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Pulsars, Gravitational Waves, and Cosmic Bursts

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following discussions with NANOGrav and many others

Radio Futures II
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Outline

- Science drivers
- Current capabilities:
  - What we need for the next 5 years: Arecibo & GBT
- What will the next decade look like?
  - Ensure that the US retains leadership position
  - Need substantial (~100 hours/month) access to ≳300-m scale facility
    - Build on existing resources
    - New telescope? Upgrade facilities? Join collaborations?

Science Questions

- What is the cosmic history of black hole formation and growth?
- What other sources of low-frequency gravitational waves exist?
- What is the correct theory of strong gravity?
- W

NSF Big Idea #6: Windows on the Universe: the Era of Multi-Messenger Astrophysics

- Why do pulsars shine?
- What is the origin of fast radio bursts?
- Where are intergalactic baryons & magnetic fields?

See talks from Radio Futures I

Priorities

To maintain and grow US leadership and student training in pulsars, gravitational waves, and fast transients:

1. Ensure ≳Arecibo sensitivity with **significant share of observing time** for pulsar searching & timing

    1.a. Continue to upgrade capabilities of Arecibo & GBT

    1.b. Gain sufficient access to MeerKAT/SKA1 & FAST

    1.c. Develop new concept with simplified requirements (not necessarily SKA)

2. Develop FRB experiments

    2.a. Merge into larger facilities as population is defined

4 Technique Areas

Pulsar searching

- New & interesting systems, population statistics
- Requires timing to exploit

➡ **Crucial capability: survey speed**

Pulsar timing

- Binary evolution, GR, EoS
- Gravitational waves

➡ **Crucial capabilities: collecting area, integration time, & cadence**

FRB searching

- Numbers for population, logN/logS, spectral diversity, pulse shape, …

➡ **Crucial capability: FOV**

FRB localization

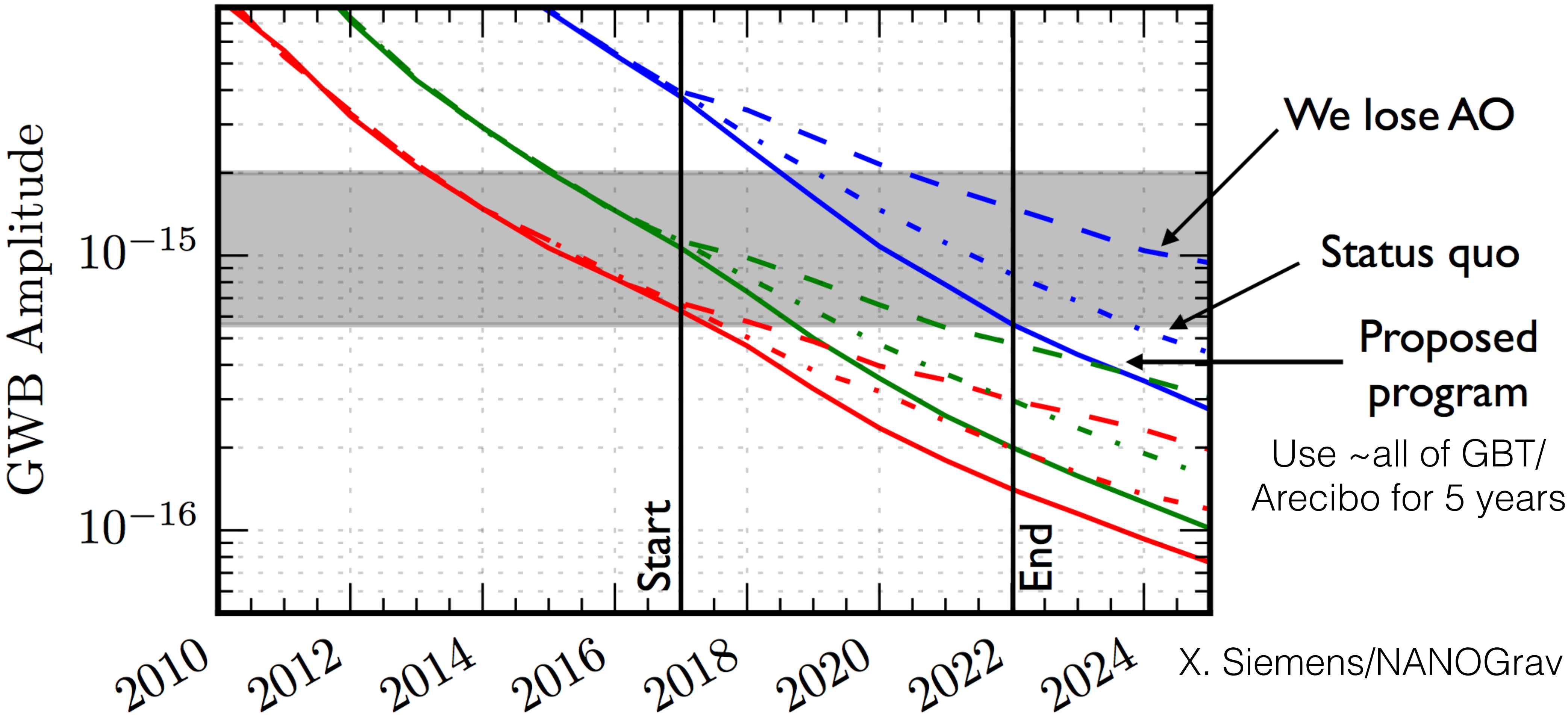
- Precision cosmology, progenitors, microphysics

➡ **Crucial capability: angular resolution**

What NANOGrav Can Do

- Soon:
  - Detect stochastic low-frequency GW background
- Eventually:
  - Characterize background:
    - Probe sub-pc environments of supermassive BHs: "spectral shape describes environment"
  - Detect individual SMBH systems, connect with multi-messenger probes

Background Prospects

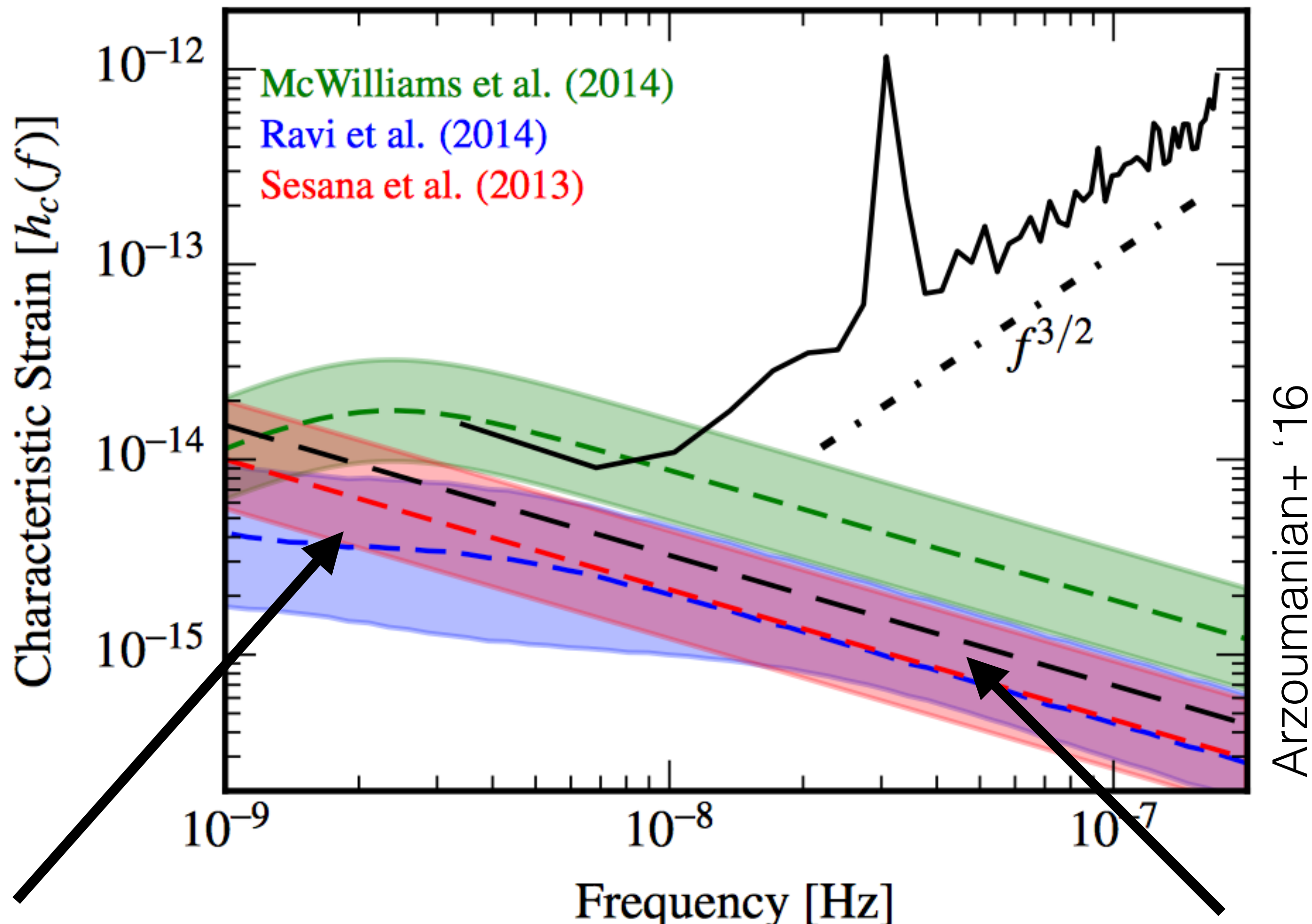


90% chance of detecting the background around the low-middle of expected amplitudes by the end of the 5 years

Even odds of detecting the background at very lowest levels by end of 5 years

Having to **profoundly** rethink our understanding of galaxy evolution by end of 5 years

Spectral Characterization



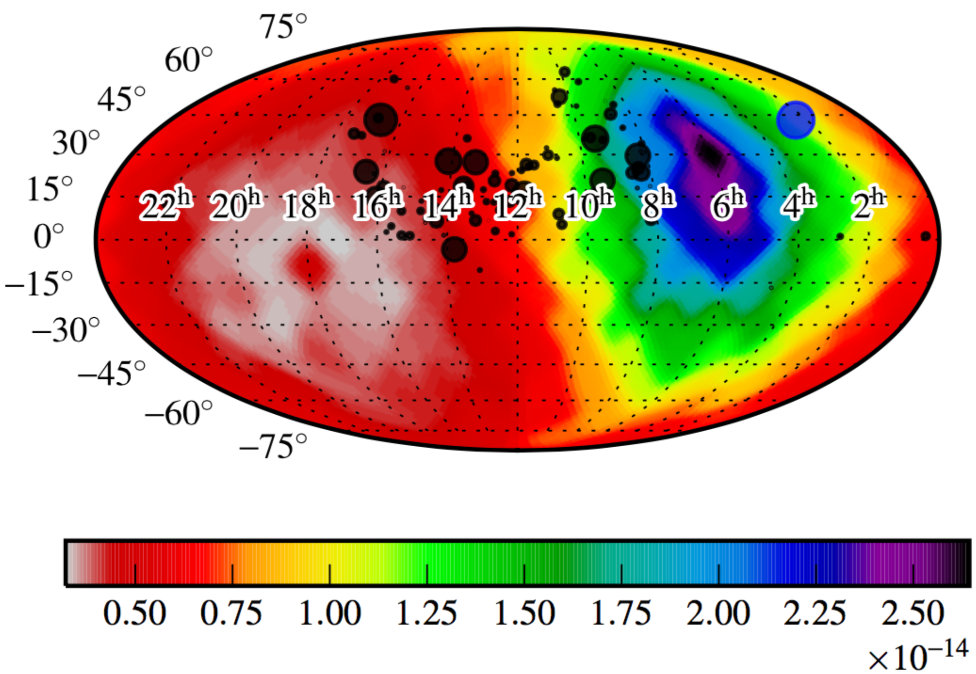
Low-frequency shape determined by environment:

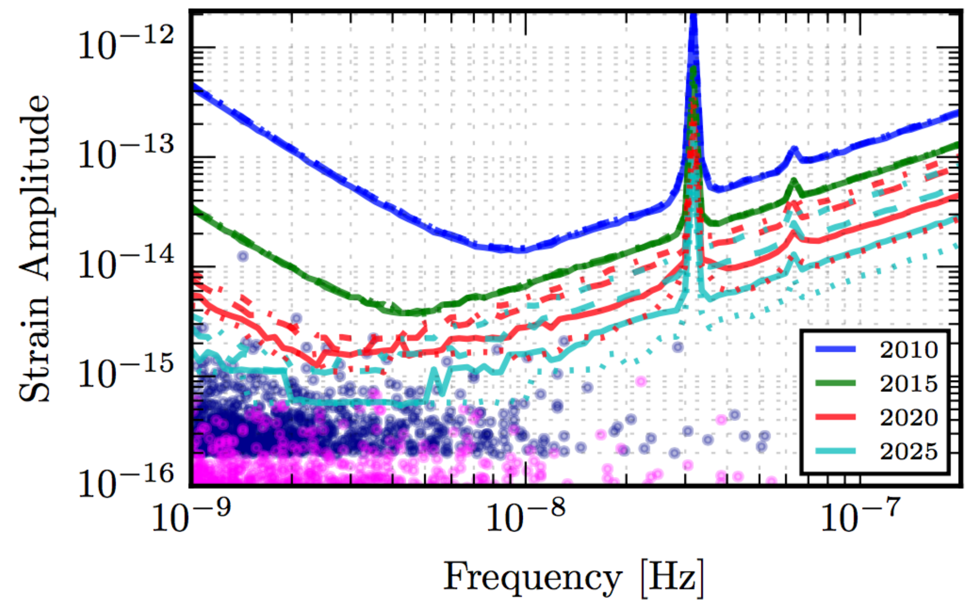
- stellar hardening
- circumbinary disks
- orbital eccentricity

High-frequency shape determined by GW emission:

- merger rates
- stalling fractions
- ties to observed correlations

CW Detection Regime





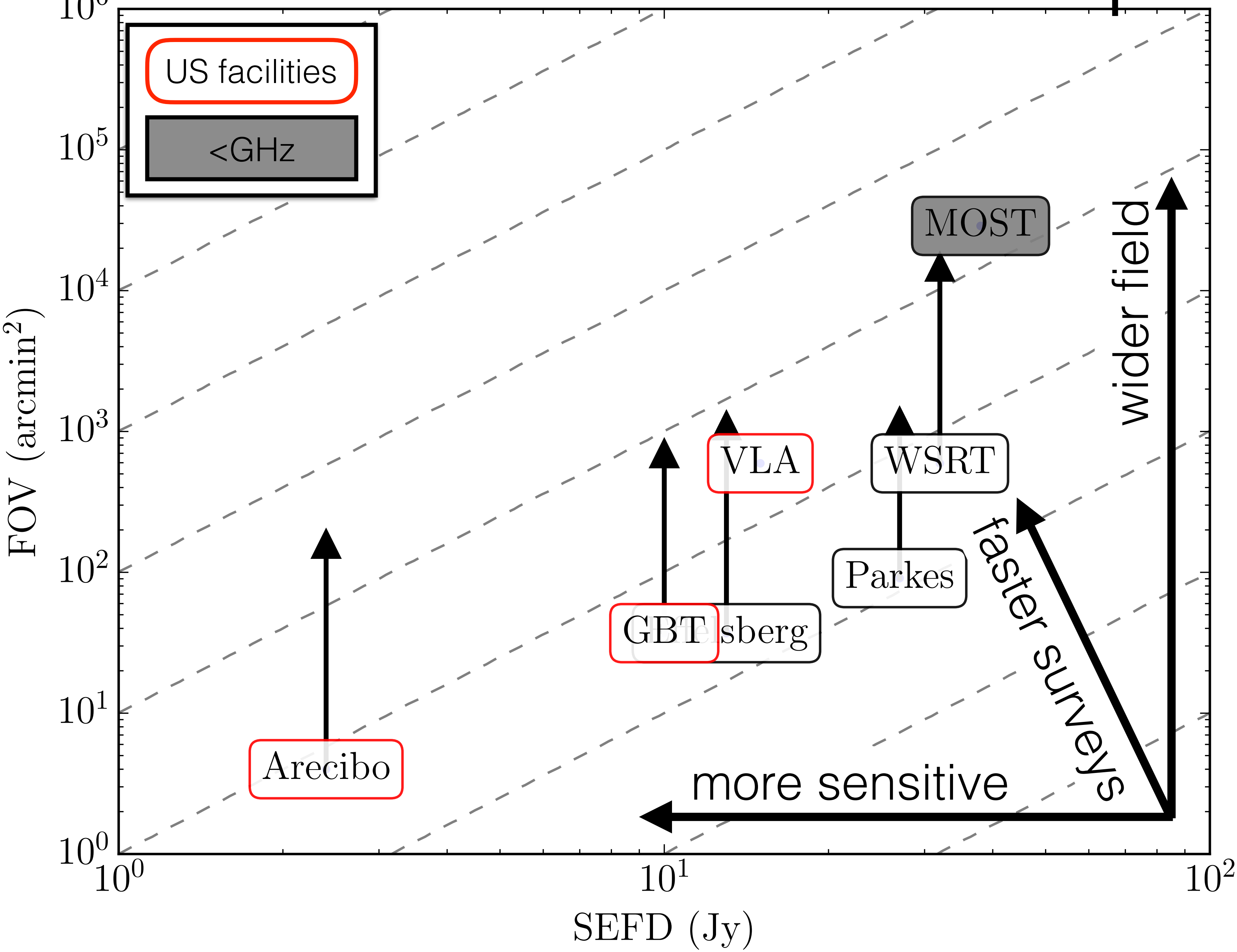
Individual systems visible in GW:
connect with optical, radio, X-ray, …

What NANOGrav Needs

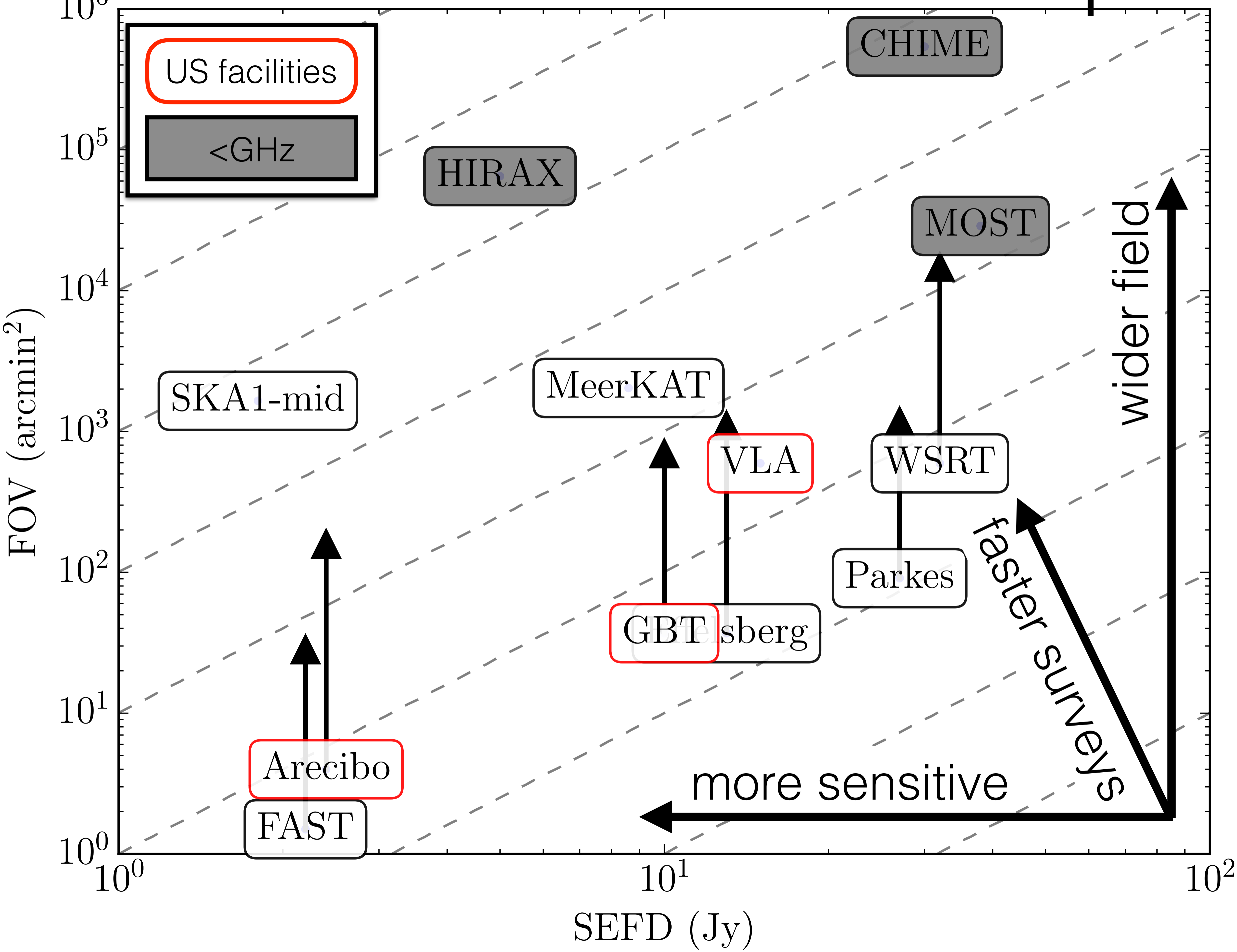
- More pulsars
- At high cadence
- With sensitive telescopes
- As soon as possible

What are the prospects over the next 10 years?

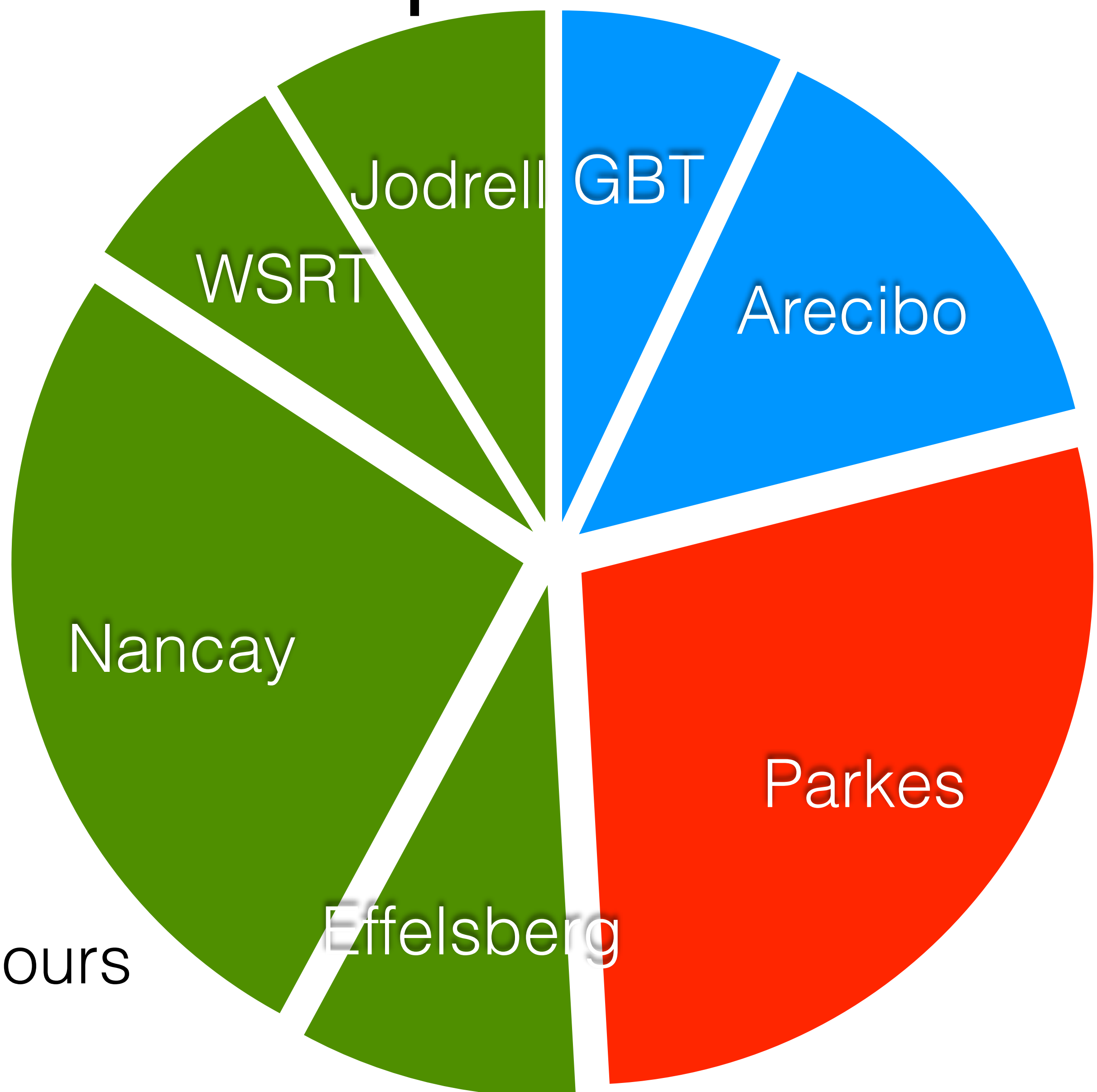
Current ~GHz Landscape



Future ~GHz Landscape



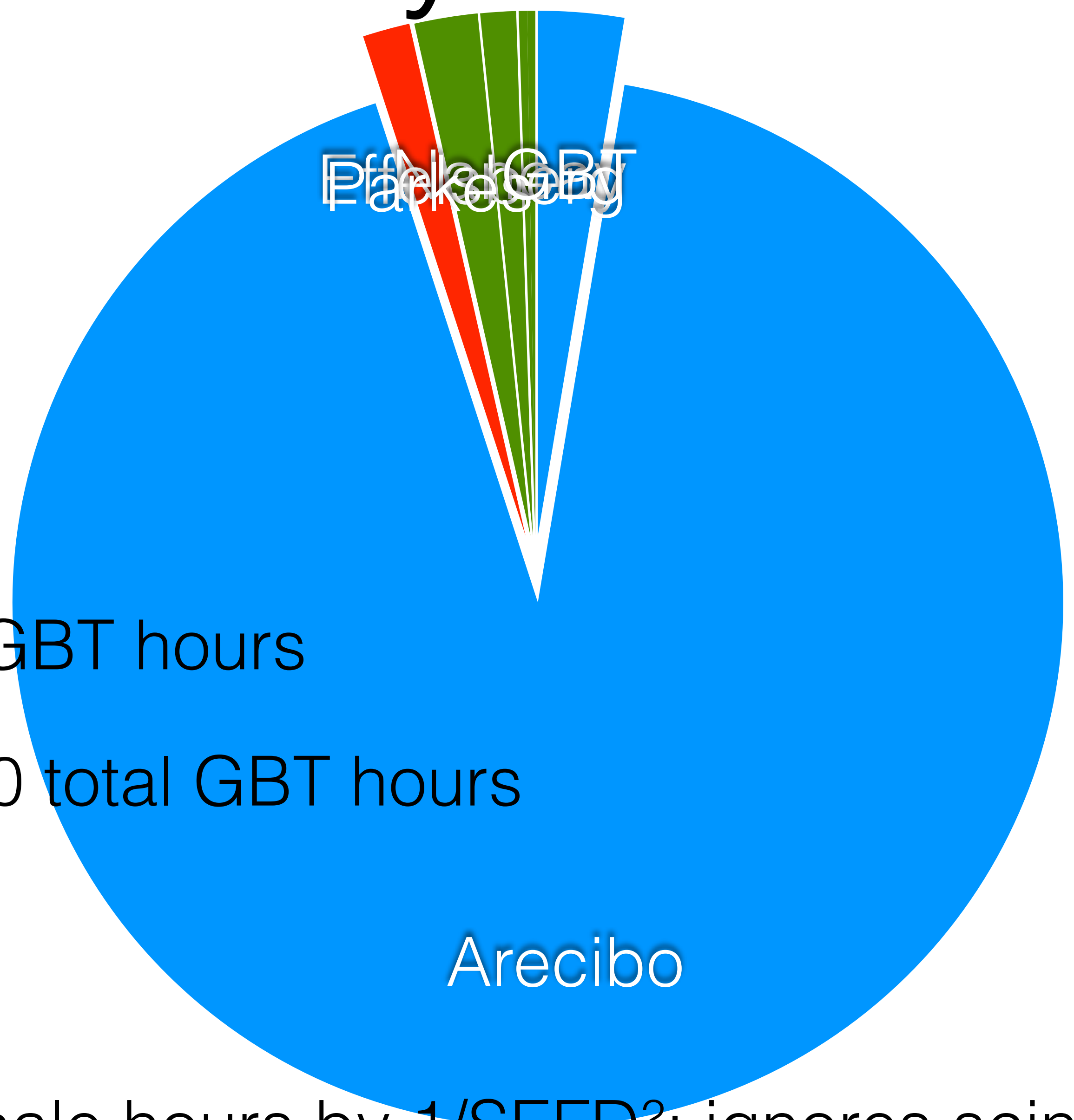
IPTA Comparison: Hours



~6000 total hours

PPTA from V. Ravi; EPTA are best-guesses

Scale by Sensitivity



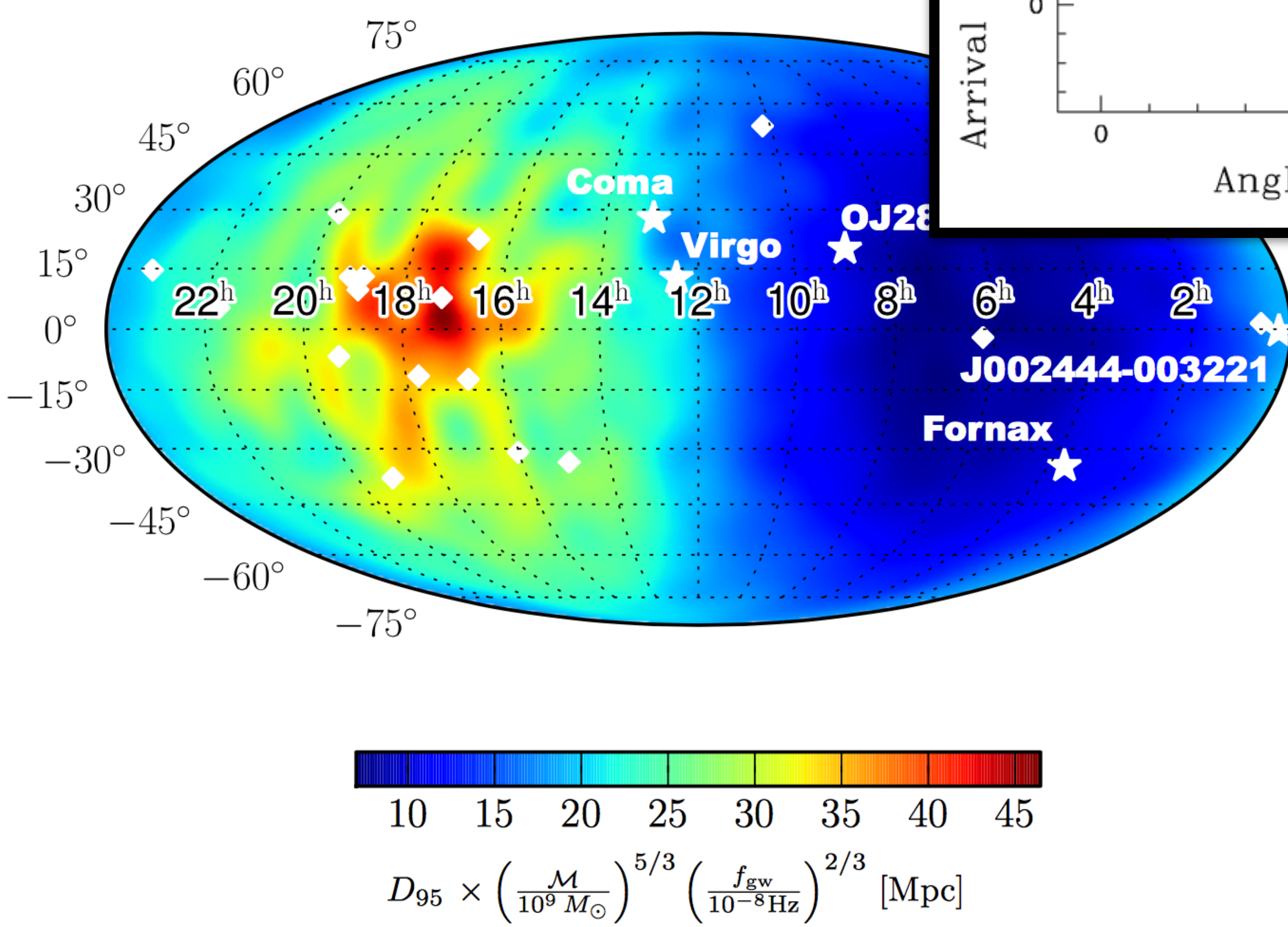
~15,000 total GBT hours

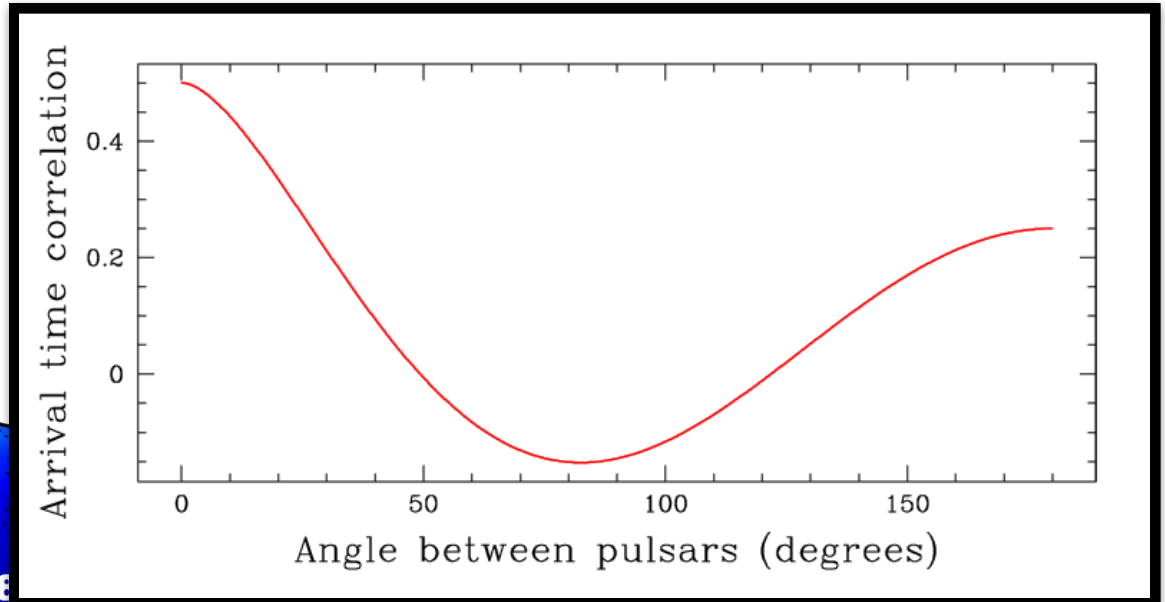
MeerKAT: ~800 total GBT hours

scale hours by 1/SEFD^2: ignores scintillation & jitter

One Isn't Enough

Need multiple telescopes to sample the sky





Arzoumanian+ '14

The next 5 years: Arecibo & GBT

- Highest precision pulsar timing requires AO and GBT
  - We **need** continued Arecibo & GBT access
- Current GBT + Arecibo program:
  - 1200 hours/year for NANOGrav timing
  - ~400 hours/year for other timing (double pulsar, triple system, globular clusters, …)
  - ~600 hours/year of searching (GBNCC, PALFA, …)
    - Still finding exotic systems *and* new NANOGrav MSPs
- Can we push this further?
  - 6500 hours/year of timing advances time to detection by several years

The next 5 years

- VLA capable for timing, but oversubscription makes this challenging
  - L-band sensitivity not as good as GBT
  - No 800 MHz capability
  - But very good for higher frequency
  - Searching still not feasible
- FAST and MeerKAT ***could*** eventually replace Arecibo & GBT in terms of raw sensitivity but
  - Depends on the instrumentation and and observing programs
  - Not enough time available (~400 hours/year for MSP timing: needs to include Parkes pulsars)
  - access for US community far from clear: no obvious open skies policy
  - ➡ Will evaluate MeerKAT and FAST telescopes in this timeframe

The next 5 years: Experiments

- CHIME offers good FRB detection, localization harder
  - Build outriggers? Or better processing?
  - Will contribute to NANOGrav but cannot replace >GHz coverage of GBT or AO
- HIRAX OK for FRB rates; pulsar contribution unclear
- DSA-10: rates are TBC, but really needs full deployment for full impact
- None of these is open-skies for US: but some are US led

The next 5 years: m-waves

- V-LITE/LOBO, LOFAR, LWA, MWA, HERA, …
  - will help with pulsar searching (LOFAR!)
  - could help with pulsar timing, but quantitative improvement needs to be demonstrated
  - Cannot replace precision GHz timers
  - FRB case not clear: no detections at <800 MHz
  - But low-frequency time-domain explorations worthwhile, relatively cheap

Next 15 years: Paths to Science

1. Retain GBT/AO
2. Invest in FAST/MeerKAT/SKA1: gain significant share: ~$5M-$50M
    - Contribute hardware
    - Contribute complete telescope ($$$)
    - Contribute to data handling capability
3. New instrumentation for current facilities (Arecibo, GBT, etc): ~$10M
    - Ultra-wideband feeds, PAFs, etc.
    - Wide-band or wide area? Depends on the science area
    - Requires continued operations of Arecibo/GBT
    - Could be combined with #2: e.g., new instrumentation for MeerKAT or SKA1 to gain access
4. New facilities: >$100M
    - Pulsar timing array telescope
    - Prototype in ~5 years? Base off existing facilities (CHIME, MOST, MeerKAT)? Integrate with ngVLA?

Options not exclusive. Can pick more than 1!

#1: Retain GBT/AO

- Strengths:
  - Do not need *direct* investment
  - Development largely done
  - Can we increase share on GBT/Arecibo?
    - Even more time will lead to more science: speed up GW background detection significantly
- Weaknesses:
  - How to continue current level of GBT/Arecibo access? Need >1000 hours/year minimum.
  - Will science pass us by?
  - Support among different constituencies may render our priorities irrelevant

#2: Buy In

- Strengths:
  - Gain meaningful access
  - Development done by others
  - Enhance international partnership and presence
- Weaknesses:
  - Level of investment needed now may be significant
  - Telescopes (FAST, MeerKAT, SKA1) still likely to be highly oversubscribed, may require large collaboration
  - Priorities and programs may be fixed already

#3: New Instrumentation

- Strengths:
  - Modest cost (MRI, ATI, etc)
  - Leverage significant investment in facilities
  - Long track record, retain flexibility
  - Do not need to expand user-base
  - Can offer as contributions for buy-in of international projects
- Weaknesses:
  - Require continued telescope operations if intended for GBT/Arecibo
  - Still need telescope time

#4: New Facilities

- Strengths:
  - Design telescope(s) to needs
  - Large amount of time would be available
  - May open new capabilities
  - Can offer as contributions for buy-in of international projects
  - Work within ngVLA framework?
- Weanesses:
  - Lots of $ (MREFC?)
  - Lots of development needed (but this can be good!)
  - Will it satisfy enough US constituencies?

New Facilities

- Develop the concept for pulsar timing array telescope, and/or FRB telescope (DSA? LASA?)
- Challenge of SKA is it's trying to do everything for everyone (=$$ $)
  - Very capable telescope, but outside the reach of a single country
  - Limited time available for any single project
  - What parameters are essential: think of a concept first and match it to a telescope later
- MeerKAT & ngVLA have most capabilities, but won't have the time available

Simplistic Minimal Requirements

	PSR Search	PSR Time	FRB Search	FRB Localize
Freq Coverage	<2 GHz (exclude GC)	1-10 GHz (most 1-2 GHz)	?	<2 GHz
FOV	deg^2	—	many deg^2	deg^2
Re				
Fully Steerable?	—	~hour of tracking	—	—
Collecting Area	$\gtrsim$Arecibo	$\gtrsim$Arecibo	?	—
Bandwidth	—	~GHz	—	—

cadence & duty cycle are key: need ~100 hours/month

What Would We Build?

- Do not need:
  - high-frequency (coordinate w/ ngVLA?)
  - lots of angular resolution
  - fully steerable (do need ~hour of tracking)
- Need:
  - collecting area
  - FOV
  - Available time
  - Northern hemisphere: maintain NANOGrav pulsars as contribution to IPTA

What Would We Build?

1. Cylinder(s)

2. Large-*N*, small-*D* dishes

3. Small-*N*, large-*D* dishes

4. Others

Cylinder(s)

- Build on UTMOST
  - Long tracks at relatively low cost
  - Significant correlator development done
- Localization is 1D without outriggers
  - Add outriggers for arcsec localization, or separate cylinders
- ~4 cylinders would give ~Arecibo of area
  - Can work as subarrays
  - Mesh surface can work up to ~2 GHz
- Keep single uncooled feed design
  - Number will need to scale up with frequency
- Potential sites could take advantage of available infrastructure (GB, VLA, …), offer additional benefits

The World Is Flat(tening)

- The US still has dominant facilities:
  - VLA, GBT, Arecibo
  - Open skies is a huge contributor to success
- But next generation facilities are moving elsewhere:
  - FAST (China)
  - MeerKAT/SKA (South Africa/Australia)
  - LOFAR (Netherlands)
  - MWA (Australia)
  - CHIME (Canada)
  - HIRAX (South Africa)
  - UTMOST (Australia)

Collaboration & Competition

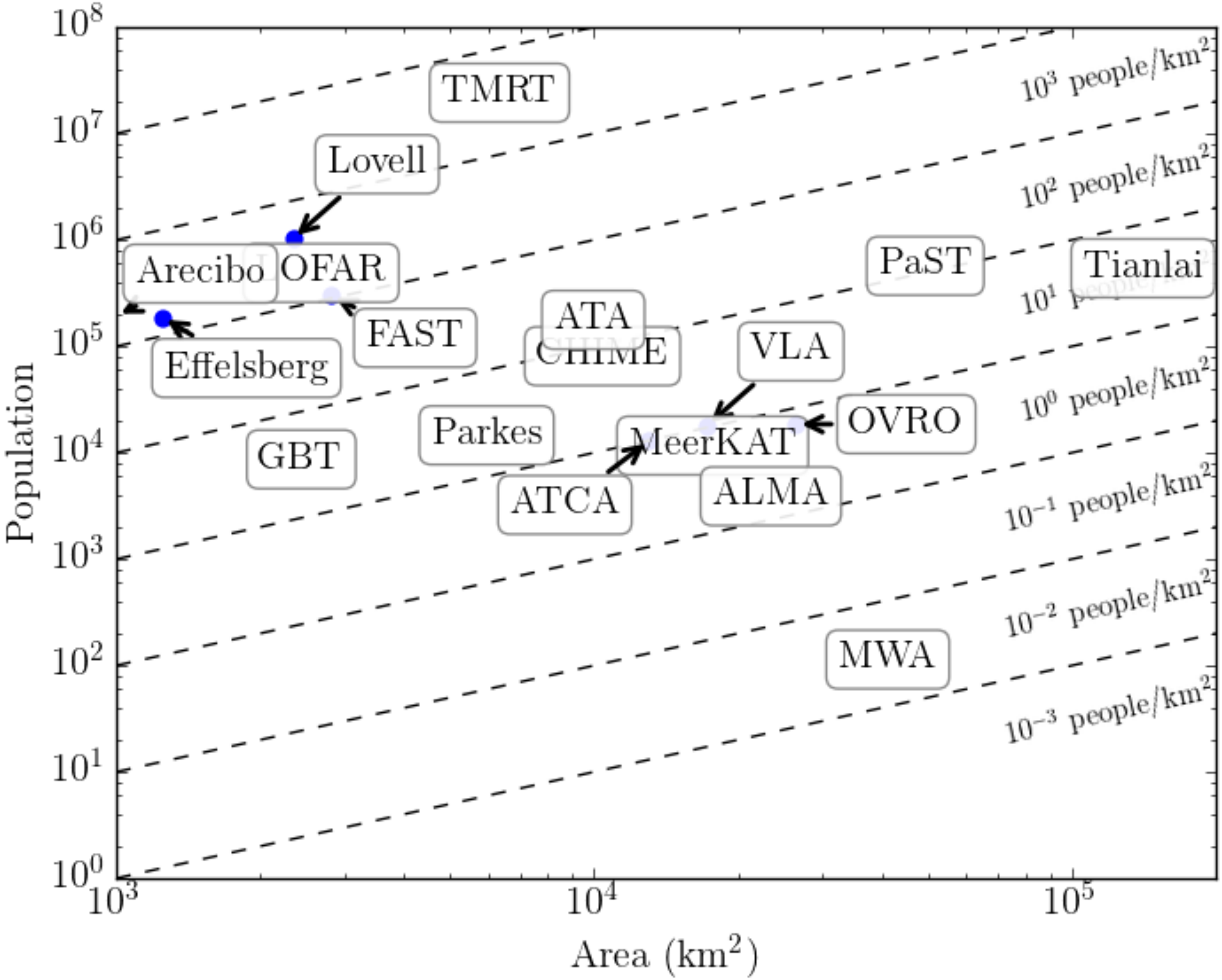
- International Pulsar Timing Array: great forum for collaboration, but does not generate data on its own
- Individual US Co-Is on next-gen international projects, but no official US presence
- Losing US facilities would hurt US ***and*** international efforts (IPTA detection limits worse; even worse after detection)
  - There is not enough time to do all that needs to be done without US facilities
  - SKA: pulsar searching & timing are key projects, but not enough time allocated to realize science potential (and we can do it first!)
- Pulsar Timing Array Telescope:
  - SETI is obvious partner
  - Any others?

Conclusions

- We are at a critical time for pulsars/fast transients:
  - International projects about to take off
  - Gravitational wave astronomy has started, and low-free GW background could be just around the corner
  - Very interesting time in FRBs (Shri has payed out a $1000 bet)
- The US community needs to invest now, or they will become irrelevant
  - Even staying put takes work and $$
- A Pulsar Timing Array Telescope would qualitatively change the field
  - Thousands of hours for new timing and surveys
  - Go from a GW detection experiment to measuring spectrum and identifying sources
- If not, we need to ensure long-term stability through collaboration and targeted upgrades
- Strategic planning meeting Dec or Jan: let me know if you are interested (kaplan@uwm.edu)

Hardware Developments

- FLAG: 19-beam PAF for GBT, cooled, T_{rec}<17 K
- ALPACA: ~40 element PAF for Arecibo
    - Great for pulsar searching, may need to put on GBT
- UWB feeds from ATNF:
    - Great for timing & transients, depends on RFI environment
- UWB @ GBT would give factor of 2 improvement in efficiency
- ATNF RocketPAF (MkIII): T_{rec} < 20K from 600 MHz to 1.5 GHz, goes up to 2 GHz
- ASTRON L-band apperture array for SKA phase 2
- 4-8 GHz PAF from ASTRON
- MPIfR wants a cooled PAF from ATNF
    - S or C band
- CASPER: amazing backends keep improving



Population
Area (km²)
TMRT
Lovell
Arecibo
LOFAR
FAST
Effelsberg
GBT
Parkes
ATA
CHIME
ATCA
VLA
MeerKAT
OVRO
ALMA
PaST
Tianlai
MWA
10³ people/km²
10² people/km²
10¹ people/km²
10⁰ people/km²
10⁻¹ people/km²
10⁻² people/km²
10⁻³ people/km²

Large-*N* Small-*D*

- hundreds x 12m dishes, densely packed
  - GBT→Arecibo of area
  - Allows subarrays for flexibility
  - Base on MeerKAT to avoid NRE costs and gain buy-in?
  - Center on VLA: save on infrastructure & function as part of ngVLA?
  - Synergies with DSA for FRB science?
- 2 cooled feeds:
  - 0.8-3 GHz
  - 3-12 GHz
- Or: combine with RocketPAF and use larger dishes?
- More flexible design: primary mission is time-domain science, but other constituencies could contribute required elements

Small-*N* Large-*D*

- few x 70m simple dishes, densely packed
  - GBT→Arecibo of area
  - Cheap mesh surface (or similar) can work up to ~2 GHz
  - Allows subarrays for flexibility
  - Much smaller number of feeds: can connect up to ngVLA frequency range
    - Use PAFs?
  - Backend electronics relatively simple
  - Center on VLA: save on infrastructure?
    - Could also help with 0-spacings if have right receivers

Others: Simplify further?

- Should FRBs dominate design considerations?
    - Could get by with separate facilities (DSA, LASA, HIRAX, CHIME, …)
- Will MeerKAT/SKA1 find all of the pulsars anyway?
    - Could settle for intermediate steps (just wide-field instrumentation)
- If we drop pulsar searching & FRB populations:
    - FOV requirements much less
    - Would this end up with something different?