Title: Testing gravity in the centre of the Galaxy

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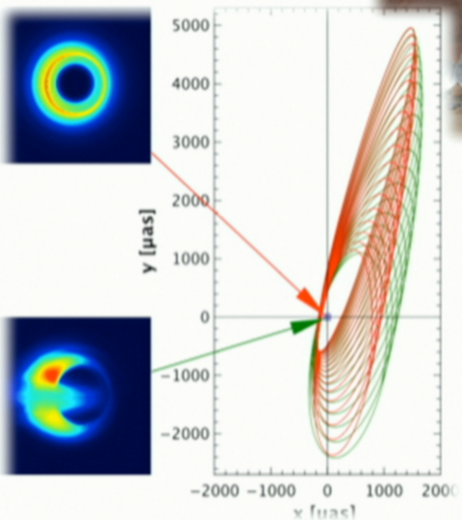
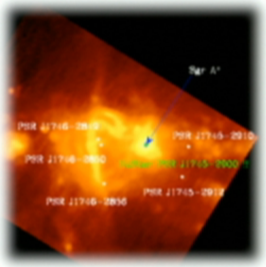
Abstract: The supermassive black hole in the centre of the Milky Way, Sgr A*, is an ideal target for testing the properties of black holes. A number of experiments are being prepared or conducted, such as the monitoring of stellar orbits, the search for radio pulsars or the recording of an image of the shadow of a event horizon. The talk puts these efforts in context with other tests of general relativity and its alternatives. I will also compare the approaches in the Galactic centre, while concentrating in particular on the prospects of using pulsars as probes, also in combination with event horizon imaging.

Testing theories of gravity in the centre of the Galaxy





Michael Kramer

Max-Planck-Institut für Radioastronomie

Jodrell Bank Centre for Astrophysics, University of Manchester

Understanding Gravity

General relativity conceptually different than description of other forces

But GR has been tested precisely, e.g. in solar system

Classical tests:

- Mercury perihelion advance
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Modern tests in solar system (see PPN formalism by Will & Nordvedt), e.g.

- Lunar Laser Ranging (LLR)
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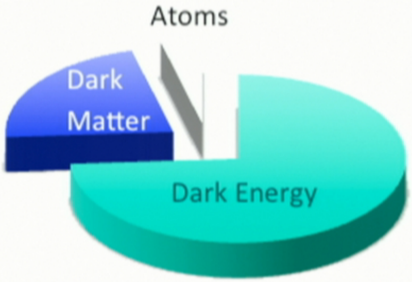
See recision cosmology: Inflation?

Dark Matter?

Dark Energy?



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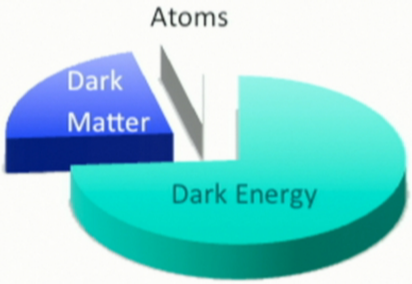

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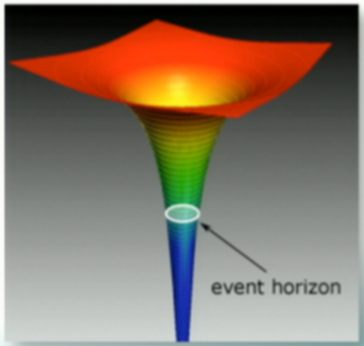

Better: Will Einstein have the last word on (macroscopic) gravity

or does GR fail far below the Planck energy?

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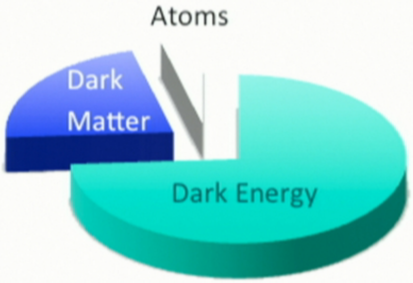

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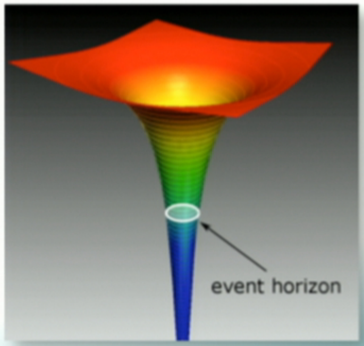

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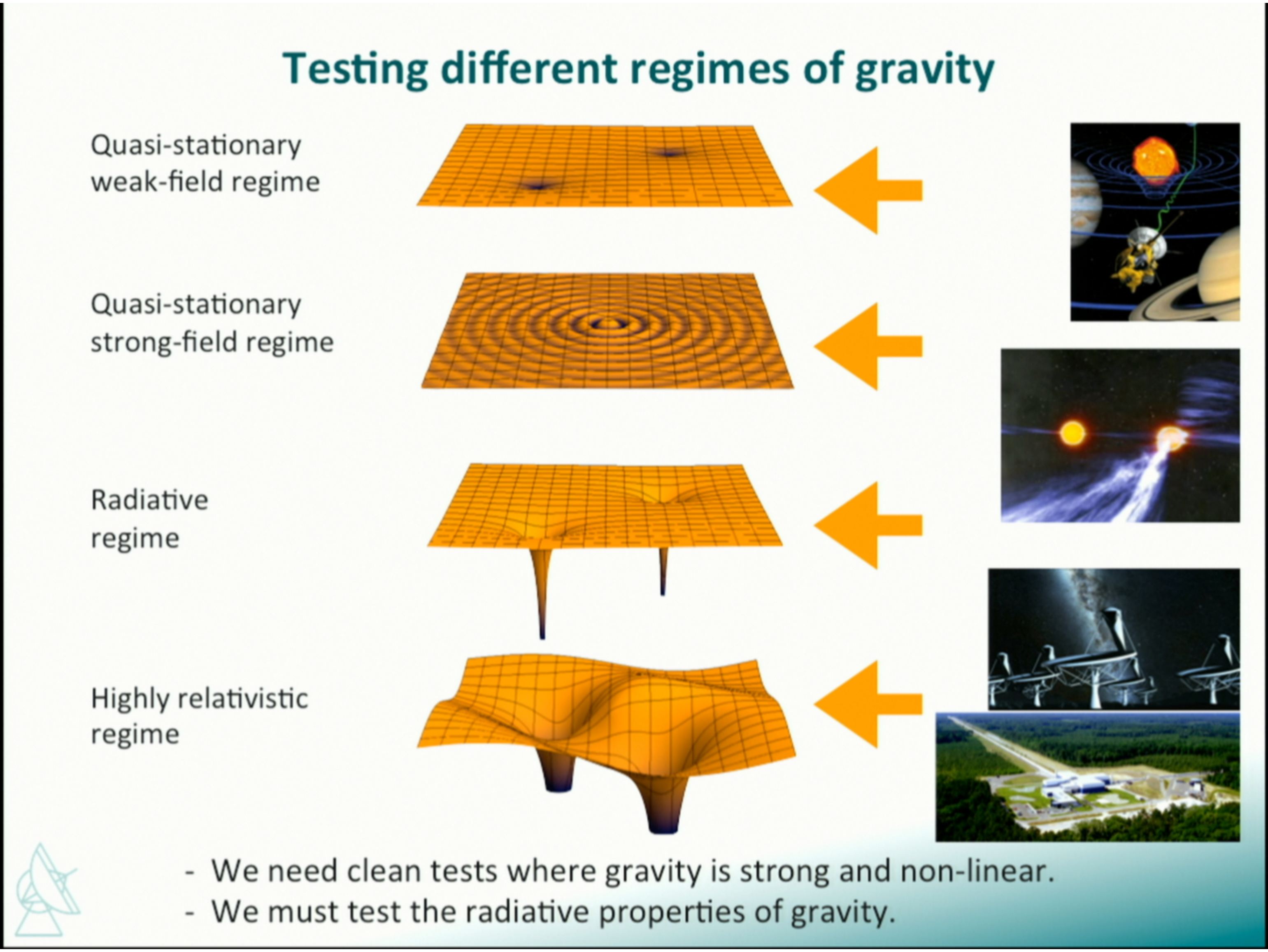


Testing different regimes of gravity

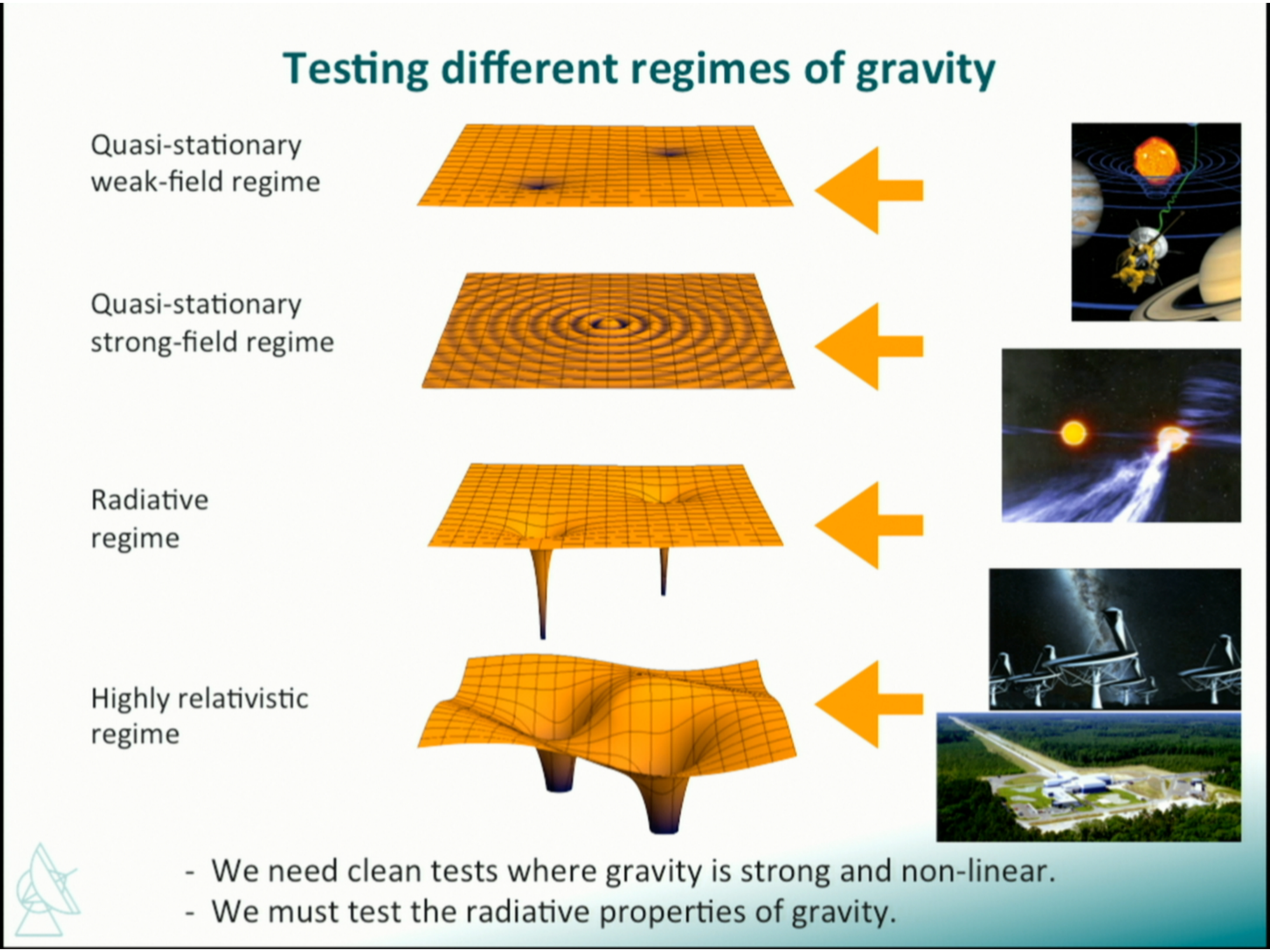
Quasi-stationary
weak-field regime

Quasi-stationary
strong-field regime

Radiative
regime

Highly relativistic
regime

- We need clean tests where gravity is strong and non-linear.
- We must test the radiative properties of gravity.



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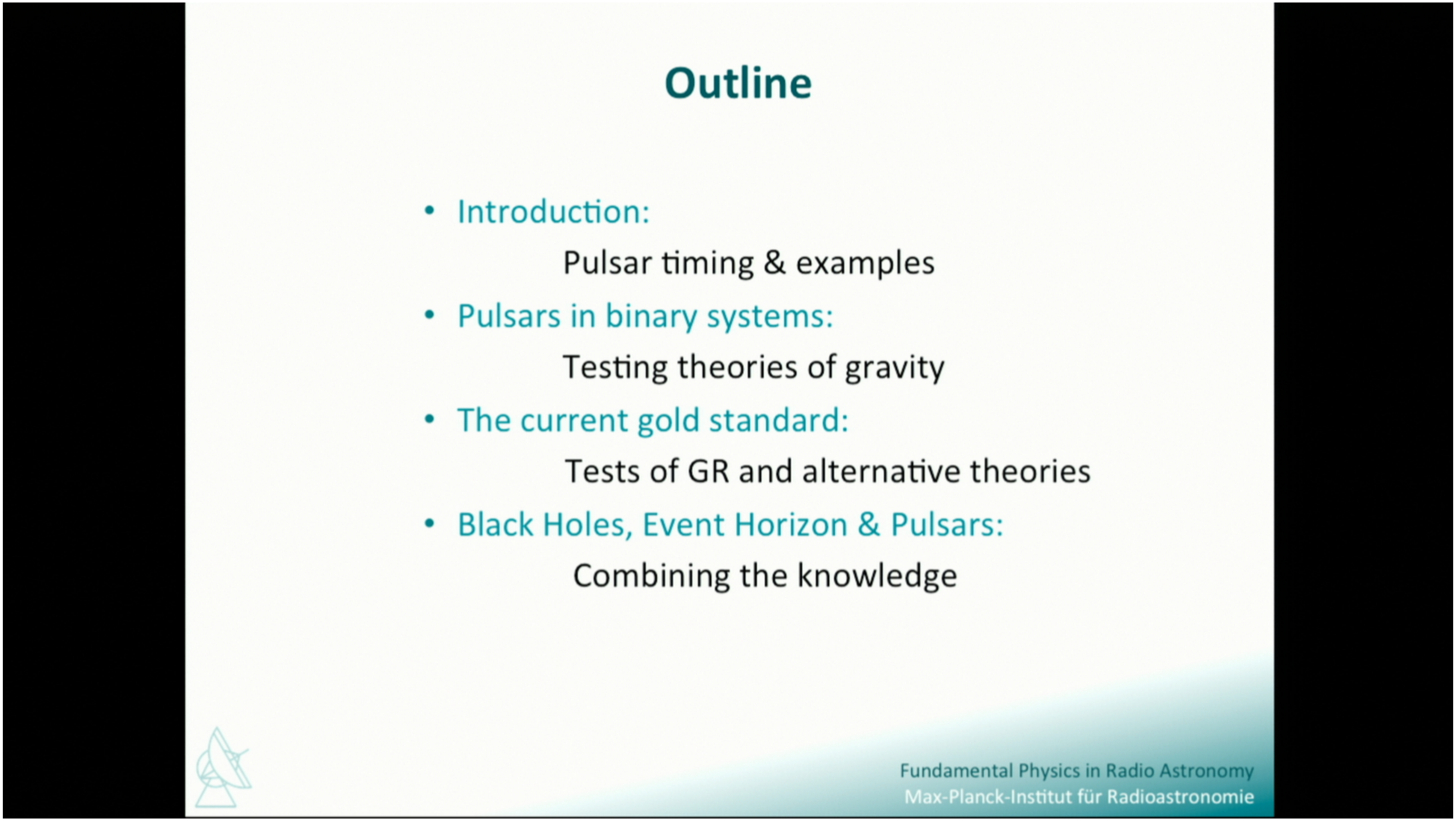


Outline

- Introduction:
  - Pulsar timing & examples
- Pulsars in binary systems:
  - Testing theories of gravity
- The current gold standard:
  - Tests of GR and alternative theories
- Black Holes, Event Horizon & Pulsars:
  - Combining the knowledge

A “simple” and clean experiment: Pulsar Timing

- Pulsars are…

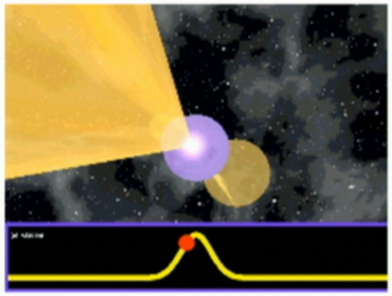
  …cosmic lighthouses

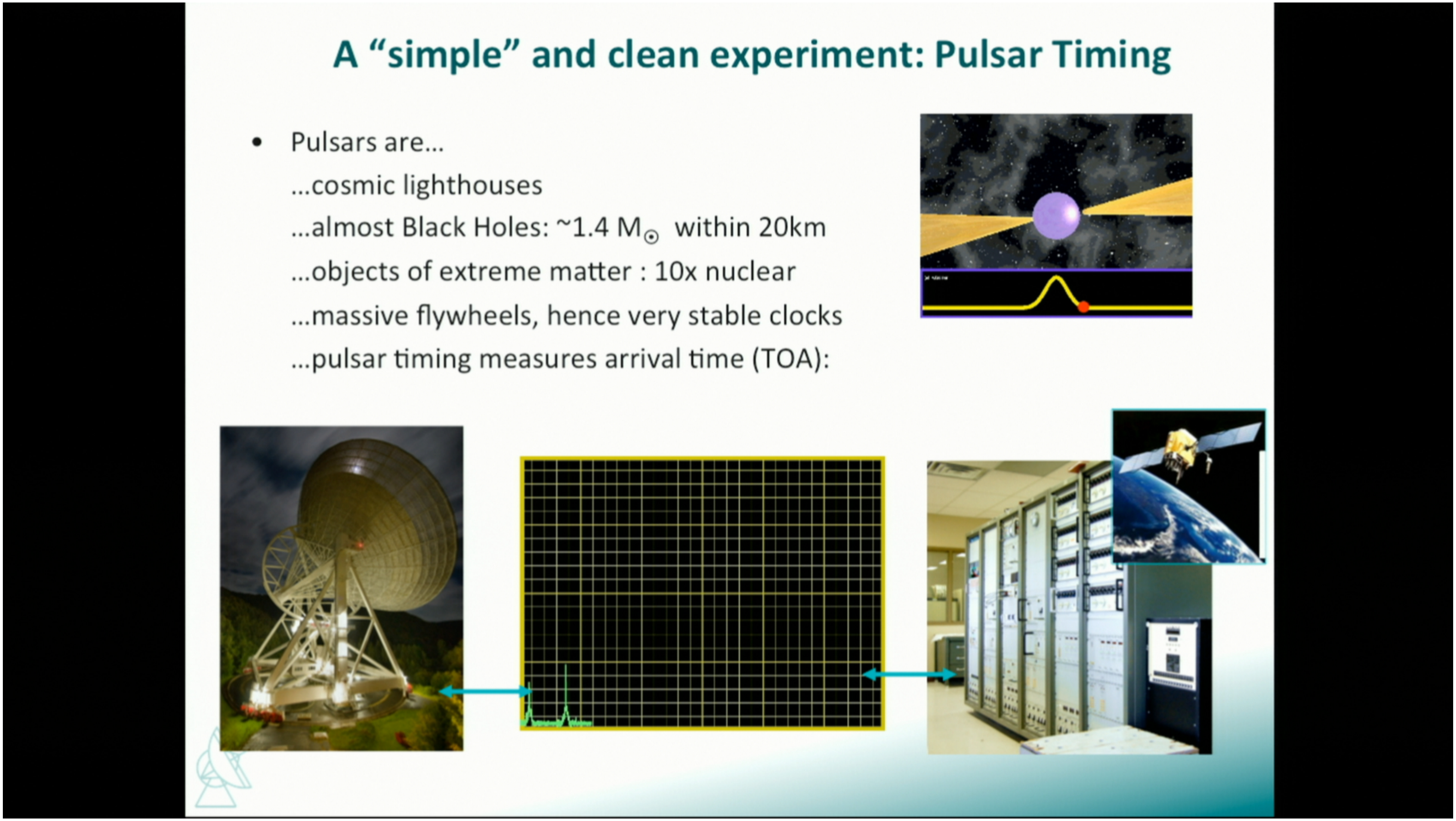
  …almost Black Holes: ~1.4 $M_\odot$ within 20km

  …objects of extreme matter : 10x nuclear

  …massive flywheels, hence very stable clocks

  …pulsar timing measures arrival time (TOA):





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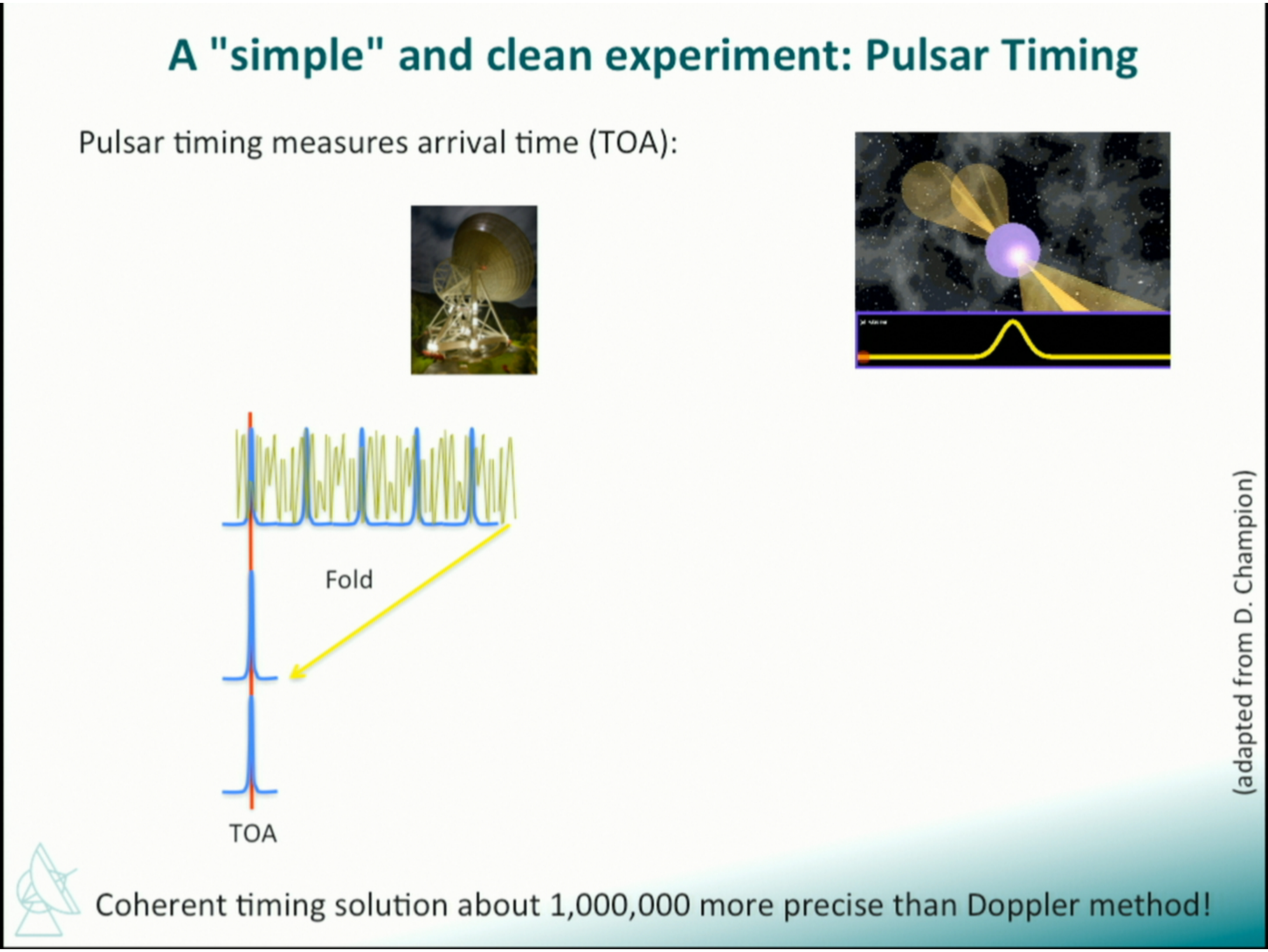

A "simple" and clean experiment: Pulsar Timing

Pulsar timing measures arrival time (TOA):

Fold

TOA

(adapted from D. Champion)

Coherent timing solution about 1,000,000 more precise than Doppler method!

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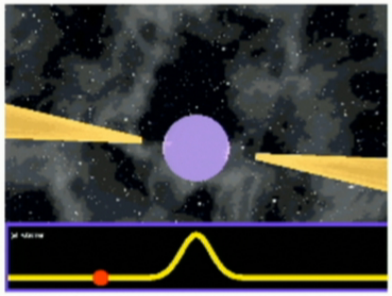

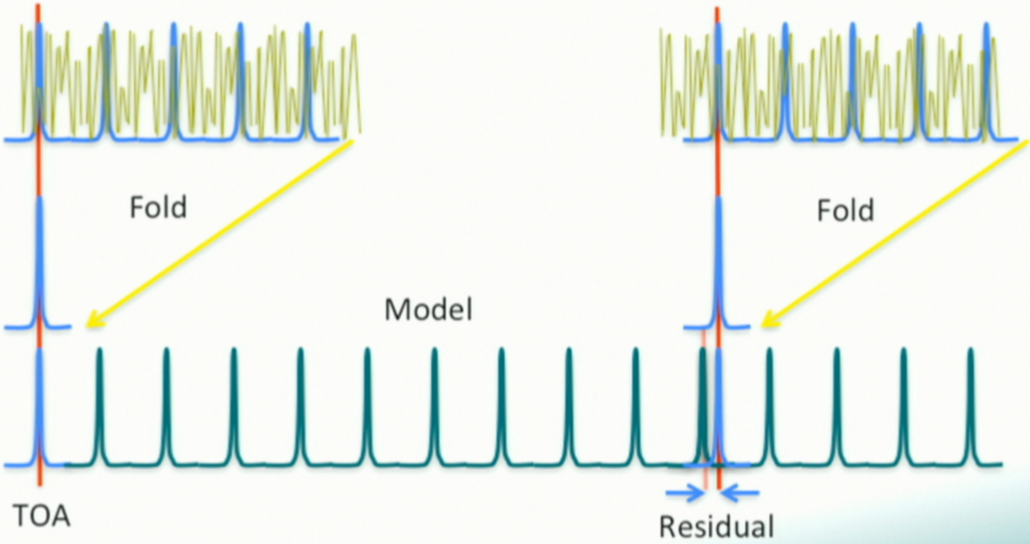

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Coherent timing solution about 1,000,000 more precise than Doppler method!

Our (usual) laboratories: Pulsars with companions

~ 2500 radio pulsars

1.40 ms (PSR J1748-2446ad)
8.50 s (PSR J2144-3933)

~ 10% binary pulsars

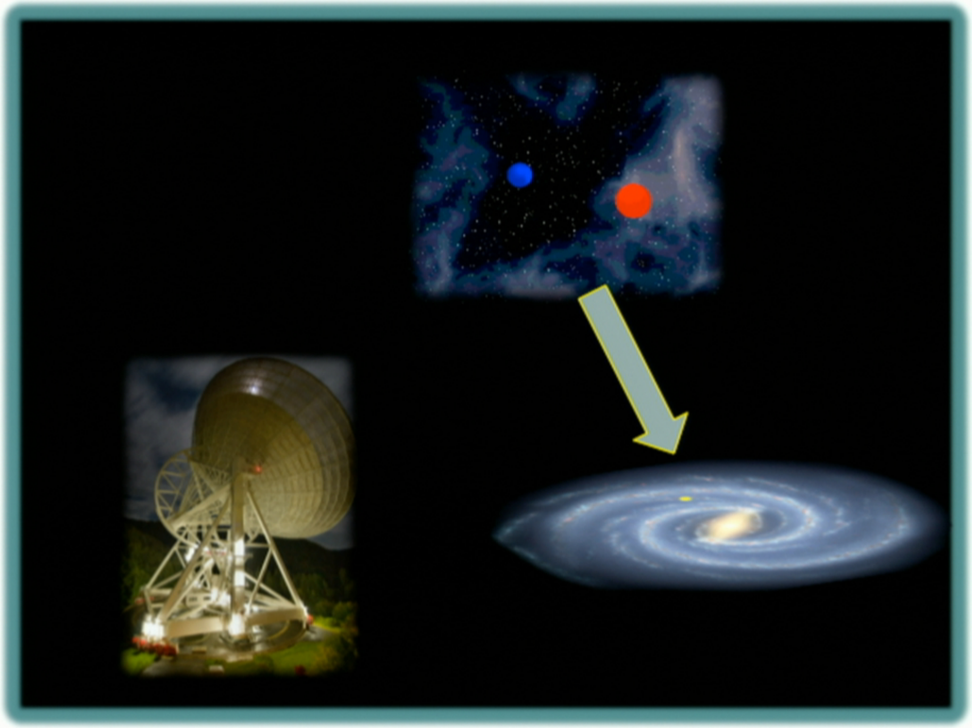
Orbital period range

94 min (PSR J1311-3430)
5.3 yr (PSR J1638-4725)

Companions

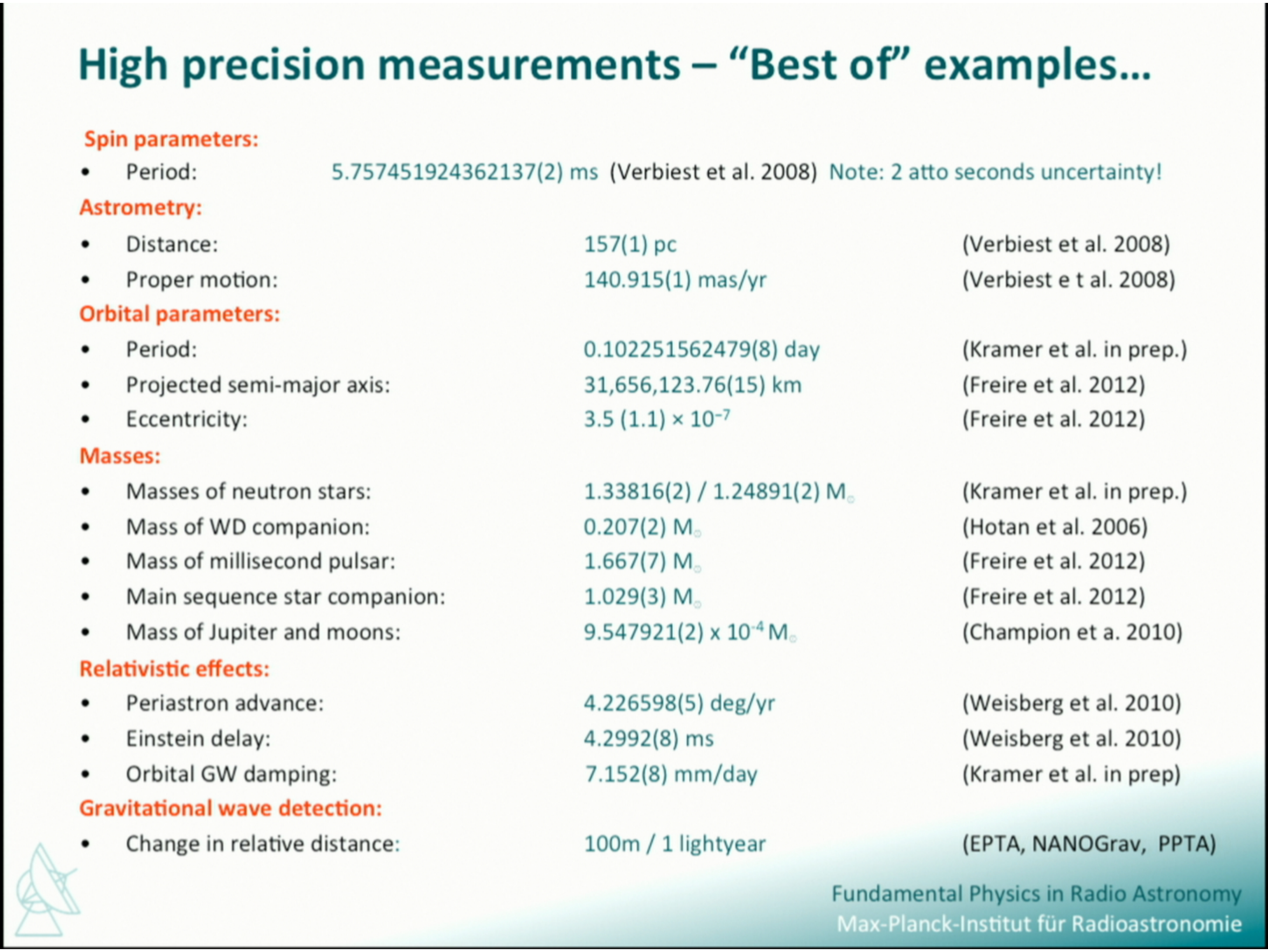
MSS, WD, NS, planets

See summary of V. Kaspi



Measure (=time!) how a pulsar falls as a test mass in the gravitational potential of a companion (and in the Galaxy)

... a <u>clean</u> experiment with very high precision!



High precision measurements – “Best of” examples…

Spin parameters:

Period:	5.757451924362137(2) ms	(Verbiest et al. 2008) Note: 2 atto seconds uncertainty!

Astrometry:

Distance:	157(1) pc	(Verbiest et al. 2008)
Proper motion:	140.915(1) mas/yr	(Verbiest e t al. 2008)

Orbital parameters:

Period:	0.102251562479(8) day	(Kramer et al. in prep.)
Projected semi-major axis:	31,656,123.76(15) km	(Freire et al. 2012)
Eccentricity:	$3.5\,(1.1) \times 10^{-7}$	(Freire et al. 2012)

Masses:

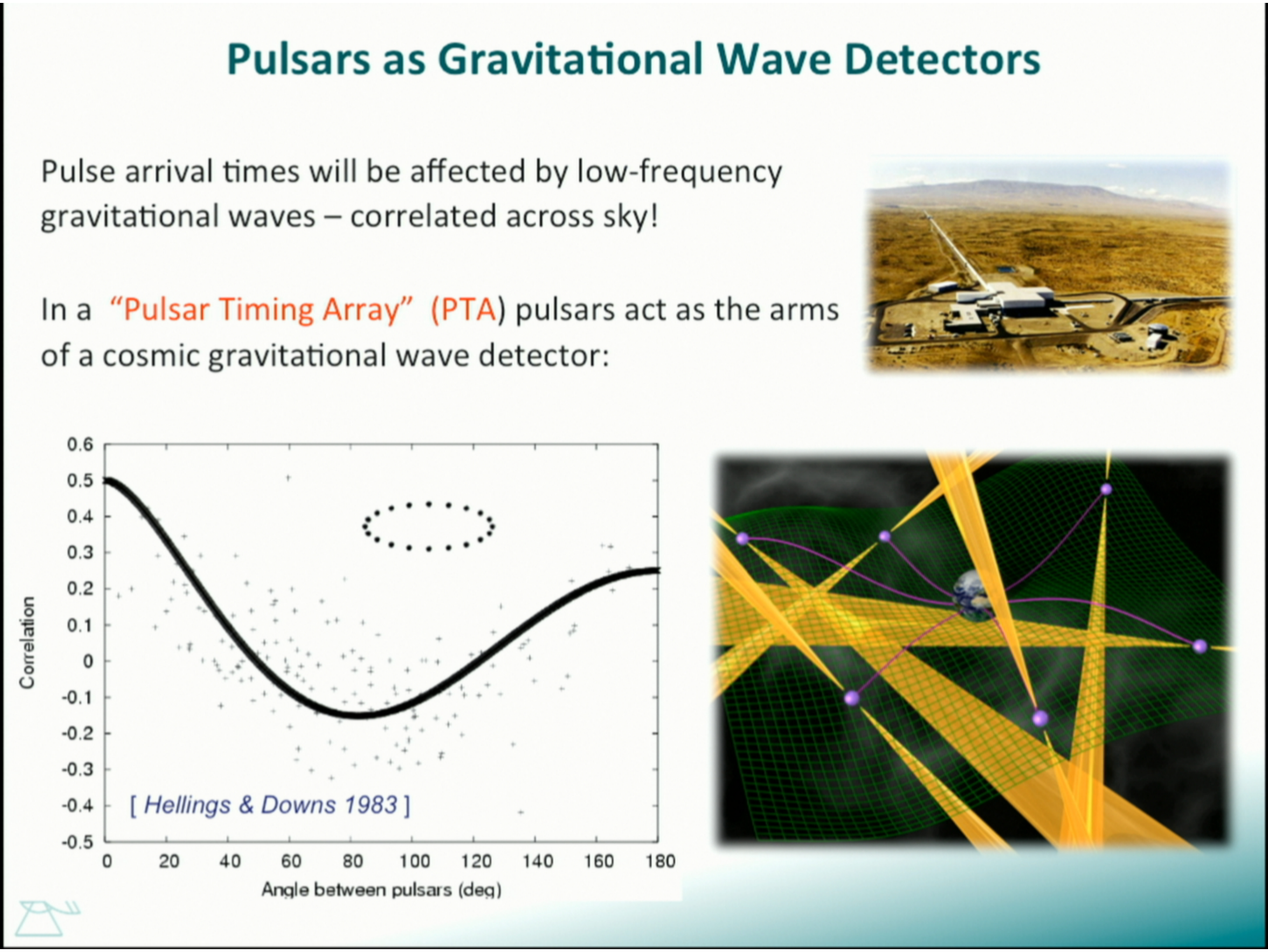
Masses of neutron stars:	1.33816(2) / 1.24891(2) $M_\odot$	(Kramer et al. in prep.)
Mass of WD companion:	0.207(2) $M_\odot$	(Hotan et al. 2006)
Mass of millisecond pulsar:	1.667(7) $M_\odot$	(Freire et al. 2012)
Main sequence star companion:	1.029(3) $M_\odot$	(Freire et al. 2012)
Mass of Jupiter and moons:	$9.547921(2) \times 10^{-4}\,M_\odot$	(Champion et a. 2010)

Relativistic effects:

Periastron advance:	4.226598(5) deg/yr	(Weisberg et al. 2010)
Einstein delay:	4.2992(8) ms	(Weisberg et al. 2010)
Orbital GW damping:	7.152(8) mm/day	(Kramer et al. in prep)

Gravitational wave detection:

Change in relative distance:	100m / 1 lightyear	(EPTA, NANOGrav, PPTA)

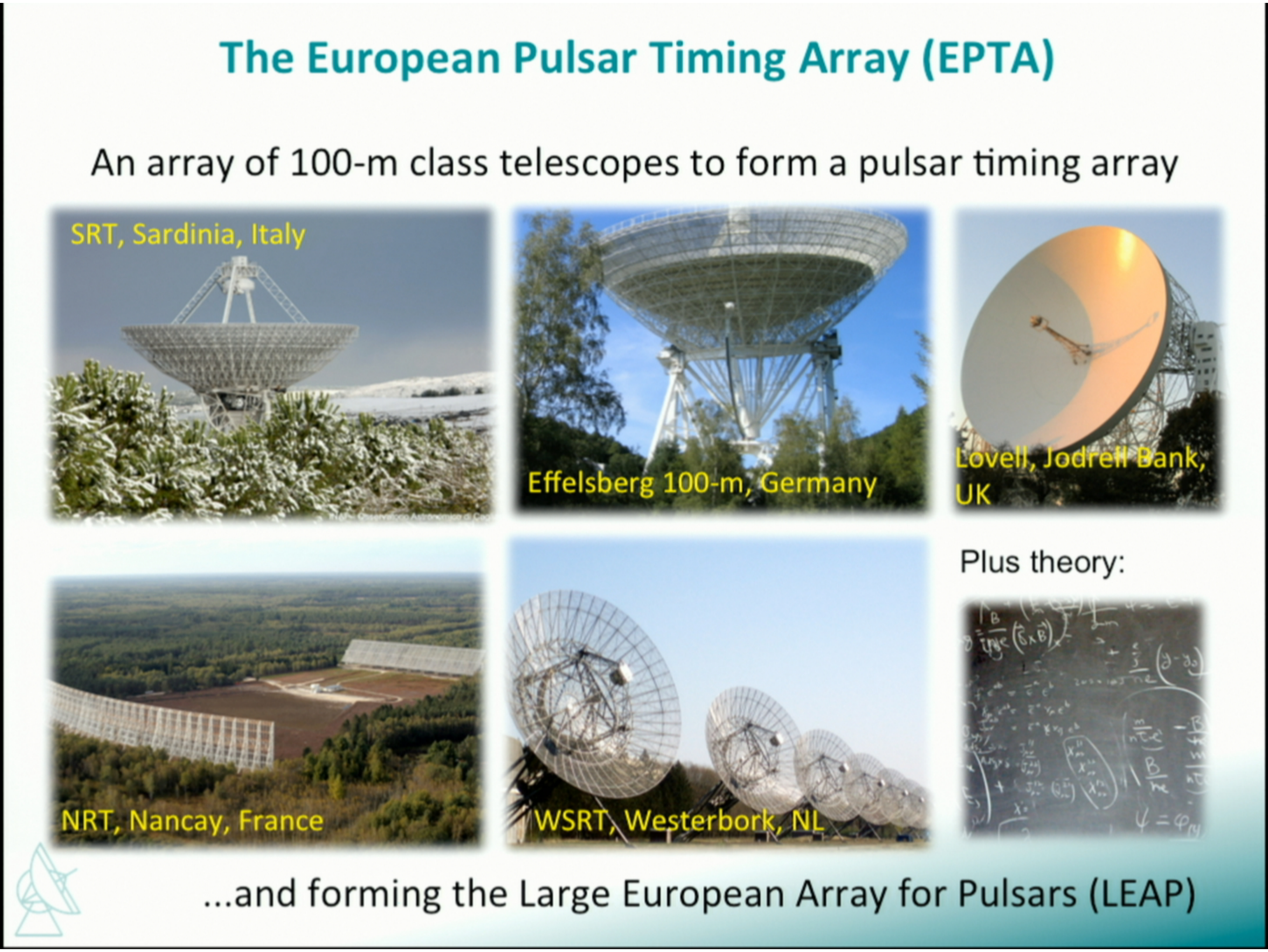


Pulsars as Gravitational Wave Detectors

Pulse arrival times will be affected by low-frequency gravitational waves – correlated across sky!

In a "Pulsar Timing Array" (PTA) pulsars act as the arms of a cosmic gravitational wave detector:

[*Hellings & Downs 1983*]



The European Pulsar Timing Array (EPTA)

An array of 100-m class telescopes to form a pulsar timing array

SRT, Sardinia, Italy

Effelsberg 100-m, Germany

Lovell, Jodrell Bank, UK

NRT, Nancay, France

WSRT, Westerbork, NL

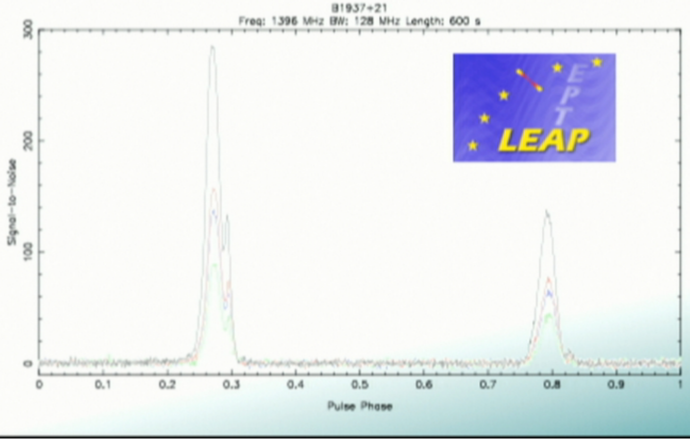
Plus theory:

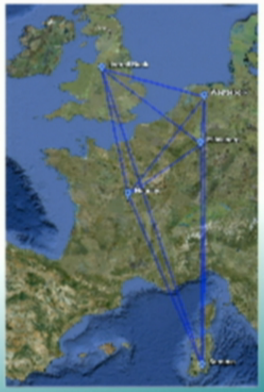
...and forming the Large European Array for Pulsars (LEAP)

The Large European Array for Pulsars (LEAP)

"The best and most sensitive pulsar instrument right now"

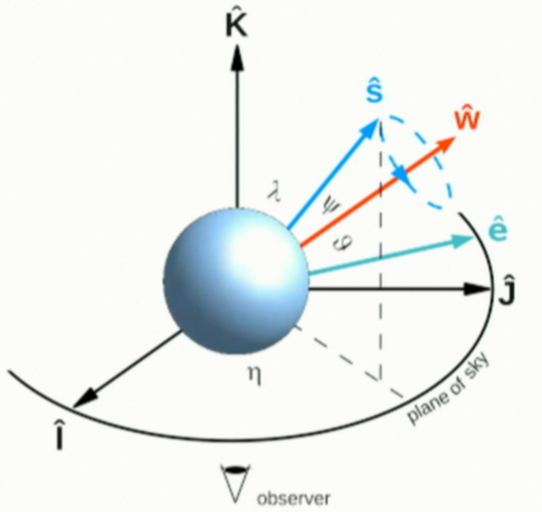
- Coherently adding ("phasing up") the 6 of the 5 biggest fully-steerable telescopes in the world.
- Forming a telescope with an equivalent size of a 200 m dish.
- A LEAP in collecting area seeing most of the sky.
- LEAP can produce ToAs and images
- Funded by ERC Advanced Grant (PI Kramer)
- Integreal part of EPTA observing monthly

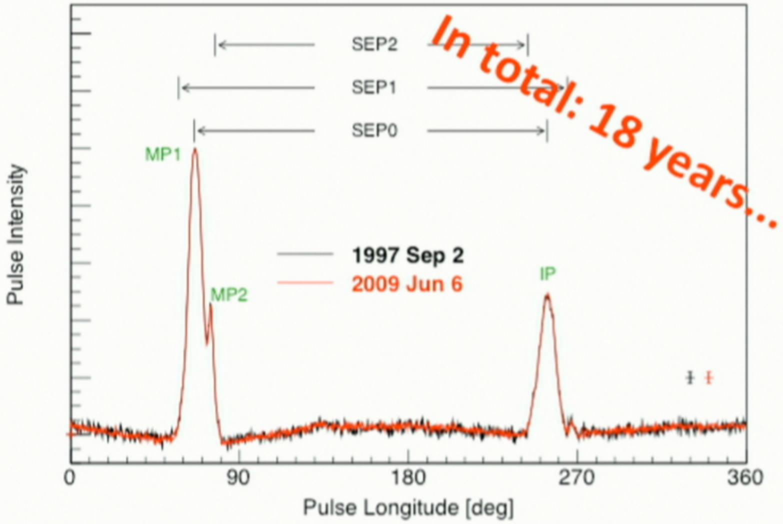




Limits on theories of gravity from EPTA Effelsberg data

- Best test on existence of preferred frames, i.e. gravitational Lorentz invariance, thanks to unique long-term Effelsberg data set:





In total: 18 years...

- Idea: Look for profile changes in isolated pulsars
- Inspected two pulsars in detail: no changes found over 18 years!
- Important: Longest, uninterrupted coherently dedispersed data existing!

$$\boxed{\hat{\alpha}_1 = -0.4^{+3.7}_{-3.1} \times 10^{-5} \quad (95\% \text{ C.L.})}$$

[Shao & Wex 2012]

$$\boxed{|\hat{\alpha}_2| < 1.6 \times 10^{-9} \quad (95\% \text{ C.L.})}$$

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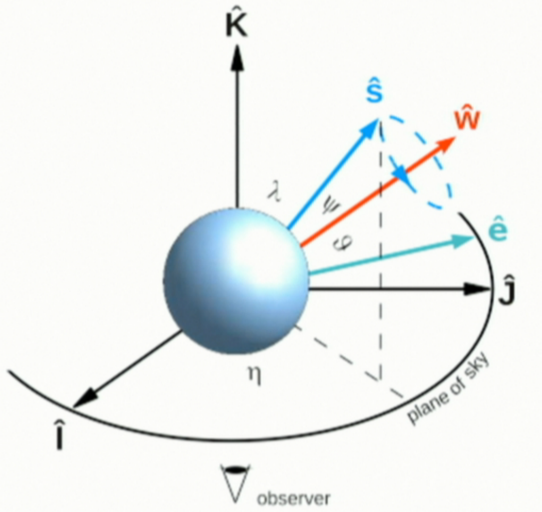

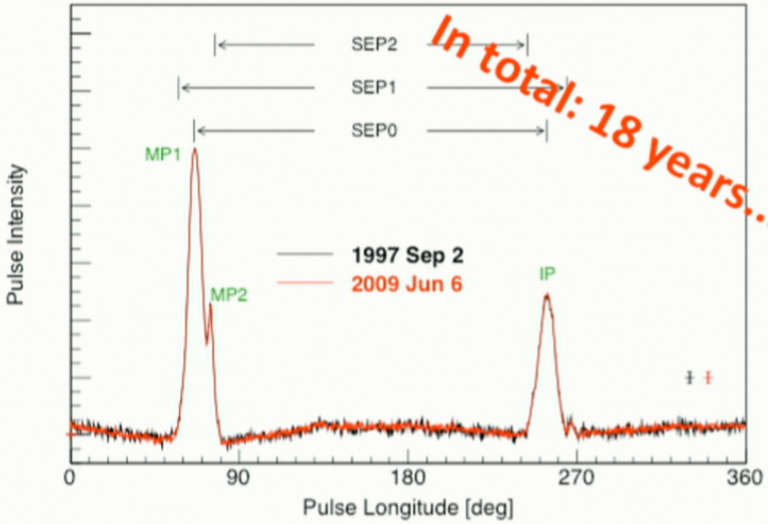

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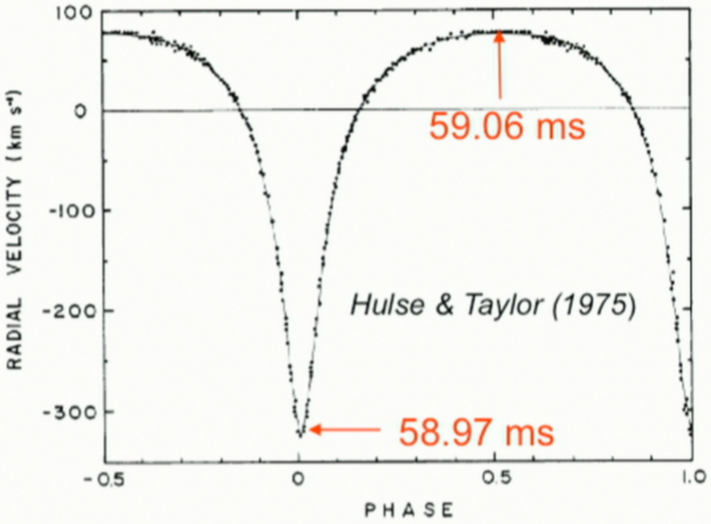
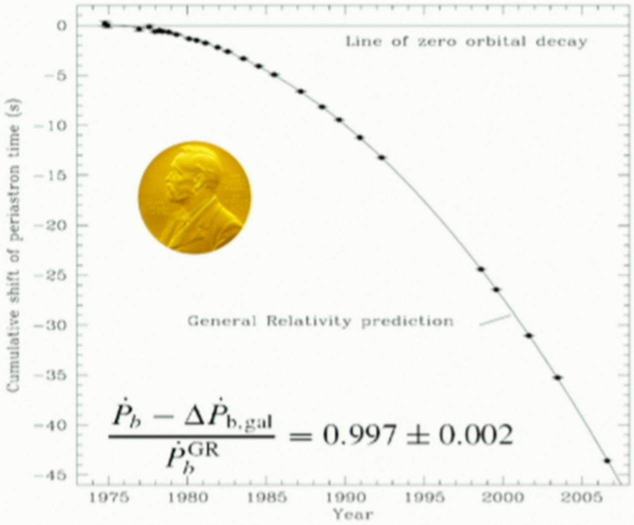
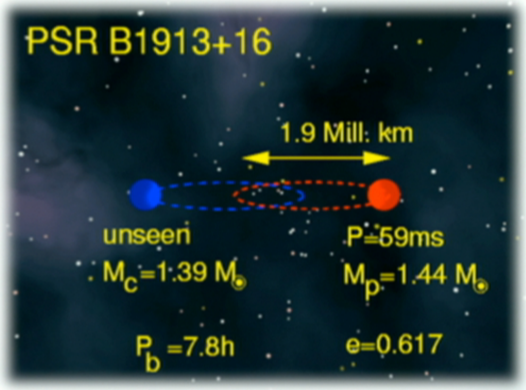
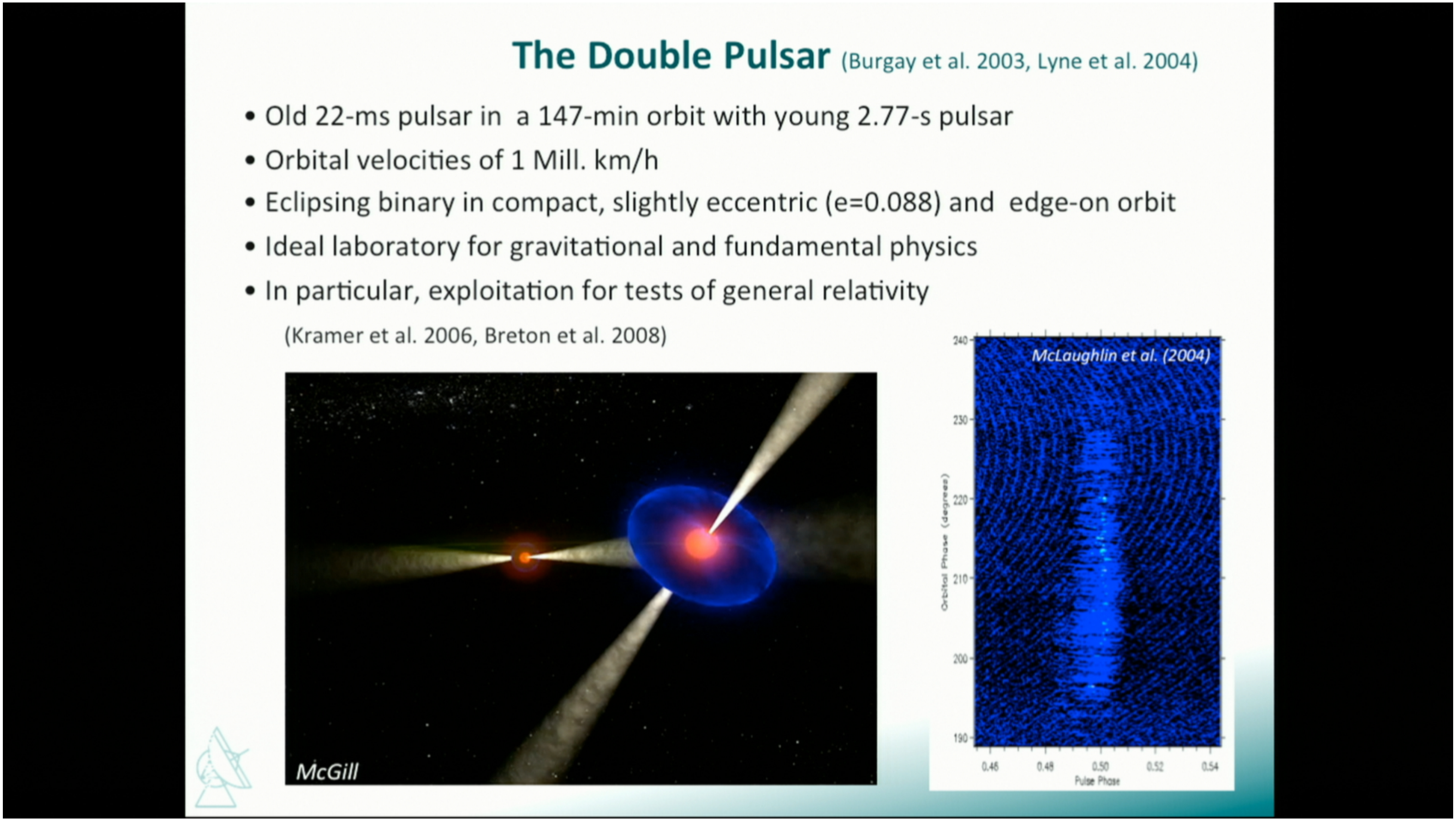
The first binary pulsar: Hulse-Taylor pulsar





$$\frac{\dot{P}_b - \Delta\dot{P}_{\rm b,gal}}{\dot{P}_b^{\rm GR}} = 0.997 \pm 0.002$$





The Double Pulsar (Burgay et al. 2003, Lyne et al. 2004)

- Old 22-ms pulsar in a 147-min orbit with young 2.77-s pulsar
- Orbital velocities of 1 Mill. km/h
- Eclipsing binary in compact, slightly eccentric (e=0.088) and edge-on orbit
- Ideal laboratory for gravitational and fundamental physics
- In particular, exploitation for tests of general relativity

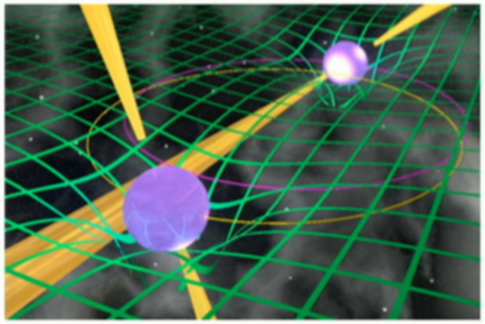
(Kramer et al. 2006, Breton et al. 2008)

McGill

McLaughlin et al. (2004)

Double Pulsar: a unique relativistic double-line system

- We can measure two orbits ➔ mass ratio



$$R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B} = 1.0714 \pm 0.0011$$

Note: theory-independent to 1PN order!

(Damour & Deruelle 1986, Damour 2005)

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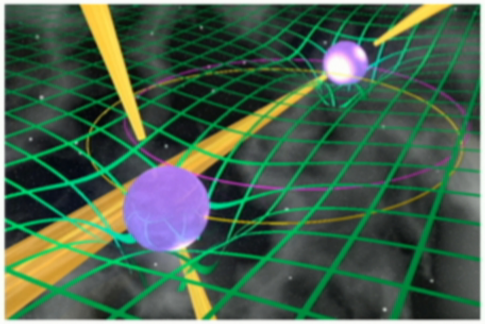

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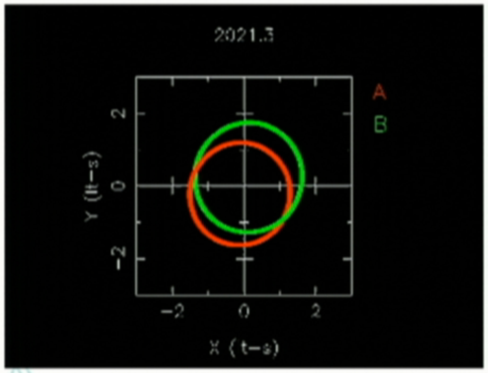
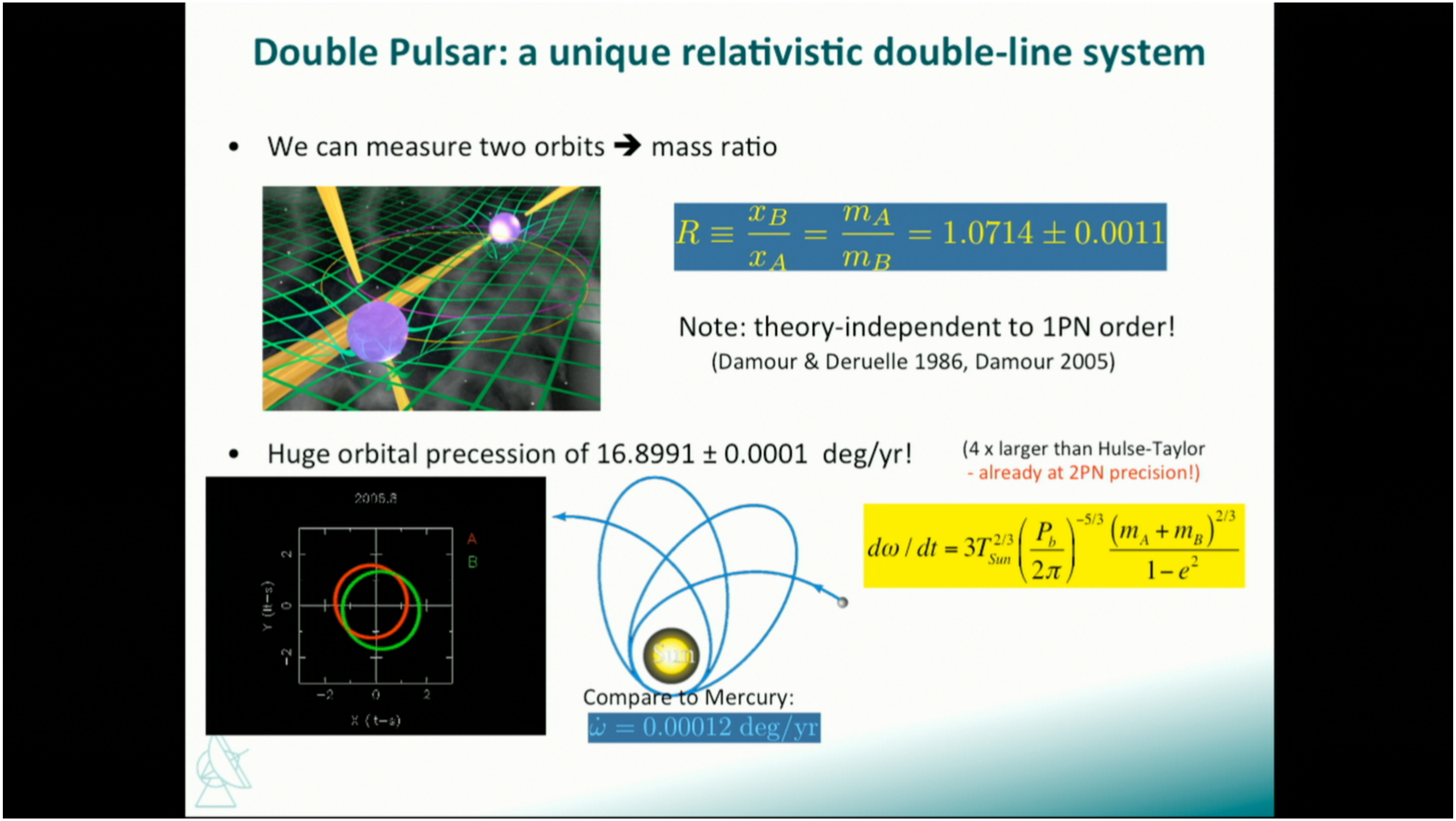
- Huge orbital precession of 16.8991 ± 0.0001 deg/yr!

(4 x larger than Hulse-Taylor
- already at 2PN precision!)



Compare to Mercury:
$\dot{\omega} = 0.00012$ deg/yr



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$$d\omega / dt = 3T_{Sun}^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{(m_A + m_B)^{2/3}}{1-e^2}$$

Compare to Mercury:

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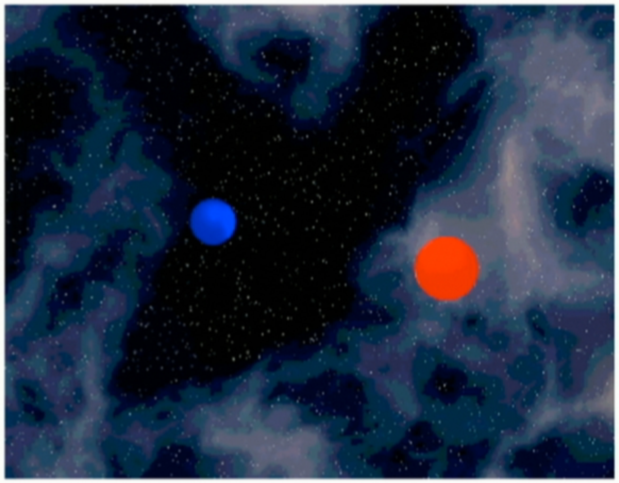
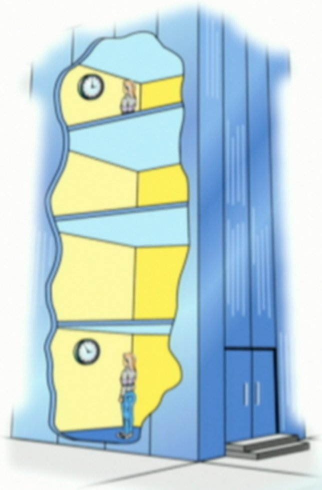
Double Pulsar: five tests in one system!

- Huge orbital precession of 16.8991 ± 0.0001 deg/yr!
- Clock variation due to gravitational redshift: 383.9 ± 0.6 microseconds!

$$\frac{\text{Obs.Val.}}{\text{Exp.(GR)}} = 1.000 \pm 0.002$$





- As other clocks, pulsars run slower in deep gravitational potentials

- Changing distance to companion (and felt grav. potential) during elliptical orbit

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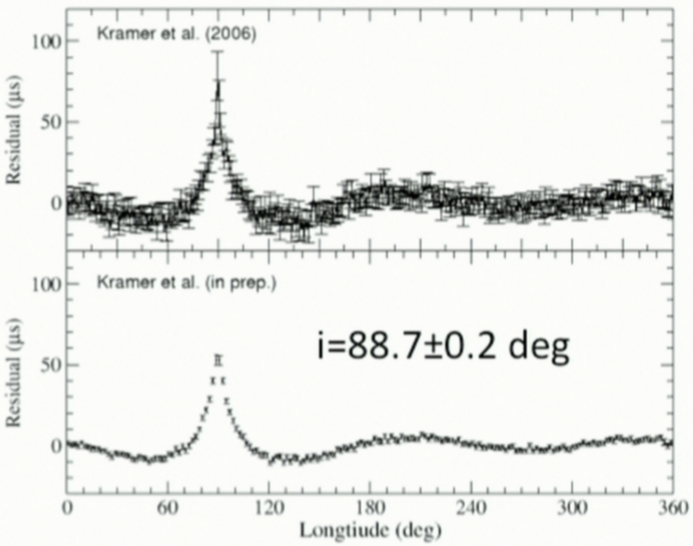
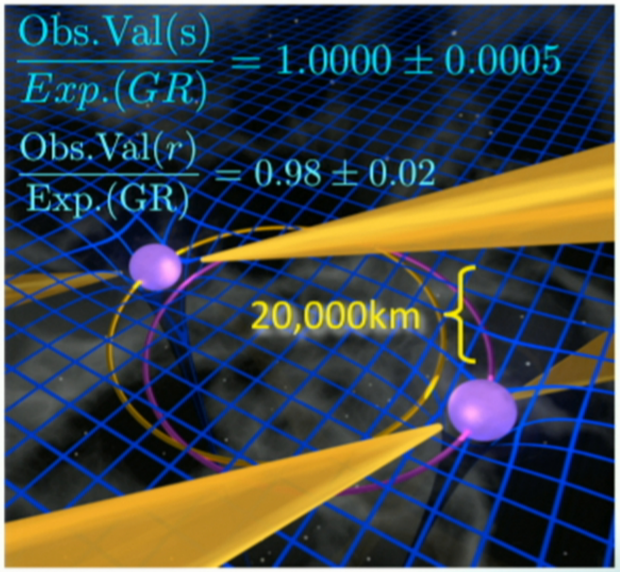


i=88.7±0.2 deg



$$\frac{\mathrm{Obs.Val}(s)}{Exp.(GR)} = 1.0000 \pm 0.0005$$

$$\frac{\mathrm{Obs.Val}(r)}{\mathrm{Exp.(GR)}} = 0.98 \pm 0.02$$

- At superior conjunction, pulses from pulsar A pass B in 20,000km distance
- Space-time near companion is curved ➔Additional path length
    - ➔ Delay in arrival time – depending on geometry and companion mass

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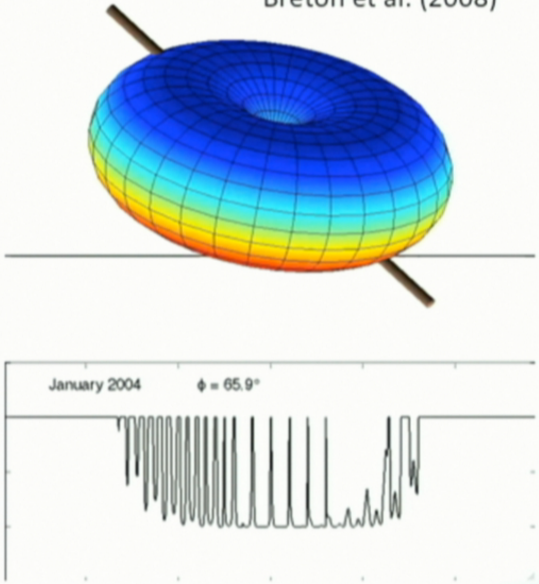
- Relativistic spin precession: $\Omega_B = 4.8(7)$ deg yr^{-1}

$$\frac{\text{Obs.Val.}}{\text{Exp.(GR)}} = 0.93 \pm 0.13$$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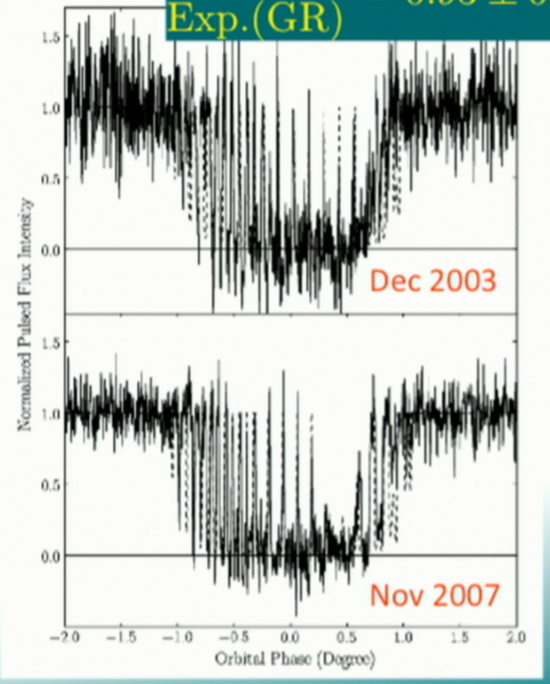

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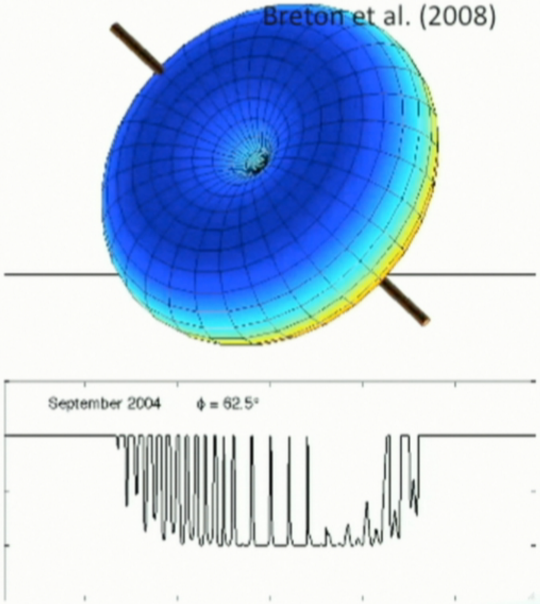
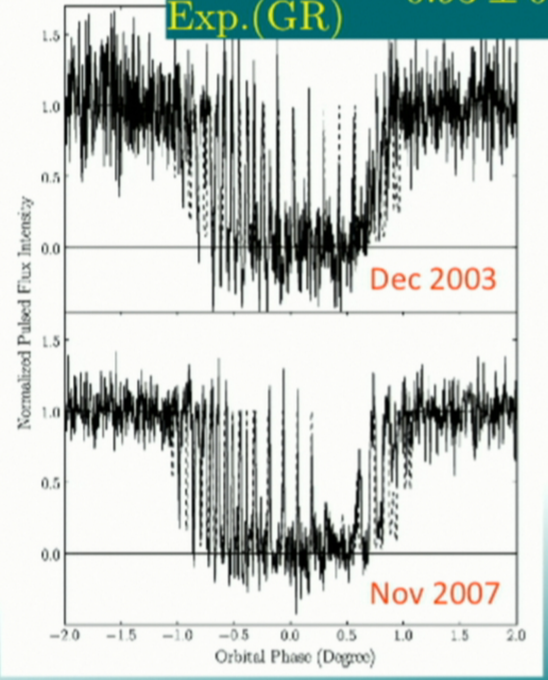
$$\frac{\text{Obs.Val.}}{\text{Exp.(GR)}} = 0.93 \pm 0.13$$



Breton et al. (2008)



Double Pulsar: five tests in one system!

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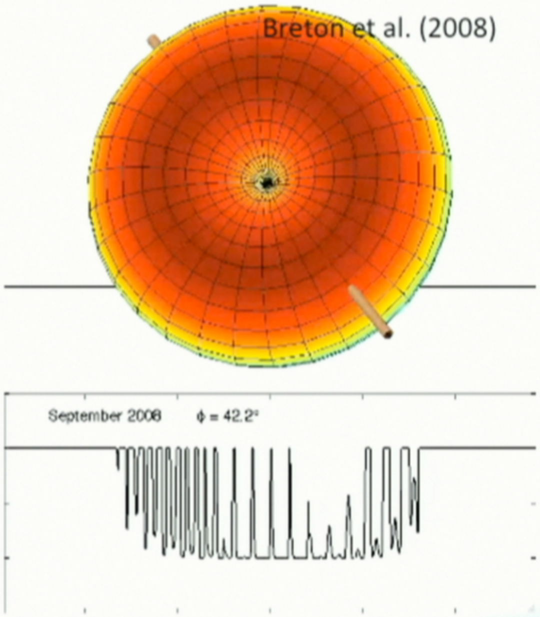
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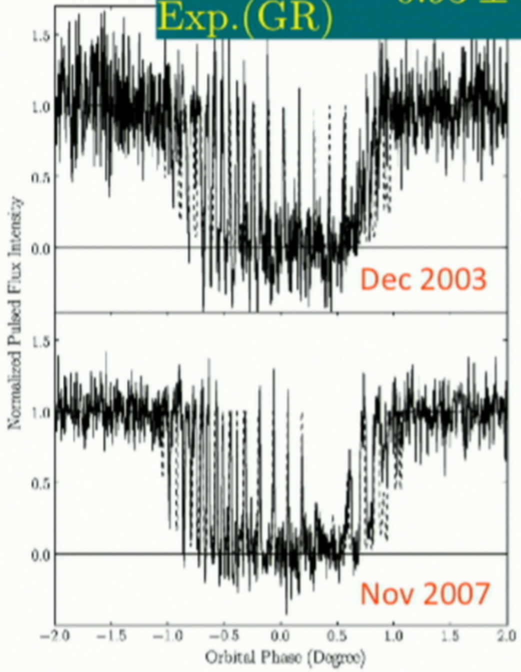

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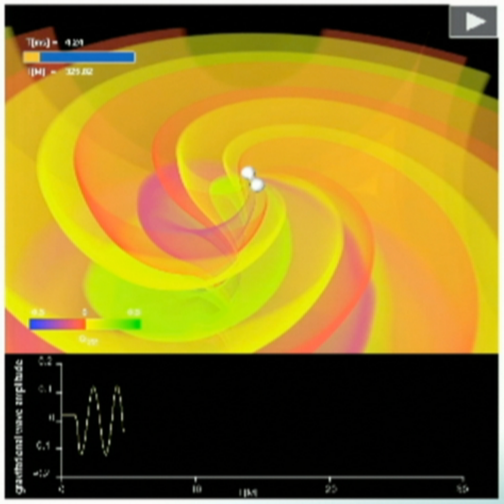
- Pulsars approach each other by

7.152 ± 0.008 mm/day

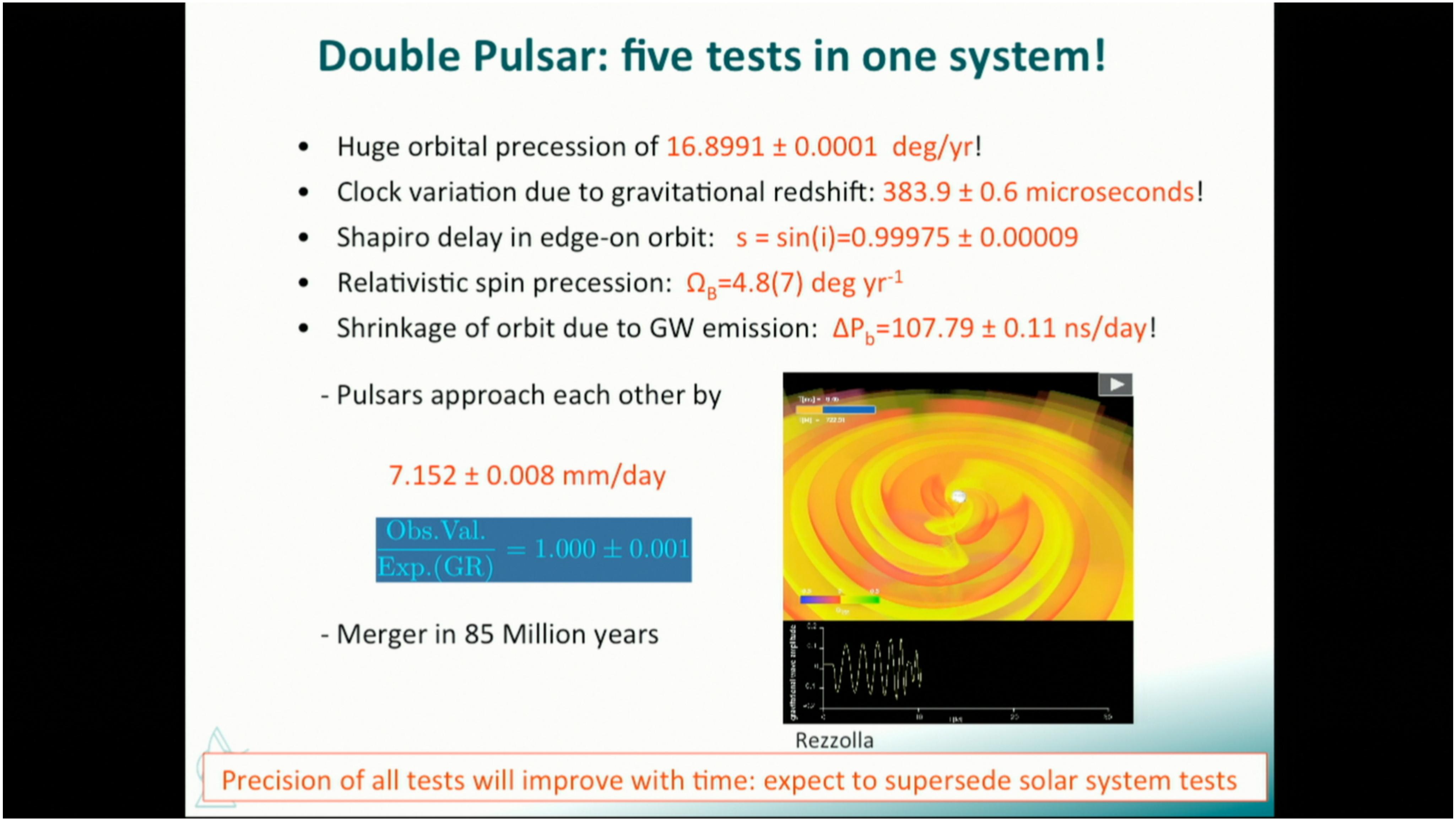
$$\frac{\text{Obs.Val.}}{\text{Exp.(GR)}} = 1.000 \pm 0.001$$

- Merger in 85 Million years



Rezzolla

Precision of all tests will improve with time: expect to supersede solar system tests



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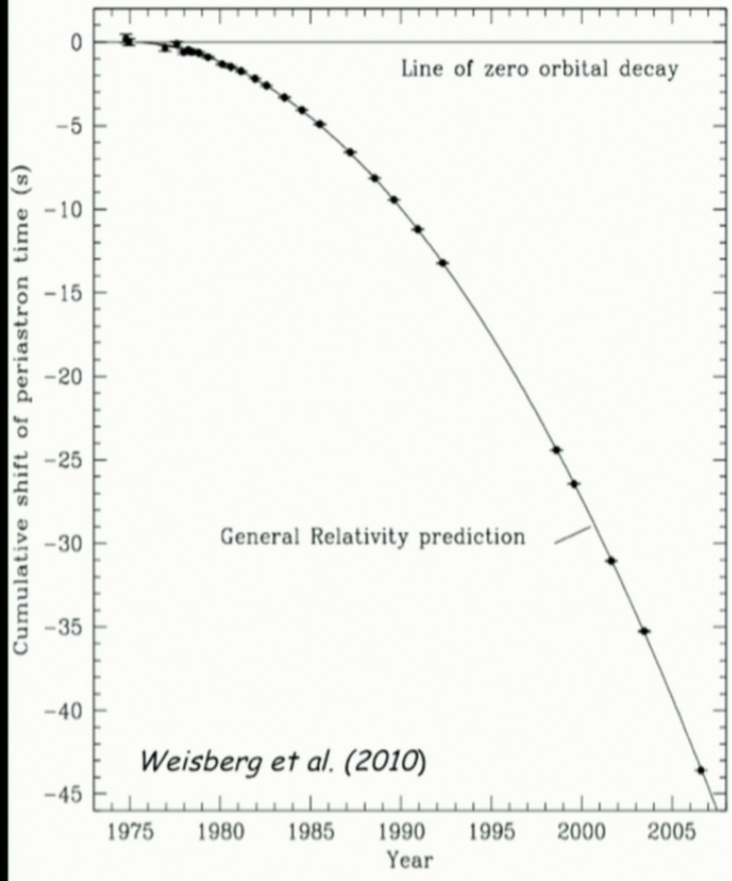
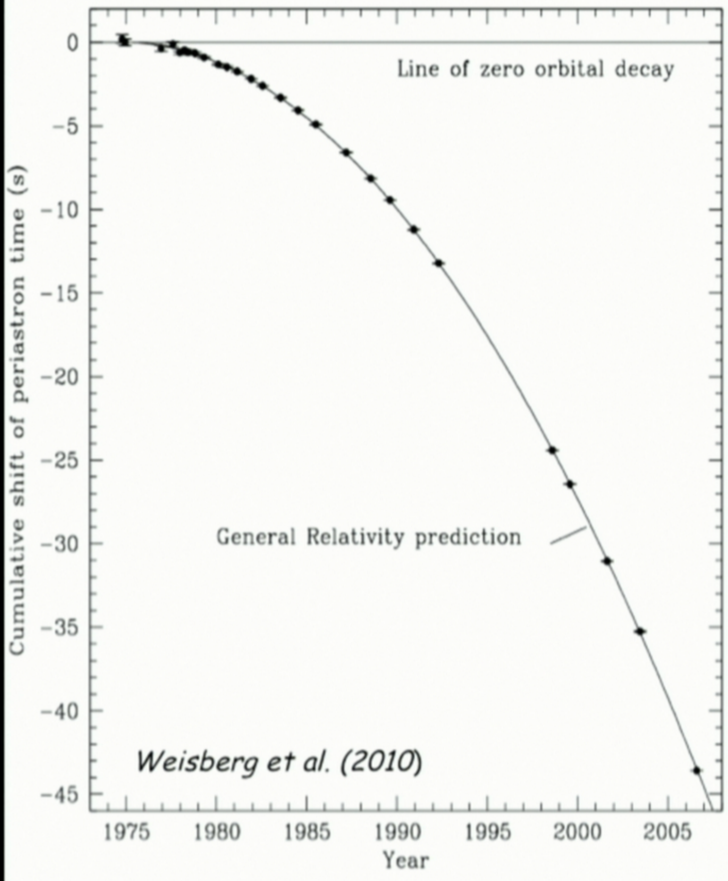
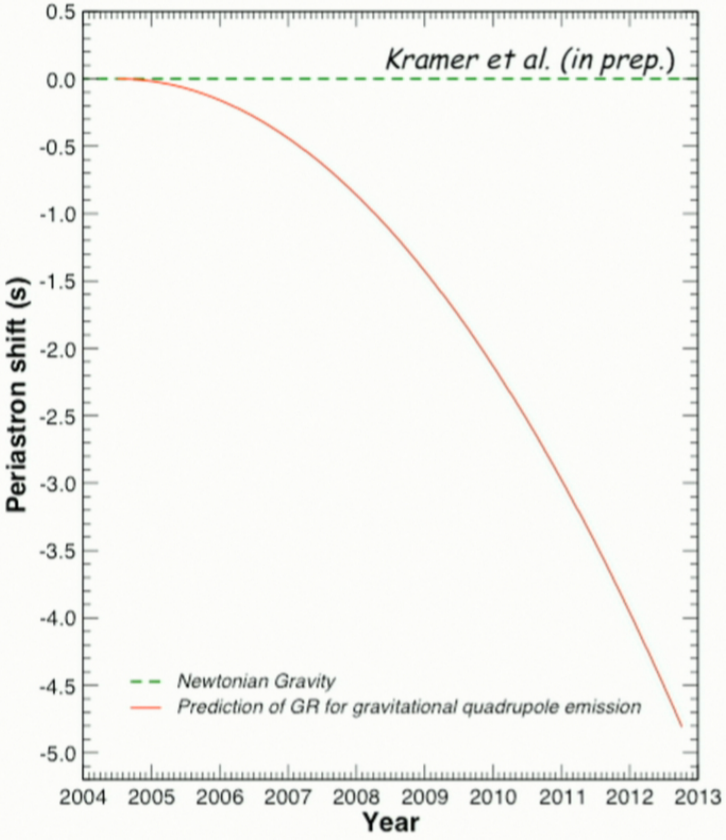
Gravitational wave emission: H-T vs D-PSR



Weisberg et al. (2010)

Gravitational wave emission: H-T vs D-PSR





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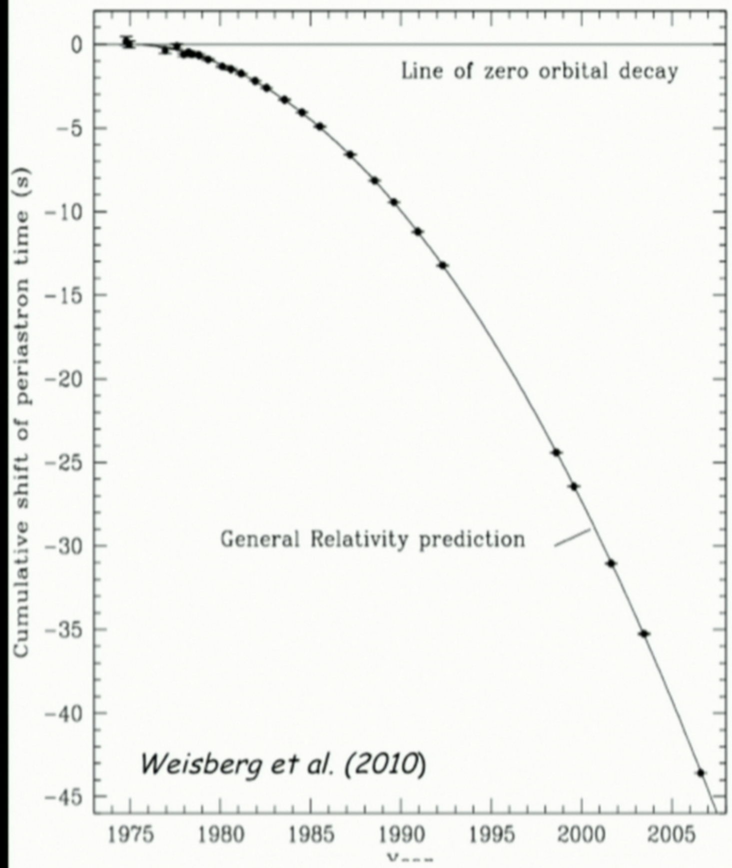
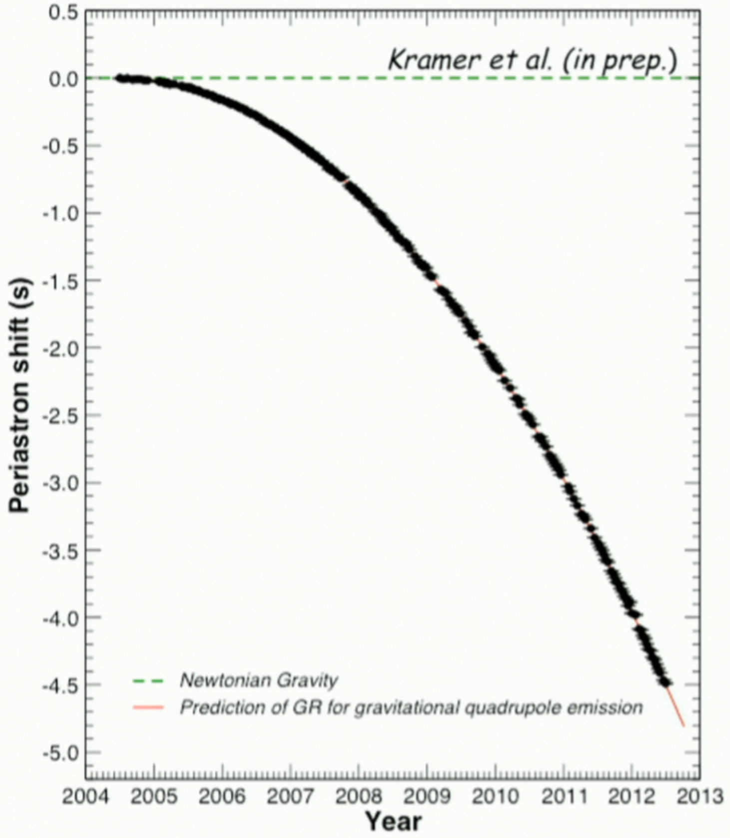
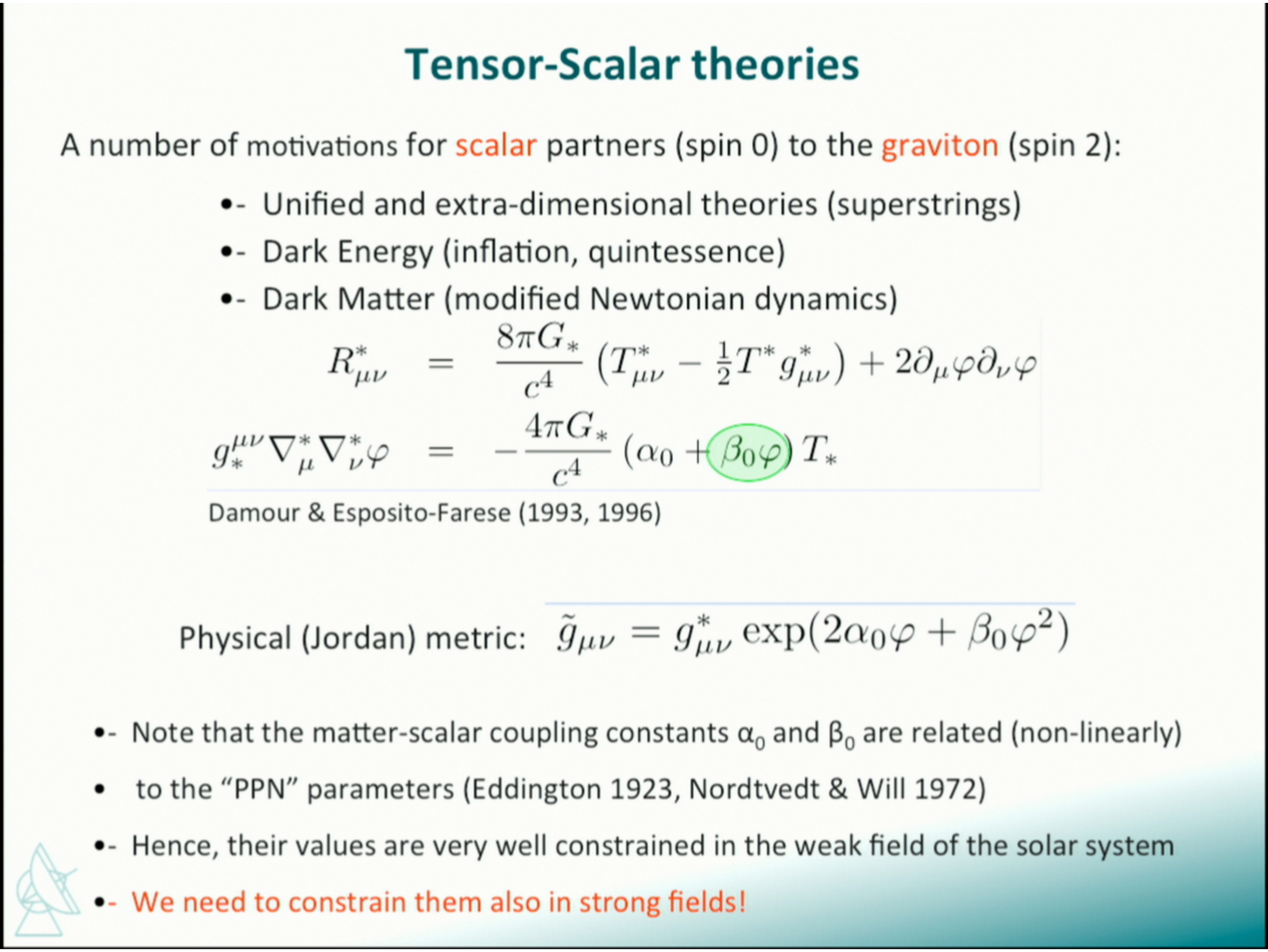




Best evidence for the existence of gravitational waves by far – to better than 0.03%!



Tensor-Scalar theories

A number of motivations for scalar partners (spin 0) to the graviton (spin 2):

- Unified and extra-dimensional theories (superstrings)
- Dark Energy (inflation, quintessence)
- Dark Matter (modified Newtonian dynamics)

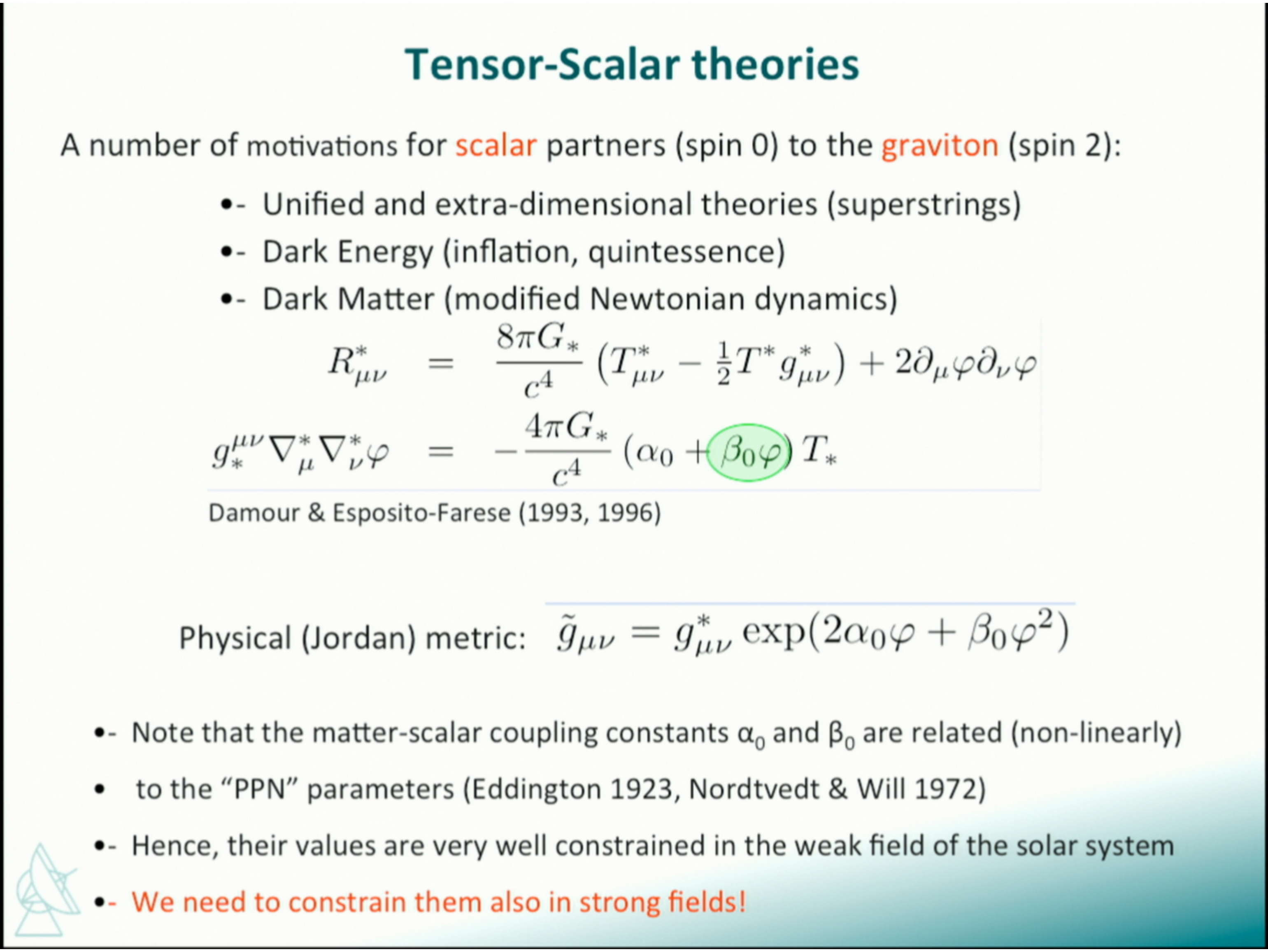
$$R^*_{\mu\nu} = \frac{8\pi G_*}{c^4}\left(T^*_{\mu\nu} - \tfrac{1}{2}T^* g^*_{\mu\nu}\right) + 2\partial_\mu\varphi\partial_\nu\varphi$$

$$g_*^{\mu\nu}\nabla^*_\mu\nabla^*_\nu\varphi = -\frac{4\pi G_*}{c^4}\left(\alpha_0 + \beta_0\varphi\right)T_*$$

Damour & Esposito-Farese (1993, 1996)

Physical (Jordan) metric: $\tilde{g}_{\mu\nu} = g^*_{\mu\nu}\exp(2\alpha_0\varphi + \beta_0\varphi^2)$

- Note that the matter-scalar coupling constants α_0 and β_0 are related (non-linearly)
- to the "PPN" parameters (Eddington 1923, Nordtvedt & Will 1972)
- Hence, their values are very well constrained in the weak field of the solar system
- We need to constrain them also in strong fields!



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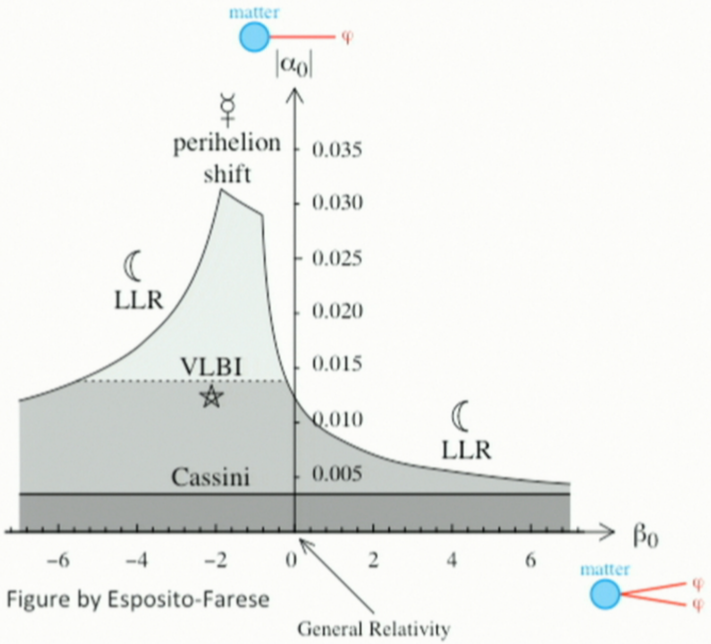

Figure by Esposito-Farese

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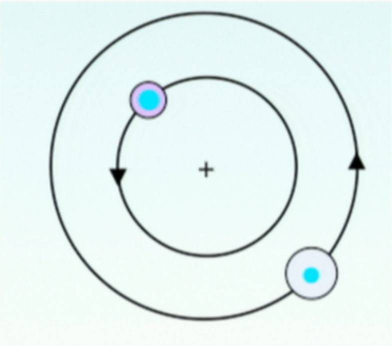
Dipolar Gravitational Radiation in Binary Systems?

Unlike GR, most alternative theories of gravity – including tensor-scalar theories – predict other radiation multipoles that dominate the energy loss of the orbital dynamics:

$$\text{Energy flux} = \frac{\text{Quadrupole}}{c^5} + O\left(\frac{1}{c^7}\right) \quad \text{spin 2}$$

$$+ \frac{\text{Monopole}}{c}\left(0 + \frac{1}{c^2}\right)^2 + \underset{\substack{\uparrow \\ \propto (\alpha_A - \alpha_B)^2}}{\frac{\text{Dipole}}{c^3}} + \frac{\text{Quadrupole}}{c^5} + O\left(\frac{1}{c^7}\right) \quad \text{spin 0}$$

Hence, visible in orbital decay:



$$\dot{P}_{\mathrm{b}}^{\mathrm{quadrupole}} \propto \left(\frac{v}{c}\right)^5$$

$$\underset{\substack{\uparrow \\ \boxed{= 0 \text{ in GR}}}}{\dot{P}_{\mathrm{b}}^{\mathrm{dipole}}} \propto \left(\frac{v}{c}\right)^3 \underbrace{(\alpha_A - \alpha_B)^2}_{\substack{\sim 0 \text{ in Double Pulsar} \\ \text{since } \alpha_A \approx \alpha_B}}$$

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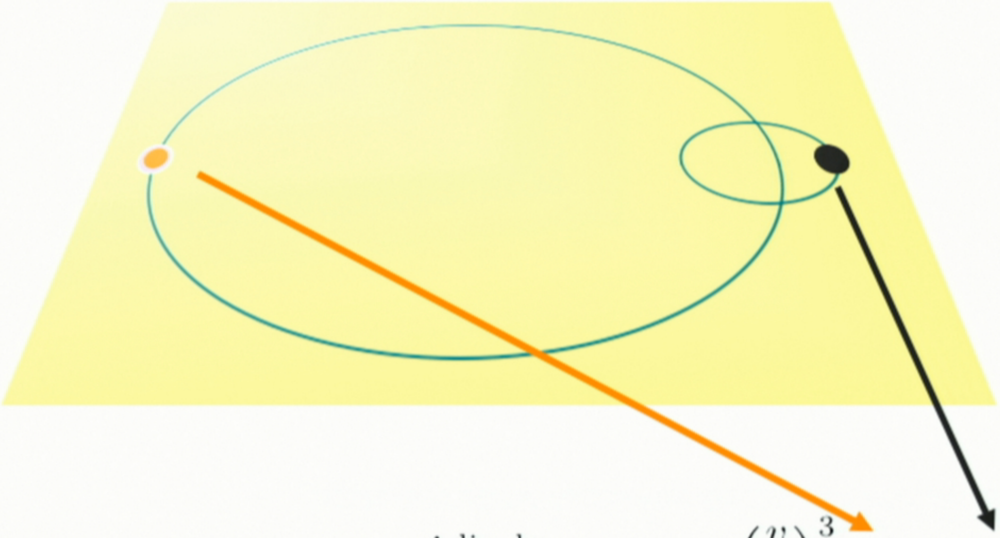


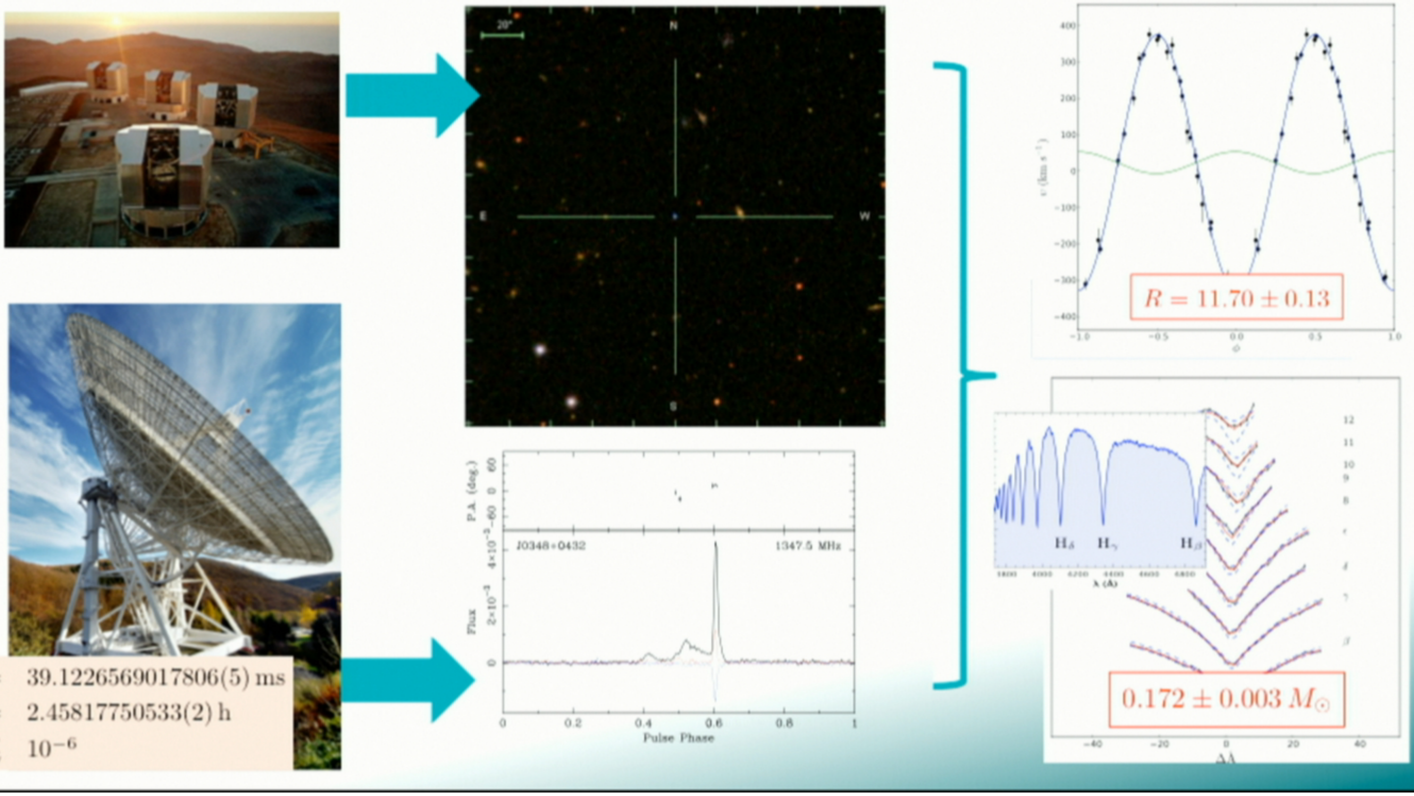
$$\dot{P}_{\rm b}^{\rm dipole} \propto \left(\frac{v}{c}\right)^3 (\alpha_A - \alpha_B)^2$$

- PSR-BH system would be best as BH would have zero scalar charge
- But PSR – WD system also effective lab – in particular if PSR is massive!

The "next best thing": PSR-WD

- PSR J0348+0432: first massive NS in relativistic orbit (Lynch et al. 2013)
- Combining VLT, Effelsberg, Arecibo & GBT data, new record mass measured:

  $M=2.01\pm0.04\ M_\odot$ (Antoniadis et al., 2013)



$P = 39.1226569017806(5)$ ms

$P_b = 2.45817750533(2)$ h

$e \lesssim 10^{-6}$

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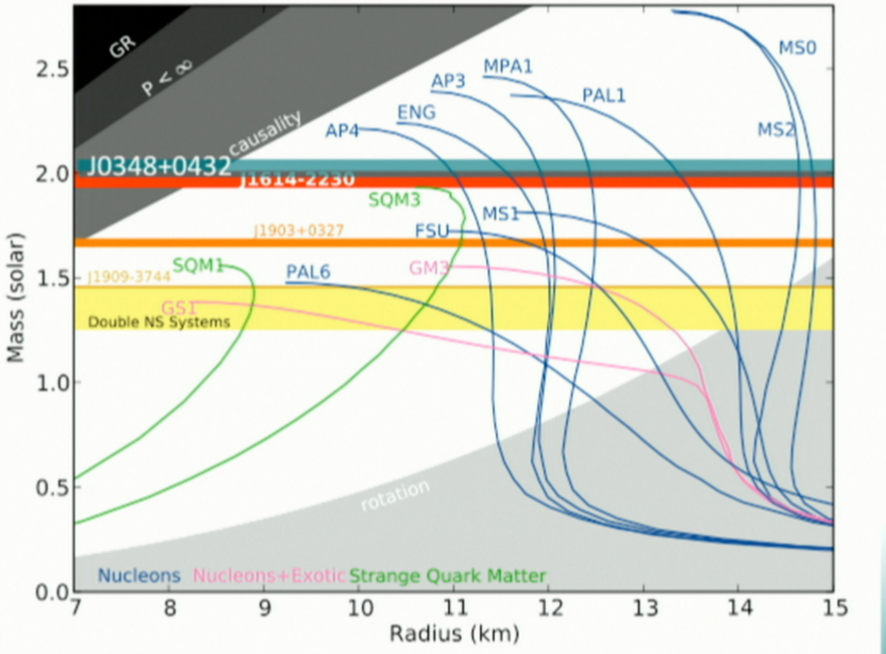
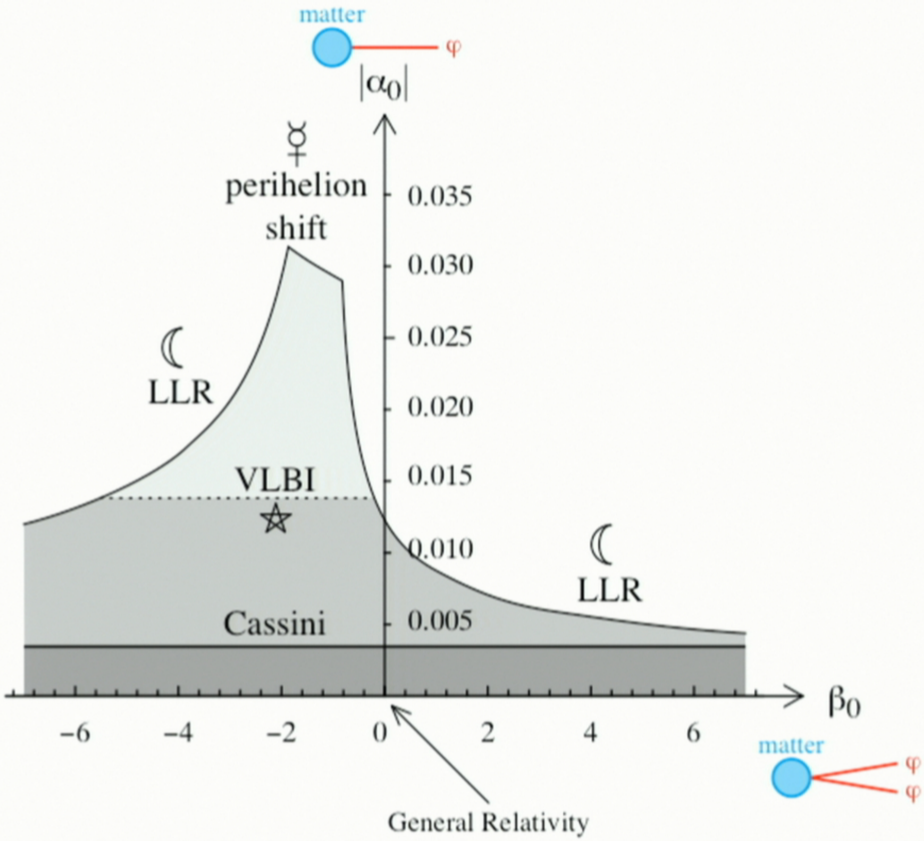
No vast improvement for EoS (though comforting!) but probing different fields!



Constraining tensor-scalar gravity



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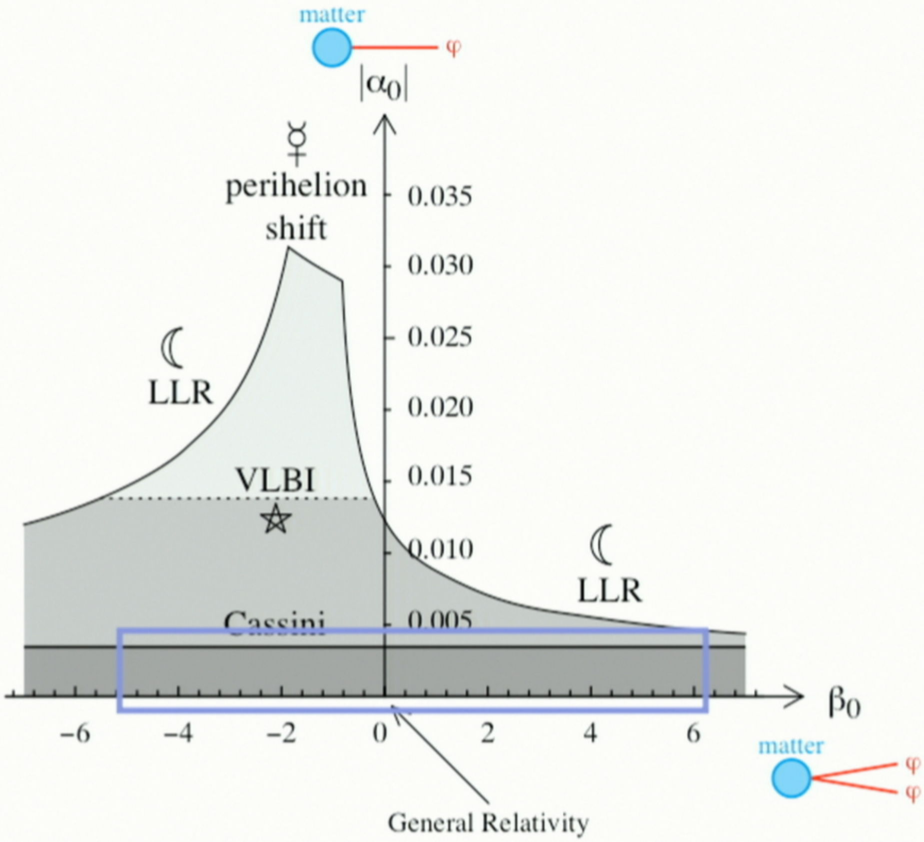

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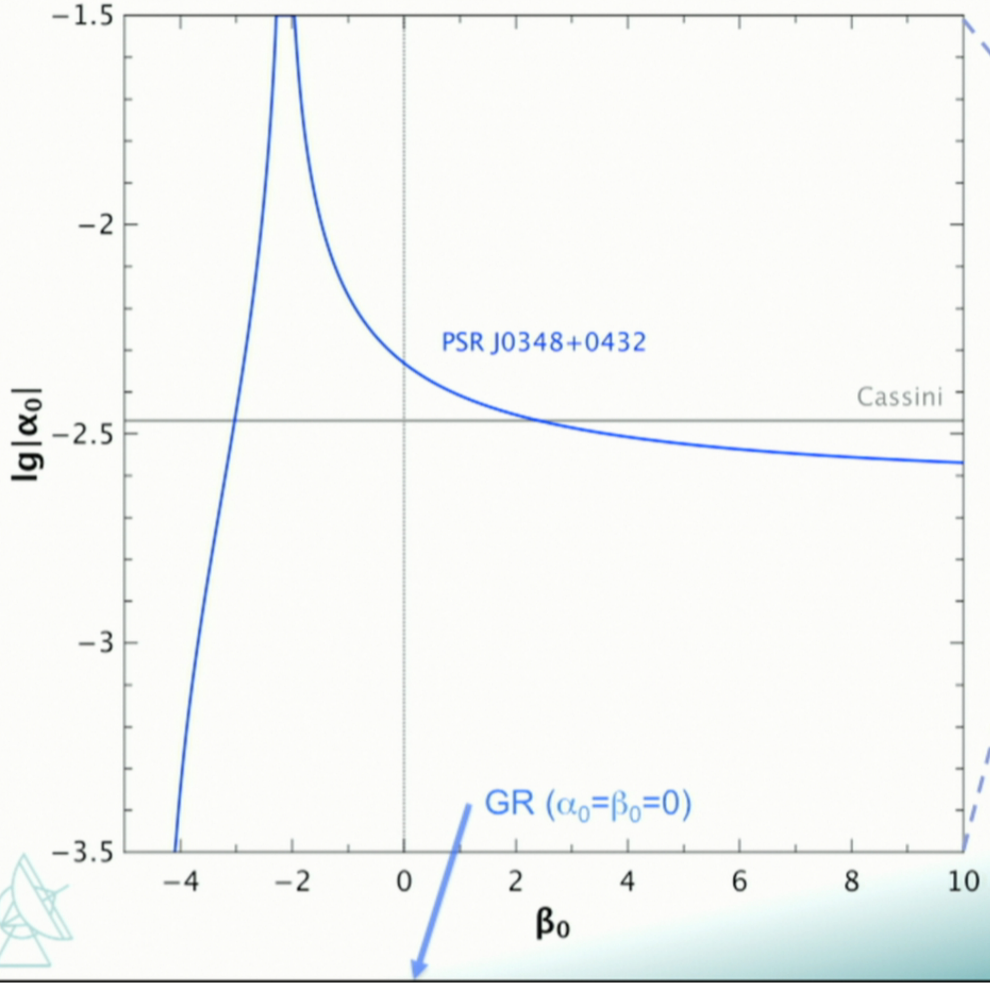

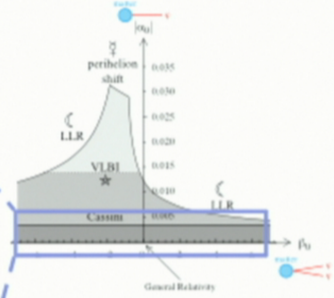

PSR J0348+0432:

Freire et al. (priv. comm.)

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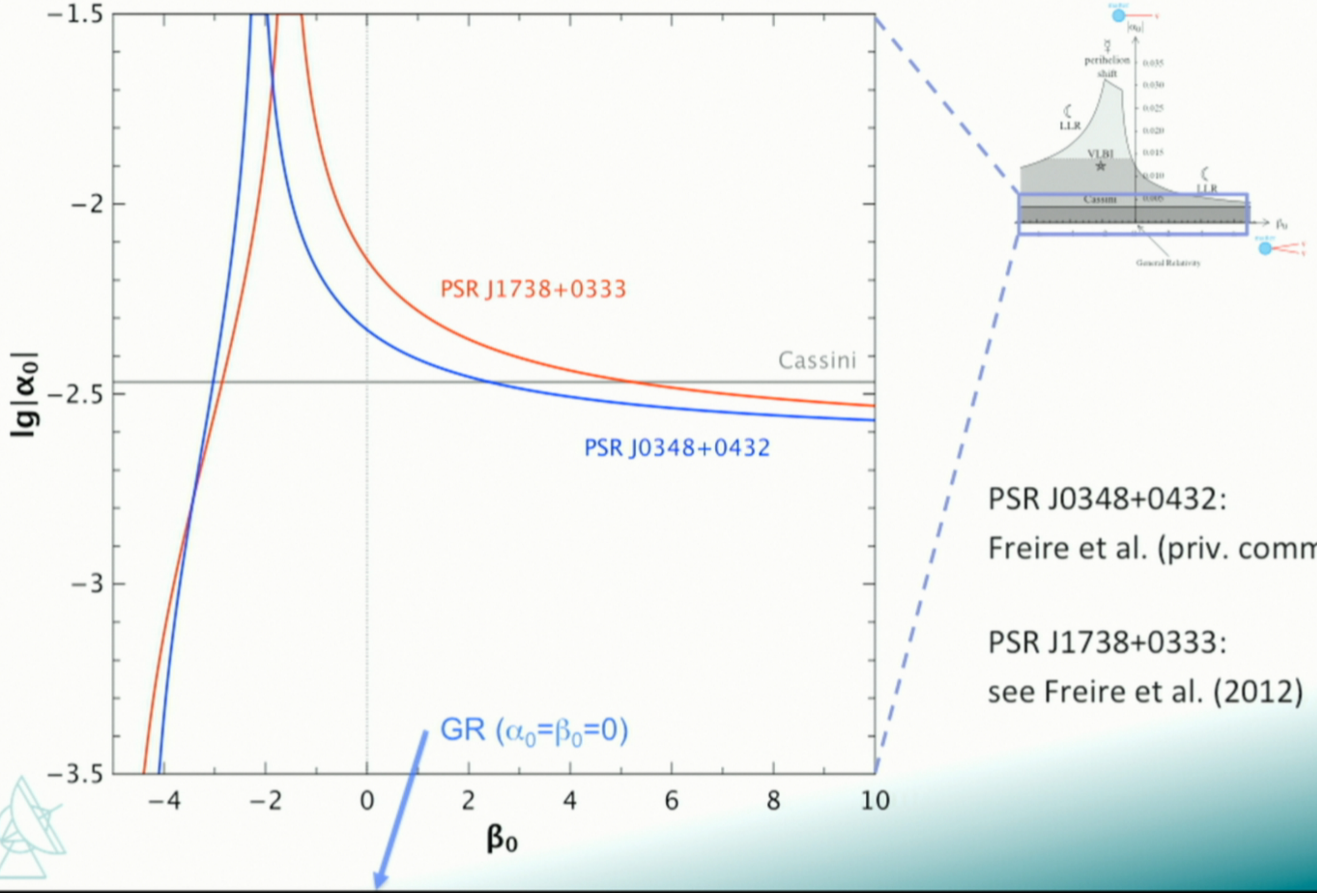
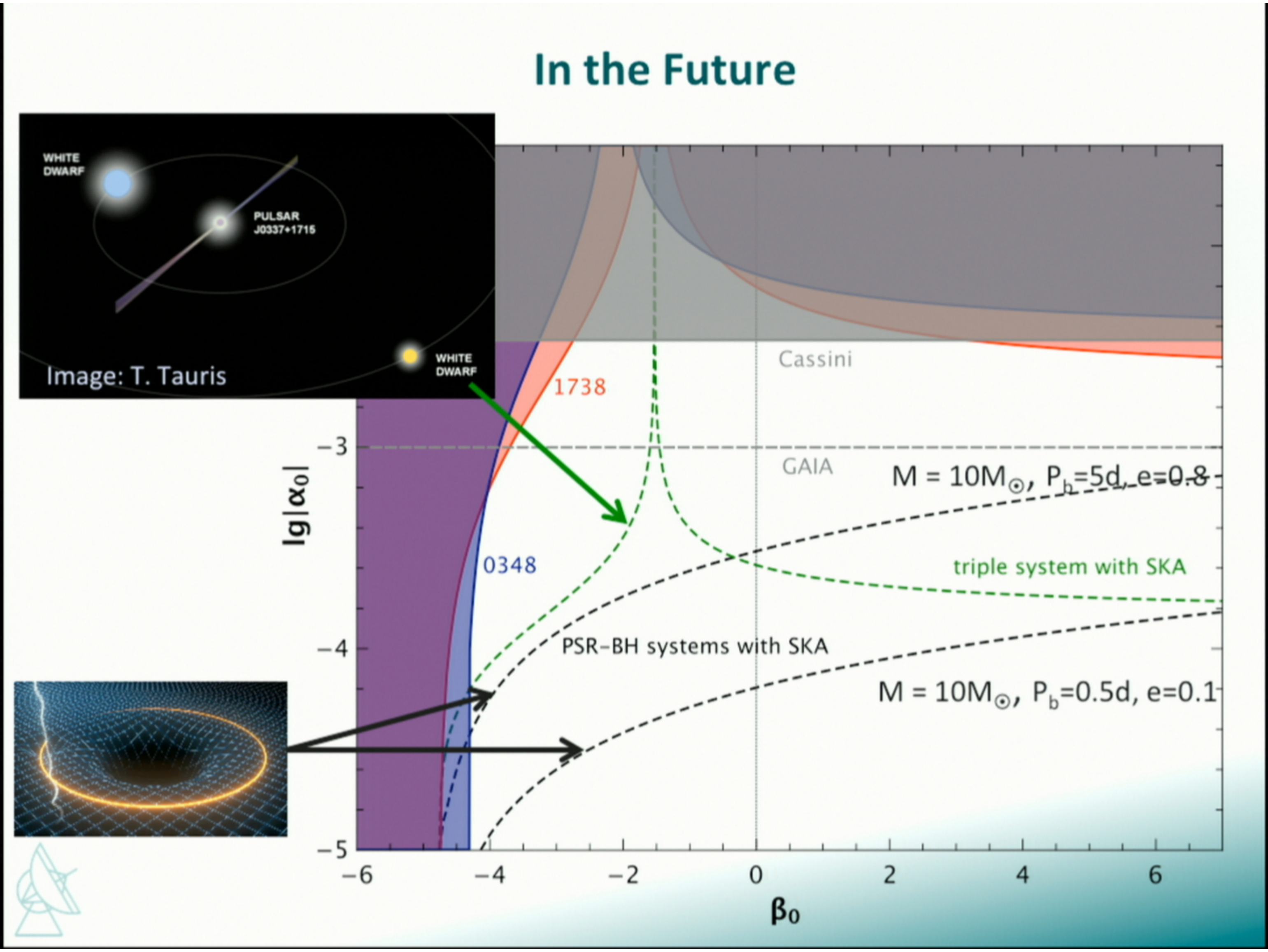


PSR J0348+0432:
Freire et al. (priv. comm.)

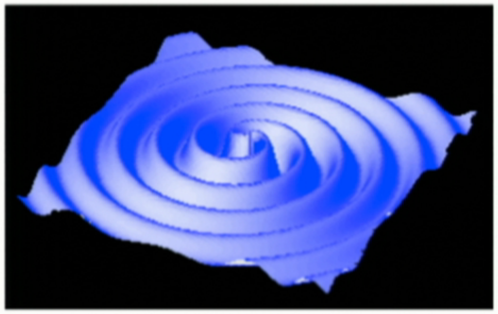
PSR J1738+0333:
see Freire et al. (2012)

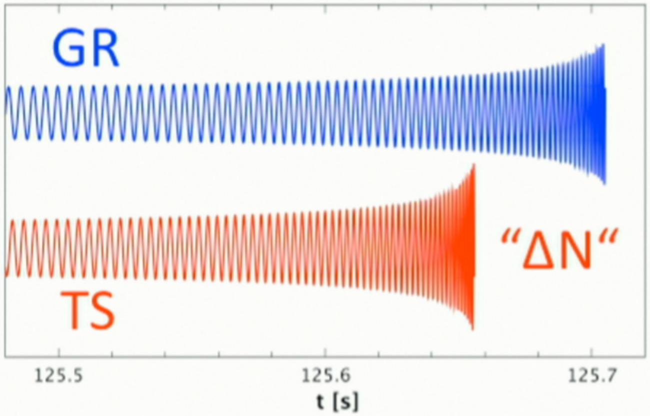


In the Future

Implications for LIGO/VIRGO

- Merger of binaries with NS companion main source of expected LIGO population
- Expected signal will differ for tensor-scalar theories
- Example: merger of $1.3M_\odot$ and $2M_\odot$ NS:





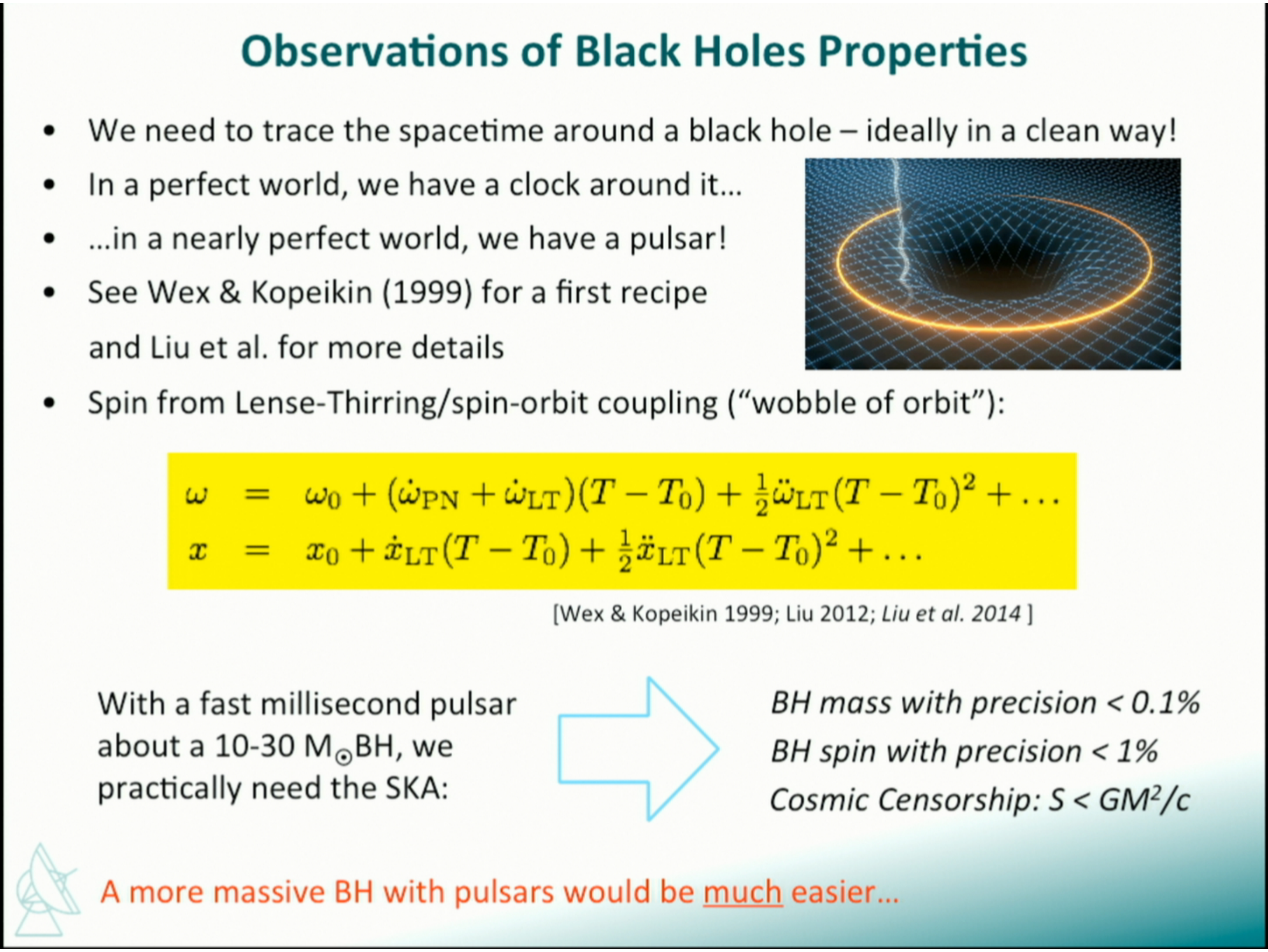
$$\boxed{\frac{\dot{n}_{\rm b}}{n_{\rm b}^2} = \frac{m_A m_B}{(m_A+m_B)^2}\,\frac{96}{5}\left(\frac{v}{c}\right)^5}$$

vs.

$$\boxed{\frac{\dot{n}_{\rm b}}{n_{\rm b}^2} = \frac{m_A m_B}{(m_A+m_B)^2}\left[\frac{96}{5}\left(\frac{v}{c}\right)^5\kappa_{AB} + \left(\frac{v}{c}\right)^3\frac{(\alpha_A-\alpha_B)^2}{1+\alpha_A\alpha_B}\right]}$$

From J0348+0432 → ΔN <0.5 - less than ½ a cycle!

It is sufficient to work with GR templates even for massive NSs!



Observations of Black Holes Properties

- We need to trace the spacetime around a black hole – ideally in a clean way!
- In a perfect world, we have a clock around it…
- …in a nearly perfect world, we have a pulsar!
- See Wex & Kopeikin (1999) for a first recipe and Liu et al. for more details
- Spin from Lense-Thirring/spin-orbit coupling (“wobble of orbit”):

$$\begin{aligned} \omega &= \omega_0 + (\dot{\omega}_{\rm PN} + \dot{\omega}_{\rm LT})(T - T_0) + \tfrac{1}{2}\ddot{\omega}_{\rm LT}(T - T_0)^2 + \ldots \\ x &= x_0 + \dot{x}_{\rm LT}(T - T_0) + \tfrac{1}{2}\ddot{x}_{\rm LT}(T - T_0)^2 + \ldots \end{aligned}$$

[Wex & Kopeikin 1999; Liu 2012; *Liu et al. 2014*]

With a fast millisecond pulsar about a 10-30 $M_\odot$BH, we practically need the SKA:

BH mass with precision < 0.1%

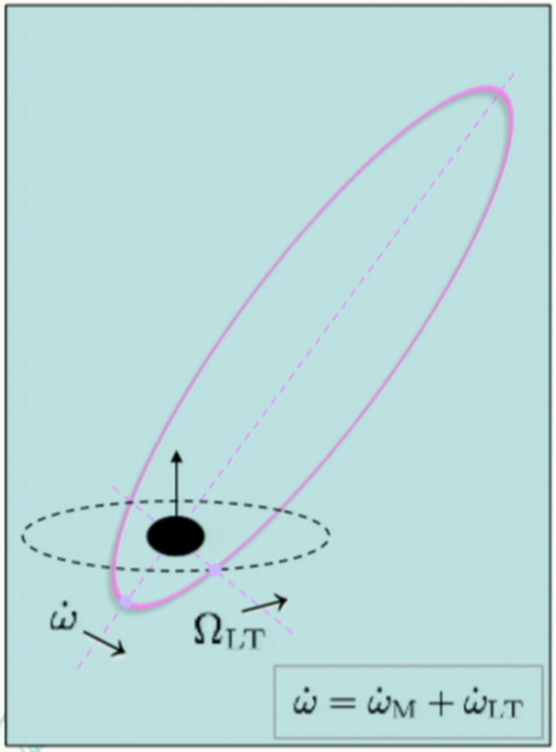
BH spin with precision < 1%

Cosmic Censorship: $S < GM^2/c$

A more massive BH with pulsars would be <u>much</u> easier…

Relativistic effects for a pulsar orbit around Sgr A*

Pulsar in a 0.3 yr eccentric (e=0.5) orbit around Sgr A*



Semi-major axis:	72 AU = 860 R_S
Pericenter distance:	36 AU = 430 R_S
Pericenter velocity:	0.042 c (~ 20 × Double Pulsar)

Pericenter advance:

1pN:	2.8 deg/yr,	ΔL ~ 1.8 AU/yr
2pN:	0.014 deg/yr,	ΔL ~ 1,400,000 km/yr

Einstein delay:

1pN:	15 min
2pN:	1.6 s

Propagation delay (i = 0° / i = 80°):

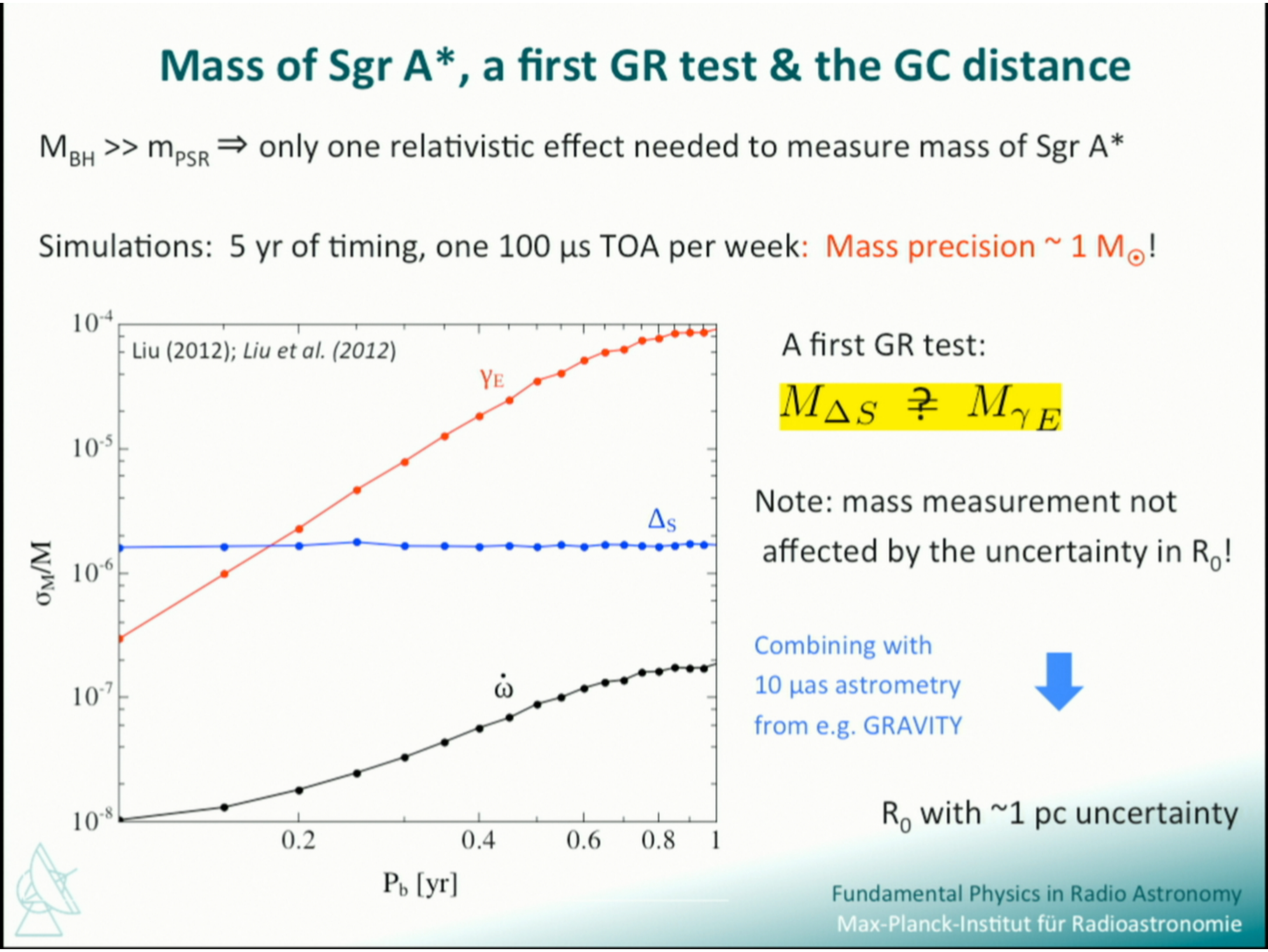
Shapiro 1pN:	46.4 s	/ 246.9 s
Shapiro 2pN:	0.2 s	/ 8.0 s
Frame dragging:	0.1 s	/ 6.5 s
Bending delay (P = 1s):	0.2 ms	/ 4.2 ms

Lense-Thirring precession:

Orbital plane $\Omega_{\rm LT}$: 0.052 deg/yr, ΔL ~ 10^7 km/yr

Similar contribution to $\dot{\omega}$

Geod. precession 1.4 deg/yr



Mass of Sgr A*, a first GR test & the GC distance

$M_{BH} >> m_{PSR} \Rightarrow$ only one relativistic effect needed to measure mass of Sgr A*

Simulations: 5 yr of timing, one 100 μs TOA per week: Mass precision ~ 1 $M_\odot$!

A first GR test:

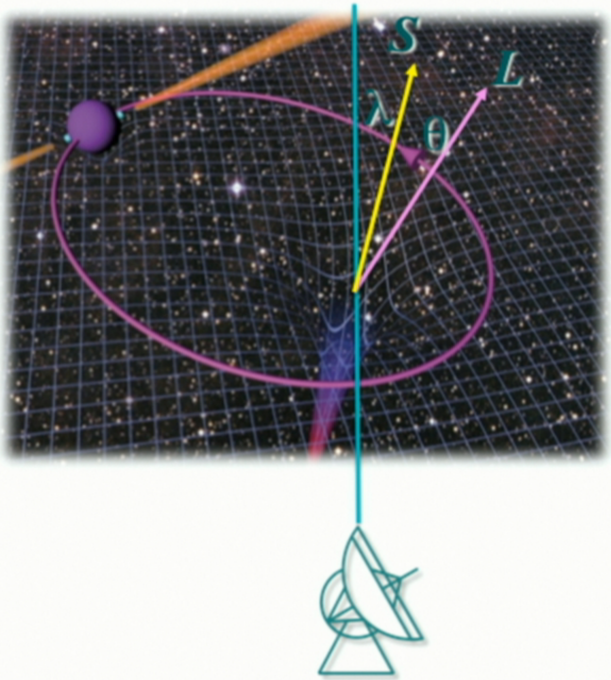
$$M_{\Delta S} \overset{?}{=} M_{\gamma E}$$

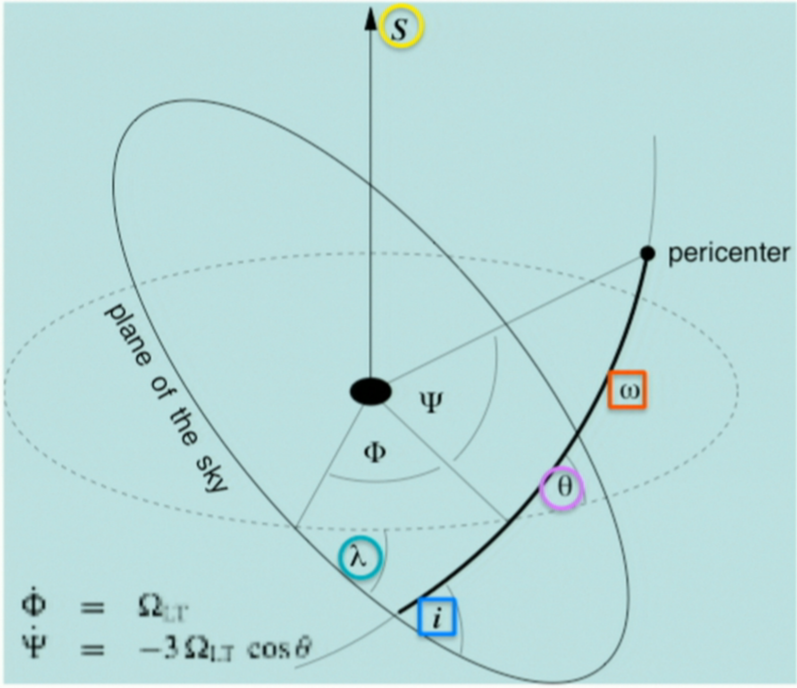
Note: mass measurement not affected by the uncertainty in R_0!

Combining with
10 μas astrometry
from e.g. GRAVITY

R_0 with ~1 pc uncertainty

Determining the spin of the Sgr A* - incl. direction!





$$\dot{\Phi} = \Omega_{\rm LT}$$
$$\dot{\Psi} = -3\,\Omega_{\rm LT}\cos\theta$$

Testing Cosmic Censorship Conjecture:

$$\chi \equiv \frac{c}{G}\frac{S}{M^2} \leq 1$$

[Wex & Kopeikin 1999, Liu et al. 2012]

$$\boxed{\omega} = \omega_0 + \dot{\omega}_0(T - T_0) + \tfrac{1}{2}\ddot{\omega}_0(T - T_0)^2 + \ldots$$
$$\boxed{x} = x_0 + \dot{x}_0(T - T_0) + \tfrac{1}{2}\ddot{x}_0(T - T_0)^2 + \ldots$$

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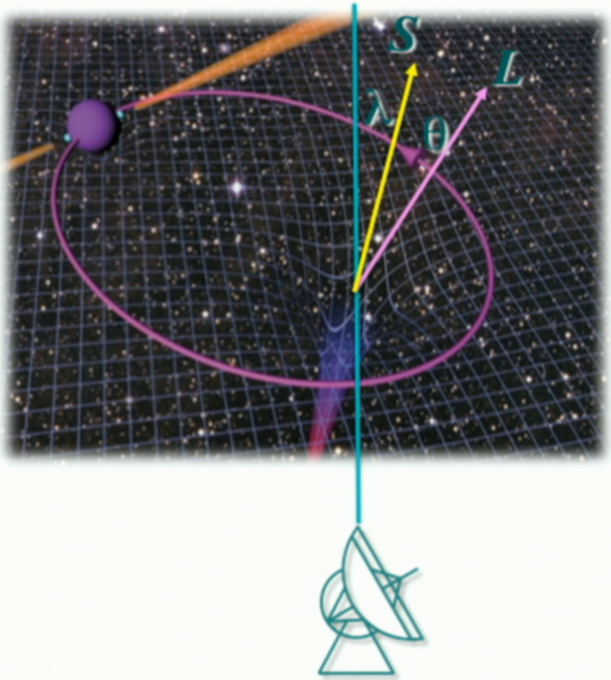

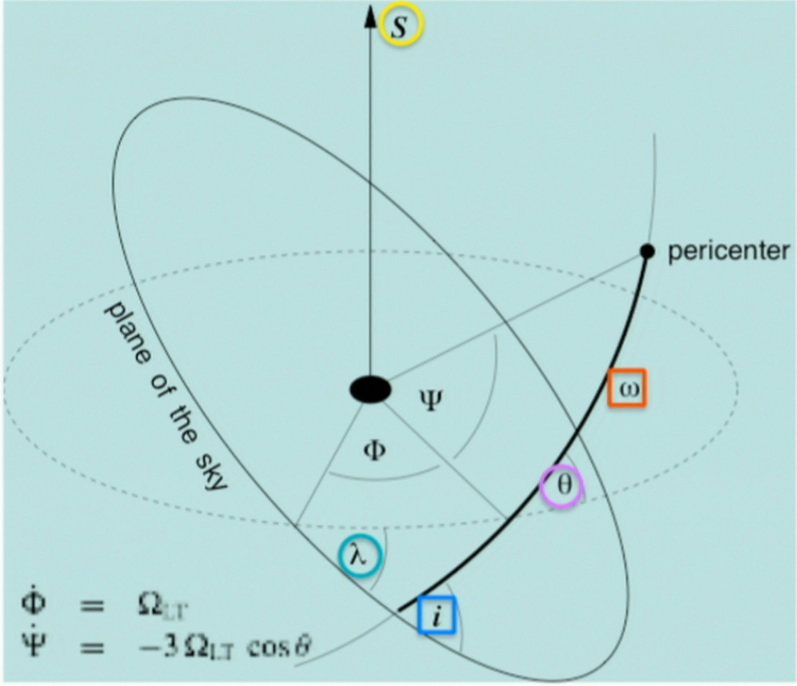

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Spin determination

Pulsar orbit

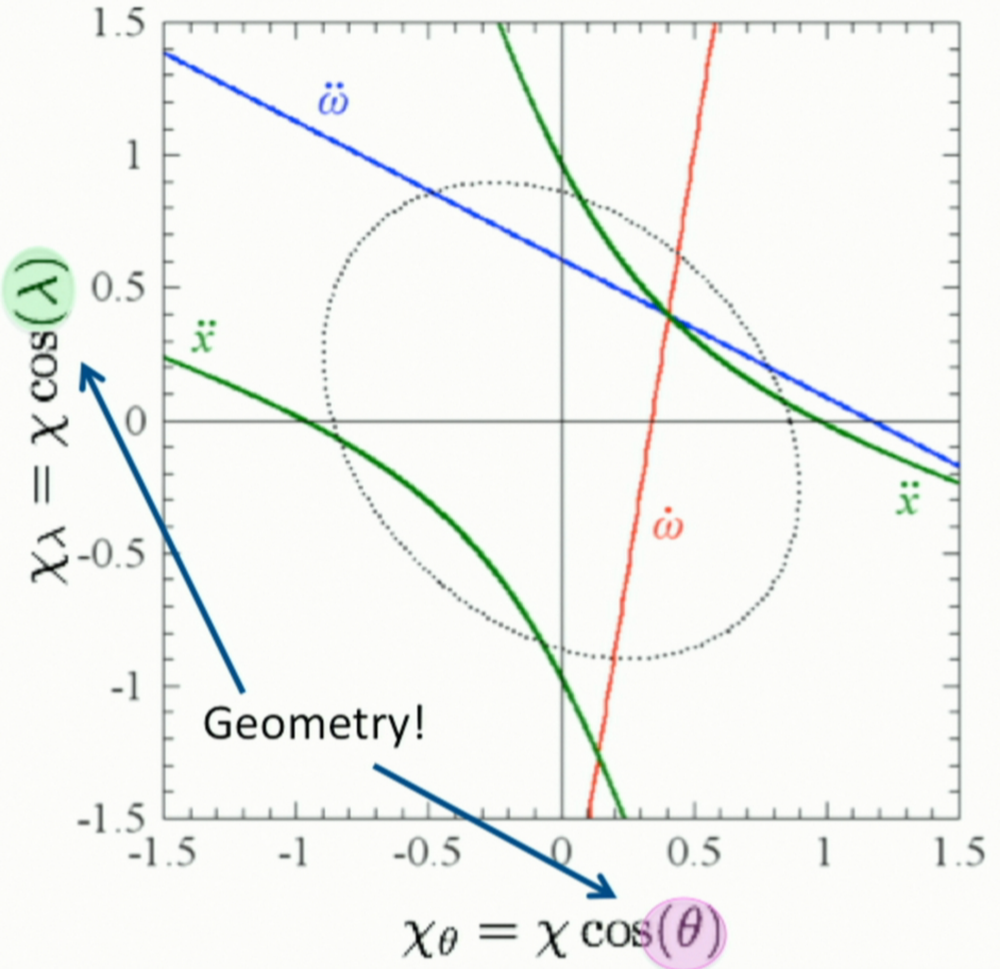
P_b = 0.3 yr
e = 0.5
Φ_0 = 45º
Ψ_0 = 45º
θ = 60º
λ = 60º

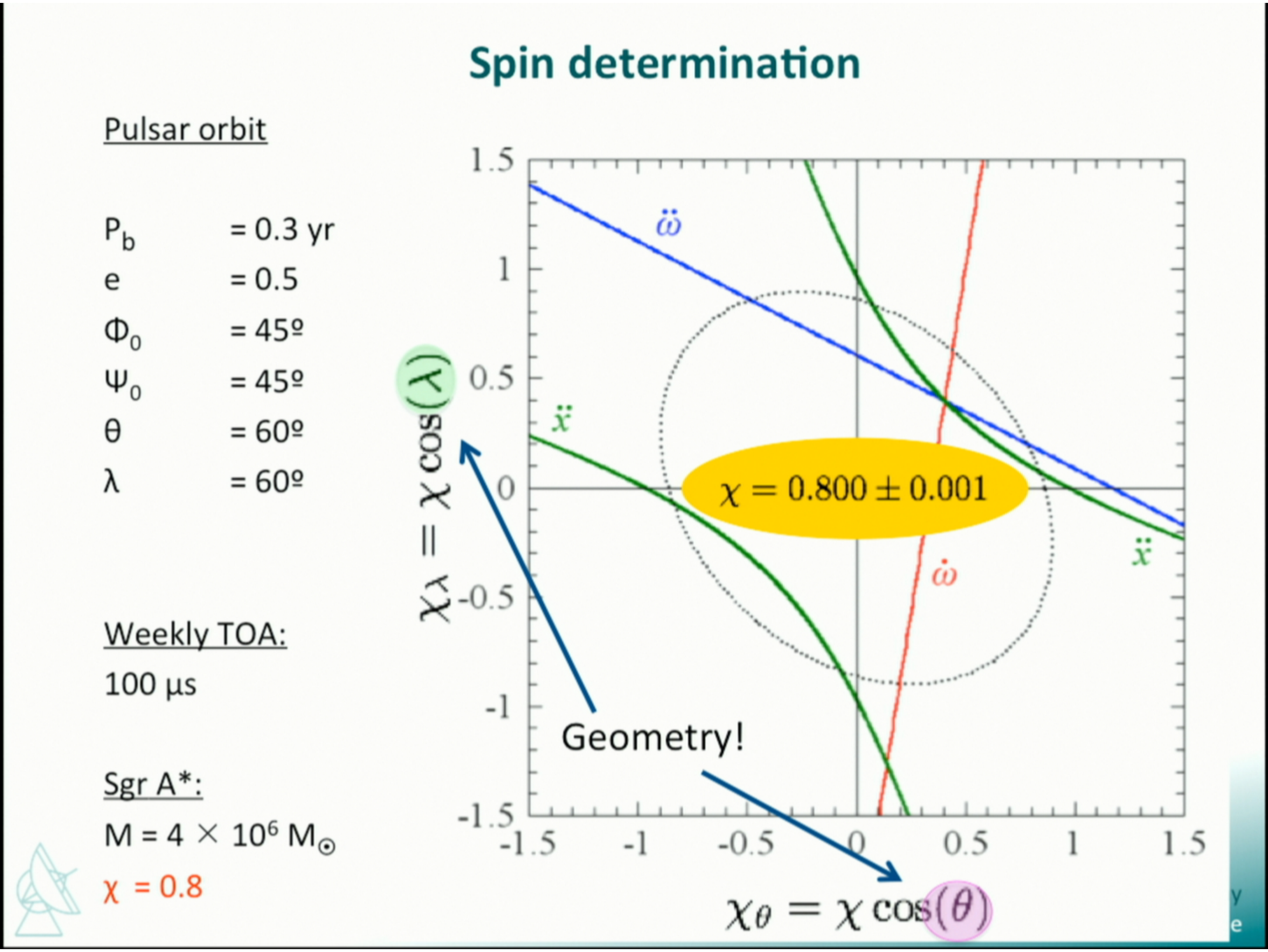
Weekly TOA:

100 μs

Sgr A*:

M = 4 × 10^6 $M_\odot$
χ = 0.8





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Weekly TOA:

100 μs

Sgr A*:

M = 4 × 10^6 $M_\odot$
χ = 0.8

$\chi = 0.800 \pm 0.001$

Geometry!

A naked Kerr singularity

Pulsar orbit

P_b = 0.3 yr

e = 0.5

Φ_0 = 45º

Ψ_0 = 45º

θ = 60º

λ = 60º

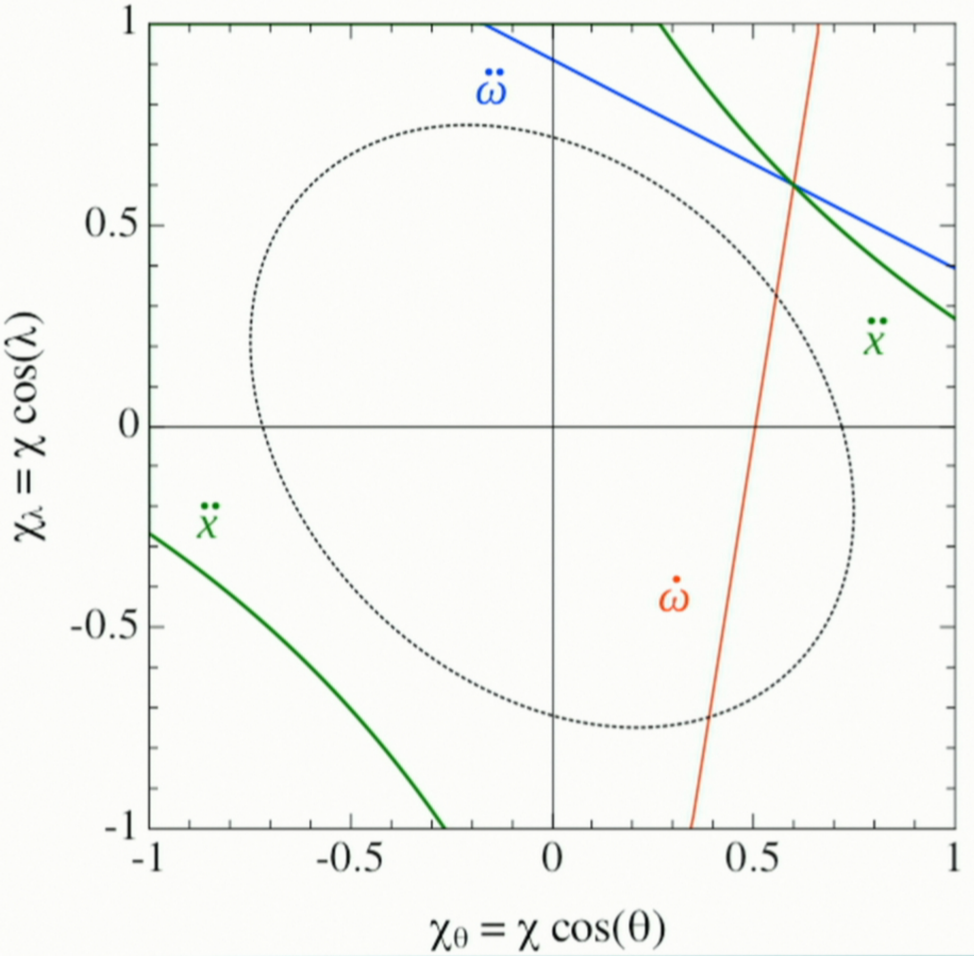
Weekly TOA:

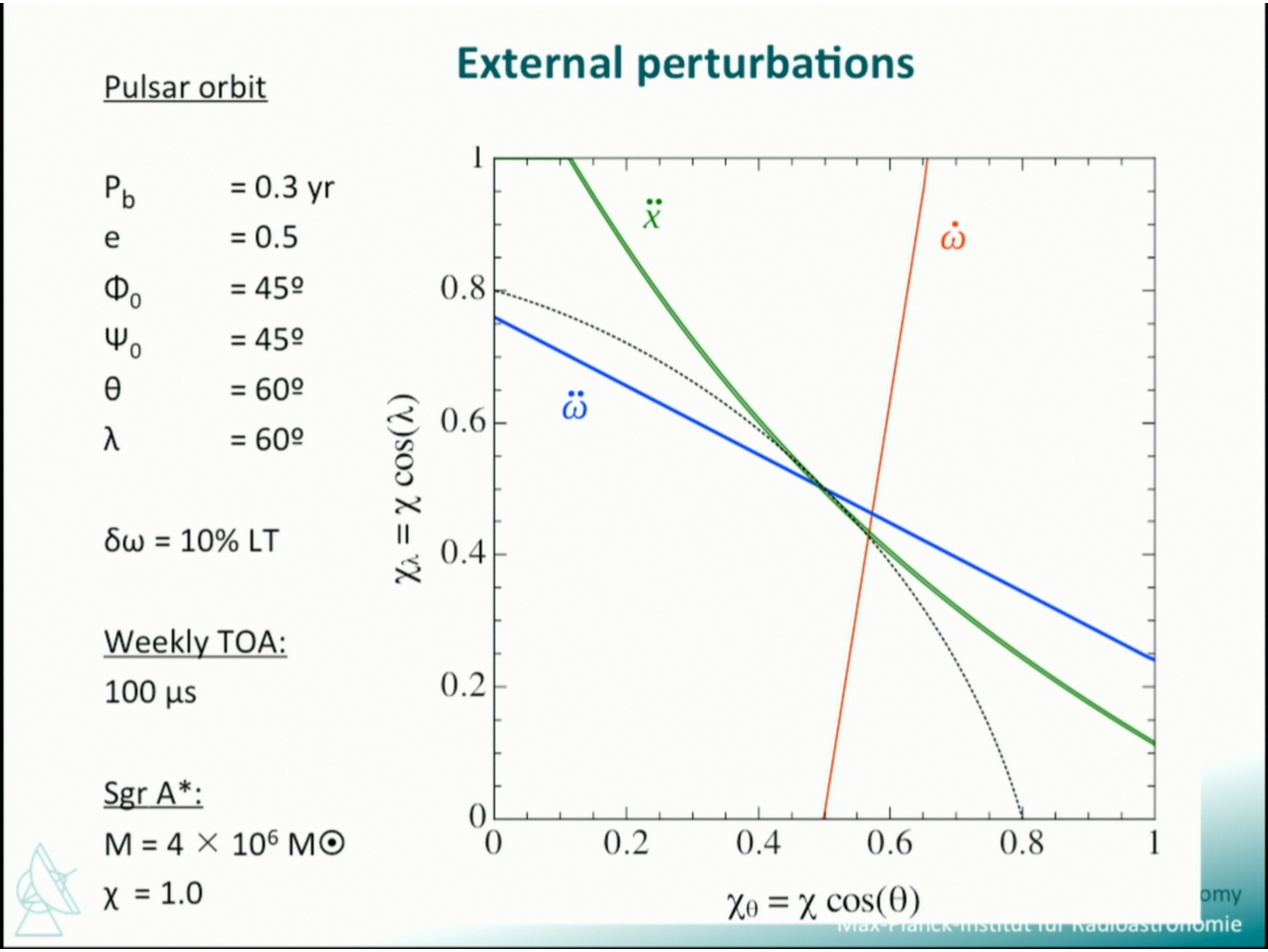
100 μs

Sgr A*:

$M = 4 \times 10^6 M_\odot$

χ = 1.2





External perturbations

Pulsar orbit

P_b = 0.3 yr
e = 0.5
Φ_0 = 45º
Ψ_0 = 45º
θ = 60º
λ = 60º

δω = 10% LT

Weekly TOA:
100 μs

Sgr A*:
M = 4 × 10^6 M$\odot$
χ = 1.0

omy
Max-Planck-Institut für Radioastronomie

External perturbations

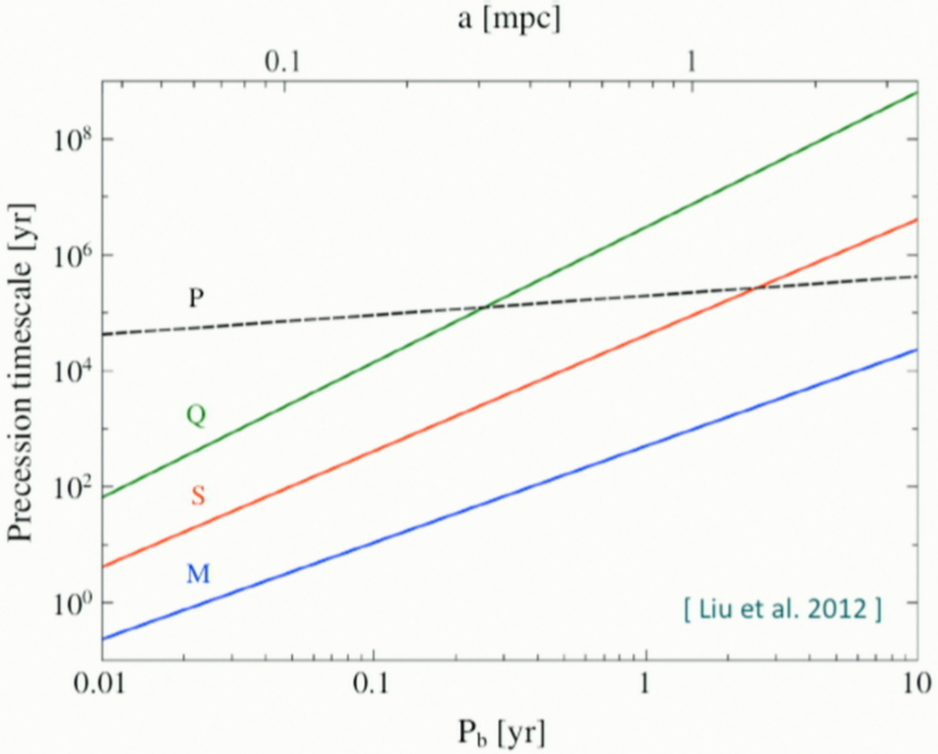
Pulsar orbit

P_b = 0.3 yr
e = 0.5
Φ_0 = 45º
Ψ_0 = 45º
θ = 60º
λ = 60º

$\delta\omega$ = 10% LT

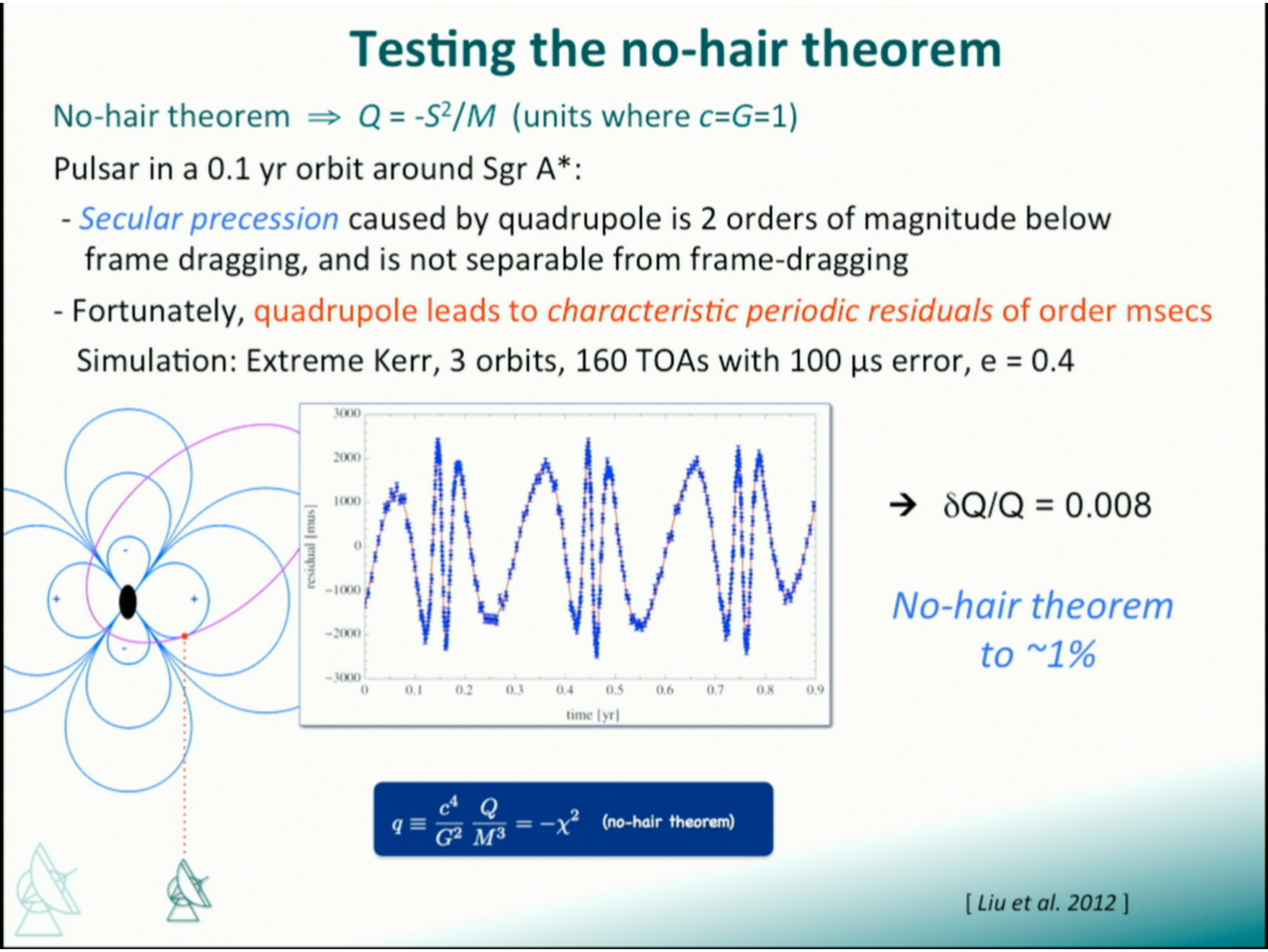
Weekly TOA:
100 µs

Sgr A*:
$M = 4 \times 10^6 M_\odot$
χ = 1.0



[Liu et al. 2012]

- Here: stellar population 10^3 stars/mpc (cf. Merritt et al. 2010)
- Effect of perturbations immediately detectable
- We want orbits with P_b<0.3 yrs
- Mass measurement easy



Testing the no-hair theorem

No-hair theorem ⇒ $Q = -S^2/M$ (units where $c=G=1$)

Pulsar in a 0.1 yr orbit around Sgr A*:

- *Secular precession* caused by quadrupole is 2 orders of magnitude below frame dragging, and is not separable from frame-dragging
- Fortunately, quadrupole leads to *characteristic periodic residuals* of order msecs

Simulation: Extreme Kerr, 3 orbits, 160 TOAs with 100 μs error, e = 0.4

→ $\delta Q/Q = 0.008$

No-hair theorem to ~1%

$$q \equiv \frac{c^4}{G^2}\frac{Q}{M^3} = -\chi^2$$ (no-hair theorem)

[*Liu et al. 2012*]

Testing the no-hair theorem

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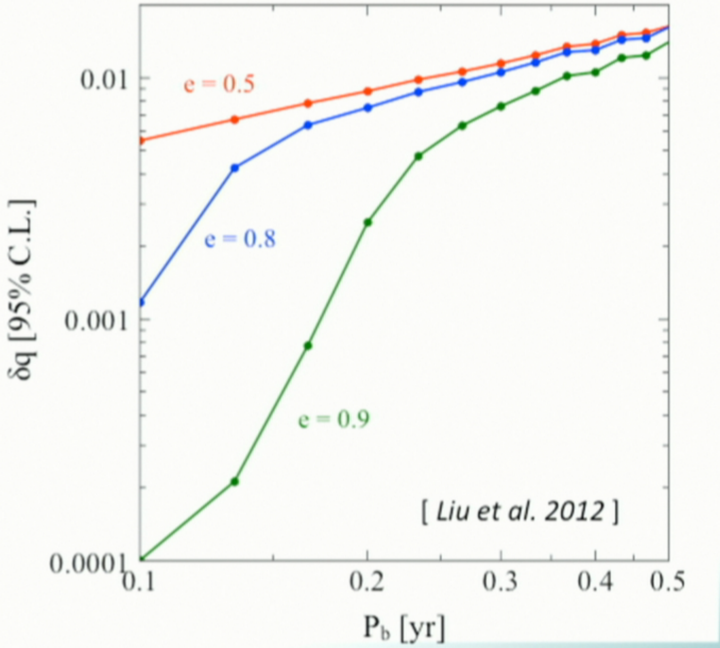
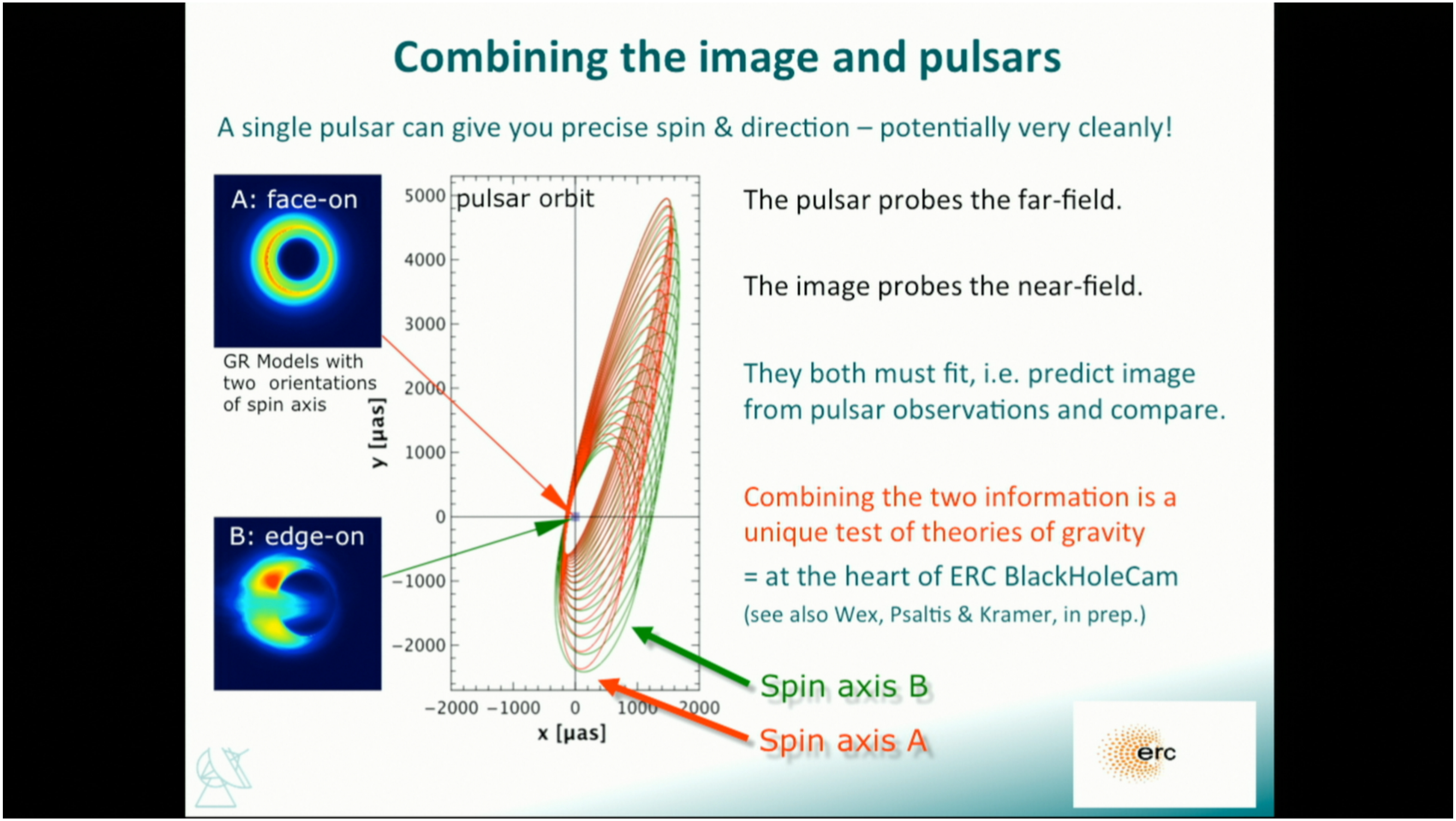


[*Liu et al. 2012*]

Actual precision will depend on eccentricity

- and may be much better!



Combining the image and pulsars

A single pulsar can give you precise spin & direction – potentially very cleanly!

GR Models with two orientations of spin axis

The pulsar probes the far-field.

The image probes the near-field.

They both must fit, i.e. predict image from pulsar observations and compare.

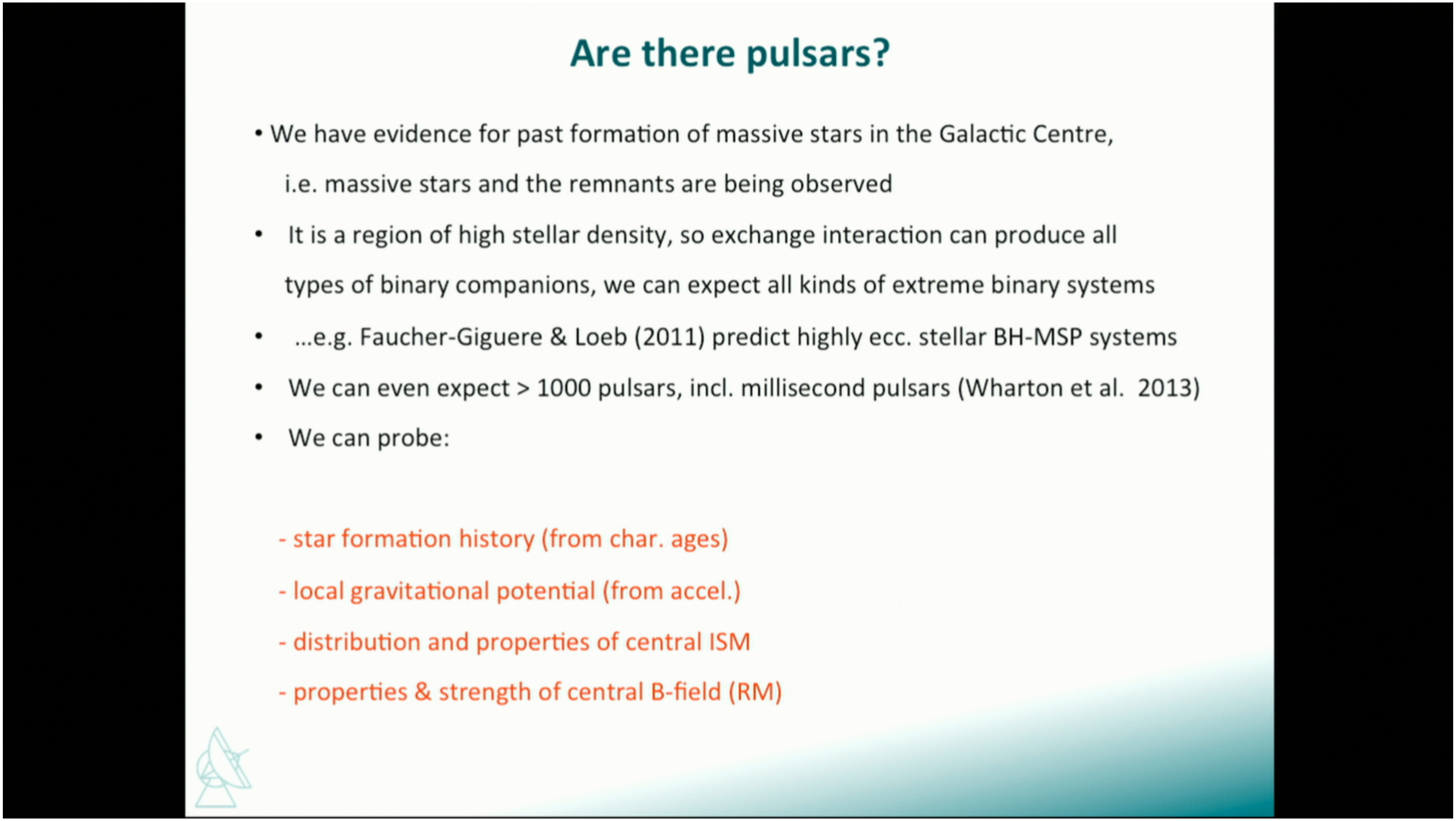
Combining the two information is a unique test of theories of gravity

= at the heart of ERC BlackHoleCam

(see also Wex, Psaltis & Kramer, in prep.)

Are there pulsars?

- We have evidence for past formation of massive stars in the Galactic Centre, i.e. massive stars and the remnants are being observed
- It is a region of high stellar density, so exchange interaction can produce all types of binary companions, we can expect all kinds of extreme binary systems
- …e.g. Faucher-Giguere & Loeb (2011) predict highly ecc. stellar BH-MSP systems
- We can even expect > 1000 pulsars, incl. millisecond pulsars (Wharton et al. 2013)



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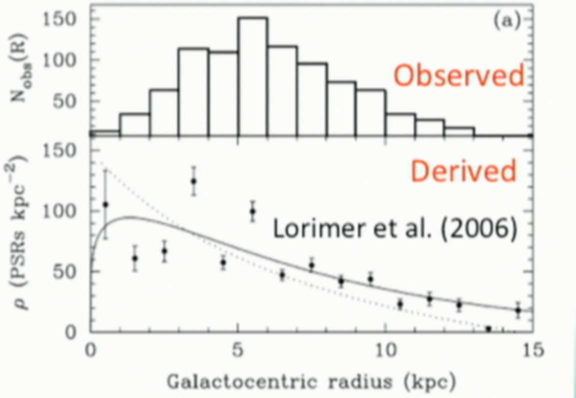

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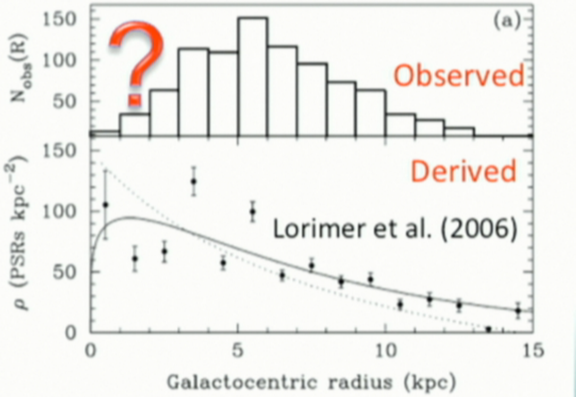


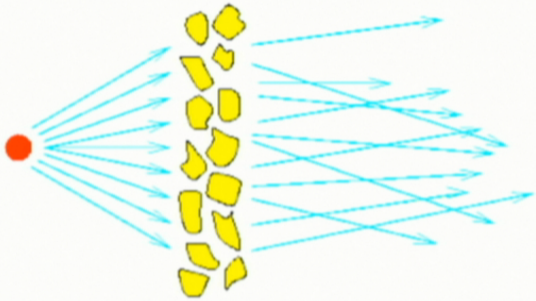
Observed

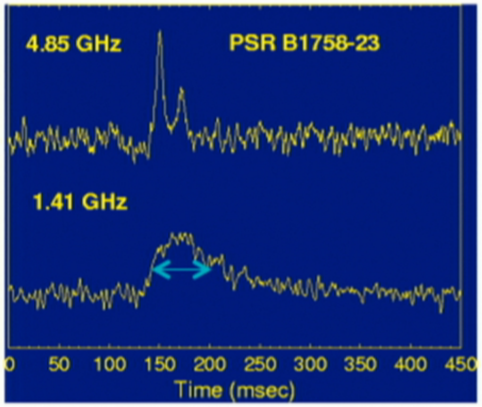
Derived

Lorimer et al. (2006)

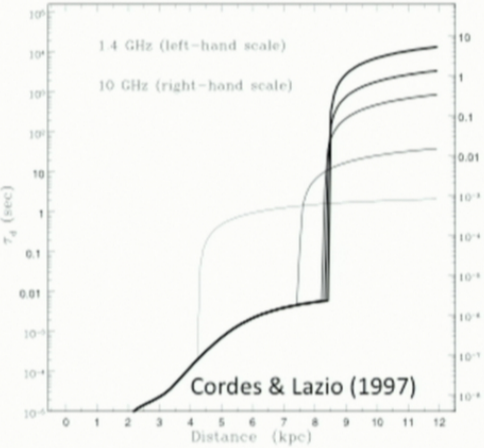
Selection effects – Why is it so hard?

The inhomogeneous ionized ISMs smears and scatters the pulses (NB: dispersion is easy…) :

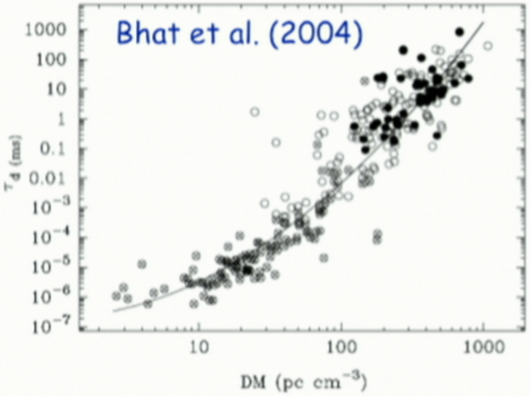




Expected scattering time may be enormous:



Cordes & Lazio (1997)



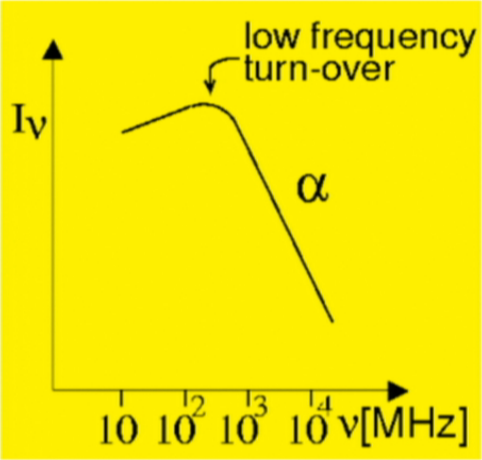
Bhat et al. (2004)

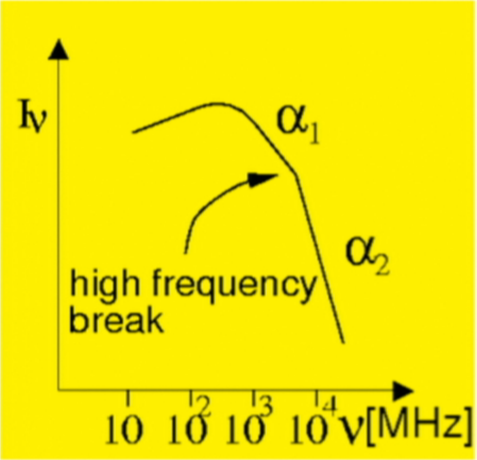
→ In particular at the centre:

At "normal" search frequencies pulses may be undetectable!

Why not observing at very high frequencies?

- Pulsars generally have steep flux density spectra

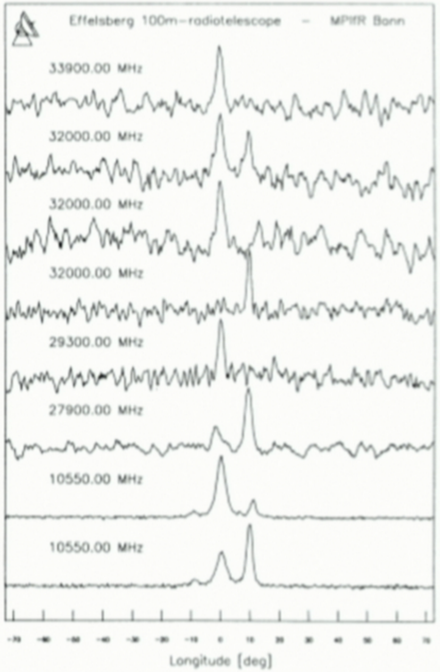




Observations at mm-wavelengths

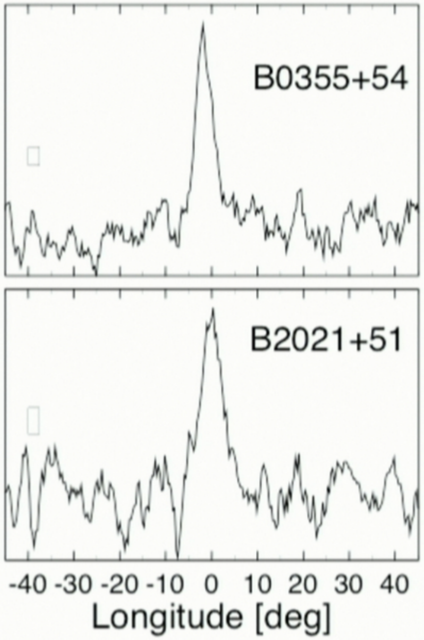
Pulsars have been detected at mm-wavelengths, e.g.:

9mm



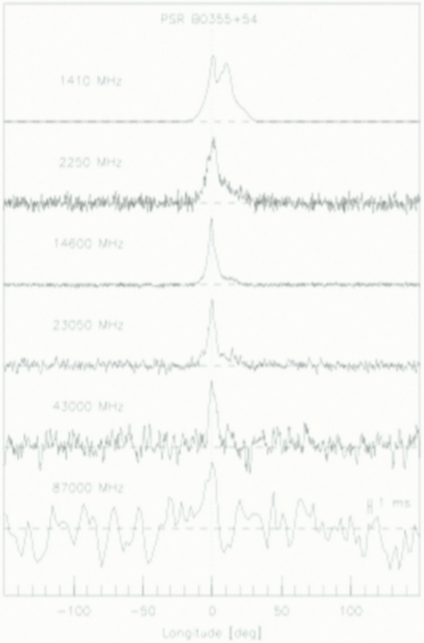
Kramer et al. (1996)

7mm



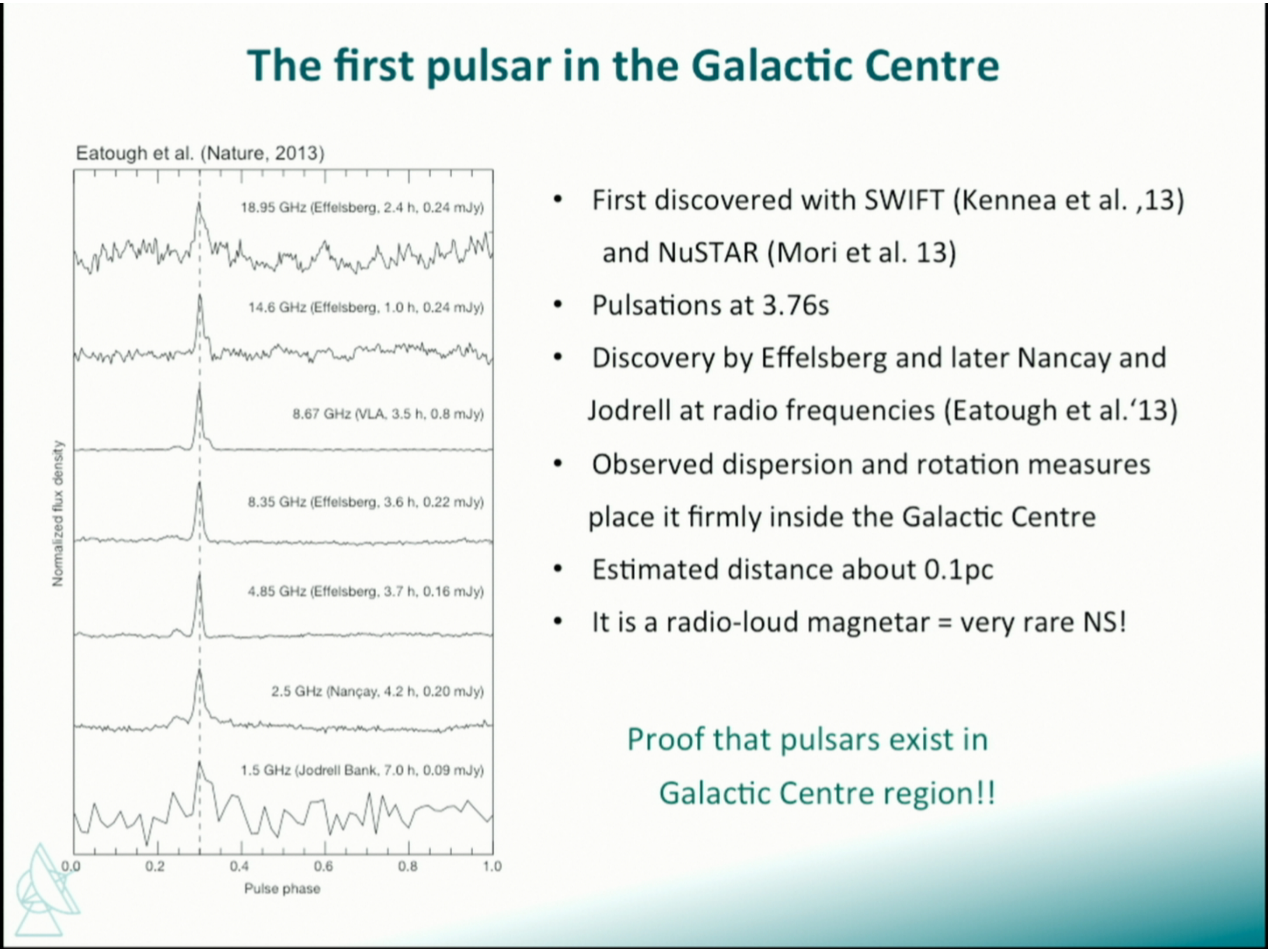
Kramer et al. (1997)

3mm



Morris et al. (1997)

But we still need pulsars...!



The first pulsar in the Galactic Centre

Eatough et al. (Nature, 2013)

- First discovered with SWIFT (Kennea et al. ,13) and NuSTAR (Mori et al. 13)
- Pulsations at 3.76s
- Discovery by Effelsberg and later Nancay and Jodrell at radio frequencies (Eatough et al.'13)
- Observed dispersion and rotation measures place it firmly inside the Galactic Centre
- Estimated distance about 0.1pc
- It is a radio-loud magnetar = very rare NS!

Proof that pulsars exist in Galactic Centre region!!

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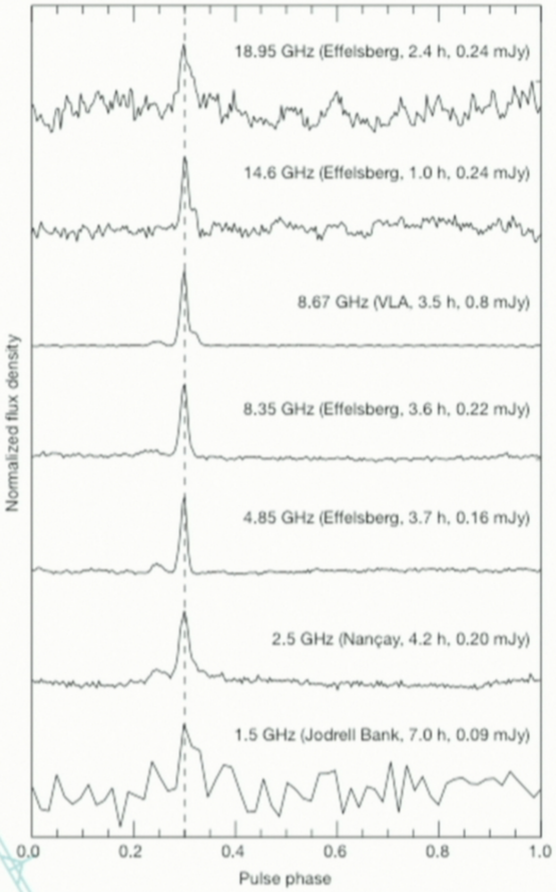

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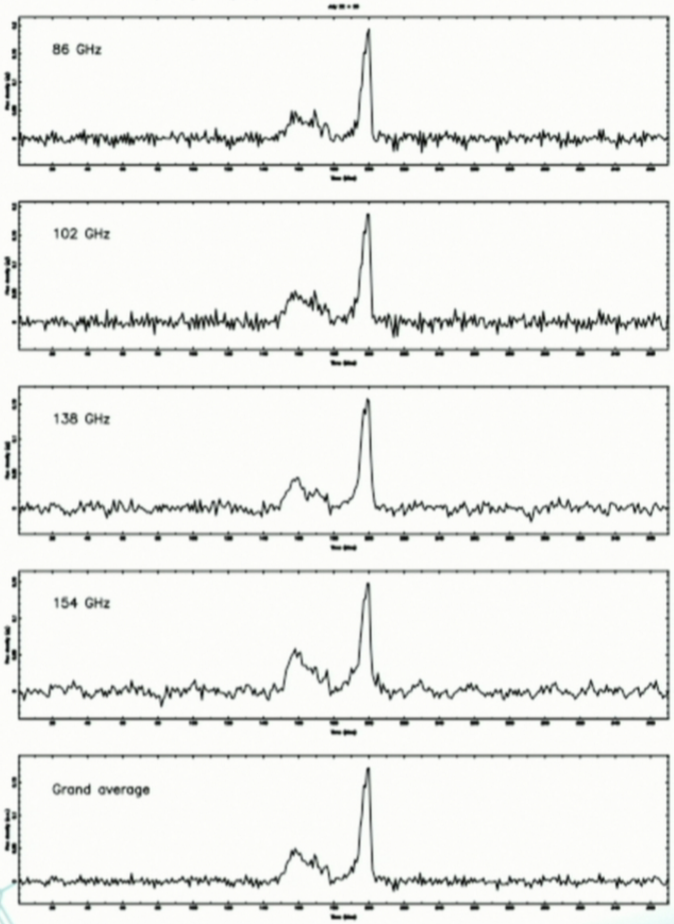
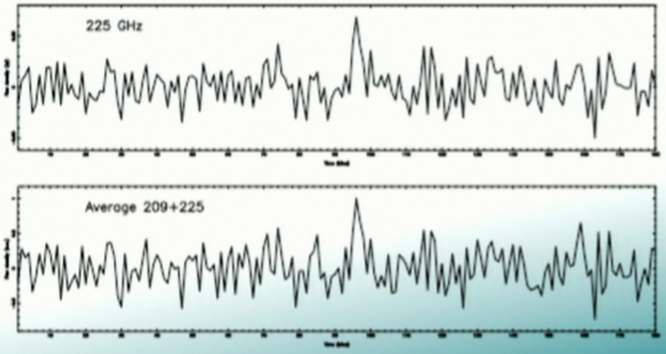
Record observations of the GC Magnetar

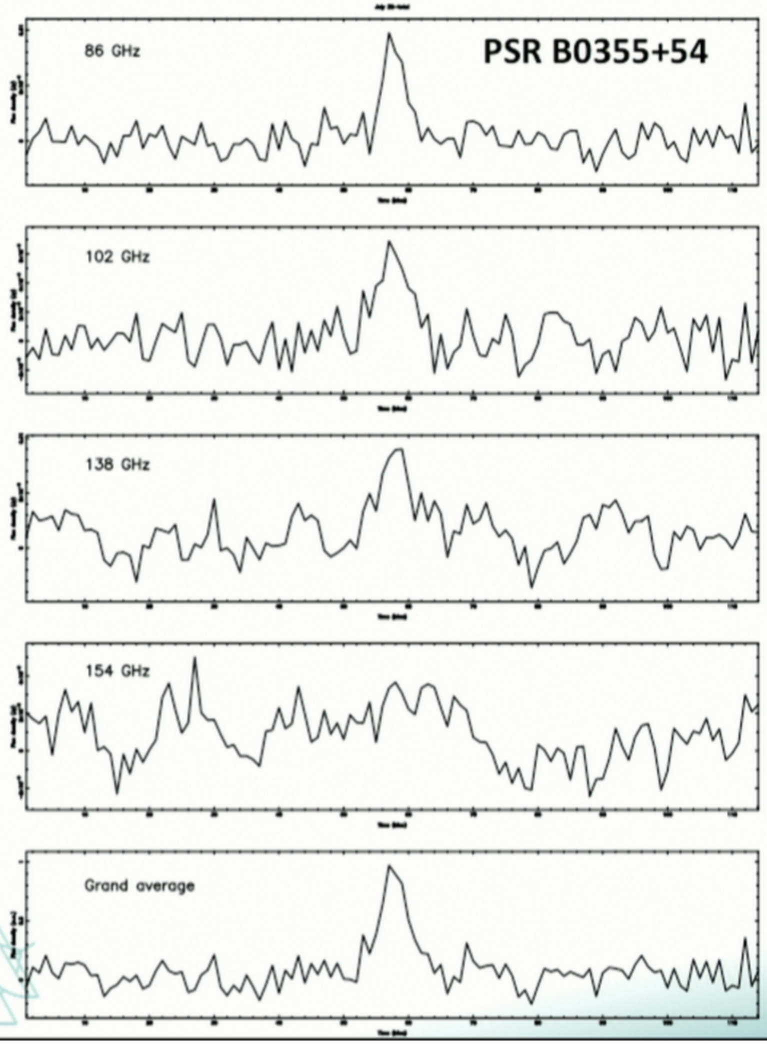
Torne et al. (in prep.)



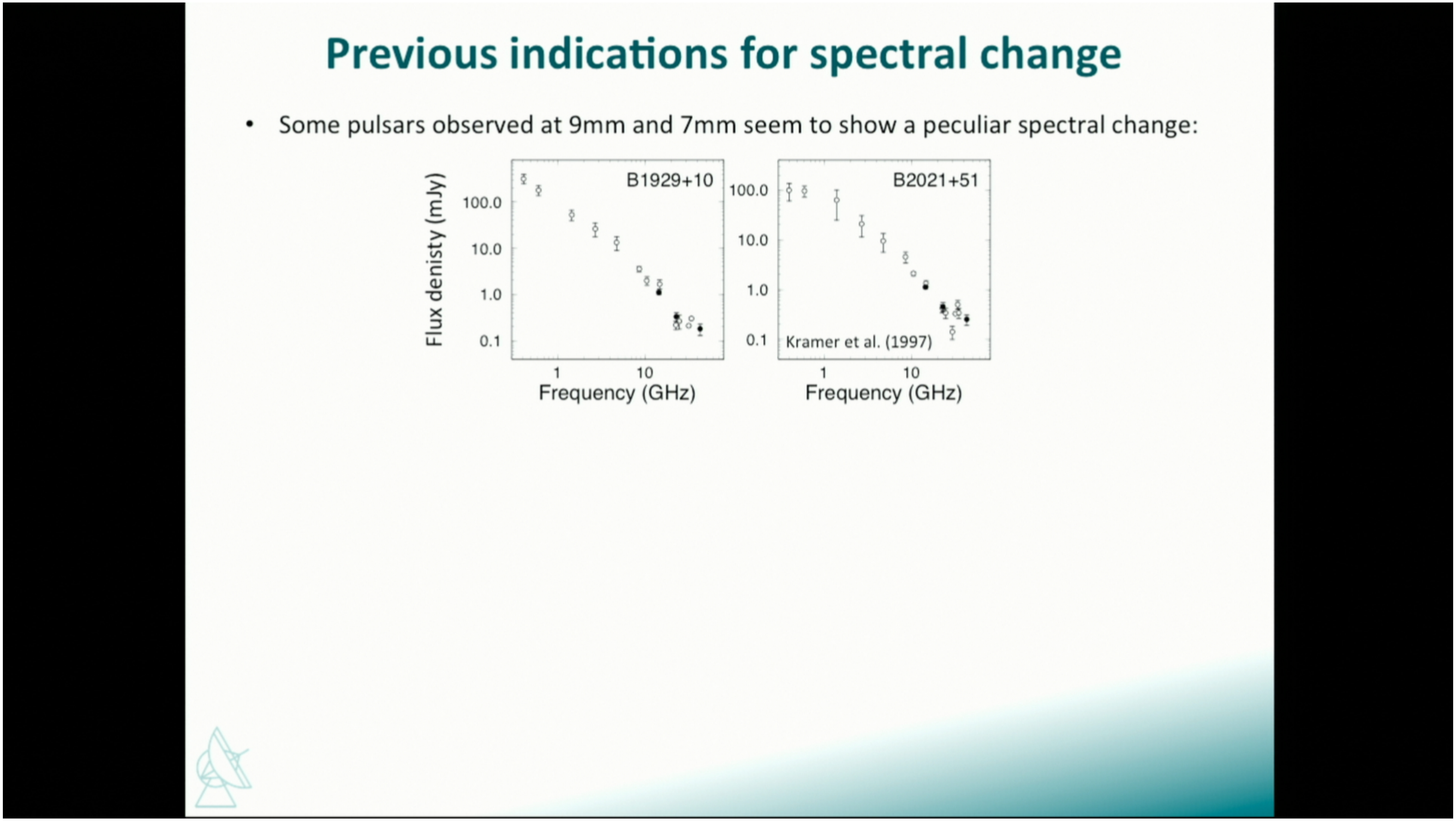
- Detection up to 154 GHz, perhaps even 225 GHz!
- Single pulses up to 154 GHz!
- Simultaneous observations with Pico Veleta and Effelsberg: 5-154 GHz



Recent observations of pulsars & magnetar at high frequencies



- Preliminary results from observations at Pico Veleta (Torne et al. to be sub.)
- New record!
- Change of spectrum?



Previous indications for spectral change

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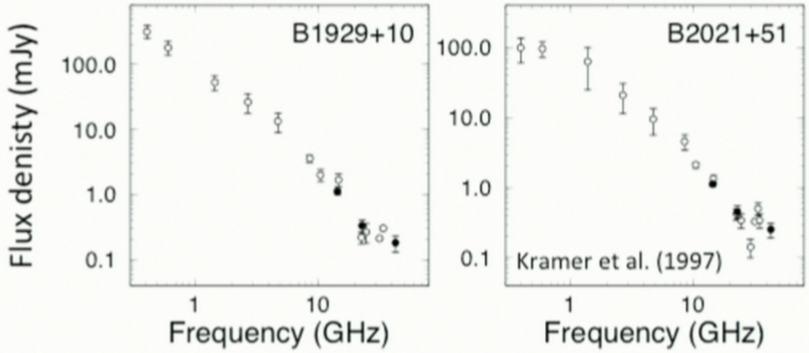
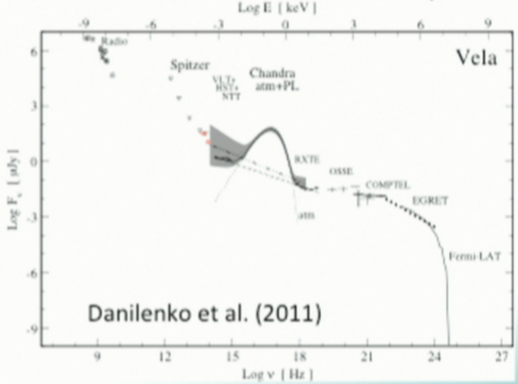
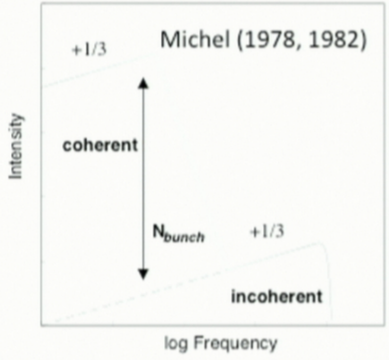

Kramer et al. (1997)

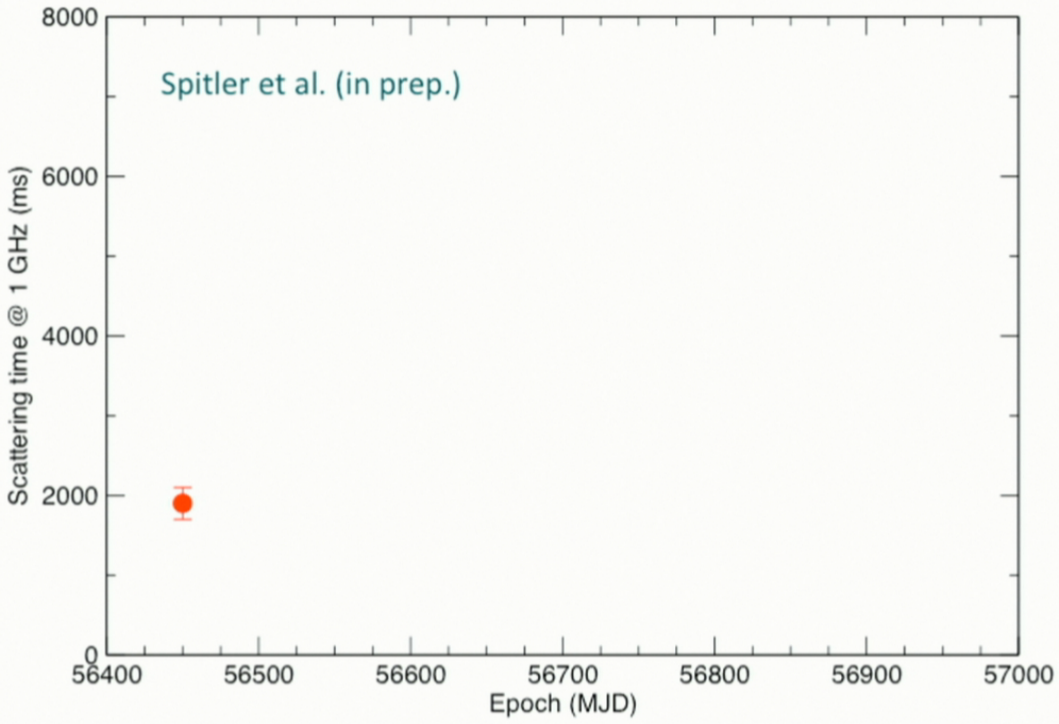
- This does not come totally unexpected, e.g. we know from the Crab that its infrared flux density is much higher than the high-frequency radio flux density
- Similar observations also for Vela– and possibly expexted:


Danilenko et al. (2011)


Michel (1978, 1982)

Where are the pulsars? – Scattering revisited

- Based on our measurements of the scattering for the magnetar (Spitler et al. 2013) lots of people have claimed that there are not any pulsars, since scattering so low
- However, medium is very turbulent and there is a lot of "weather" – new result:



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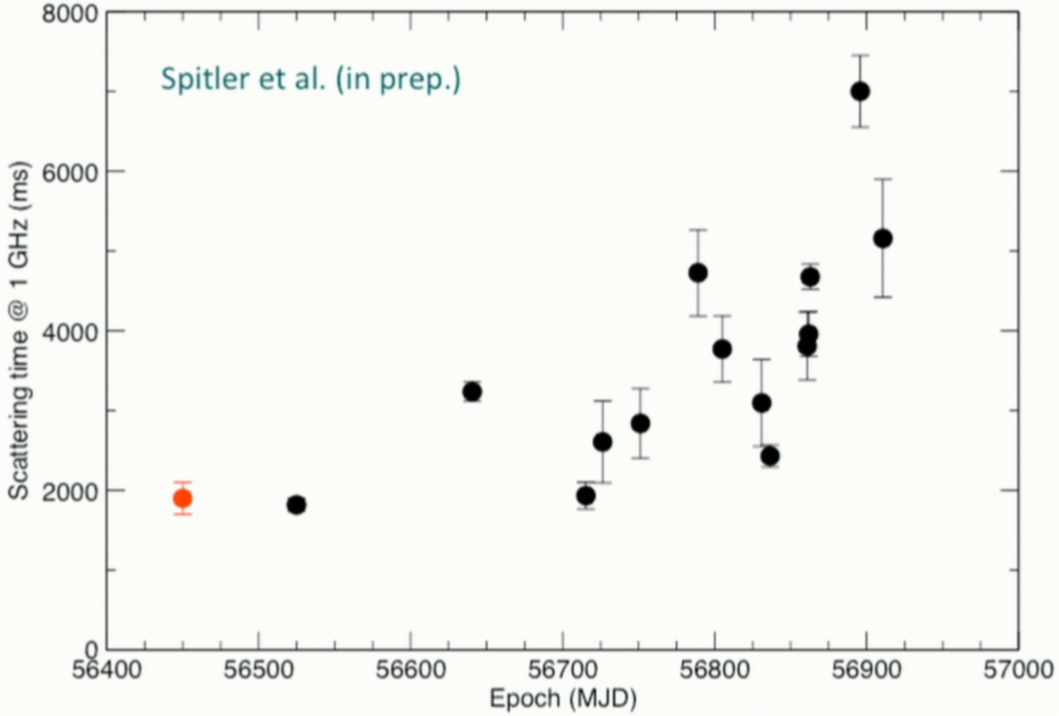
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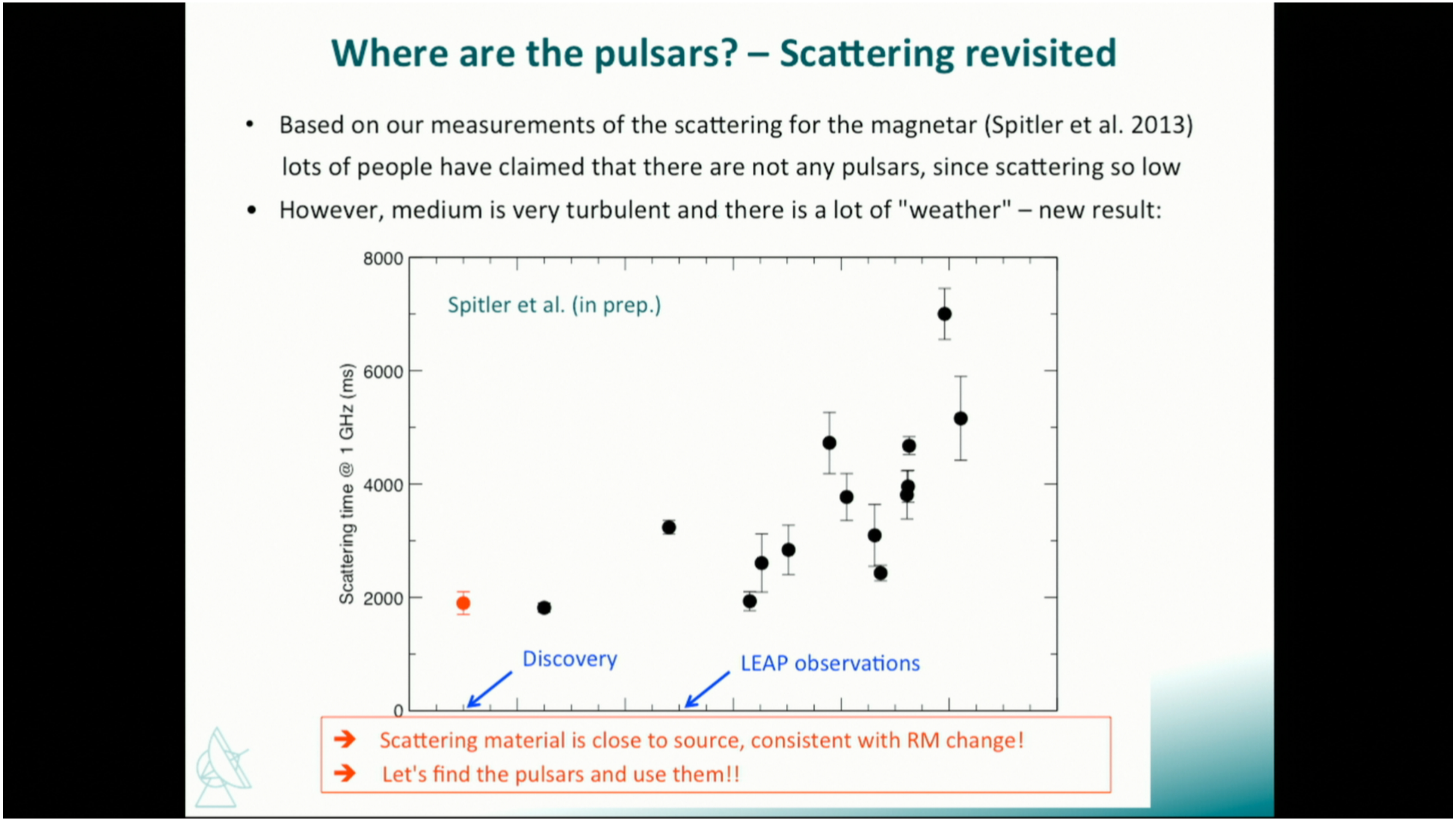

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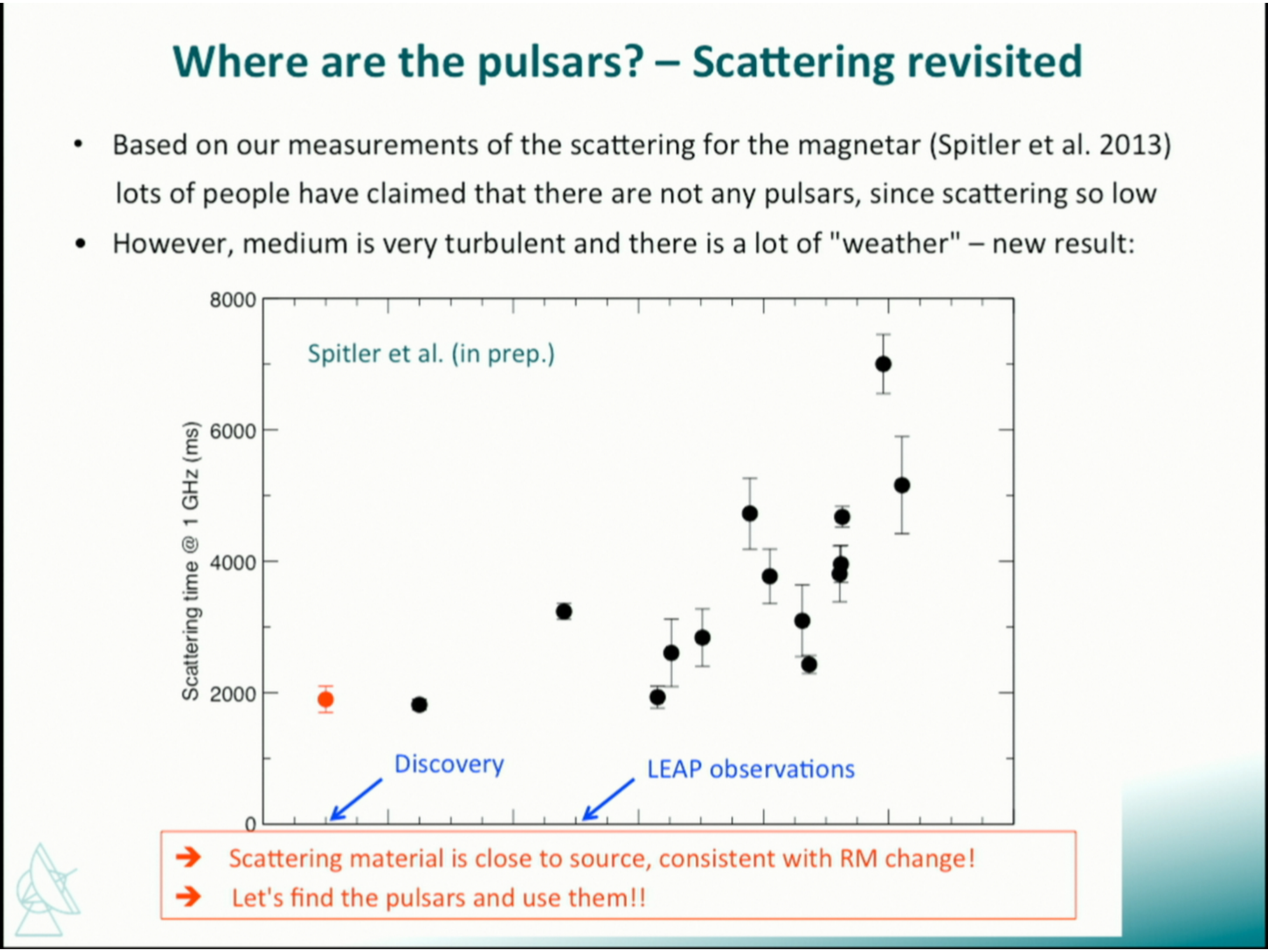
➔ Scattering material is close to source, consistent with RM change!

➔ Let's find the pulsars and use them!!



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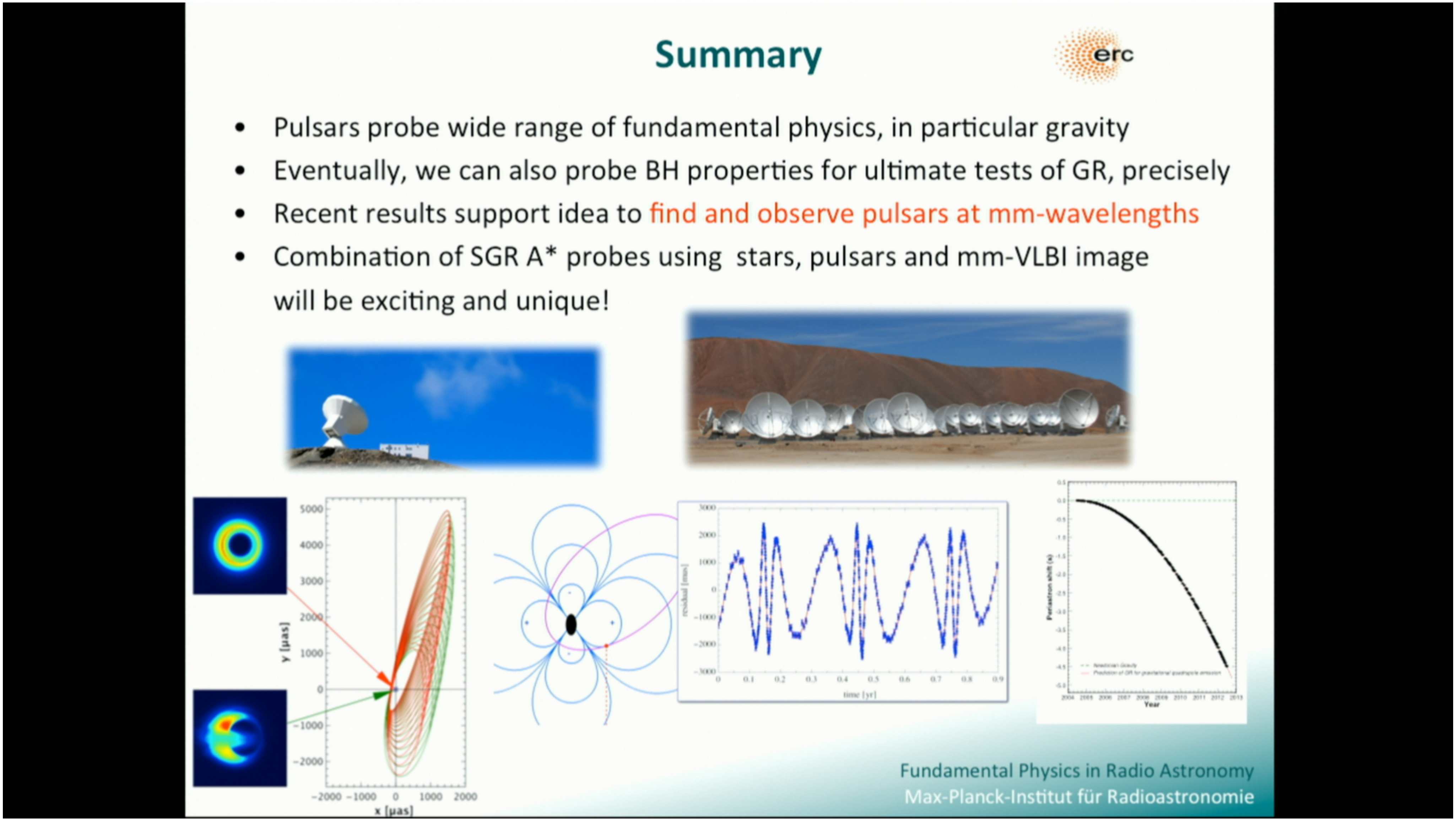

Summary

- Pulsars probe wide range of fundamental physics, in particular gravity
- Eventually, we can also probe BH properties for ultimate tests of GR, precisely
- Recent results support idea to find and observe pulsars at mm-wavelengths
- Combination of SGR A* probes using stars, pulsars and mm-VLBI image will be exciting and unique!