


BURSTT Telescope: Surveying and Localizing Fast Radio Bursts in Nearby Universe

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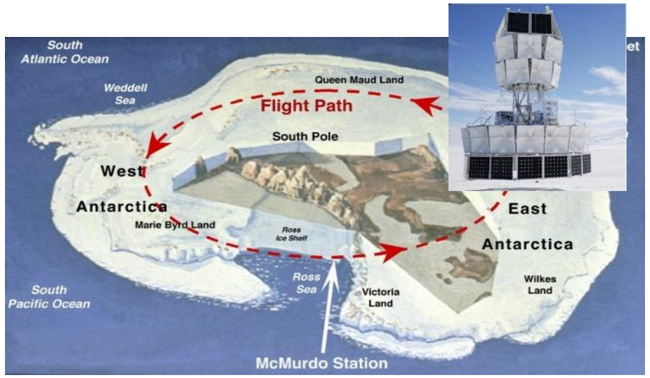
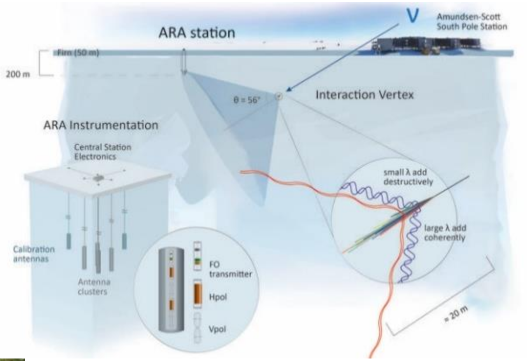
3SOA25, Vietnam

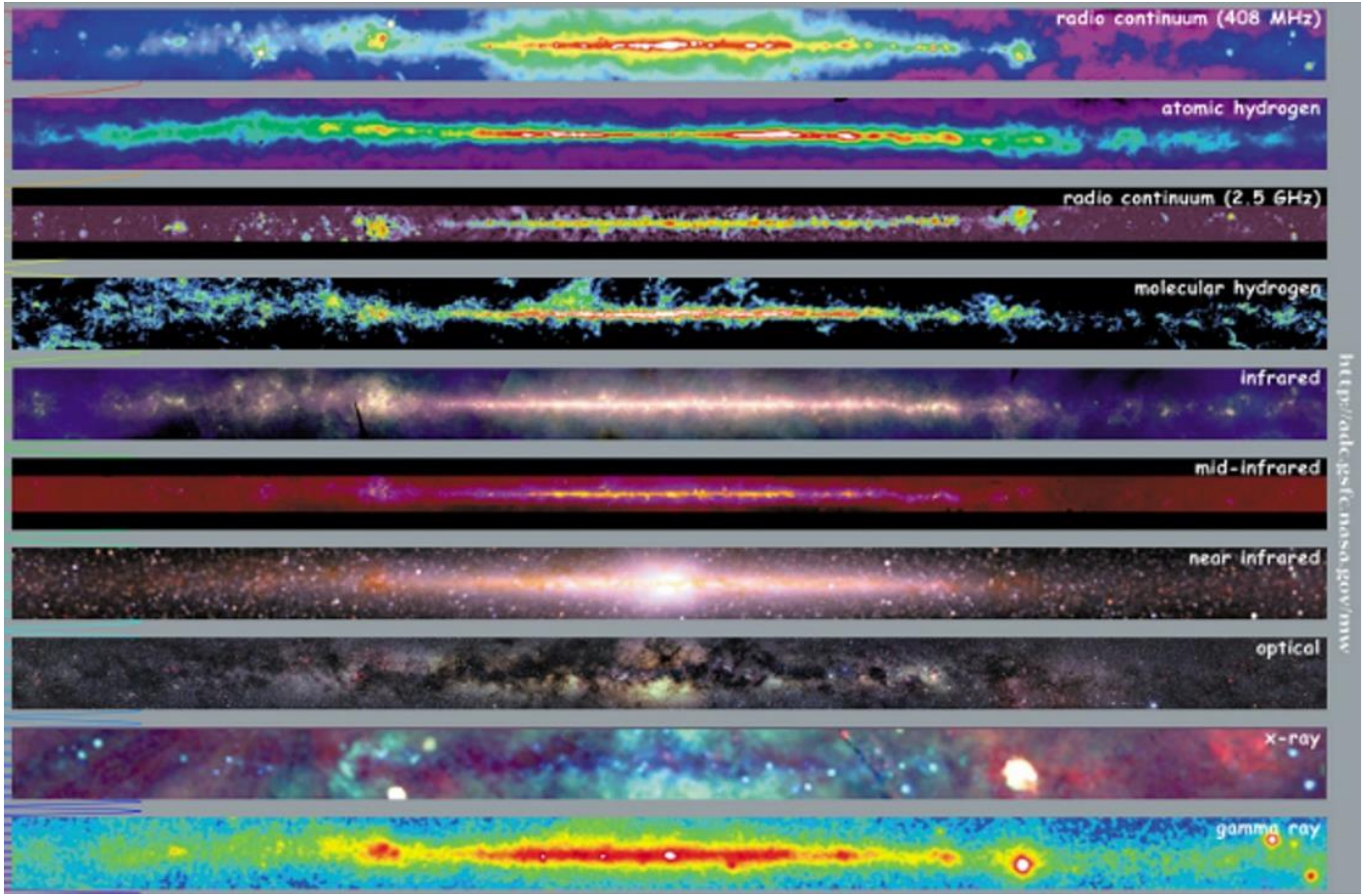
About me

- PhD at NTU → postdoc at LeCosPA / ASIAA
- Build **radio** telescopes from the ground up, to discover radio **transients** from the **unknown** phenomena
- **Ultra-high-energy cosmic neutrino** (E >10^{17} eV) : detecting radio pulse of ~1-10 ns duration
  - TAROGE: high mountain in Taiwan
  - TAROGE-M: in Antarctica
  - also ANITA, ARA, ARIANNA in Antarctica
- **Fast radio burst** with ~1 ms duration
  - BURSTT telescope





Milky Way under multi-wavelengths



radio continuum (408 MHz)

atomic hydrogen

radio continuum (2.5 GHz)

molecular hydrogen

infrared

mid infrared

near infrared

optical

X ray

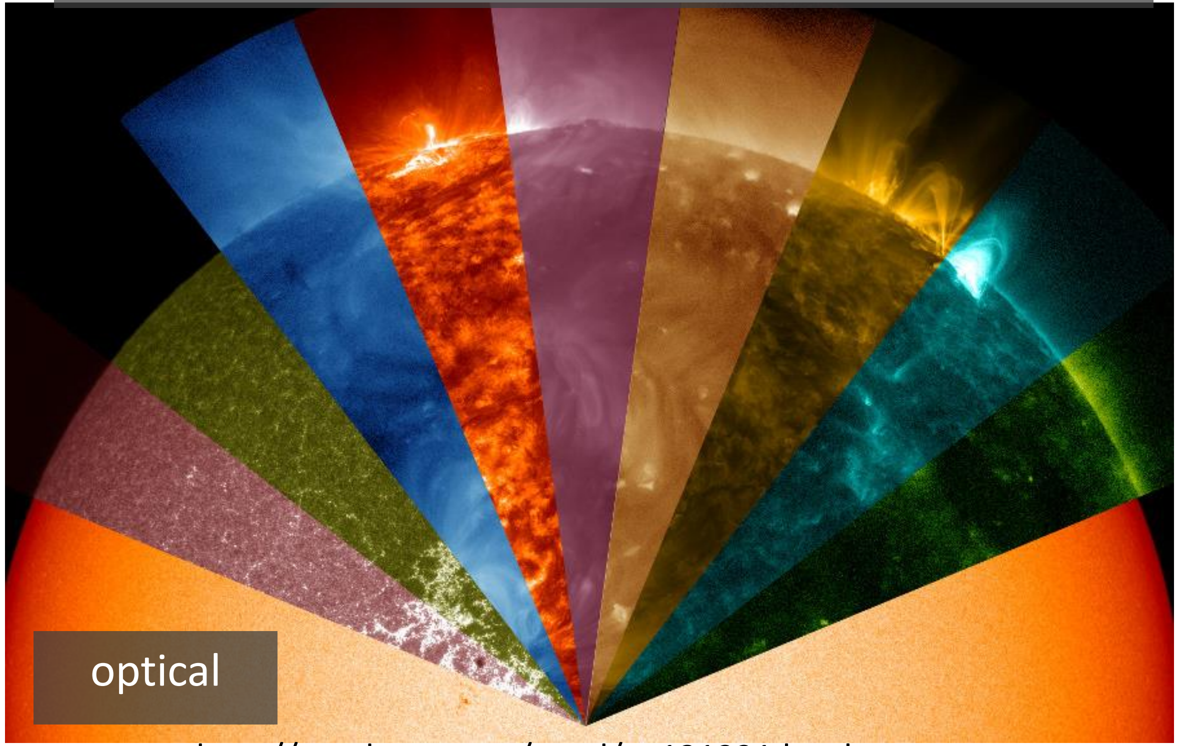
γ ray

Multi-wavelength astronomy

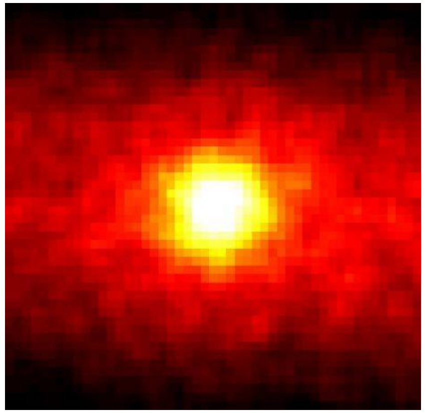
- Reveal different structures and phenomena beyond perception of human eyes

Sun under multi-wavelengths

left to right: UV λ=170 nm to 9.4 nm



http://apod.nasa.gov/apod/ap131221.html

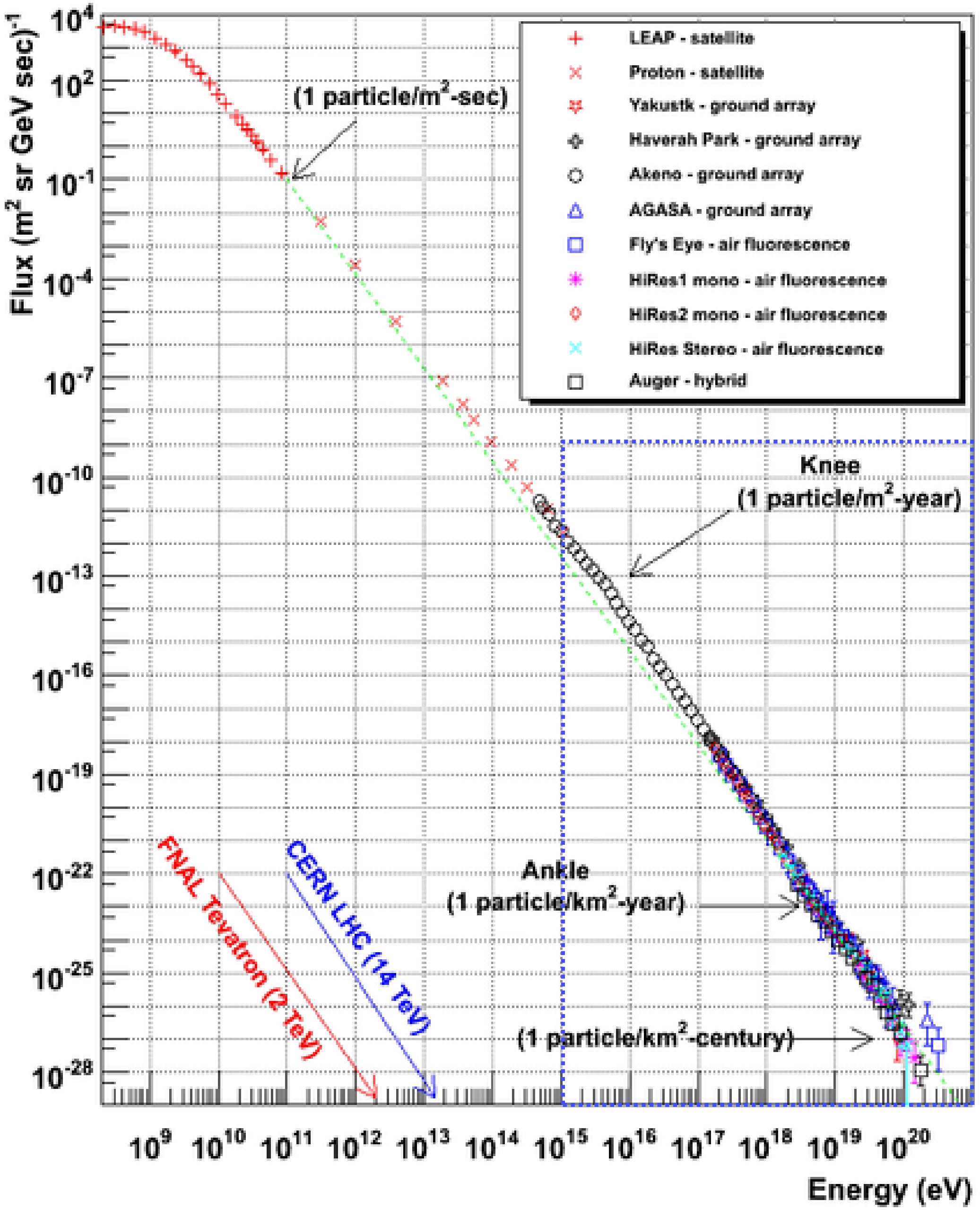


neutrino “image” of the Sun by Super-K → see the core of nuclear fusion

Ultra-high energy cosmic rays (UHECRs)

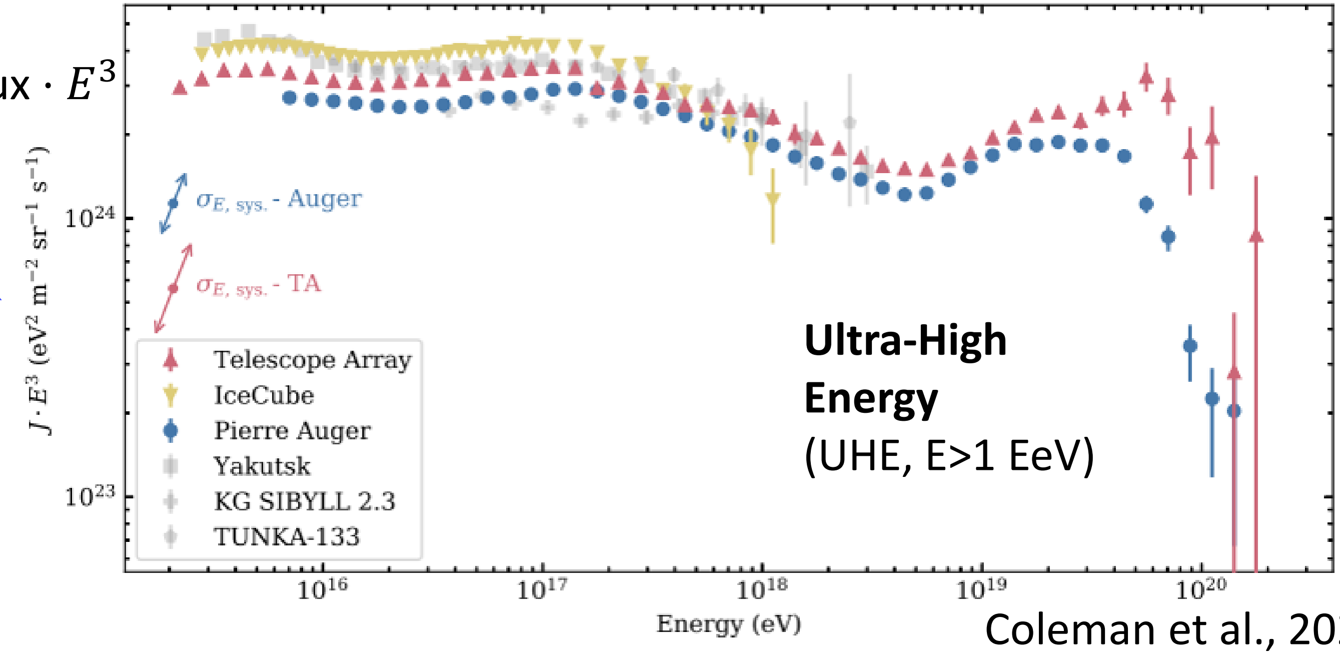
Cosmic Ray Spectra of Various Experiments

credit: W. Hanlon, 2009



- cosmic rays: charged particles from space, mostly protons and nuclei
- power-law spectrum with spectral break
  - suggesting transition from Galactic to extragalactic origin and different composition
- Most energetic particles ever observed: > **10^{20} eV** !
  - but from where and how?

flux $\cdot\, E^3$



Coleman et al., 2022

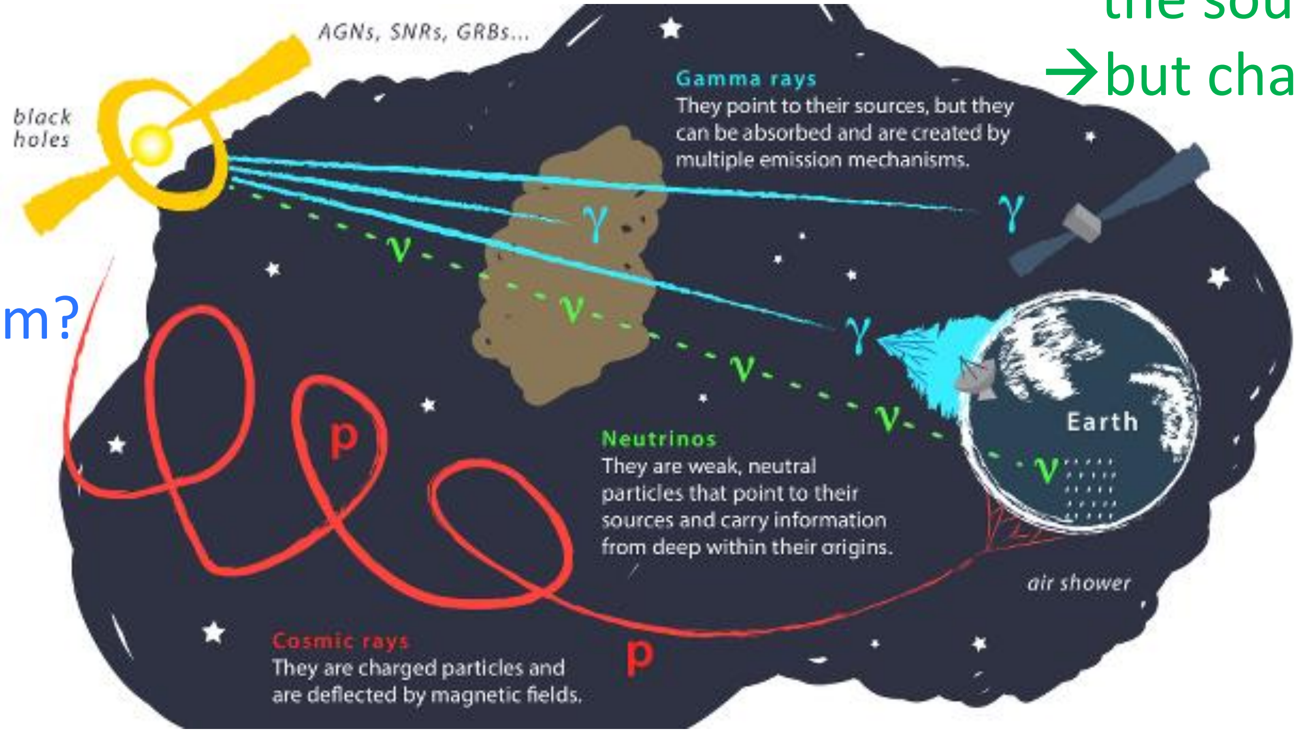
Ultra-high energy cosmic rays and neutrinos
(UHECRs & UHECNs)

1 EeV = 10^{18} eV

- **Ultra-High Energy** (UHE, E>1 EeV) cosmic rays up to 100 EeV observed
- → the missing key to resolve UHECR mysteries

Neutrinos：
charge neutral → not deflected
weakly interacting →not disturbed
→ tracing the sources
→bringing info deep inside the sources
→but challenging to detect

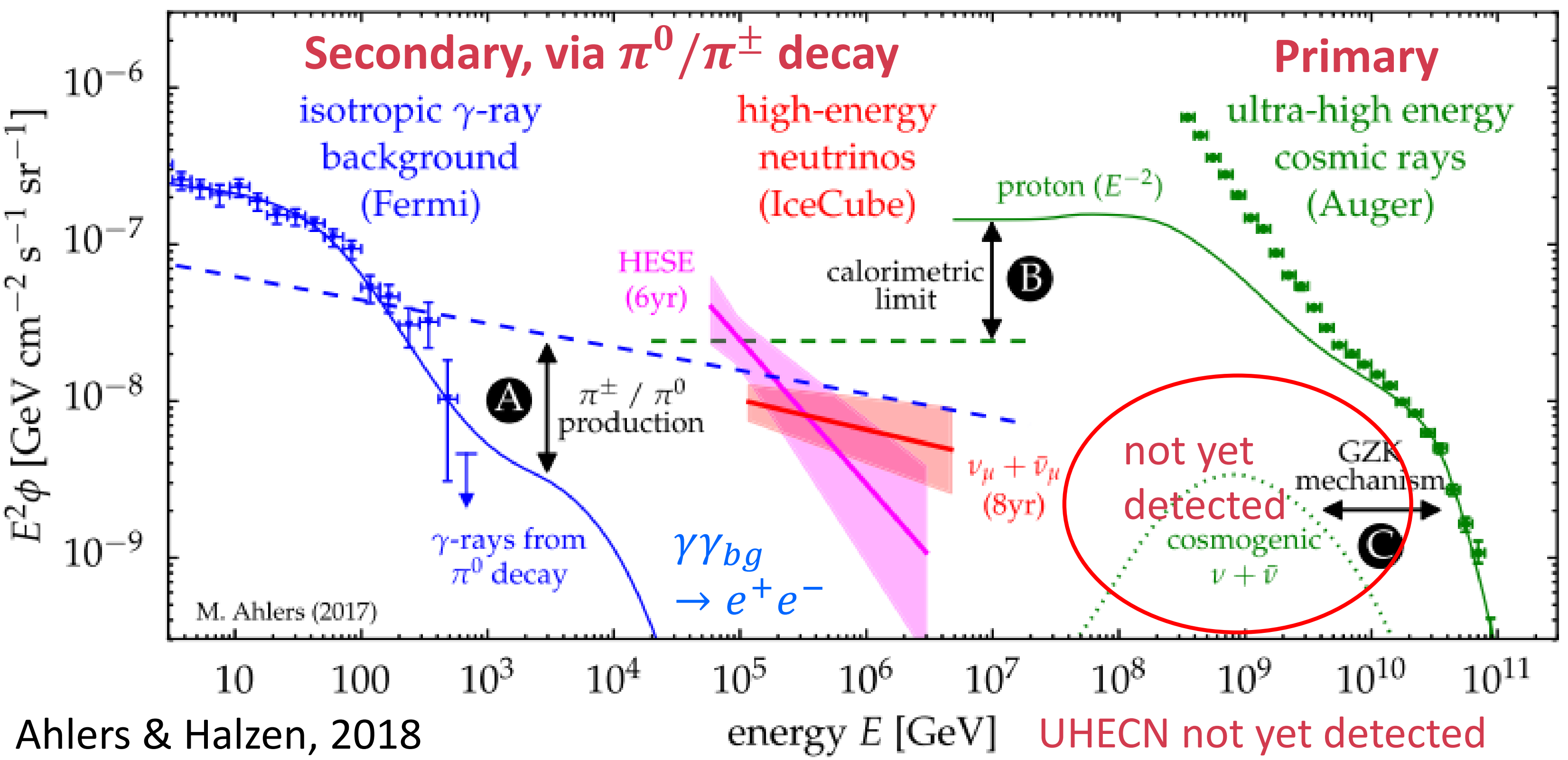
UHECR mysteries:
- source?
- acceleration mechanism?
- composition?



credit: Icecube observatory

Cosmic ray：
charged
→ deflected by B-field
→lose directional info

Multi-Messenger Astrophysics at Highest Energies



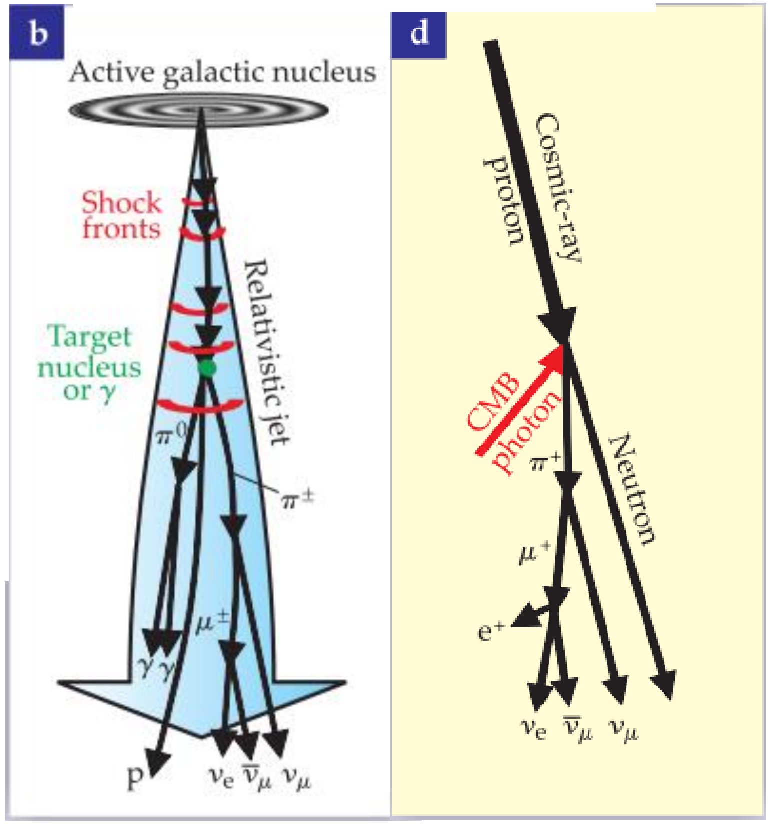
Ahlers & Halzen, 2018

UHECN not yet detected

$$\pi^+ \to \nu_\mu + \mu^+ \to \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+,$$

$$\pi^- \to \bar{\nu}_\mu + \mu^- \to \bar{\nu}_\mu + \nu_\mu + \bar{\nu}_e + e^-,$$

$$\pi^0 \to \gamma\gamma,$$



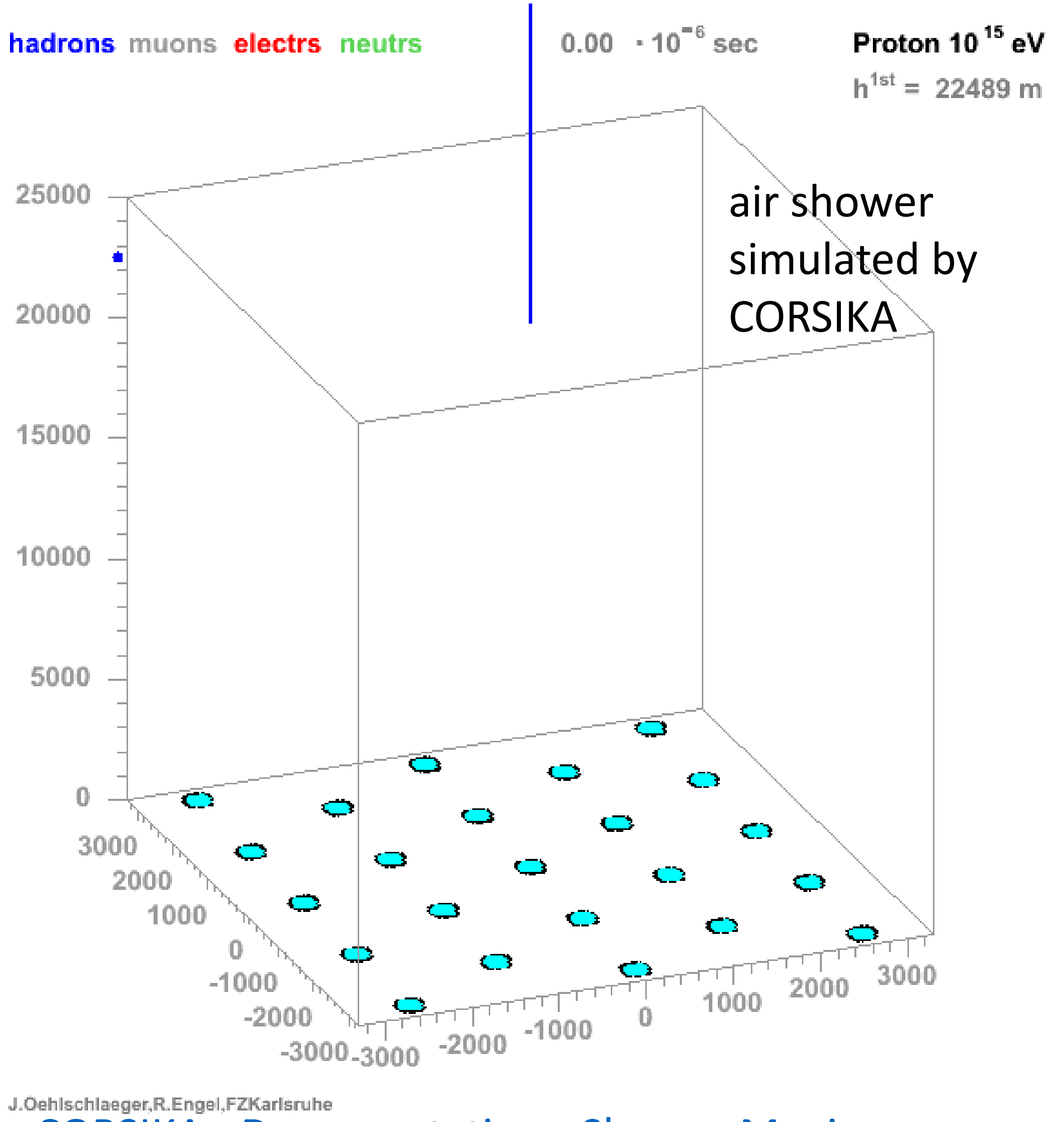
Astrophysical ν   Cosmogenic (GZK) ν

Halzen & Klein, 2008

- UHECR beyond >50 EeV and γ-ray >1 PeV are attenuated by cosmic background photons

→ UHECN: the unique messenger to resolve UHECR mysteries

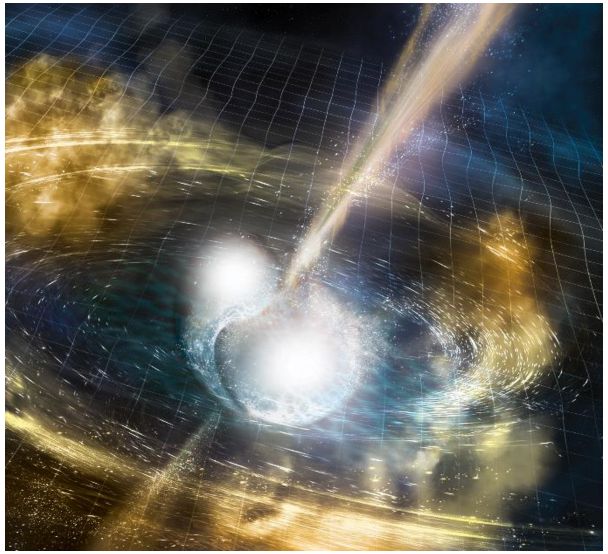
Indirect detection with extensive air shower



air shower simulated by CORSIKA

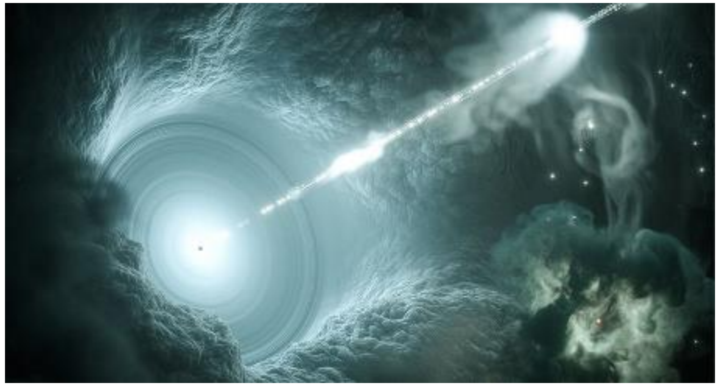
- UHE particles has low flux (< 1 /km^2/year):
  - direct detection is inefficient
- interaction with medium on Earth
  - cosmic rays: in atmosphere
  - neutrinos: in Earth crust, water & ice
- secondary electrons and positrons emit EM waves
  - optical & **radio**
- secondary muons are penetrating
  - particle detector

KIT - CORSIKA - Documentation - Shower Movies



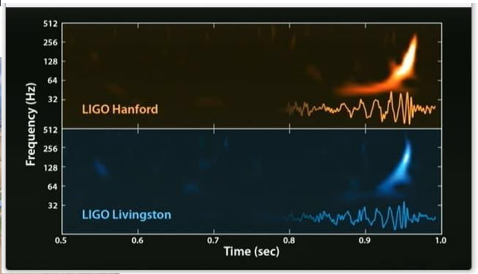
photons & GW from binary neutron star merger

Fermi-LAT



photons & neutrino from blazar (active galactic nuclei)

LIGO



Photons

To see

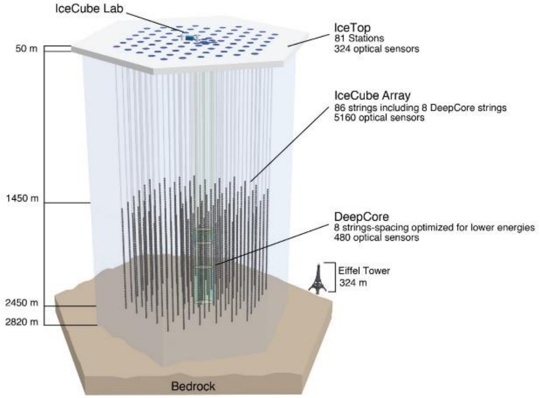
Gravitational waves

To listen

Neutrinos (& CRs)

To taste

Icecube



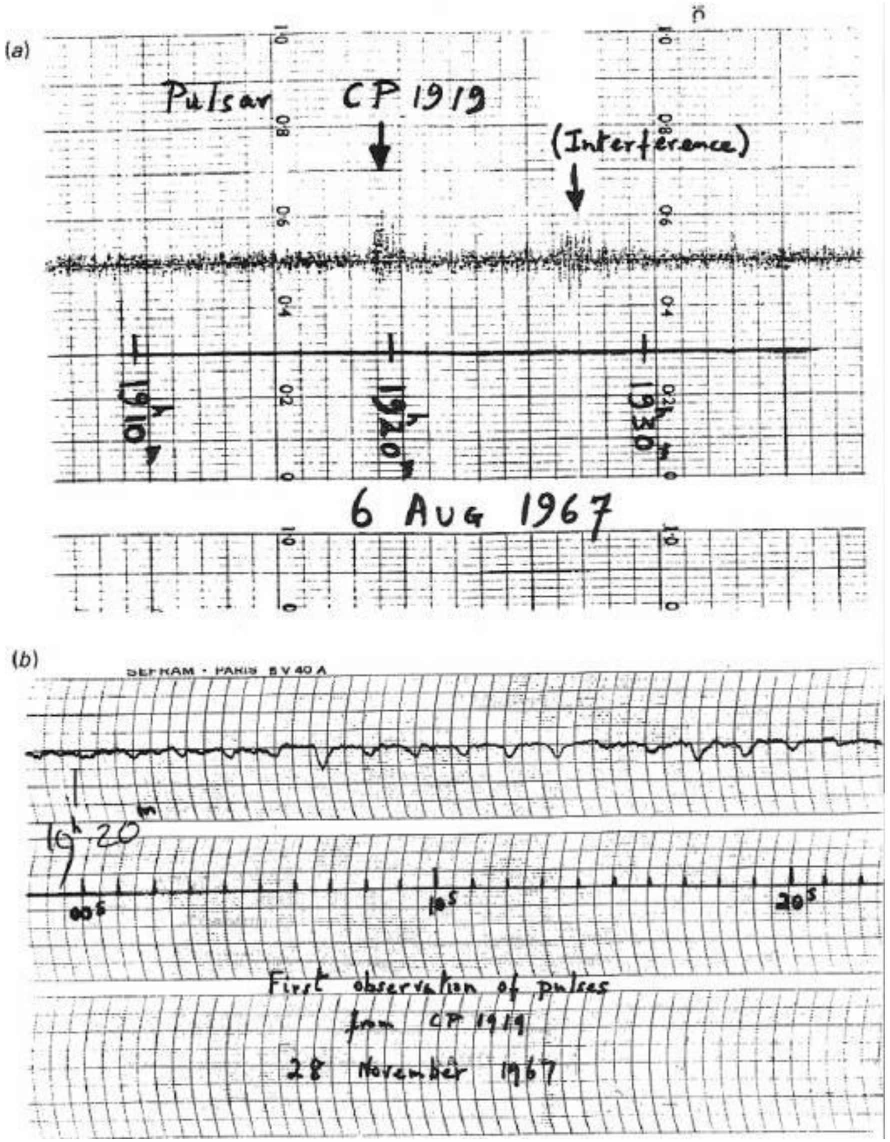
Multi-Messenger Astrophysics

Discovery of Fast Radio Burst

Discovery of pulsar (neutron star)

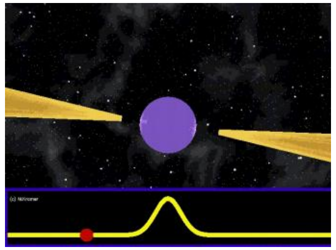
- by Jocelyn Bell, 1967
  - was PhD student at University of Cambridge
- periodic pulses
  - “the little green men”

→ pulsars (pulsating star)



pulsar PSR B1919+21
period 1.337302088331 second

(Arzoumanian et al., 1991)



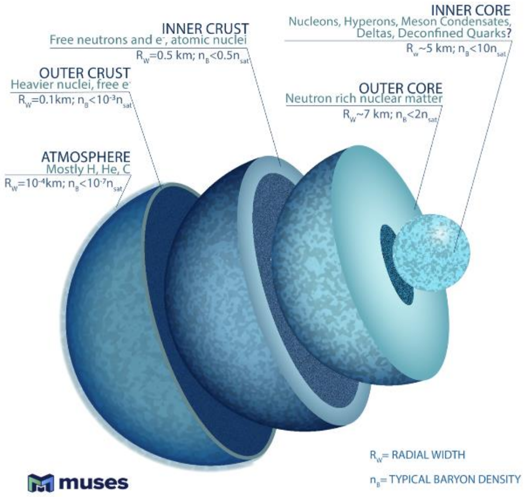
credit: Michael Kramer

credit: Cavendish Laboratory

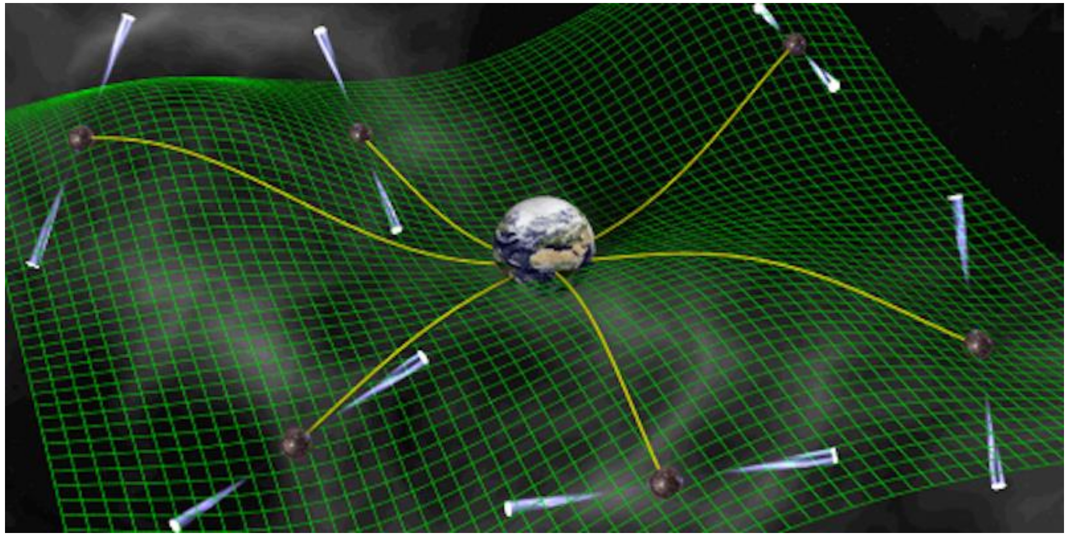
The discovery was recognized by the Nobel Prize. However, only her advisor, Antony Hewish, was awarded…

Pulsar / Neutron star at the frontier of physics

credit: ESA



credit: MUSES, UIUC



credit: D. Champion/Max Planck Institute for Radio Astronomy

- extreme state of matter
  - 1.4 solar mass contained within ~10 km radius
  - density ~10^{17} g/m^3 ~ density of atomic nuclei

  → study strong interaction (QCD), exotic matter

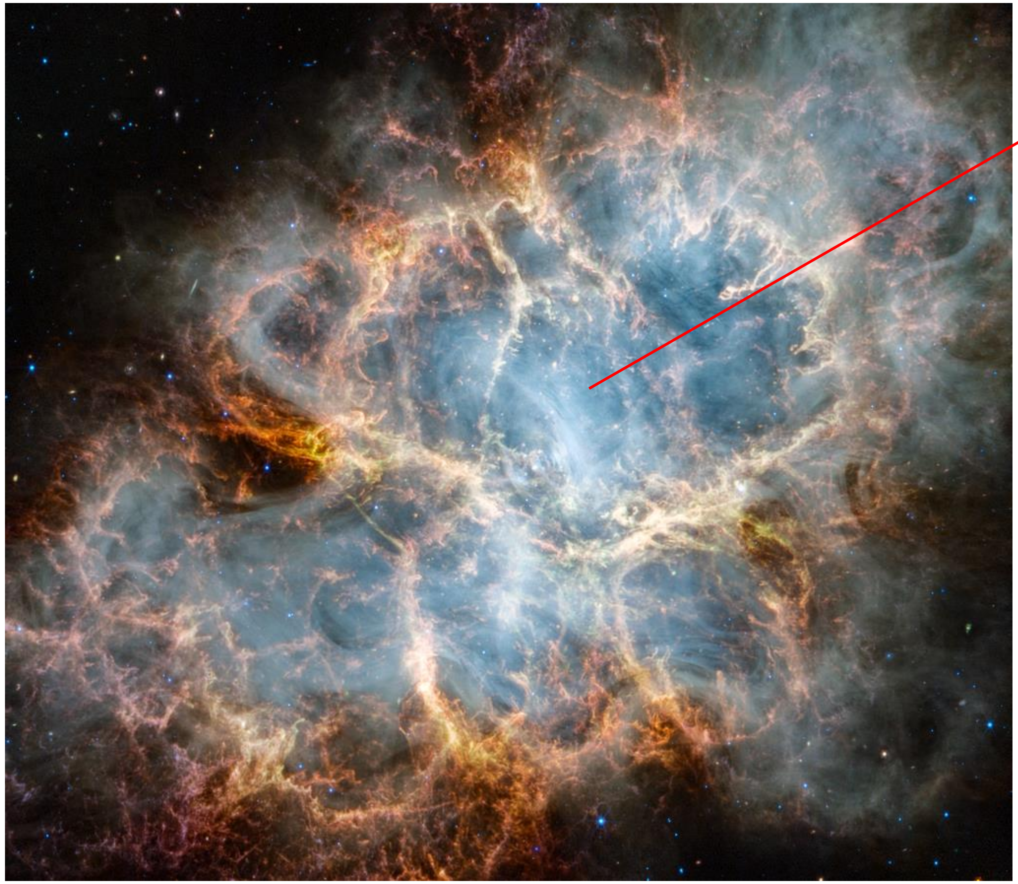
- extremely precise timing: the most precise natural clock
  - comparable to atomic clock

→ pulsar timing array for detecting gravitational wave background

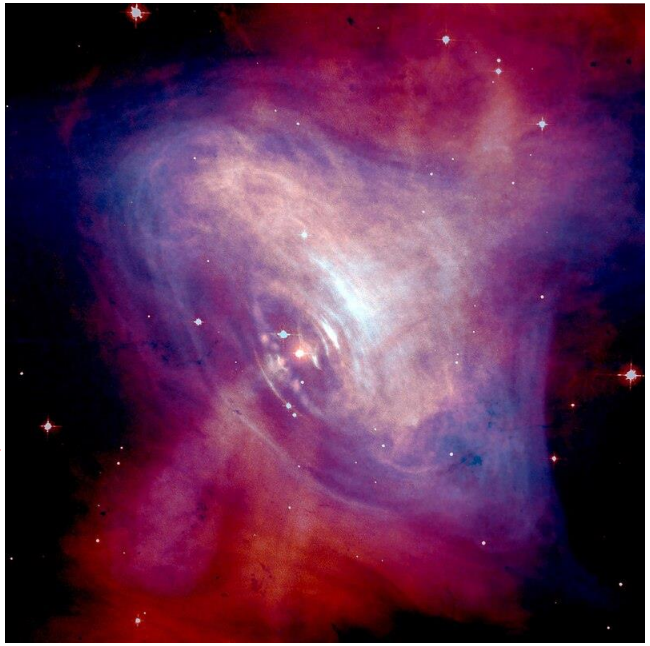
→ cosmic inflation, super-massive black hole mergers

Crab pulsar

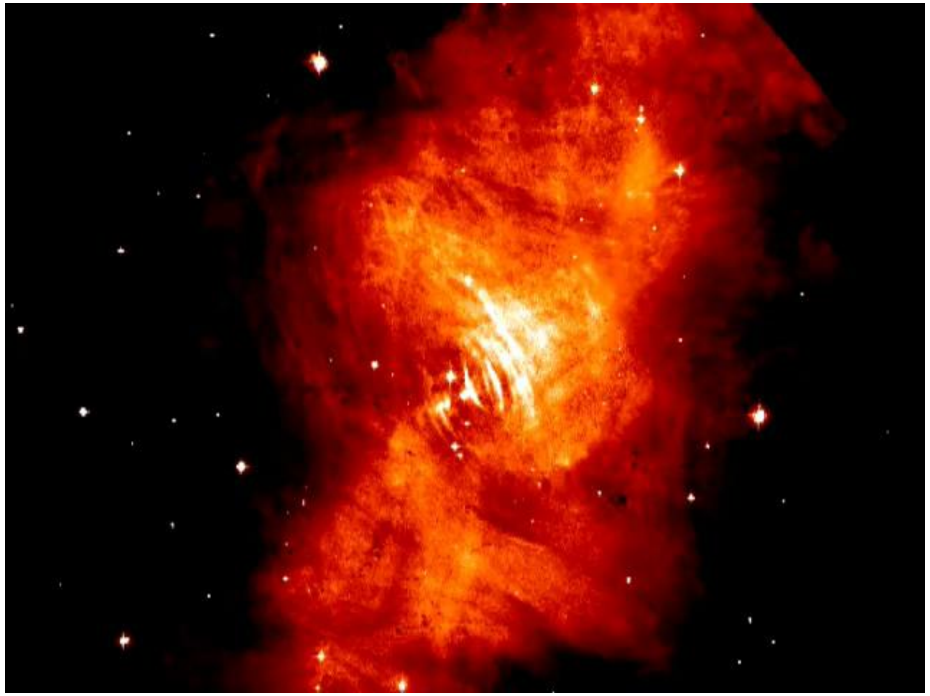
- inside Crab Nebula: remnant of supernova exploded in 1054 AD



credit: JWST



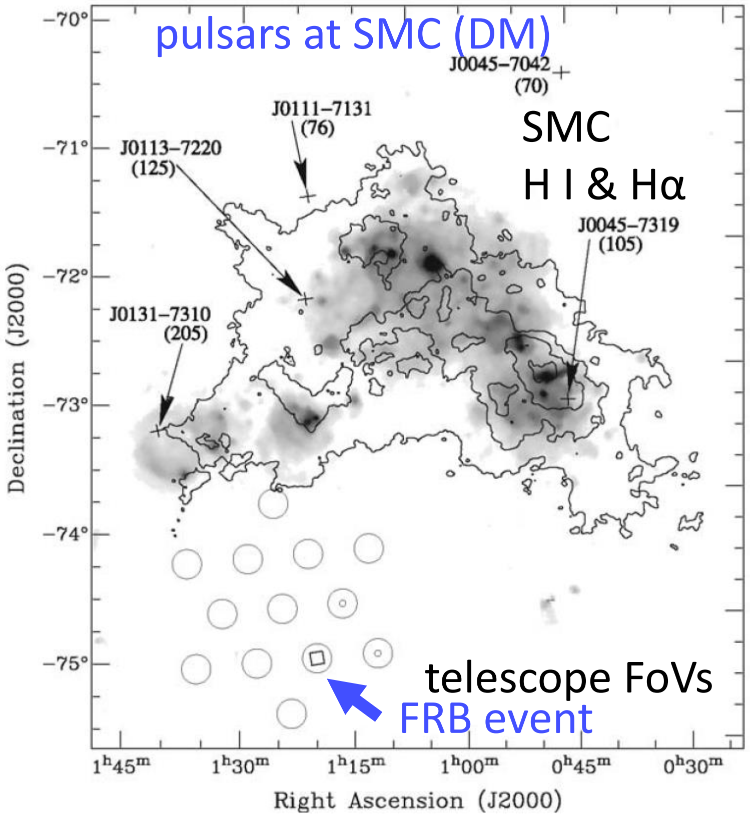
credit: HST, Chandra

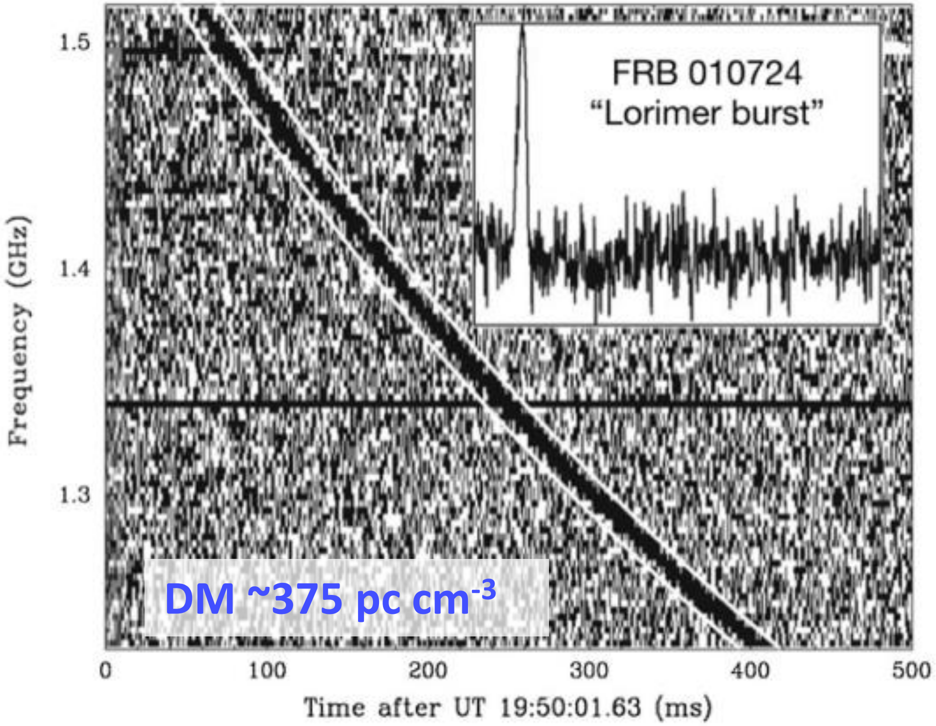


credit: HST

Discovery of Fast Radio Burst (FRB) in 2007

Parkes Telescope (D=64 m, Australia)





- Accidentally found in archival data in 2001 for pulsar survey
- Direction close to Small Magellanic Cloud (SMC)
- but pulse is highly dispersed more than expected

  → suggests the source is from beyond SMC

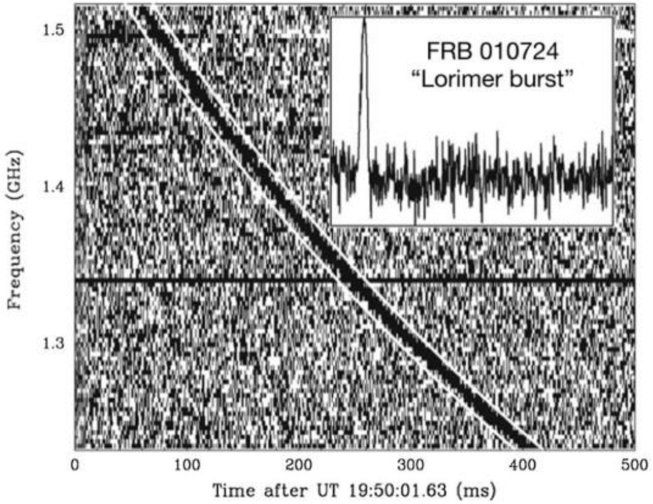
D. Lorimer+, Science, 2007; Zhang, Rev. Mod. Phys., 2023

https://www.shawprize.org/laureates/2023-astronomy/

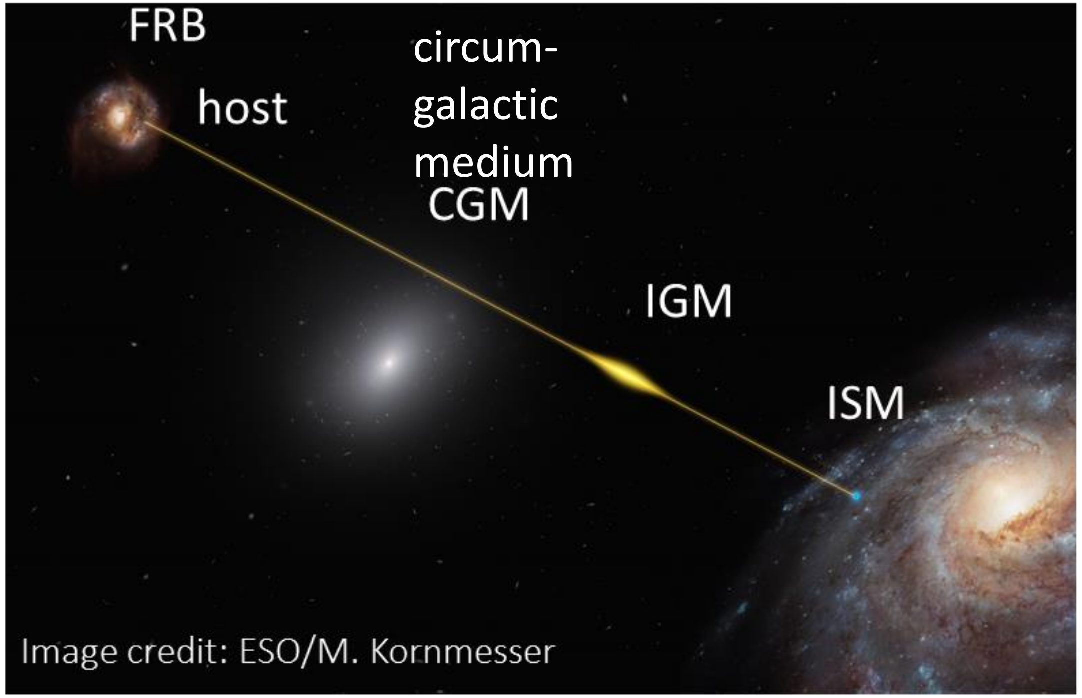
awarded by Shaw Prize in astronomy in 2023

Matthew Bailes Duncan Lorimer Maura McLaughlin

FRB feature: highly dispersed radio pulse



DM ~375 pc cm^{-3}



- radio wave propagating through plasma in the Universe
- Delay proportional to the amount of free electrons
  - → FRB can measure the matter contents in Universe
  - → FRB intrinsic duration: only ~millisecond

Dispersion delay between frequency ν_1 and ν_2

$$\Delta t = t(\nu_1) - t(\nu_2) = \frac{e^2}{2\pi m_e c}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right)\mathrm{DM}$$

$$\simeq (4.15\ \mathrm{ms})\left(\frac{1}{\nu_{1,\mathrm{GHz}}^2} - \frac{1}{\nu_{2,\mathrm{GHz}}^2}\right)\frac{\mathrm{DM}}{\mathrm{pc\,cm^{-3}}}$$

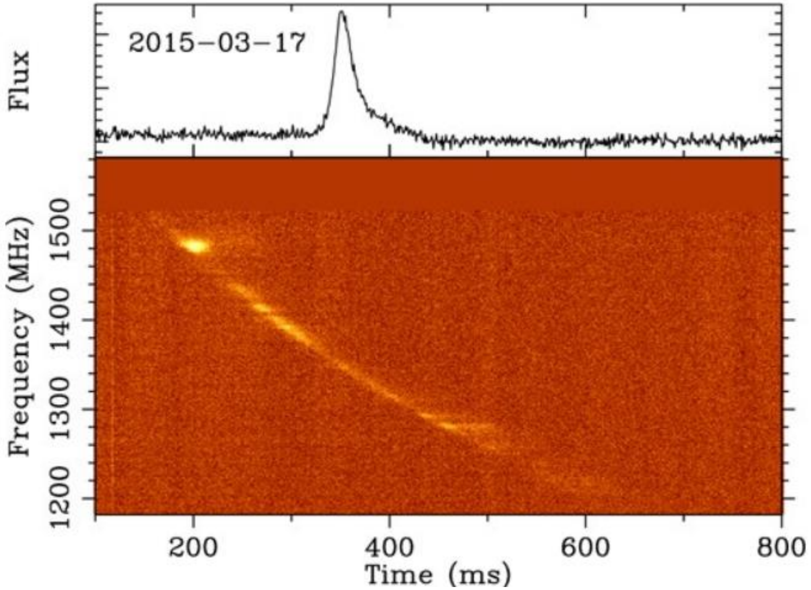
D. Lorimer+, Science, 2007
Zhang, Rev. Mod. Phys., 2023

Dispersion Measure (DM): $\mathrm{DM} = \int_0^D n_e dl$

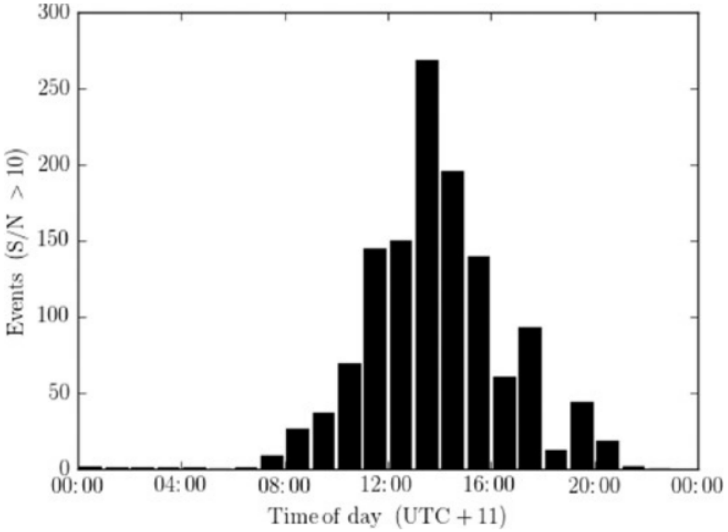
integrated column density of free electrons along line of sight

More similar events, but confusing

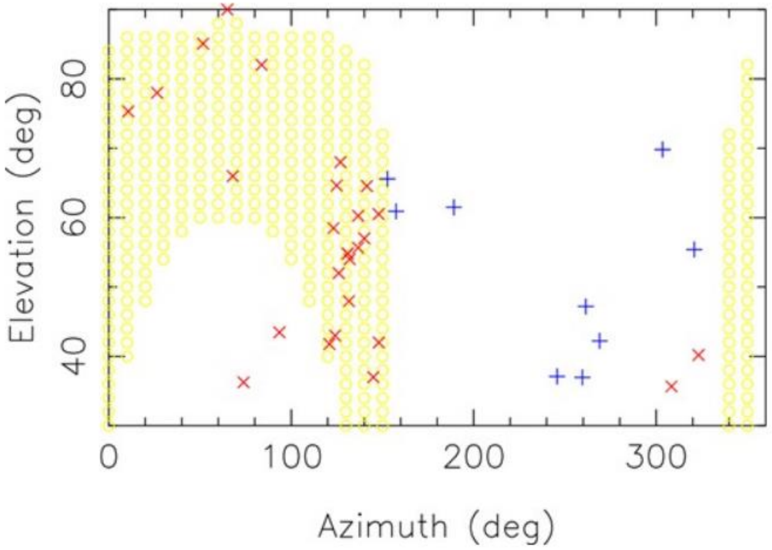
“Peryton” events



clustering at daytime



directional distribution



E. Petroff+, MNRAS, 2015

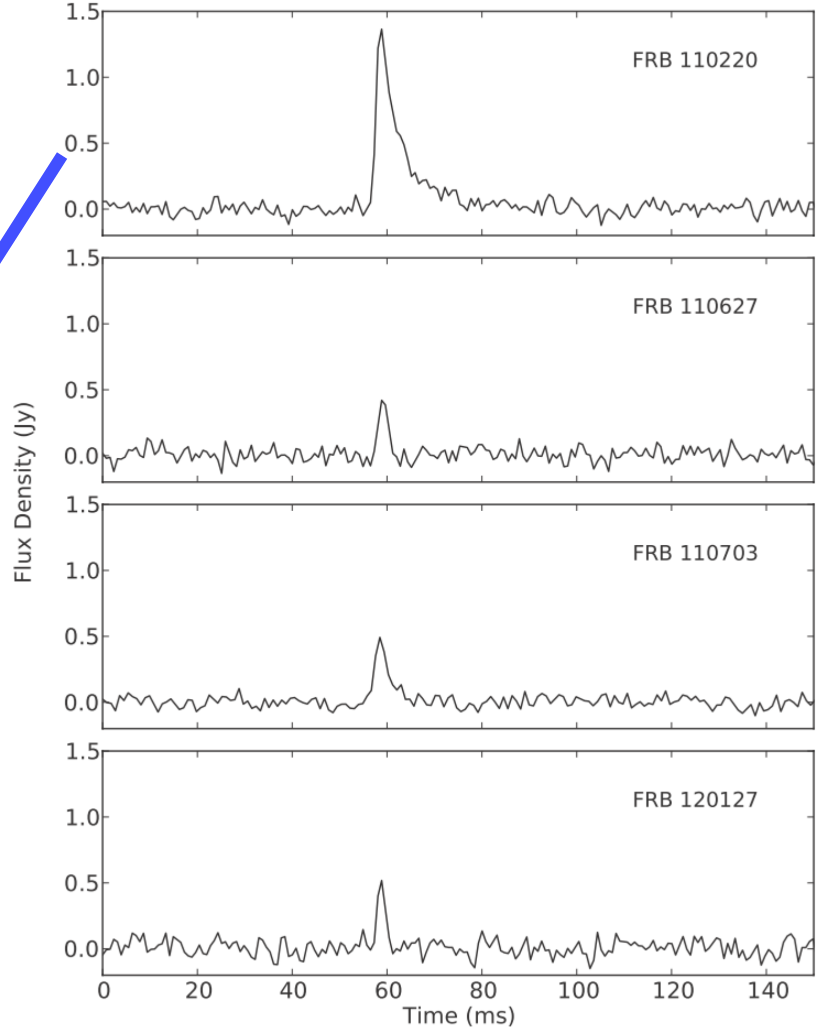
- Parkes telescope detect several tens of similar events, but they look like man-made

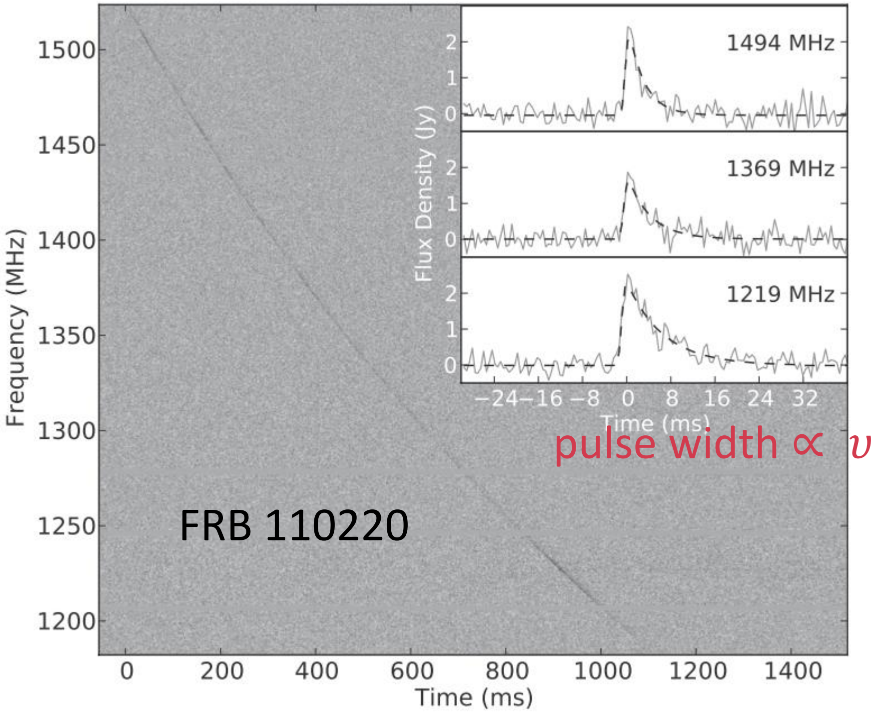
Source:
on-site microwave oven was open before it’s off, around lunch time
→ radio-frequency interference (RFI) can be a headache for astronomy

More FRBs detected

- 4 more FRBs discovered Thornton et al. in 2013
  - >40⁰ from Galactic plane
  - no multi-wavelength counterpart
- with high DM beyond Galactic contribution
- frequency-dependent pulse width
  → scattering in cold plasma → confirming celestial origin

pulses after de-dispersion





pulse width ∝ υ^{-4}

Thornton+, Science, 2013

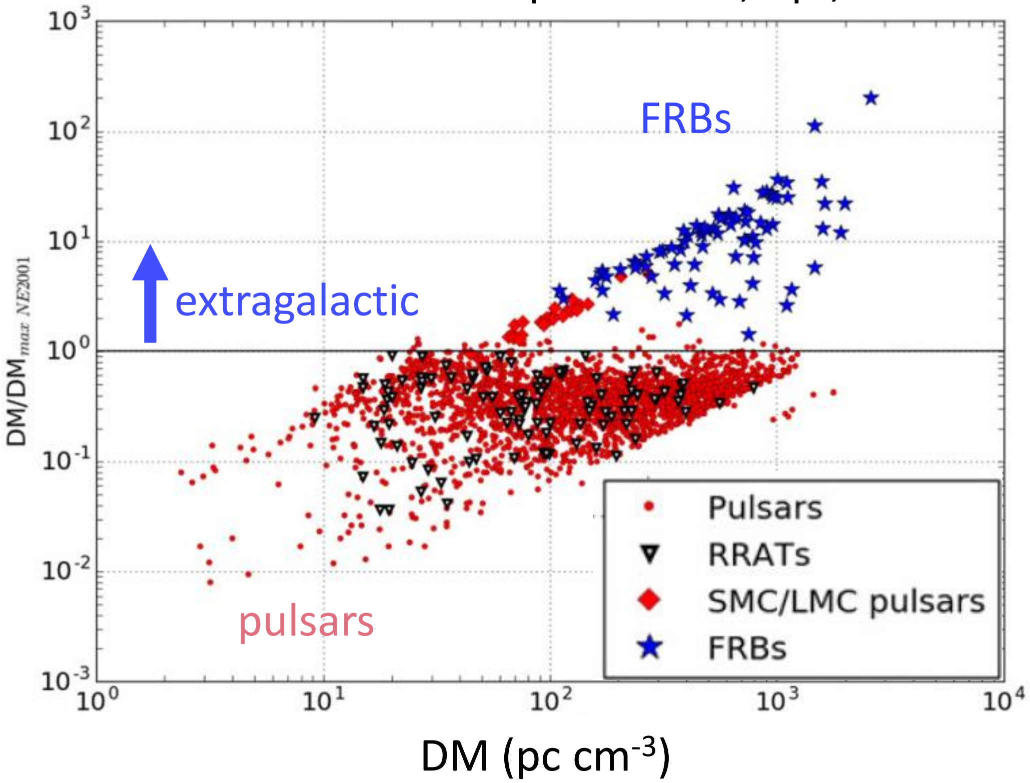
FRB: mysterious origin & observational challenges

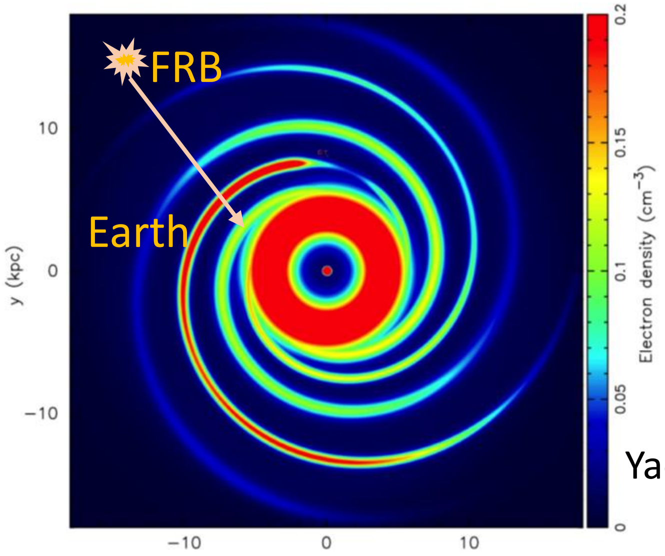
FRBs are extragalactic

- All with high DMs beyond Galactic contribution
  - mainly contributed by plasma in IGM
  - → **extragalactic** origin
- except 1 from Galactic magnetar
  - FRB 20200428 → SGR1935+2154
  - radio & X-ray emission

$$\frac{DM}{\max Galactic\ DM}$$

Spitler et al., ApJ, 2014



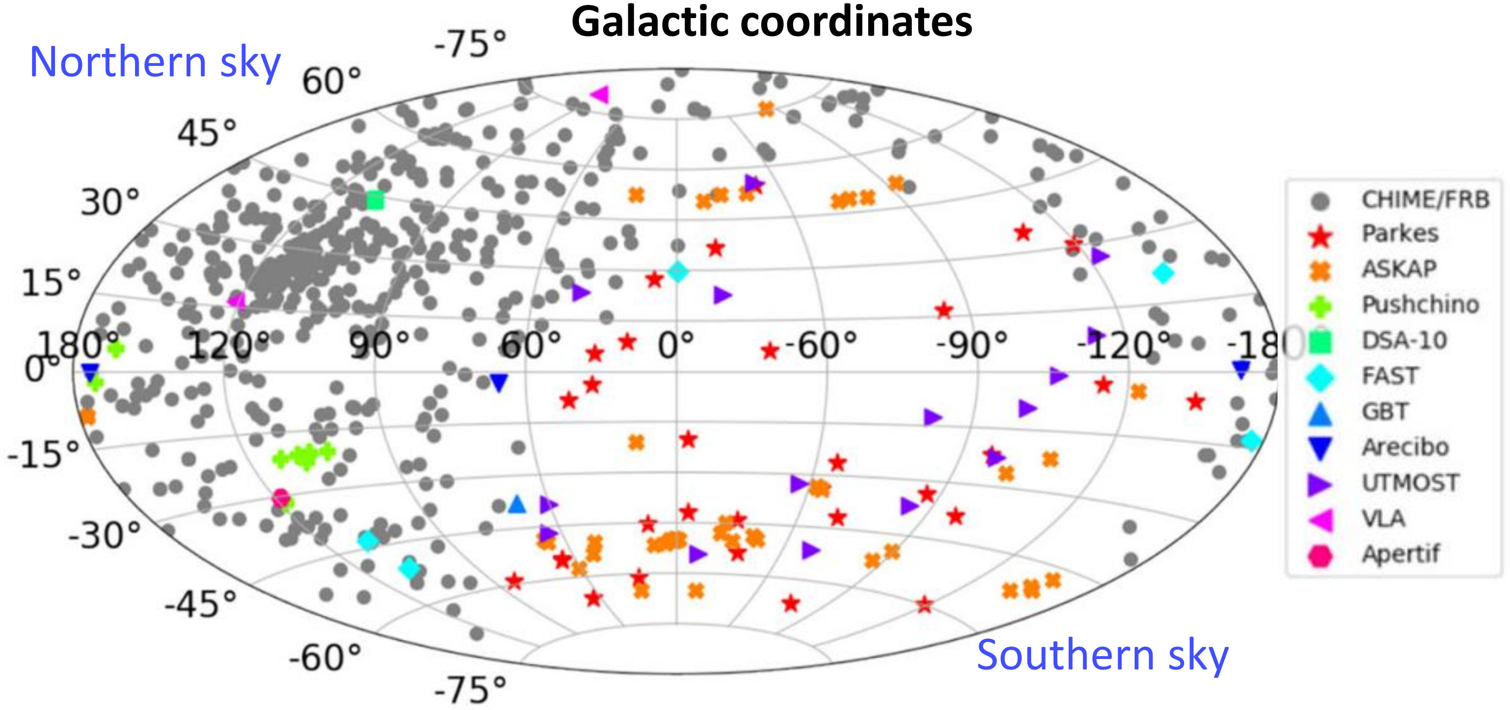


Galactic electron density model

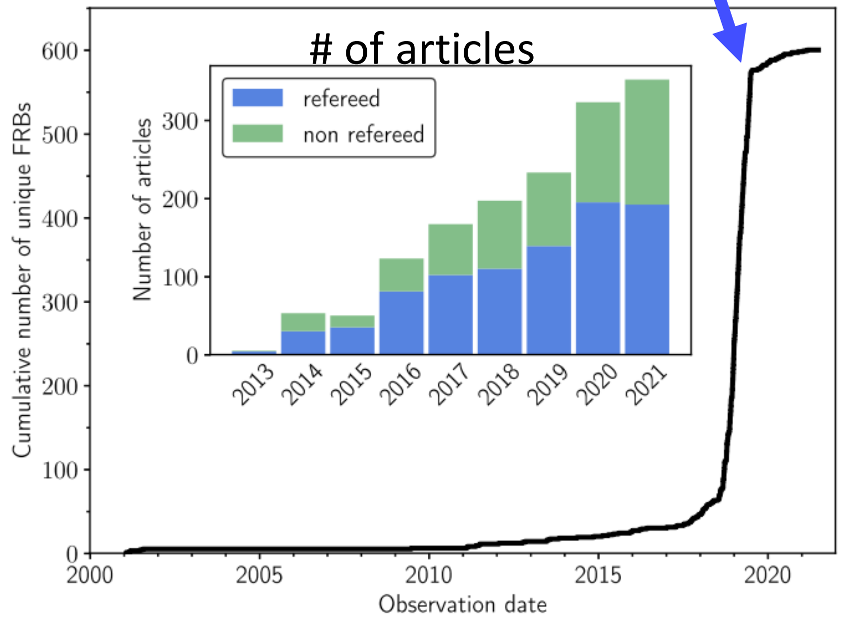
Yao et al., 2016 (YMW16)

Ref: Petroff+, A&A Rev., 2019; 2022

Sky Map of FRBs



CHIME/FRB
1st catalog
in 2021
(+536 FRBs)

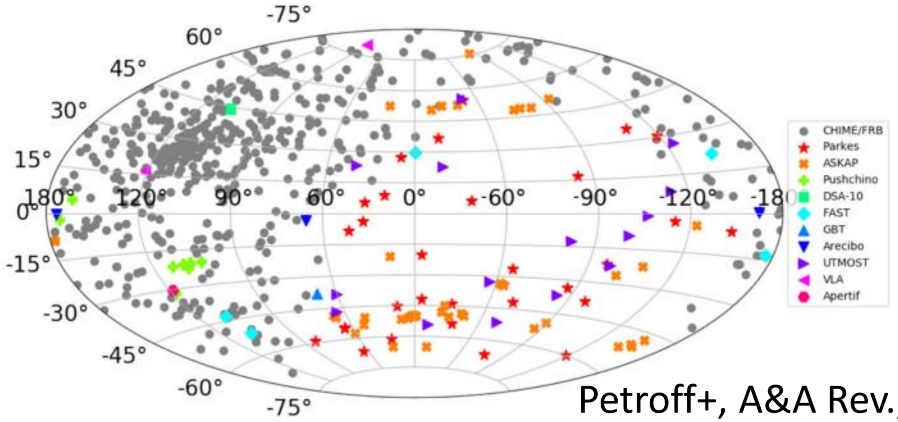


- ~1000 FRB detection published; > 4000 FRBs detected (mostly by CHIME/FRB)
- Detection reported from 110 MHz to 8 GHz
- Bright: 50 mJy – 100 Jy : **several days of solar energy released in milliseconds!**
  - isotropic equivalent energy: 10^{35} -10^{43} erg (10^{28} - 10^{36} J)
- ~isotropic distribution (after sky coverage correction)

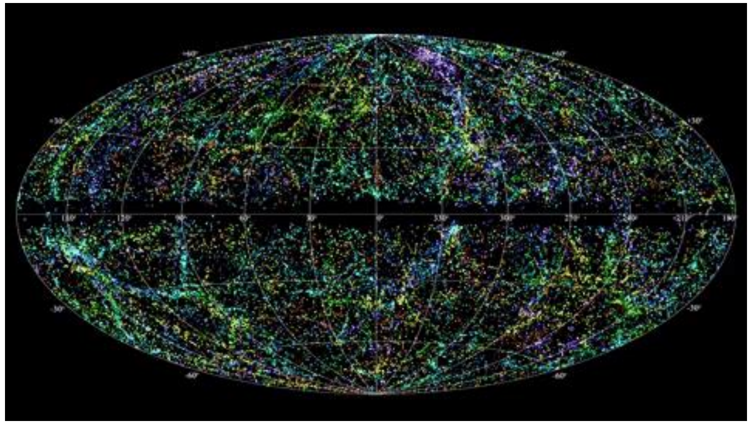
→ FRBs are extragalactic, but their origin still unknown

Ref:
Petroff+, A&A Rev., 2022
CHIME/FRB, 2021

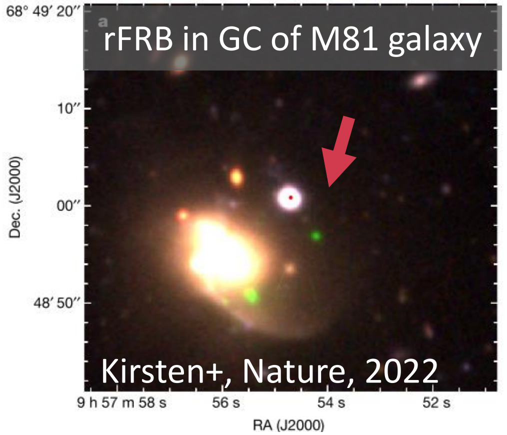
FRB characteristics



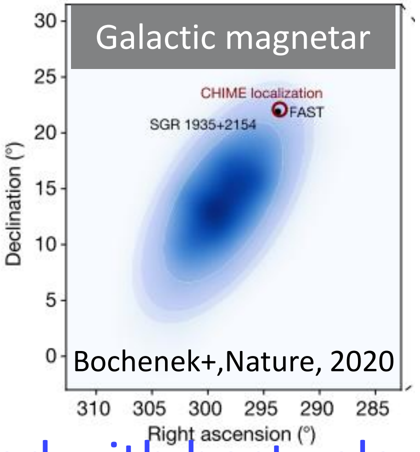
Petroff+, A&A Rev., 2022



- >4000 FRBs discovered since 2007 (~1000 published)
- all-sky FRB event rate (fluence > 1 Jy ms): **~1000/day**

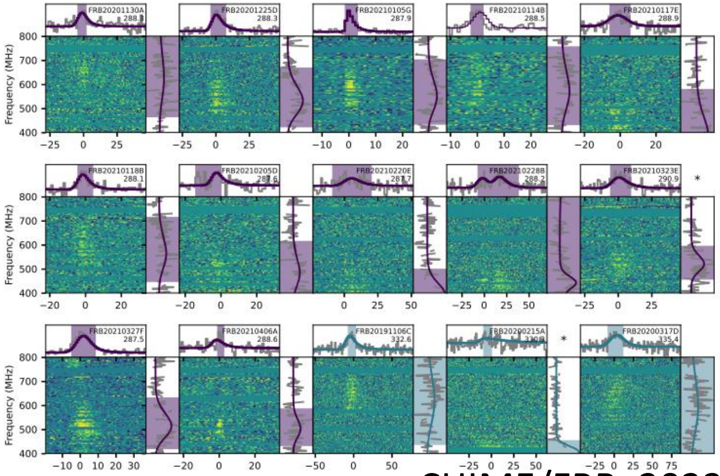


Kirsten+, Nature, 2022



Bochenek+,Nature, 2020

- ~50 FRBs are repeaters
  - not from catastrophic events (e.g. Supernovae)

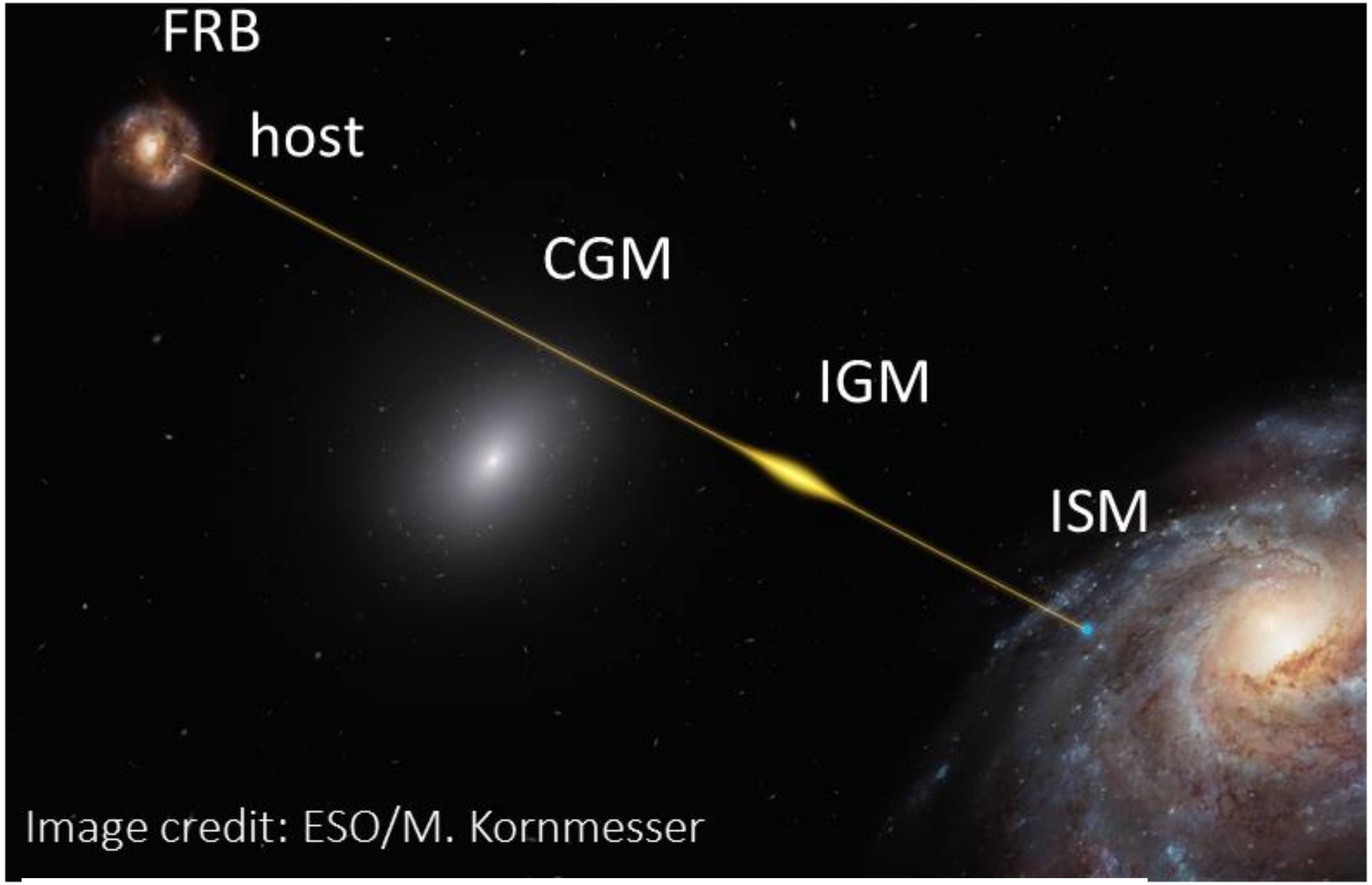


CHIME/FRB, 2023

- only ~100 FRBs localized with host galaxies
  - diverse host: globular cluster (in M81), elliptical galaxy, star-forming galaxy, etc.
  - 1 FRB associated with a Galactic magnetar
- Diverse temporal and spectral properties
  - e.g. quasi-periodicity, wide / narrow band

Petroff+, A&A Rev., 2019,2022; [FRB Theory Wiki (frbtheorycat.org)](frbtheorycat.org)

Mystery and potential of FRBs



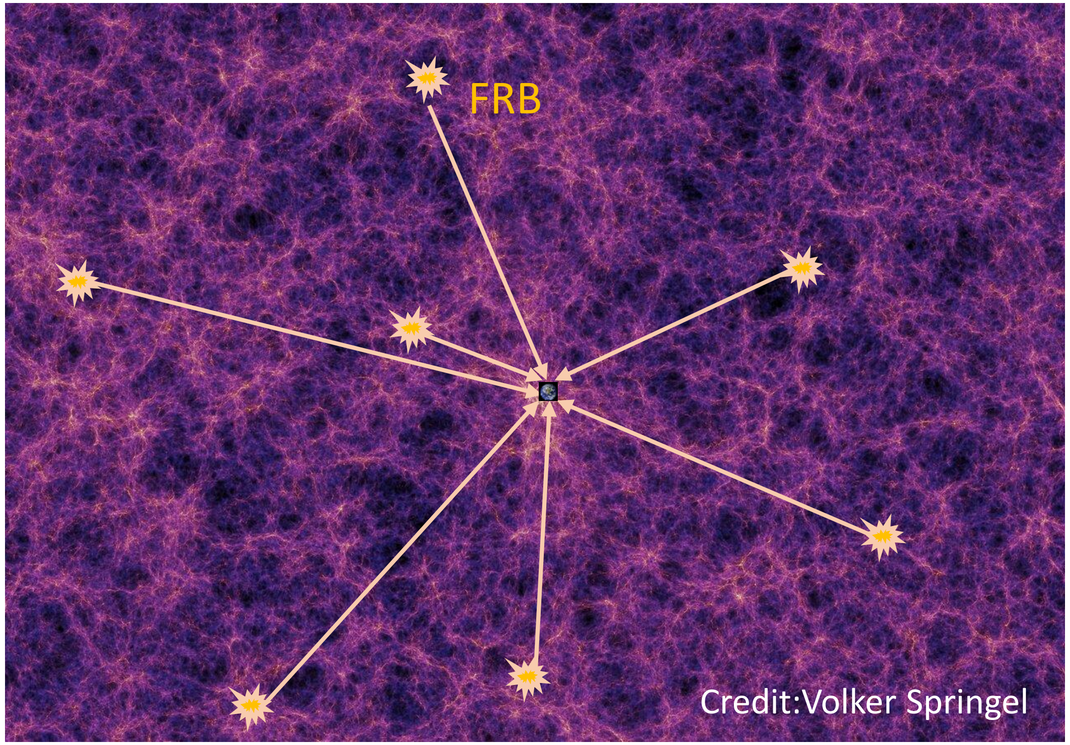
$$\mathrm{DM} = \mathrm{DM}_{\mathrm{MW}} + \mathrm{DM}_{\mathrm{halo}} + \mathrm{DM}_{\mathrm{IGM}} + \frac{\mathrm{DM}_{\mathrm{host}} + \mathrm{DM}_{\mathrm{src}}}{1+z}$$

cosmological time dilation

- Mystery of FRB's origin:
  - Where are they from?
  - Do all FRBs repeat?
  - How many source populations?
  - Radio emission mechanism?
    - Various FRB models: WD, NS, pulsar, magnetar, BH, AGN, etc.
- FRBs as cosmological probe
  - coherent pulse traveling cosmological distances
  - potential standard candle? → further understanding needed
  - $\mathrm{DM}_{\mathrm{IGM}}$ → cosmic baryon contents and distribution

Zhang, Rev. Mod. Phys., 2023
Petroff+, A&A Rev., 2019, 2022

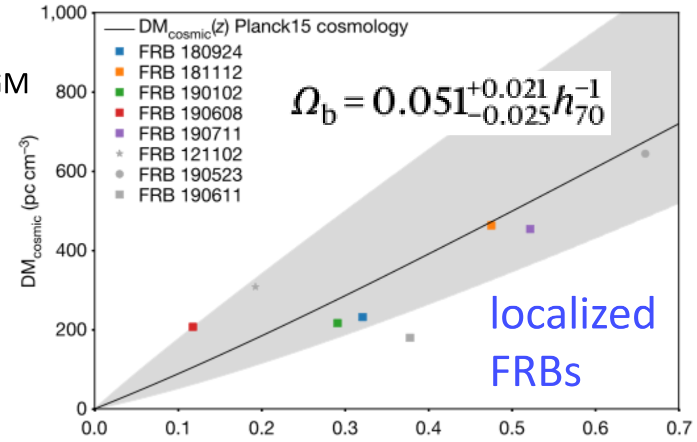
FRBs as cosmological probes



localized FRBs with known redshift z & DM

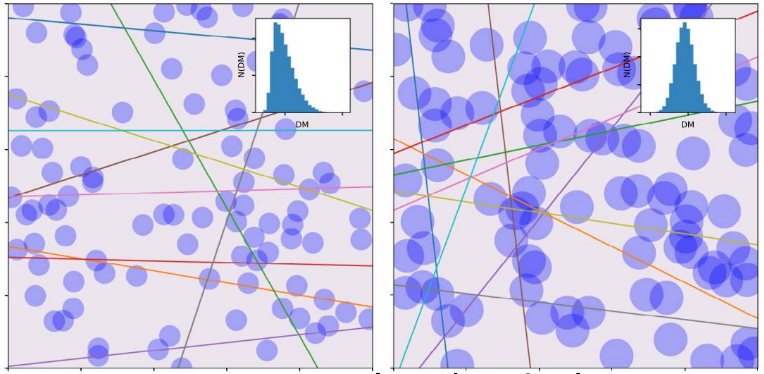
Macquart+, Nature, 2020

DM$_{IGM}$



redshift z

- Ω_b consistent with CMB and BBN
  - solve "missing baryon problem"



Bhandari & Flynn, 2021

- DM variance can constrain galaxy halo distribution

$$\mathrm{DM} = \int_0^D n_e dl$$

baryon fraction in IGM

X: ionization fraction

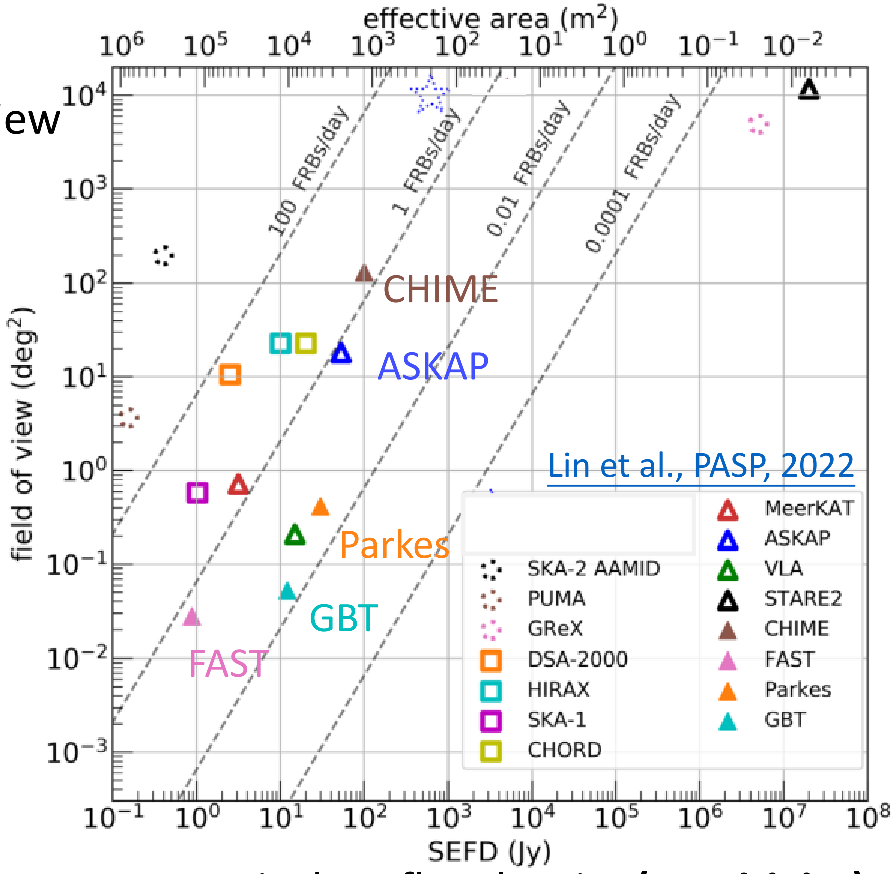
$$\langle \mathrm{DM_{IGM}} \rangle = \Omega_b \frac{3H_0 c}{8\pi G m_p} \int_0^z \frac{(1+z') f_{\mathrm{IGM}} \left[\frac{3}{4} X_{e,\mathrm{H}}(z') + \frac{1}{8} X_{e,\mathrm{He}}(z')\right]}{\left[\Omega_{\mathrm{M}}(1+z')^3 + \Omega_\Lambda (1+z')^{3[1+w(z')]}\right]^{1/2}} dz'$$

Hubble parameter $H_0 = 62 \pm 9\,\mathrm{km\ s^{-1}\ Mpc^{-1}}$ with 9 localized FRBs (Hagstotz+, MNRAS, 2022)

Petroff+, A&A Rev., 2019; 2022
Zhang, Rev. Mod. Phys., 2023

Active telescopes searching FRBs

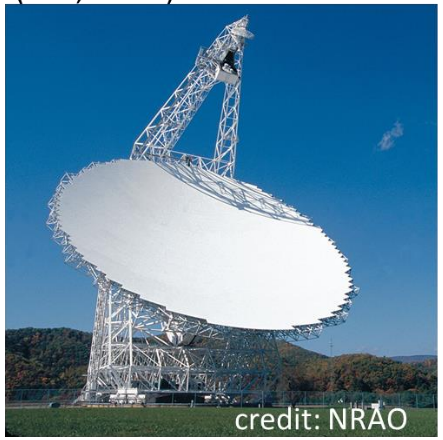
Field of view (deg^2)



system equivalent flux density **(sensitivity)**

FAST (500m, China)

Green Bank Telescope (GBT, 100m)



Parkes (64m, Australia)

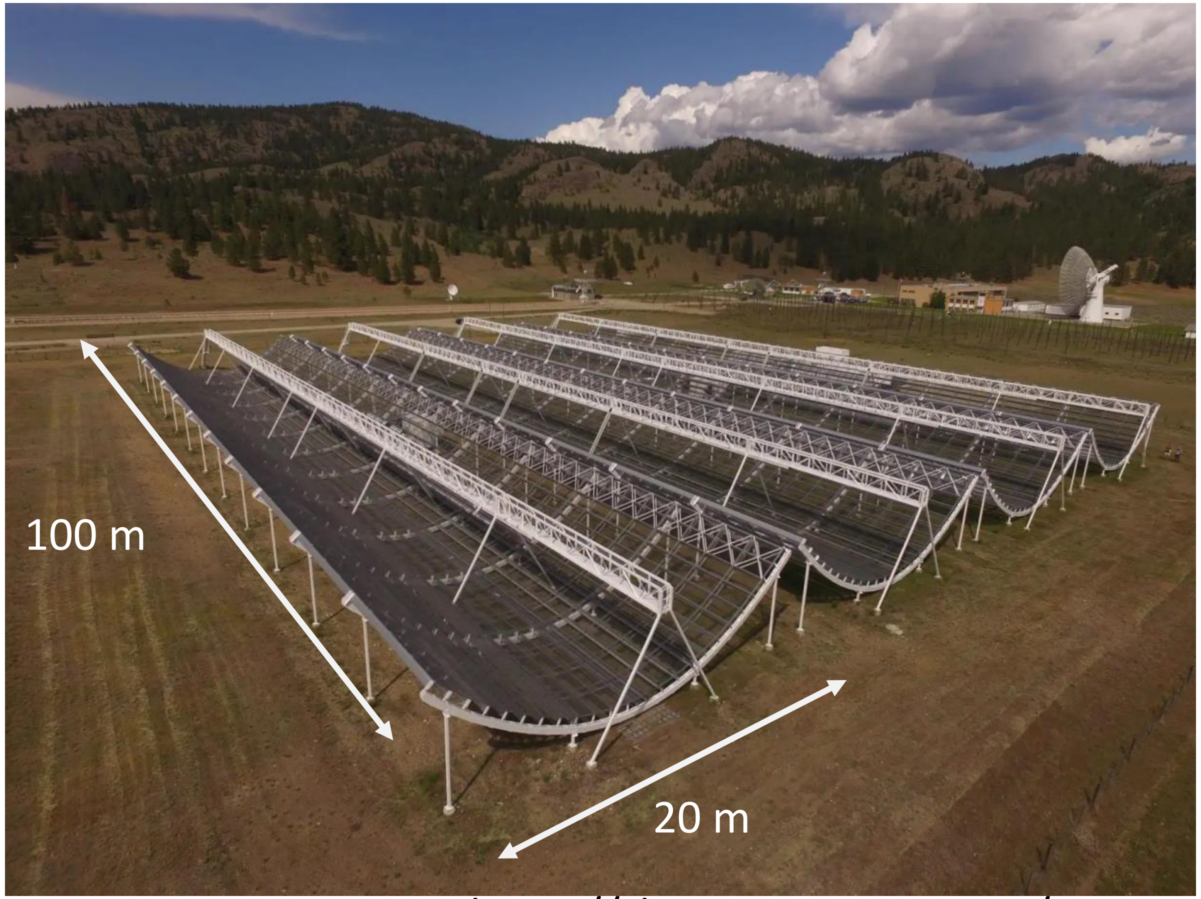
ASKAP (36* 12m, Australia)

CHIME/FRB (Canada)

- Most of them not designed for FRBs
  - **sensitive but narrow field of view (FoV)**
  - **poor angular resolution**: hard to identify host

DSA-110 (110* 4.65 m dish, USA)

CHIME/FRB project



https://chime-experiment.ca/en

- CHIME = Canadian Hydrogen Intensity Mapping Experiment
  - originally for 21 cm H-line survey
  - 256 antennas x 4 cylinders x 2 polarizations
- Field of view (FoV) ~110^o x 2^o covered by 1024 beams
- 400-800 MHz divided into 1024 channels
- detect ~ 1 FRB /day
  - redshift z ~ 0.3-0.5

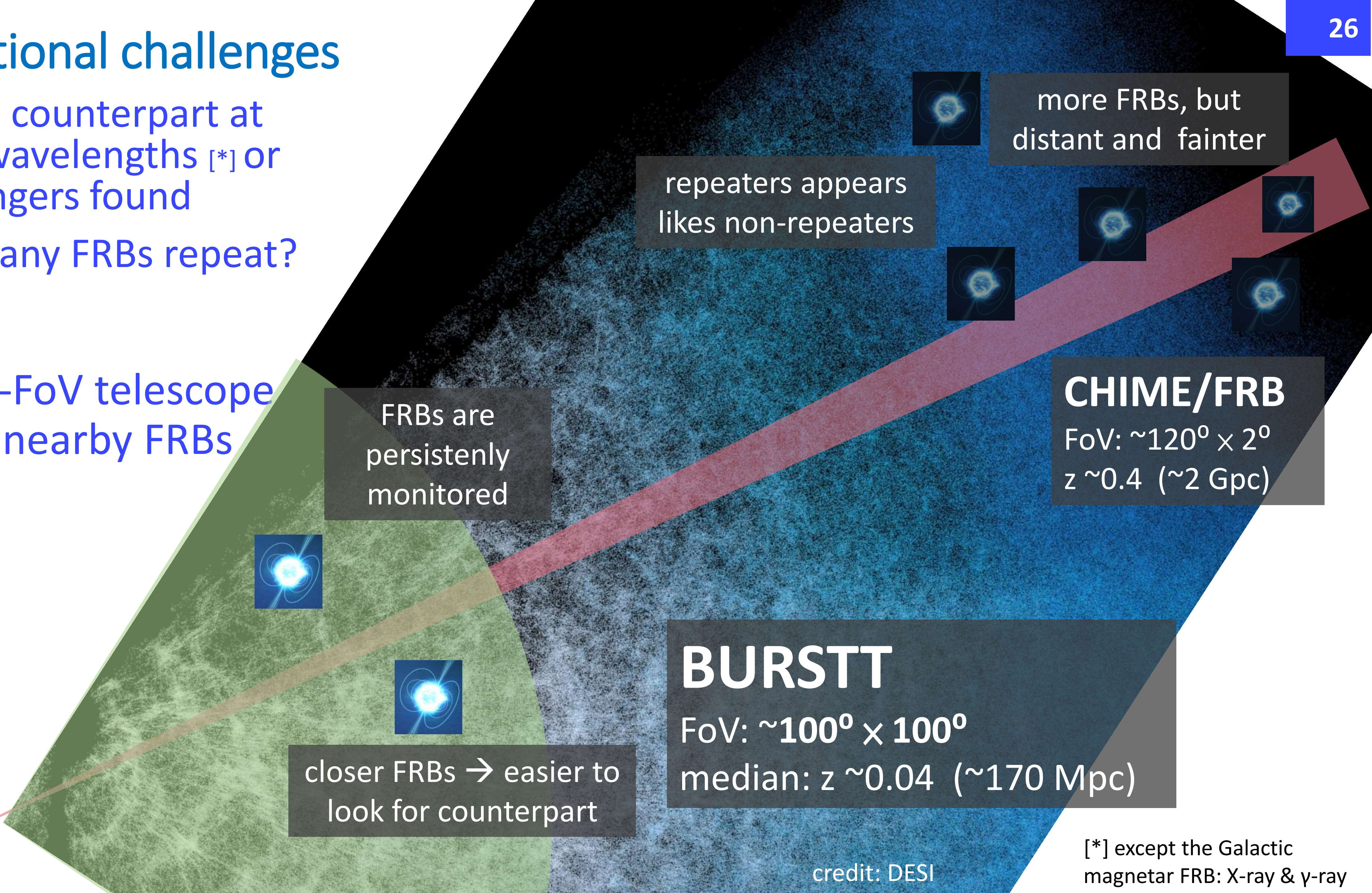
CHIME/FRB, ApJ, 2018

Observational challenges

- No FRB counterpart at other wavelengths [*] or messengers found
- How many FRBs repeat?

Solution

→ a wide-FoV telescope to survey nearby FRBs



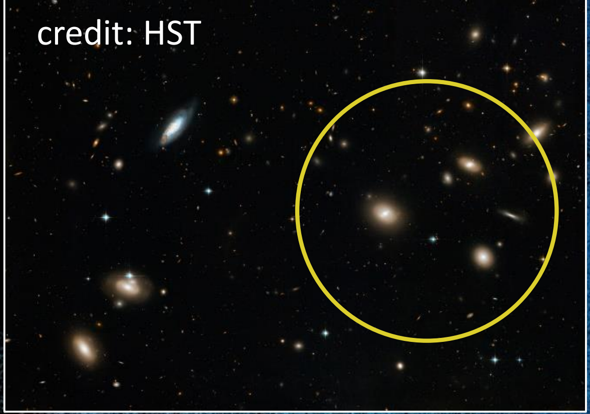
[*] except the Galactic magnetar FRB: X-ray & γ-ray

Observational challenges

- What are FRB's sources?
- No FRB counterpart

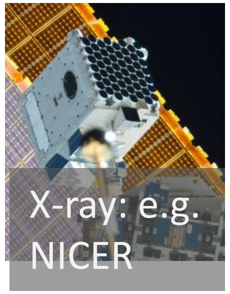
Solution

- localized nearby FRBs with <1" resolution
  - for identifying host galaxy
  - follow-up multi-wavelength observations



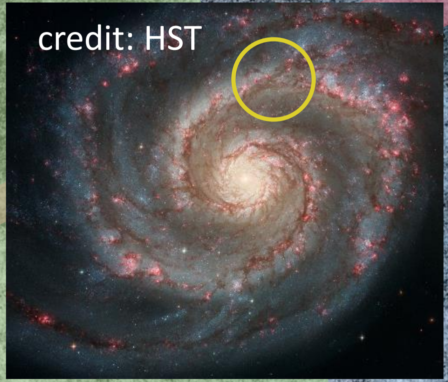
cannot localize host galaxy well

CHIME/FRB
FoV: ~120° × 2°
z ~0.4 (~2 Gpc)
~10' resolution [*]



X-ray: e.g. NICER

optical: e.g., ePESSTO+



identify host galaxy, even source region

BURSTT
FoV: ~100° × 100°
median range: z ~0.04 (~170 Mpc)
Localization: 1"-0.1" resolution

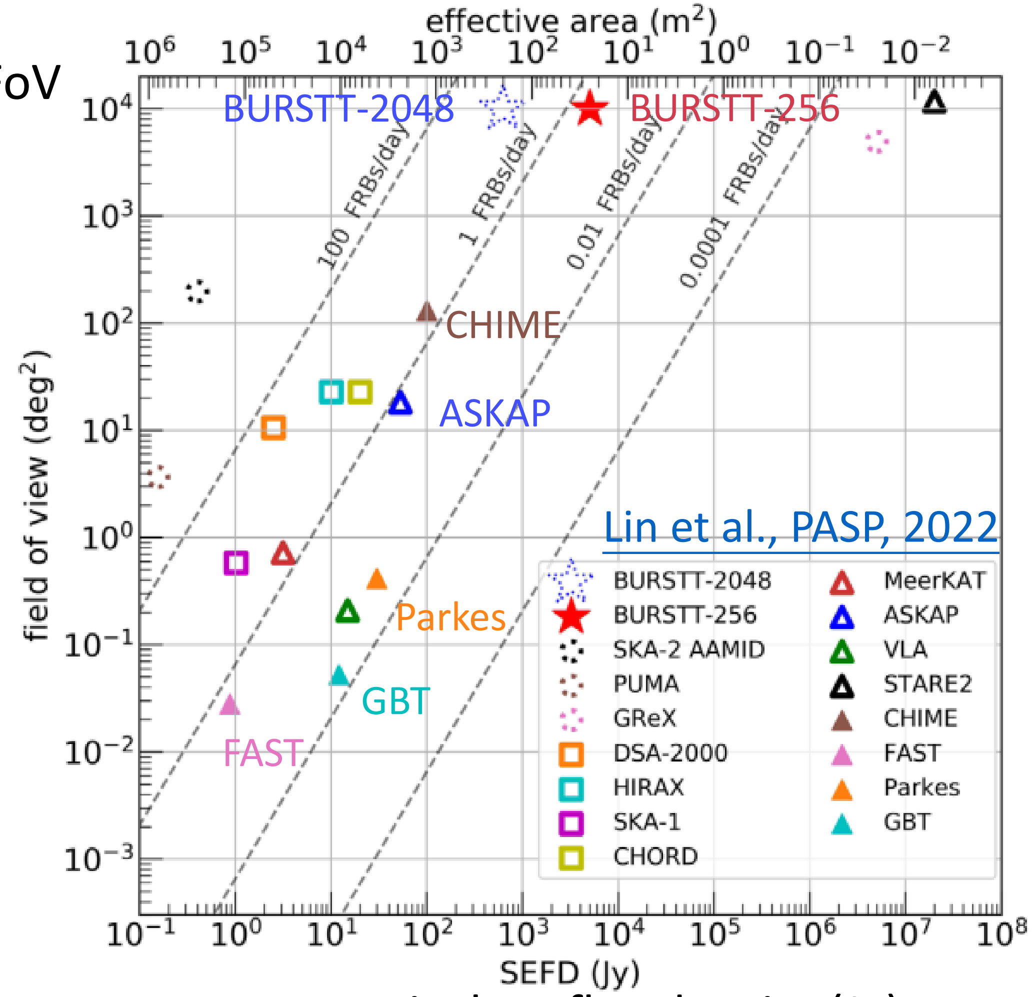
credit: DESI

[*] CHIME alone; it now has outriggers for <1" resolution

Bustling Universe Radio Survey Telescope in Taiwan (BURSTT) 台灣宇宙電波爆廣角監測實驗

- Telescope dedicated to FRB survey
  → to understand the nature of FRBs
- Wide instantaneous FoV: ~100° × 100° deg^2
- Localization with 1”-0.1” resolution
- Expected to detect and localize ~100 bright nearby FRBs / year
  - fluence ≥ 100 Jy ms
  - z ~0.04
- 1st phase: BURSTT-256 (2022-2026)
  - 2nd phase: BURSTT-2048 (2026-)

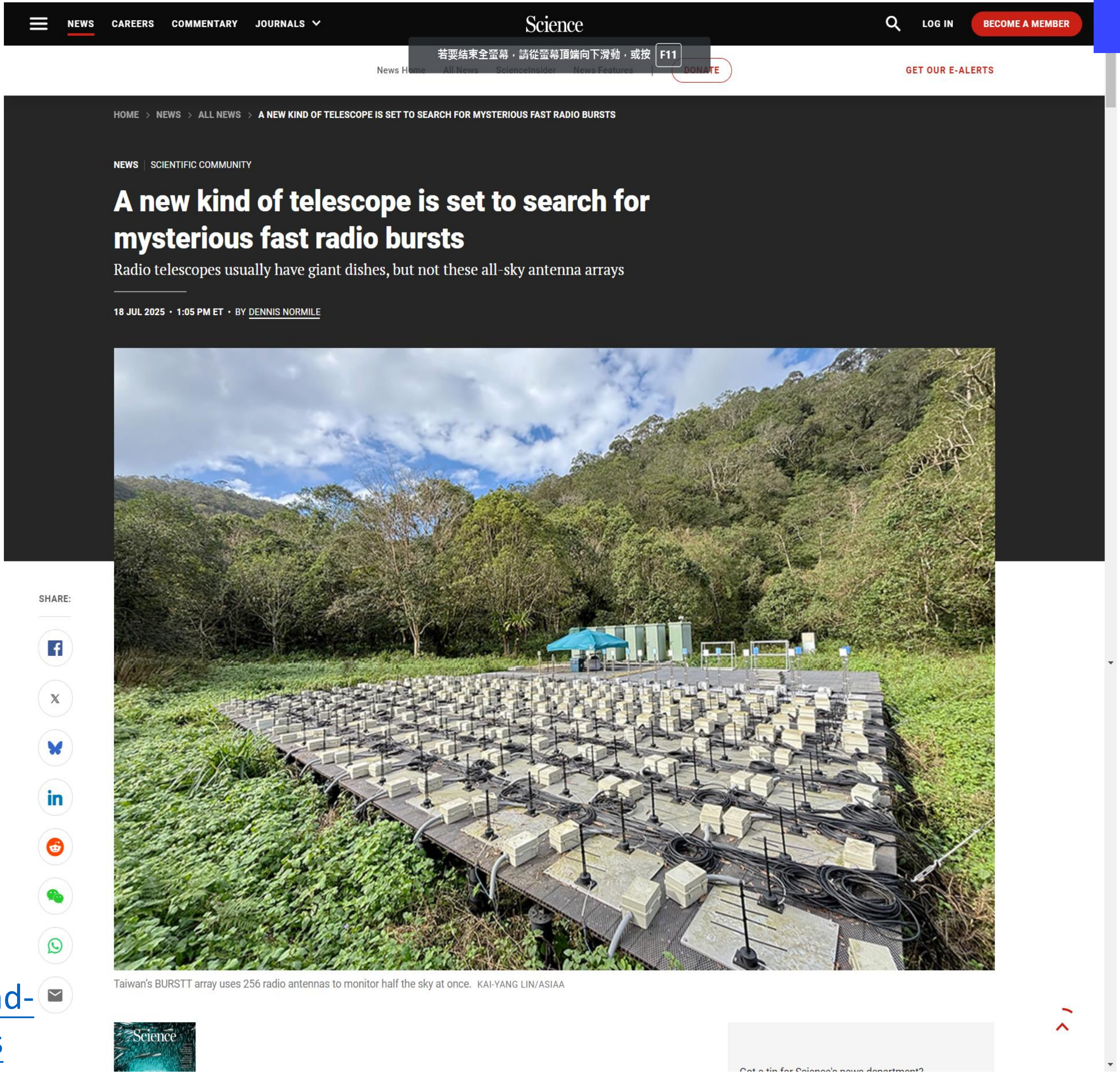
FoV



system equivalent flux density (Jy)

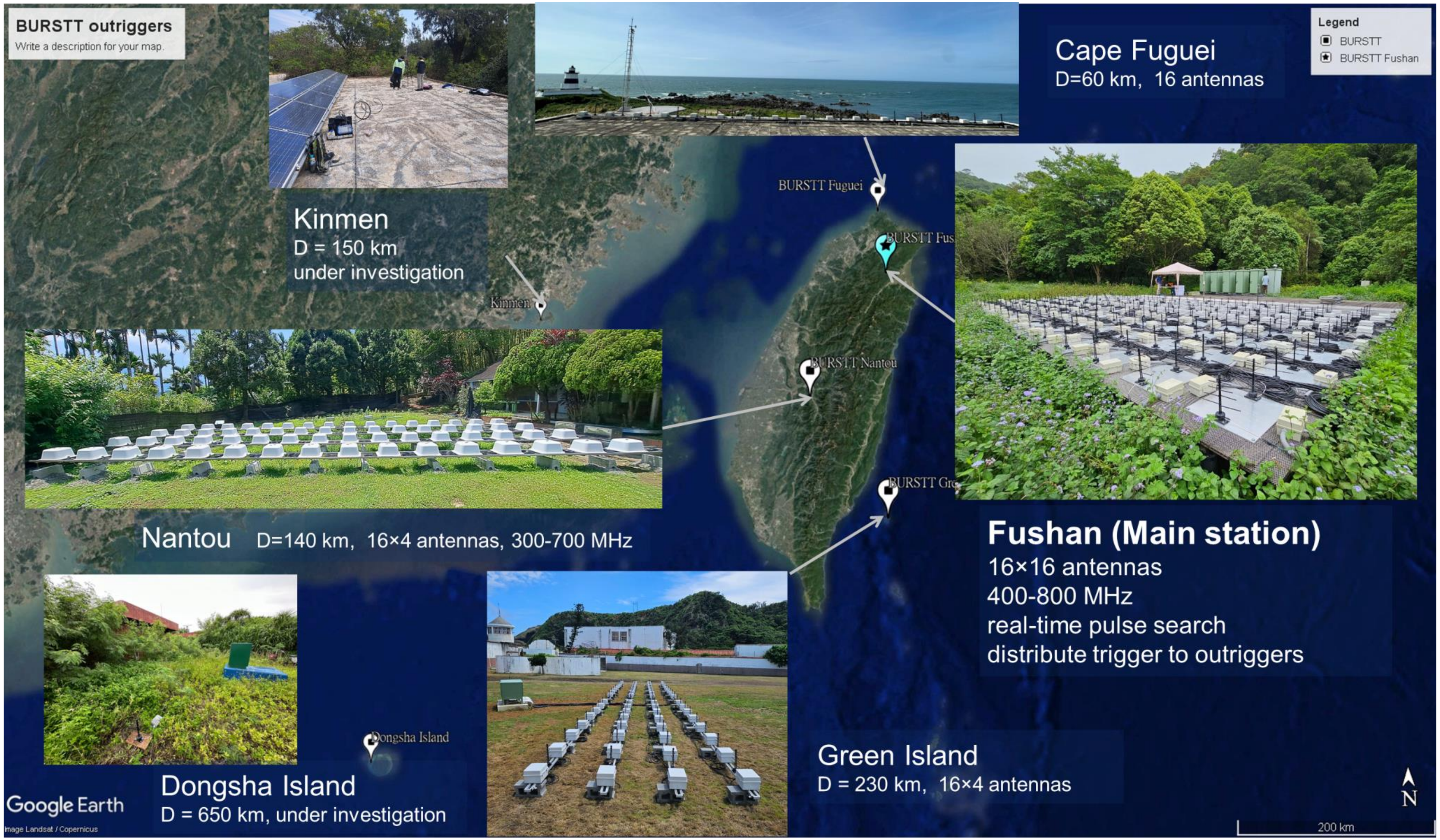
More about BURSTT: https://www.burstt.org ; https://www.asiaa.sinica.edu.tw/facility/burstt.php

- The new design of BURSTT is featured in Science News article
  - 2025-07-18



https://www.science.org/content/article/new-kind-telescope-set-search-mysterious-fast-radio-bursts

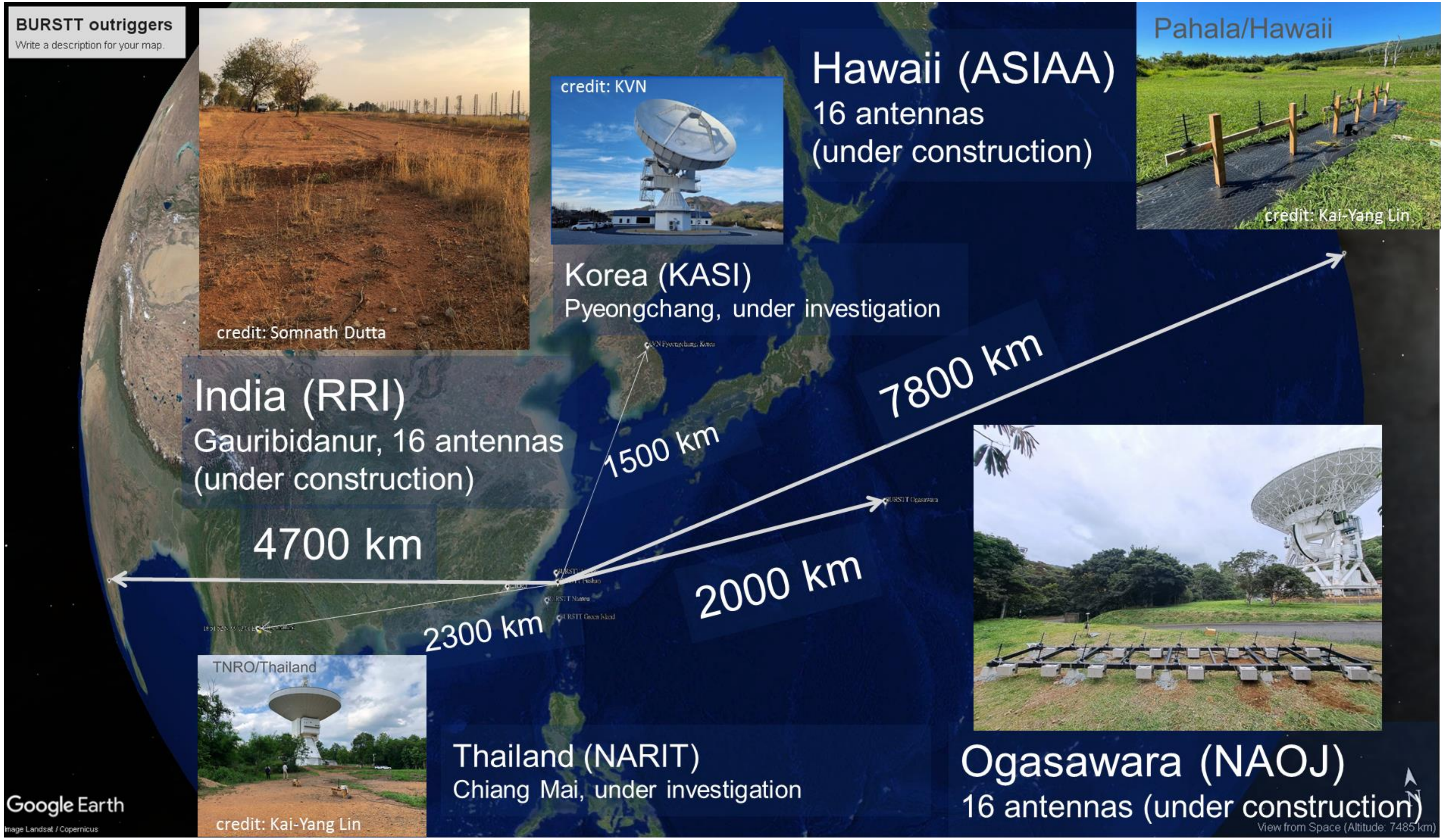
BURSTT: main & outrigger stations in Taiwan



- O(100) km baseline → locating FRB with < 1” resolution

(λ/D) = (0.5m / 100km)
at 600 MHz

BURSTT: international outrigger stations



- O(1000) km baseline → locating FRB with < 0.1” resolution

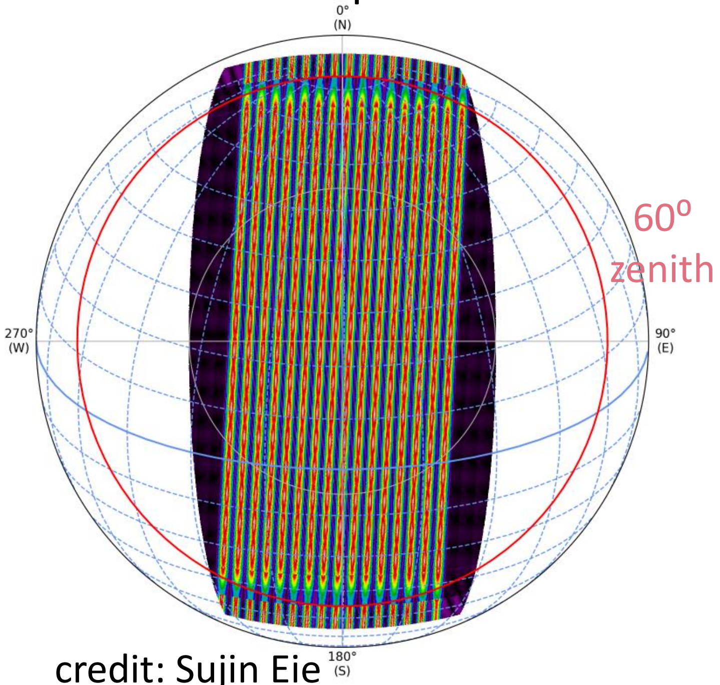
Q&A and break time

- Next: how to look for a good site for BURSTT telescope → RF survey

BURSTT: Real-time beamforming and pulse search

16×16 beams over FoV

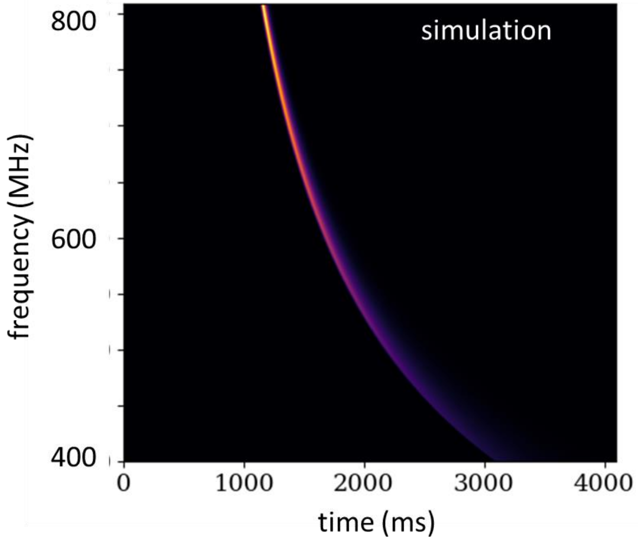
~2.5° x 5° per beam



credit: Sujin Eie

Search dispersed pulse

up to DM = 1000 pc/cm^3



Xilinx ZCU216
RFSoC FPGA × 16

RFSoC: RF system-on-chip

- **channelize**
- **1st beamforming**
- **RFI reduction**

baseband data
104 GB/s

Intel Xeon servers × 4

- **2nd beamforming**
- **baseband ring buffer**
- **up-channelized intensity**

intensity data
1 GB/s

trigger

Intel Xeon server × 1

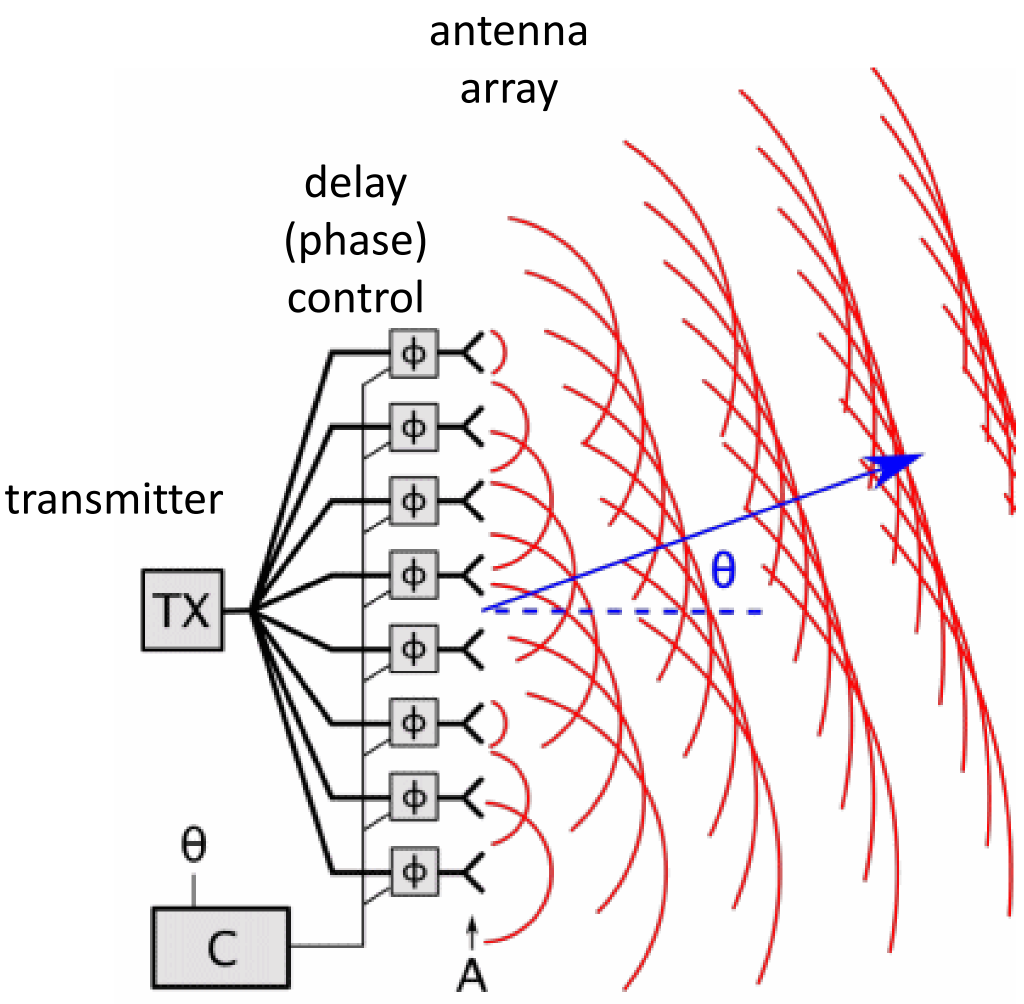
- **pulse search with ‘bonsai’ software (by CHIME/FRB)**
- **send trigger**

Lin et al., PASP, 2022

Beamforming / phased array

- Antenna array
- Correcting geometric delay to each array, given a desired direction
- Sum up signals from (to) antennas coherently

  → effectively a larger antenna
- Advantage: no moving part
  - faster scan
  - mechanically robust
  - multiple beams possible

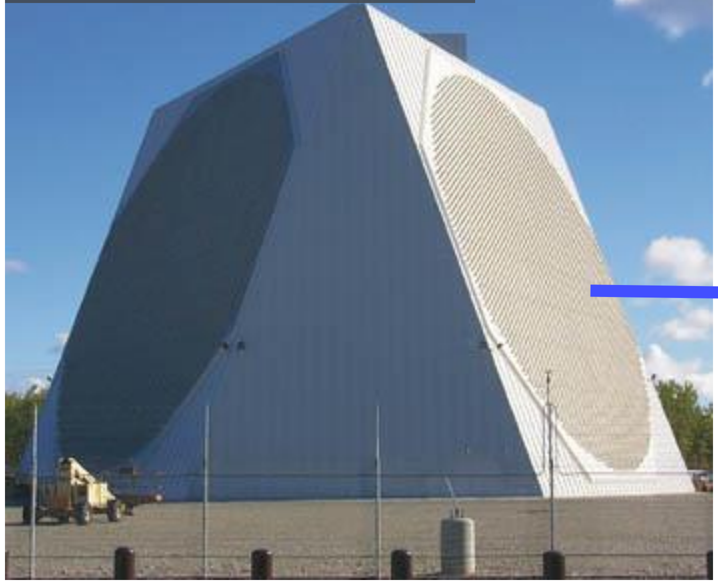


source: Wikipedia

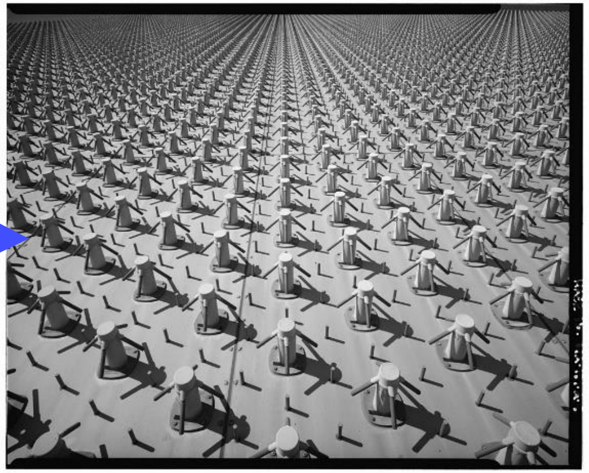
Phased array example

- military and weather radar: transmitter and receiver

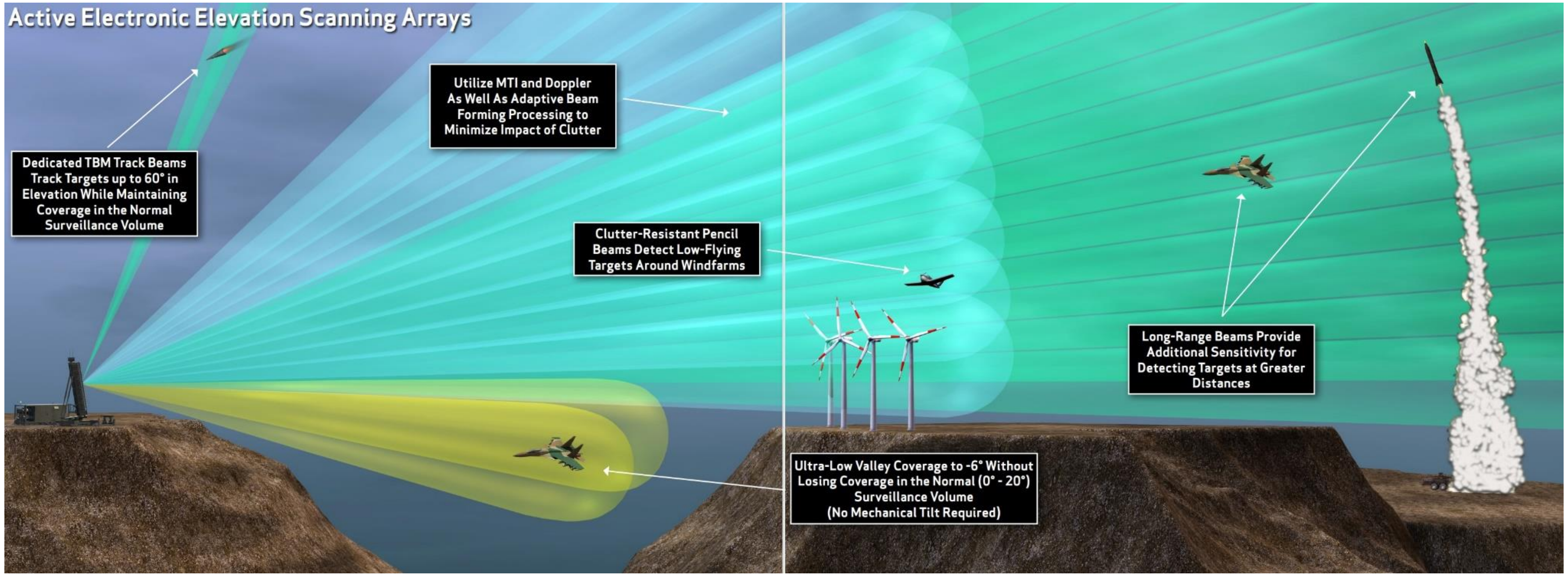
US PAVE PAWS radar
(5000 km range)



source: Wikipedia

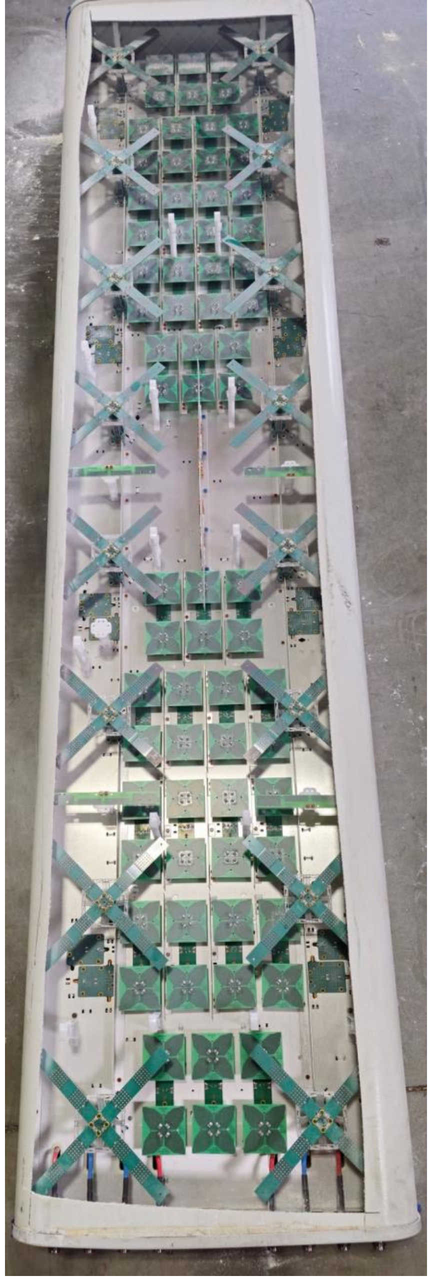


AN/TPS-59



Phased array example

- panel antenna for base station of mobile network



https://www.reddit.com/r/cellmapper/comments/153k6hg/inside_peek_base_station_antenna_rosenberger/

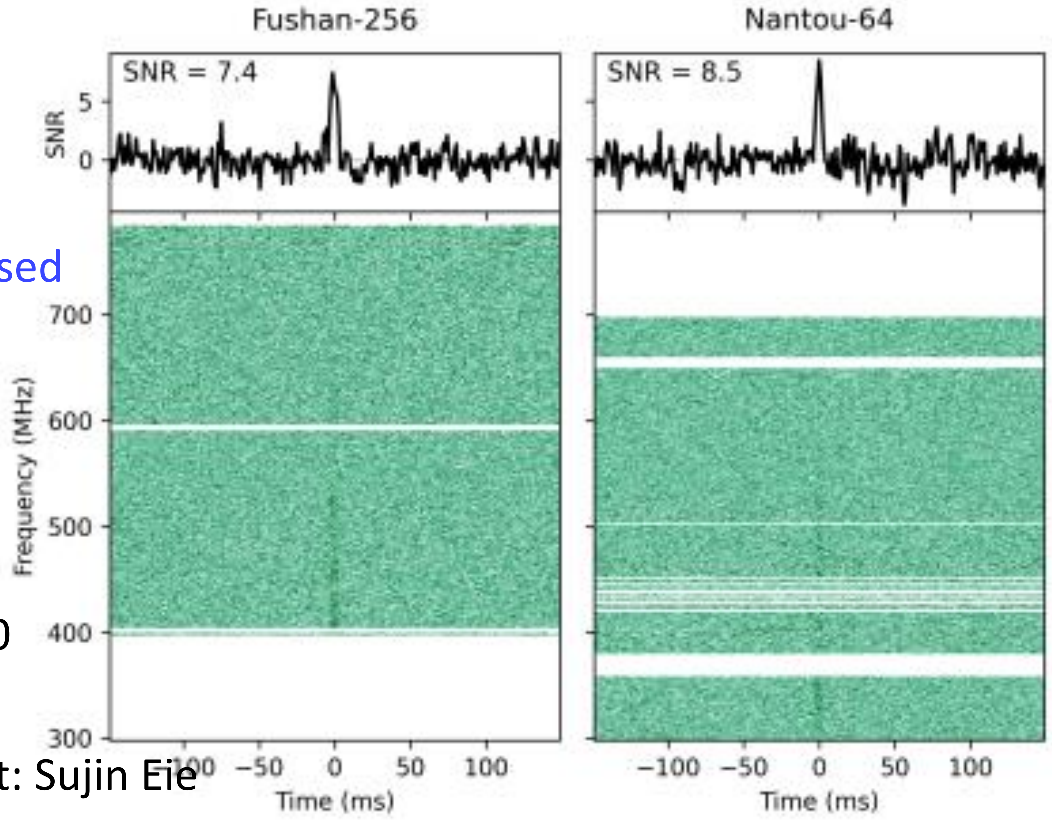
Simultaneous pulse detection of B0329+54 pulsar by BURSTT

(Nov 2024)

- DM: 26.76 pc/cm^3
  - ~5300 ly distance
- regular pulse: period=0.7145 s
- Pulses are found in offline search

→ proof of telescope design, data acquisition and analysis pipeline

De-dispersed intensity waterfall plot



300-800 MHz

Credit: Sujin Eie

Time (300 ms span)

Ref: ATNF pulsar catalogue

Simultaneous detection of Crab pulsar Giant Radio Pulses (GRPs) by BURSTT

(Nov 2024)

optical & X-ray

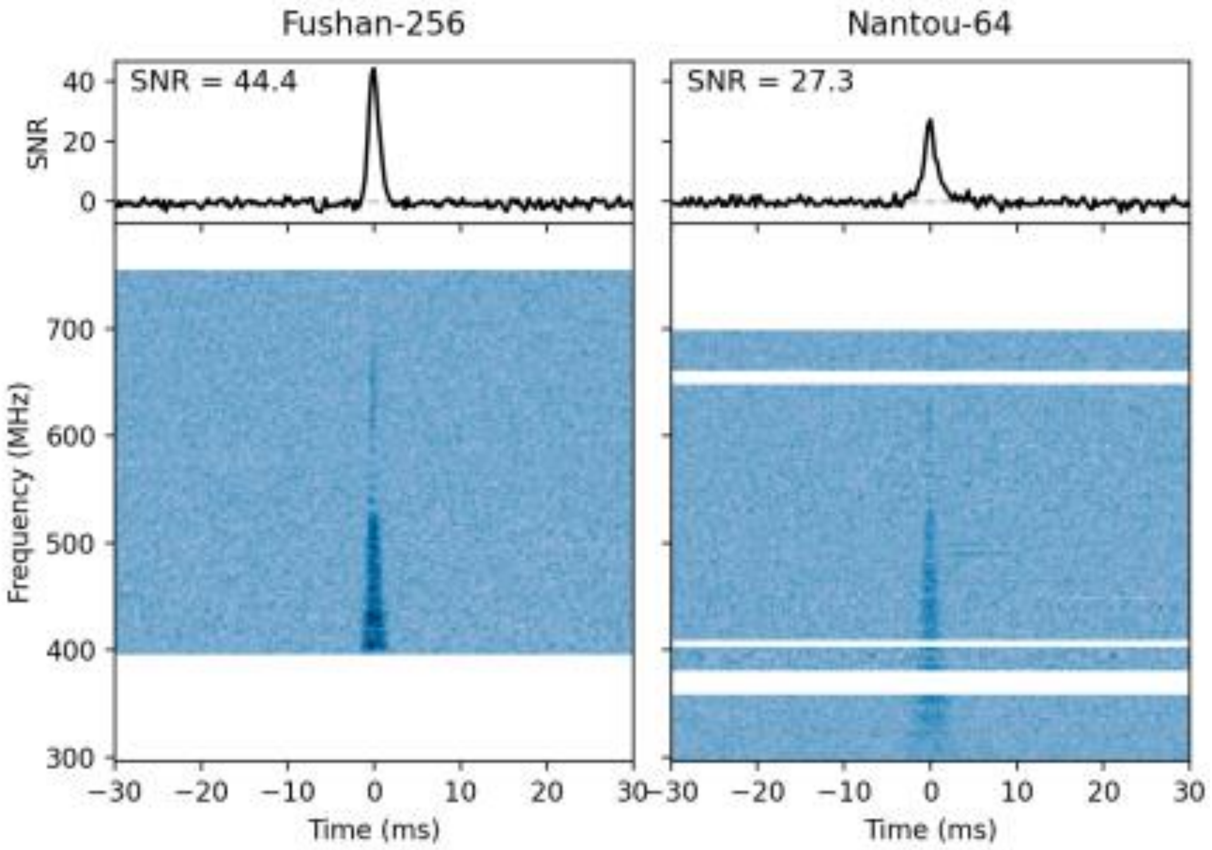
Credit: NASA/CXC/ASU/J. Hester et al

- DM: 56.77 pc/cm^3 ; **stochastic**
  - distance ~6200 light year
- flux density up to up to ~10^6 Jy
- Pulses are found in offline search

→ proof of telescope design, data acquisition and analysis pipeline

De-dispersed intensity waterfall plot

300-800 MHz



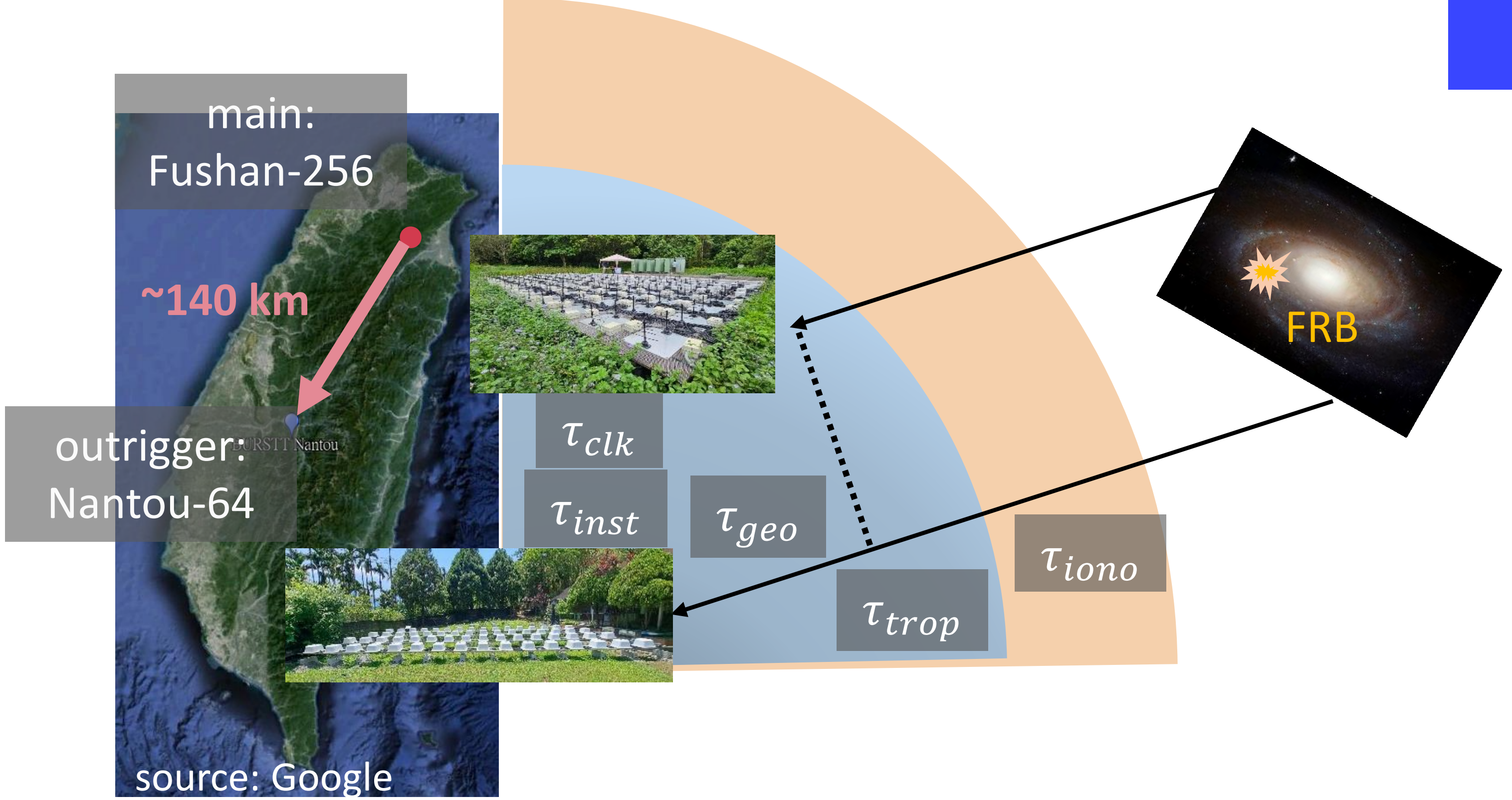
Credit: Sujin Eie

Time (60 ms span)

Ref: ATNF pulsar catalogue

Very-Long-Baseline Interferometry (VLBI) test

- Target: achieve ~0.1 ns timing accuracy between stations for <1” resolution



cross-correlate baseband data between stations

baseline vector: by GNSS and calibration

by dual-frequency GNSS data or modelling

by calibration with multiple sources

total observed delay

geometric delay to source

ionospheric delay

instrumental delay

$$\tau_{obs} = \tau_{geo} + \tau_{clk} + \tau_{iono} + \tau_{trop} + \tau_{inst}$$

offset between reference clocks

tropospheric delay

by Rb clock and GNSS data

by GNSS data or modeling

Schuh & Behrend, 2012

VLBI test with B0329+54 single pulses

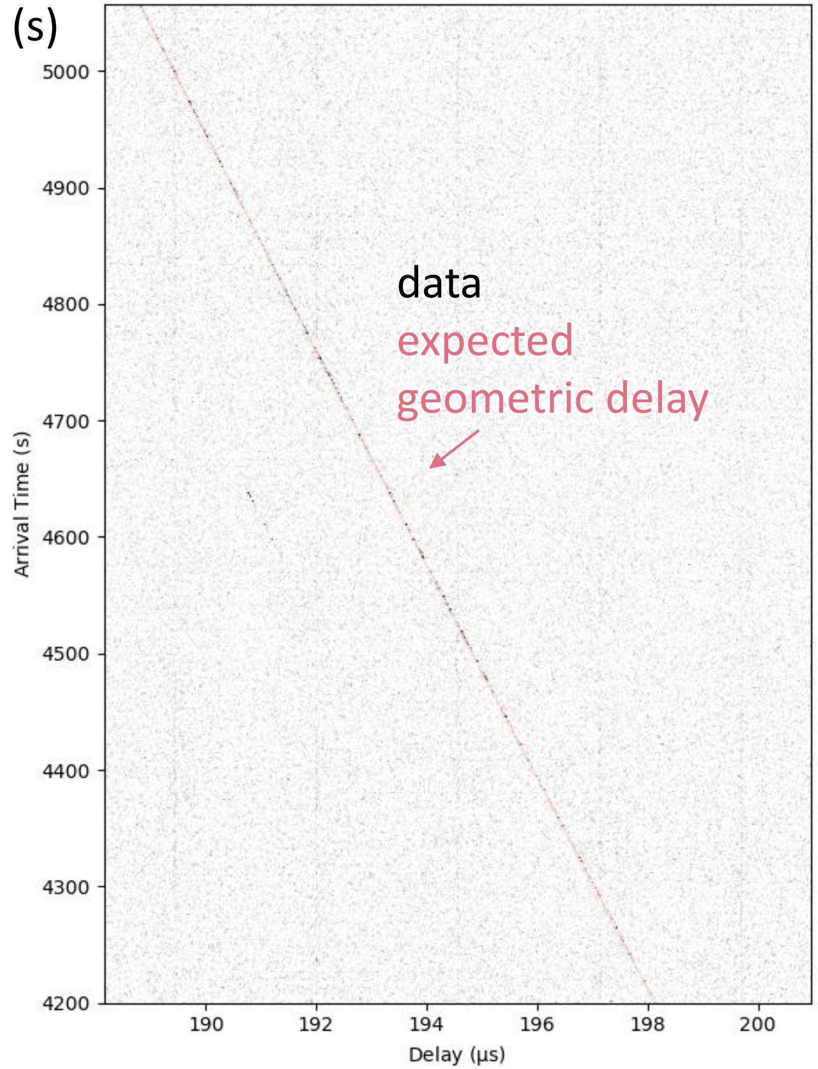
- cross-correlate ~15-min Fushan & Nantou baseband data at 400-700 MHz
- geometric delay and clock offset corrected
- residual delays consistent with ionospheric one:
  - ~2 ns scatter: to be understood

  → close to our 0.1 ns goal

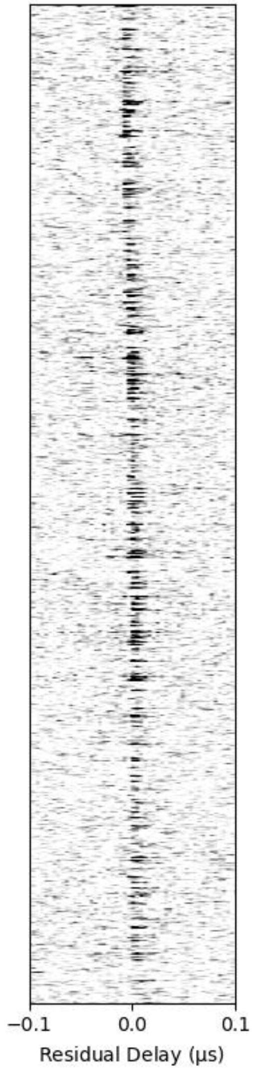
$$\tau_{obs} = \boldsymbol{\tau_{geo}} + \boldsymbol{\tau_{clk}} + \boldsymbol{\tau_{iono}} + \tau_{trop} + \tau_{inst}$$

pulse time (s)

pulse delay between Fushan and Nantou (µs)

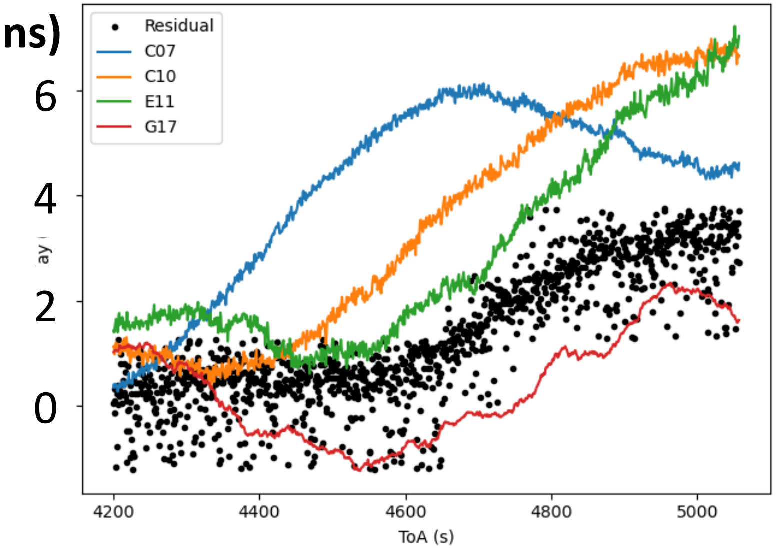


residual delay (µs)



clock corrected

residual delay (ns)



pulse time (s)

colored: ionospheric delays derived from GNSS satellites near LoS

data

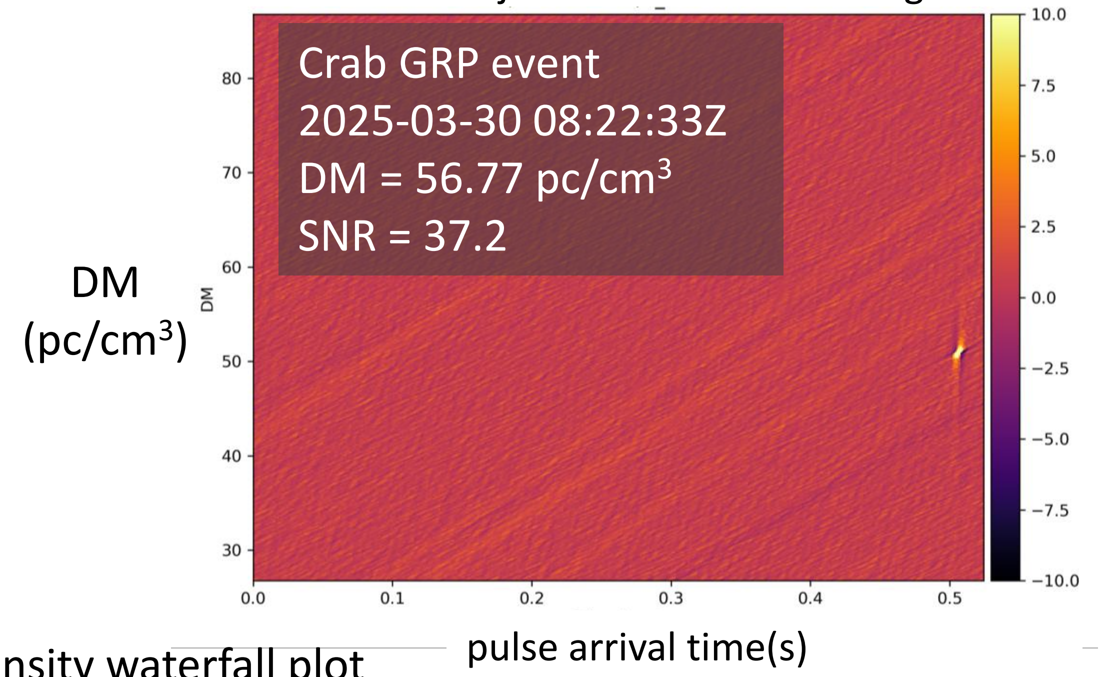
credit: Daniel Baker

Status of BURSTT real-time pulse search

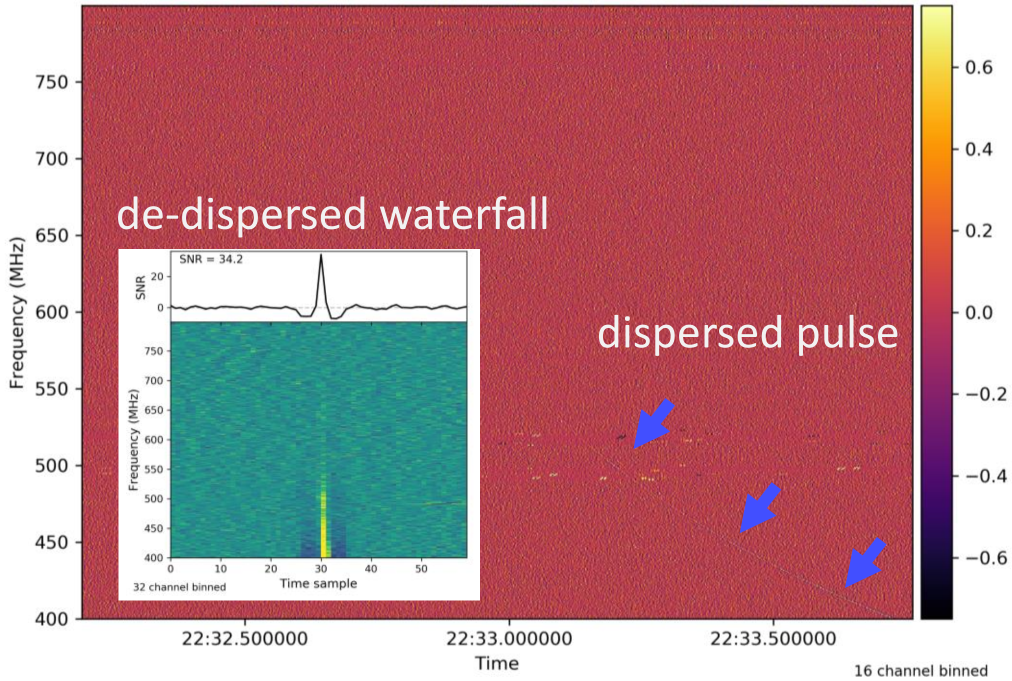
- Stochastic Crab pulsar Giant Radio Pulses are routinely detected
  - DM = 56.77 pc/cm^3
  - some FRBs might be bright GRPs of extragalactic pulsars
- Ongoing works:
  - verifying data saved upon triggers
  - tuning parameters to reduce false triggers
  - optimizing performance for 256 and more beams

First FRB detection is about to happen!

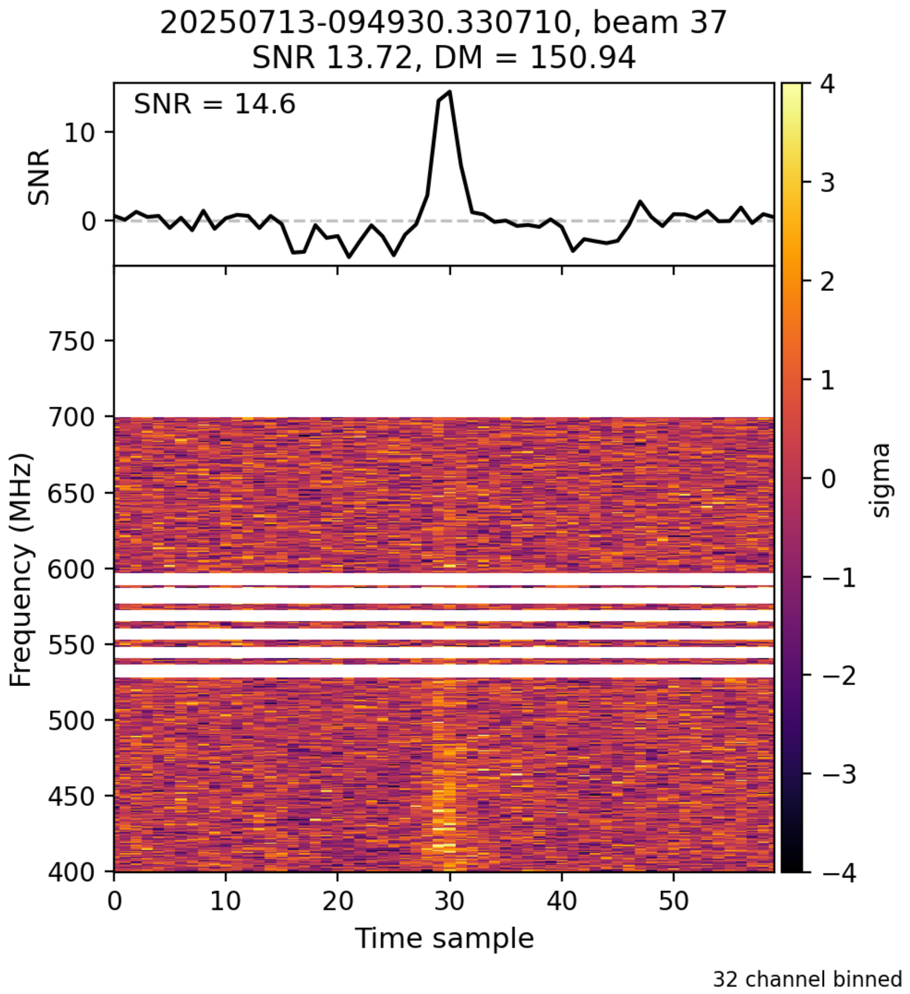
Credit: Sujin Eie & Yao-Huan Tseng



Intensity waterfall plot



First FRB Event!



de-dispersed waterfall

- high DM, from high Galactic latitude
- → outside the Galaxy

Event ID:	20250713_094930Z
Trigger Time (UTC):	2025-07-13 09:49:30.330
Local Time (UTC+8):	2025-07-13 17:49:30
DM (pc/cm^3):	150.934
SNR:	13.7

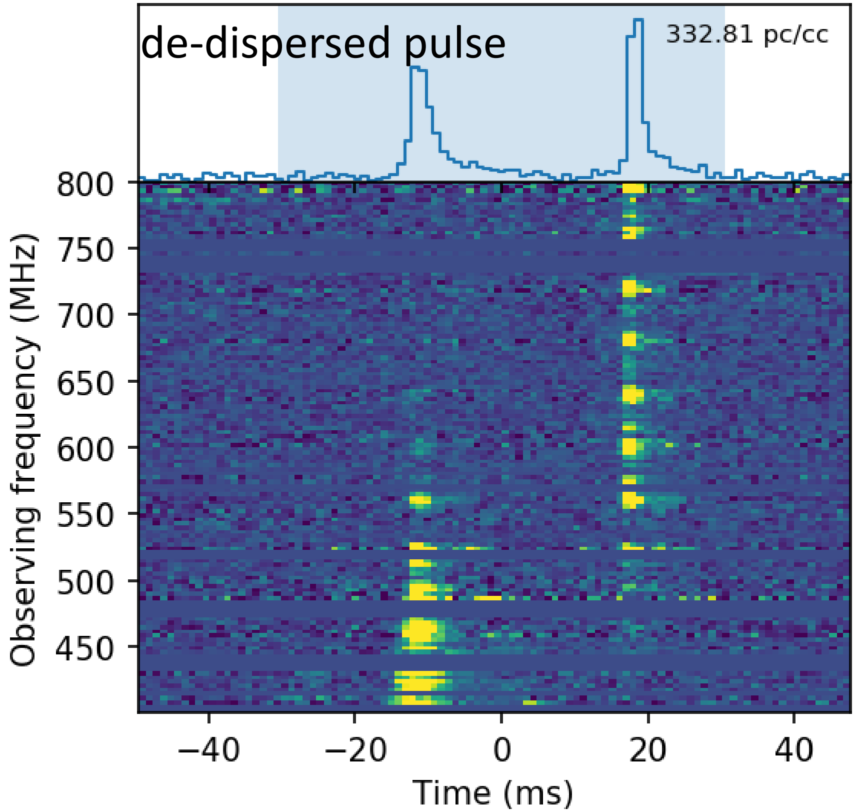
Summary

- BURSTT: dedicated telescope for surveying and localizing nearby FRBs → better understanding of FRB's nature
  - How many portions of FRBs repeat? → wide FoV survey for long-term monitoring
  - Where and What are the sources? → 0.1-1" localization identifies source environment and facilitates follow-up search of counterparts
- 1 main and 3 outrigger stations have been deployed in 2024
- Detected pulses from pulsars
- VLBI test with ~140 km single baseline for 1" angular resolution is in progress
  - single pulses from pulsar B0329+54;
- Real-time pulse search being tuning and optimized
- 1st FRB detection in Jul 2025!
- BURSTT will soon have
  - 3 international 16-antenna outriggers in 2025 → 0.1" resolution

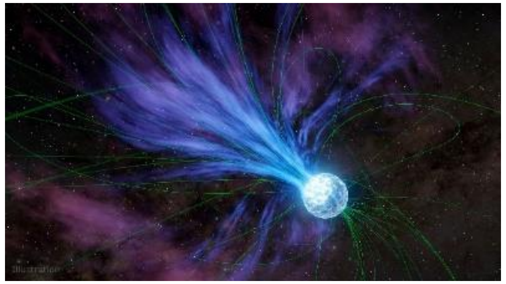
Thank you!

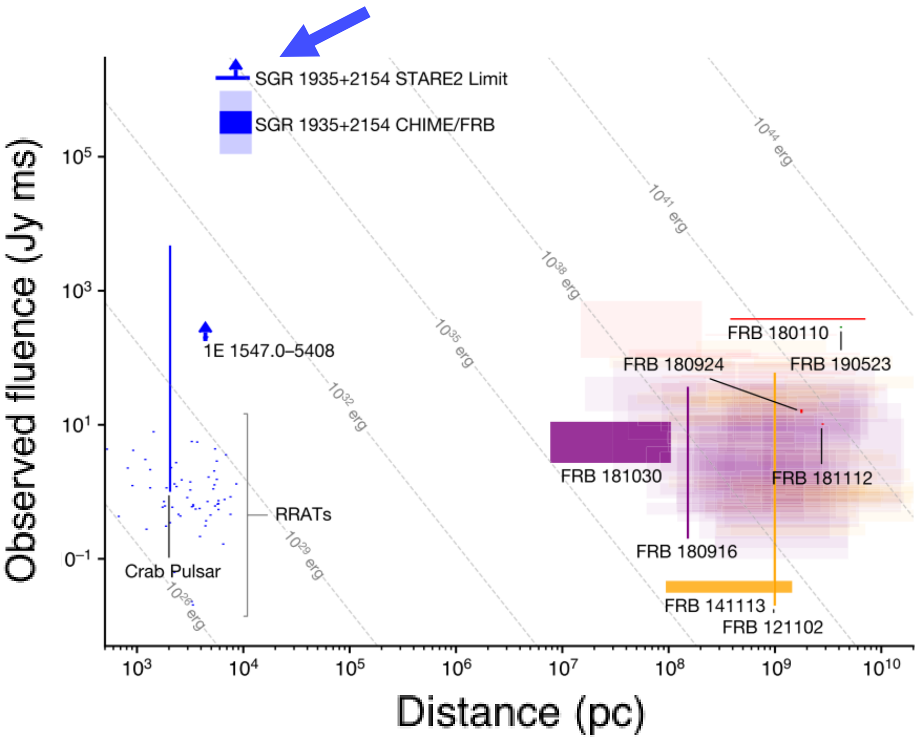
Backup

FRB 20200428 from Galactic magnetar



neutron star with strong B-field (10^9-10^{11} T)





CHIME/FRB, Nature, 2020

- coincidence with X-ray burst from SGR1935+2154
- The only FRB in MW: DM = 332.62 pc cm^{-3}
  - vs max Galactic DM along LoS: 500-700 pc cm^{-3}
- energy comparable to weaker extragalactic FRBs

→ More nearby FRBs to verify the origin

FRB 20200428 from Galactic magnetar

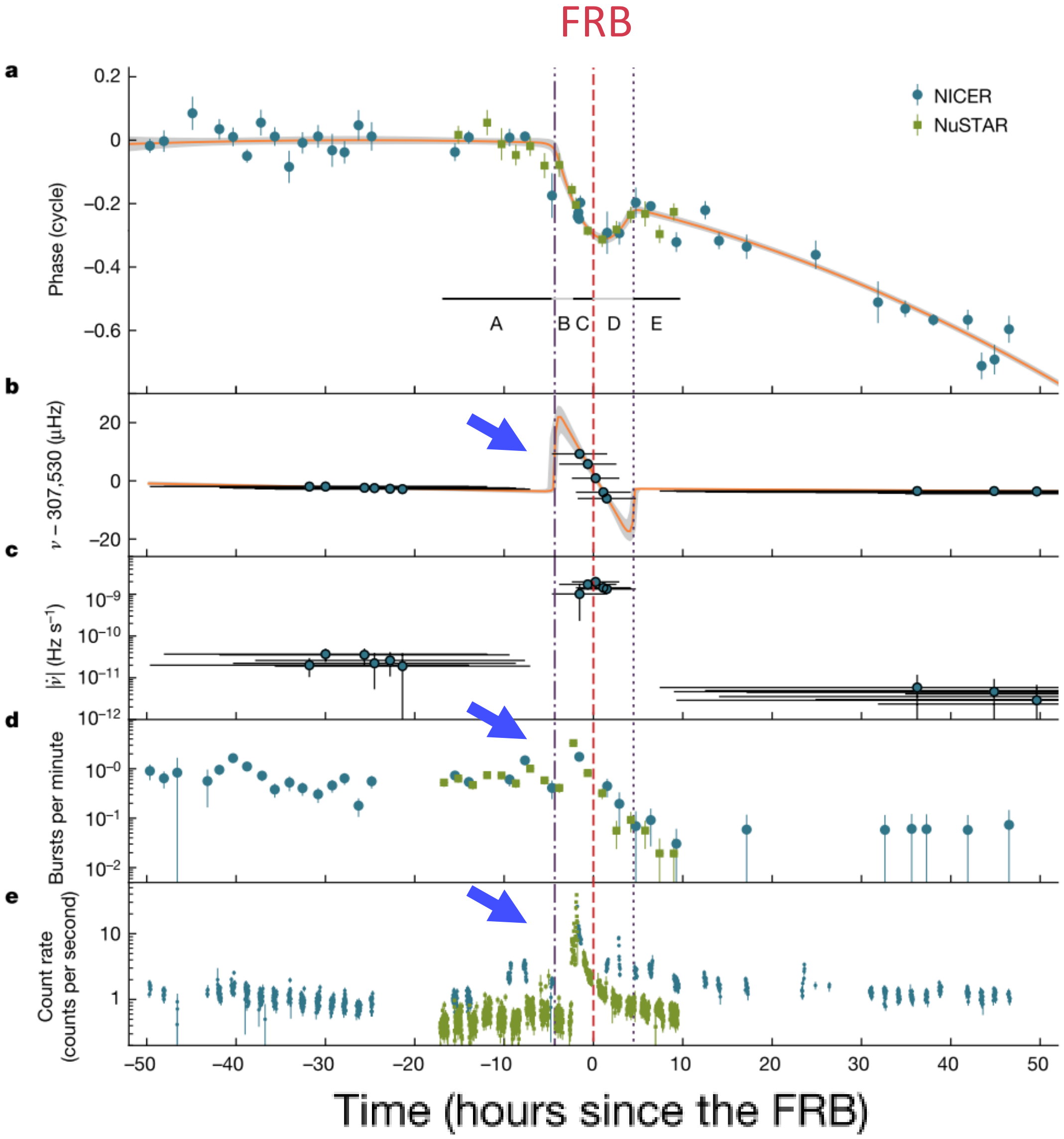
X-ray pulse evolution

magnetar spin freq.

spin freq. change

X-ray burst rate

X-ray count rate



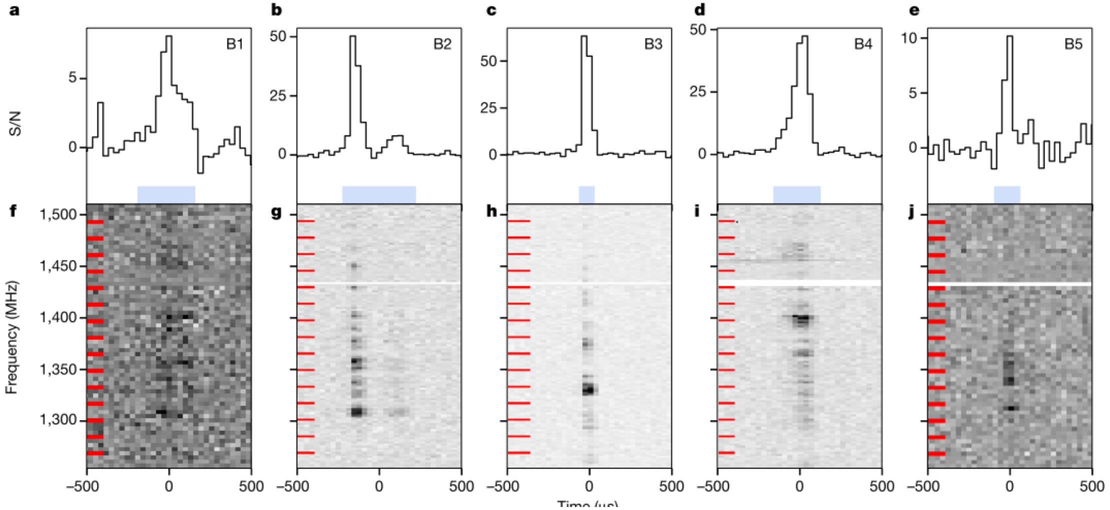
- coincidence with X-ray burst from SGR1935+2154
- 2-8 keV X-ray obs → magnetar spin
- FRB associated with rapid spin changes of the magnetar

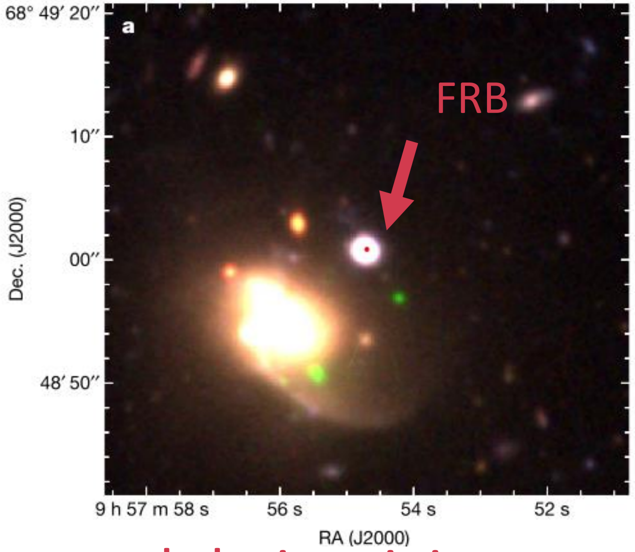
→ FRB counterpart sheds light on its emission mechanism

Hu+, Nature, 2024

Repeating FRB 20200120E in M81 galaxy

- Follow-up observation by European VLBI network
  - detected 5 bursts
  - DM = 87.8pc cm^{-3}
- FRB located in globular cluster
  - with milliarcsecond resolution
  - old stars (>10 Gyr), unlikely from magnetar
  - induced by neutron star of compact binary?
- The only extragalactic FRB with local environment identified so far

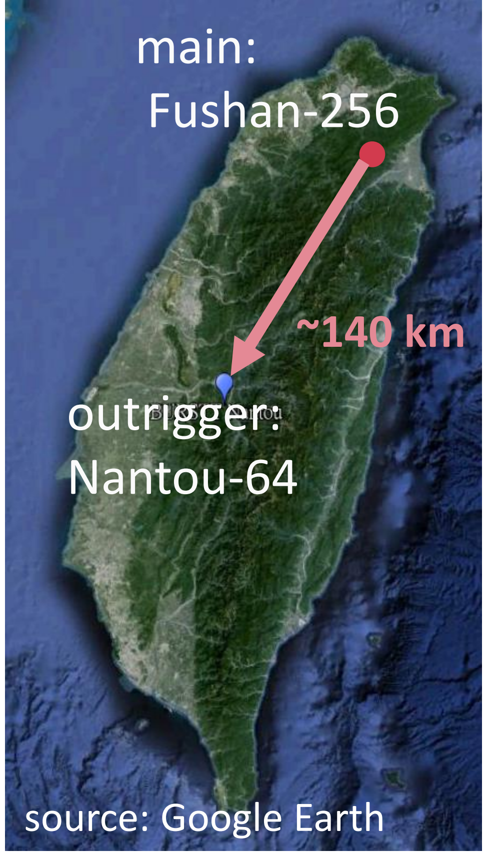




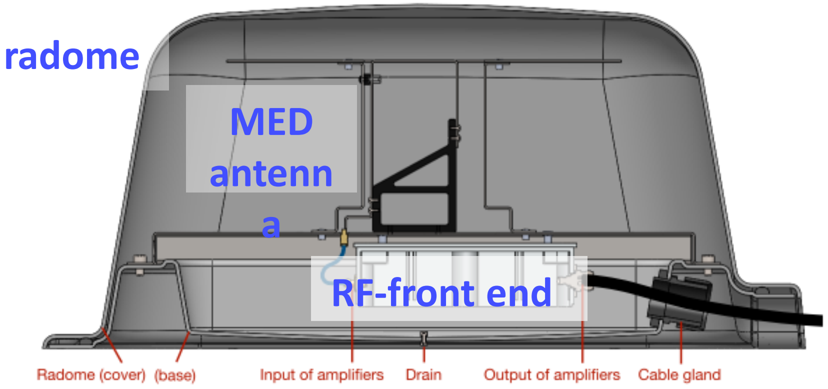
→ More nearby FRBs to reveal their origin

Kirsten et al., Nature, 2022

BURSTT outrigger station at Nantou



- ~140 km distance to main station ~1" resolution for localization
- search pulse at main array at 400-800 MHz, sending trigger to outrigger at 300-700 MHz
  - low-frequency measurement for FRBs



credit: Shih-Chieh Su & Jiwoo Nam

- custom-design Magneto-Electric Dipole (MED) antennas
  - ~7 dBi at **300**-800 MHz
  - wide and symmetric main beam: ~100° × 100°
  - low-profile : 45 × 45 × 17 cm with weatherproof radome
  - integrated RF-front end

BURSTT-64 at Nantou

EMI-Shielding room

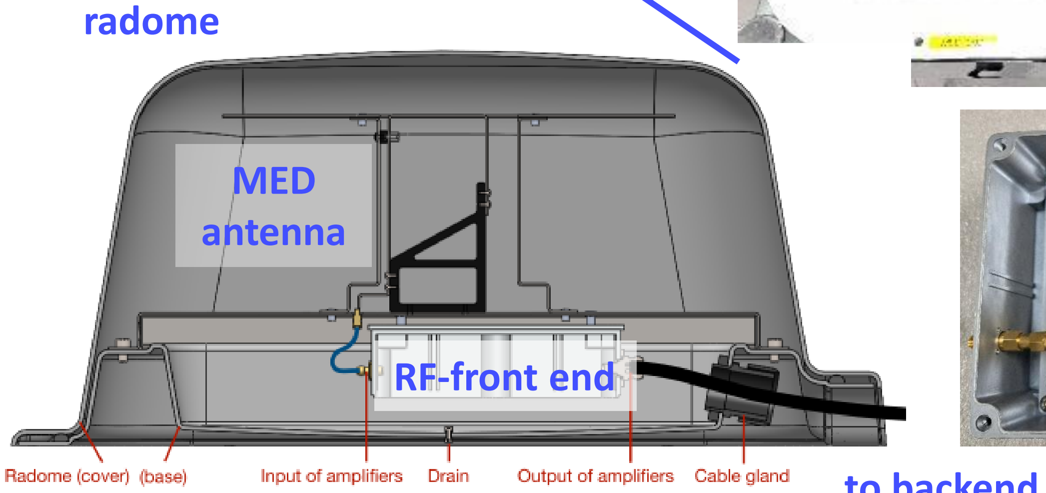
DAQ system

Low-loss coaxial cables & surge protectors

- antenna spacing:
  - 1m in E-W
  - 2m in N-S
- antenna positions are calibrated to mm accuracy
  - by differential GPS measurements & photogrammetry

Antenna array 16×4

BURSTT-Nantou outrigger station



credit: Shih-Chieh Su & Jiwoo Nam

~60 dB gain,
750 MHz LPF

- custom design Magneto-Electric Dipole (MED) Antenna
  - ~7 dBi at **300**-800 MHz
- wide FoV: ~$100^{o} \times 100^{o}$
  - symmetric radiation pattern at E- and H-planes
- low-profile
  - L $\times$ W $\times$ H = 45 $\times$ 45 $\times$ **17** cm
- weatherproof radome
- integrated RF-front end