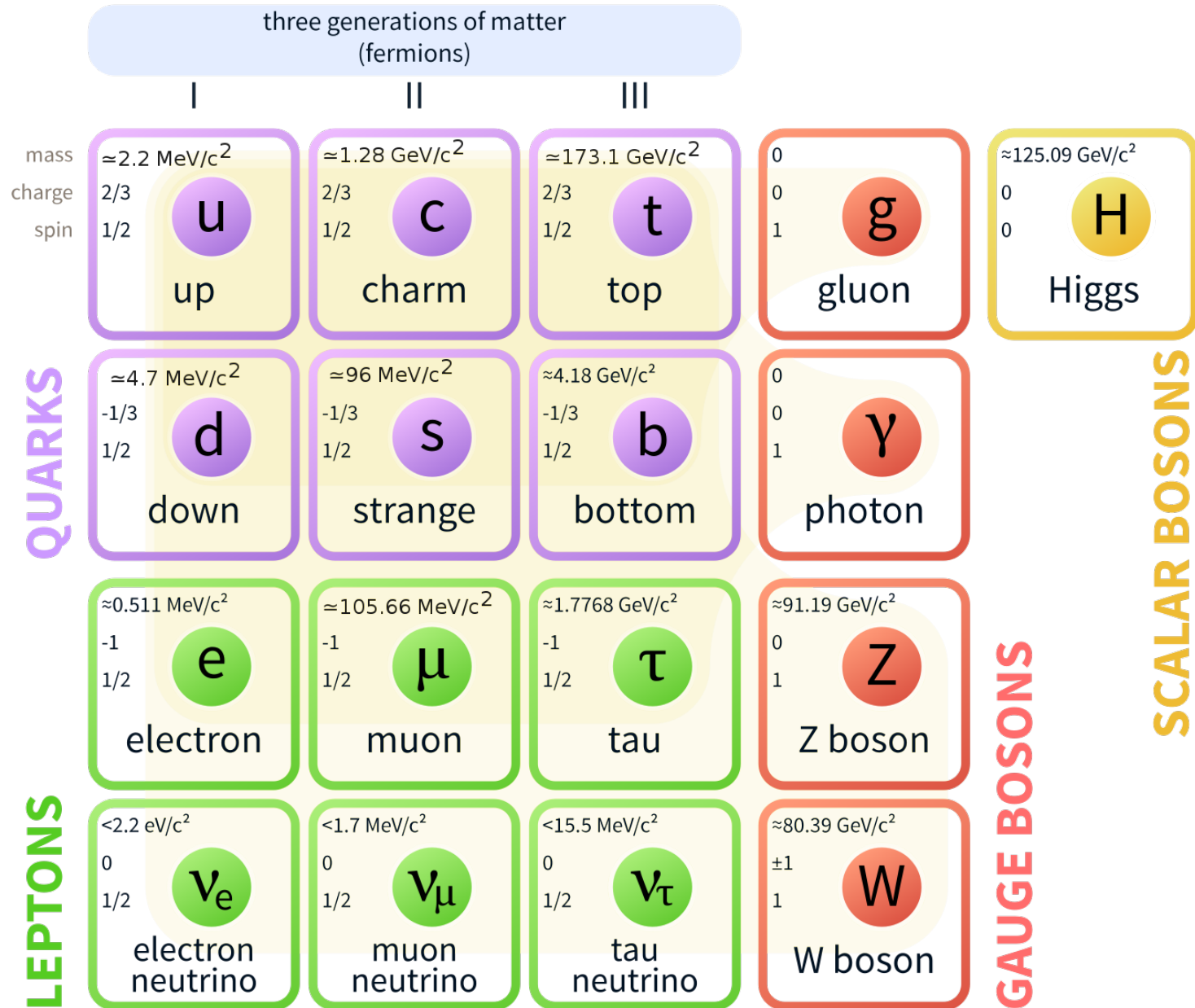


Testing General Relativity using the Square Kilometre Array

Willem van Straten

Institute for Radio Astronomy & Space Research
Auckland University of Technology

Standard Model of Elementary Particles



Self-consistent but incomplete

- Baryon asymmetry
- Gravitation
 - dark energy
 - dark matter
- Neutrinos
 - oscillations
 - non-zero mass

Quantum gravity?

"I consider it quite possible that physics cannot be based on the field concept, i.e., on continuous structures. In that case, nothing remains of my entire castle in the air, gravitation theory included, [and of] the rest of modern physics."

- Albert Einstein

Some things to test

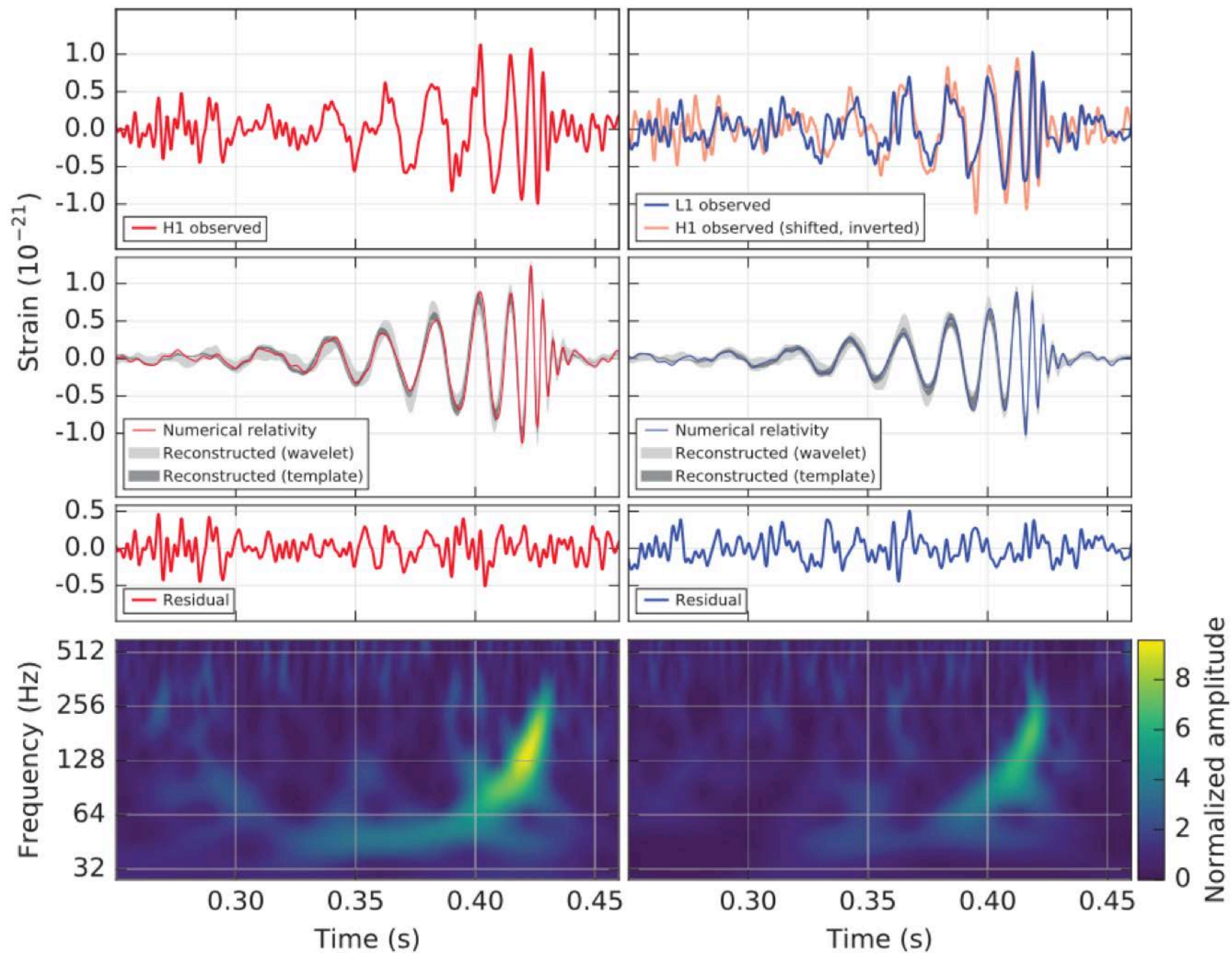
- “no hair” theorem
- “cosmic censorship” hypothesis
- strong equivalence principle
- gravitational waves

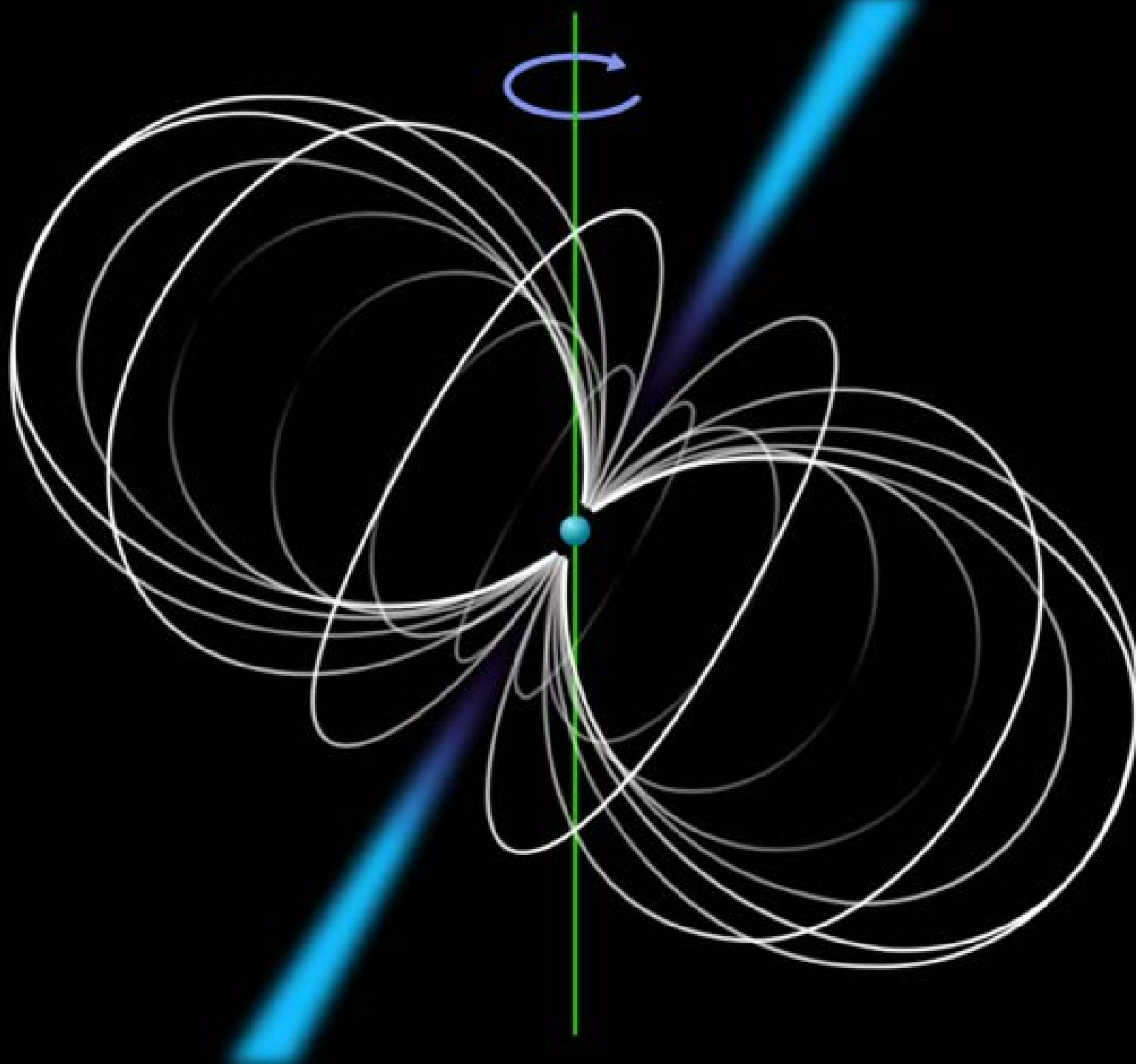
Some things to test

- “no hair” theorem
- “cosmic censorship” hypothesis
- strong equivalence principle
- ~~gravitational waves~~

Hanford, Washington (H1)

Livingston, Louisiana (L1)







"We did the work ourselves and cheerfully sledge-hammered all one summer." Burnell and antenna.

Builders Make Discoveries

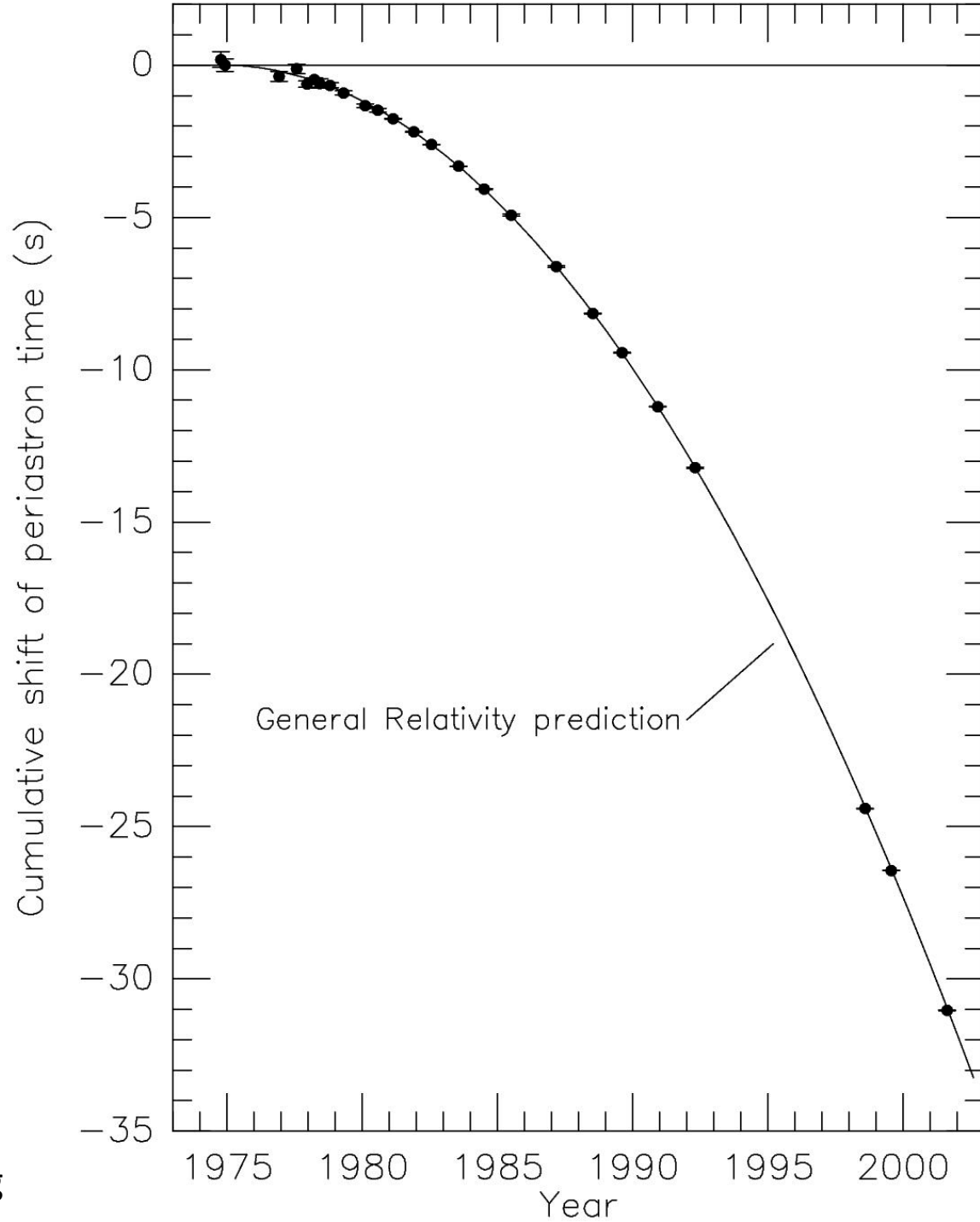
- Jocelyn Bell and Anthony Hewish
- Arno Penzias and Robert Wilson
- John Bolton and Gordon Stanley
- Ron Ekers
- John D. Kraus
- Grote Reber
- Karl Jansky
- ...

Pulsars are Intrinsically Interesting

- ultra-dense matter
 - 10 x nuclear density
- strongest magnetic fields known
 - greater than quantum critical field strength
- Relativistic surface velocity
 - $\sim 10\%$ speed of light

Pulsars: Fundamental Physics

- Precision tests of General Relativity
- Search for nHz gravitational waves
- Relativistic plasma physics
- Equation of state of ultradense matter
- Superfluid neutron star interior



Credit: J. Weisberg

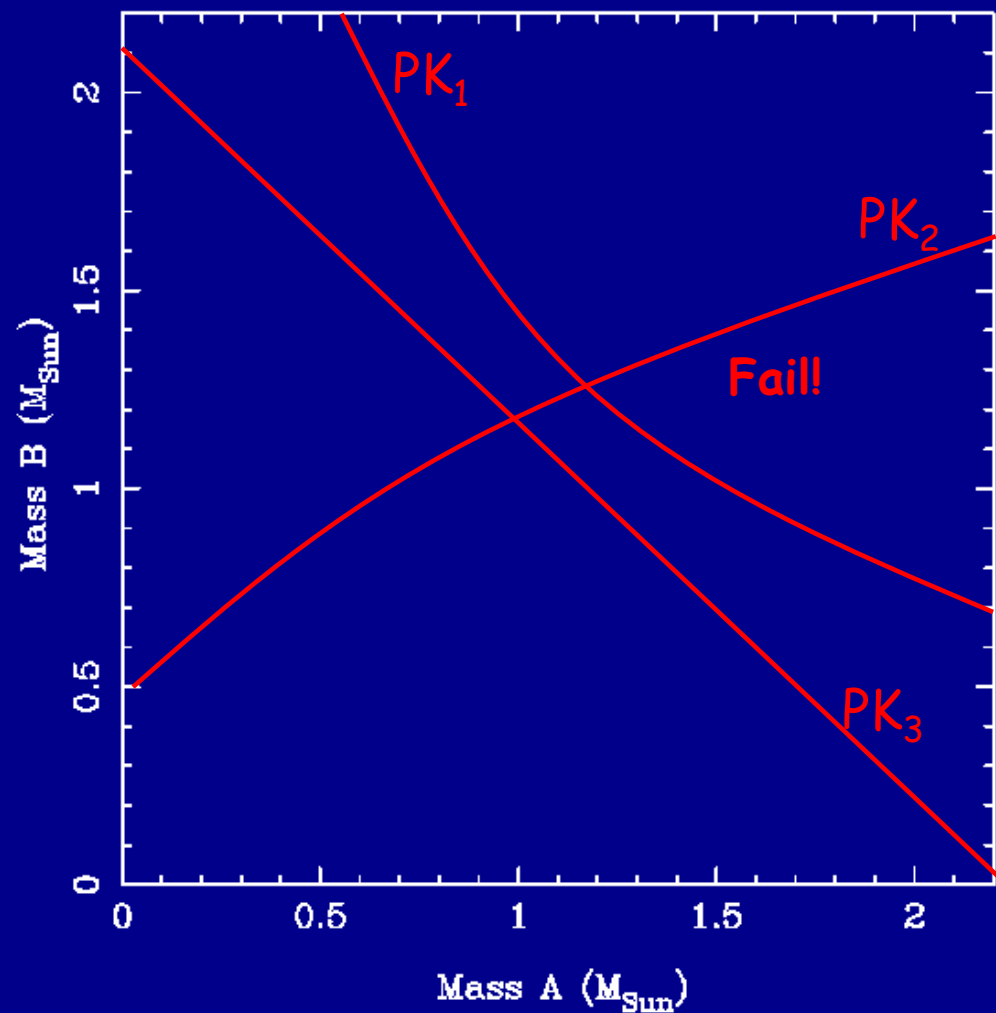
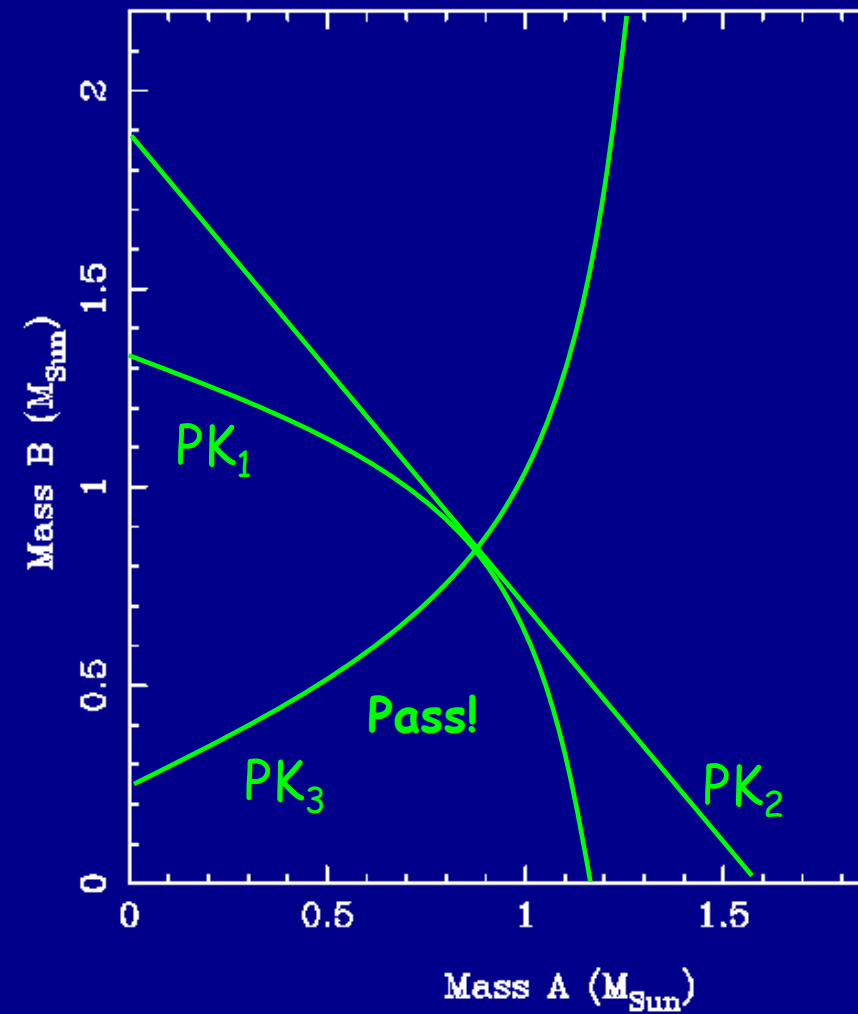
Post-Keplerian Parameterization

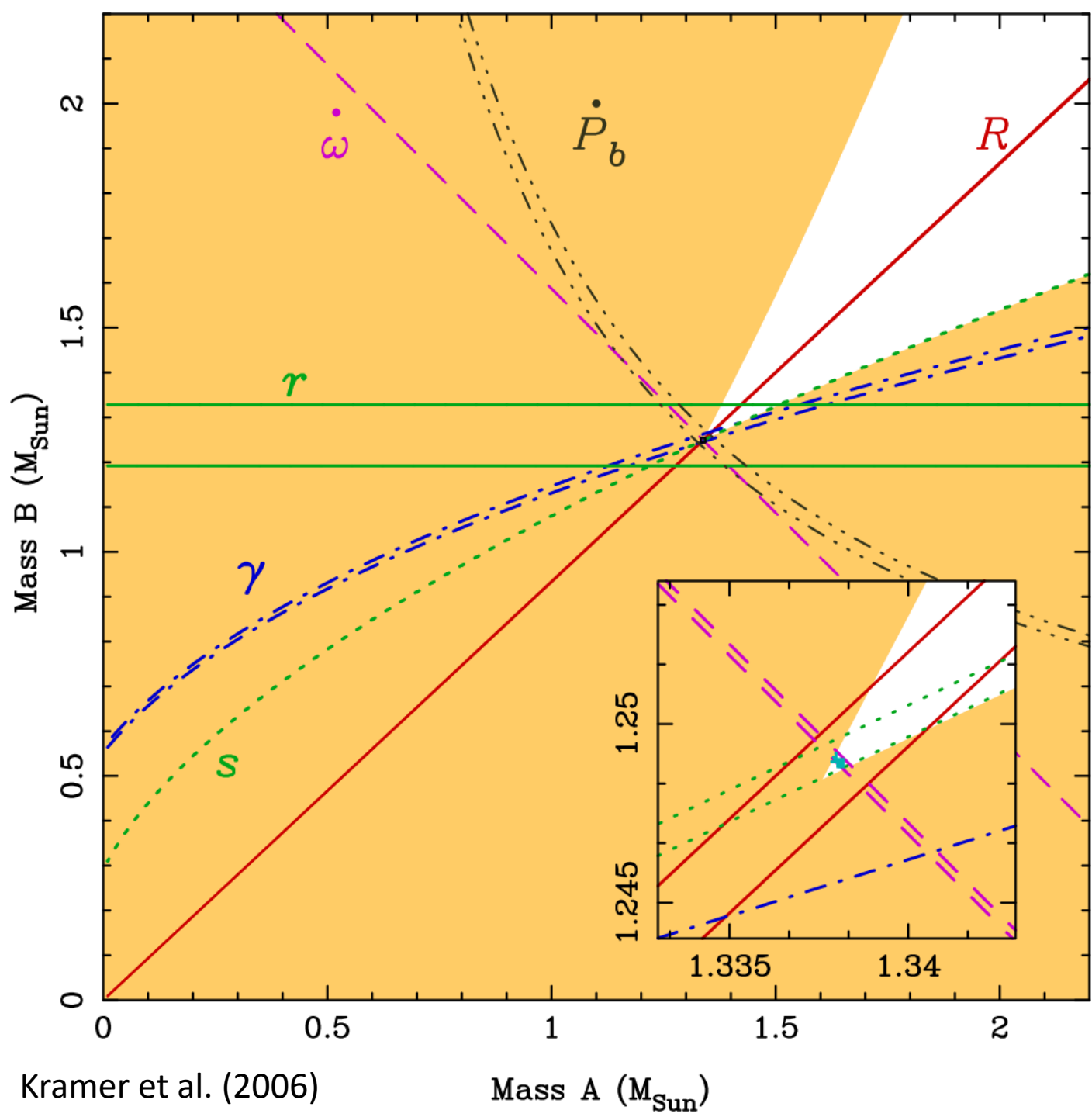
Keplerian:

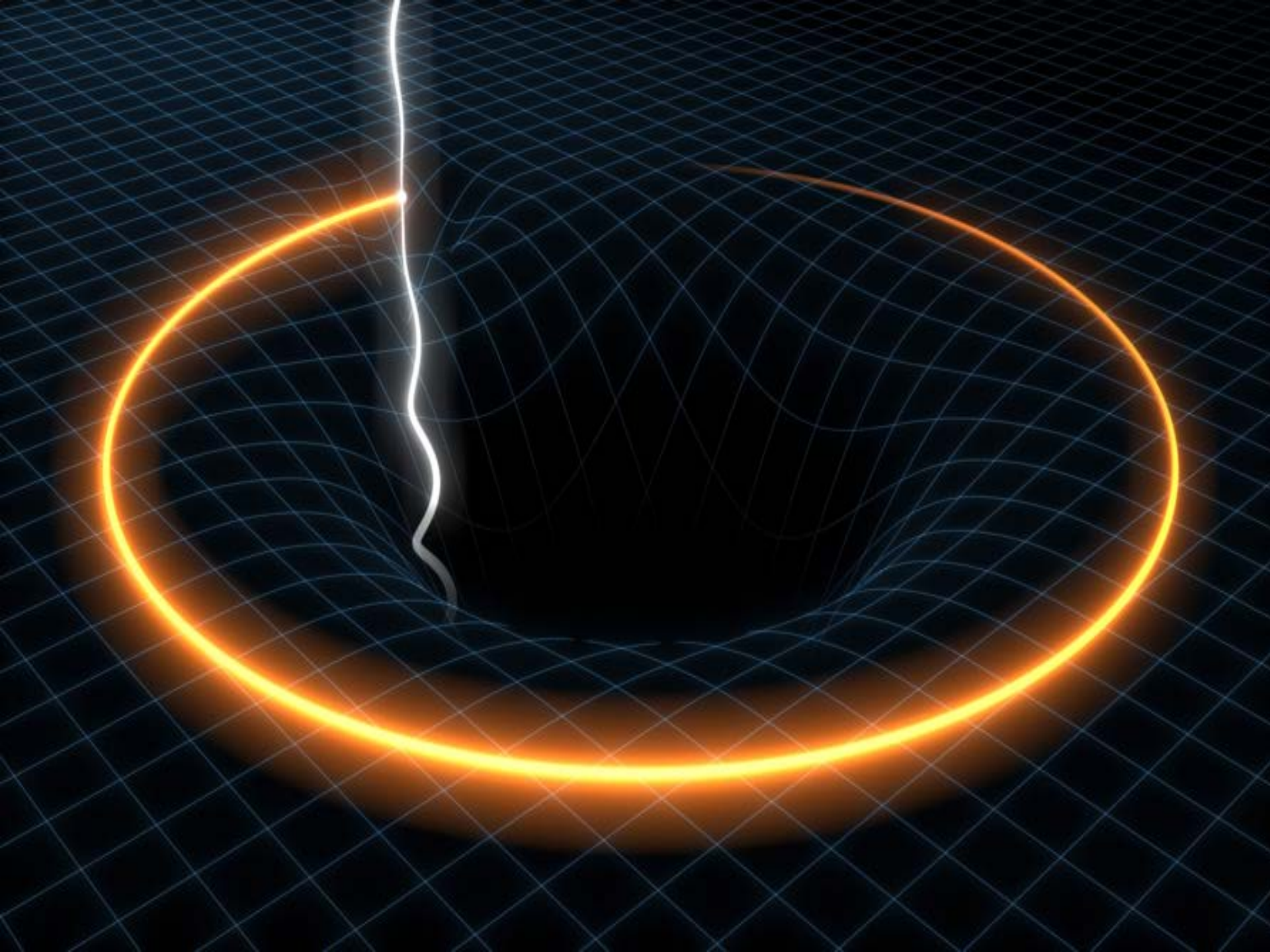
- P_b - orbital period
- T_0 - time of periastron
- ω - longitude of periastron
- e - eccentricity
- x - semi-major axis

Post-Keplerian:

- dP_b/dt - orbital decay
- $d\omega/dt$ - periastron advance
- γ - gravitational redshift
- r - range of Shapiro delay
- s - shape of Shapiro delay
- δ_θ - distortion of orbit
- de/dt
- dx/dt







Pulsar – Black Hole Binary

- Cosmic Censorship Conjecture:
 - “no naked singularities” (GR limits BH spin)
 - spin-orbit coupling
- No-Hair Theorem:
 - GR: predicts BH quadrupole moment
 - anisotropy of BH gravitational field

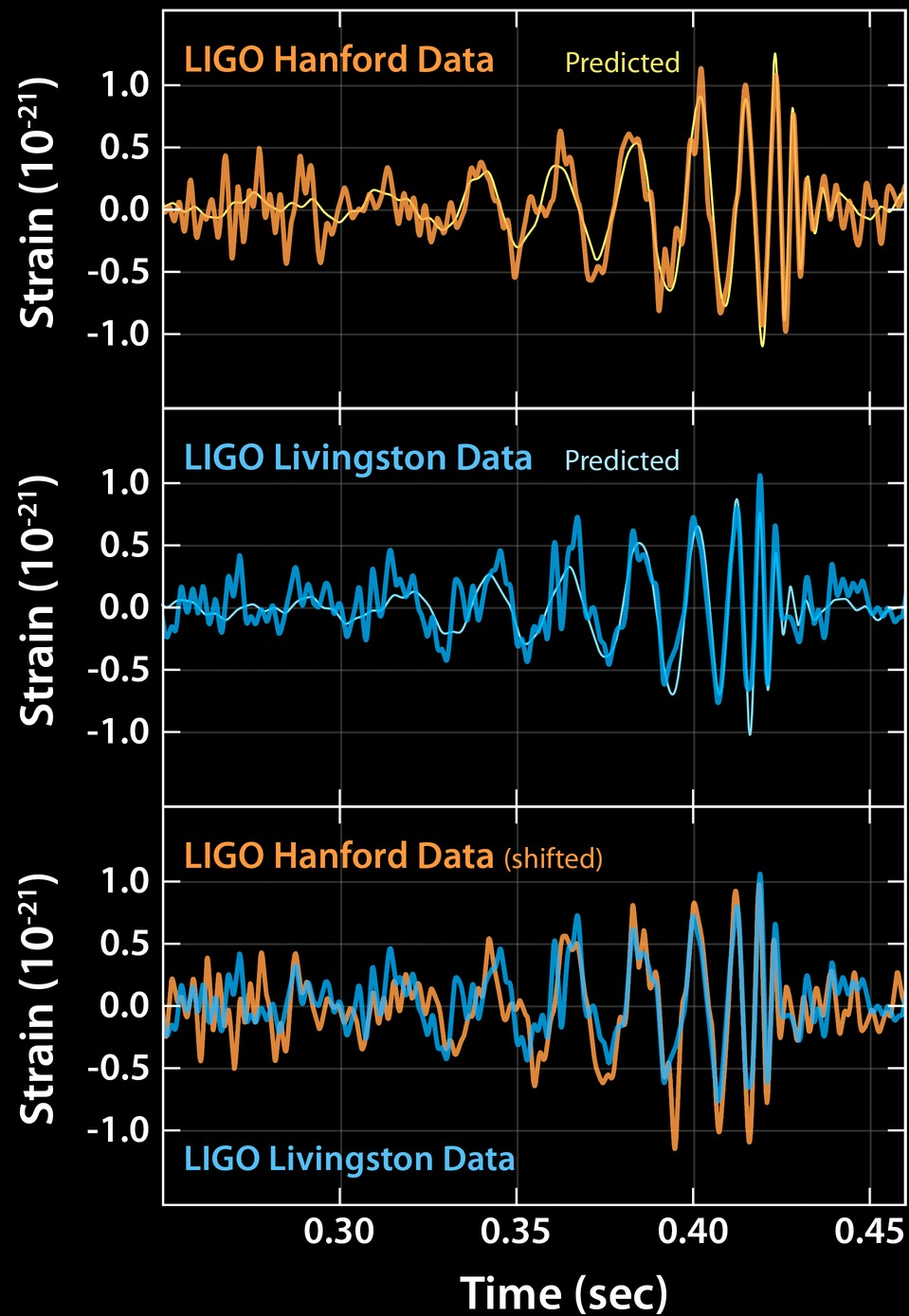
Where are They?

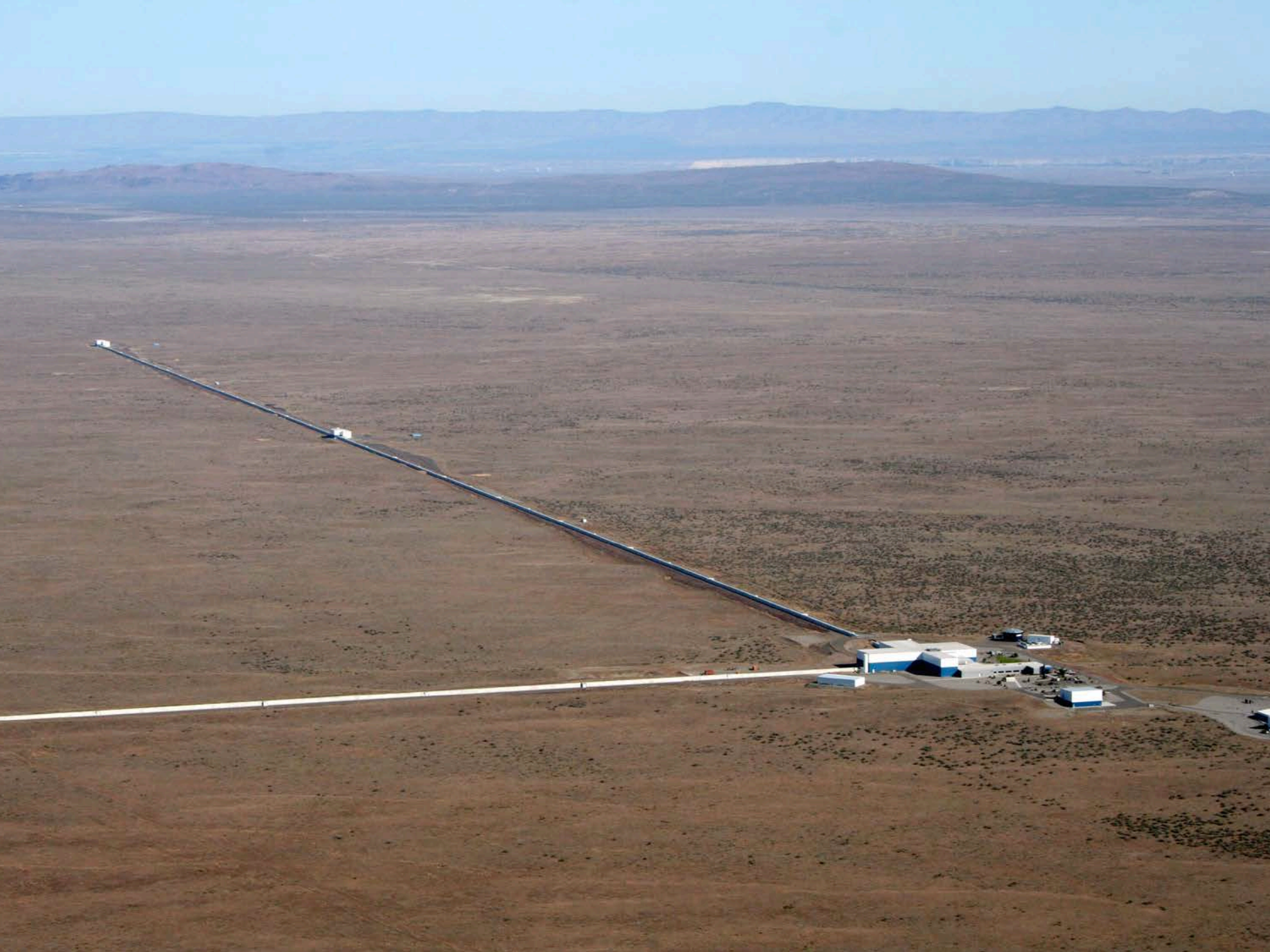
After 50 years of pulsar surveys,
no PSR-BH binary discovered



Square Kilometre Array – Data rate

Attribute	1995 (PMBS)	2008 (HTRU)	202X (SKA Phase I)
Time Resolution	250 us	64 us	50 us
Spectral Resolution	3 MHz	390 kHz	20 kHz
Smearing (DM=100)	1.2 ms!	165 us	8 us
Bits per sample	1 bit	2 bit	8 bit
Filter bank	2496 hand-tuned filters	1024 channels	15,000 channels
Number of Beams	13	13	1,500
Data Rate	2.2 MB/hr	190 GB/hr	600 TB/hr
	54 GB/day	4.5 TB/day	14.4 PB/day

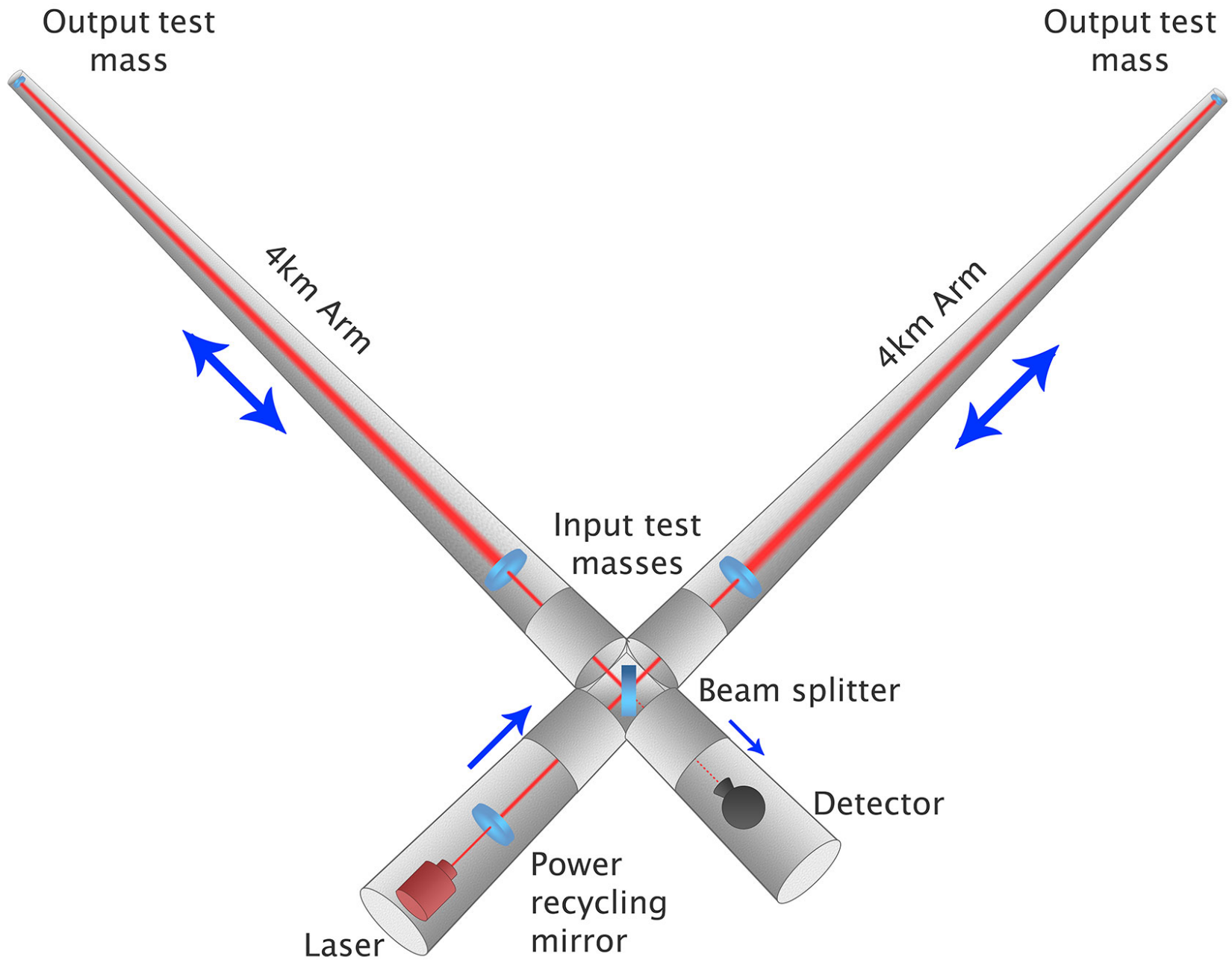




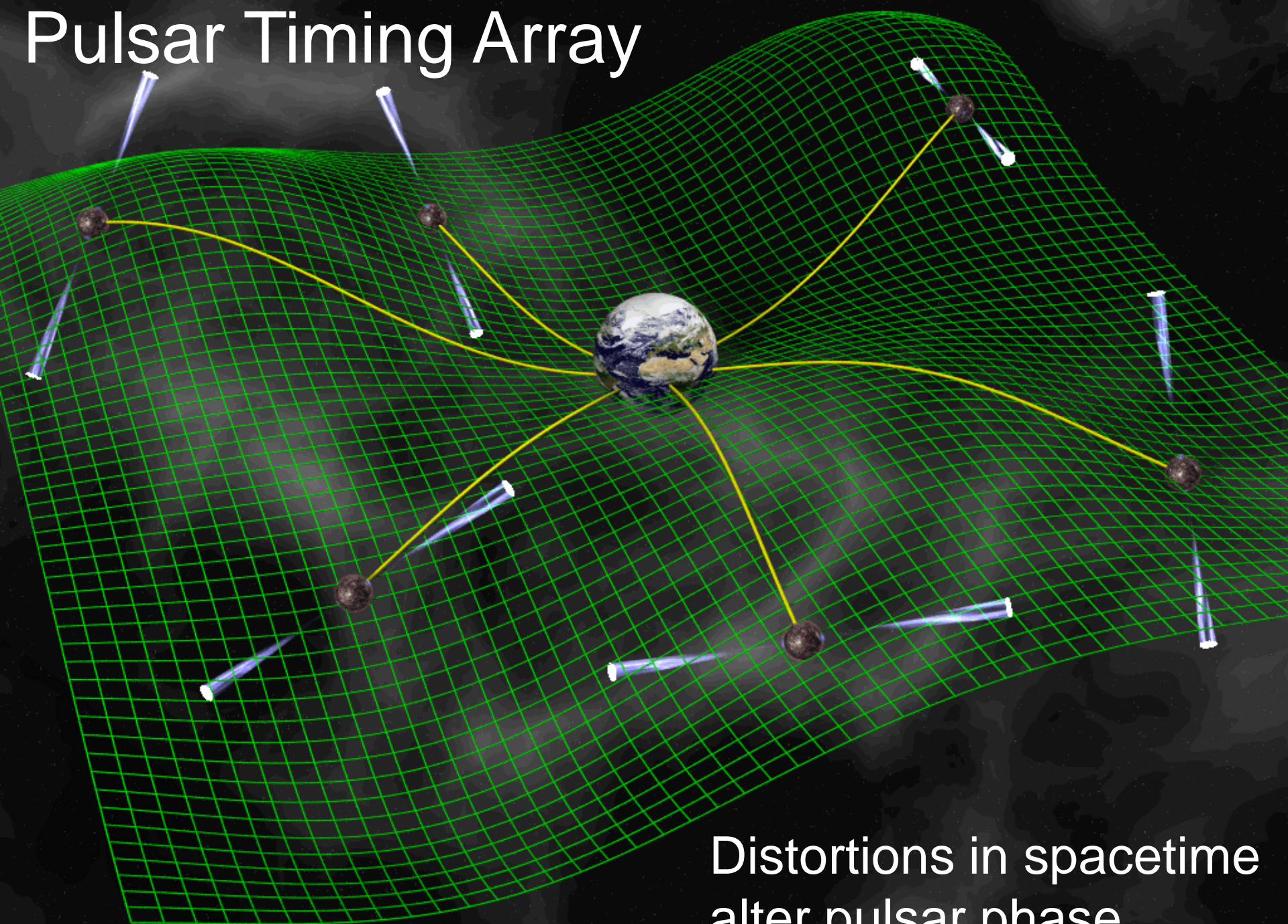


minuscule seismic tremors
the wind in Hanford
the water near Livingston
fluctuations in the power grid
distant lightning storms
passing cars
airplanes
wolves
...

"There are ten thousand other
tiny things, and I really mean
ten thousand. And every
single one needs to be
working correctly so that
nothing interferes with the
signal." - Rainer Weiss



Pulsar Timing Array



Distortions in spacetime
alter pulsar phase

Gravitational Wave Detection is Challenging

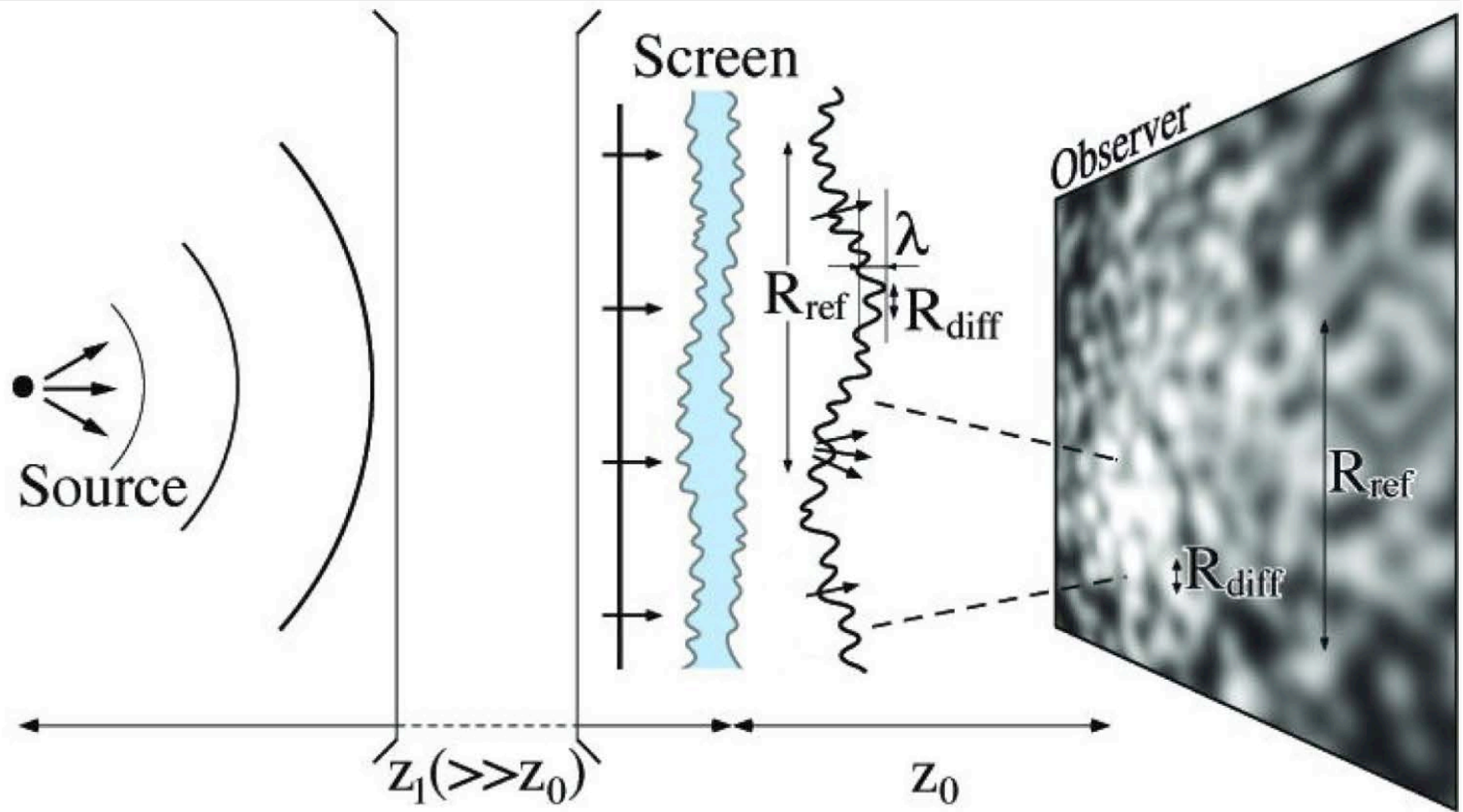
- Pulsar intrinsic
 - Stochastic impulsive emission (white noise)
 - Spin irregularity (red noise)
- Interstellar medium
 - Variations in electron density along line of sight (red)
 - Multipath propagation (scattering)
- Within solar system
 - Errors in the solar system ephemeris (dipolar)
 - Errors in the definition of time on Earth (monopolar)

Gravitational Wave Detection is Challenging

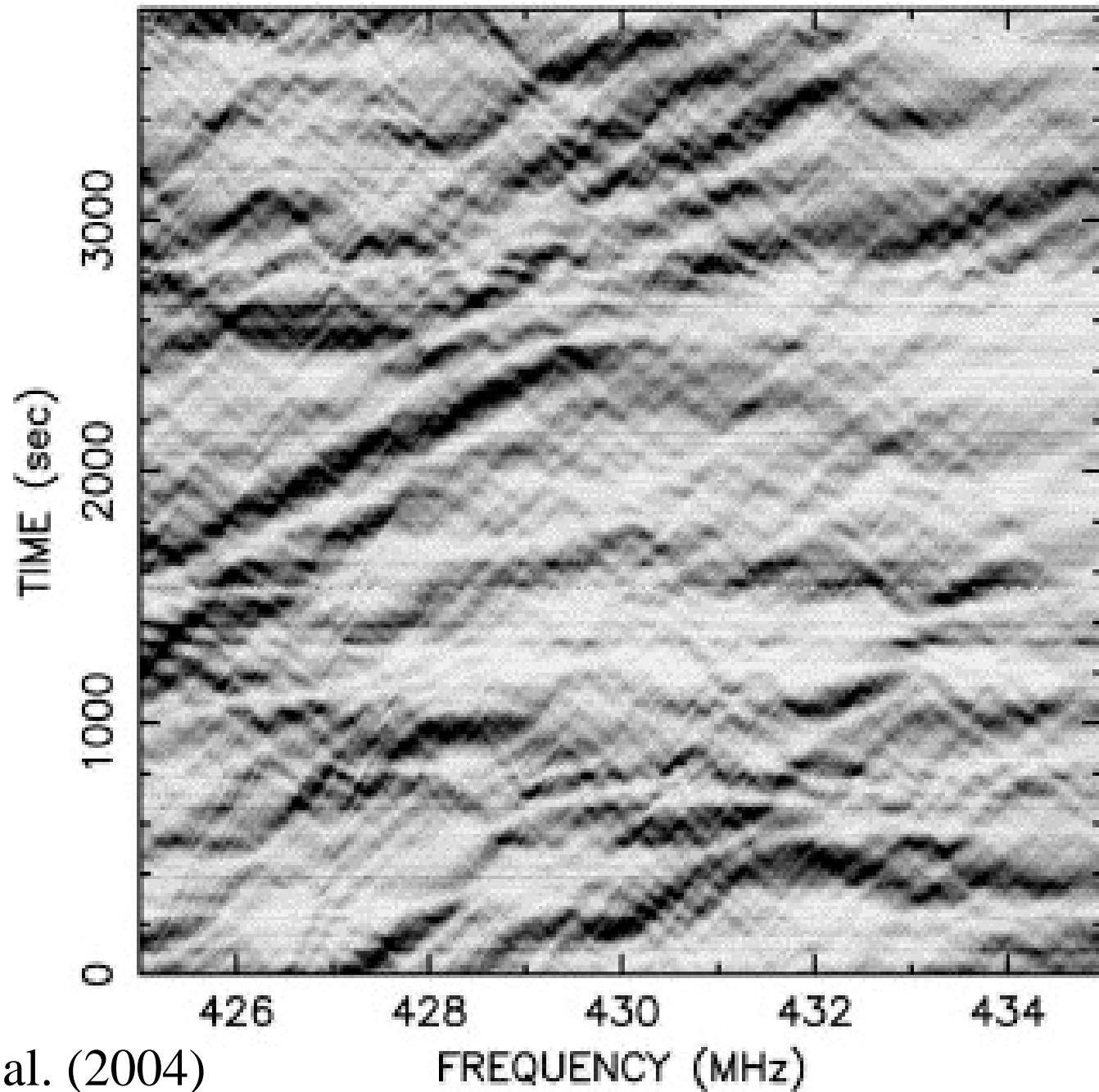
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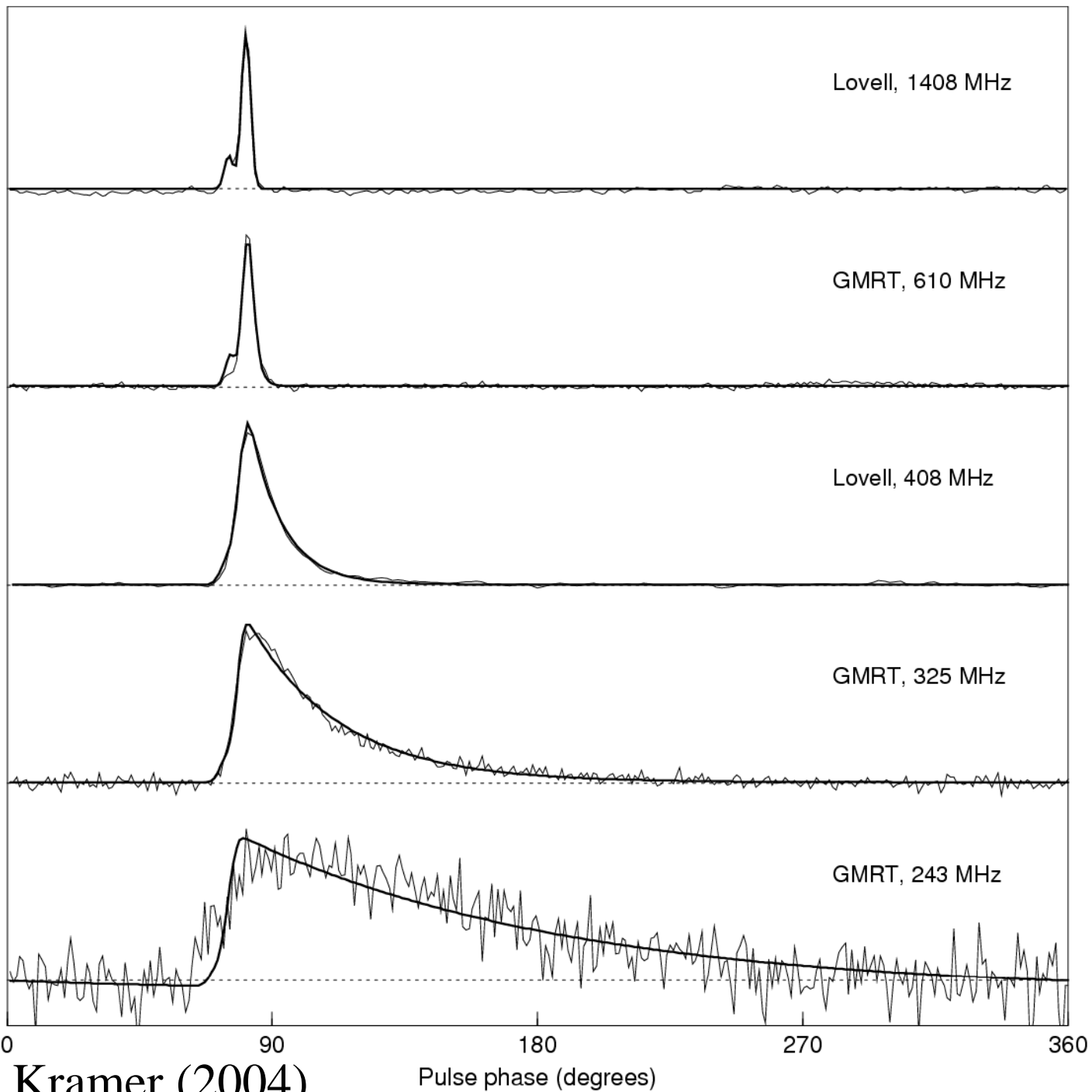
NASA, ESA and J. Hester (ASU)

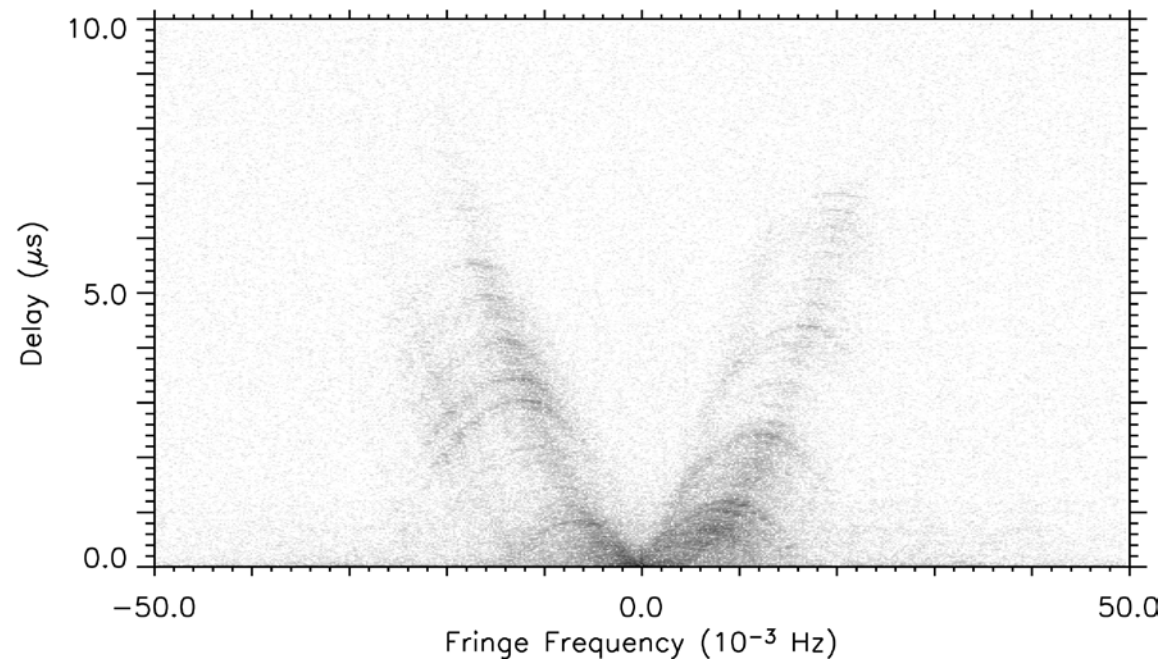
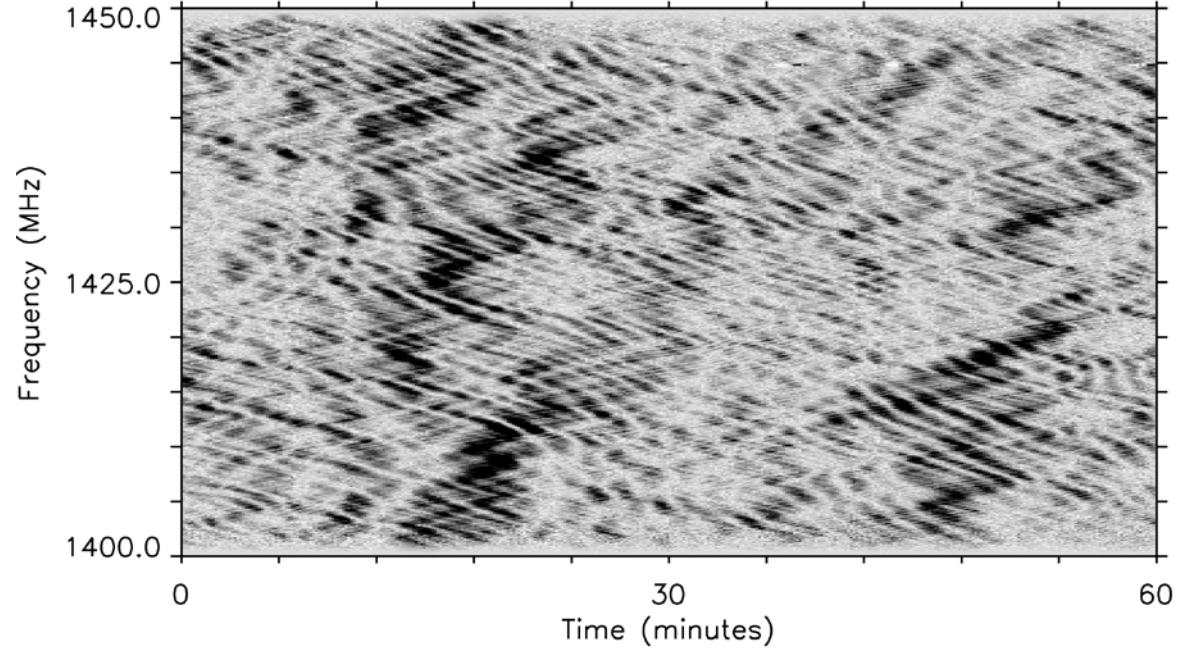


PSR 1133+16 0.430 GHz MJD 45988 2894018

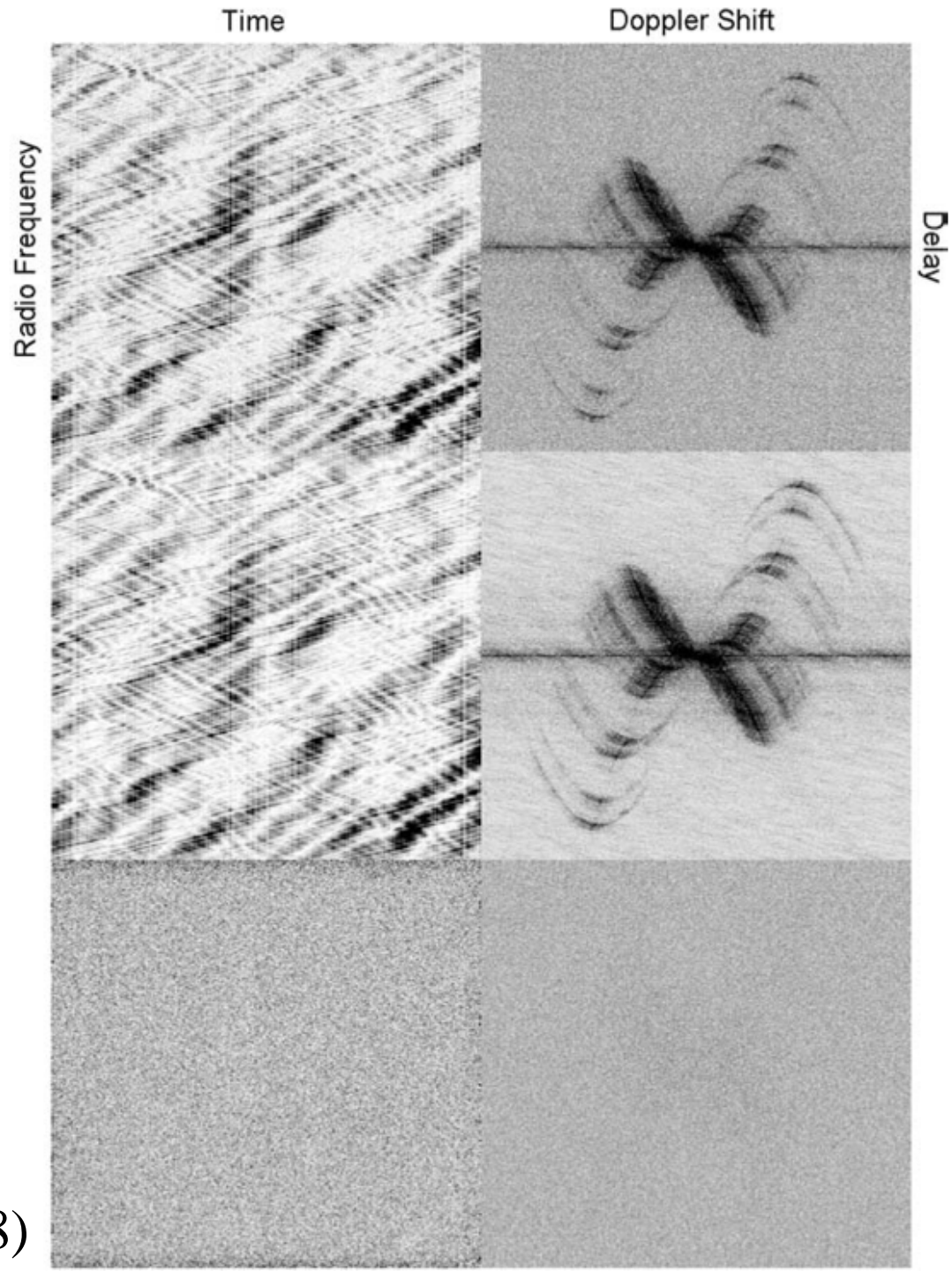


Lazio et al. (2004)

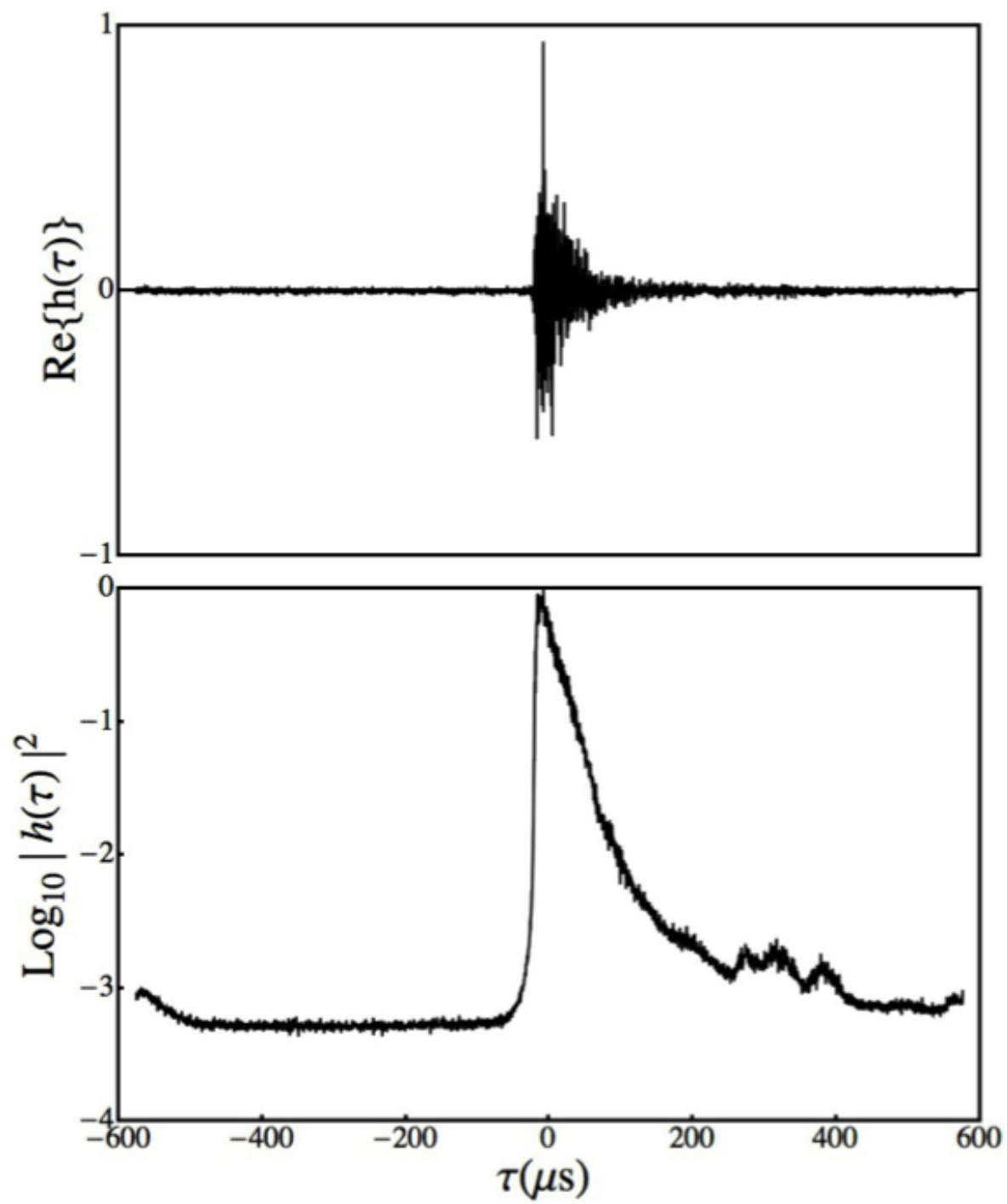


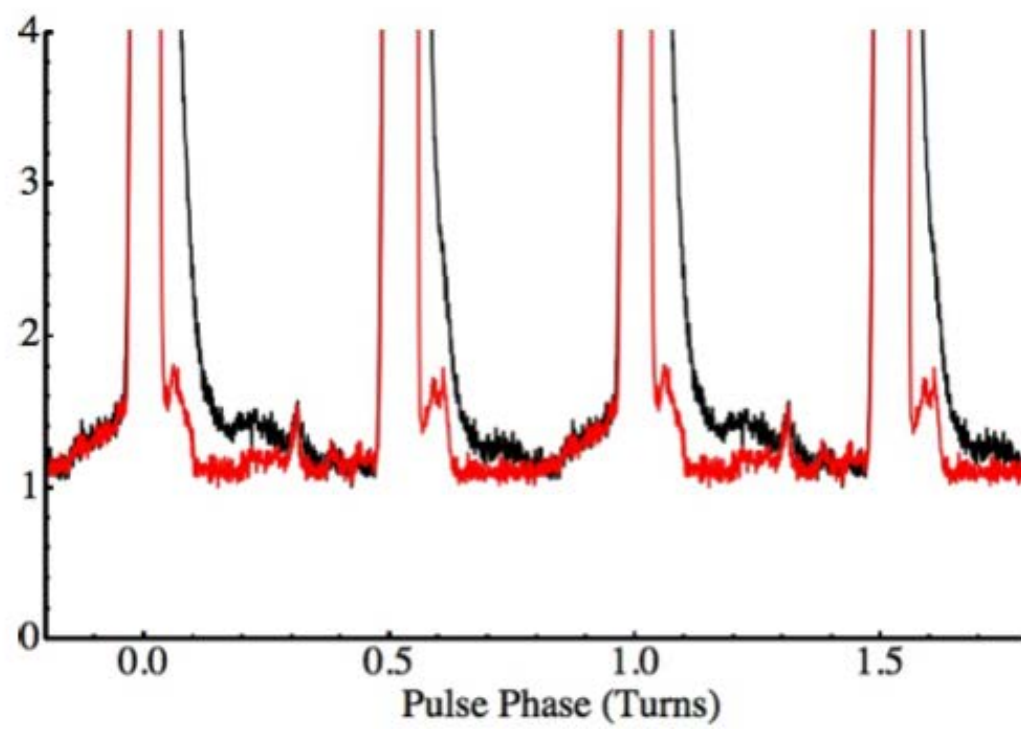
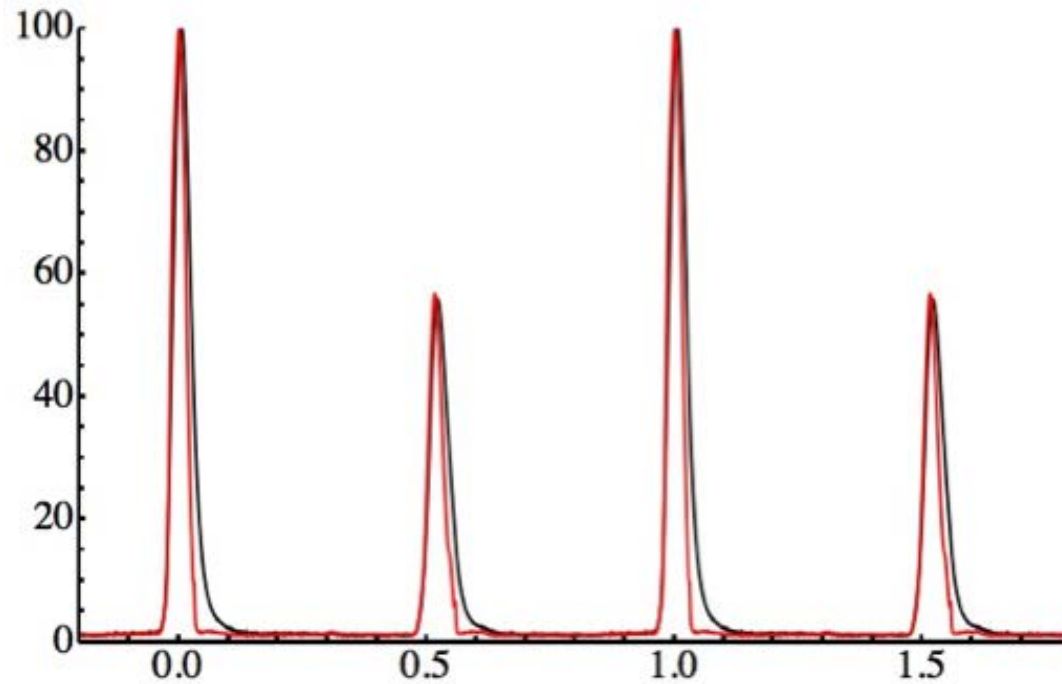


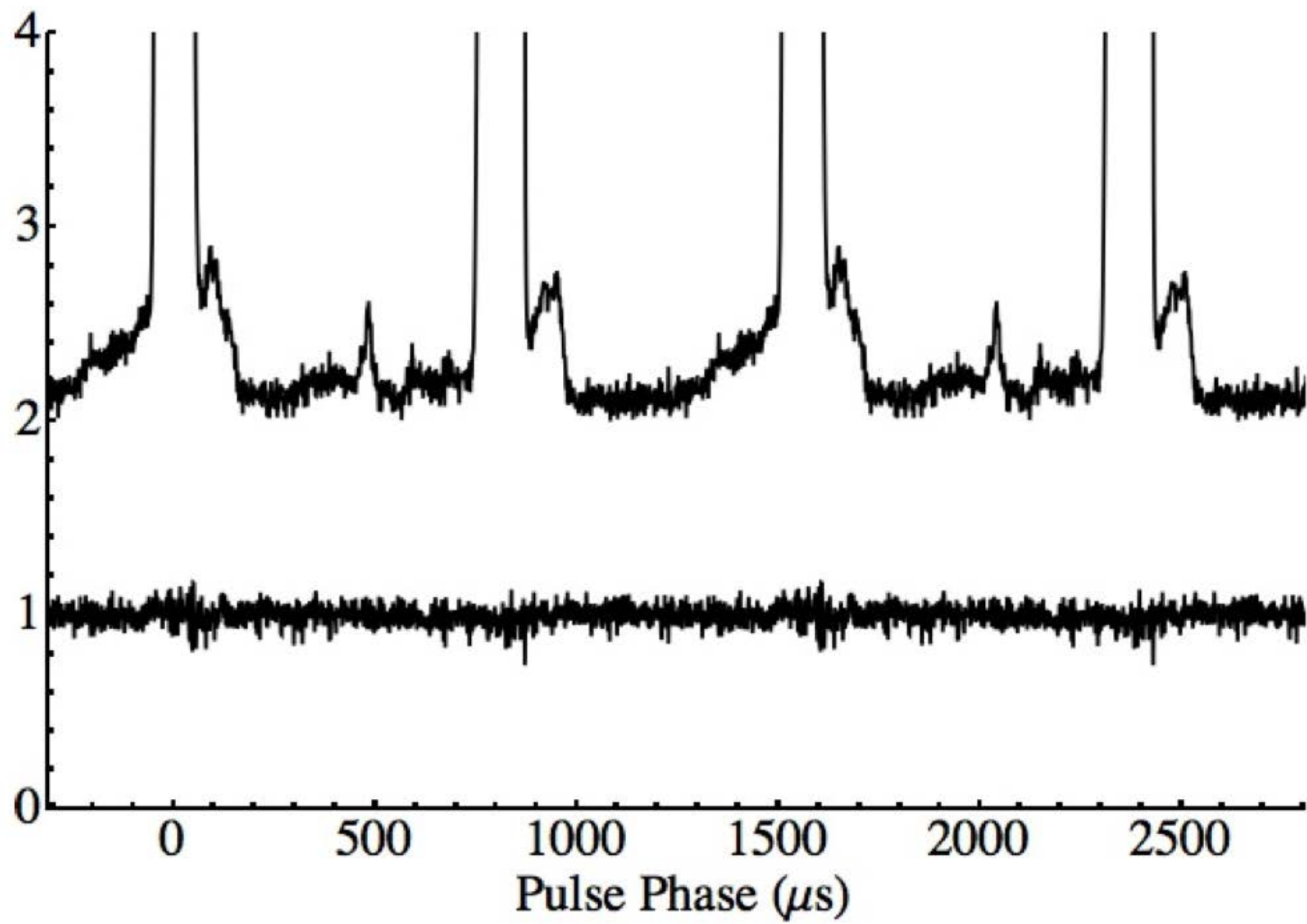
Credit: Dan Stinebring

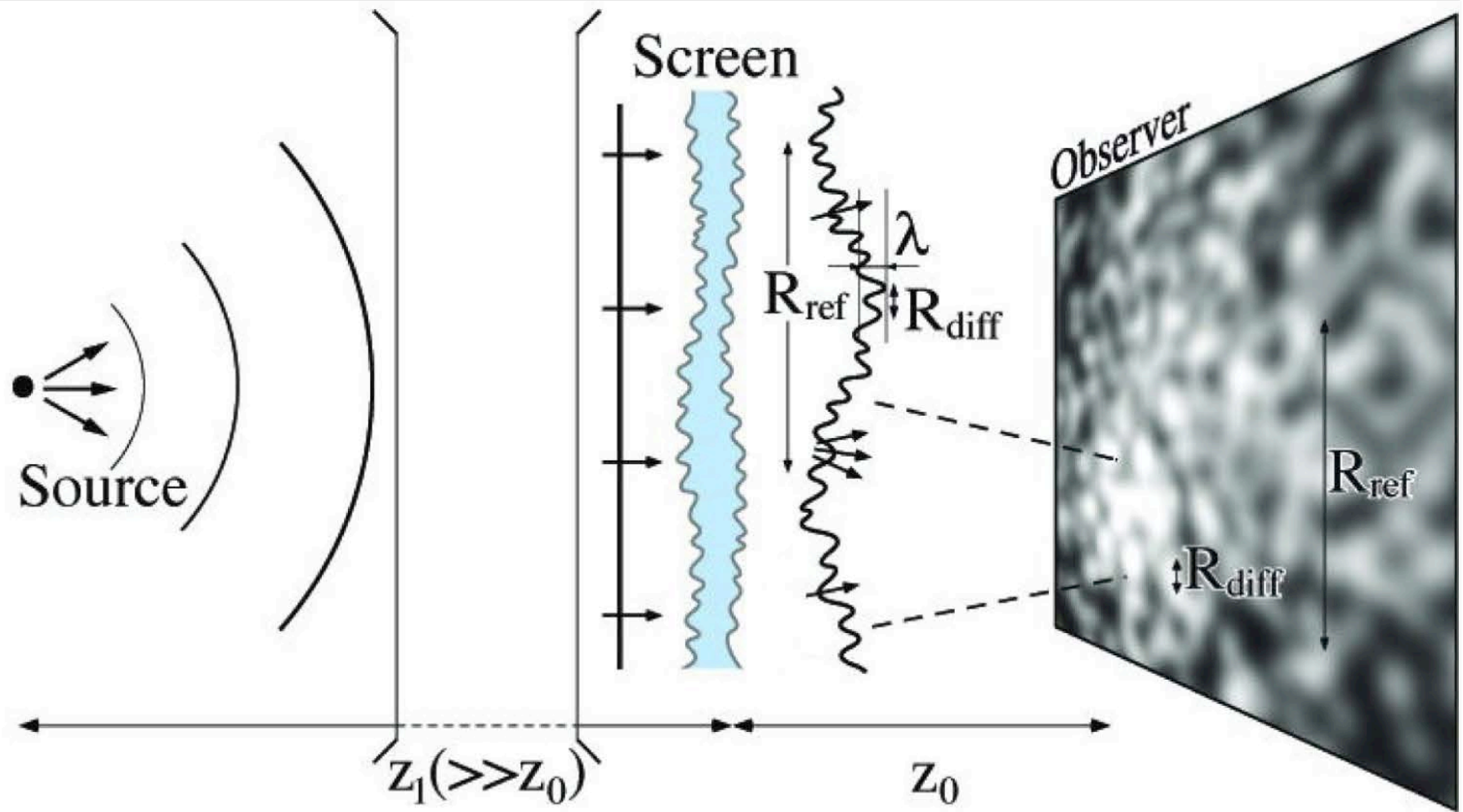


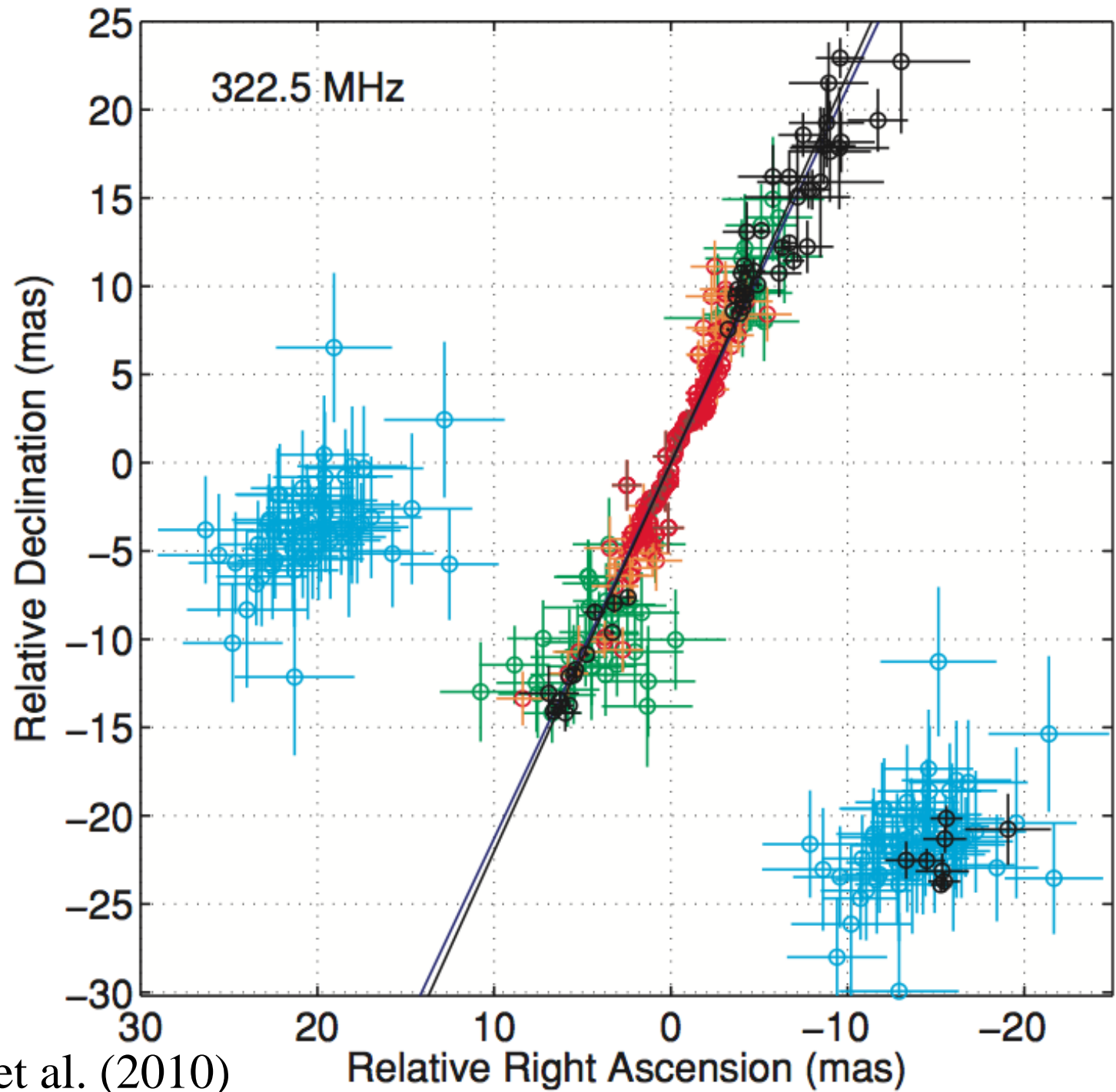
Walker et al (2008)

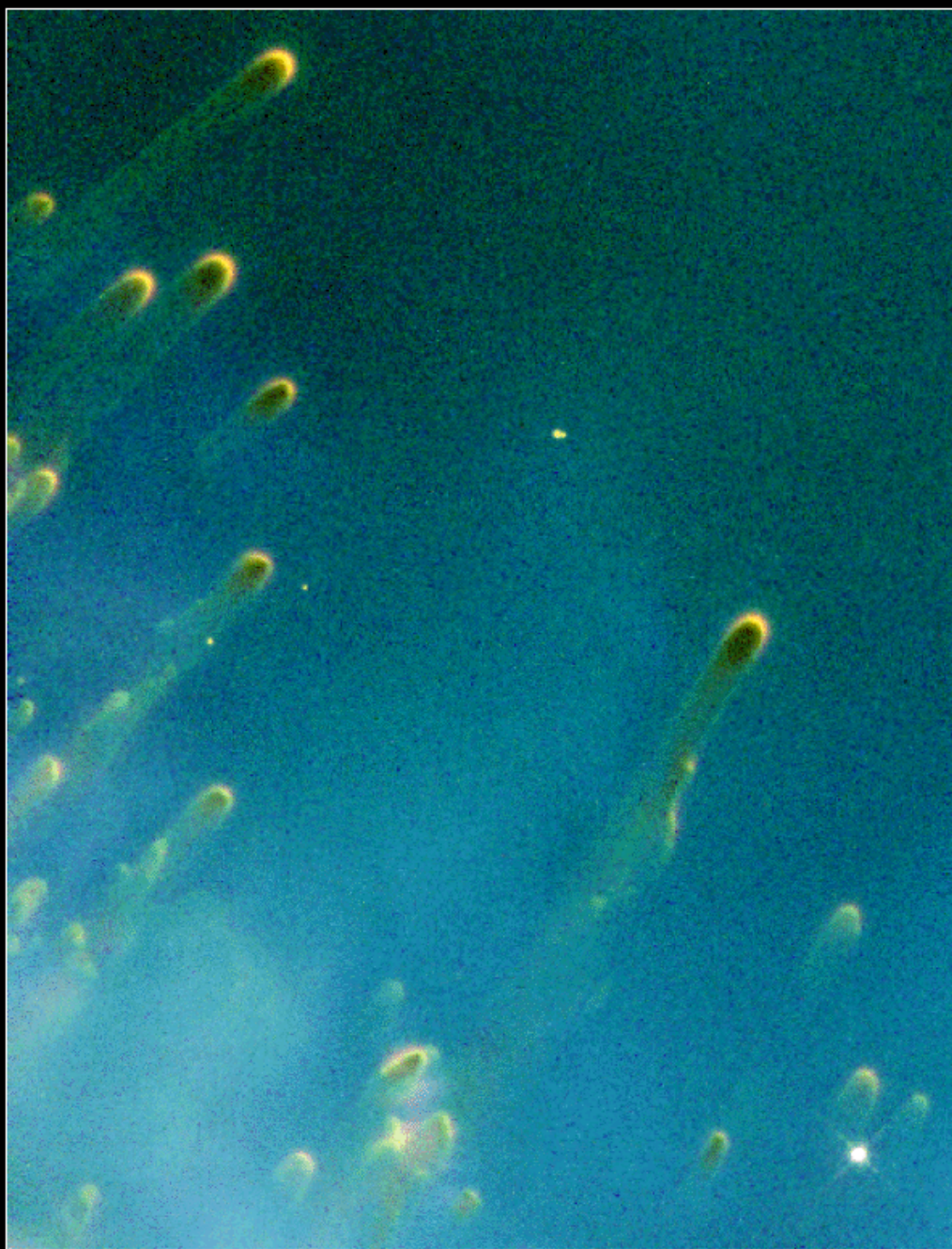








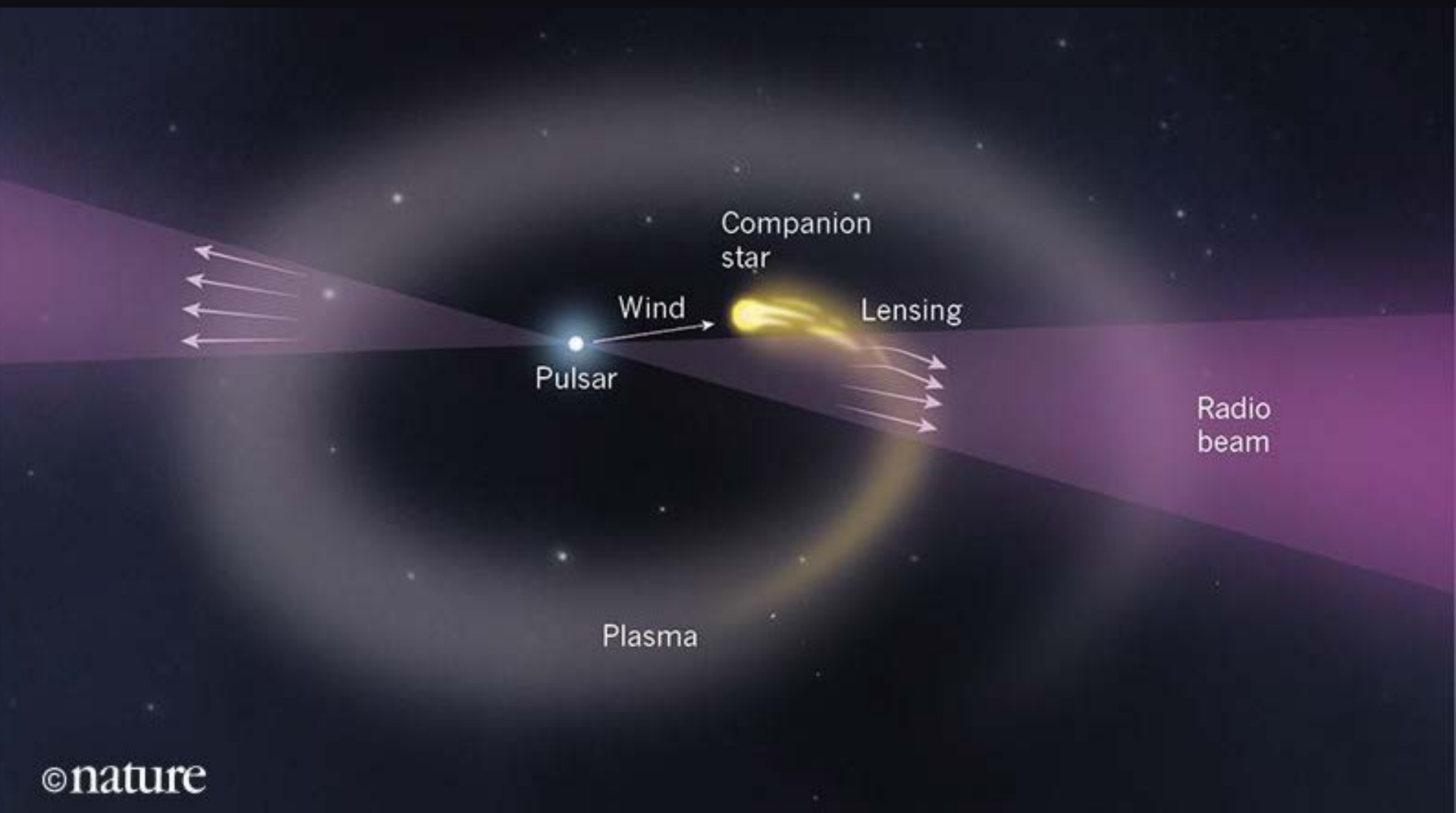




Helix Nebula Detail

HST • WFPC2

PRC96-13b • ST ScI OPO • April 15, 1996 • C.R. O'Dell (Rice Univ.), NASA



Main et al. (2018)

Magnification implies source
sizes of the order 5 – 15 km

Pulsar magnetosphere (light
cylinder radius) ~ 76 km

Conclusions

- ~ 100 -fold increase in probability of detecting a pulsar - black hole (10 years of SKA1)
- More pulsars = greater sensitivity to low-frequency Gravitational Wave Background
- New images of invisible ionized interstellar medium