Title: Neutron Stars in the Galactic Center

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Abstract: <span>I will discuss the prospects for finding additional radio pulsars in the Galactic center region and their utility for probing general relativity and other constituents in the region. This will include discussions of neutron star populations; radio wave scattering in and toward the Galactic center; issues and progress in discovering pulsars; and the precision to which discoverable pulsars can be timed</span>

# Neutron Stars & Transient Sources in the Galactic Center

Jim Cordes, Cornell University

Why search?

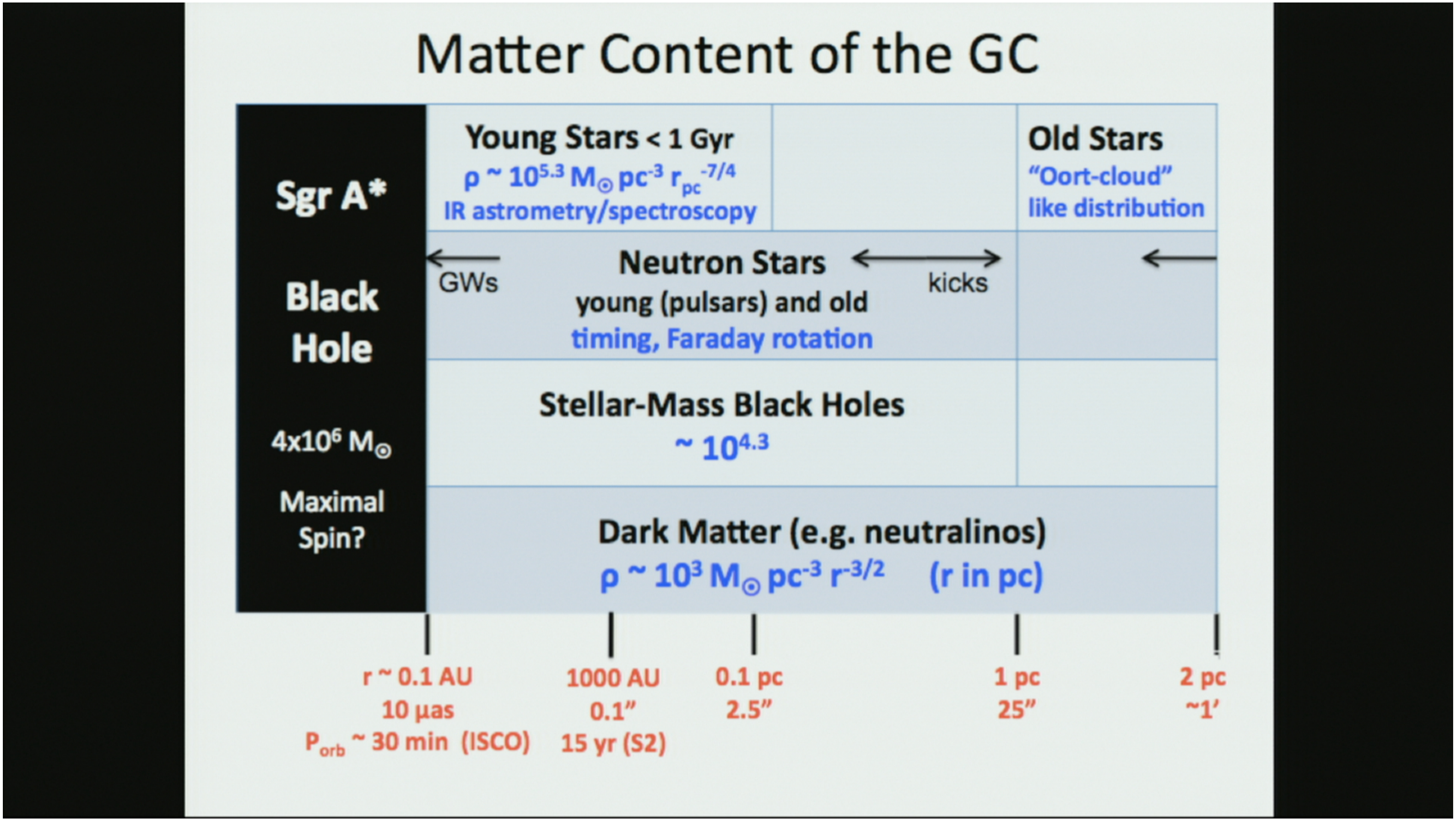
- Compact objects, extreme GR, plasmas, the unknown
- The Payoff: Pulsars = Event Horizon Clocks
- How many NS in the GC: N >> 1
- Where are they? a NS `Fermi paradox'

Detection issues on ms time scales (environment)

Radio-wave scattering stories

Scattering PSF issues relevant to EHT

A cm/mm/sub-mm program for pulsars/transients


Matter Content of the GC
Sgr A*
Black Hole
4x10⁶ M⊙
Maximal Spin?
Young Stars < 1 Gyr
ρ ~ 10^5.3 M⊙ pc^-3 r_pc^-7/4
IR astrometry/spectroscopy
Old Stars
"Oort-cloud" like distribution
GWs
Neutron Stars
kicks
young (pulsars) and old
timing, Faraday rotation
Stellar-Mass Black Holes
~ 10^4.3
Dark Matter (e.g. neutralinos)
ρ ~ 10³ M⊙ pc^-3 r^-3/2 (r in pc)
r ~ 0.1 AU
10 µas
P_orb ~ 30 min (ISCO)
1000 AU
0.1"
15 yr (S2)
0.1 pc
2.5"
1 pc
25"
2 pc
~1'

# NS/Transients Payoffs

Gravity:

- NS-Sgr A* + NS-NS + NS-BH binaries
  - Strong field tests
  - Precision mass of Sgr A*
  - Spin of Sgr A* and test of no-hair theorem
- MSPs and GW detection (MSPs = difficult!)

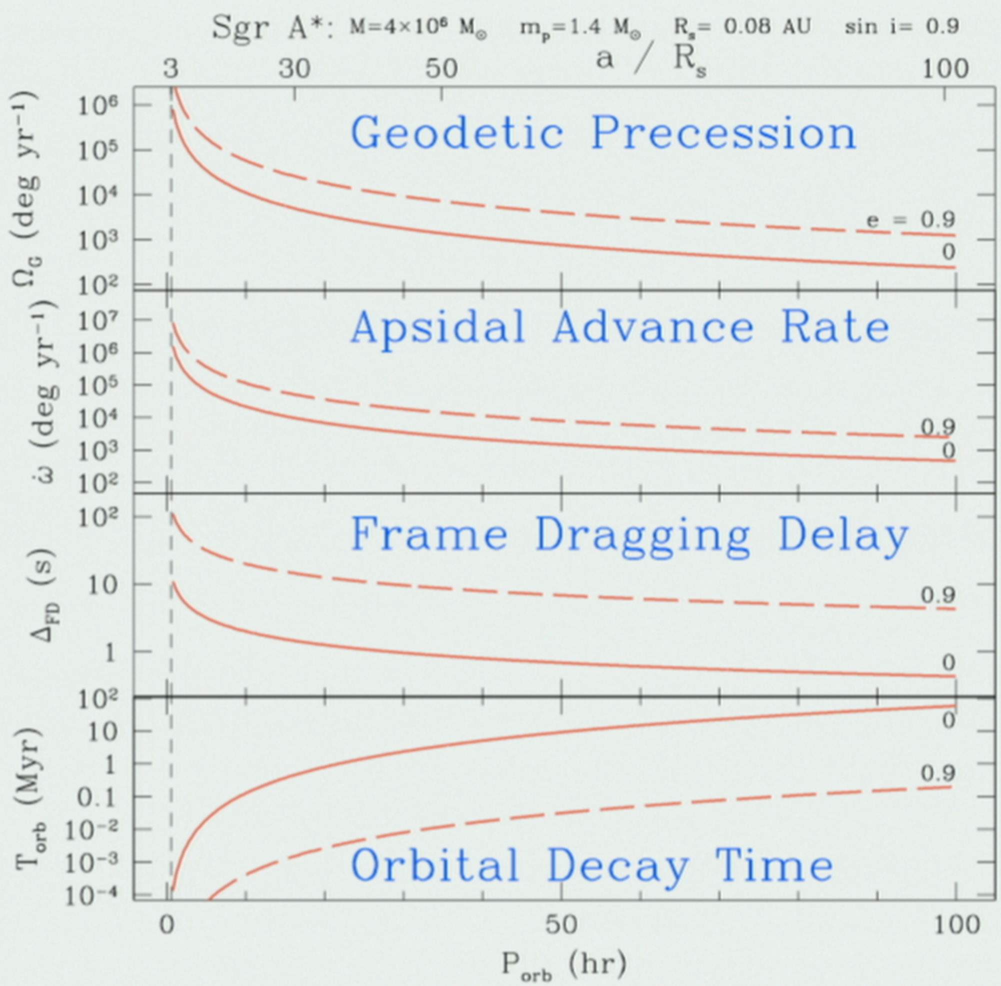
Environment:

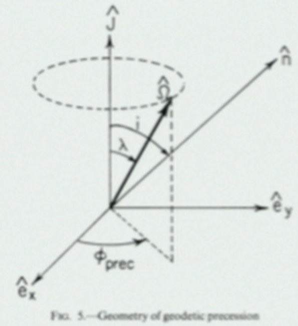
- Pulses = probes of electron density + B (turbulence)
- Dispersion, scattering Faraday rotation (DM, SM, RM)

Stellar evolution and populations

- NS = beneficiaries of the paradox of youth
- Or … is there a missing pulsar problem?
- Or … an excess magnetar process?

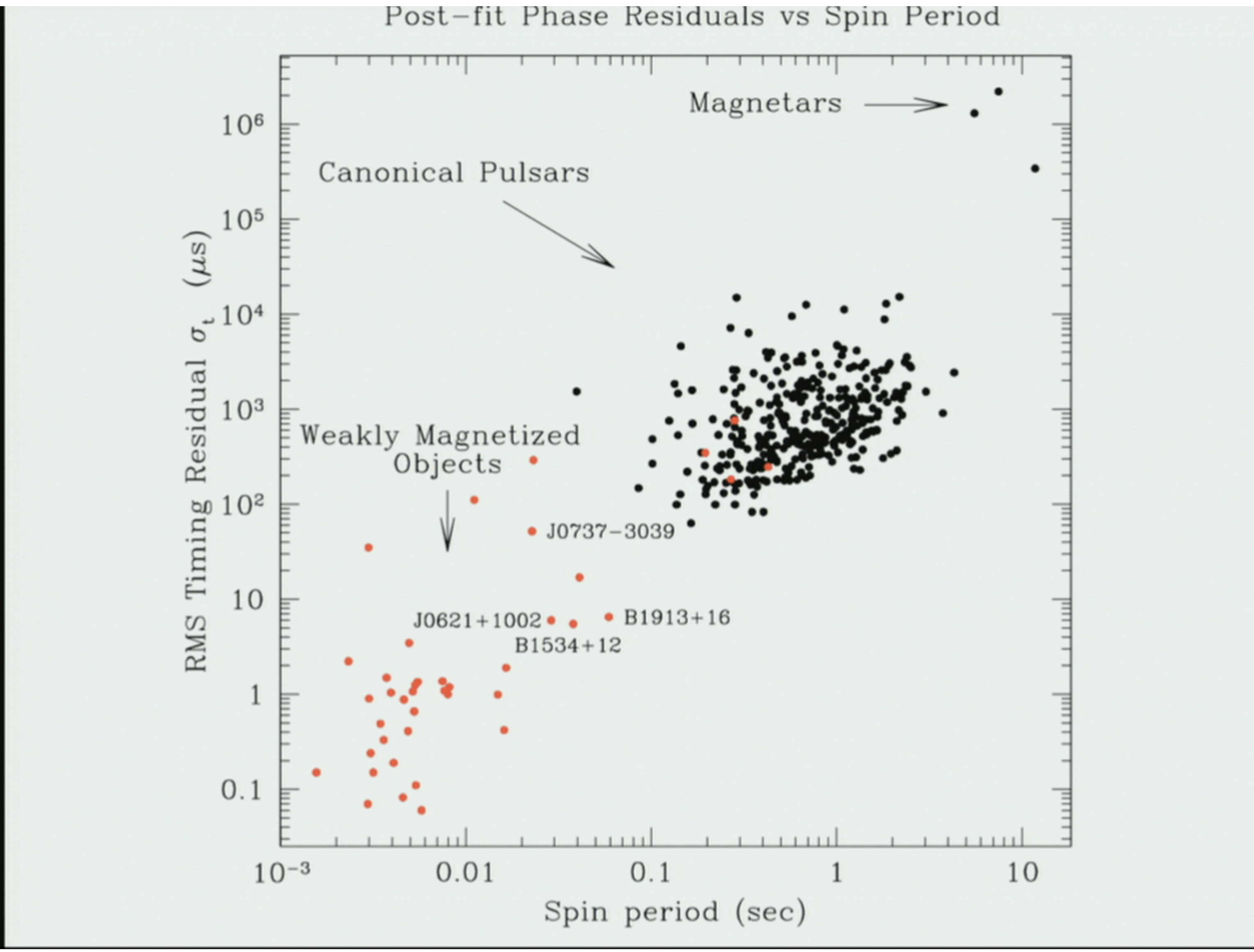
# Post-Keplerian Effects for Pulsars Orbiting Sgr A*



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

Orbital lifetime: $T_{orb}$ ~ 80 Myr for NS-Sgr A* binary in a 100-hr orbit


Post−fit Phase Residuals vs Spin Period
Magnetars
Canonical Pulsars
Weakly Magnetized Objects
J0737−3039
J0621+1002
B1534+12
B1913+16
RMS Timing Residual σt (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

# Constraints on GC Pulsar Numbers

Wharton et al. 2012, ApJ, 753, 108

Overall: 100 to 1000 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 $\gamma$ -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 (Wharton et al.)
- 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 et al. 2010)
- 1 magnetar detection → 500 pulsars if like Galactic disk

# If N is Large, Where are They?

## There are no pulsars in the GC!

- IMF favors magnetar formation (Dexter & O'Leary 2014)
- NS destroyed by dark matter (Bramante & Linden 2014)

## They're there but hard to detect I: extrinsic effects

- Pulsars are preferentially in compact binaries + SgrA* orbit and/or they precess → more sophisticated algorithms (cf globular cluster pulsars)
- Radio wave scattering (multipath) is in fact large *despite the magnetar J1745-2900*

## They're there but hard to detect II: intermittency

- Emission is quenched (episodically) by environmental effects
  - Poisoning of the magnetosphere (no $e^{\pm}$ pairs → no coherent radio)
  - Accretion or particle injection from reconnection in magnetotails

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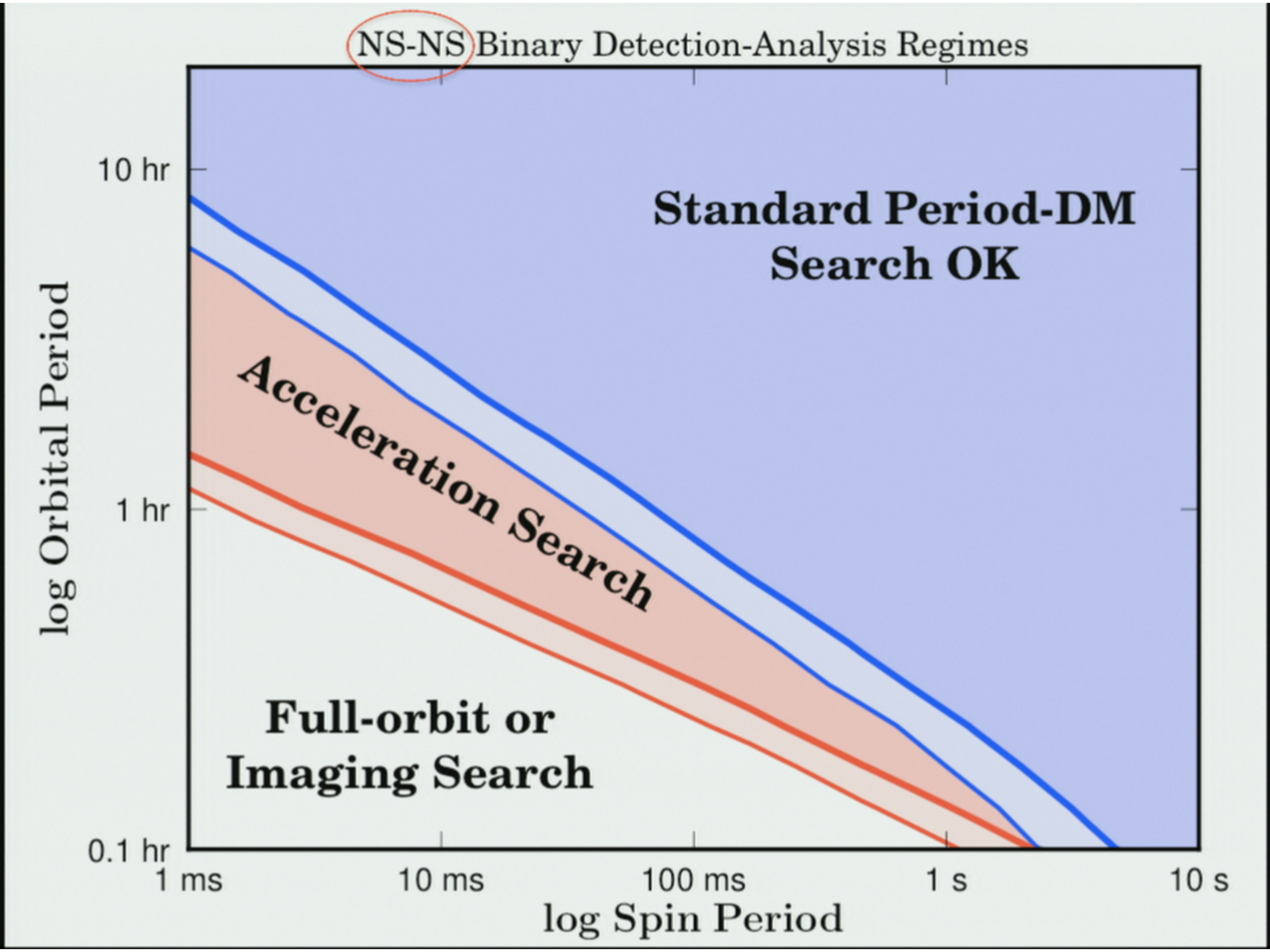
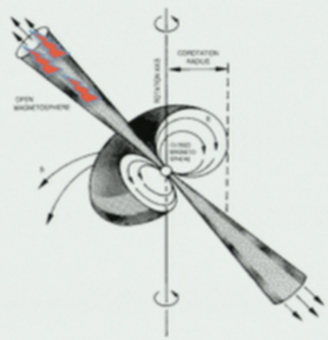
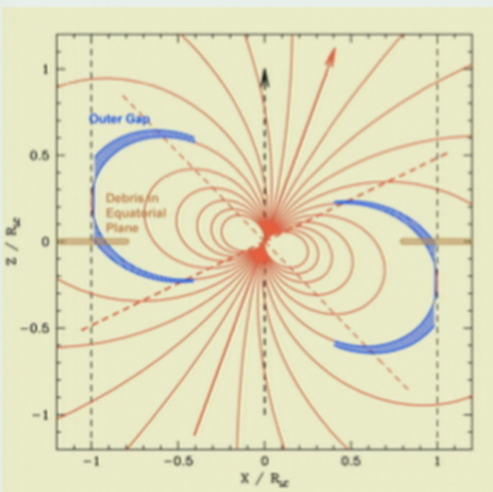


NS-NS Binary Detection-Analysis Regimes
Standard Period-DM
Search OK
Acceleration Search
Full-orbit or
Imaging Search
10 hr
1 hr
0.1 hr
log Orbital Period
1 ms
10 ms
100 ms
1 s
10 s
log Spin Period

# Discrete Emission States in Magnetospheres

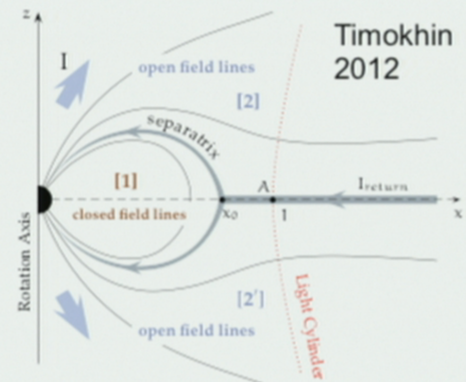


- Pulsar emission requires coherence from a two-stream instability --- from counterstreaming $e^{\pm}$ pairs
- Pair cascades require accelerating vacuum gaps
- Very few particles are needed to poison the gaps
- Several objects switch between pulsar (MSP) and accreting X-ray states




JMC + Shannon 2008

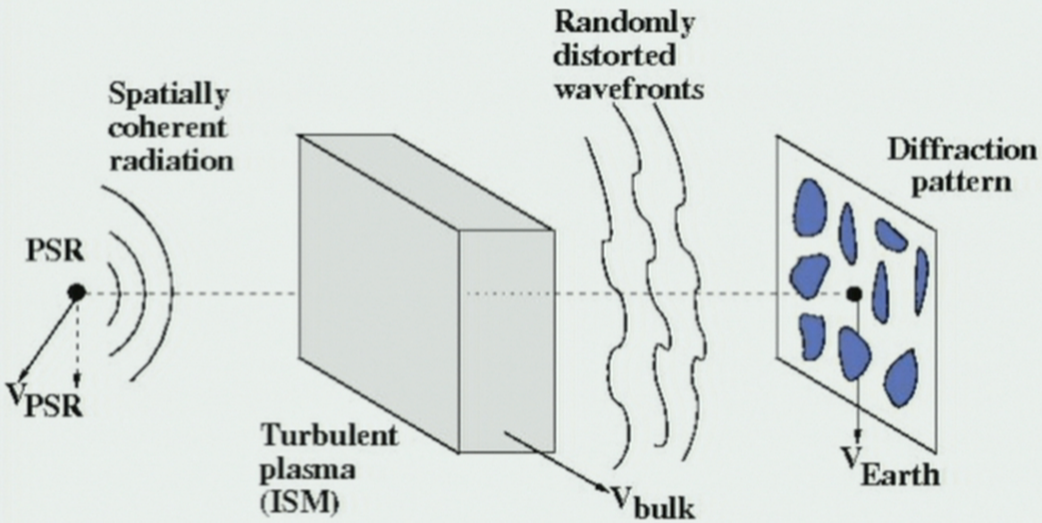
Deich et al. 1986




Timokhin 2012

**Figure 1.** Configuration of the magnetic field in the magnetosphere of an aligned rotator with a Y null point – Y-configuration. After the null point $x_0$ the separatrix goes along the equatorial plane. The volume current $I$ flows in the open field line zones [2] and [2′]. The current circuit closes somewhere beyond the LC. There could be a volume return current along some open field lines, but the largest part of it flows along the separatrix.

# Scattering in the ISM from $\delta n_e$ (sub-AU scales)




- Electron density variations ~ power-law spectrum
- Constructive interference maxima = "scintles"
- Image speckles closely related to scintles
- Corrugation of images and scattered pulse shapes are from finite scintle/speckle numbers

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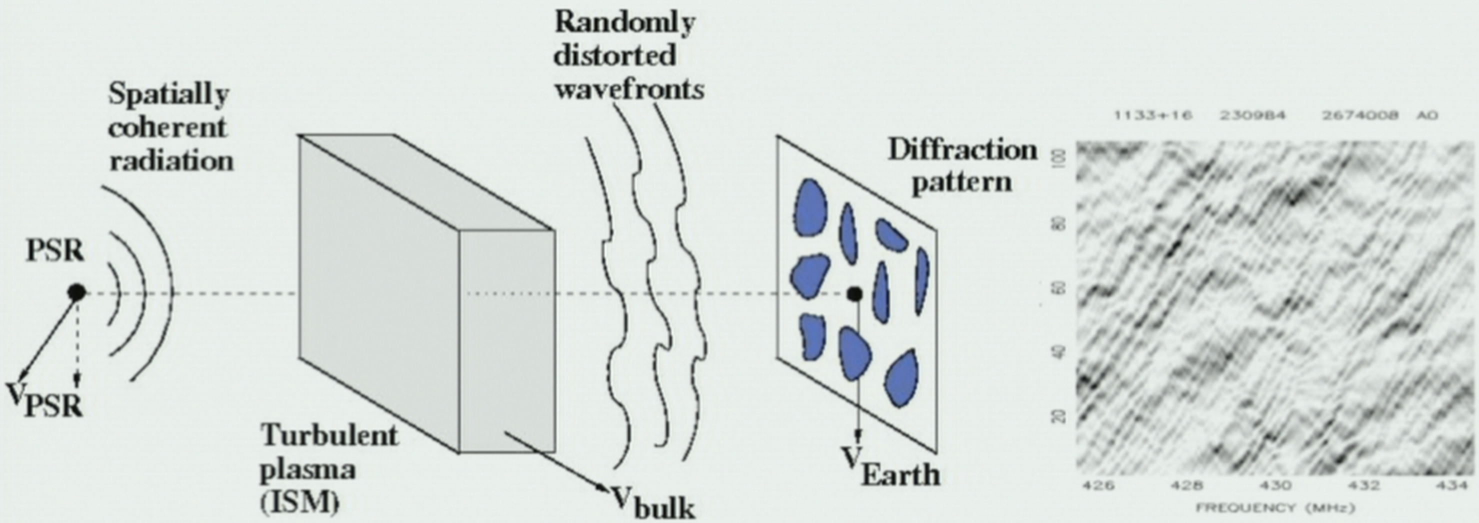


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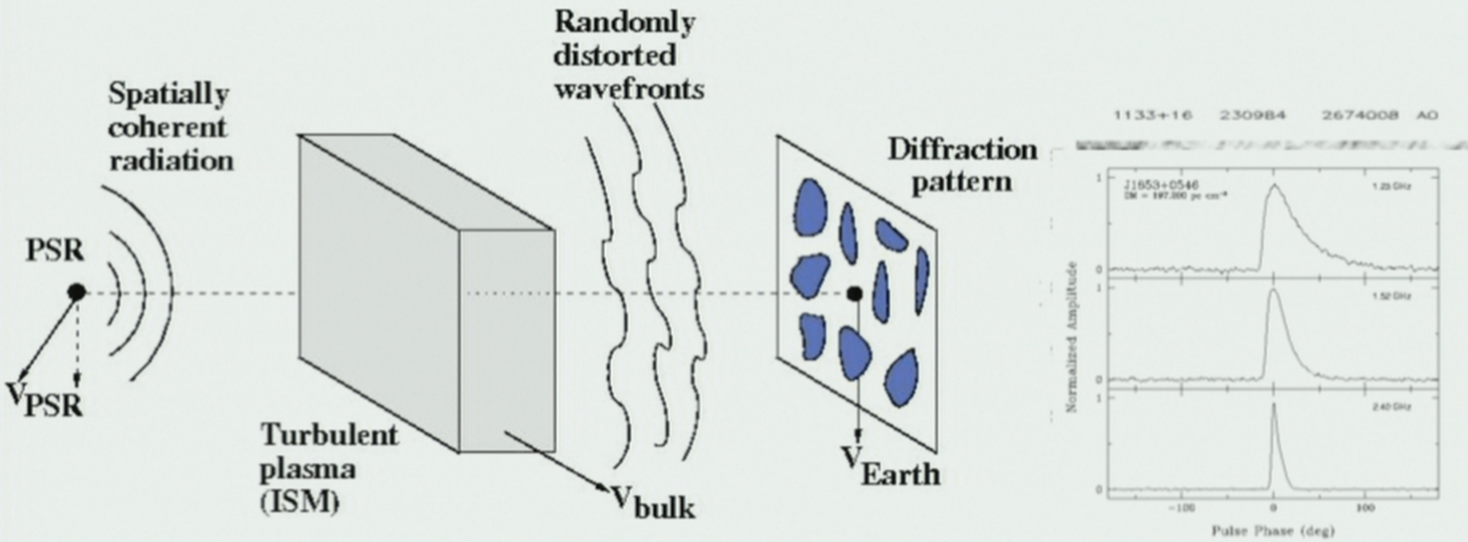


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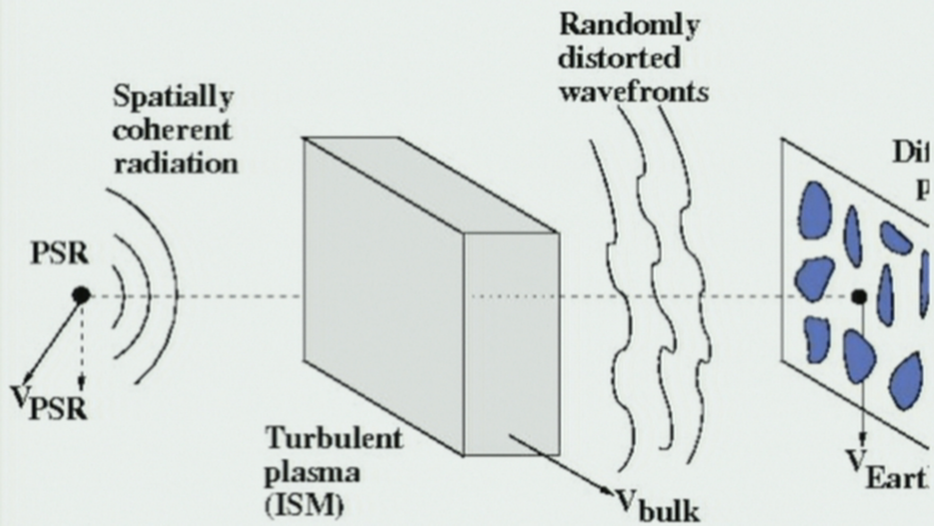


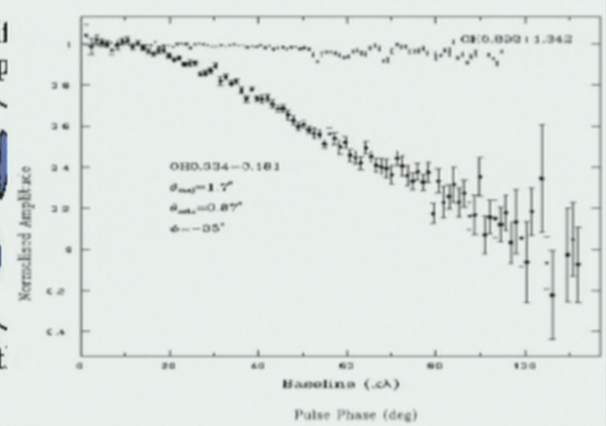

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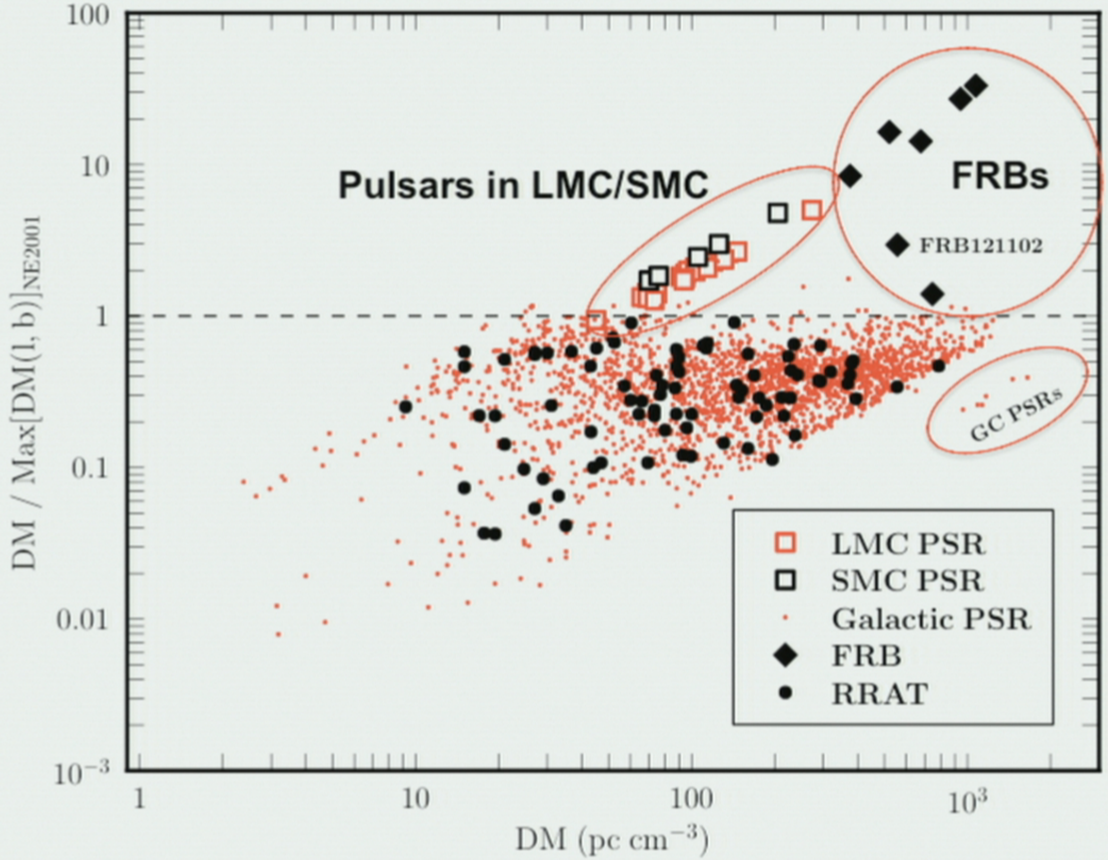
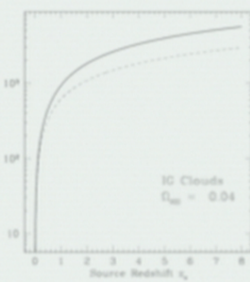
# The GC Scattering Story

- GC scattering region needed
    - Sgr A* + OH masers + background extragalactic sources
    - How patchy?
- NE2001
    - Full-Galactic model based on scattering + dispersion of ~1000 sources + multiwavelength priors on Galactic structure
    - GC component predicts DM ~ 1500 for Sgr A* and 2000 sec of pulse smearing at 1 GHz
- Magnetar J1745-2900
    - Angular scattering ~ same as Sgr A* (Bower + 2013)
    - Temporal scattering << NE2001 prediction (Spitler + 2013)
    - Location of dominant scattering region(s)?
    - Variability of temporal scattering (Effelsberg, VLA data)
        - Unusual compared to other pulsars
        - Likely due to dynamics of GC region
- The magnetar and Sgr A* may not be sampling exactly the same scattering regions

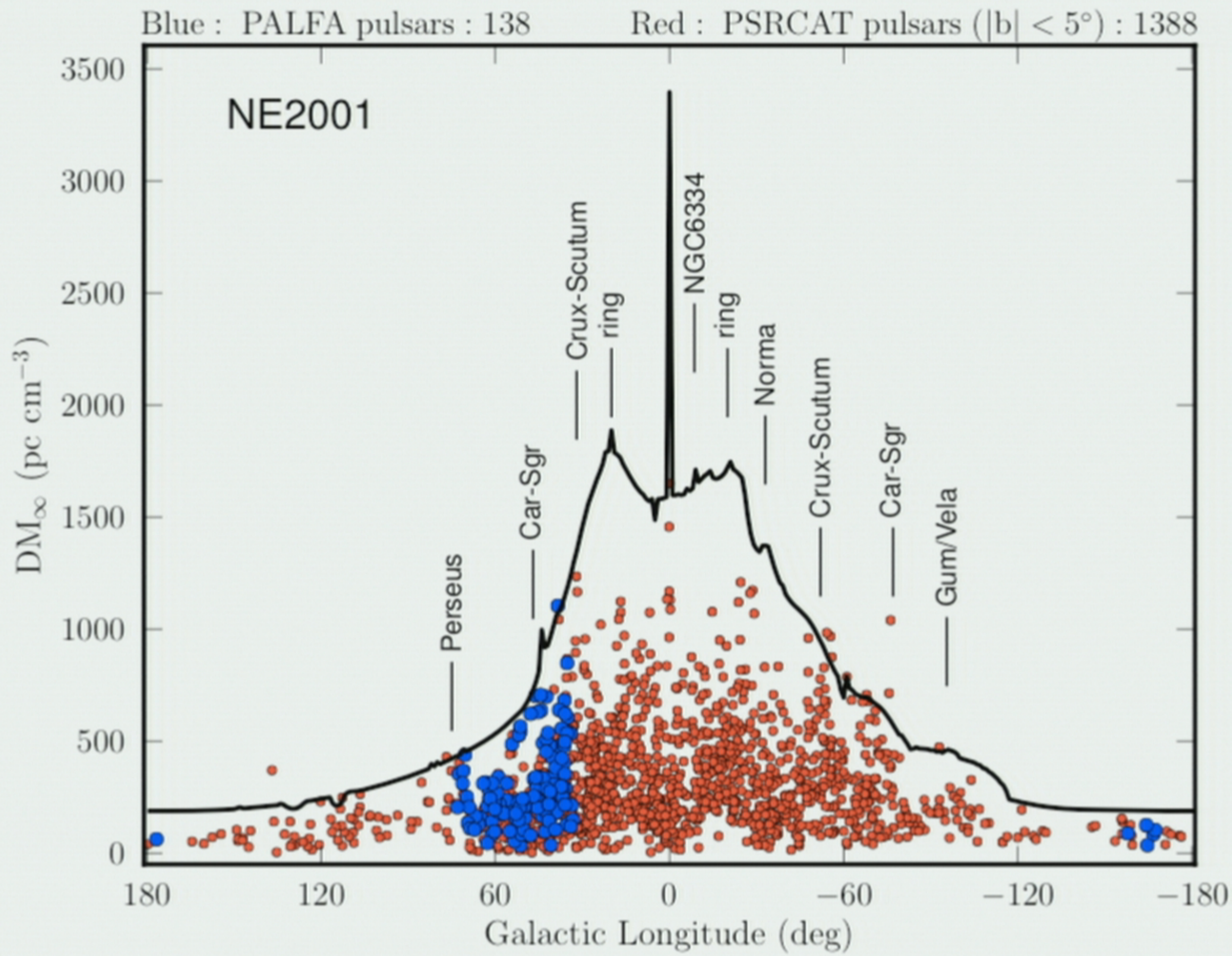
# Galactic & Extragalactic Populations



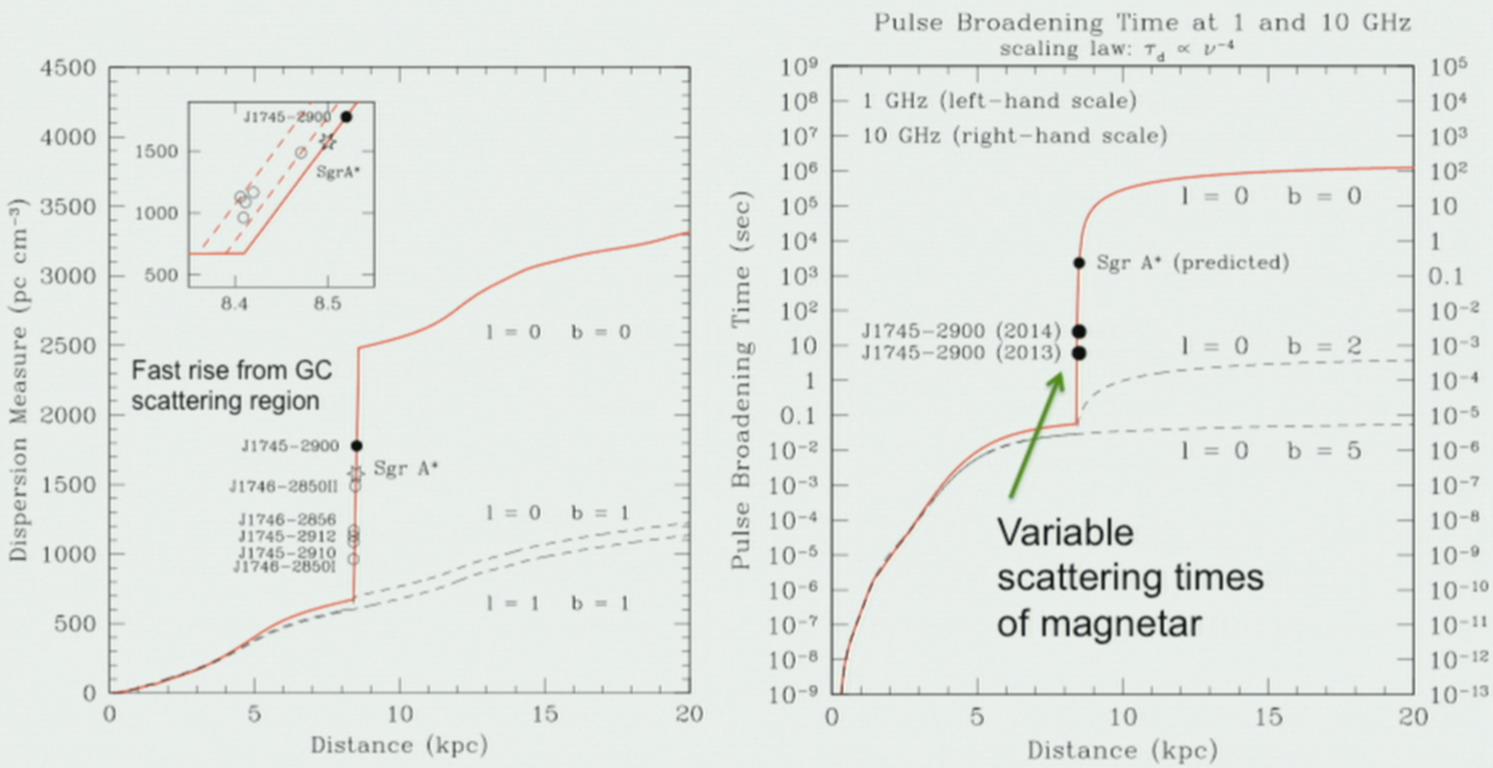

Spitler et al. 2014



# Comparison of DM integrated through the Galaxy with Pulsar DMs

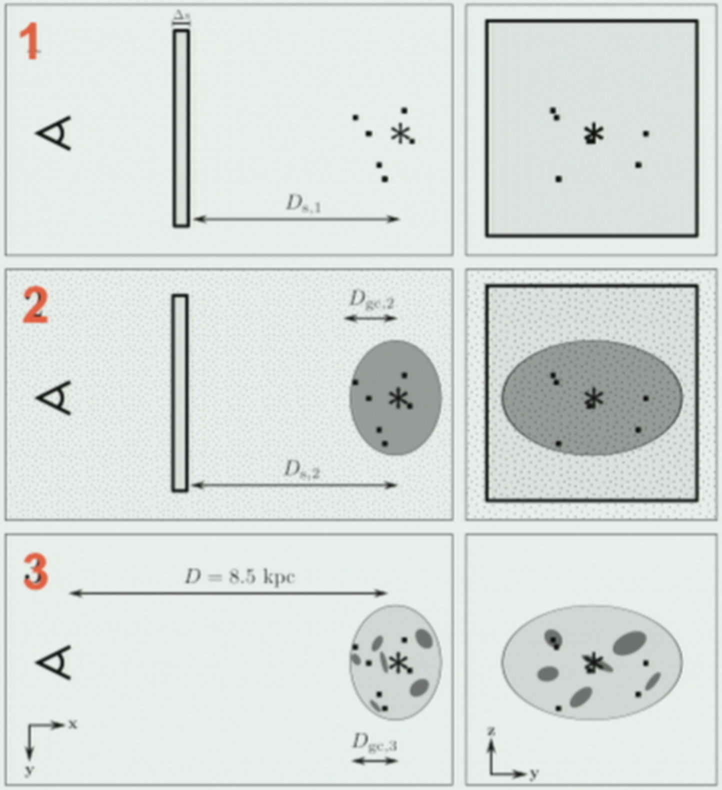


# Dispersion & Scattering Toward the GC
# NE2001 Model + GC objects



# GC Scattering Geometries

Side view | Observer view




**1 — One screen only**

HII region ~ 0.5 deg diameter, 2 kpc from Sun?

Implies dense gas in GC does no scattering

**2 — Screen + Galactic disk + uniform, GC region**

More consistent with Gal structure

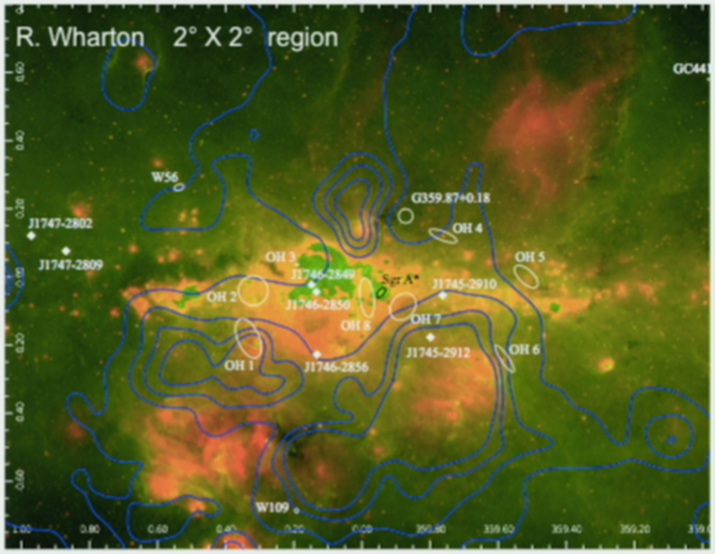
Requires tuning to get OH/IR maser scattering correct

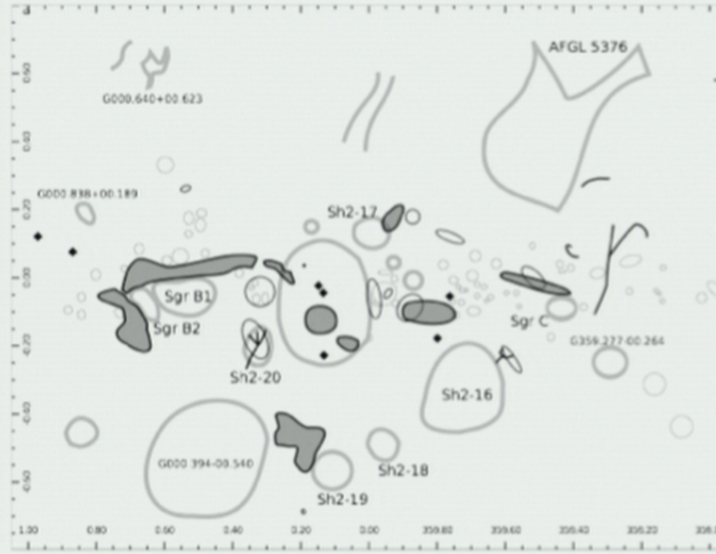
**3 — Multiple scattering regions in GC + foreground Gal. disk**

Multiple GC regions with similar properties provide degrees of freedom.

Most consistent with scattering variablity of magnetar

# Galactic Reality



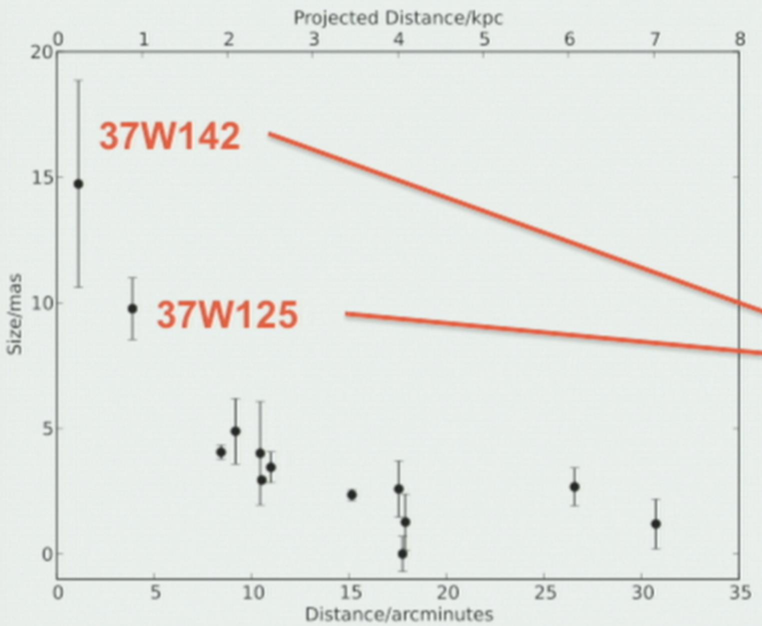

10 GHz continuum (blue contours)
GLIMPSE 8, 24μ (green, red)
White diamonds = radio pulsars
White ellipses = scattering disks x100

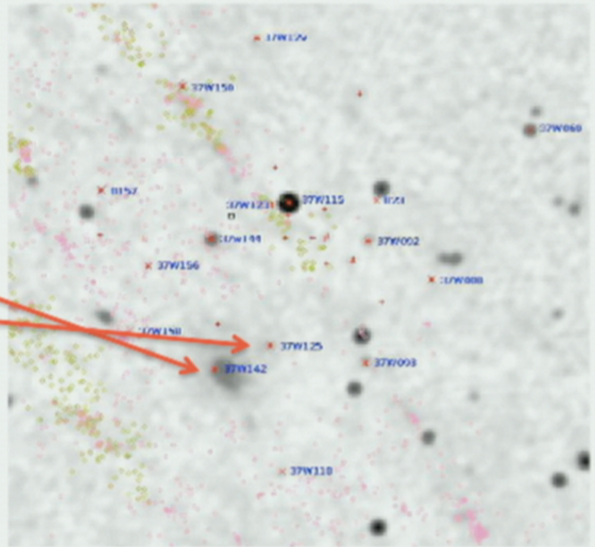
Finding chart:
Labeled HII regions
Grey → candidate HII regions
Black diamonds = pulsars
Ellipses = scattering disks x 100

***No obvious correlation of scattering of GC sources with foreground structures***

# M31 ≈ MW Scattering

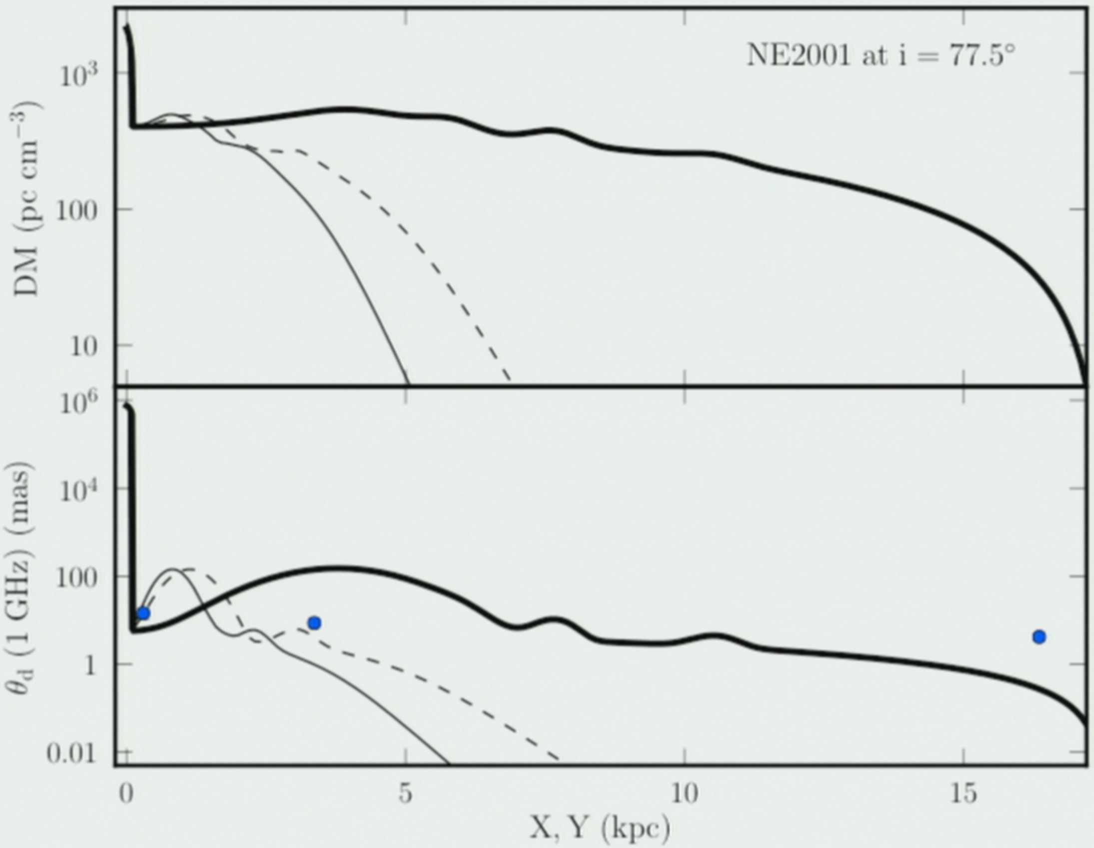
Morgan et al. 2013




Red "x" with blue labels: detected sources. Red "+": unresolved B90 sources (major axis >6″ ) that would be detected at 6.6σ were all of their flux density concentrated in a compact area. Green diamonds: H ii regions from Walterbos & Braun (1992). Pink circles: H ii regions from Azimlu et al. (2011). Black square: pointing center.

# NE2001 integrated with M31's inclination




Scattering of background sources consistent with MW scattering; but no bg sources that sample M31's GC

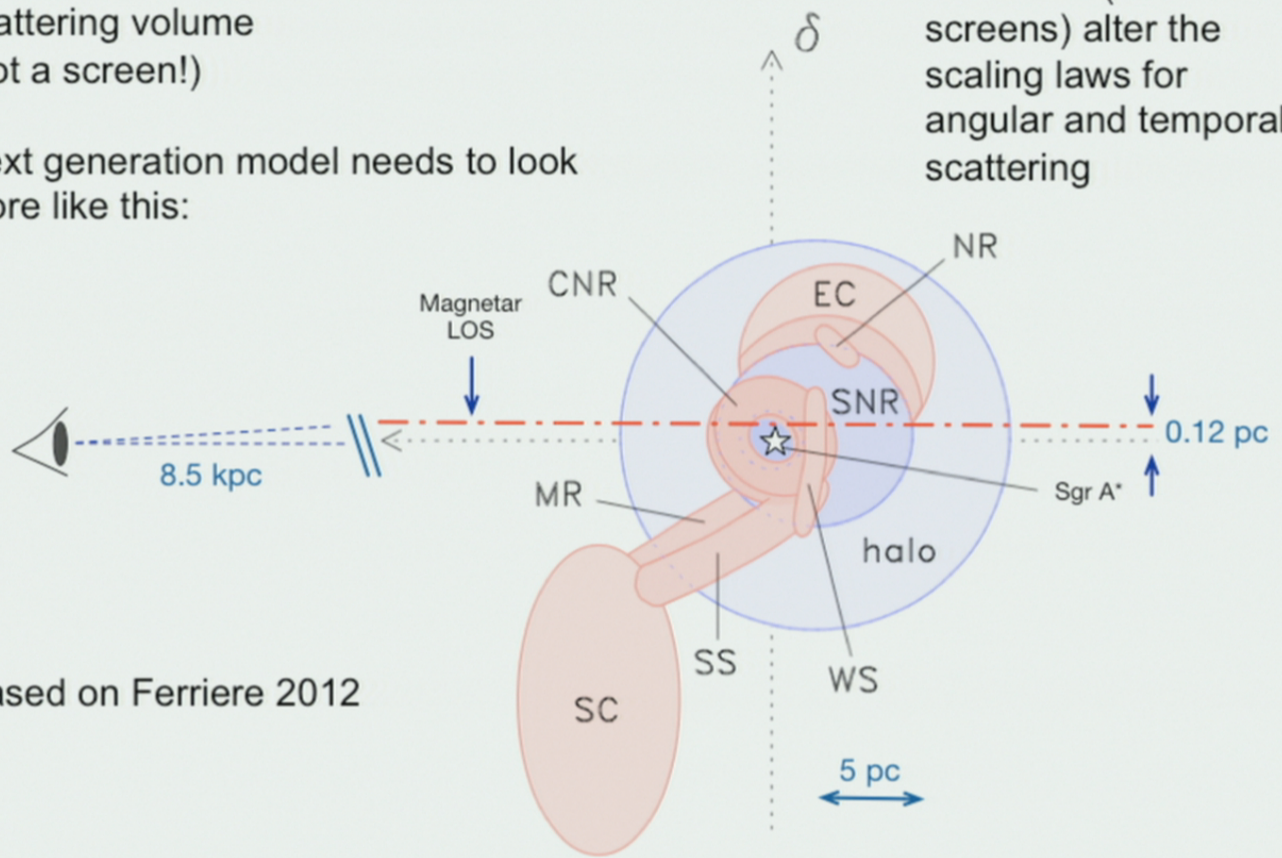
Blue points: VLBI diameters of background sources from Morgan et al. 2013

# GC Structures

NE2001 has a uniform ellipsoidal scattering volume (not a screen!)

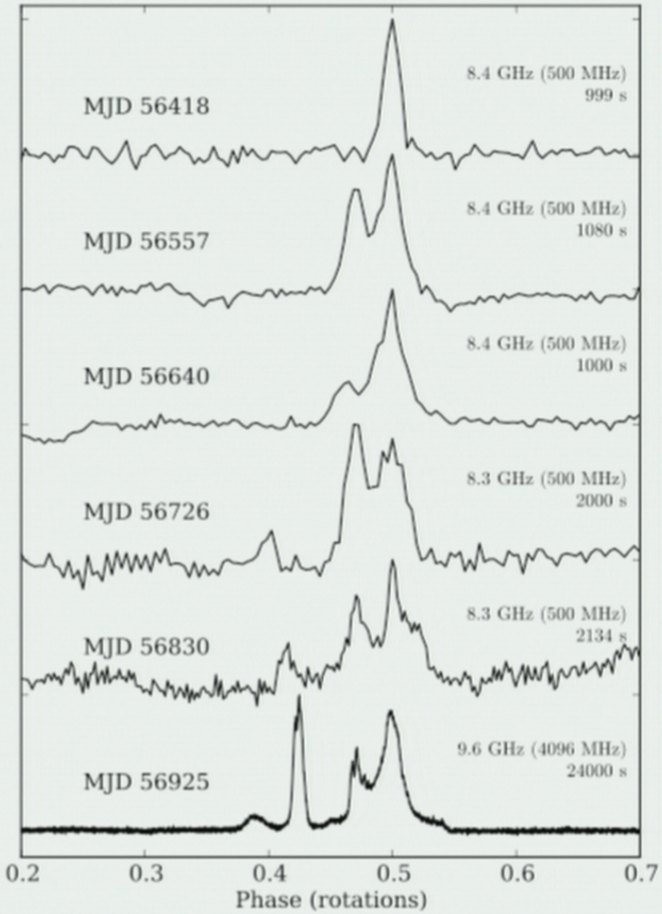
Next generation model needs to look more like this:

Filaments (truncated screens) alter the scaling laws for angular and temporal scattering




Based on Ferriere 2012

# Synoptic Magnetar Observations




Spitler et al. 2014 (Effelsberg)

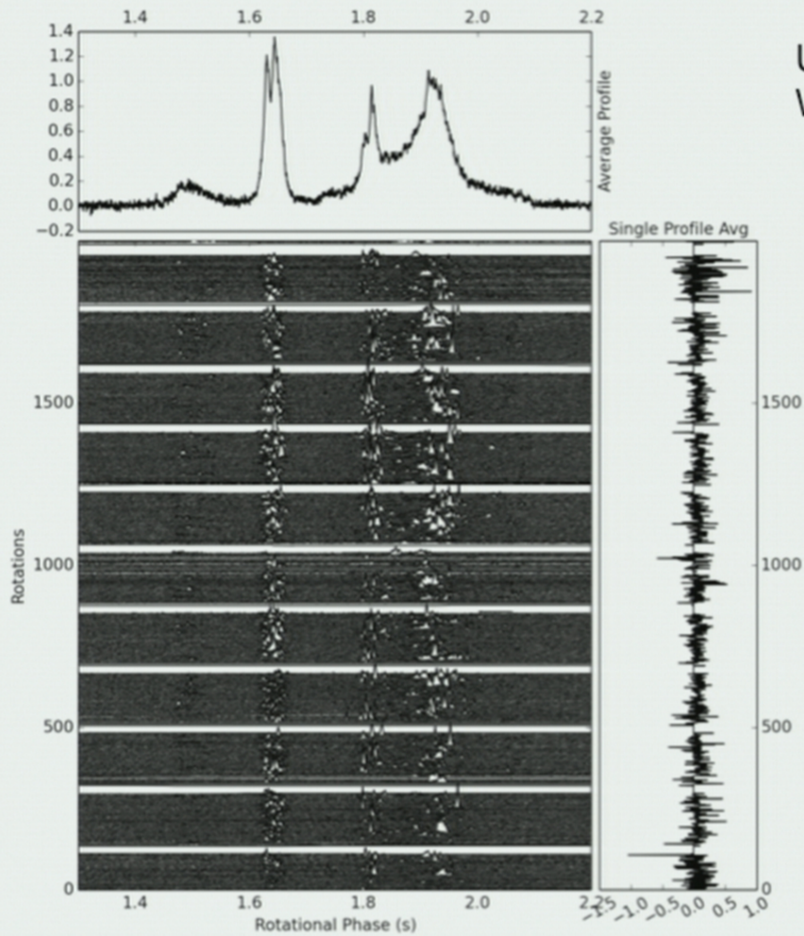
**The magnetar pulse shape has changed from 1 to ~6 components in 1.5 yr**

Effelsberg, unpublished (Spitler, Kramer et al.)

VLA, unpublished: new 4 GHz fast-dump capability

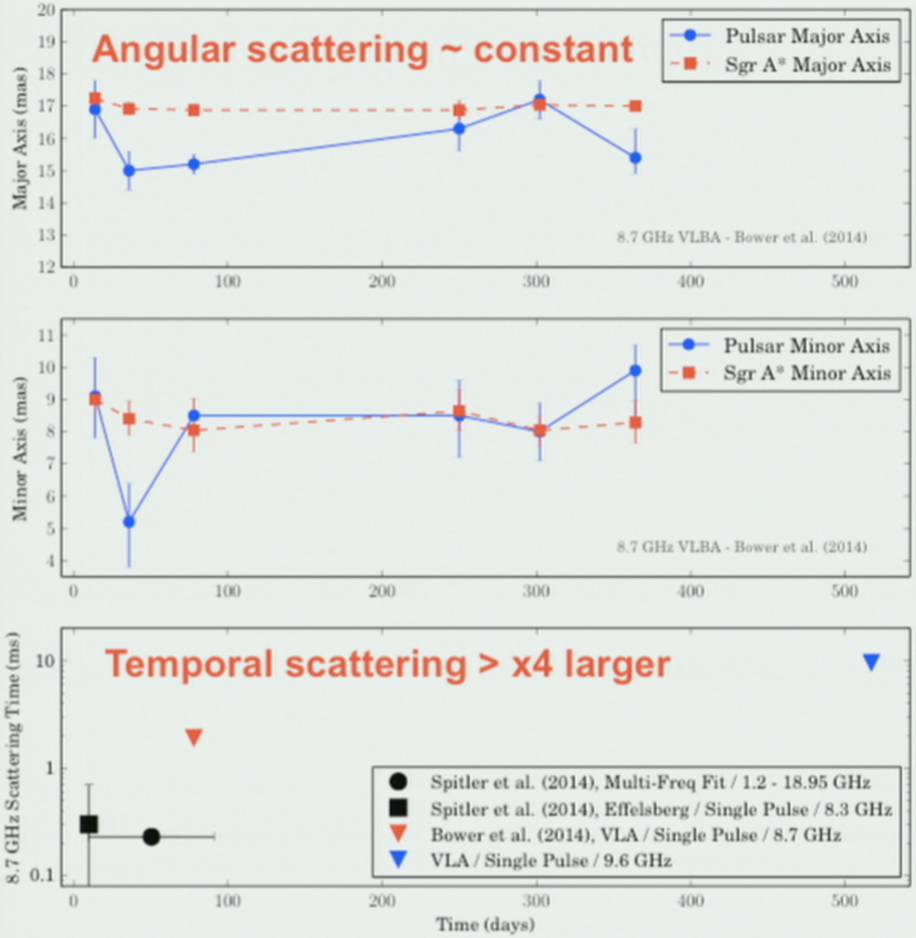
Wharton, Demorest, Ransom, Lazio, JMC …

# Single Pulses Similar to Canonical Pulsars

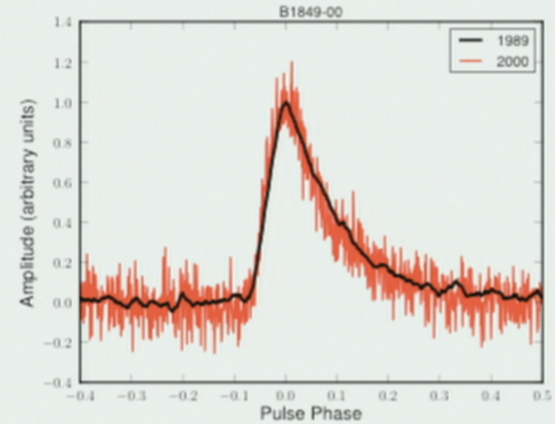



Unpublished VLA data 8-12 GHz
Wharton, Demorest, Ransom et al.

# Angular vs. Temporal Scattering: Sgr A* and Magnetar




**Comparison: strongly scattered pulsar in Galactic disk**



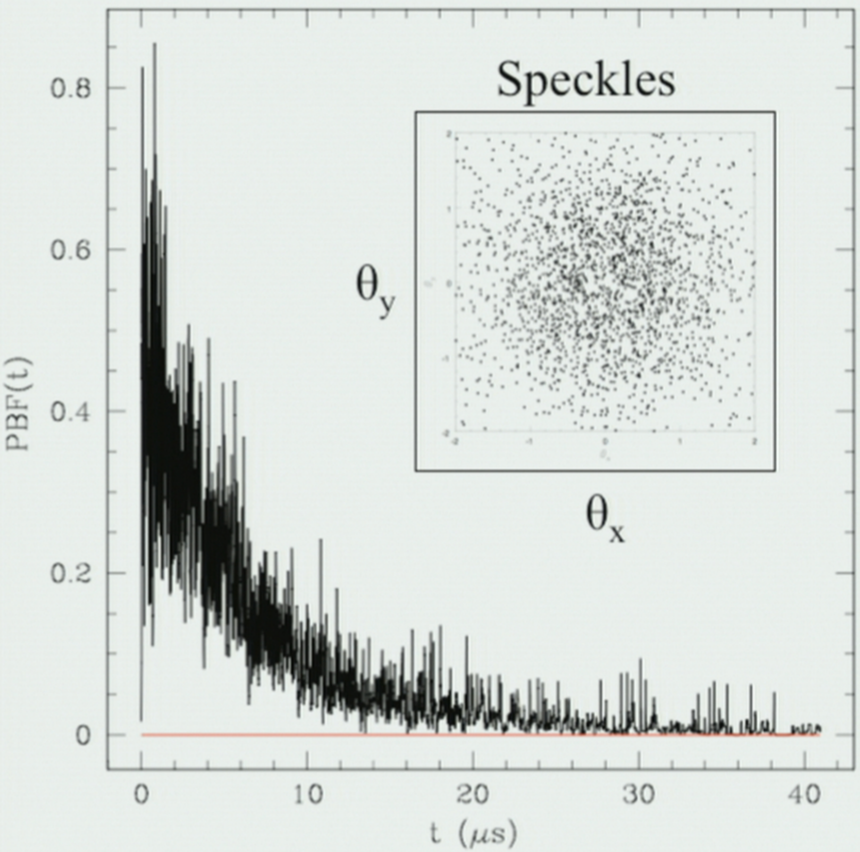

**Stability of scattering time over 11 years**

Effelsberg (Kramer et al.)

Arecibo (JMC)

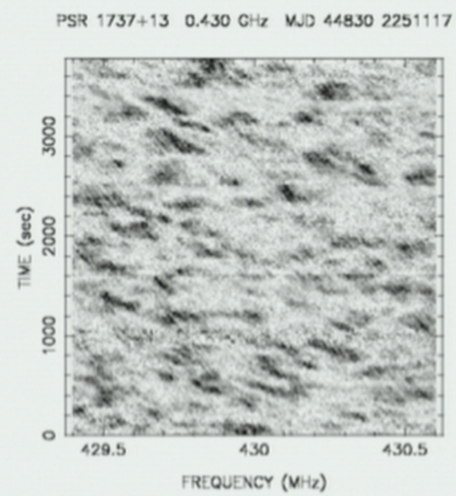
VLA data: Wharton, Demorest, Ransom et al. 2014 (unpublished)

# Stochasticity of the Pulse Broadening Function and Point Spread Function



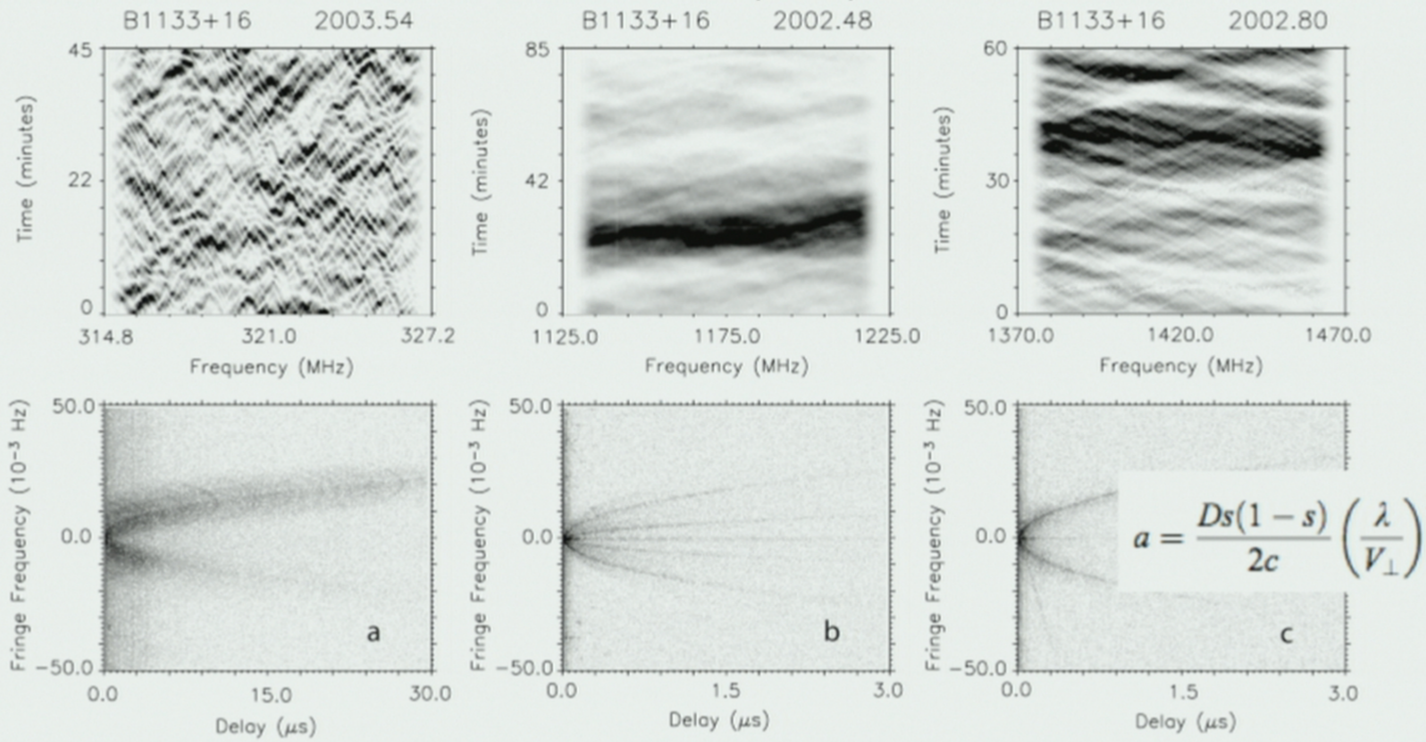

$N_{speckles} = N_{scintles}$

$N_{scintles}$ = number of bright patches in the time-bandwdith plane



# Scintillation Arcs demonstrate that the ISM has Kolmogorov-like structure on small scales (< $10^4$ km)

Stinebring et al. 2001, Walker & Melrose (2004), Hill et al. 2005, Cordes et al. (2006), Brisken et al. (2010)




$$a = \frac{Ds(1-s)}{2c}\left(\frac{\lambda}{V_\perp}\right)^2$$

# Scattering PSF and EHT

- Stochastic effect is seen in precision millisecond pulsar timing data (<100 ns)
- $N_s$ Speckles → stochastic PSF
- Astrometric error → deconvolution error

$$\Delta\theta_{astrometric} \sim \theta_{scattering} / N_s^{1/2}$$

- Estimate $N_s \sim \nu^{-5}$ and $\Delta\theta_{astrometric} \sim \nu^{1/2}$
- Applies only to strong scattering
- Transition to weak scattering at ~ 100 GHz
  - PSF becomes $(1-\varepsilon)\delta(\theta) + \varepsilon$ x gaussian halo
- Effects are stochastic and epoch dependent if scattering varies

# The Dynamics of Detection

## [pulsars and transients]

### Synoptic time-domain surveys are required

- Transients = transient
- Most pulsars are ~ steady (apart from interstellar scintillations)
- Magnetars
  - on/off state triggering not understood
  - Scattering in the GC is epoch dependent for J1745-2900
- Pulsar intermittency (seconds to months):
  - Markov processes suggesting random state changes
  - Inherent or environmental?
  - Crust quakes vs injection (asteroids, magnetic reconnection jets)

### Burst sources with low repetition rates

- Giant-pulse model for `FRBs' = extragalactic bursts
- Radio luminosities ~ 10^12 x Crab pulsar
- Large DMs could be associated with Galactic centers
- NS magnetospheres can supply energetics + coherent emission [Cordes & Wasserman, to be submitted]
- Triggering?

# Frequency Ranges: the connection to EHT

- Pulsar spectra typically ‘low pass’

  $\sim f^{-\alpha}$, $<\alpha> \sim 1.6$

  - Coherence mechanism ←→ bunching ~ 1-10 cm
  - Disk: Favor 0.4 to 2 GHz to tradeoff flux vs. scattering
  - Galactic center: Large scattering → X band and above
- Flat spectrum pulsars and magnetars
  - Spectra ~ f^0 extending to 150 GHz (magnetars)
  - Extreme form of coherence process or induced scattering
  - Inverse Compton scattering boost from m → mm
- Some evidence for spectral upturns in standard pulsars at 40-80 GHz (Morris et al 1998, Kramer et al.)

# Summary/Conclusions

"*Reports of my dearth are greatly exaggerated*"

-- Galactic center pulsars

- Many reasons for non-detections compared to naïve sensitivity estimates
- Scattering in the Galaxy and GC are very complex; a new model is needed
- Payoffs from GC pulsars are very high
  - Synoptic, sensitive pulsar/transient campaigns at cm and mm wavelength (ALMA, VLA, GBT, LMT)
- Pulsar scattering/scintillation observations can inform PSF variability in time and wavelength