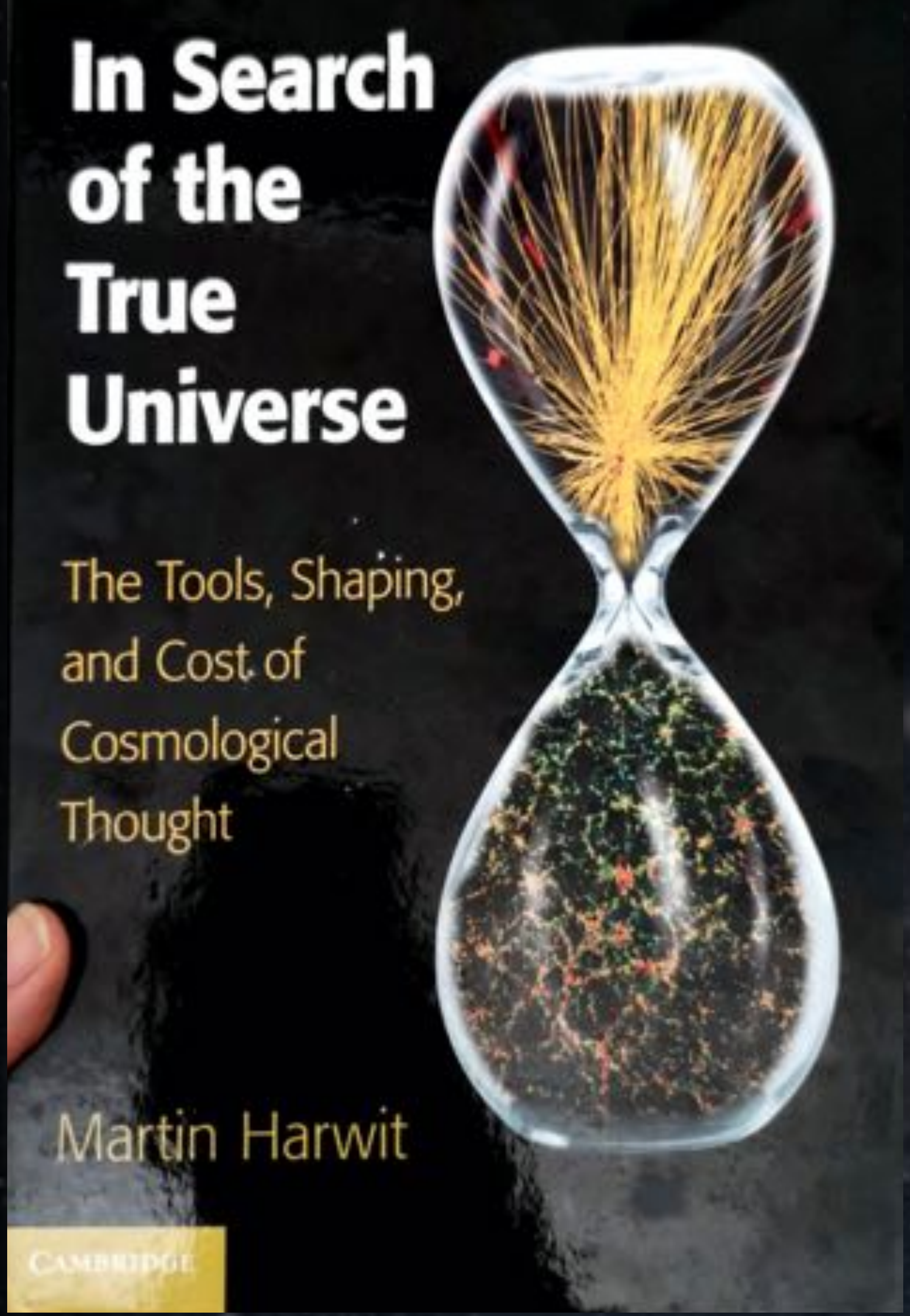
Five-hundred-meter **A**perture **S**pherical radio **T**elescope **FAST**

Bridging the centuries

- *Faraday style*

NAOC 中国科学院国家天文台
NATIONAL ASTRONOMICAL OBSERVATORIES, CHINESE ACADEMY OF SCIENCES

FAST



Looking Back

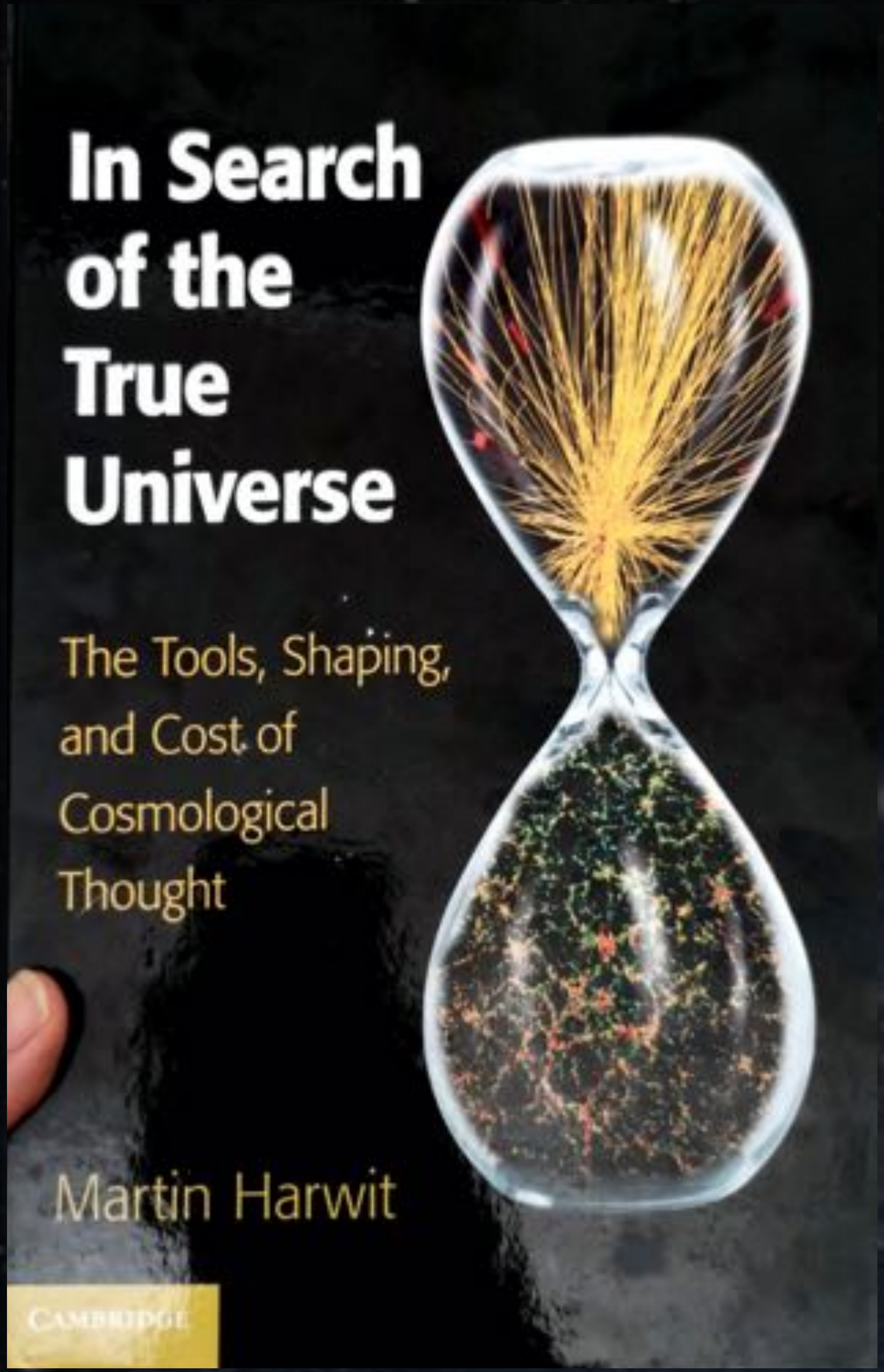
Between the end of World War II and the early 1970s, astronomy was enriched through the discovery of some 14 new and unanticipated major phenomena listed below. Only two of the discoveries resulted from observations in the optical regime. Both could well have been made with instrumentation available before World War II, or with marginally improved techniques. These two involved:

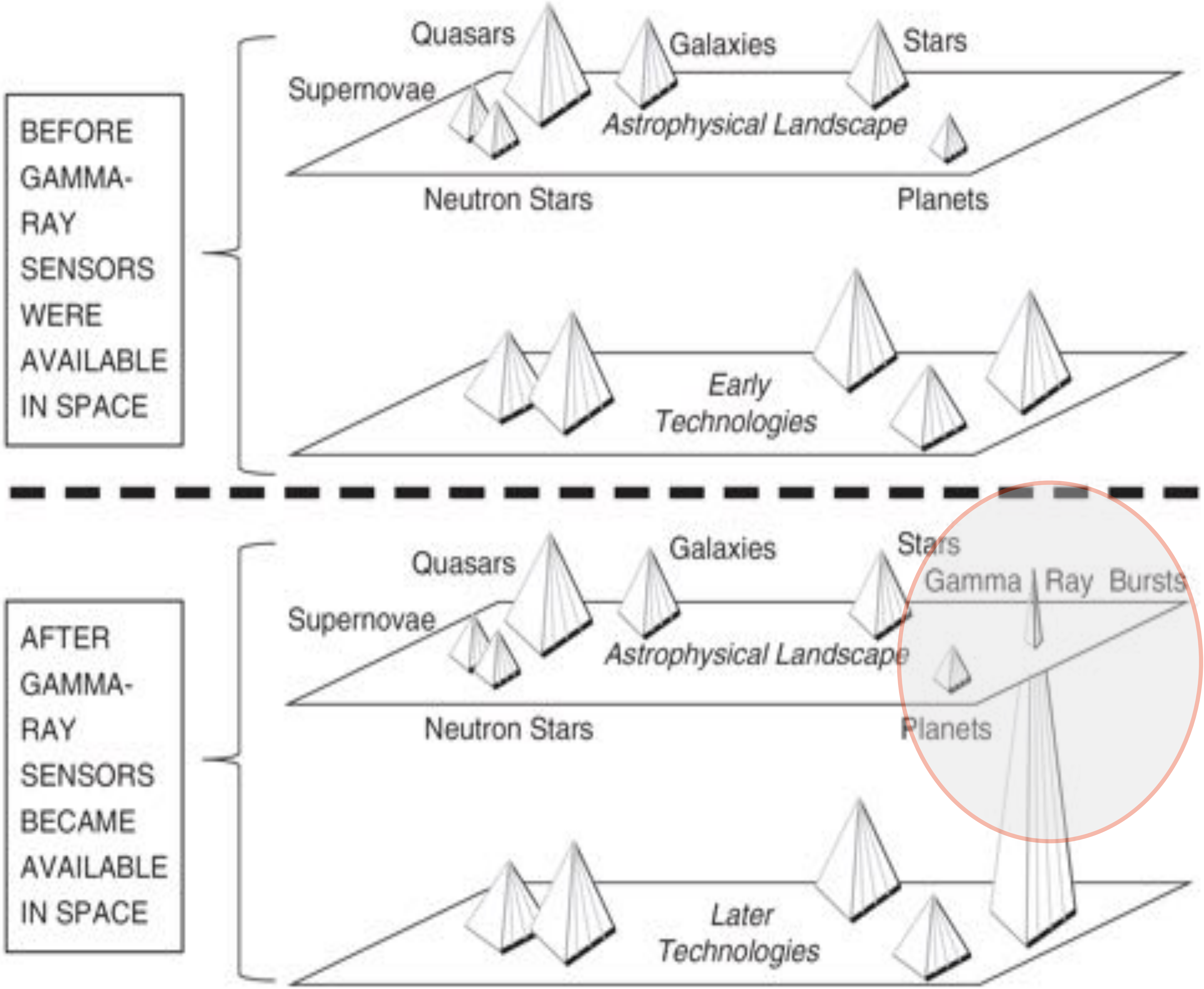
Magnetic Variable stars, 1947, and
Flare stars, 1949

But twelve other major discoveries became possible only through the use of techniques and instrumentation initially designed for military purposes during World War II or the Cold War. This list of discoveries included:

Radio galaxies, 1946–54
X-ray stars, 1962
Quasars, 1963
The Cosmic microwave background, 1965
Infrared stars, 1965
X-ray galaxies, 1966
Cosmic masers, 1967
Pulsars, 1967
Superluminal radio sources, 1971
Infrared galaxies, 1970–72
Interstellar magnetic fields, 1972
Gamma-ray bursts, 1973

《In Search of the True Universe》
Martin Harwit





Martin Harwit


Arecibo
Puerto Rico

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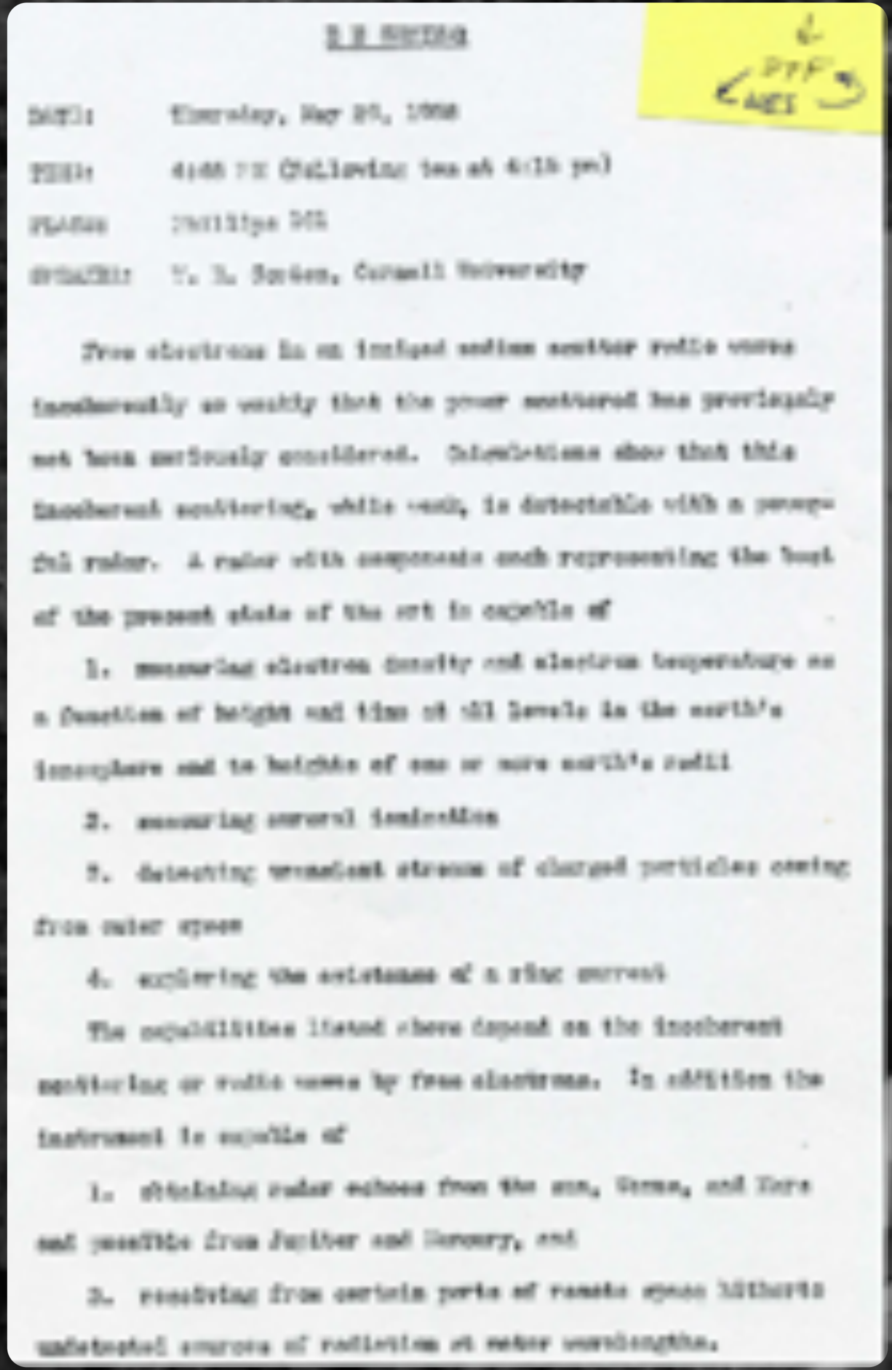
美丽的“错误”

1958


DATE: Thursday, May 29, 1958

PLACE: Phillips

SPEAKER: W. E. Gordon, Cornell University

Free electrons in an ionized medium scatter radio waves incoherently so weakly that the power scattered has previously not been seriously considered. Calculations show that this incoherent scattering, while weak, is detectable with a powerful radar. A radar with components each representing the best of the present state of the art is capable of

1. measuring electron density and electron temperature as a function of height and time at all levels in the earth's ionosphere and to heights of one or more earth's radii
2. measuring auroral ionization
3. detecting transient streams of charged particles coming from outer space
4. exploring the existence of a ring current

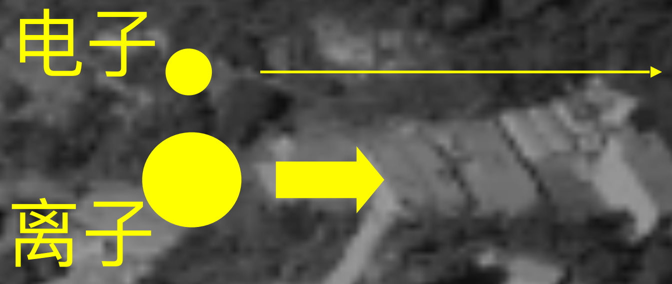
The capabilities listed above depend on the incoherent scattering of radio waves by free electrons. In addition the instrument is capable of

1. obtaining radar echoes from the sun, Venus, and Mars and possibly from Jupiter and Mercury, and
2. resolving from certain parts of remote space hitherto undetected sources of radiation at meter wavelengths.

报告人： William E. Gordon

地点： 康奈尔大学电子工程系

时间： May 29, **1958**



Scatter from individual electrons

=> Echo bandwidth of 100s of kHz=》 需要**数百米级天线！**

Ken Bowles （美国国家标准局）

– bandwidth reflected ion velocities not electron velocities.

Gordon： 1958 URSI meeting

公布了修正的结果**只需几十米天线**。但是康奈尔大学和

ARPA–(Advanced Research Projects Agency)

依然决定资助**超大型**望远镜！

1957-1958

大国博弈

苏联
Sputnik
1957.10.4

1957.12.16
美国海军
首次卫星实验

January 31, 1958

JPL
Jet Propulsion Laboratory
California Institute of Technology

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“和平”的太空竞赛 1946-1958

“This is the President of the United States speaking. Through the marvels of scientific advance, my voice is coming to you from a satellite circling in outer space. My message is a simple one. Though this unique means, I convey to you and all mankind, America’s wish for peace on earth and good will to men everywhere.”

National Aeronautics and Space Agency

July, 1958; 美国政府通过建立“航空航天局”

航天计划从**ARPA**转向**NASA**

- Internal conflicts of capitalism inevitably generate wars.
- Much depends on health and vigor of our own society.

（赢得冷战）我们必须规划和展现一个远比过去更为正面的和有建设性的世界蓝图。。。

乔治-凯南“长电报”-1946

“Long Telegram” 1946

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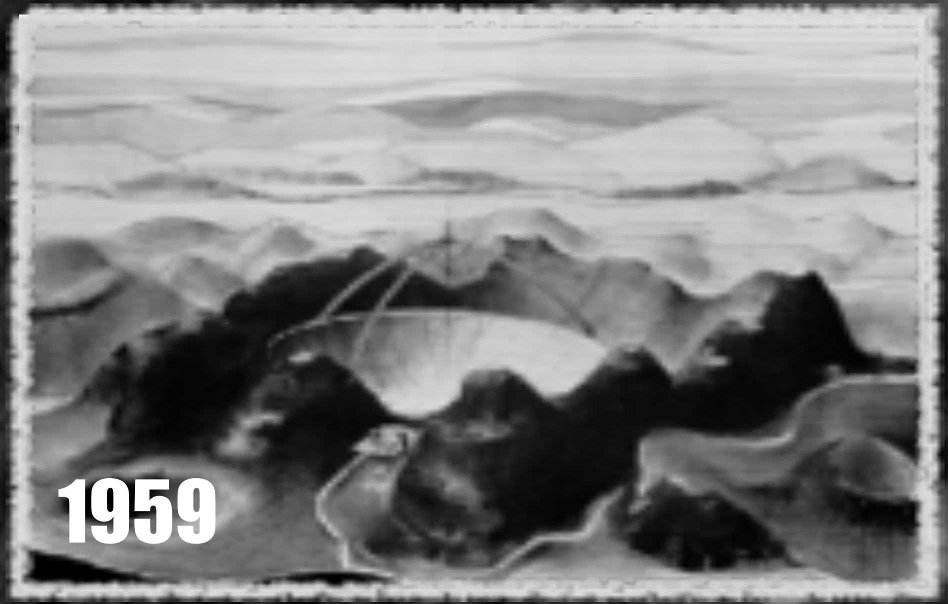
Arecibo: 巨人的梦想

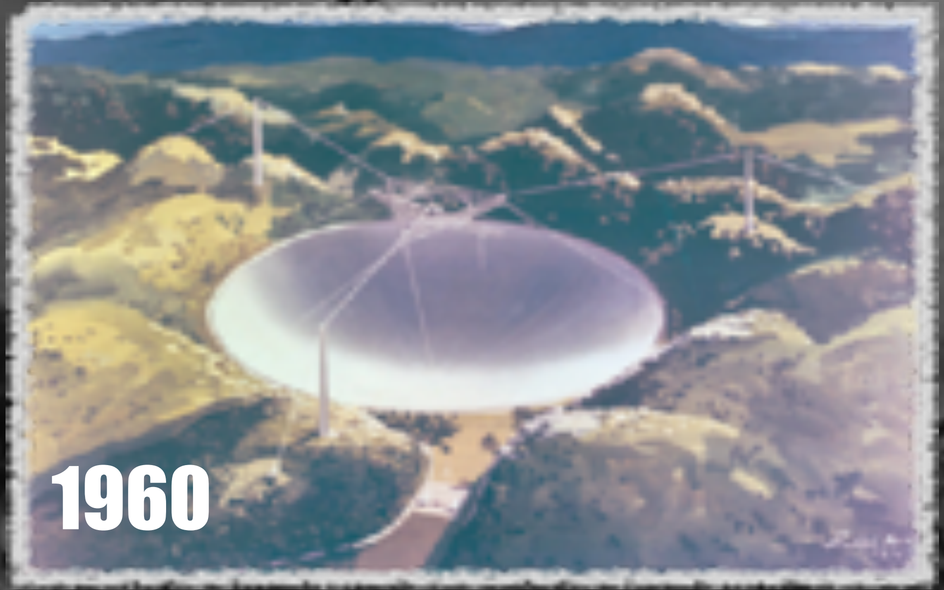
1963

Cornell faculty, William Gordon, proposed the project around 1958 to

ARPA–(Advanced Research Projects Agency)

- **Construction between 1960-1963**
- **Total cost: $9.3M**





发现 • 双中子星

1973-1993

阿雷西博望远镜里程碑

"We find that Einstein's theory passes this extraordinarily stringent test with a fractional accuracy better than 0.4%."

Gravitational Wave Exists!

"It necessarily follows that gravitational radiation exists and has a quadrupolar nature."

——Nobel speech by J.Taylor (1993)

1996


2002

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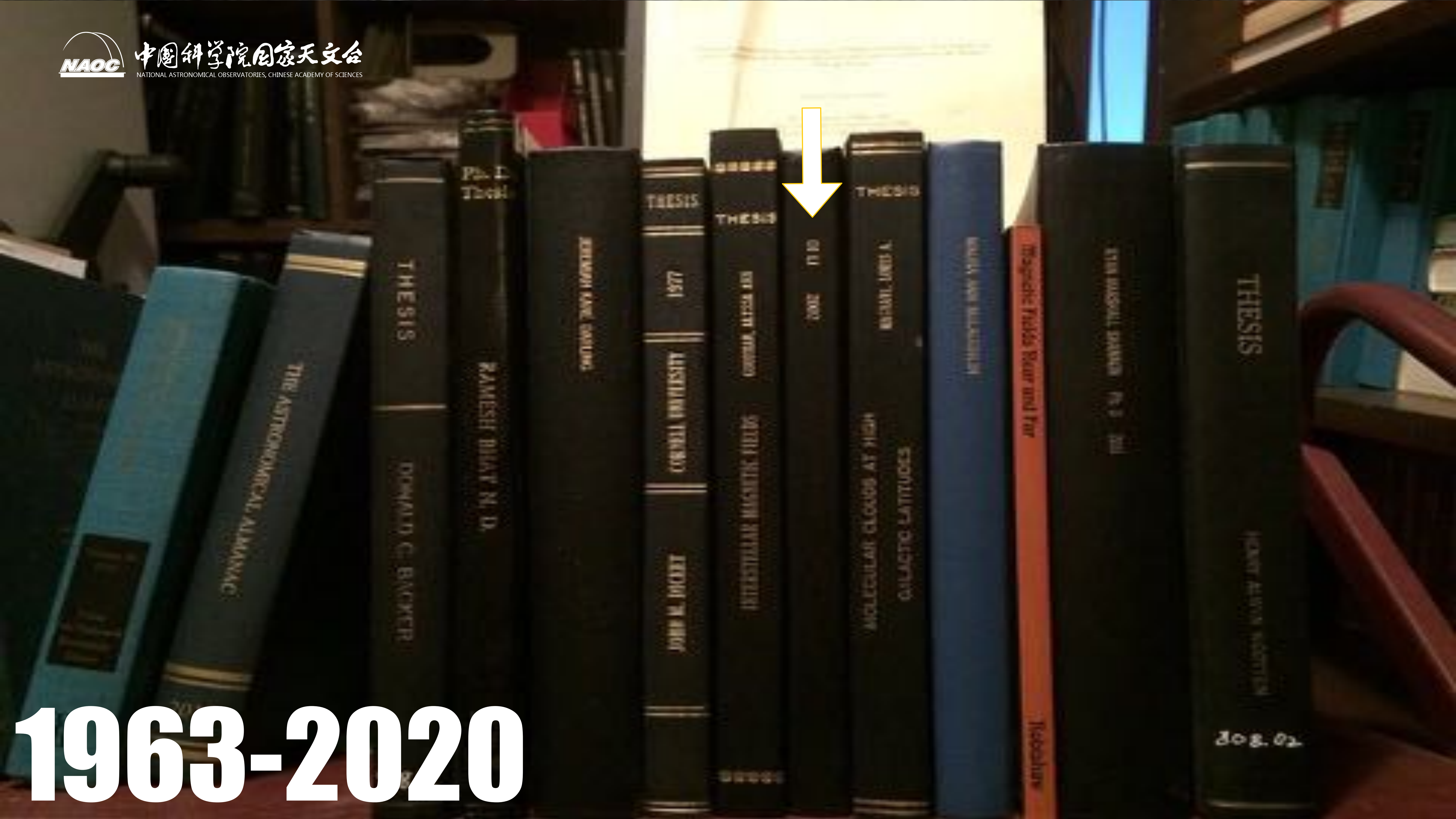
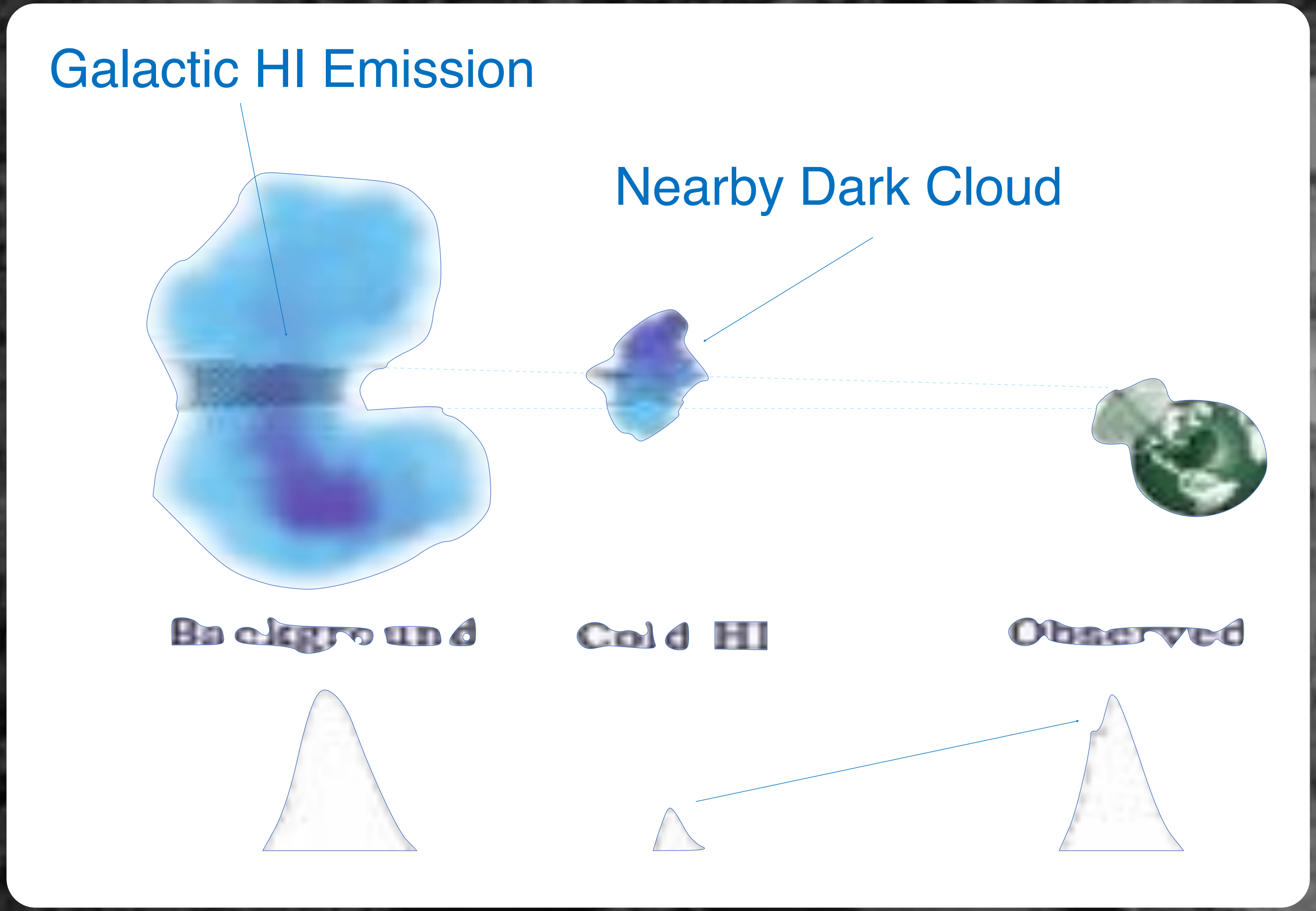
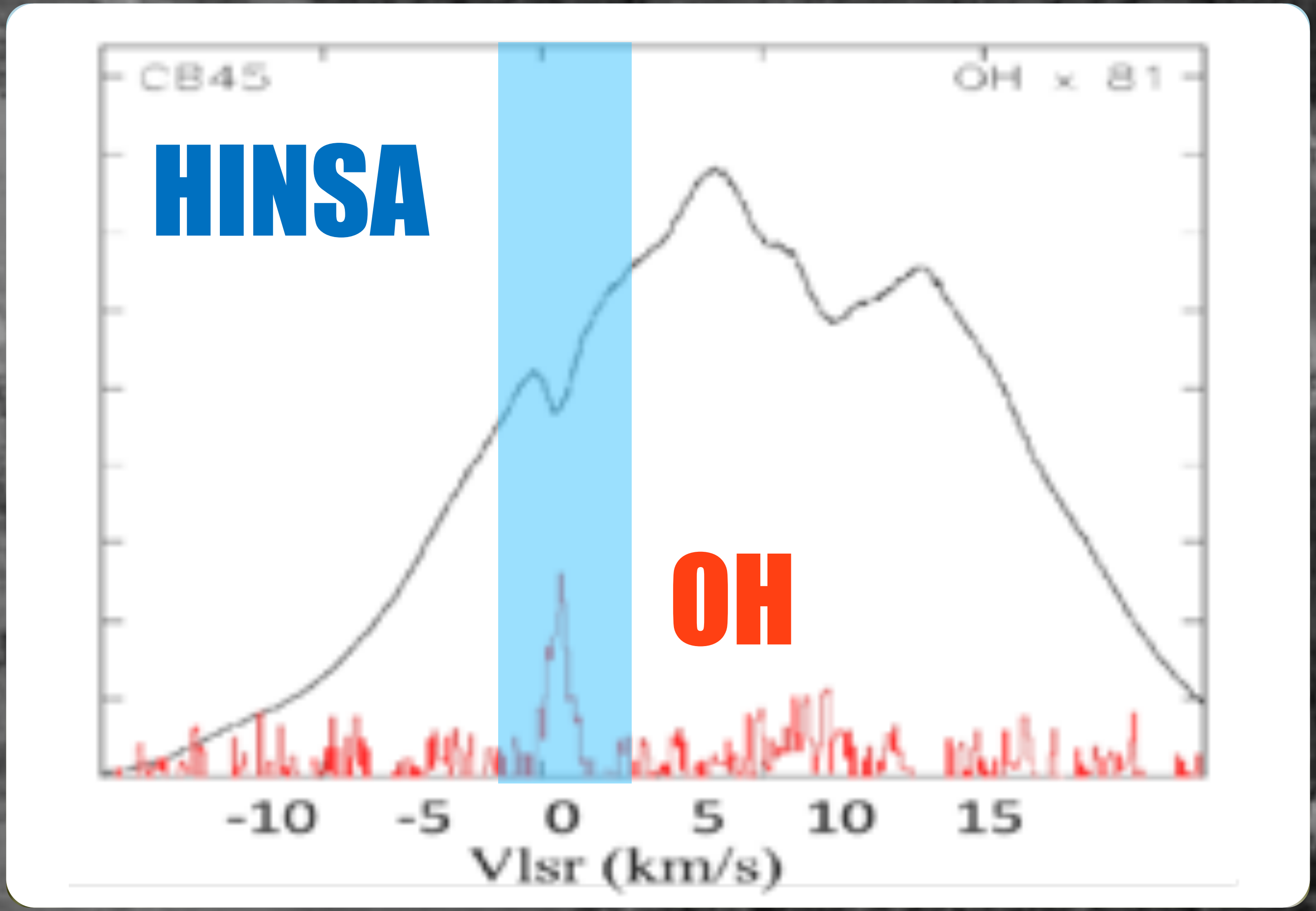


1963-2020

发现• 氢气的窄线自吸收（HINSA）



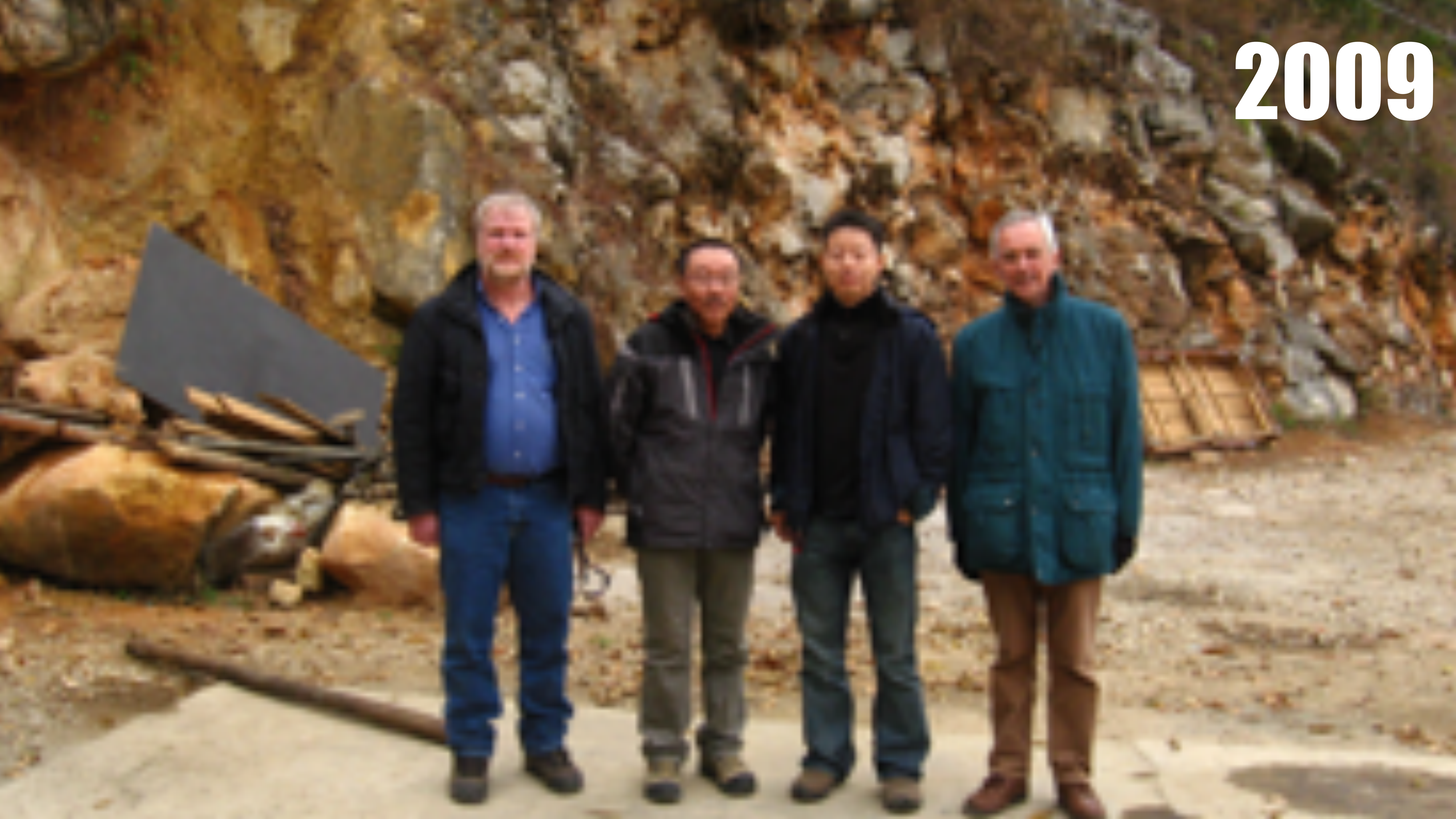
Li & Goldsmith 2003



阿雷西博天文台

创新天文观测方法—测量暗云的年龄（“氢纪年”）

A New Method for ‘Hydrogen-dating’ ISM Clouds


2009


2012
2012年2月14日
“射电天文前沿及FAST早期科学”973项目启动会

2015-2016

first light

2016.9.19


FAST
Guizhou, China

Observables

a) HI 21cm (imaging & galaxies)

b) Pulsars (FRBs)

c) Molecular Spectroscopy

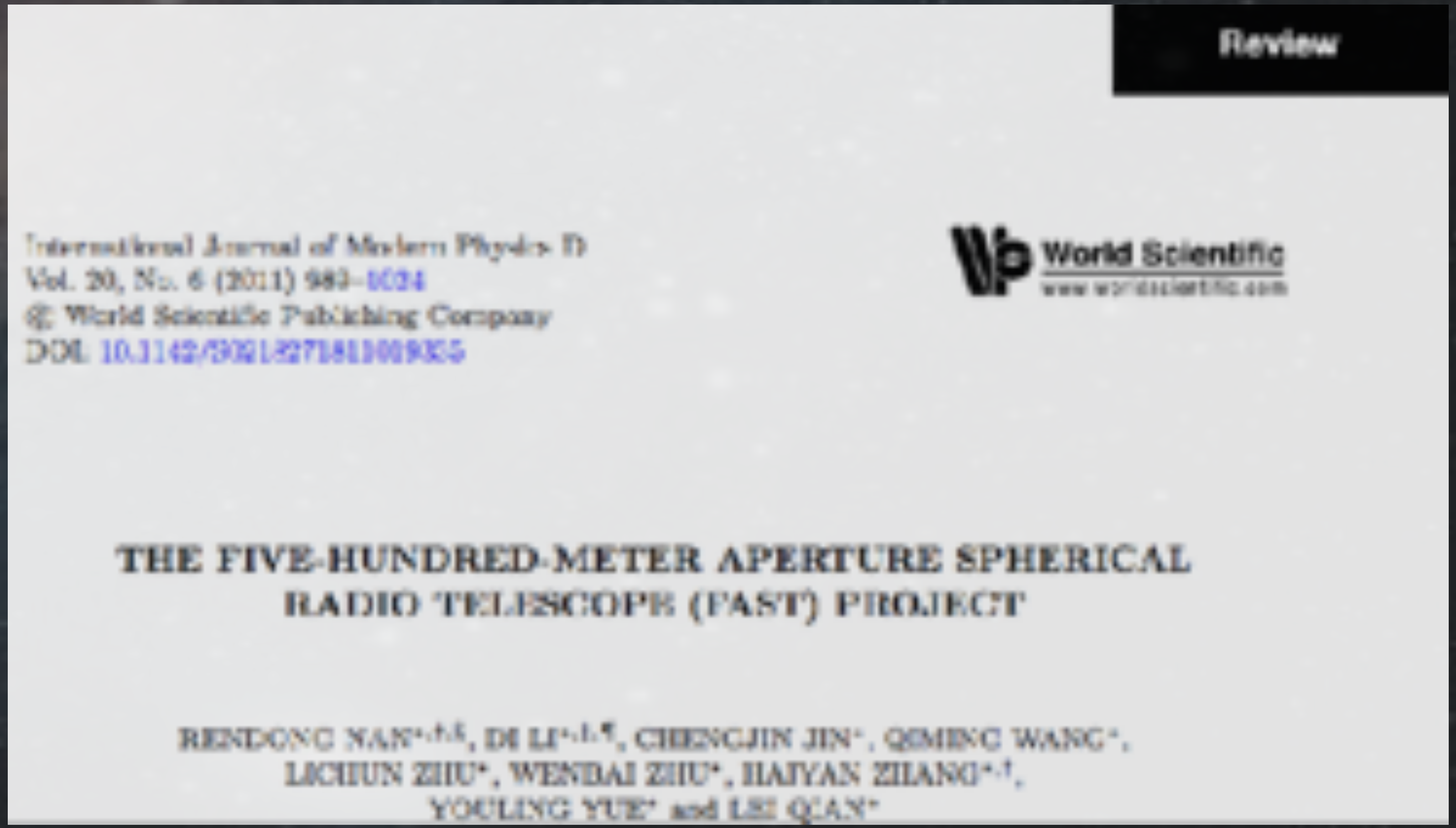
d) VLBI

e) SETI

NO large-scale survey has simultaneously observed HI and pulsar. Why?

continuous coverage

70 MHz～3 GHz


Review

International Journal of Modern Physics D
Vol. 20, No. 6 (2011) 989–1024
© World Scientific Publishing Company
DOI: 10.1142/S0218271811019335

World Scientific

THE FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE (FAST) PROJECT

RENDONG NAN, DI LI, CHENGJIN JIN, QIMING WANG, LICHUN ZHU, WENBAI ZHU, HAIYAN ZHANG, YOULING YUE and LEI QIAN

Nan, **Li,** Jin et al. 2011, IJMR-D, 20, 989
(>500 google scholar citations)

Li & Pan, 2016, Radio Science, 51, 7
Li et al. 2018, IEEE Microwave, Vol. 19, Issue 3

Commensal Radio Astronomy FAST Survey

CRAFTS
The Commensal Radio Astronomy FAST Survey
FAST多科学目标同时扫描巡天

unprecedented commensality
pulsar, galaxy, imaging, and FRB

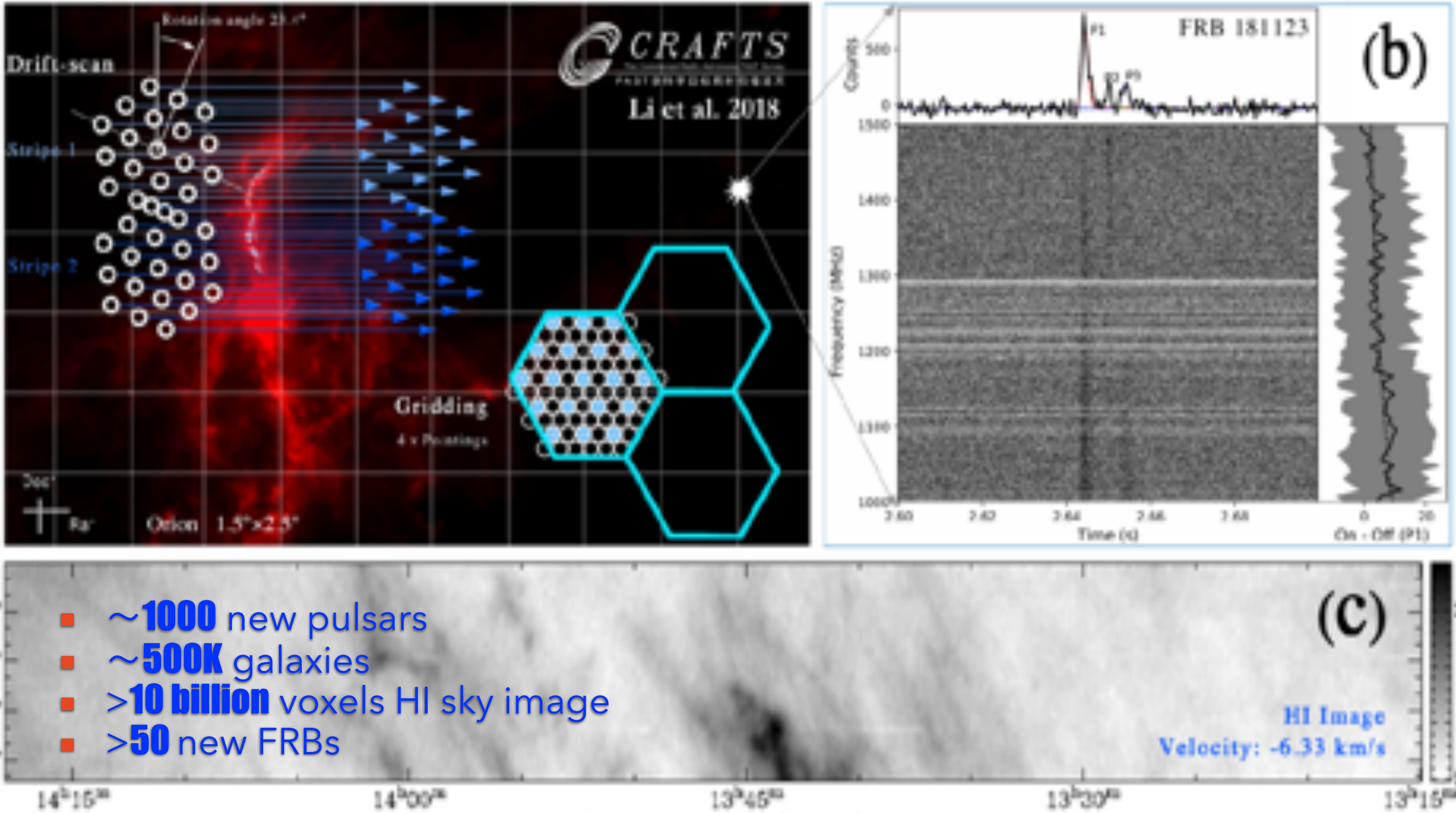
利用高时频噪声注入**自主专利**技术，**世界首创**了脉冲星搜索、中性氢成像、星系搜索和快速射电暴同时观测巡天。

FAST 'big data' stream
pulsar: 19 x 8bit x 4 x 4k x 2x10^4 per second
HI: 19 x 8bit x 4 x 1M x 2 /s

- 6 GB/s
- 25TB/h
- 550TB/day
- 10 PB/ year

FAST多科学目标同时扫描巡天
The Commensal Radio Astronomy FAST Survey

Li et al. 2018, Invited Review
IEEE Microwave, Vol 19, Issue 3, p112


Drift-scan
CRAFTS
Li et al. 2018
Stripe 1
Stripe 2
Gridding
Orion 1.5°×2.5°
FRB 181123
(b)
Counts
Frequency (MHz)
Time (s)
(c)
~1000 new pulsars
~500K galaxies
>10 billion voxels HI sky image
>50 new FRBs
HI Image
Velocity: -6.33 km/s
14h15m
14h00m
13h45m
13h30m
13h15m

2017

Oct. 10, 2017

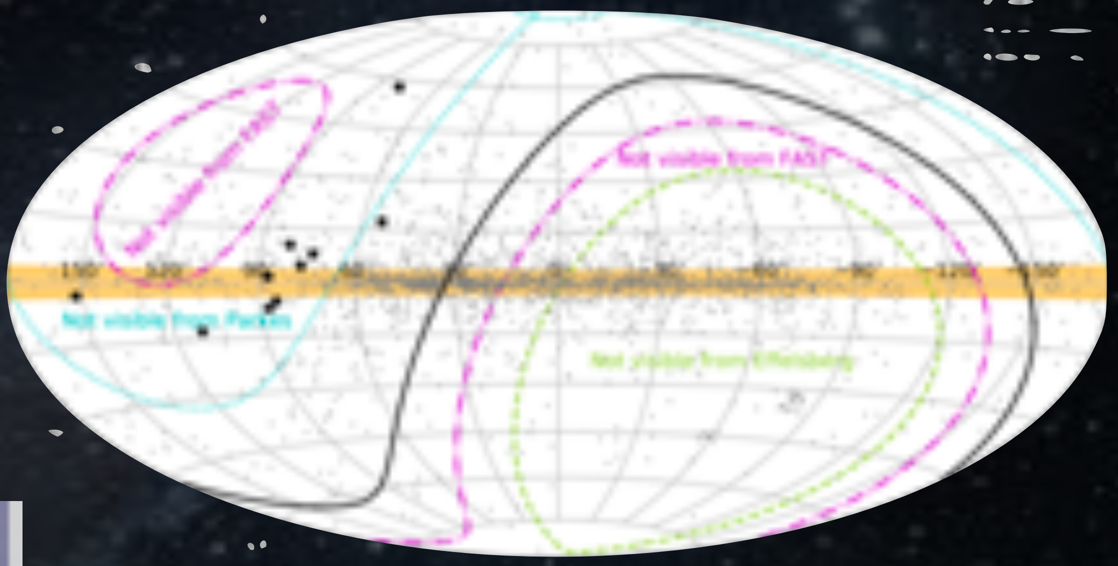
First FAST Science Results

CRAFTS

CRAFTS Team on Site

with Dr. Neil deGrasse Tyson
@ June 21, 2018

Systematic Timing of **CRAFTS** pulsars



First papers on systematic follow up timing of FAST pulsars

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **495**, 3515–3530 (2020) doi:10.1093/mnras/staa1328
Advance Access publication 2020 May 14

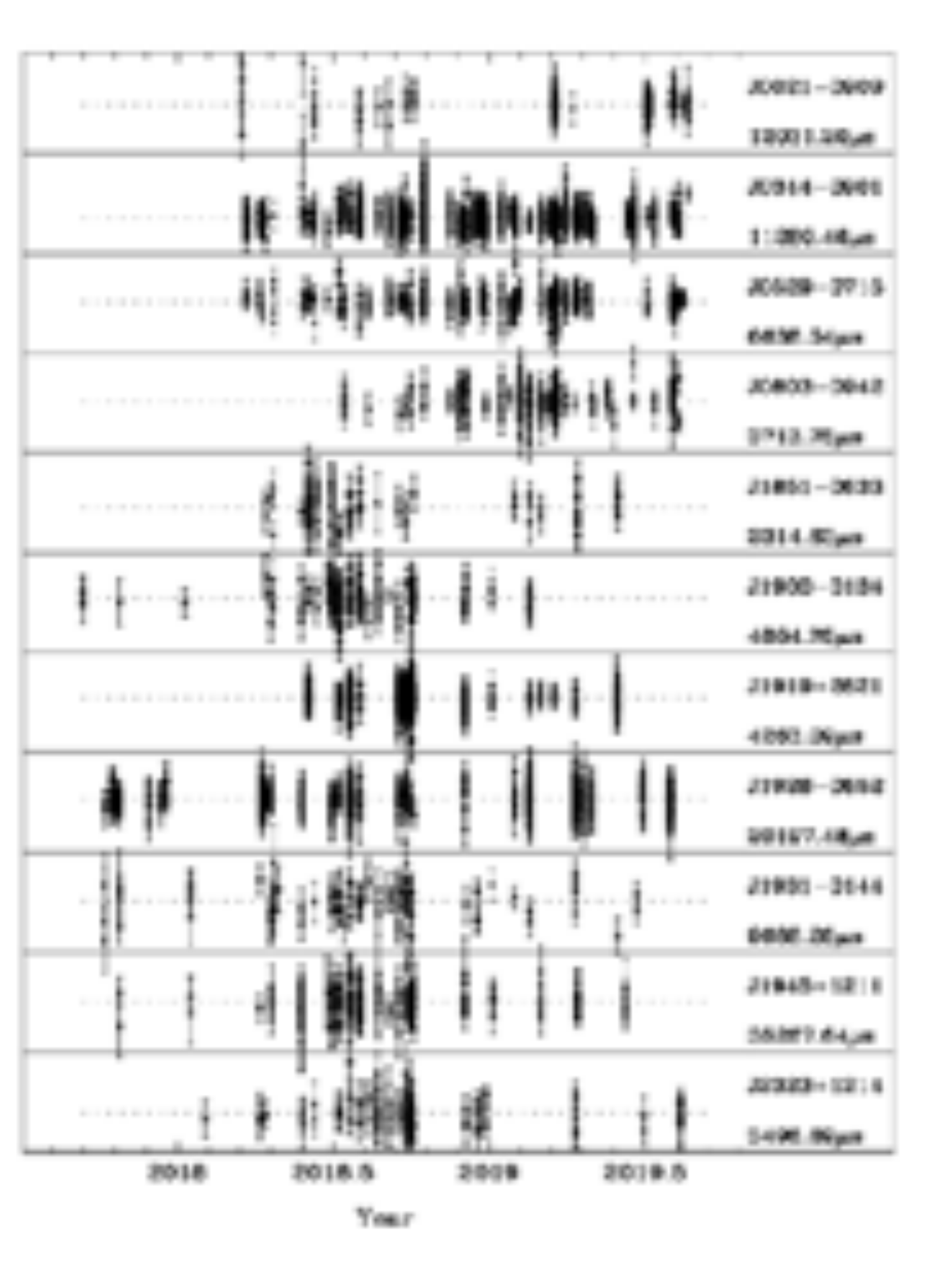
An in-depth investigation of 11 pulsars discovered by FAST

A. D. Cameron[1,2★] D. Li[1,3★] G. Hobbs[1,2] L. Zhang,[1,2,3] C. C. Miao,[1,3]

Cameron, Li et al. 2020 (MNRAS)

FAST early discoveries: Effelsberg follow-up

M. Cruces,[1*] D. Champion,[1] D. Li,[2] M. Kramer,[1] W. W. Zhu,[2] P. Wang,[2] A. D. Camero[3,4,5] G. Hobbs,[3] P. Freire,[1] E. Graikou[1] Y. Mao,[2] and the CRAFTS collaboration
[1] Max Planck Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[2] CAS Key Laboratory of FAST, NAOC, Chinese Academy of Sciences, Beijing 100101, China
[3] CSIRO Astronomy and Space Science, PO Box 76, Epping, NSW 1710, Australia
[4] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Mail H30, PO Box 218, VIC 3122, Australia.
[5] ARC Center of Excellence for Gravitational Wave Discovery (OzGrav), Swinburne University of Technology, Mail H11, PO Box 218, VIC 3122, Australia.



Cruces, Champion, Li et al. 2021 (A&A)

FAST's first Milli-Second Pulsar (MSP)

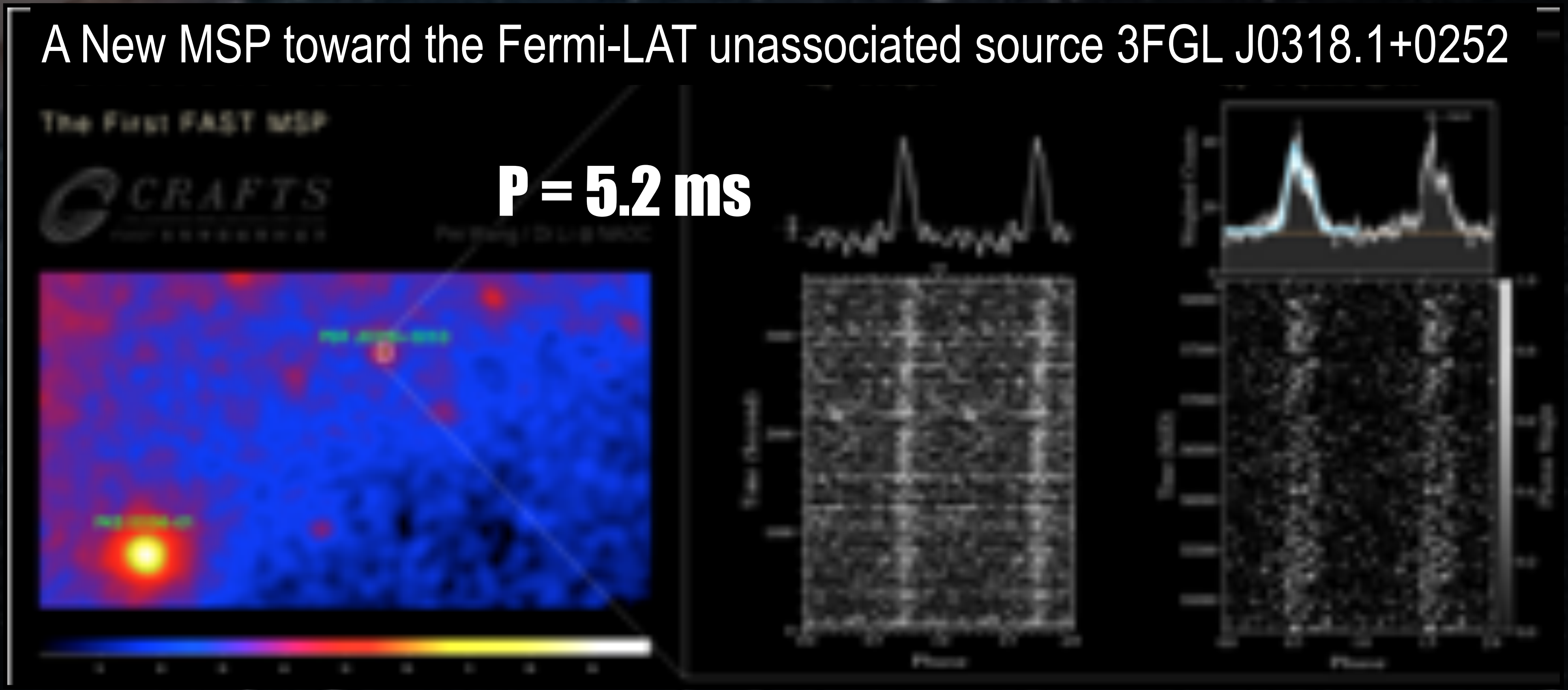
3FGL J0318.1+0252
FL8Y J0318.2+0254

Fermi unidentified source
GBT, Arecibo non-detection

2018

- **2018.2.27** 1hr tracking with FAST's UWB
- **2018.4.12** Wang, P. et al. detected the signal using GZNU servers
- **2018.4.18** C. Clark of the Fermi team identify the γ-ray pulsar counterpart
- **2018.4.23** HKU's Pablo confirms its lack of X-ray
- **2018.4.28** ATel announcement （Wang et al. Atel#10851, 《SCPMA》）
- **2018.5.2** International pulsar timing array （IPTA) distribute the ephemeris to its partners

✗	**Arecibo**, 327 MHz, 3h	<60 μJy
√	**FAST**, 550 MHz, 1h	~60 μJy
✗	**FAST**, 1.25 GHz, 4h	~20 μJy



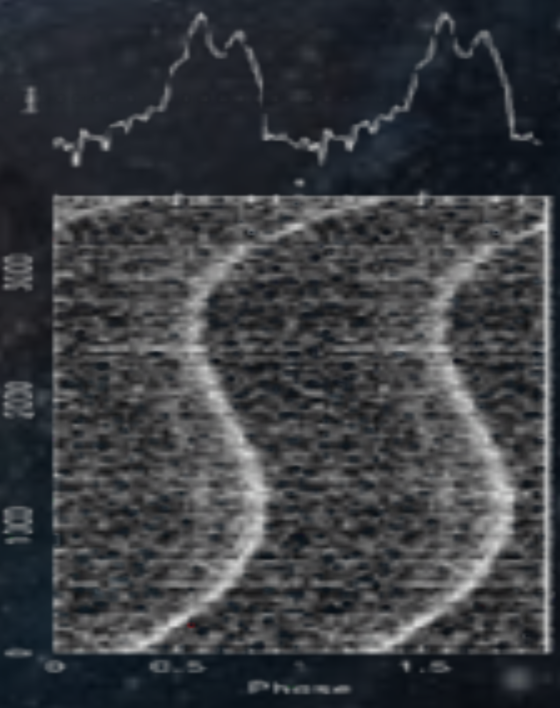
Pulsar searches of Fermi sources with FAST

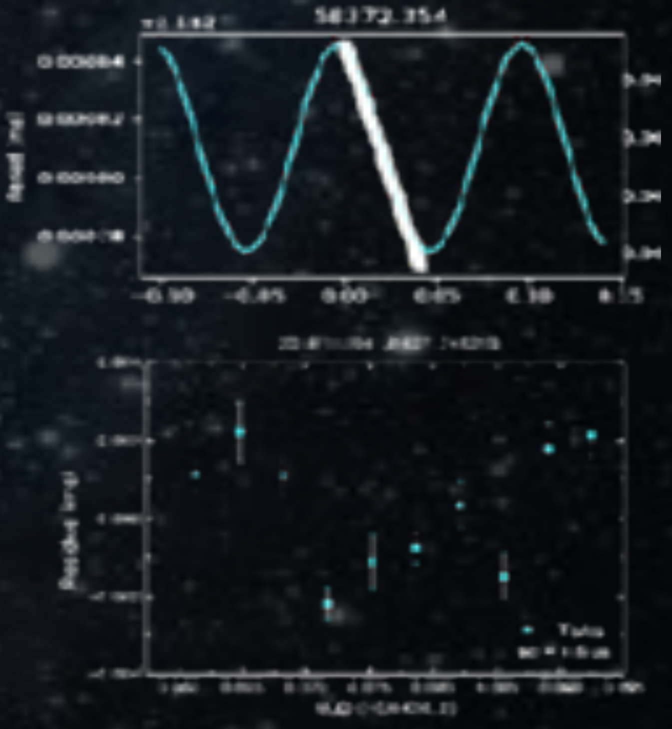
FAST-Fermi•LAT MoU

- December 2017, MoU signed between the FAST team and the LAT Collaboration
- >3033 sources in 3FGL, 1904 have confirmed, AGN (1738), PSR (>200), ~1129 unconfirmed sources
- More than 30 targets be searched, **5** new pulsars/ MSPs are discovered by FAST.

Spin period is **2.2 milliseconds**, an estimated distance of about **4.4 kpc**, and as

4FGL J1627.7+3219

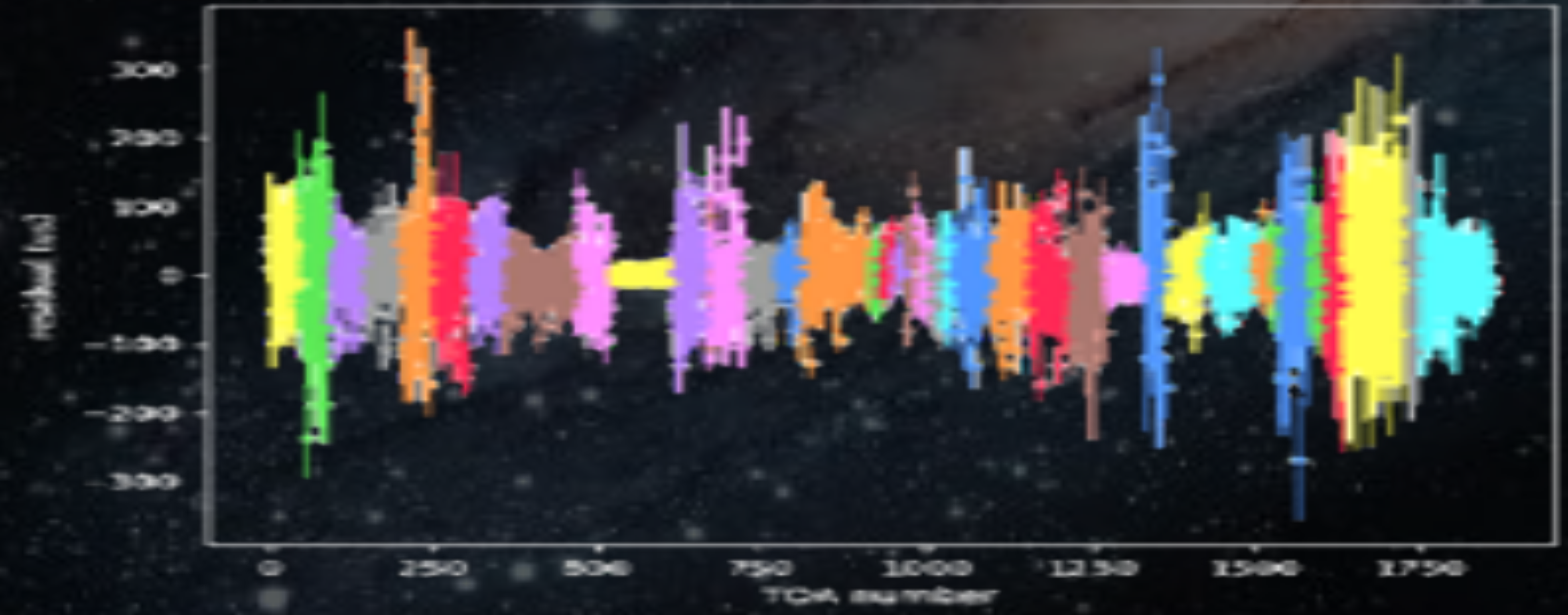




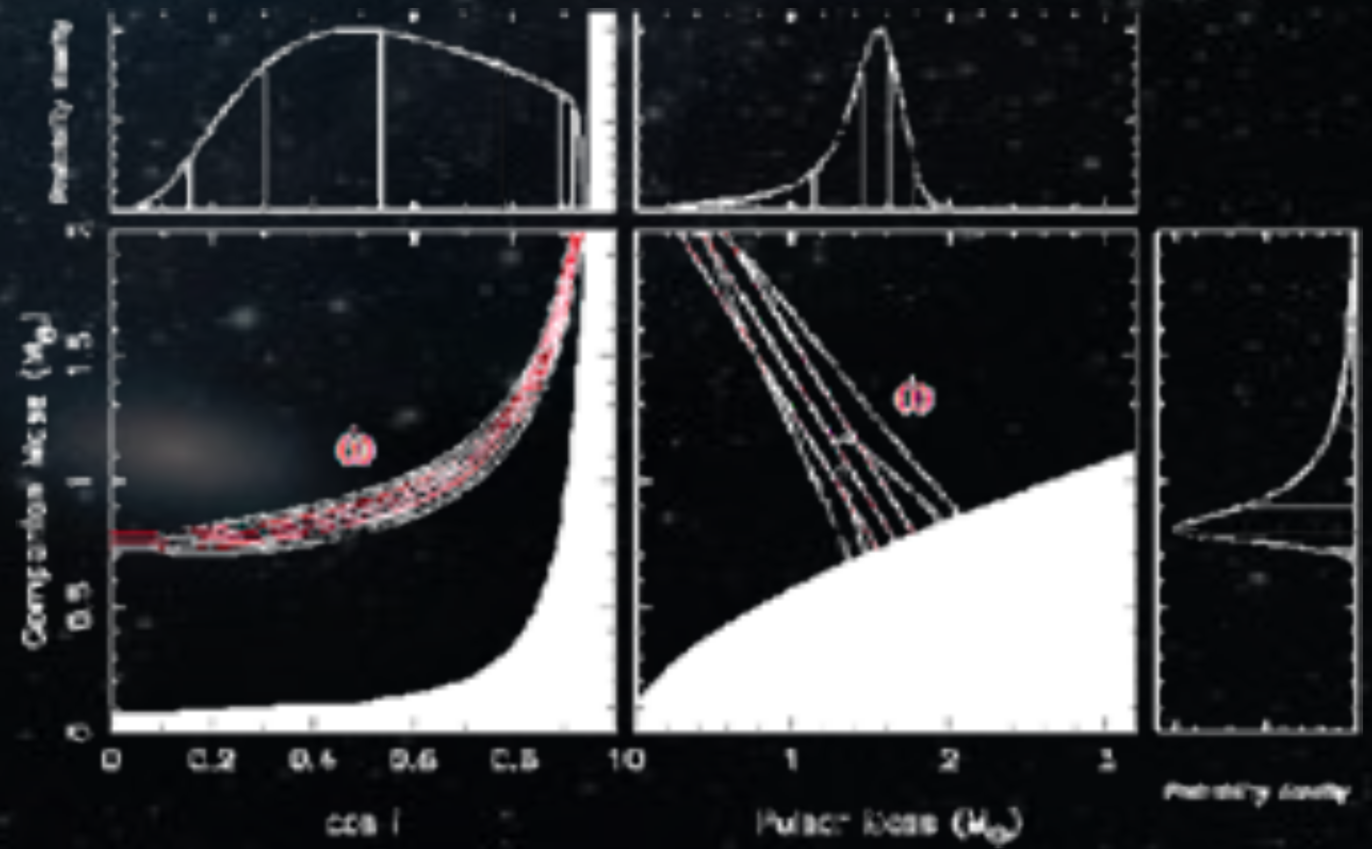
FAST首个双中子星系统

C69-DNS system （W.W. Zhu）

- Total 44 sessions of observations span 339 days
- 23 sessions 2019a-082-P (Chenchen Miao)
- 15 sessions orbital campaign DDT (Weiwei Zhu)
- 6 sessions Timing KSP （Nina Wang）



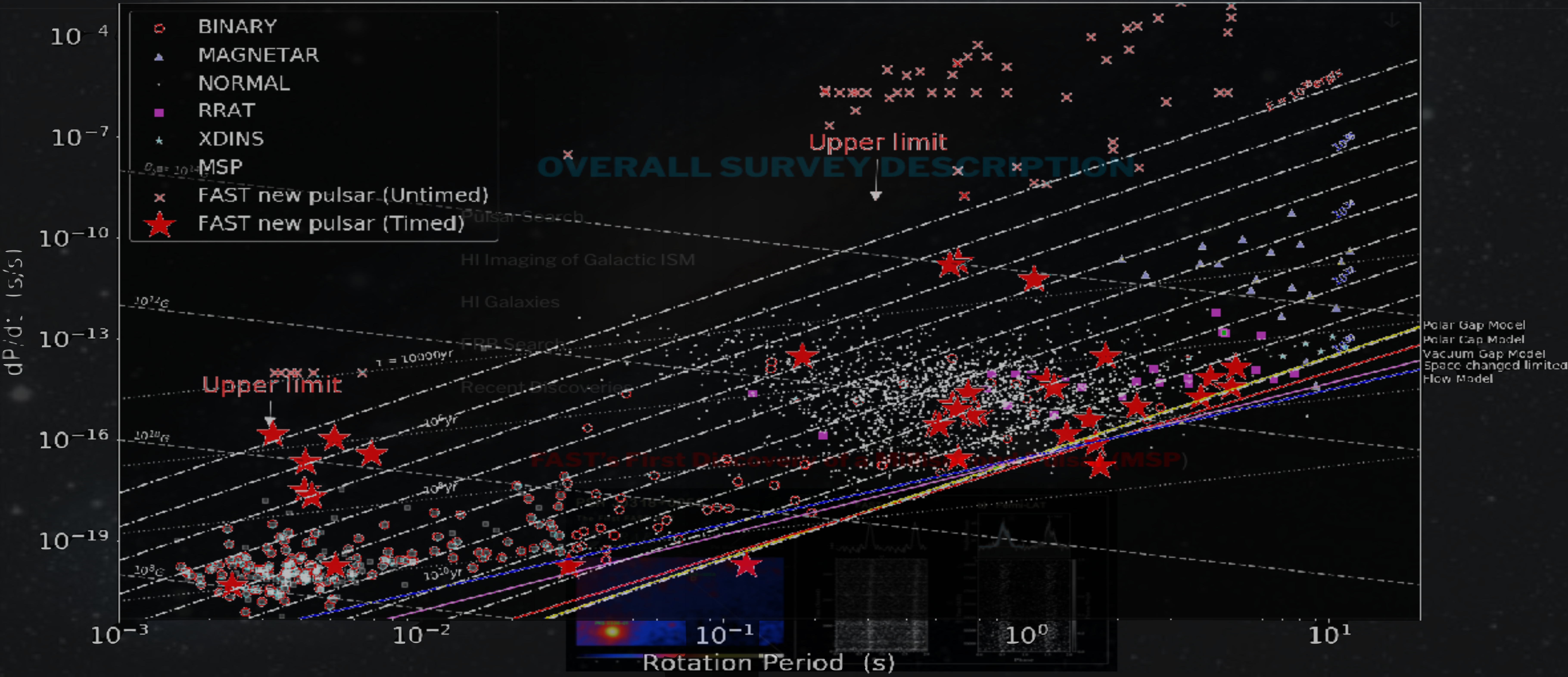
Fully connected timing solution using DDGR



双中子星整体质量小，有可能是特殊系统！

Confirmed new pulsars > 130, including >44 MSPs, binaries (DNS), etc.

http://crafts.bao.ac.cn

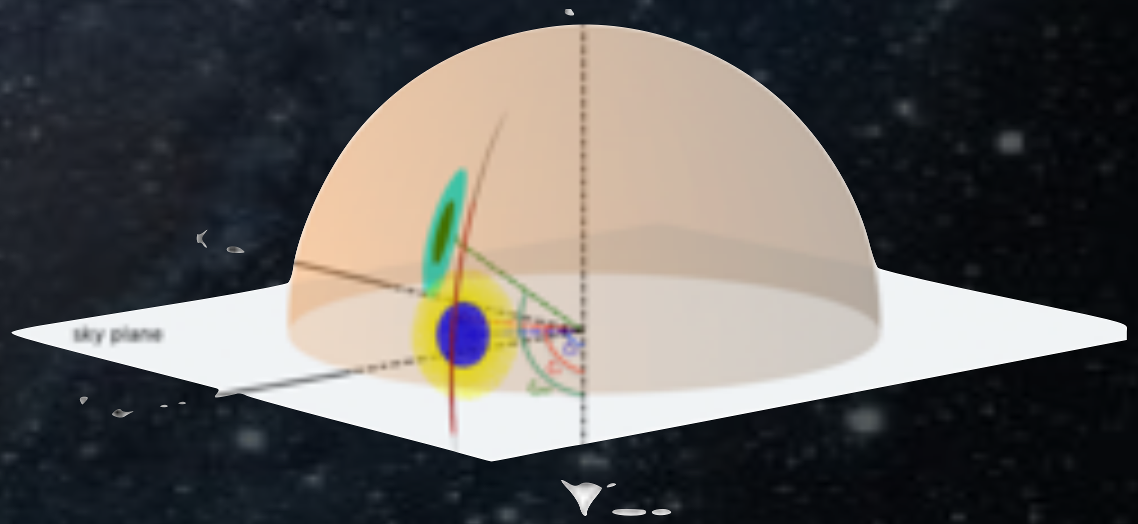


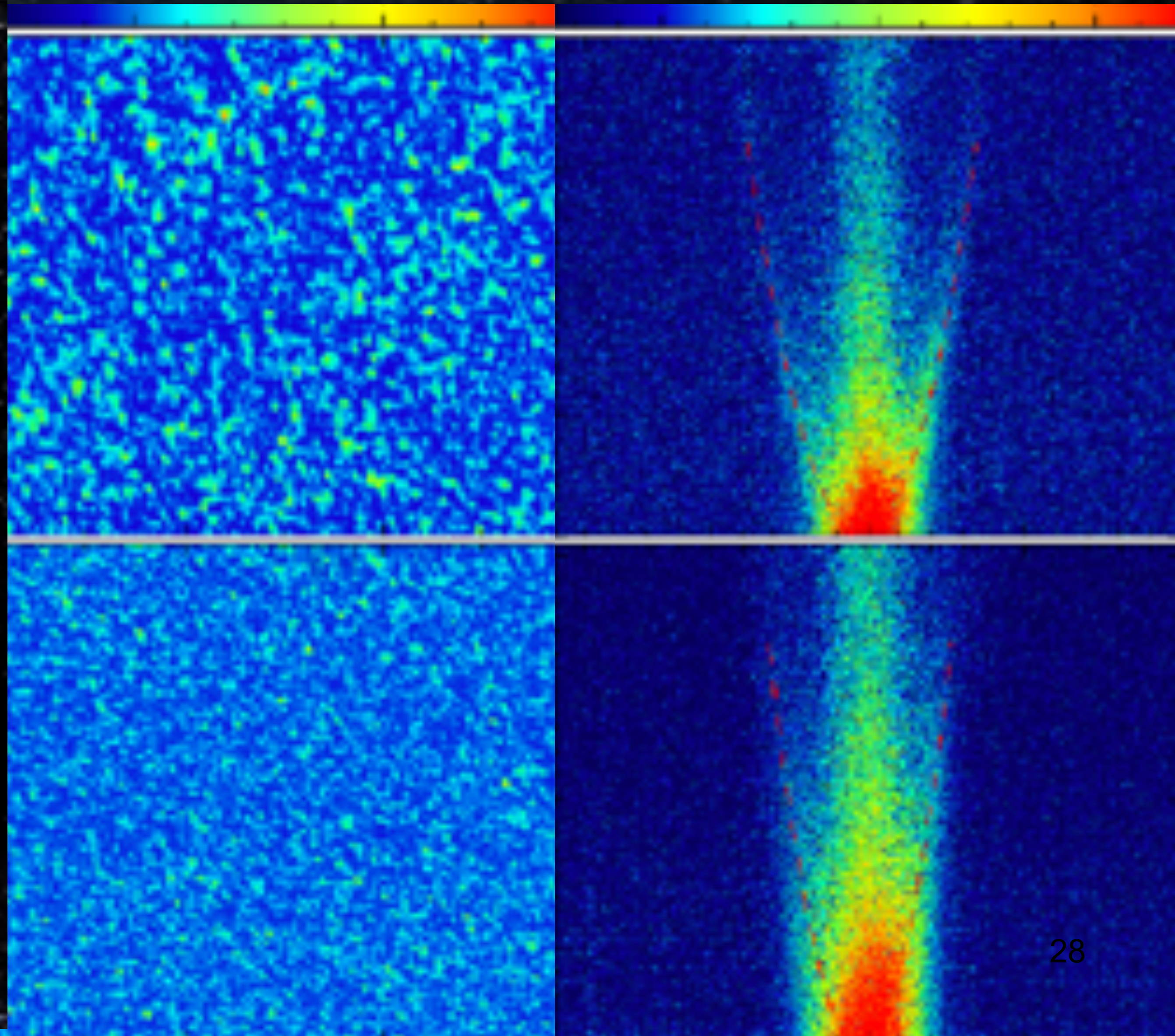
nature astronomy
LETTERS
https://doi.org/10.1038/s41550-021-01360-w
Check for updates

Evidence for three-dimensional spin–velocity alignment in a pulsar

Jumei Yao[1,2], Weiwei Zhu[1], Richard N. Manchester[3], William A. Coles[4], Di Li[1,5,6], Na Wang[2], Michael Kramer[7,8], Daniel R. Stinebring[9], Yi Feng[1], Wenming Yan[2], Chenchen Miao[1], Mao Yuan[1], Pei Wang[1] and Jiguang Lu[1]

Twinkling pulsar





«Nature Astronomy»
https://dx.doi.org/10.1038/s41550-021-01360-w

OH/HI Absorption

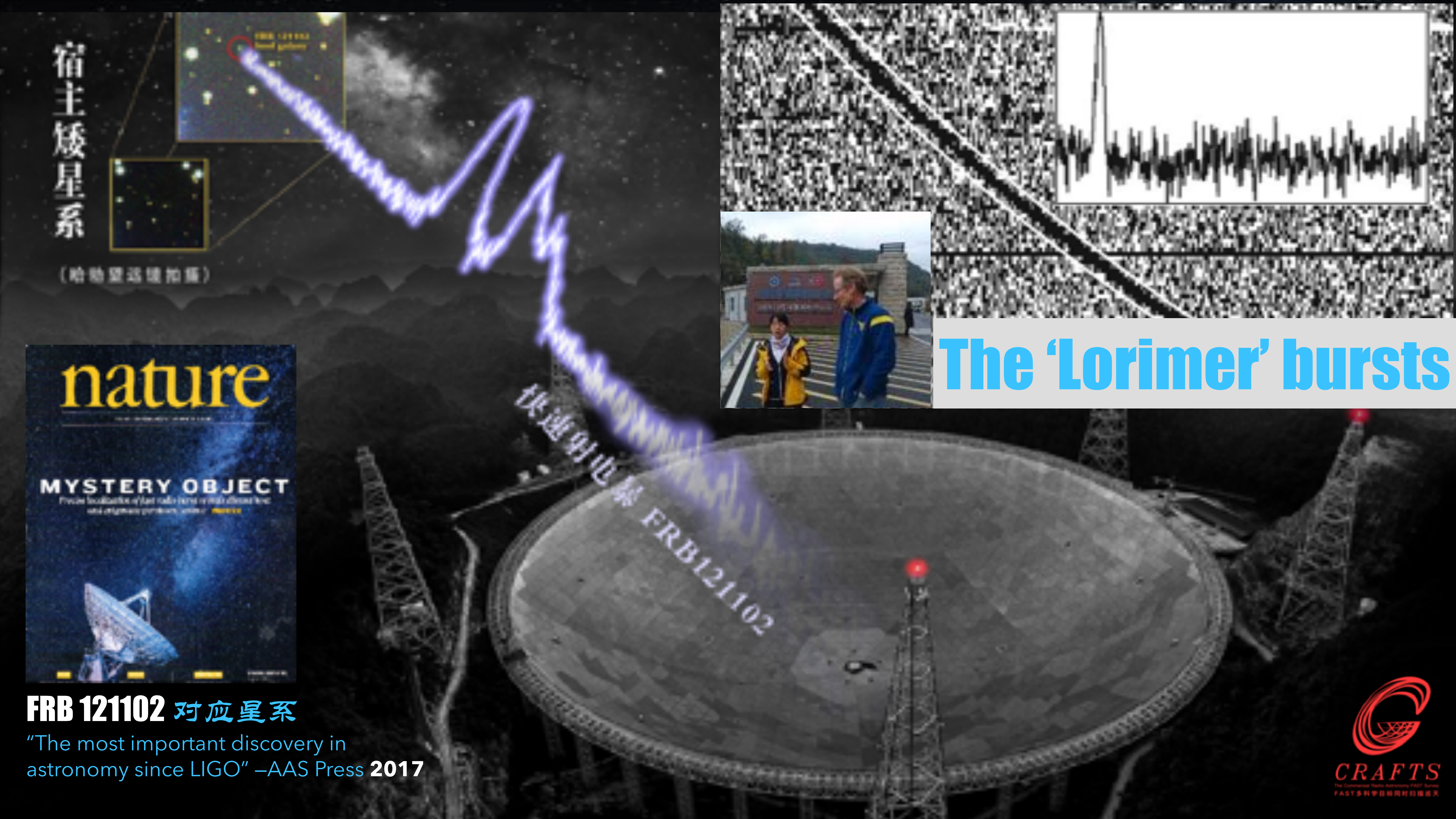
Searched 9 extra-galactic HI absorbers for OH absorption:

- We found no detection but derived the most stringent OH-abundance upper limit:

  [OH]/[HI] < 5.45×10^{-8}

- A decreasing trend of [OH]/[HI] with decreasing redshift
- Intervening absorbers have a higher [OH]/[HI]

Zheng, **Li** et al. 2020, MNRAS, 499, 3085


宿主矮星系
(哈勃望远镜拍摄)
nature
MYSTERY OBJECT
快速射电暴 FRB121102
The ‘Lorimer’ bursts
FRB 121102 对应星系
“The most important discovery in astronomy since LIGO” –AAS Press 2017
CRAFTS

Contents [hide]

Hosted by the Institut Spatial de McGill MSI McGill Space Institute in collaboration with University of Cape Town, University of KwaZulu-Natal, Inyuvesi Yakwazulu-Natali

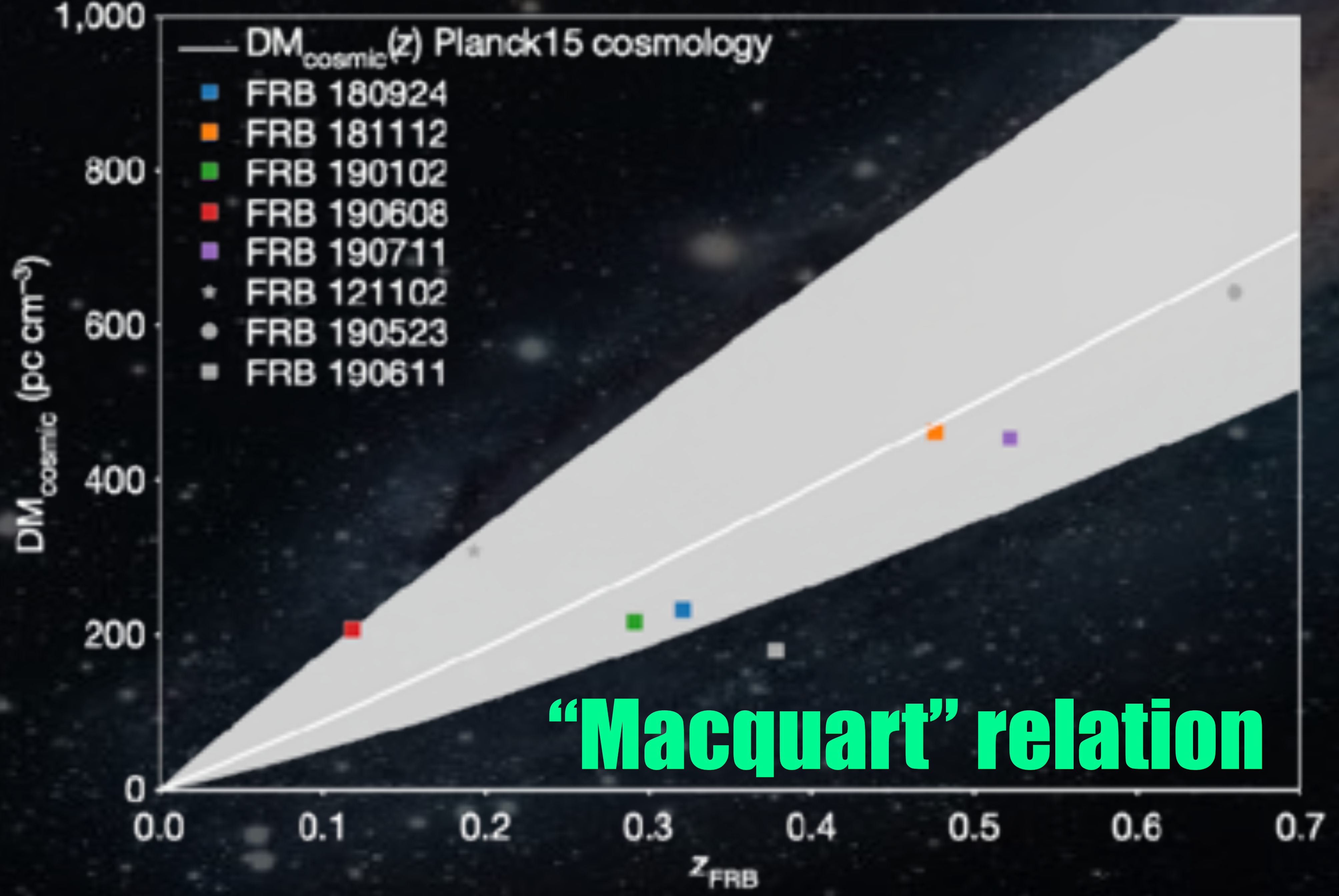
> 50 categories of models, no concensus

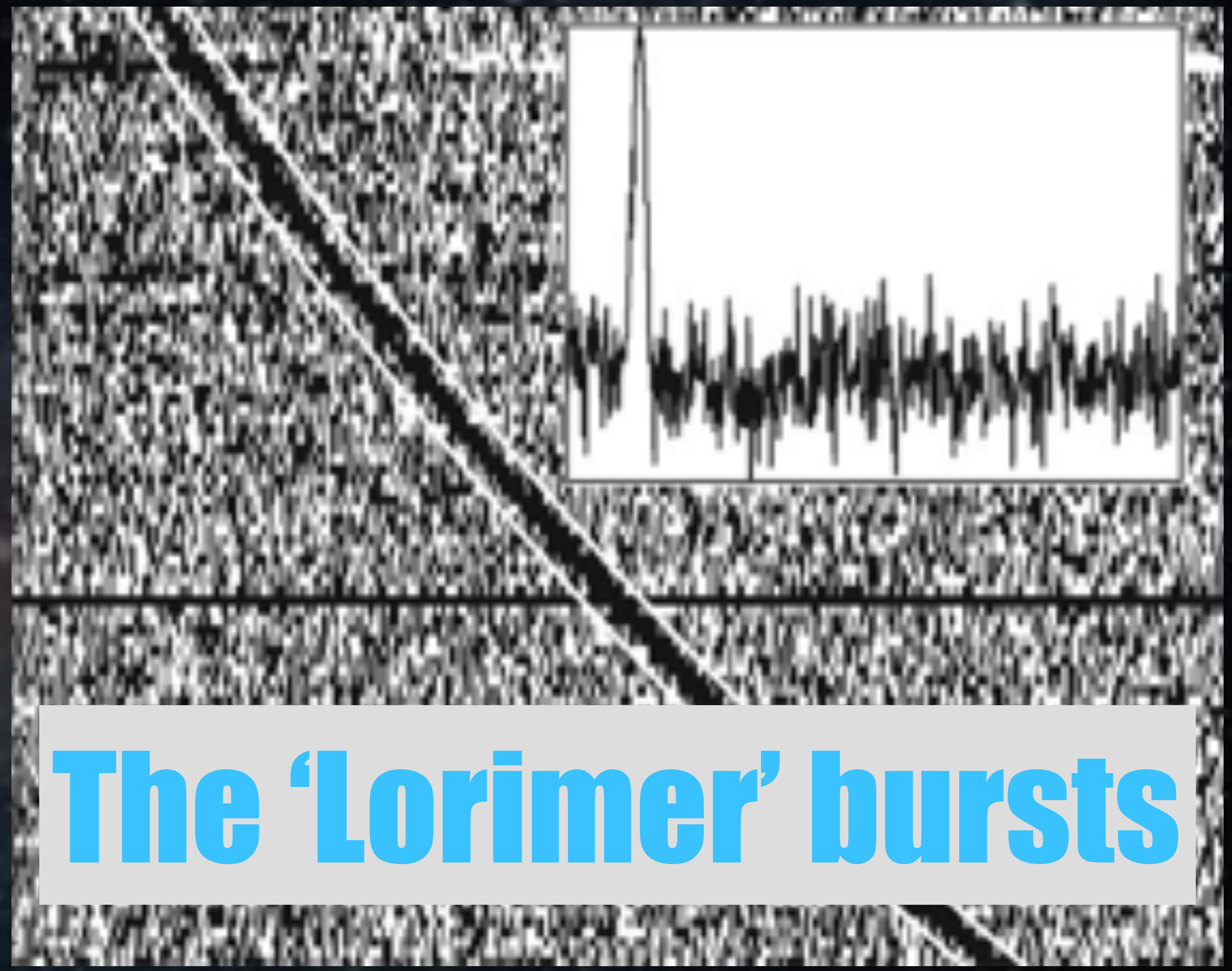
Welcome to the FRB Theory Wiki!

Name	Category	Progenitor	Type	Energy Mechanism	Emission Mechanism	LF Radio Counterpart	HF Radio Counterpart	Microwave Counterpart	THz Counterpart	O/IR Counterpart	X-ray Counterpart	Gamma ray Counterpart	GW Counterpart
NS-WD Accretion	Accretion	NS-WD	Repeat	Mag. reconnection	Curv.	Yes	–	–	–	–	–	Yes, but unlikely detectable	–
AGN-KBH	AGN	AGN-KBH Interaction	Repeat	Maser	Synch.	Yes	–	–	–	Supernova	–	Yes	Yes
AGN-SS	AGN	AGN-Strange Star Interaction	Repeat	Electron oscillation	–	Yes	–	–	–	Thermal	–	Yes	Yes
Jet-Caviton	AGN	Jet-Caviton Interaction	Both	Electron scattering	Bremsst.	Yes	Yes	–	–	–	–	Possible GRB	Yes
Wandering Beam	AGN	Wandering Beam	Repeat	–	Synch.	Yes	–	–	–	–	Yes	–	–
NS to BH (DM-induced)	Collapse	NS to BH	Single	Mag. reconnection	Curv.	Yes	–	–	–	–	–	–	Yes
NS to KNBH	Collapse	NS to KNBH	Single	Mag. reconnection	Curv.	Yes	–	–	–	–	Possible afterglow	Possible GRB	Yes
NS to Quark Star	Collapse	NS to Quark Star	Single	β-decay	Synch.	Yes	–	–	–	–	Yes	Yes	Yes
SS Crust	Collapse	Strange Star Crust	Single	Mag. reconnection	Curv.	Yes	–	–	–	–	–	–	Yes
Axion Cloud and BH	Collision / Interaction	Superradiant Axion Cloud and BH	Repeat	Laser	Synch.	Yes	–	–	–	–	–	–	Yes

FRB: a Cosmic Probe

$$\mathrm{DM}_{\mathrm{FRB}}(z) = \mathrm{DM}_{\mathrm{MW,ISM}} + \mathrm{DM}_{\mathrm{MW,halo}} + \mathrm{DM}_{\mathrm{cosmic}}(z) + \mathrm{DM}_{\mathrm{host}}(z)$$





$$\langle \mathrm{DM}_{\mathrm{cosmic}} \rangle = \int_0^{z_{\mathrm{FRB}}} \frac{c\bar{n}_e(z)\mathrm{d}z}{H_0(1+z)^2\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

Macquart+ 2020, *A census of baryons in the Universe from localized fast radio bursts*, **Nature**

Commensal Radio Astronomy FAST Survey

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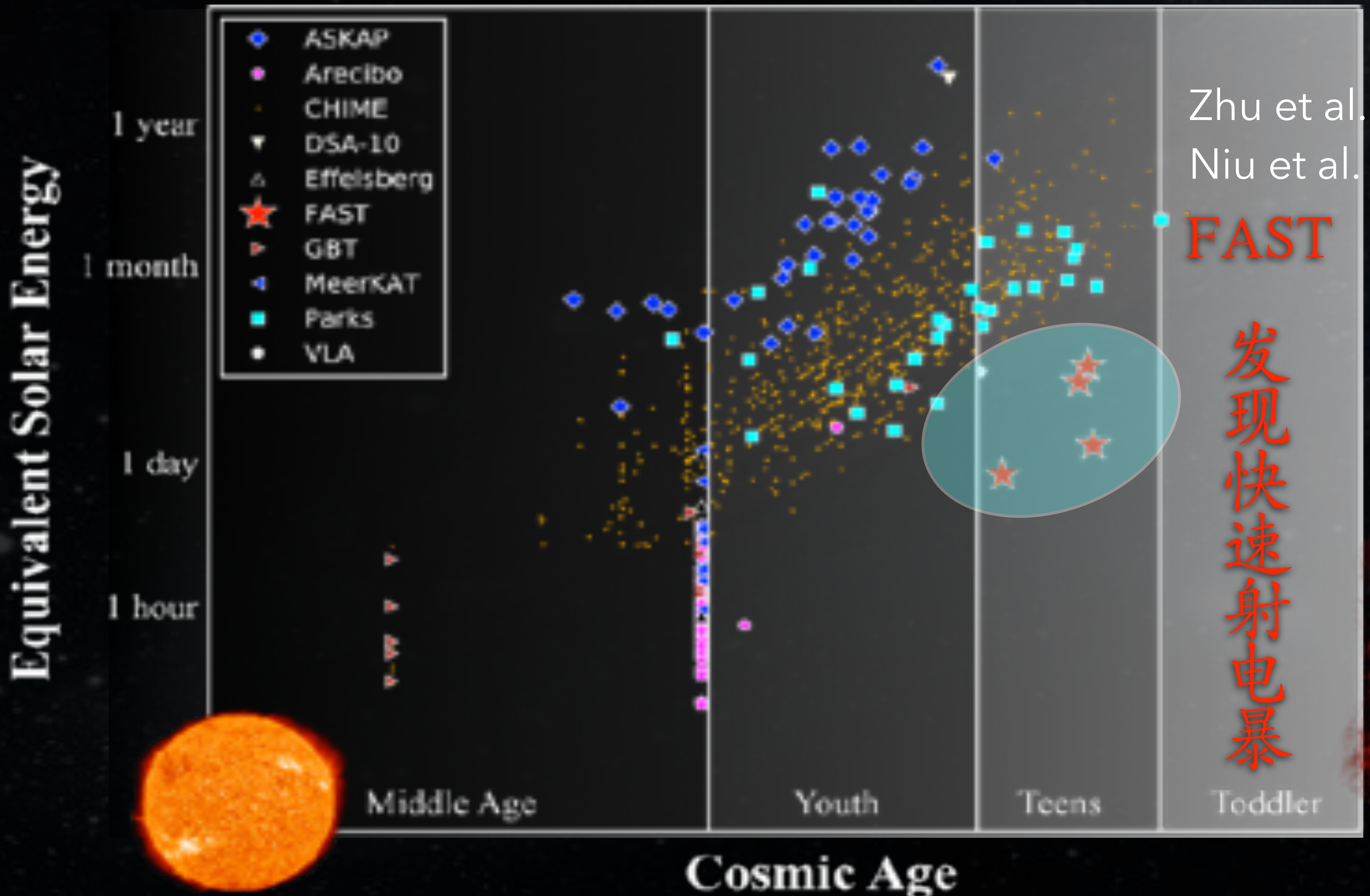
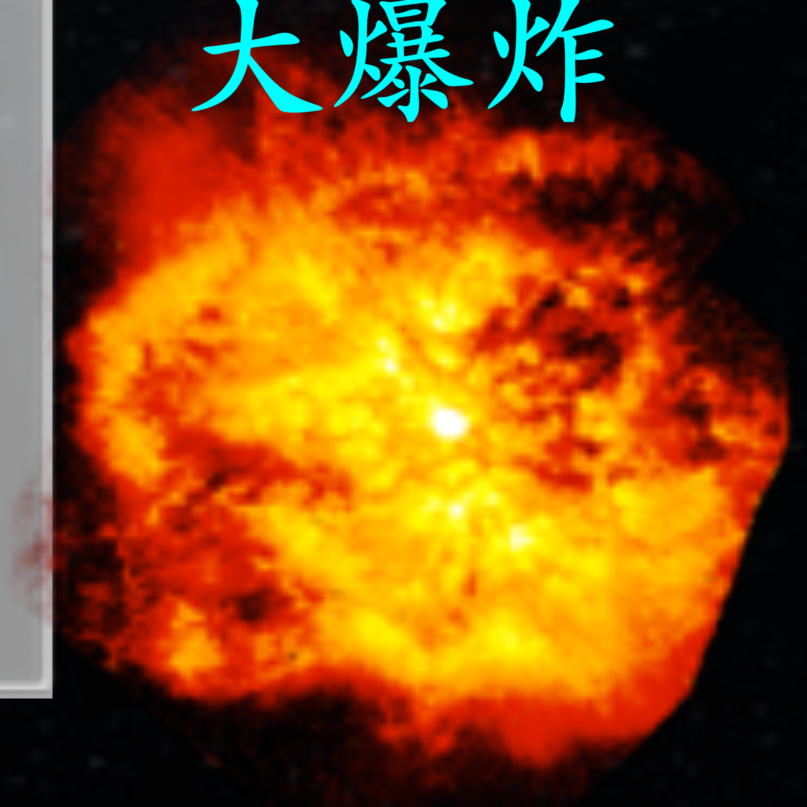


Zhu et al. 2020 ApJL

Niu et al. 2021 ApJL

FAST

发现快速射电暴



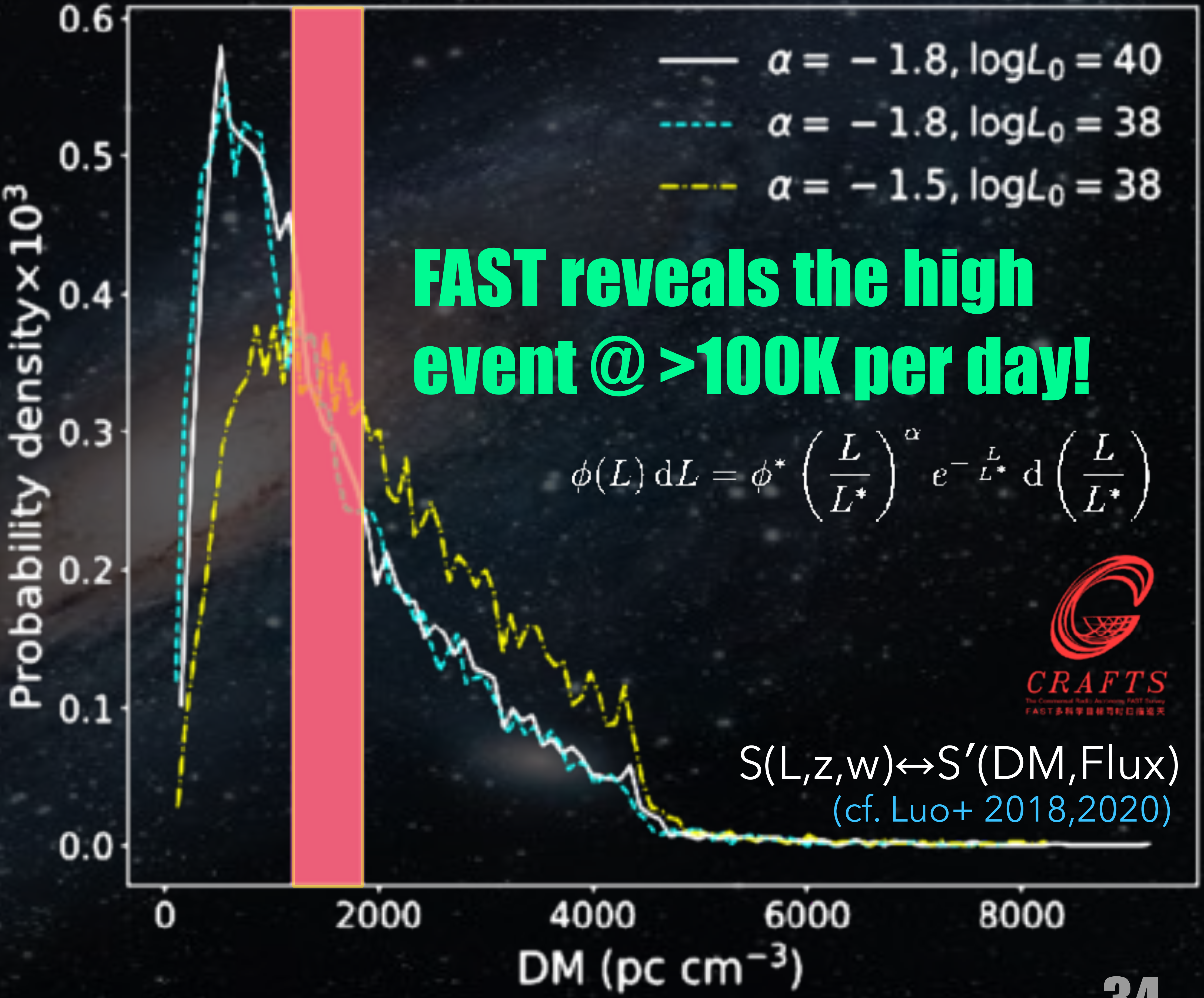
CRAFTS

CRAFTS 2018 FRBs

- **Four** events in a total of **1667 hours** in 2018, corresponds to an all sky rate of **1.2×10^5 sky^{-1} day^{-1}** at the 95% confidence interval above 0.0146 Jy ms, by far the deepest such estimate.
- ~1 per 400 FLAN hours (cf. Li 2016)

- PDF of FAST-FRB's I
sensitive to the slop
luminosity function
brightness L_0.

- FAST will have sign
probability (>10%)
cm^{-3} (Also Zhar

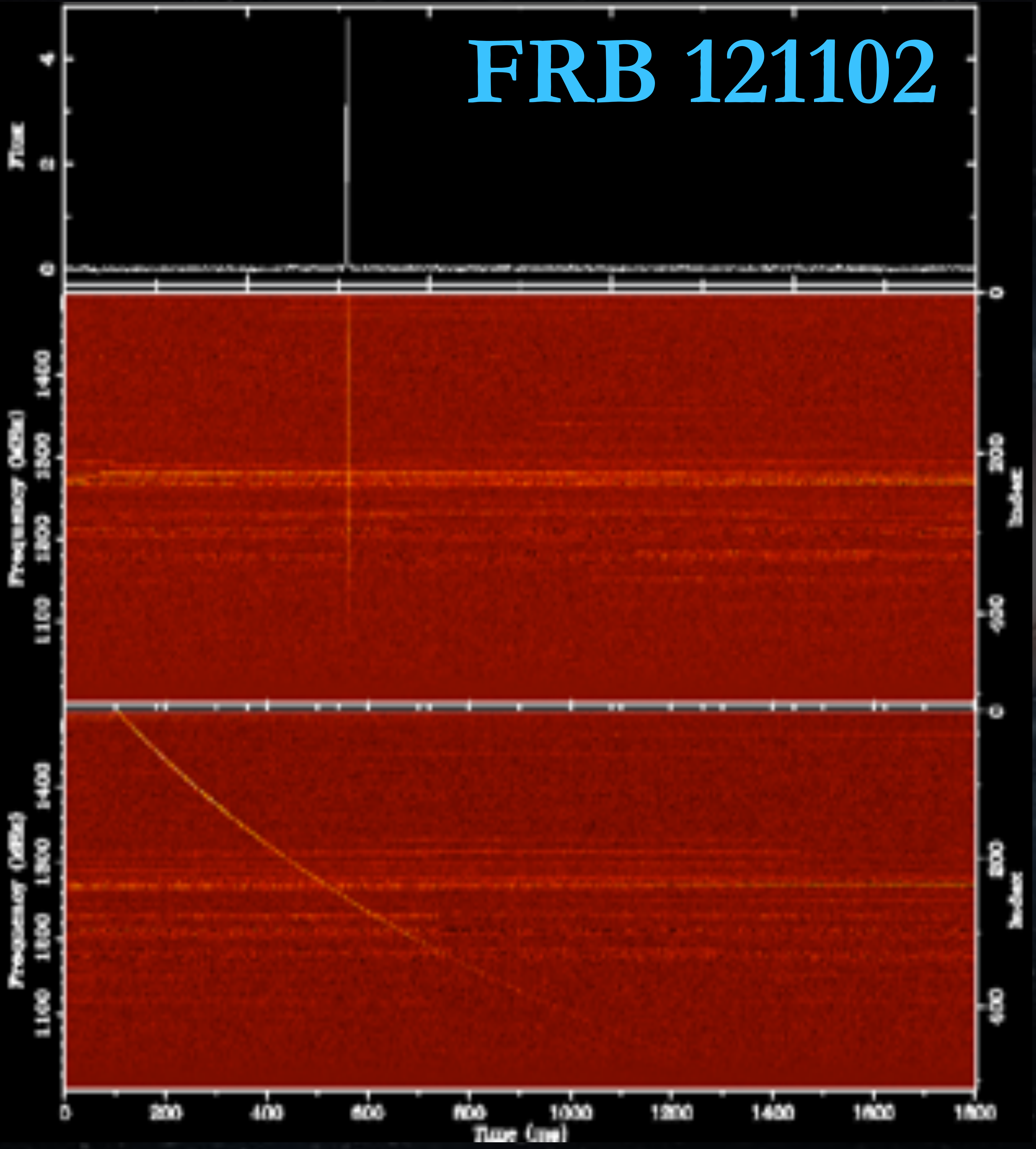


FAST reveals the high event @ >100K per day!

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

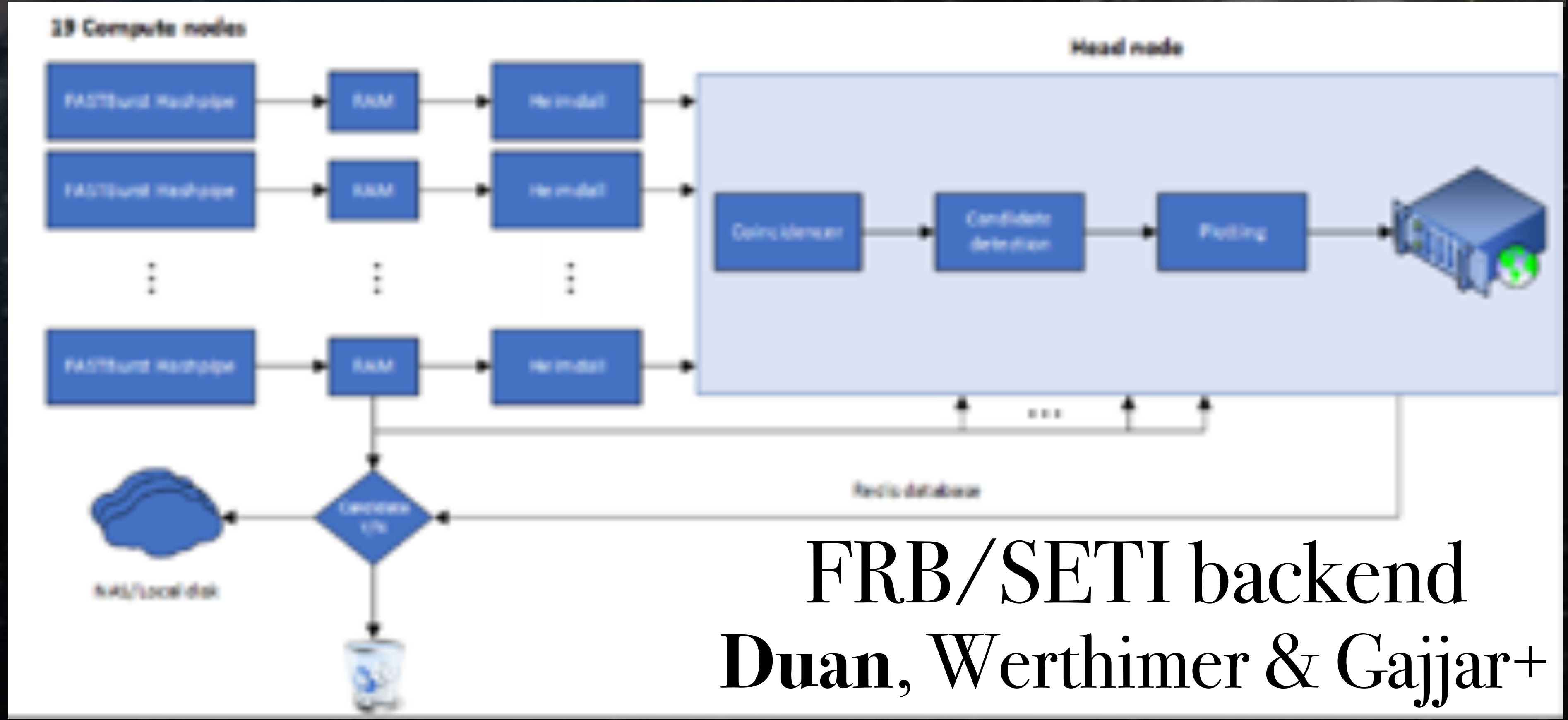
CRAFTS

S(L,z,w)↔S′(DM,Flux)
(cf. Luo+ 2018,2020)



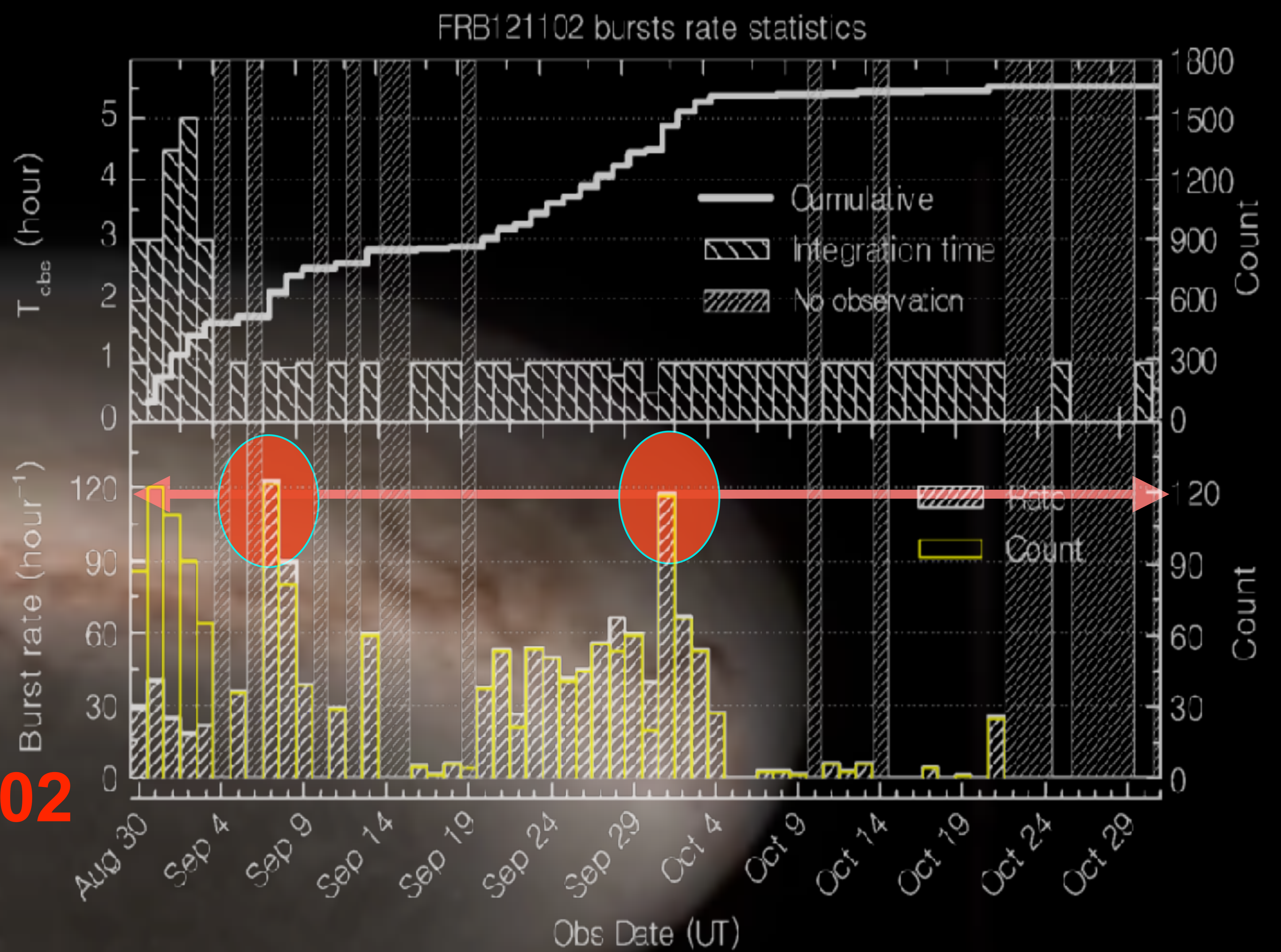
Zhang+ 2019

Li et al. 2019 ATel #*13064*



FRB/SETI backend

Duan, Werthimer & Gajjar+



FRB 121102

2021

"1652 pulses in 59 days!" - Li et al. 2021

FRB121102 Burst Energy Statistics

$$E \simeq \frac{4\pi D_L^2}{(1+z)} \mathcal{F}_\nu \nu_c = (10^{39}\ \mathrm{erg}) \frac{4\pi}{(1+z)} \left(\frac{D_L}{10^{28}\ \mathrm{cm}}\right)^2 \frac{\mathcal{F}_\nu}{\mathrm{Jy}\cdot\mathrm{ms}} \frac{\nu_c}{\mathrm{GHz}}$$

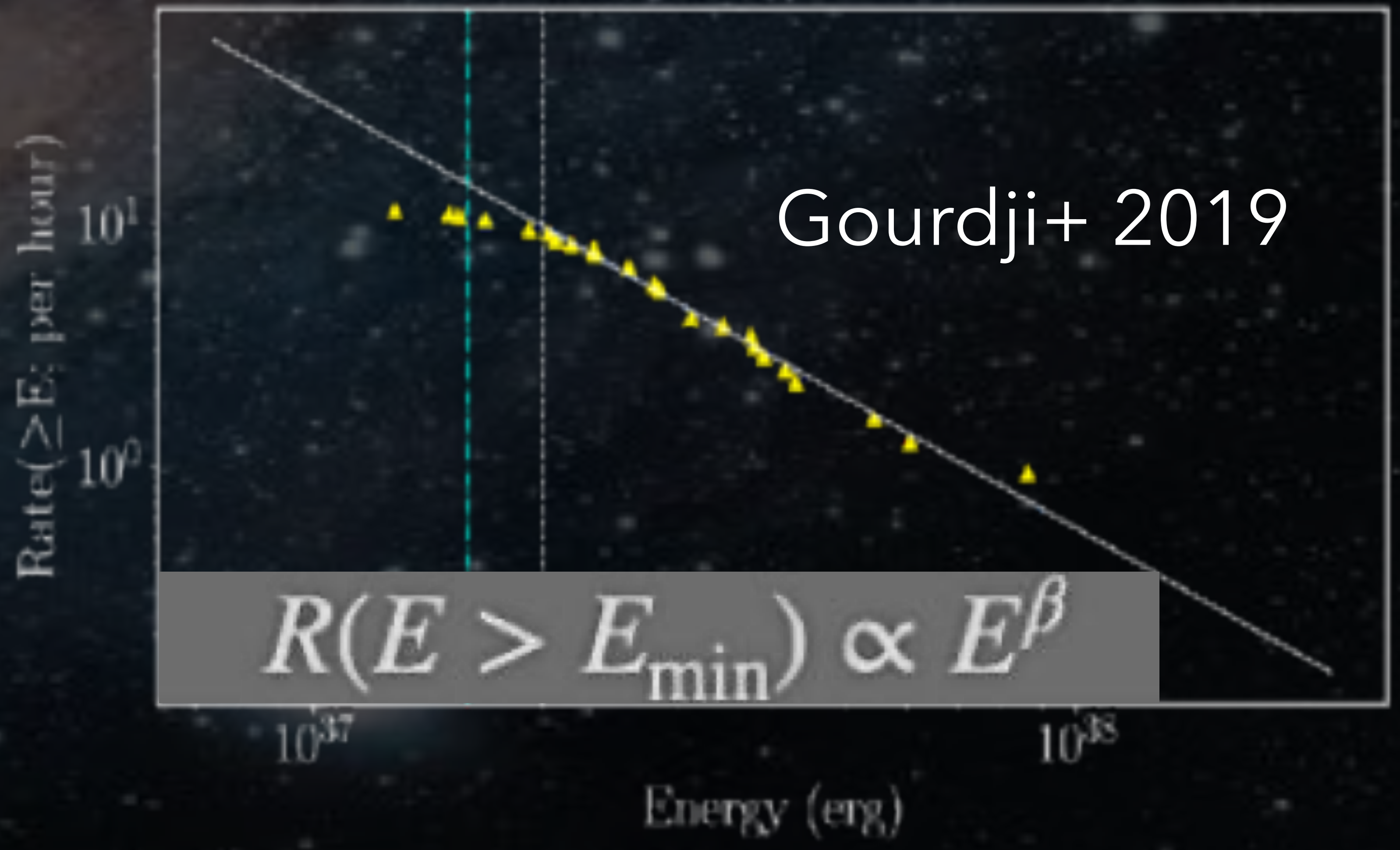
(Zhang 2018)

Cumulative burst energy distribution:

β= -0.7 JVLA, AO, GBT Law+ 2017

β= -1.8±0.3 AO Gourdji+2019

β= -1.2±0.2 Effelsberg Cruces+ 2020



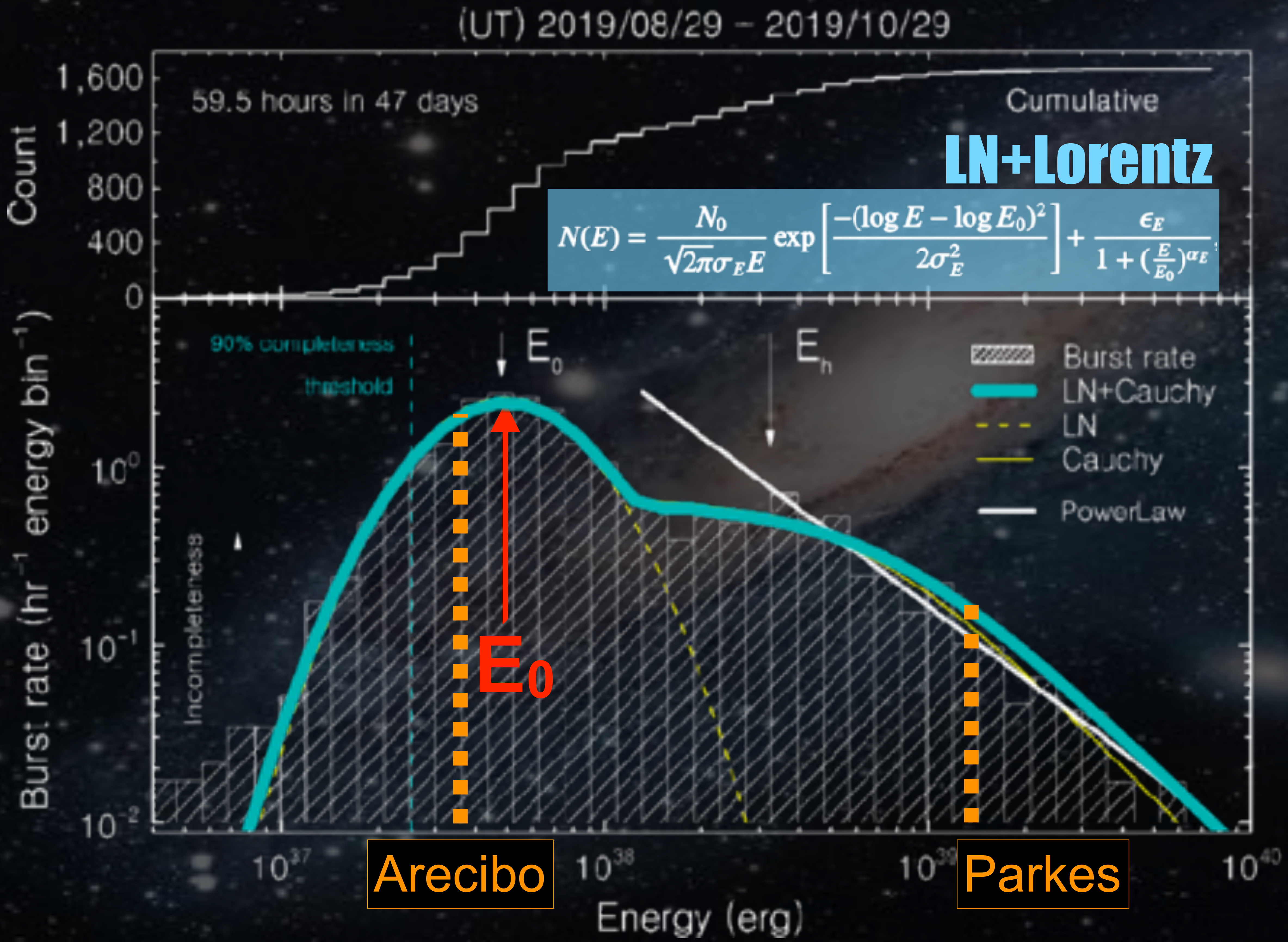
$R(E > E_{min}) \propto E^\beta$

FAST L-band 1.25GHz flux calibration

1σ = 2.1 mJy (1ms) z=0.193, D_L=949Mpc, 1Jy ms = 1.07x 10^{39} erg

7σ = 15 mJy **4×10^{36} erg < Energy < 8.0×10^{39} erg**

Burst Rate Energy Distribution - **bimodel**

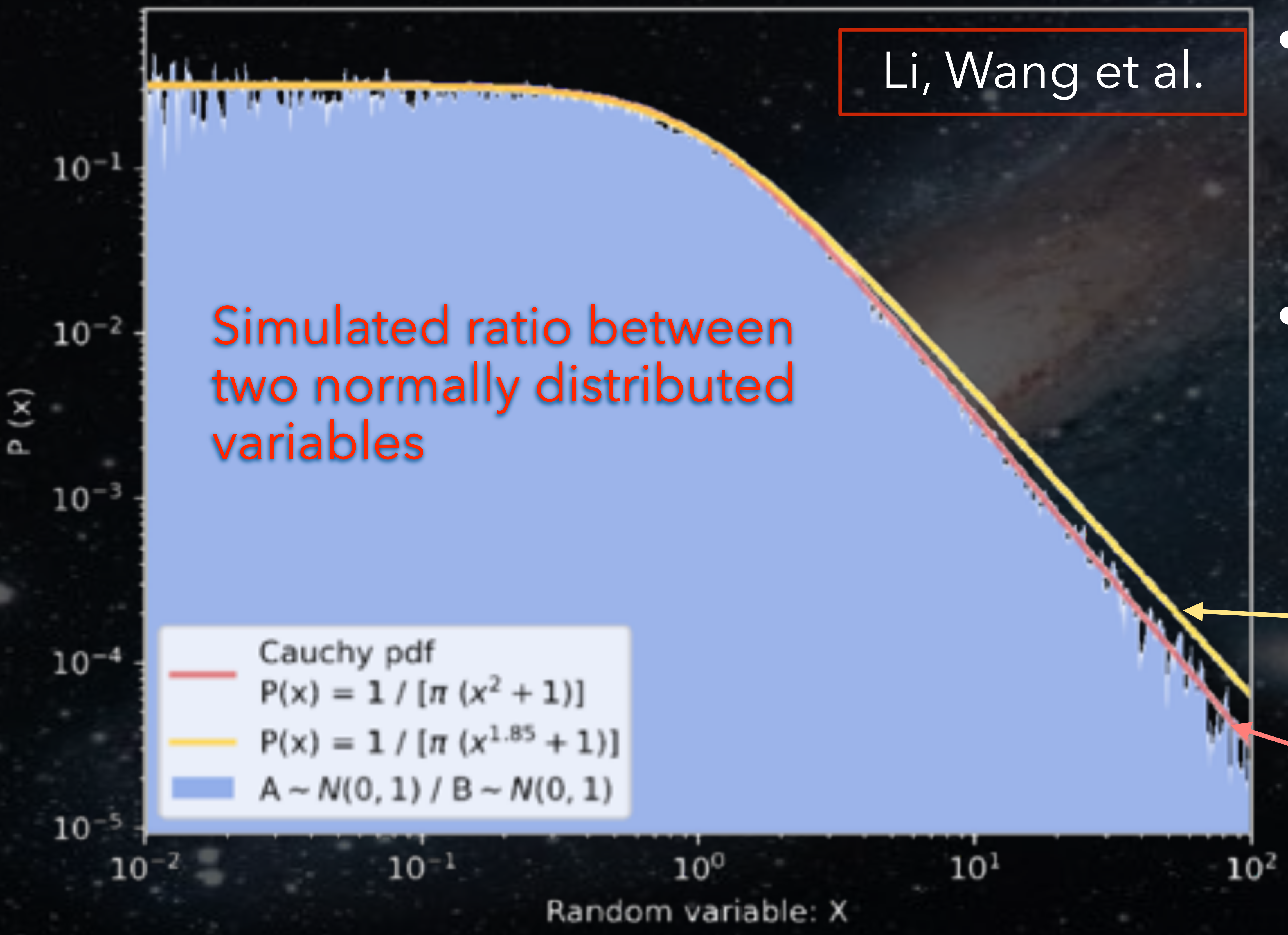


$$N(E) = \frac{N_0}{\sqrt{2\pi}\sigma_E E}\exp\left[\frac{-(\log E - \log E_0)^2}{2\sigma_E^2}\right] + \frac{\epsilon_E}{1+(\frac{E}{E_0})^{\alpha_E}}$$

Function	Energy range	Reduced χ^2	R^2
PowerLaw	F	✗ 0.689(8)	0.104(6)
	H	0.004(1) ✓	0.999(1)
Lognormal	F	✗ 0.056(9)	0.86(8)
Cauchy	F	✗ 0.438(1)	0.113(1)
Lognormal + Cauchy	F	0.037(4) ✓	0.931(7)

Li, **Wang** et al. 2021

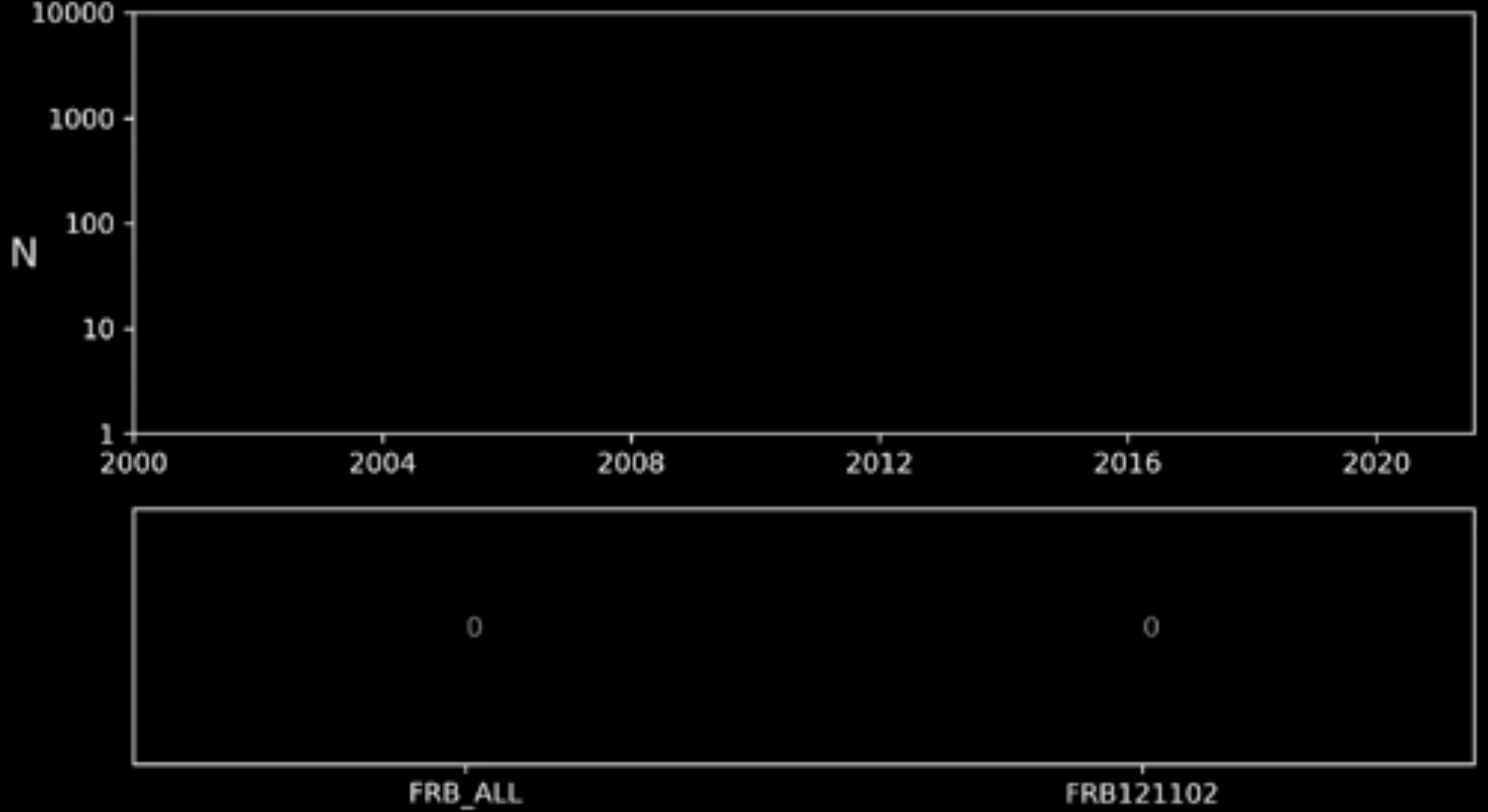
Burst Rate Energy Distribution - bimodel



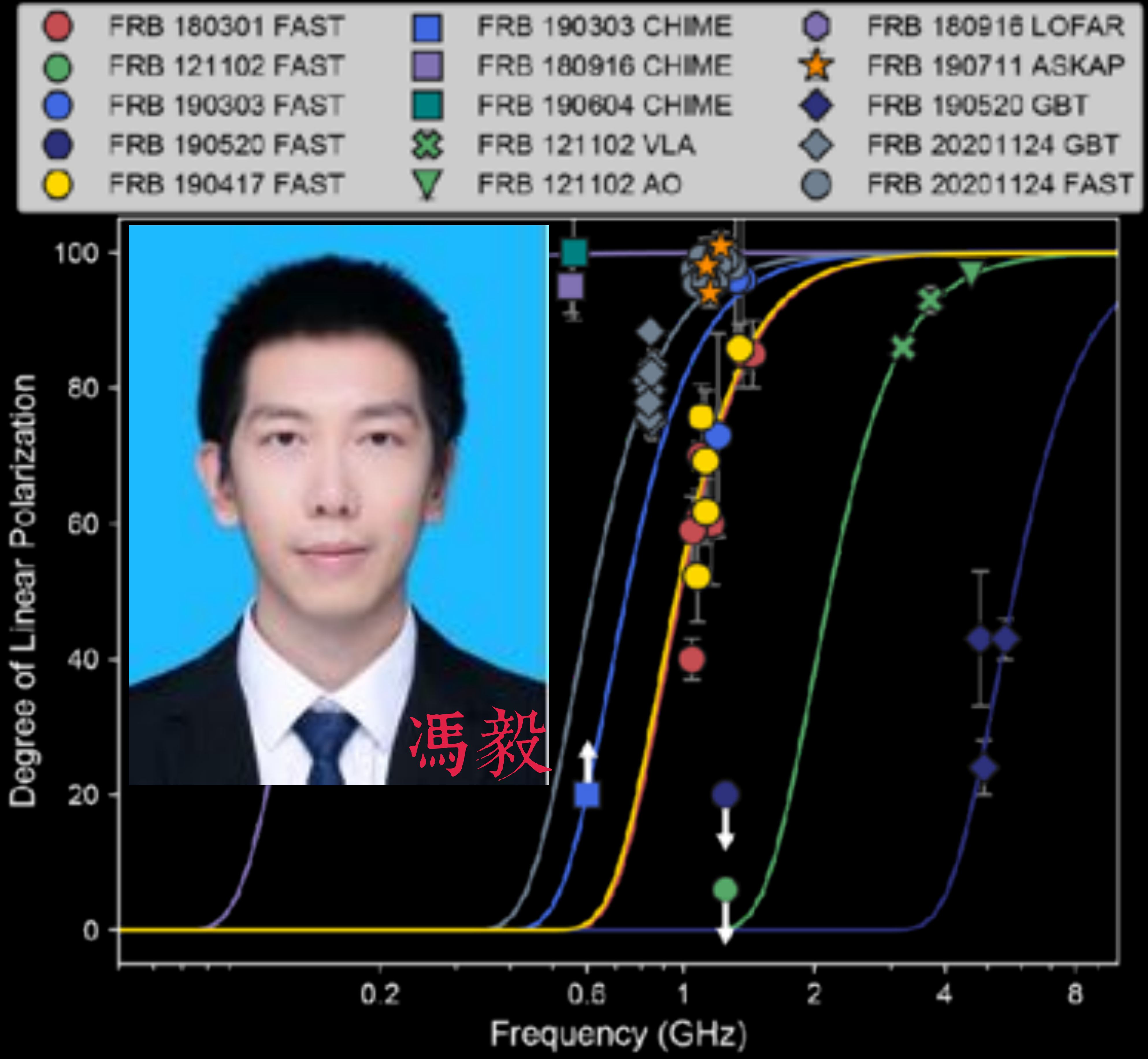
- The Lorentz/Cauchy function describe the ratio between two normally distributed variables
- The best-fit index of 1.85 (generalized Cauchy function) is close to 2 within one σ ~ 0.3

$$p(x) = \frac{1}{\pi(x^{\alpha} + 1)}$$

$$p(x) = \frac{1}{\pi(x^{2} + 1)}$$


10000
1000
100
N
10
1
2000
2004
2008
2012
2016
2020
0
0
FRB_ALL
FRB121102


nature



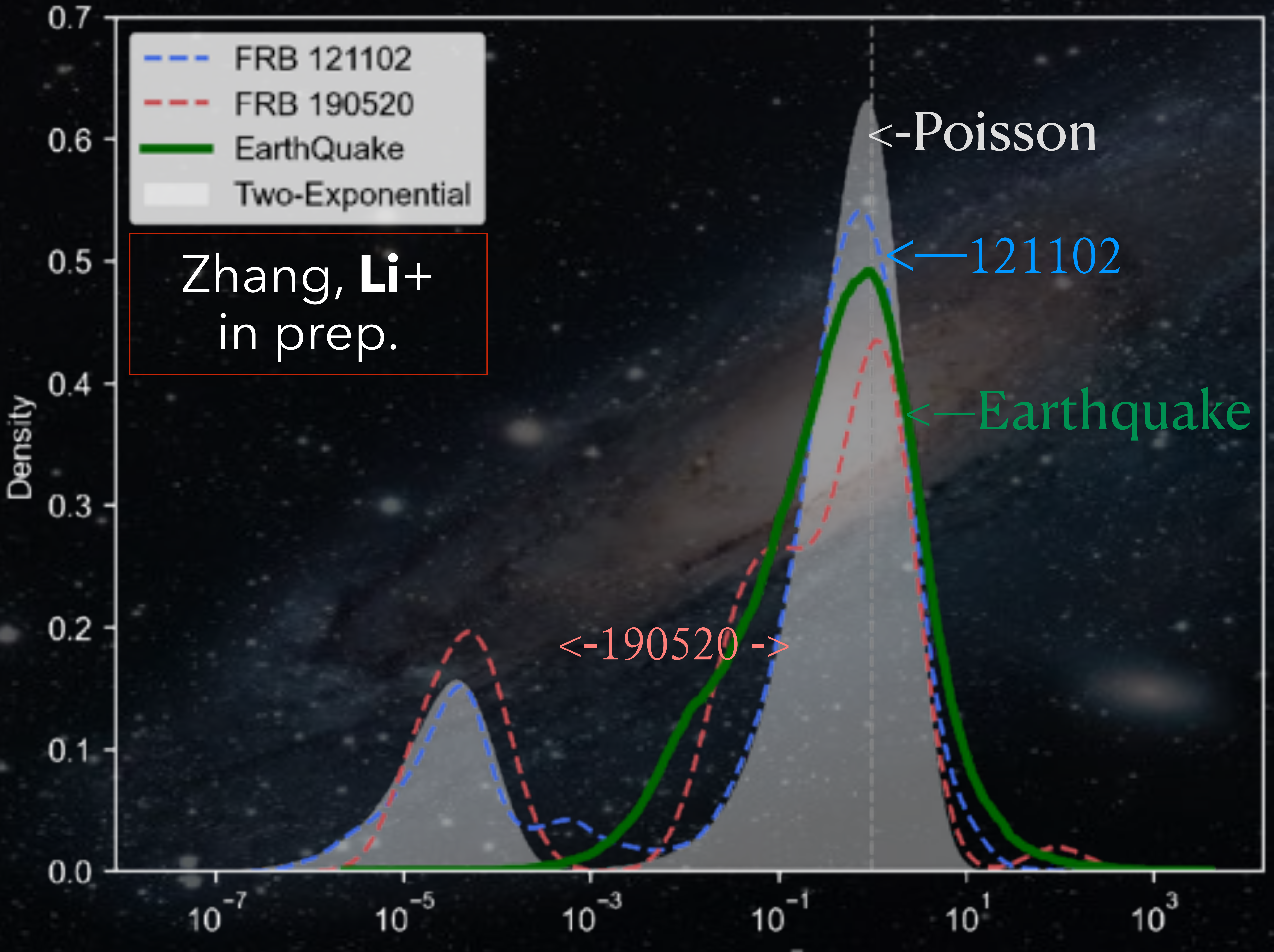
FAST揭示重复FRB偏振特性

- 复重复暴的偏振度存在由高频向低频减弱的趋势。我们提出了解释FRB偏振频率演化的统一机制，由一个参数描述，揭示FRB环境，限制其起源。

$$\%L \propto \exp(-2\lambda^4 \sigma_{RM}^2)$$

- 科学》杂志三位审稿正面评价：
  - “certainly **novel** and deserves to be published in **Science**；
  - “**Interesting** development”
  - This is a **beautiful** result that provides a **huge** clue … **sensational** …”

Feng & Li* et al. 2021
Science, under review



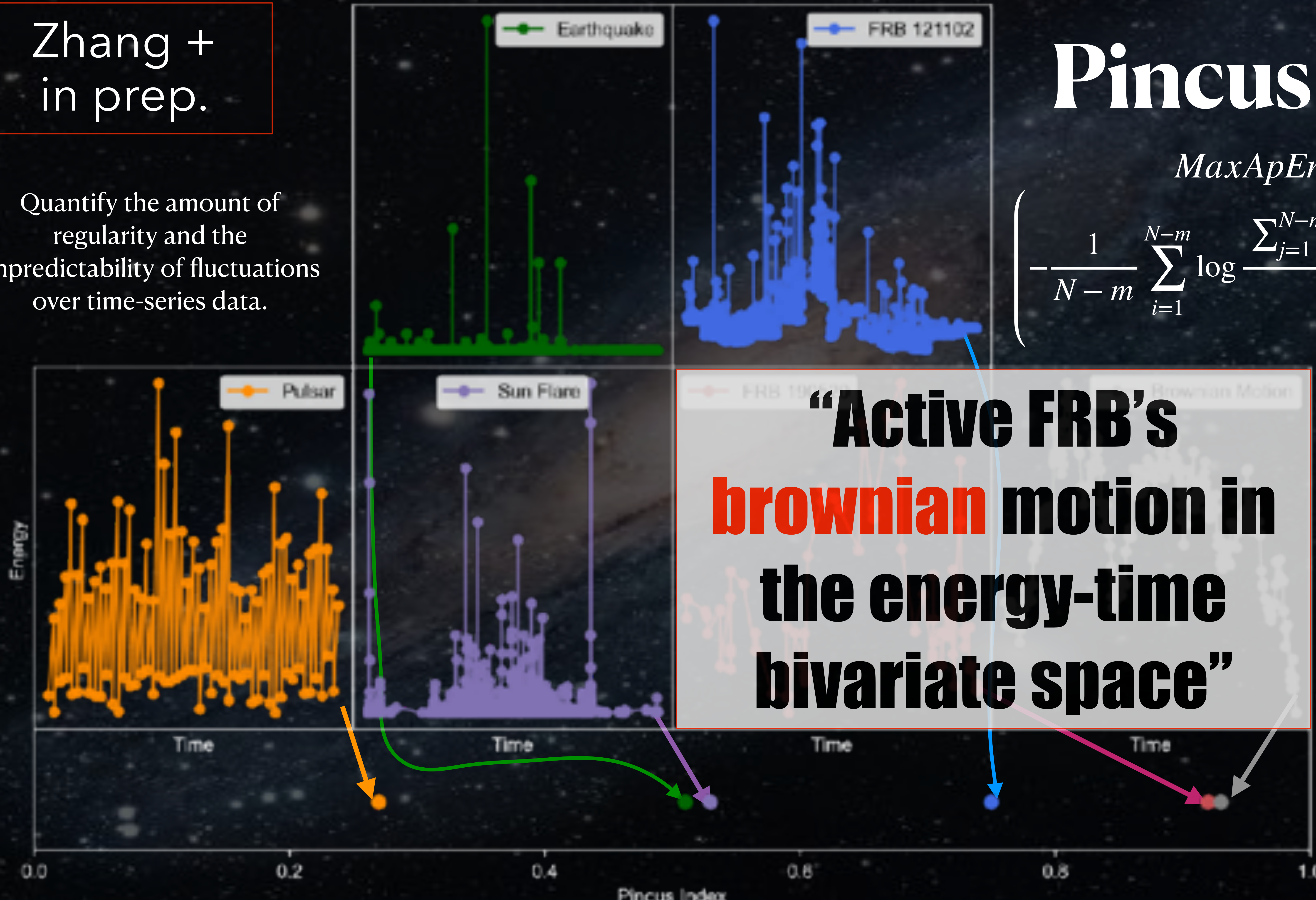
Normalized Waiting Time of two FRBs and Earthquake

Zhang + in prep.

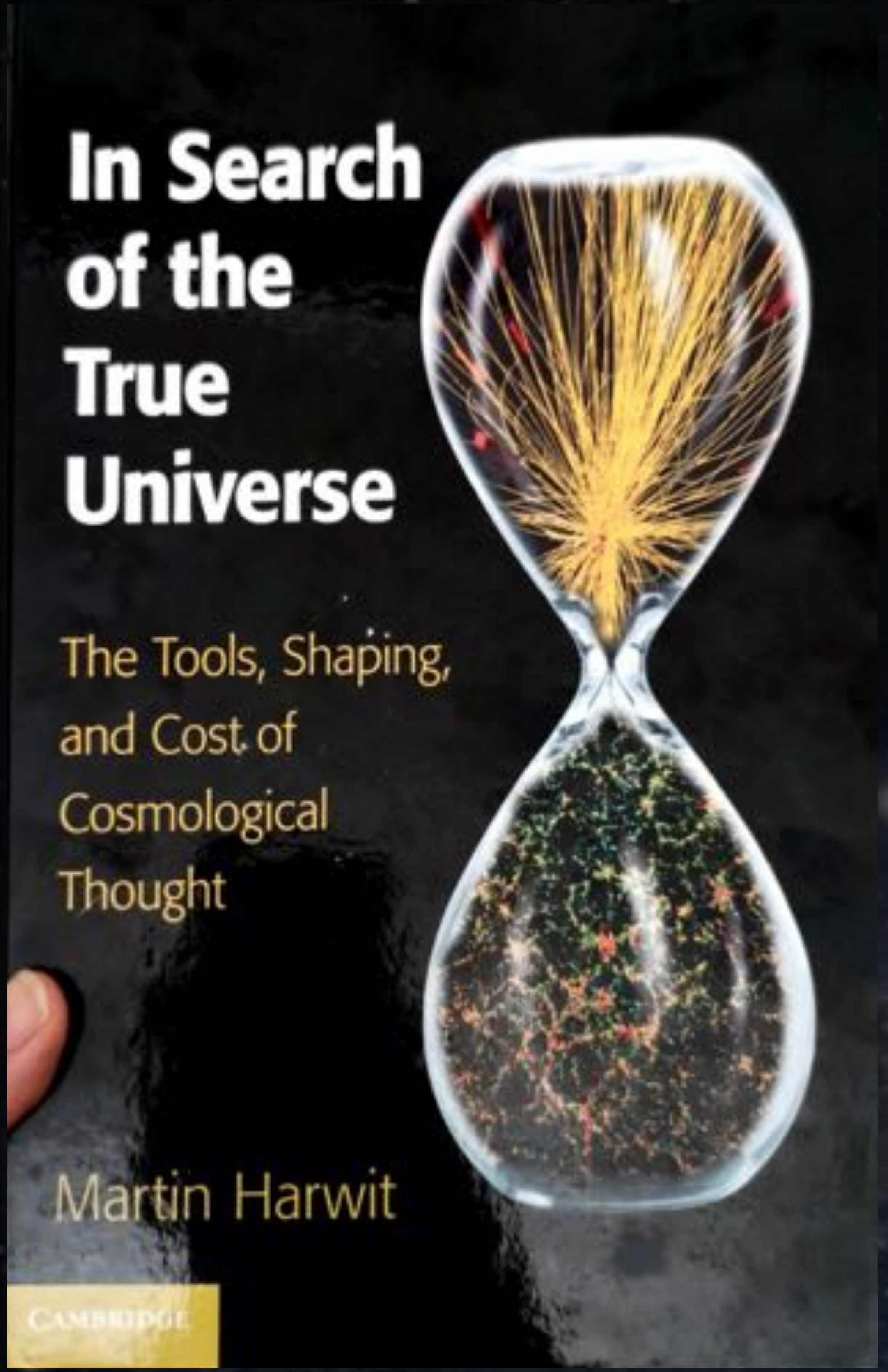
Pincus Index

Quantify the amount of regularity and the unpredictability of fluctuations over time-series data.

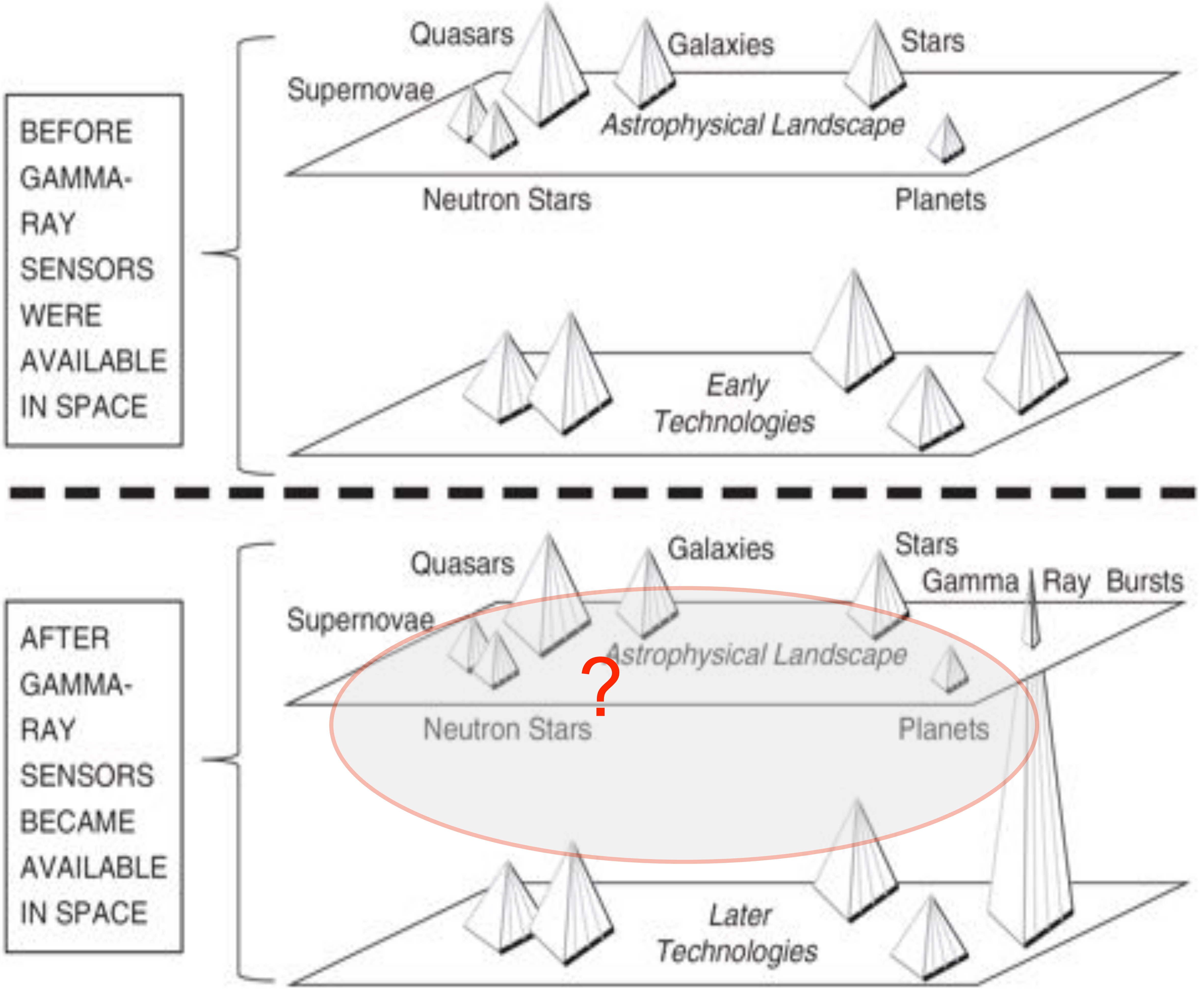
$$MaxApEn = \max_{r} \left(-\frac{1}{N-m} \sum_{i=1}^{N-m} \log \frac{\sum_{j=1}^{N-m} dist(x_j, x_i) < r}{N-m} \Bigg|_{m}^{m+1} \right)$$



"Active FRB's brownian motion in the energy-time bivariate space"



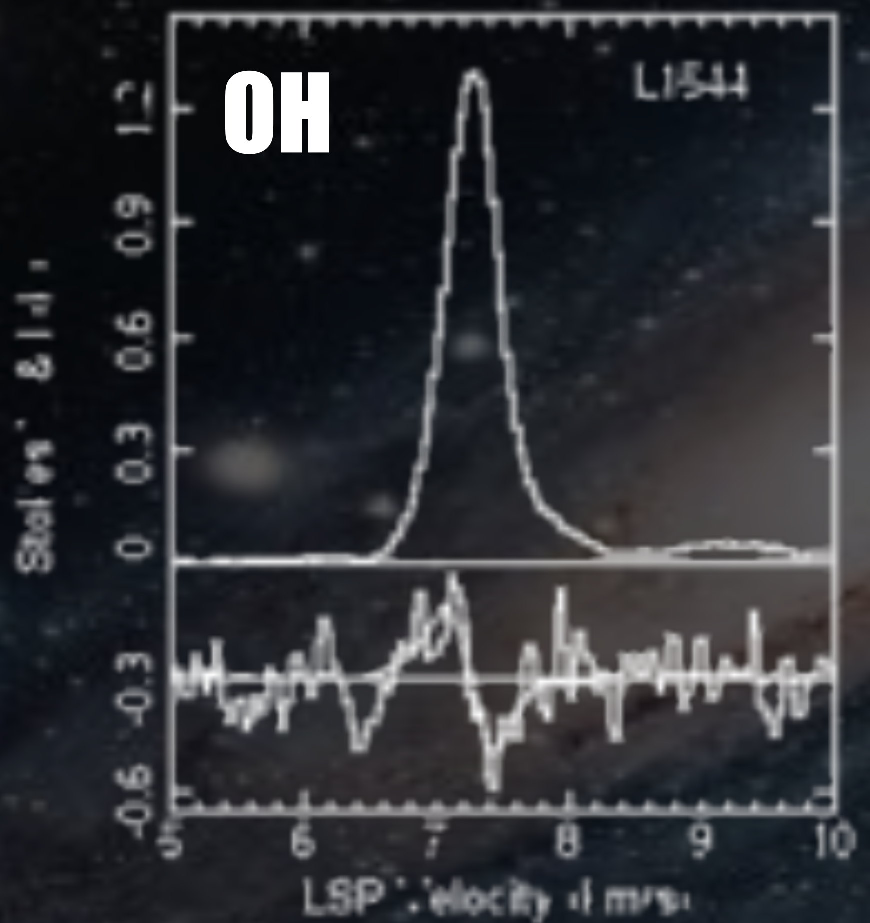
Martin Harwit

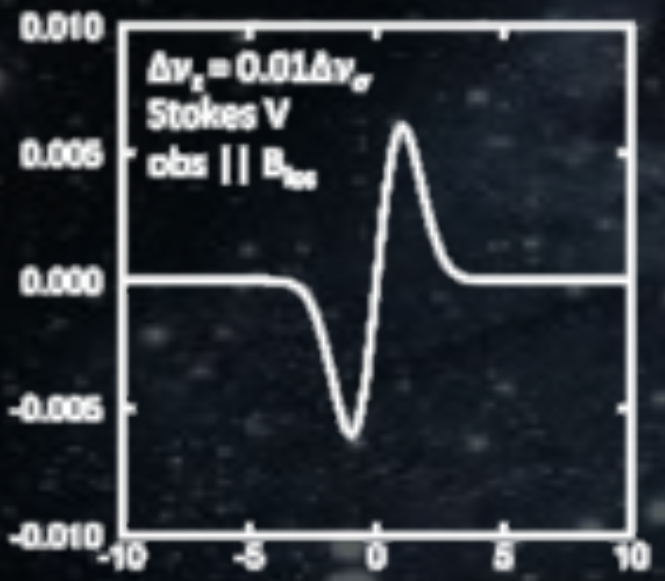


Zeeman Effect (**B**) in Molecular Gas

- 测量星际磁场是世界难题，尤其分子气体。
- 目前直接探测的原理只有一种：赛曼效应。成功测量到赛曼效应的分子只有三种：OH，CN，和CCS。
- 利用阿雷西博望远镜，Li & Goldsmith 命名了 HINSA（HI Narrow Self-Absorption 2003）方法示踪冷原子气体，并成功利用其探测分子云

HINSA极有潜力成为赛曼探针。



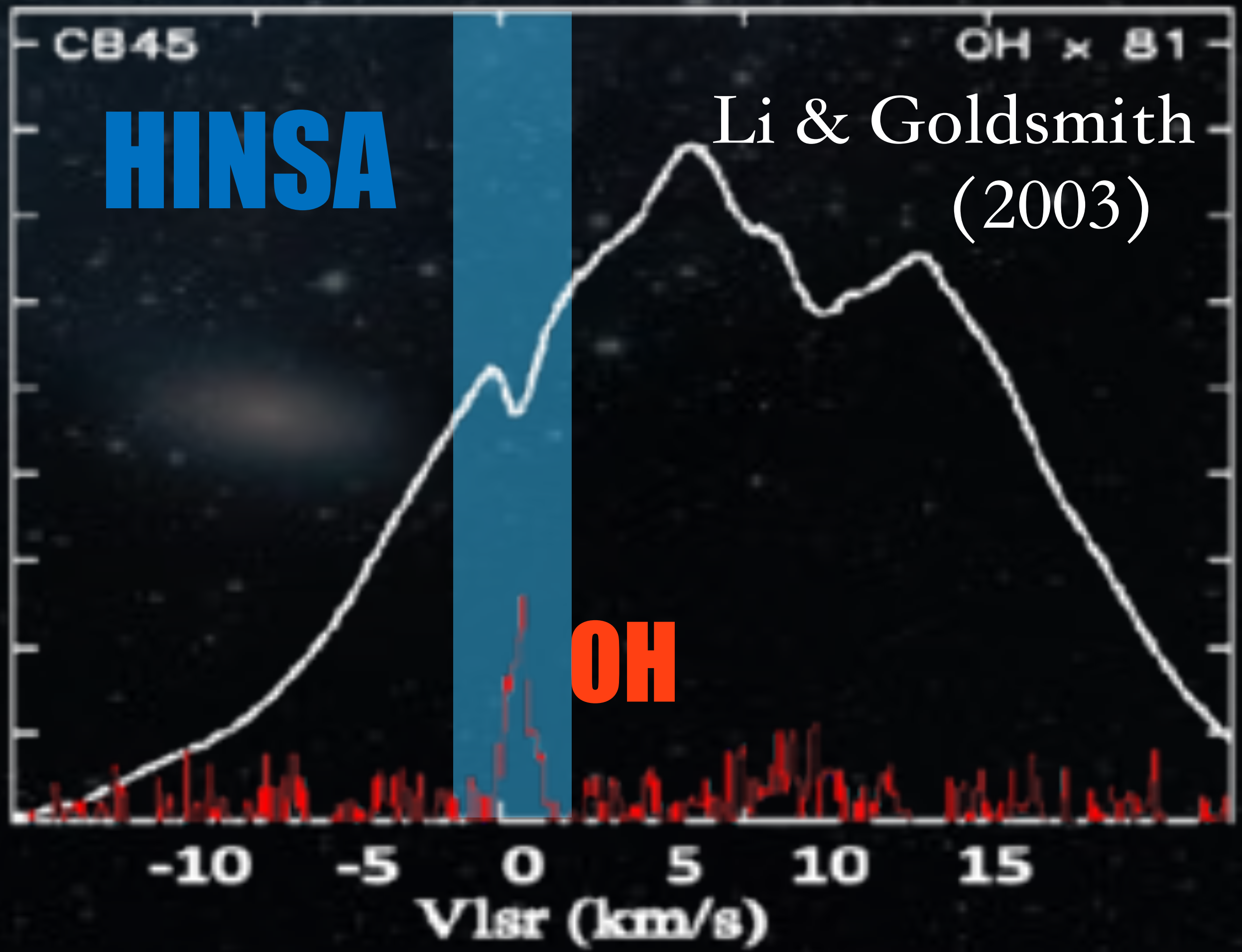


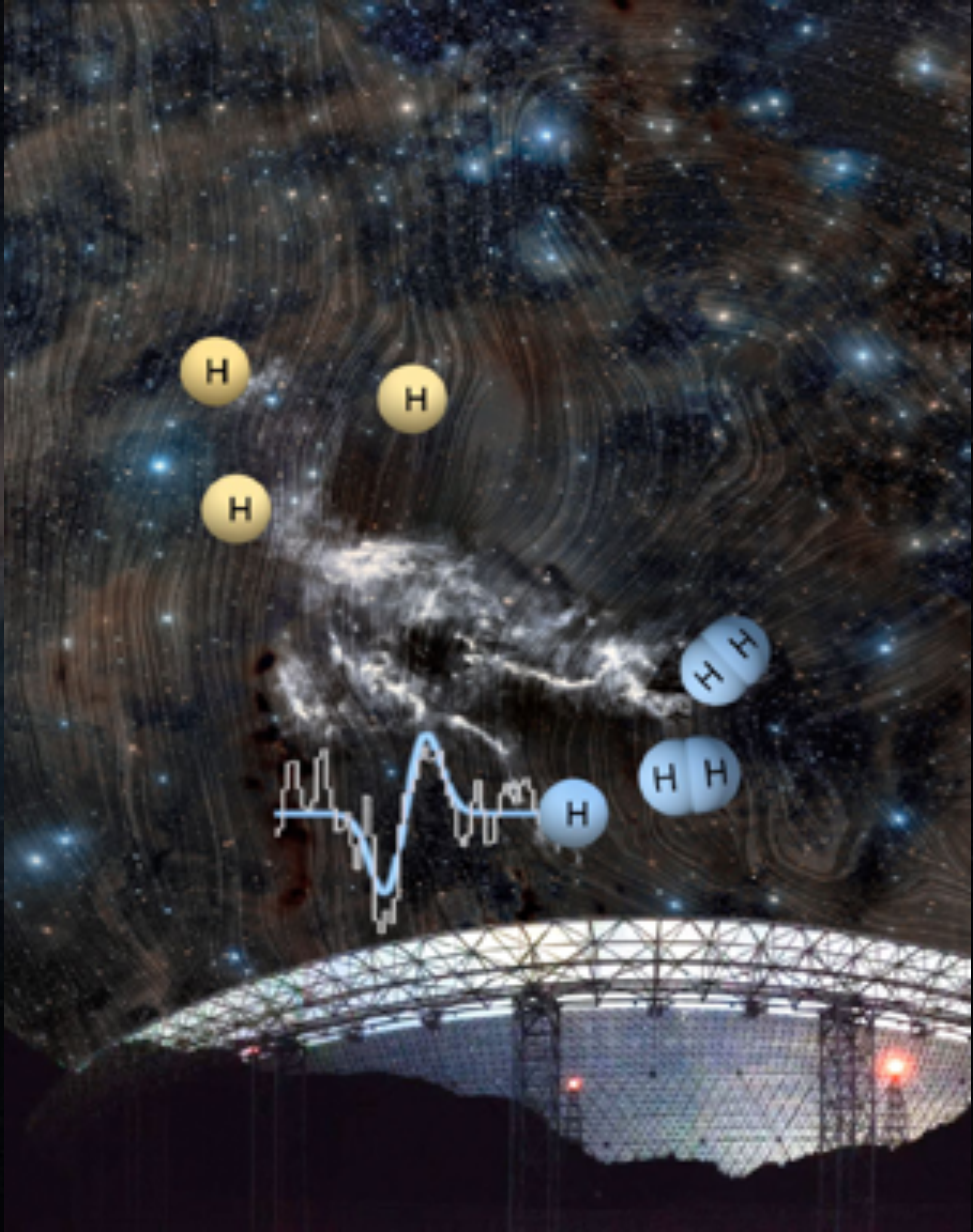
OH Crutcher et al. 2000

CN Crutcher et al. 1999

CCS Nakamura et al. 2019

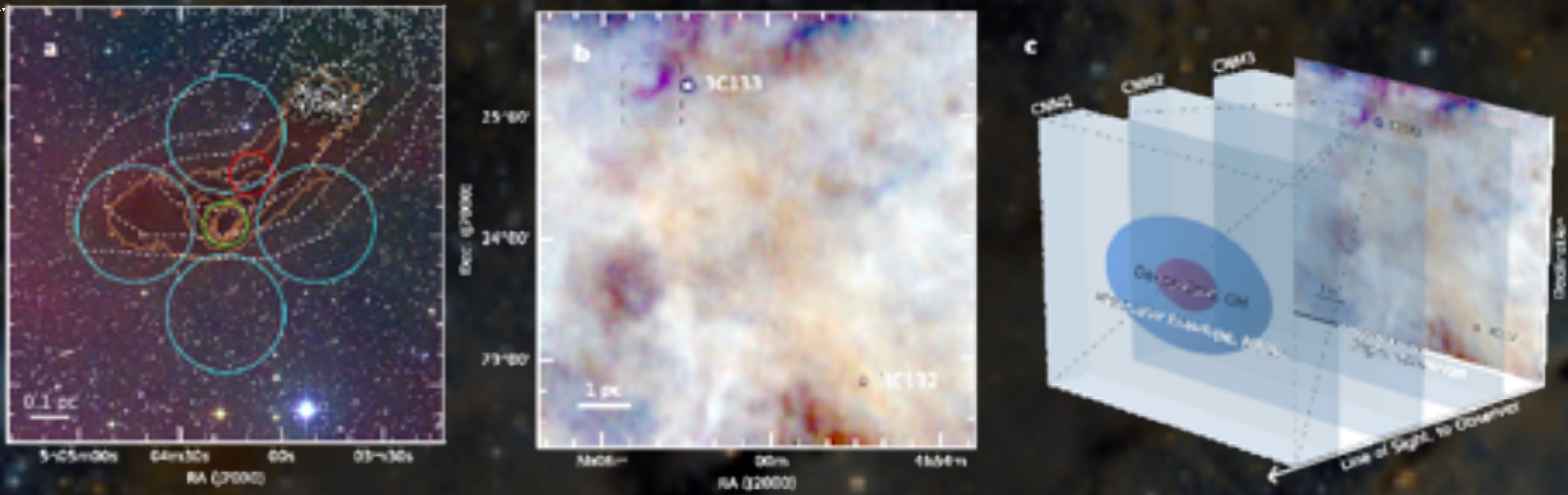
现有3种Zeeman探针

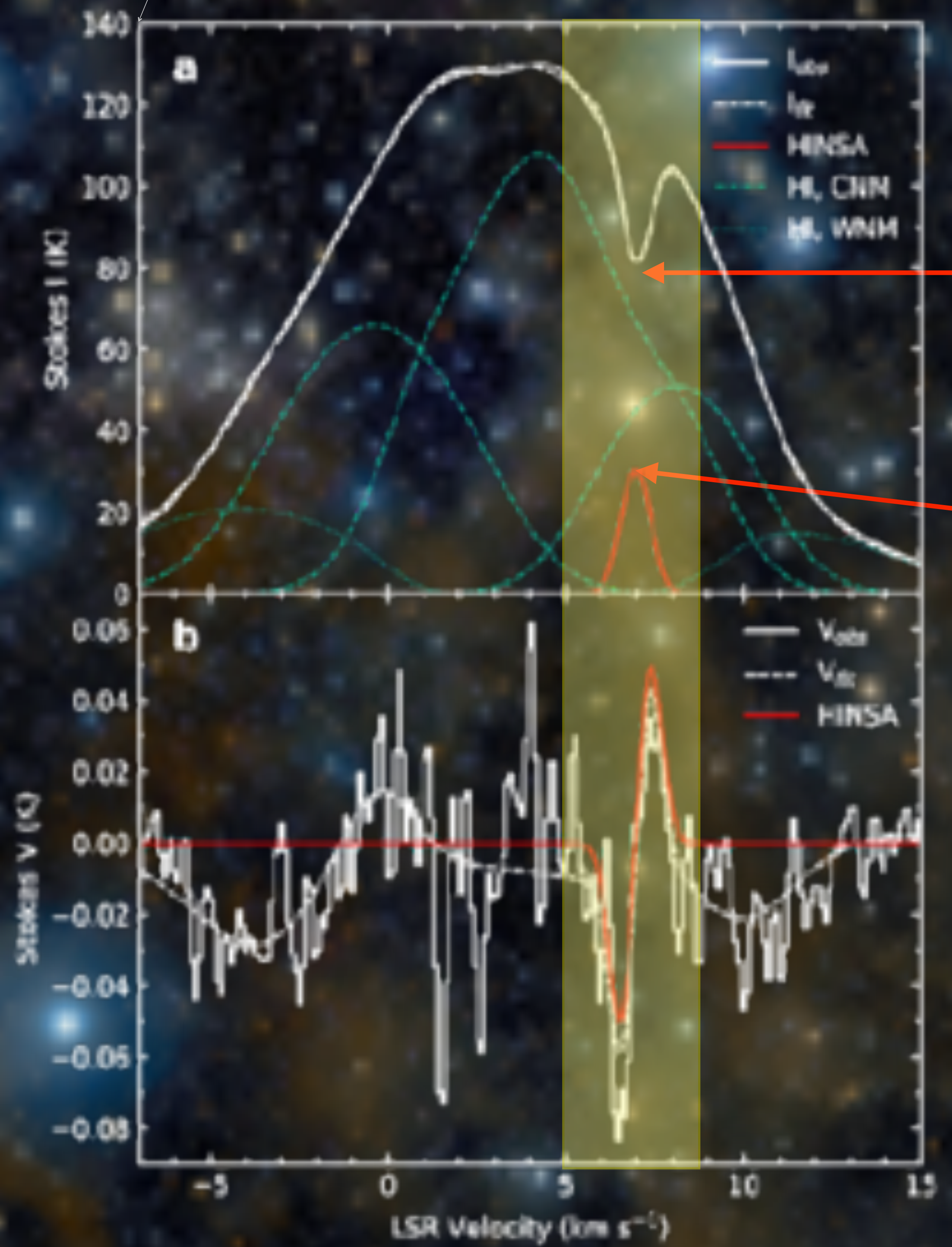




- Reconstruct Muller matrix (Heiles)
- Calibrating the Zeeman responses, particularly to extended sources
- Give HINSA experiment another go

Lyn 1544





HI Narrow Self–Absorption HINSA

Li & Goldsmith (2003)

- First detection of magnetic field strength in dense molecular gas with an atomic tracer (HINSA): **B = 3.8 ± 0.3 μG**
- Revealing **a coherent B** structure from atomic gas to dense molecular gas, suggesting that star forming clouds achieve **supercritical state** earlier than predictions from canonical models

(Ching, **Li**, Heiles+ 2021 **Nature** accepted)

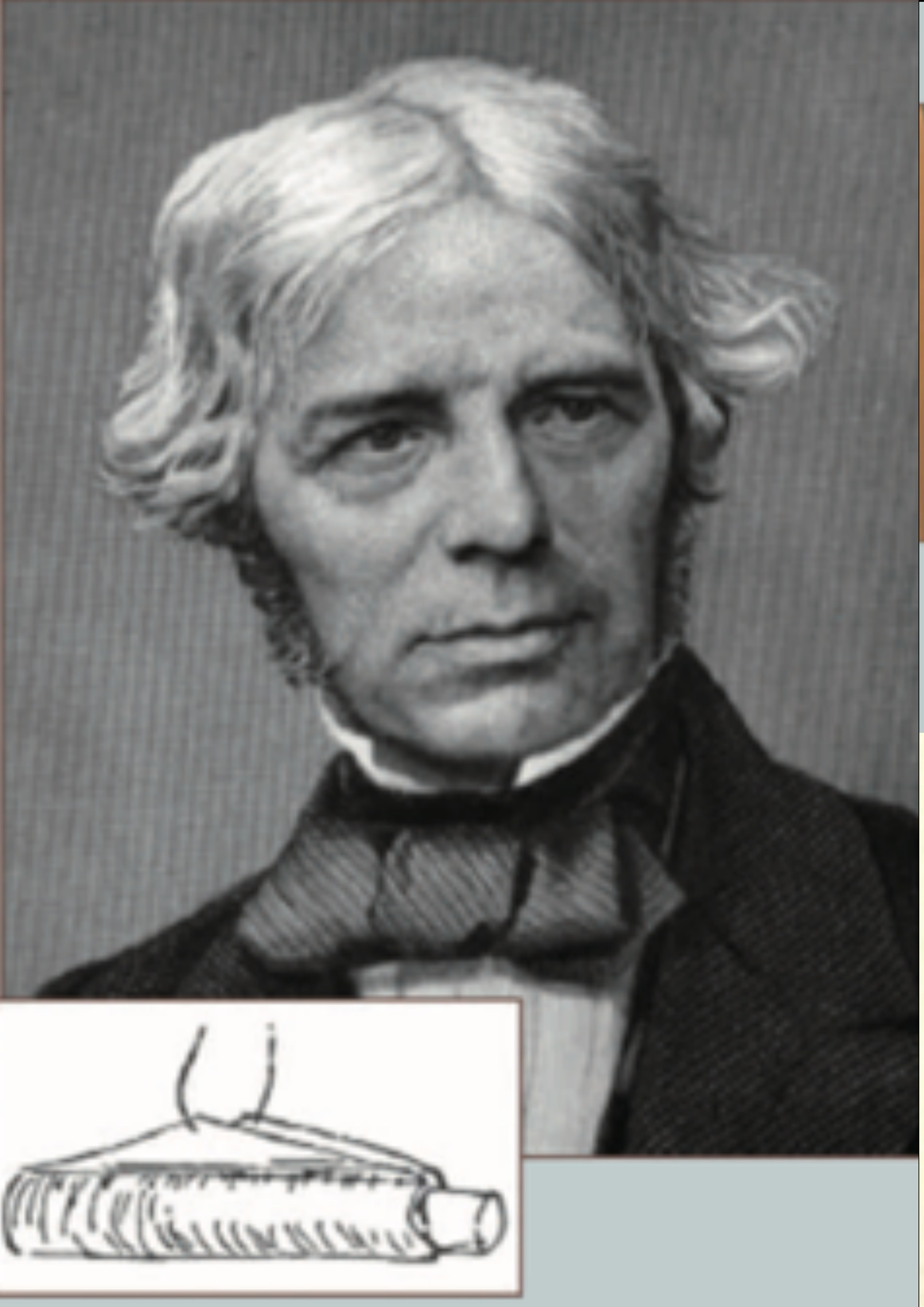


图2　迈克尔·法拉第的蚀刻肖像，插入部分展示的是他在1831年10月17日的日记中的一张图，这一天他发现了电磁感应现象

图1　法拉第的《电学的实验研究》三卷本，分别发表于1839年，1844年和1855年，右侧是第一卷的扉页

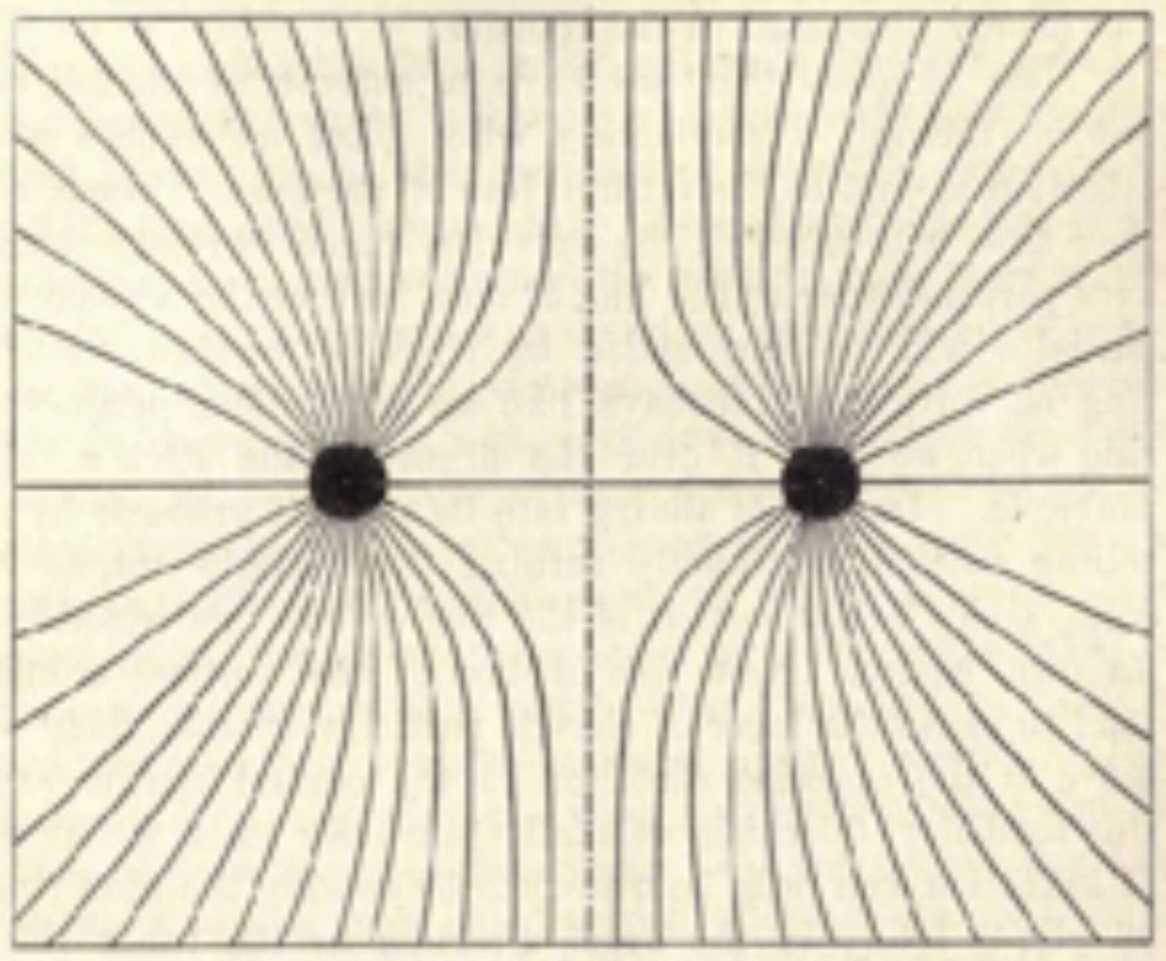


Fig. 18.

I am obliged to **feel my way** by **facts** placed closely **together.**

Faraday 1822

The way in which Faraday made use of his idea of lines of force in coordinating the phenomena of magneto-electric induction shows him to have been in reality a **mathematician of a very high order**—one from whom the mathematicians of the future may derive valuable and fertile methods. . . .

Maxwell 1867