Dynamic Universe

from Galileo to FAST/Cosmic Antennae

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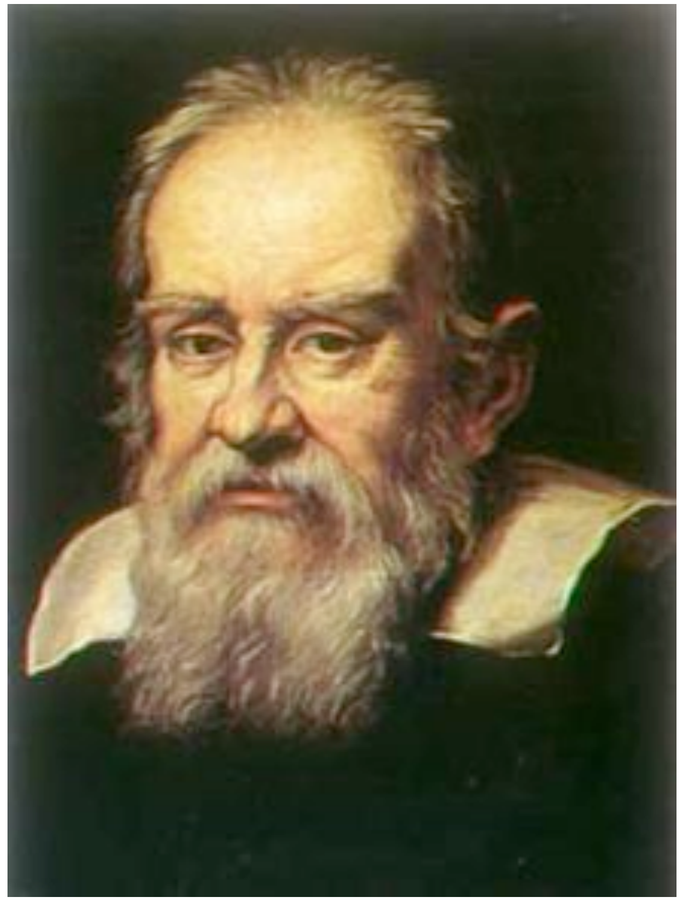
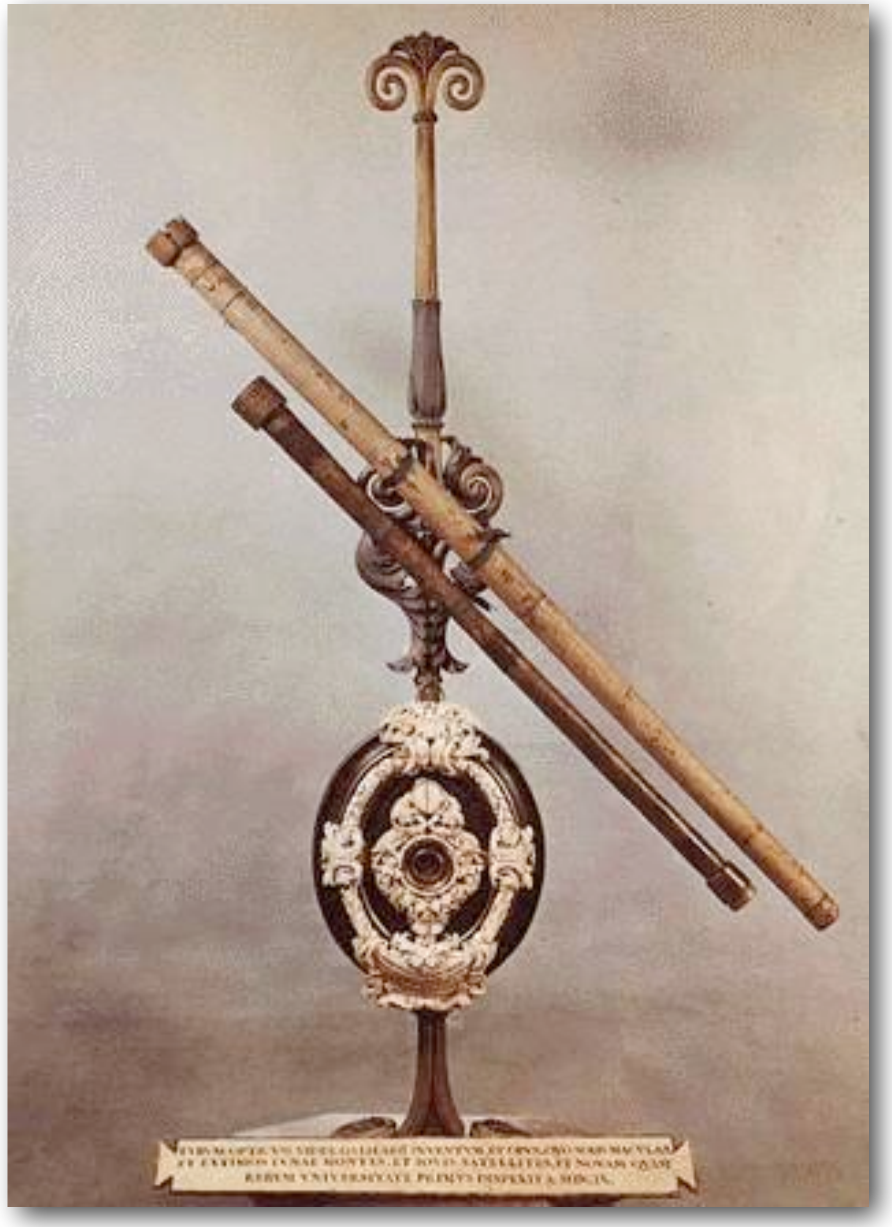
Department of Astronomy, Tsinghua University

Cosmic Antennae

Galileo Galilei 伽利略

1564 – 1642 Italian astronomer, physicist and engineer, polymath



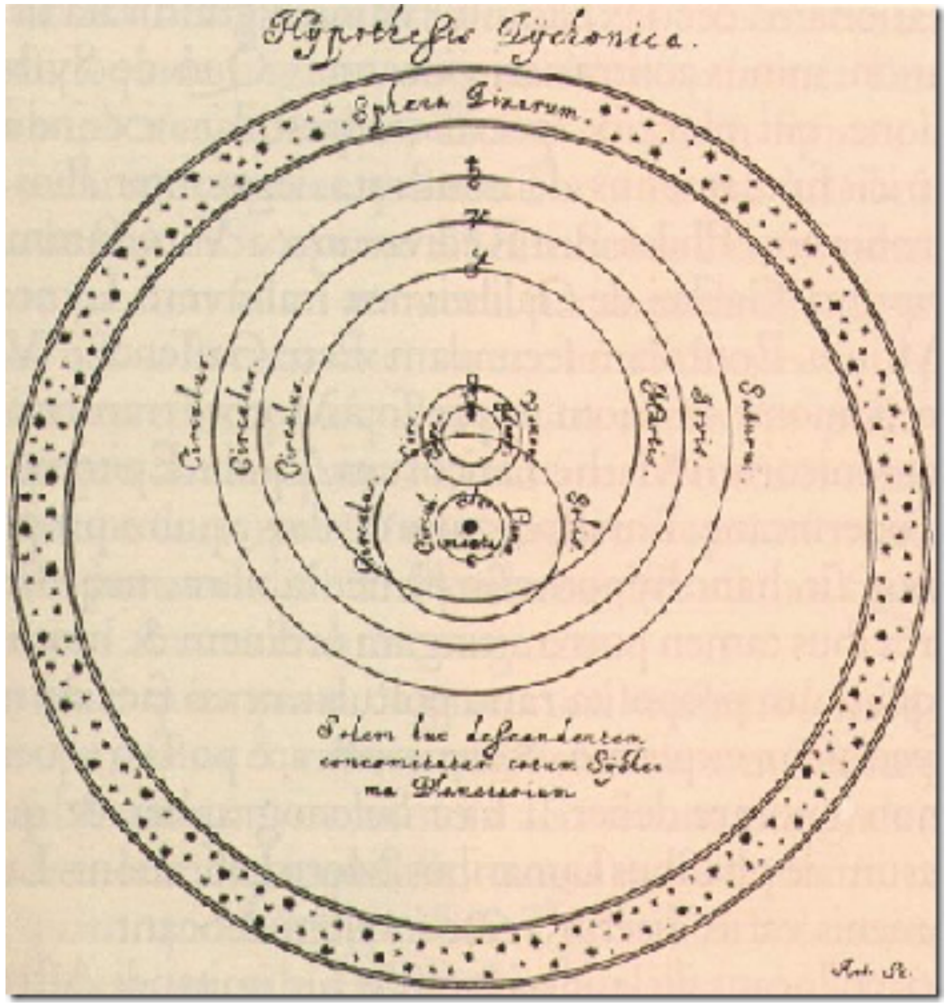


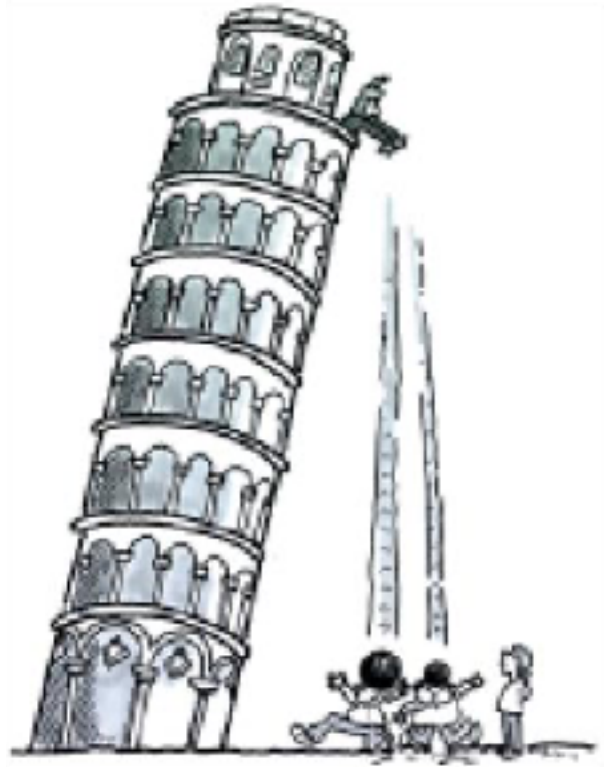
宗教裁判所
Inquisition

伽利略

eppur si muove 1633

Au da city



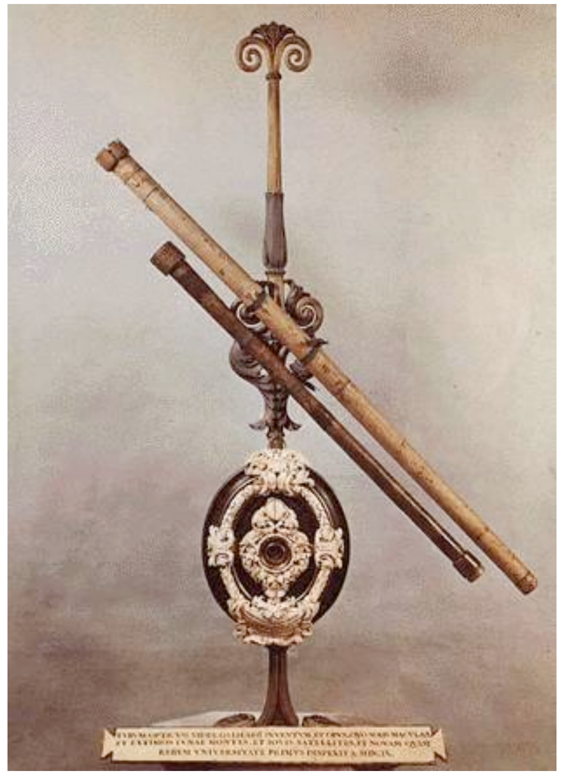


原理

Physics

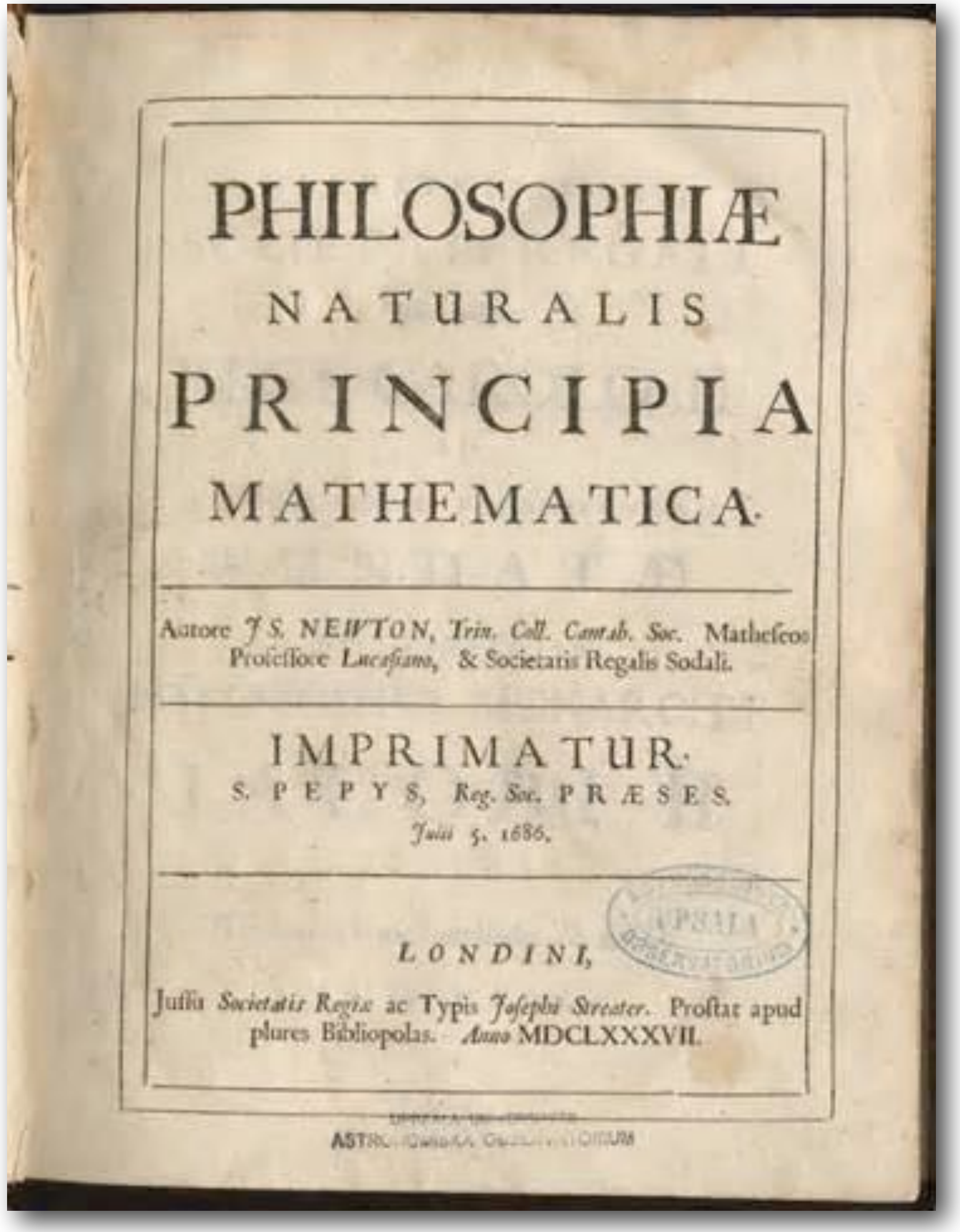
发现

Astronomy



Newton

(1642 – 1726) mathematician, physicist, astronomer, alchemist, theologian

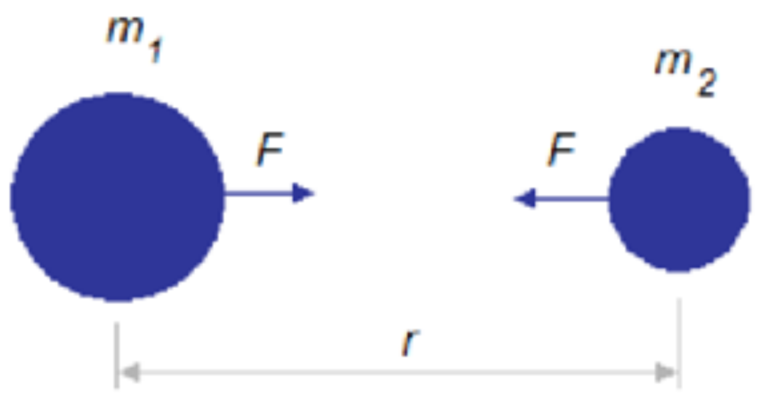

PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

Autore *J S. NEWTON*, *Trin. Coll. Cantab. Soc.* Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

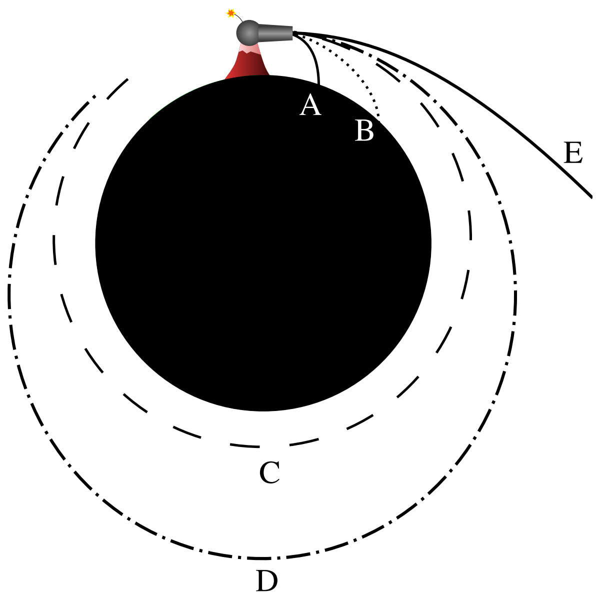
IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,

Jussu *Societatis Regiæ* ac Typis *Josephi Streater*. Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.



$$F = G\frac{m_1 m_2}{r^2}$$



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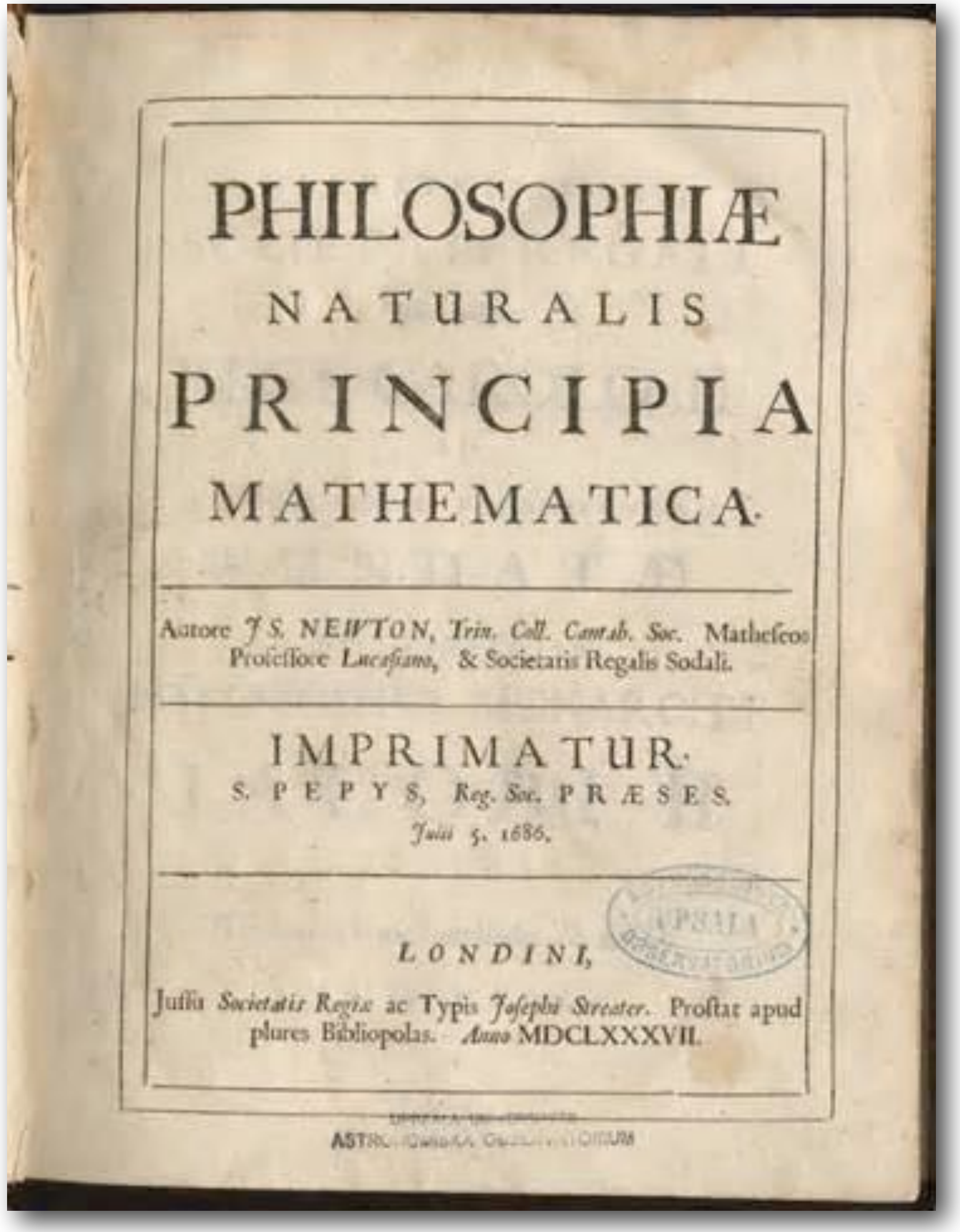

PHILOSOPHIÆ
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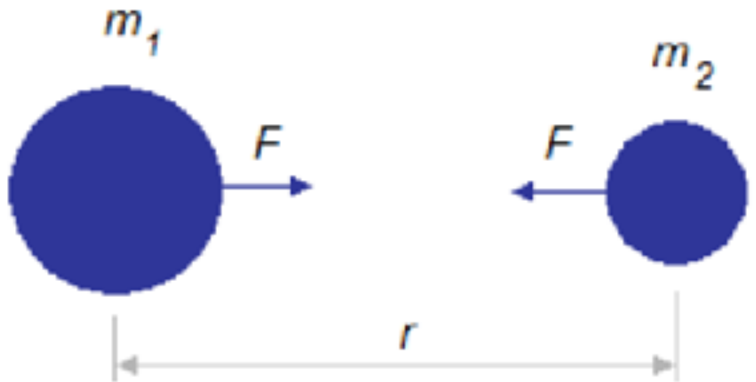

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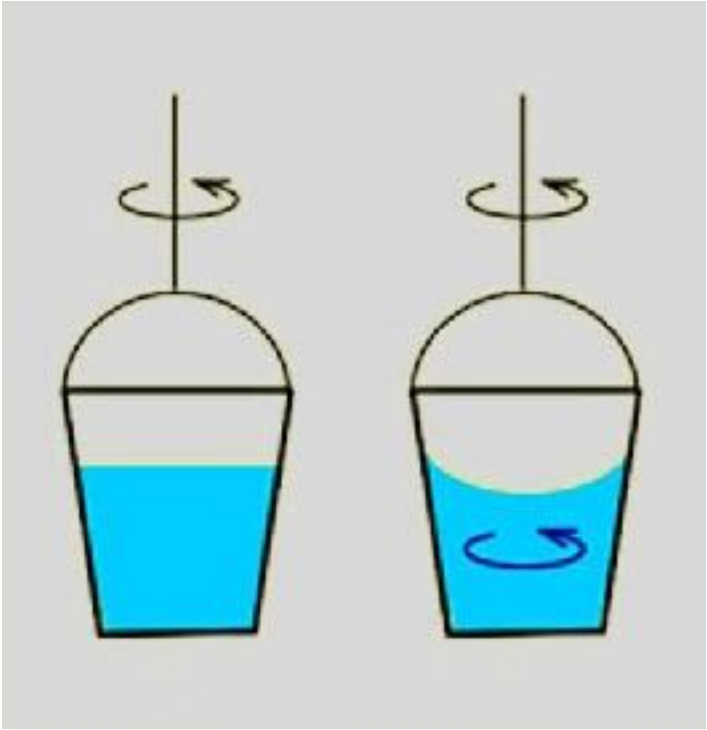
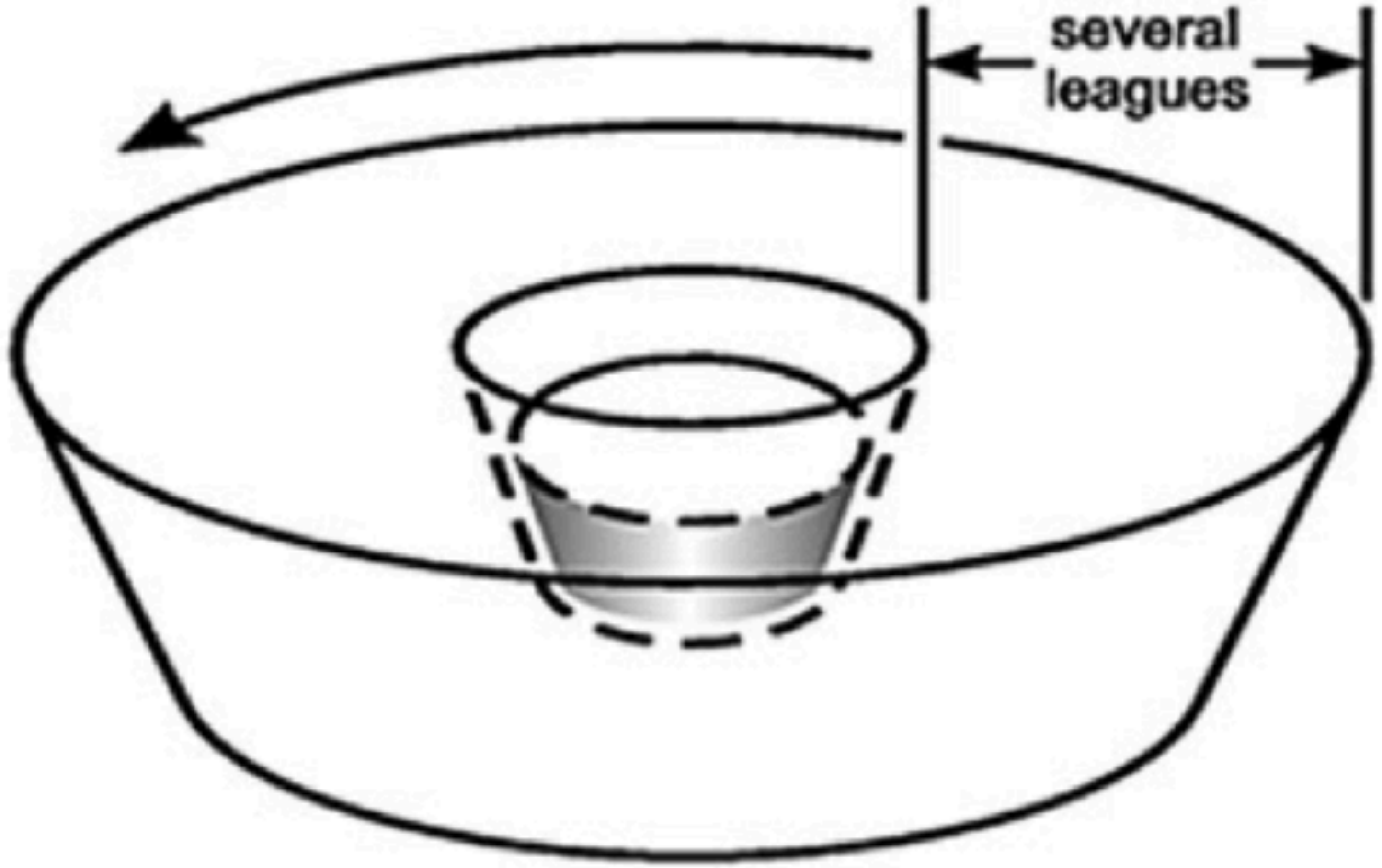


Ernst Mach

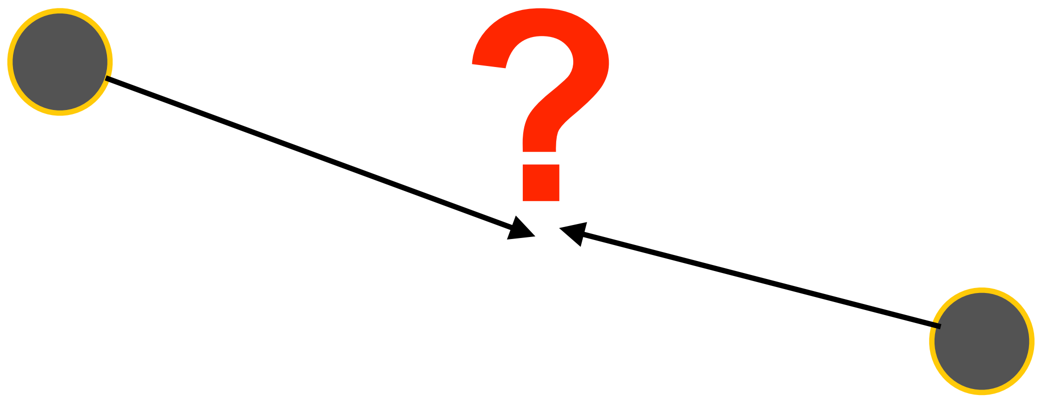
(1838 – 1916) Austrian German; physicist and philosopher



"Space, Time, and Spacetime" edited by Petkov (chapter: Overduin)

Ernst Mach (1838–1916) and his revision of Newton's bucket experiment: would the water still climb up the walls if the bucket were *arbitrarily large and massive?*

Everitt et al. (2011) *"Gravity Probe B: Final Results of a Space Experiment to Test General Relativity"* *Physical Review Letters*. **106** (22): 221101.



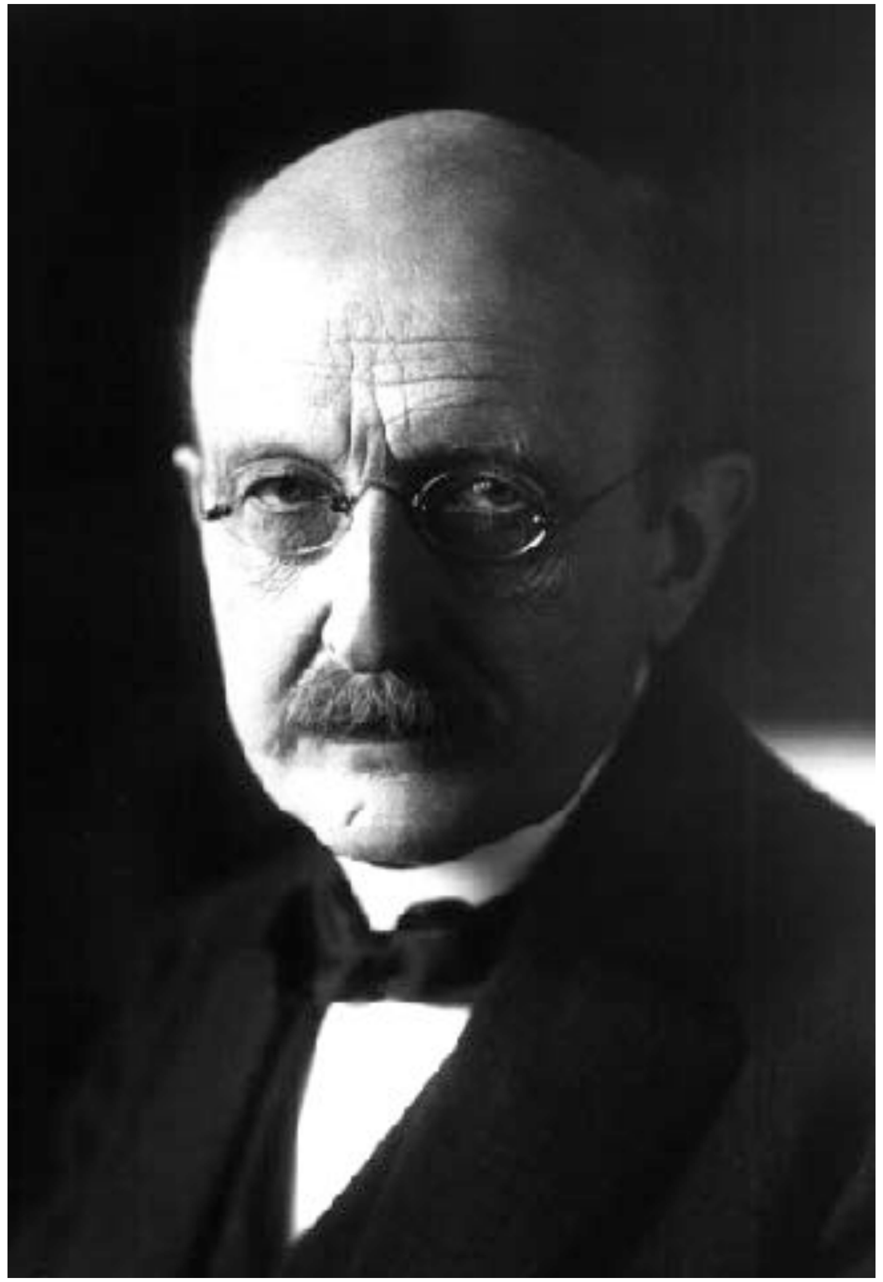
"An empty space, that there is no space field, is non-existent." —**Einstein**

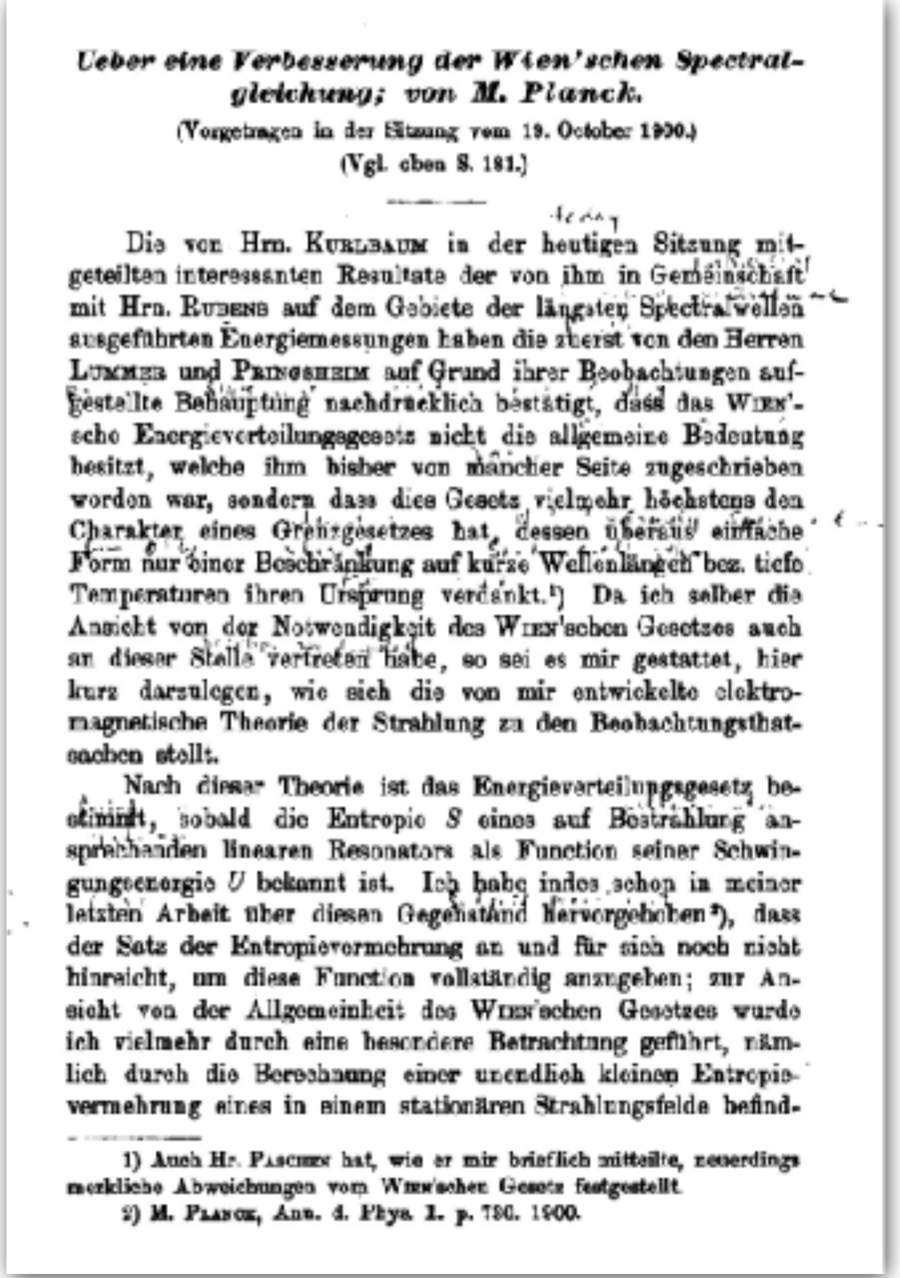
《*Relativity: the special and the general theory*》 1916

(English translation by Robert W. Lawson)

Max Planck

1858 – 1947 German theoretical physicist





Ueber eine Verbesserung der Wien'schen Spectralgleichung; von M. Planck.

(Vorgetragen in der Sitzung vom 19. October 1900.)

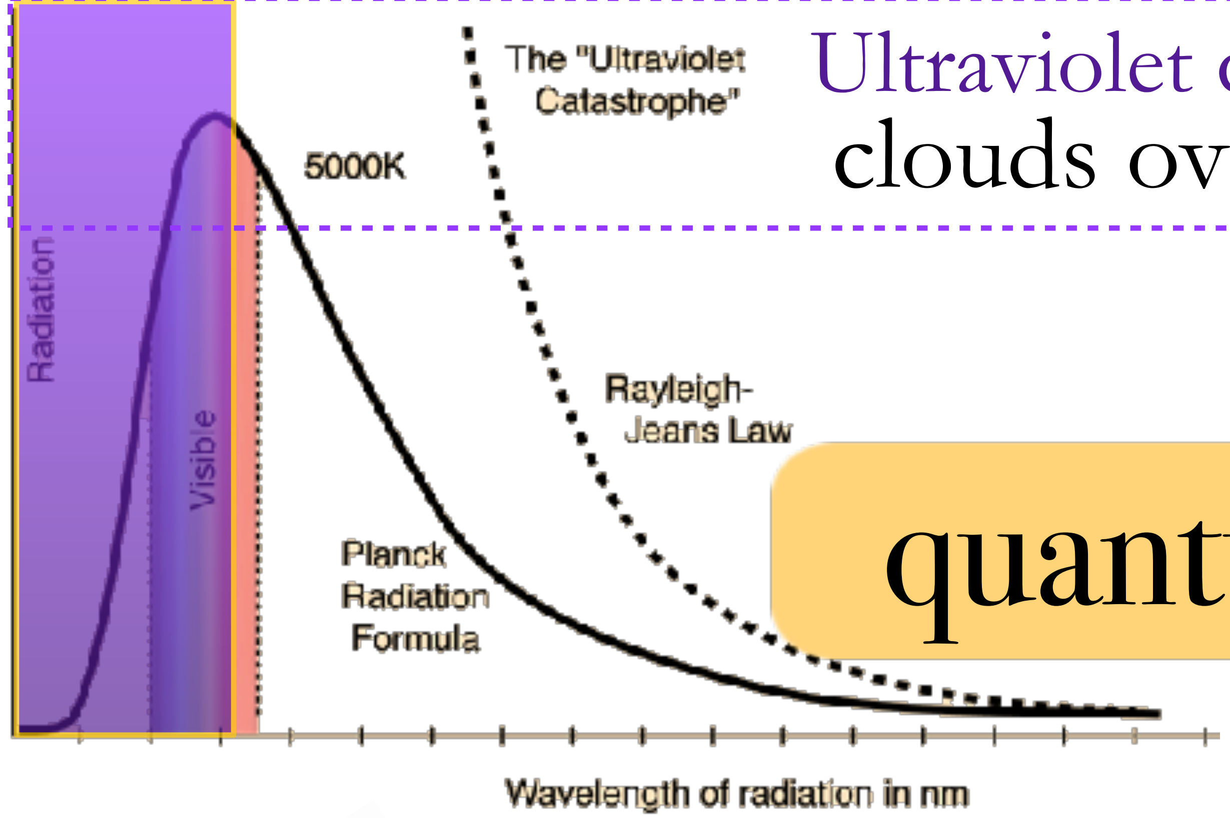
(Vgl. oben S. 181.)

Die von Hrn. Kurlbaum in der heutigen Sitzung mitgeteilten interessanten Resultate der von ihm in Gemeinschaft mit Hrn. Rubens auf dem Gebiete der längsten Spectralwellen ausgeführten Energiemessungen haben die zuerst von den Herren Lummer und Pringsheim auf Grund ihrer Beobachtungen aufgestellte Behauptung nachdrücklich bestätigt, dass das Wien'sche Energieverteilungsgesetz nicht die allgemeine Bedeutung besitzt, welche ihm bisher von mancher Seite zugeschrieben worden war, sondern dass dies Gesetz vielmehr höchstens den Charakter eines Grenzgesetzes hat, dessen überaus einfache Form nur einer Beschränkung auf kurze Wellenlängen bez. tiefe Temperaturen ihren Ursprung verdankt.[1] Da ich selber die Ansicht von der Notwendigkeit des Wien'schen Gesetzes auch an dieser Stelle vertreten habe, so sei es mir gestattet, hier kurz darzulegen, wie sich die von mir entwickelte elektromagnetische Theorie der Strahlung zu den Beobachtungsthatsachen stellt.

Nach dieser Theorie ist das Energieverteilungsgesetz bestimmt, sobald die Entropie S eines auf Bestrahlung ansprechenden linearen Resonators als Function seiner Schwingungsenergie U bekannt ist. Ich habe indes schon in meiner letzten Arbeit über diesen Gegenstand hervorgehoben[2]), dass der Satz der Entropievermehrung an und für sich noch nicht hinreicht, um diese Function vollständig anzugeben; zur Ansicht von der Allgemeinheit des Wien'schen Gesetzes wurde ich vielmehr durch eine besondere Betrachtung geführt, nämlich durch die Berechnung einer unendlich kleinen Entropievermehrung eines in einem stationären Strahlungsfelde befind-

1) Auch Hr. Paschen hat, wie er mir brieflich mitteilte, neuerdings merkliche Abweichungen vom Wien'schen Gesetz festgestellt.

2) M. Planck, Ann. d. Phys. 1. p. 730. 1900.

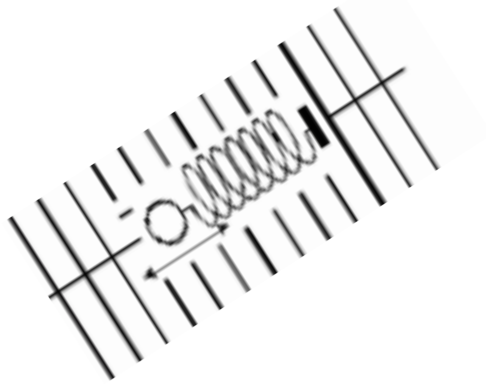


Ultraviolet catastrophe

clouds over physics

quantum

$$E_{photon} = h\nu$$



$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}$$

Dynamic Universe

The first person to carry out a modern survey of the night sky, Fritz Zwicky's astronomical observations led to a new picture of a turbulent Universe that is punctuated by violent events.

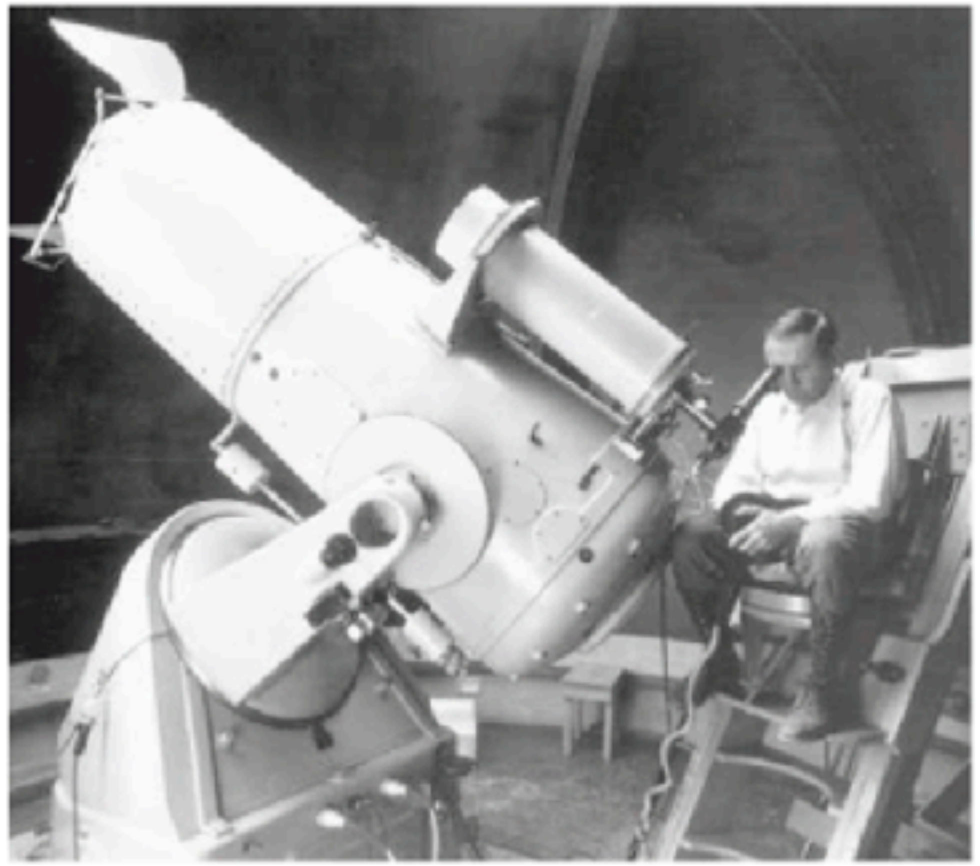
Freeman Dyson

The Swiss physicist Fritz Zwicky (1898–1973) was responsible, more than anyone else, for a profound change in our view of the astronomical Universe. Before Zwicky, the ancient aristotelian view of the celestial sphere as a region of eternal harmony and tranquillity was still largely intact, and the job of an astronomer was to make accurate maps of an unchanging landscape. After Zwicky, the modern view of the Universe emerged, as a dynamic scene dominated by violent events. The job of an astronomer today is to record and interpret the processes of change.

Zwicky's great work was done in the 1930s when he was an associate professor of physics at Caltech, the California Institute of Technology. He had been trained at the Swiss Federal Institute of Technology as an X-ray crystallographer and had no official credentials as an astronomer. But he saw an opportunity arising from two unconnected events that happened almost simultaneously.

First, in 1928, the Rockefeller Foundation awarded a large sum of money to Caltech for the construction of a major astronomical observatory. Second, in 1930,

the northern sky. Two major discoveries that emerged from his survey were supernovae and dark matter. Zwicky observed 20 supernovae, a large enough sample to allow him to classify them into several types and infer their different modes of origin. His discovery of dark matter came from studying the motions of individual galaxies in rich clusters of galaxies, and from calculating that the visible mass in the clusters was insufficient by a large factor to cause the observed motions.



Using the Schmidt telescope, Fritz Zwicky discovered dark matter.

CALIFORNIA INSTITUTE OF TECHNOLOGY

flict with his colleagues at Caltech. They considered him crazy and he considered them stupid. He never became an accepted member of the astronomical community, but followed his own path. During the Second World War he was director of research at the Aerojet Corporation, which developed rockets for the military. At the same time he organized the Committee for Aid to War-stricken Scientific Libraries. This collected massive quantities of scientific books and journals and distributed them to libraries that had been disrupted or destroyed during the war. He founded the committee in 1941 and ran it with his habitual enthusiasm and efficiency. For this work he received the Medal of Freedom from President Harry Truman in 1949.

Besides his revolutionary work as an observer and organizer, Zwicky made revolutionary contributions to theoretical astronomy. He published papers about neutron stars, supernovae, black holes and gravitational lenses, long before these subjects became fashionable. His thinking was based on a personal philosophy which he called the 'morphological approach'. The idea is that you first make a complete list of all

动态宇宙

"The first person to carry out a modern survey of the night sky, Fritz Zwicky's astronomical observations led to a new picture of a turbulent Universe that is punctuated by violent events."

The 2023 Prize in Astronomy

Matthew Bailes
Duncan Lorimer
Maura McLaughlin

for the discovery of fast radio bursts (FRBs).

Learn More About the Laureate >

Astronomy
+ the 'New' Frontier

since **2000:** laureates **19**
10 achievements in **7** years

SHAW PRIZE

Laureates	Year	Achievement
R.Davis,Jr. M.Koshiba R.Giacconi	2002	cosmic neutrinos, cosmic X-ray sources — **2004**
J.C.Mather G. Smoot	2006	CMB anisotropy
S.Perlmutter B.P.Schmidt A.G.Riess	2011	accelerating expansion of the Universe
T.Kajita A.B.McDonald	2015	neutrino oscillations
R.Weiss B.C. Barish K.S. Thorne	2017	gravitational waves
James Peebles; Michel Mayor Didier Queloz	2019	physical cosmology; Habitable exoplanet
Roger Penrose; Reinhard Genzel Andrea Ghez	2020	black hole formation; Galactic center supermassive compact object

Shaw + Nobel

A Bright Millisecond Radio Burst of Extragalactic Origin

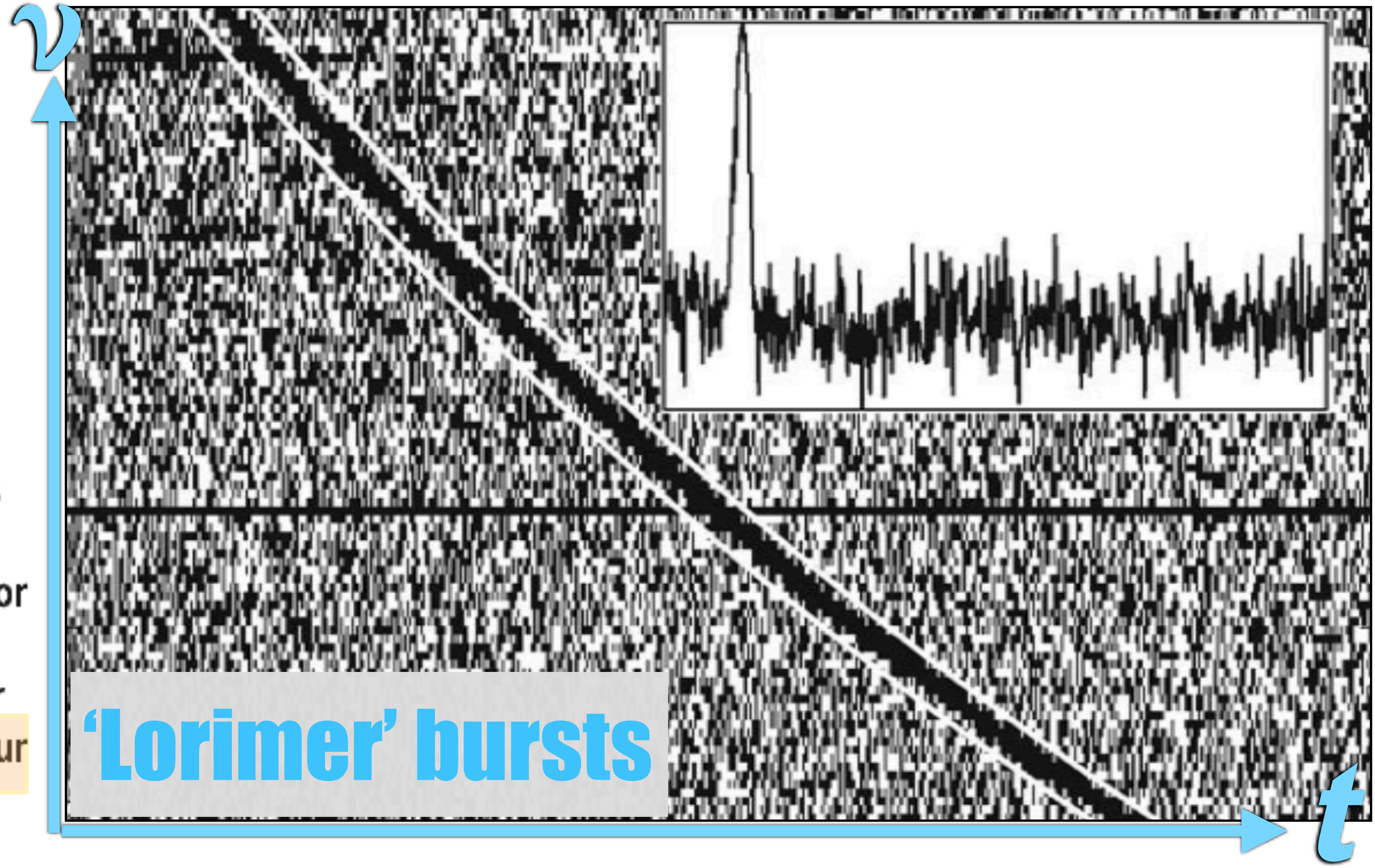
2007

D. R. Lorimer,[1,2]* M. Bailes,[3] M. A. McLaughlin,[1,2] D. J. Narkevic,[1] F. Crawford[4]

Pulsar surveys offer a rare opportunity to monitor the radio sky for impulsive burst-like events with millisecond durations. We analyzed archival survey data and found a 30-jansky dispersed burst, less than 5 milliseconds in duration, located 3° from the Small Magellanic Cloud. The burst properties argue against a physical association with our Galaxy or the Small Magellanic Cloud. Current models for

Hundreds of similar events could occur every day…

further bursts were seen in 90 hours of additional observations, which implies that it was a singular event such as a supernova or coalescence of relativistic objects. Hundreds of similar events could occur every day and, if detected, could serve as cosmological probes.



A Population of Fast Radio Bursts at Cosmological Distances

2013

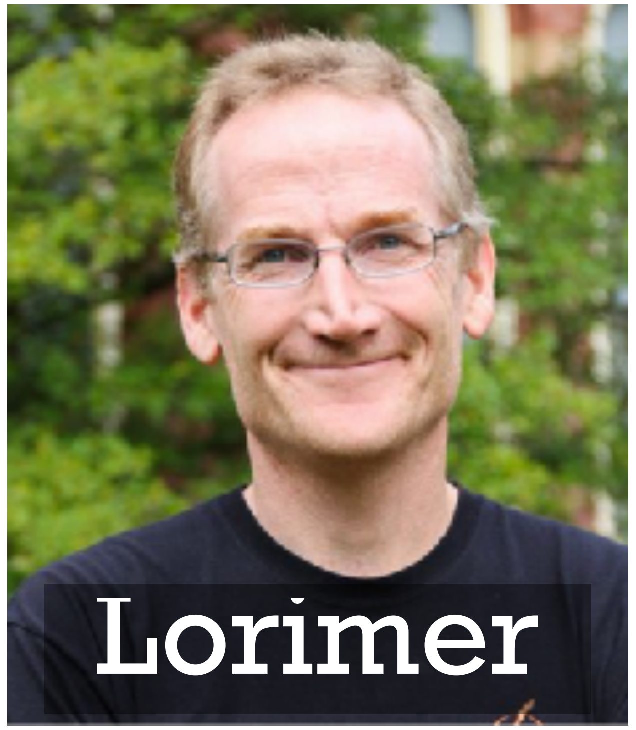
D. Thornton,[1,2]* B. Stappers,[1] M. Bailes,[3,4] B. Barsdell,[3,4] S. Bates,[5] N. D. R. Bhat,[3,4,6] M. Burgay,[7] S. Burke-Spolaor,[8] D. J. Champion,[9] P. Coster,[2,3] N. D'Amico,[10,7] A. Jameson,[3,4] S. Johnston,[2] M. Keith,[2] M. Kramer,[9,1] L. Levin,[5] S. Milia,[7] C. Ng,[9] A. Possenti,[7] W. van Straten[3,4]

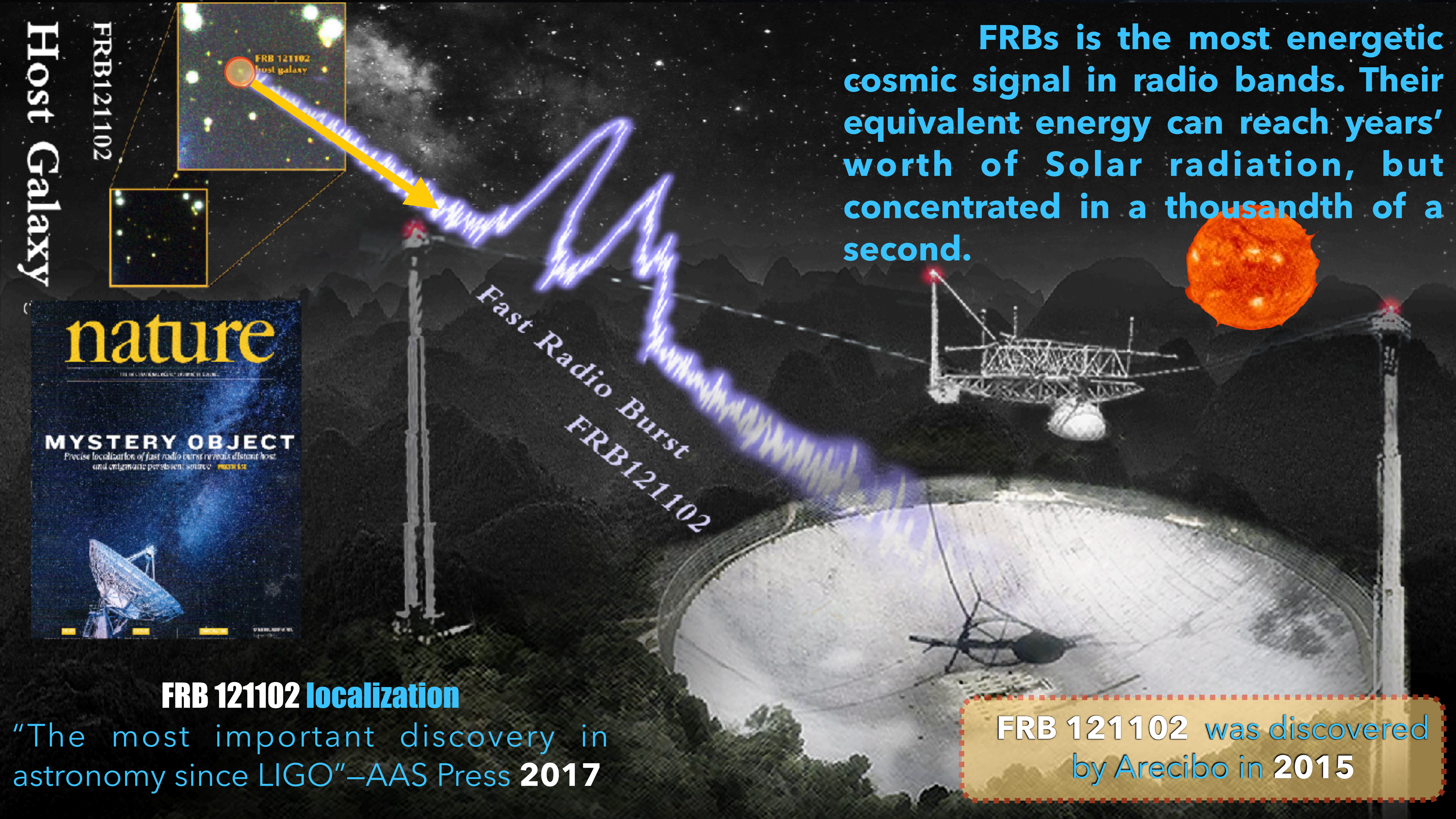
Searches for transient astrophysical sources often reveal unexpected classes of objects that are useful physical laboratories. In a recent survey for pulsars and fast transients, we have uncovered four millisecond-duration radio transients all more than 40° from the Galactic plane. The bursts' properties indicate that they are of celestial rather than terrestrial origin. Host galaxy and

Determine the baryonic content of the universe

association with the bursts. Characterization of the source population and identification of host galaxies offers an opportunity to determine the baryonic content of the universe.

FRB Discovers





FRBs is the most energetic cosmic signal in radio bands. Their equivalent energy can reach years' worth of Solar radiation, but concentrated in a thousandth of a second.
Host Galaxy
FRB121102
FRB 121102
host galaxy
Fast Radio Burst
FRB121102
nature
MYSTERY OBJECT
Precise localization of fast radio burst reveals distant host
and enigmatic persistent source
FRB 121102 localization
"The most important discovery in astronomy since LIGO"–AAS Press 2017
FRB 121102 was discovered by Arecibo in 2015

Arecibo

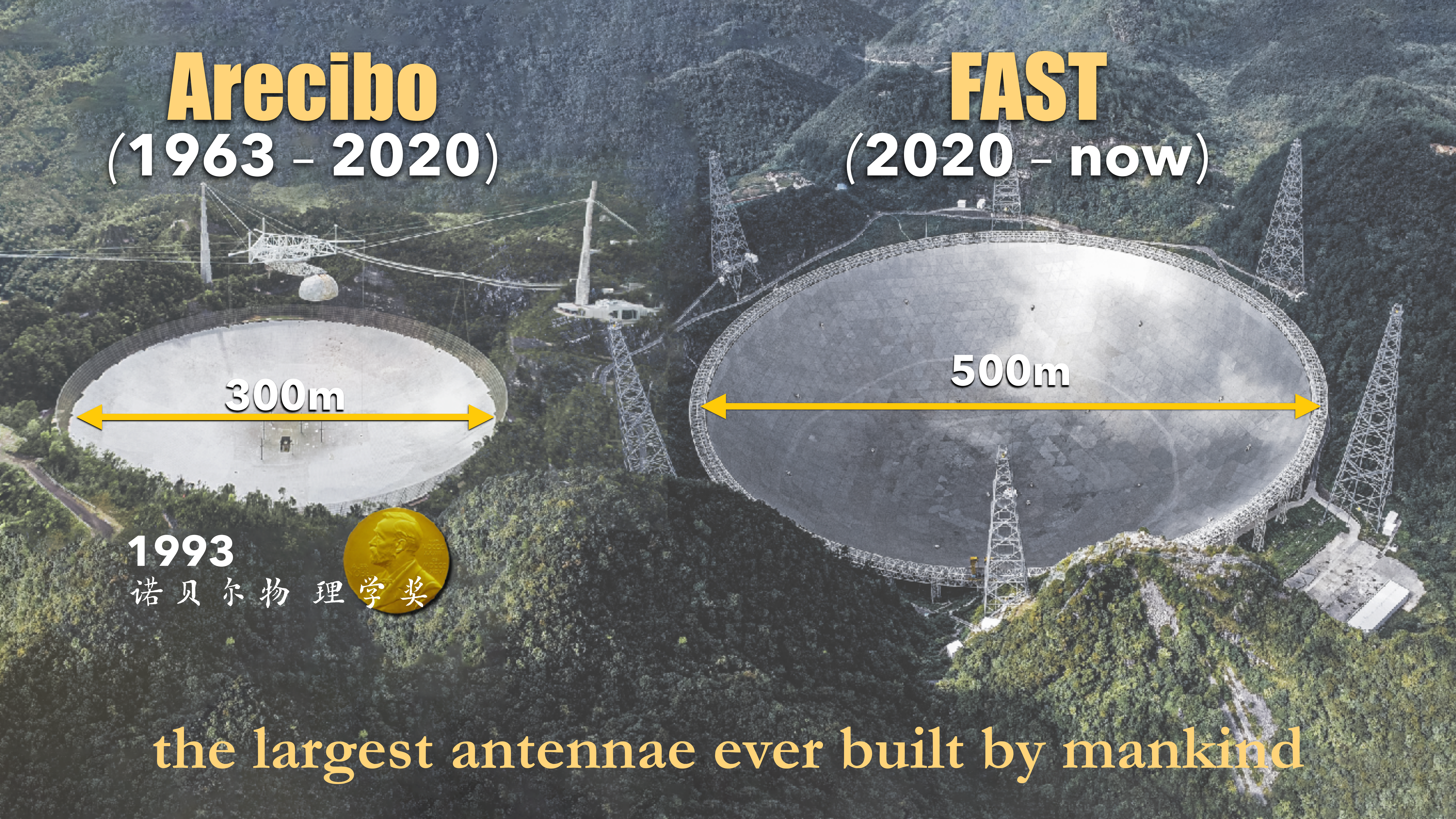
(1963 – 2020)

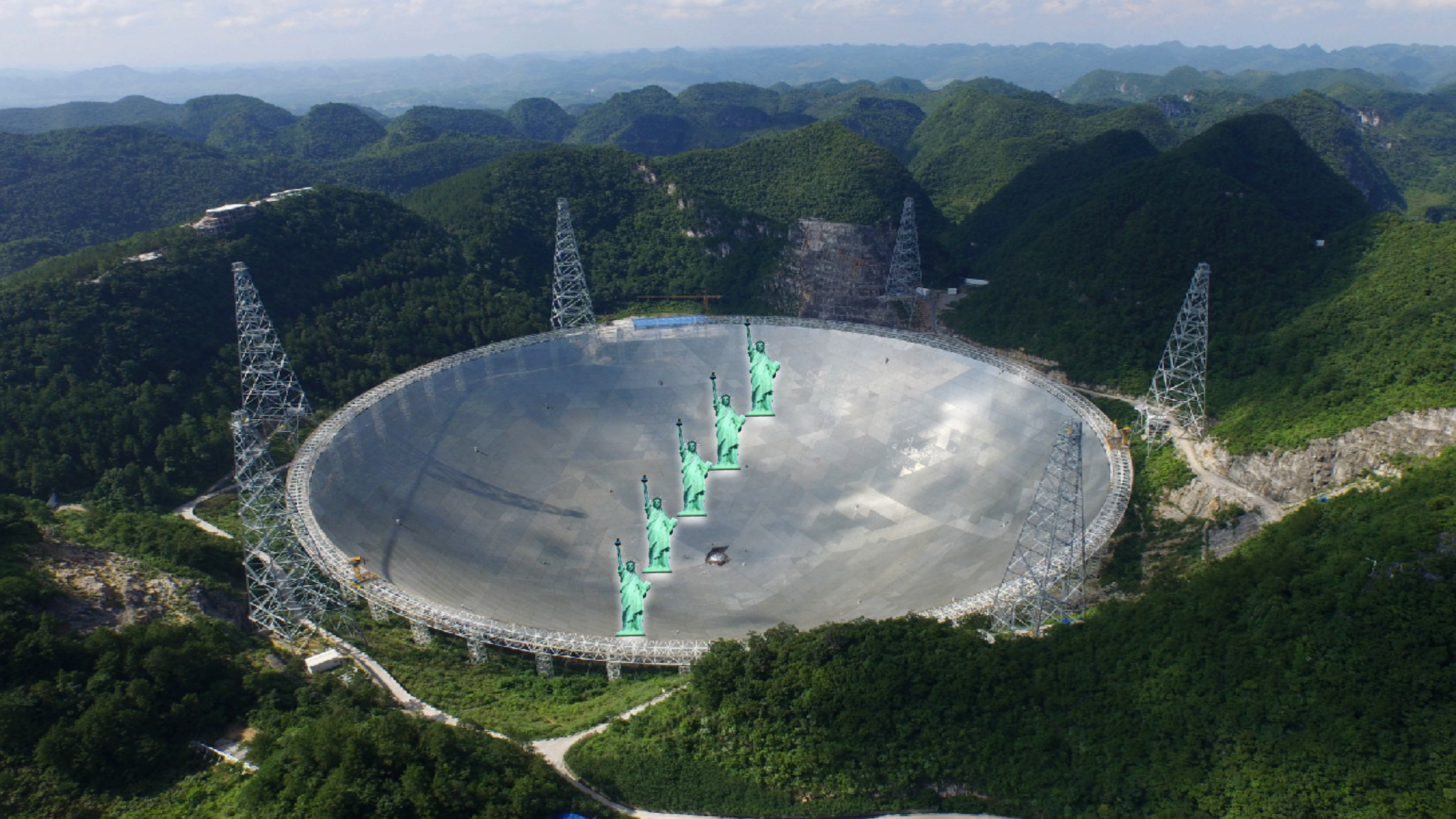
1963 commissioned

mercury spin, double neutron stars, the first exoplanet etc.

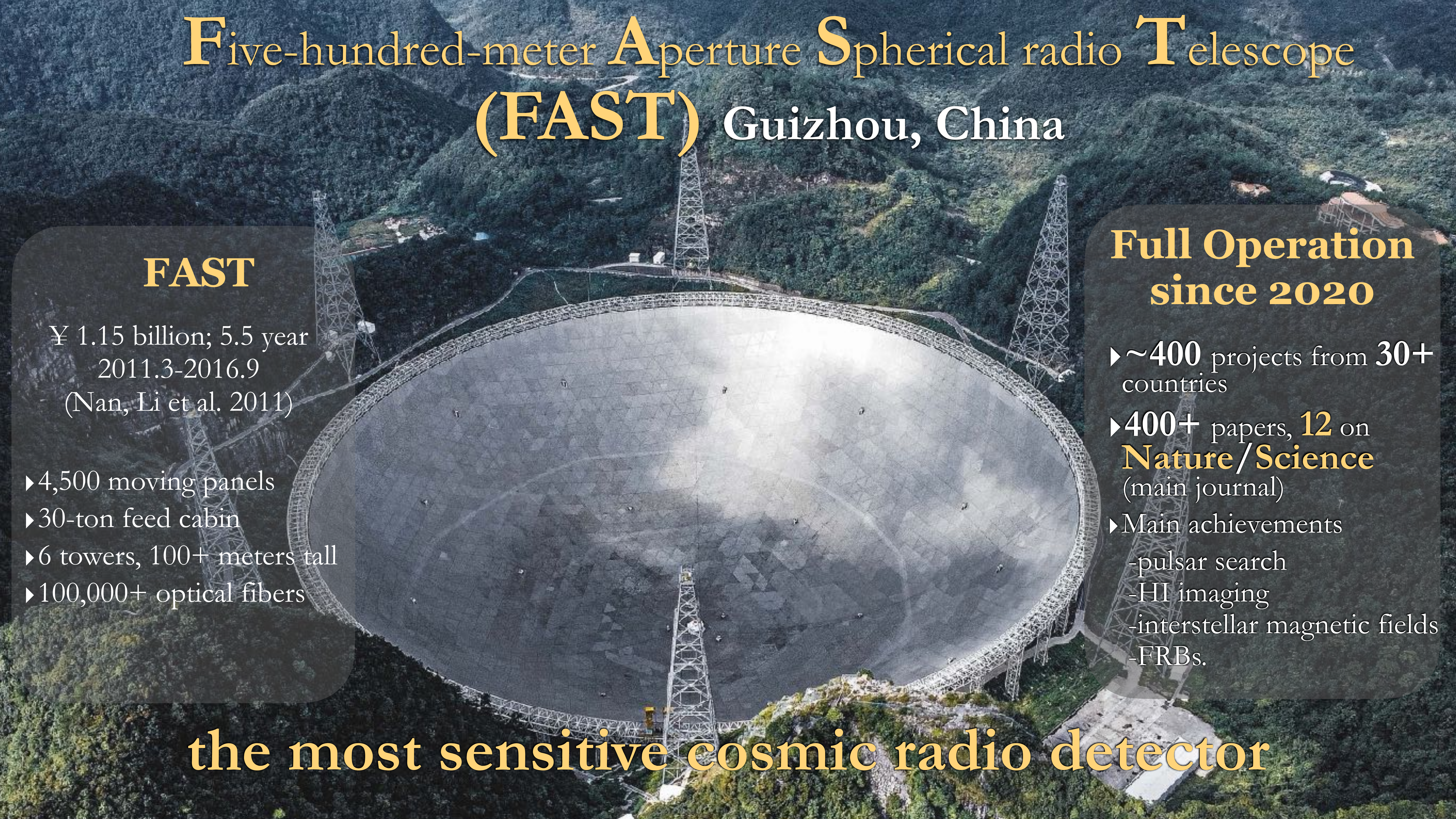
1993 Nobel prize in Physics

2020.12.1 collapsed


Arecibo
(1963 - 2020)
FAST
(2020 - now)
300m
500m
1993
诺贝尔物理学奖
the largest antennae ever built by mankind




Five-hundred-meter Aperture Spherical radio Telescope
(FAST) Guizhou, China
FAST
¥ 1.15 billion; 5.5 year
2011.3-2016.9
(Nan, Li et al. 2011)
4,500 moving panels
30-ton feed cabin
6 towers, 100+ meters tall
100,000+ optical fibers



Five-hundred-meter Aperture Spherical radio Telescope (FAST) Guizhou, China

FAST

¥ 1.15 billion; 5.5 year
2011.3-2016.9
(Nan, Li et al. 2011)

- 4,500 moving panels
- 30-ton feed cabin
- 6 towers, 100+ meters tall
- 100,000+ optical fibers

Full Operation since 2020

- **~400** projects from **30+** countries
- **400+** papers, **12** on **Nature/Science** (main journal)
- Main achievements
  - -pulsar search
  - -HI imaging
  - -interstellar magnetic fields
  - -FRBs.

the most sensitive cosmic radio detector

HI Narrow Self Absorption

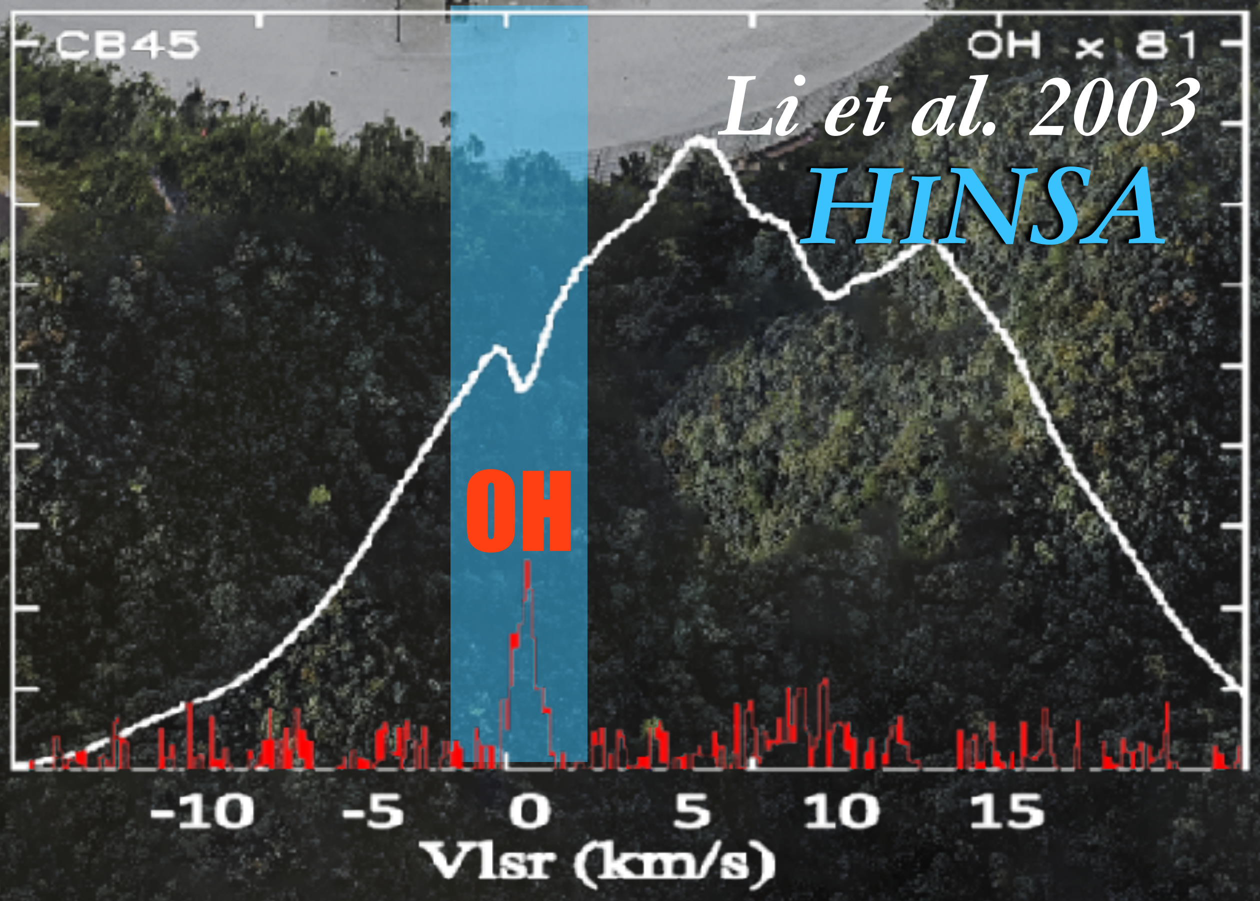
原子氢的窄自吸收

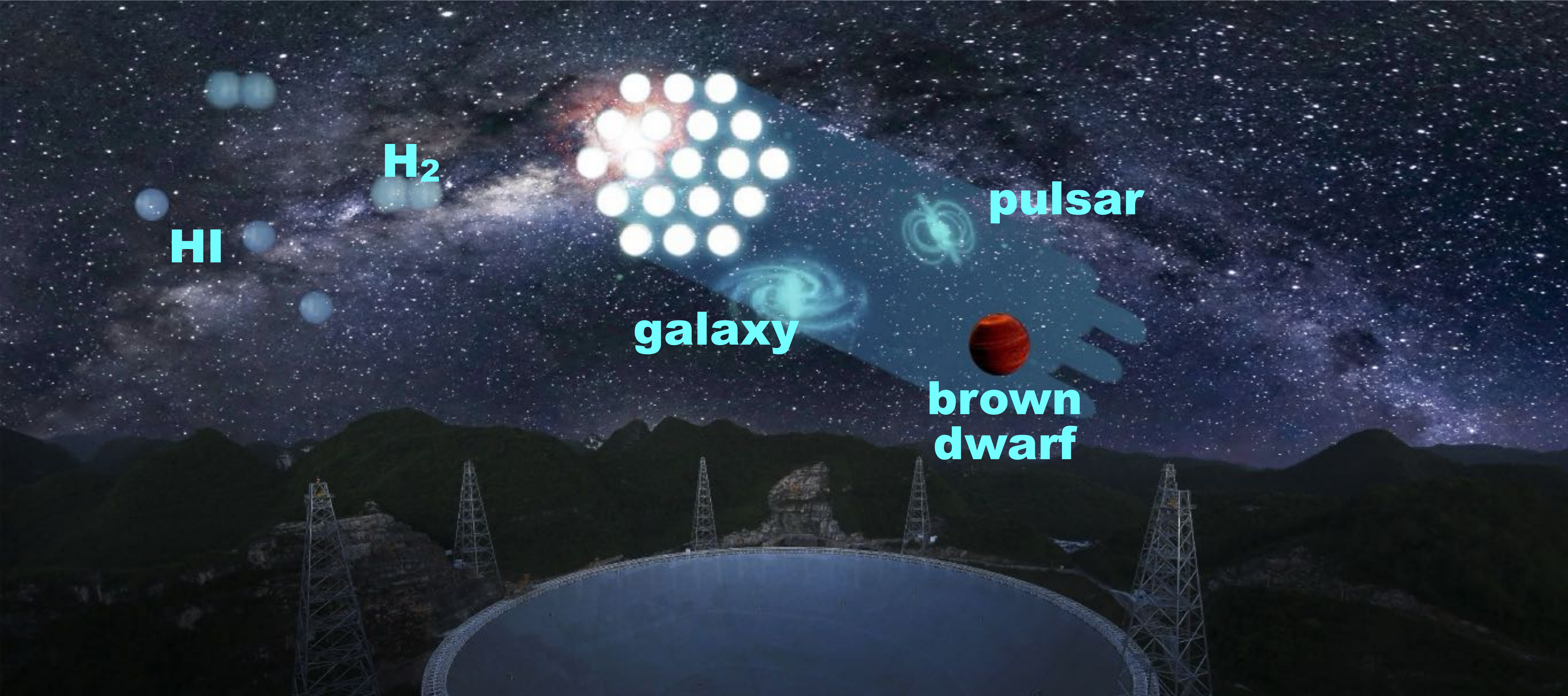
First HINSA Zeeman Detection

reveals a weak B = 3.8 ± 0.3 μG coherent field that puts molecular cores in supercritical state

《**Science**》 news:

"…**revolutionary** (革命性)."





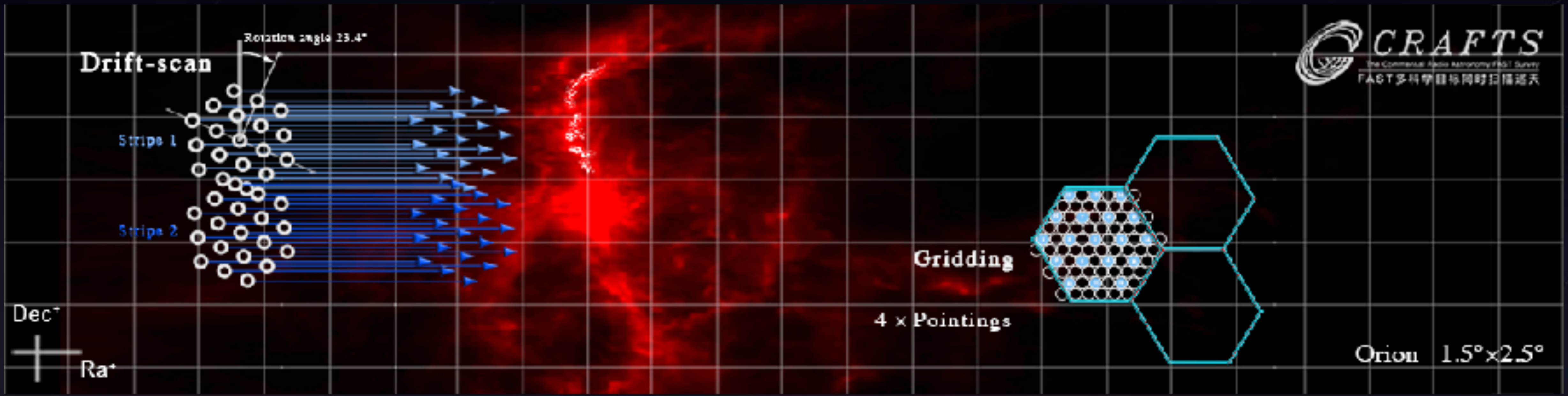
*Based on a novel high-cadence CAL technique, **CRAFTS** is the* ***first commensal survey*** *of HI imaging, pulsars, galaxies, and FRBs .*

***C**ommensal **R**adio **A**stronomy **F**AS**T** **S**urvey*

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

Li et al. 2018
IEEE Microwave

Status of pulsar discoveries from CRAFTS

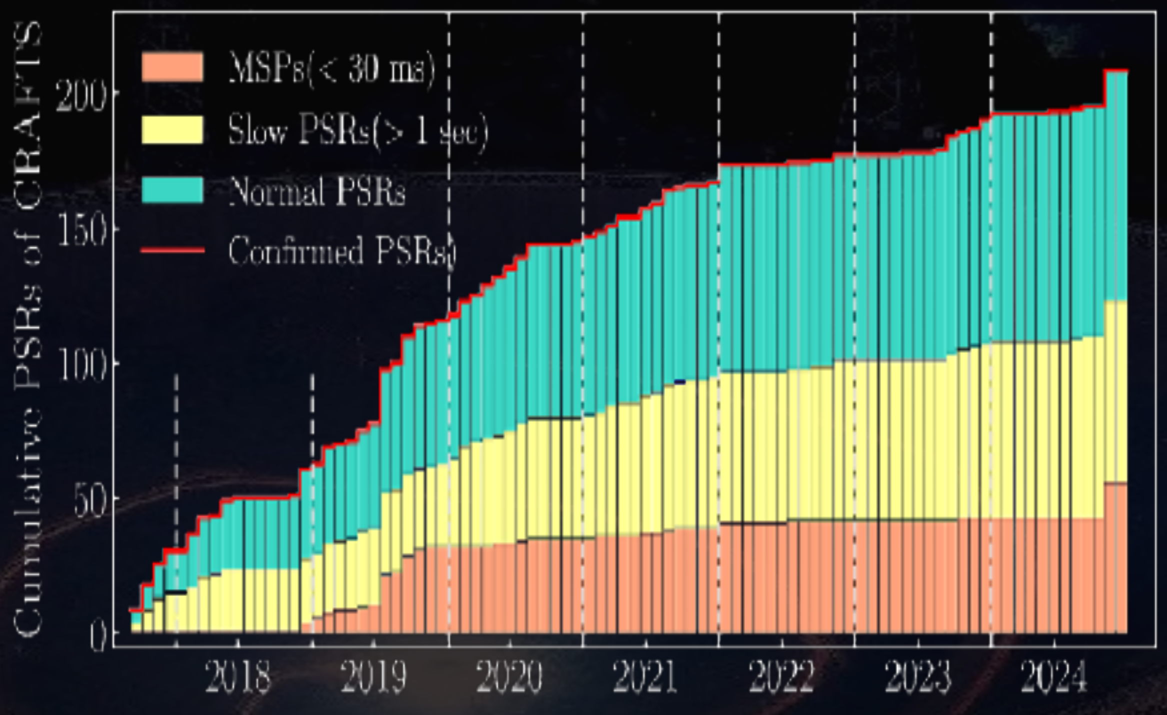


Confirmed
222 New Pulsars
Discovery

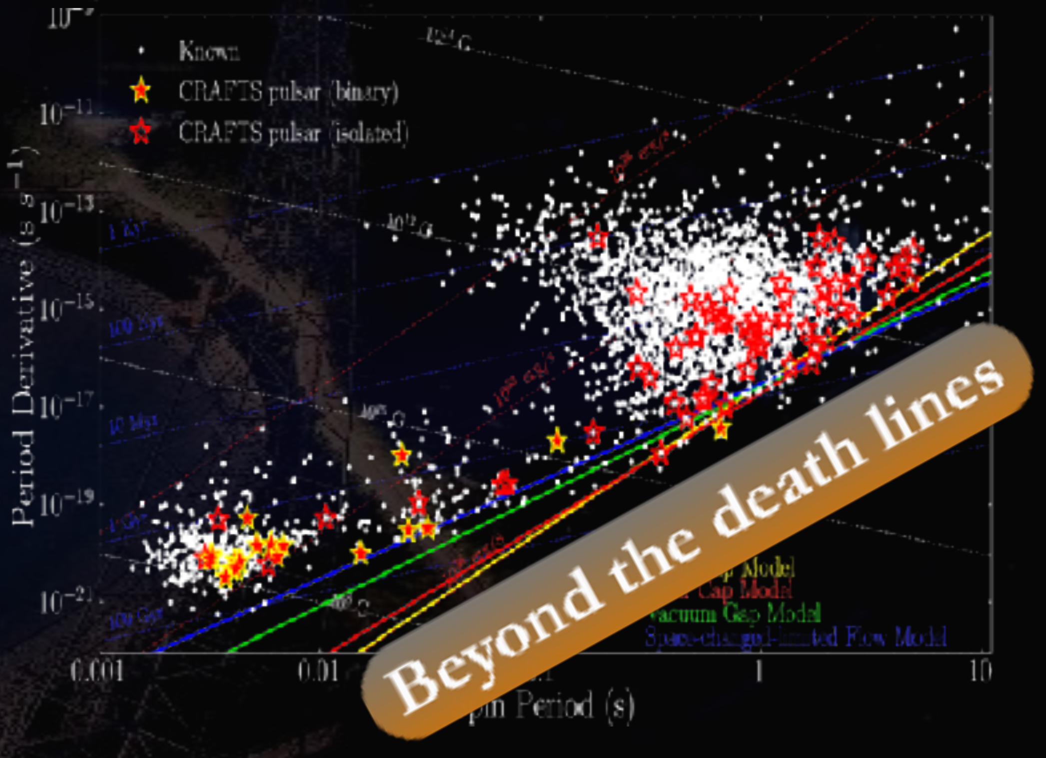
- 65 MSPs
- 21 Binary (including 3 DNS)
- ~35 RRATs
- ~90 Pulsars were Published

~90 Pulsars have full time solution
International collaborative pulsar timing

CRAFTS Catalog & Data Release
http://crafts.bao.ac.cn/pulsar/
https://fastro.scidb.cn/en
86GB+, 7 datasets
100,000 Views, 5200+ Downloads
>200 Citation, from 20+ Countries

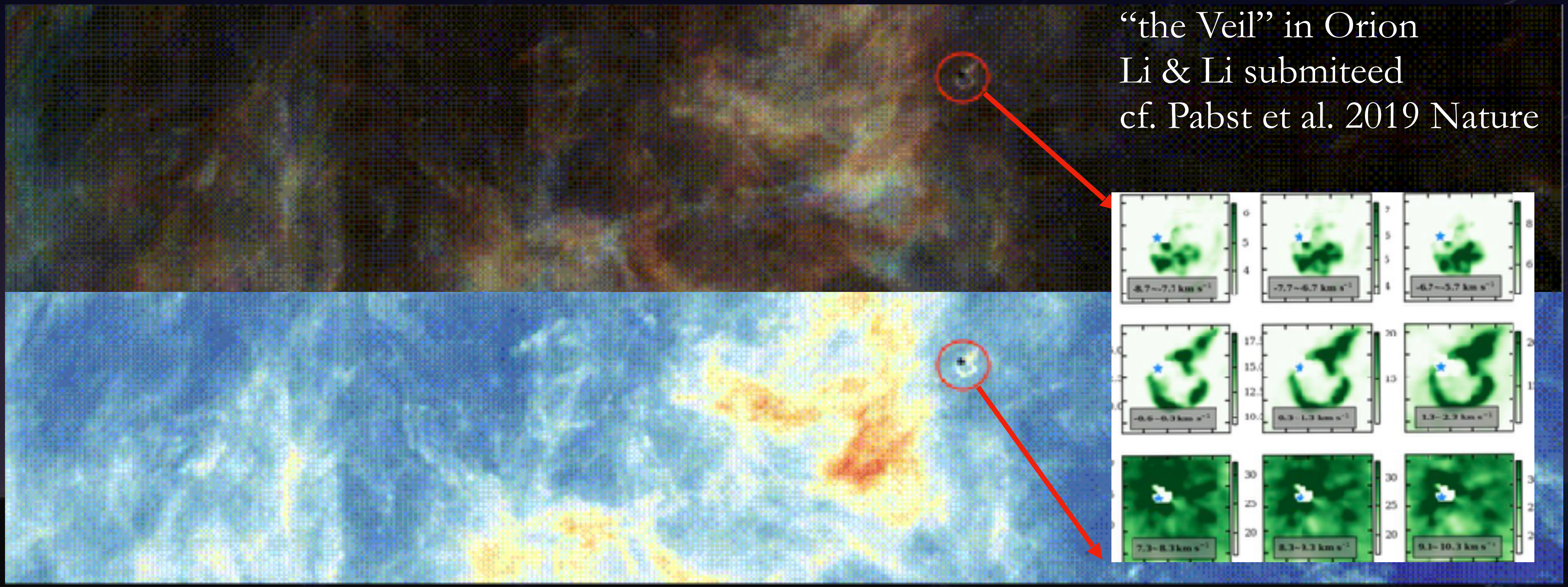


Date of discovery (Year)



P-Pdot Diagram

CRAFTS HI Data Release

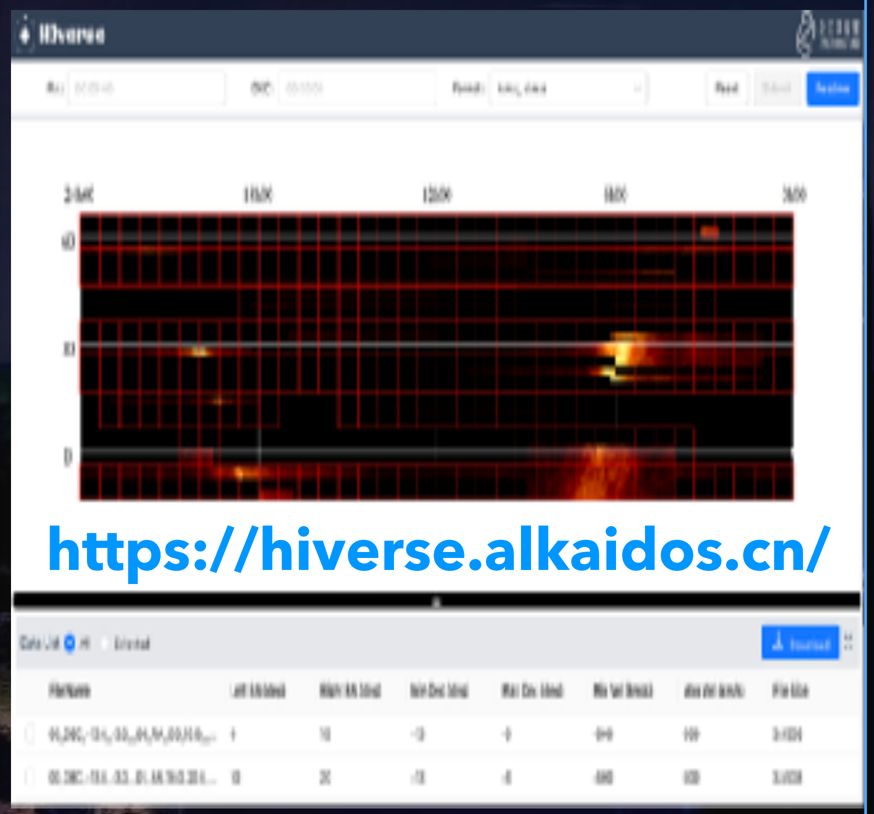


"the Veil" in Orion
Li & Li submiteed
cf. Pabst et al. 2019 Nature

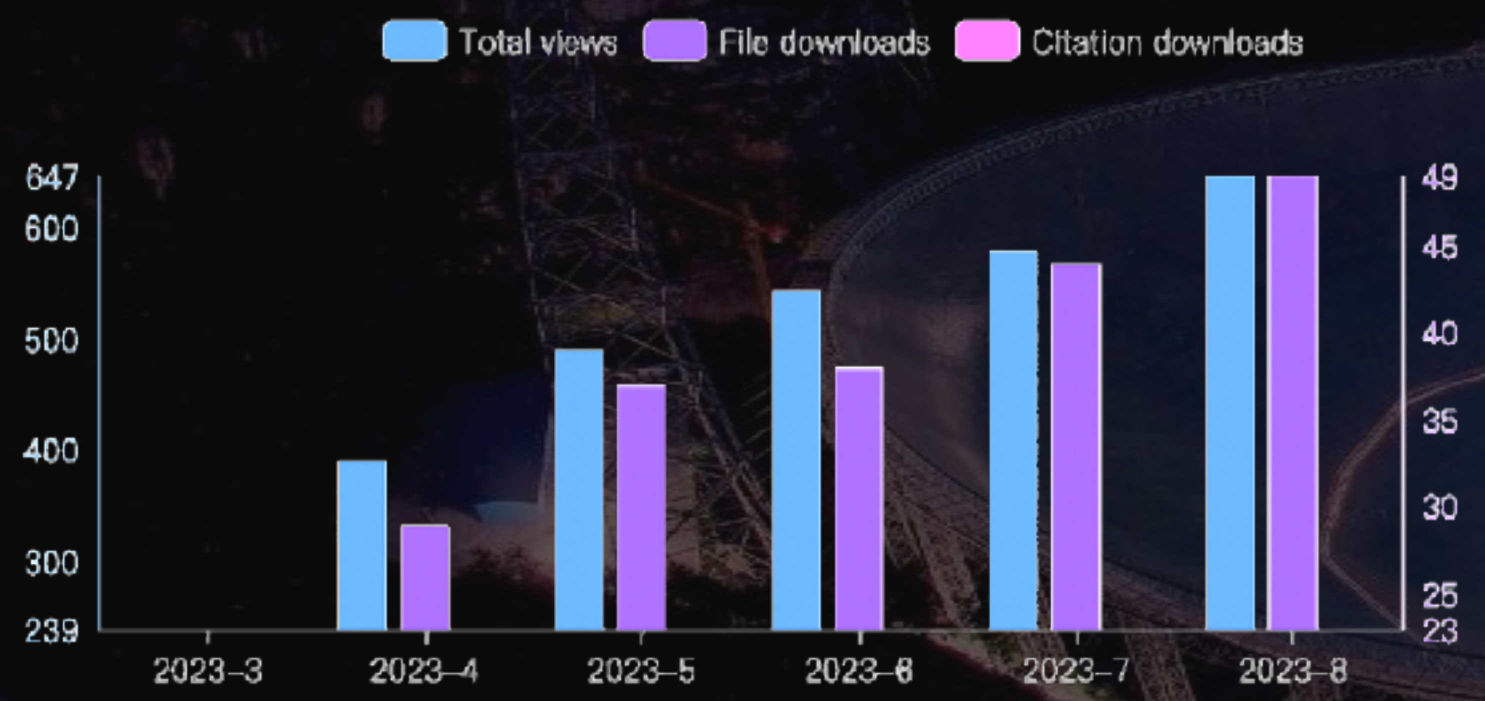
2024.2 Release

4738 deg^2

Narrow-band Data Cube



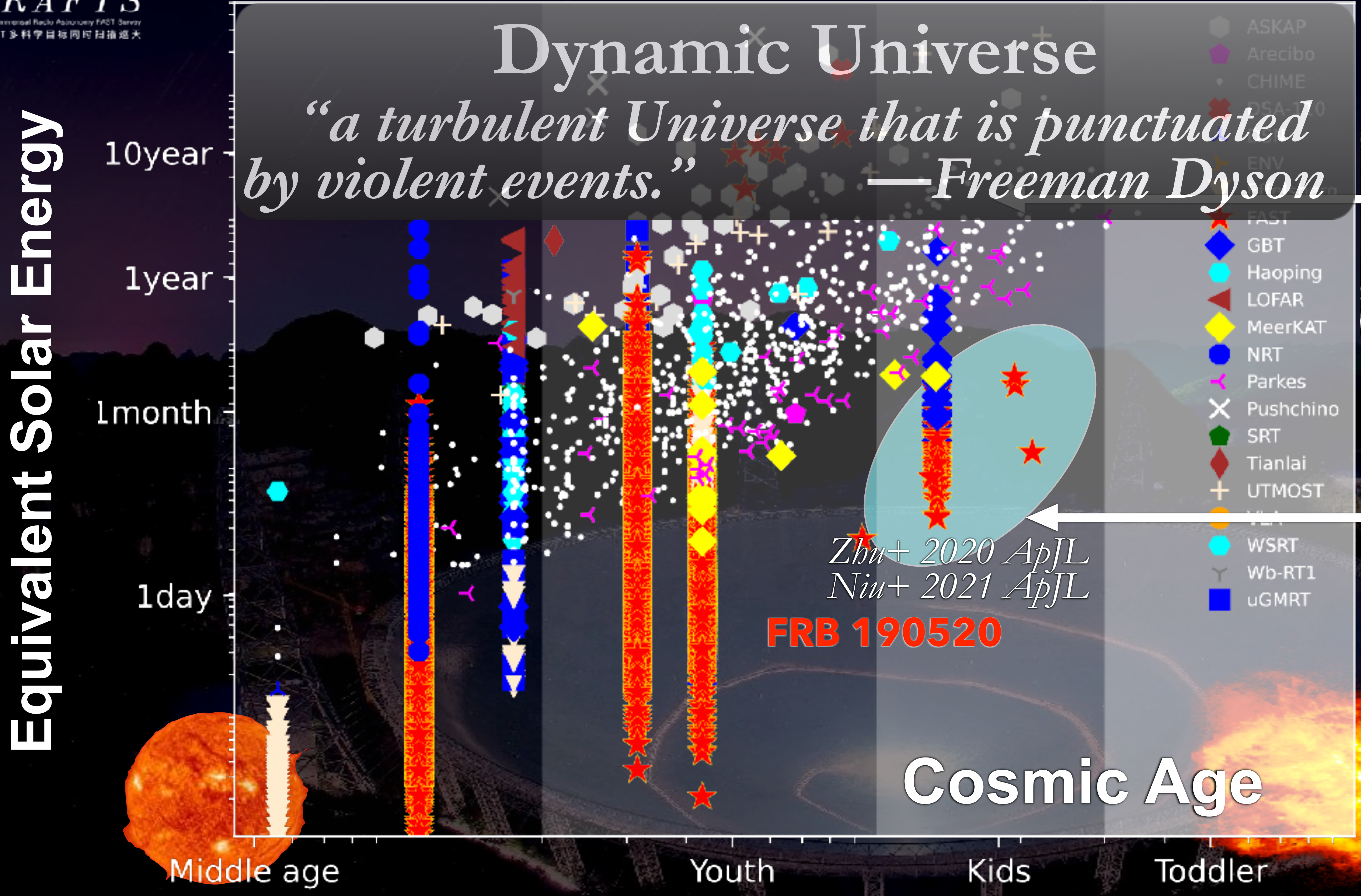
https://hiverse.alkaidos.cn/

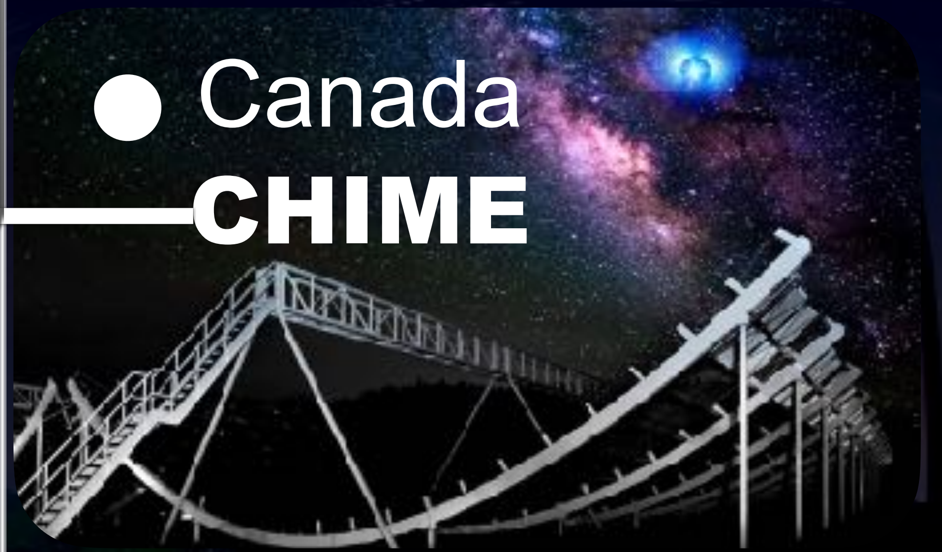


- Pre-release (Orion)
  http://groups.bao.ac.cn/ism/CRAFTS/202303/t20230321_736552.html
- Narrow band HI data releases
  https://doi.org/10.57760/sciencedb.07779
- CRAFTS Data Community
  http://groups.bao.ac.cn/ism/CRAFTS/202309/t20230906_752058.html

CRAFTS

CRAFTS reveals a high event rate >120K per day!





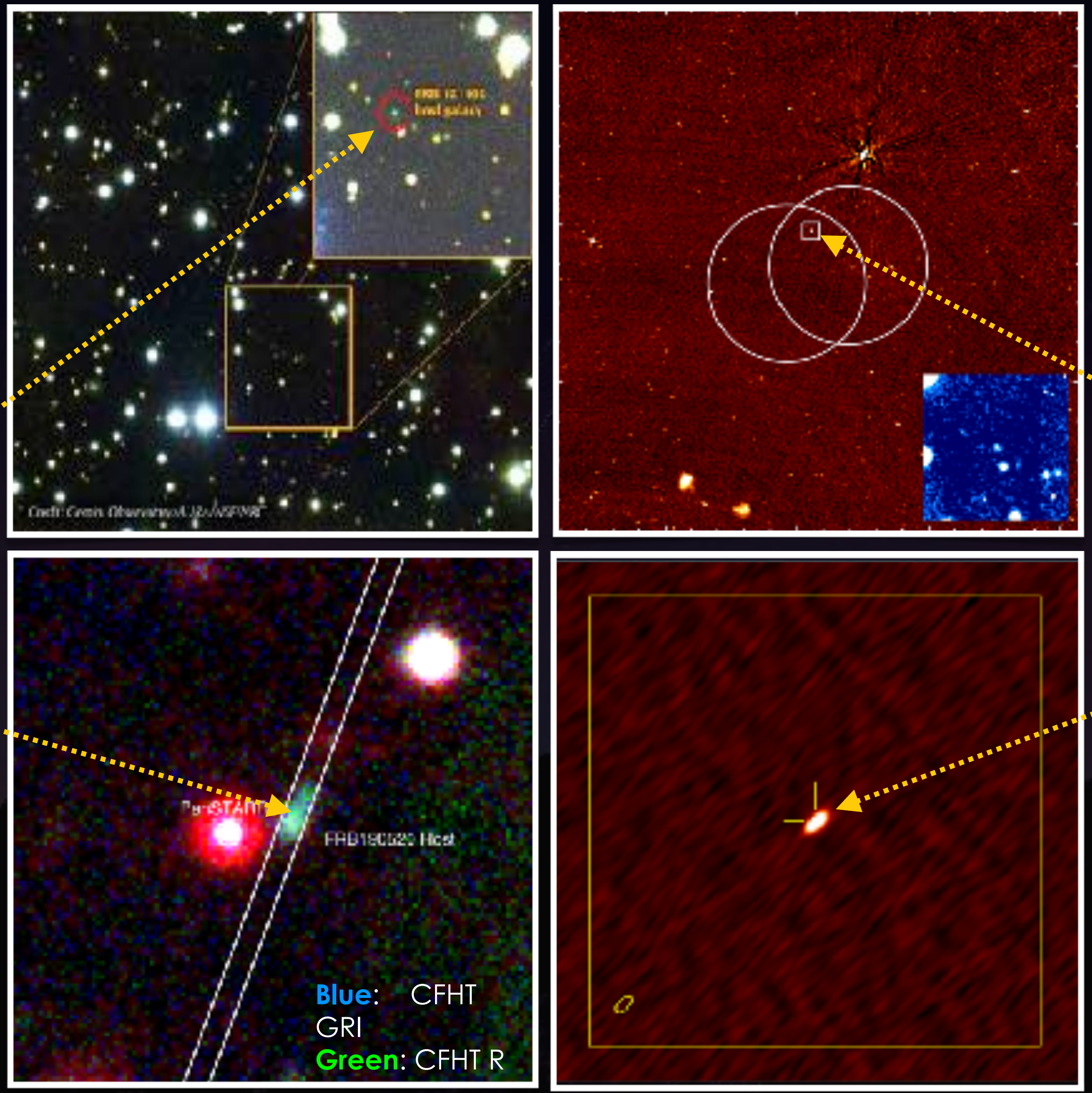
Big Bang

FRB 190520
CRAFTS
C.H. Niu
2019.5.20 CRAFTS scan: discovery
nature
Niu et al. 2022, Nature, 606, 873
The first persistently active FRB.
• Facilitate followup campaign e.g. Anna-Thomas* & Li* 2023 Science
• Give rise to >10 models
• Voted into "Top 10 Scientific Achievements" China 2022
2022.6.30《 Nature 》


持续射电源 PRS
Persistent Radio Source PRS
Credit Niu et al. 2022 / Saxton（NRAO）

FRB 121102

HOST GAL



PRS

FRB 190520

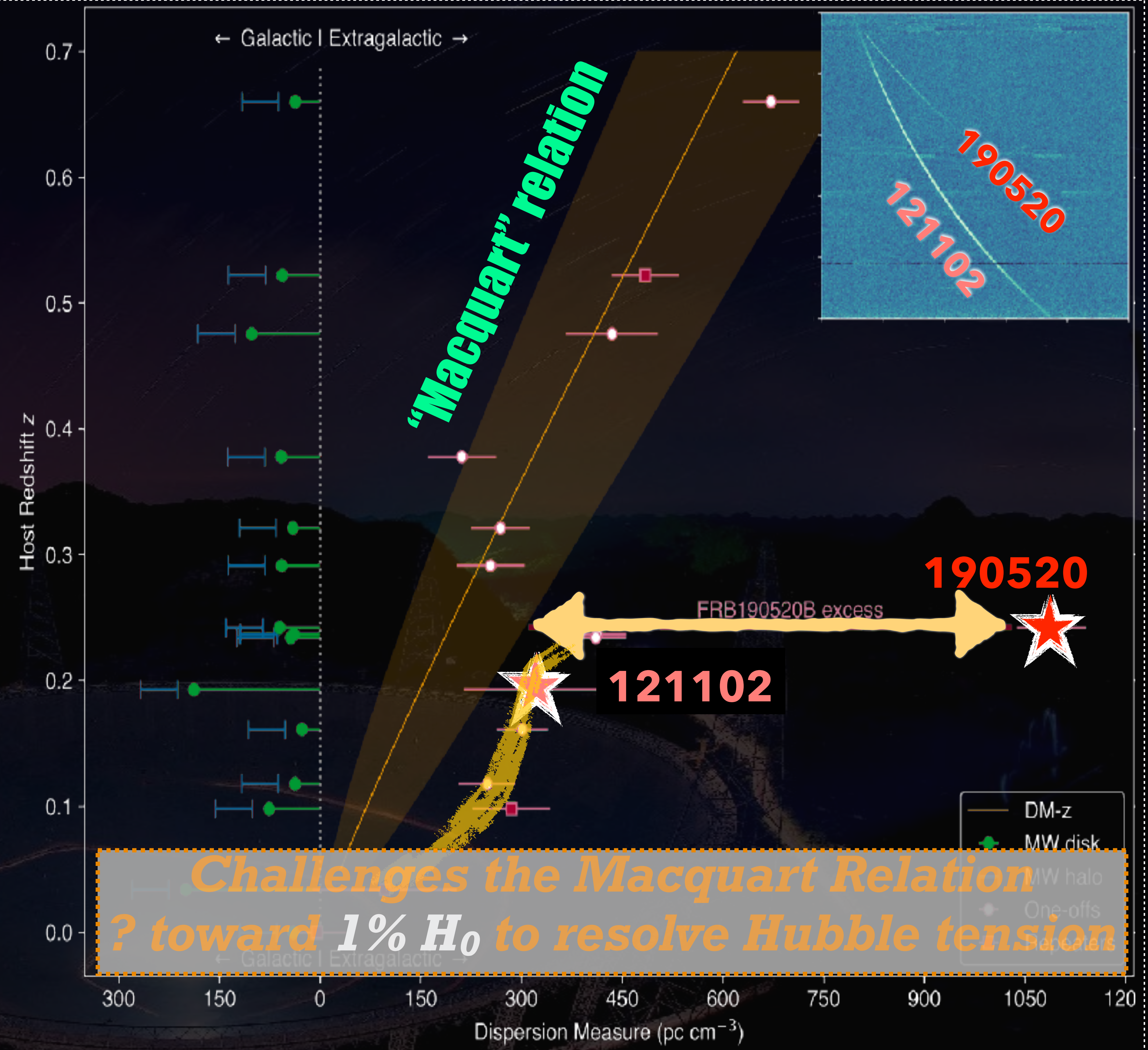
190520

a *hipper* and *weirder* brother of 121102

largest **DM$_{host}$**

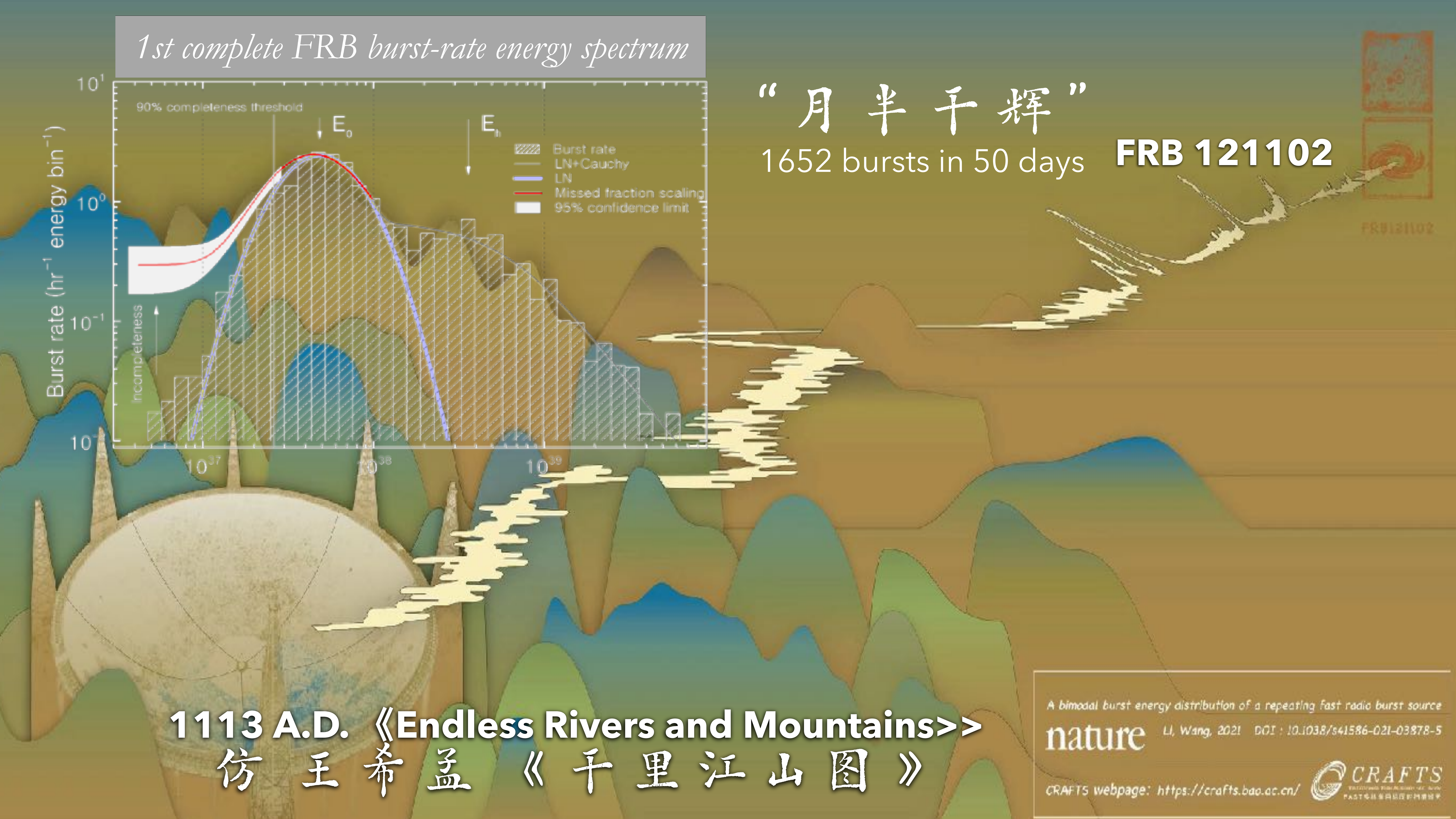
Only two **PRS**

1st & only **Persistently Active**



Challenges the Macquart Relation

? toward 1% H_0 to resolve Hubble tension



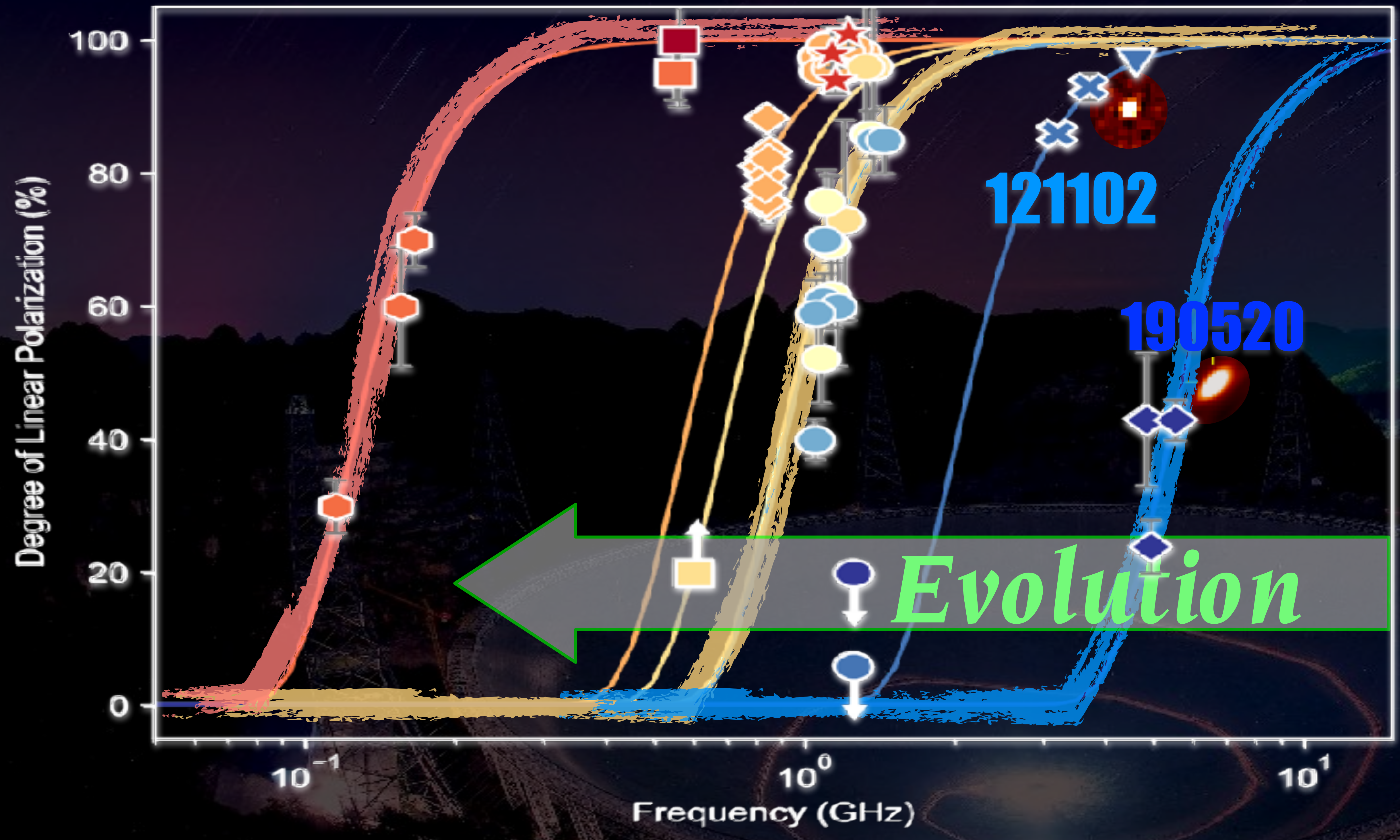
1st complete FRB burst-rate energy spectrum
Burst rate (hr^{-1} energy bin^{-1})
90% completeness threshold
E_0
E_h
Burst rate
LN+Cauchy
LN
Missed fraction scaling
95% confidence limit
Incompleteness
10^1
10^0
10^{-1}
10^{37}
10^{38}
10^{39}
“月半千辉”
1652 bursts in 50 days
FRB 121102
1113 A.D. 《Endless Rivers and Mountains>>
仿 王希孟《千里江山图》
A bimodal burst energy distribution of a repeating fast radio burst source
nature
Li, Wang, 2021 DOI : 10.1038/s41586-021-03878-5
CRAFTS webpage: https://crafts.bao.ac.cn/
CRAFTS

FAST+GBT

reveal FRB's environment

$$1 - e^{(-2\lambda^4 \sigma_{RM}^2)}$$

Multi-path Scattering



Unifying repeating fast radio bursts

Feng, **Li*** et al. 2022 Science, 375, 1266

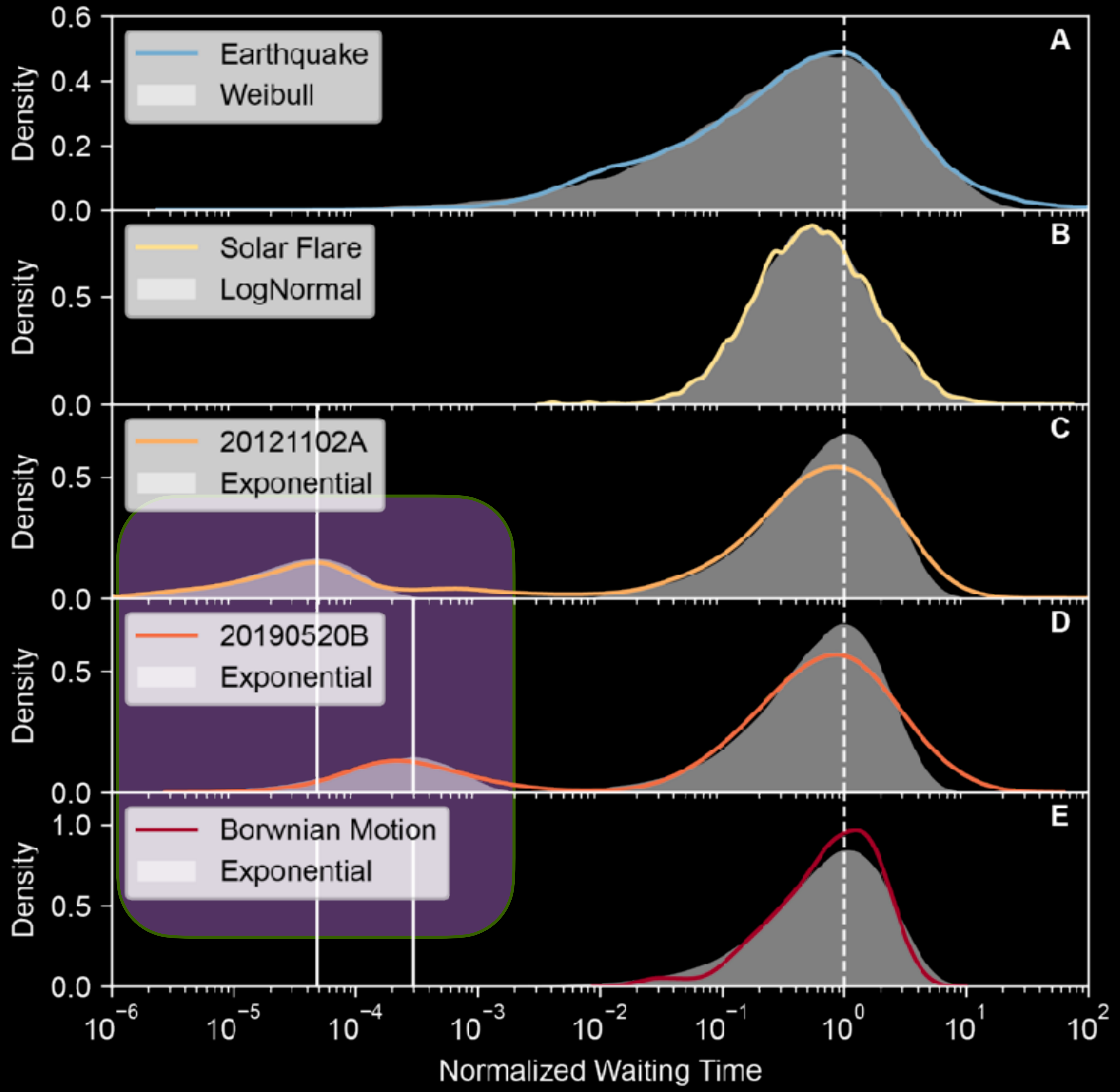
FRB Waiting Time

Normalization: inverse of the average event rate; ~1 hour for earthquakes; 7 hours for flares; 88 s and 123 s for two FRBs

Weibull distribution: earthquakes have a higher rate of occurrence with short time intervals.

FRB emission seems to result from **two Poisson** processes.

Zhang, Li* et al. 2024
Science-Bulletin



Randomness Pincus index

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

Random
constant unpredictability

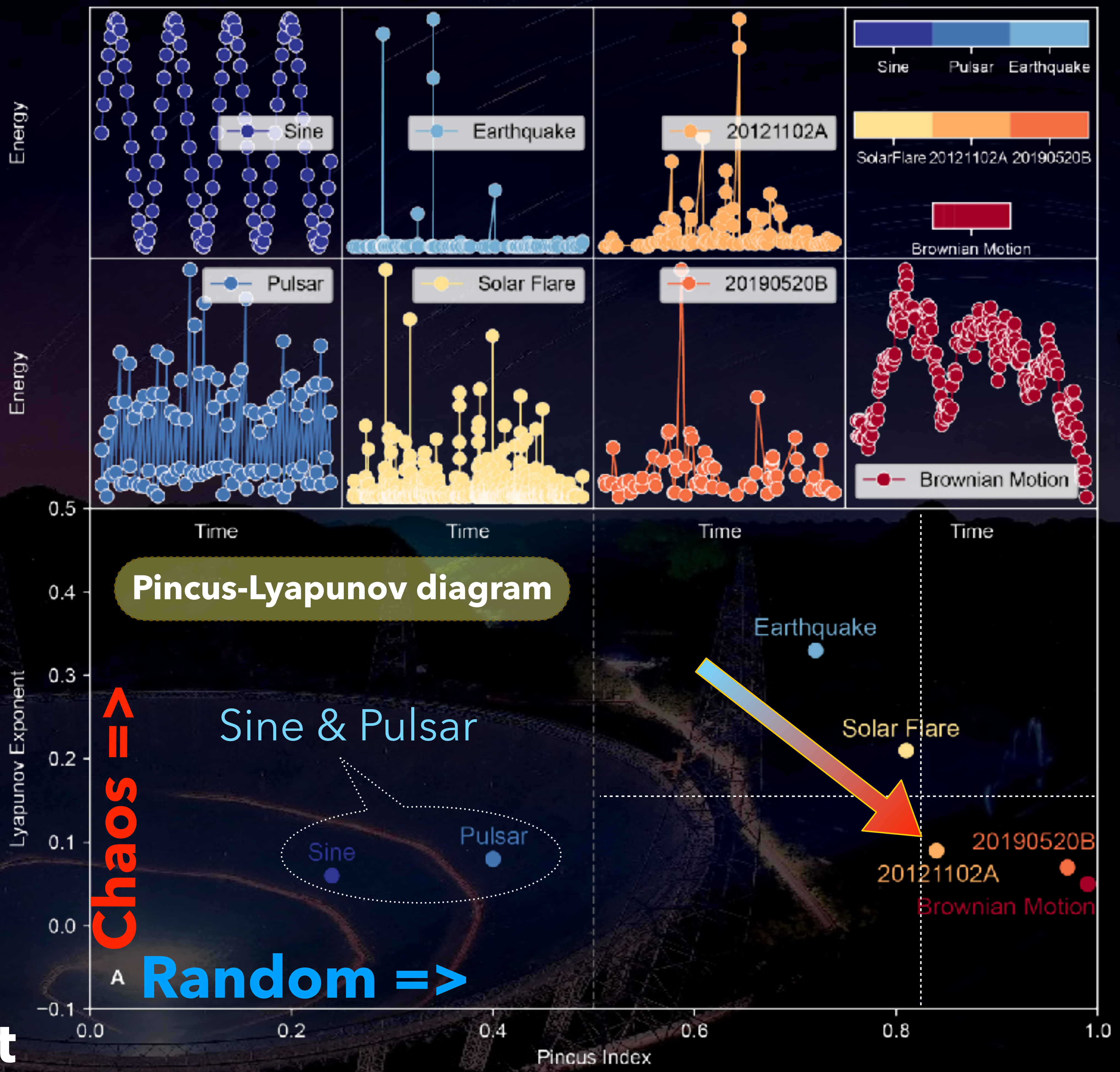
PLD
Pincus-Lyapunov Diagram

dynamic events
on Energy-Time phase space

Chaos
exponential growth in unpredictability

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

Chaos Lyapunov exponent



FRB

God's dices in the E-t phase space?

Pincus-Lyapunov diagram

- FRBs have **no spin-related periodicity!**
- FRBs' arrival times have **no dependence** on energy.
- FRBs events roam the energy-time space like a **Brownian motion**, much less chaotic than earthquakes, but more random.
- Spin trigger unlikely.

«Science Bulletin»

- Multi-discipline journal
- IF ~20 (ranked #5 among all comprehensive journals)

Zhang, Y.K.

Fast Radio Burst (FRB) 快速射电暴

Robustly Known 确切知道

- 相干辐射 "coherent" emission
  $E(\ell \simeq c \cdot \Delta t)$ ... emission zone size scale
  $$T = \frac{S\ell^2}{2k(\nu\omega)^2} \simeq 10^{35} - 10^{41}\ K$$
- 重复 Repeat (≥ partial)
- magneto-ionic 磁化等离子体
  RM, σ_{RM}, θ_{pol}
- radio loud $E_X/E_R \sim 10^5$; $<10^8$
- stochasticity >> periodicity (ms → ~10s)

Educated Guess 合理推测

- 致密天体 compact object (stellar)
- non-catastrophic
- source (swing...) + environment (persistent trends)
- ? PRS

Hypothesis 假说

- 磁星 magnetar
- repeat ≠ non-repeat, thus, diverse origin ?
- VS
- repeat ⟹ non-repeat (evolution)
- MY_BET
- SN ⇒ PRS ⇒ Repeater (Active) ⇓ Repeater (Sporadic) ⇐ Single

Fast Radio Bursts unified picture

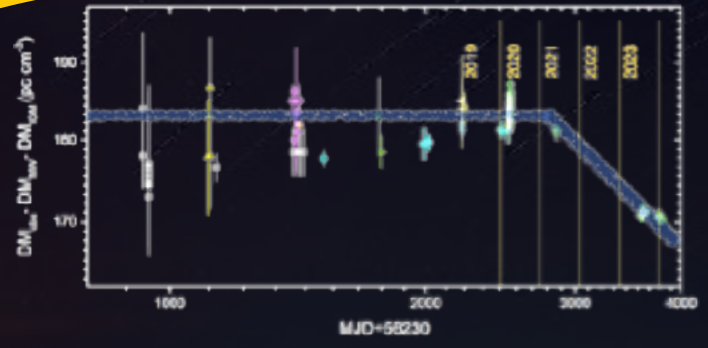
清華大學天文系
Department of Astronomy, Tsinghua University

PRS fades/DM decreases

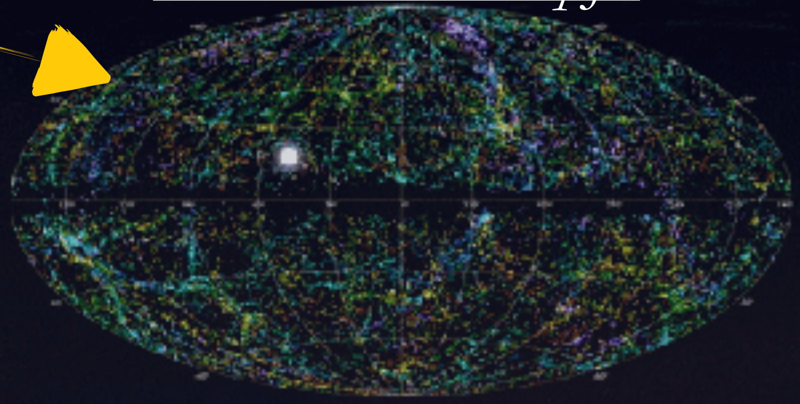
CHIME 2021 *ApJS*

lights up the PRS

Chatterjee+ 2017 Nature
Niu+ 2022 ***Nature***



Wang+ ***NA under review***



Niu+ 2022 ***ApJ***

explosion
hypernova?

compact binaries
Reshma+ 2023 ***Science***

stochastic
Li+ 2021 ***Nature***
Zhang+ 2024 ***Science Bull.***

Active Repeater

bursting through
complex plasma
Feng+ 2022 ***Science***

normal FRB
Single/repeat?

rate drops
pol. Stabilizes

MG XVII

The 17th Marcel Grossmann Meeting – MG XVII

July 9, 2024, Pescara (Italy)

MARCEL GROSSMANN AWARDS

PESCARA 2024

Individual Awards

Goes to

DI LI

"For his groundbreaking contributions to the scientific definition of the most sensitive radio telescope and his numerous innovations in characterizing the dynamic universe, resulting in precise measurements of the interstellar magnetic field and advancing the field of fast radio bursts into a high-statistics era".

"For his groundbreaking contributions to the scientific definitions of the most sensitive radio telescope and his numerous innovations in characterizing the dynamic universe

TEST

Institutional Awards

"For the innovative detection and comprehensive analysis of a large population of fast radio bursts, significantly increasing their statistics, including repeating sources, which have boosted our understanding of their origin and their application in mapping the universe structure and composition".

Goes to:

CHIME/FRB Team

- presented to Professor **Victoria Kaspi**

ICRANet and ICRA

"For the innovative detection and comprehensive analysis of a large population of fast radio bursts …"

2024 Marcel Grossmann Awards

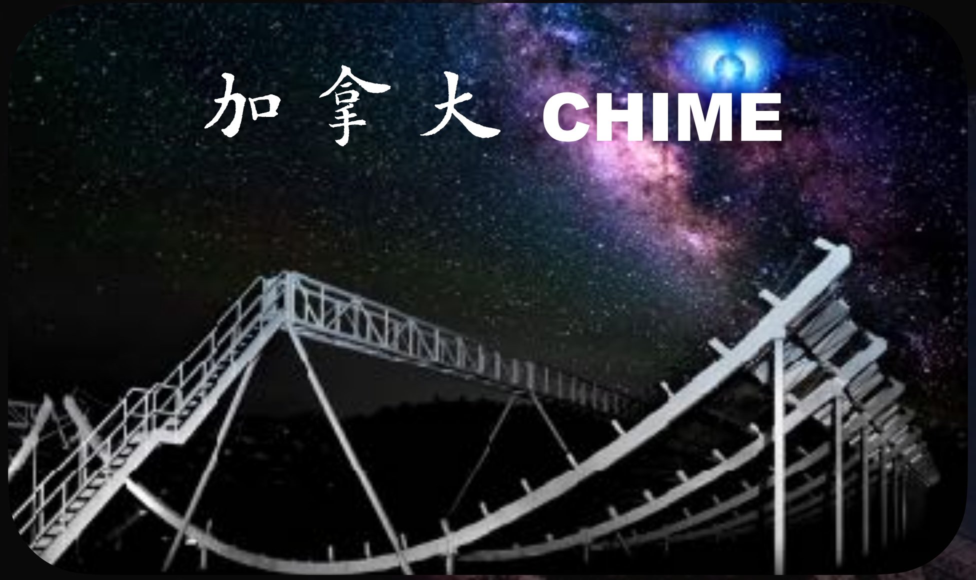
1

Each recipient is presented with a silver casting of the TEST sculpture by the artist A. Pierelli. The original casting was presented to His Holiness Pope John Paul II on the first occasion of the Marcel Grossmann Awards.

Breaking the detection limits

$$\nu = \frac{c}{\lambda}$$

FOV视场 = λ /D   threshold 探测极限 = 1/D^2



望远镜	threshold	detection rate
中国天眼 FAST	0.01 Jy x 21	17/yr
加拿大 CHIME	0.21 Jy	1500/yr x 88

Bottleneck: detection rate

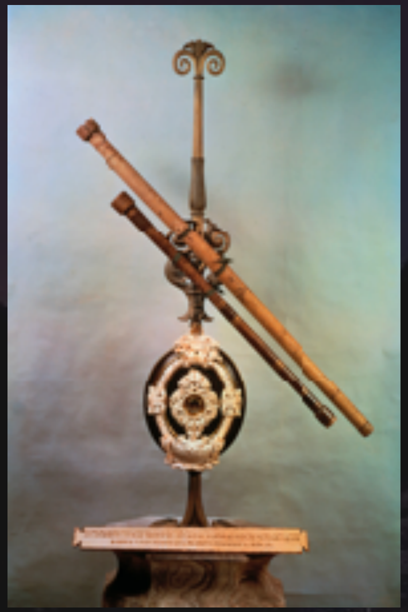
from mirrors to field camera

Focusing-amplification

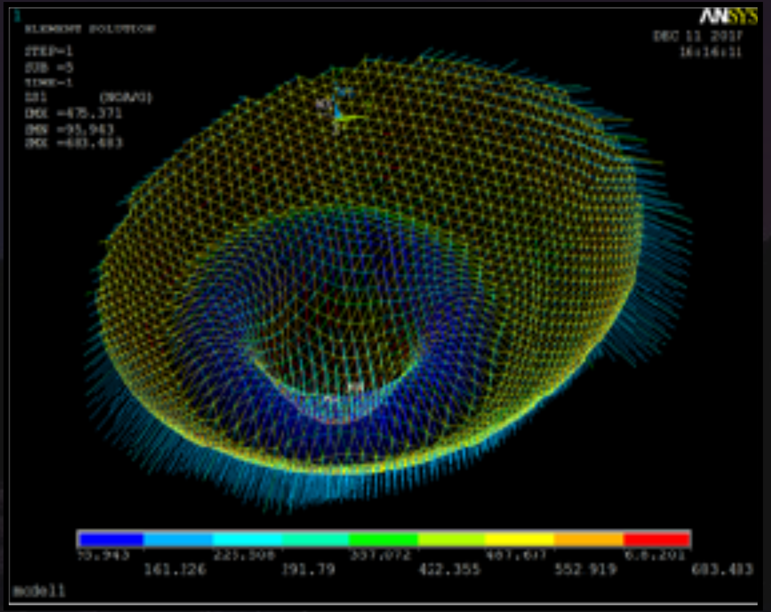
Field sensing + computation

FOCUS

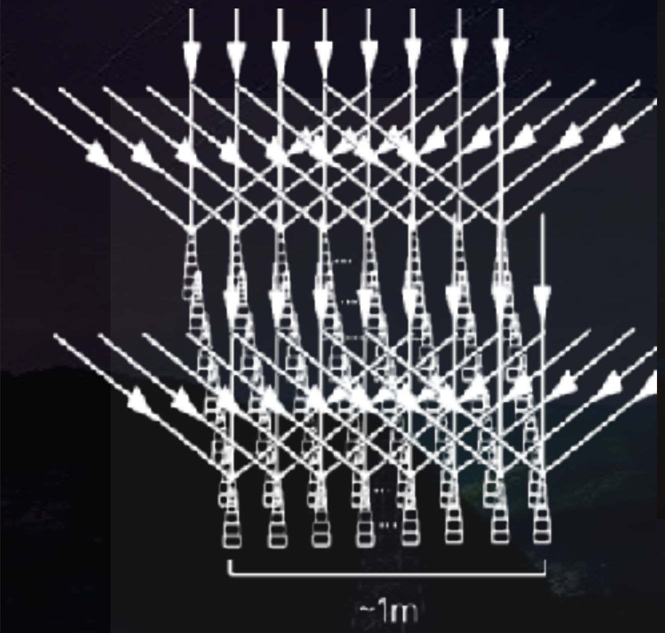
伽利略
GALILEO

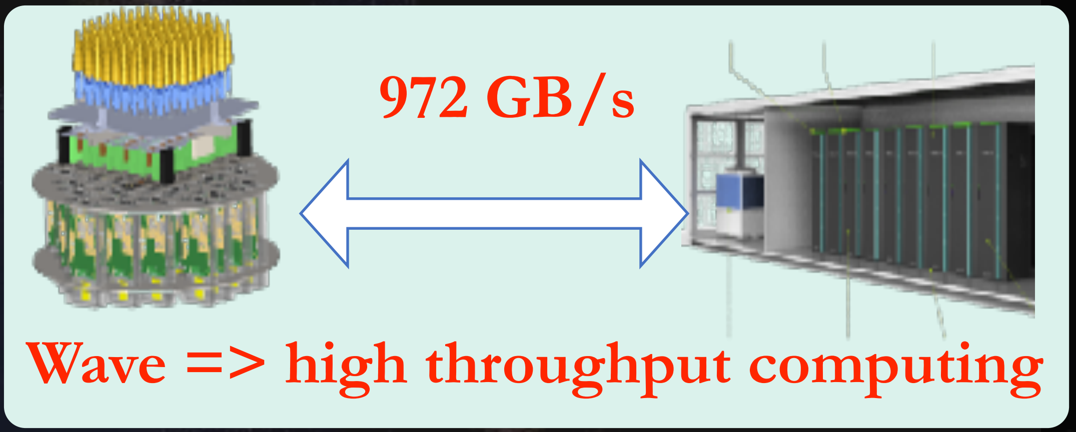


中国天眼 FAST
Active Surface



COMPUTE





Telescope - partial quantum computer

Field camera - digital quantum computer

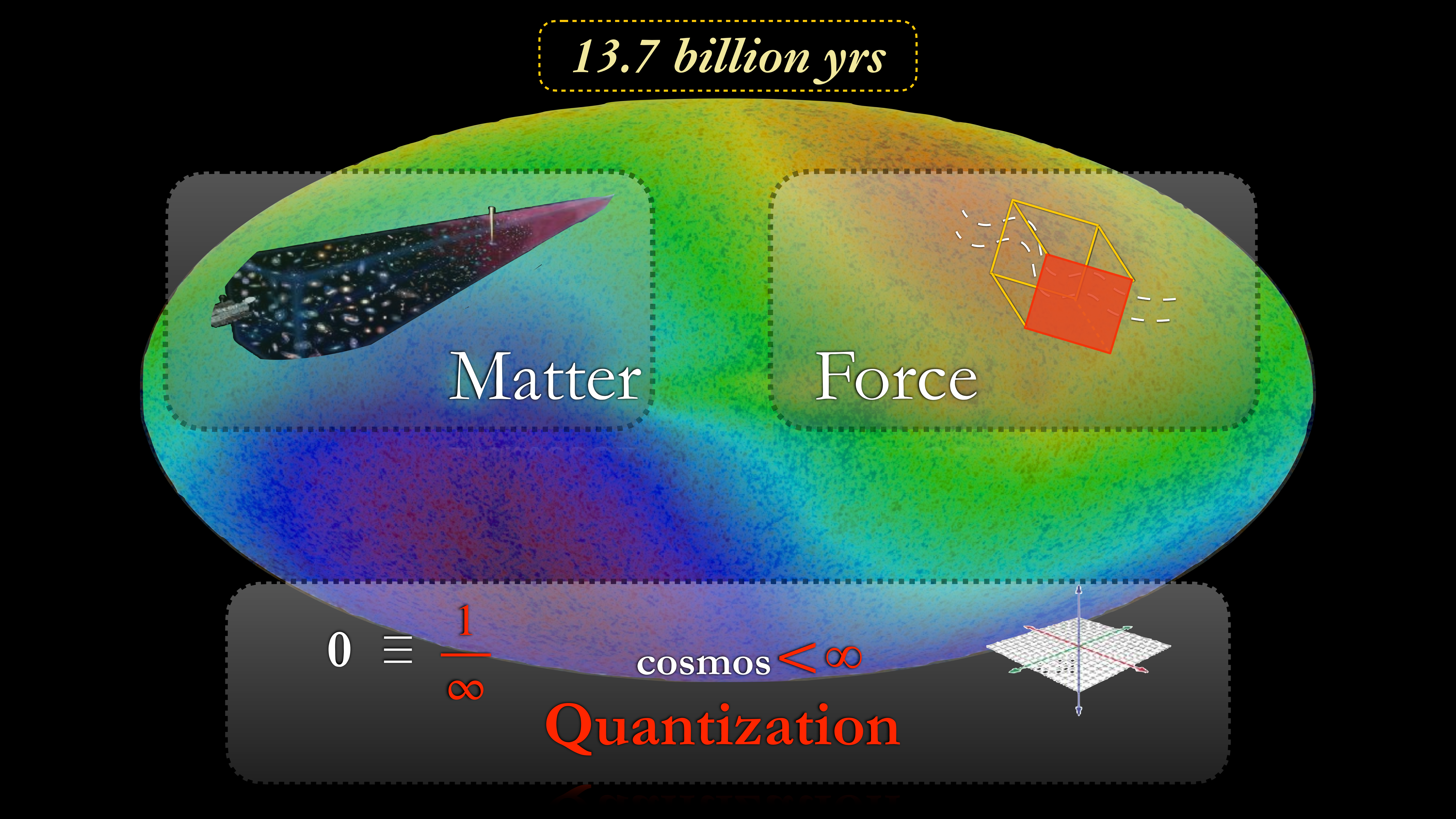
清華大學天文系
Department of Astronomy, Tsinghua University

Cosmic Antennae

宇宙触角

Cosmic Ant·ennae

COSMIC ANTENNAE

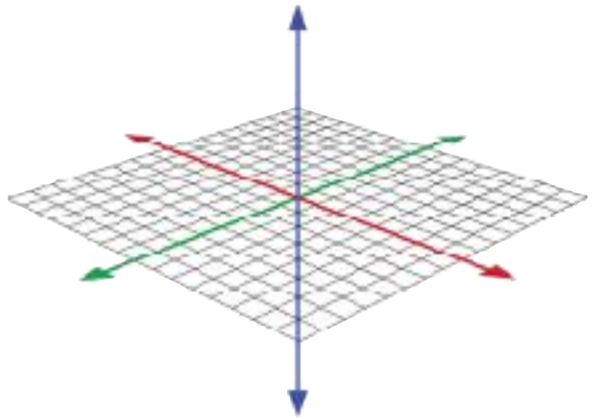


13.7 billion yrs
Matter
Force
$0 \equiv \frac{1}{\infty}$
cosmos $< \infty$
Quantization

$$\mathbf{0} \equiv \frac{1}{\infty}$$

Universe $< \infty$ =» no singularity

=» no absolute symmetry / conservation



=» only "relative" relativity

Li 2025 in prep.

Cosmic Time Frontier “时间前沿”

“能量前沿”

The Energy Frontier Report:

the future of US particle physics (2021 US Community Study)

02

“时间前沿”

The Cosmic Time Frontier

2023-2024 weekend coffee discussion notes

$$E = h\nu \qquad \nu = \frac{c}{\lambda}$$

$$\delta t < \frac{1}{2\nu}$$

$$\Delta t \, \Delta E \geqslant \frac{h}{4\pi}$$

?

the finite Universe

t = *13.7 billion yrs* $Z_{CMB} \sim 1100$

Dynamic Universe

FRB Discovery
2007
Lorimer et al.
Shaw Prize 2023

FRB Systematic
2017-now
FAST+CHIME
ASKAP, SKA,
Arecibo, etc.
Marcel Grossman Award 2024

FRB Origin/Physics
CHORD, DSA,
Cosmic Antennae …
2030?

New science
time frontier?
2035 ?

Computing senses cosmos