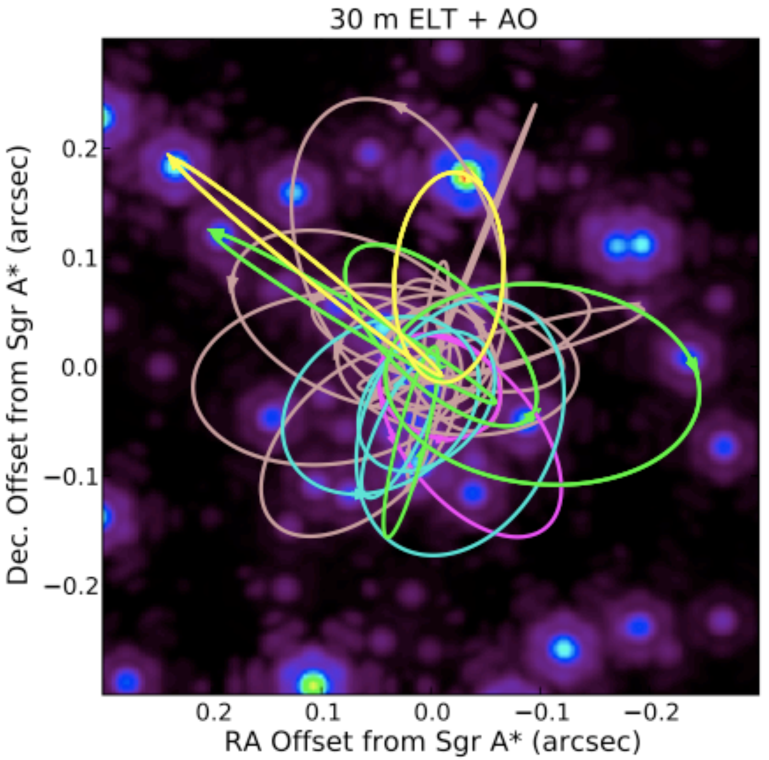
A Pulsar Trifecta for the Galactic Center: Gravity, Dark Matter, and Exotic Stellar Populations

J. Cordes (Cornell)

- Scientific returns
- Evidence for a Galactic center pulsar population
    - nearby pulsars, SN rate, radio point sources, diffuse Fermi
    - constraints from the radio spectrum of Sgr A*
- IR astrometry + pulsar timing complementarity
- A radio program for the decade

Pulsars Orbiting Sgr A*



← ~ 5000 AU →

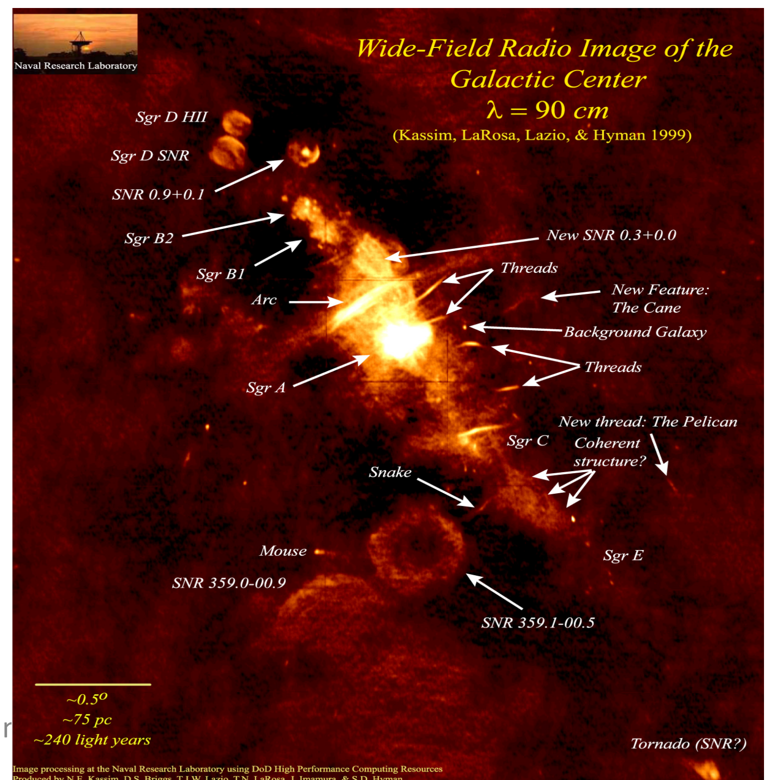
Simulation for TMT+AO
Ghez et al. (Astro2010)

Stellar populations near Sgr A*:

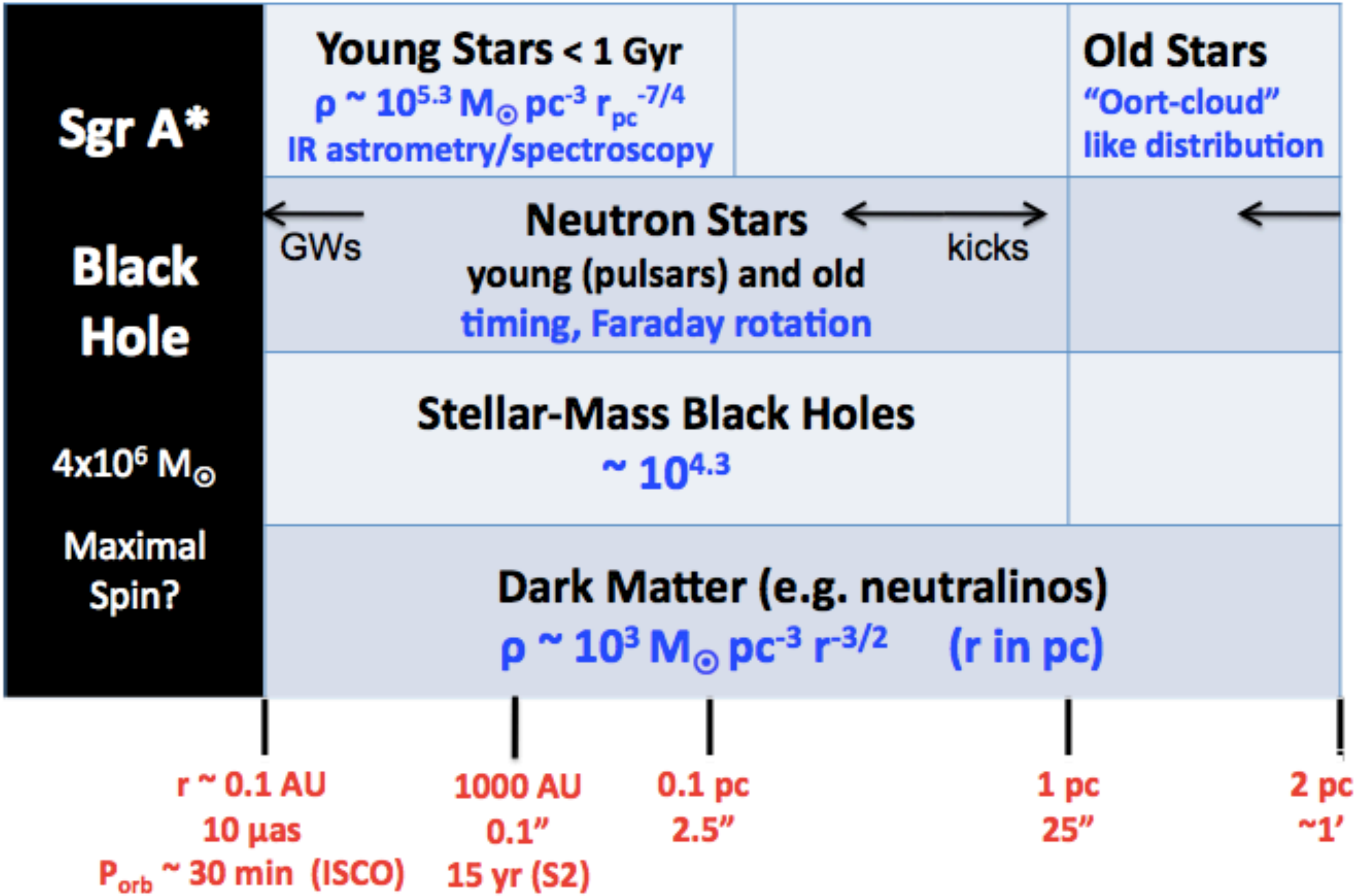
- Post-MS OB giants, supergiants
- B stars within 1 arc sec

Origins not understood but:

- these are progenitors of neutron stars
- many should be active pulsars
- some should be on very compact orbits



Matter Content of the GC



Basic Questions about the GC

How do black holes work?

What controls the masses, spins, and radii of compact objects?

What is dark matter?

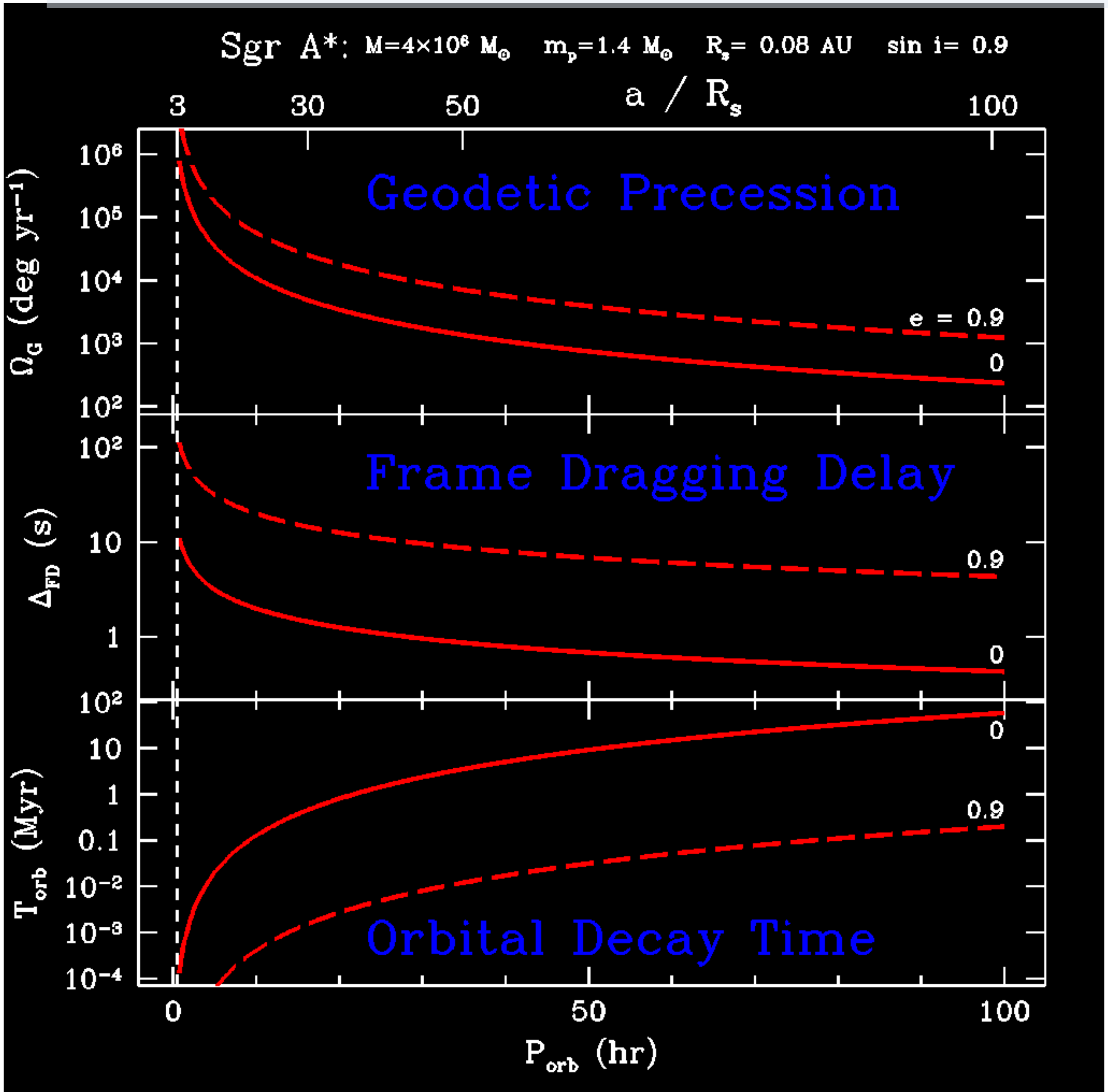
Basic Questions about the GC

- 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*?

Punchlines

- GC pulsars can provide fundamental measurements about gravity and probe the complexity of stellar, DM populations
- Radio timing ≥ 10^3 times better than IR astrometry in orbital precision
- Canonical pulsars (~1 s, 10^{12} G) and millisecond pulsars expected near Sgr A*
    - CPs are detectable but MSPs are not (radio)
- Expect ≤ a few × 100 CPs within 10” of Sgr A* that beam toward Earth
- CPs suffice for the timing program
    - GR effects and dark-matter perturbations are very large
- A program of searching and timing will make use of the GBT, DSN, EVLA, MeerkAT, and the SKA

Post-Keplerian Effects for Pulsars Orbiting Sgr A*

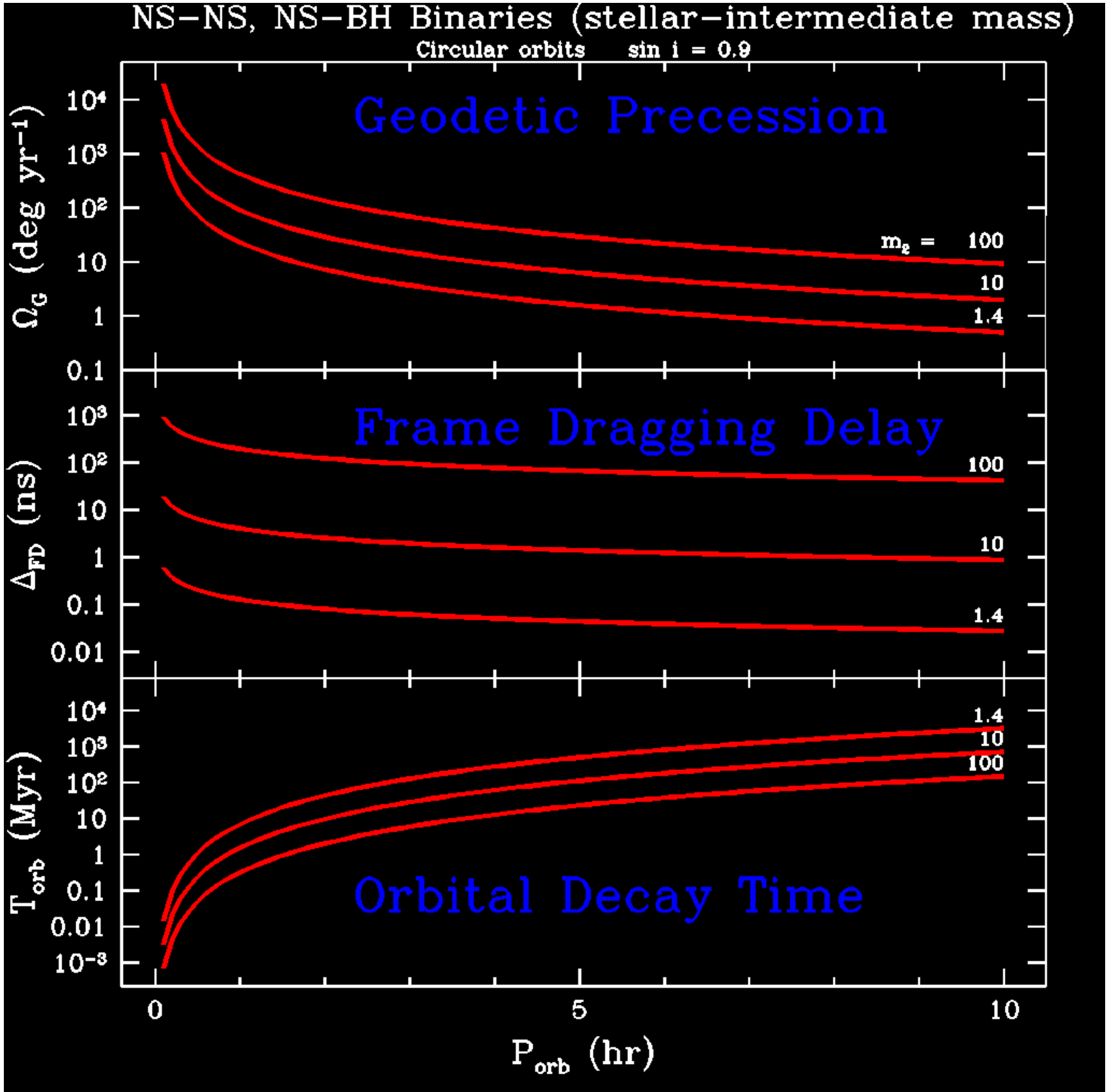


Effects are large enough so that even long-period pulsars with signficant timing noise are suitable for measuring relativistic effects

Motivations and issues:

Cordes & Lazio 1997
Wex & Kopeikin 1999
Kramer et al. 2004
Pfahl & Loeb 2004
Deneva et al. 2009

Post-Keplerian Effects in Compact Binaries



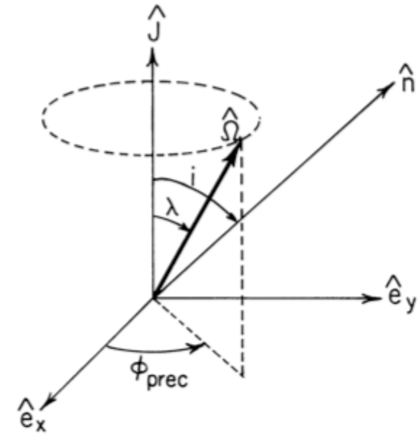


FIG. 5.—Geometry of geodetic precession

Frame-dragging due to companion's spin (Lense-Thirring precession)

T_{orb} = 7 Myr for NS-NS binary in a 1-hr orbit

Strong-field Effects in Pulsar Timing

Strong-field beamed emission when pulsar is in weaker field

Wang et al. 2009

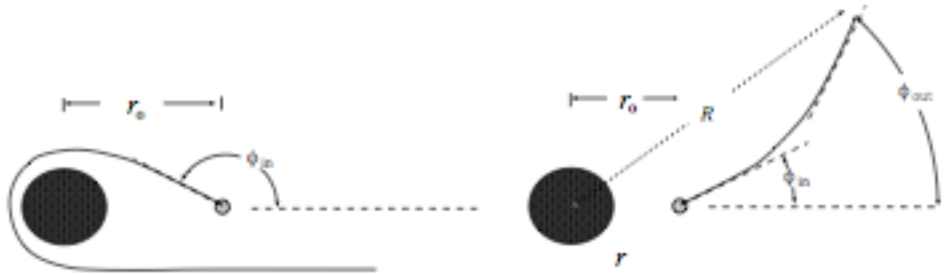


Fig. 1.— Photon path from radial coordinate r_0 to R. The path on the right indicates mild bending of the path due to spacetime curvature. On the left is shown the highly bent photon path which has an impact parameter near the critical value of photon capture, and a ϕ_{out}, at large R, of 2π.

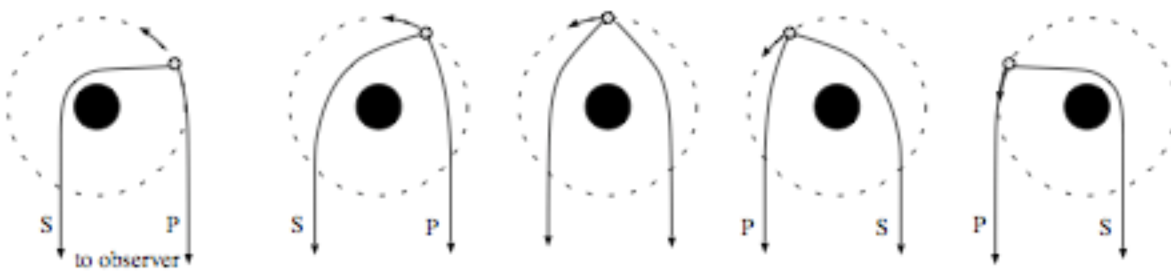


Fig. 6.— Prograde and retrograde photon trajectories. The pulsar is shown orbiting in the counterclockwise direction around a much more massive black hole. The leftmost cartoon shows that the observing radio telescope receives a primary (P) direct pulse and a highly bent secondary (S) pulse. The subsequent panels show trajectories as the pulsar continues its orbtial motion. The primary trajectory has increased bending and the secondary less, until the pulsar is directly opposite the receiver and the two trajectories are symmetric. The following panels shows how the prograde trajectory then becomes the primary (less bent) trajectory.

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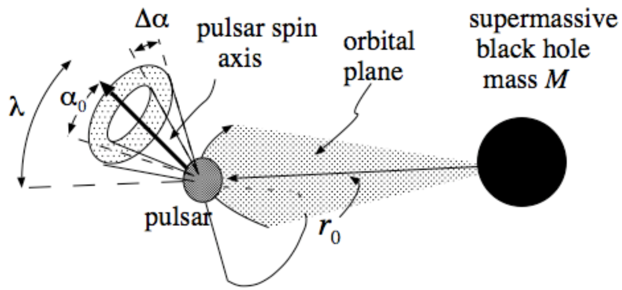
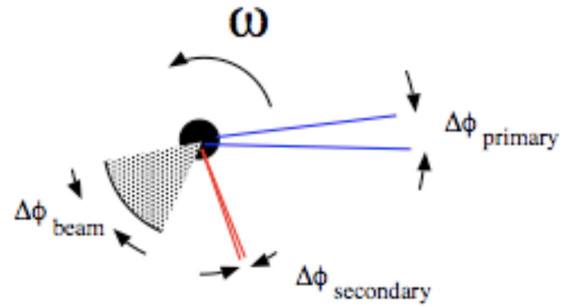
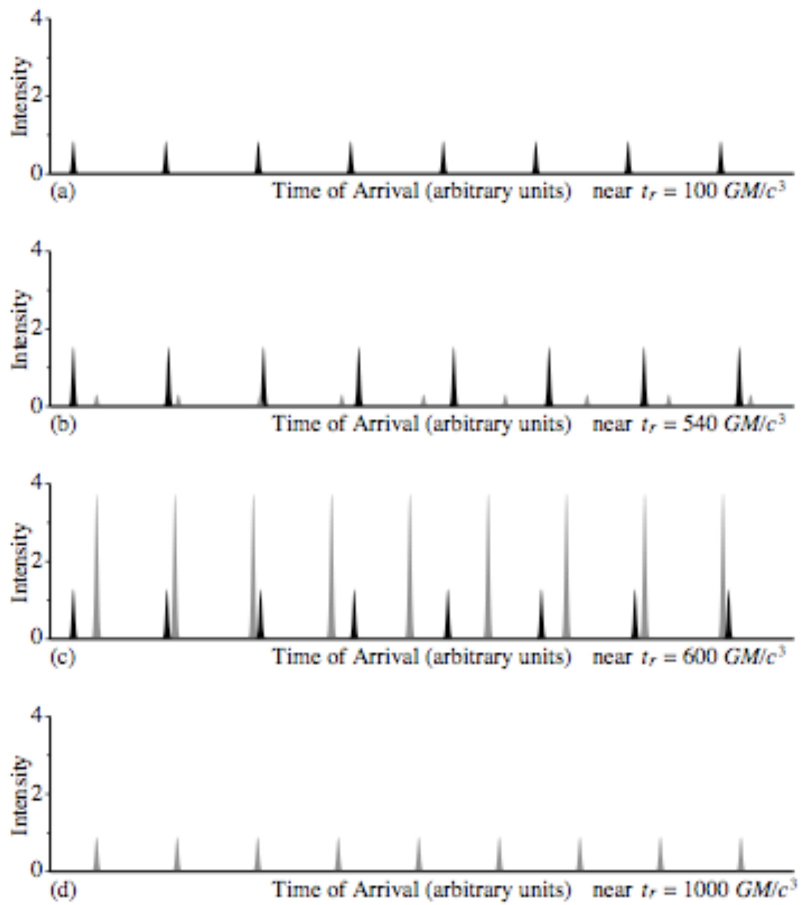




"Keyhole" directions for observed primary pulse



Wang et al. 2009

Fig. 9.— The appearance of received radio pulses for several orbital epochs of a pulsar orbiting with radius $30 \times GM/c^2$. The pulsar rotation rate is assumed to be much greater than the orbital frequency.

Constraints on Pulsar Numbers

- Overall: ~100s in inner 100 pc beamed toward us
  - Massive young stars:
    - ~100 NS in last 6 Myr (Bartko+ 2010)
  - Supernova rate: (gamma, X rays)
    - ~100 to 400 r < 150 pc (Diehl et al 2006; Crocker + 2010)
  - Diffuse γ-rays:
    - population of MSPs ~1000s r < 200 pc (Abazajian 2010, Boyarsky+ 2010)
  - Radio point sources (steep spectrum):
    - ~1000 r < 150pc (Lazio + JMC)
  - Diffuse radio flux contamination of Sgr A* spectrum:
    - < 200 r < 1 arcsec (R. Wharton, Cornell GS)
  - Radio pulsars in a GC population:
    - five within ~100 pc (Johnston + 2006; Deneva + 2009) → 1000s r < 300 pc
    - Non detections in GBT survey of Sgr A* → < 90 r < 1 pc (Macquart +)

DISCOVERY OF THREE PULSARS FROM A GALACTIC CENTER PULSAR POPULATION

J. S. Deneva[1], J. M. Cordes[1], and T. J. W. Lazio[2]

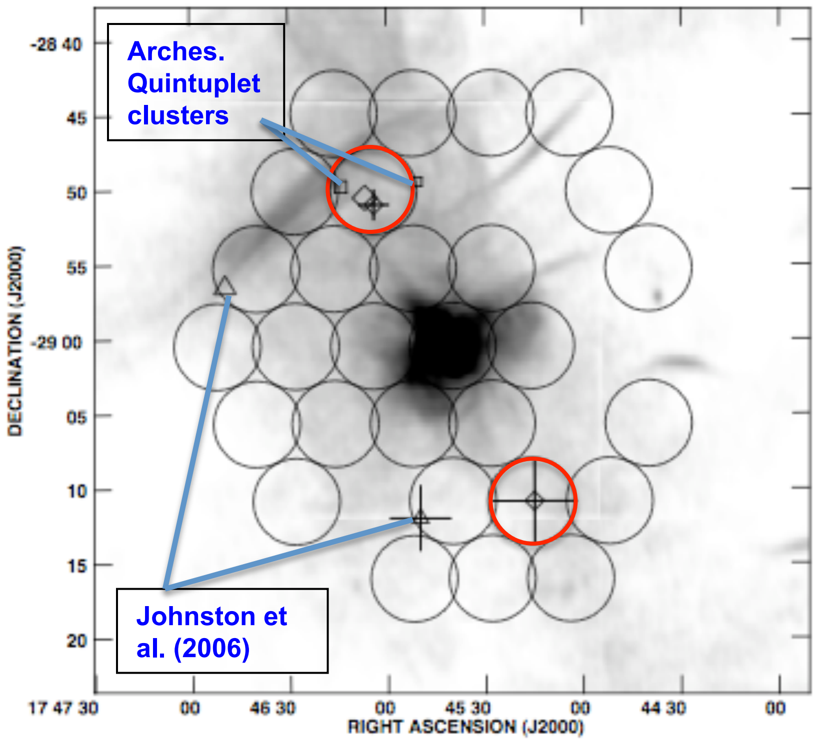


Fig. 1.— The grid of 2 GHz survey pointings from 2007 overlaid on a 0.33 GHz image of the Galactic center (LaRosa et al. 2000). Circles correspond to the 5.8′ FWHM beam size of the Green Bank telescope at 2 GHz. Diamonds denote the positions of J1746−2850I, J1746−2850II, and J1745−2910, and triangles denote the positions of J1746−2856 and J1745−2912. Crosses show actual position uncertainties. For J1746−2850I and J1746−2856 the position uncertainties are smaller than the marker size. Squares show the positions of the Arches and Quintuplet clusters; the squares are four times larger than the actual cluster sizes.

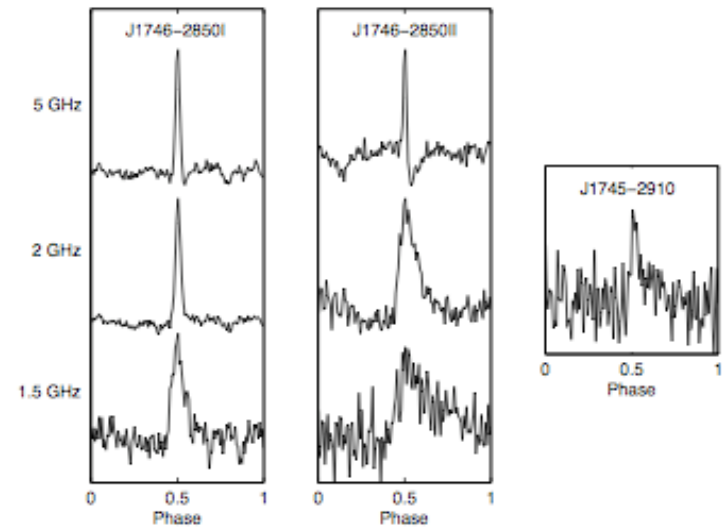
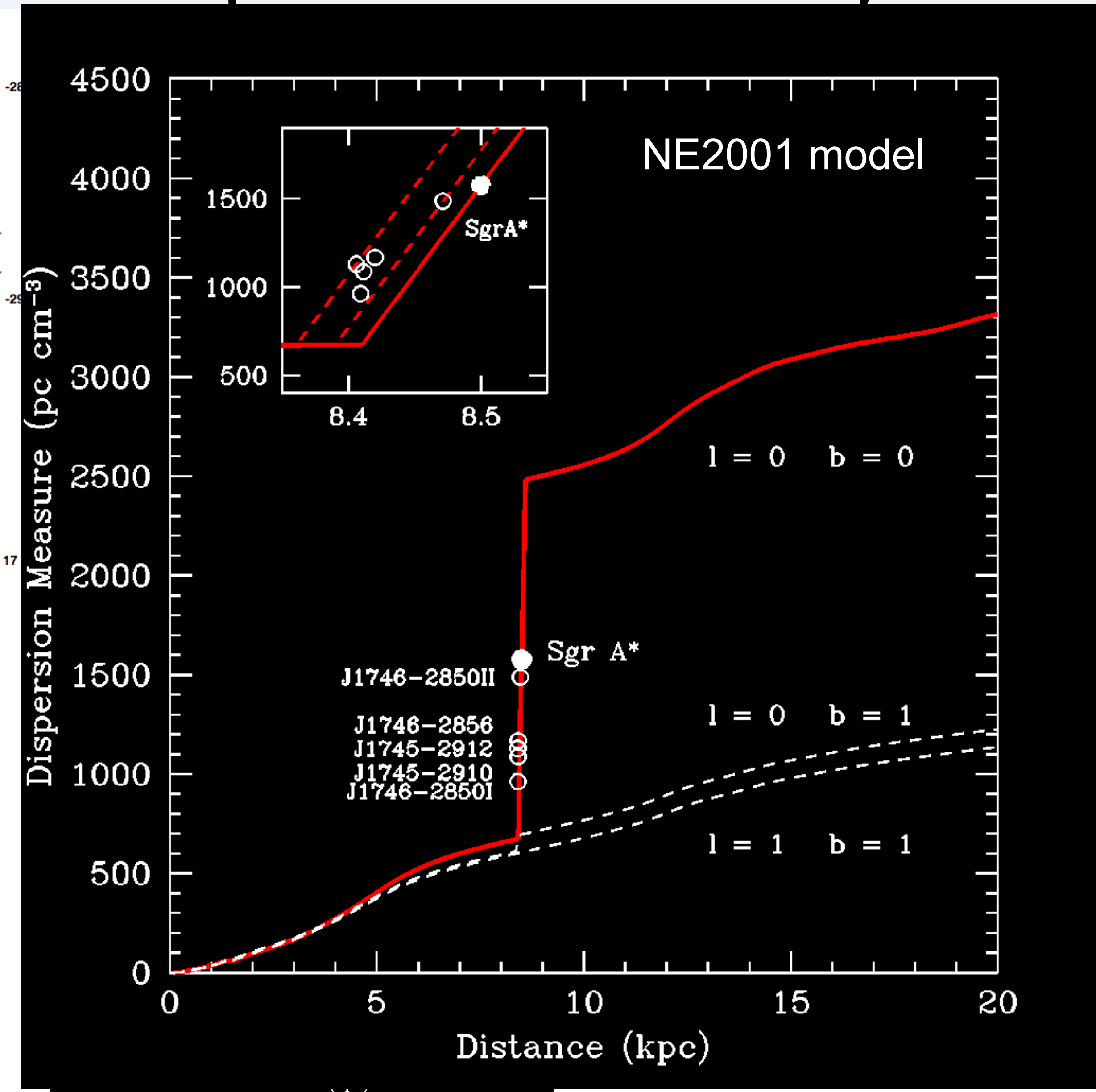


Fig. 2.— Pulse profiles at 5, 2, and 1.5 GHz for J1746-2850I (left), J1746-2850II (middle), and J1745-2910 (right). The 1.5 GHz profile for J1746-2850I and the 2 GHz profiles for J1746-2850I and J1746-2850II are cumulative averages over all observations at the respective frequency. The 5 GHz profiles for the two pulsars are from a single observation. The 1.5 GHz profile for J1746-2850II is from the single L-band detection of this pulsar, and the 2 GHz profile for J1745-2910 is from the discovery pointing for the object. Scattering broadening results in an exponential tail to the pulse profiles at 2 and 1.5 GHz. J1746-2850II is scattered most severely of the three pulsars due to its high DM.

Interpretation of Early Discoveries



kes 64m:

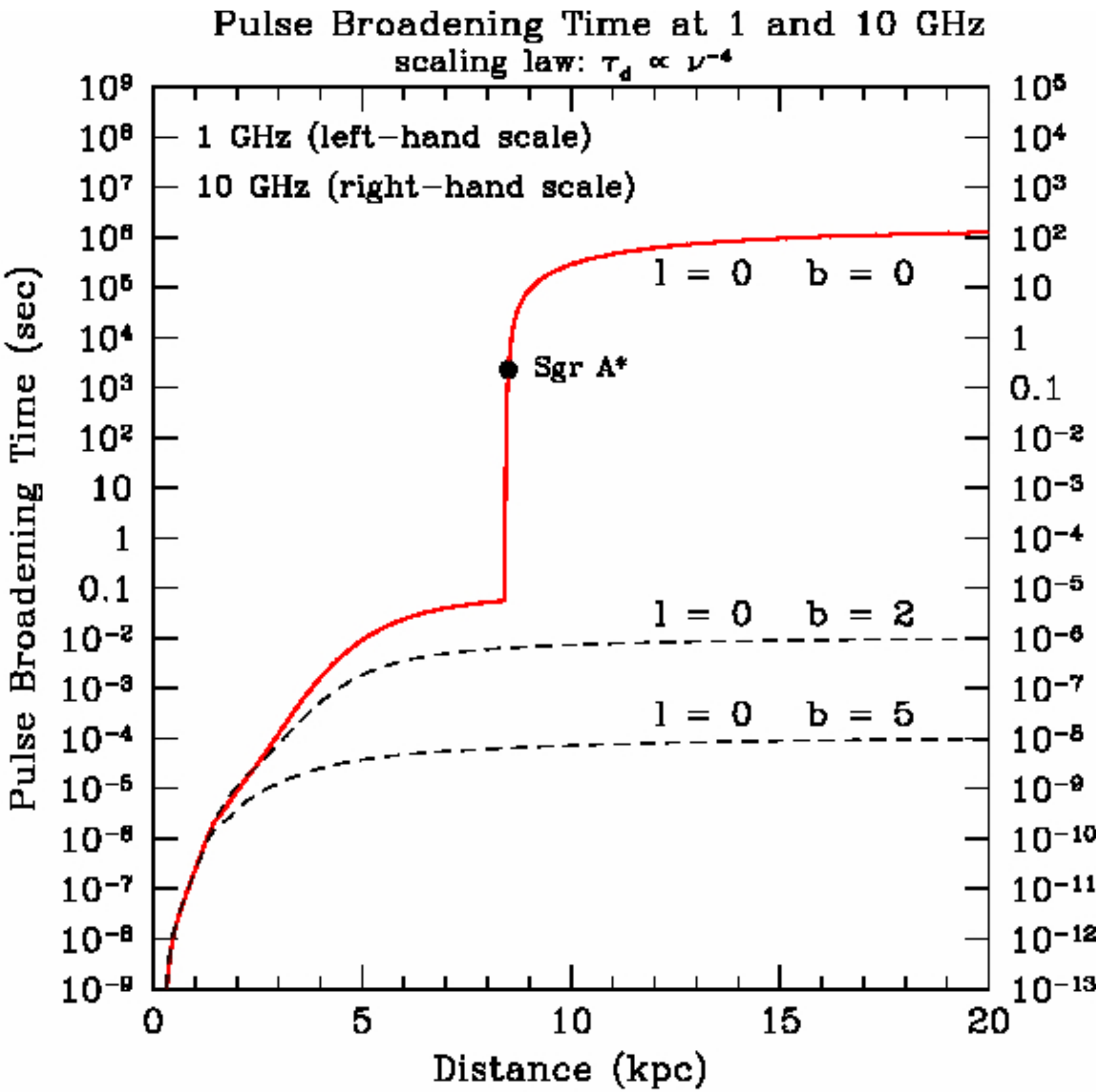
s found with high

T 100m:
zio (in prep)
ars
ke (14 kyr)
known DM
Johnston et al.

e of the existence
f pulsars

t the pulsars reside
(and probably less)

Pulse Broadening from Radio Wave Scattering



15 GHz => 1/5 smaller pulse broadening than 10 GHz

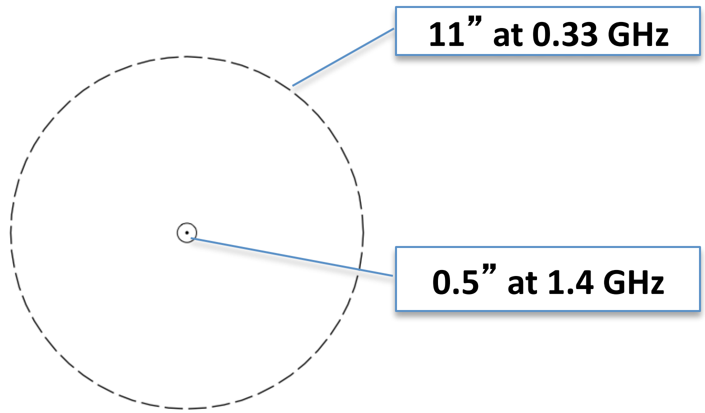
Sgr A* angularly broadened by electron-density variations to about 1 arc sec at 1 GHz

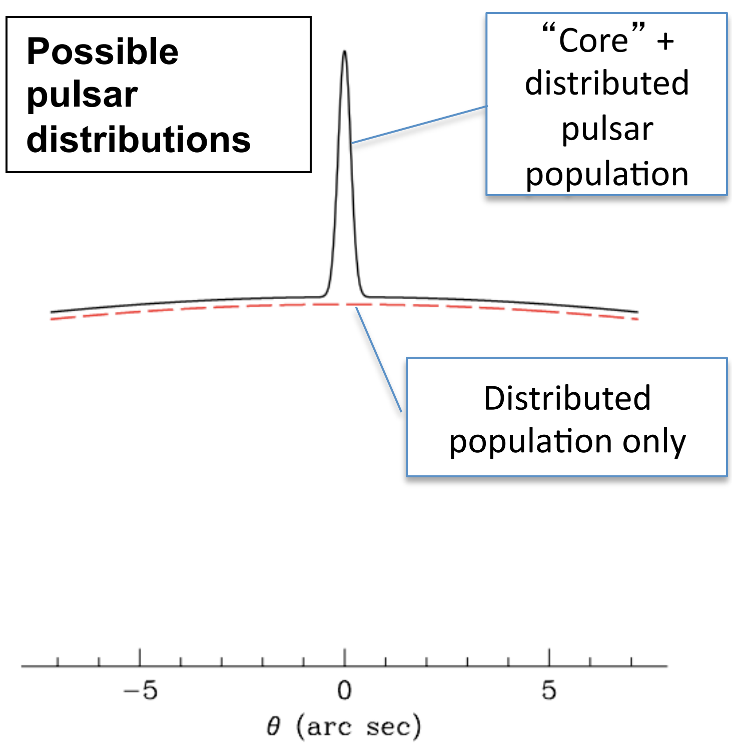
Pulsars near Sgr A* will be temporally broadened to $\tau_d \approx 2000$ sec ν^{-4}, ν in GHz

Need ≥ 10 GHz to reach Sgr A*

Can reach GC pulsars on the near side using lower frequencies where pulsars are stronger

Flux confusion between Sgr A* and distributed emission





Scattering diameter of Sgr A*

$$\theta_s = 1.18\,\nu^{-2}\ \mathrm{arc\ sec}$$

(Bower et al. 2006)

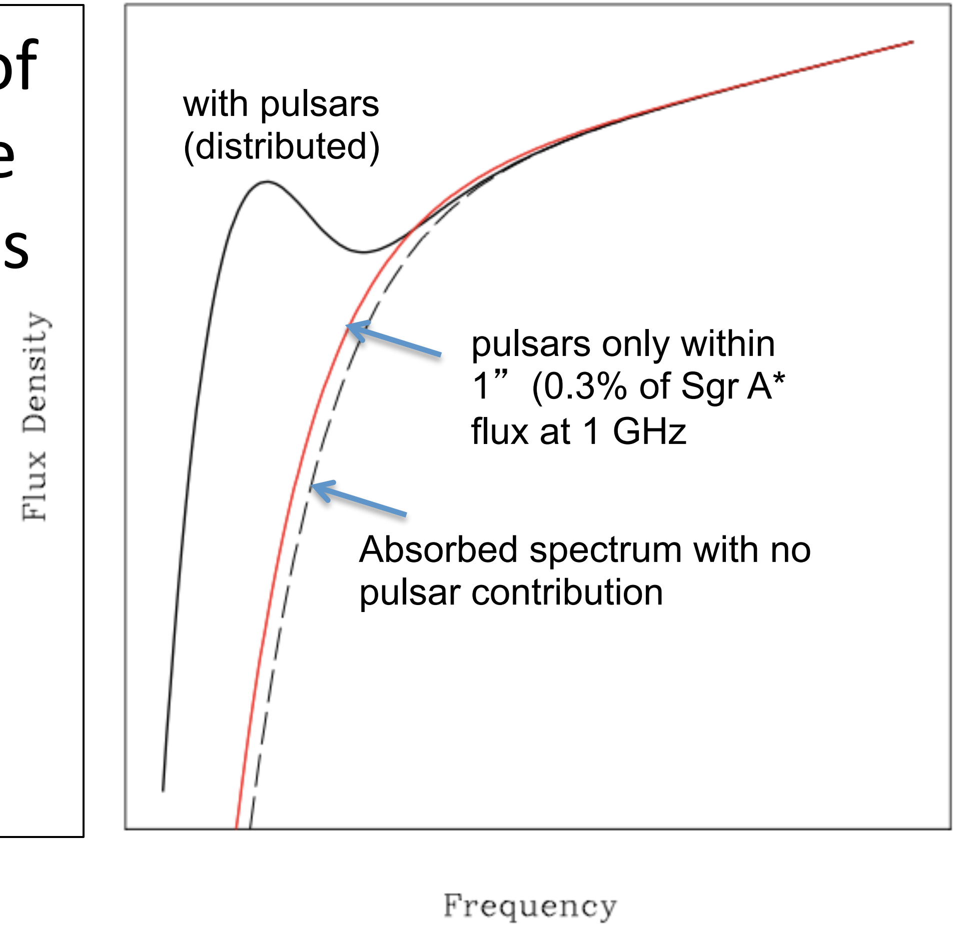
- Flux density of “Sgr A*” includes all flux within the scattering diameter
- Ratio of confused solid angle:

$$\frac{\Omega_{s,0.327\ \mathrm{GHz}}}{\Omega_{s,1.4\ \mathrm{GHz}}} = 335$$

Apparent Spectrum of Sgr A*

The measured spectrum of the scattered point source flat and steep components (pre-absorption):

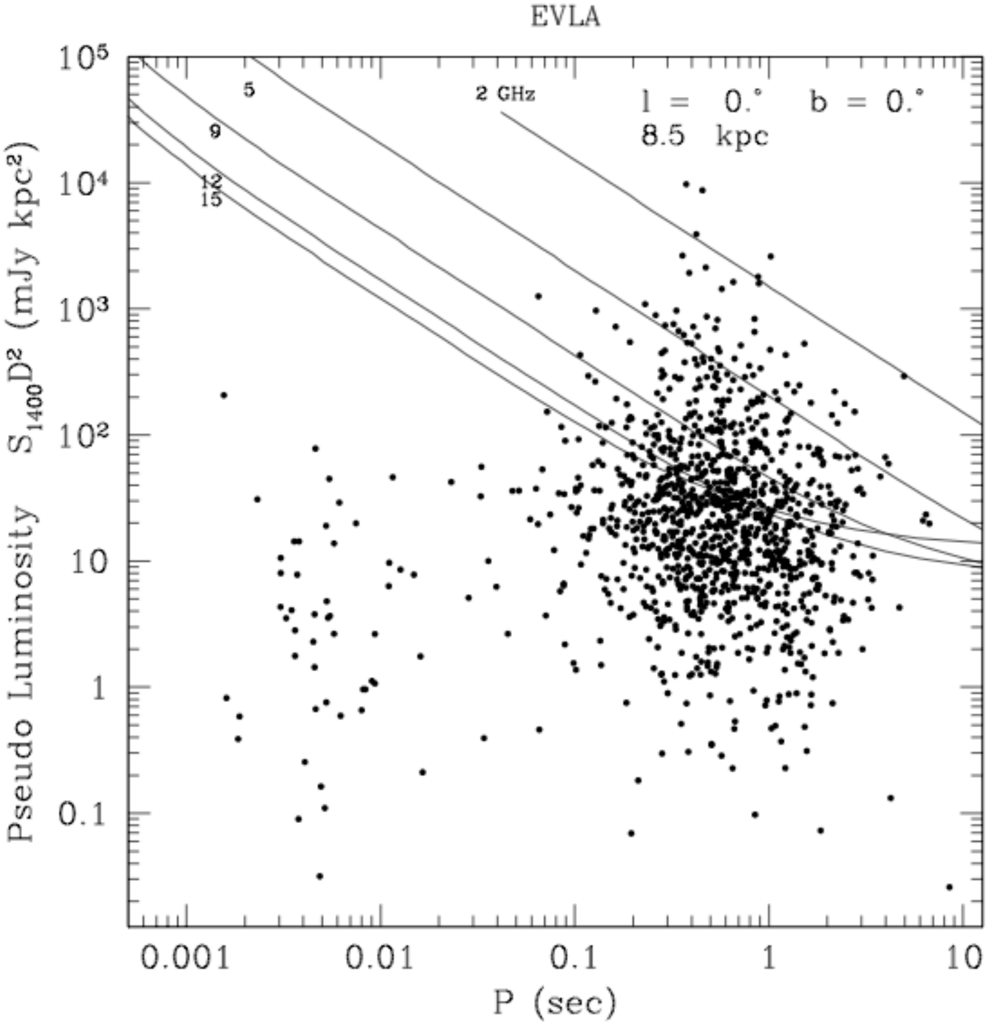
$$\left(\nu^{0.2}, \nu^{-3.7}, \nu^{-4.7}\right) \times e^{-(\nu_1/\nu)^2}$$



$$\begin{aligned} S_\nu &= \left[S_\nu(\text{Sgr A}*) + S_{\nu,\text{res}}(\text{psr})\right] e^{-\tau_\nu} \\ &\approx \left\{S_{\nu,0}(\text{Sgr A}*)\nu^{0.2} + n_\Omega S_0\left[\Omega_{b,0}\nu^{-3.7} + \Omega_{s,0}\nu^{-5.7}\right]\right\} e^{-(\nu_1/\nu)^2} \end{aligned}$$

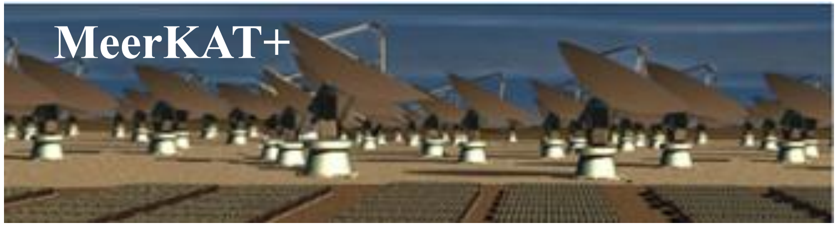
Prospects for Discovery of Pulsars in the GC

Detection curves for pulsars at the position of Sgr A*.
Nearer pulsars: curves ↓



Detection curves for pulsar periodicity surveys assume:

- 6-hr pointings
- 20% bandwidth
- perfect dedispersion
- perfect removal of orbital delays
- assumes same period and luminosity distribution as for Galactic disk pulsars



Orbit Determination: IR Astrometry/Doppler vs. Radio Timing

IR Astrometry/Doppler

- Confusion limits on detectability of faint stars, N limited to ~ 100 stars
- Keck/VLT:
  - diffraction limit ~ 50 mas => a (1+e) > 400 AU
  - Astrometry: ~2 mas
- ELT/TMT: ~3-4x better
  - 0.5 mas ~ 4 AU
- GRAVITY/VLTI: 10 μas ⇔ 0.08 AU
- Doppler:
  - 10 km/s line-width limited
  - 10^3 km/s orb velocity => 1% precision => 1 AU

Weinberg et al. 2006

Eisenhauer et al. 2008

Pulsar Surveys/Timing

- No confusion limits
- Difficulty in finding & timing pulsars: scattering
- TOA precision
  - (pulse-width)/ (S/N)
  - pulse modulations/jitter
  - scattering broadening
- 10 ms => 10^{-5} AU spatial resolution (10^3 – 10^5 better)
- scattering effects rectifiable with high-ν observations with large collecting area (GBT-> EVLA -> SKA(core)

Summary

- Discovering and timing GC pulsars transformational
    - stellar populations (NS, BH, main-sequence)
    - strong gravity
    - dark matter
    - properties of Sgr A*
- Requires large A_e/T for surveys and timing
- Needs high frequencies (10 to 20 GHz) GHz to mitigate radio-wave scattering effects
- Modest channelization needed (~100ch/GHz)
- Time resolution also modest (~1 ms) for initial pulsar targets (but don't forget millisecond pulsars)