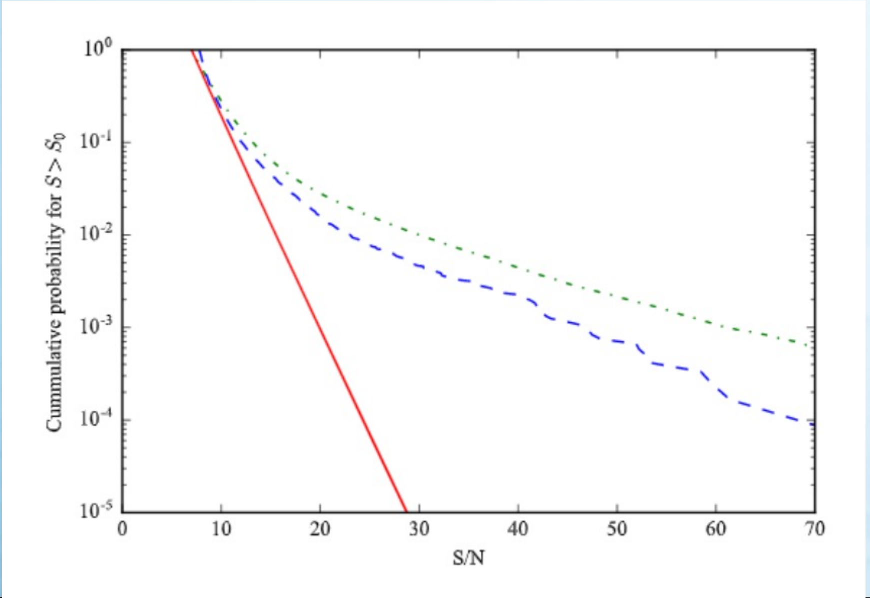


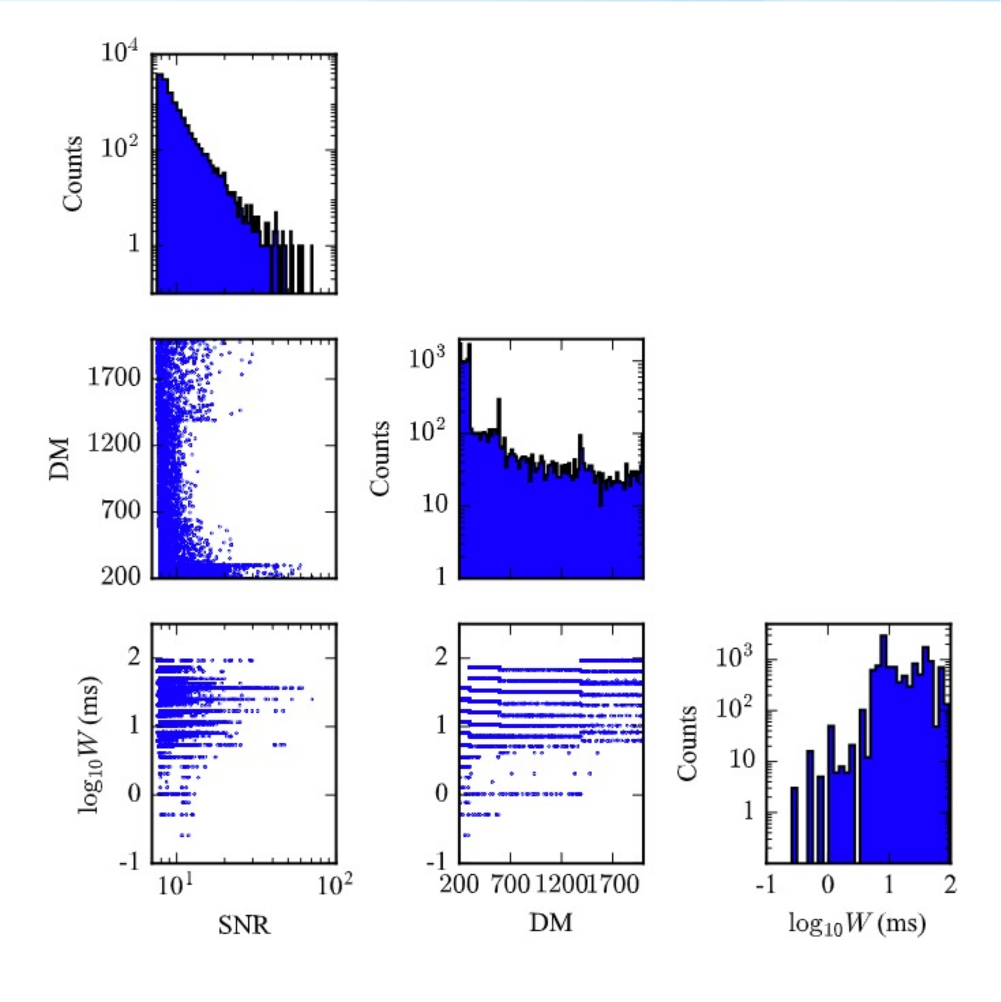
Zhang et al., 2020

The source can be real, and we studied the red noise impact. We find out that this burst **can be also induced by low level (6% RMS amplitude) red noise**.



Zhang et al., 2020





Lesson learnt:

1. It is very hard for small telescope to study FRB even with detection. The SNR is too low to confirm, even the candidate rate is high.
2. Need to understand correlated noise, when reporting event rate.

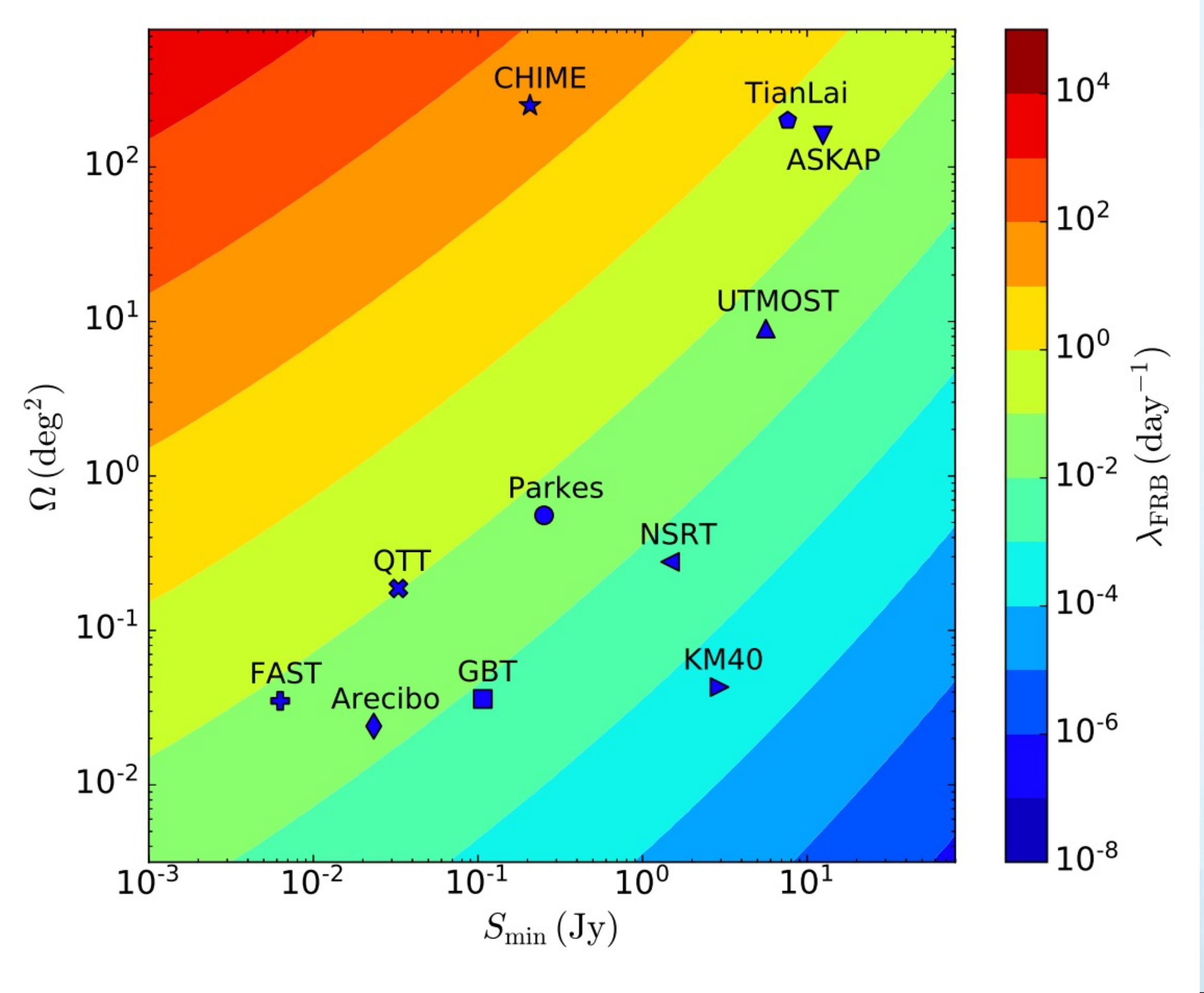
We need some larger telescopes with multi-beam receiver Or multiple telescopes to form an array (SKA).

When FAST made the open calls, we start to apply time.

Story 3: FAST observations

At 2019, the two key problems left on the table are

1. Where the radiation comes from?
2. How the radiation was generated?



Luo et al., 2020

Intrinsic (magnetosphere)
or
propagation amplification(maser)

Polarisation as a probe for radiation mechanism

Polarisation is a statistical quantity describing the spin of photon or oscillating electric field direction of radio wave

High temprature radio wave is generated via

- Intrinsic coherent radiation --- radiating electron is in coherent state
- maser mechanism --- propagation leads to coherency

Over ms timescale, it is hard to change the maser enviroment, if we see polarsiation changes over such a short time scale, we know the radiation mechanism must be coherent radiation.

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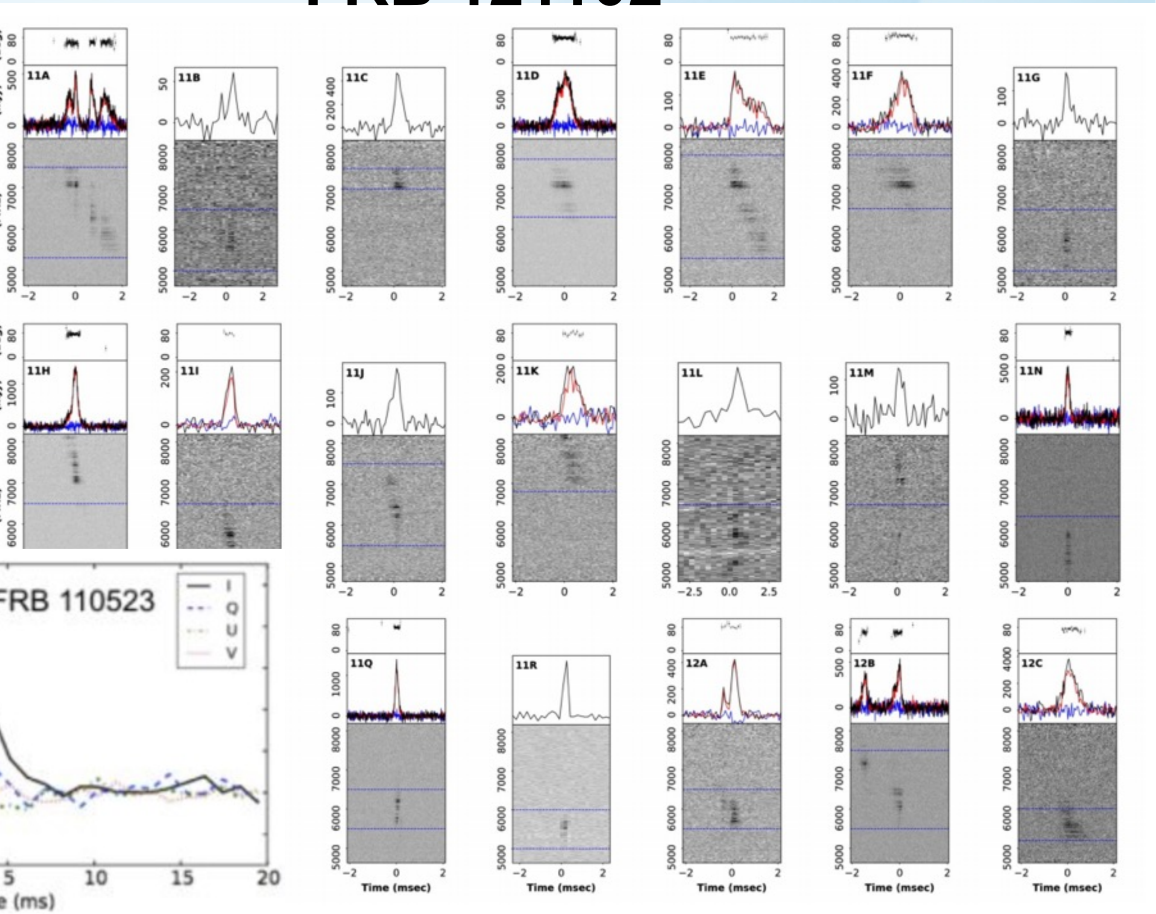
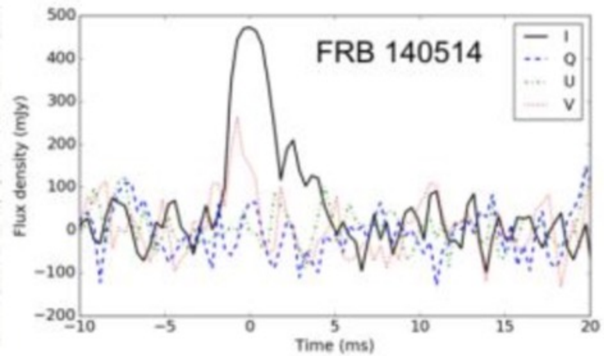
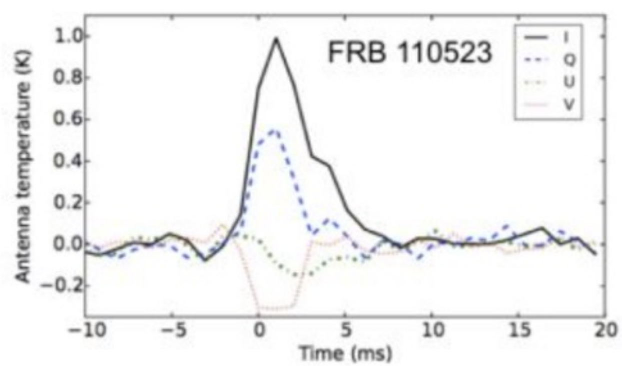
FRB polarisation was inconclusive

- Flat PA
- high linear polarisaiton
- low circular polarisation
- Repeating/non-repeating can be different

FRB 121102

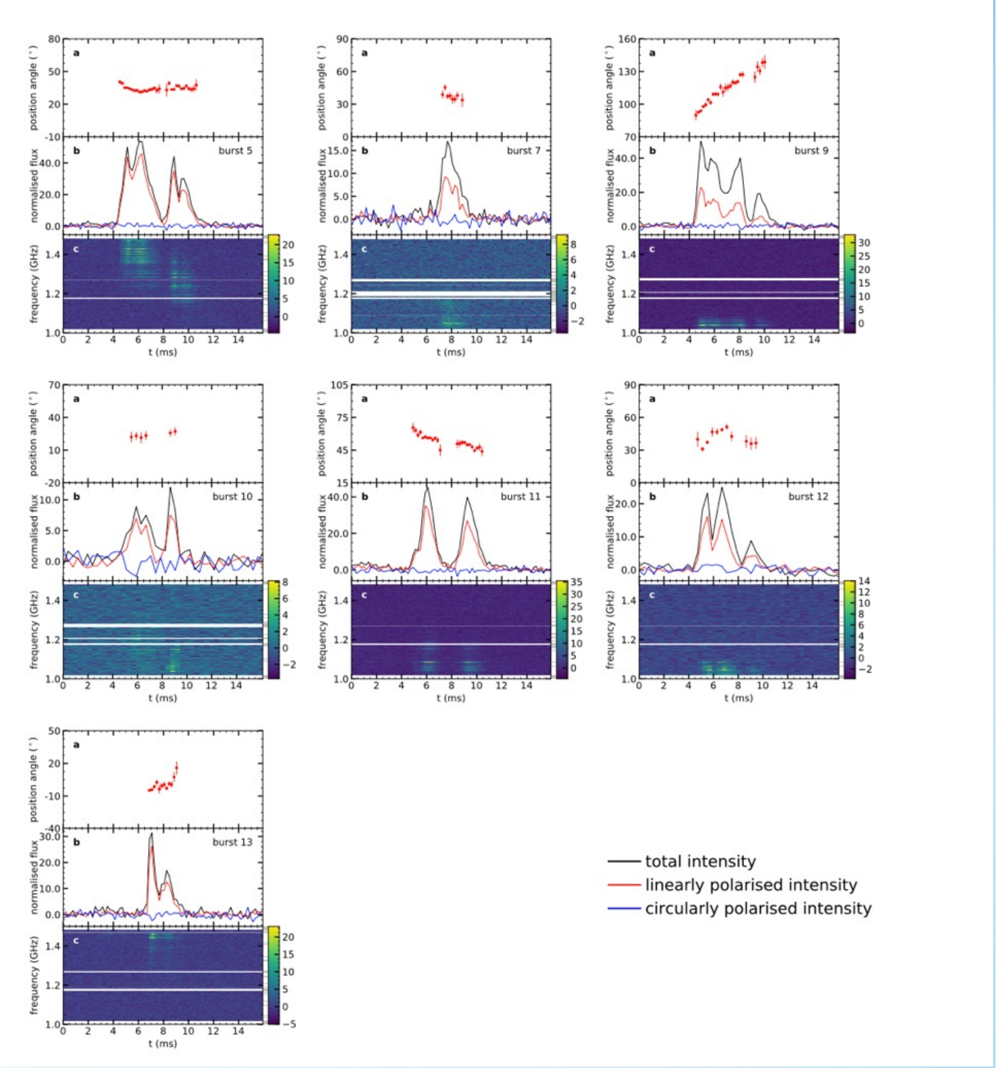






Polarisation

- FRB 180301 has very diverse morphology of polarisation.
- Not seen in any other repeater.
- Such morphology complexity tells that FRB radiation mechanism should not be maser mechanism.
- Fast swing of PA angle give hints on magnetosphere origin.



Luo et al., 2020

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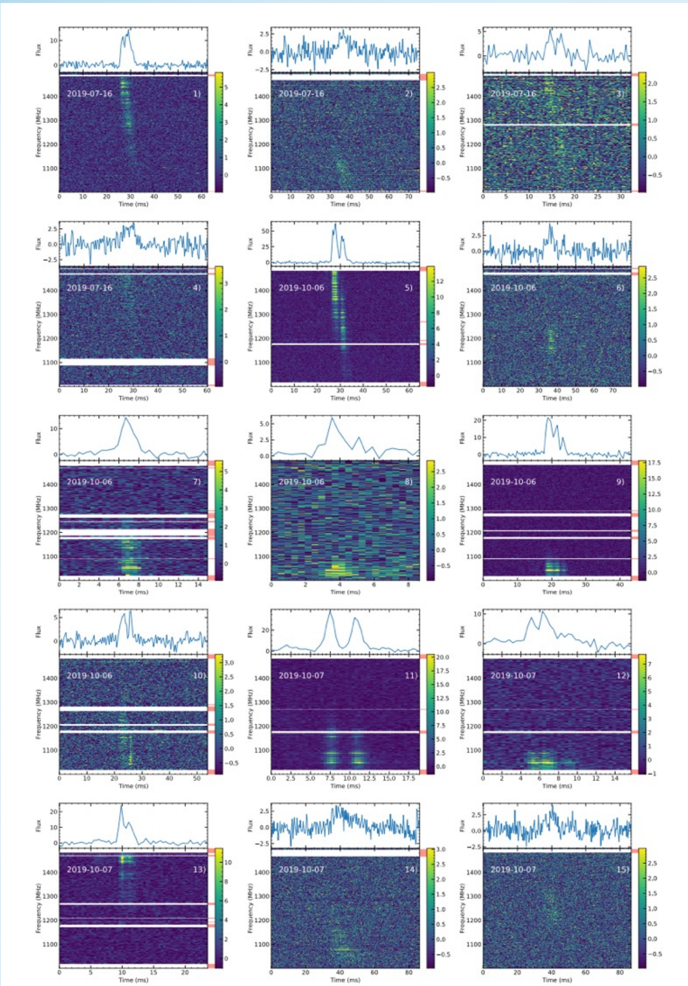
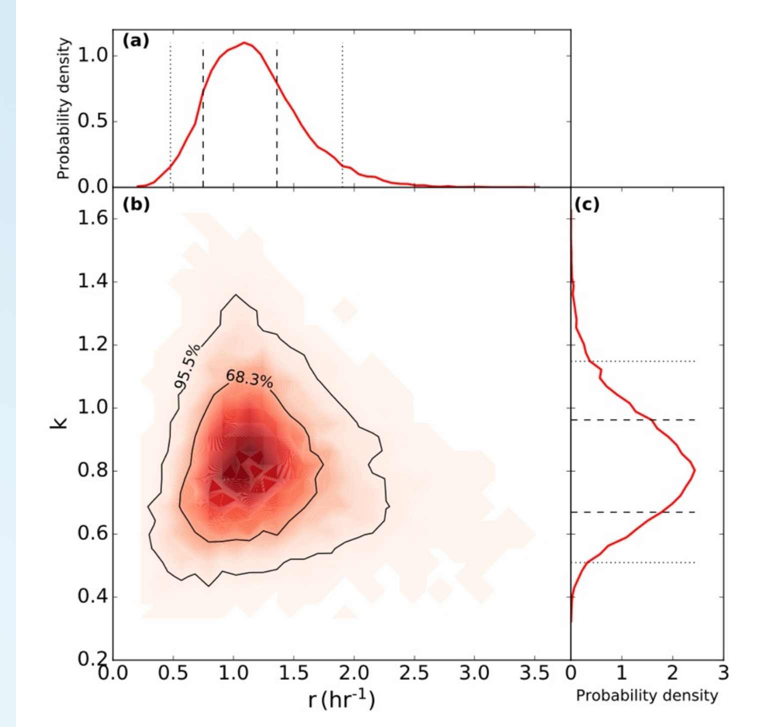
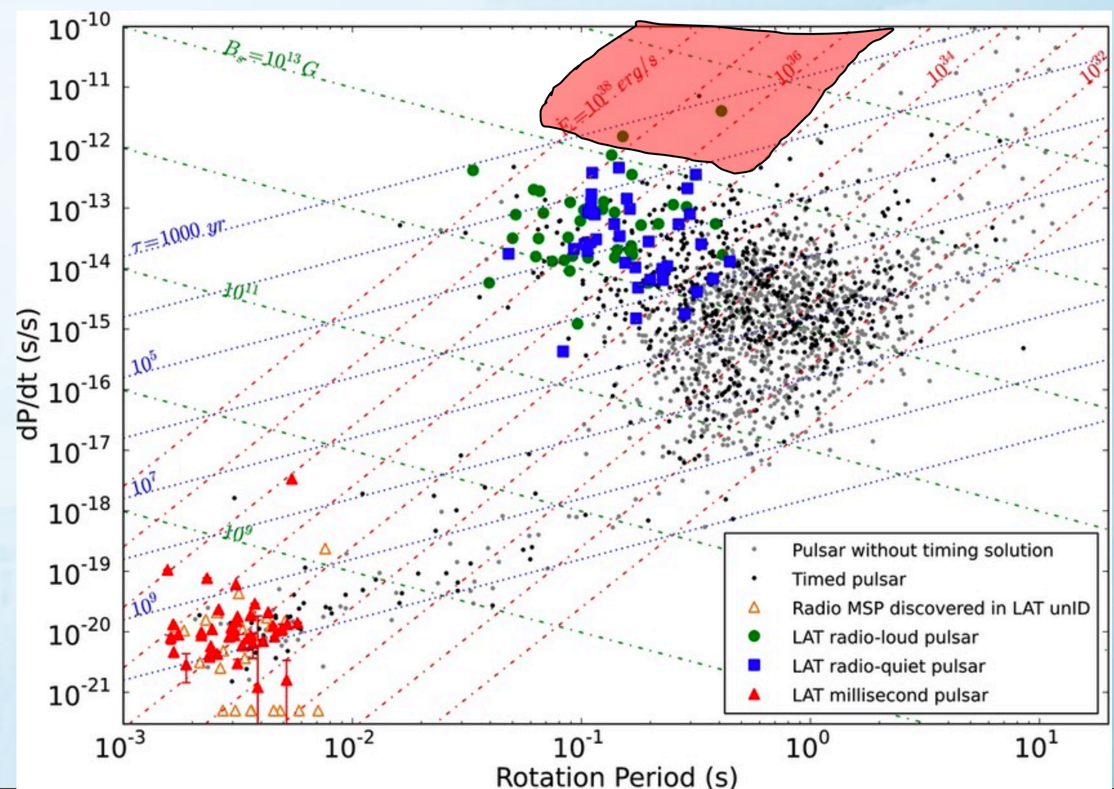
Event rate



The average active phase energy loss rate is about 1E35 erg/s. (1 pulse per hour)





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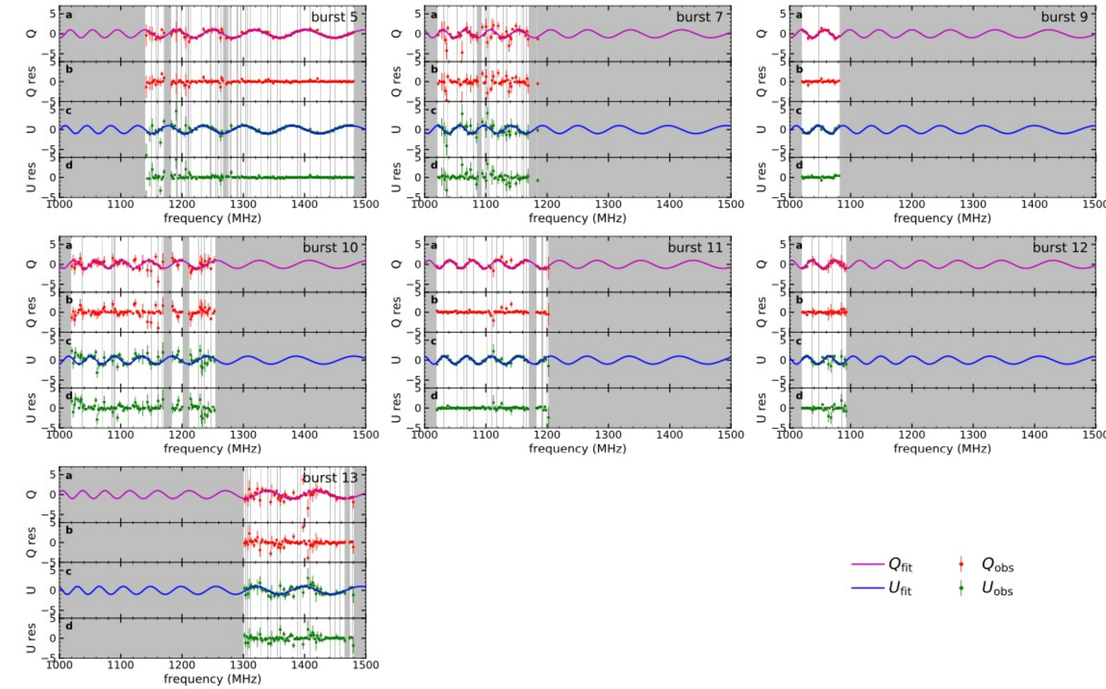
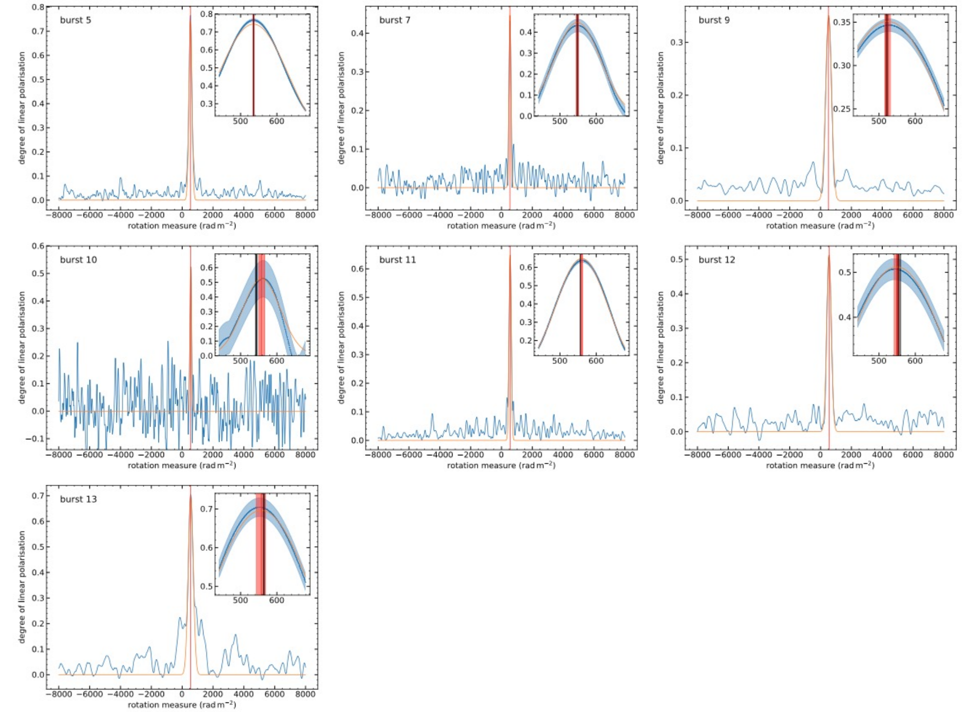
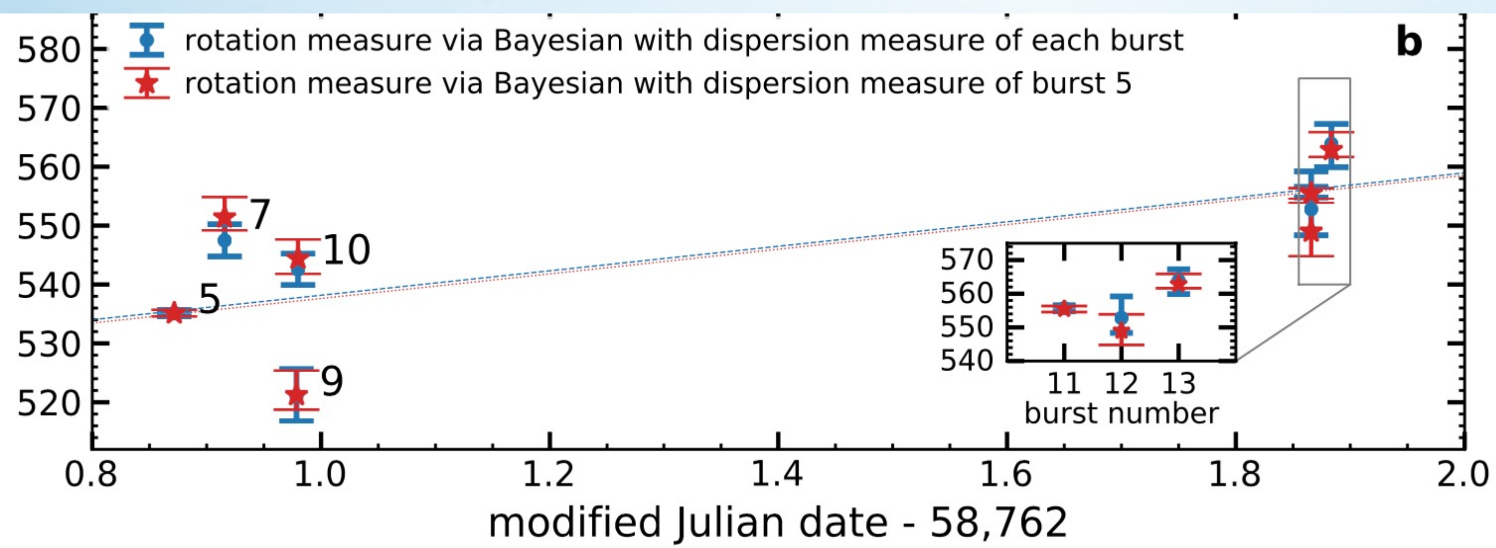


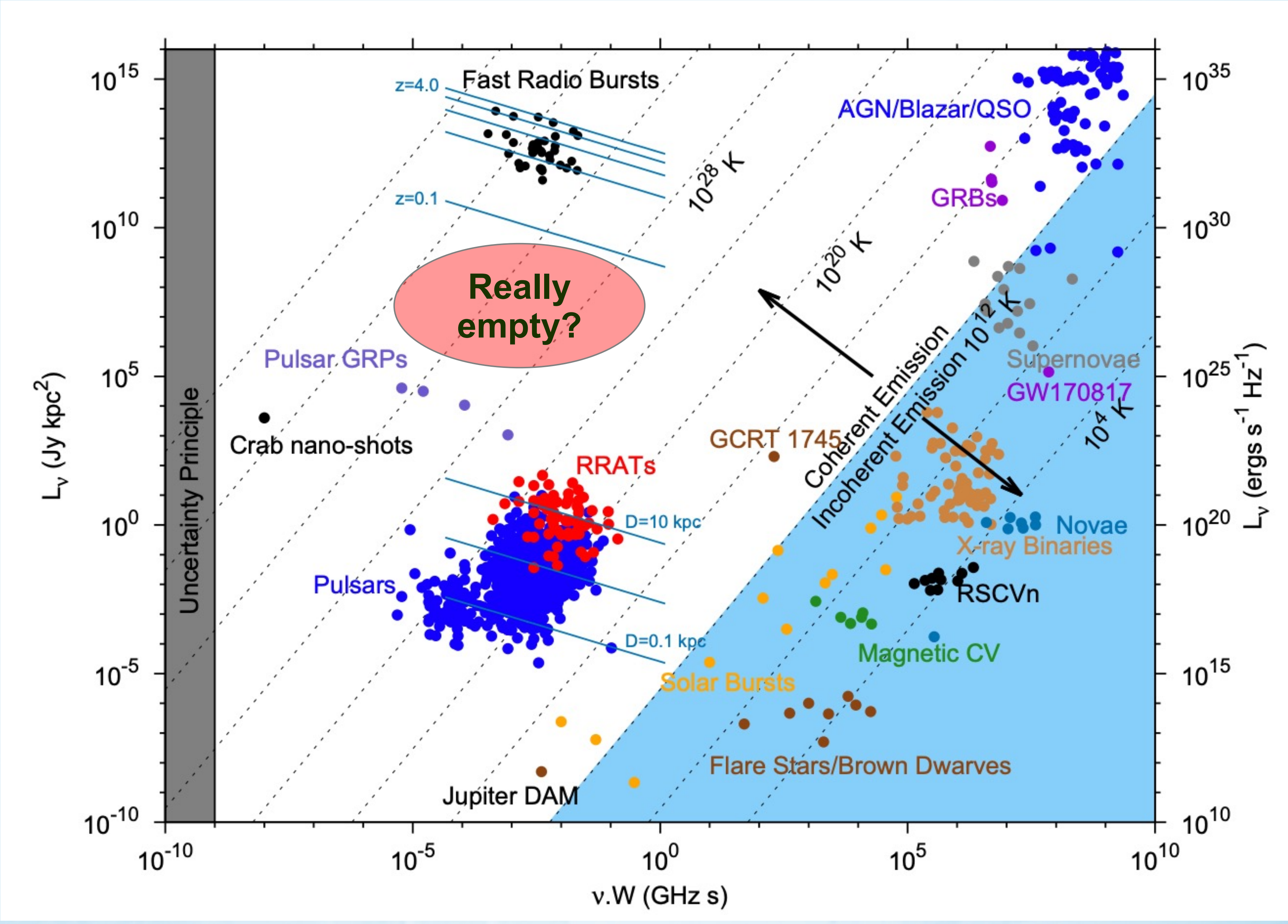


The source have very simple Faraday spectrum structure, if one measure with revised RM synthesis method (Schnitzeler & Lee 2015) The possible systematics are well understood. We detected more than 6-sigma RM variation (increasing).



Magnetosphere? What kind of magnetosphere?

Story 4



What type of magnetosphere radiation?

Keane 2019

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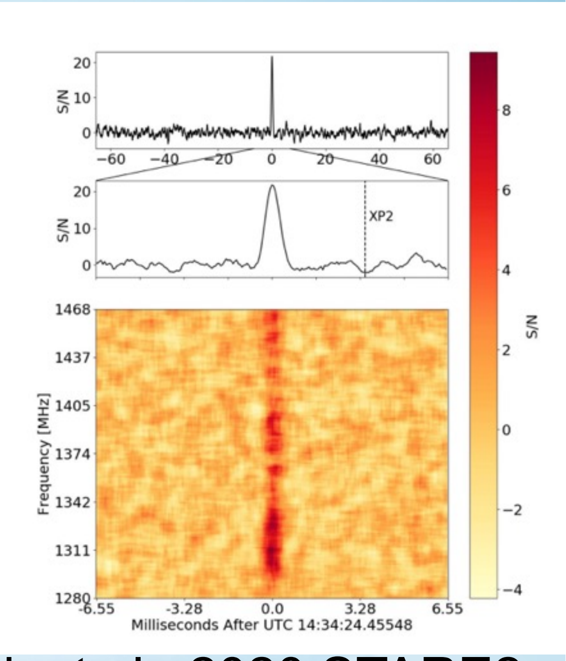
SGR 1935+2154

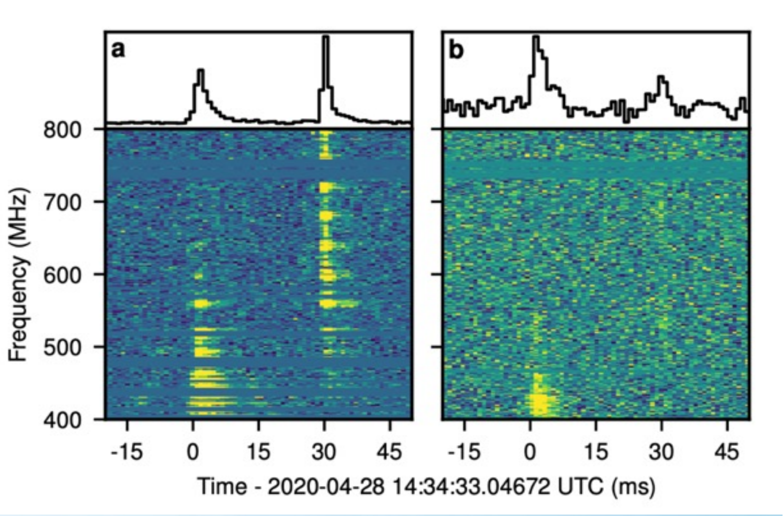
April. 2020，Swift/BAT team noted high energy activities.

CHIME and STARE2 found MJy level radiation.

We performed FAST observation



Bochenek et al., 2020 STARE2



CHIME/FRB coll. 2020

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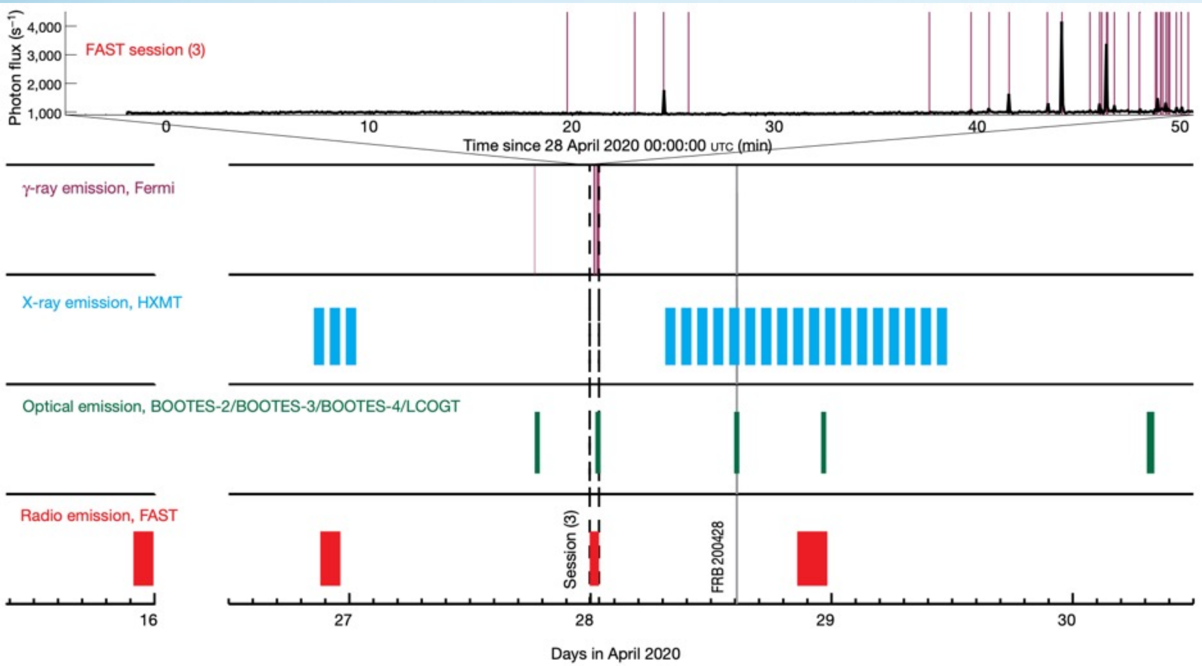
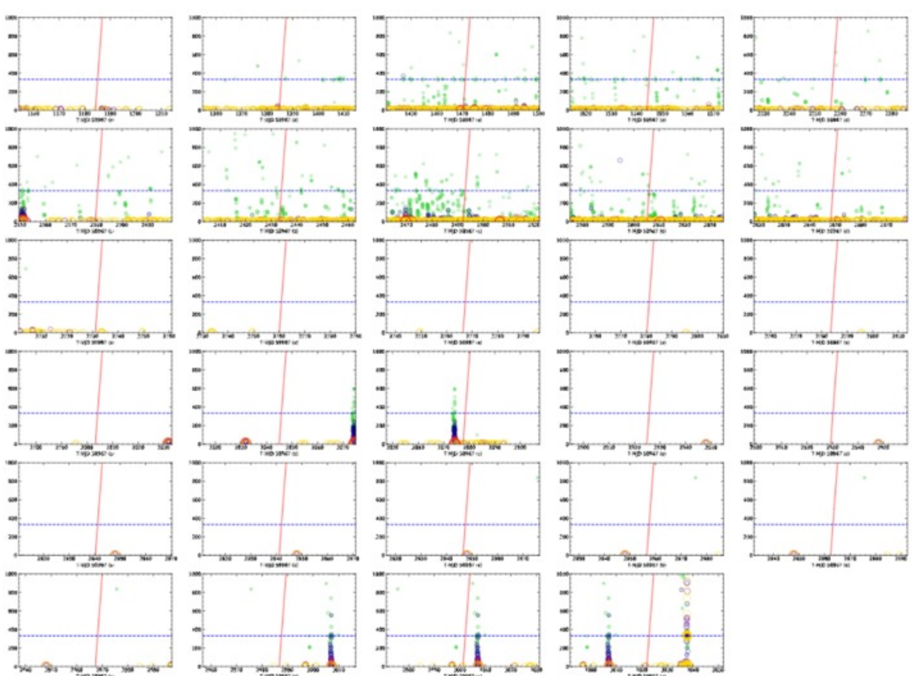
SGR J1935+2154

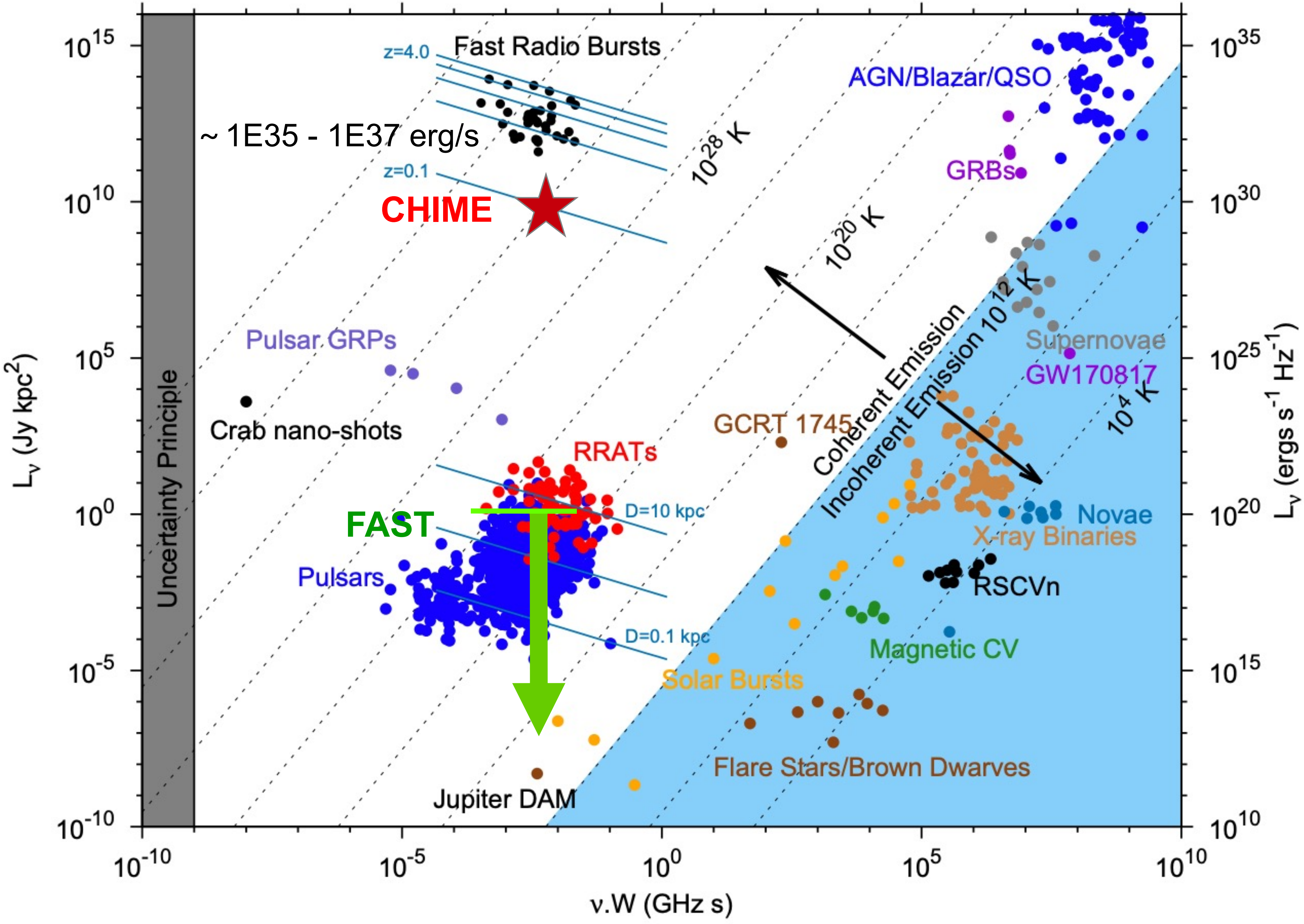


Lin et al., 2020



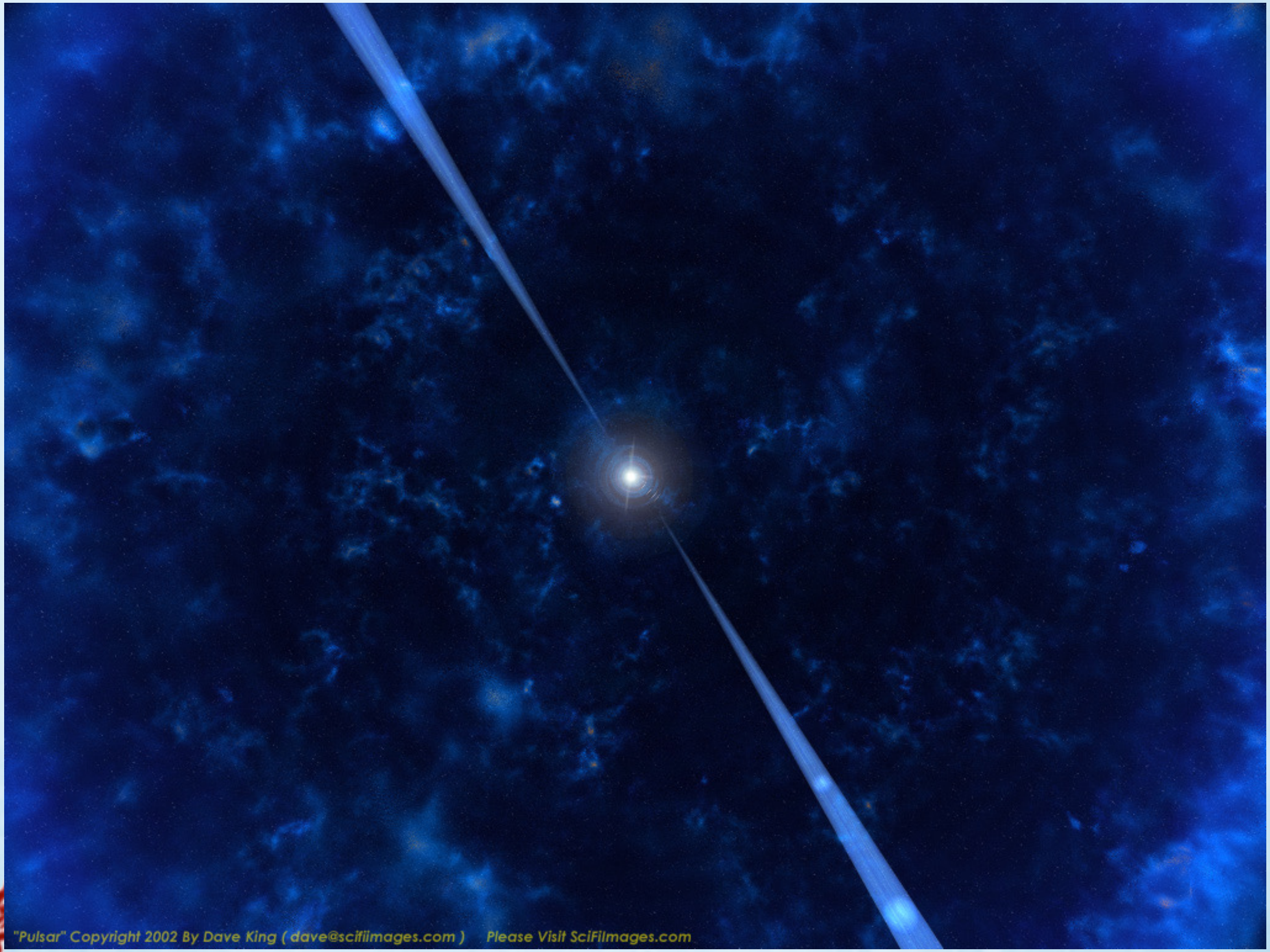
1. Not all high energy burst associating with radio bursts. FRB is generated in an extreme condition.

2. We detected normal radio pulse from SGR J1935+2154 and measured its polarisaiton property. The SGR indeed share common features with AXPs in radio band.

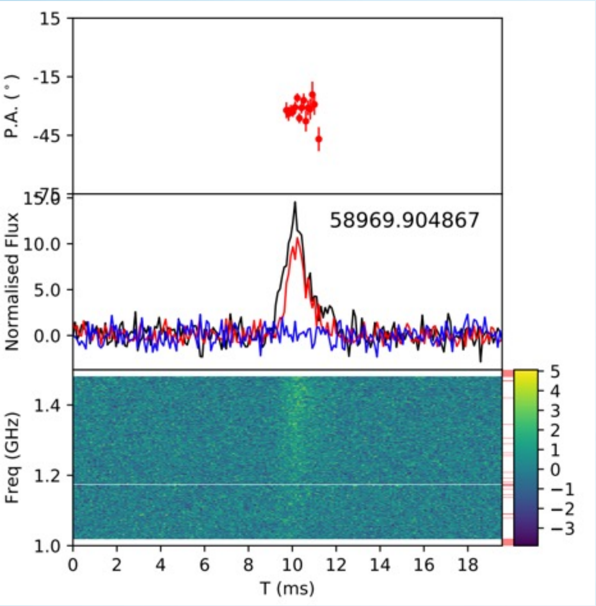


Fast Radio Bursts
z=4.0
z=0.1
~ 1E35 - 1E37 erg/s
CHIME
AGN/Blazar/QSO
GRBs
10^{28} K
10^{20} K
10^{12} K
10^{4} K
Coherent Emission
Incoherent Emission
Supernovae
GW170817
Pulsar GRPs
Crab nano-shots
GCRT 1745
RRATs
D=10 kpc
D=0.1 kpc
FAST
Pulsars
Novae
X-ray Binaries
RSCVn
Magnetic CV
Solar Bursts
Flare Stars/Brown Dwarves
Jupiter DAM
Uncertainty Principle
L_ν (Jy kpc^2)
L_ν (ergs s^{-1} Hz^{-1})
ν.W (GHz s)

Story 4.5: Monster turns vanilla

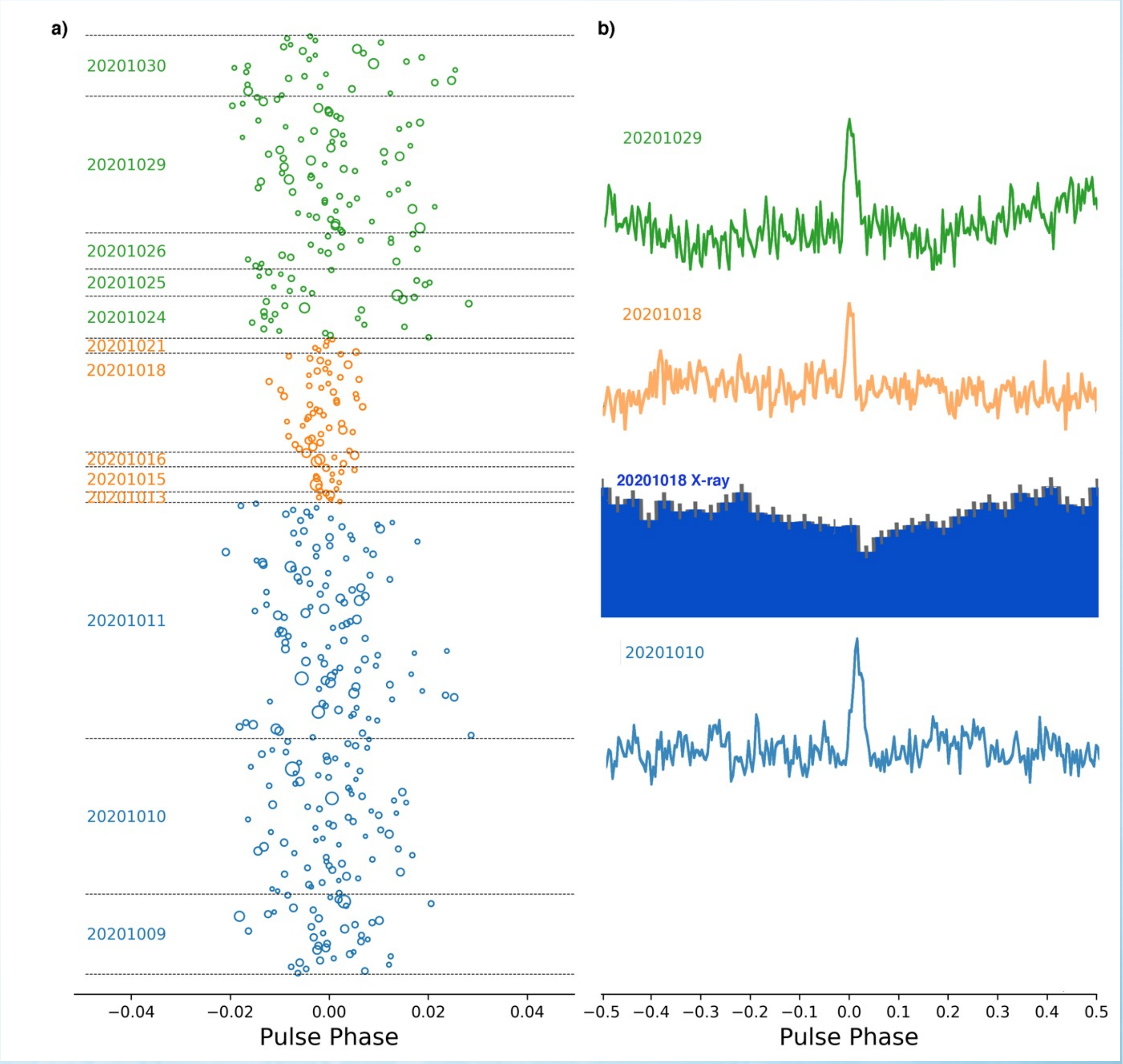


Story 4.5: SGR1935 become a radio pulsar



Zhang et al., Atel

Considering pulse duty cycle
Average radio Flux ~1E24-1E26 erg/s



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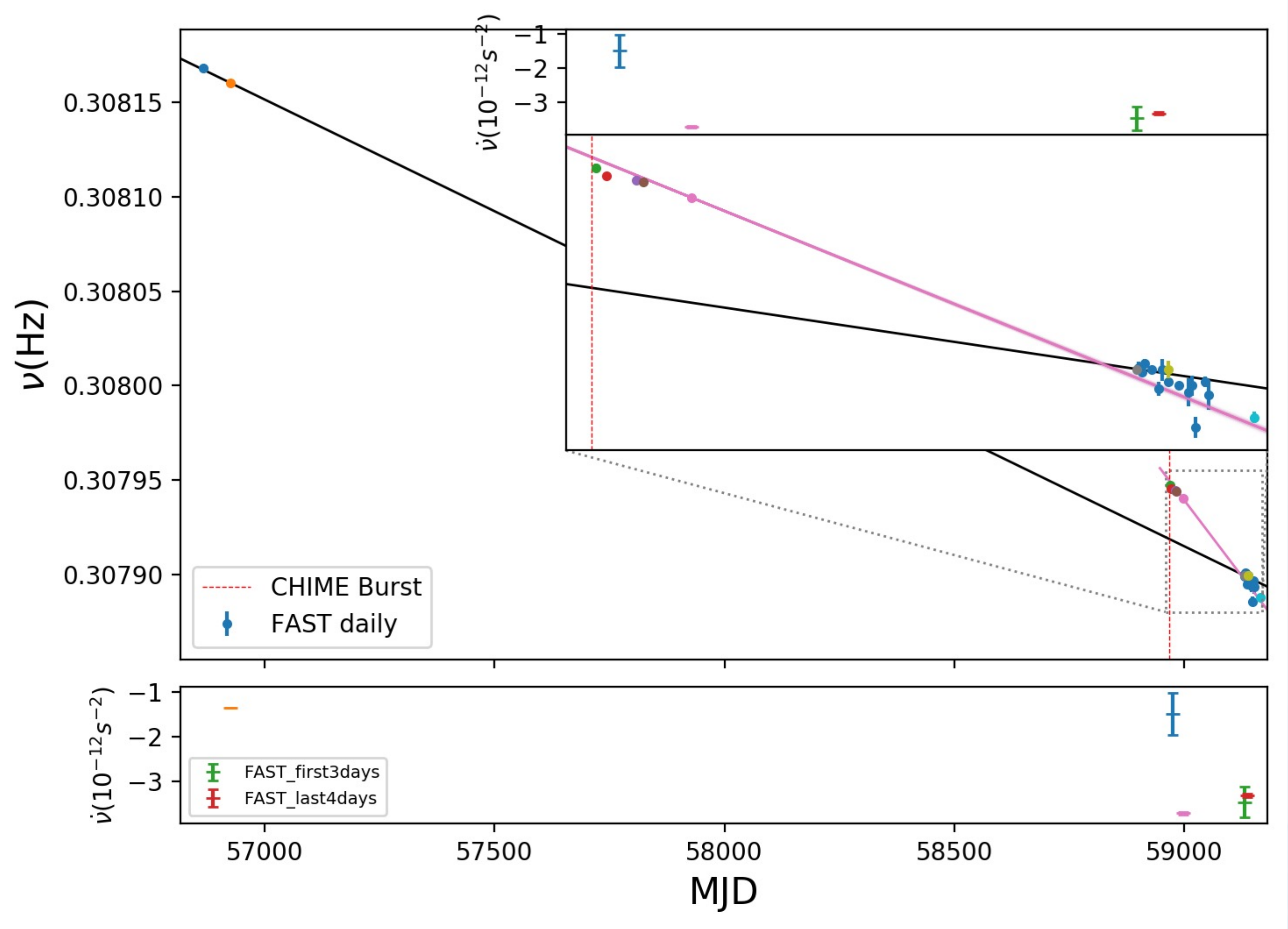
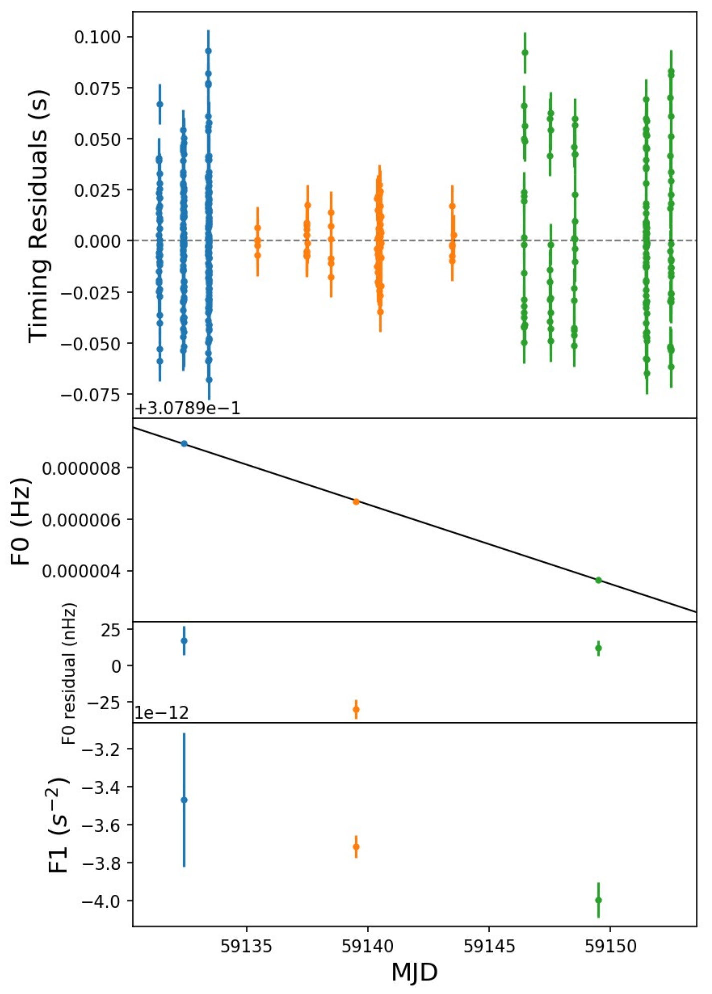
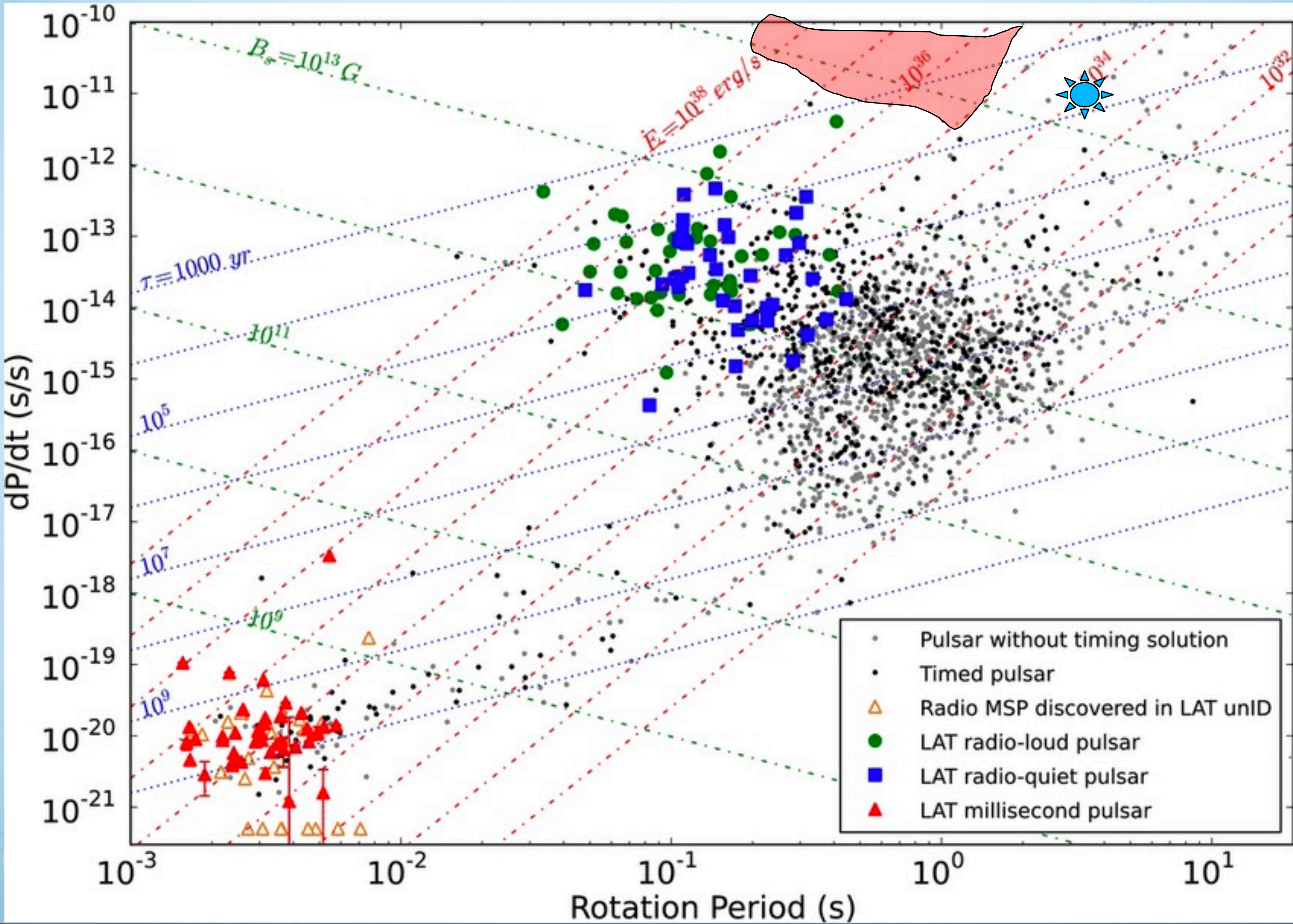
Someone, in prep

Very complicated timing behaviour







$B_s = 10^{13}\,G$
10^{11}
10^{9}
$\dot{E} = 10^{38}\ erg/s$
10^{36}
10^{34}
10^{32}
$\tau = 1000\ yr.$
10^{5}
10^{7}
10^{9}
Pulsar without timing solution
Timed pulsar
Radio MSP discovered in LAT unID
LAT radio-loud pulsar
LAT radio-quiet pulsar
LAT millisecond pulsar
dP/dt (s/s)
Rotation Period (s)

Conclusion

- FRBs are real, but may contain contaminations.
- Hope you are convinced that we do need big telescope or an array.
- FRB should come from magnetosphere,but still many unknowns

Future

1. What is the energy deposit processes ? i.e. how the rotation energy is build up in the magnetosphere. Note normally, only ~1E-6 energy is converted to radio pulse. So we need something like 1E40-1E41 erg. To generate repeating FRBs, There must be a energy deposit processes to quickly (mins to hours) charge magnetosphere, at efficiency close to 100 % even beam effects considered (spin down power 1E36-1E38).
2. What triggers the monster? Why FRB does not release energy in a pulsar way?
3. We know that the wave growth rate in pulsar magnetosphere is inefficient for pulsar radio emission. What kind of wave growth rate support FRB radiation, or why there is coherent electron state in FRB environment?
4. For large population, what we can learn from comic magnetic field and ionization history? How we can remove the host environment systematics?

Thanks

We are also working on 1. Chinese pulsar timing array to detect GWs, 2. Chinese SKA pilot low frequency (50-250Mhz) observation of pulsar, FRBs, and probably detecting high energy particles.

We are hiring post-docs. If interested, please do not hesitate to contact us.

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