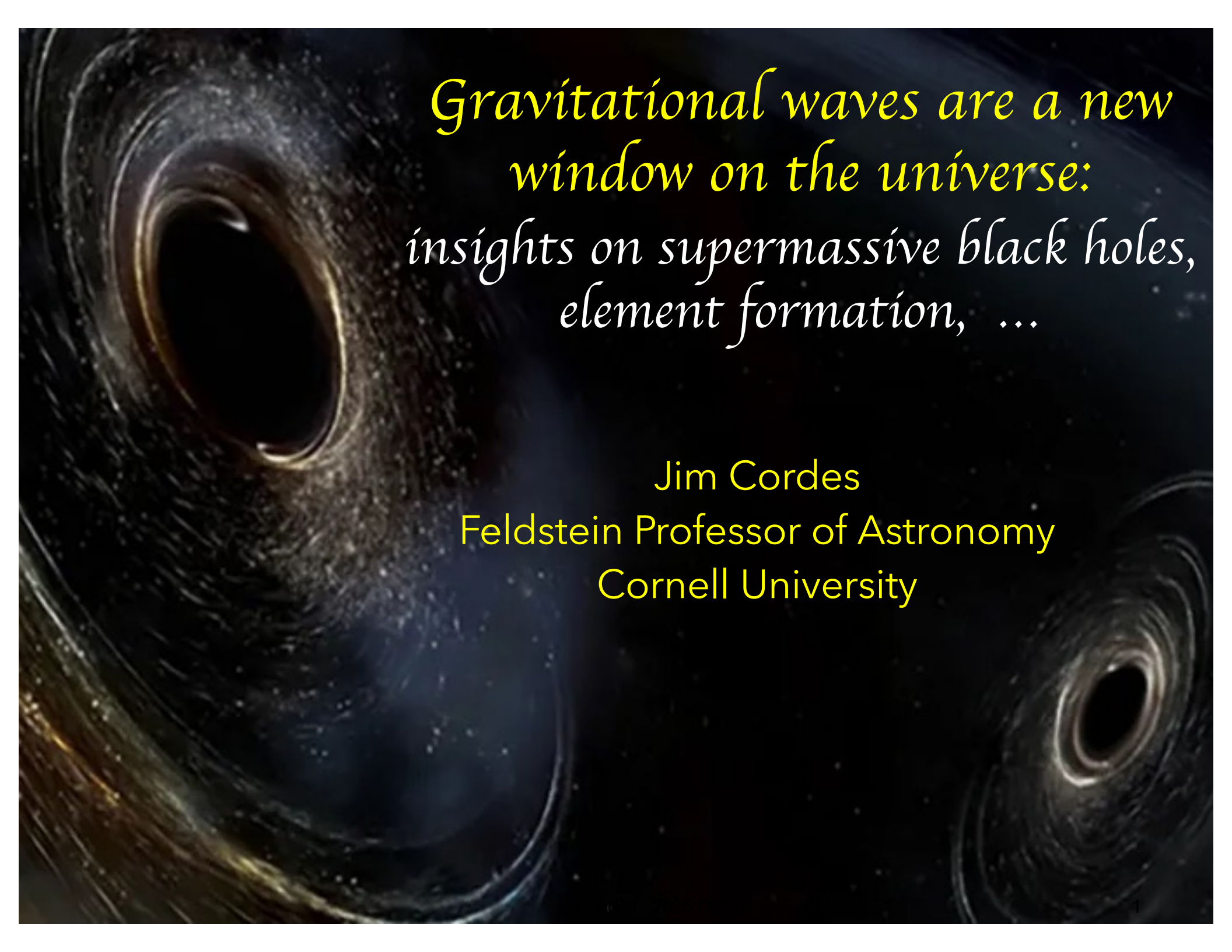
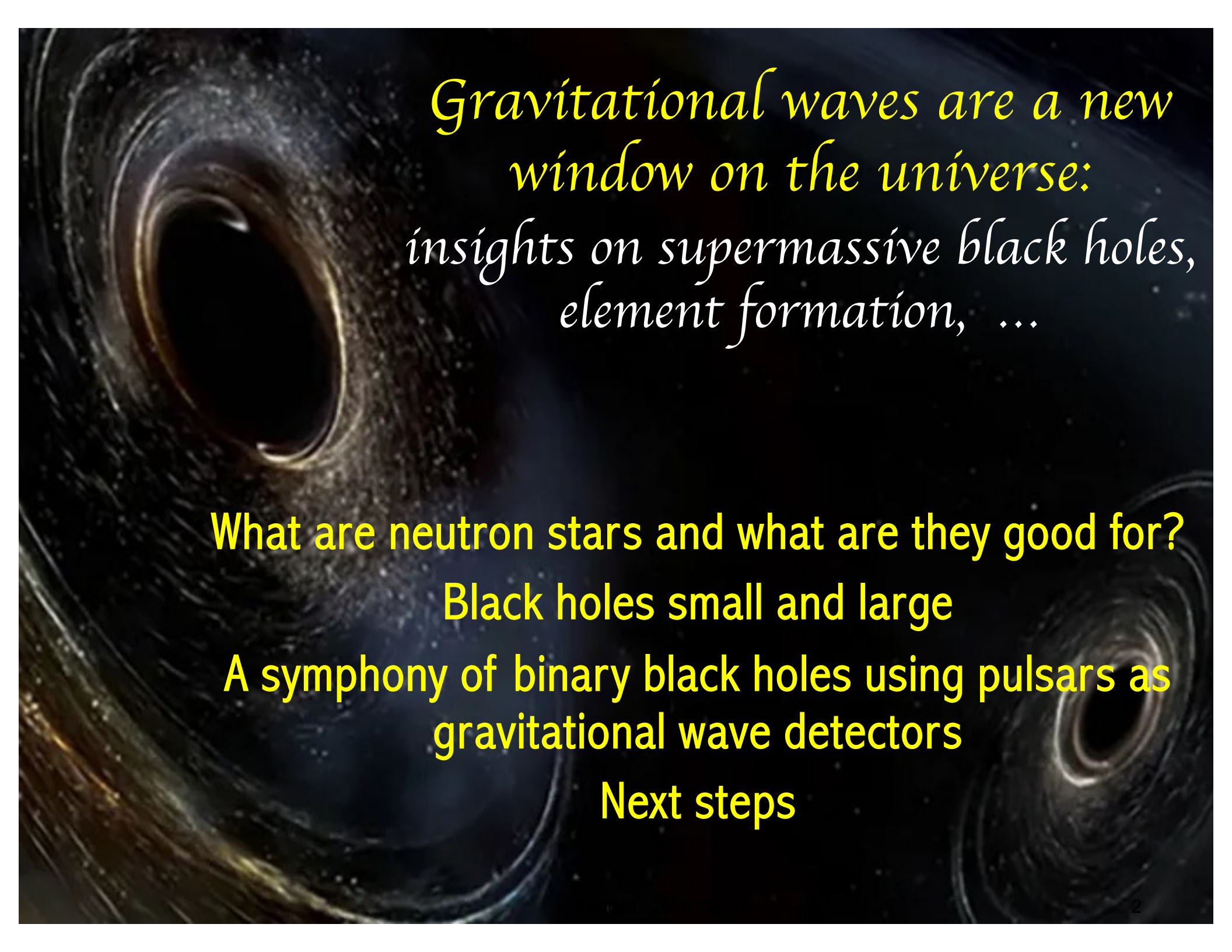




*Gravitational waves are a new
window on the universe:
insights on supermassive black holes,
element formation, ...*

Jim Cordes
Feldstein Professor of Astronomy
Cornell University



*Gravitational waves are a new
window on the universe:
insights on supermassive black holes,
element formation, ...*

What are neutron stars and what are they good for?

Black holes small and large

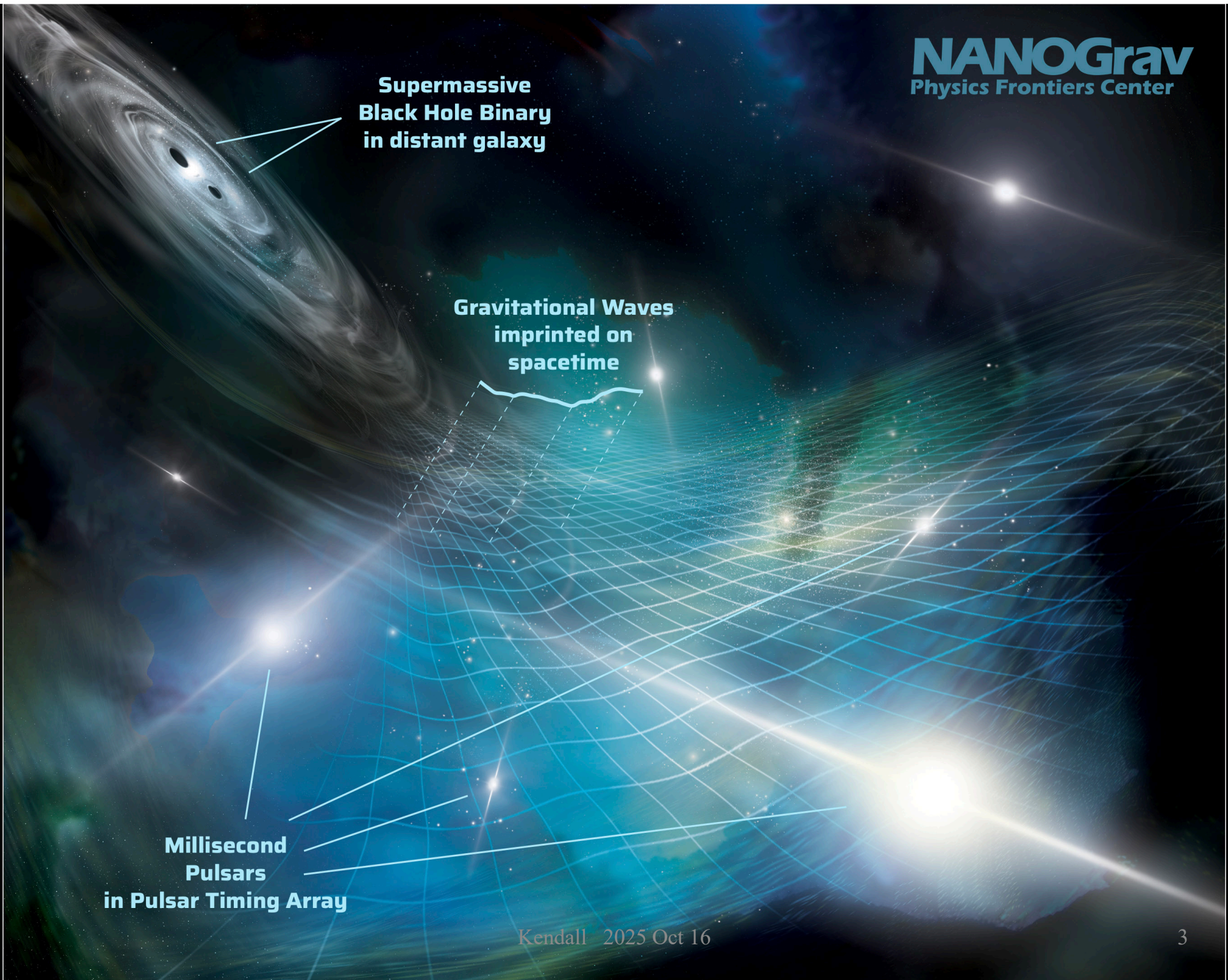
**A symphony of binary black holes using pulsars as
gravitational wave detectors**

Next steps

**Supermassive
Black Hole Binary
in distant galaxy**

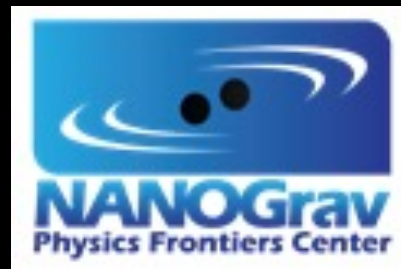
**Gravitational Waves
imprinted on
spacetime**

**Millisecond
Pulsars
in Pulsar Timing Array**

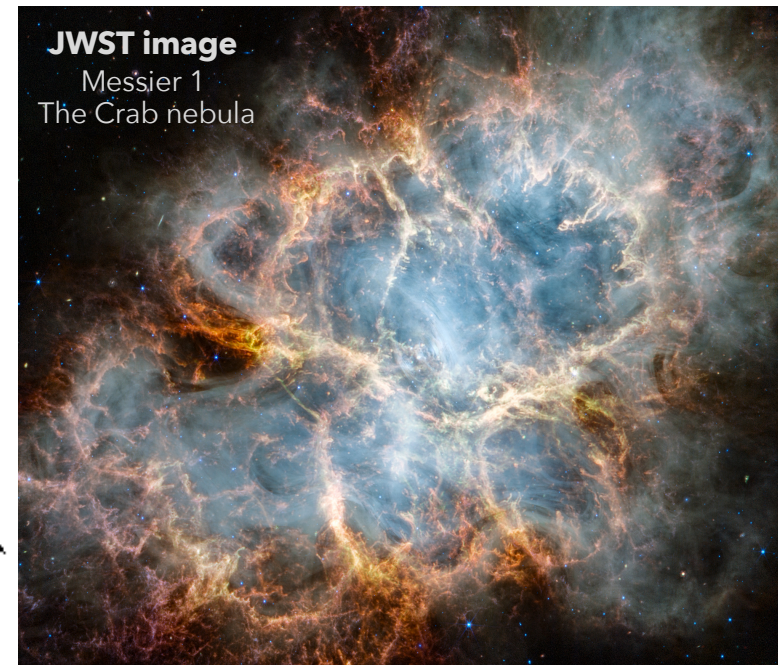
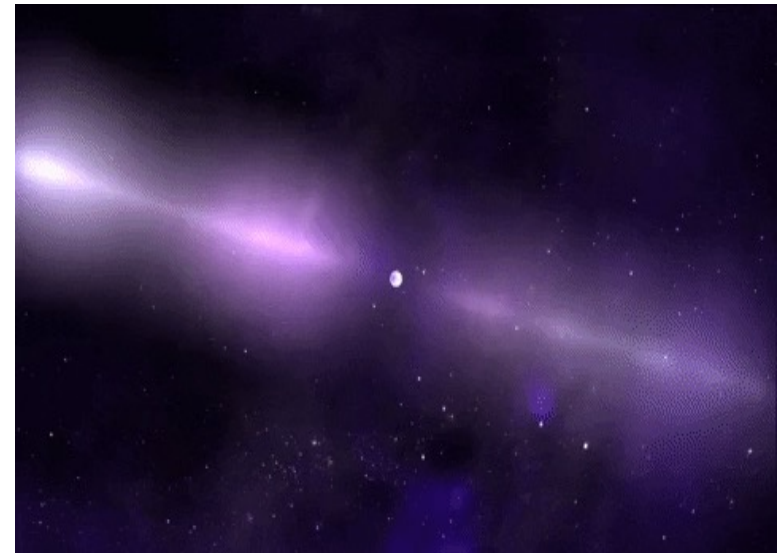
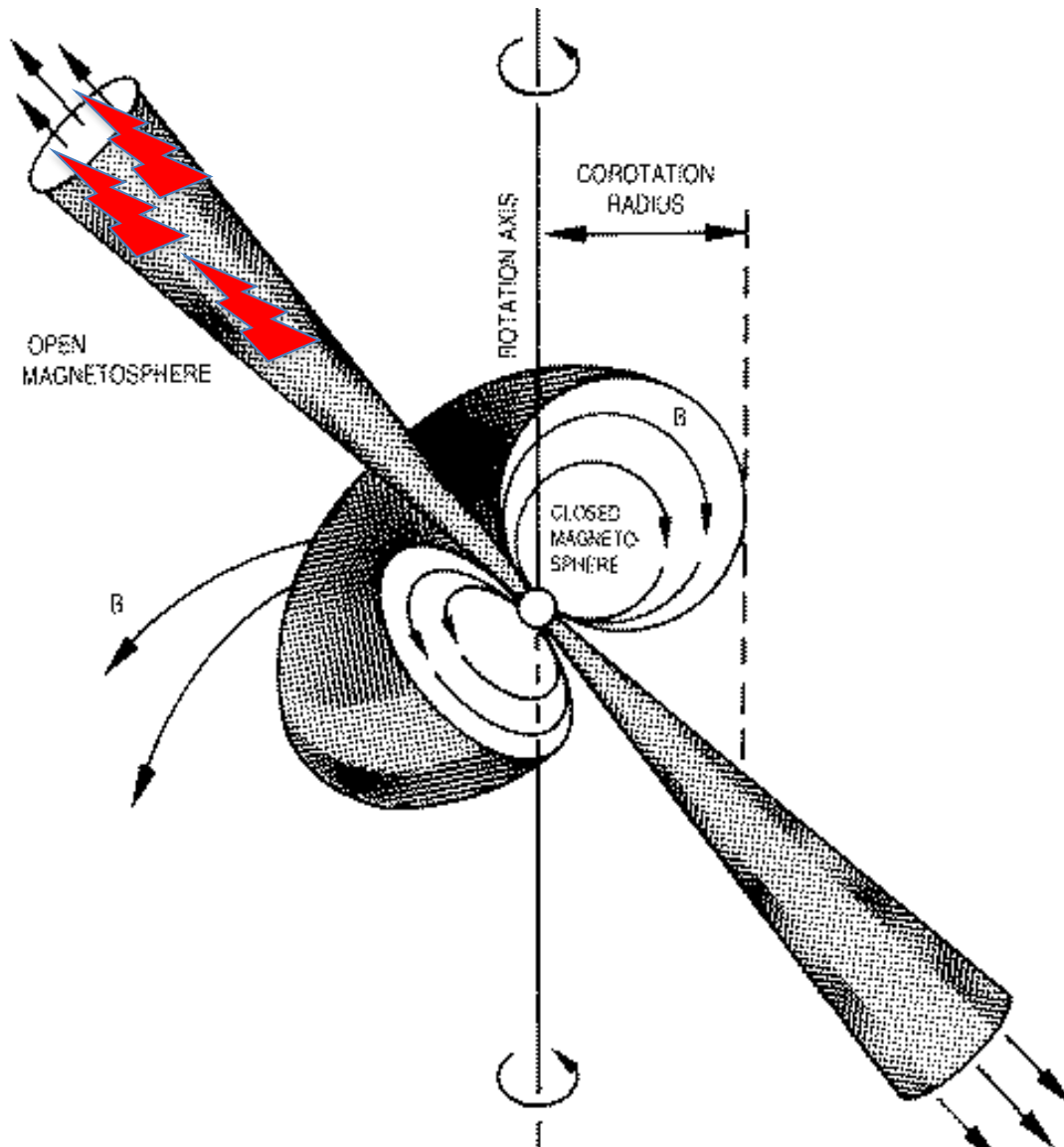




Arecibo telescope 1963-2020

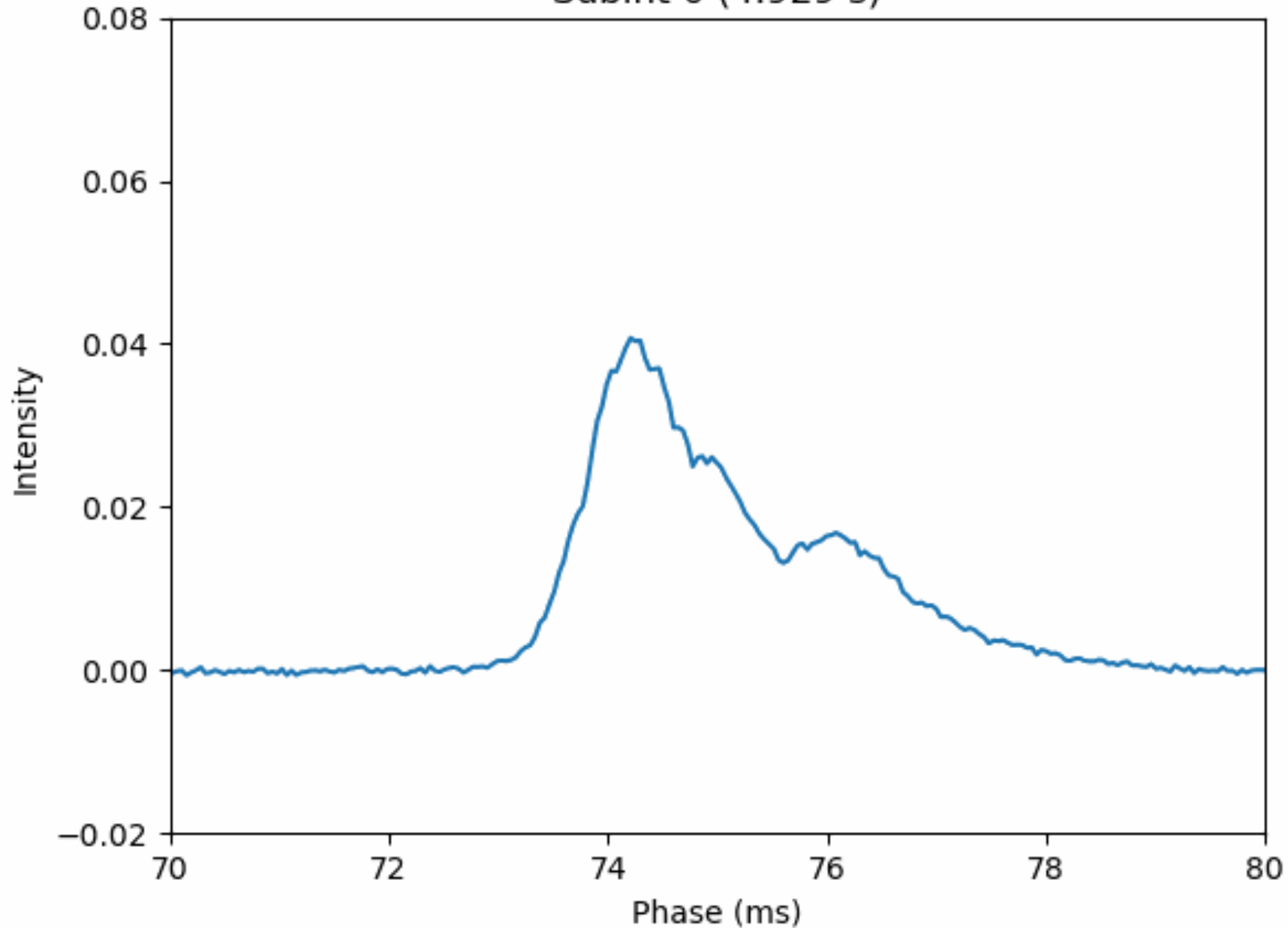


Pulsars are rapidly rotating neutron stars produced in supernova explosions



Vela pulsar $P = 89 \text{ ms}$ 8s averages ~ 100 pulses

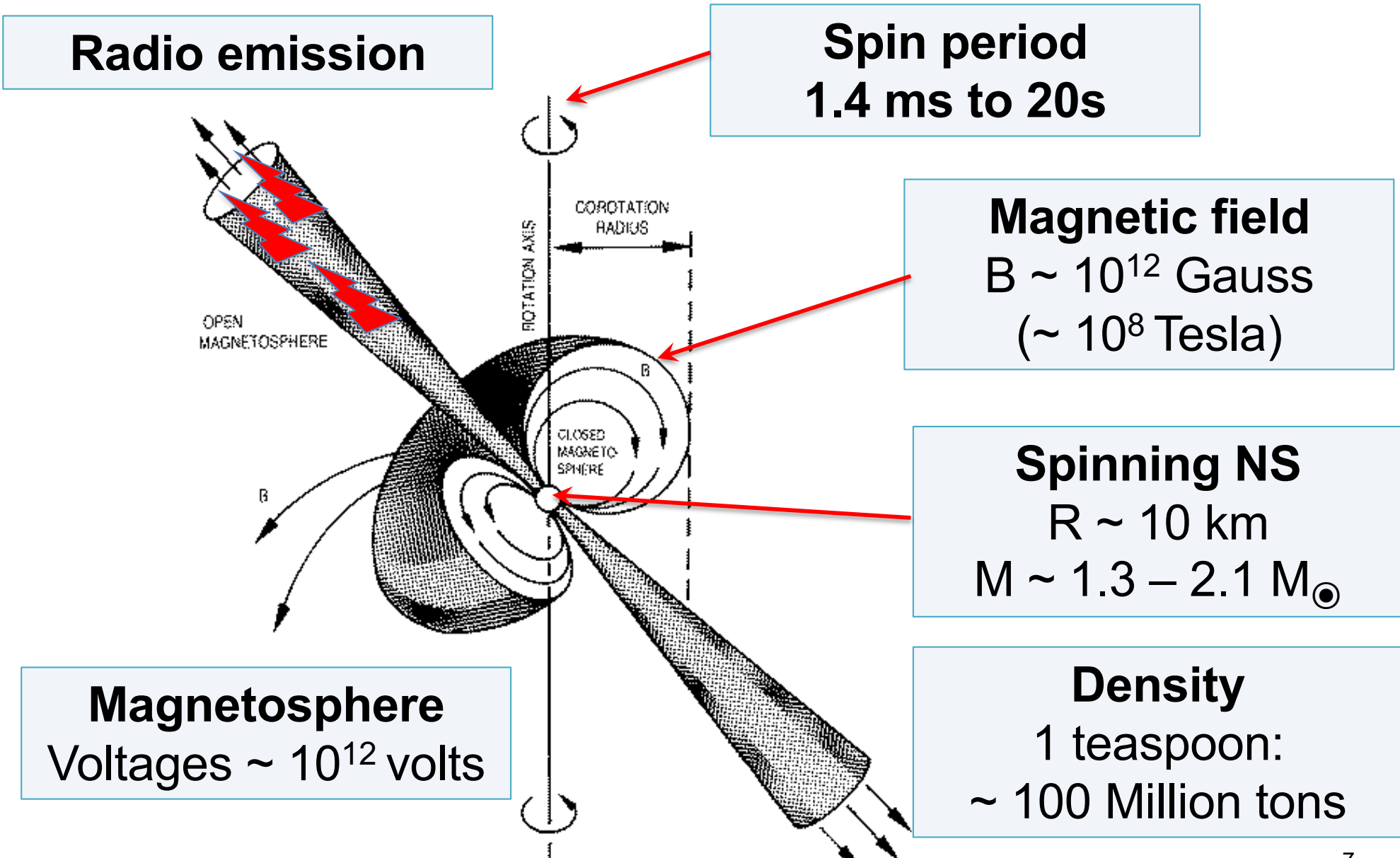
Subint 0 (4.929 s)



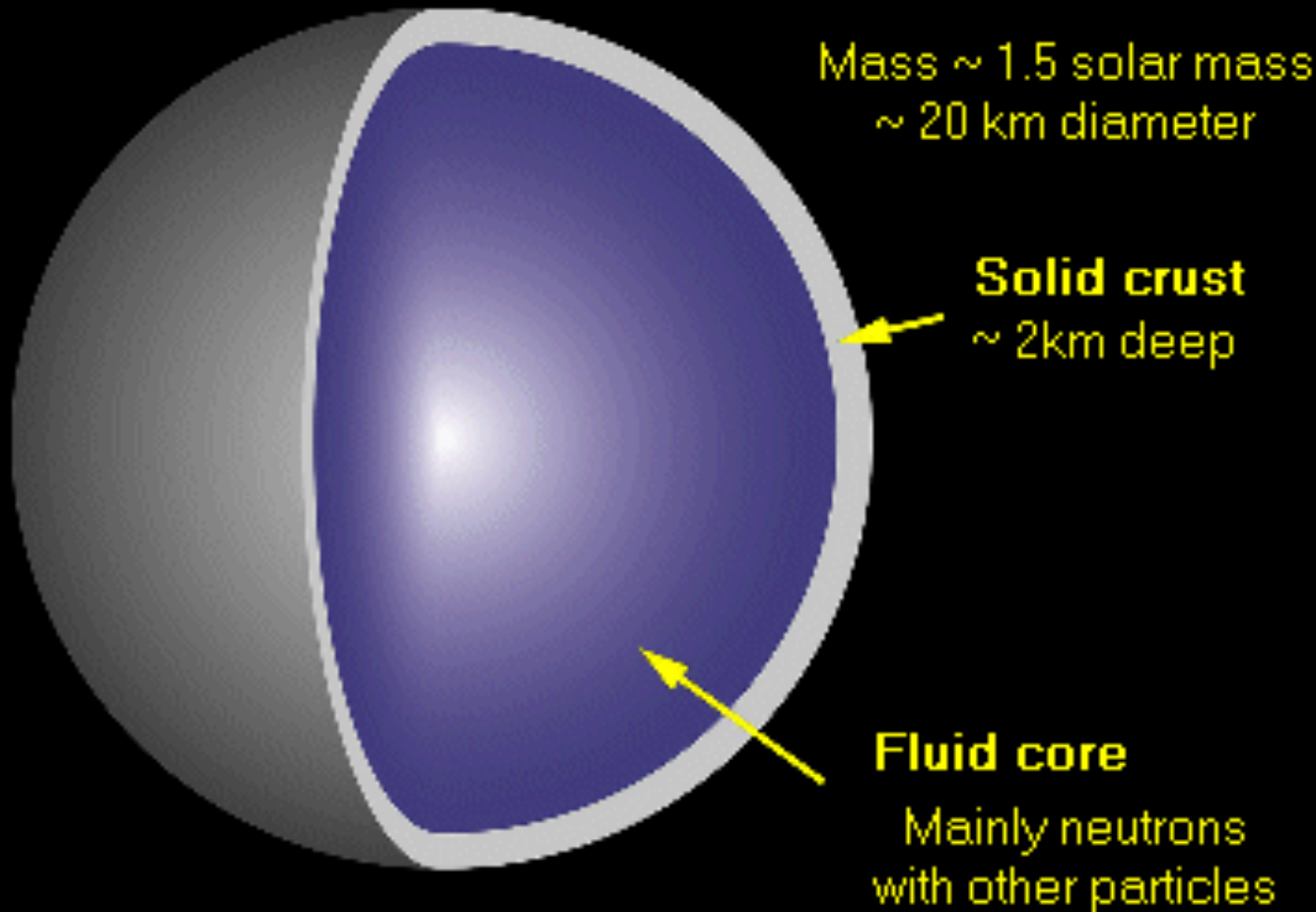
Data: M.Kerr, Parkes Telescope

Animation: Ross Jennings Ph.D. '21

Pulsars exert extreme gravity and electric fields on their surroundings



Neutron star



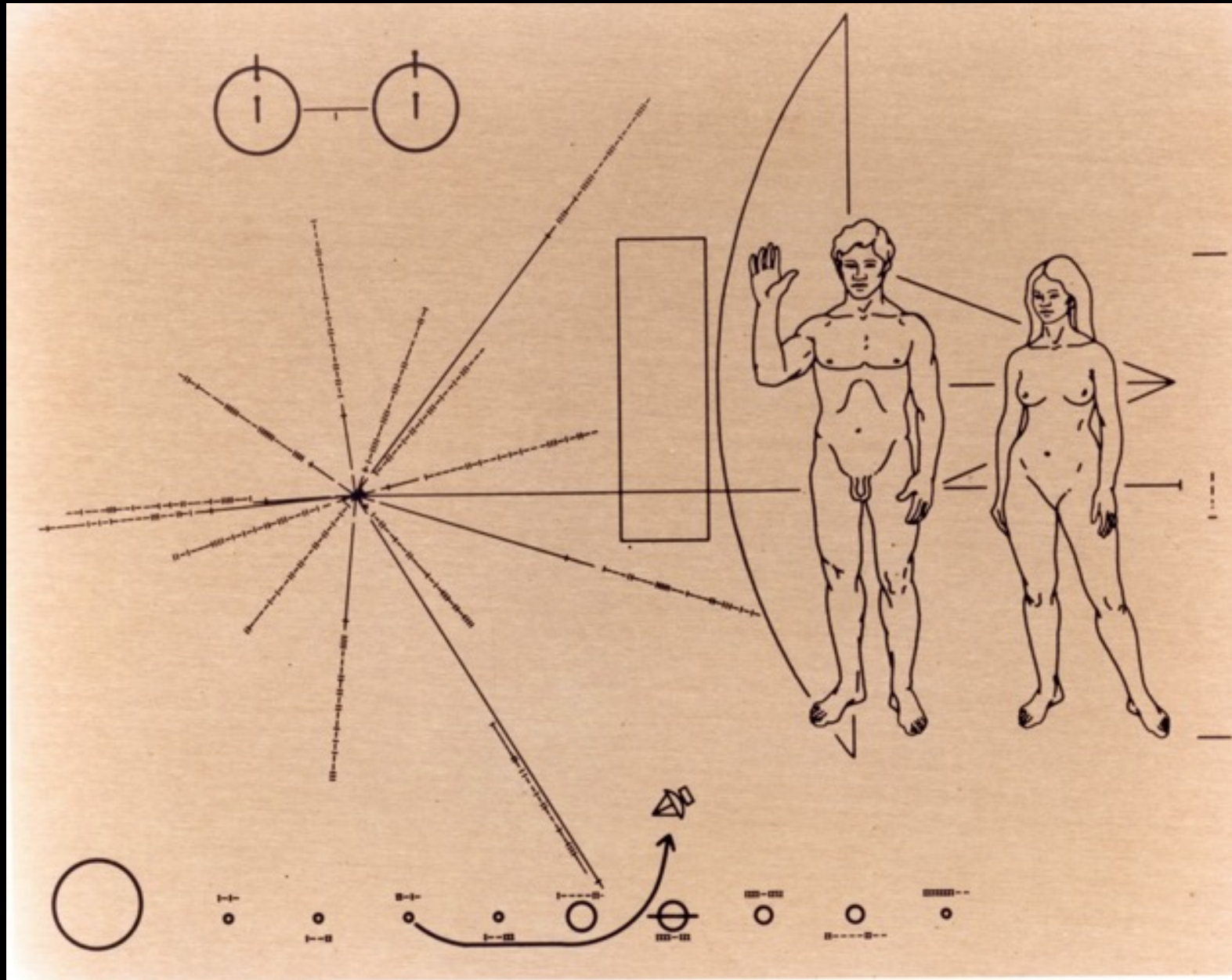
- Neutron - 1932
- Neutron star concept - 1933
- Models (Oppenheimer-Volkoff) - 1939
- Discovery - 1967

Low-mass stars	→ white dwarfs	(Earth size, mostly carbon)
Medium-mass stars	→ neutron stars	(Ithaca size)
High-mass stars	→ black holes	(size ill determined)

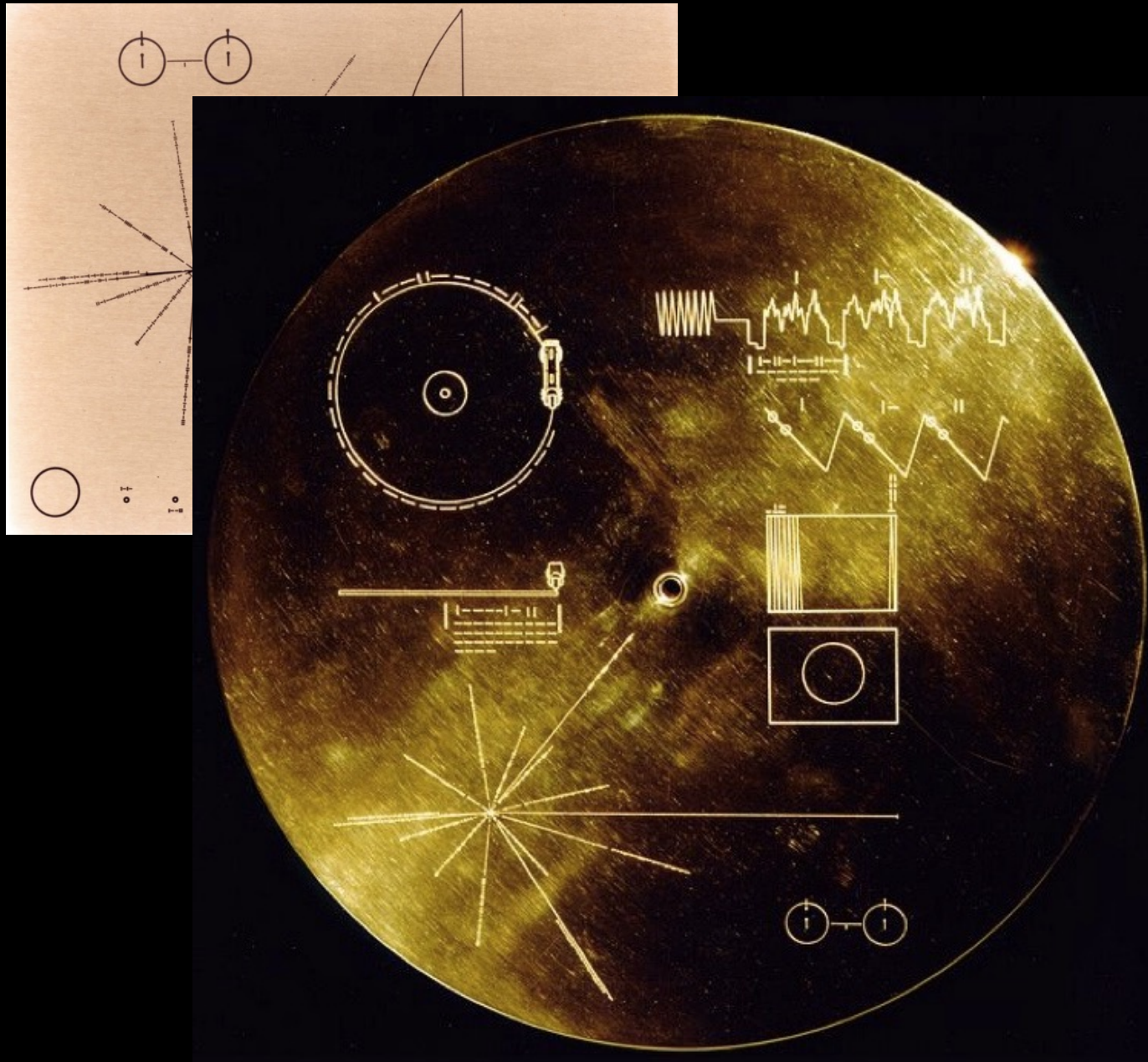
Pioneer 10, 11 spacecraft plaques

1972, 1973
launches

Sagan and
Drake



Voyager 1, 2 spacecraft gold records (1977 launch)



Selling energy products



Selling record albums and tshirts



As random number generators/cryptography



ELSEVIER

Astronomy and Computing

journal homepage: www.elsevier.com/locate/ascom

Full length article

Physical publicly verifiable randomness from pulsars

J.R. Dawson^{a,b,*}, G. Hobbs^a, Y. Gao^c, S. Camtepe^d, J. Pieprzyk^{d,e}, Y. Feng^{f,g},
S. Bradbury^{a,h}, W. Zhu^{f,g}, D. Li^{f,g,i}

+

My early consulting in 1979:

Pulsar random numbers for reconciling the MX Missile system with
the SALT II agreement

For today: tools for fundamental physics



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New Astronomy Reviews 48 (2004) 1413–1438

New Astronomy
Reviews

Pulsars as tools for fundamental physics and astrophysics

J.M. Cordes ^{a,*}, M. Kramer ^b, T.J.W. Lazio ^{c,1}, B.W. Stappers ^d,
D.C. Backer ^e, S. Johnston ^f

+

THE ASTROPHYSICAL JOURNAL LETTERS, 952:L37 (30pp), 2023 August 1

© 2023. The Author(s). Published by the American Astronomical Society.

OPEN ACCESS

<https://doi.org/10.3847/2041-8213/ace18b>



CrossMark

The NANOGrav 15 yr Data Set: Constraints on Supermassive Black Hole Binaries from the Gravitational-wave Background

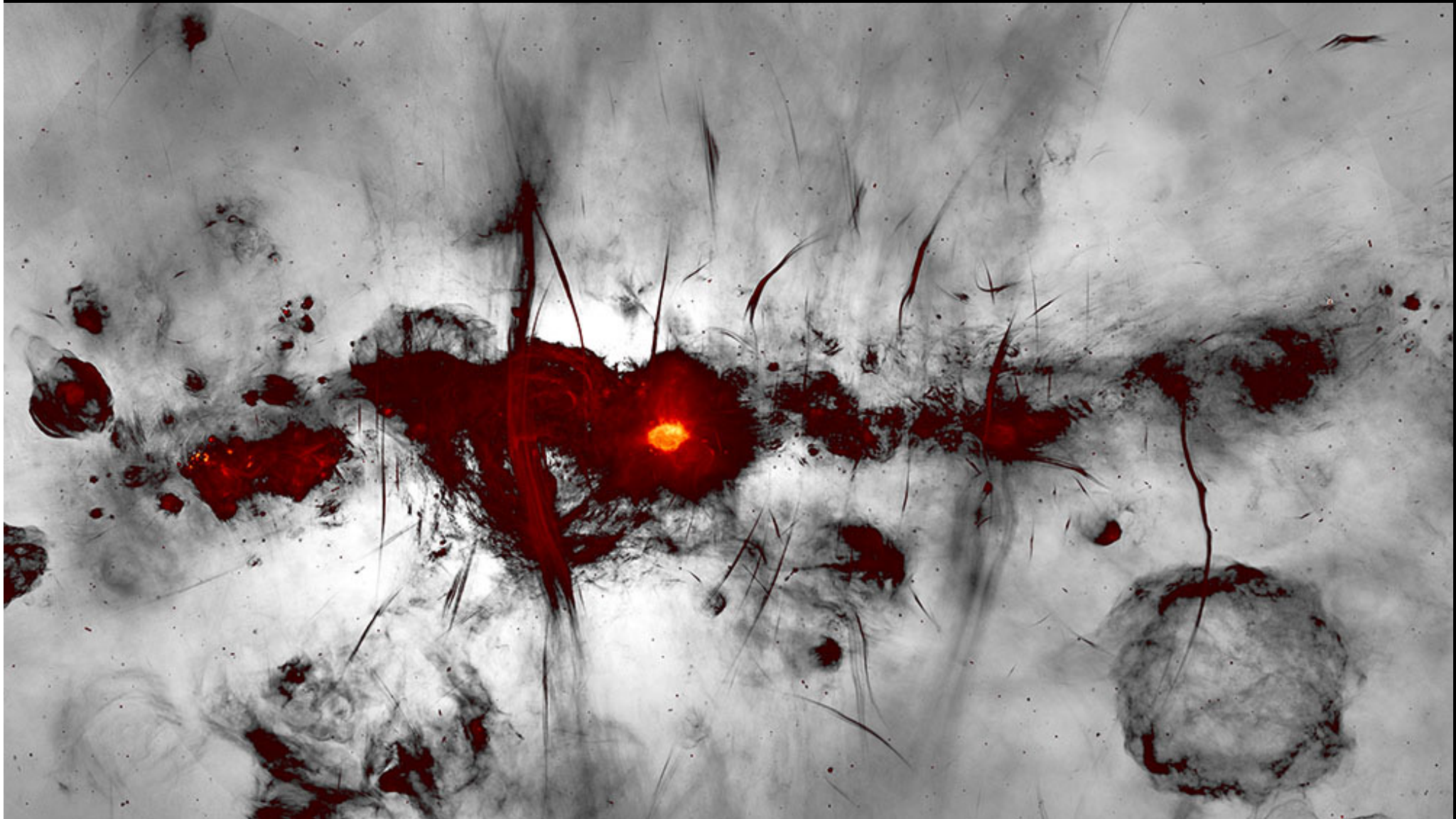
A short history of black holes

- 1783 John Mitchell Newtonian physics
- 1796 Pierre-Simon Laplace ditto
- 1915/16 Einstein + Schwarzschild
- 1939 Oppenheimer-Snyder (collapse of stars)
- 1963 Kerr (spinning black holes)
- 1963 Schmidt et al. Discovery of quasars (3C 273)
- 1968 Wheeler coined 'black hole'
- 1971 First identified stellar-mass black hole
 - » Cygnus X-1 (X-ray source + massive star)
 - » ~ 20 solar masses
- 1964 Salpeter and Zeldovich
 - » Active galactic nuclei as accreting supermassive black holes
- Present All galaxies have central black holes
 - » Some active, others inactive (fed by stars)

Radio image: Galactic center of the Milky Way

2.5 deg across

radio image at 1.3 GHz from MeerKAT (South Africa)

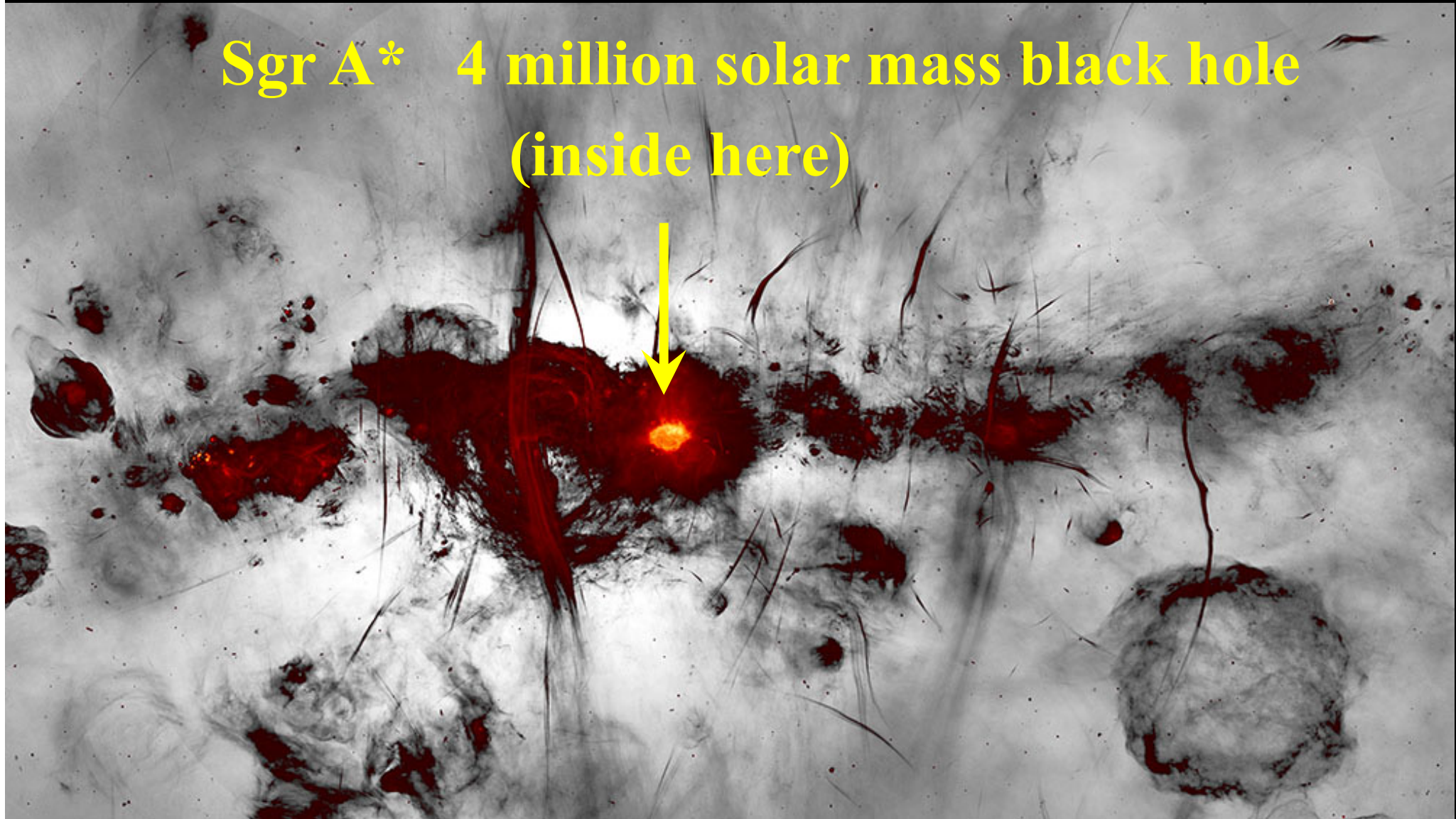


Radio image: Galactic center of the Milky Way

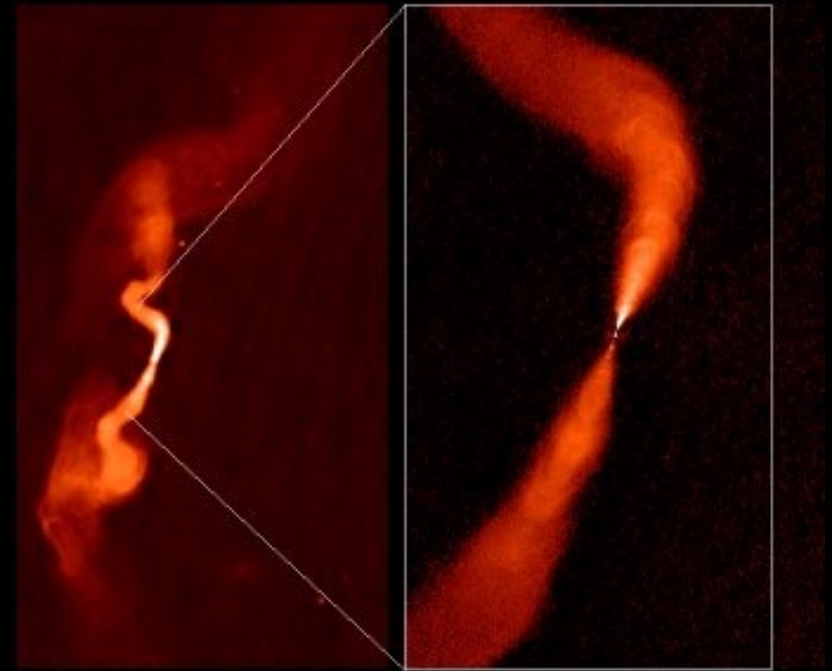
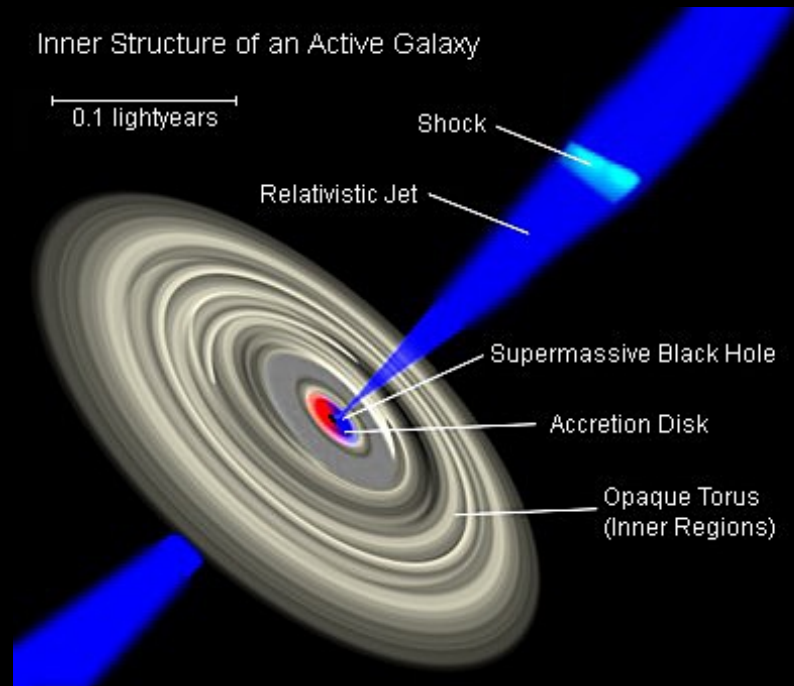
2.5 deg across

radio image at 1.3 GHz from MeerKAT (South Africa)

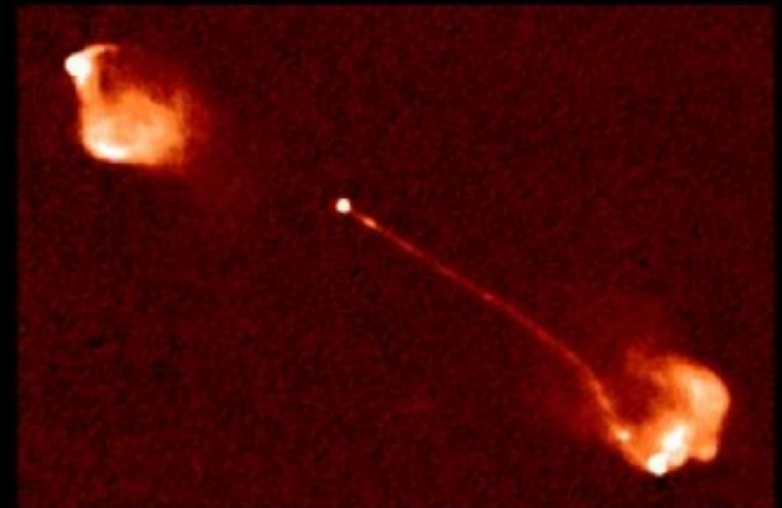
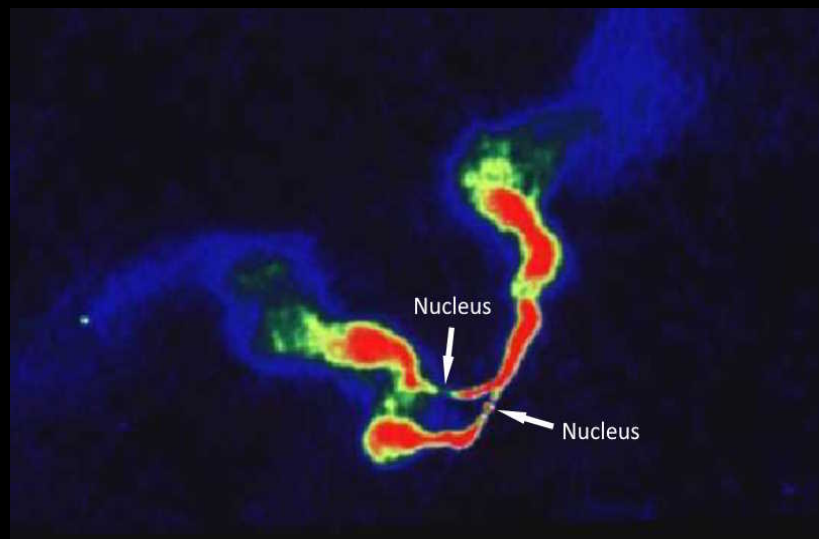
**Sgr A* 4 million solar mass black hole
(inside here)**



Sources of nanohertz GWs: supermassive black hole binaries



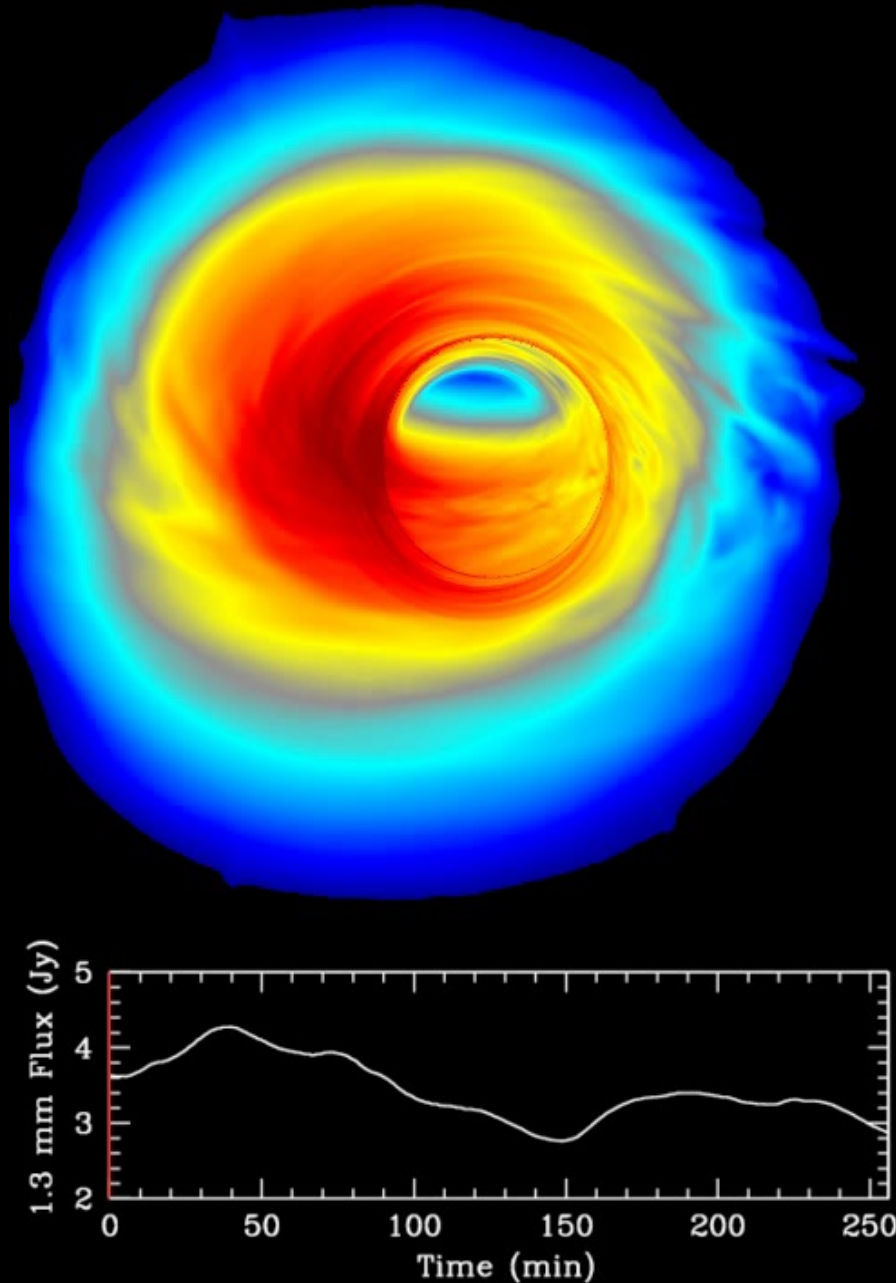
FR Class I source: radio galaxy 3C31



FR Class II source: quasar 3C175

Simulation of gravitational lensing around Sgr A*

Gravitational lensing of the accretion disk around Sgr A* (the $4.6 \times 10^6 M_{\odot}$ black hole in the center of the Galaxy.)



Can be imaged with very long baseline interferometry (radio telescopes)

Event Horizon Telescope = VLBI Array

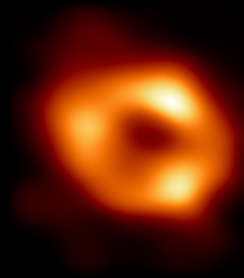
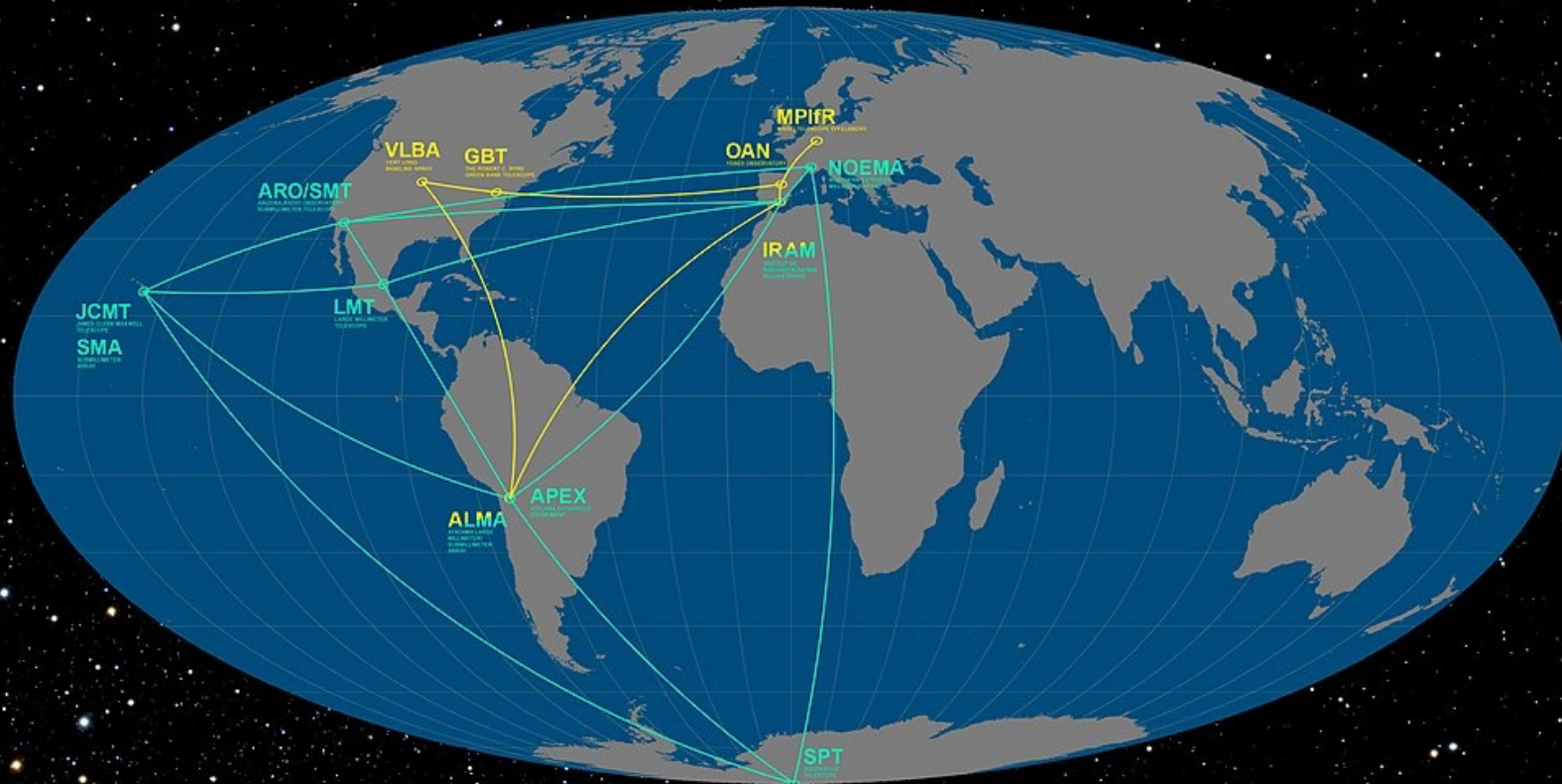


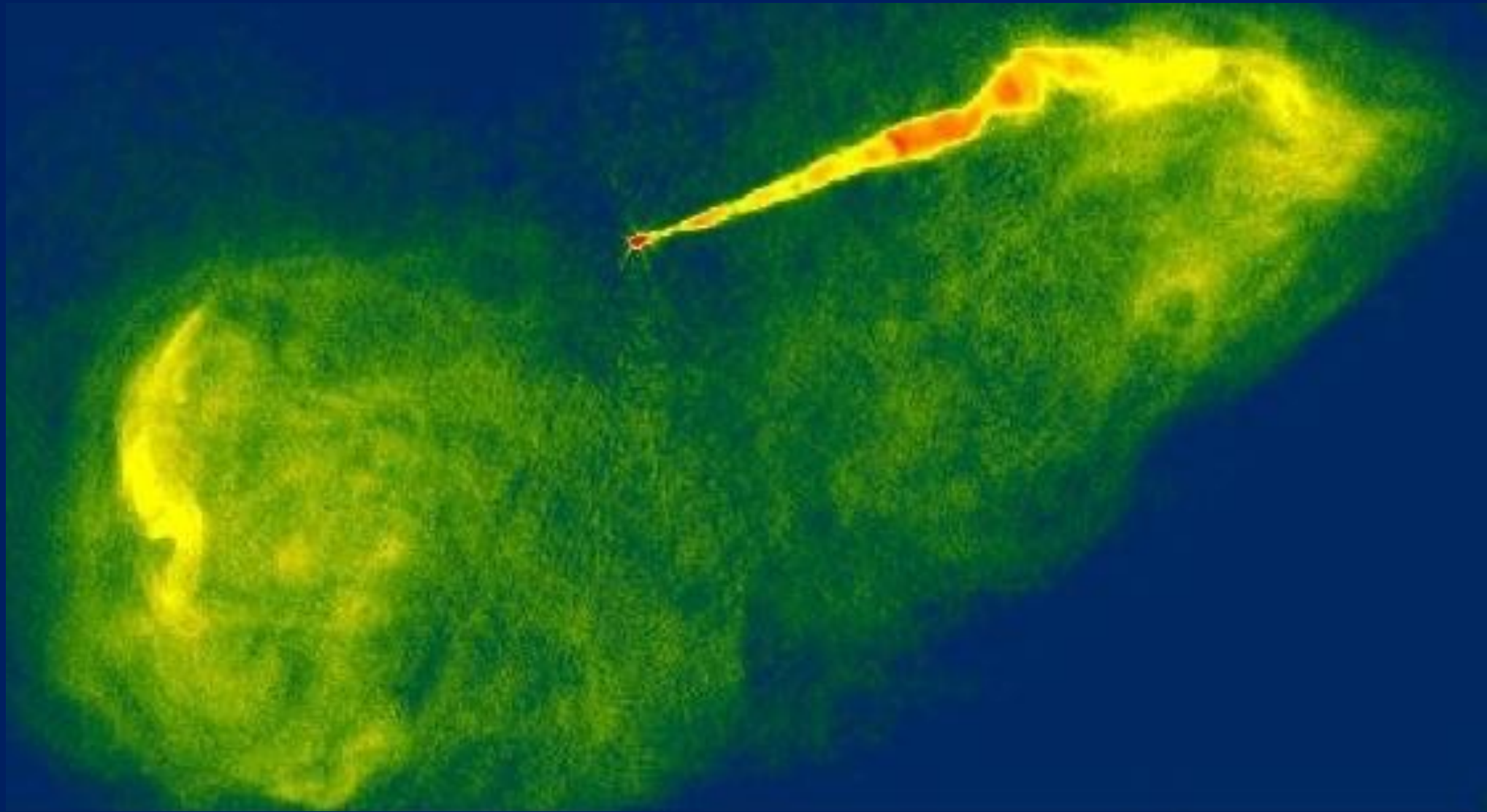
Image of Sgr A*
4 million solar
masses

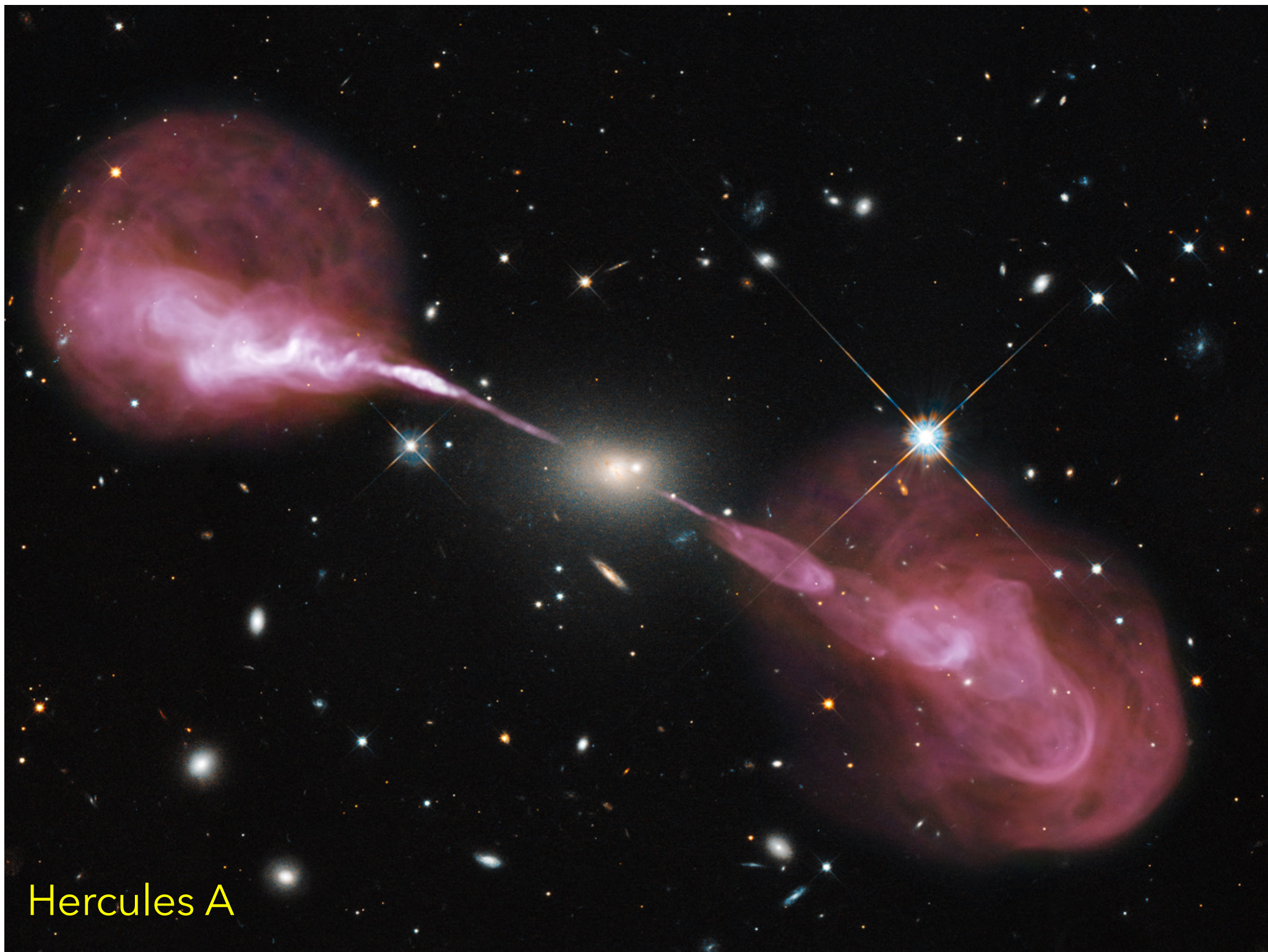


Image of M87 black hole
9 billion solar masses



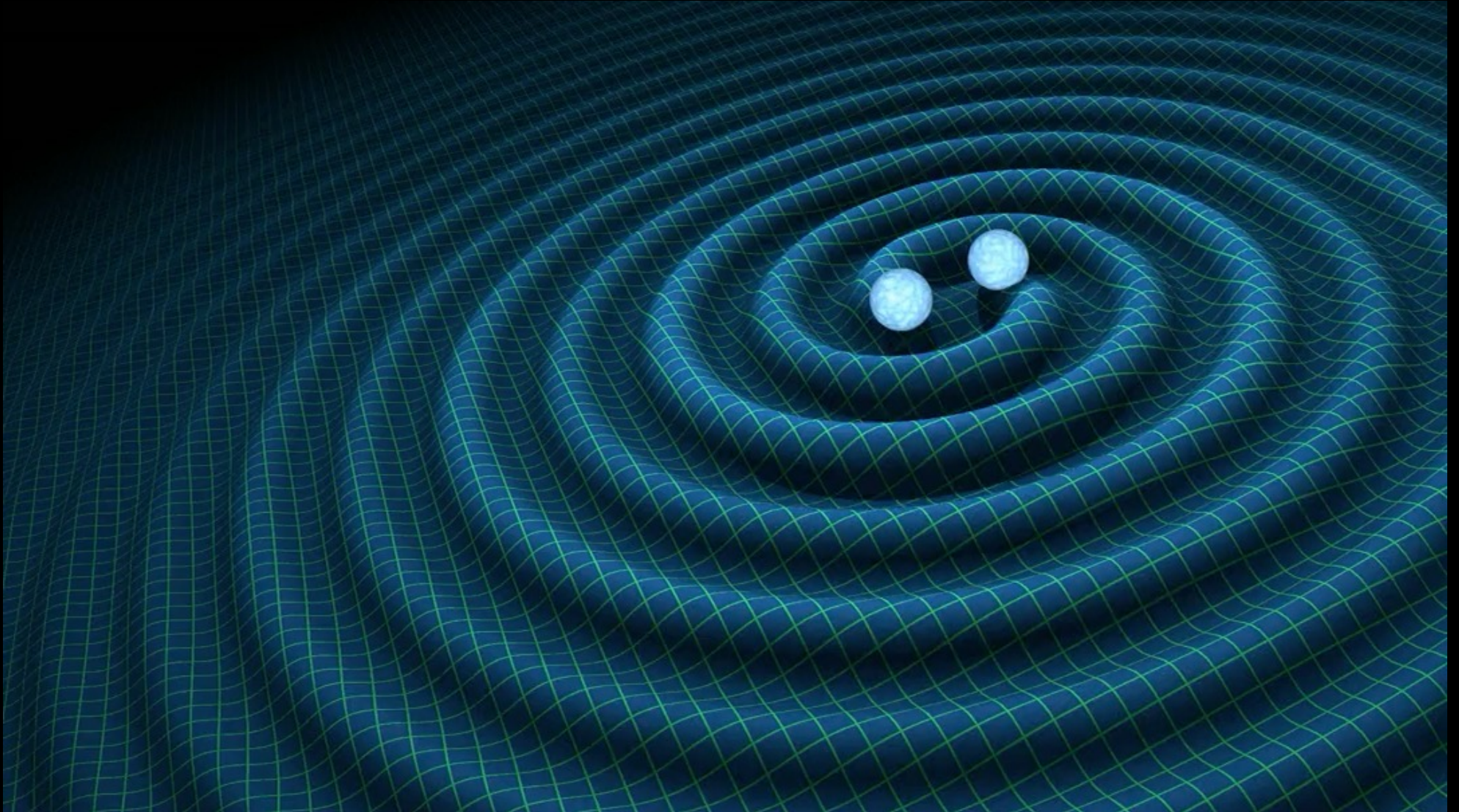
Virgo A Messier 87





Hercules A

A binary system is like a cosmic eggbeater that stirs spacetime



Gravitational Waves

An animation of artist's concept of gravitational wave propagation (LIGO/Caltech)

Gravitational waves move the goalposts



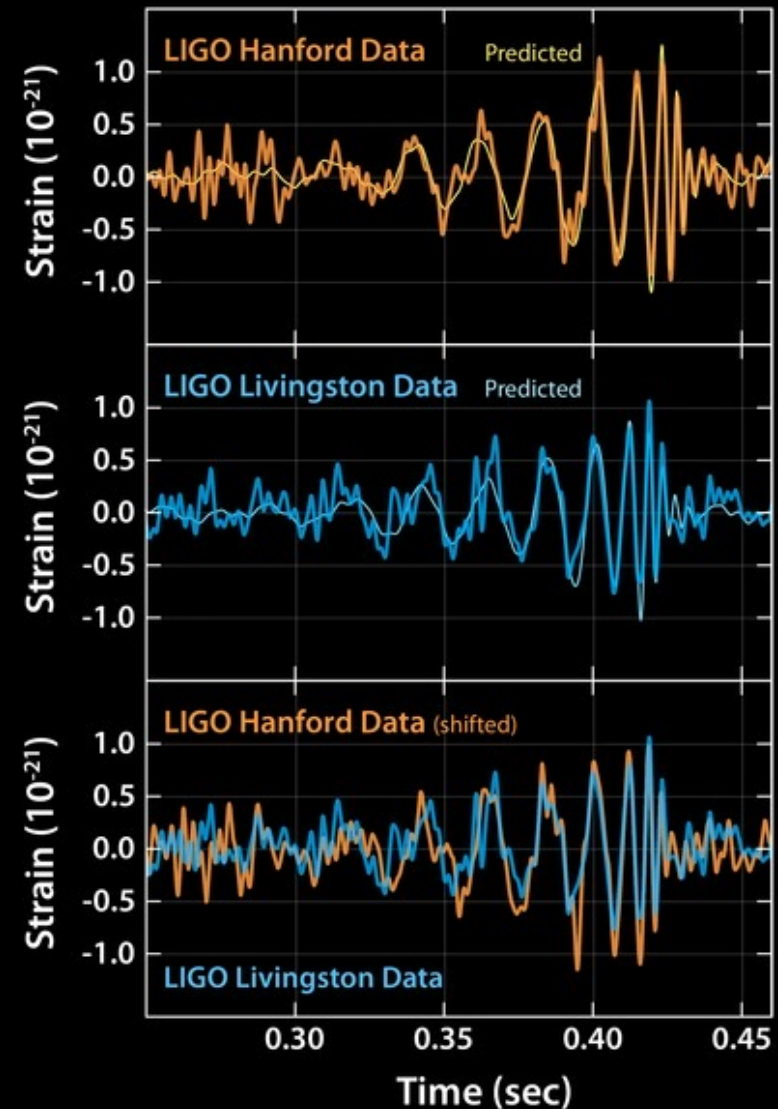
A gravitational wave of strength h changes a distance L by an amount ΔL

$$\Delta L/L \sim h$$

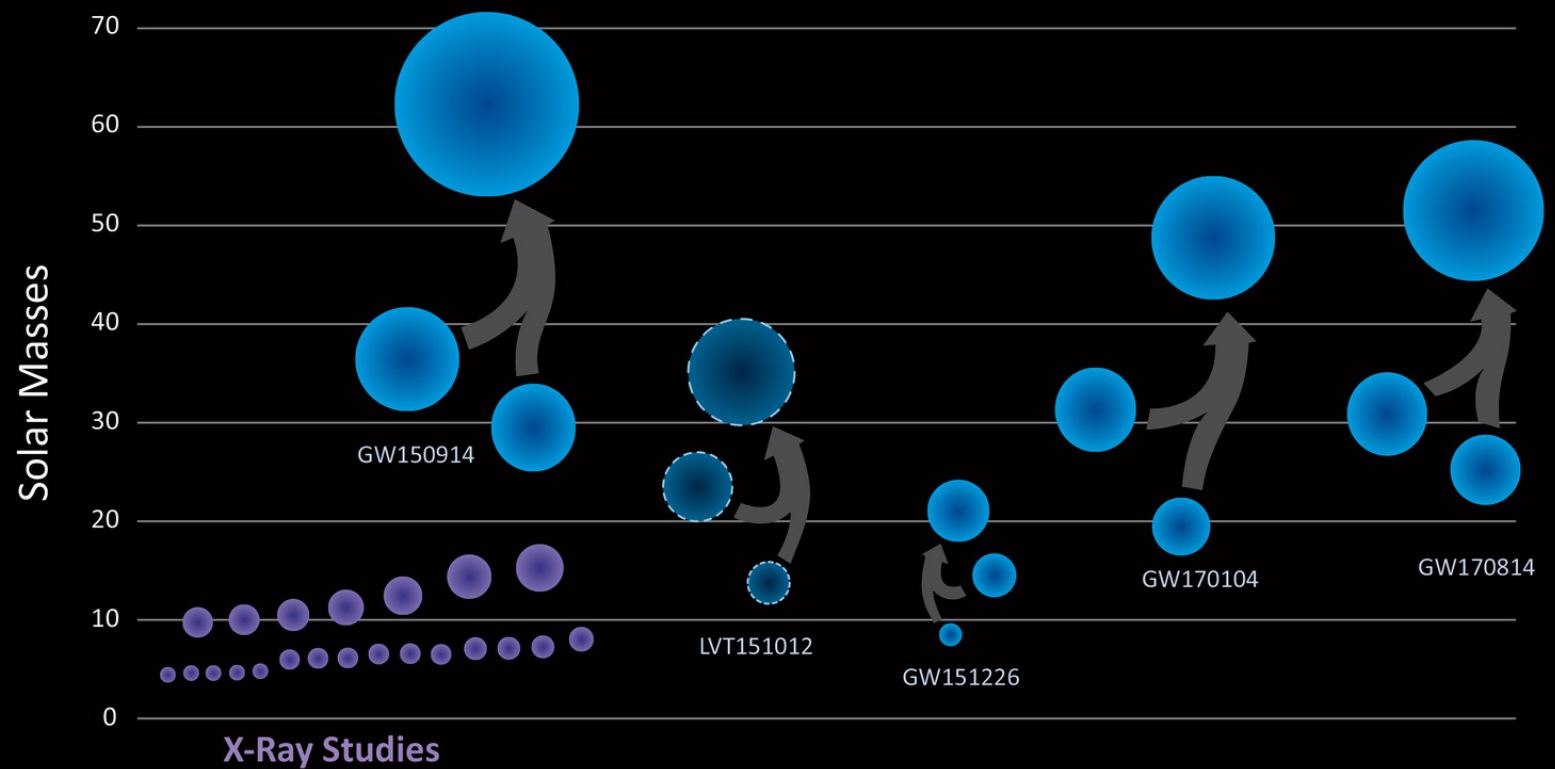
LIGO = Laser interferometer GW observatory



First direct detection of GWs (2015)
Merger of two 30 solar mass BHs



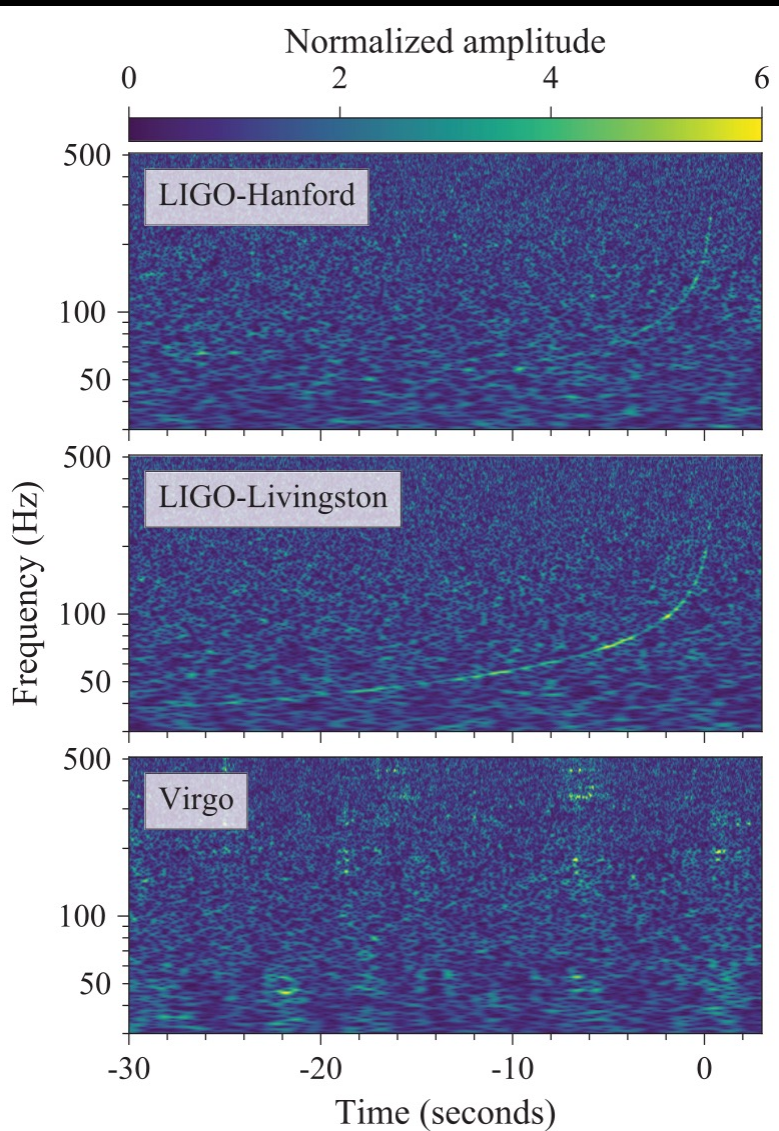
Black Holes of Known Mass



LIGO/VIRGO

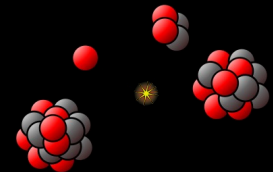
GW170817 — A Multimessenger Rosetta Stone

Breakthrough of the Year 2017 -- Science



Merger of two neutron stars (NS + NS)

- GWs detected first
- *Short gamma ray burst* (< 1 sec)
- Optical detection + rest of EM spectrum
- Initial state: heavy NS $\rightarrow$ black hole
- Neutron-rich material $\rightarrow$ heavy elements
- **Kilonova** driven by radioactive decay of heavy elements (r-process)
- 16k Earth masses of heavy elements formed
- **10 Earth masses worth of gold and platinum**





2017
BREAKTHROUGH
of the YEAR

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

ANATOMY OF A
KILONOVA

Aftermath of
the merger
between two
neutron stars

PAGES 36, 64, 67, 71,
75, 80 & 85

HEALTH
**LESSONS FROM
SILICON VALLEY**
Former funder seeks tech
disruption for biomedicine
PAGE 23

MOLECULAR ECOLOGY
**EVOLUTION
IN ACTION**
Tracing mutations in 60,000
generations of bacteria
PAGES 42 & 45

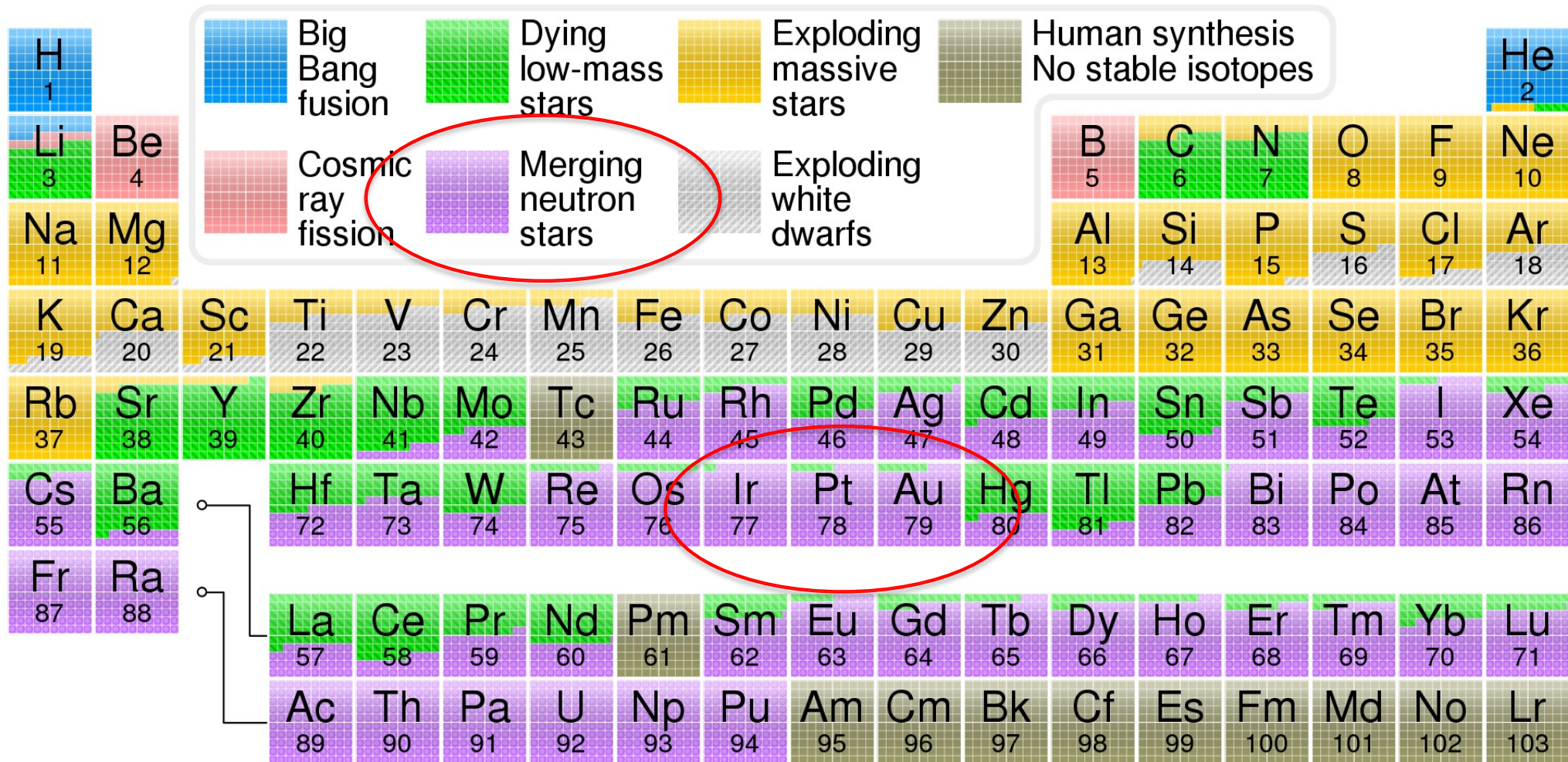
GENOMICS
**CHROMOSOME
COMPLEXITY**
Two mechanisms that guide
3D structure of the genome
PAGES 30 & 51

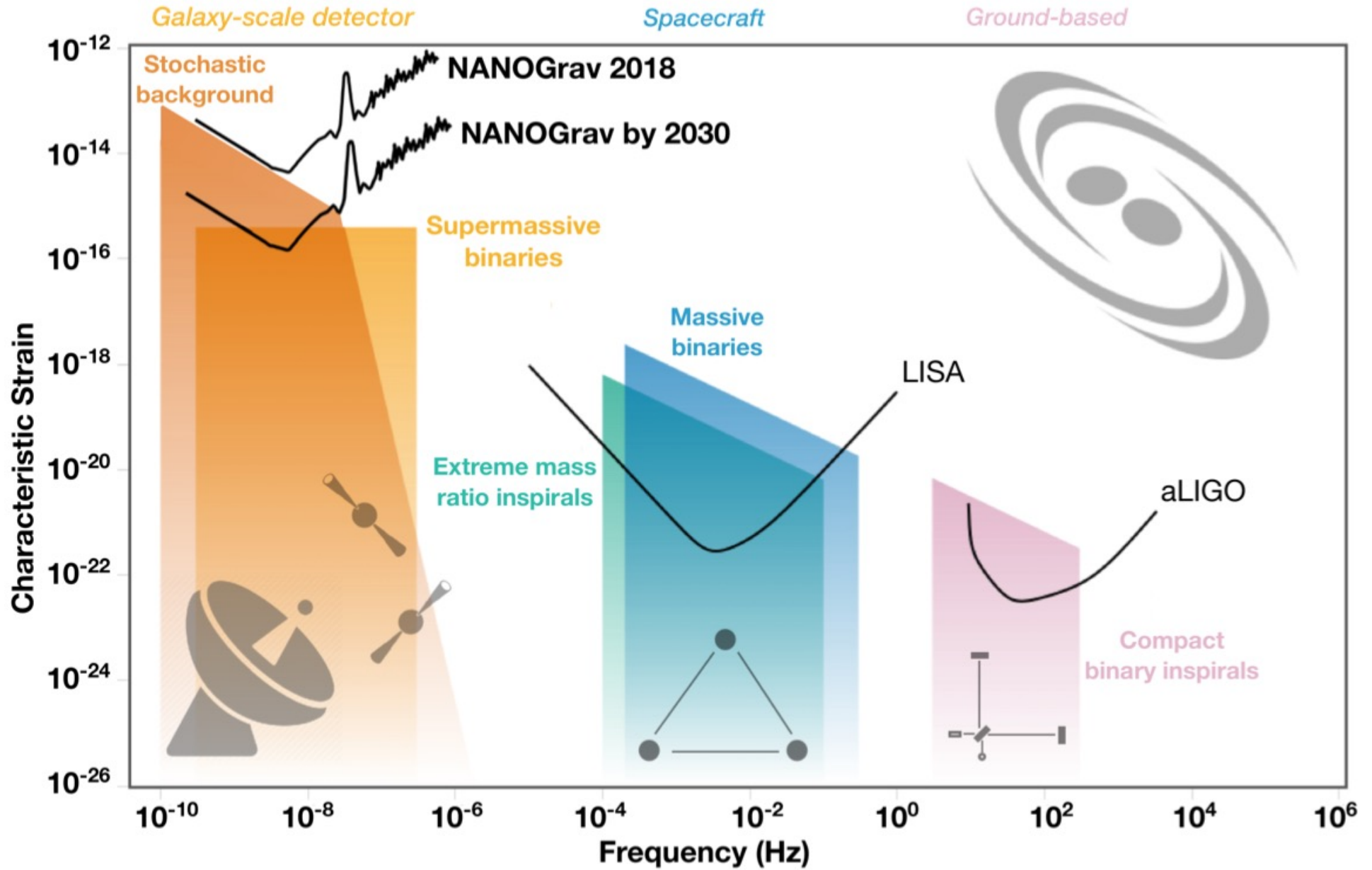
NATURE.COM/NATURE
2 November 2017 \$10
Vol. 551, No. 7678



Origin of the elements

Our gold rings came from mergers of neutron stars





**Supermassive
Black Hole Binary
in distant galaxy**

**Gravitational Waves
imprinted on
spacetime**

**Millisecond
Pulsars
in Pulsar Timing Array**

A deep space photograph showing two large spiral galaxies, NGC 5427 and NGC 5426, in the process of colliding. The galaxies are tilted towards each other, with their spiral arms beginning to interact and pull towards the centers. The background is a dark field filled with numerous smaller, distant stars and galaxies.

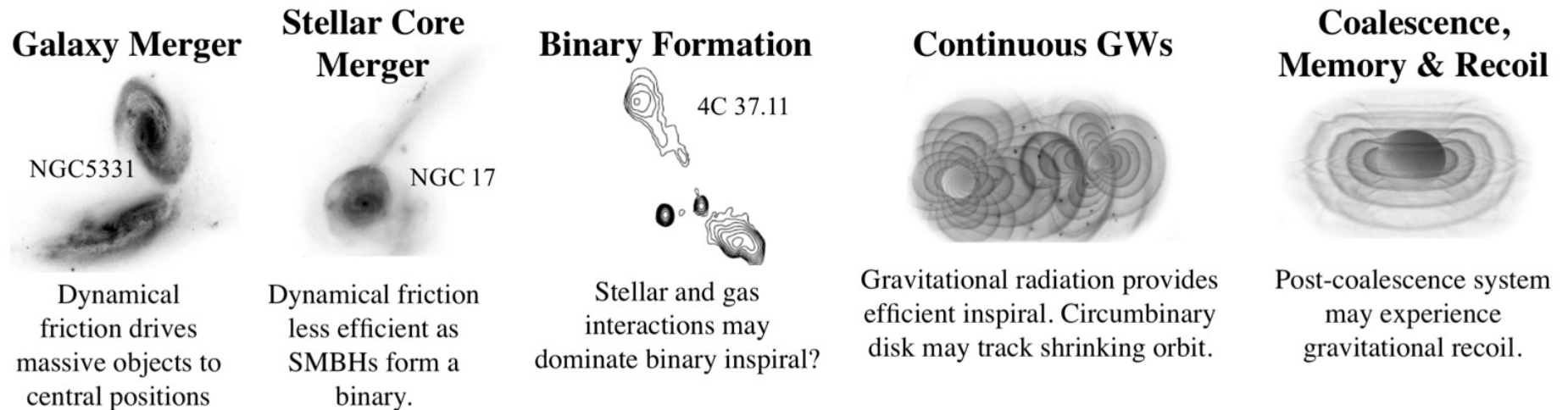
Colliding galaxies NGC 5427 and NGC 5426

Their central black holes
will form a binary and
eventually merge

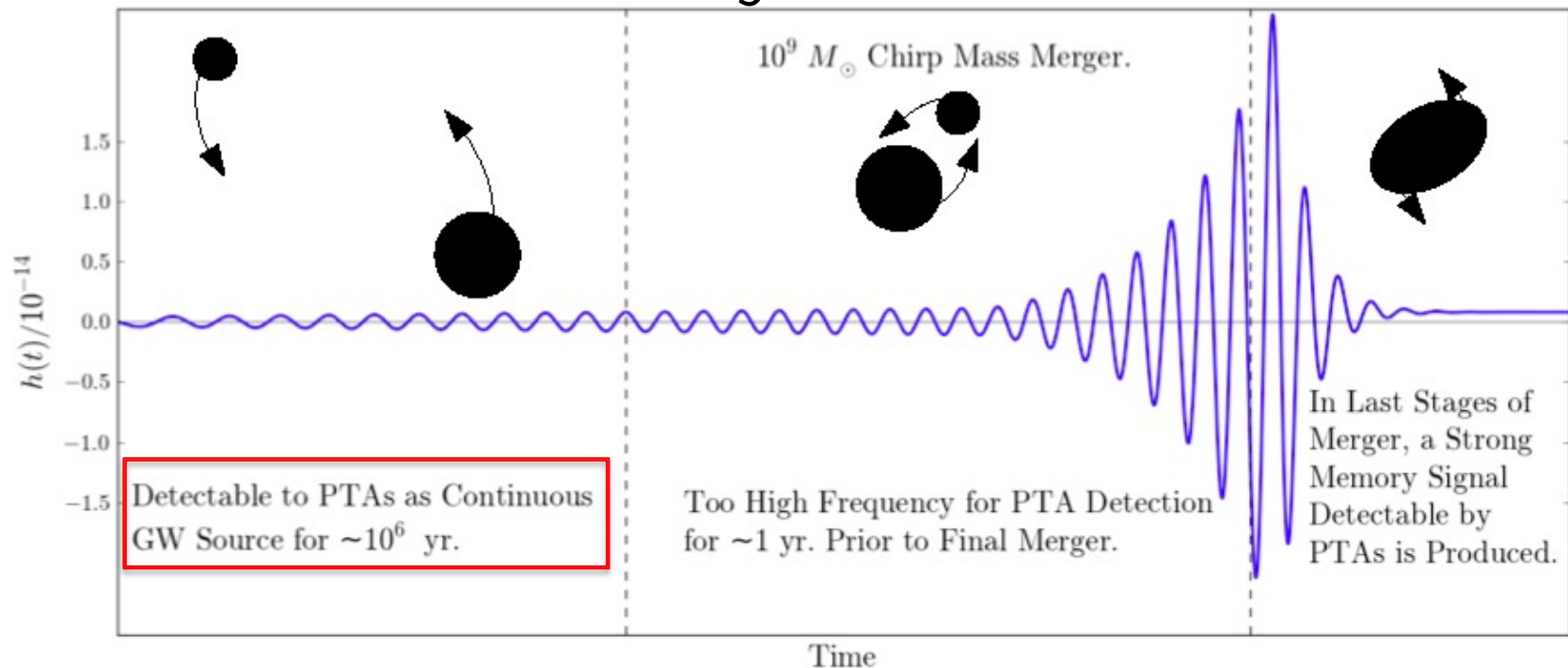
Andromeda and the
Milky Way will collide
eventually

[a few Gyr from now]

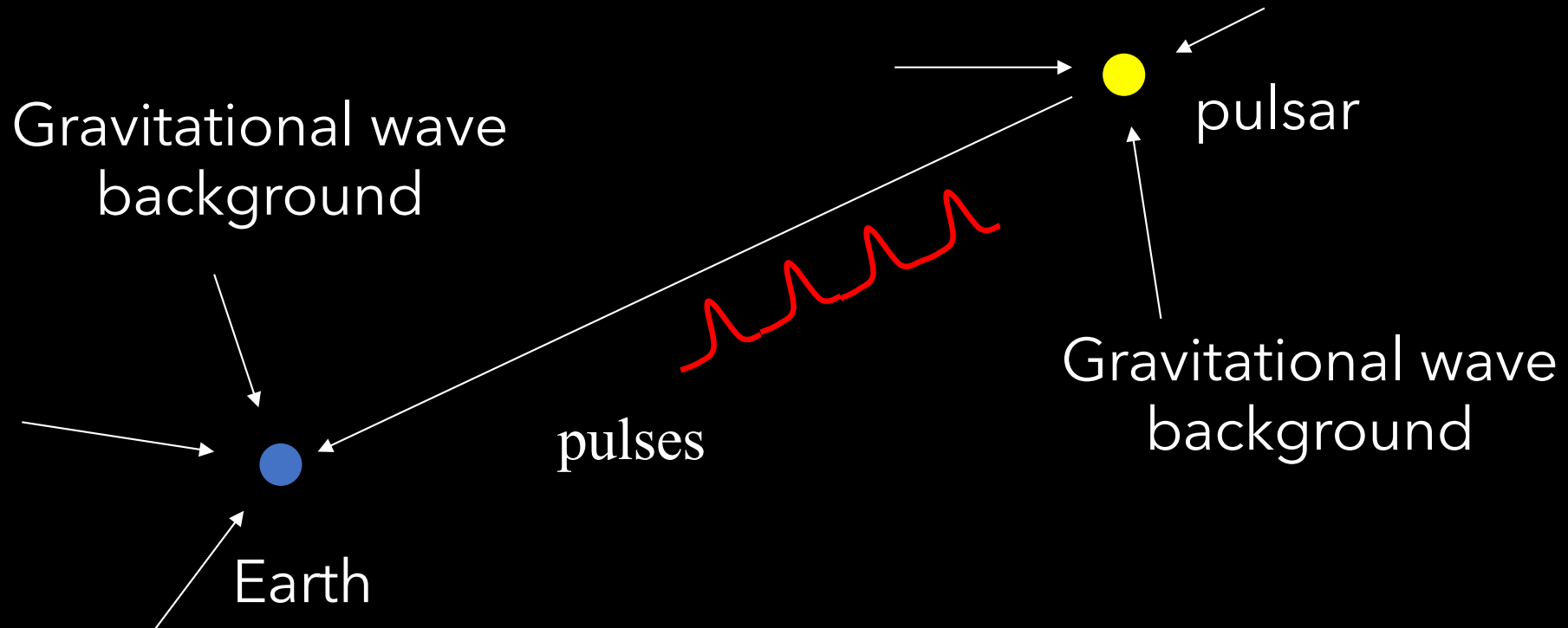
From galaxy mergers to supermassive blackhole binary inspirals



PTA Signal Detection

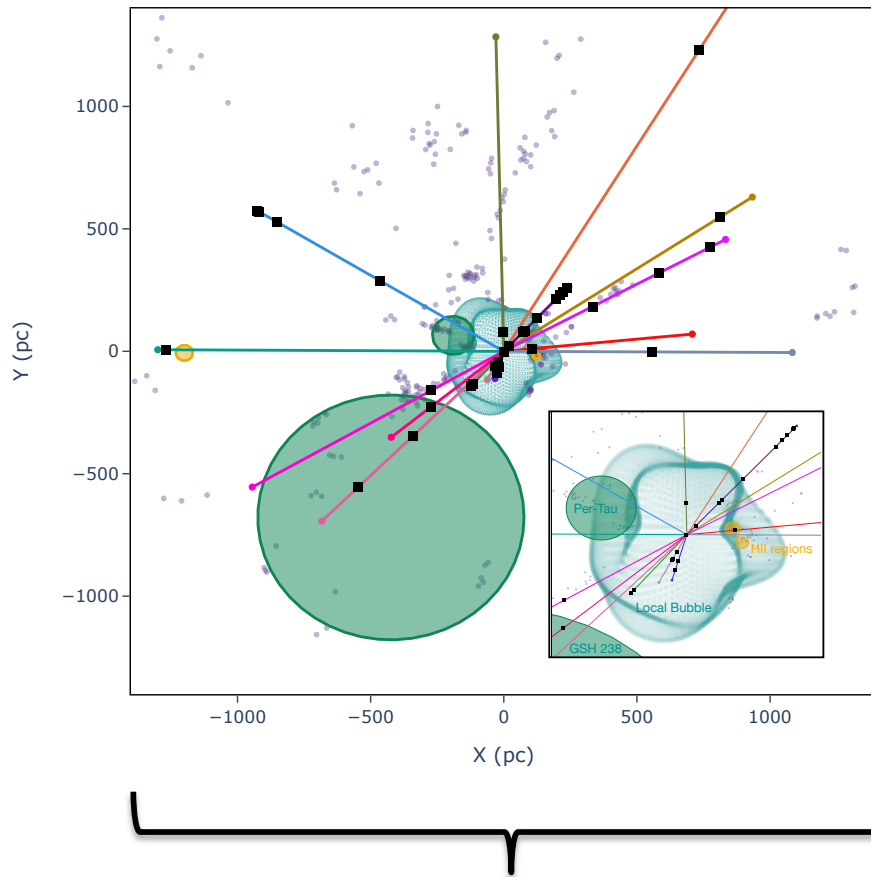


Pulsars as Gravitational Wave Detectors



The entire universe is filled
with gravitational waves

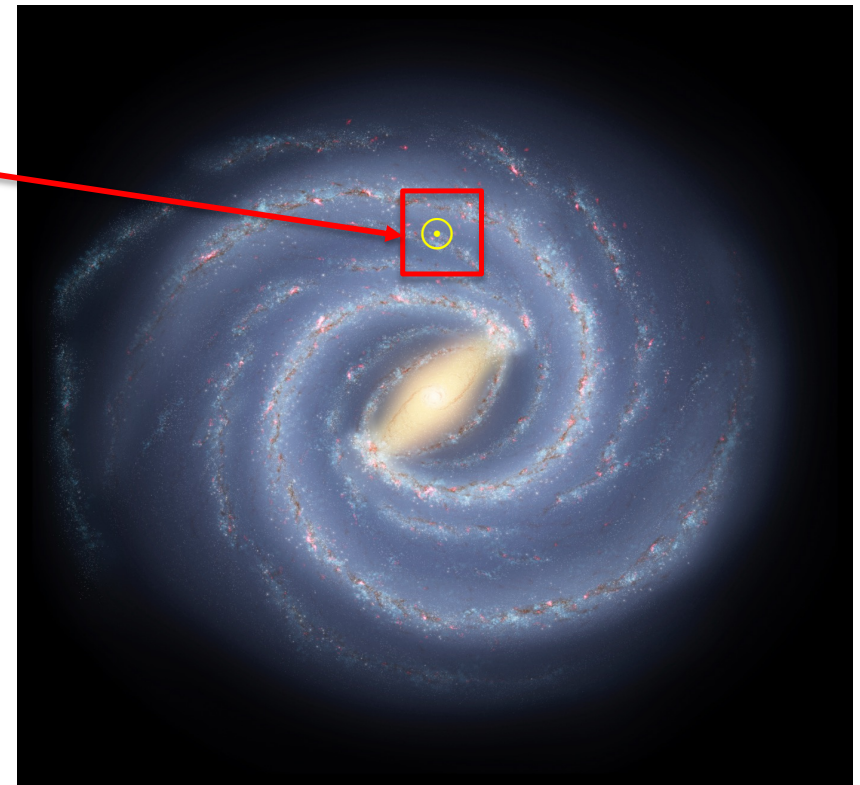
The NANOGrav pulsar gravitational wave detector



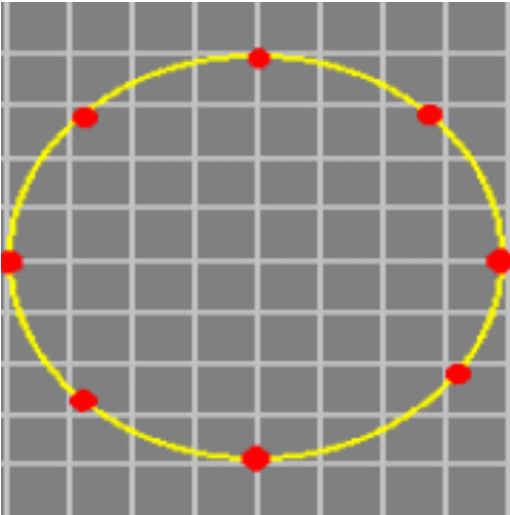
~10,000 light years

The solar system is bathed in gravitational waves

Pulses from all pulsars are affected similarly



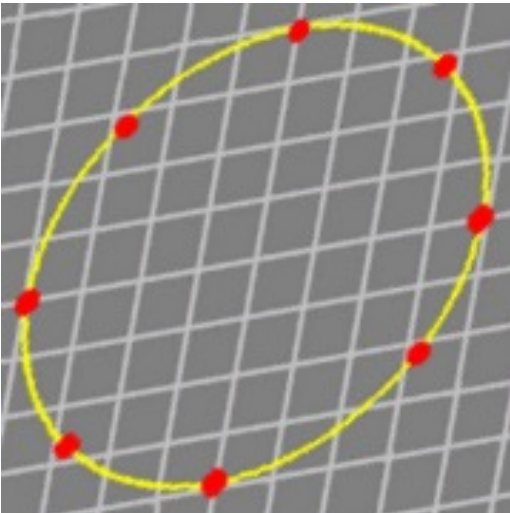
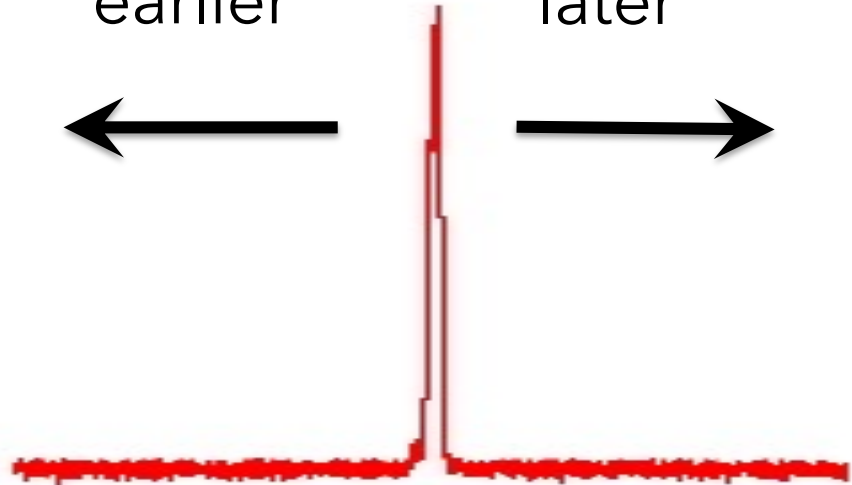
Gravitational wave effect on pulsar timing



**Pulses arrive earlier for $\frac{1}{2}$ cycle
and later for the other $\frac{1}{2}$ cycle**

earlier later

← →



Mission impossible?
About 100 ns over a 15 yr period

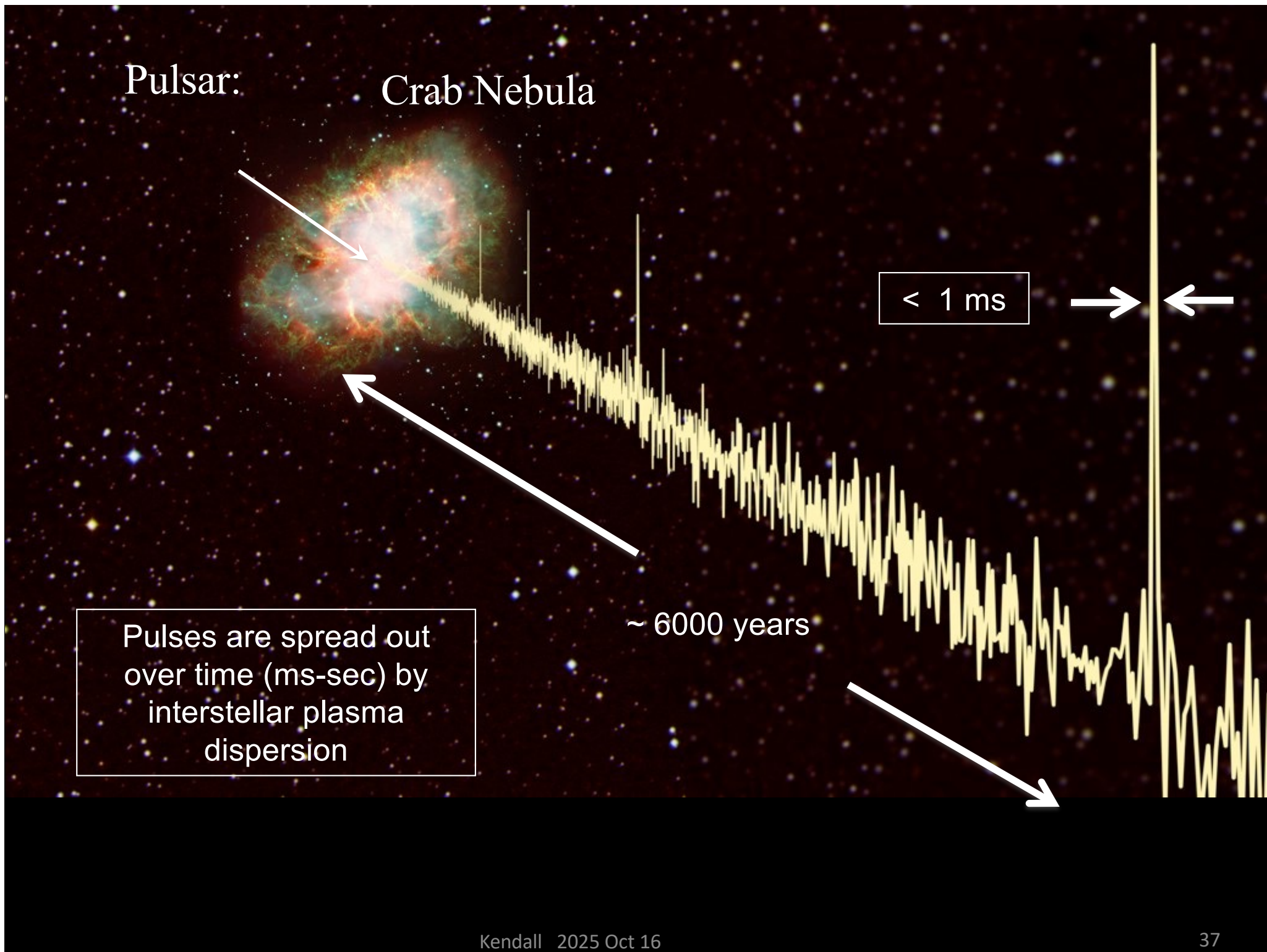
Pulsar:

Crab Nebula

$< 1 \text{ ms}$

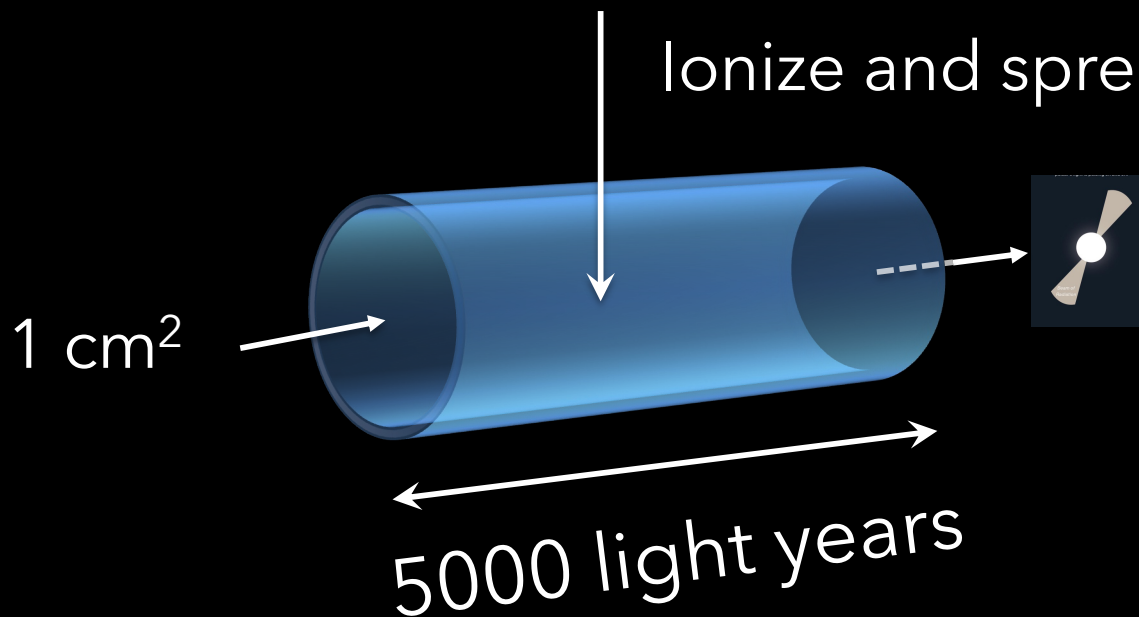
Pulses are spread out
over time (ms-sec) by
interstellar plasma
dispersion

$\sim 6000 \text{ years}$





Drop of water ~ 0.05 g
 $\sim 1.7 \times 10^{21}$ molecules

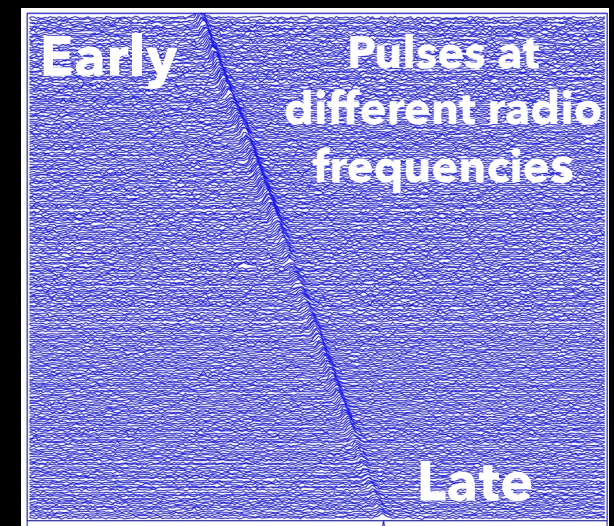


Ionize and spread over cylinder

Causes an **easily**
measured effect
(dispersion)

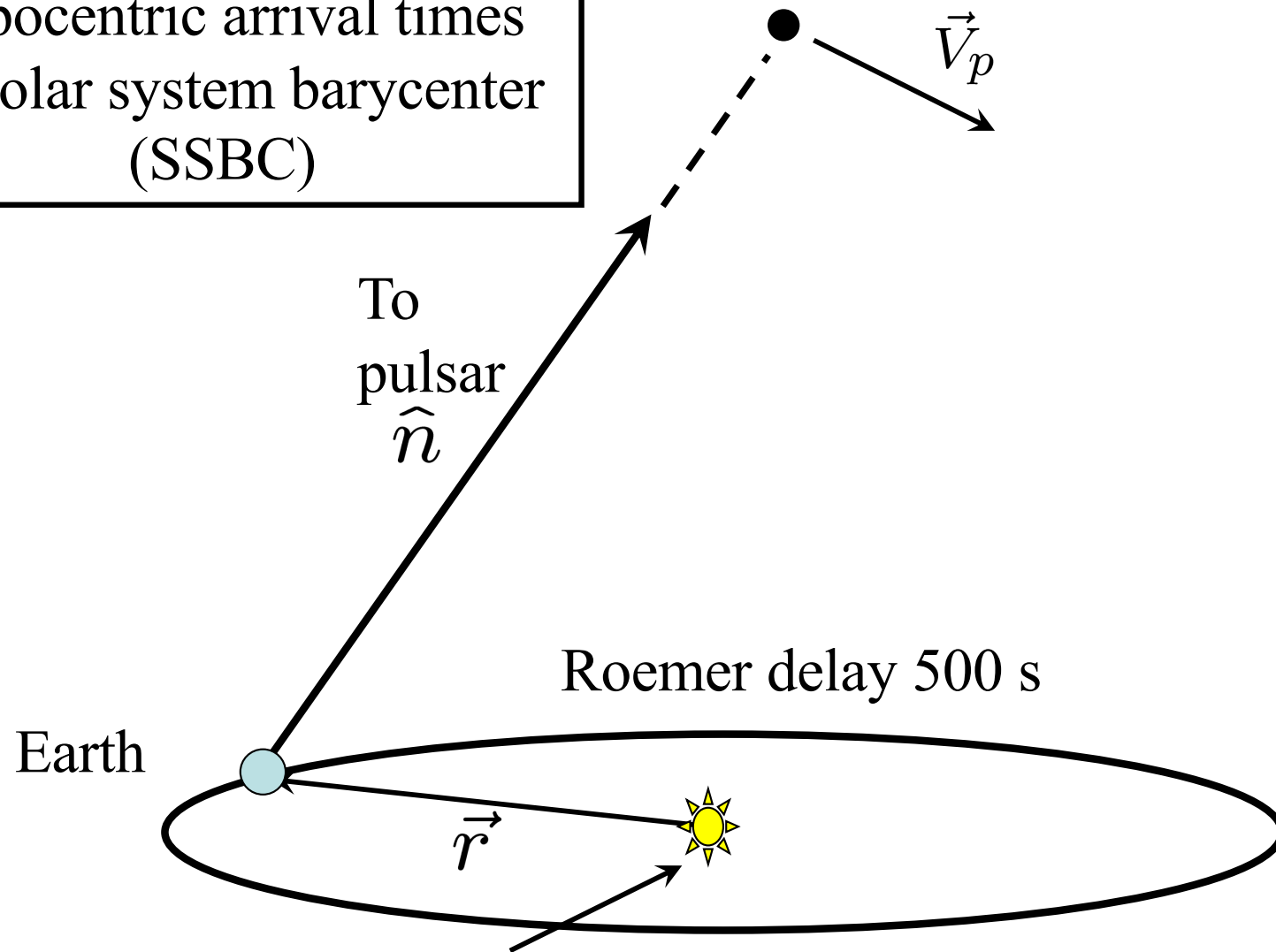
Measurements are sensitive
enough to measure 1
millionth of a drop of ionized
water in this way

Frequency
 $\leftarrow 100 \text{ MHz} \rightarrow$



Time
 $\leftarrow 1 \text{ sec} \rightarrow$

Topocentric arrival times
→ solar system barycenter
(SSBC)



Solar system barycenter is near the sun's photosphere

Known to up to ~ 100 ns

JPL Ephemerides: DE421, DE430, DE435, DE436

https://en.wikipedia.org/wiki/Jet_Propulsion_Laboratory_Development_Ephemeris

NANOGrav Announcement 2023 July

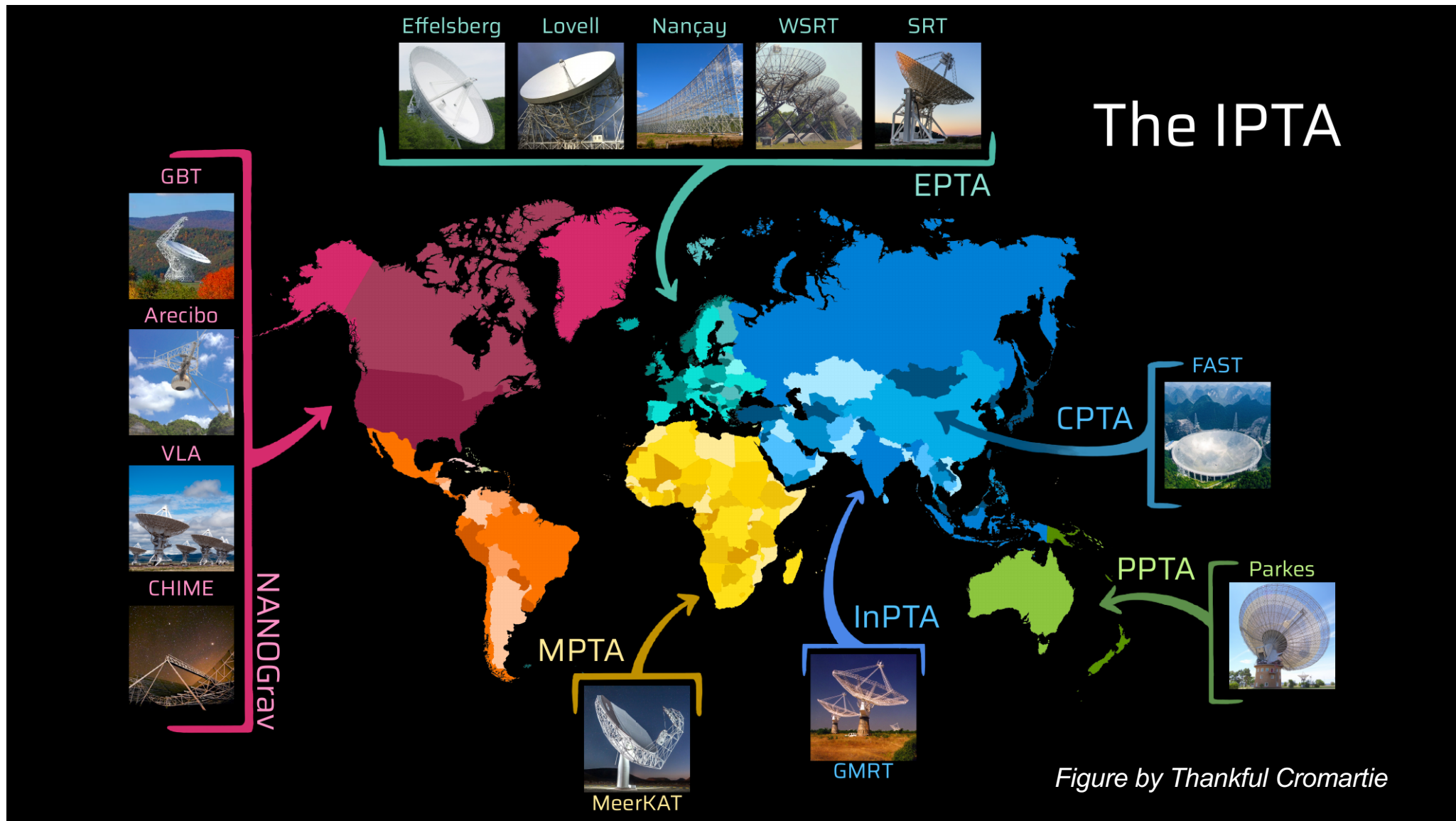
Based on the NANOGrav 15 yr Data Set

Coordinated with overseas groups: Australia, China, Europe, India

Five papers

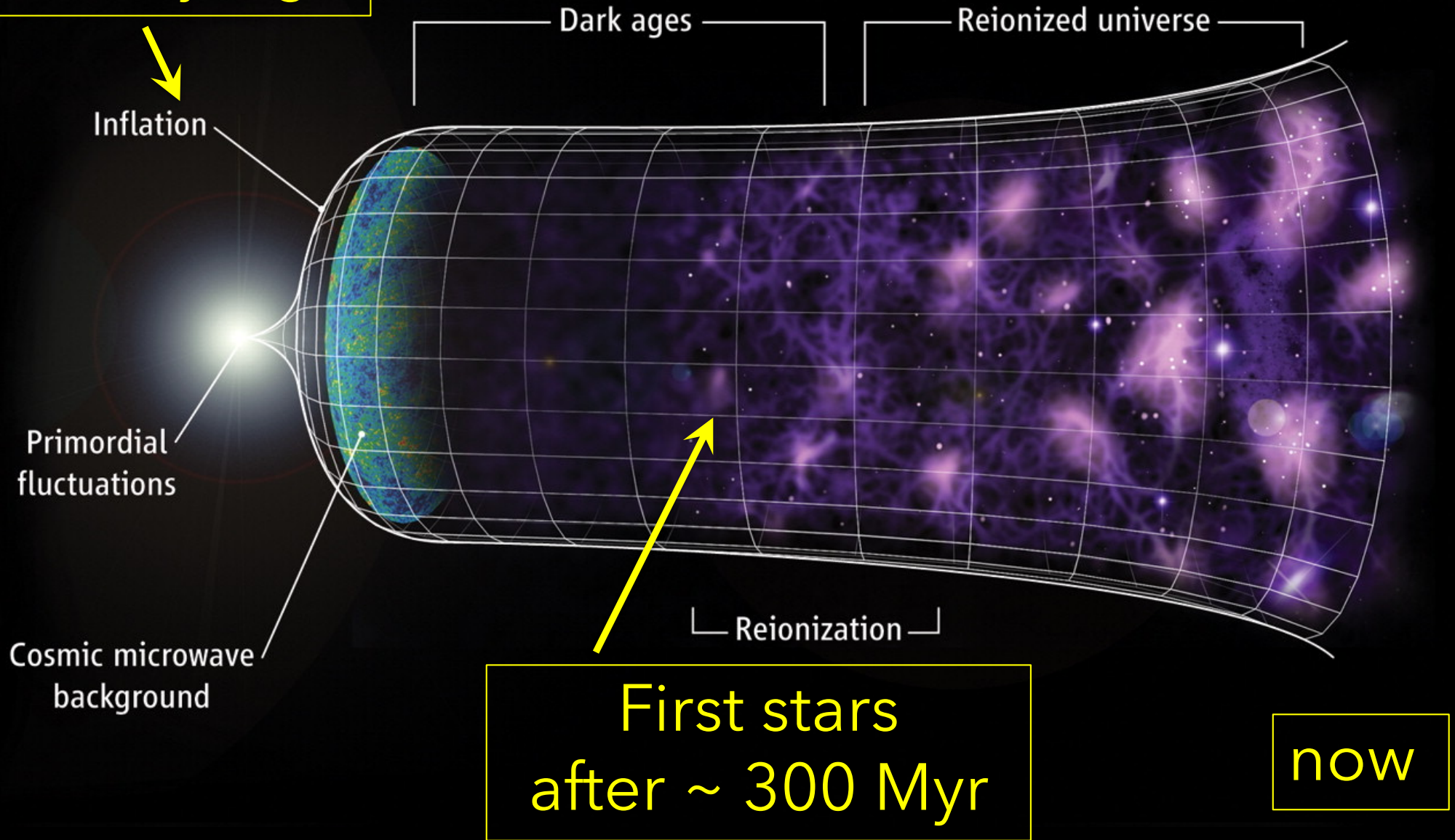
Astrophysical Journal Letters + press event at the NSF

- *Evidence for a Gravitational-wave Background*
 - *Observations and Timing of 68 Millisecond Pulsars*
 - *Detector Characterization and Noise Budget*
 - *Constraints on Supermassive Black Hole Binaries from the Gravitational-wave Background*
 - *Search for Signals from New Physics*



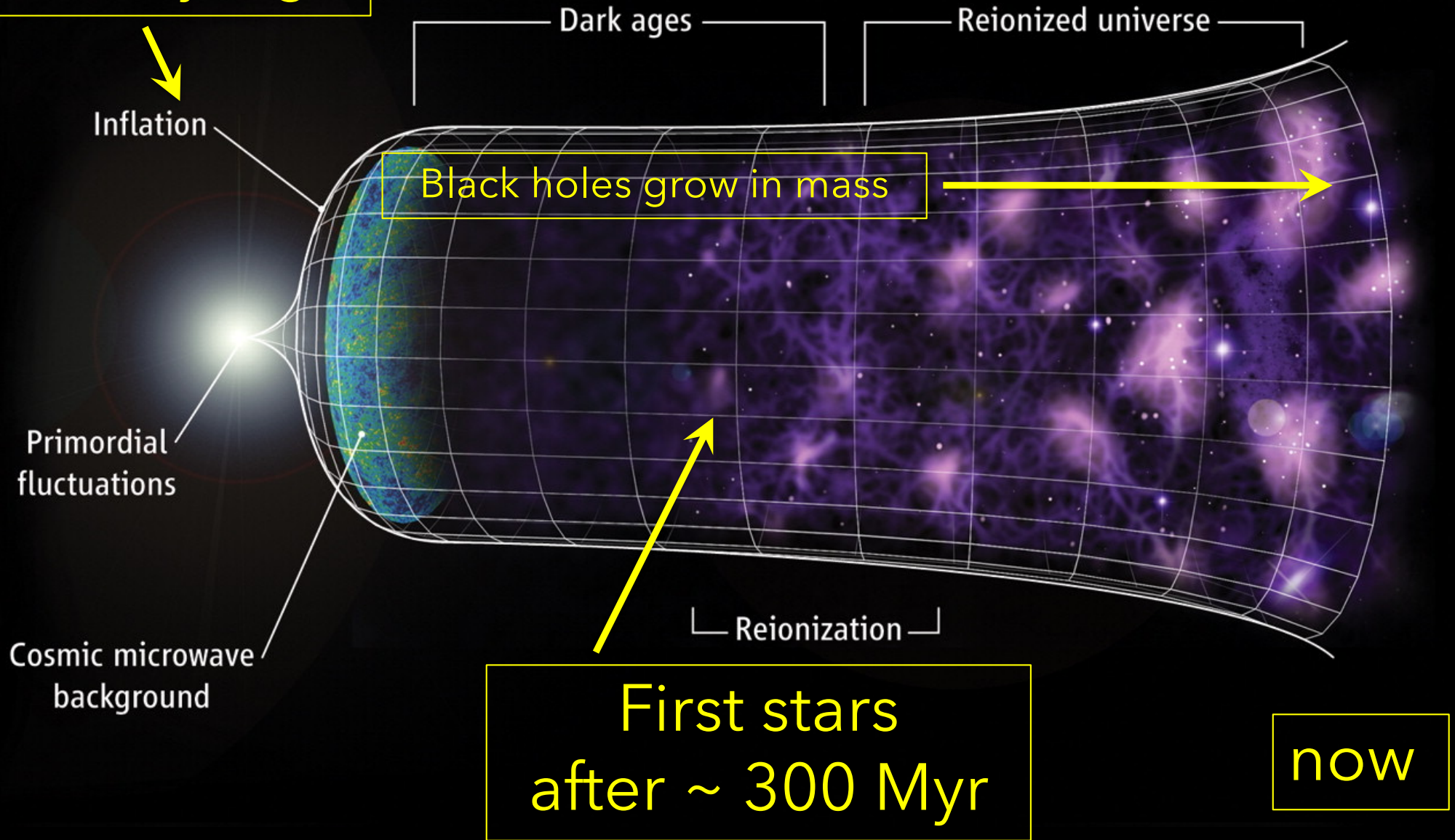
Goal: understand black-hole formation and evolution over cosmic time

13.7 Gyr ago



Goal: understand black-hole formation and evolution over cosmic time

13.7 Gyr ago



Next step for NANOGrav = next generation telescope



DSA-2000: A Radio Survey Camera
First light ~ 2028-2029

Site in
Nevada

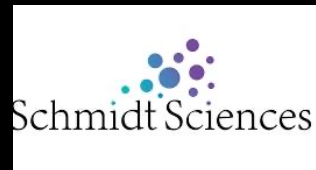
FDR
2026

Antenna development funded by Schmidt Sciences

2000 x 5m dishes (0.7 – 2 GHz) spanning 15 x 19 km
Will survey 34,000 deg² to 500 nJy/beam (plus intermediate and deep tiers)

**Principal instrument for the North American pulsar timing array
community (NANOGrav) [200 MSPs]**

Caltech



The end

Extra slides

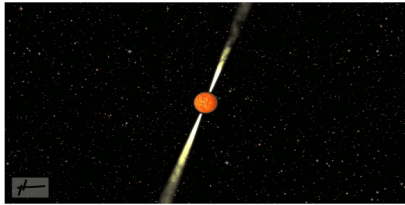


Animation of black hole merger

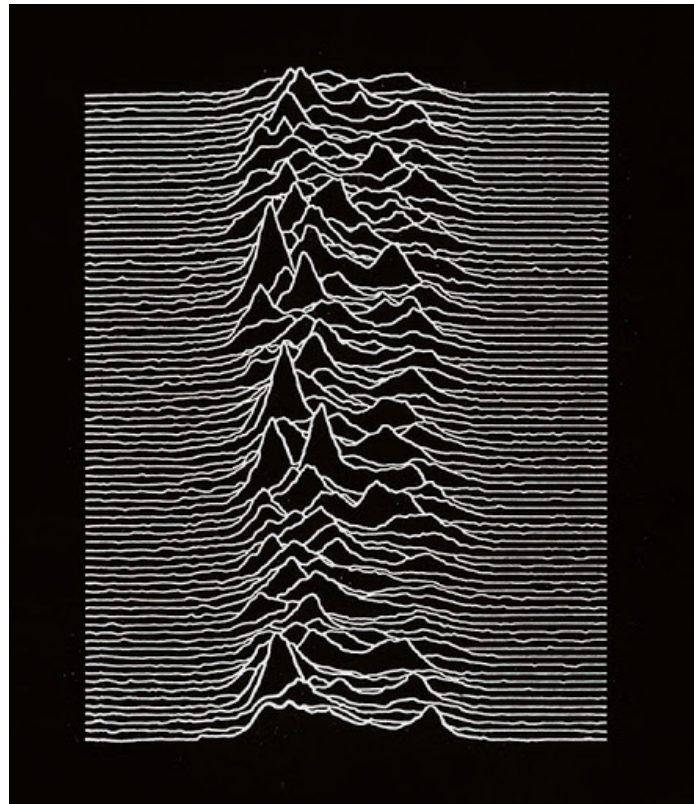
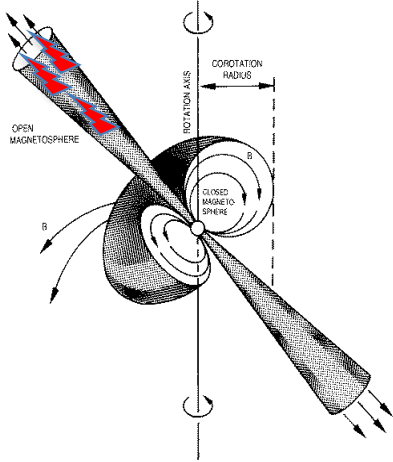


https://youtu.be/I_88S8DWbcU

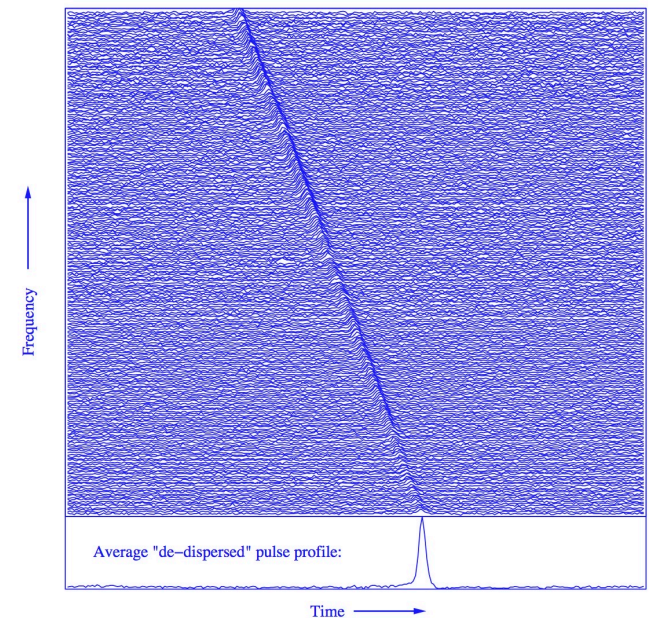
Pulsars are ideal probes of interstellar plasma



Individual pulses
(Hal Craft 1970 thesis)



Pulses affected by
index of refraction of
interstellar medium



$\delta\text{DM}(t)$

$R(t)$

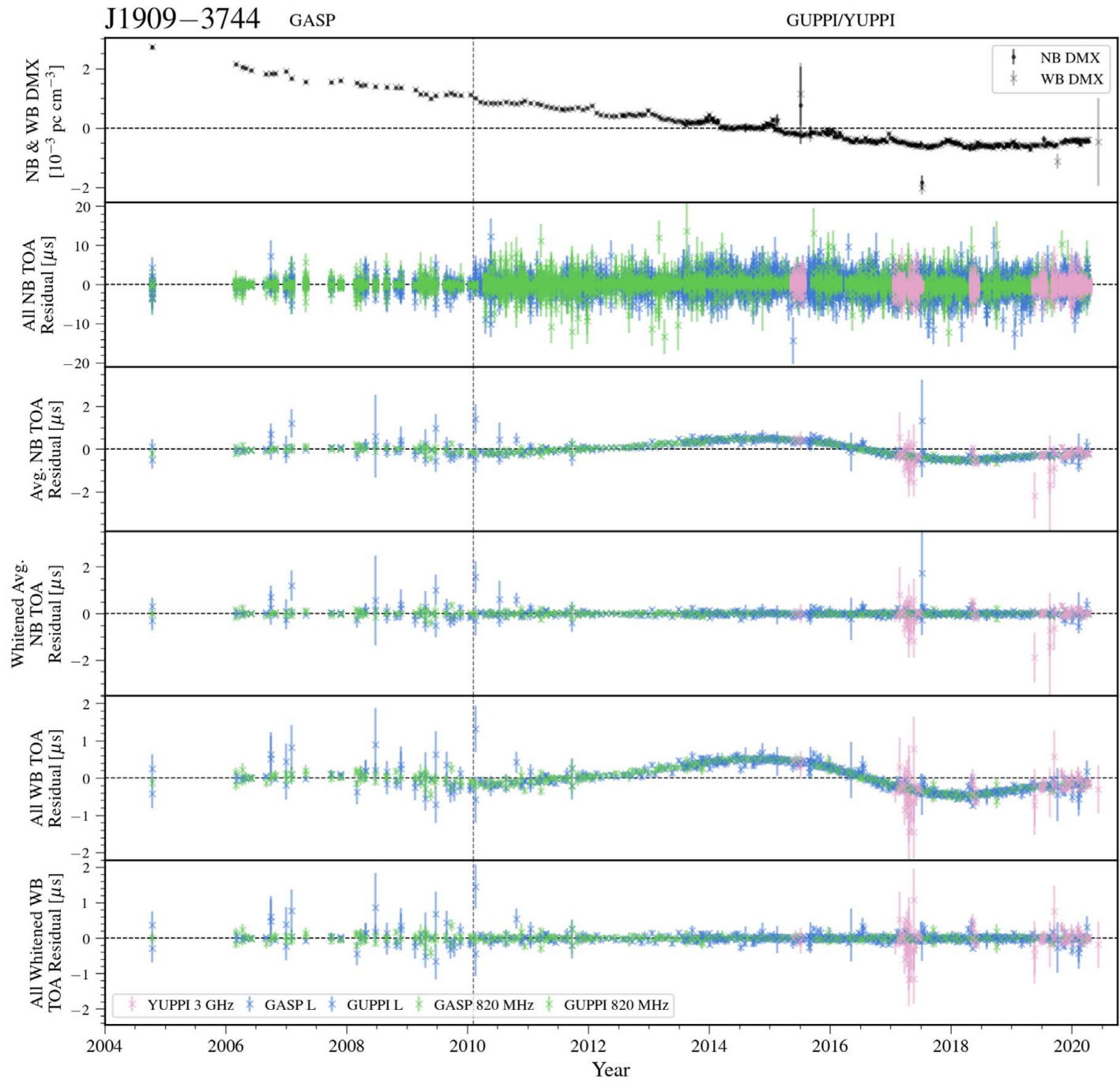


Figure 53. Narrowband and wideband timing residuals and DMX time series for J1909-3744. See Figure 8 for details.

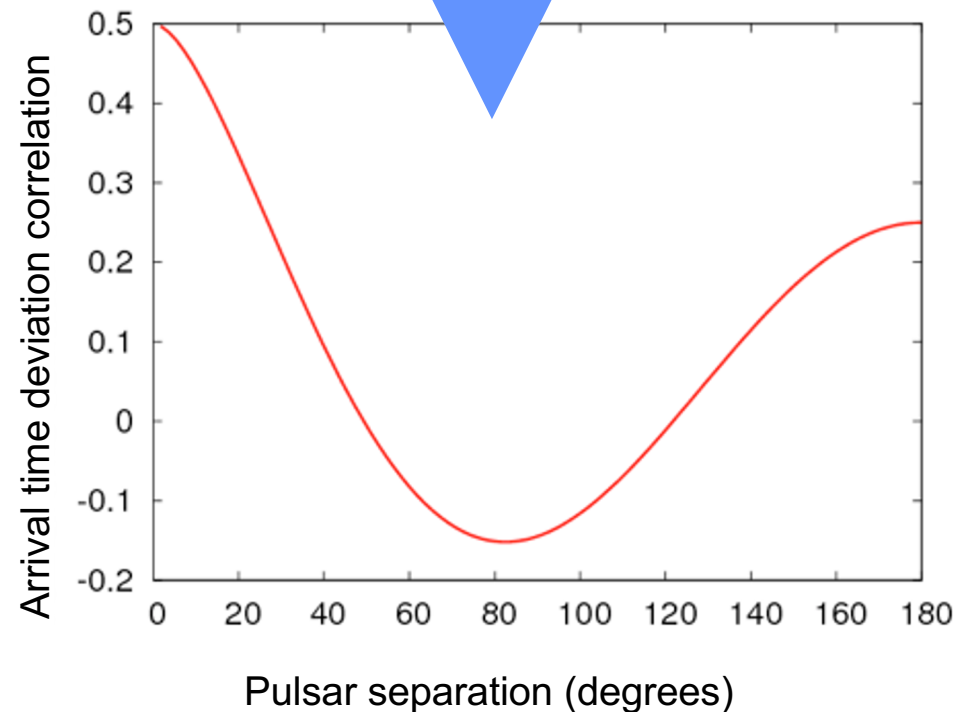
A Galactic-scale GW detector: The Pulsar Timing Array

GW perturbations are correlated among different pulsars.

This quadrupolar correlated signature is predicted exactly from General Relativity.



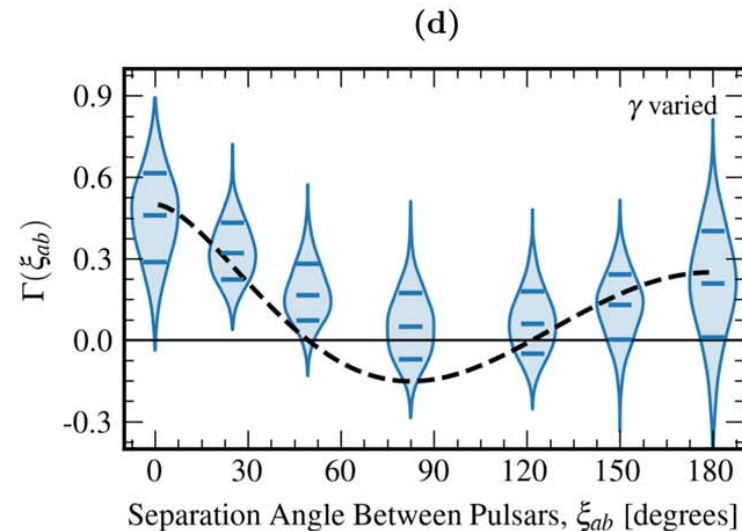
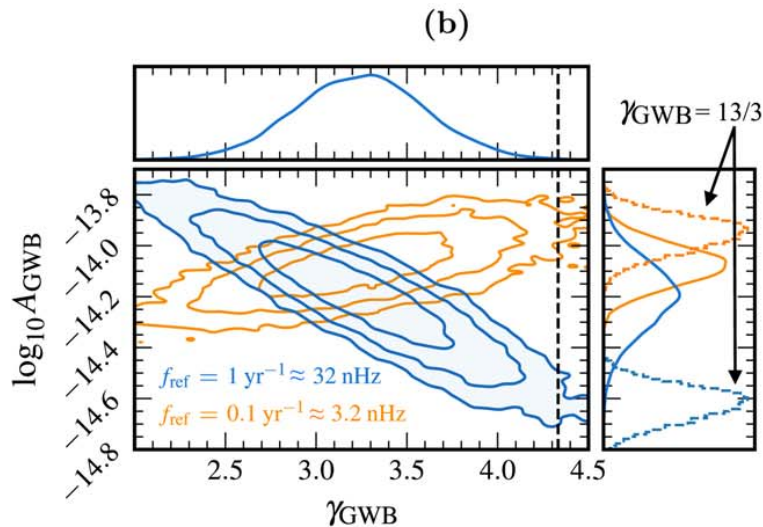
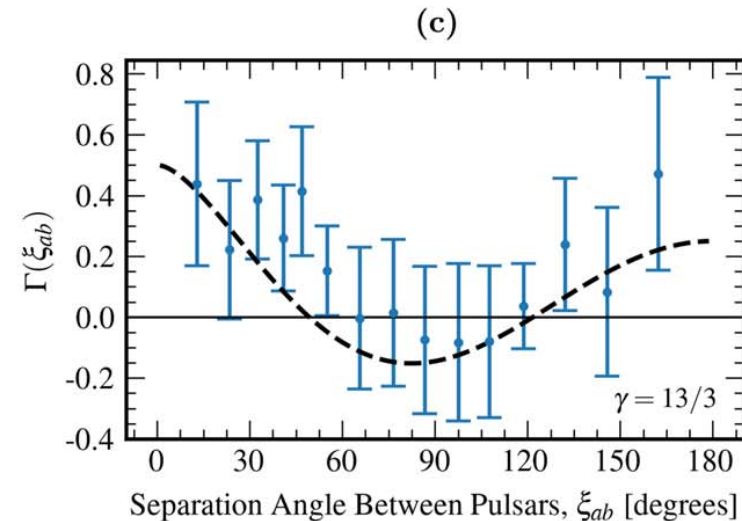
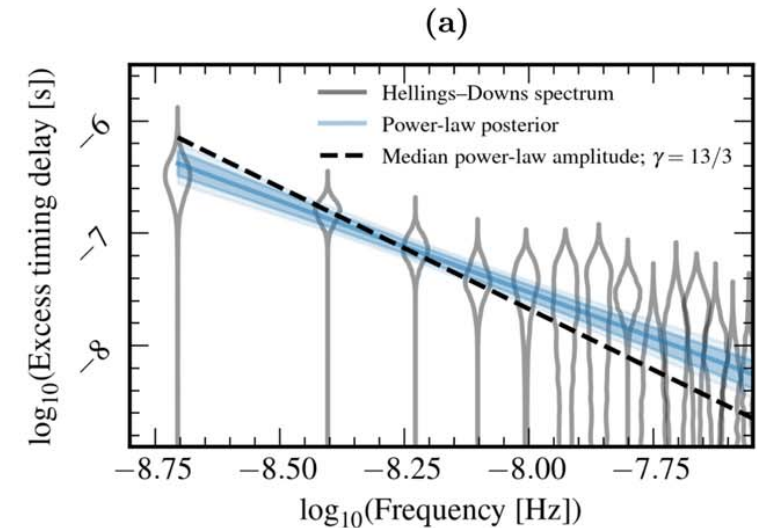
We observe an ensemble of MSPs to extract the correlated signal from the noise.



Evidence for the stochastic background

Spectrum of GW timing signal
 Δt_{gw}

Correlation of Δt_{gw} between
pulsars vs. angular separation



The original idea concerned effects of GWs on spacecraft uplink/downlink signals

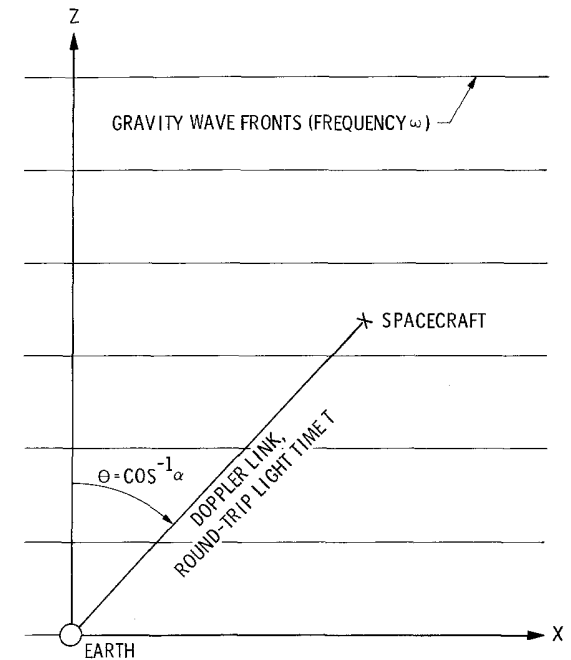
GRG Vol.6, No.5 (1975), pp. 439 - 447.

RESPONSE OF DOPPLER SPACECRAFT TRACKING TO GRAVITATIONAL RADIATION†

FRANK B. ESTABROOK and HUGO D. WAHLQUIST

*Jet Propulsion Laboratory,
California Institute of Technology,
Pasadena, California 91103*

Revised version received 16 January 1975



ABSTRACT

A calculation is made of the effect of gravity waves on the observed Doppler shift of a sinusoidal electromagnetic signal transmitted to, and transponded from, a distant spacecraft. We find that the effect of plane gravity waves on such observations is not intuitively immediate and in fact can have surprisingly different spectral signatures for different spacecraft directions and distances. We suggest the possibility of detecting such plane waves by simultaneous coherent Doppler tracking of several spacecraft.

PULSAR TIMING MEASUREMENTS AND THE SEARCH FOR GRAVITATIONAL WAVES

STEVEN DETWEILER

1979 ApJ

Sazhin 1978

Department of Physics, Yale University

Received 1979 June 4; accepted 1979 July 6

large $h(t)$!

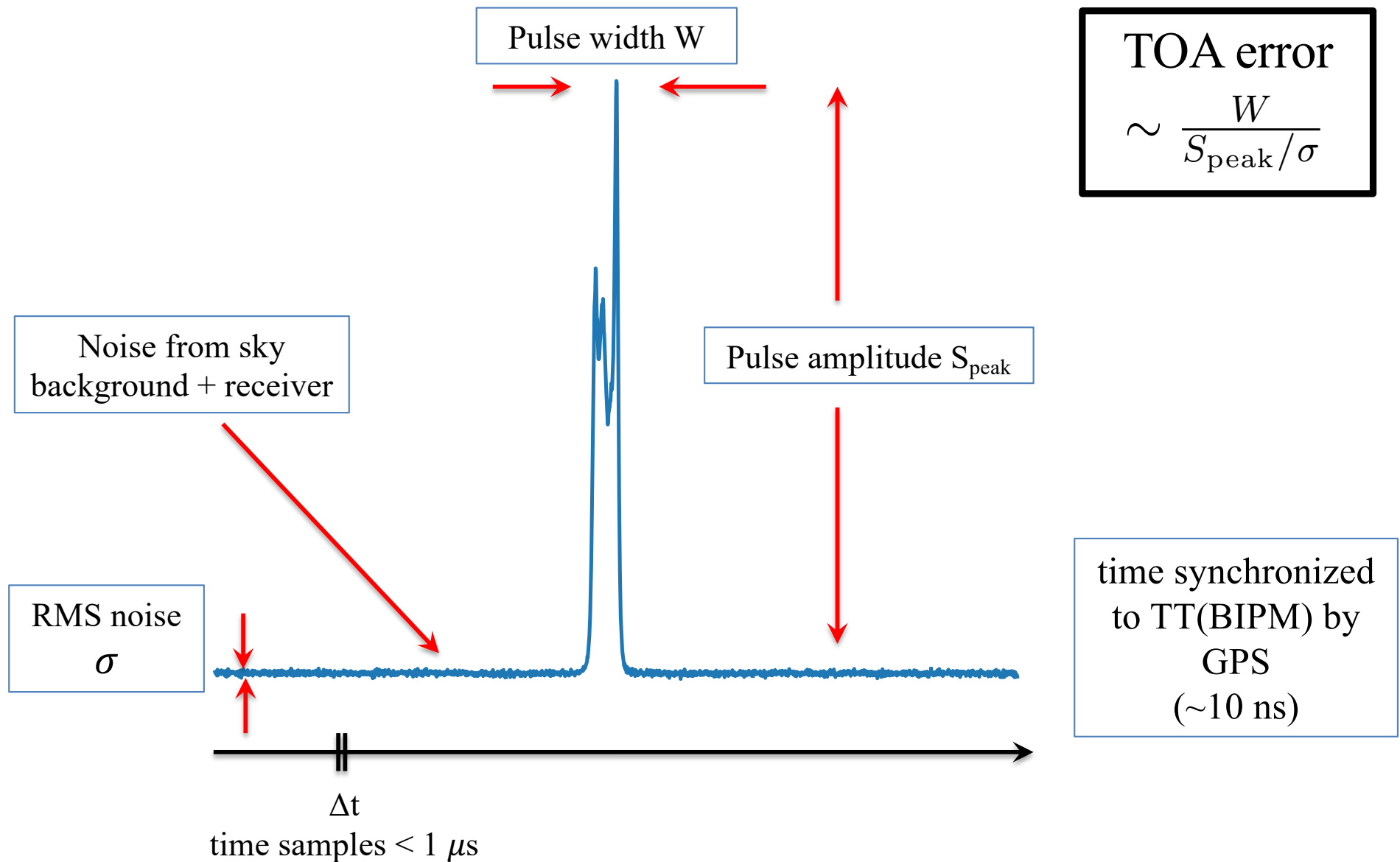
ABSTRACT

Pulse arrival time measurements of pulsars may be used to search for gravitational waves with periods on the order of 1 to 10 years and dimensionless amplitudes $\sim 10^{-11}$. The analysis of published data on pulsar regularity sets an upper limit to the energy density of a stochastic background of gravitational waves, with periods ~ 1 year, which is comparable to the closure density of the universe.

Subject headings: cosmology — gravitation — pulsars — relativity

- 1979: the fastest known pulsar was the Crab pulsar
 - $P = 33$ ms ... a lousy clock!
 - We measure the spin rate of the crust
 - The internal superfluid spins slightly faster
 - 'spin noise' is from crust-superfluid interactions
- 1982: Millisecond pulsars discovered
 - B1937+21 = 1.56 ms pulsar; much more spin stable (but still not good enough)
- Now: about 485 MSPs known (173 in globular clusters) with different spin qualities; some are excellent clocks

How well can a pulse arrival time be measured?



Difficulties of GW Detection $\Delta L/L \sim h$

Pulsar Timing Array

$$L \sim cT \sim 3 \text{ pc}$$

$$h_{\min} \sim 10^{-16} - 10^{-14}$$

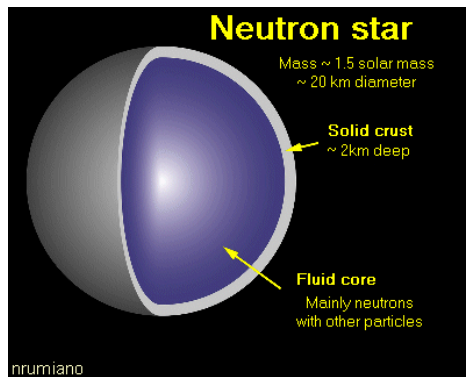
$$\Delta L \sim 10^3 \text{ to } 10^5 \text{ cm}$$

Ground-based Interferometer

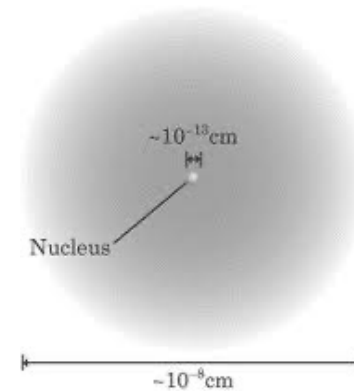
$$L \sim 4 \text{ km} \times 50 \text{ reflections}$$

$$h_{\min} \sim 10^{-23}$$

$$\Delta L \sim 10^{-16} \text{ cm}$$



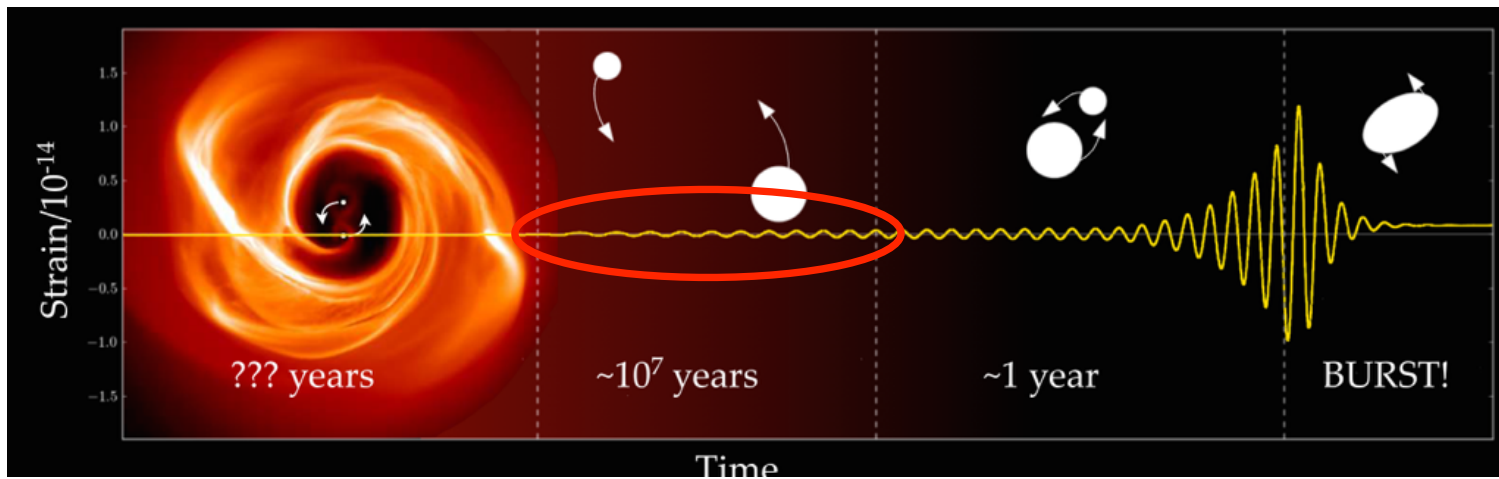
$$10^{-3} R_{\text{NS}}$$



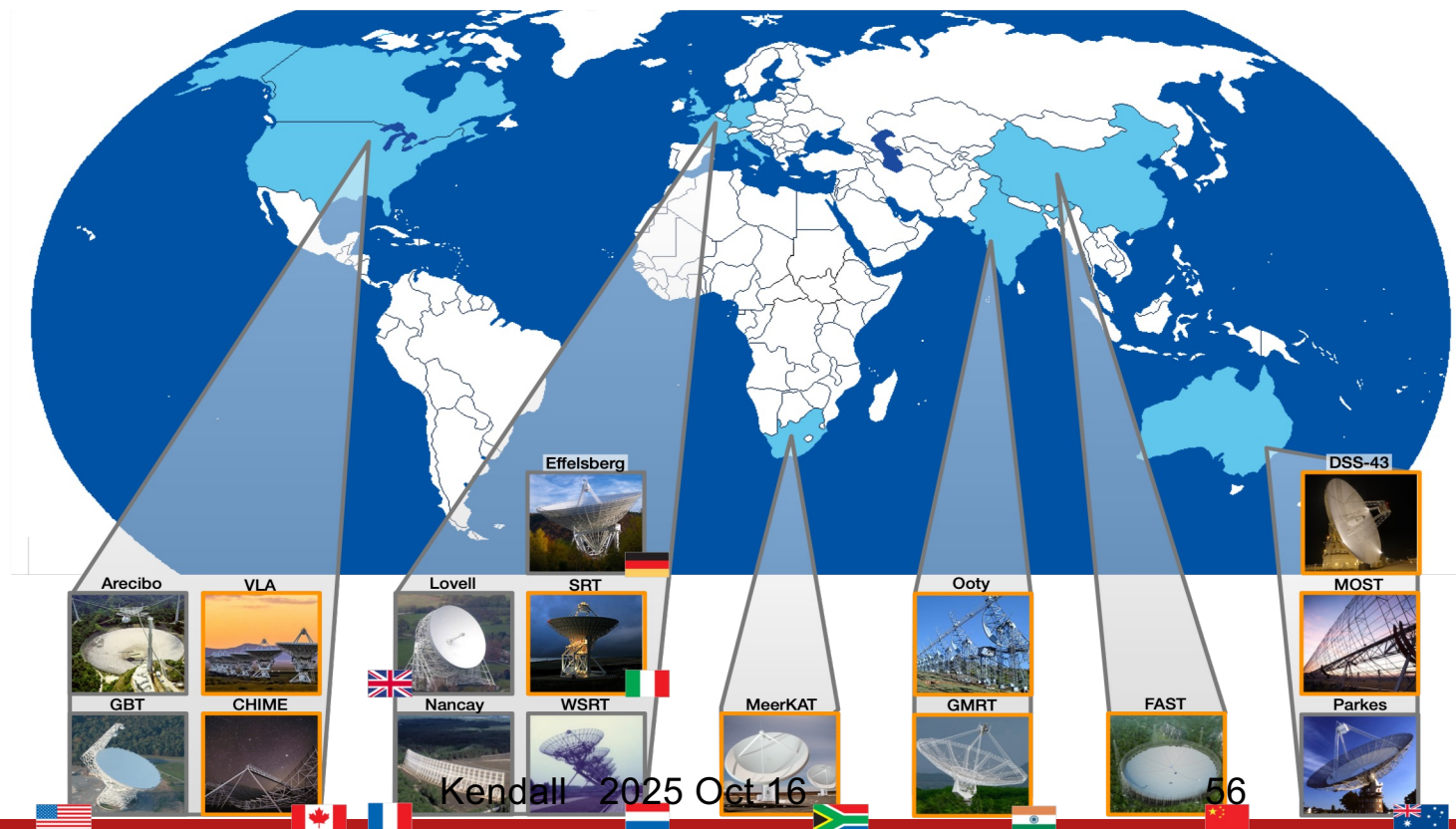
$$10^{-3} R_{\text{nucleus}}$$

PTA: δt includes:

- Translational motion of the NS ~ 100 to 1000 km/s
- Orbital motions of the pulsar and observatory: $10\text{s} - 100\text{s}$ km/s
- Interstellar propagation delays: ns to seconds



Pulsar timing arrays: an international partnership

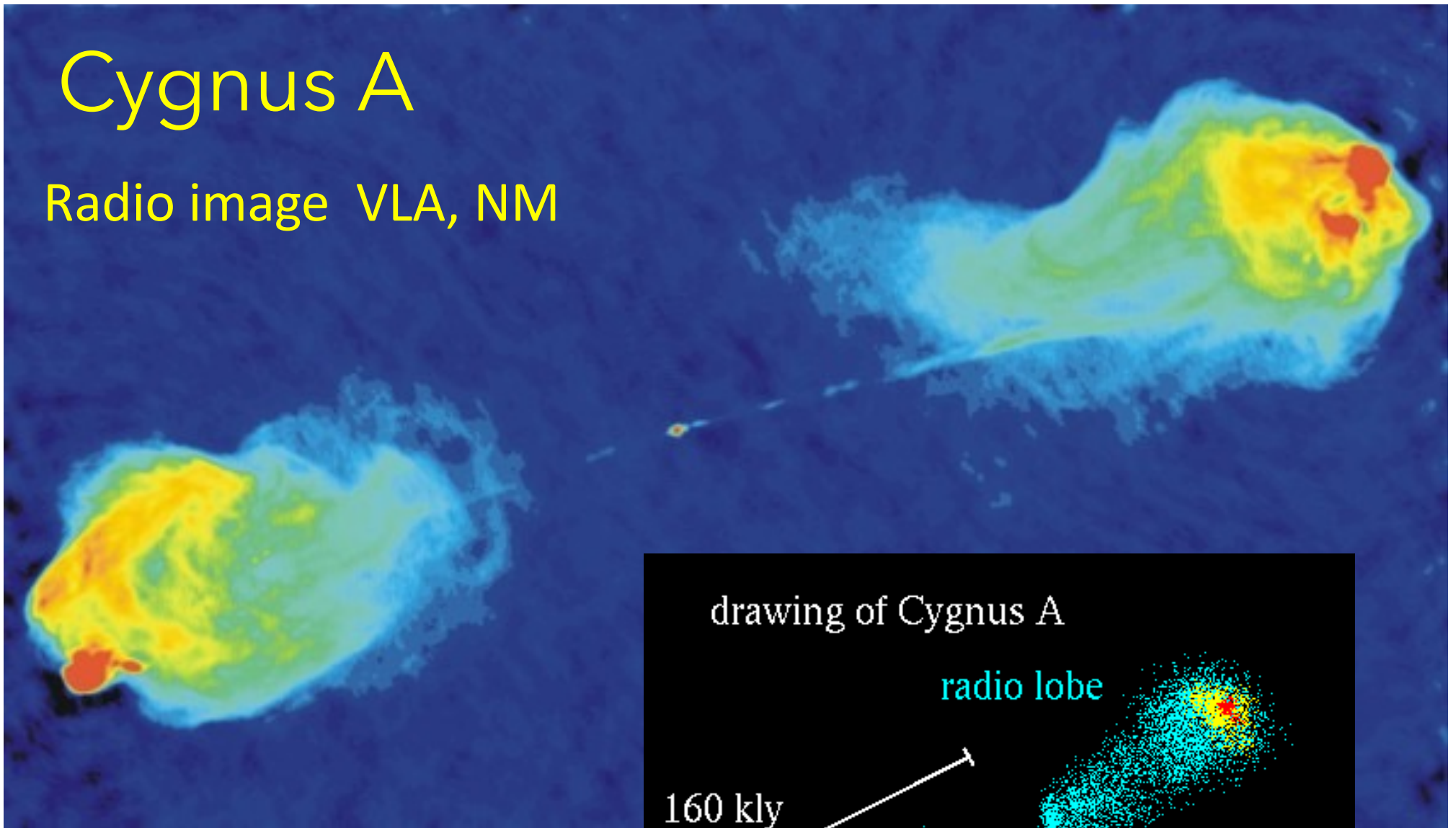


FIRST COSMIC EVENT OBSERVED IN GRAVITATIONAL WAVES AND LIGHT

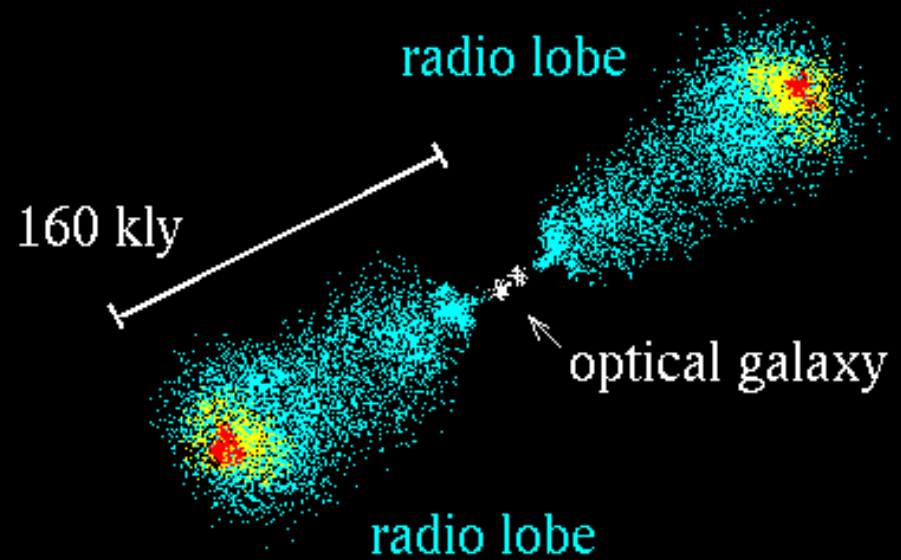


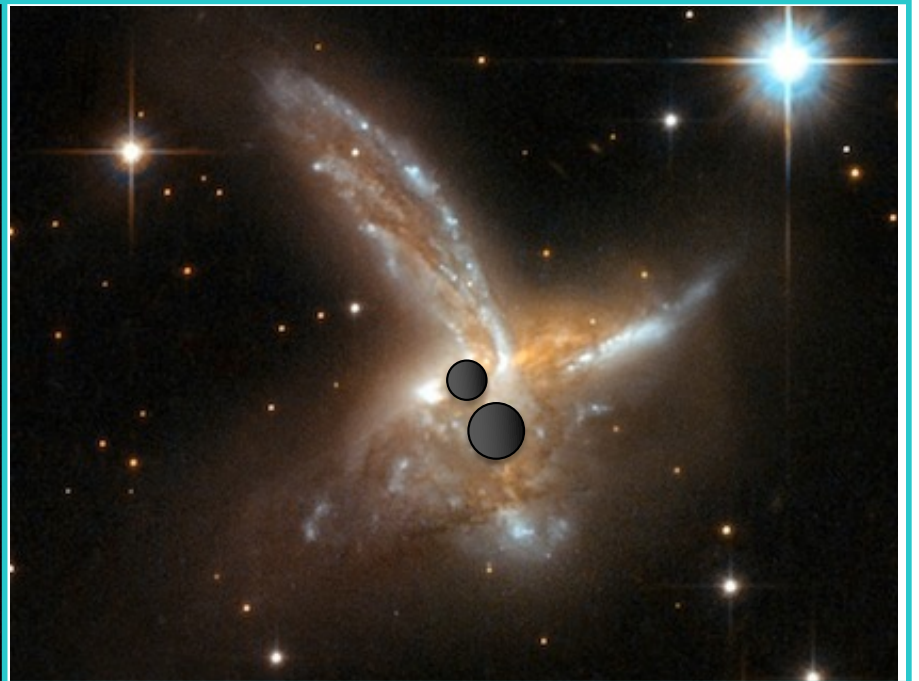
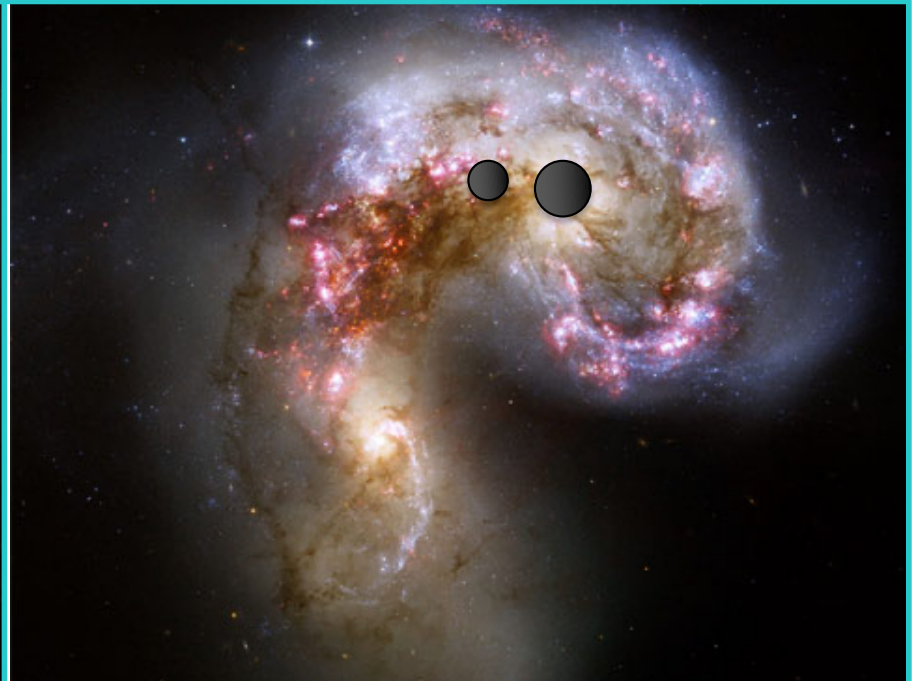
Cygnus A

Radio image VLA, NM



drawing of Cygnus A





Fractional frequency stability

$$y = \frac{\delta f(\tau)}{f}$$

Magnetars:
off scale

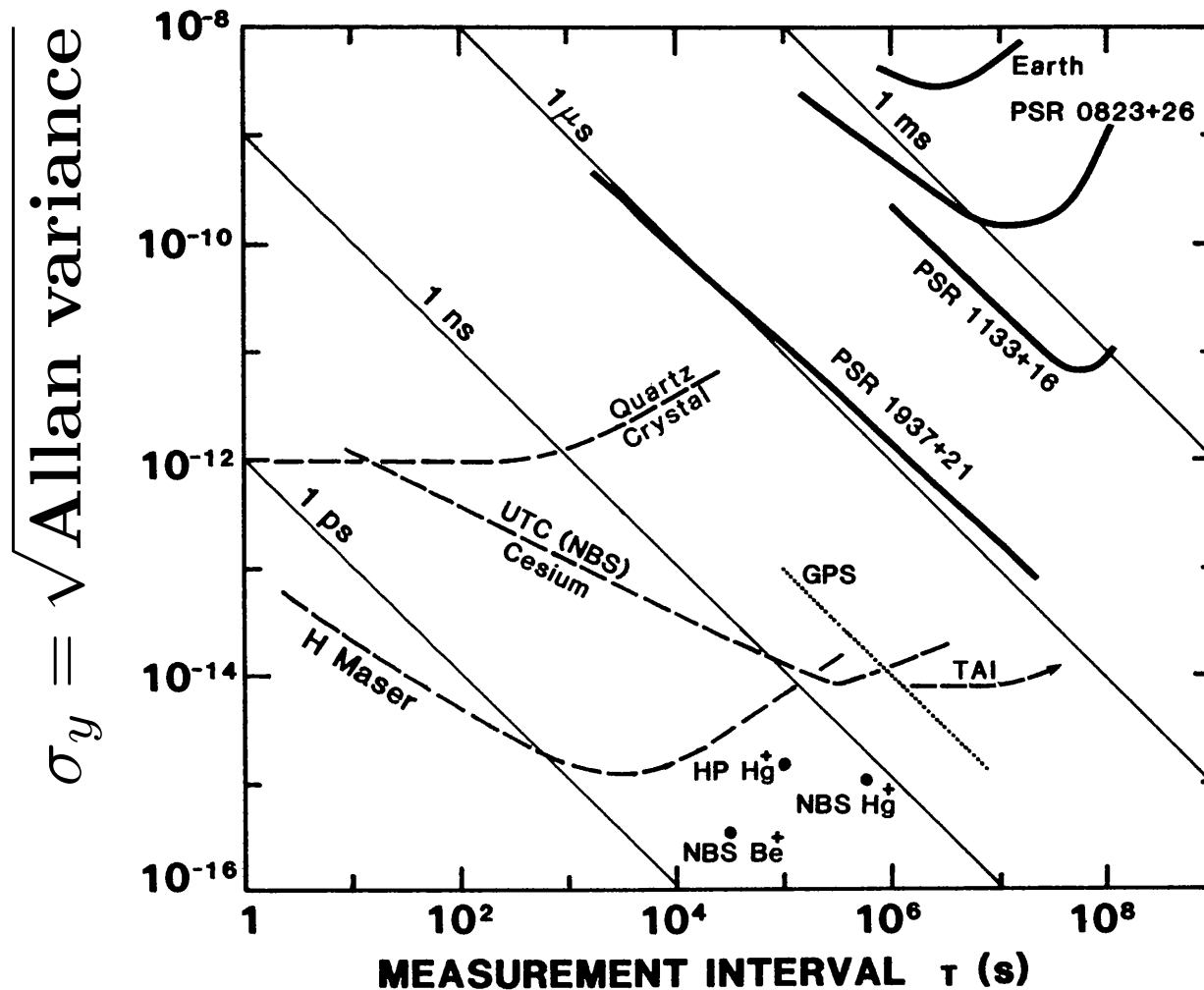


Figure 5 Fractional frequency stability. The heavy solid lines give estimates of the fractional frequency stability of the rotation of the Earth based on UT1 measurements and of several pulsars (Cordes & Downs 1985, Davis et al. 1985). The line for PSR 1937+21 results from a stability analysis of the residuals presented in Figure 3. The dashed lines give the stabilities of several laboratory standards and International Atomic Time (TAI). The dotted line gives the stability of the Global Positioning Satellite (GPS) “common-view” time-transfer link (Allan & Weiss 1980). Circles indicate the stability of several trapped-ion atomic clocks (Prestage et al. 1985, Wineland 1984).

Backer & Hellings
ARAA, 1986