Pulsars with the SKA and its pathfinders

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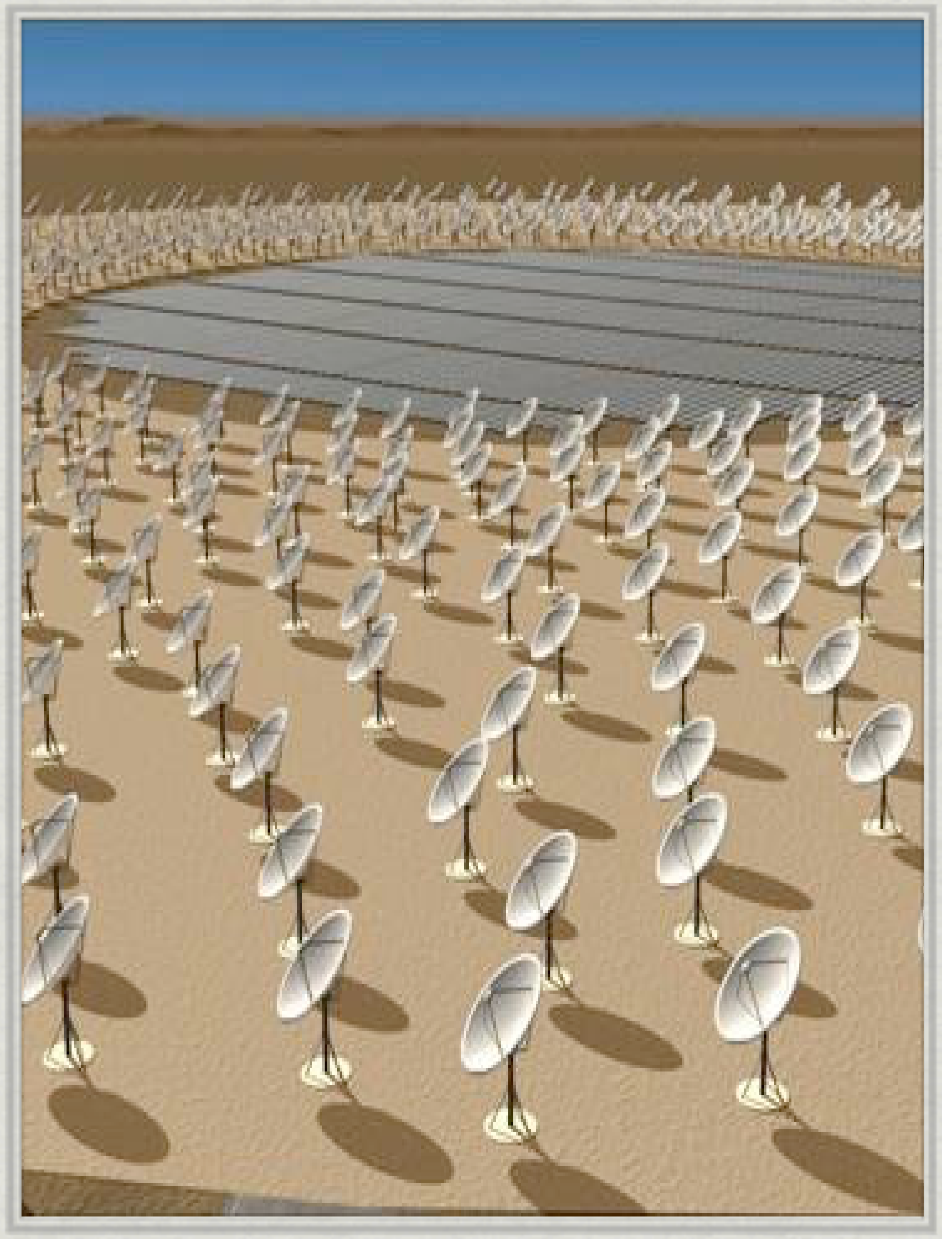
with help from M. Kramer, R. Smits, J. van Leeuwen, J. Cordes, J. Hessels

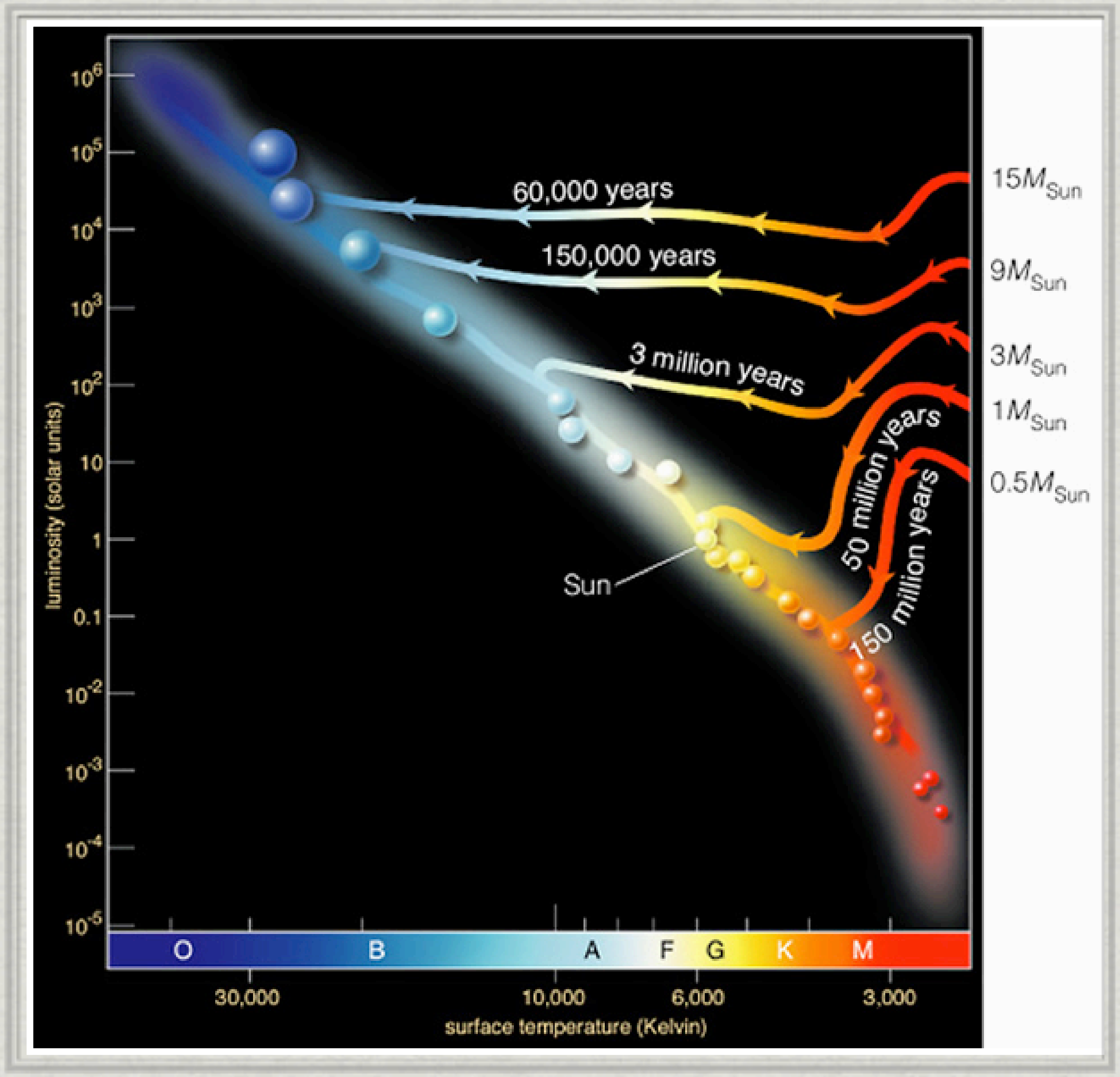
Outline

- Pulsars A Primer
- SKA Key science
  - Black Holes
  - Gravitational Waves
- Some Challenges
- Pathfinders
  - Description & Science



Pulsars

- Remnant of SNe
- Rotating Neutron Stars
- $M = 1.4M_{\odot}$, $R=10km$
- $P = 0.0013 - 8.5$ s
- $B = 10^{8} - 10^{14}$ G
- Mainly Radio emitters
- Emit in narrow beam
- Clock like stability



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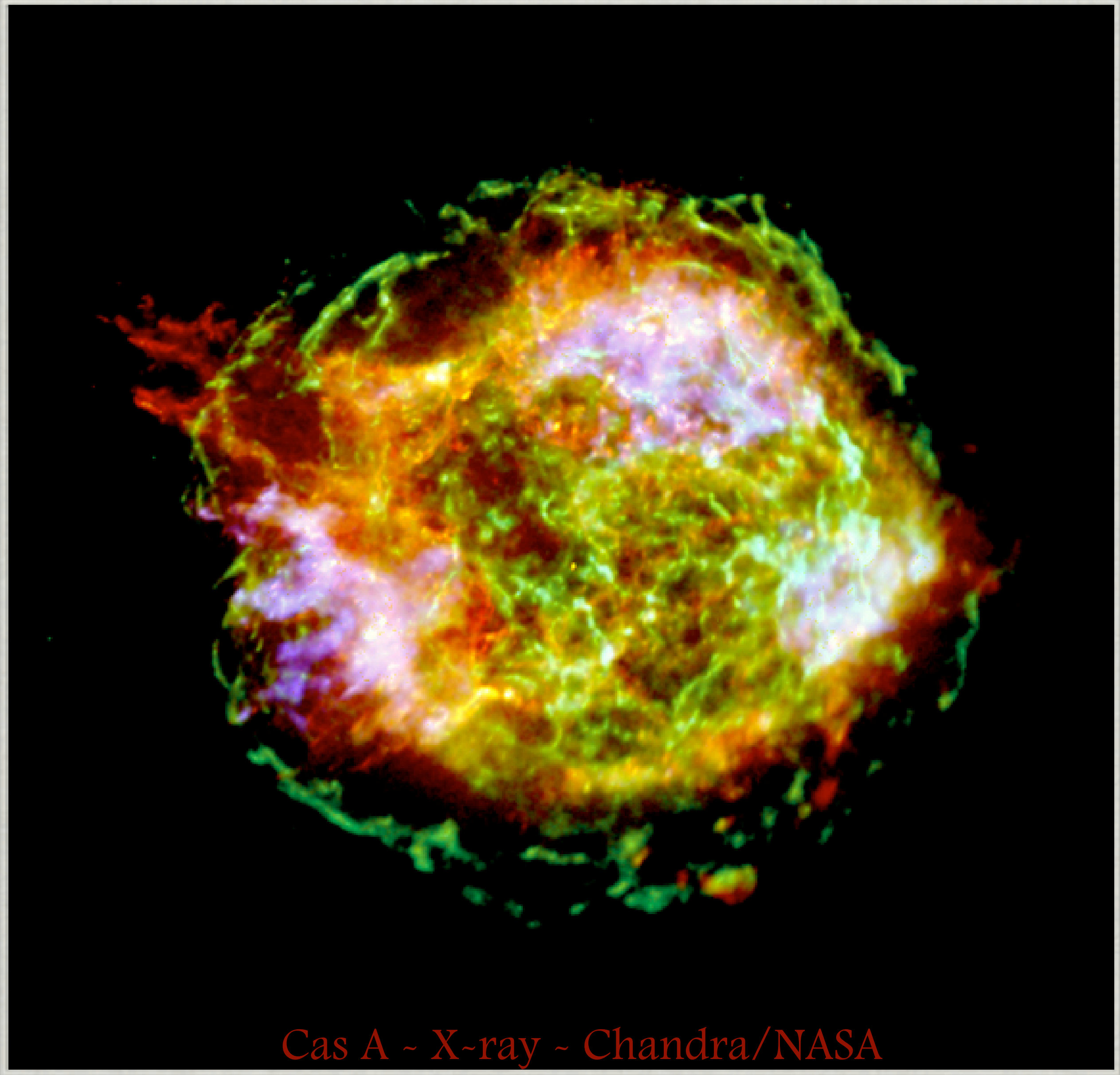
Cas A - X-ray - Chandra/NASA

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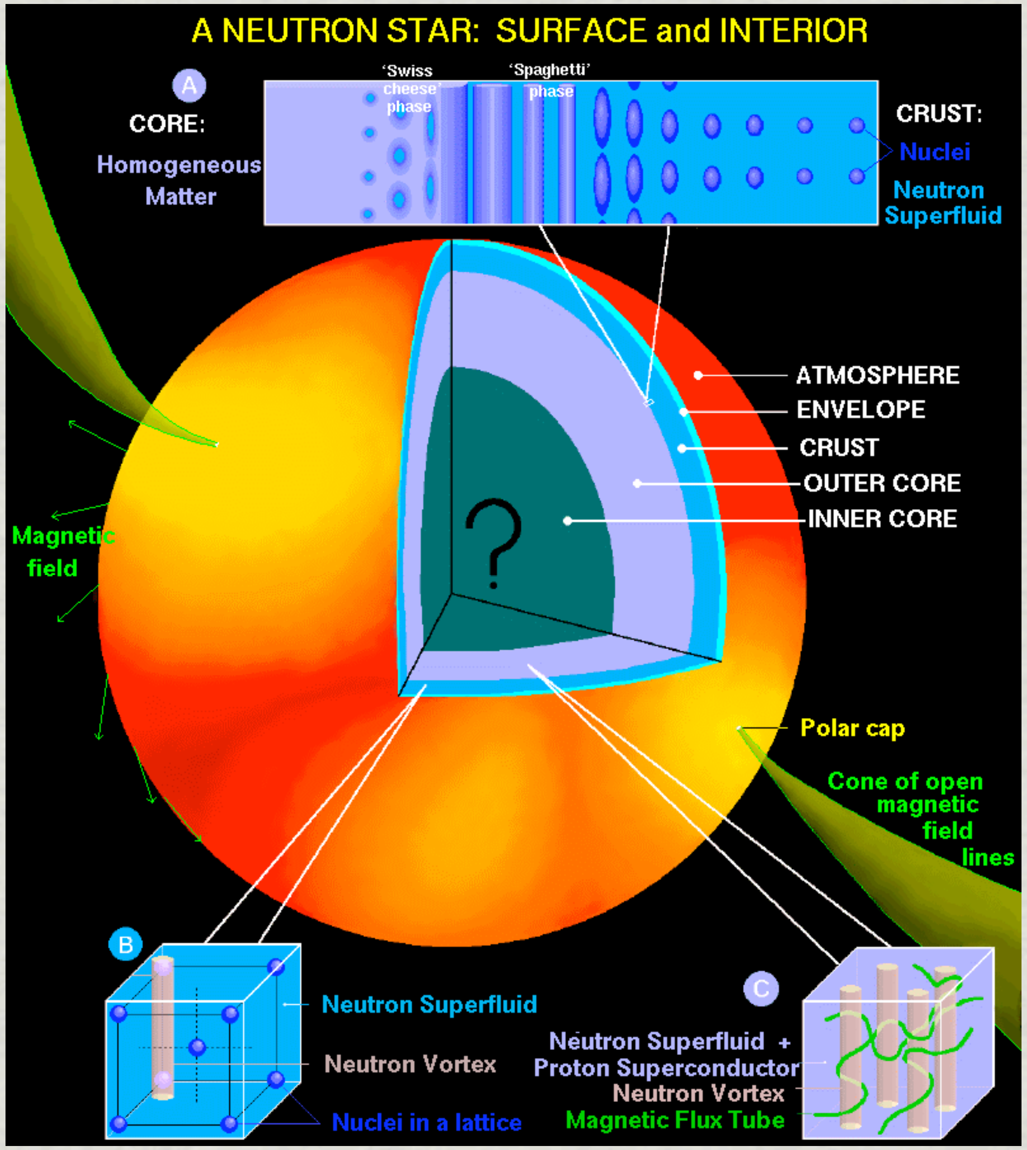

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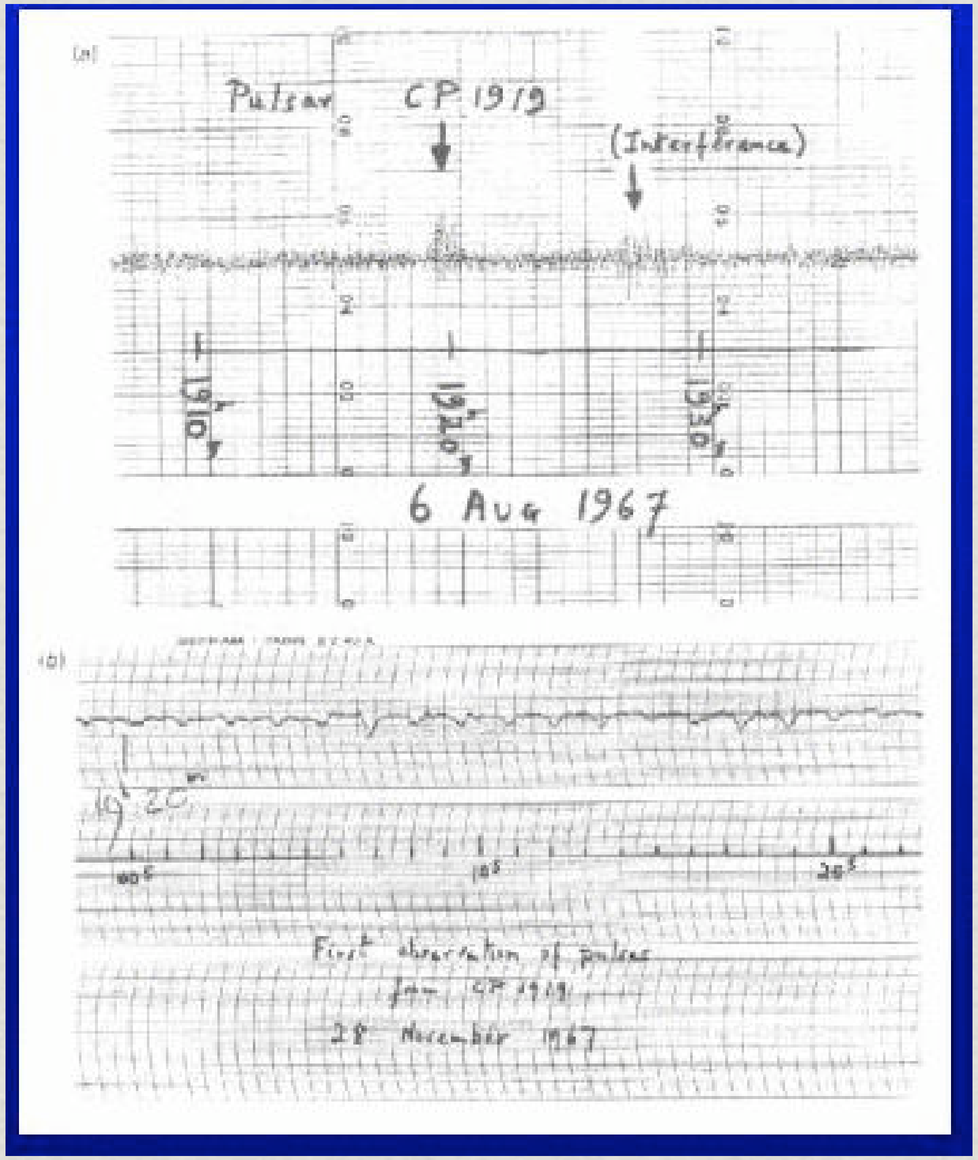

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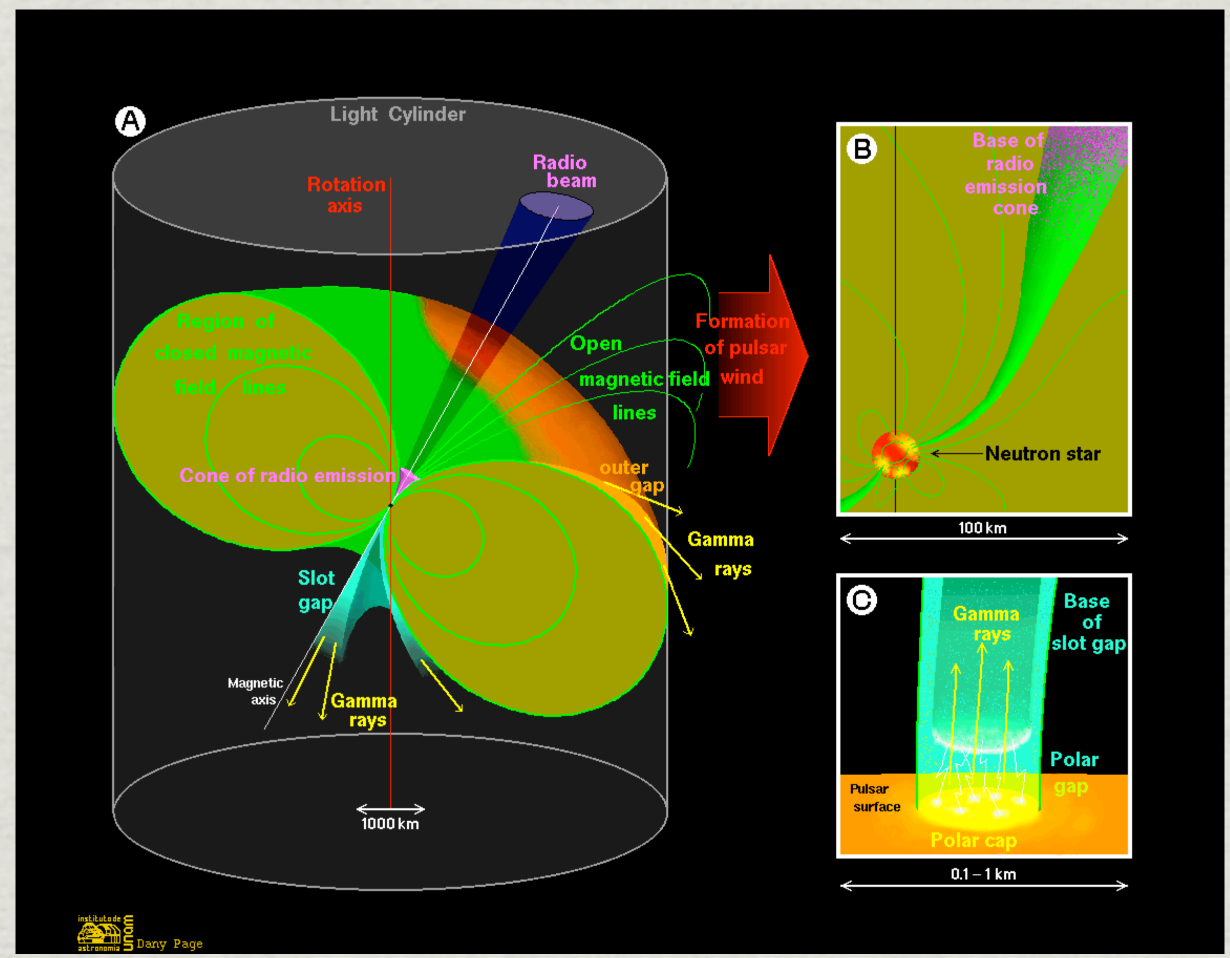
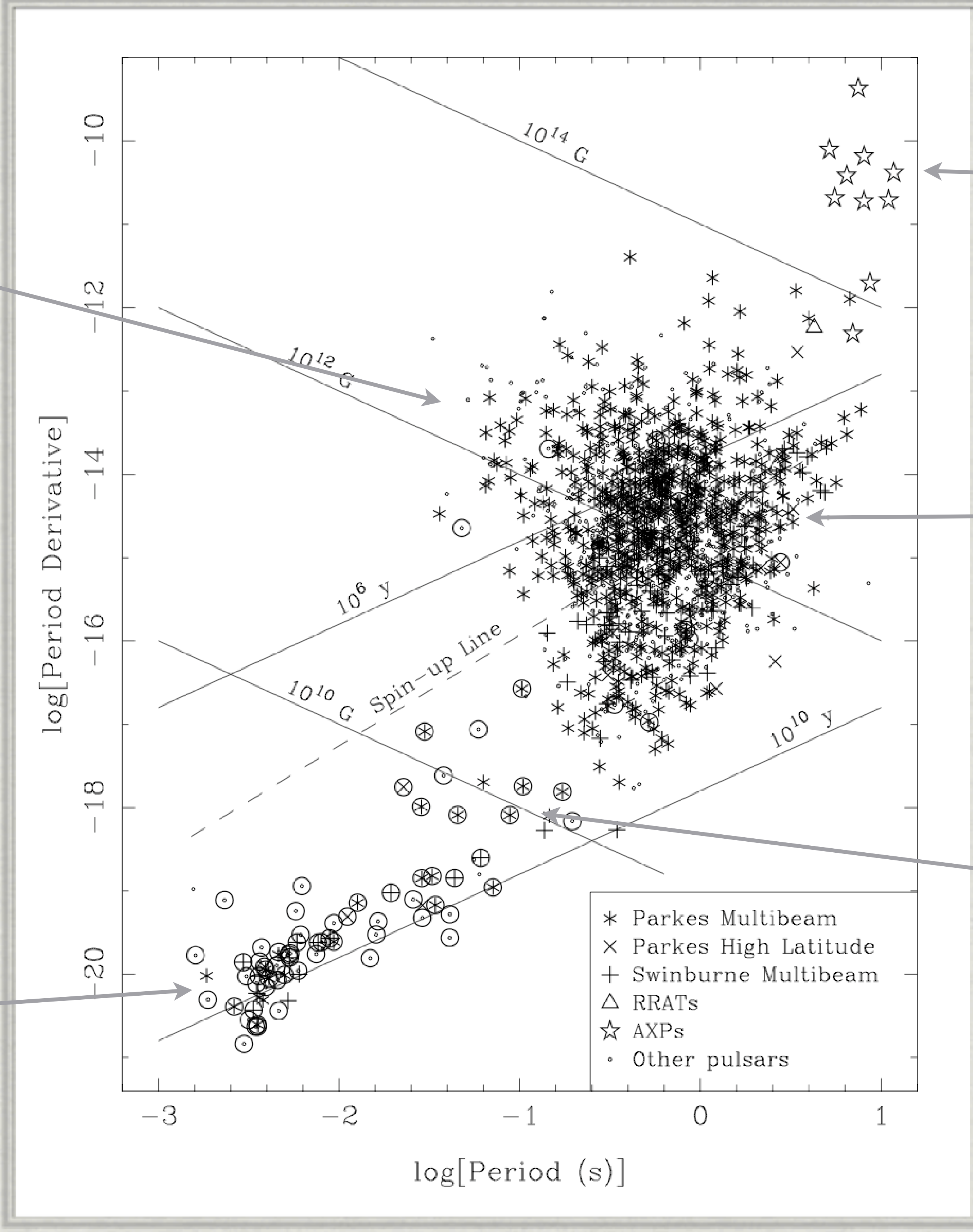


P-Pdot Diagram

YOUNG PULSARS

- SPIN FAST
- ASSOCIATED SNRS
- ENERGETIC
- GLITCH



MAGNETARS

- SPIN SLOWLY
- VERY HIGH B
- NOT ROT^{N} POWERED
- FEW RADIO

"NORMAL" PULSARS

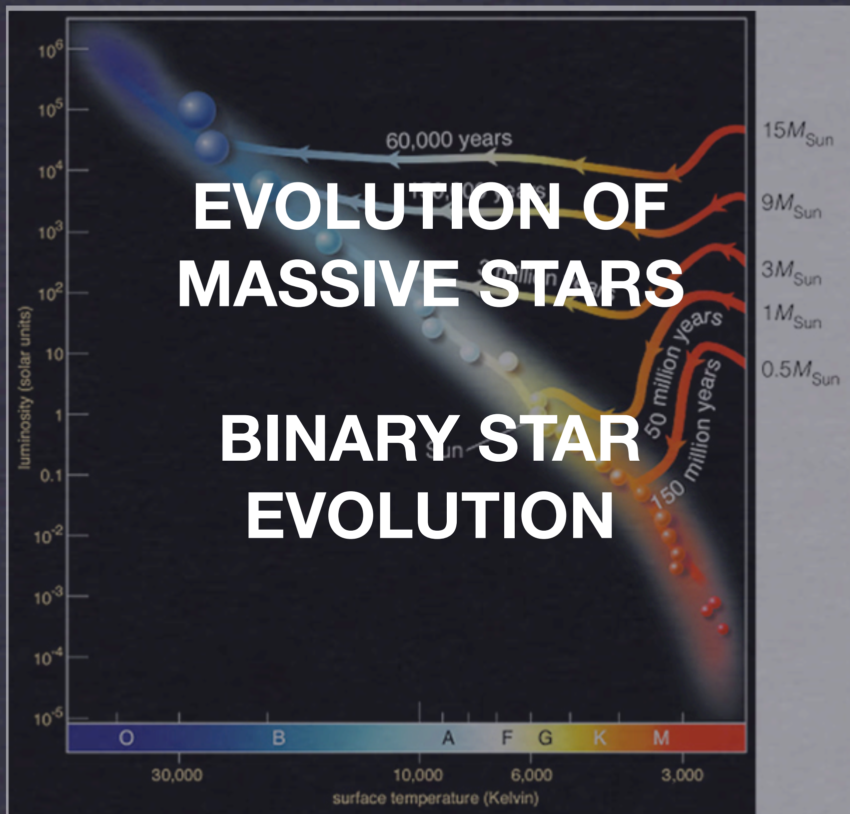
- BULK OF PSRS
- GREAT PSR STUDIES
- LOTS GOING ON
- NOBEL PRIZE

DOUBLE NEUTRON STARS

- SPIN QUITE FAST
- GREAT FOR GR TESTS
- INCL. DOUBLE PSR
- NOBEL PRIZE

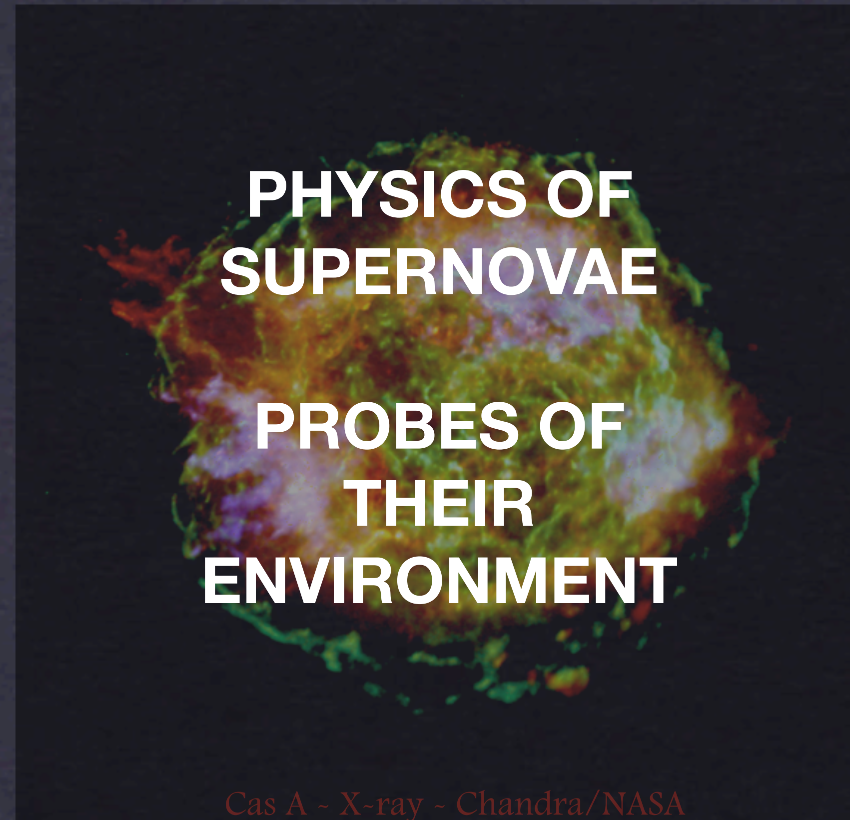
MILLISECOND PULSARS

- SPIN VERY FAST
- USUALLY BINARY
- VERY STABLE
- BEST CLOCKS



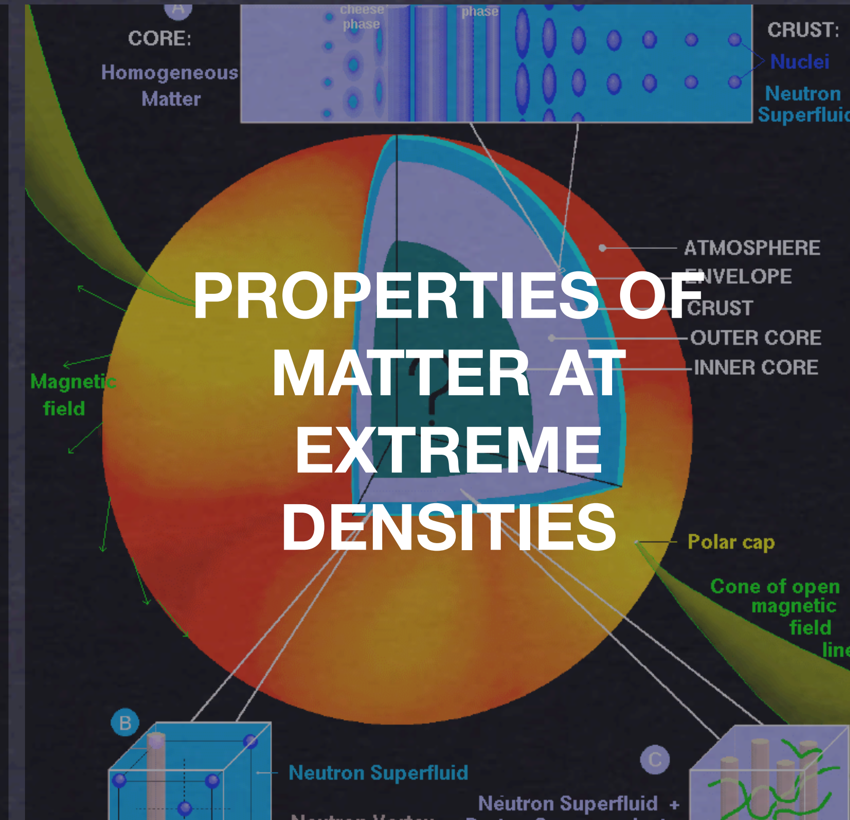
EVOLUTION OF MASSIVE STARS

BINARY STAR EVOLUTION

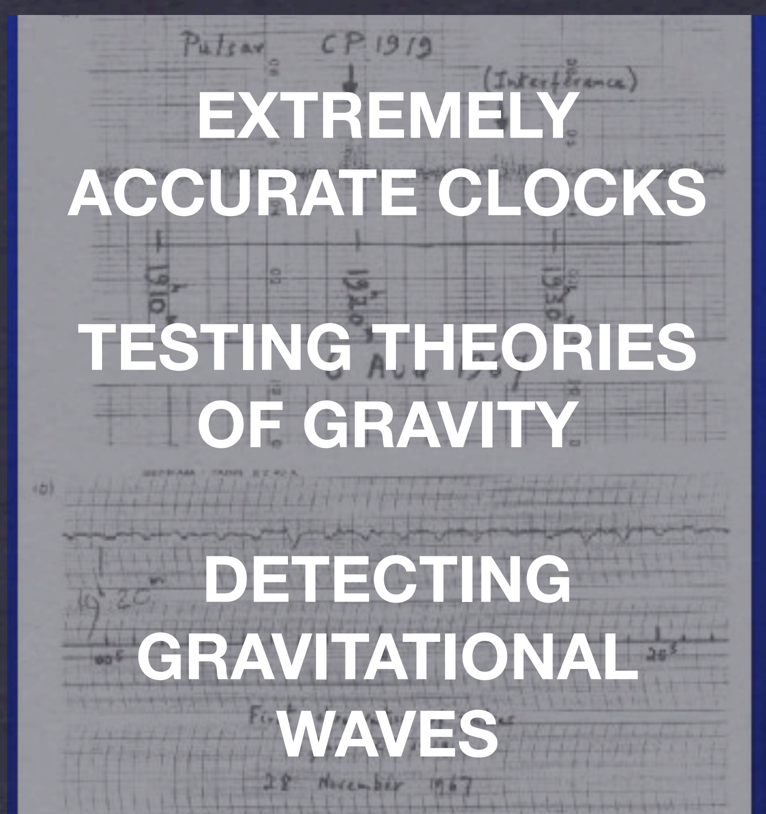


PHYSICS OF SUPERNOVAE

PROBES OF THEIR ENVIRONMENT



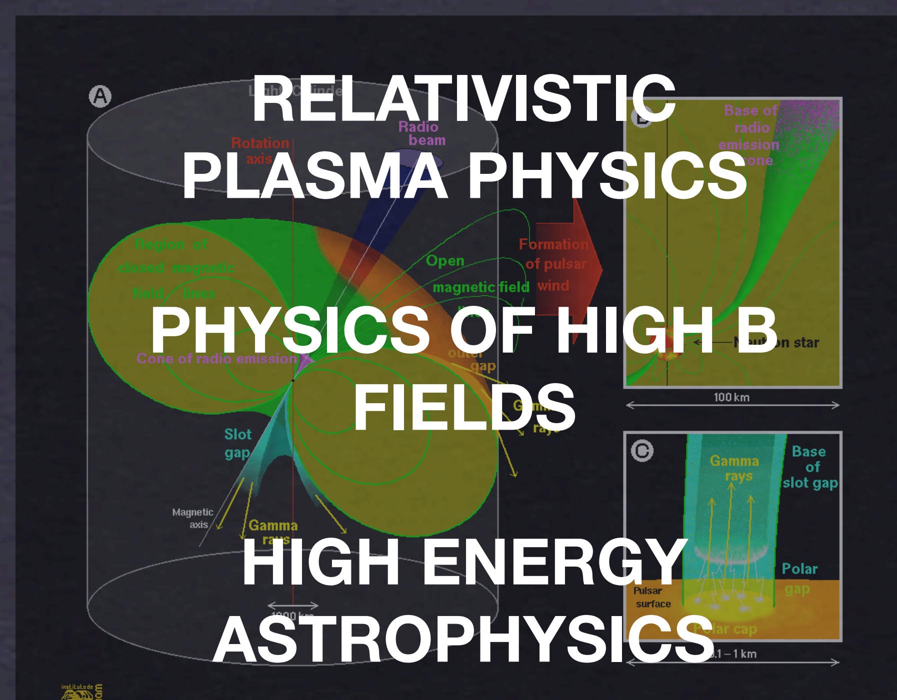
PROPERTIES OF MATTER AT EXTREME DENSITIES



EXTREMELY ACCURATE CLOCKS

TESTING THEORIES OF GRAVITY

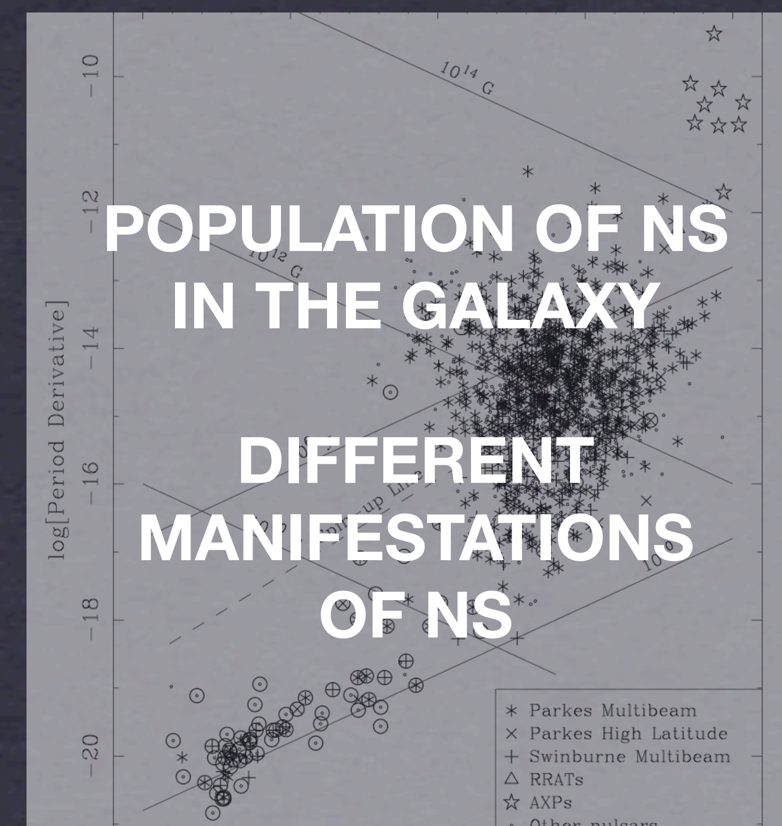
DETECTING GRAVITATIONAL WAVES



RELATIVISTIC PLASMA PHYSICS

PHYSICS OF HIGH B FIELDS

HIGH ENERGY ASTROPHYSICS



POPULATION OF NS IN THE GALAXY

DIFFERENT MANIFESTATIONS OF NS

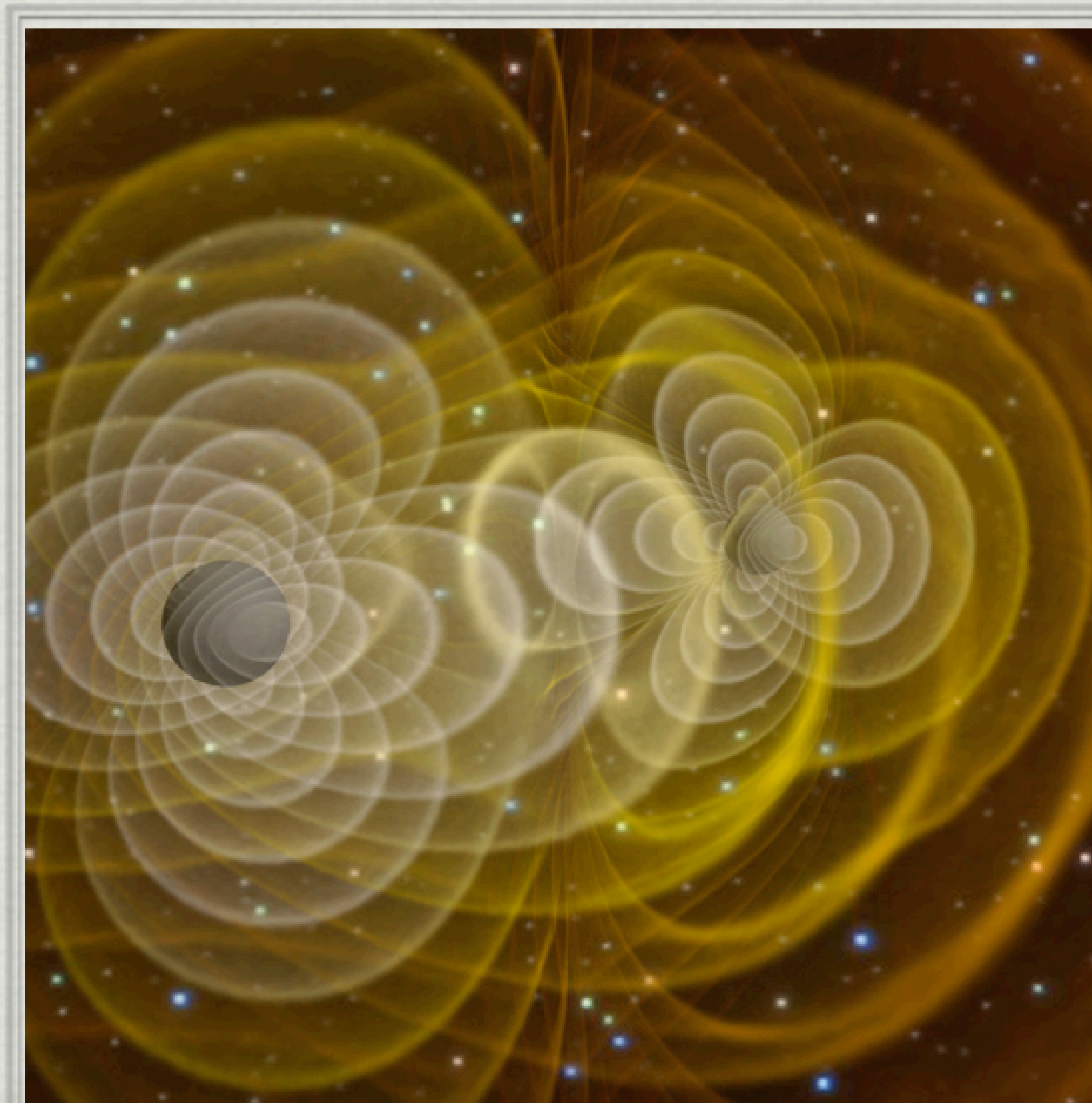
WHY ARE THEY INTERESTING?

WIDE RANGE OF SCIENCE ALL OF WHICH WILL BE ENHANCED WITH THE SKA!

Key Science: Gravity Tests Using PSRs & BHs

GALACTIC CENSUS: 30000 PSRS, 1000 MSPS

- PFE Antenna Array
- PTA for GW detection
- PSR-BH system
- Measure BH properties
- supermassive BH in GC
- Testing GR with BHs



NASA

Testing Einstein

Experiments in Solar System provide accurate tests

... but only in weak gravitational field!

Physics may be different in strong gravitational fields

Energy in gravitational field is given by: $\epsilon = E_{gravity}/mc^2$

SOLAR SYSTEM

$\epsilon_{sun} \sim 0.000001$

$\epsilon_{earth} \sim 0.000000001$

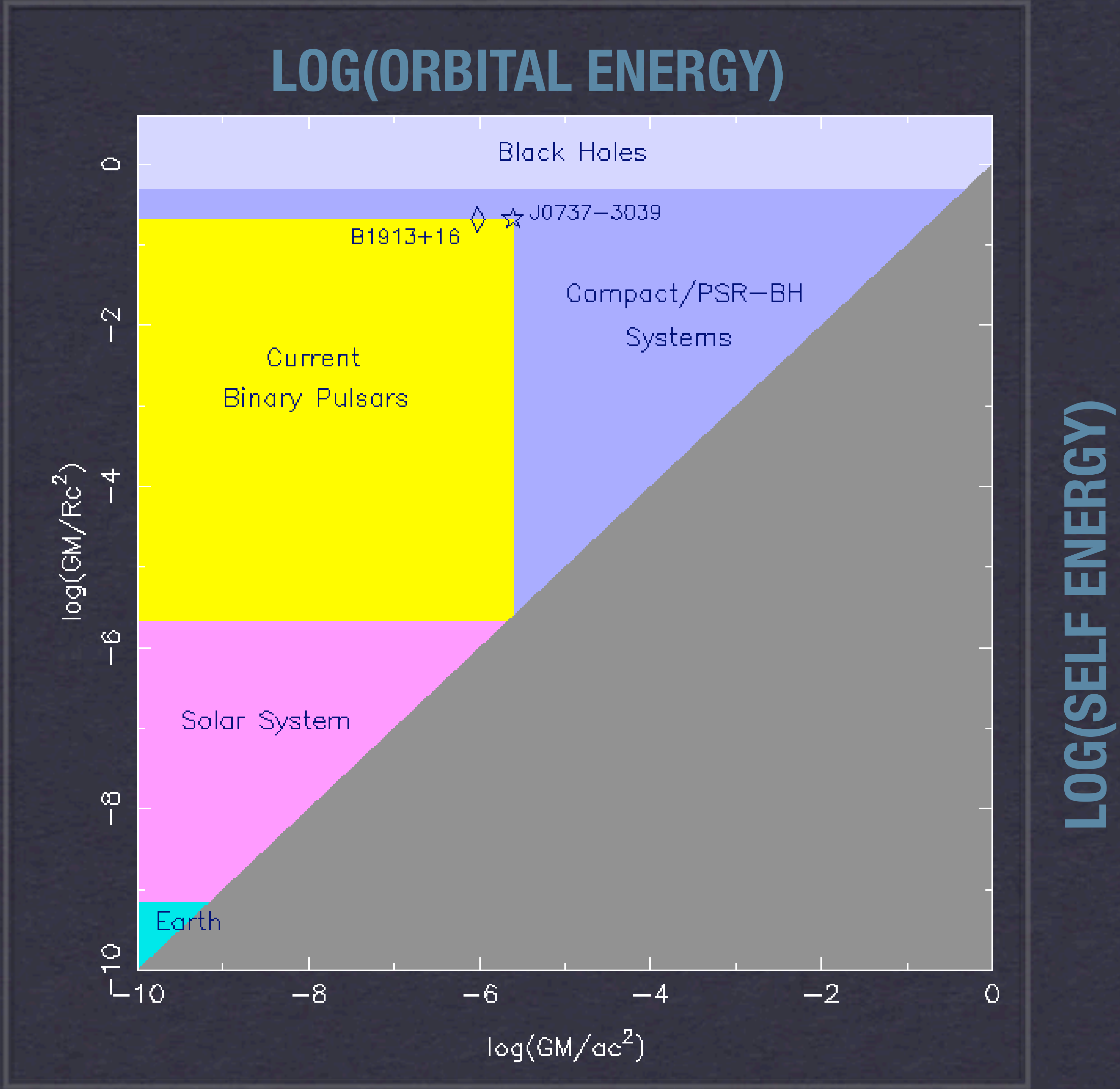
$\epsilon_{moon} \sim 0.0000000001$

NEUTRON STARS & BH

$\epsilon_{NS} \sim 0.15$

$\epsilon_{BH} \sim 0.5$

Excellent tests of Gravity



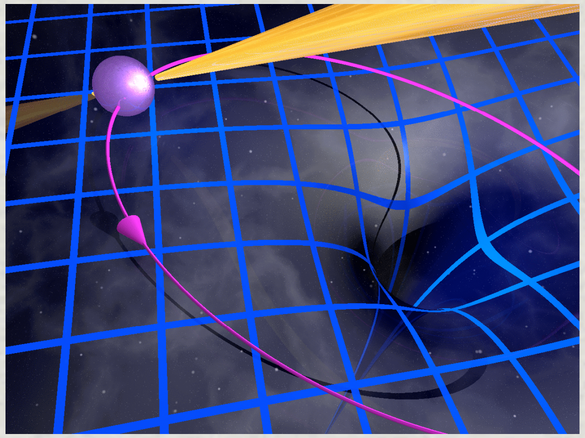
Properties of Black Holes

BLACK HOLE SPIN:

- Astrophysical BHs are expected to rotate:

$\chi \equiv c/G * S / M^2$ where s = angular momentum

- Results in relativistic spin-orbit coupling
- Visible as a precession of the orbit:



Kramer

Measure higher order derivatives of secular changes in the semi-major axis and longitude of periastron.

see Wex & Kopeikin (1999)

- Very difficult. Very high timing precision needed. Not possible today!

Properties of Black Holes

BLACK HOLE QUADRUPOLE MONENT:

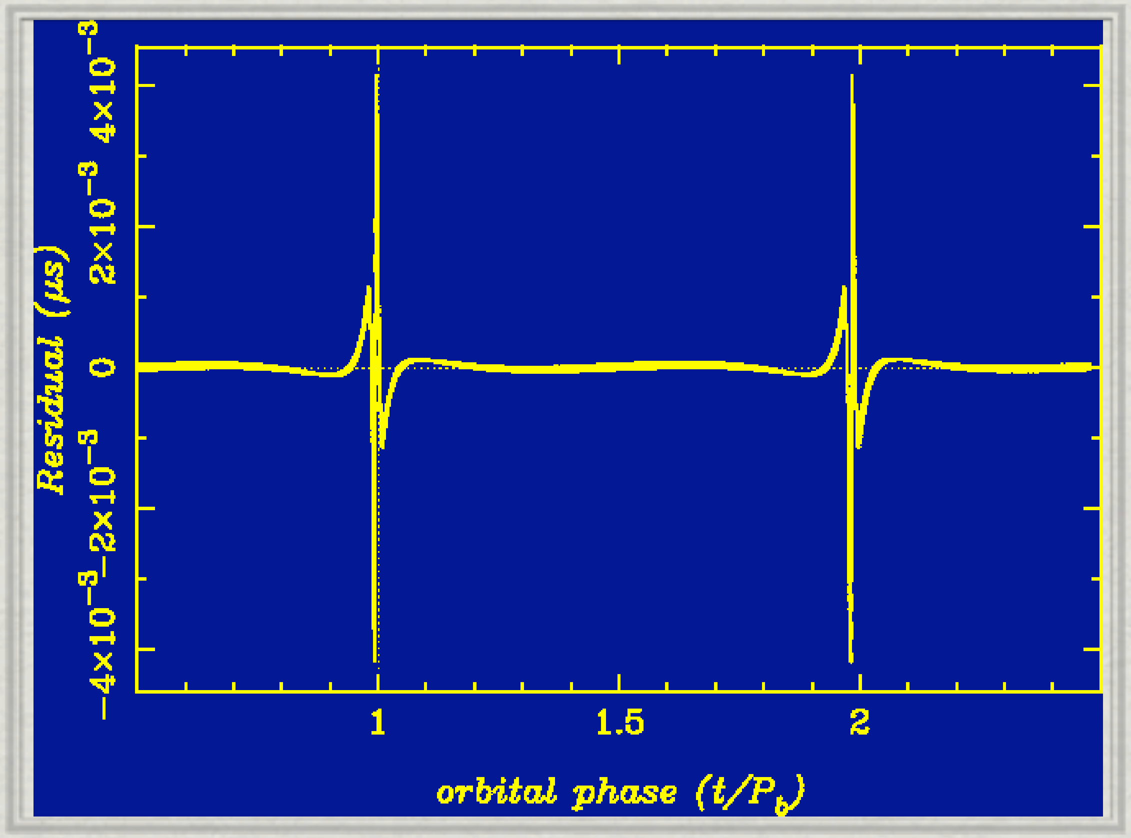
- Spinning black holes are oblate

  $q \equiv c^4/G^2 * Q/M^3$ where Q = quadrupole moment

- Results in classical spin-orbit coupling
- Visible as transient signals

  in timing residuals:

- Even more difficult.
- Requires the SKA!



Wex & Kopeikin (1999)

Cosmic Censorship Conjecture

- In GR at centre of BH, space-time diverges in point of infinite density: a singularity!
- Physics of singularities are unknown
- What happens to space-time when it “sees” a singularity?

Penrose (1969): “Cosmic Censorship Conjecture”

All singularities are hidden within the Event Horizon of the Black Hole!

They cannot be seen by the outside world, i.e.

There are no “Naked Singularities” allowed!

Important Stuff!

Whereas Stephen W. Hawking (having lost a previous bet on this subject by not demanding genericity) still firmly believes that naked singularities are an anathema and should be prohibited by the laws of classical physics,

And whereas John Preskill and Kip Thorne (having won the previous bet) still regard naked singularities as quantum gravitational objects that might exist, unclothed by horizons, for all the Universe to see,

Therefore Hawking offers, and Preskill/Thorne accept, a wager that

When any form of classical matter or field that is incapable of becoming singular in flat spacetime is coupled to general relativity via the classical Einstein equations, then

A dynamical evolution from generic initial conditions (i.e., from an open set of initial data) can never produce a naked singularity (a past-incomplete null geodesic from scri-plus).

The loser will reward the winner with clothing to cover the winner's nakedness. The clothing is to be embroidered with a suitable, truly concessionary message.

Stephen W. Hawking, John P. Preskill, Kip S. Thorne
Pasadena, California, 5 February 1997

But seriously...

- For all compact massive, BH-like objects we'll be able to measure spin, χ , very precisely

- In GR, for Kerr-BH we expect: $\chi \leq 1$

- But if we measure:

$\chi > 1 \quad \Leftrightarrow$ Event Horizon Vanishes

$\Leftrightarrow$ Naked Singularity!

- Then either GR is wrong or the Conjecture is violated

No Hair Theorem

- Like in Newtonian physics, one expects a relationship between χ and q
- In GR, this relationship is very simple
- For Kerr-BH we expect

$$q = -\chi^2$$

IT REFLECTS THE "NO HAIR" THEOREM

THE BH HAS LOST ALL INFORMATION ABOUT THE COLLAPSED PROGENITOR STAR, BUT

AN ASTROPHYSICAL (UNCHARGED) BH IS FULLY DESCRIBED BY ITS MASS AND SPIN!

No Hair Theorem

If we measure:

$$q \neq -\chi^2$$

either GR is wrong, i.e "no-hair" theorem is violated

or we have discovered a new kind of object, e.g. a Boson star with

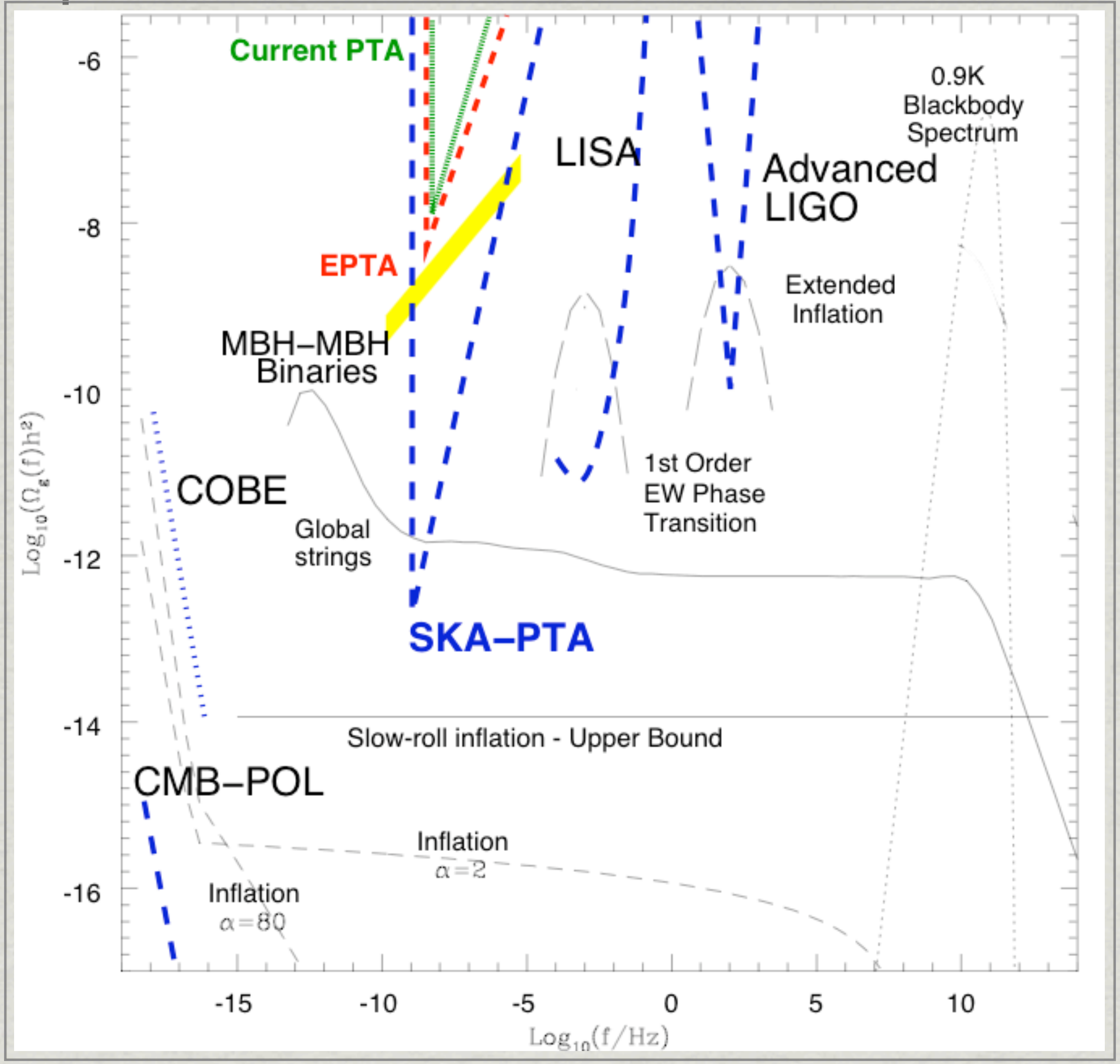
$$q \lesssim -10\chi^2$$

Direct Detection of GWs

The Gravitational Wave Spectrum

$h_c(f) = A f^{\alpha}$

$\Omega_{gw}(f) = (2\pi^{2/3}H_0^2)f^2h_c(f)^2$



Supermassive BHs

***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

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

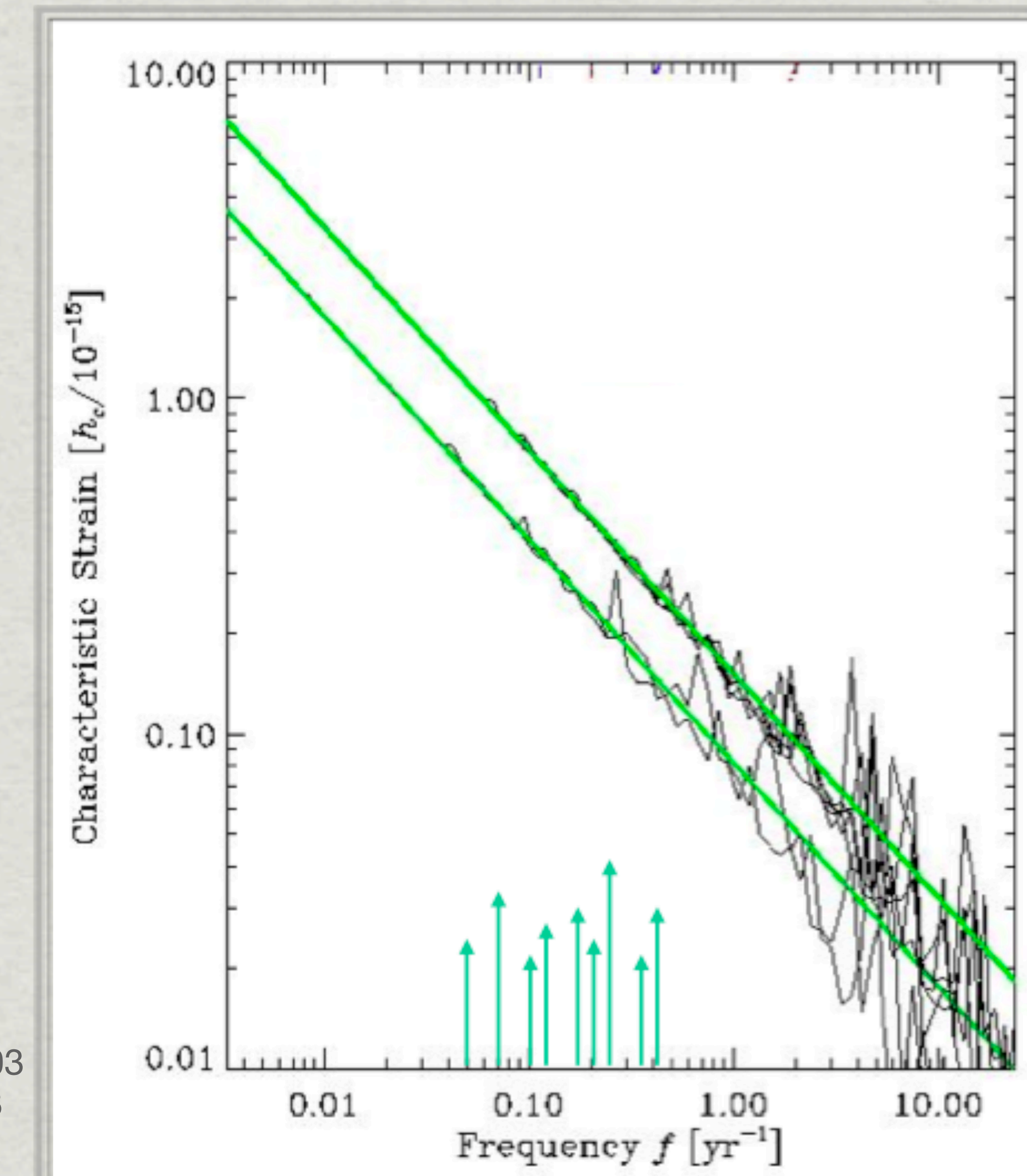
Stochastic (mean-square)

One number: Amplitude

$h_c = 10^{-15} - 10^{-14}$

$\alpha = -2/3$

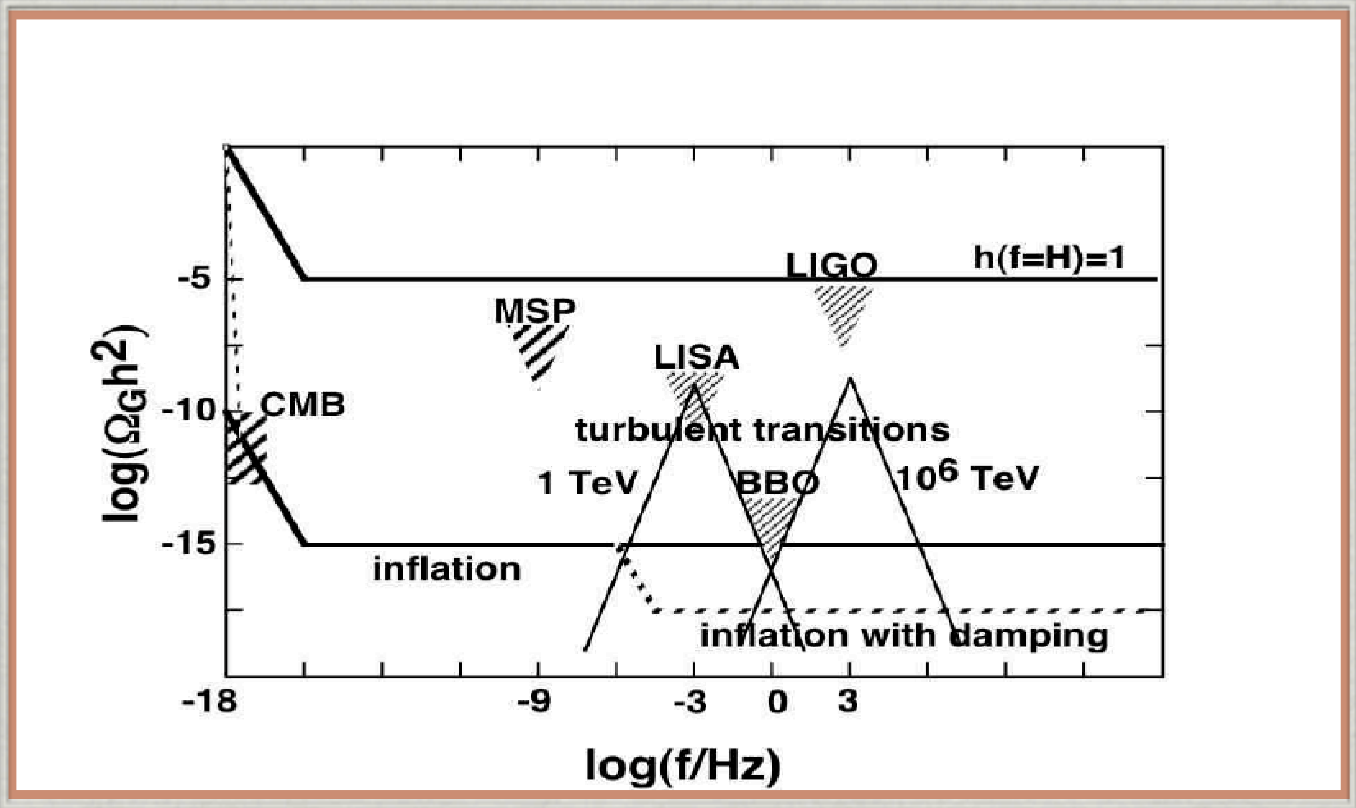
BACKER & JAFFE '03
WYITHE & LOEB '03
ENOKI ET AL '04



Relic GWs

- Inflation
  - quantum fluctuations
  - inflationary gen. B fields
- During Phase Transitions
  - Bubble collisions
  - Topological defects
  - Primordial turbulence
  - Magnetic fields

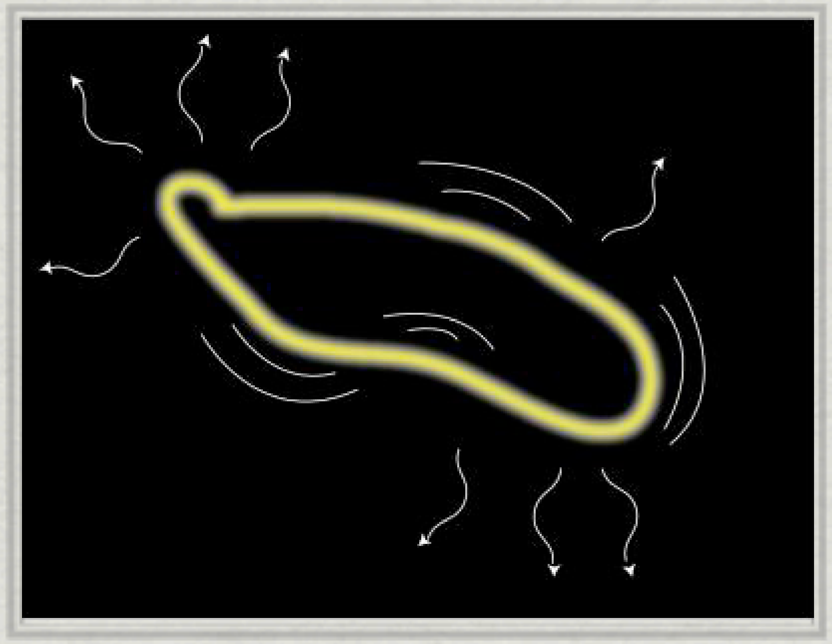
Hogan 2006



Strings

- Loops form and oscillate & emit GWs
- New Loops are formed from strings
- There is a whole range of loop sizes
- This leads to a stochastic background
- Expected spectrum has $\alpha = -7/6$
- Amplitude is in range 10^{-16} - 10^{-14}

Space.com



What is a PTA?

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

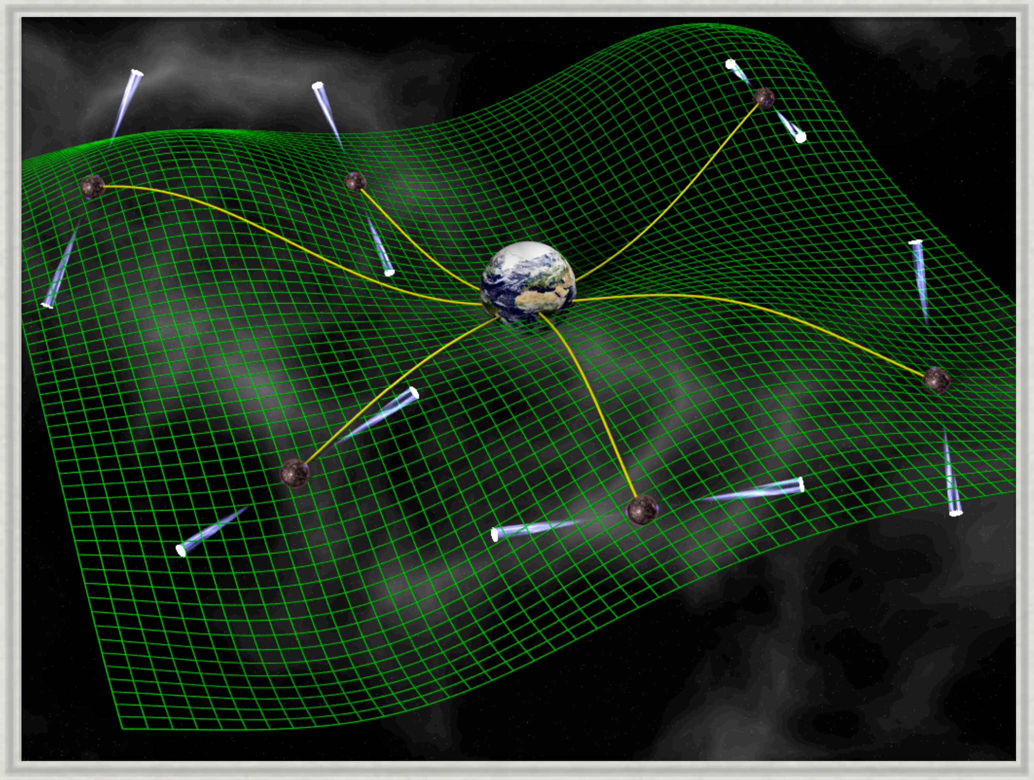
$$\ell = s + \frac{1}{2}\hat{s}^i\hat{s}^j\int_p^e h_{ij}ds = s + \frac{1}{2}\hat{s}^i\hat{s}^j\left[H_{ij}(e) - H_{ij}(p)\right]$$

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

Need an observable proportional to the wave

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

GWs are proportional to the time derivative of pulsar arrival time residuals



Kramer/Champion

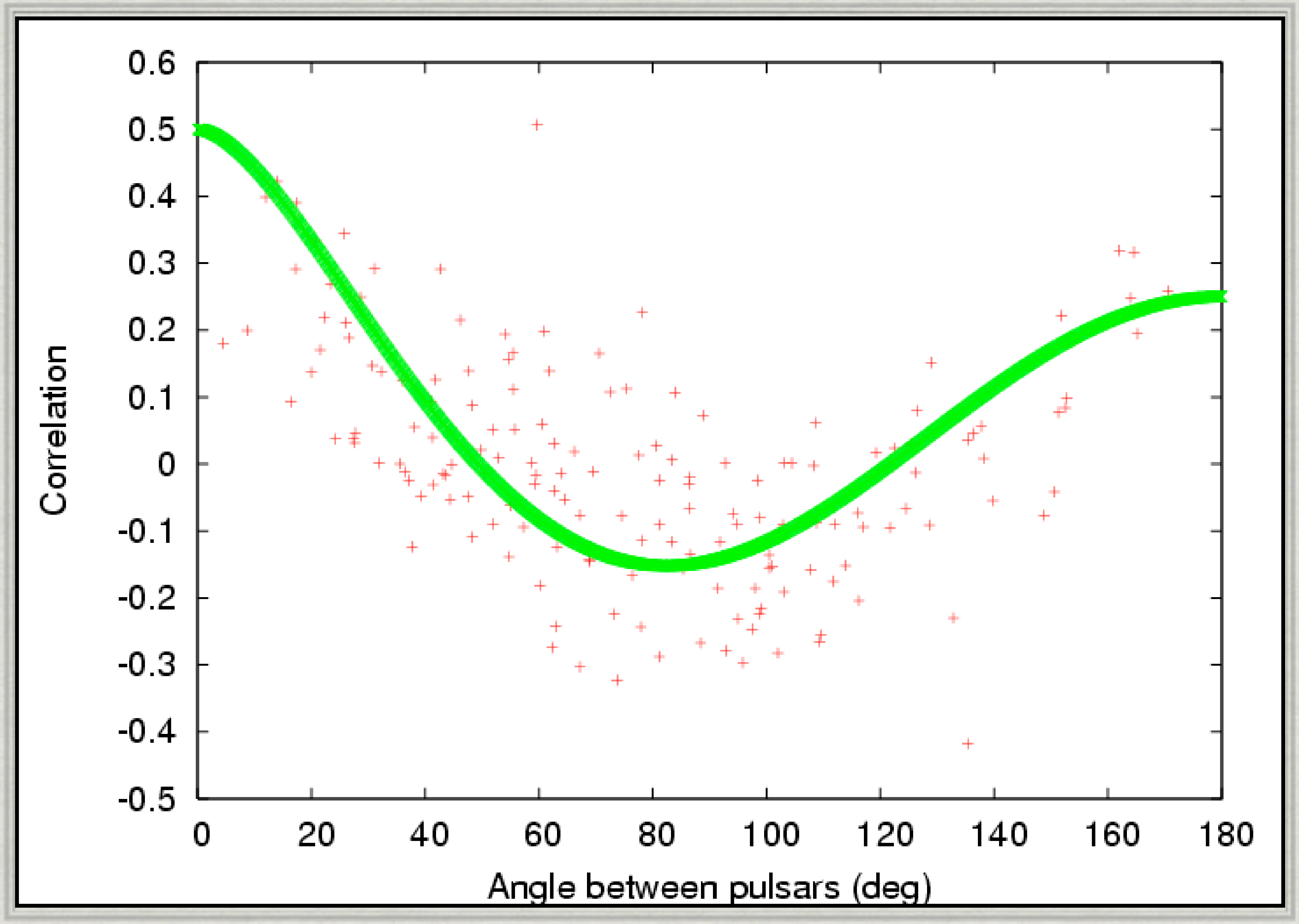
Every pulsar in every direction has correlated timing noise due to this term. This allows a weighted correlation analysis to optimally use data from multiple pulsars

The PTA

- With observations of many pulsars widely distributed on the sky we can in principle detect a stochastic gravitational wave background resulting from binary BH systems in galaxies, relic radiation, etc ...
- Gravitational waves passing over the pulsars are uncorrelated
- Gravitational waves passing over the Earth produce a correlated signal in the TOA residuals for all pulsars
- Requires observations of at least 20 MSPs over 5 - 10 years; with at least some down to 100ns (SKA should give us 10ns!) and will give the first direct detection of gravitational waves.
- A timing array can also detect instabilities in terrestrial time standards - establish a pulsar timescale
- It can also improve knowledge of Solar system properties, e.g. masses and orbits of the four outer planets and asteroids.

Idea first discussed by Foster & Backer 1990

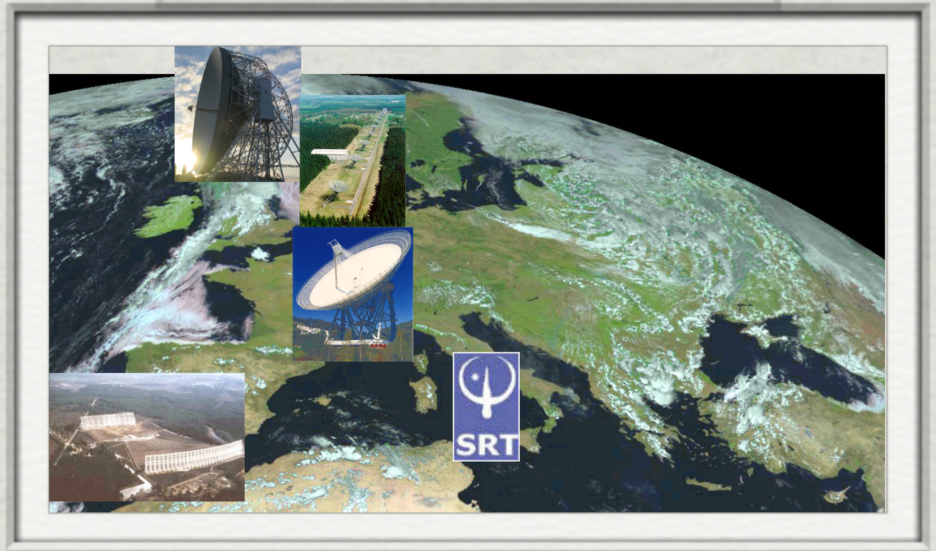
An example correlation



Jenet

Current Efforts

- PPTA in Australia
  - 1 telescope, lots of time, good funding
- EPTA in Europe
  - 4/5 telescopes, working on funding
- nano-Grav in US
  - 2 telescopes (big), just getting started
- All give vital input for SKA!



Where are we now?

- Combined data from PSRs B1937+21 & B1855+09

  It was assumed that $\Omega_{gw}(f)$ is constant (α = -1)

  Kaspi et al (1994) report $h_c(f=1/yr) < 1.1x10^{-14}$, $\Omega_{gw}h^2 < 6x10^{-8}$ (95% confidence)

  McHugh et al (1996) report $h_c(f=1/yr) < 1.32x10^{-14}$, $\Omega_{gw}h^2 < 9.3x10^{-8}$

  Frequentist Analysis using Monte-Carlo simultaions yield

  $h_c(f=1/yr) < 1.5x10^{-14}$, $\Omega_{gw}h^2 < 1.2x10^{-7}$

- Parkes PTA Current Status:

  20 pulsars for 2 years, 5 with RMS < 300ns.

  Combining this data with the Kaspi et al data yields.

  $\alpha = -2/3$: $A<1.3x10^{-14}yrs^{-2/3}$ $\Omega_{gw(1/20\ yrs)}h^2 < 1.2x10^{-8}$

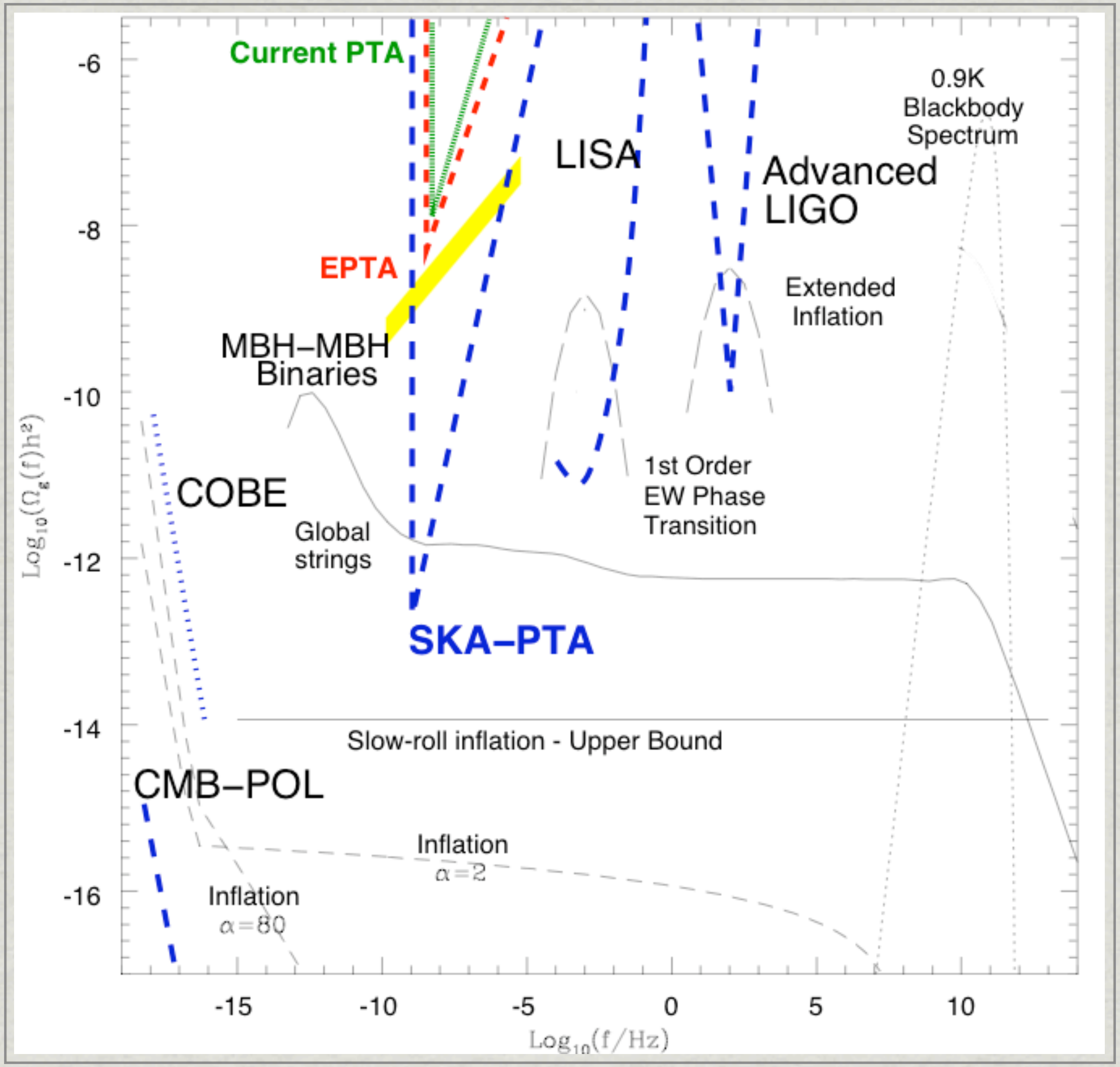
- Goal of all current PTAs:

  10 pulsars for 5 years, each RMS < 100ns.

  $\alpha = -2/3$: $A<3.8x10^{-16}yrs^{-2/3}$ $\Omega_{gw(1/5\ yrs)}h^2 < 2.6x10^{-11}$

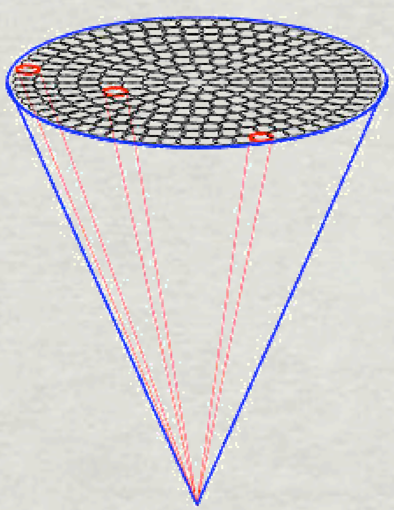
The SKA will be best.

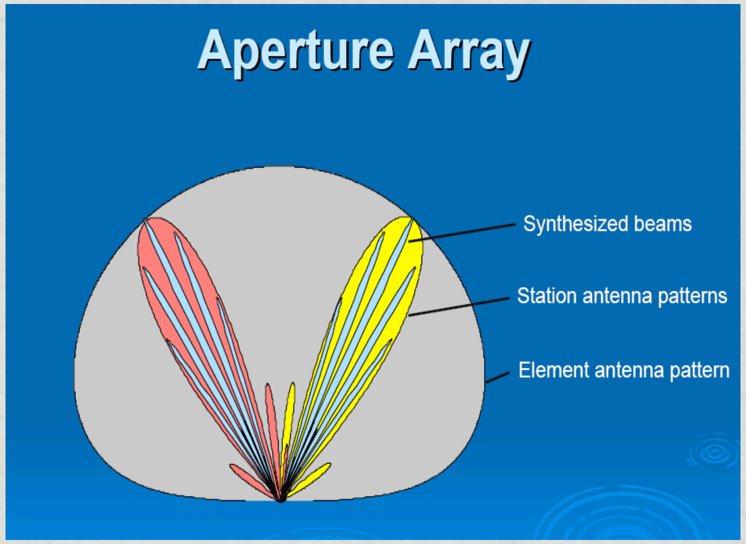
- Time 10's of MSPs to sub 100 ns precision and some down to 10ns precision.
- Not only detect gravitational waves directly but also be able to study the spectrum
- Also have excellent sensitivity to "local" single sources, events.

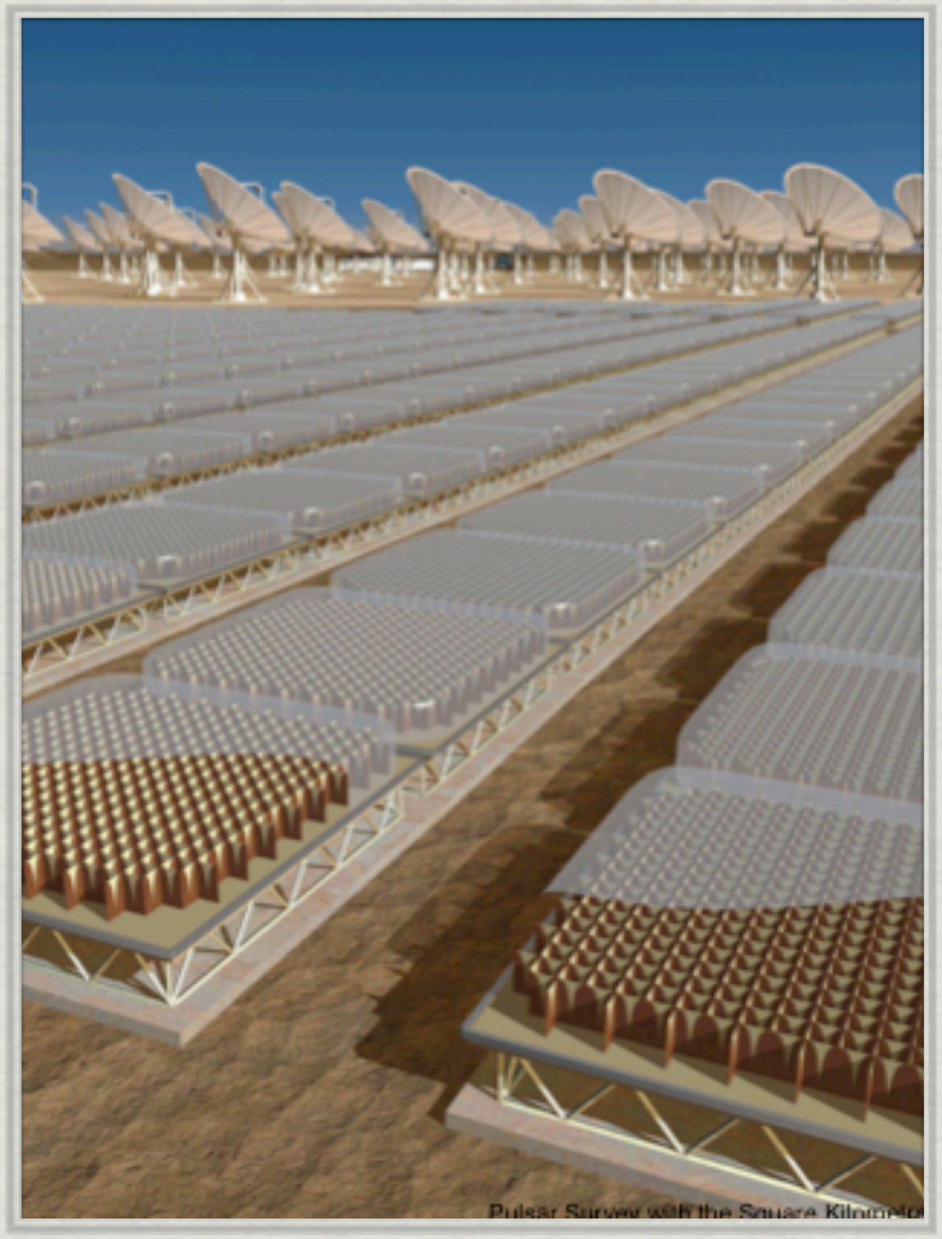


But how do we find them?

- Ideal scenario has all collecting area in one dish.
- Not practical for other applications nor cost effective
- End up with a sparse array.
- $N_{pix} \sim (b_{max}/D)^2 \sim 10^4 - 10^9$







see Smits et al

Can we search for them?

BEAM FORMING

$$N_{ops} = 2 \cdot 10^{15} \left(\frac{N_{dish}}{500}\right) \left(\frac{B}{0.5\,\mathrm{GHz}}\right) \left(\frac{N_{pol}}{2}\right) \left(\frac{D_{core}}{1\,\mathrm{km}}\right)^2 \left(\frac{15\,\mathrm{m}}{D_{dish}}\right)^2 \mathrm{ops}$$

DATA RATE

$$\begin{aligned} DR_{dish} &= 4\,500 \times 1 \cdot 10^8 \left(\frac{D_{core}}{1\,\mathrm{km}}\right)^2 \left(\frac{15\,\mathrm{m}}{D_{dish}}\right)^2 \left(\frac{100\,\mu\mathrm{s}}{T_{samp}}\right) \left(\frac{B}{500\,\mathrm{MHz}}\right) \left(\frac{12\,\mathrm{kHz}}{\Delta\nu}\right) \\ &\quad \times \left(\frac{N_{pol}}{2}\right) \left(\frac{N_{bits}}{2}\right) \mathrm{Bps} \\ DR_{AA} &= 6\,500 \times 2.5 \cdot 10^8\,\mathrm{Bps} = 1.6\,\mathrm{TB/s} \end{aligned}$$

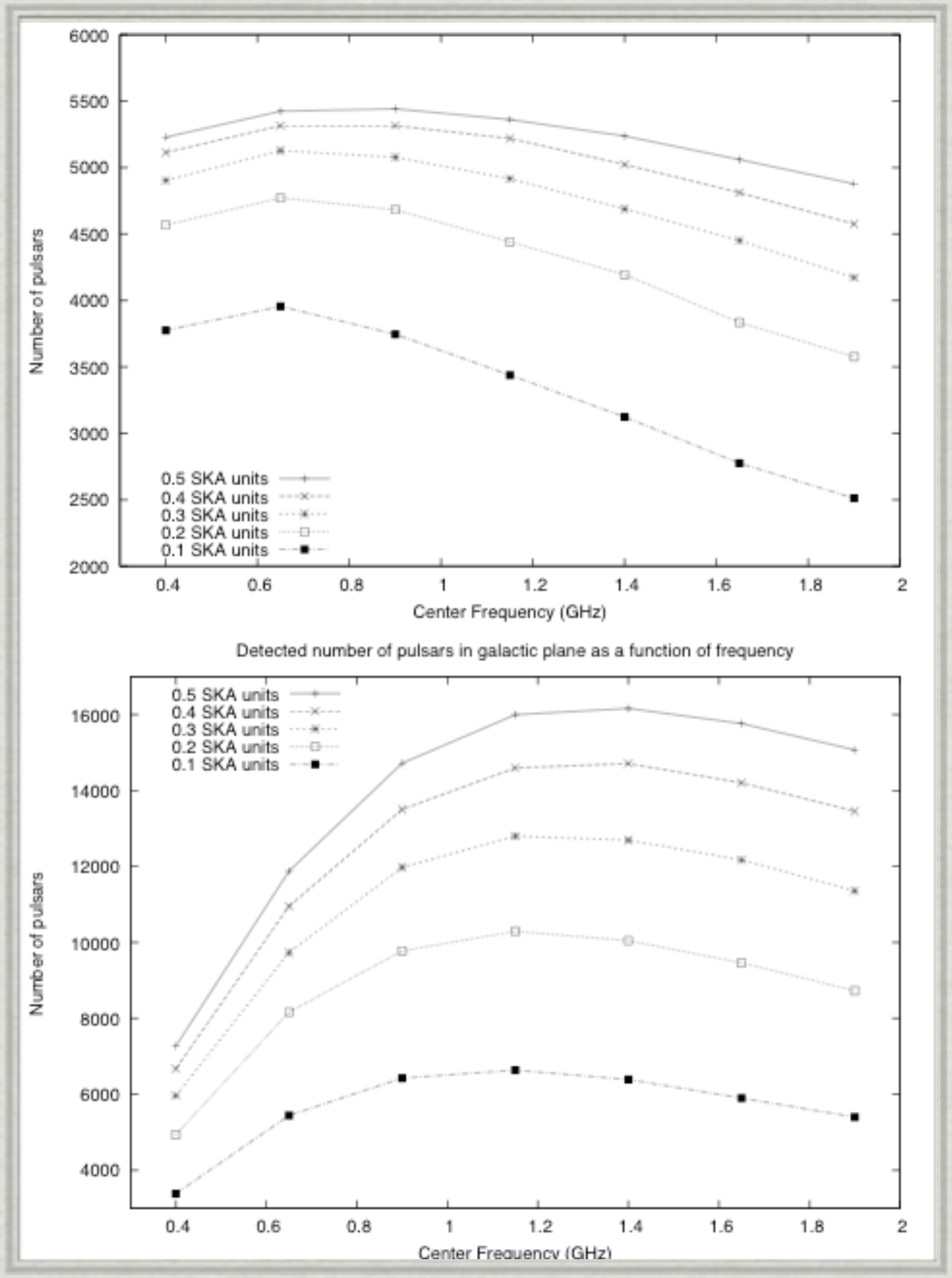
REAL TIME ANALYSIS

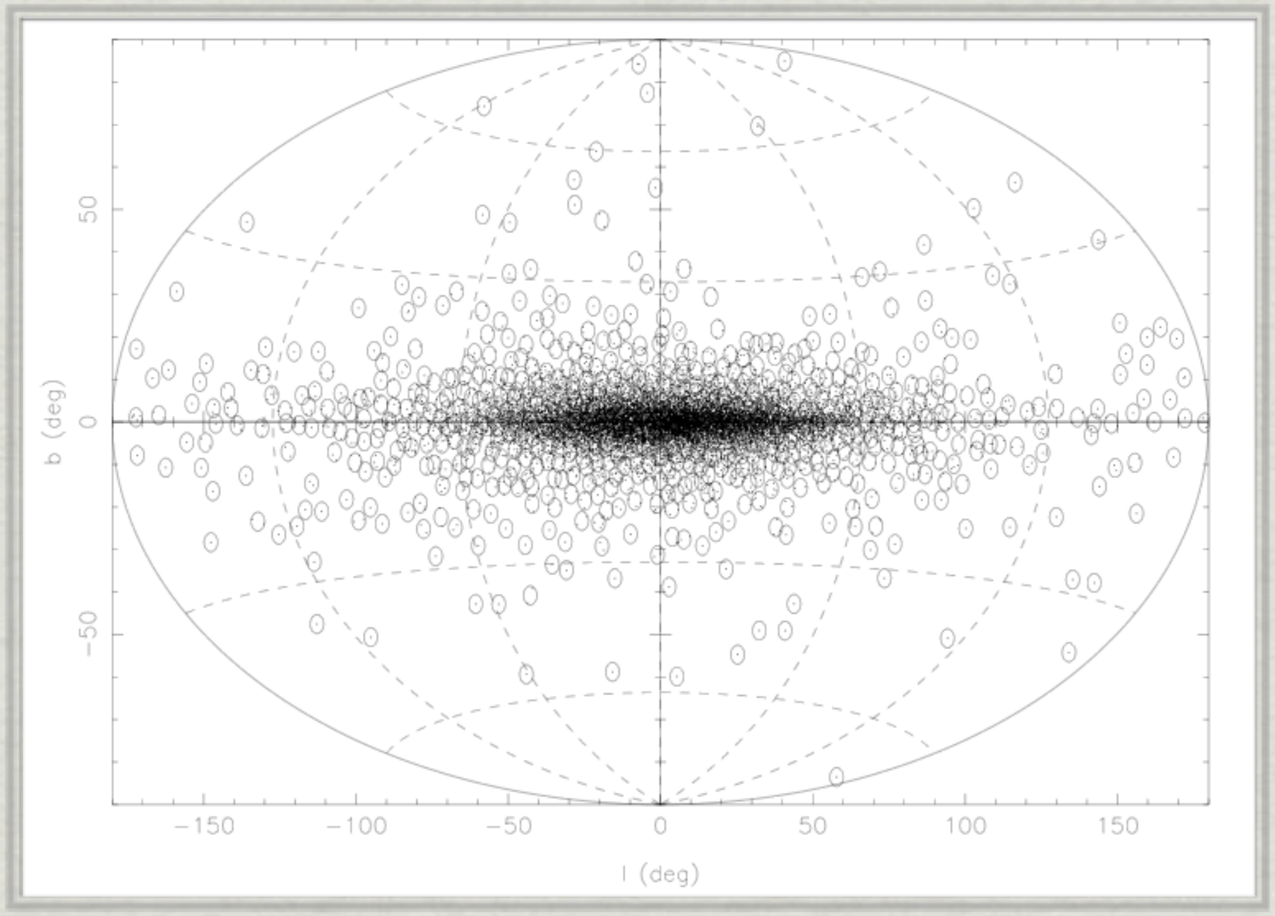
SHIFT EACH FREQUENCY CHANNEL WITH TRIAL DM AND SUM OVER FREQUENCY.
RE-SAMPLE THE TIME-SERIES WITH TRIAL ACCELERATIONS.
FOURIER TRANSFORM THE DATA AND SEARCH FOR PEAKS.

$$N_{oa} = \left(\frac{D_{core}}{D_{dish}}\right)^2 N_{DM} N_{acc} \cdot 5 N_{samp} \log_2(N_{samp})$$

$$\begin{aligned} N_{oa\_dish} &= 4\,500 \times 2.8 \cdot 10^{12}\,\mathrm{ops} = 12\,\mathrm{Pops} \\ N_{oa\_AA} &= 6\,500 \times 6.1 \cdot 10^{12}\,\mathrm{ops} = 40\,\mathrm{Pops} \end{aligned}$$

How many of them?



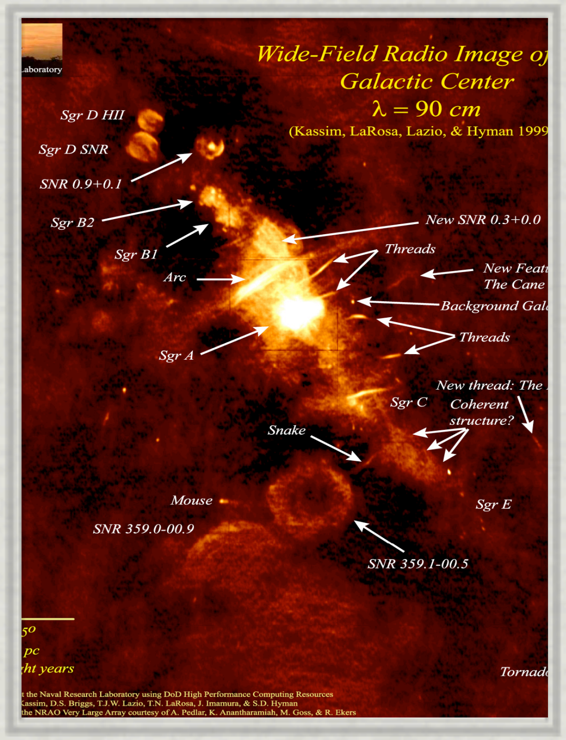


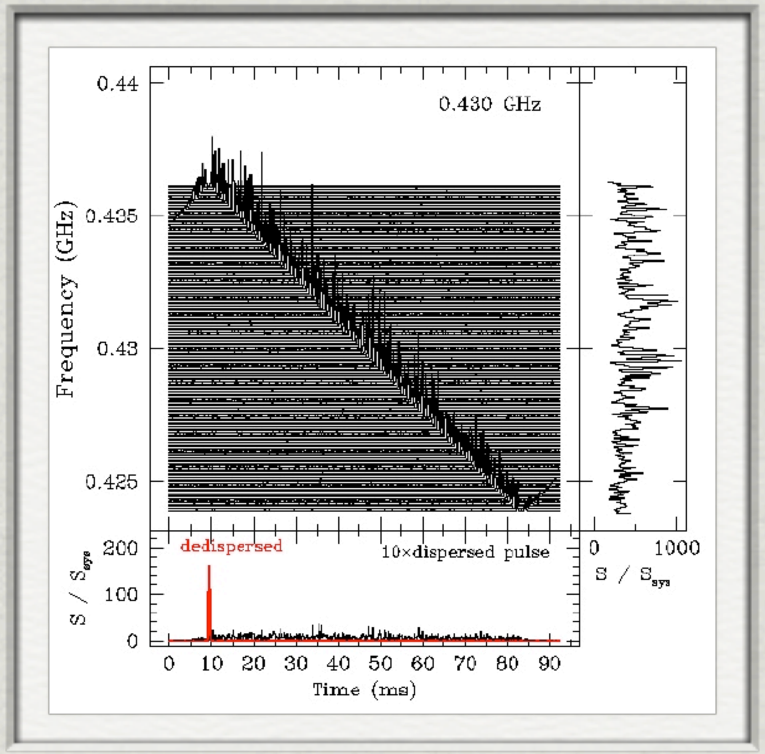
10,000 - 30,000

see Smits et al

Much more science...

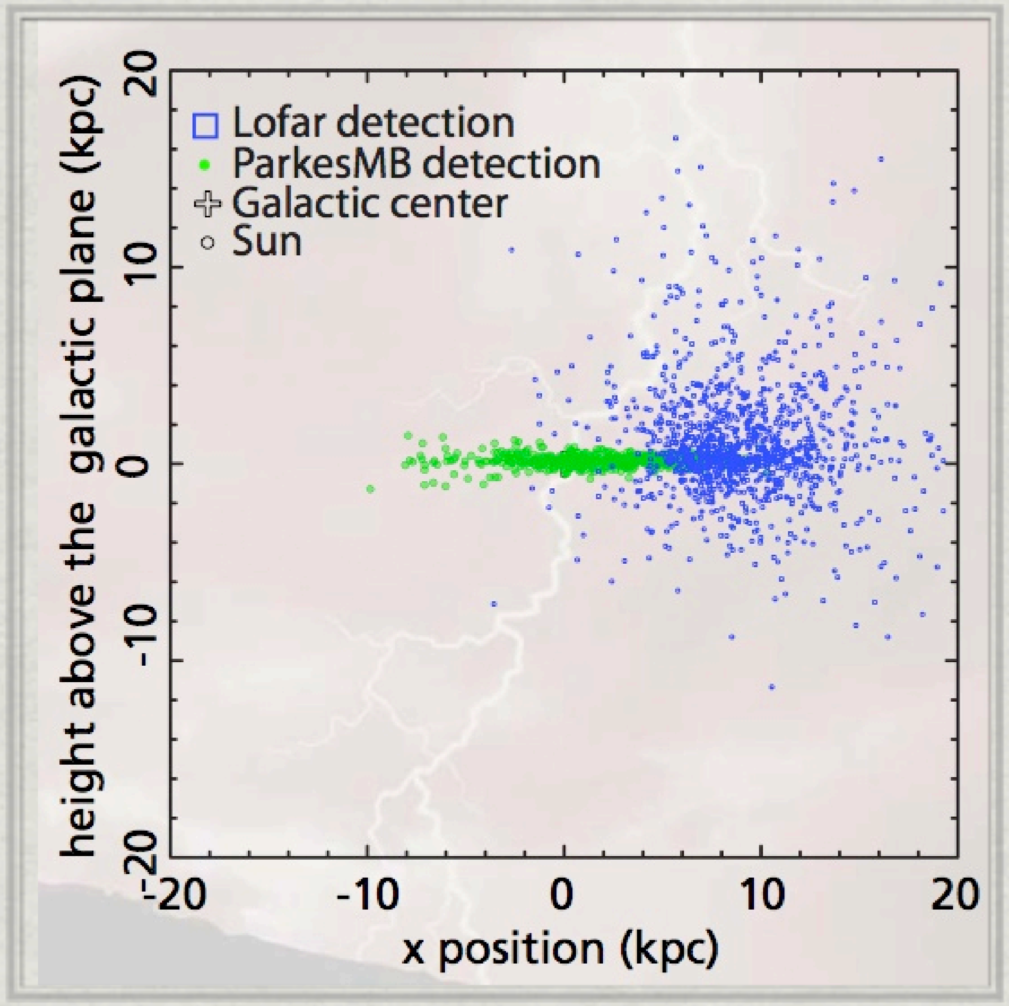
- Probing Spacetime near SGR A*
- A full Galactic census
- Search local group galaxies for pulsars
- Detect giant pulses out to Virgo!



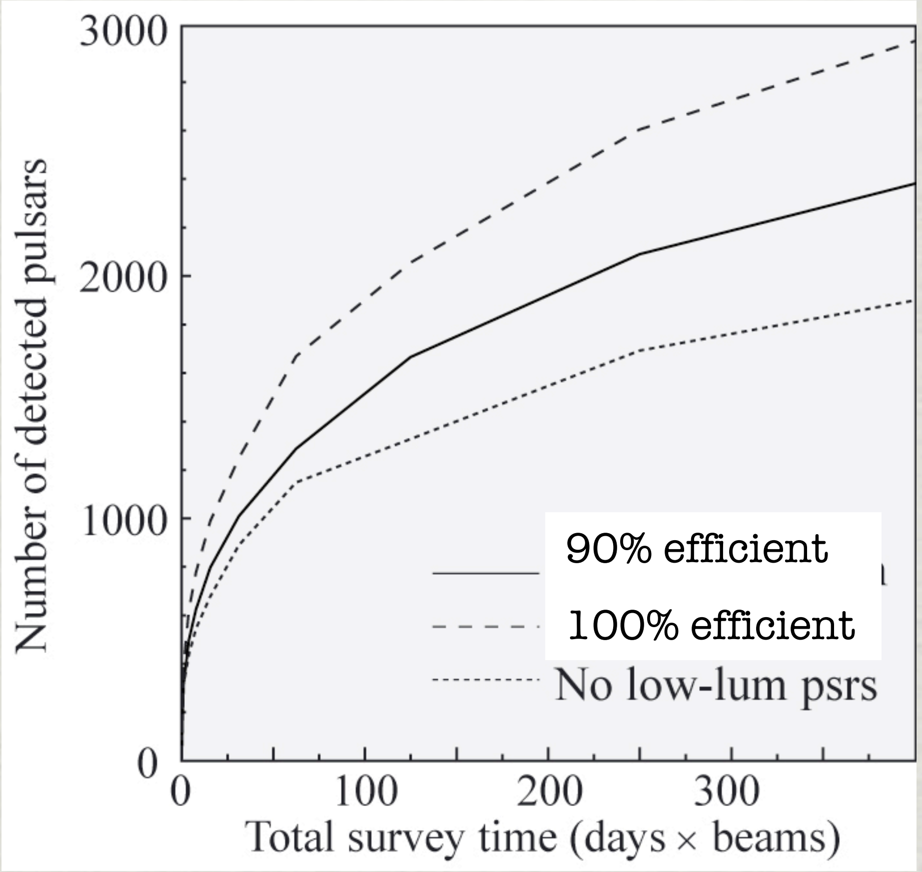


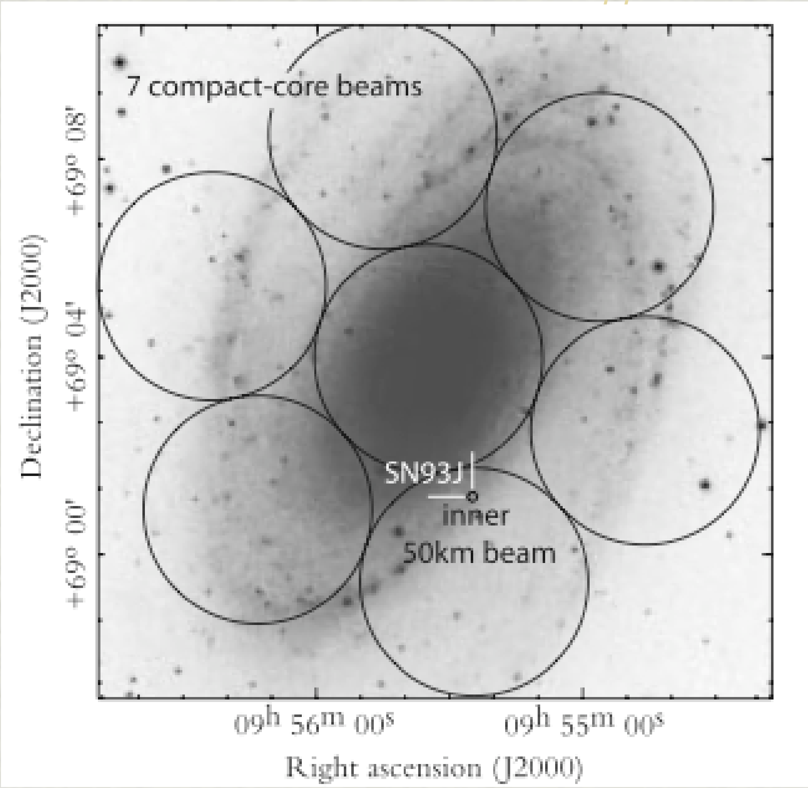
LOFAR

- >1000 new pulsars
- entire "local" population
- best Lum function until SKA



van Leeuwen & Stappers 2006





meerKat (& ATA/ASKAP)

- INCOHERENT ADDITION OF DISHES, AND 600 SECONDS INTEGRATION TIME: at 1.4 GHz with 256 MHz BW:
- 6-m dishes will find 175 pulsars and
- 15-m dishes will find 370 pulsars (but will take 6.25 times longer).

ALREADY >1000 PULSARS IN SKY SEEN FROM

SH SO NONE NEW

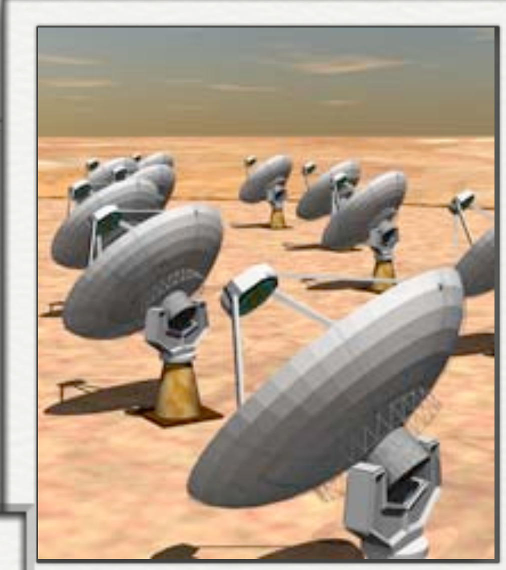
SO AN INCOHERENT SURVEY IS NOT COMPETITIVE WITH THESE PARAMS.

IF WE HAD THE FULL FOV AND COLLECTING AREA A SIMILAR SURVEY WOULD

FIND 1600 PULSARS OF WHICH A FEW HUNDRED WOULD BE NEW.

SUCH A SURVEY WOULD TAKE ABOUT 31 DAYS OF OBSERVING TIME IF WE USED 6-M DISHES.

meerKat



ASKAP

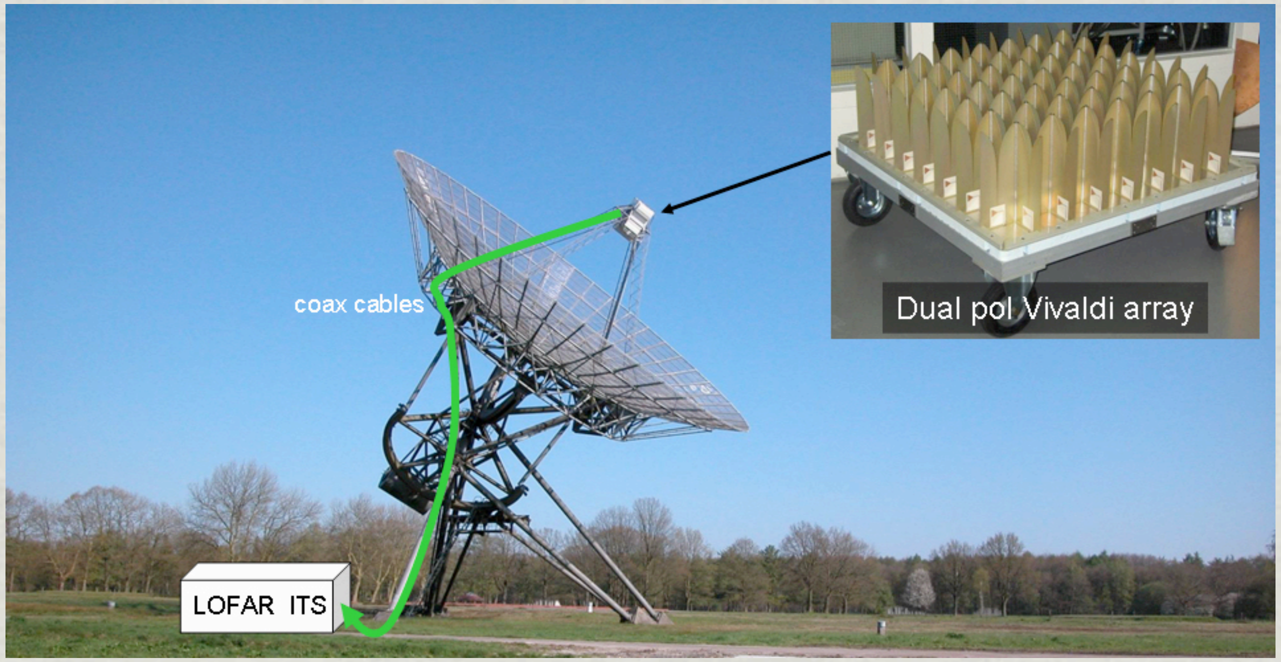
ATA

FAST

- Illuminated area of 300m dish.
- > 2.25 times more sensitive than Arecibo
- Can see more of the sky
- Will find many thousands of new pulsars
- Good for binaries

APERTIF

- 21 times the FoV of the WSRT
- Very high survey figure of merit.
- All sky survey could find many hundreds of new pulsars



Conclusions

- Lots of exciting and new physics will be opened up by the SKA and the pulsars it will discover and time.
- Was Einstein right, what are the Black Hole properties, do naked singularities exist, are BHs hairy?
- What does the gravitational wave background look like. Do GWs have properties different from those expected in GR?
- Lots of work to be done, how to find the pulsars, how to time them, new models for timing them...
- Pathfinders will also allow us to great and new pulsar science but the richest prizes will be for the SKA.