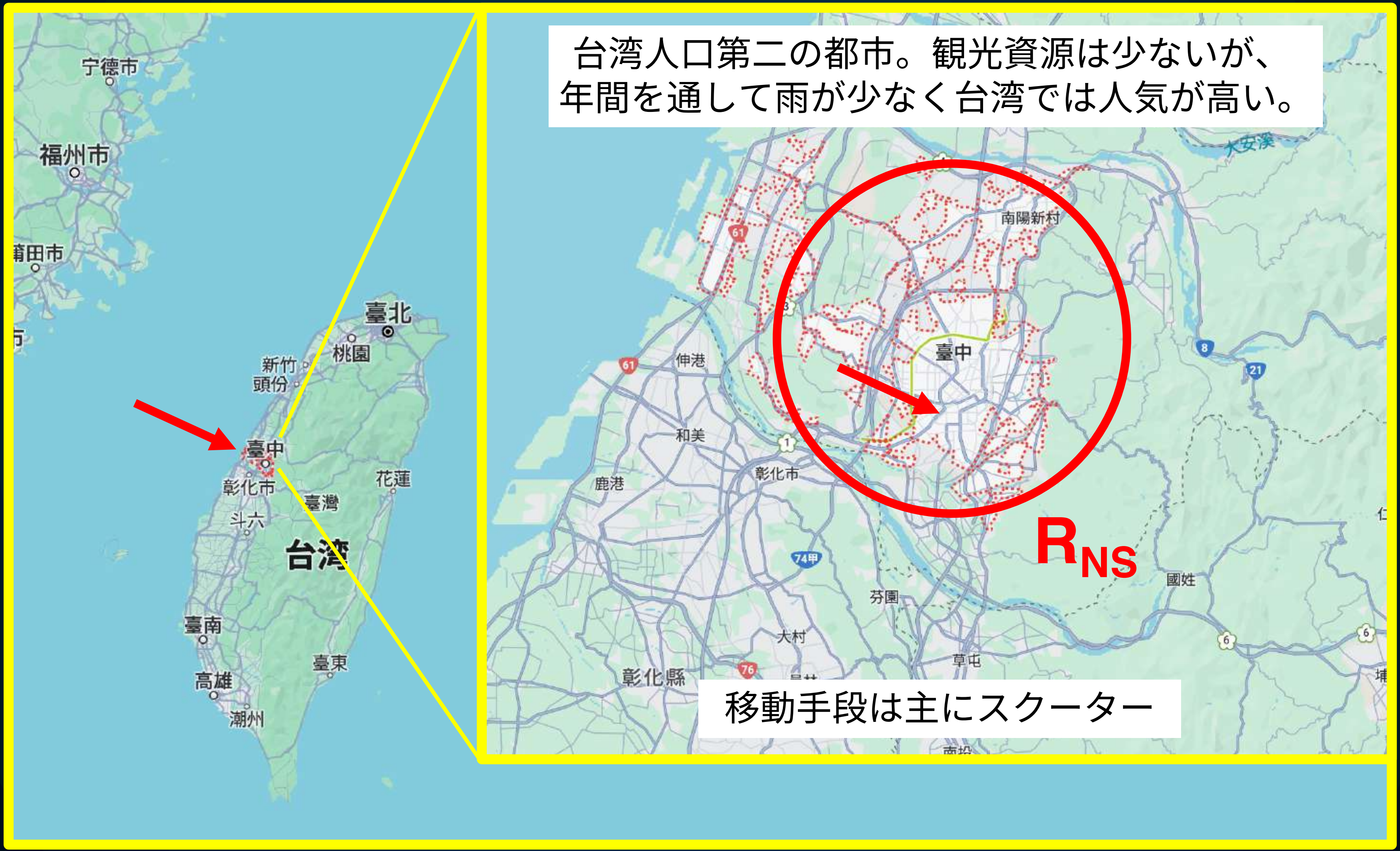
ICRR/HEA 小研究会@那覇
22 Mar, 2024

Astrophysical Burst Phenomenology

Shotaro Yamasaki
National Chung Hsing University (NCHU), Taiwan

U. Tokyo/Astro. (PhD) → ICRR (Postdoc) →
Hebrew U. (Postdoc) → NCHU (Postdoc)

National Chung Hsing University (國立中興大學)



台湾人口第二の都市。観光資源は少ないが、年間を通して雨が少なく台湾では人気が高い。

移動手段は主にスクーター

National Chung Hsing University (國立中興大學)

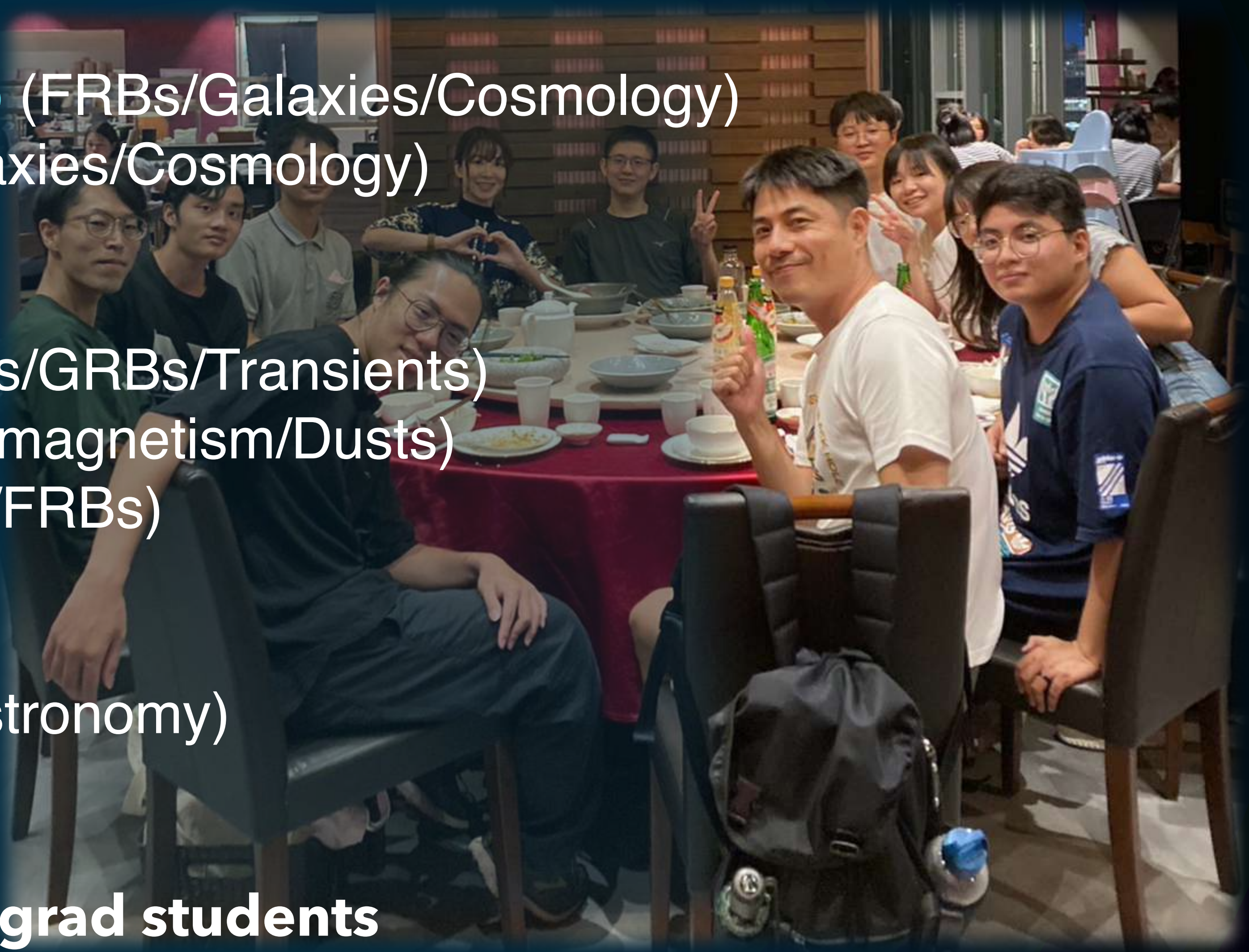
台中市最大の国立大学

(個人的に) 鹿児島大学に似ている

日本統治時代の1919年に設置された**台湾総督府農林専門学校**を起源とする。1928年に台北帝国大学に統合されたが、1942年に再独立、第二次世界大戦後に大学となり現在に至っている。

物性/量子論寄りの物理学部に
Astro が最近 (2019)できた

Astrophysics group at NCHU



- **Senior members**
  - ➢ Prof. Tetsuya Hashimoto (FRBs/Galaxies/Cosmology)
  - ➢ Prof. Yu-Yen Chen (Galaxies/Cosmology)
- **Postdocs**
  - ➢ Shotaro Yamasaki (FRBs/GRBs/Transients)
  - ➢ Lapo Fanciullo (Cosmic magnetism/Dusts)
  - ➢ Shyam Sunder (Pulsars/FRBs)
- **PhD students**
  - ➢ Yuri Uno (SETI/Radio astronomy)
  - ➢ Vignesh Vavilla (FRBs)
- **2 MSc students + 5 undergrad students**

Astrophysics group at NCHU

FRB Taiwan 2023 @NCHU on Jan. 2023

Talk plan

Recent topics from different "burst" phenomena

Fast Radio Bursts

- **Do all FRBs repeat?**
  (SY, Goto, Lin & Hashimoto 2023)
- **IGM baryon fluctuation**
  (Hsu, SY et al. 2023, submitted)
- **BURSTT FRB Science (review)**

Magnetar bursts

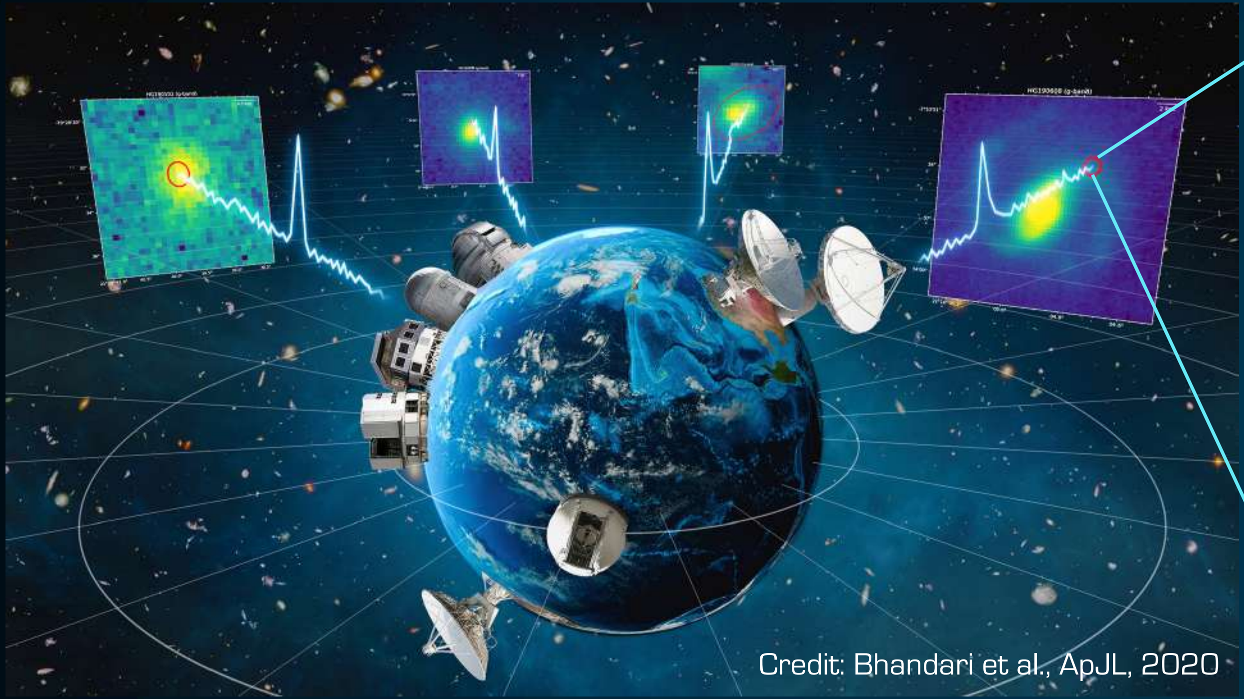
- **Magnetar burst stochasticity**
  (SY, Gogus & Hashimoto 2023)

Gamma-Ray Bursts

- **Analytic SSC SED**
  (SY & Piran 2022; SY, Piran, Derishev in prep.)

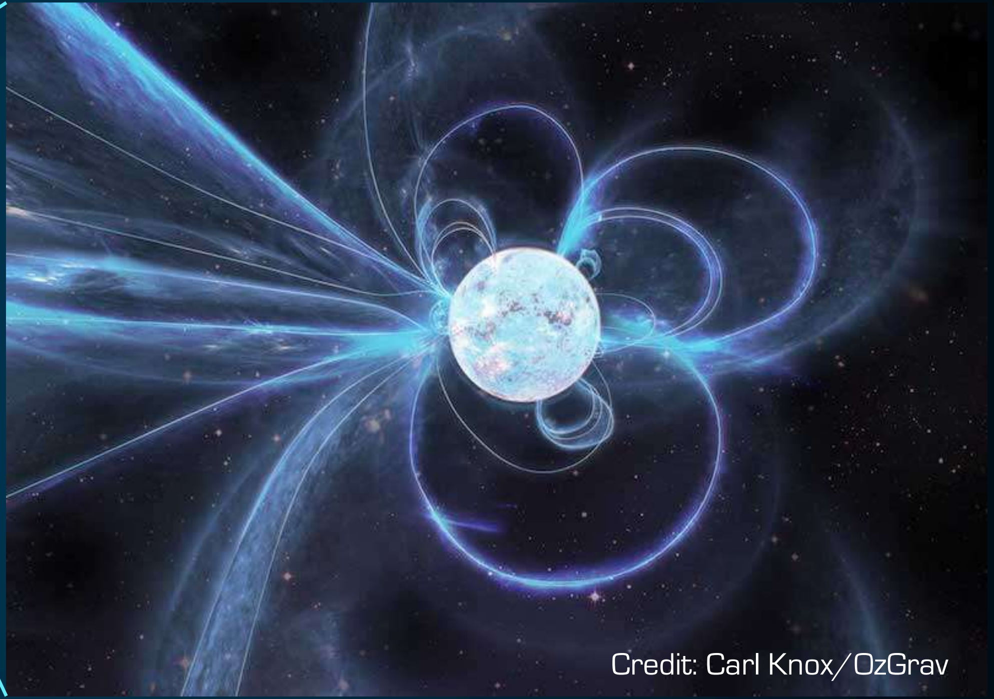
Fast Radio Bursts (2007~)

Fast Radio Bursts



Credit: Bhandari et al., ApJL, 2020

Magnetar



Credit: Carl Knox/OzGrav

Bright short coherent radio pulses / Highly dispersed by propagation effects (>>300 pc/cc)/ Some repeats / Host galaxies identified (cosmological)/ Peculiar repeating sources / Galactic magnetar

and more…

Shaw Prize 2023 for the discovery of FRBs

“FRBs”

I. Do all FRBs repeat?

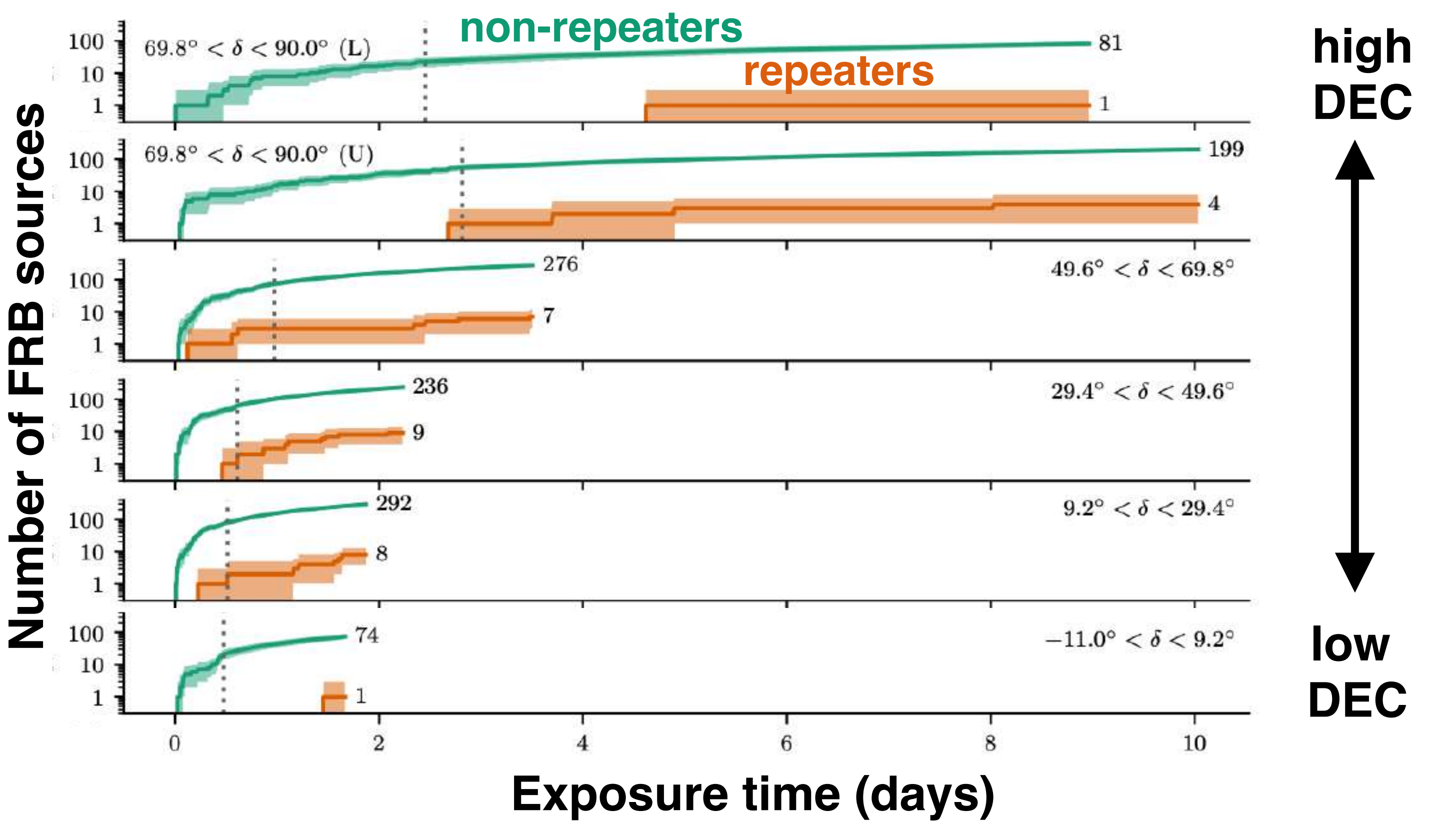
“The true fraction of repeating FRBs revealed through CHIME source count evolution”

SY, Goto, Ling, Hashimoto 2024, MNRAS, 527, 1158

Image credit: CHIME Experiment

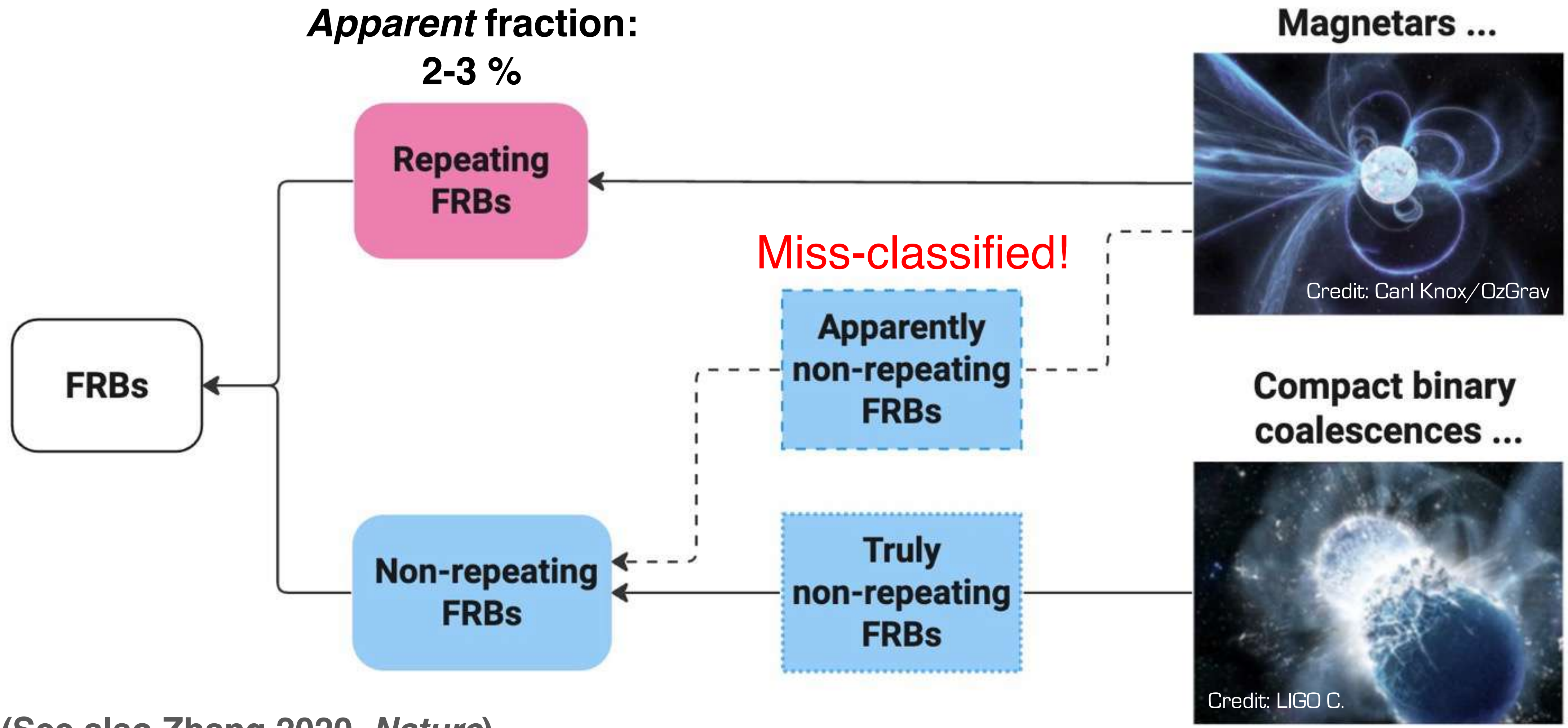
Do all FRBs repeat?

An ongoing FRB survey by Canadian Hydrogen Intensity Mapping Experiment (CHIME)



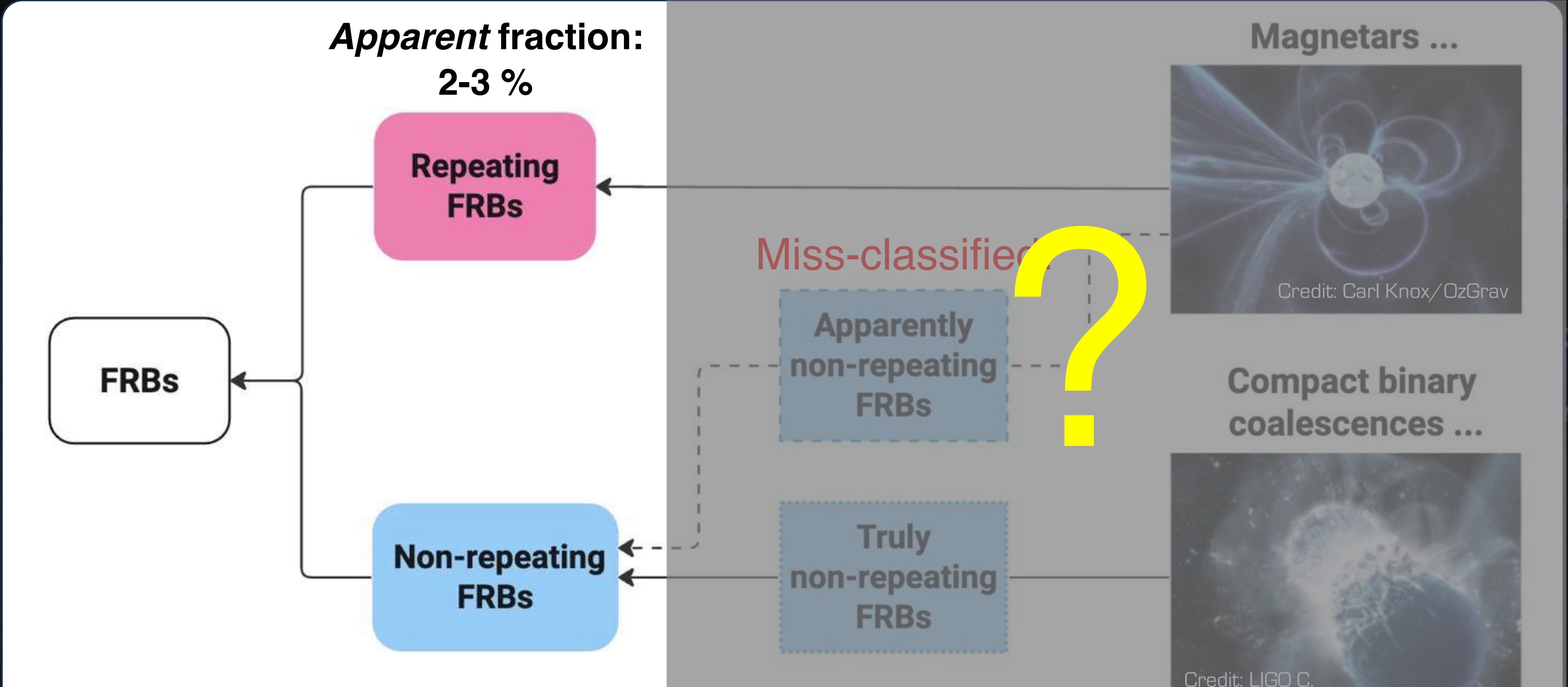
- **NO** – *apparent* repeater fraction: **2-3 %** (CHIME/FRB C. 2023)
- However, *true* repeater fraction is unknown due to observational biases

Bias 1: Incomplete classification



(See also Zhang 2020, *Nature*)

Bias 1: Incomplete classification



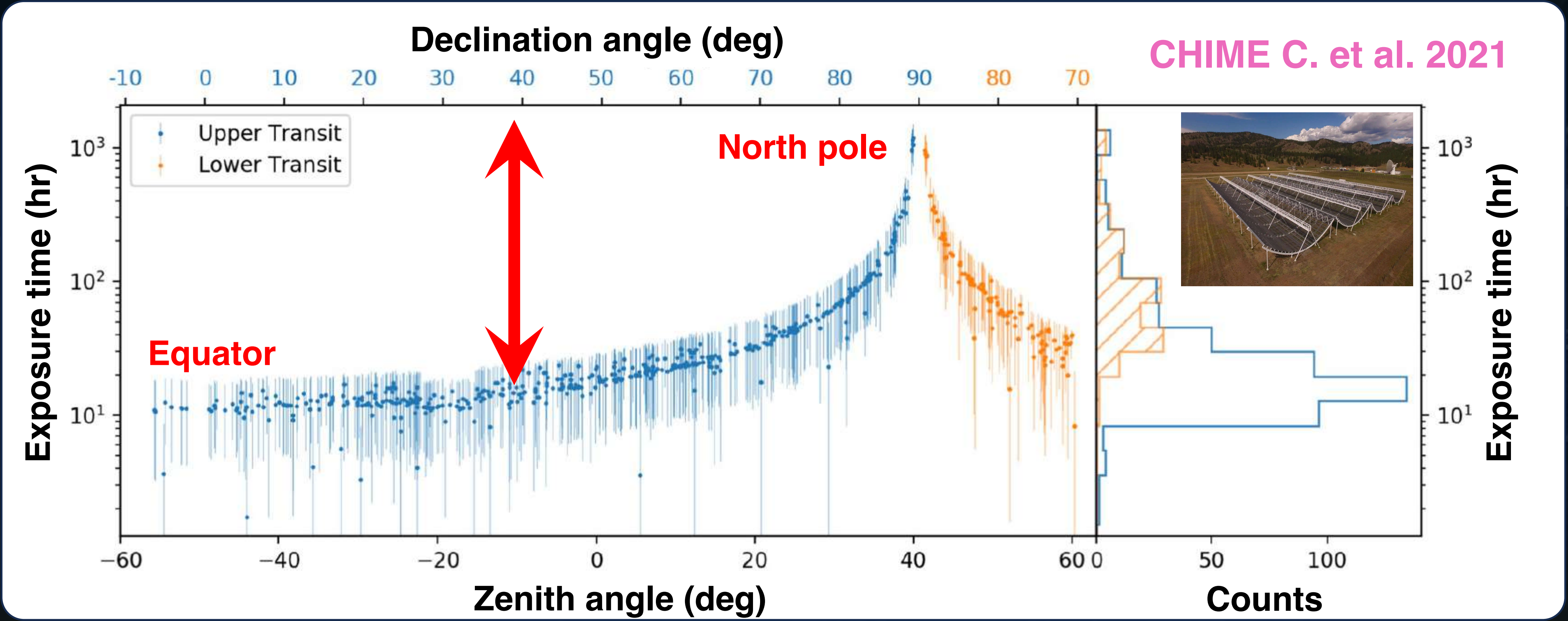
(See also Zhang 2020, *Nature*)

Bias 1: Incomplete classification (contd.)

FRB classification is inevitably incomplete!

Apparent (observed) repeater fraction < *True* repeater fraction

Bias 2: Nonuniform sky exposures



- Sweeping northern sky once (δ < 70 deg) and twice (δ > 70 deg) per day
- Exposure time: highly depends on source's declination angle

Correcting observation

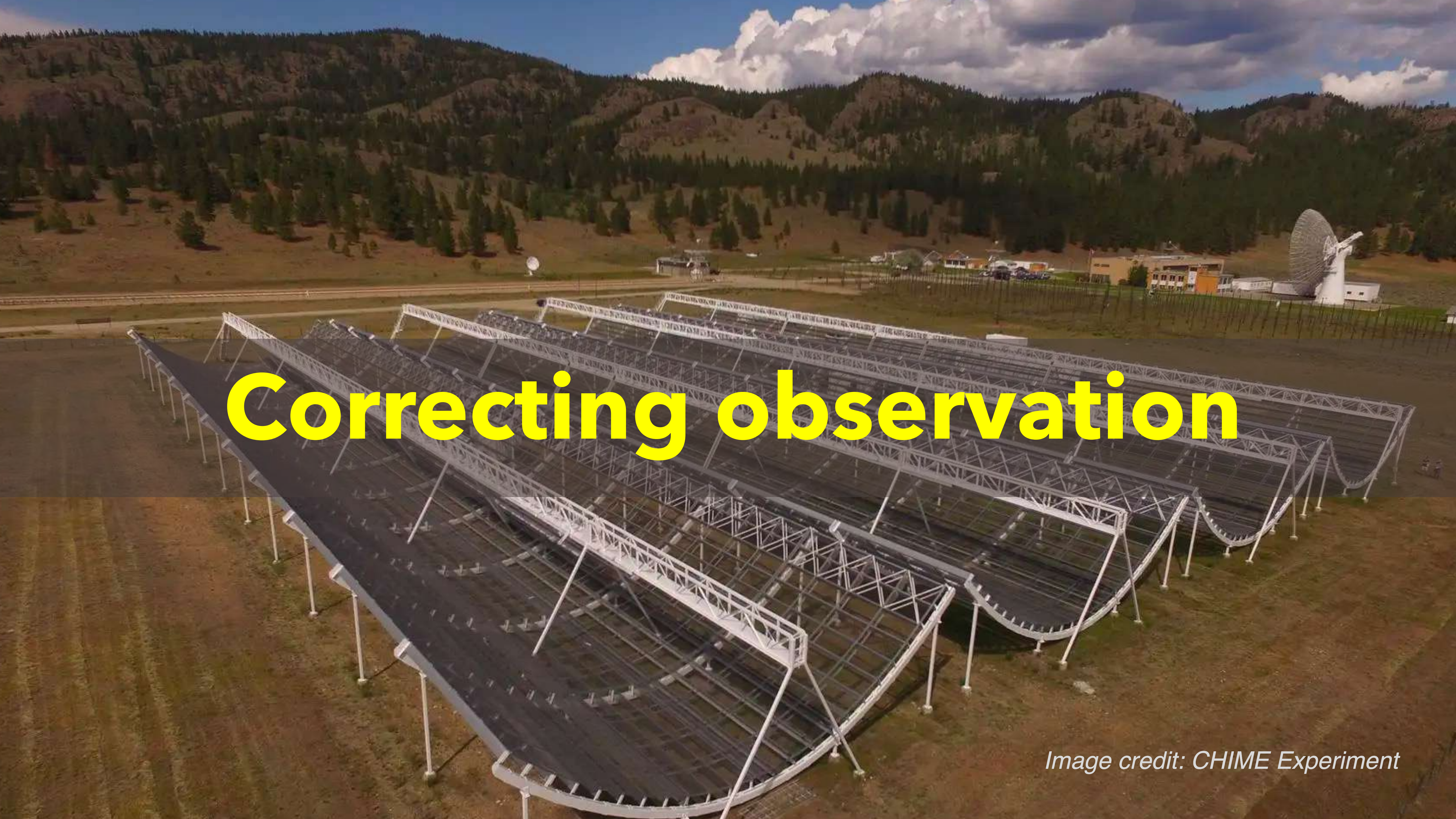
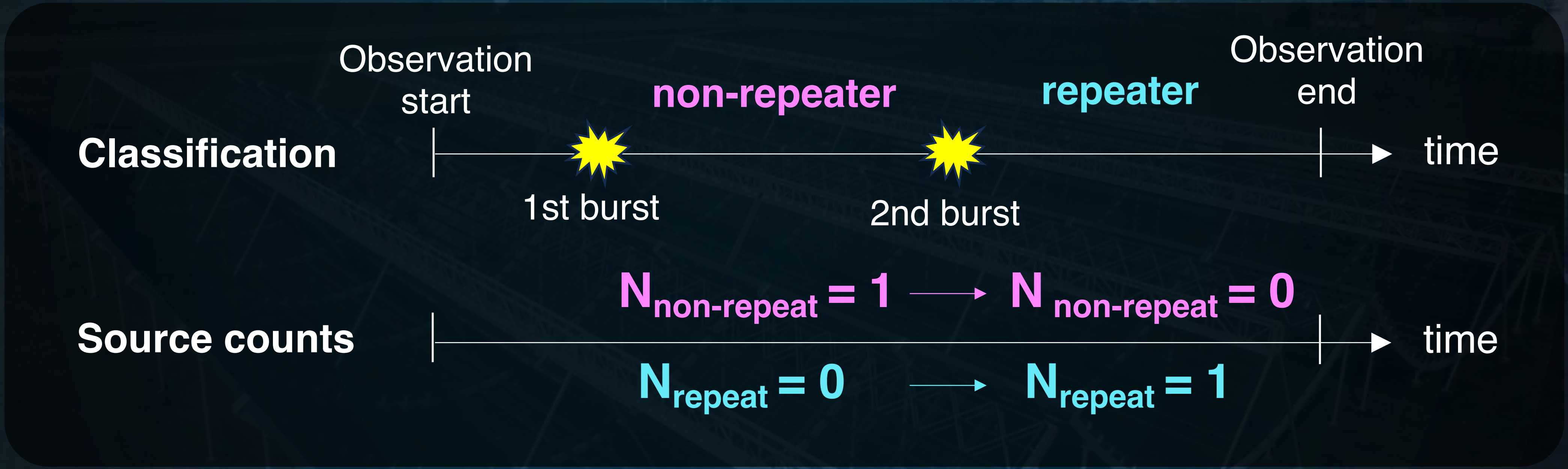


Image credit: CHIME Experiment

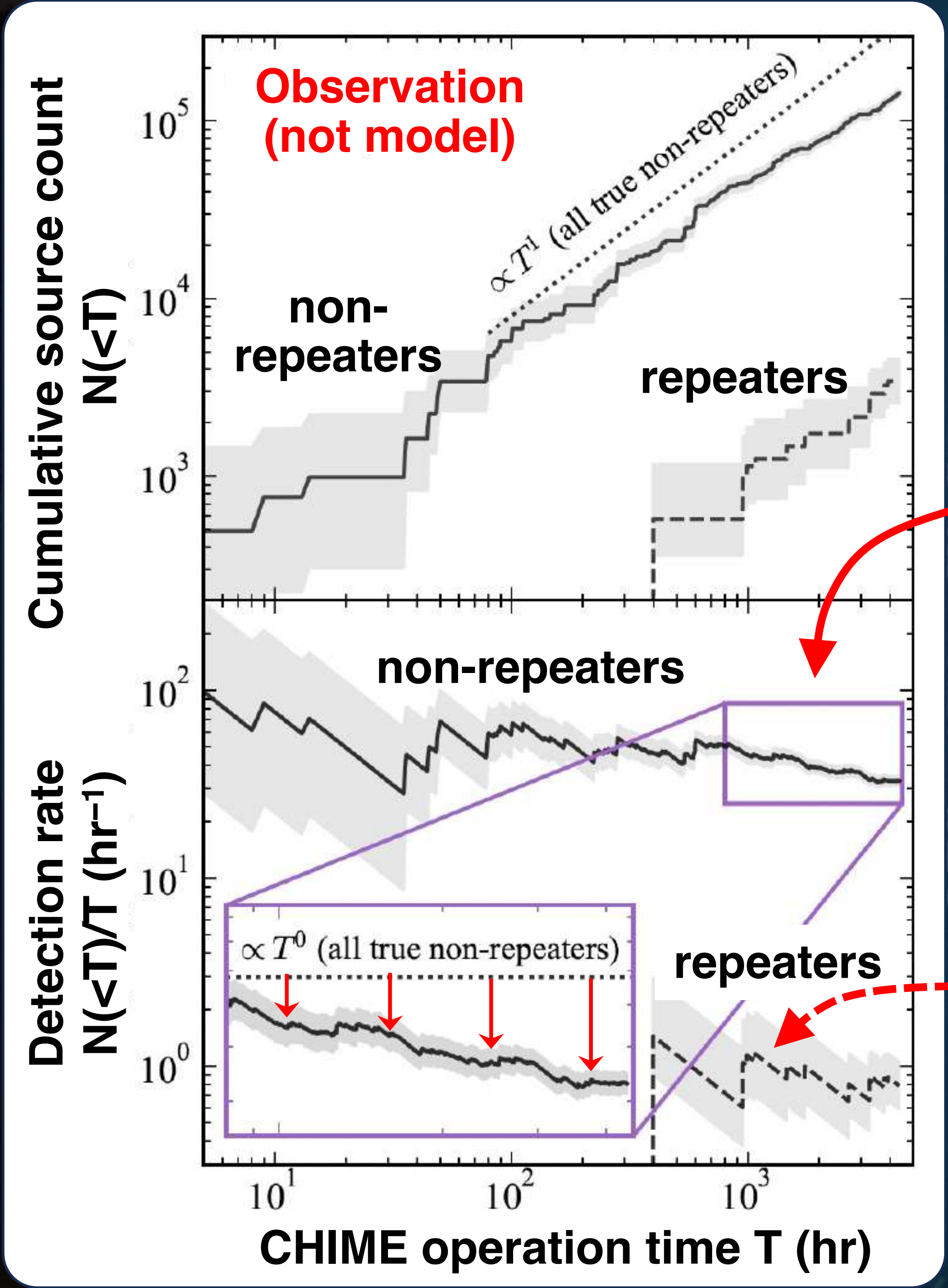
Addressing observational biases

1. **Time-dependent** classification (i.e. temporal switch from non-repeaters to repeaters)



2. Weighting FRB source count by **on-source time fraction**
→ **Directionally-uniform** all-sky source count evolutions

"Corrected" observations



- **393 bursts** detected during Dec 31, 2018 - Jul 1, 2019
- Discovery of **significant decrease (x2) in non-repeater detection rate** after ~10^3 hours

→ Cannot be explained by true non-repeaters alone!

→ Likely due to the temporal switch of non-repeaters into repeaters…

- Repeater's detection rate remains constant

→ repeaters may have a broad repeat rate distribution

Population modeling

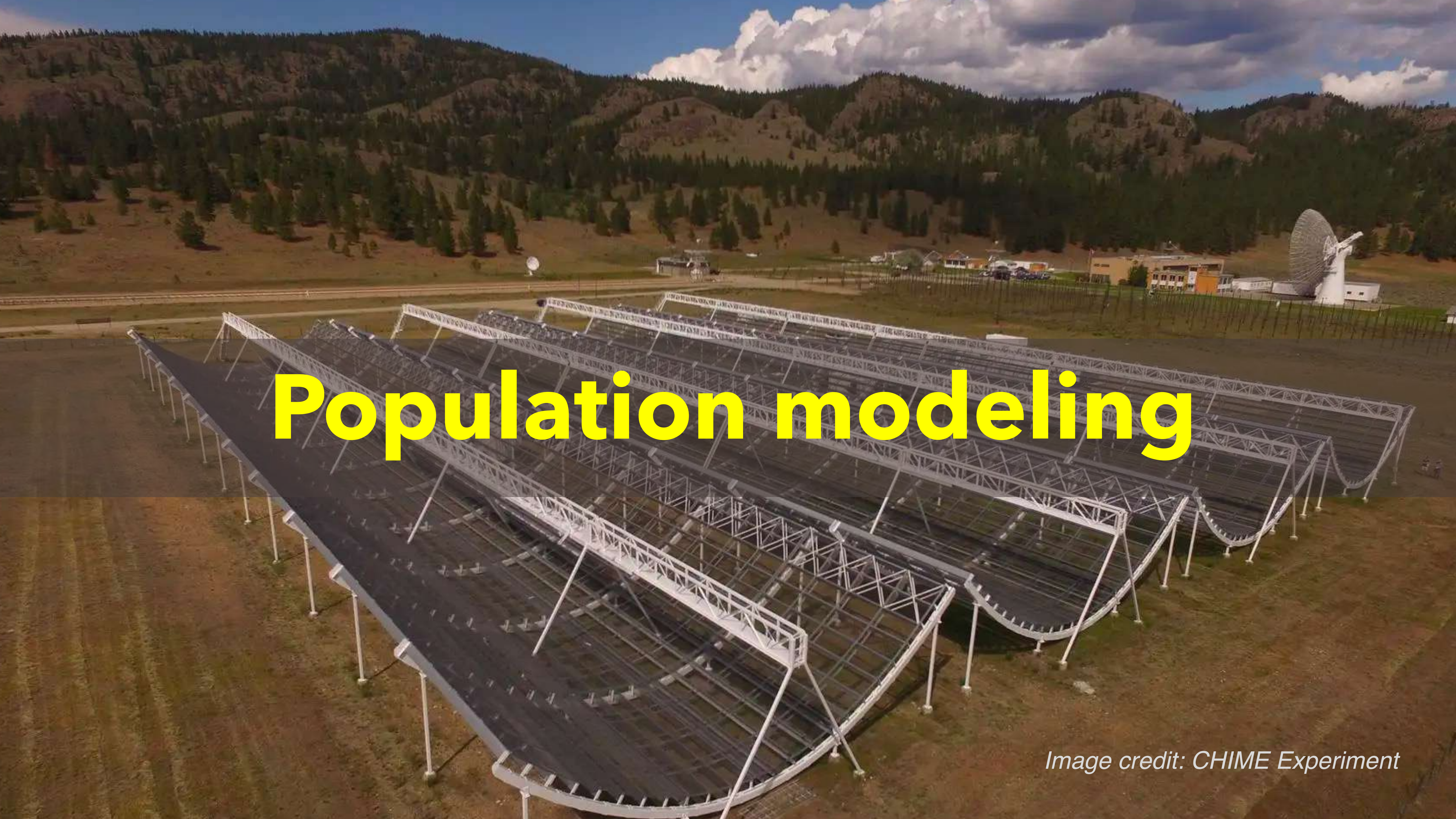
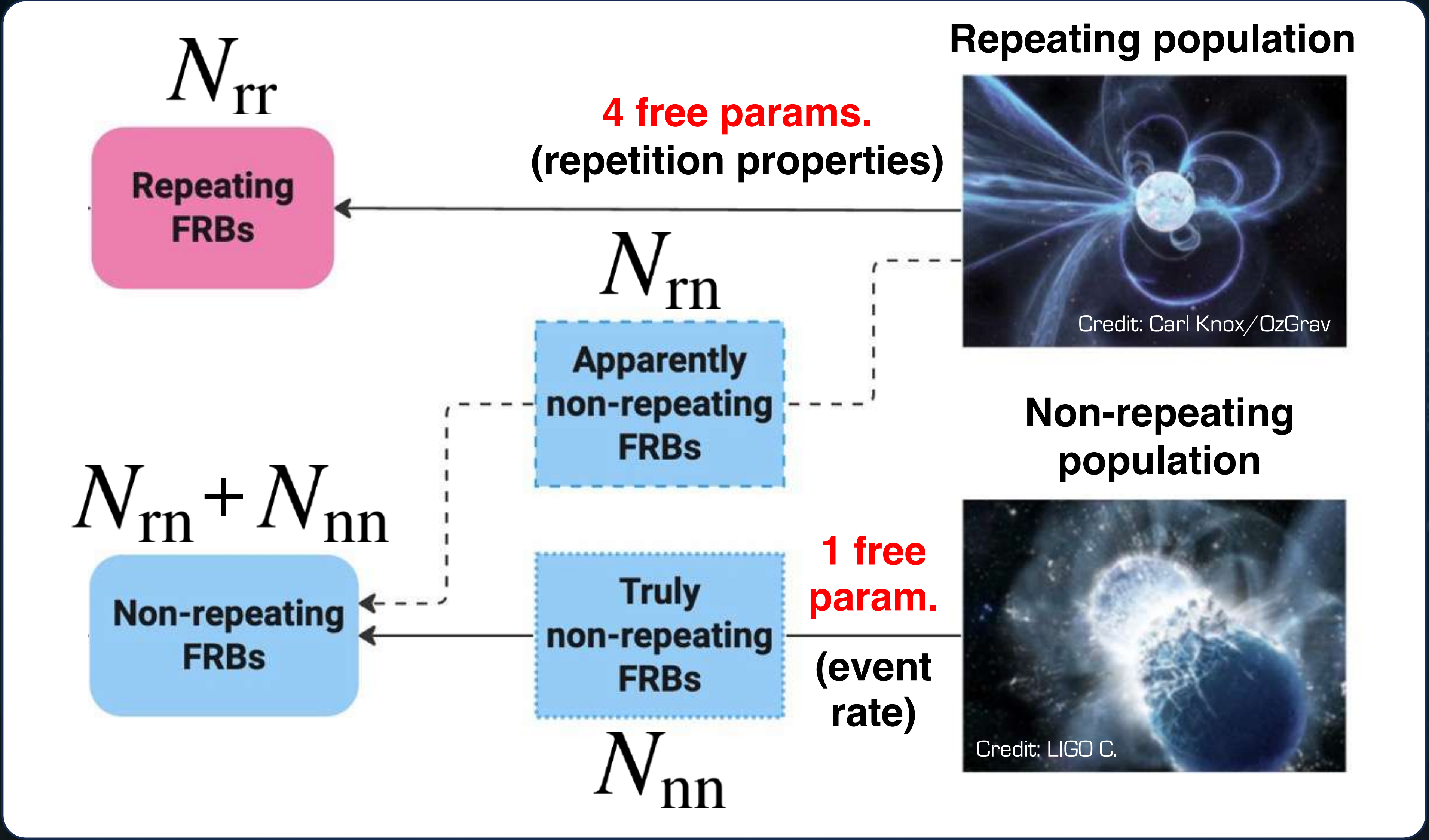


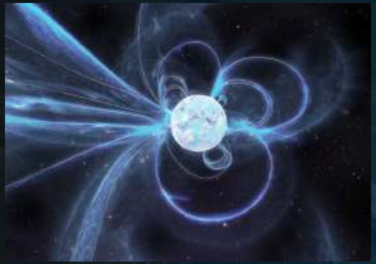
Image credit: CHIME Experiment

A Monte-Carlo model of two populations



MCMC results (5 free params)

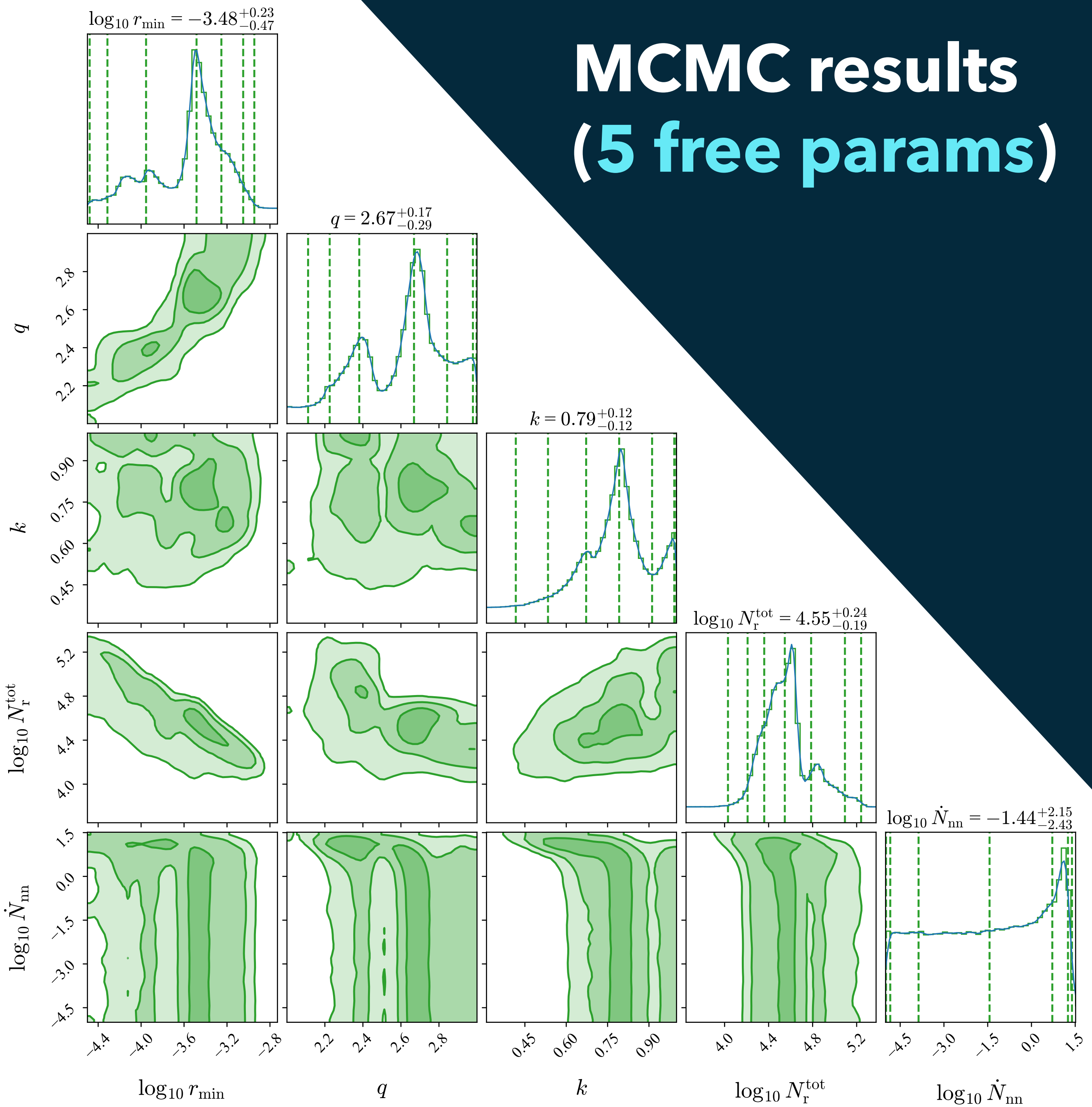
Repeating population



- minimum repetition rate
- repetition rate distribution power-law index –q
- Weibull clustering parameter k
- total # of repeating sources

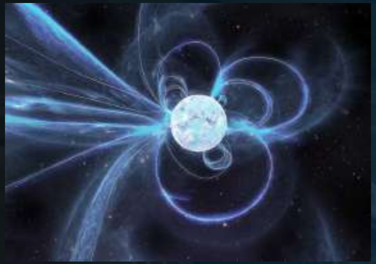
Non-repeating population

- “truly” non-repeating FRB occurrence rate



MCMC results (5 free params)

Repeating population



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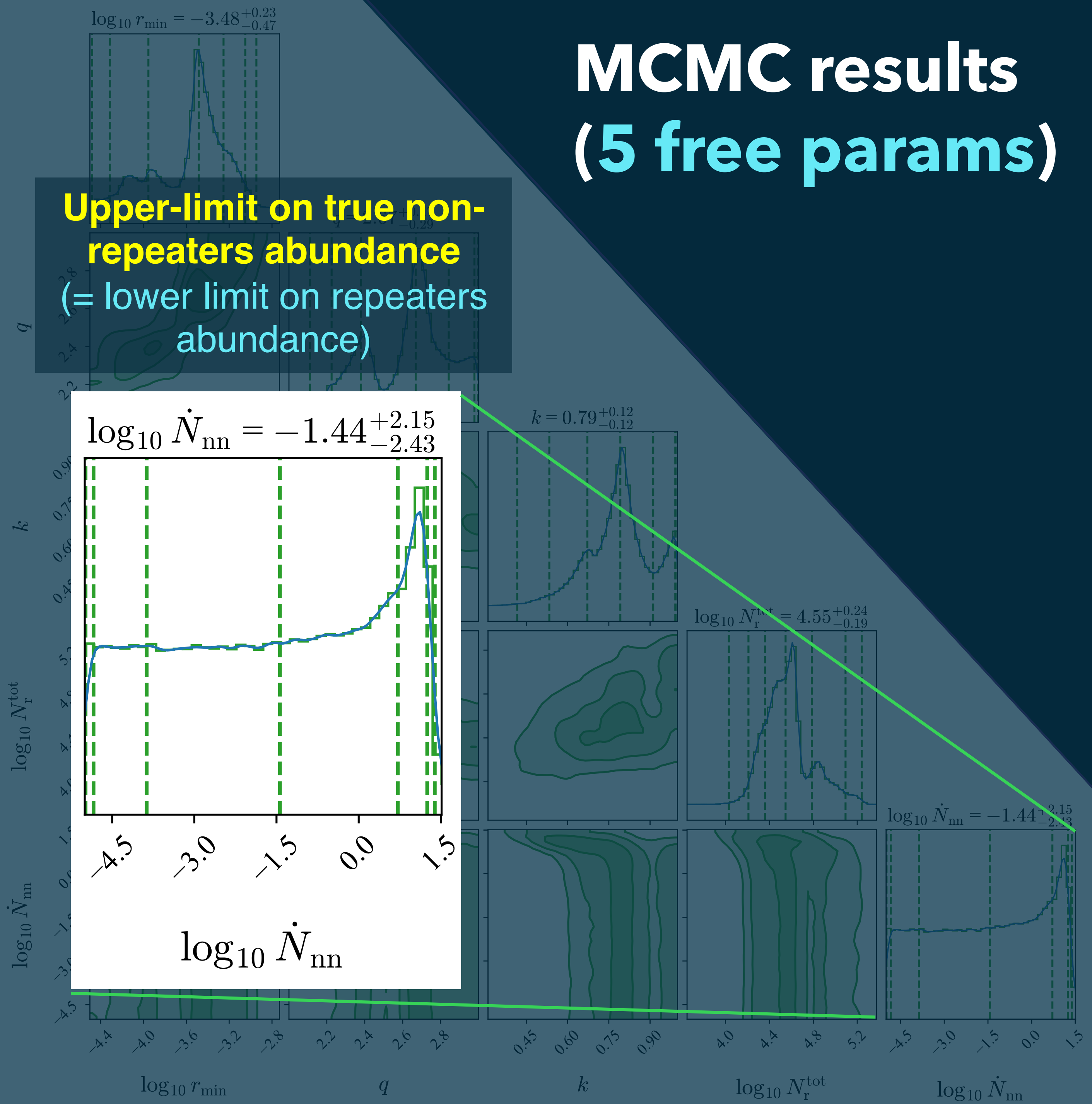
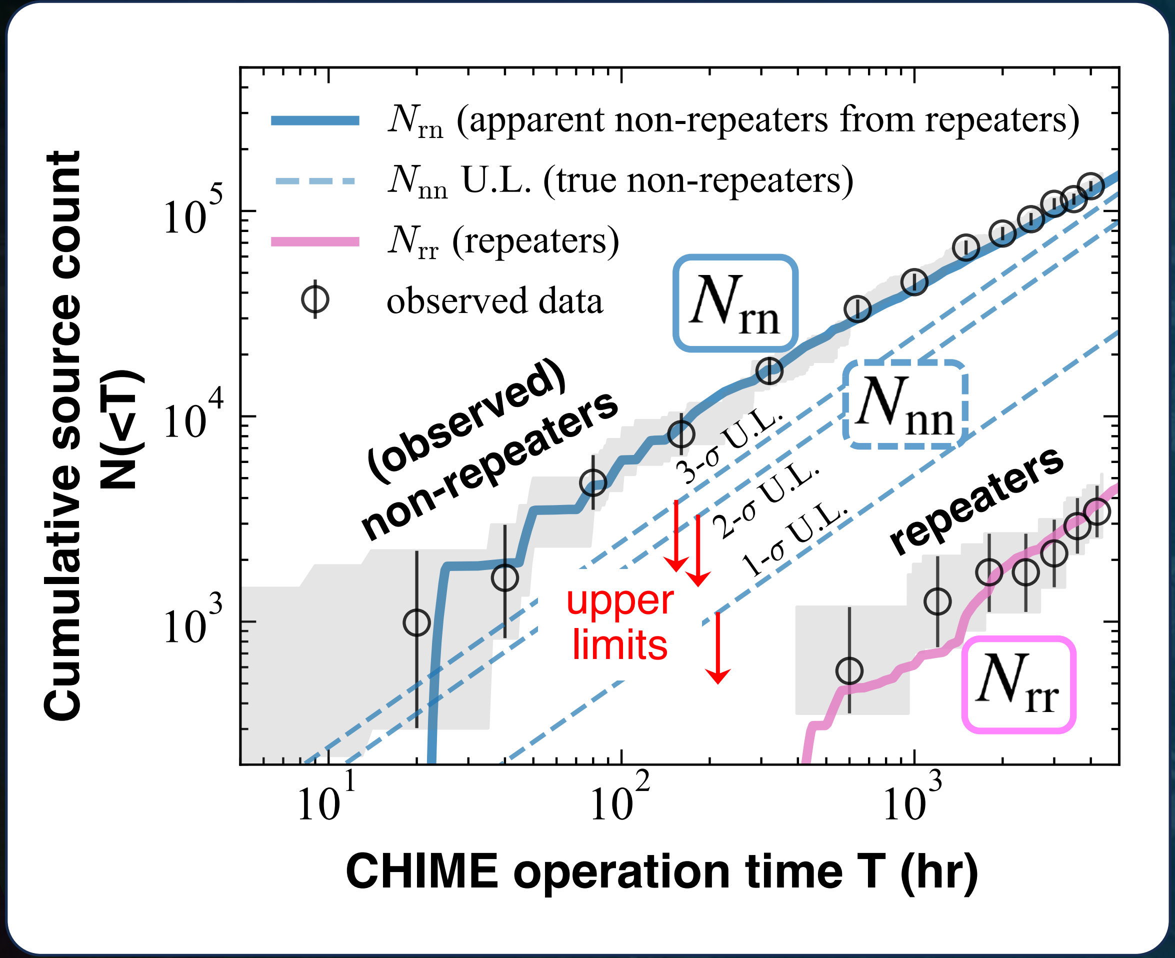


True repeater fraction



from repeaters

$$f_r \equiv \frac{N_{rr} + N_{rn}}{N_{rr} + N_{rn} + N_{nn}}$$

from repeaters   true non-repeaters

- True repeater fraction **~>50%** (2σ) or even **~100%** (1σ) **>>** apparent value of **2-3%** (CHIME C. 2023)
- Among 393 FRBs, **at least ~ 200 could be actually repeaters, while only 15 are known repeaters!**

Implications

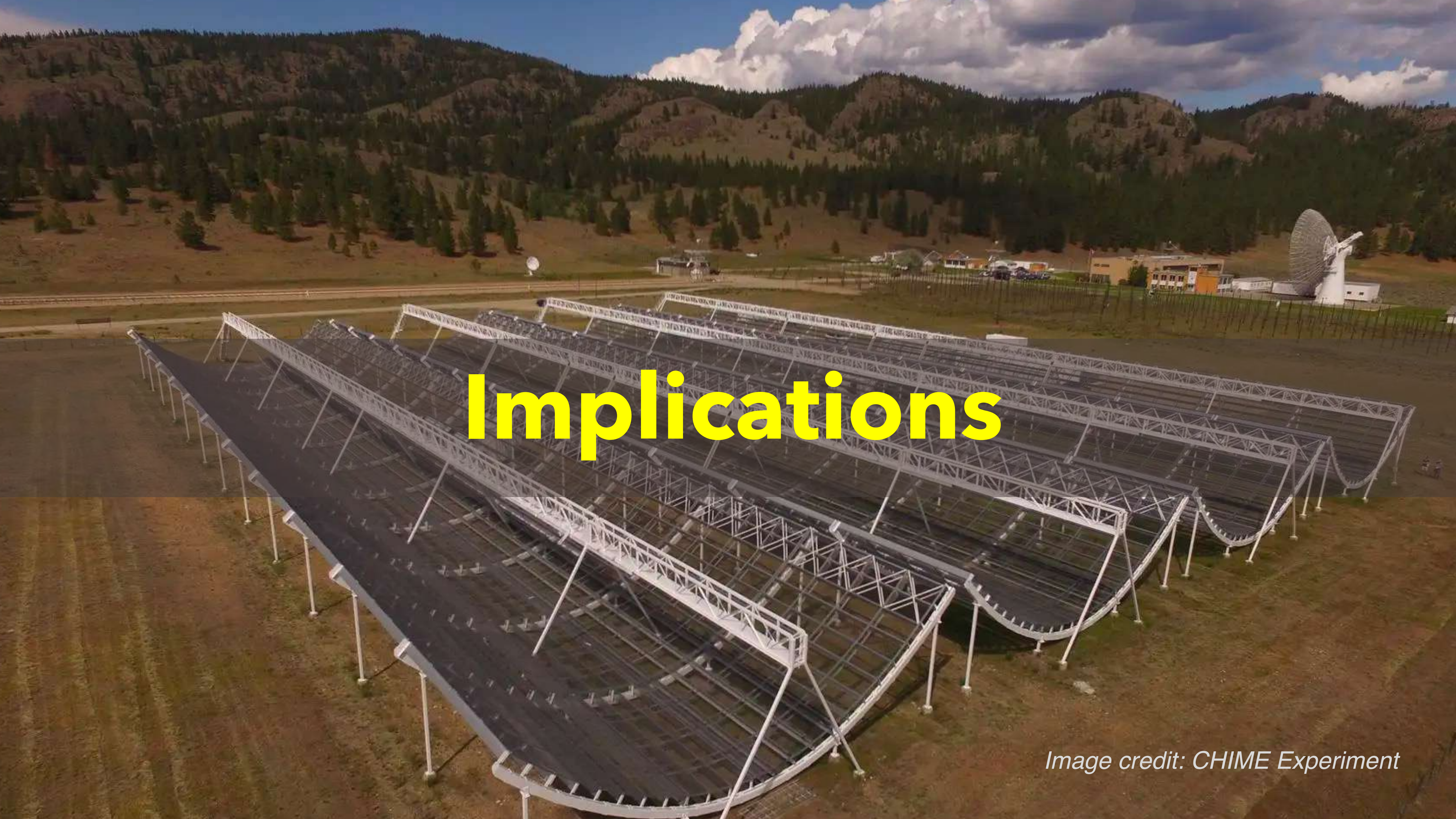
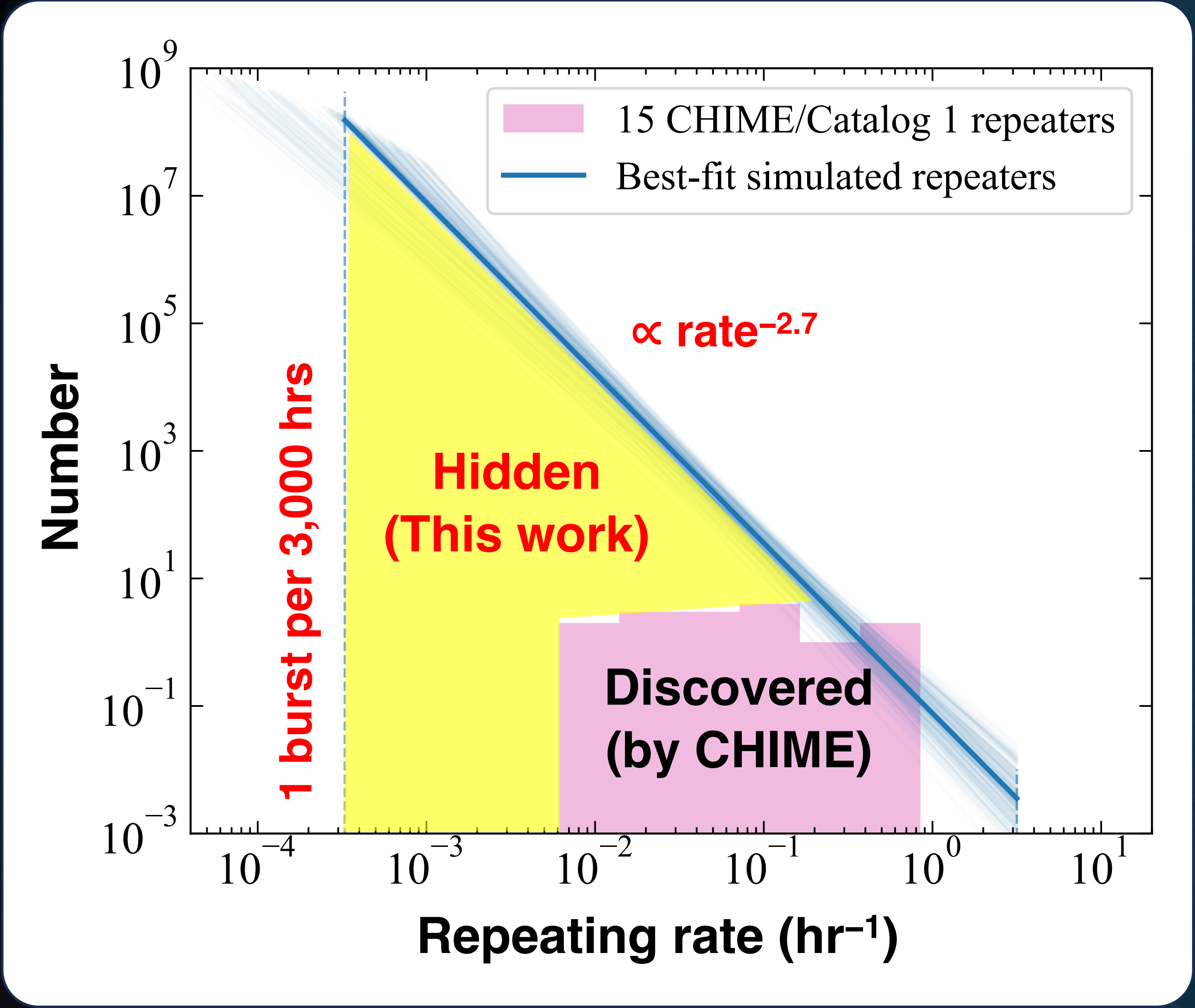


Image credit: CHIME Experiment

Comparison with observed repeating population



- Very low typical repetition rate: **1 burst per 3,000 hours**
- CHIME preferentially detects rarer (**x 10^4**) and more frequently (**x $10^{1.5}$–$10^{3.5}$**) repeating sources
  = **A huge hidden population?**
- Low repeat rate demands a new theory
- FRB progenitor volume density must be revised

Conclusions

- Apparent repeater fraction **2-3 %** (CHIME/FRB C. 2023) is *NOT* the true repeater fraction due to observational biases
- After important corrections, we discovered **a significant decrease in the average detection rate of non-repeater after 10^3 hours** for the first time
- We derived the true repeater fraction **~> 50% (2σ)** – Among **393** FRBs, **at least ~ 200** could be actually repeaters, while only **15 are** known repeaters!
- Very low typical repetition rate (**1 burst over 3,000 hrs**) + a huge population (**x10^4 what we see**) is still hidden – demanding new theories

"FRBs"

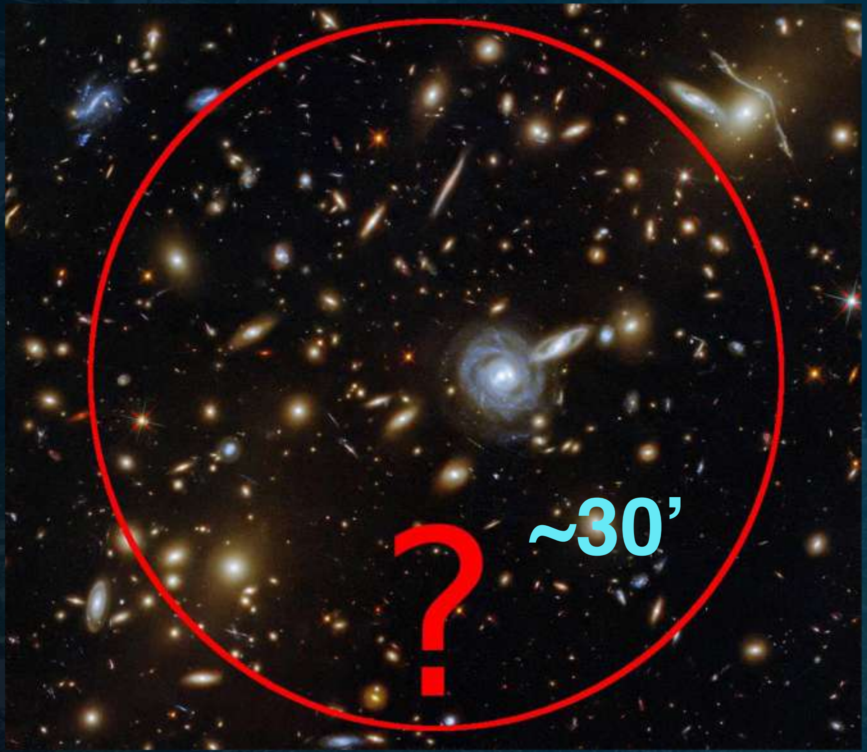
III. BURSTT science (review)

"Burstling Universe Radio Survey Telescope in Taiwan"

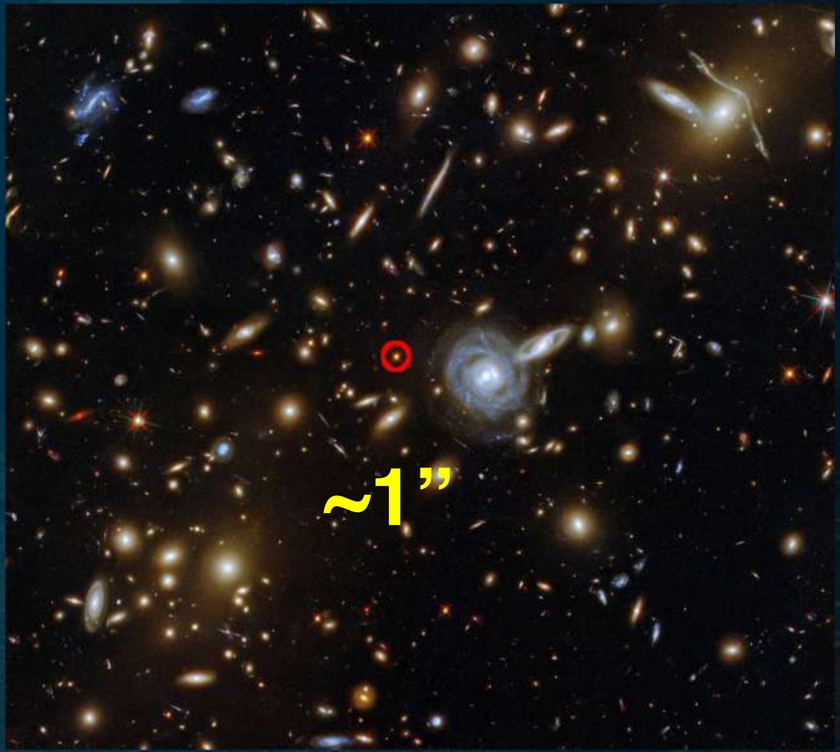
Lin, SY, et al. 2022, PASP, 134, 094106 + © Tetsuya Hashimoto

Bottlenecks vs solutions

Previous observations:
poor localization capability



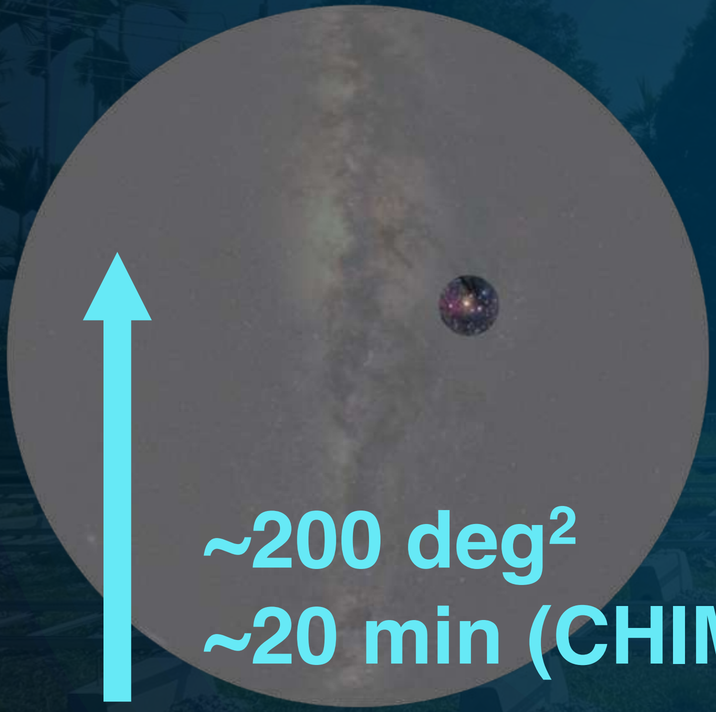
Need for
accurate localization ⇒ VLBI



Bottlenecks vs solutions

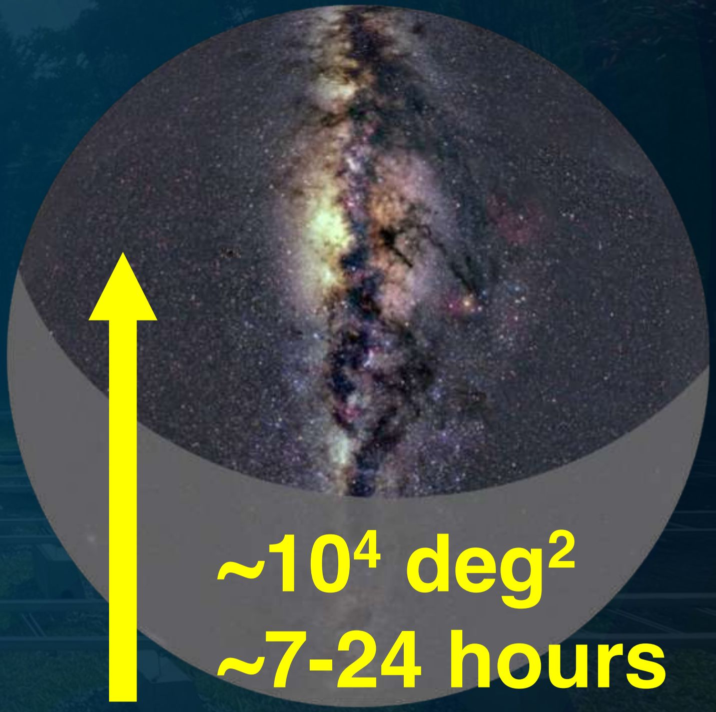
Previous observations:
large FoV + short exposure

Need for
very large FoV + long exposure



~ 200 deg^2
~ 20 min (CHIME)

No detection if an FRB happens here



$\sim 10^4$ deg^2
~ 7-24 hours

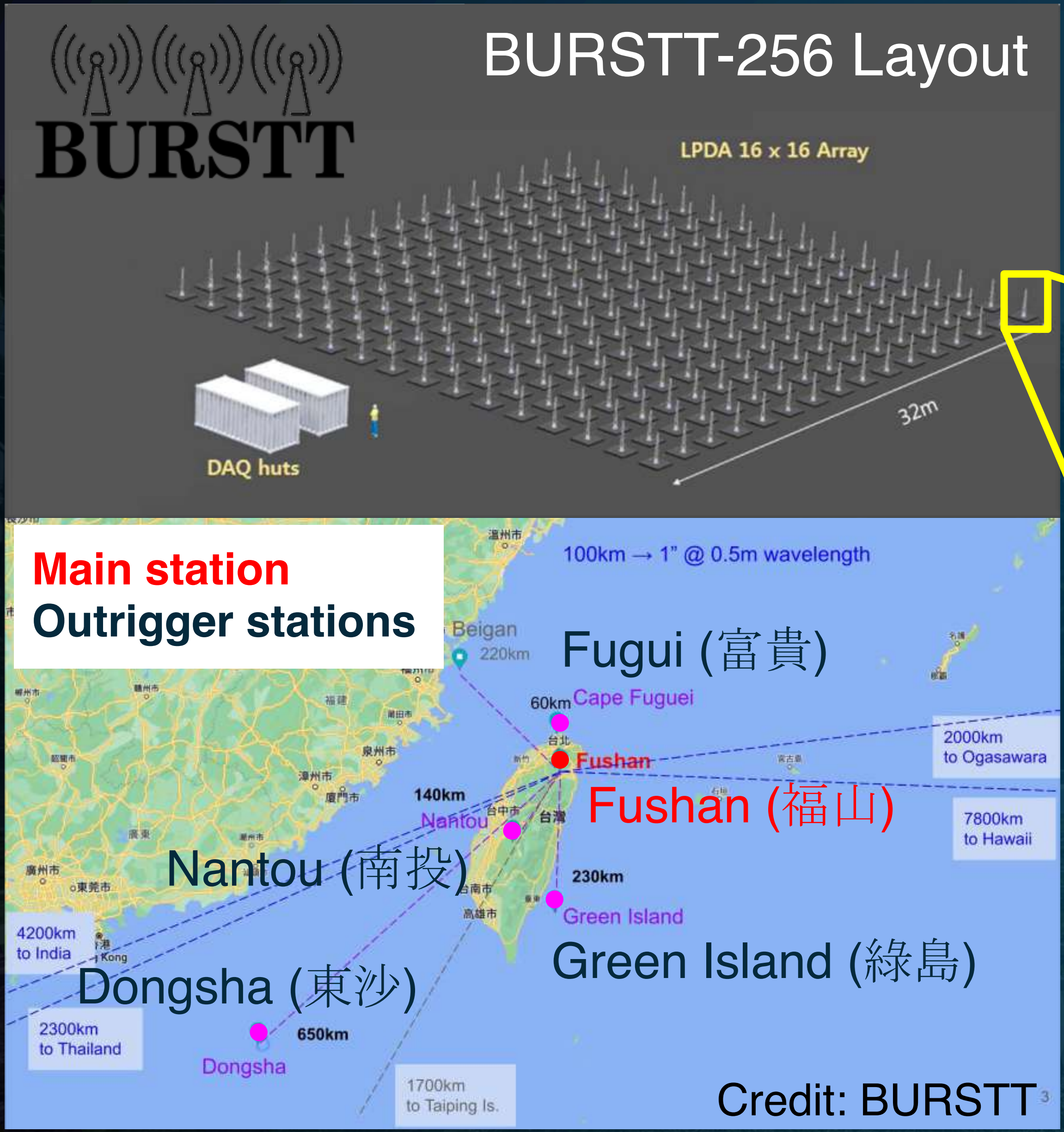
can detect

Bottlenecks vs solutions

Previous observations:
large FoV + short exposure

Need for
very large FoV + long exposure

Bustling Universe Radio Survey Telescope in Taiwan (BURSTT)



Operation begins around late 2024!

Log-periodic dipole array antenna

PI: Ue-Li Pen (ASIAA)

Nantou (南投) outrigger station (Feb-Mar 2024)


Now finishing the deployment of all 64 (16x4) dipole antennas

Publications of the Astronomical Society of the Pacific, 134:094106 (14pp), 2022 September https://doi.org/10.1088/1538-3873/ac8f71

CrossMark

BURSTT: Bustling Universe Radio Survey Telescope in Taiwan

Hsiu-Hsien Lin[1,2], Kai-yang Lin[1], Chao-Te Li[1], Yao-Huan Tseng[1], Homin Jiang[1], Jen-Hung Wang[1], Jen-Chieh Cheng[1], Ue-Li Pen[1,2,3,4,5], Ming-Tang Chen[1,6], Pisin Chen[7,8], Yaocheng Chen[7,8], Tomotsugu Goto[9], Tetsuya Hashimoto[10], Yuh-Jing Hwang[1], Sun-Kun King[1], Derek Kubo[6], Chung-Yun Kuo[7,8], Adam Mills[6], Jiwoo Nam[7,8], Peter Oshiro[6], Chang-Shao Shen[1], Hsien-Chun Tseng[1], Shih-Hao Wang[7,8], Vigo Feng-Shun Wu[1], Geoffrey Bower[6], Shu-Hao Chang[1], Pai-An Chen[1], Ying-Chih Chen[7,8], Yi-Kuan Chiang[1], Anatoli Fedynitch[11], Nina Gusinskaia[2,4], Simon C.-C. Ho[9], Tiger Y.-Y. Hsiao[9,12], Chin-Ping Hu[13], Yau De Huang[1], José Miguel Jáuregui García[2], Seong Jin Kim[9], Cheng-Yu Kuo[14], Decmend Fang-Jie Ling[15], Alvina Y. L. On[9,10,16], Jeffrey B. Peterson[17], Bjorn Jasper R. Raquel[10,18], Shih-Chieh Su[7,8], Yuri Uno[10], Cossas K.-W. Wu[9], Shotaro Yamasaki[10], and Hong-Ming Zhu[2]

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[17] Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh PA 15213 USA
[18] Department of Earth and Space Sciences, Rizal Technological University, Boni Avenue, Mandaluyong, 1550 Metro Manila, Philippines
Received 2022 June 17; accepted 2022 September 5; published 2022 September 26

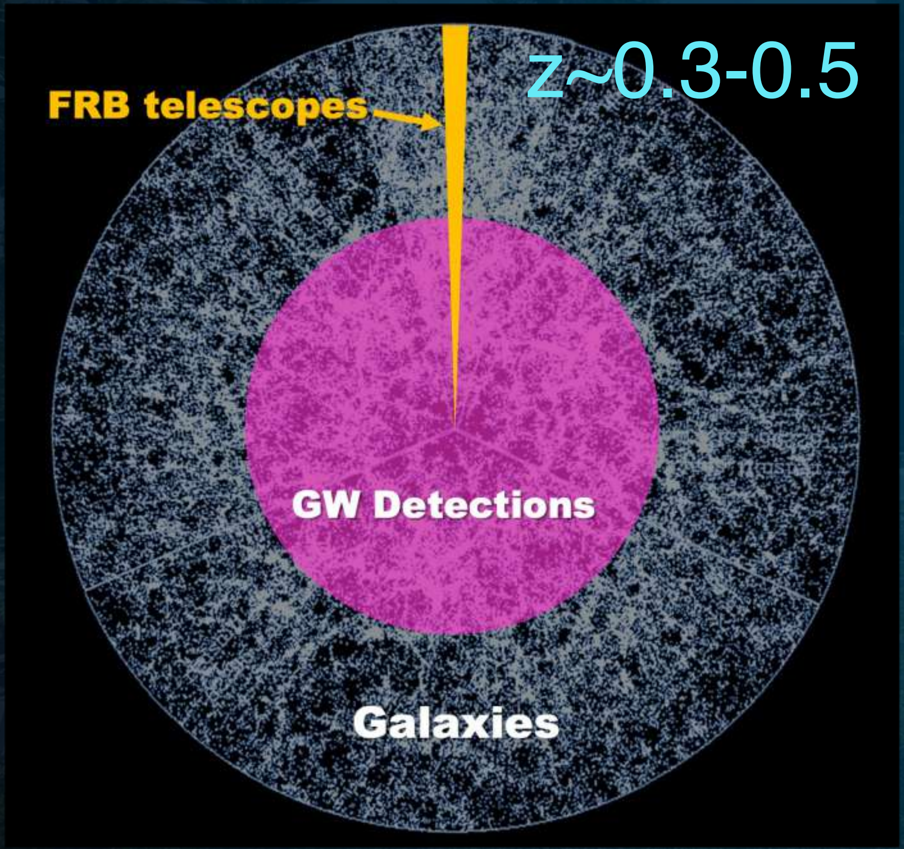
BURSTT
Collaboration

See **Lin et al. 2022**
for basic design
and its science

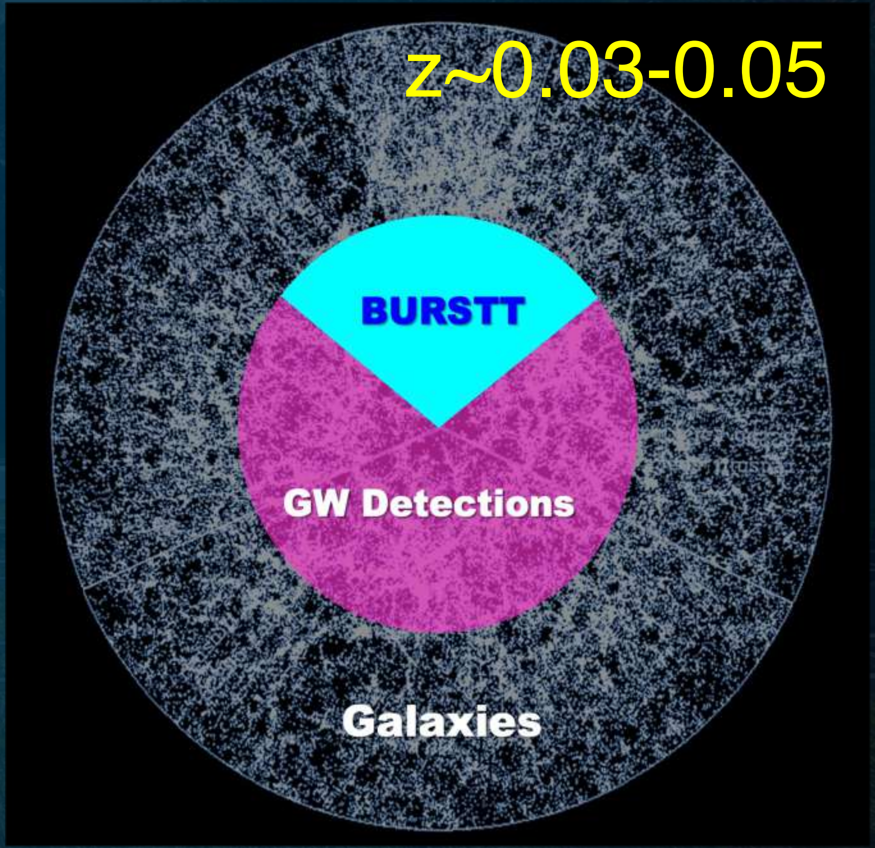
~> 50 members
(mostly TW)

Bottlenecks vs solutions

Previous observations:
mismatch with multi-messengers



BURSTT:
synergy with multi-messengers



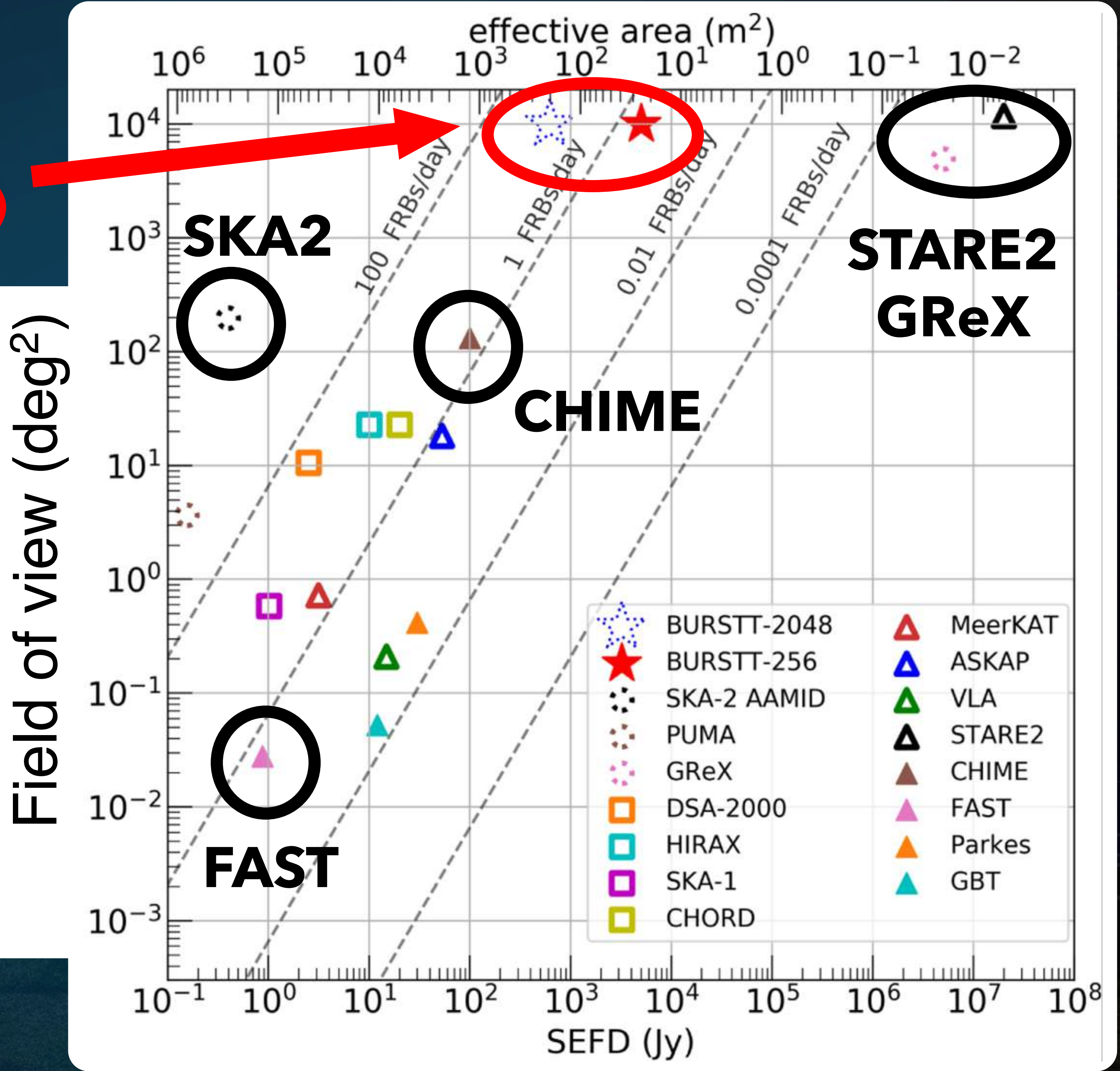
BURSTT

(~100 FRBs yr^{-1})

The Main Properties of the BURSTT

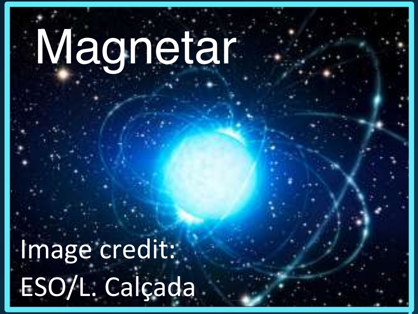
Quantity	Value	
Project	BURSTT-256	BURSTT-2048
SEFD	~5000 Jy	~600 Jy
Effective area	40–200 m^2	320–1600 m^2
Number of antennas (main station)	256	2048
(outrigger stations)	64	
Polarization	single	
E-W FoV	~100°	
N-S FoV	~100°	
Daily exposure time	24 hr (North pole) ~10 hr (45°) ~7 hr (Equator)	
Frequency range	300–800 MHz	TBD
Bandwidth	400 MHz	⩾ 400 MHz
Number of frequency channels	1024	TBD
E-W baseline	~8000 km (Northern Taiwan to Hawaii)	
N-S baseline	~300 km (Northern to Southern Taiwan)	

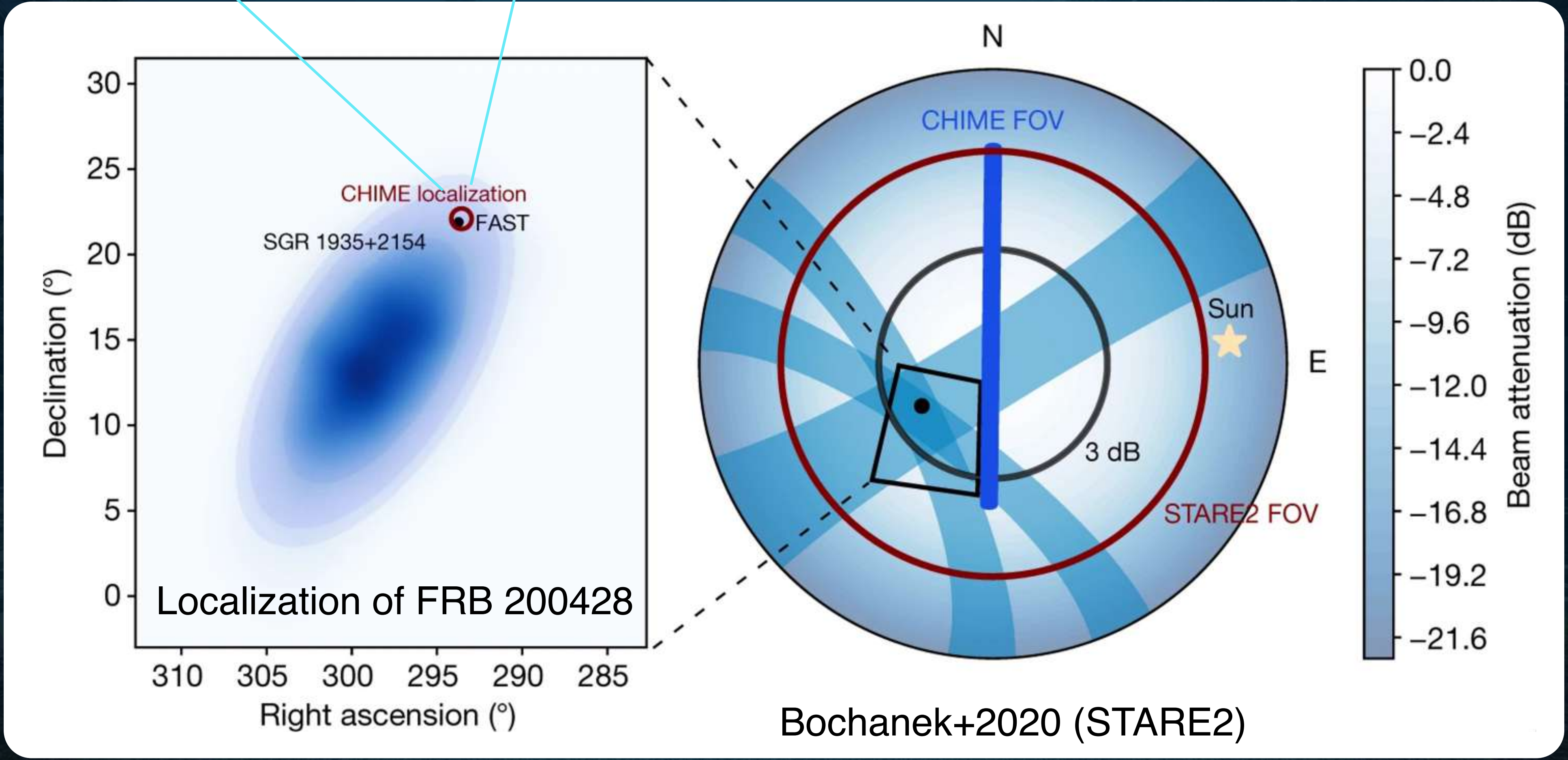
Low freq.



Lin et al. 2022

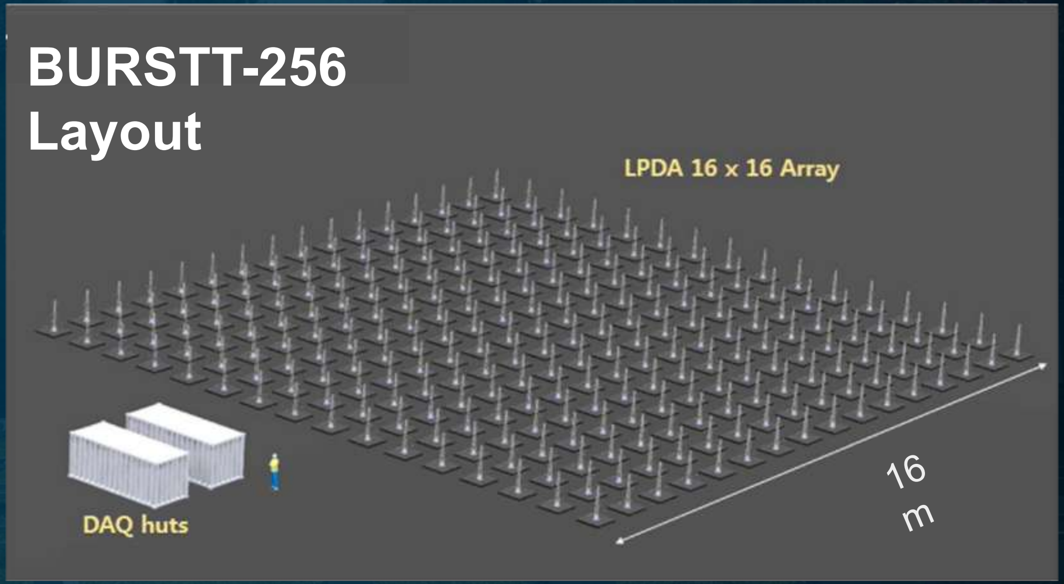
1. Direct identification of FRB progenitors





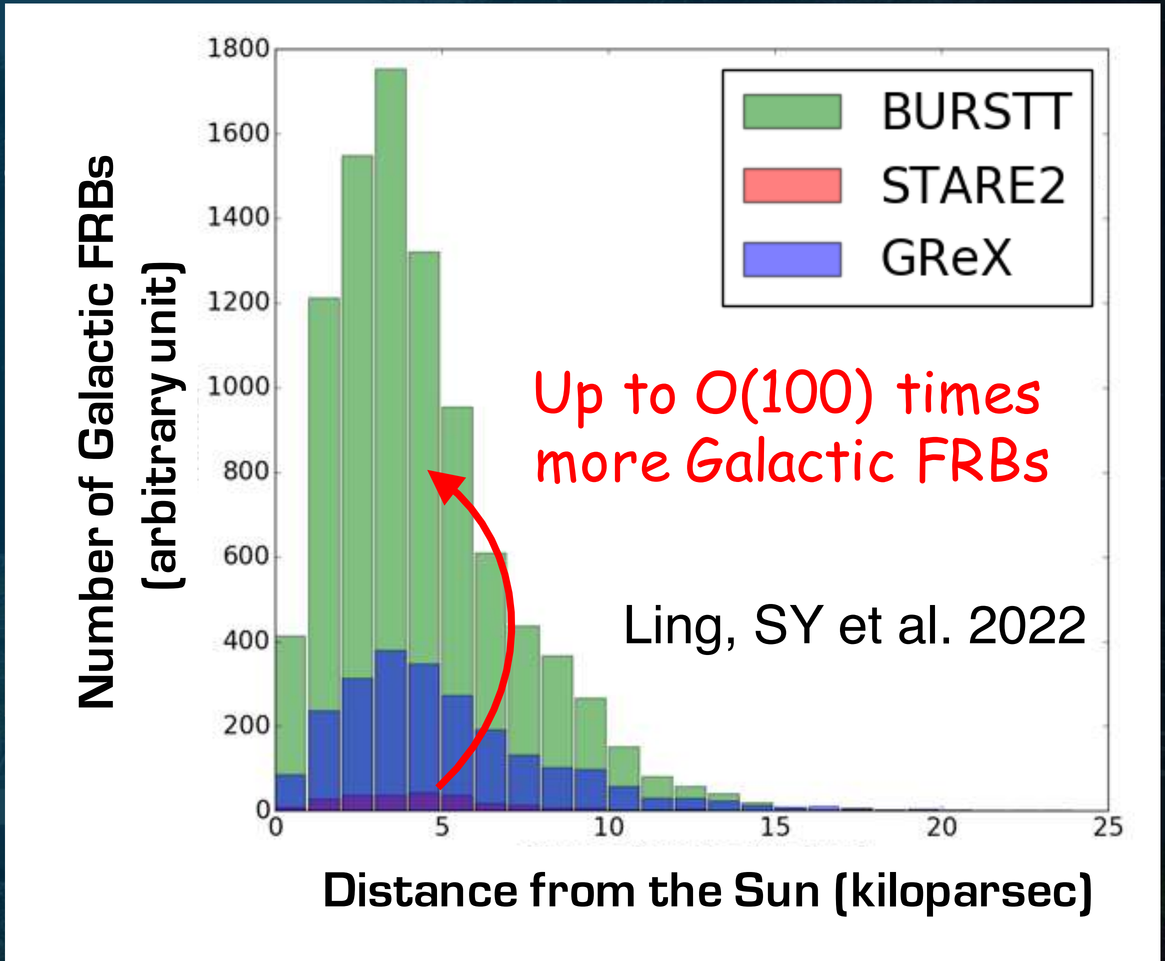
1. Direct identification of FRB progenitors

BURSTT

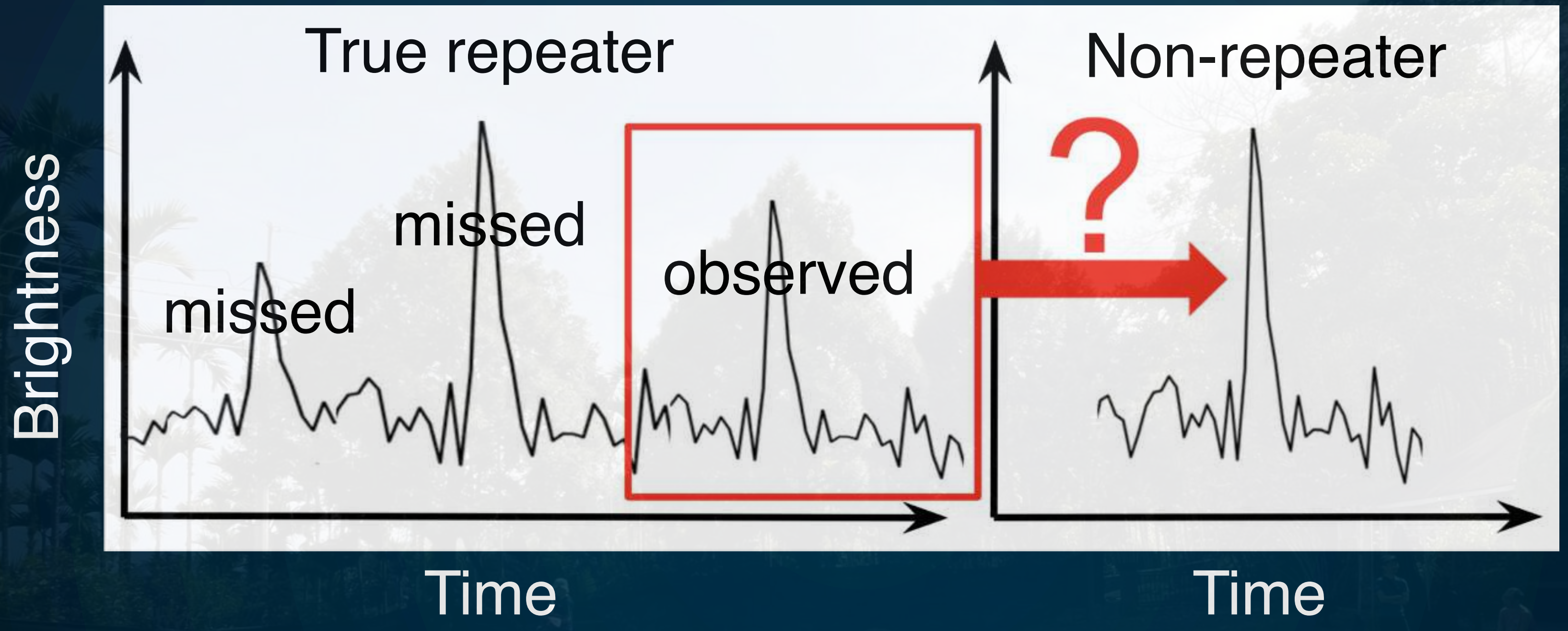


→ increase progenitor ids.

1. Direct identification of FRB progenitors



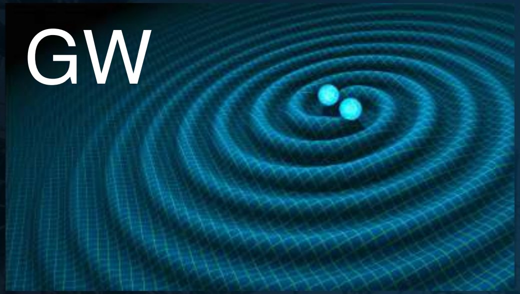
2. Complete census of nearby FRBs



Determination of true repeater fraction (cf. SY+2024)
→ Long-monitoring high-cadence observations needed

BURSTT will address w/ 25 times larger (longer) FoV (obs. time) than CHIME

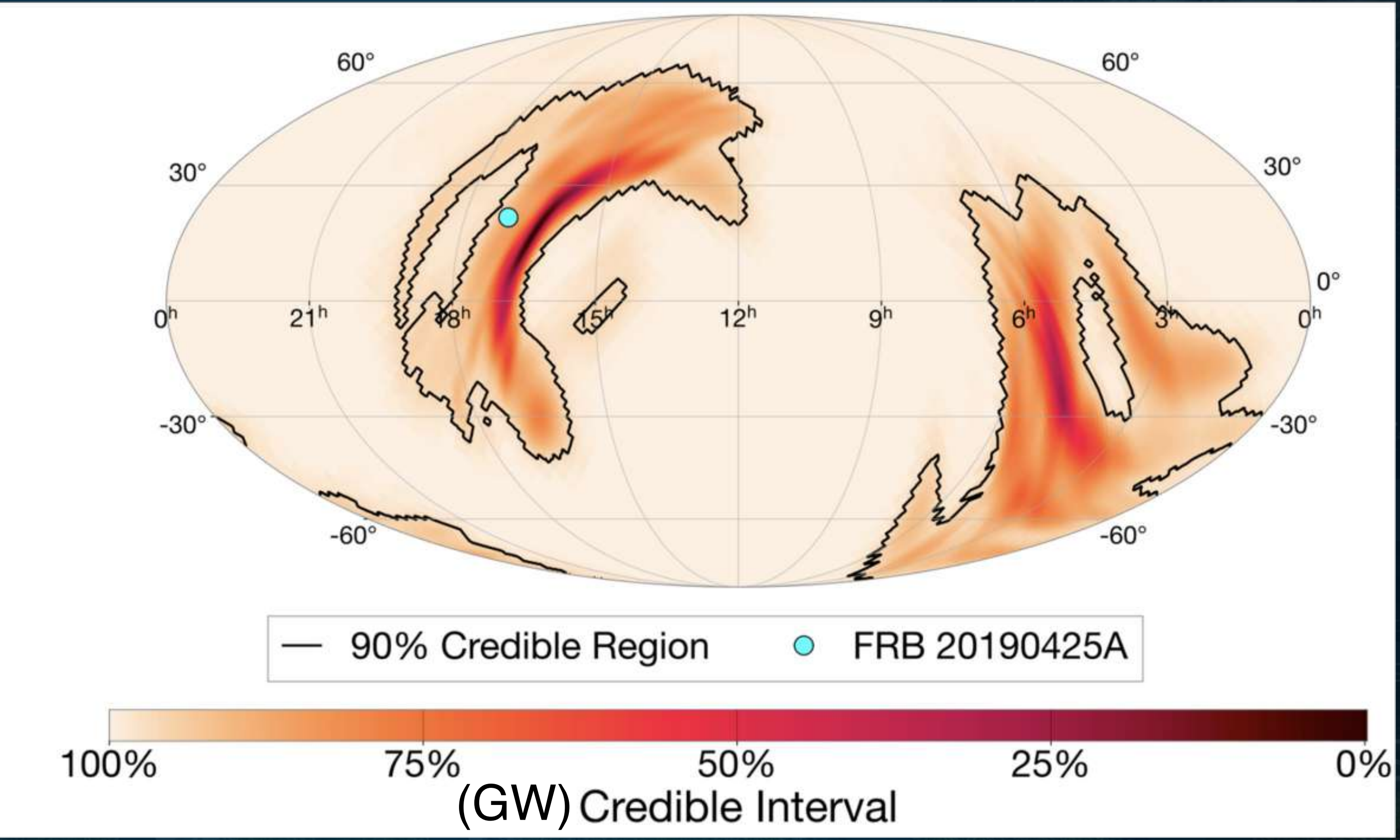
3.1 FRB counterparts - multi-messengers



+ ?

cf. Totani 2013;
Wang+2016;
SY+2018...

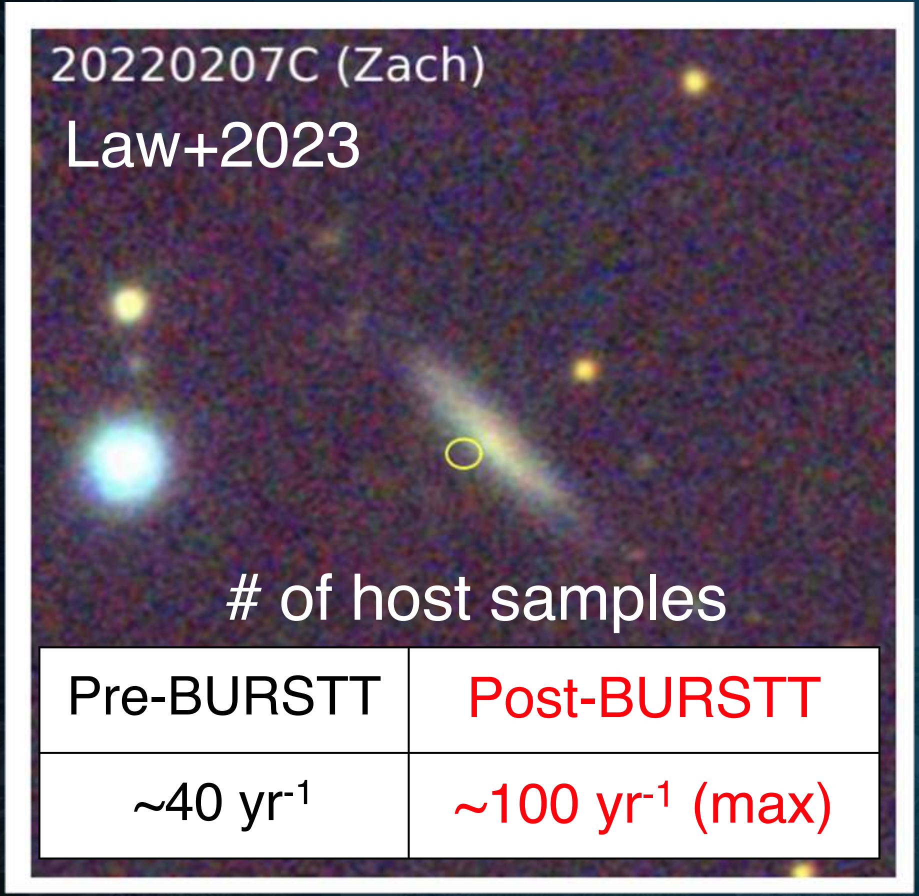
Moroianu et al. 2023, *Nature Astronomy*



(See also Radice et al. 2024 for discussion on association)

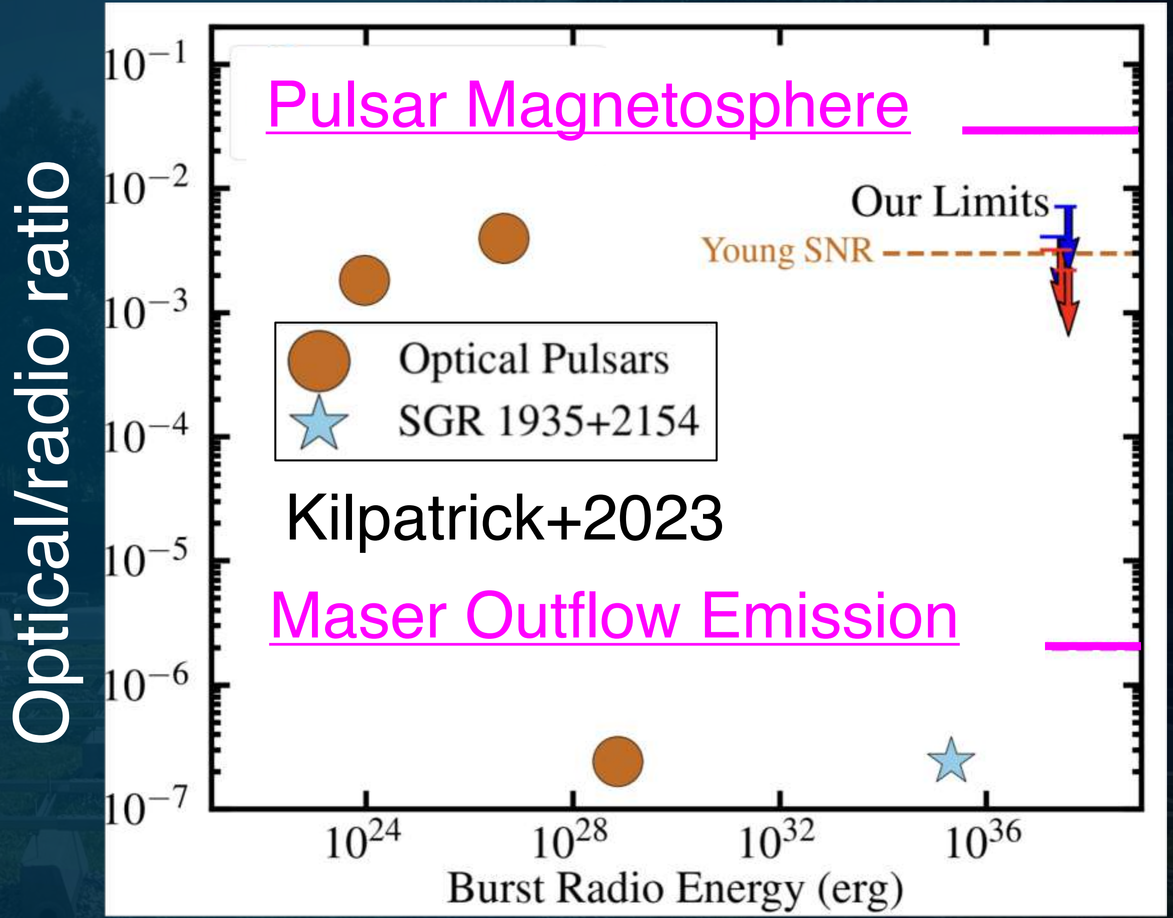
3.2 FRB counterparts - multi-wavelengths

Host identification



Pre-BURSTT	Post-BURSTT
~40 yr^{-1}	~100 yr^{-1} (max)

Prompt counterparts



Host environments + Progenitor types + Emission mechanisms

FRB conference in Yilan (宜蘭) 24-27 June 2024

Invited Speakers

Di Li (NAOC)

Kai-Yang Lin (ASIAA)

Nobuyuki Sakai (NARIT)

Souichiro Morisaki (University of Tokyo)

Teruaki Enoto (Kyoto University)

Tomonori Totani (University of Tokyo)

Ting-Wen Lan (NTU)

Yuanpei Yang (Yunnan University)

Zamri Zainal Abidin (University Malaya)

and more…

“Magnetars”

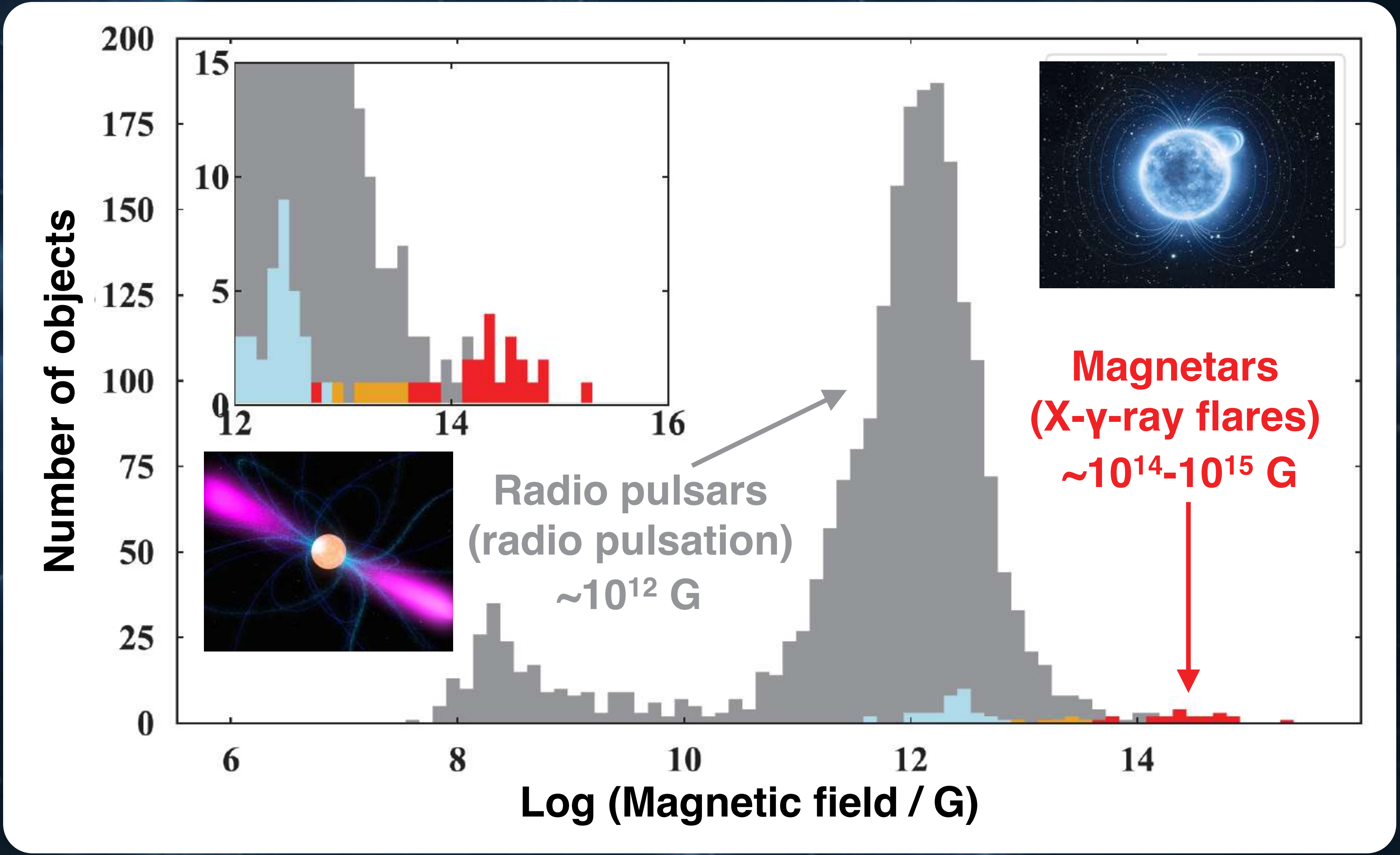
II. Magnetar bursts stochasticity

“Quantiying the chaos and randomness in magnetar bursts”

SY, Gogus, Hashimoto 2023, MNRAS, 528, L133

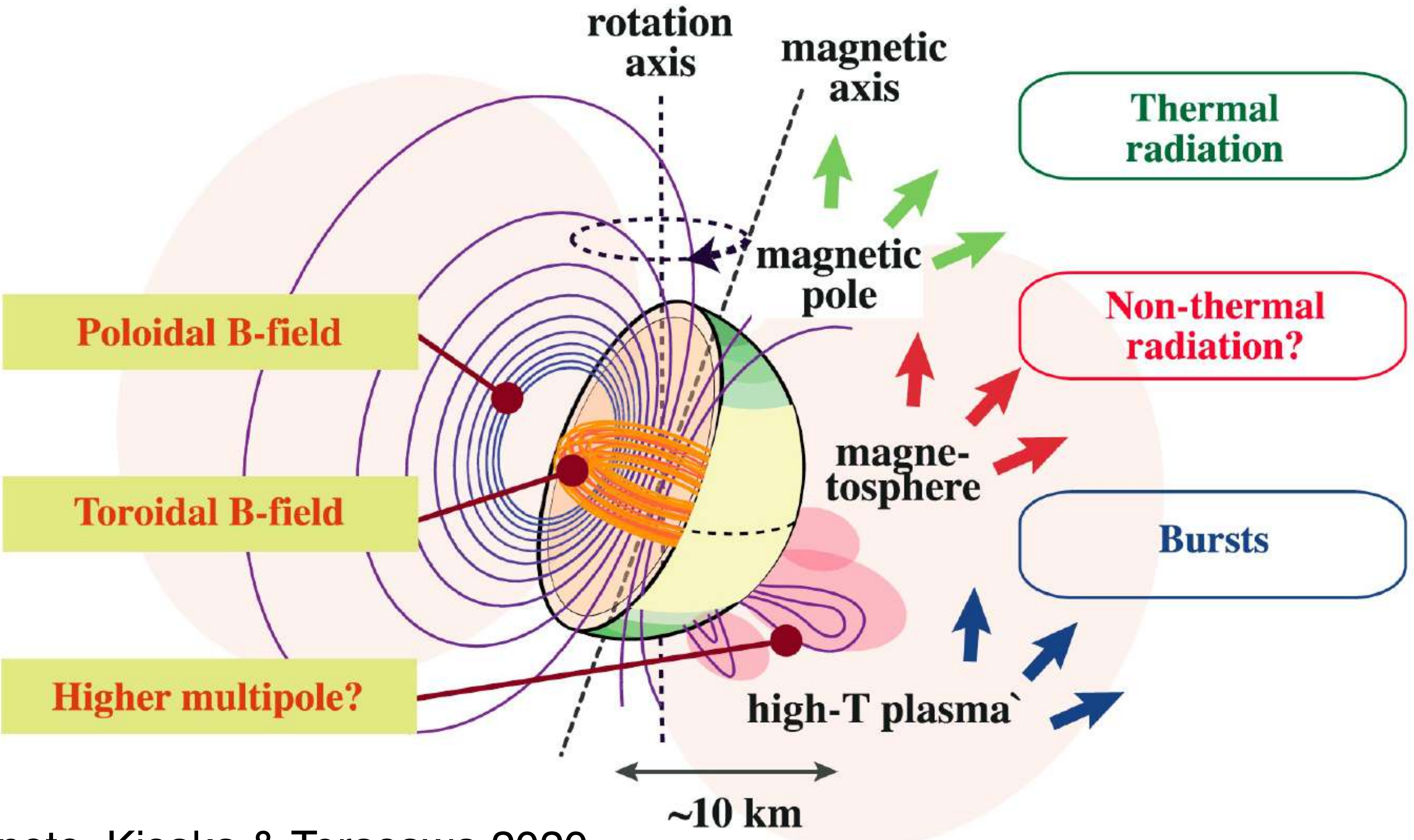
Credit: Carl Knox/OzGrav

Magnetar = Highly Magnetized Neutron Star (和田さんトーク)



Enoto, Kisaka & Terasawa 2020

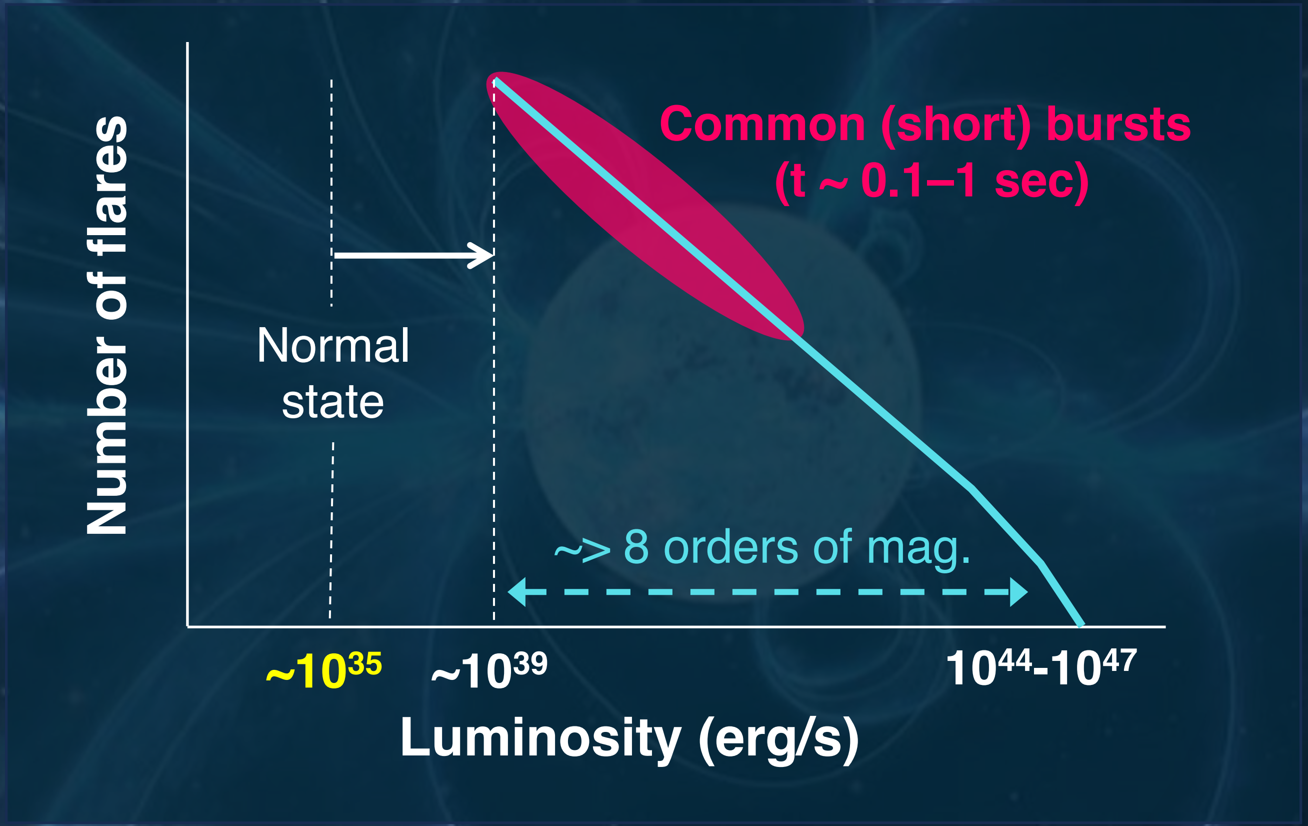
Magnetar Radiations



Enoto, Kisaka & Terasawa 2020

Bursts/Flares from Magnetars

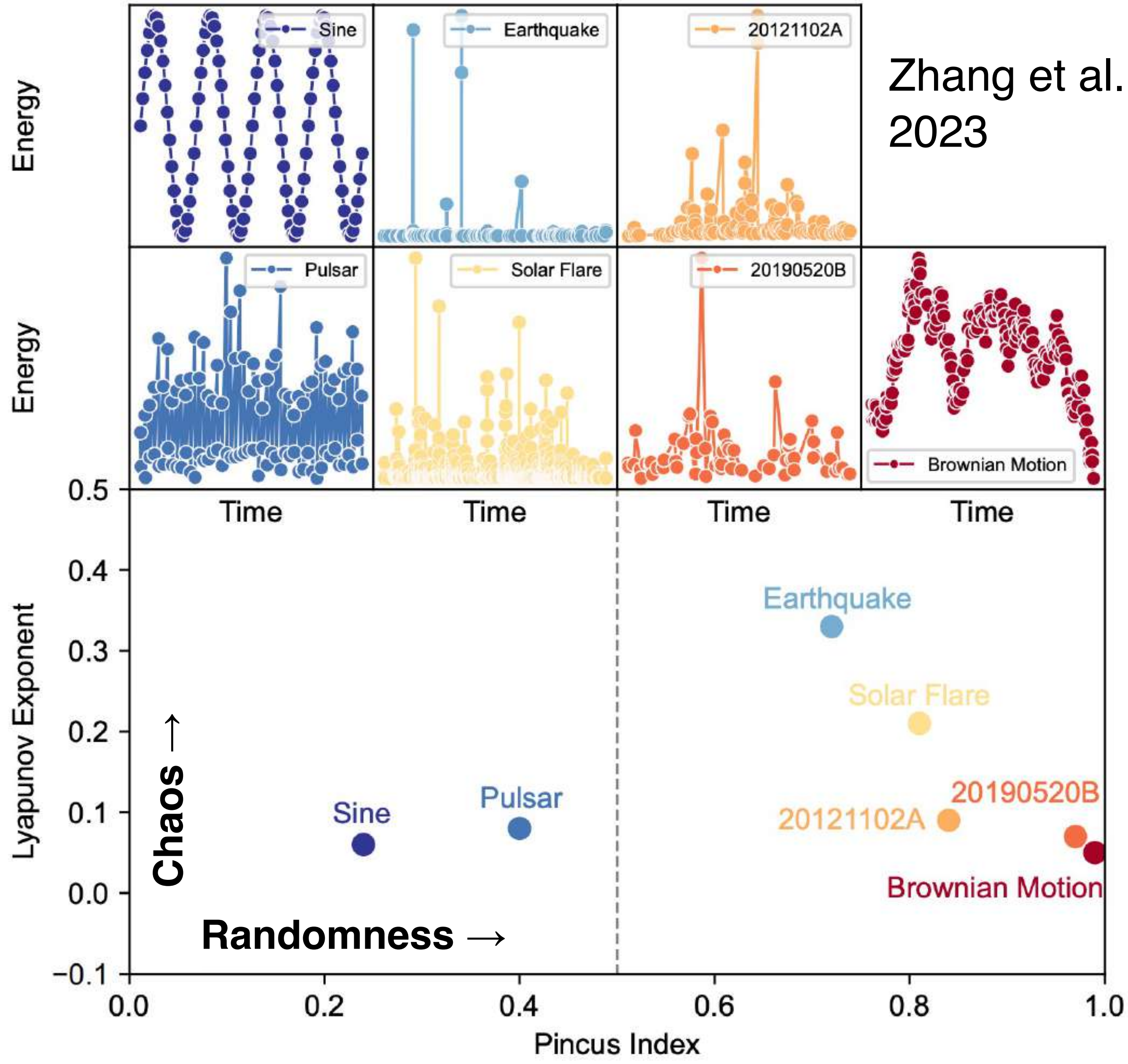
(see Kaspi & Beloborodov 17; Enoto+20 for recent reviews)



- **Continuous luminosity distribution** (e.g. Cheng+96; Gogus+01; Nakagawa+07)
- **Likely related to FRBs** – FRB 200428 from SGR 1935+2154 (e.g. CHIME/FRB+20; Bochanek+20)

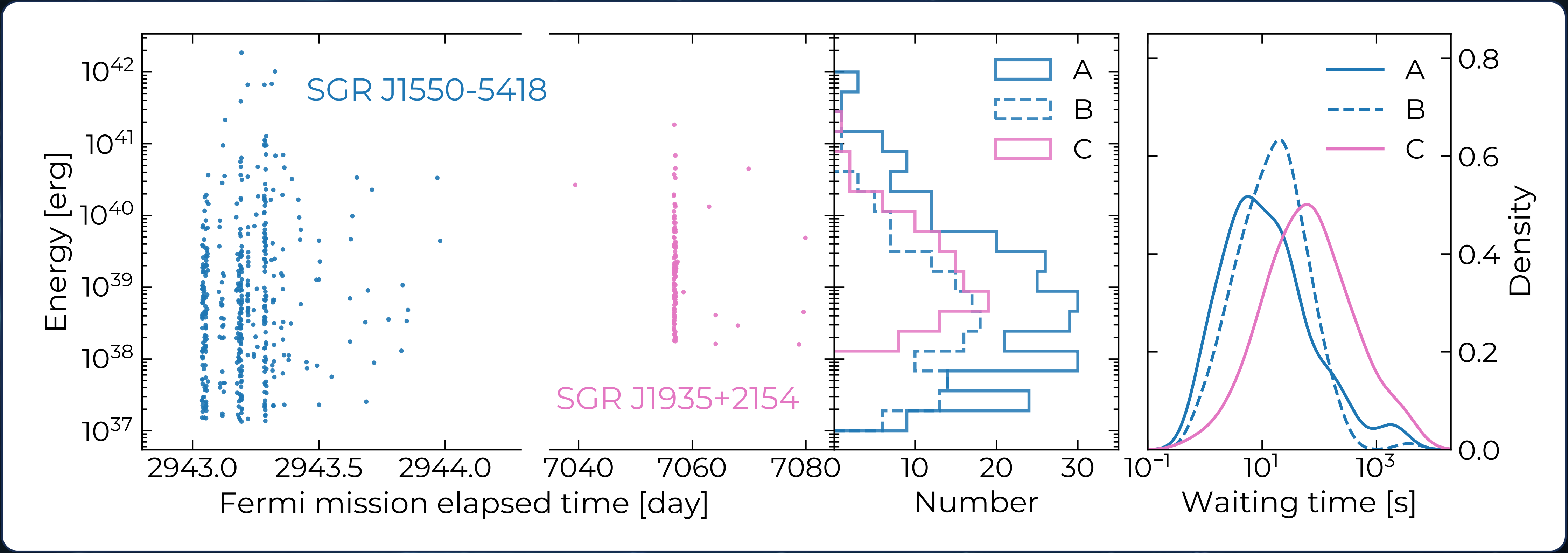
Stochasticity study of FRBs

- A new method for a dynamical analysis of active FRBs' behaviors in the time-energy domain proposed by Zhang et al. 2023
- Randomness (x-axis) & chaos (y-axis)
- Comparing earthquakes and Solar flares
- Magnetars are the leading candidate of FRB progenitors
- Where are bursts from magnetars situated on chaos–randomness plane?



Zhang et al. 2023

Burst time series from active magnetars



- Categorize all short bursts into sets of time series corresponding to each uninterrupted observing session less than 50 mins (~a half of Fermi's orbital window)

- Select two data sets A (280 bursts) and B (145 bursts) for **SGR J1550–5418** and a single data set C (105 bursts) for **SGR J1935+2154**

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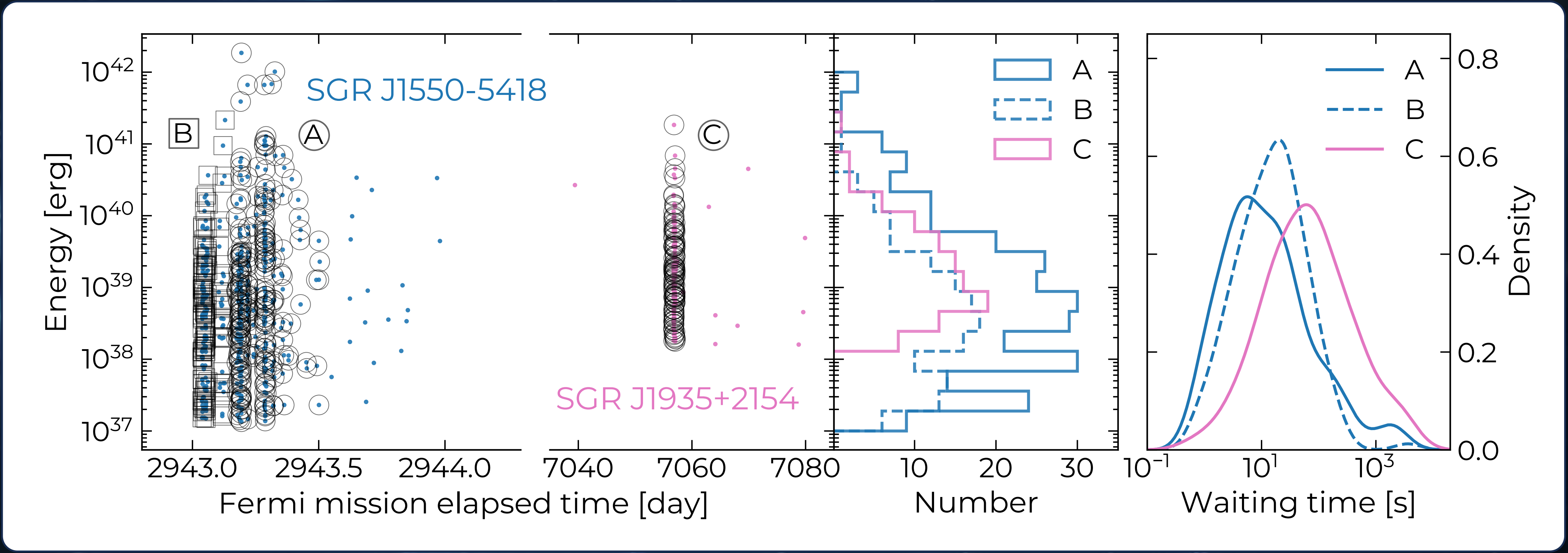

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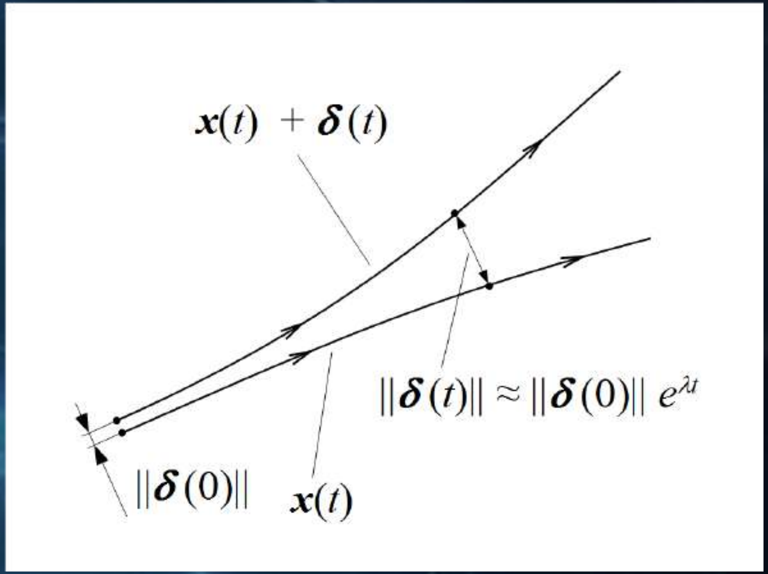
Quantifying chaos and randomness

- **Lyapunov Exponent** (chaos): dependence on initial cond.

$$\lambda(x_0) = \lim_{n\to\infty} \frac{1}{n} \sum_{i=0}^{n-1} \ln|f'(x_i)|, \quad x_{i+1} = f(x_i)$$

Positive Lyapunov Exponent = signature of chaos



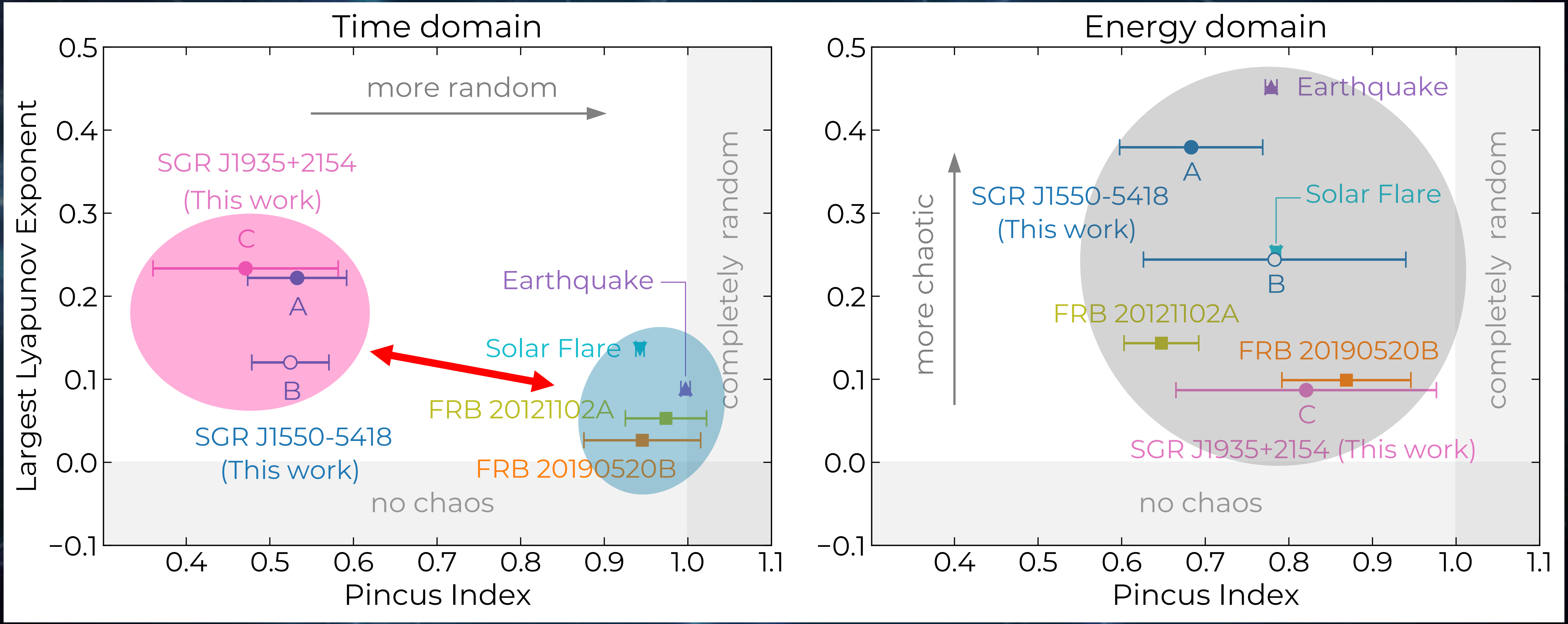
- **Maximum Pincus Index** (randomness)

$$\mathcal{PI} = \frac{\mathrm{ApEn}_{\max}(m; \mathbf{x}_{\mathrm{original}})}{\mathrm{ApEn}_{\max}(m; \mathbf{x}_{\mathrm{shuffled}})}, \quad \mathrm{ApEn}_{\max}(m; \mathbf{x}) = \max\left(-\frac{1}{N-m} \sum_{i=1}^{N-m} \ln \left. \frac{\sum_{j=1}^{n} d(\mathbf{x}_i^m, \mathbf{x}_j^m) < r}{N-m} \right|_m^{m+1} \right)$$

Likelihood that two points that are close in *m*-dim space, remain close in (*m + 1*)-dim space

- Consider differential sequences of time $\Delta T_i = T_{i+1} - T_i$ and energy $\Delta E_i = E_{i+1} - E_i$

Magnetar bursts on “chaos-randomness” plane

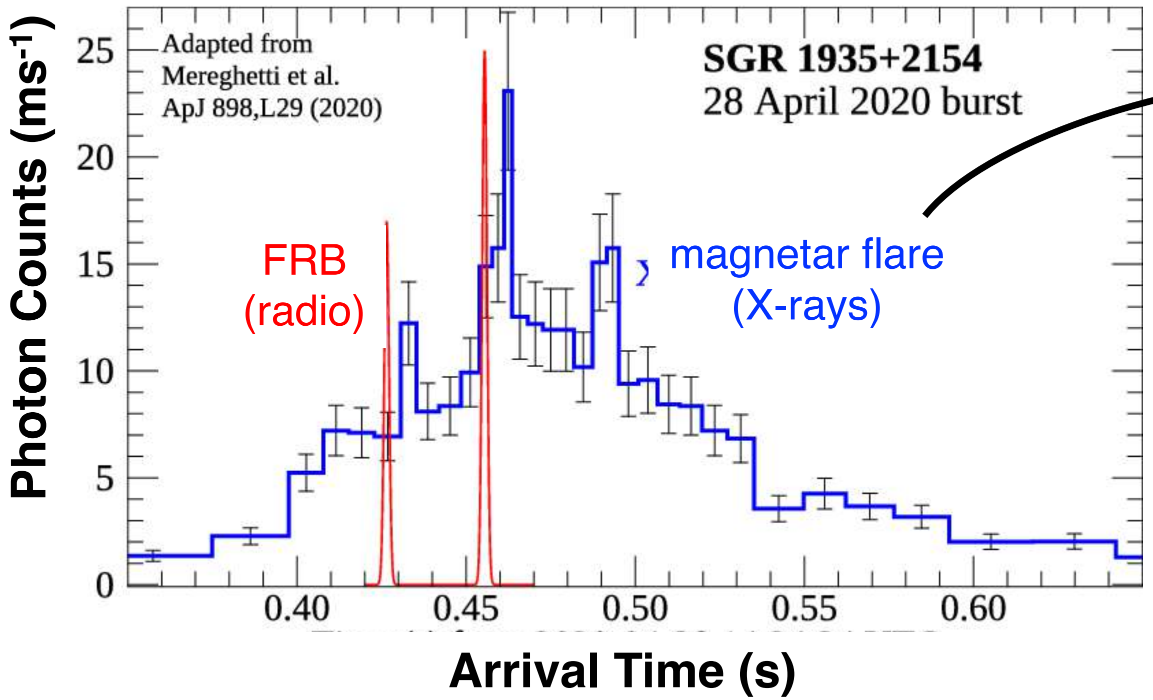


A distinct separation between magnetar bursts and the others

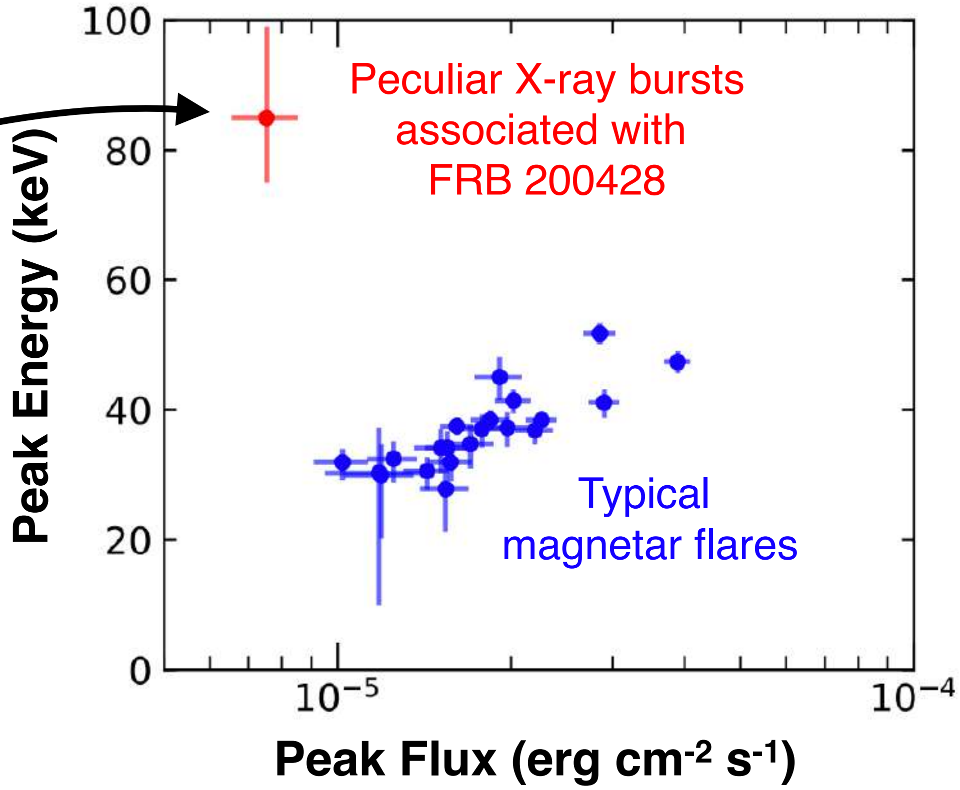
Consistent with each other due to large errors

Are FRBs only associated with special magnetar bursts?

Meregetti et al. 2020



Ridnaia et al. 2020



FRBs may primarily be linked to special magnetar bursts like peculiar X-ray bursts from SGR J1935+2154 observed simultaneously with Galactic FRB 200428

Take aways

I. FRB population are consistent with 100% repeating sources with 1 burst in 3000 hours

II. Conventional magnetar bursts are not consistent with FRBs in arrival time behavior

III. The baryon fluctuation in the intergalactic medium is imprinted in the DM of FRBs

IV. BURSTT has unique FRB samples! No such telescopes so far!