Probing the Extremes of Physical Laws with ngVLA Pulsar Observations

Thankful Cromartie

National Research Council Postdoctoral Associate | U.S. Naval Research Laboratory

Chair, NANOGrav Pulsar Timing Working Group

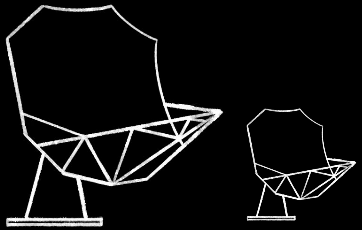
AAS Winter Meeting | January 2025

NANOGrav Physics Frontiers Center

U.S. NAVAL RESEARCH LABORATORY

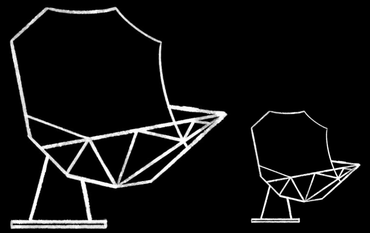
We want to:

- Discover more (and more exciting) pulsars that are **far away** (faint, scattered/dispersed); **highly accelerated**; make up the GeV excess?
- Time new pulsars to constrain the **dense matter EoS**
- Find NS-BH, NS-NS, triple systems for **tests of GR**
- Conduct complementary **pulsar timing array observations**



The ngVLA will make this possible with:

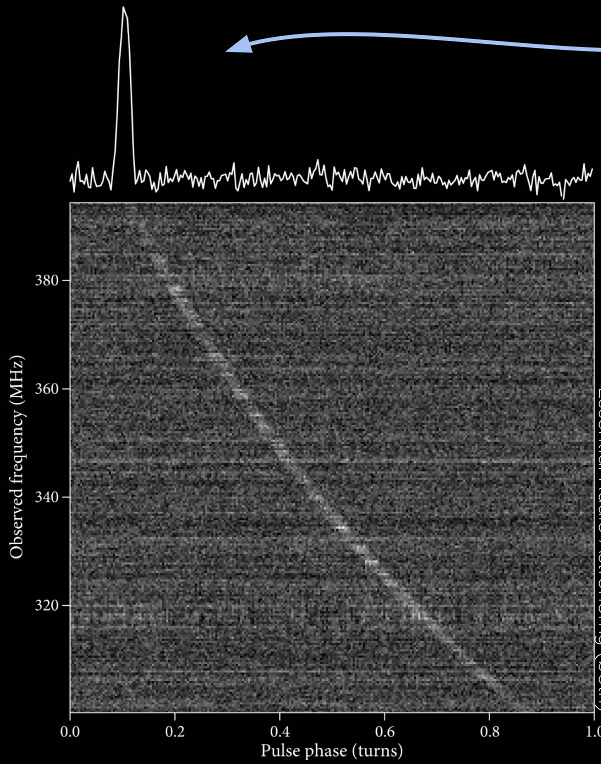
- Large collecting area + wide bandwidths = **great timing precision**
- **Good high-frequency coverage** (1.2-116 GHz, 1-20 GHz best for pulsars)
- **Sub-array capabilities**; 5-10 phased beams (jitter, PTA efficiency)
- Northern sky + higher frequencies → complements next-gen facilities



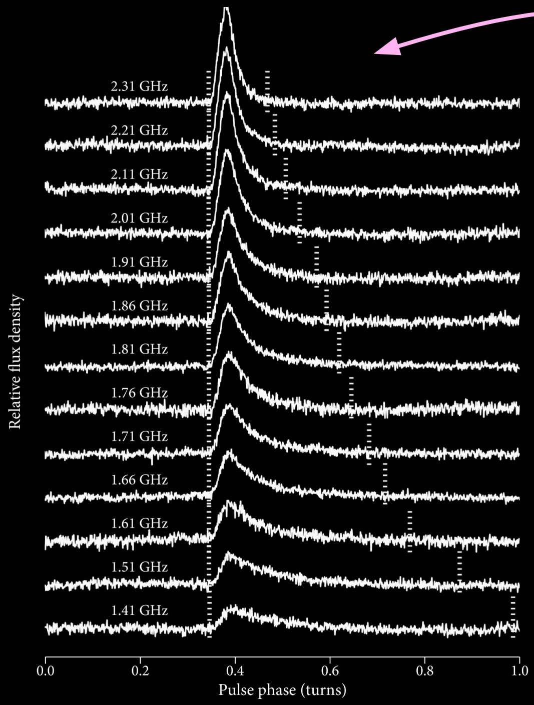
NANOGrav Physics Frontiers Center

U.S. NAVAL RESEARCH LABORATORY

Newer, cooler pulsars



Essential Radio Astronomy (both)



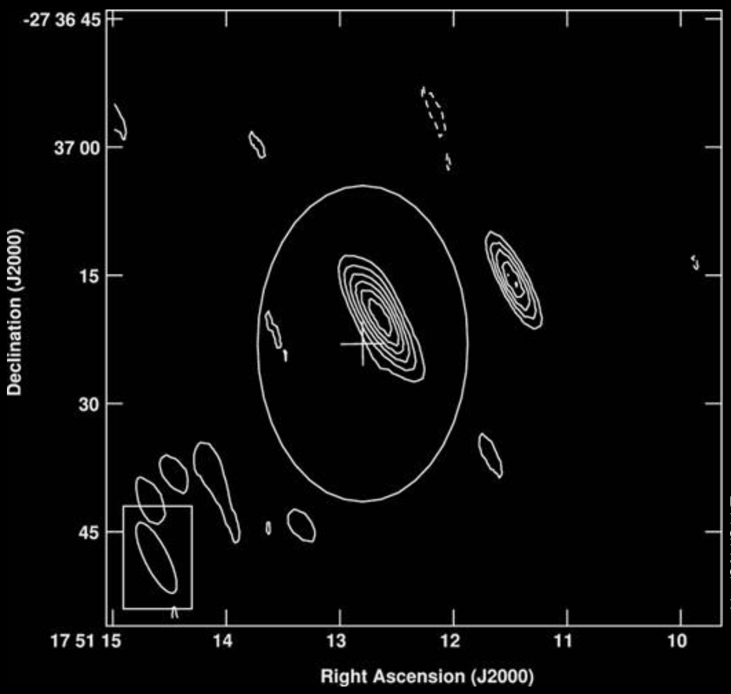
<20% known pulsars at d_{GC}

Farther = fainter, more **dispersed** (ν^{-2}), more **scattered** ($\sim\nu^{-4}$)

- Combat with high frequency → higher frequency = fainter for PSRs → need ngVLA sensitivity!

Newer, cooler pulsars

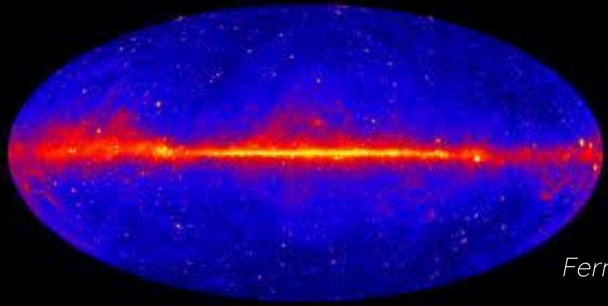
PSR 1751–2737



Bhakta+17

Creative searches (e.g. Bhakta+17, Hyman+19):

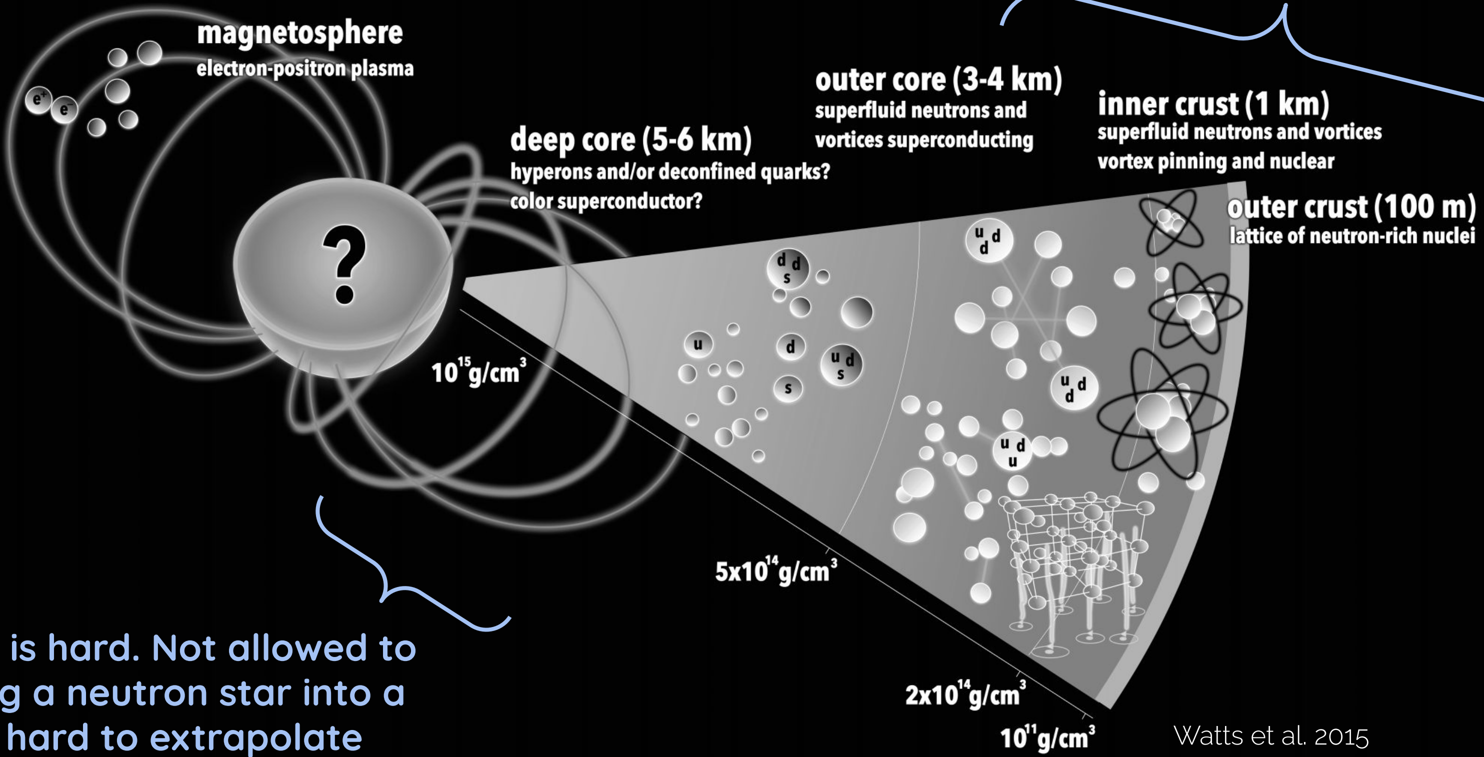
- Steep-spectrum sources in ngVLA images (GC only)
- Follow with ultra-sensitive, high-frequency pulse search
- Could follow up imaging surveys from DSA-2000, ASKAP/MeerKAT/SKA, etc.
- Discoveries could elucidate GeV excess



Fermi-LAT

Dense matter equation of state (EoS)

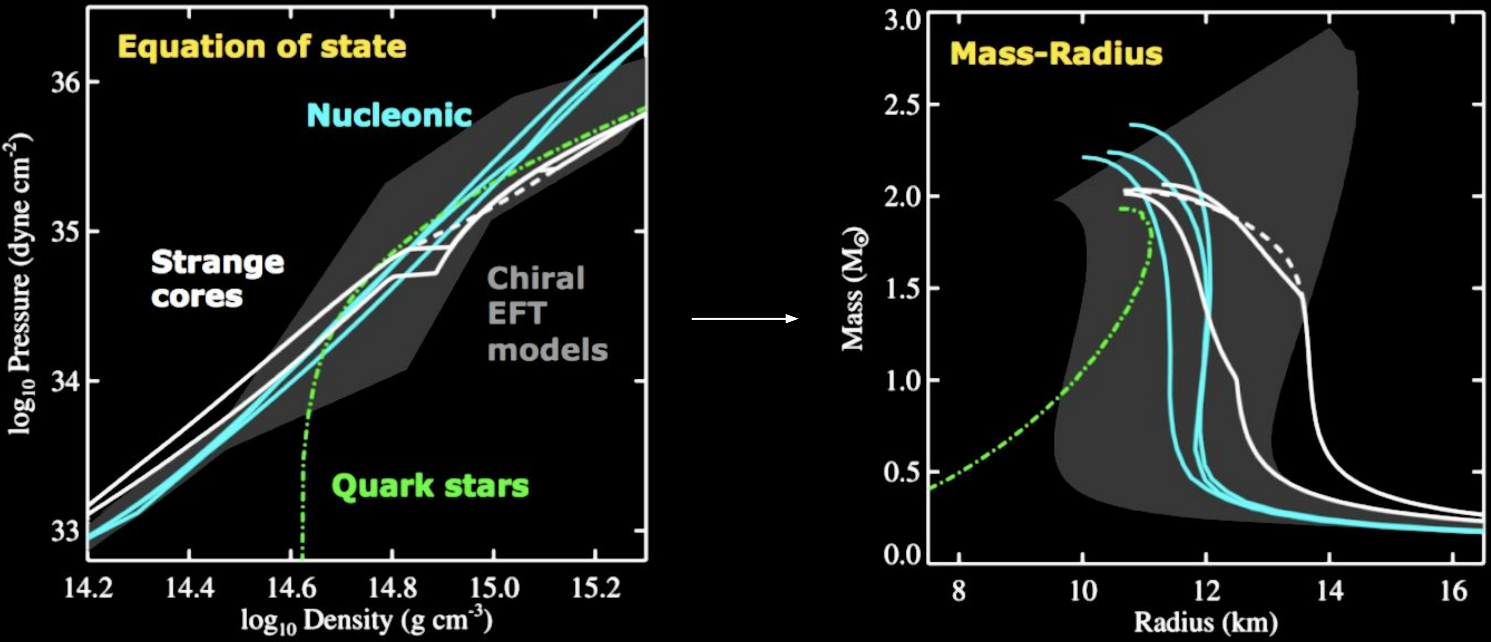
Doing ok here with computation and lab experiments



This is hard. Not allowed to bring a neutron star into a lab; hard to extrapolate

Watts et al. 2015

Dense matter equation of state (EoS)



Watts et al. 2015

Pulsar mass measurements

$$f(m_p, m_c) = \frac{4\pi^2}{G}\frac{(a \sin i)^3}{P_b^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}$$

5 Keplerian parameters + **2 post-Keplerian** parameters = **individual masses**

Projected semimajor axis: $x \equiv a \sin(i) / c$

Longitude of periastron: ω

Time of periastron passage: T_0

Orbital period: P_b

Orbital eccentricity: e

Normal timing

Rate of periastron advance: $\dot{\omega}$ and Einstein delay γ (eccentric)

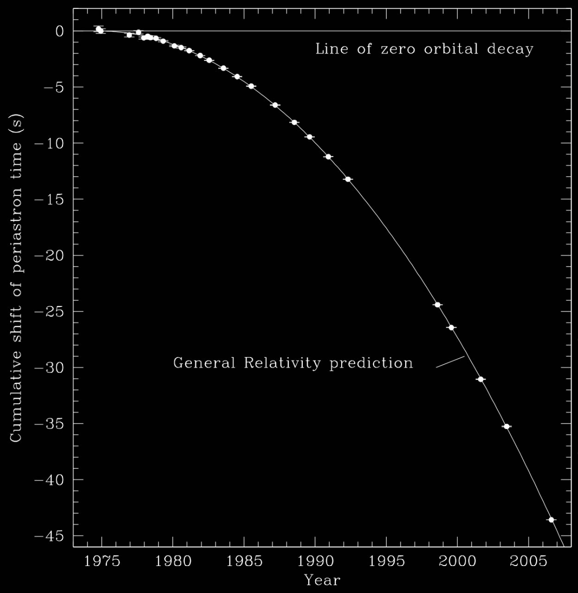
Orbital period decay $\dot{P}_b$ (long timespan)

Shapiro delay parameters r, s (edge-on)

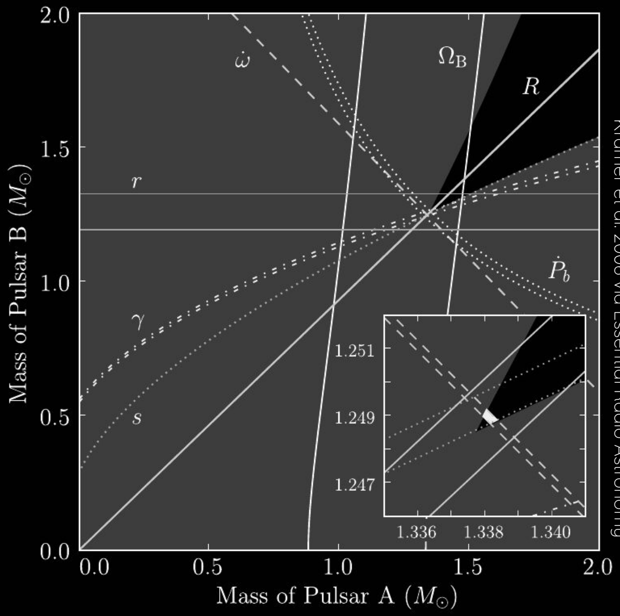
Notable PK measurements

B1913+16, the Hulse-Taylor DNS (1975):

- Compact, eccentric (3 PK; GW energy loss)



Weisberg, Nice & Taylor (2010)

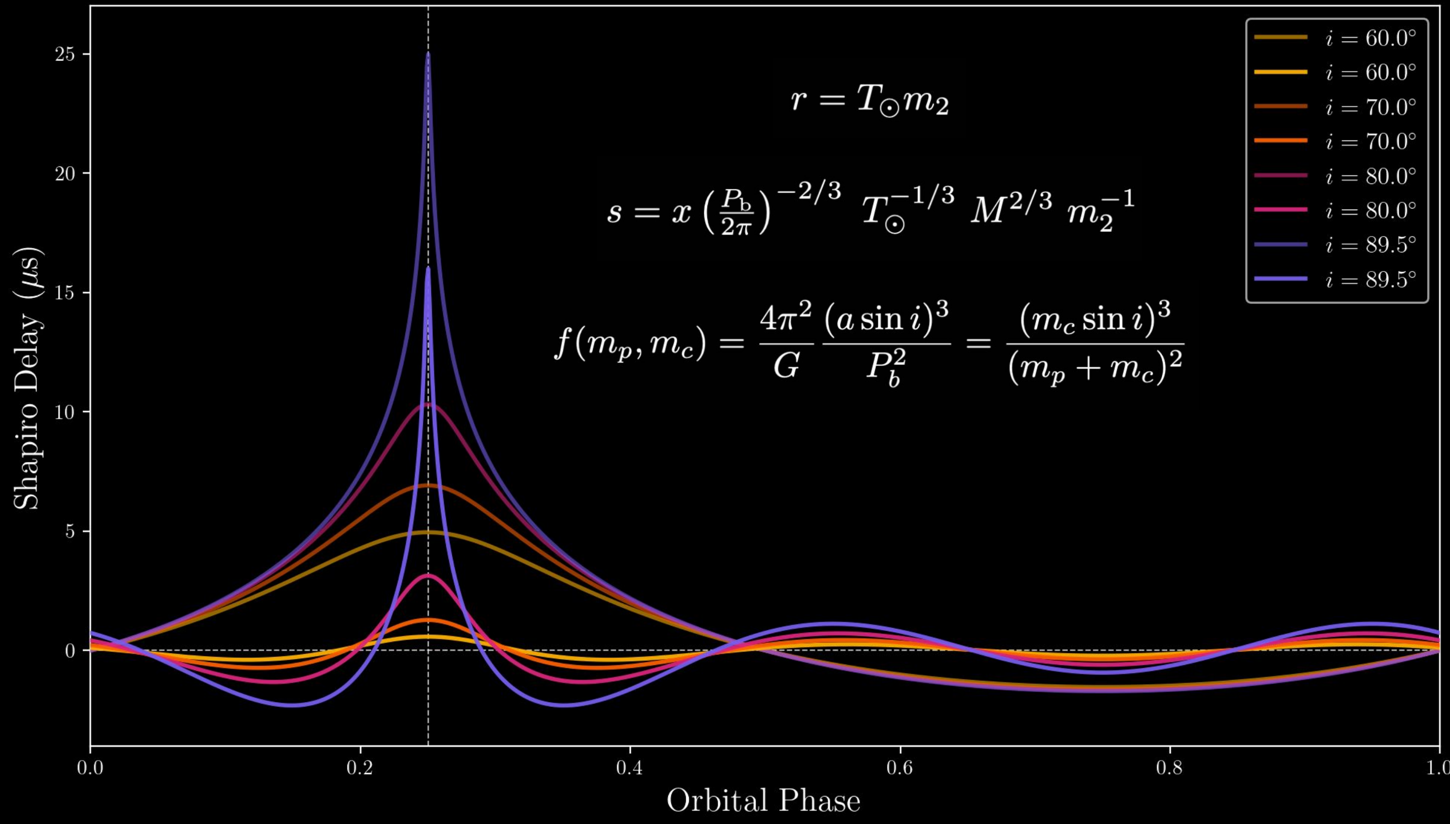


Kramer et al. 2006 via Essential Radio Astronomy

J0737-3039, the double pulsar (Burgay et al. 2003):

- Most compact, highly inclined; seven measured parameters including M/R
- Consistent independent of PK choice

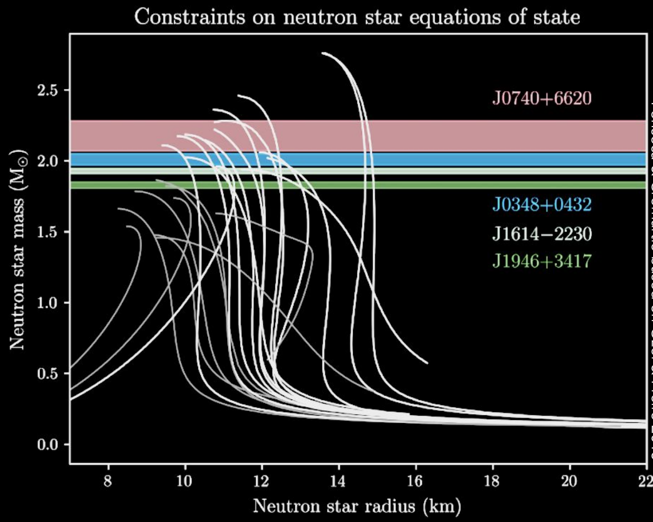
Shapiro delay measurements



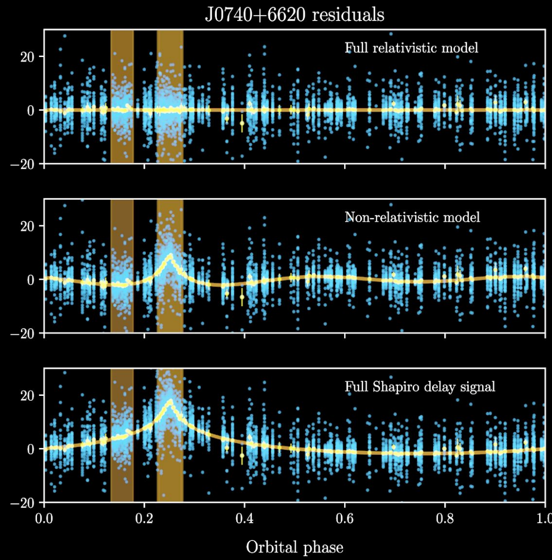
Shapiro delay measurements

J1614-2230 (Demorest+10)

- 1.97 ± 0.04 $M_\odot$ (Fonseca+16: 1.928 ± 0.017 $M_\odot$)
- First ~2 $M_\odot$ NS rules out softer EoS (hyperons, kaon condensates, etc.)



Fonseca & Cromartie based on Özel & Freire 2016



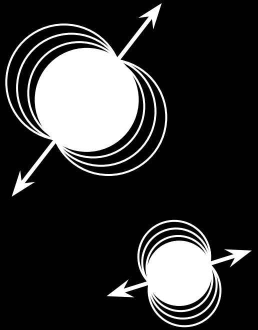
Cromartie+20

J0740+6620 (Cromartie+20, Fonseca+21)

- ~2.14 ± 0.09 $M_\odot$ (then most massive NS)
- Fonseca+21: 2.08 ± 0.07 $M_\odot$

r_{NS} from NICER + NANOGrav + XMM (Riley+21, Miller+21, Raaijmakers+21); constrains the EoS

Shapiro delay measurements



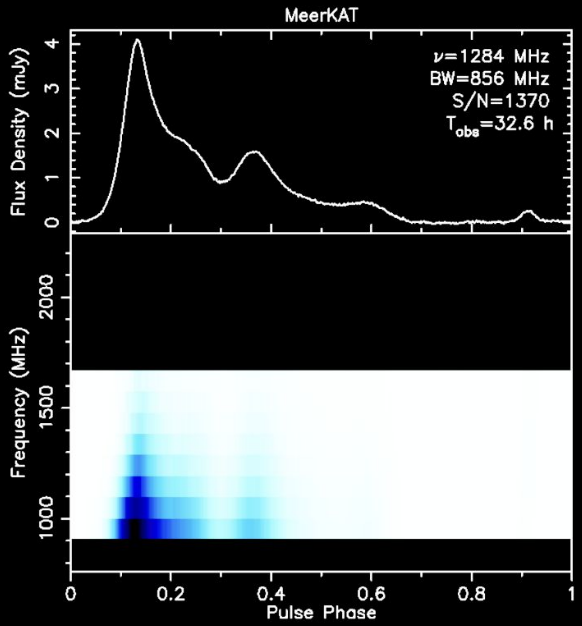
Recent success of MeerKAT's TRAPUM + RelBin programs (e.g. Kramer+21) and FAST's GPPS (473 new pulsars! Han+24) → **good, faint pulsars are out there!**

- Great mass measurements are ~rare; need high-mass PSRs but also mass *distribution*
- Highly accelerated systems → PK measurements
- A collection of new "exotic" binaries with measurable PKs would be revolutionary—radio (+X-ray/γ-ray) great for EoS
- Will **require** the ngVLA's high frequencies and sensitivity to access these sources

J0955-6150 (Serylak+22):

Eccentric (e = 0.11), significant $\dot{\omega}$ and SD

Vastly improved timing precision with MeerKAT; $m_p \sim 1.71\ M_\odot$



Compact binaries, PSR-BH binaries

No confirmed PSR-BH binaries → **rare + far away**

- J0514−4002E (Barr+24, mass gap)
- GC searches → more 3-body interactions?

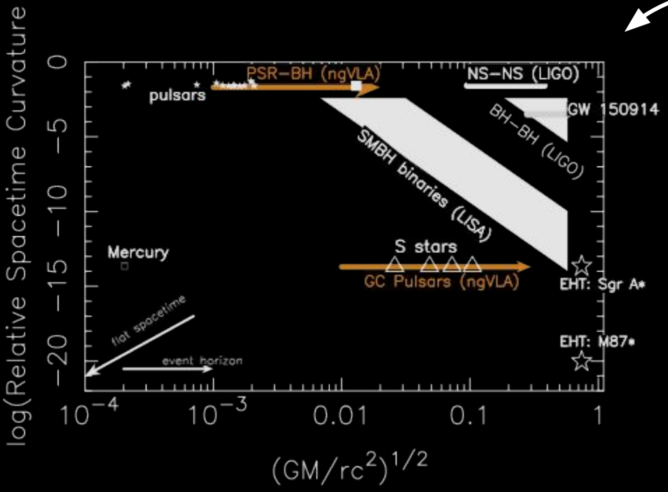
Only ~25 NS-NS binaries, one double pulsar

Acceleration is a problem!

- Hybrid methods (imaging + pulse search) help
- Pulsation searches: high sensitivity = shorter integration times (e.g. jerk searches—Tabassum+ in prep.)

Redbacks? Eclipses, better mass constraints for "messy" systems with high-frequency ngVLA

PSR-BH binaries: sample high spacetime curvature near BH for unique, more extreme GR tests

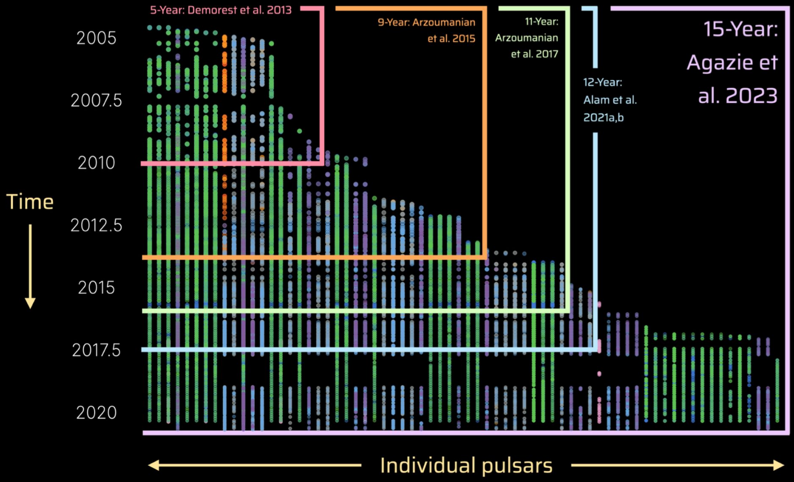


The IPTA

Recent **evidence for nHz GWB**, likely from SMBHBs (Agazie+23b, EPTA+23b, Reardon+23, Xu+23, Miles+24)

- **Continuous wave signals** (individual binaries) on the horizon

Too oversubscribed + high-frequency for “normal” PTAs, but ***complements*** N.A. facilities like DSA-2000, GBT, CHIME (IPTA)



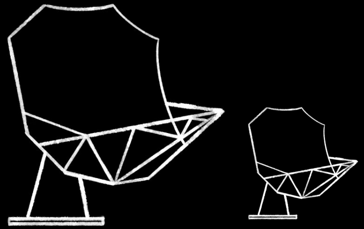
ngVLA specialized work:

- **Add faint MSPs** to the PTA (GW sensitivity ∝ N_{psr})
- Sub-arraying (efficient, some jitter-limited)
- Make **astrometric measurements** (annual parallax) that constrain “pulsar term”

NANOGrav Physics Frontiers Center
U.S. NAVAL RESEARCH LABORATORY

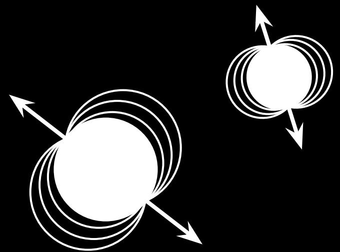
Summary

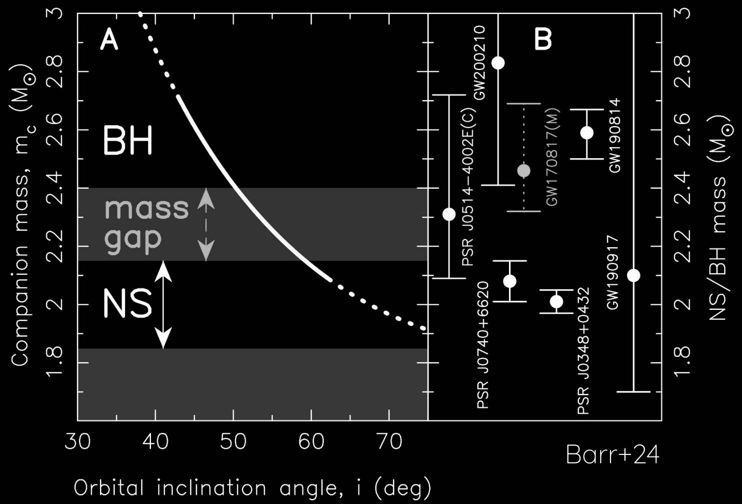
- The ngVLA will facilitate unique pulsar science with its **high frequency** range and **sensitivity**
- We expect to discover novel pulsar systems—potentially including **PSR-BH binaries**—and many new systems that will facilitate **pulsar mass measurements** via relativistic effects
    - High-precision mass measurements provide strong constraints on the **NS interior EoS**
- The ngVLA will complement other next-gen radio facilities and offer opportunities for **synergistic science** (e.g. following up steep spectrum sources in images at high frequency)
- Although the ngVLA will not be a primary telescope for PTAs, it will offer several **specific advantages** for such experiments



Thanks!

thankful.cromartie@nanograv.org




A
B
BH
mass
gap
NS
Companion mass, m_c (M_⊙)
NS/BH mass (M_⊙)
Orbital inclination angle, i (deg)
PSR J0514−4002E(C)
GW200210
GW170817(M)
GW190814
PSR J0740+6620
PSR J0348+0432
GW190917
Barr+24