Pulsar Science Requirements for Phase 1

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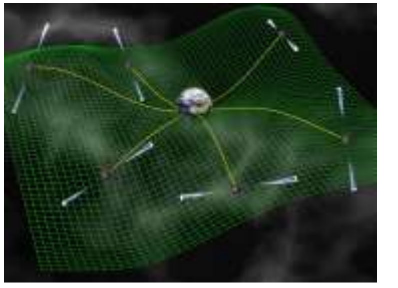
Science → Survey+Timing Requirements → Operating Modes

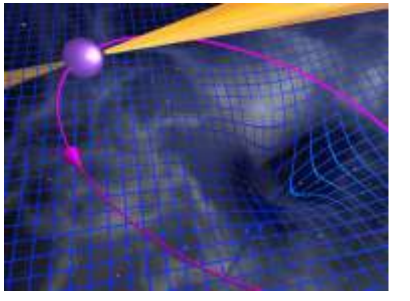
Based on discussions in pulsar community, the DRM, and input to the non-imaging science group for WP2

Baseline Pulsar Science

Kramer et al (2004), Cordes et al (2004)



- **<u>Nano-Hz gravitational waves</u>**
  - Timing of 10^x millisecond pulsars (MSPs) at < 100 ns precision
  - 5 to 10 years needed for detection of GW background(s)
  - Longer program to characterize spectrum, detect single sources
- **<u>Testing GR and other ToGs</u>**
  - precision timing of relativistic binaries
    - NS+NS, NS+BH, NS+WD



- Additional, related science:
  - Multi-messenger synergies (binary mergers → GRBs, GWs)
  - Transients (discovery space)
  - ISM studies (WIM)
    - needed for precision timing (dispersion, multipath)
  - Emission mechanism studies (coherent radiation)
    - fluctuations relevant to precision timing (pulse jitter)

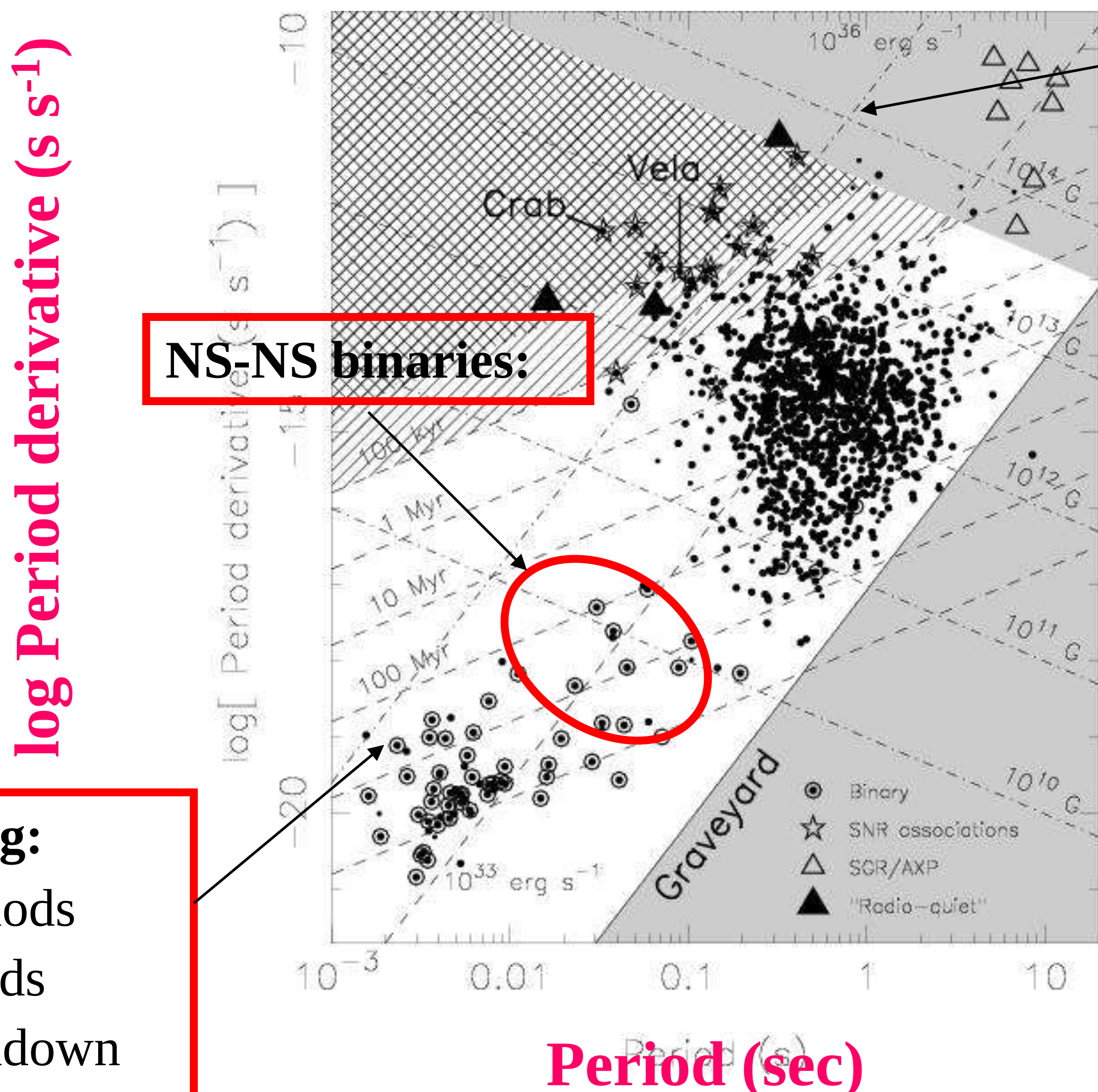
- ~~Enhanced science: (requires extension to 10+ GHz)~~
  - pulsars orbiting Sgr A* (also dark matter in the GC)

Science Requirements

- Discovery of more MSPs and binaries
    - MSPs mostly at higher Galactic latitudes
        - low DMs
        - small perturbations from multipath scattering
        - ➔ low frequencies ok for surveys
        - high frequencies may be sufficient
    - massive binaries at low and high latitudes
        - low latitudes ➔ large DMs, multipath
        - → high frequencies needed
- Long-term timing program:
    - highest precision requires high frequency observations

Assessing the Role of Spin Noise in the Precision Timing of Millisecond Pulsars

Shannon and Cordes arXiv:1010.4794 22 Oct '10



Worst timing:

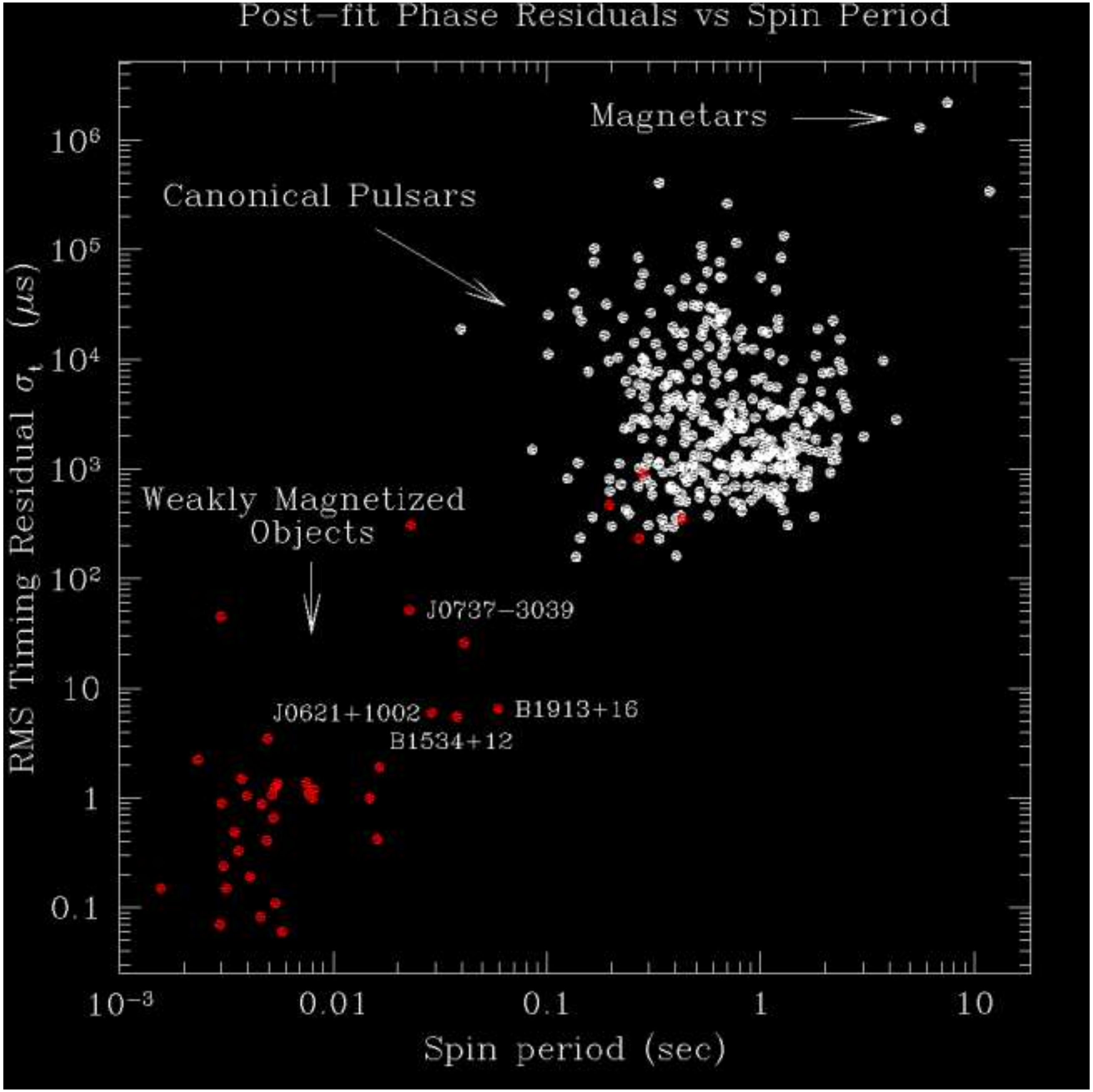
- Long periods
- Large fields
- Fast spindown

Issues:

- Differential rotation between crust and superfluid
- Torque variations
- Accretion events?
  - injected asteroids

Best timing:

- Short periods
- Small fields
- Slow spindown


Post-fit Phase Residuals vs Spin Period
Magnetars
Canonical Pulsars
Weakly Magnetized Objects
J0737−3039
J0621+1002
B1913+16
B1534+12
RMS Timing Residual σ_t (μs)
Spin period (sec)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-3}
0.01
0.1
1
10

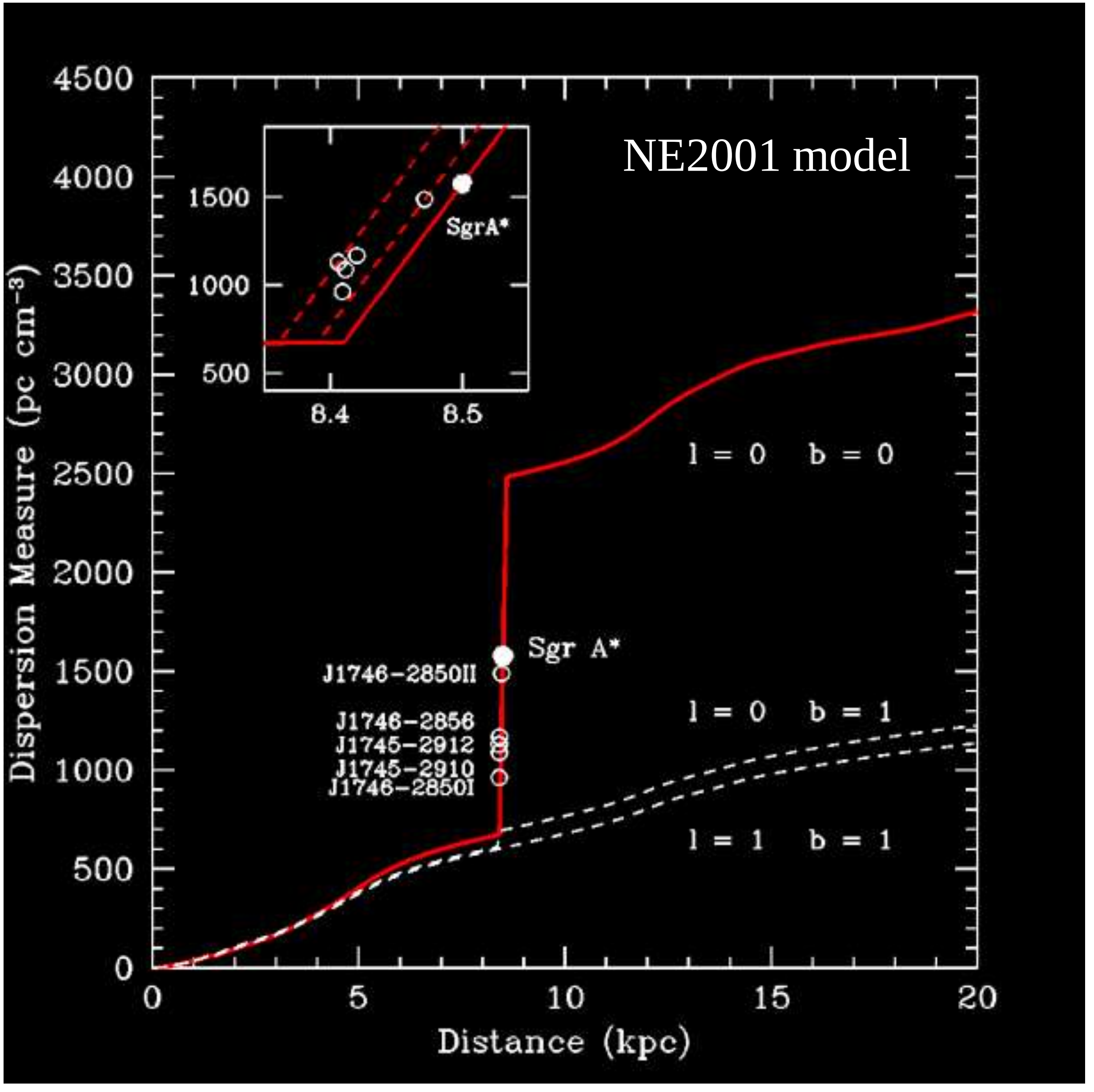
Survey Technical Requirements

- Pulsars have a very broad luminosity function
  - minimum A/T needed to take new steps toward a full Galactic census and to achieve adequate timing precision
  - up to Arecibo/FAST equivalent
  - single-pixel system ok
- Galactic plane survey $|b| \leq 5^\circ$ (excl. GC)
  - reach D_{max} ~ 15 kpc for most luminous 20% of pulsars
  - 300 deg^2 with 10 min/direction
  - 1 to 3 GHz, 1 GHz bw, 0.1 MHz channels, 64 μs samples
- Local and out-of-plane survey (D_{max} ~ 5 kpc)
  - ≥ 20,000 deg^2 with 10 min/direction
  - ≥ 0.2 GHz with 50 to 100 MHz bw, ~20 KHz channels, 64 μs
- Galactic center survey:
  - central pixel the biggest payoff (1”); useful to do inner 0.05 deg^2)
  - 8-16 GHz, 8 GHz bw, 10 MHz ch, 1 ms

Survey Technical Requirements II

- Survey methodologies:
  - Blind survey over “full” field of view (dishes, AAs)
    - Need separate survey analysis for each pixel
    - Drives requirements toward compact array (< 1 km)
    - Direct beam forming or correlation approach with fast dumps
    - Severe processing requirements
  - Targeted approach I:
    - use comprehensive, multi-λ surveys to identify point source, pulsar candidate sources
    - radio continuum x (optical + X-ray + γ-rays)
    - ➔ far smaller processing requirements, data management
  - Targeted approach II: point and shoot
    - specific regions: Galactic center

Dispersion Measures to the GC



Timing Technical Requirements I

- Arrival times = signals + noise elements
  - achromatic + chromatic components
  - > 5 year program
- Achromatic:
  - spindown (deterministic part)
  - orbital perturbations
  - gravitational wave perturbations
  - spin noise (torque variations) + phase jitter
  - solar system ephemeris errors

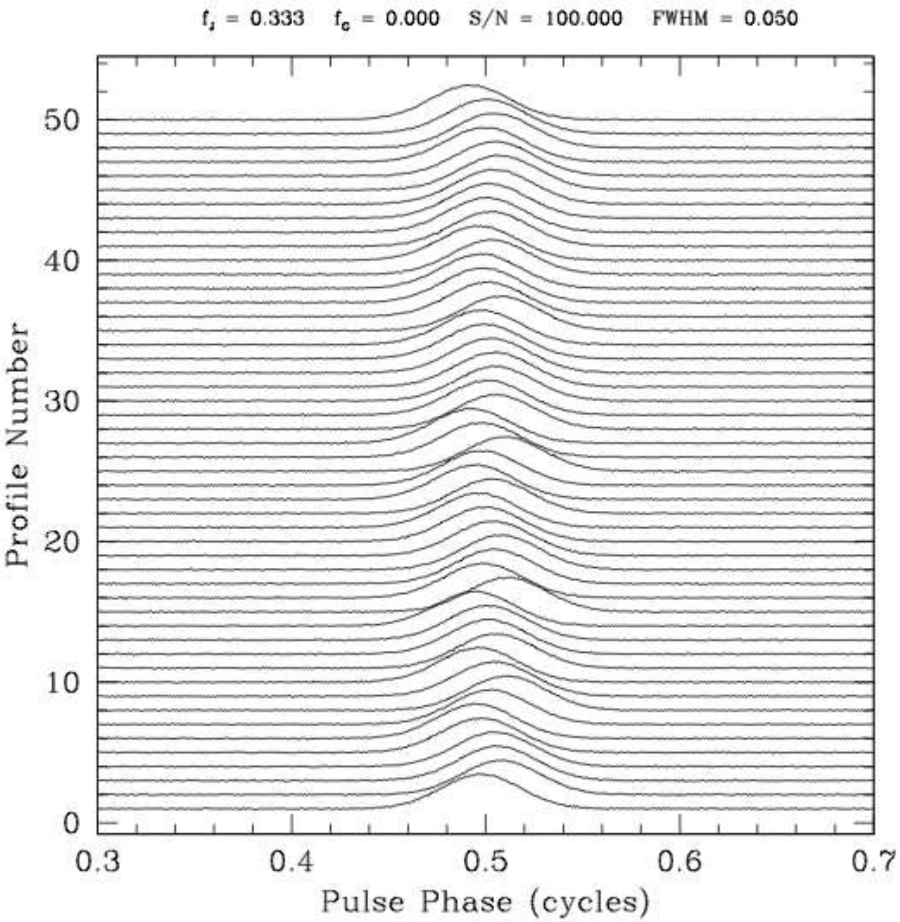
signal (spindown, orbital perturbations, gravitational wave perturbations)

noise (spin noise, solar system ephemeris errors)

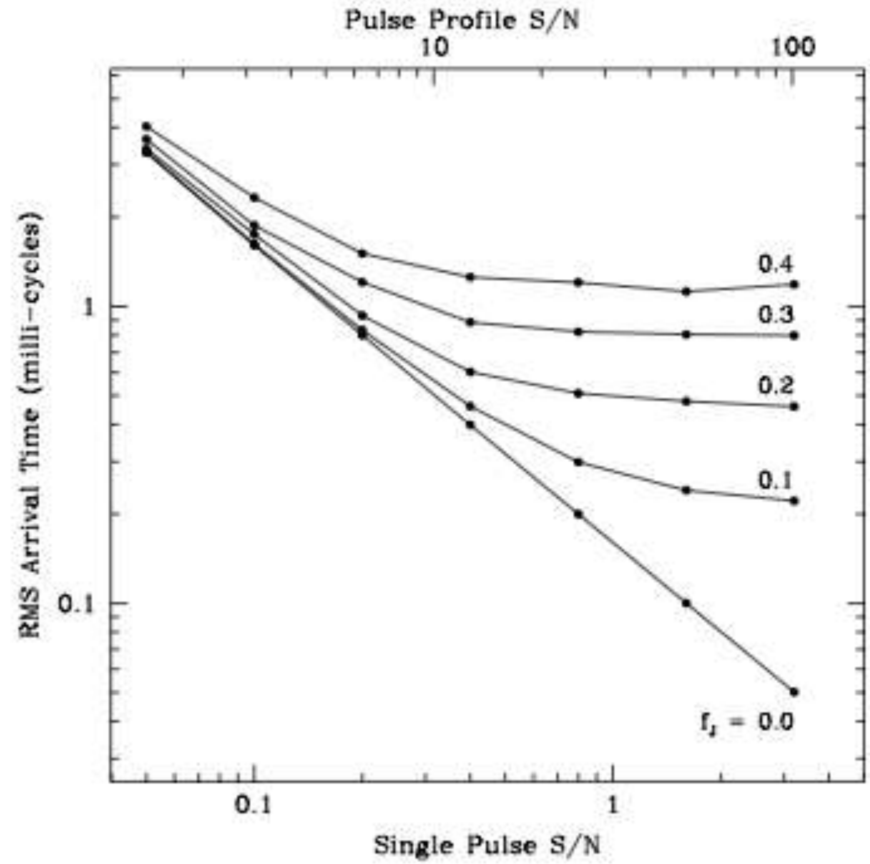
- Chromatic:
  - interstellar dispersion (+ IPM + ionosphere)
  - interstellar scattering (several terms, diverse f dependences)
- GW detection is the most demanding timing application
  - pulse widths ≥ 30 μs, need to time tag to < 100 ns ➔< 1 part in 300
- Need
  - a broad range of frequencies to separate chromatic and achromatic
  - higher frequencies so that corrections for chromatic effects are small
    - ~ one octave in the 1 to 3 GHz range
  - stable instrumentation, particularly polarization: δt_{pol} << 100 ns)

Time of Arrival Precision
A Measurement Model for Precision Pulsar TIming

Pulse phase jitter

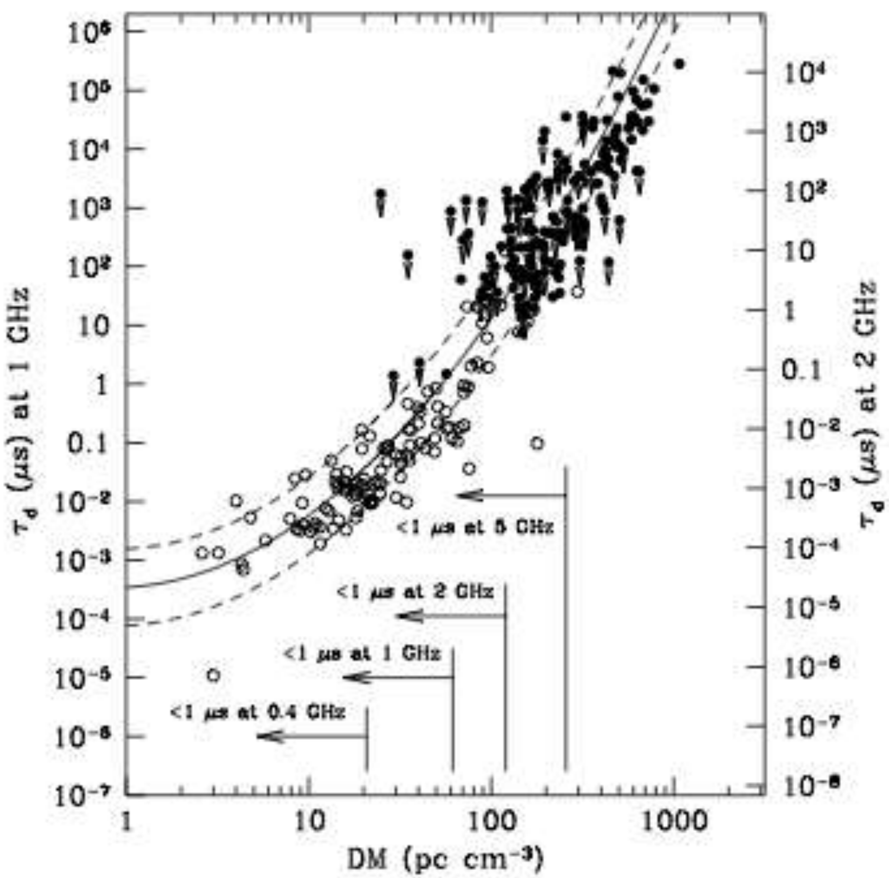


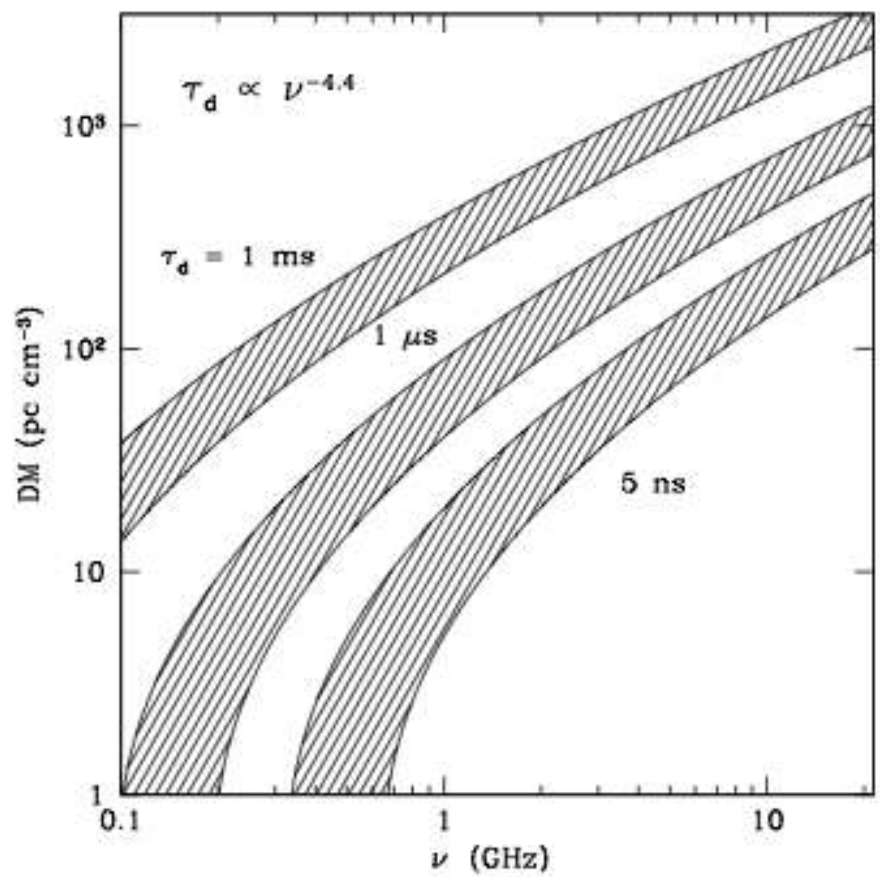
Cordes & Shannon
arXiv:1010.3785 (19 Oct '10)

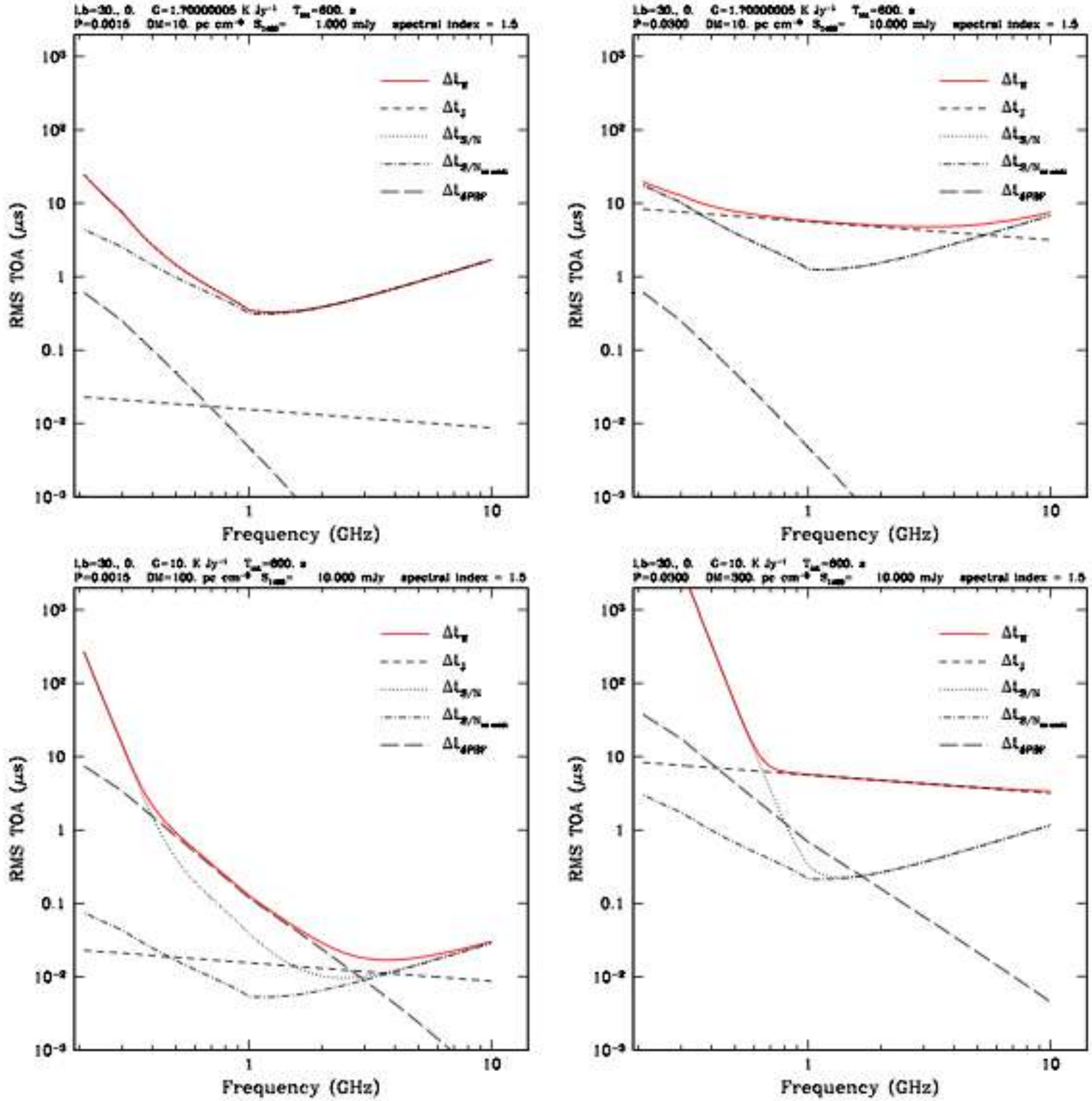


ISM Perturbations

- DM variations: simple to deal with
- Multipath and refraction: many effects, with different frequency dependences
- Dominated by time-variable pulse broadening.






l,b=30., 0. G=1.70000005 K Jy⁻¹
P=0.0015 DM=10. pc cm⁻³ 1.000 mJy spectral index = 1.5
l,b=30., 0. G=1.70000005 K Jy⁻¹
P=0.0300 DM=10. pc cm⁻³ 10.000 mJy spectral index = 1.5
l,b=30., 0. G=10. K Jy⁻¹
P=0.0015 DM=100. pc cm⁻³ 10.000 mJy spectral index = 1.5
l,b=30., 0. G=10. K Jy⁻¹
P=0.0300 DM=300. pc cm⁻³ 10.000 mJy spectral index = 1.5
RMS TOA (μs)
Frequency (GHz)

Timing Technical Requirements II

- GW detection:
  - cross correlation of timing residuals between N_{MSP} MSPs to detect correlated signal (Hellings & Downs angular correlation)
  - Strain amplitude spectrum $h(f) = 10^{-15} f^{-2/3}$ for f in cy/yr:
    - post-fit rms over a 5-yr data span $\sigma_{GW} \sim 20$ ns for each pulsar.
  - Required N_{MSP} depends on TOA measurement errors and timing noise levels
    - most optimistic estimate: N_{MSP} =20 with < 100 ns timing precision.
    - TN considerations suggest N_{MSP} could be as large as 100
  - ISM multipath + phase jitter + timing noise implies TOAs may not be noise limited
  - Phase 1 requirements:
    - need high timing throughput: N_{MSP}, integration time per TOA, and observation rate (TOAs per month)
    - benefit of subarray capability (bright pulsars require less A/T)

Minimum Requirements, etc.

- Options for improving GW detection
  - Noise limited TOAs
    - weak pulsars, small telescopes: increase bw, A/T
  - Jitter limited:
    - bright pulsars, large telescopes
    - longer integration times
  - ISM limited:
    - larger DMs worse unless multipath is mitigated
    - large bandwidths, multi-channel TOA fitting
  - Timing noise limited:
    - achromatic (like GWs)
    - need to choose low-TN pulsars
- Overall: detection significance is improved by increasing the number of MSPs timed:
  - $SNR_{CCF} \sim N_{MSP}$ for small SNR and $\sim N_{MSP}^{1/2}$ for large SNR
- Need A/T ~ 1000-2000 $m^2\ K^{-1}$ for 1-3 GHz + subarray capability

Extra Slides

Galactic Center Pulsars

Matter Content of the GC

Sgr A*

Black Hole

$4\times10^{6}\ M_\odot$

Maximal Spin?

Young Stars < 1 Gyr

$\rho \sim 10^{5.3}\ M_\odot\ pc^{-3}\ r_{pc}^{-7/4}$

IR astrometry/spectroscopy

Old Stars

"Oort-cloud" like distribution

Neutron Stars

← GWs ⟷ kicks ←

young (pulsars) and old

timing, Faraday rotation

Stellar-Mass Black Holes

$\sim 10^{4.3}$

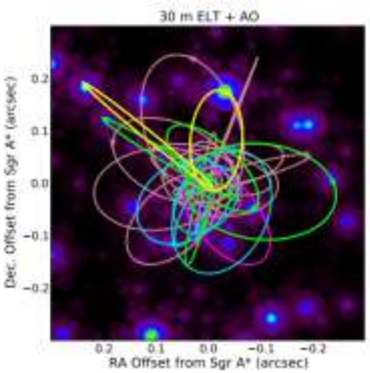
Dark Matter (e.g. neutralinos)

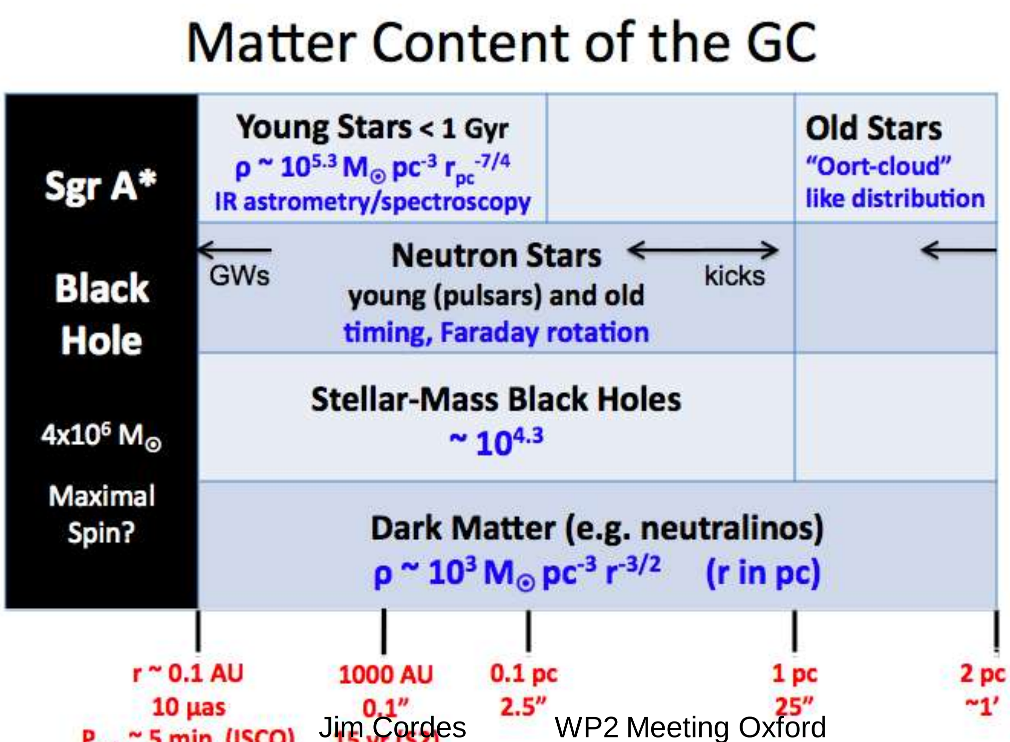
$\rho \sim 10^{3}\ M_\odot\ pc^{-3}\ r^{-3/2}$ (r in pc)

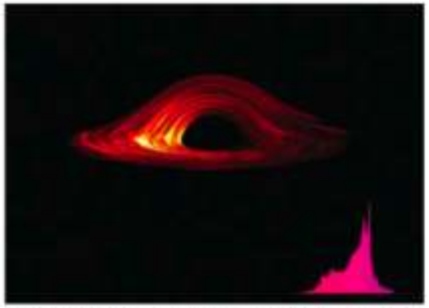
r ~ 0.1 AU	1000 AU	0.1 pc	1 pc	2 pc
10 μas	0.1"	2.5"	25"	~1'
P_{orb} ~ 5 min (ISCO)	15 yr (S2)			

Basic Questions about the GC

- **Sgr A***
  - **What is the distance to Sgr A*?**
  - **Is Sgr A* at rest in the center of the Galaxy?**
- **The black hole**
  - **What is the mass of Sgr A*?**
  - **Is Sgr A* a black hole with an event horizon?**
  - **How fast is Sgr A* spinning?**
  - **What processes take place near the innermost stable circular orbit (ISCO) and what is its radius?**
  - **Does gravitational lensing conform to GR?**
  - **Is the quadrupole moment of Sgr A* consistent with that expected from GR no-hair theorems? ($Q_2 = -J^2/M$)**
- **The star cluster**
  - **What is the origin of young stars orbiting Sgr A*?**
  - **How many compact objects --- NS and BH --- are in the star cluster around Sgr A* and what is their spatial distribution?**
- **Dark matter in the GC**
  - **Do the orbits of stars around Sgr A* conform to GR or do they probe Newtonian encounters with objects in the star cluster or perturbations from dark matter**
- **Other**
  - **What is the magnetized plasma like surrounding Sgr A*?**







Signs of spin. Predicted appearance of a turbulent accretion disk around a Schwarzschild black hole as viewed by a distant observer at an inclination angle of 80° (that is, the disk is almost edge-on). The plot in the lower right shows the profile of iron line emission from the disk, assuming that the line is excited locally by the predicted disk emission. (See also the animation at http://jilawww.colorado.edu/~pja/black_hole.html.)

Research Plan for Probing the Galactic Center with Stellar Test Particles

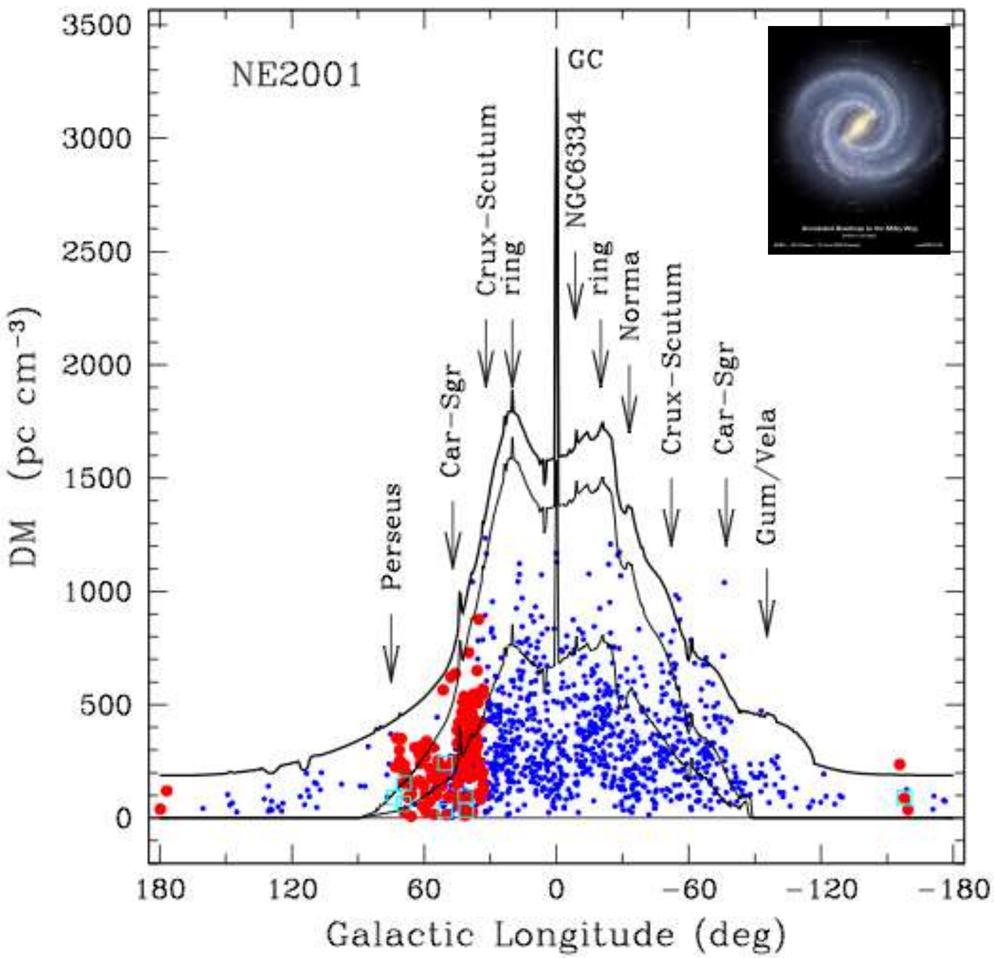
- Radio
  - Survey pulsars behind the plasma scattering screen (15 arcmin radius) with special emphasis on the inner 1 pc (25 arcsec); not confusion limited
    - need to account for intermittency from fast precession and lensing
  - Timing of isolated pulsars + those in NS,BH binaries ($\delta r < 10^{-5}$ AU)
    - constrain NS and BH populations, dark matter from orbital perturbations
    - test GR in the strong gravity regime
      - orbital and geodetic precession; frame dragging effects
      - lensing with low impact parameters
      - determine spin of central black hole and test the no-hair theorem
    - characterize magnetized plasma (DM, RM, SM)
- IR:
  - Survey for IR stars down to confusion levels (single aperture and interferometric)
    - characterize stellar populations and their origin
  - Astrometric and spectroscopic measurements for orbit determinations, including orbital perturbations from GR, dark matter and other stars

- Radio transient phase space
- Plasma propagation effects
  - IGM, ISM
- Key Source Classes and Targets:
  - Prompt GRBs and Orphan afterglows
  - Intermittent pulsars
  - Galactic center transients
  - Exploration of phase space (aka fishing expedition)
- Commensal, synoptic surveys
- Multi-λ and multi-messenger synergies
  - cross triggering
    - e.g. NS glitch events for GW searches
  - joint statistics (radio-IR, etc)

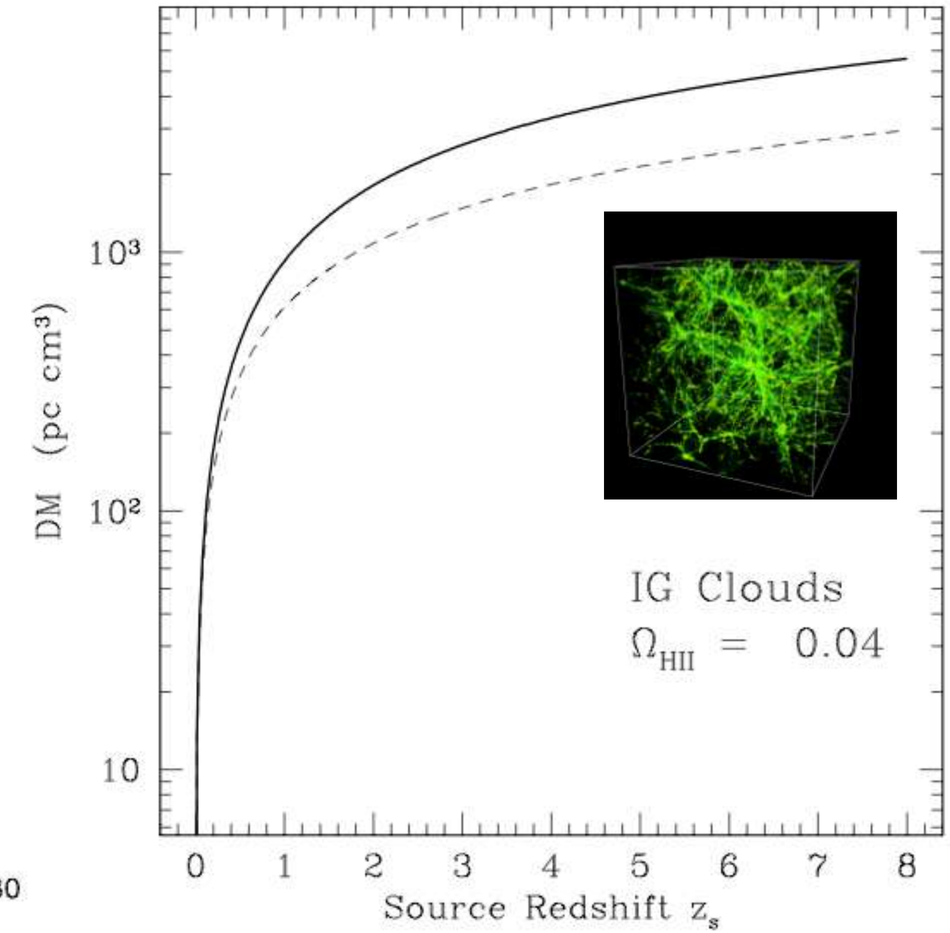
- Exotica
  - Evaporating BHs
  - ETI technomarkers
  - particle events
  - etc

Dispersion Measures

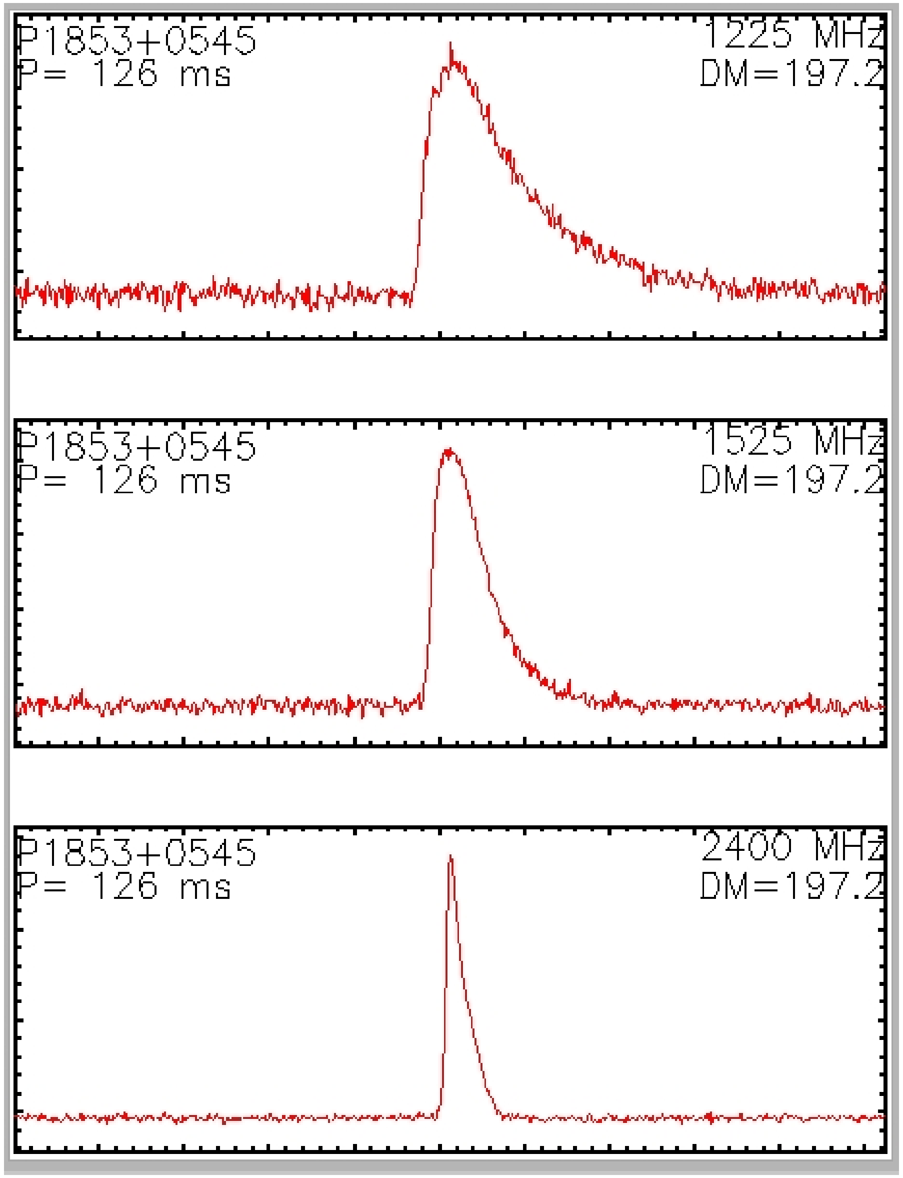
ISM (b=0)



IGM

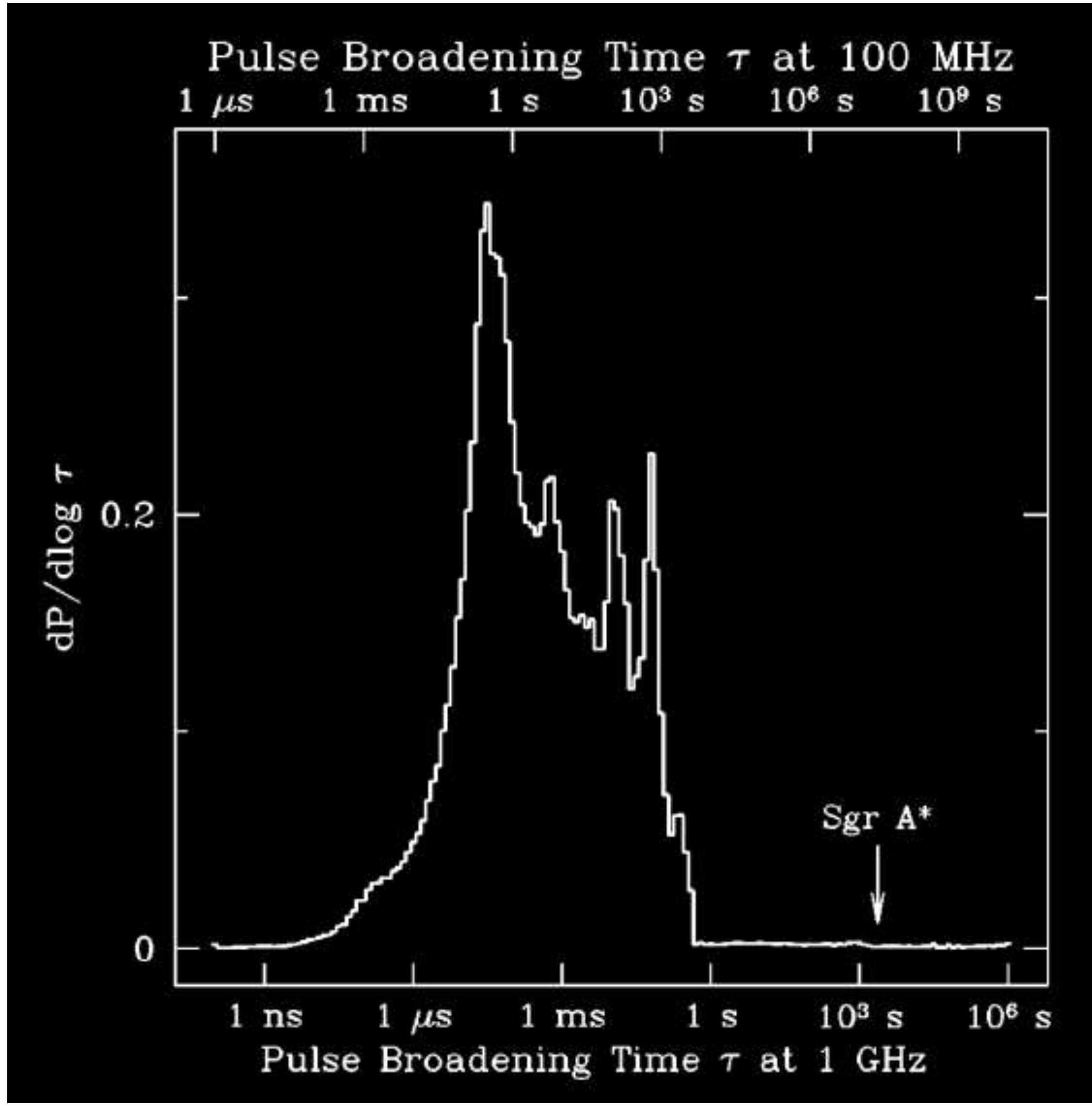


Pulse Broadening from Interstellar Scattering



What Broadening Times to Expect?

Distribution of scattering times from Galactic sources calculated using NE2001 electron density model



Points

Transients cover a huge parameter space, richly populated

- Compact objects, extreme matter states
- Intervening media (IPM, ISM, IGM)

A full census requires telescopes with:

- Widefield sampling (larger Ω_i important for survey completeness)
- High resolution ν-t processing (< ms, > kHz) (RFI excision, intrinsic)
- Low-mid-high sensitivity
- Operation as a radio synoptic survey telescope
- Commensal observations with multiple backend processors
- New algorithms + HPC + Moore's law

Sensitivity can be sacrificed for FoV:

- Flexible subarray modes
- Very bright, but rare bursts $\Rightarrow$ fly's eye mode (subarray)

Radio transient studies are part of a multi-λ program:

- Existing antennas+multipixel feeds: Arecibo, GBT, Jodrell, Parkes
- Pre-SKA arrays: LOFAR, LWA, MWA, ATA, EVLA, ASKAP, MeerKat
- Cross-λ triggers (radio ←→ optical, X-ray, γ-ray)
- Cross-λ source classification

Telescopes & Instrumentation Needed

- Radio:
  - Telescopes need to operate at ≥ 10 GHz
    - Pre-SKA: 100m-64m class telescopes
      - GBT, Effelsberg, EVLA, Parkes, Sardinia
      - pilot surveys + timing (6 pulsars already detected)
    - SKA Pathfinder (MeerKAT) (100m equivalent)
    - SKA Phase 1 (Arecibo equivalent)
    - SKA Phase 2 (10 x Arecibo equivalent)
  - Instrumentation for dedispersion, periodicity surveys and transient surveys
    - samplers, real-time processing
- IR
- High performance computing

Synergies

- mm VLBI to image event horizon
- X-ray imaging of accretion disk
  - lensing from Sgr A*
  - transients
- ELTs (E-ELT, TMT, GMT)
  - astrometry + spectroscopy of GC IR stars
  - understanding stellar populations
  - tests of GR
  - transients