Detection of the Stochastic Background of nHz Gravitational Radiation from Massive Black Holes with a Pulsar Timing Array

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OUTLINE

- The universe of coalescing Massive Black Hole binaries produces a stochastic spectrum of Gravitational Radiation at nanoHertz frequencies.
- Highly magnetized, rapidly rotating neutron stars – pulsars – provide ultra-stable, celestial clocks.
- The MBH stochastic spectrum of gravitational radiation can be detected in "short-wave" limit with a Pulsar Timing Array – a nanoHertz GW telescope.

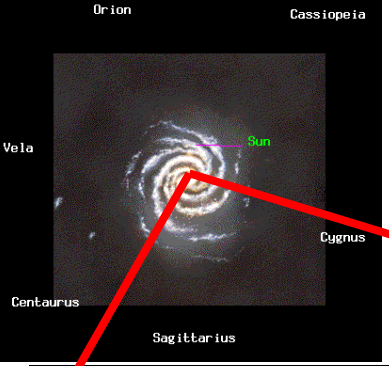
Connections to Other Lectures

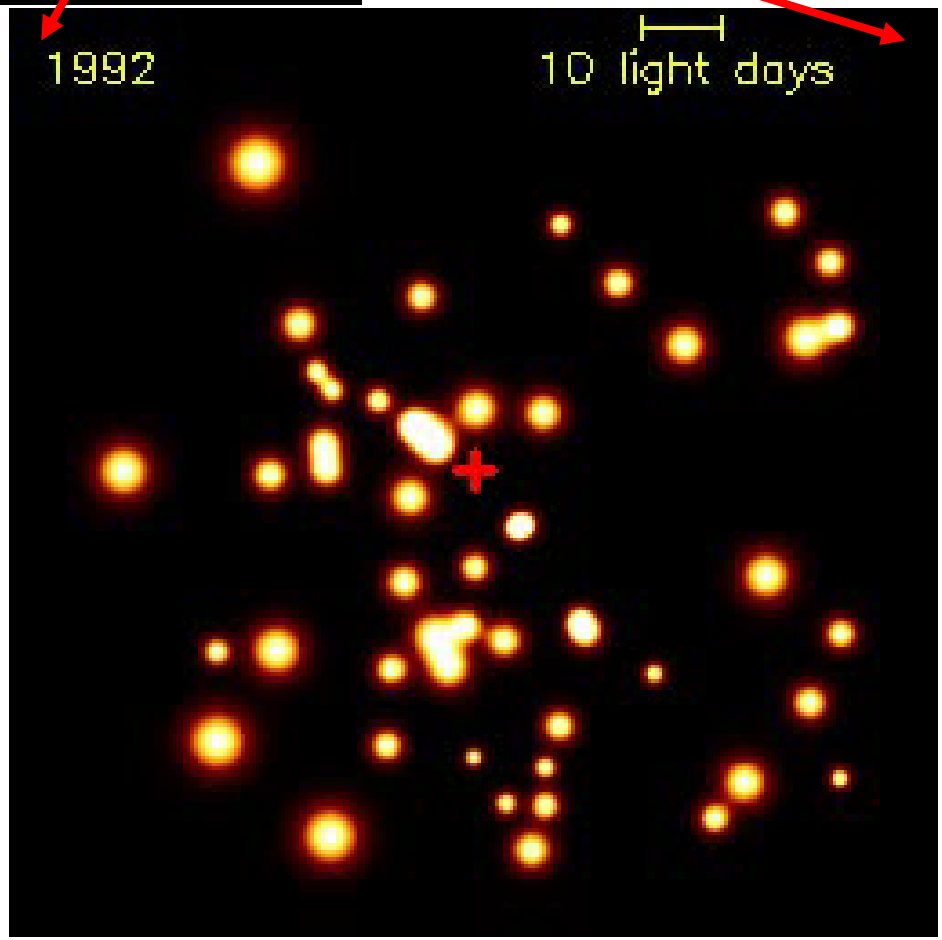
- *Tues:* Gravitational Radiation, A. Buonanno
- *Tues:* Gravity Wave Interferometers, G. Gonzalez
- *Tues:* LISA, S. Larson
- *Wed:* GR Tests with Pulsars, I. Stairs
- *Thu/Fri:* Black Holes, S. Hughes
- *Thu:* Role of Massive BHs in Structure Formation, T. Di Matteo
- *Fri:* Observations of Black Holes, A. Fabian
- *Fri:* Massive Black Hole in the Galactic Center, E. Quataert

References

- Backer & Hellings (1986) *Annual Rev Astr. Ap.*
- Backer, Jaffe & Lommen (2004) *"Massive Black Holes, Gravitational Waves and Pulsars"* Carnegie Obs. Astroph. Series. Ed. L. C. Ho, p. 439
- Jaffe & Backer (2003) *"Gravitational Waves Probe the Coalescence Rate of Massive Black Hole Binaries"* *2003ApJ...583..616*
- Focus Session: *"Pulsar Timing Array – A Nanohertz Gravitational Wave Telescope"* Center for Gravitational Wave Physics, Penn State; 05 Jul 21-23 http://cgwp.gravity.psu.edu/events/PulsarTiming/program.shtml
- Lorimer & Kramer (2005) *"Handbook of Pulsar Astronomy"* [Cambridge Univ. Press : Cambridge]

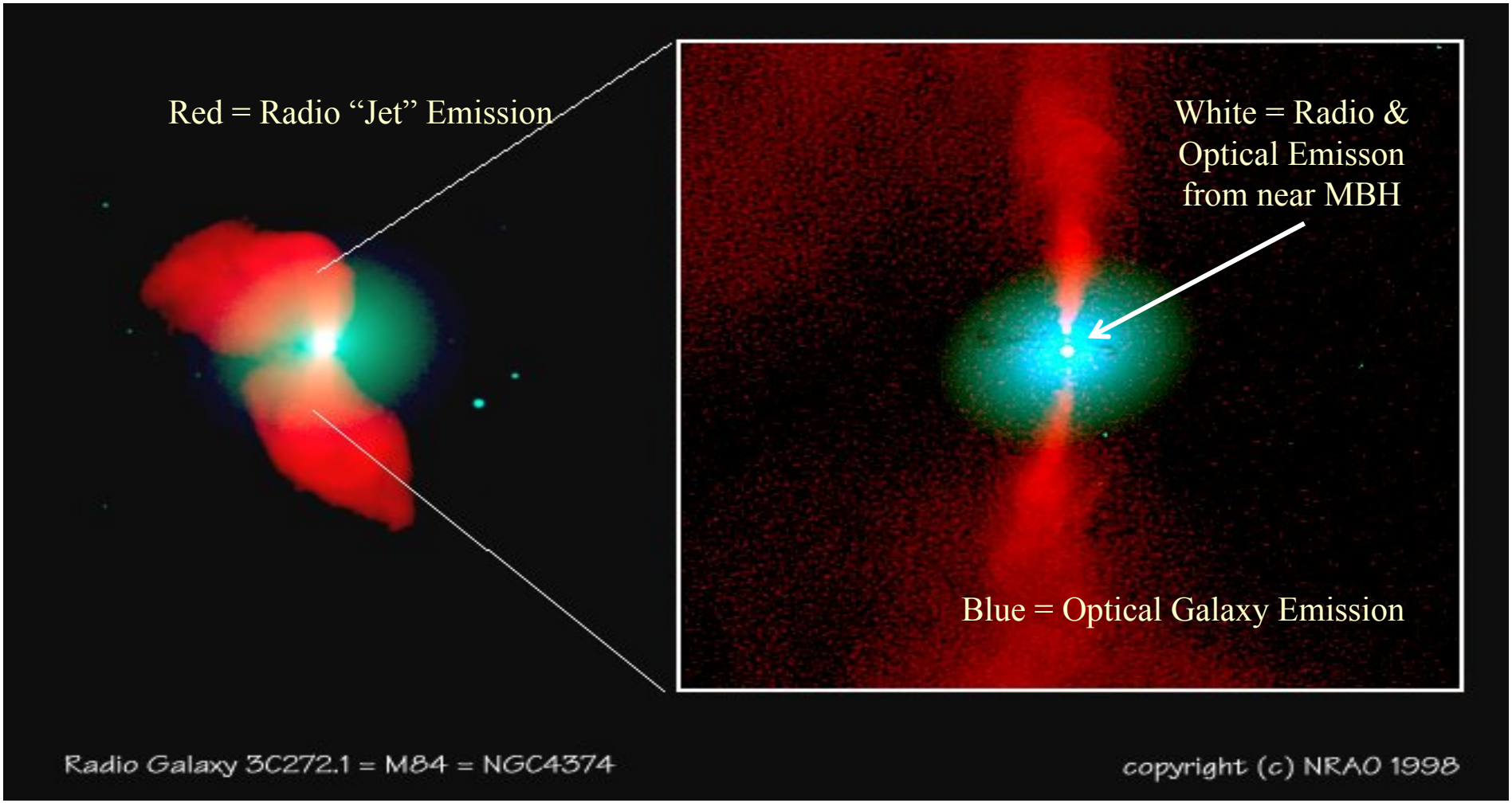
Massive Black Holes (E. Quataert, Fri)

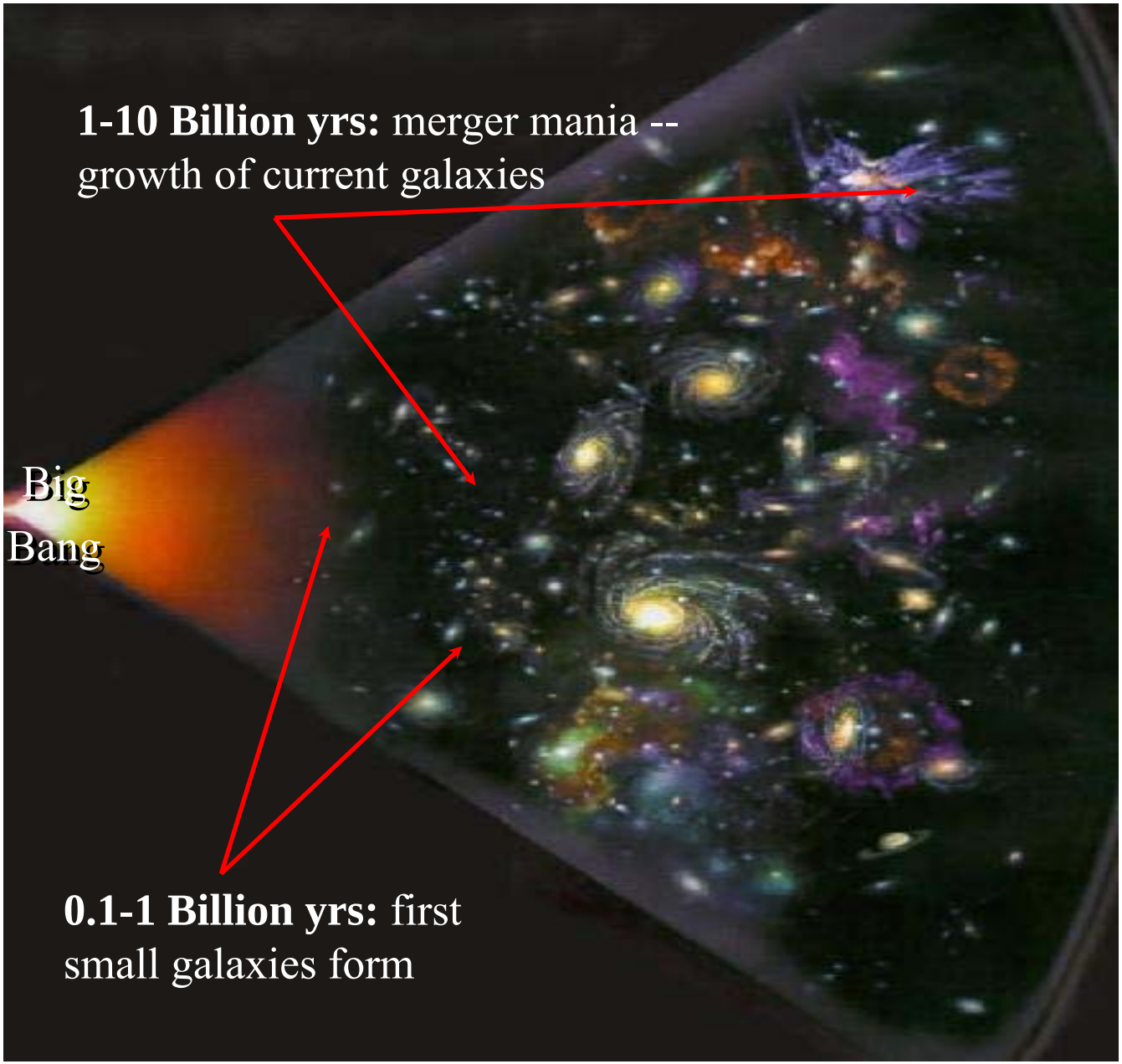




- **Sagittarius A*** – Black Hole with mass of **4 million Suns (M_s)** in the center of our Milky Way galaxy.
- **NGC 4258** – mass of **30 million M_s**, similar to many nearby galaxies.
- **Quasars and "Active" Galaxies** – jets formed by poorly understood processes; masses up to a **few billion M_s**.

Massive Black Hole in Galaxy M84 (A. Fabian, Thu)

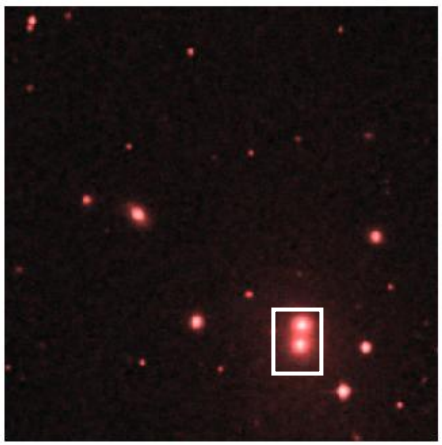




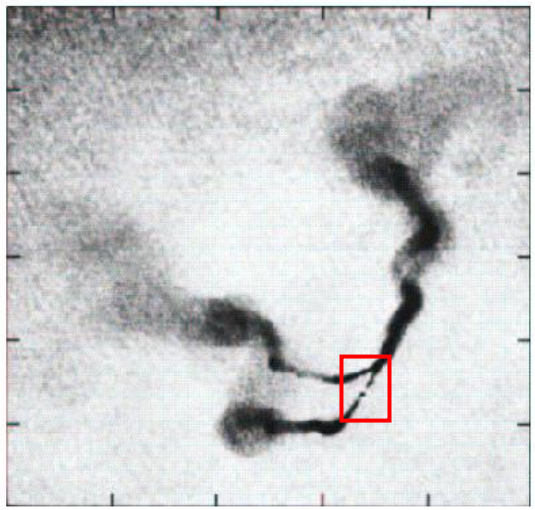
The Big Bang… and the Growth of Structures (T. Di Matteo, Thu)

Galaxy Mergers → Binary Massive Black Holes

3C75: Prelude to a massive Black Hole Binary?



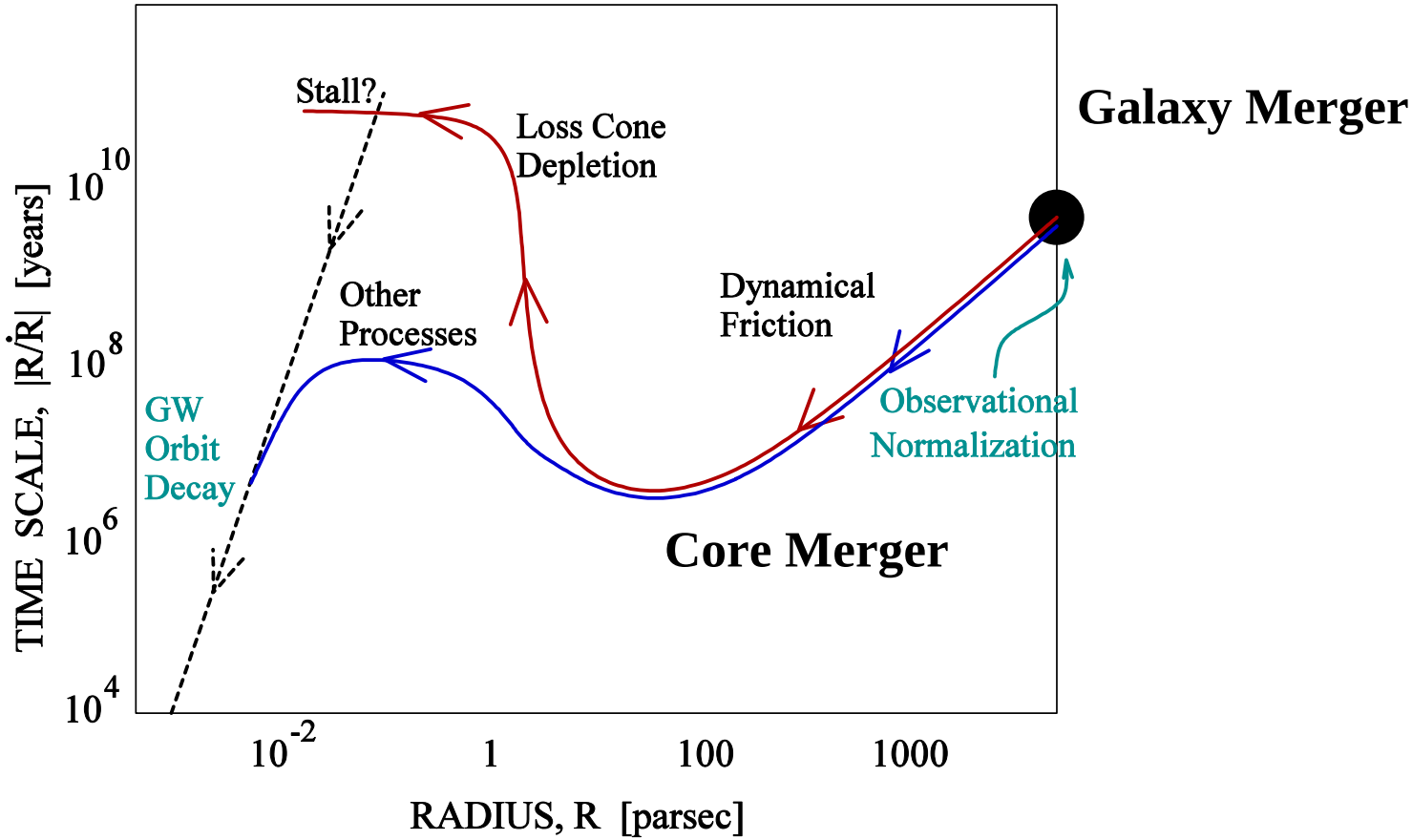
Optical image of nuclei of two galaxies



VLA Radio image of two jets, and cores

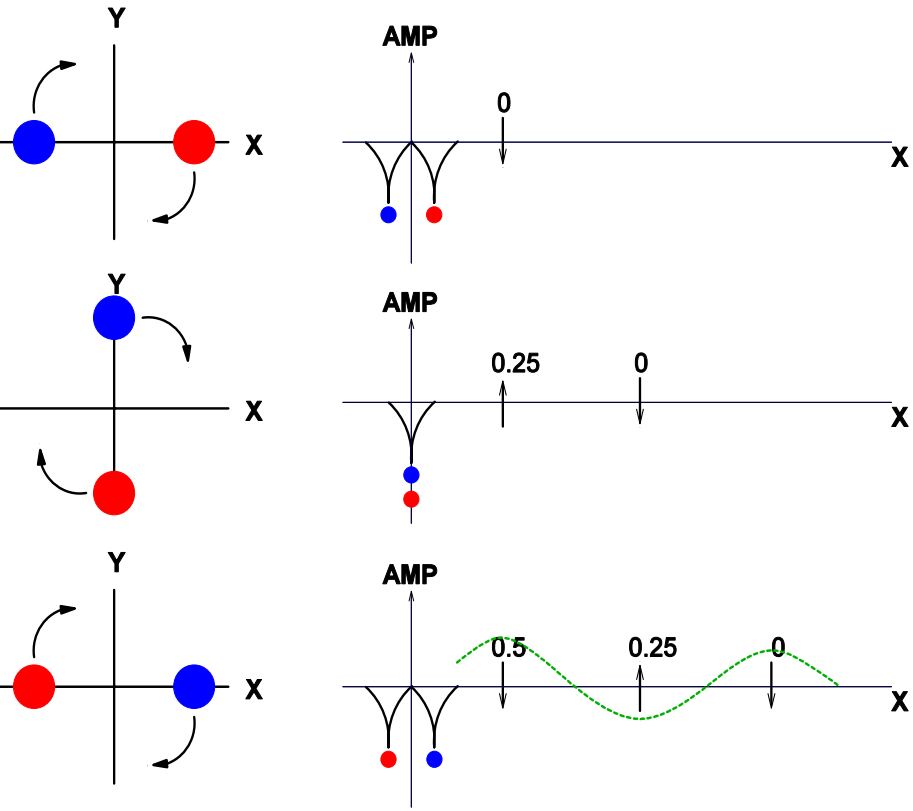
- ***Many galaxies contain Massive Black Holes*.**
- ***All galaxies grow by mergers.***
- When two galaxies with MBHs merge, the two holes will sink to a common center.
- ***Compact Massive Black Hole binaries are inevitable!***

Evolution of MBH Binary



adapted from Blandford, Begelman & Rees (1980)

Gravitational Radiation (A. Buonanno, Tues)



- Masses distort surrounding fabric of space.
- **Accelerating masses** radiate "distortions", or "ripples", in the fabric of space with dimensionless amplitude, ***h(x,t)***. This ***is*** gravitational radiation, which propagates away at speed of light.
- A **Binary MBH** ten billion light years away with orbit of 5y will produce a distortion of space by just 0.0000000000000001 (16 zeroes!).

Model Universe of MBHs

Ingredients:

Binary GW formulation (Peters & Matthews, 1965)

Galaxy mergers & MBH assembly vs redshift

MBH demographics in galaxies

Galactic dynamics & the "final parsec problem"

Cosmological parameters relating distance, redshift, volume

⇒ ***Stochastic Background of MBH Binary GWs***

(n.b., "Foreground" in case of primordial background)

Binary MBH GW Spectrum

***Merger rate + Mass function + GWs*:**

– $N(z, f, M_1, M_2)\, df \propto \varphi_1 \varphi_2 R(z) C[\Omega, z]\, \mathcal{M}^{-5/3} f^{-8/3} df/f$

MBH Mass fn

Merger rate

Cosmology

GW Timescale

$$h_c^2(f) = f \int dz\, dM_1\, dM_2\, h^2(z,M)\, N(z, f, M_1, M_2)$$
$$= \langle (\mathcal{M}/10^8 M_\odot)^{5/3} \rangle\, (f/\mathrm{yr}^{-1})^{-4/3}\, I_h$$

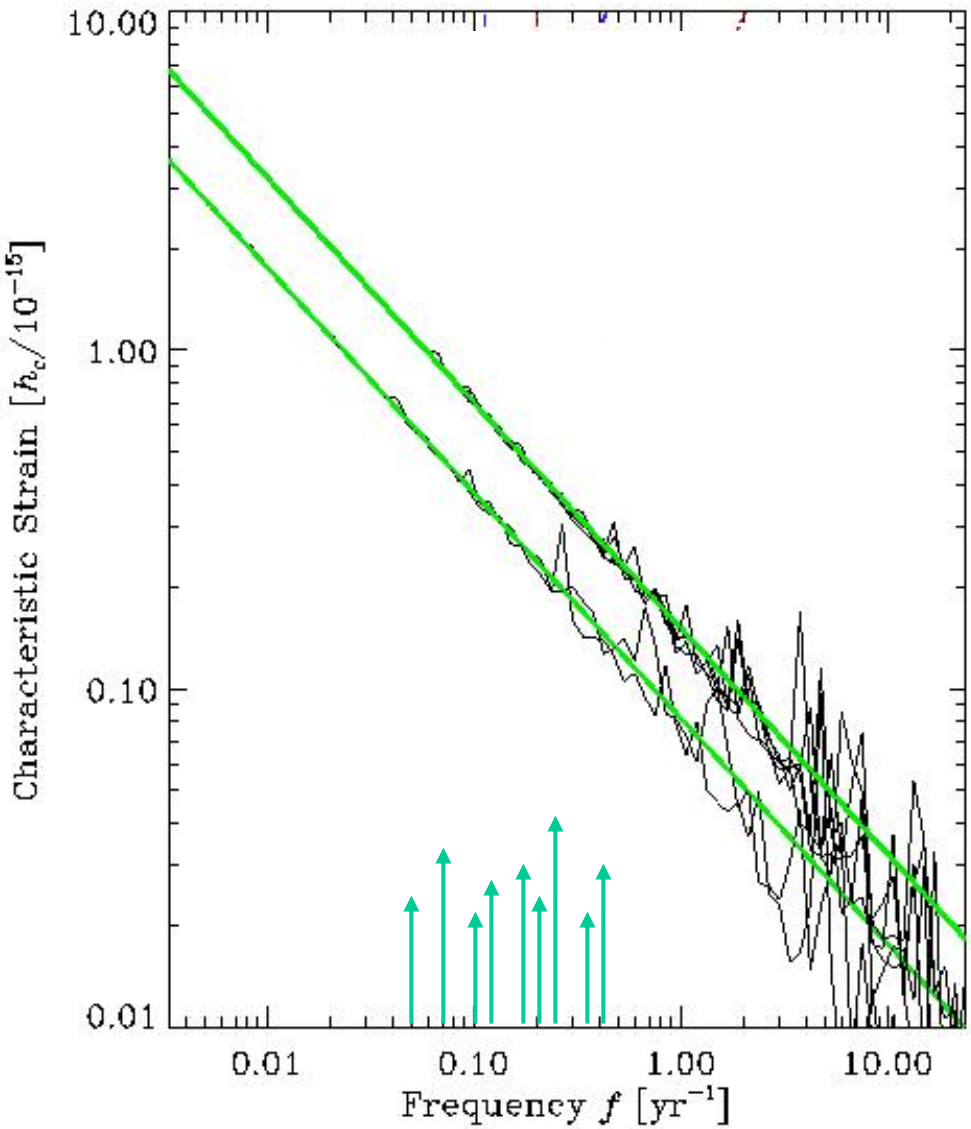
Stochastic (mean-square)

(see also Phinney 2002)

$$\mathcal{M} = (M_1 M_2)^{3/5} / (M_1 + M_2)^{1/5}$$

n.b., integral separates: $\varphi(M)\, f^{-8/3}\, I(z)$

$$I_h = \int \frac{R(z)}{R_0} \frac{dz}{E(z)(1+z)^{4/3}}$$



Stochastic Gravitational Wave Background from Massive Black Hole Binaries

Begelman, Blandford & Rees (1980)

Rajagopal & Romani (1994)

Jaffe & Backer (2003)

~One Number: Amplitude !!

Recent Updates

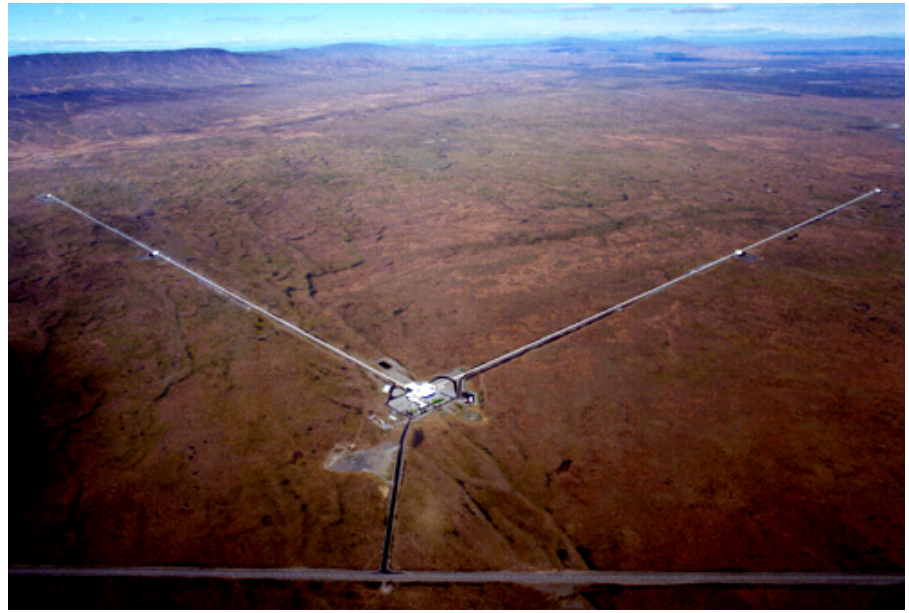
- *Wyithe & Loeb* (0211556)
  - Global merger tree model
- *Enoki et al* (0404389)
  - From Halos --> Galaxies (baryons)
- *Sesana et al* (0401543, 0409255)
  - Some explicit MBH binary/galaxy dynamics, estimated 0.1 nHz cutoff
- *Penn State Mtg*: eccentric early history?

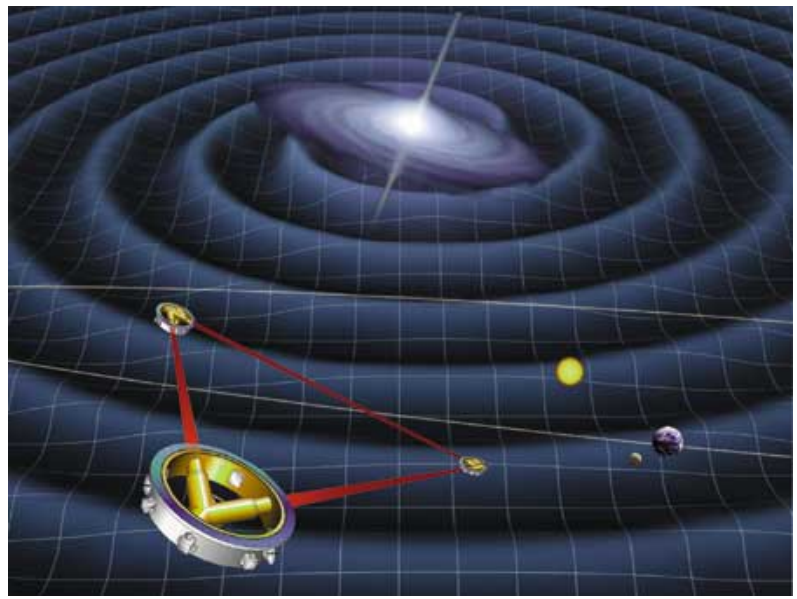
http://cgwp.gravity.psu.edu/events/PulsarTiming/program.shtml

LIGO & LISA

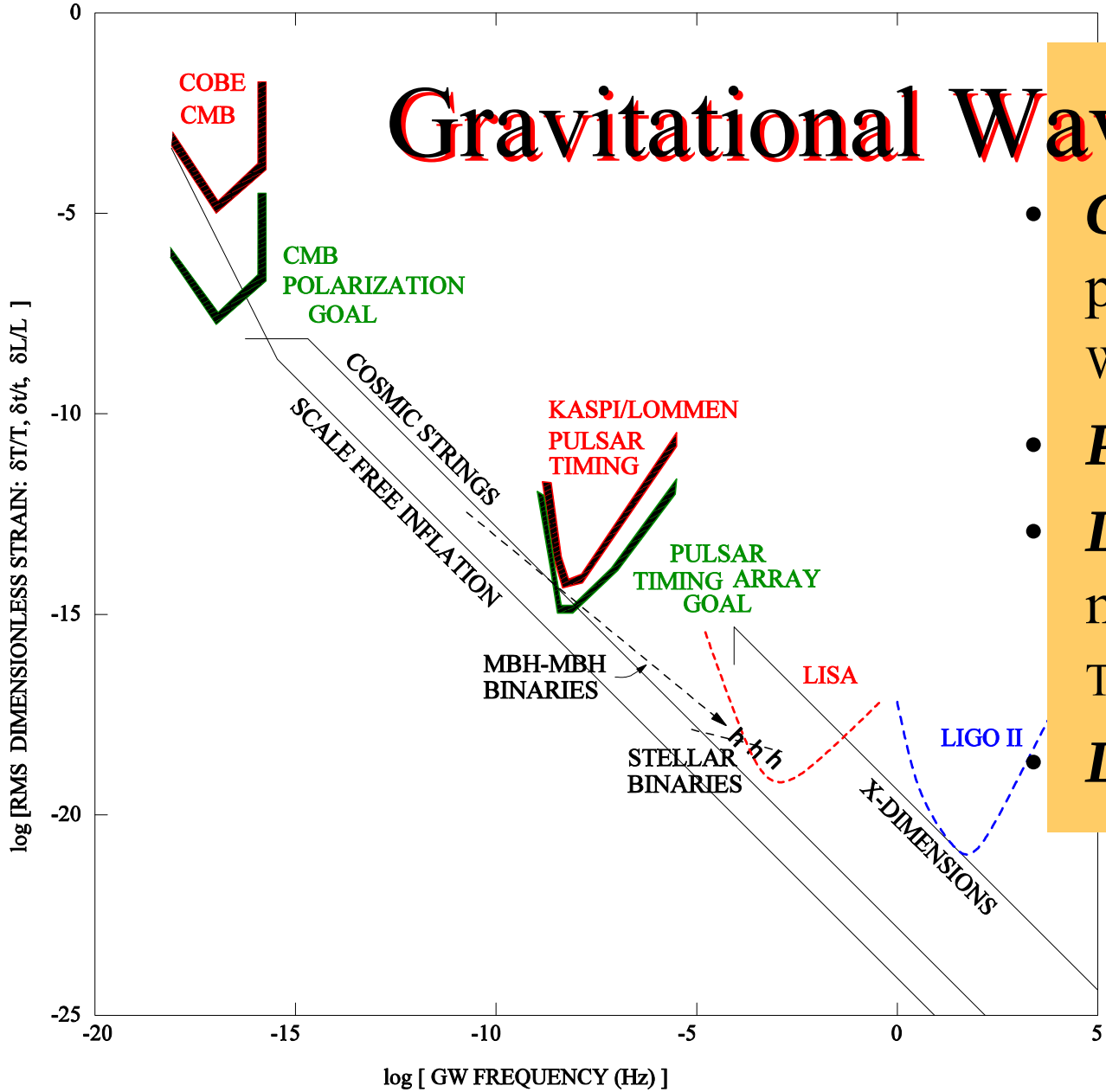
(G. Gonzalez, Tue; S. Larson, Tue)

- **LIGO** – Laser Interferometer Gravity-Wave Observatory seeks ripples from coalescing binary neutron stars and other systems: milliseconds time scale (kiloHertz).
- **LISA** – Laser Interferometer Space Array seeks ripples from final stages of coalescing binary MBHs and other systems: minutes time scale (milliHertz).



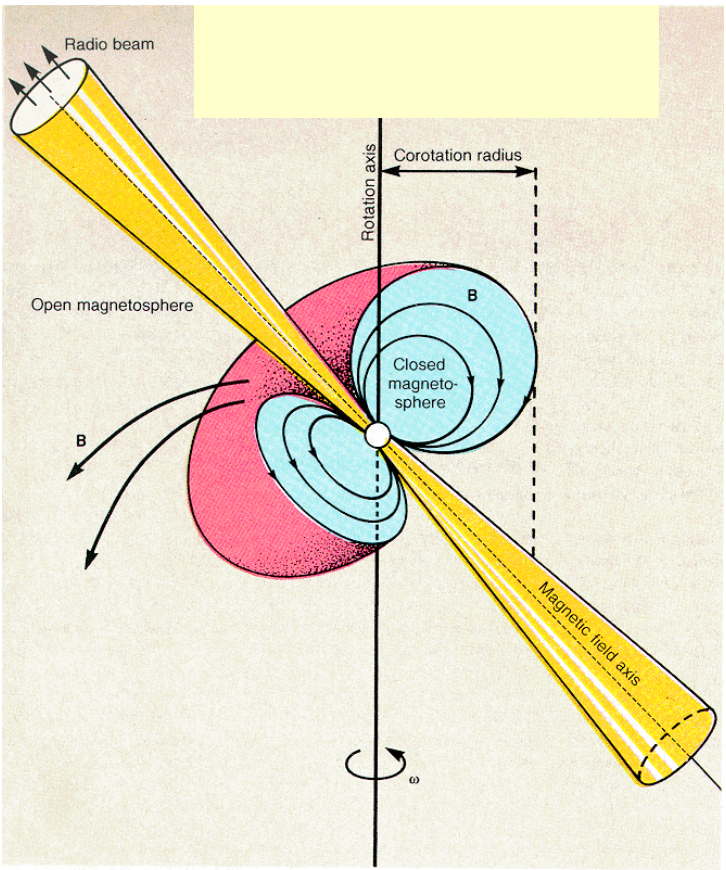


Gravitational Wave Spectrum



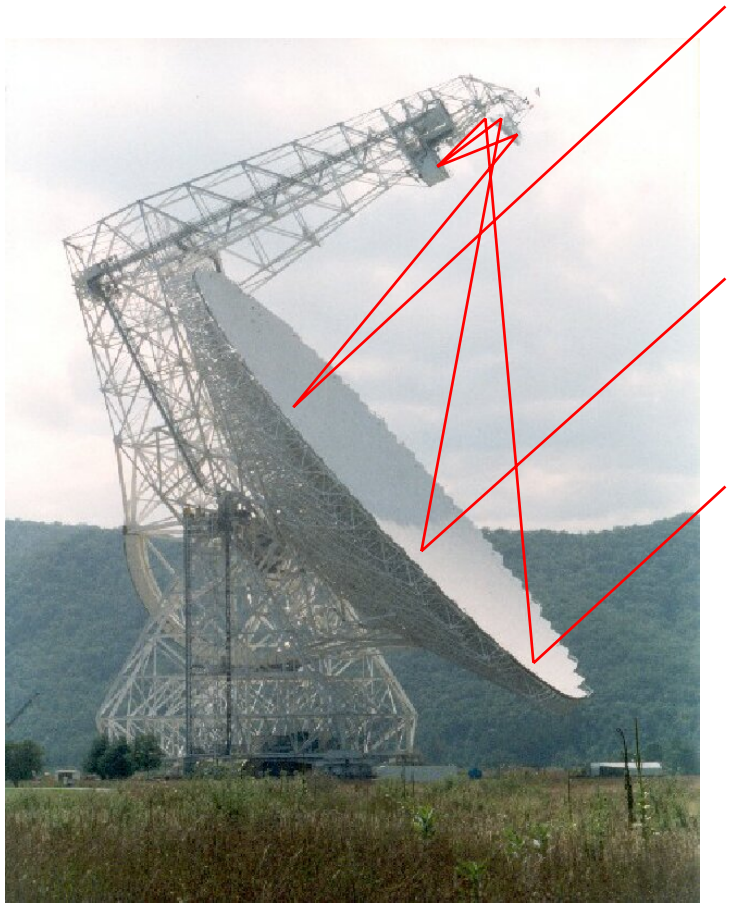
- ***CMB*** Polarization: primordial (S. Church, Wed)
- ***Pulsars***: MBH-MBH
- ***LISA***: MBH-MBH + mBH-MBH (S. Larson, Tue)
- ***LIGO***: Nstar-Nstar

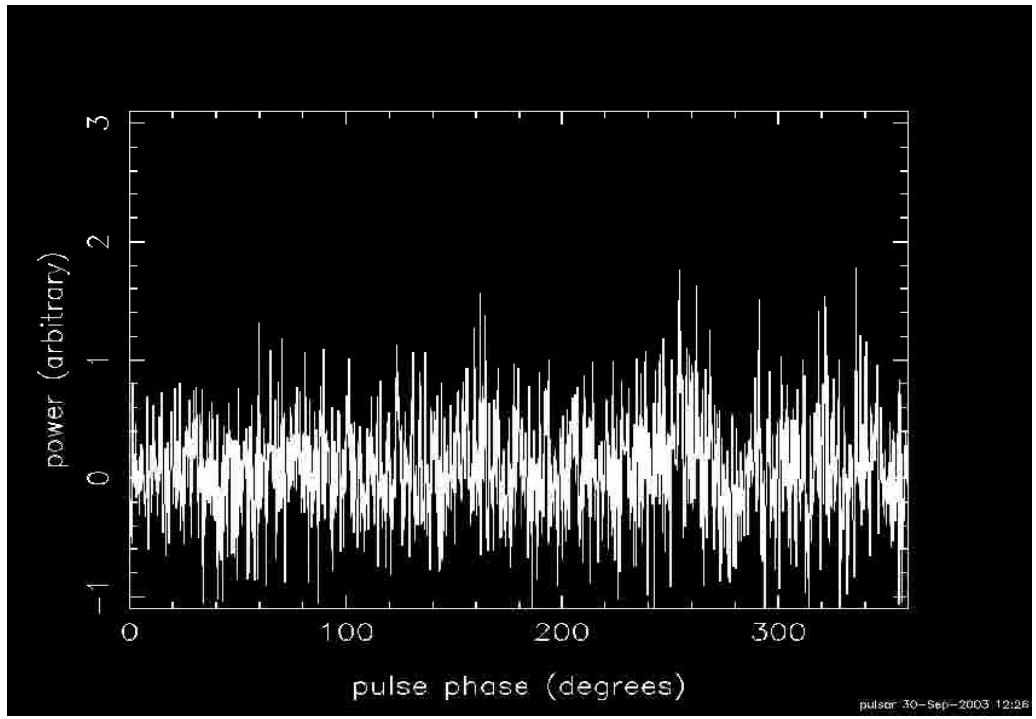
Pulsars (I. Stairs, Wed)



- **Rapidly rotating, highly magnetized neutron-rich stars.**
- **Neutron star** (at center) has a mass of the Sun and a radius of 10 km -- could fit within the ring road around the Washington (and if placed there, the entire federal bureaucracy would disappear in milliseconds!).
- "Closed" **dipole field** (**pink**/**acqua**) extends to 100 km in the fastest spinning pulsars, and to 500,000 km in the slowest and rotates rigidly with star.
- The **radio beam** (**yellow**) is driven by a voltage generated by the spinning field in conducting medium -- analogous to the spinning conductor in a fixed field common to most electric generators.

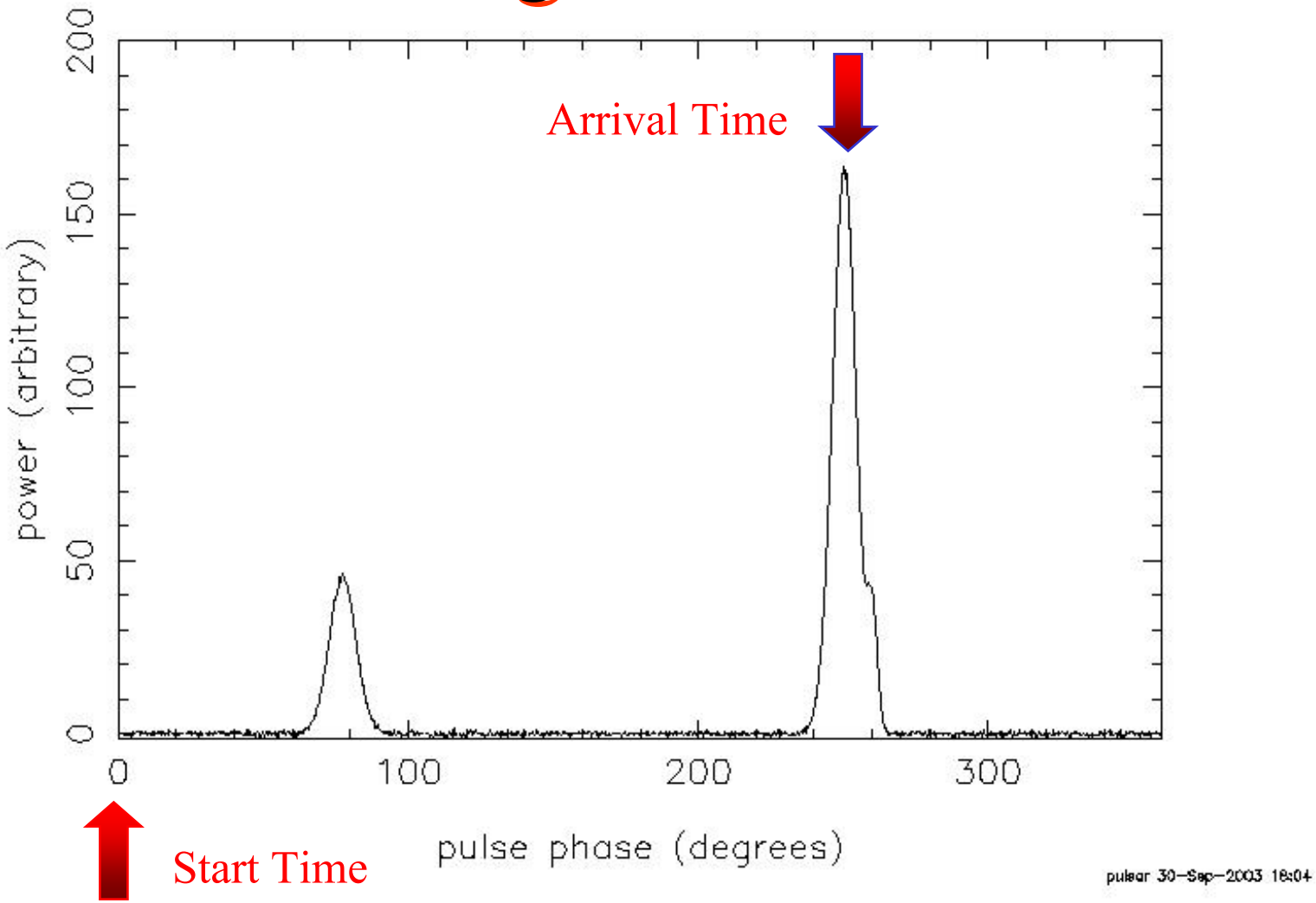
Pulsar Timing – Observations (I.S., Wed)



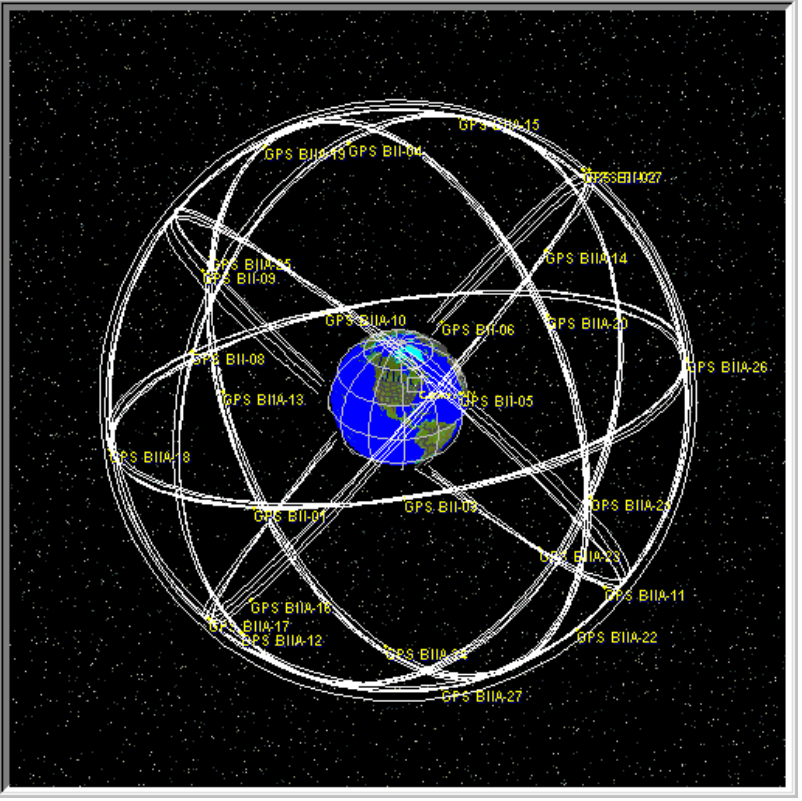


- Faint signals are detected against background noise.
- Need wide bandwidth & long integration on large telescopes.
- Low level of interference is increasingly important.

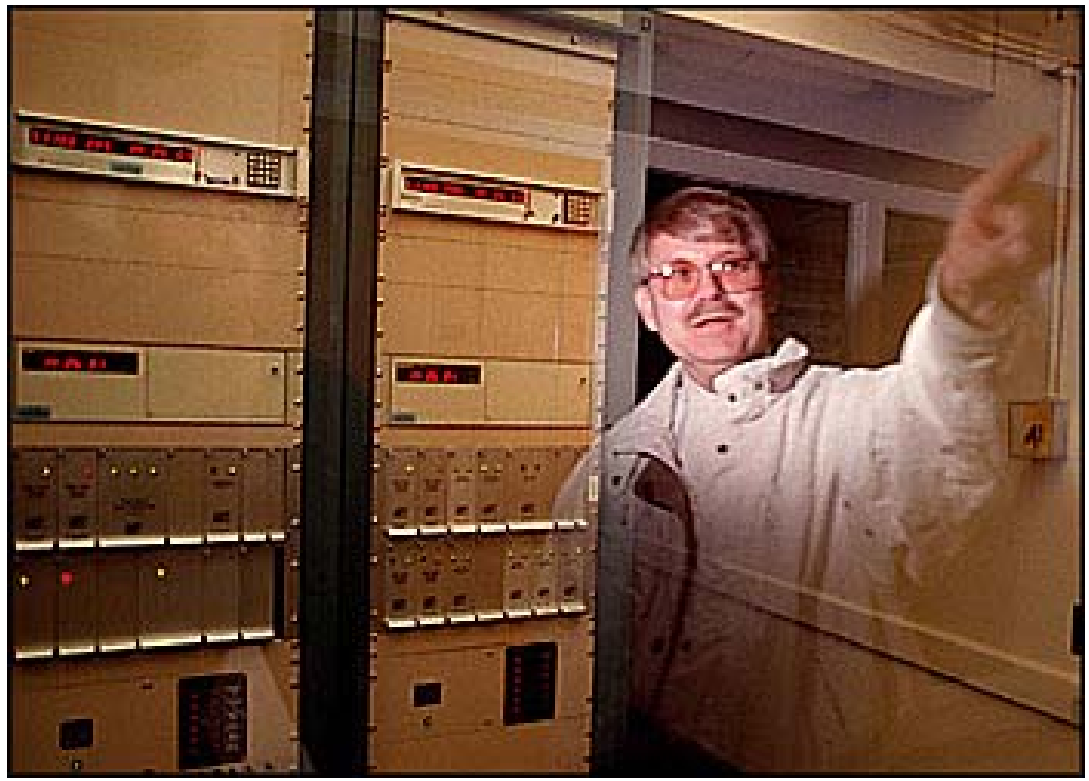
Pulsar Timing – Data Reduction



Pulsar Timing – Time

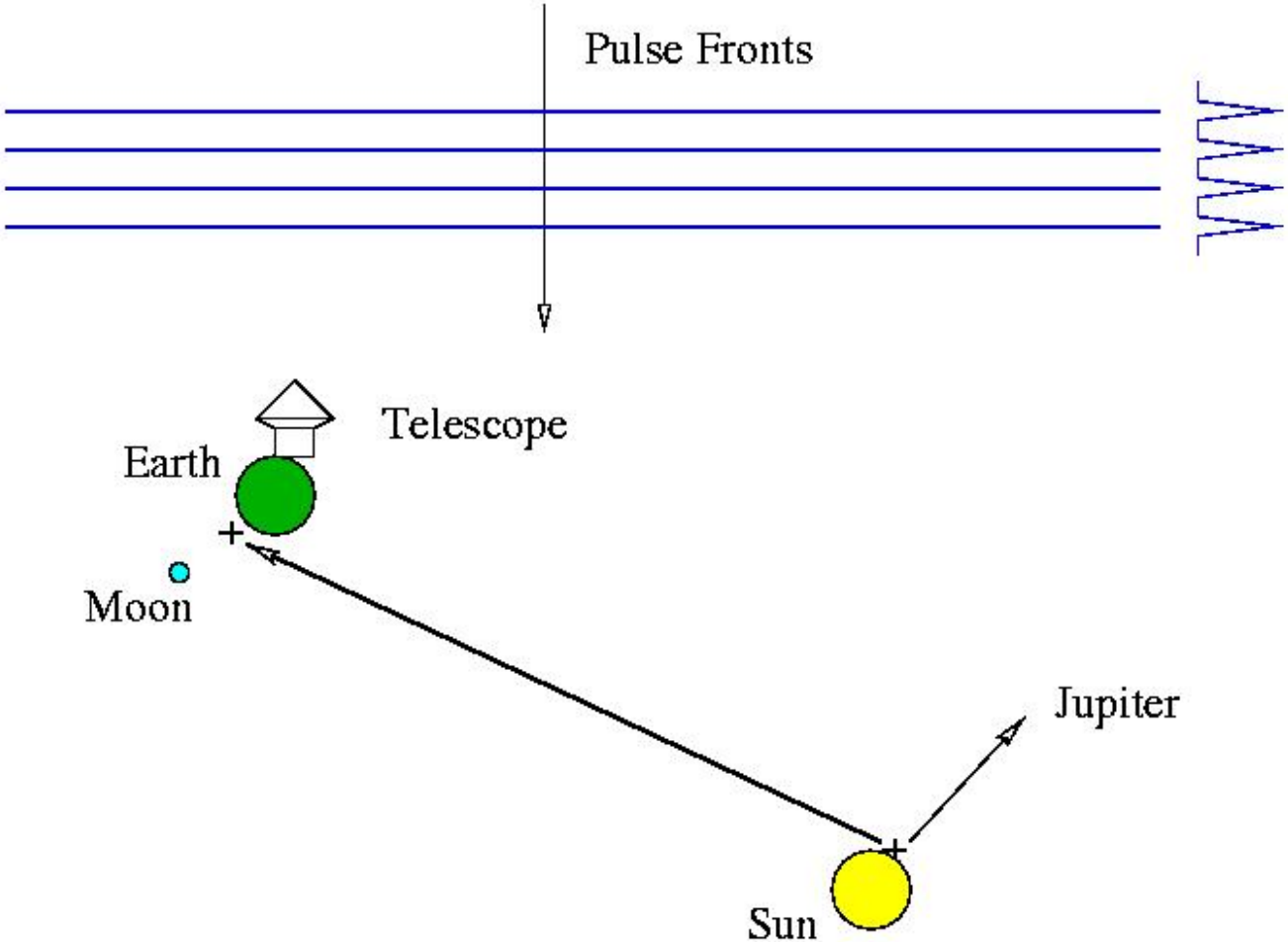


[1] The pulse arrival time at the telescope is referenced through the **GPS System** (**left**) to the **USNO** master clock ensemble in Wash., DC (**below**).



[2] **USNO** time is itself referenced via GPS to a single **International Atomic Time**. And then the relativistic effects from the moving Earth are removed to approximate a clock at rest in the center of the solar system.

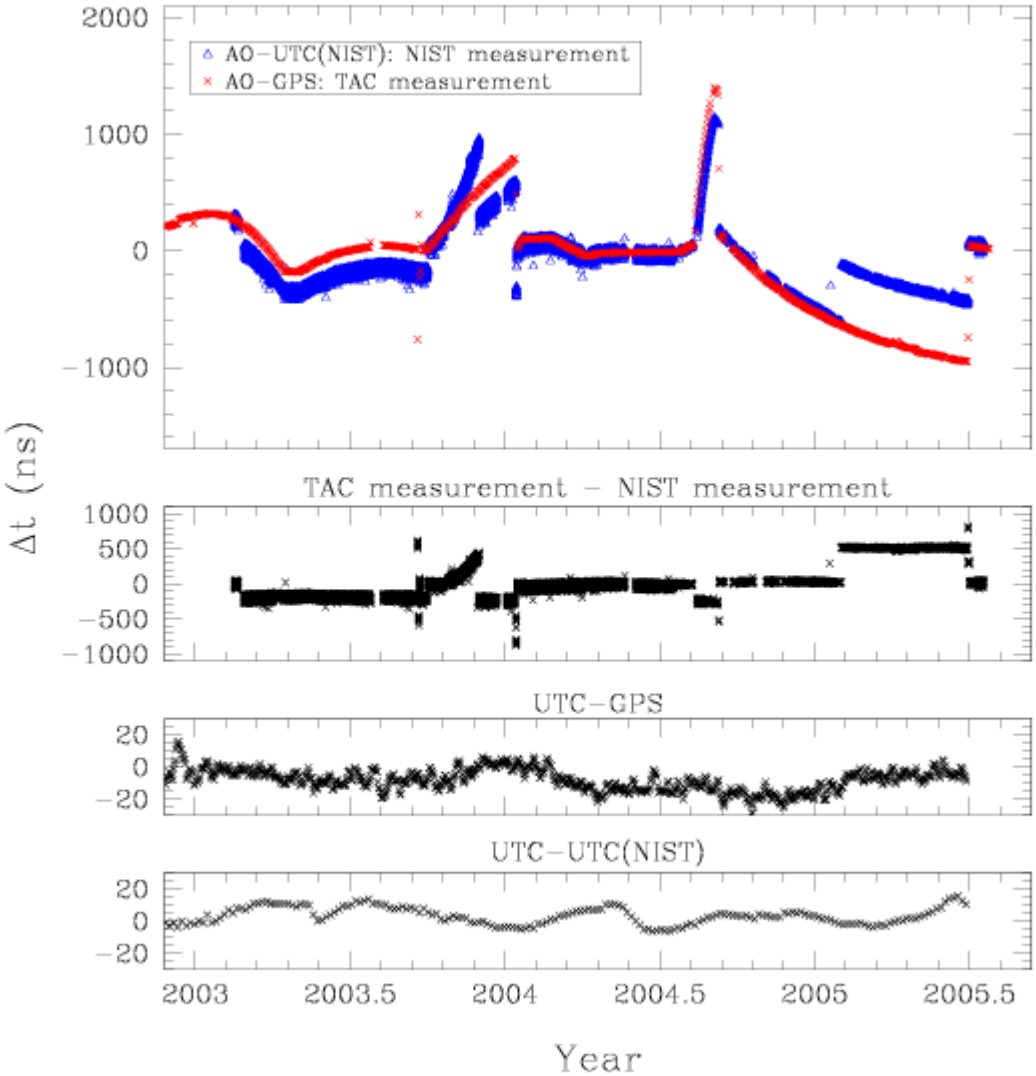
Pulsar Timing - Ephemeris



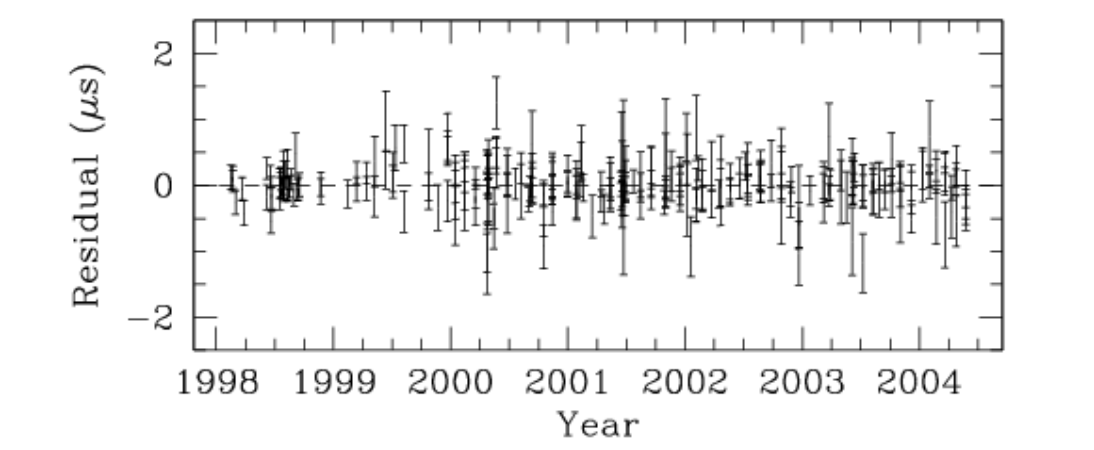
Pulsar Timing - Analysis (I.S., Wed)

- Model building
  - ***Spin*:** phase, period, slowing down rate
  - ***Astrometric parameters*:** sky position, motion, parallax
  - ***Orbital parameters* (*if in binary system*):** period, separation, phase, ..
- Residuals, R = Observations – Model
- Is model complete? Are residuals consistent with measurement errors? Or is "something" more needed?

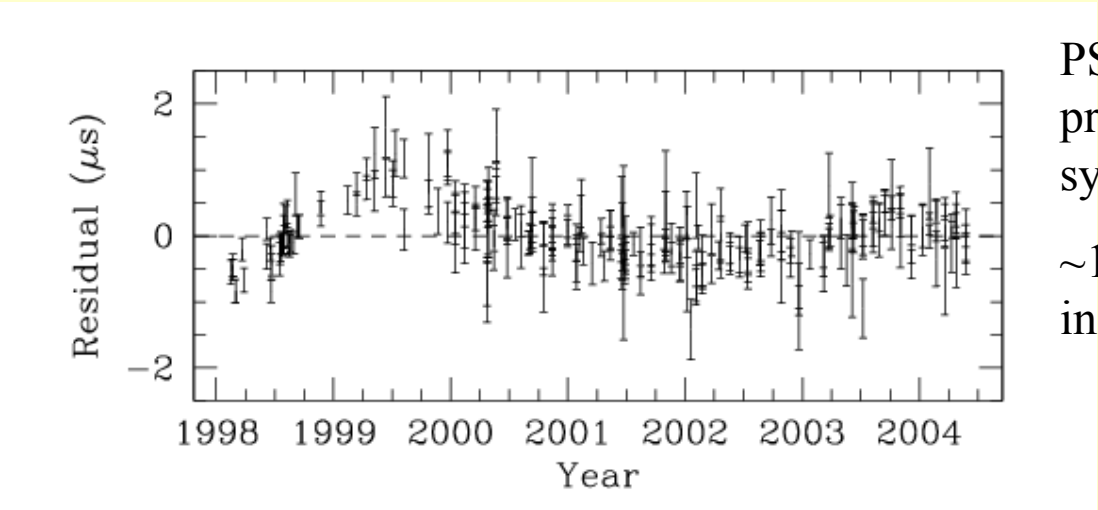
Time Transfer Errors (D. Nice)



Ephemeris Errors (D. Nice)



Arecibo data from PSR J1713+0747 analyzed using latest ***DE 405*** solar system ephemeris; Splaver et al. (2004).



PSR J1713+0747 analyzed using previous-generation ***DE 200*** solar system ephemeris.

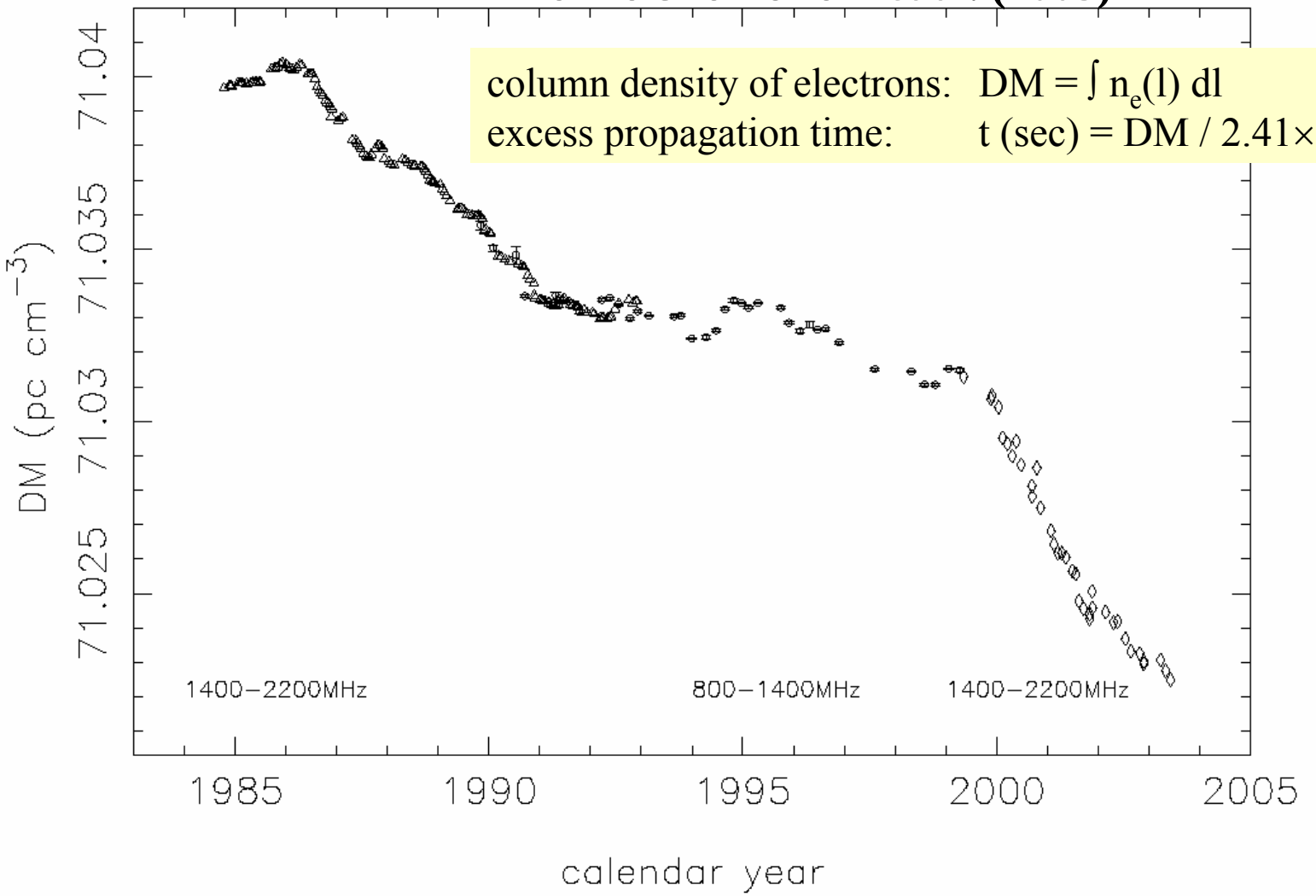
~1μs timing errors ⇔ 300 m errors in Earth position in inertial frame.

Interstellar Plasma "Weather"

Ramachandran et al. (2005)

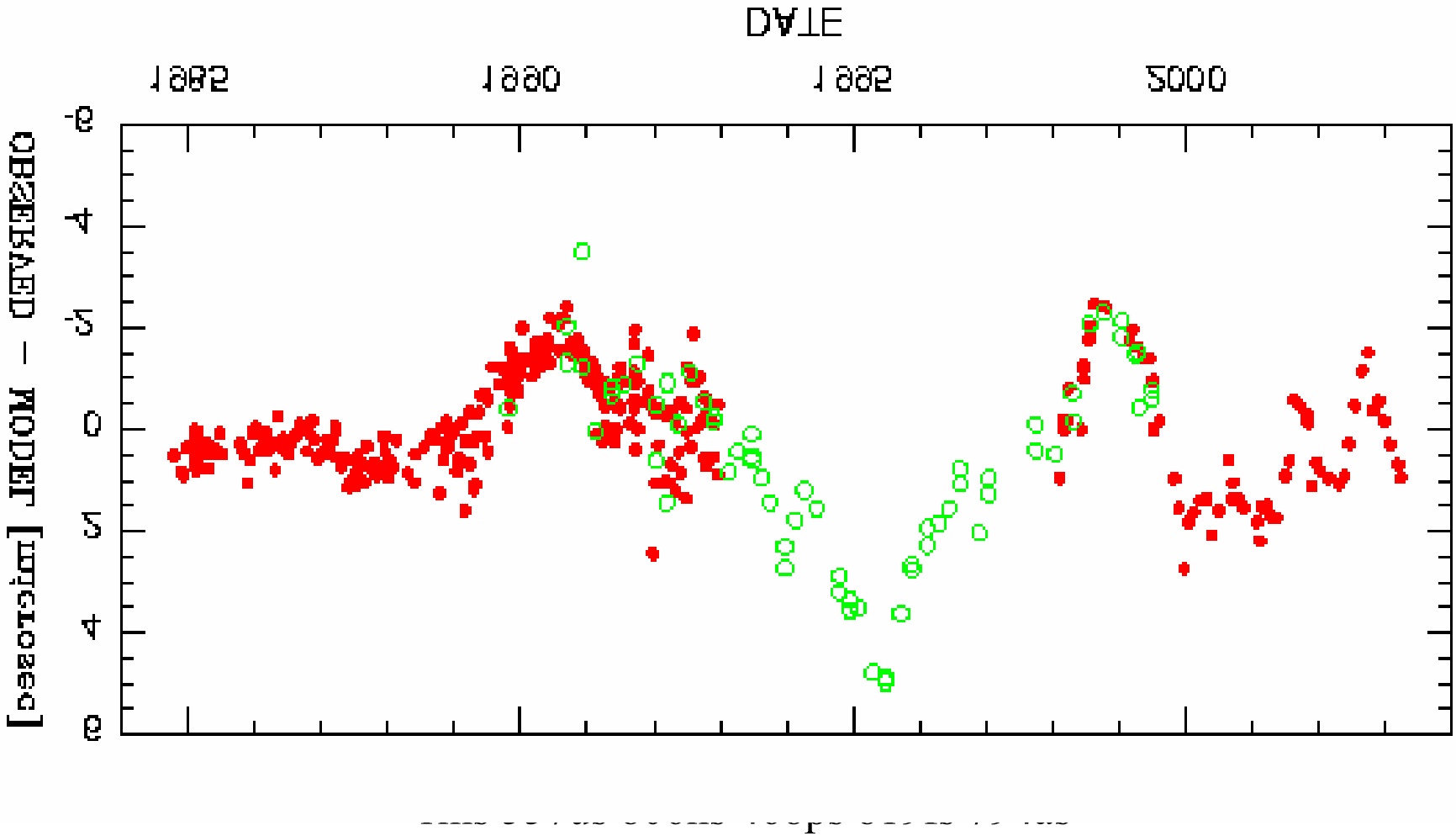
column density of electrons: $DM = \int n_e(l)\, dl$

excess propagation time: $t\ (sec) = DM / 2.41\times10^{-4}\ [f(MHz)]^2$

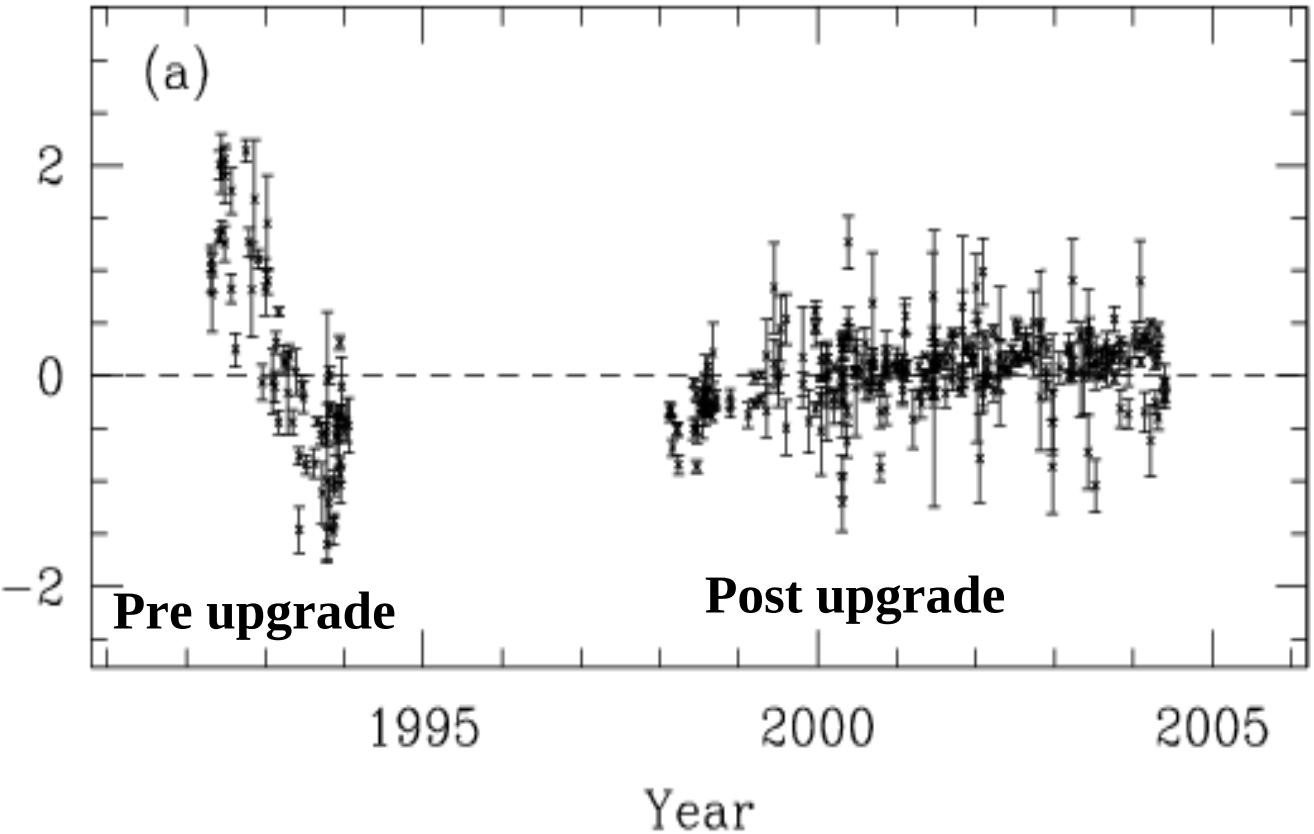


Pulsar Timing Array – B1937+21

Timing noise? Interstellar weather?



Pulsar Timing Array – 1713+0747

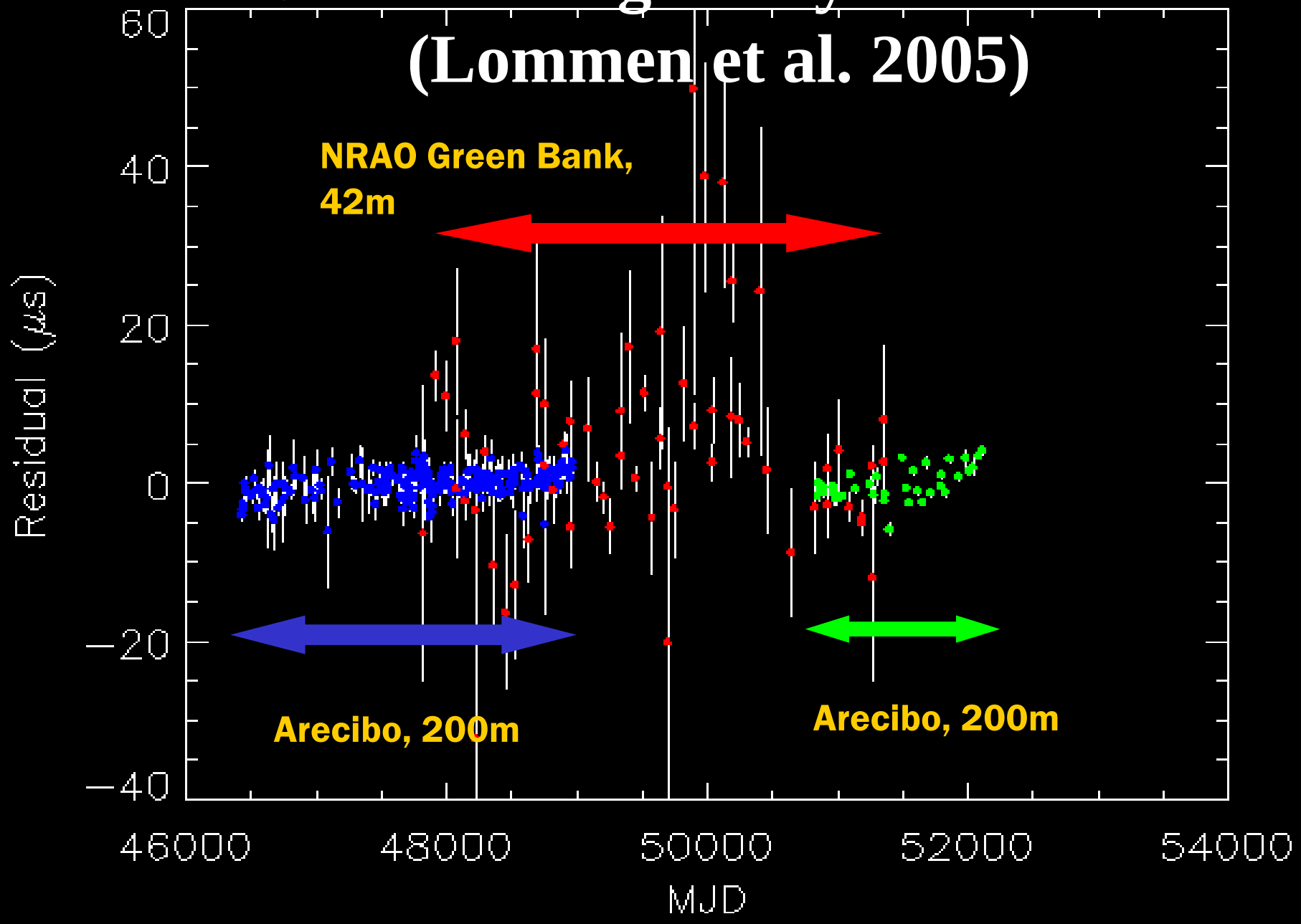


Splaver et al. (2004)

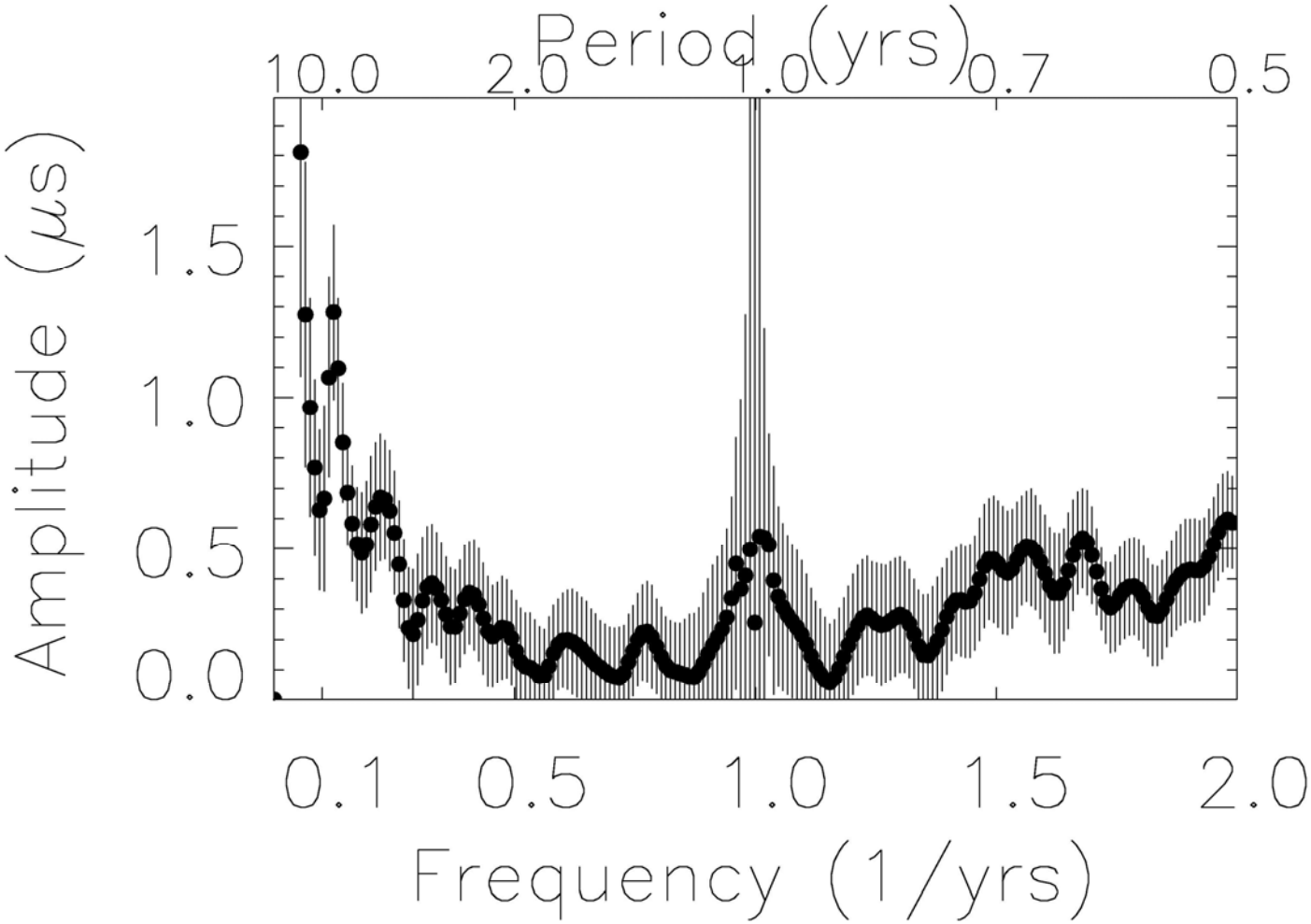
Arecibo data; no second derivative.

Timing noise?

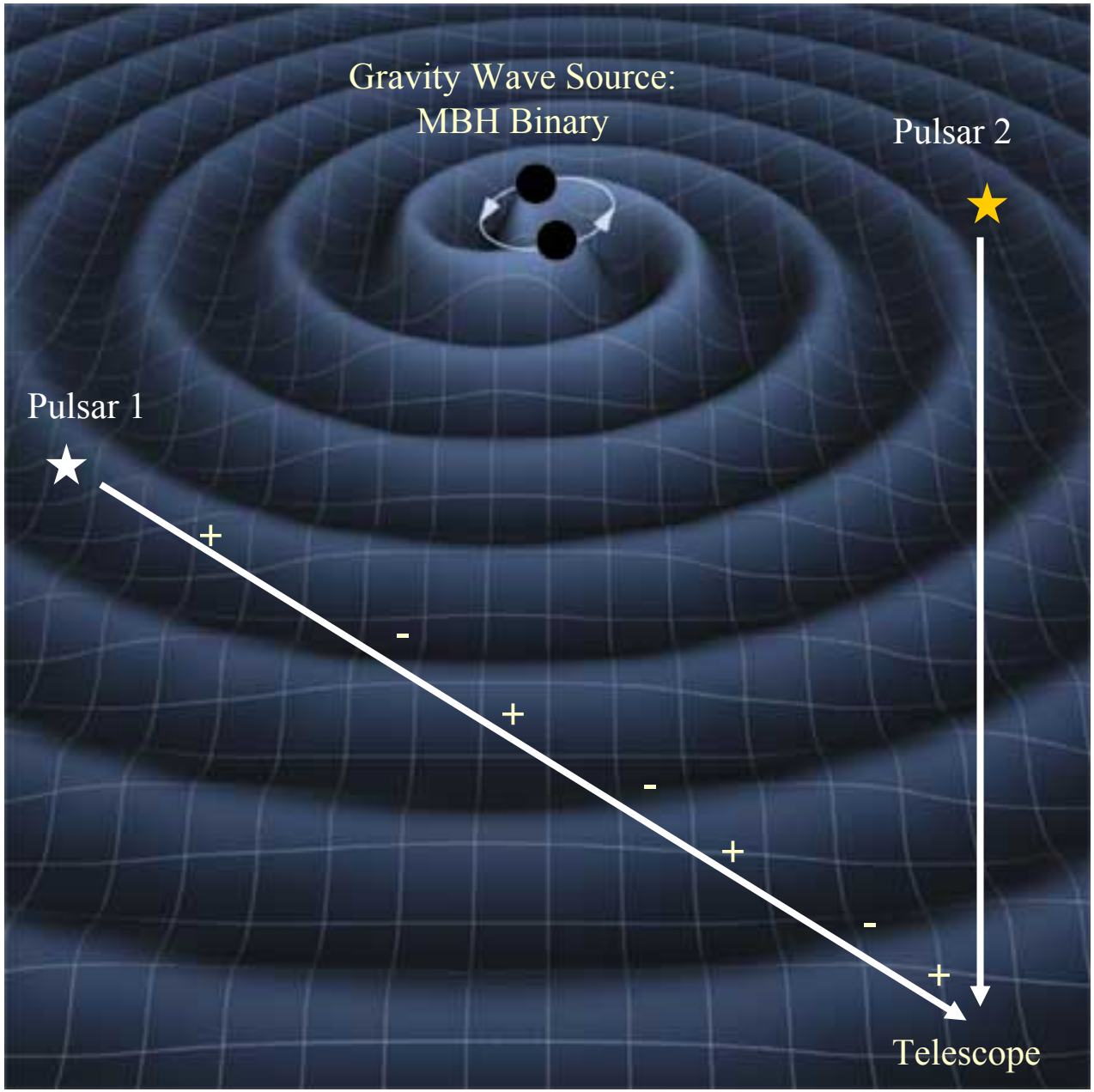
Pulsar Timing Array – B1855+09 (Lommen et al. 2005)



Periodogram Analysis – PSR B1855+09 (Lommen et al. 2005)



Gravity Wave Detection



Hellings - 1

The path of the radio signal from the pulsar to the Earth is a null path, so

$$dt^2 - ds^2 = 0$$

$$\Rightarrow \quad dt^2 = (\eta_{ij} + h_{ij})dx^i dx^j = ds^2 \left(1 + h_{ij} \frac{dx^i}{ds} \frac{dx^j}{ds} \right)$$

Approximate and integrate

$$\int_p^e dt \approx \int_p^e ds + \frac{1}{2} \int_p^e h_{ij} \frac{dx^i}{ds} \frac{dx^j}{ds} ds$$

$$\ell = s + \frac{1}{2} \hat{s}^i \hat{s}^j \int_p^e h_{ij} ds = s + \frac{1}{2} \hat{s}^i \hat{s}^j \left[H_{ij}(e) - H_{ij}(p) \right]$$

where $\quad H_{ij}(t) \equiv \int h_{ij}(t) dt$

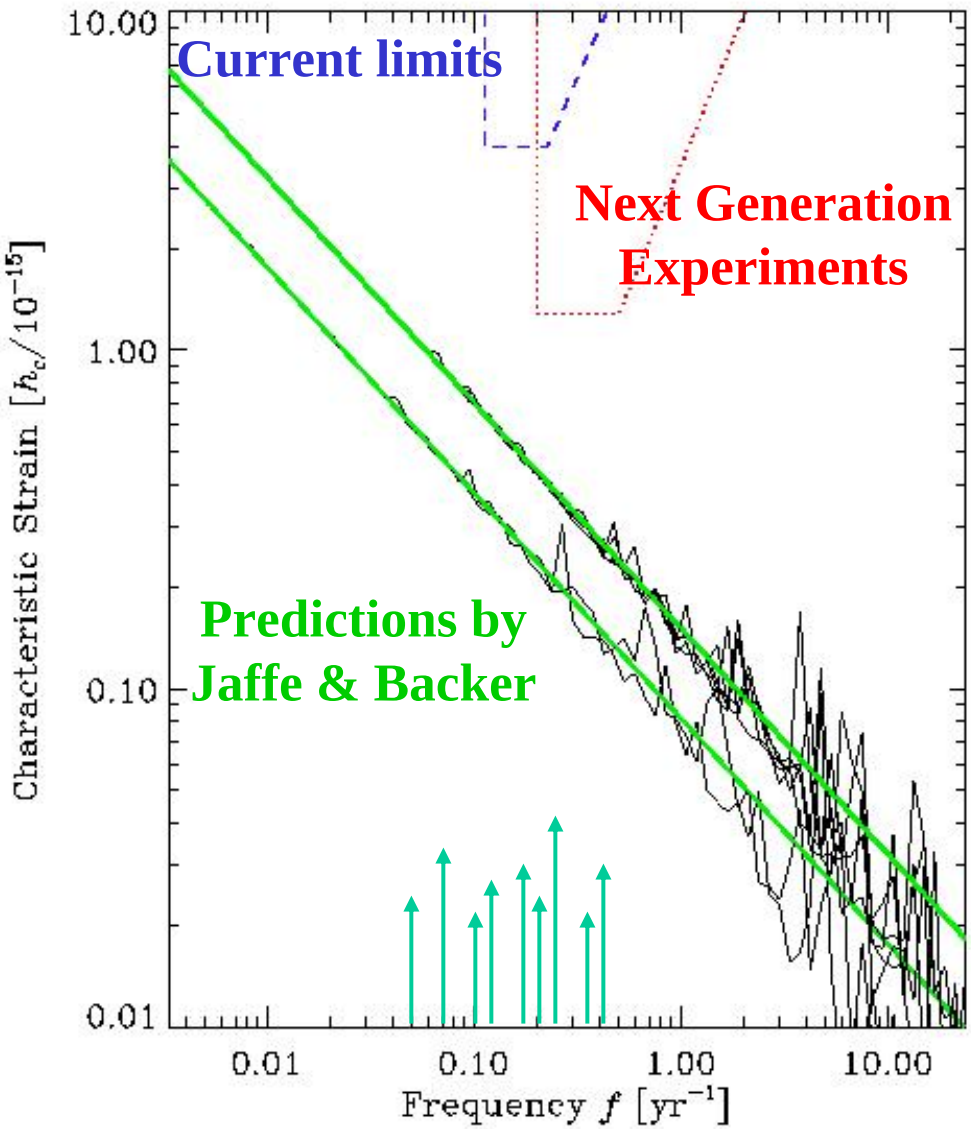
Hellings - 2

So let's get an observable that is proportional to the wave

$$\frac{d(\Delta\ell)}{dt} = \frac{1}{2}\hat{s}^i\hat{s}^j\left\{h_{ij}\left[t-(1+\hat{\mathbf{n}}\cdot\hat{\mathbf{s}})s\right]-h_{ij}\left[t\right]\right\}$$

Gravitational waves are proportional to the time derivative of pulsar arrival time residuals.

Every pulsar in every direction has correlated timing noise due to this term. This allows a weighted correlation analysis to optimally use data from multiple pulsars.



Pulsar Timing Limits on the Stochastic Gravitational Wave Background from Massive Black Hole Binaries

Pulsar Timing Array --Two Basic All-Sky Analysis Techniques

Spherical Harmonic Decomposition

$$R(t,\hat{r}) = \int \sum_{l,m} B_{lm}(\omega) Y_{lm}(\theta,\phi) e^{-i\omega t} d\omega$$

$$B_{lm}(\omega) = \int R(t,\hat{r}(\theta,\phi)) Y^*_{lm}(\theta,\phi) e^{i\omega t} dt d\Omega$$

Burke 1975

Detweiler 1979

Jaffe & Backer 2003

Demorest et al. 2005

Two-point correlation

$$C(\hat{r}_1,\hat{r}_2) = \frac{1}{T}\int_0^T R(t,\hat{r}_1) R(t,\hat{r}_2) dt$$

Hellings & Downs 1983

Jenet, Hobbs, Lee, & Manchester 2005

•N.b., clock error has monopole signature; ephemeris error has dipole signature; gravitational wave has >= quadrupole signature.

The Allen Telescope Array

SKA 2004
July 19, 2004

Summary

- **Massive Black Holes** (MBHs) exist in galaxies.
- Galaxy mergers leads to binary MBHs.
- MBH binaries produce **Gravitational Radiation.**
- LIGO/LISA are future detectors of gravitational waves, but…we might get there first with the **Pulsar Timing Array** GW telescope probe of the nanoHertz spectrum!