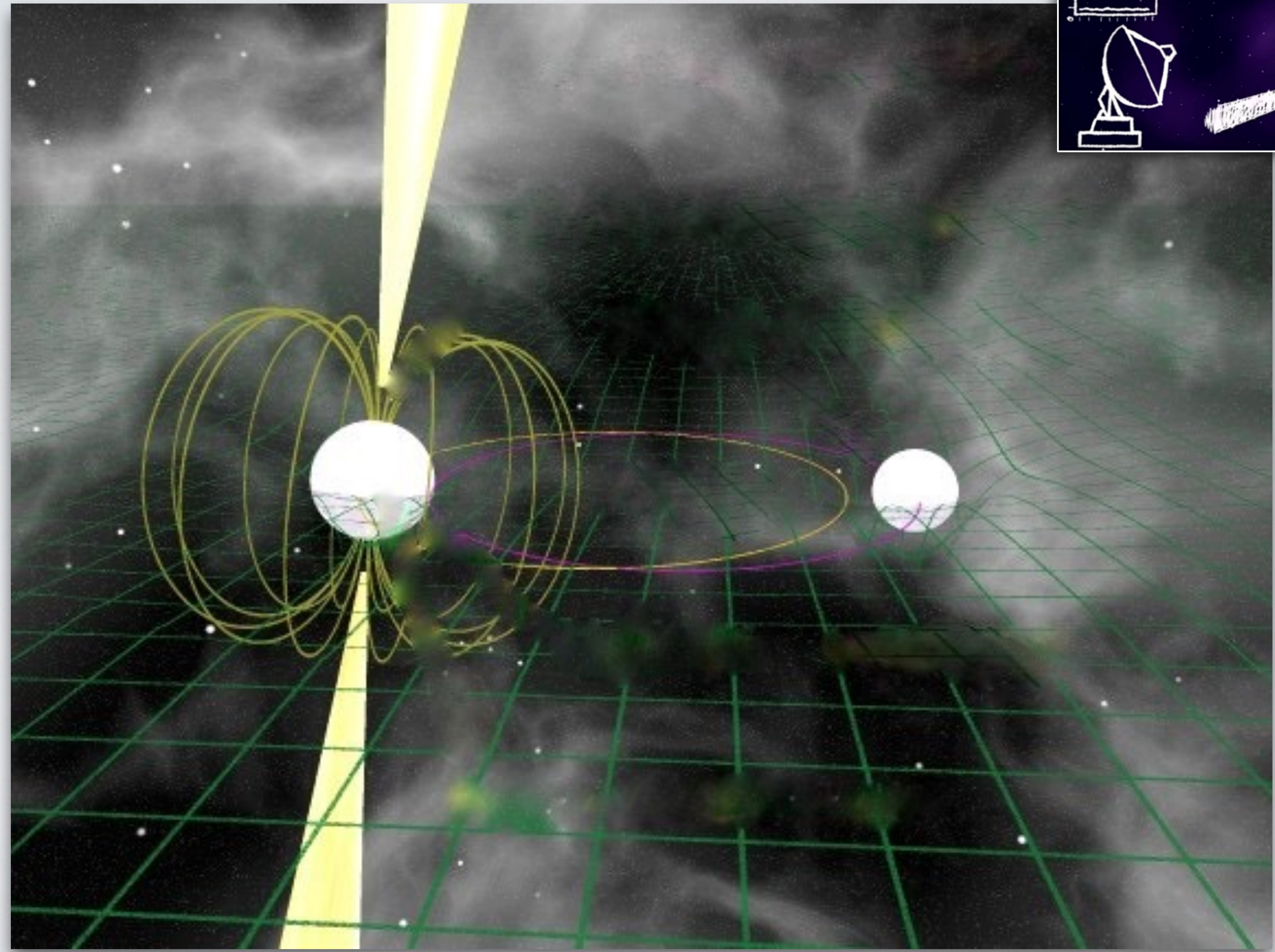
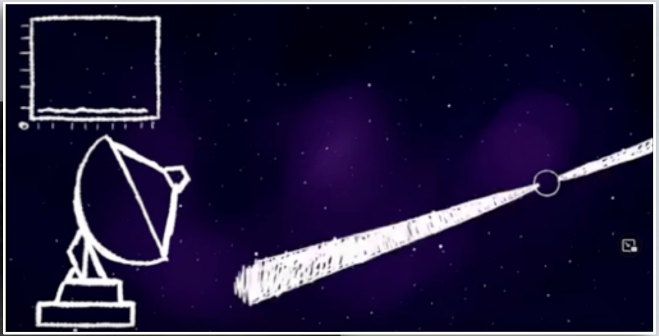
PULSARS

Recent results and next challenges towards the SKA

Marta Burgay - INAF Osservatorio Astronomico di Cagliari

The scientific impact of Pulsars





Stappers 2015

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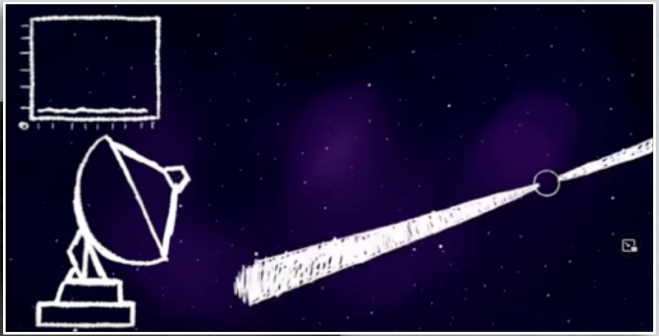

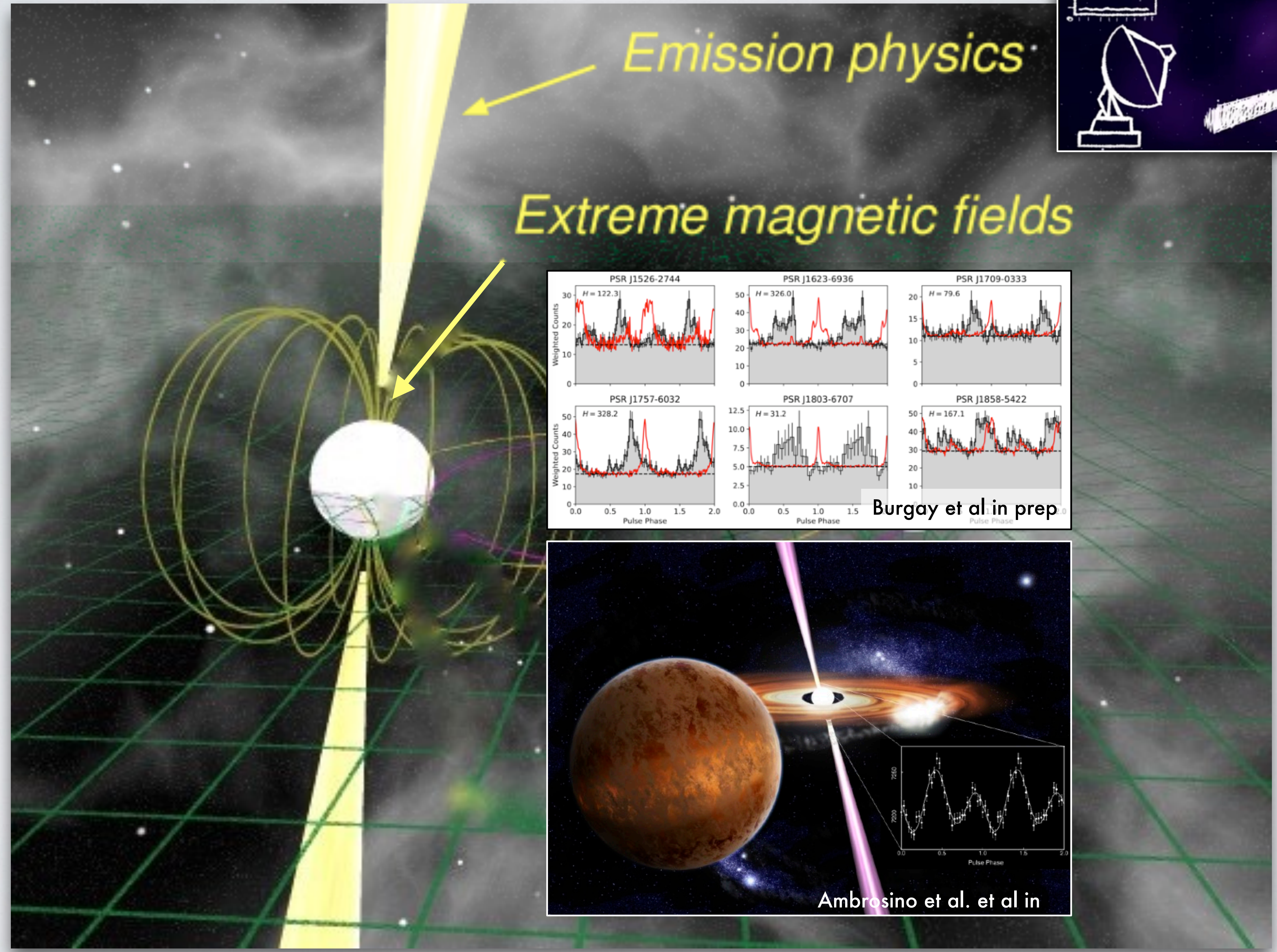

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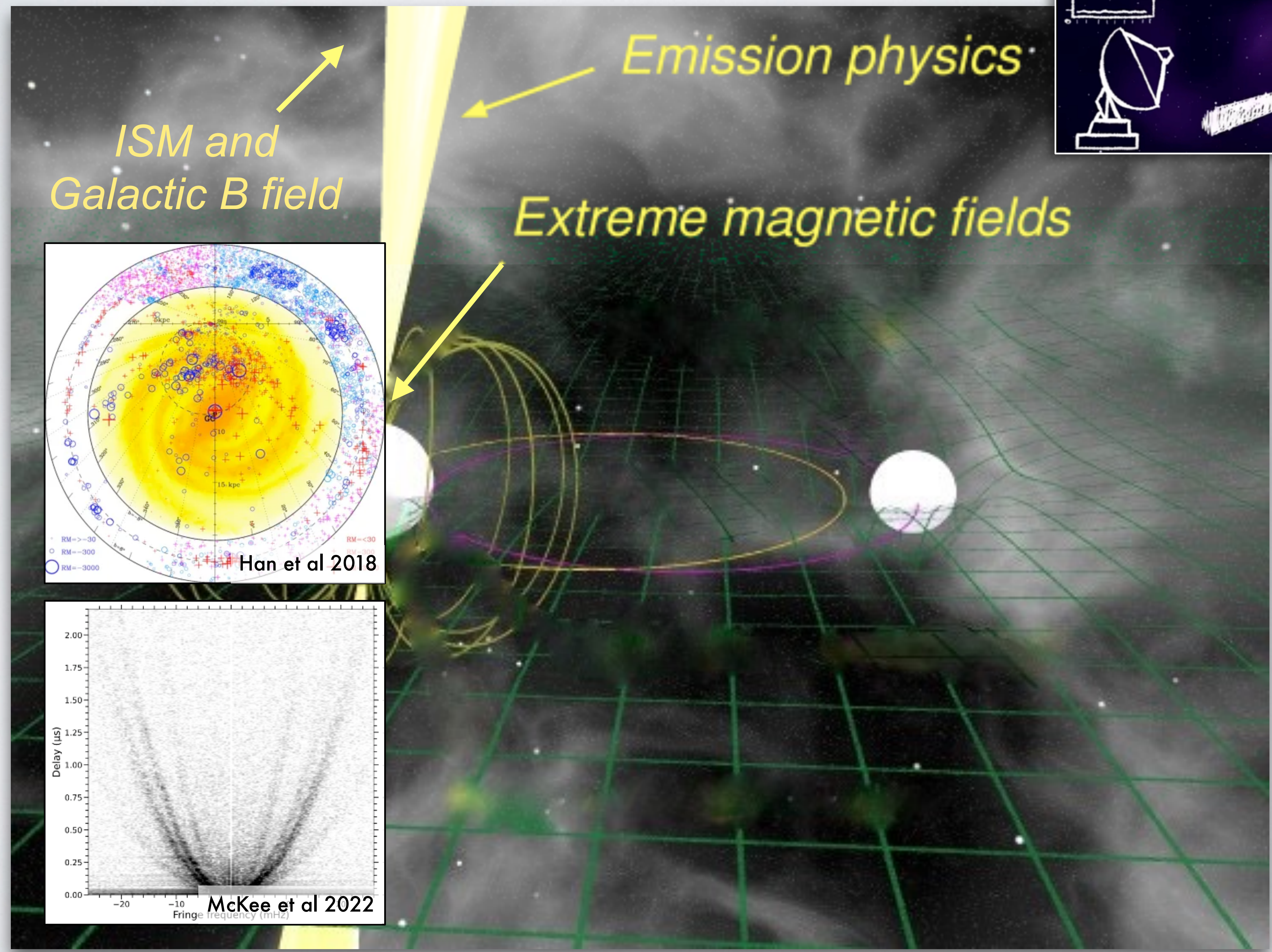

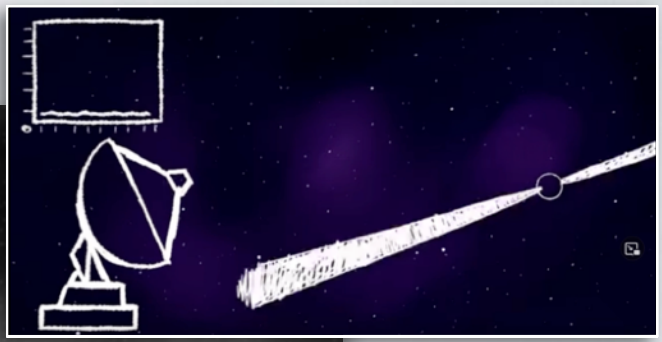

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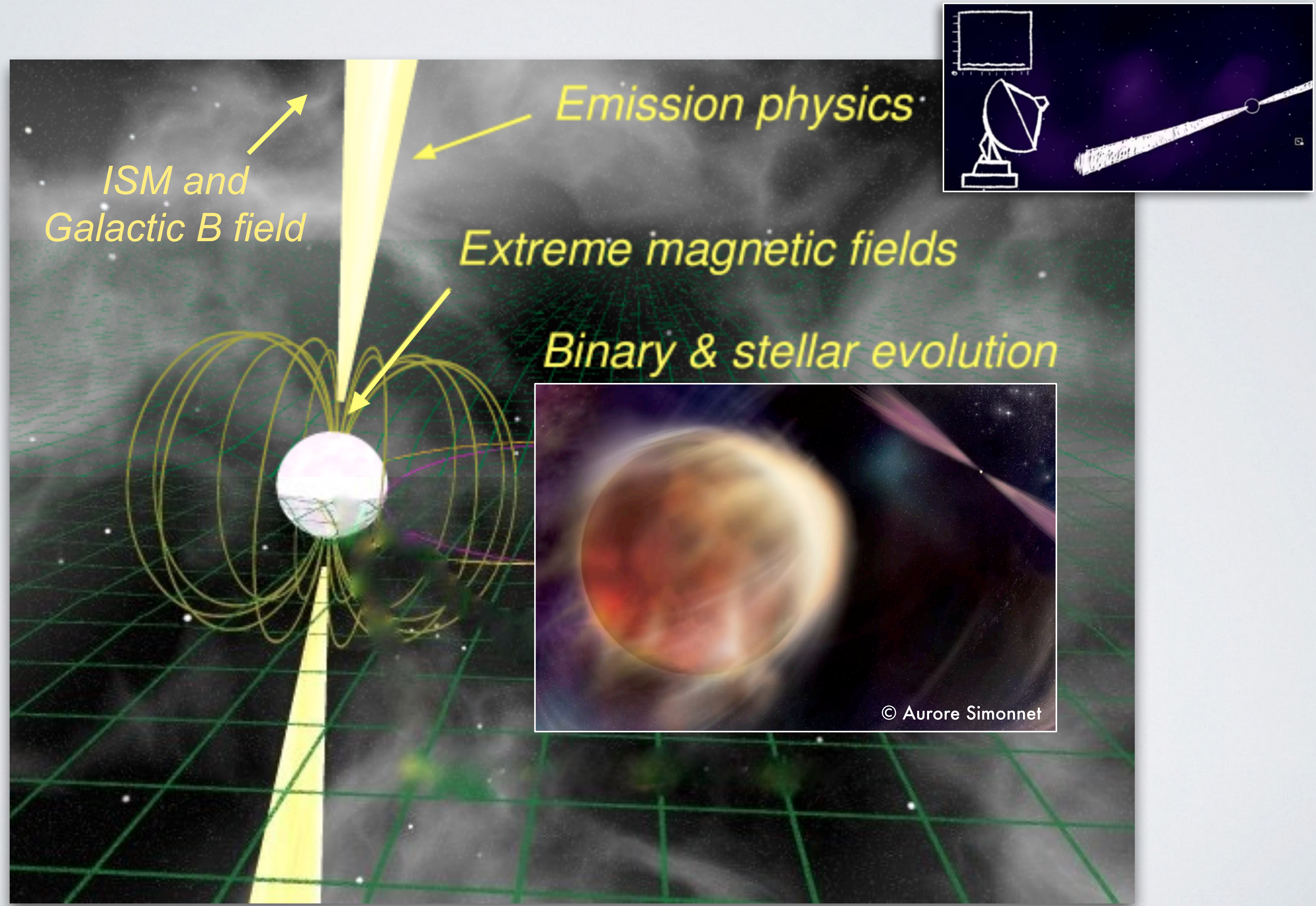

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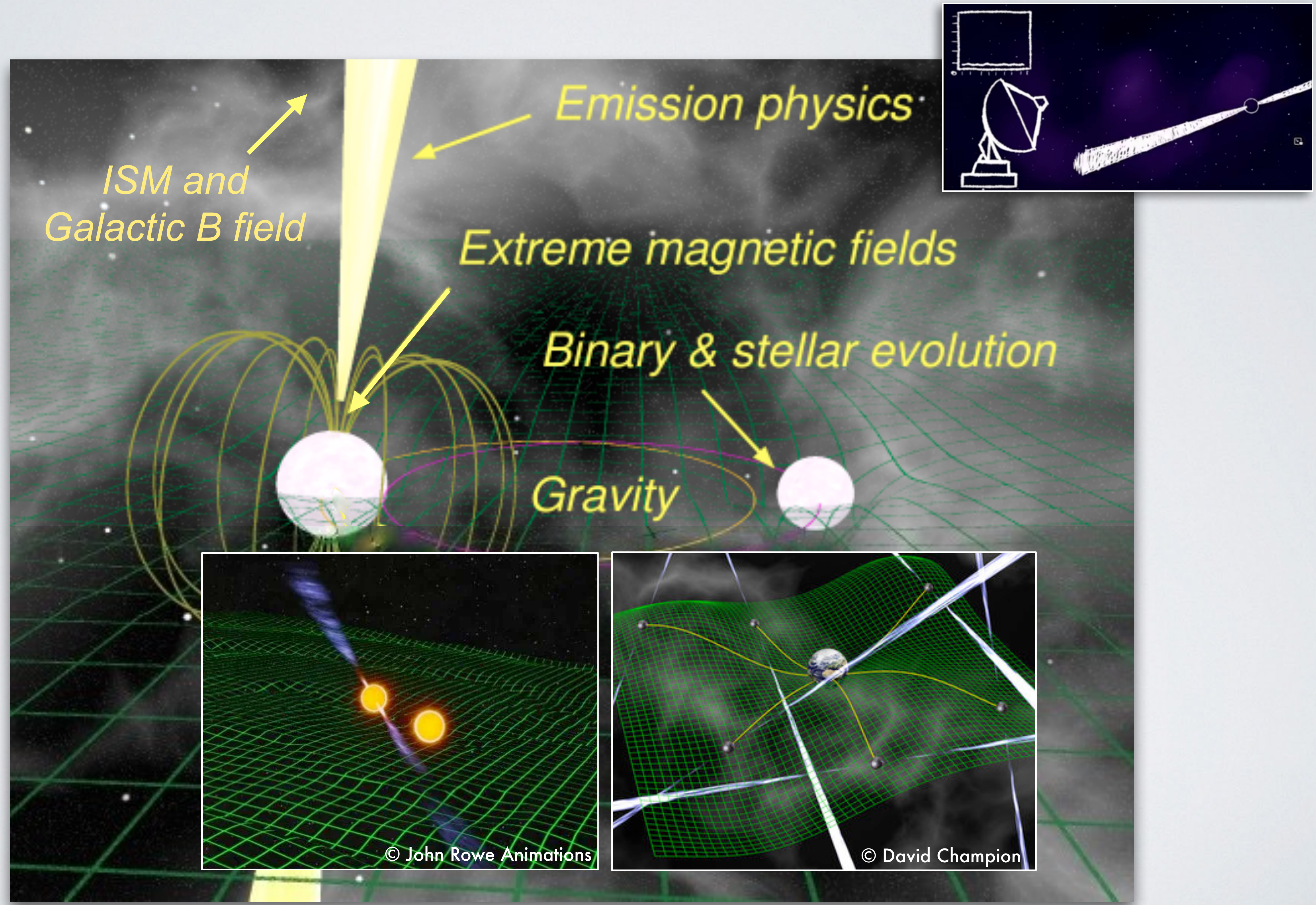

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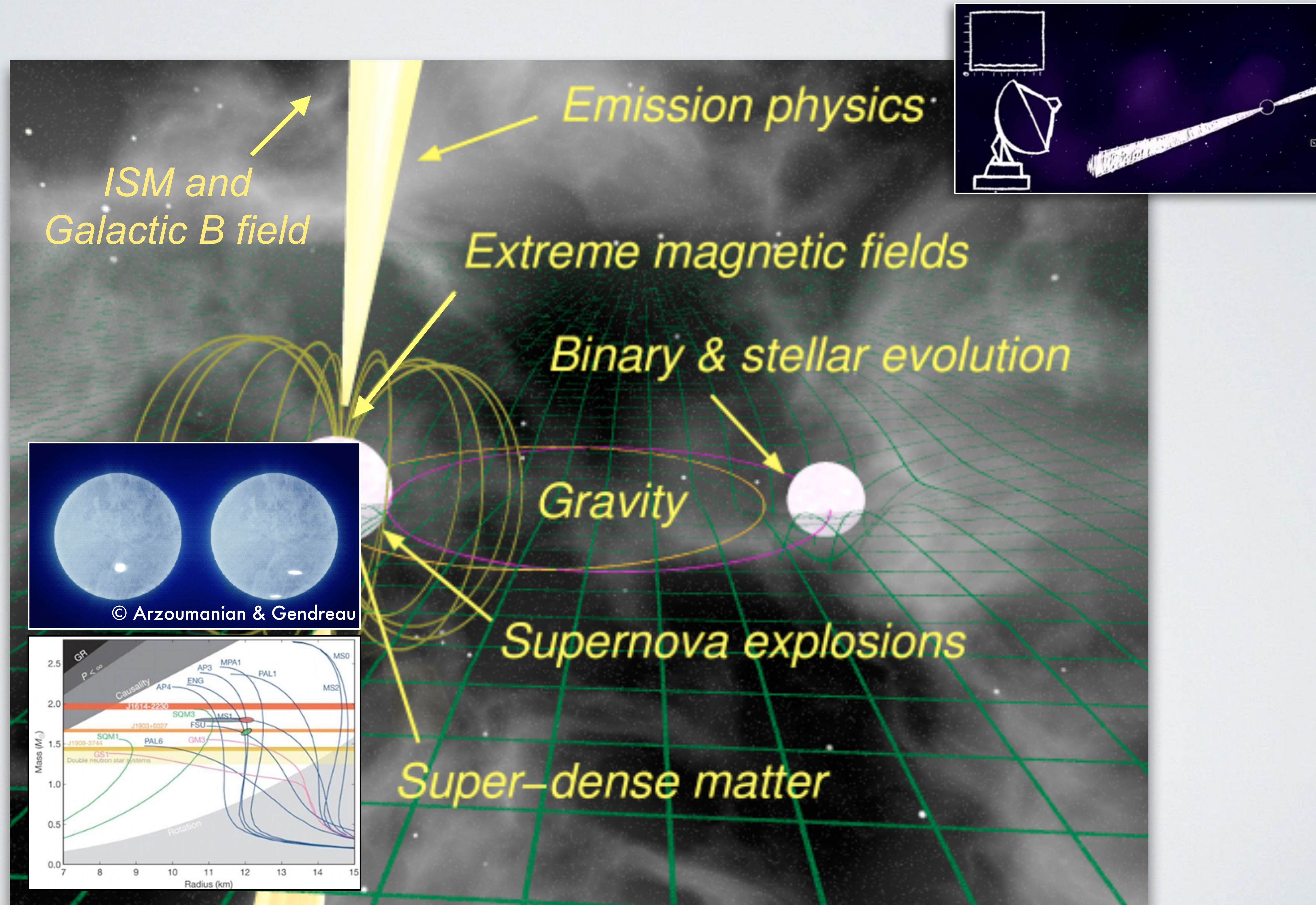

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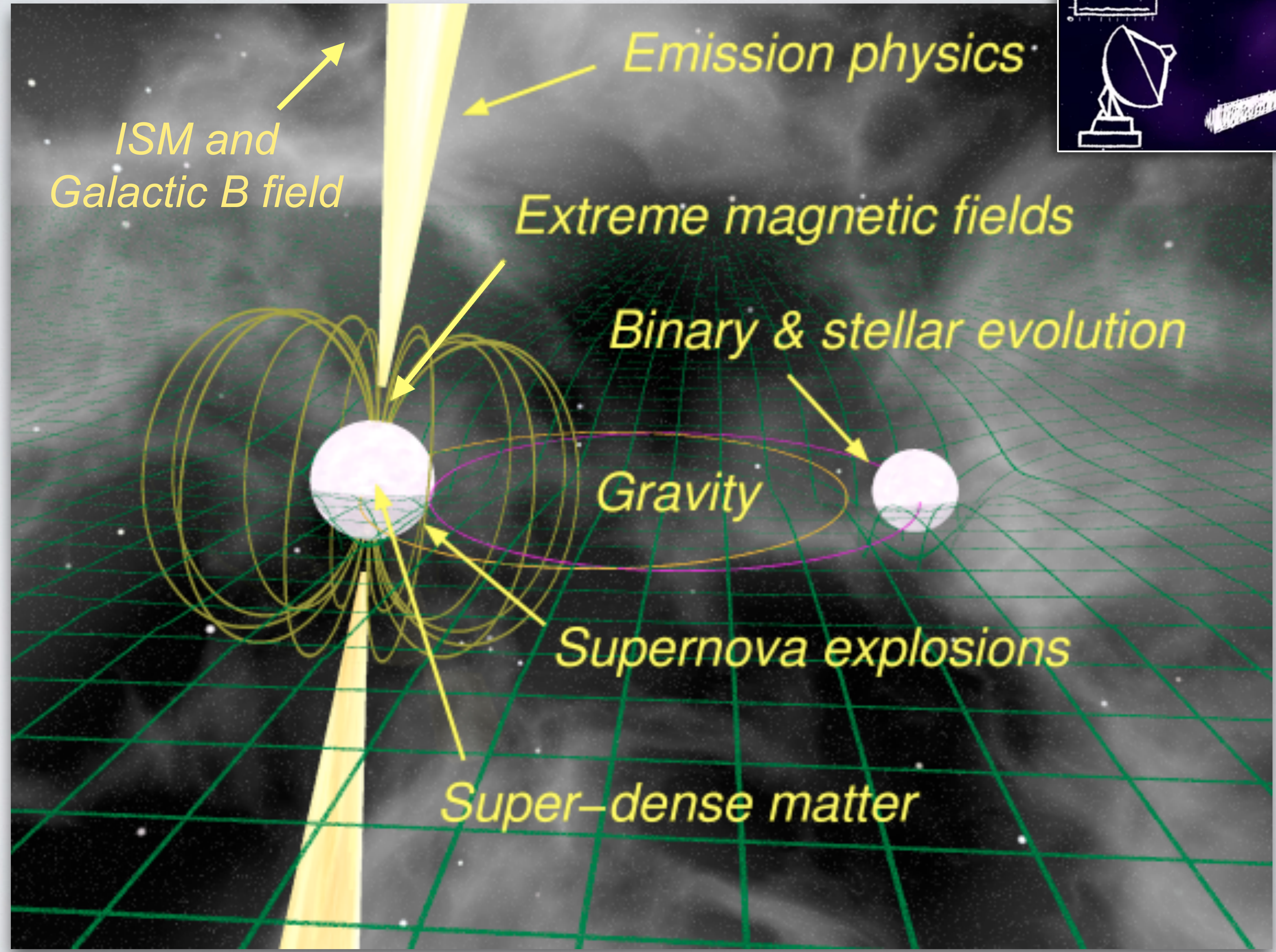
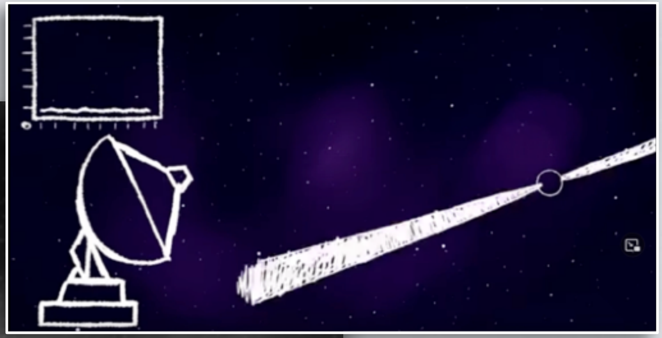
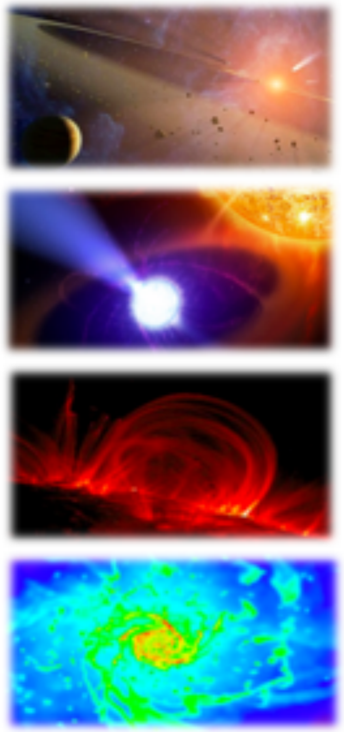




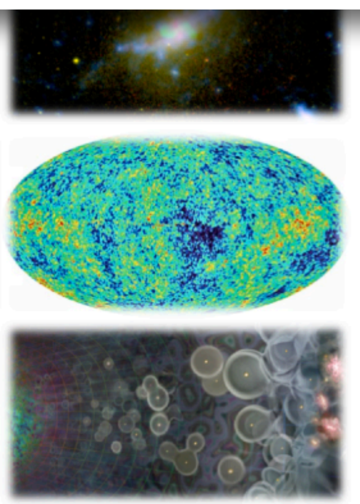
Stappers 2015

SKA Flagship Science

	SKA1	SKA2
The Cradle of Life & Astrobiology	Proto-planetary disks; imaging inside the snow/ice line (@ < 100pc), Searches for amino acids.	Proto-planetary disks; sub-AU imaging (@ < 150 pc), Studies of amino acids.
	Targeted SETI: airport radar 10^4 nearby stars.	Ultra-sensitive SETI: airport radar 10^5 nearby star, TV ~10 stars.
Strong-field Tests of Gravity with Pulsars and Black Holes	1st detection of nHz-stochastic gravitational wave background.	Gravitational wave astronomy of discrete sources: constraining galaxy evolution, cosmological GWs and cosmic strings.
	Discover and use NS-NS and PSR-BH binaries to provide the best tests of gravity theories and General Relativity.	Find all ~40,000 visible pulsars in the Galaxy, use the most relativistic systems to test cosmic censorship and the no-hair theorem.
The Origin and Evolution of Cosmic Magnetism	The role of magnetism from sub-galactic to Cosmic Web scales, the RM-grid @ 300/deg2.	The origin and amplification of cosmic magnetic fields, the RM-grid @ 5000/deg2.
	Faraday tomography of extended sources, 100pc resolution at 14Mpc, 1 kpc @ z = 0.04.	Faraday tomography of extended sources, 100pc resolution at 50Mpc, 1 kpc @ z = 0.13.
Galaxy Evolution probed by Neutral Hydrogen	Gas properties of 10^7 galaxies, <z> = 0.3, evolution to z = 1, BAO complement to Euclid.	Gas properties of 10^9 galaxies, <z> = 1, evolution to z = 5, world-class precision cosmology.
	Detailed interstellar medium of nearby galaxies (3 Mpc) at 50pc resolution, diffuse IGM down to N_H < 10^17 at 1 kpc.	Detailed interstellar medium of nearby galaxies (10 Mpc) at 50pc resolution, diffuse IGM down to N_H < 10^17 at 1 kpc.



The Transient Radio Sky	Use	
	S cos	
Galaxy Evolution probed in the Radio Continuum	Sta	
	Resolved star formation astrophysics (sub-kpc active regions at z ~ 1).	Resolved star formation astrophysics (sub-kpc active regions at z ~ 6).
Cosmology & Dark Energy	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: competitive to Euclid.	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: redefines state-of-art.
	Primordial non-Gaussianity and the matter dipole: 2x Euclid.	Primordial non-Gaussianity and the matter dipole: 10x Euclid.
Cosmic Dawn and the Epoch of Reionization	Direct imaging of EoR structures (z = 6 - 12).	Direct imaging of Cosmic Dawn structures (z = 12 - 30).
	Power spectra of Cosmic Dawn down to arcmin scales, possible imaging at 10 arcmin.	First glimpse of the Dark Ages (z > 30).



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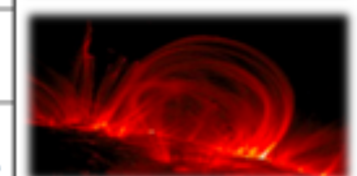
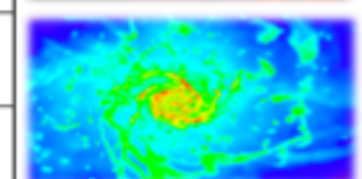

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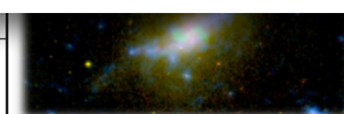
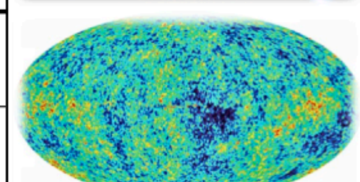
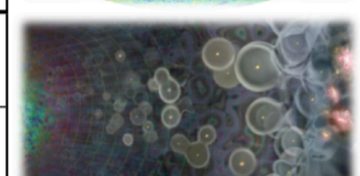

Testing GR with pulsars

The current best laboratory - PSR J0737-3039A/B

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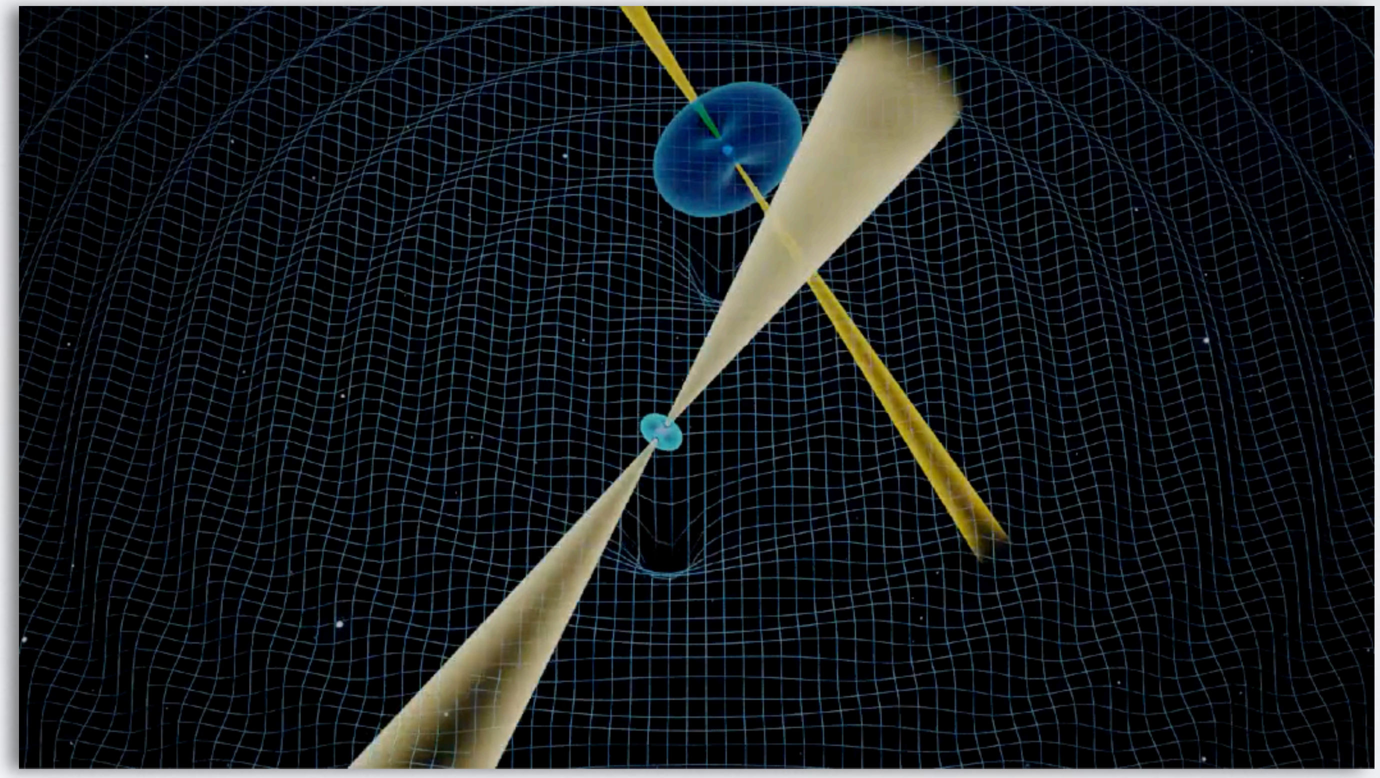
Discovered in 2003 [Burgay et al '03; Lyne et al. '04]

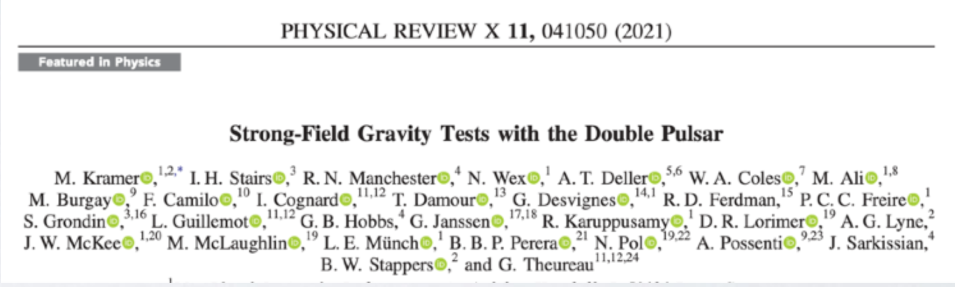
- PSR+PSR
- $P_{spin}A = 23$ ms
- $P_{spin}B = 2.7$ s
- $P_{orb} = 2.4$ hr
- Ecc = 0.09
- Orb v = 0.001 c
- i = 89.35°



System showing the largest number of relativistic effects

GR WITH THE DOUBLE PULSAR

- Kramer et al 2021: 1 million ToAs
- Precision higher than ever!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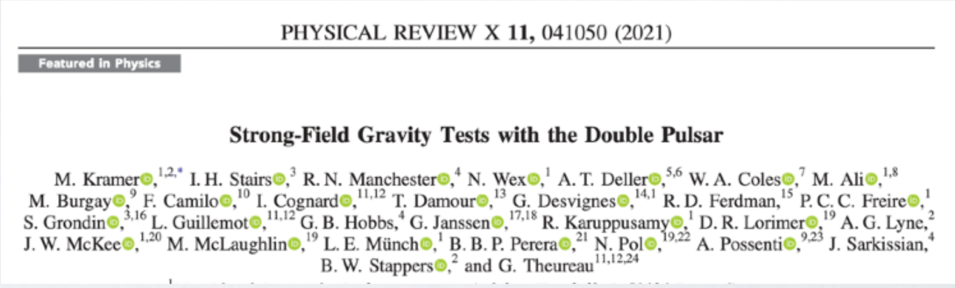
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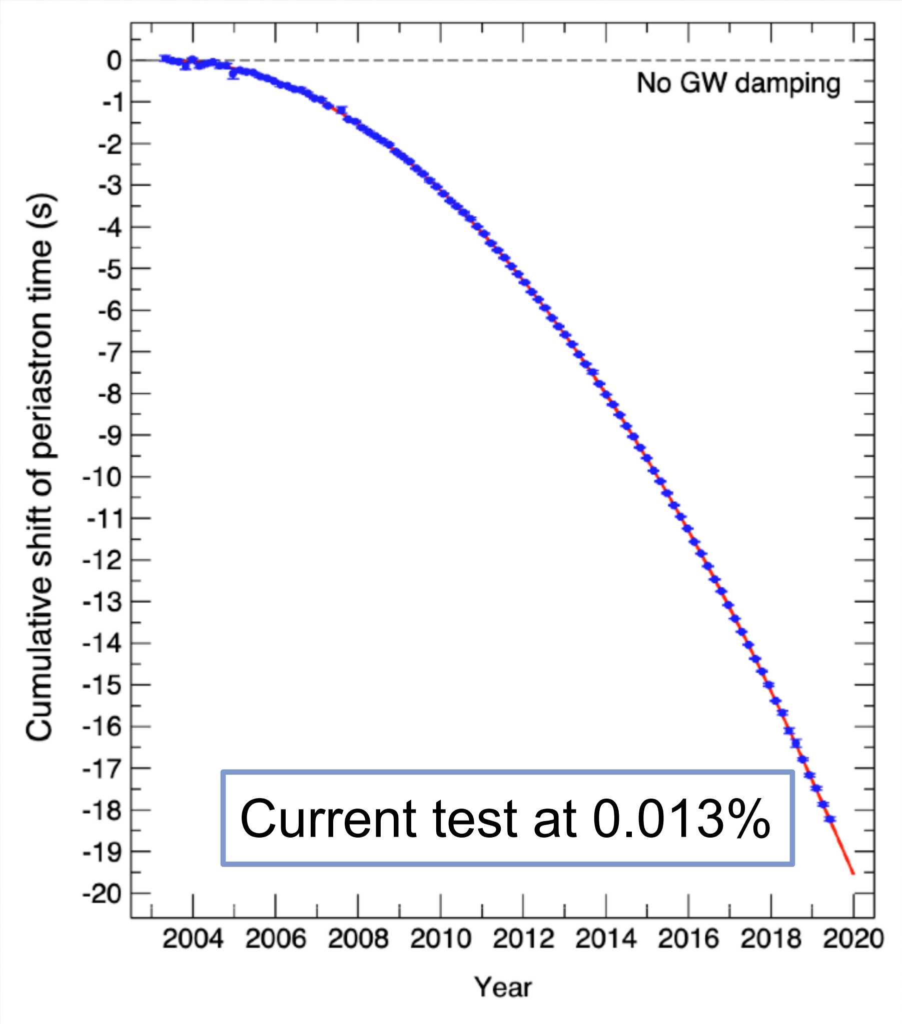

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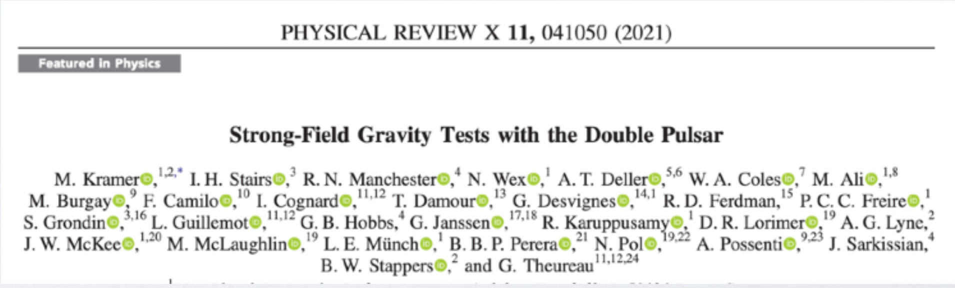
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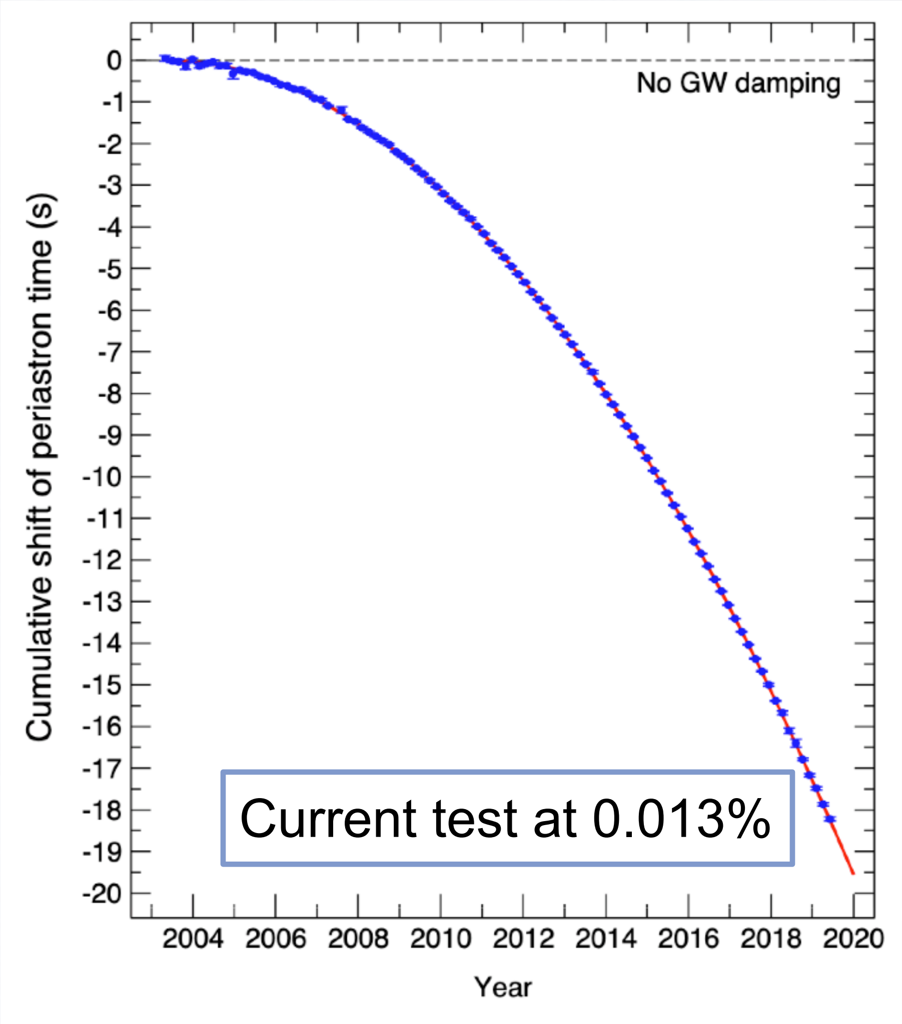
Orbit shrinks by 7 mm/day

Precision so high that we need to take into account relativistic mass loss

8.4 Million tons/s — 3.2 x 10^{-21} M_A/s



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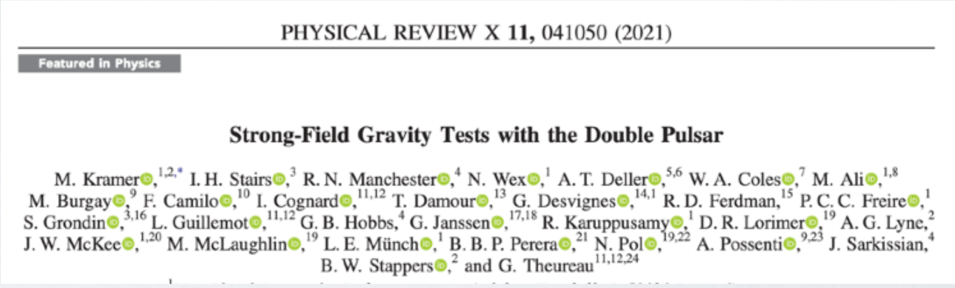
2. Need to go beyond first order



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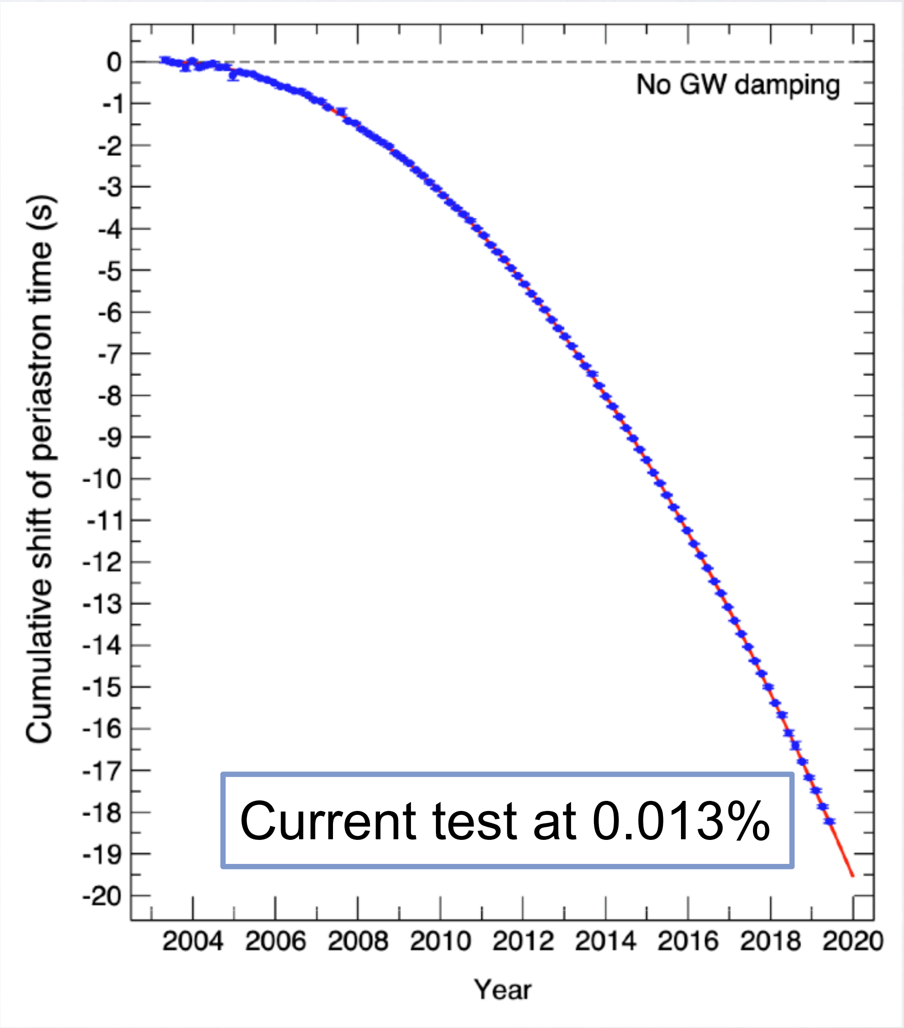
Periastron advance $\dot{\omega}$ = 16.899323(13)

Orbit has precessed by >300 deg
2PN contribution at 35σ



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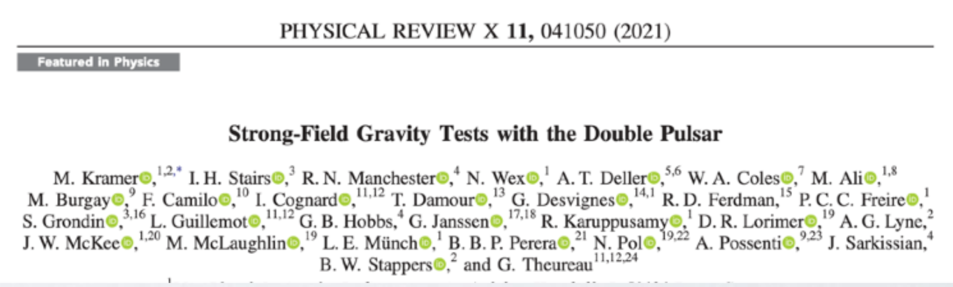

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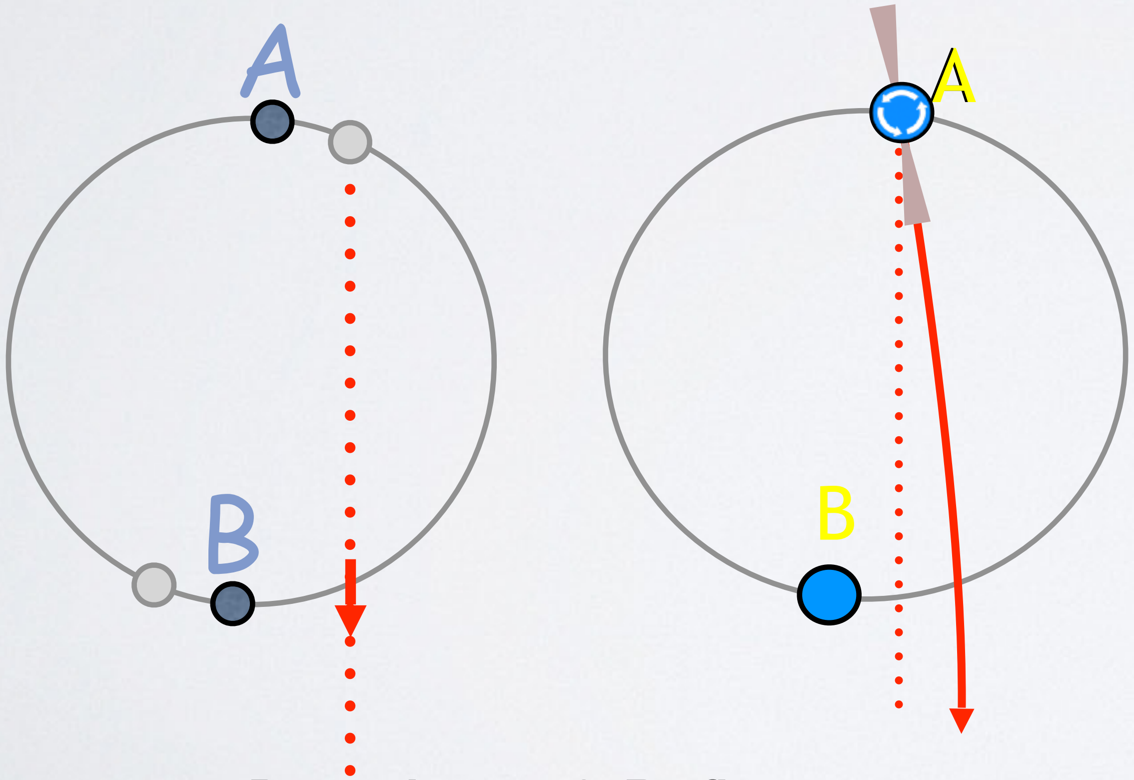
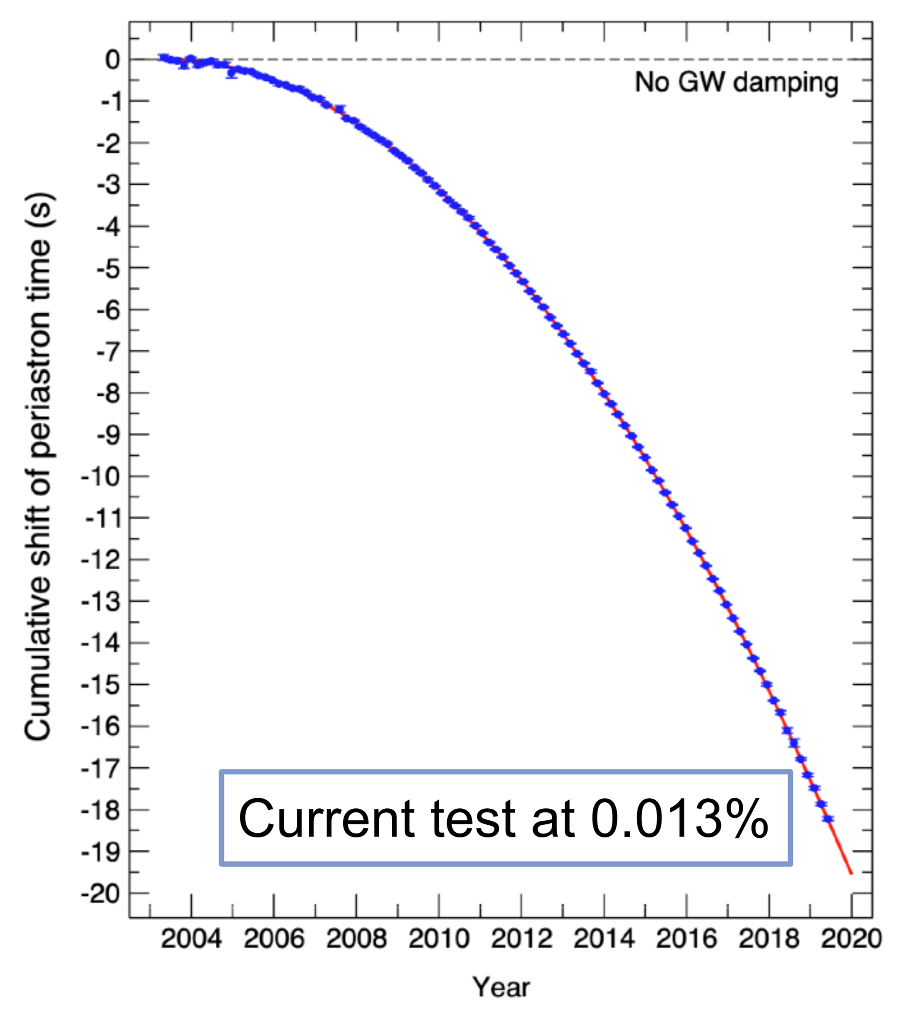


Retardation & Deflection



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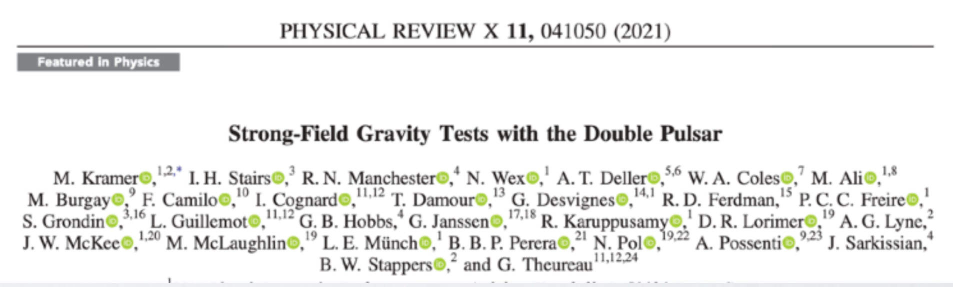

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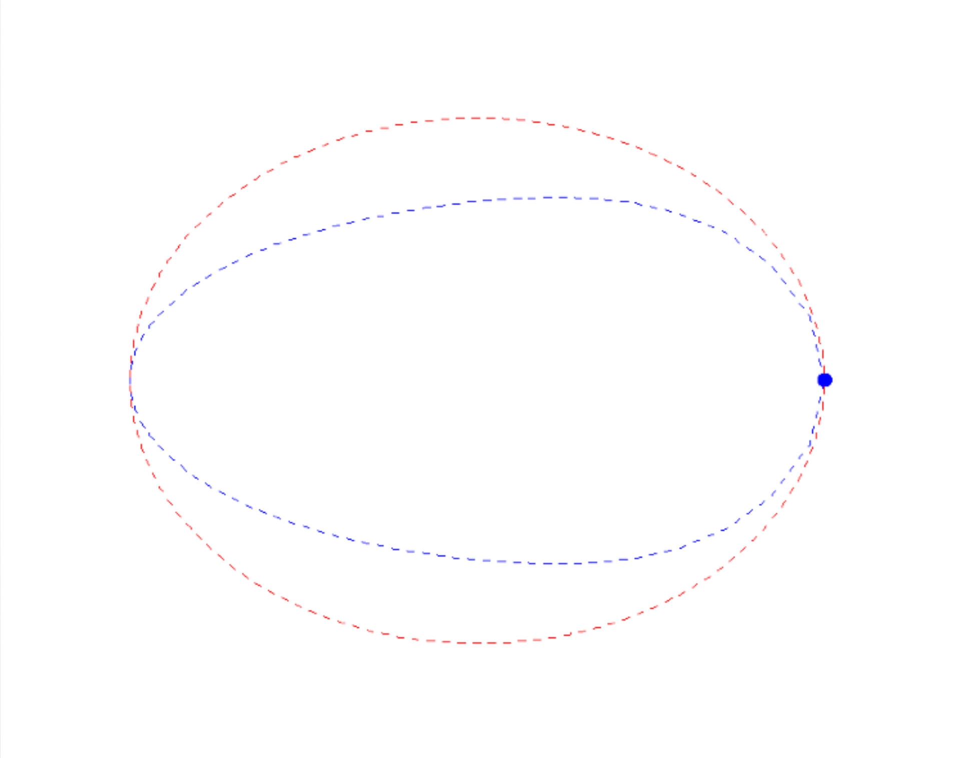

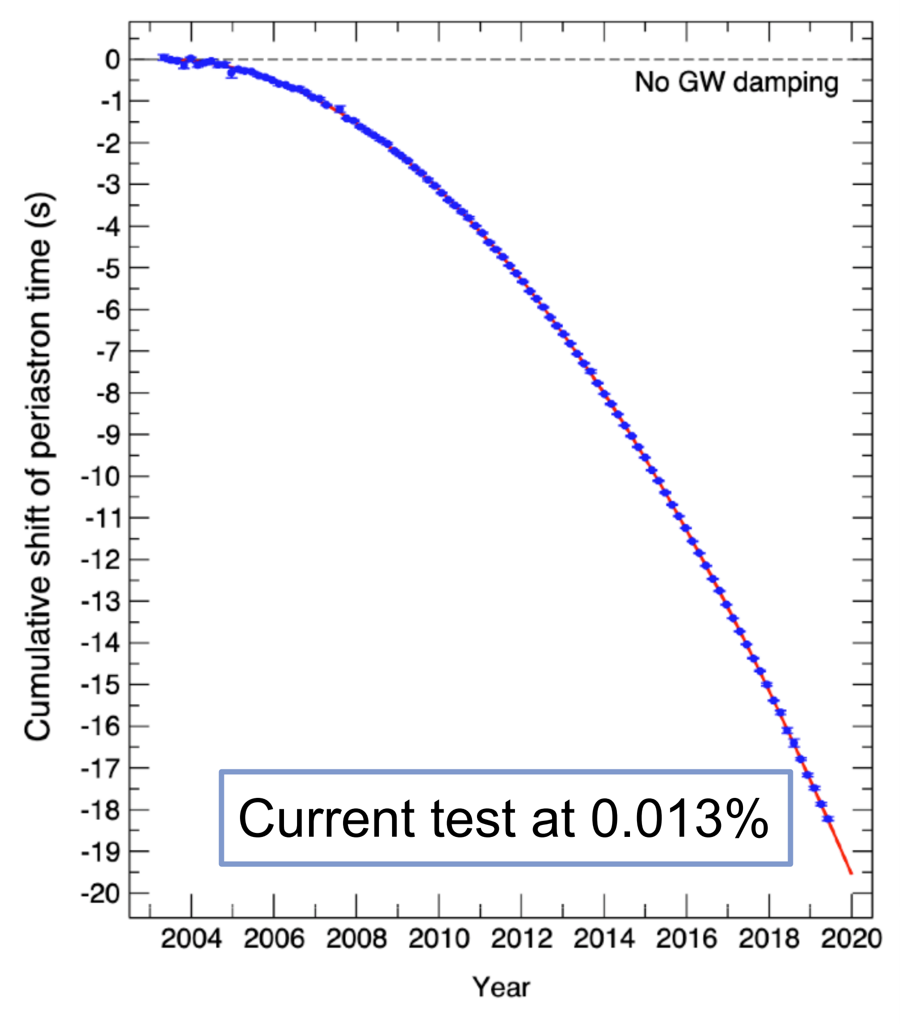

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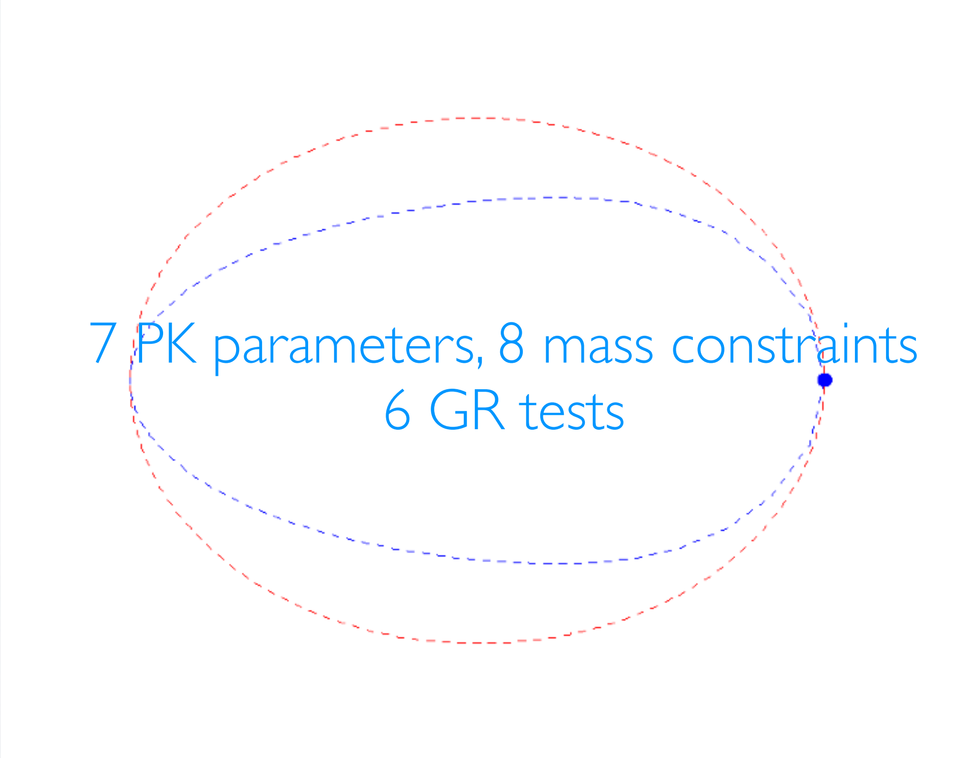
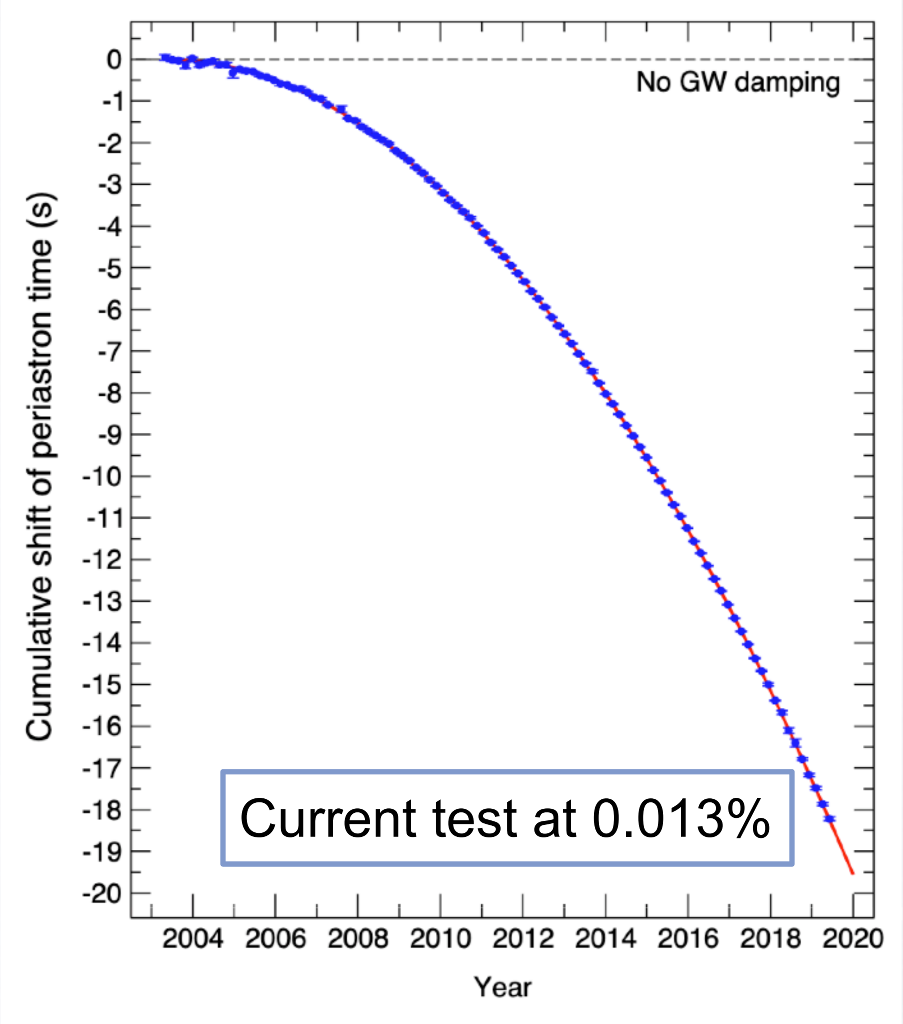
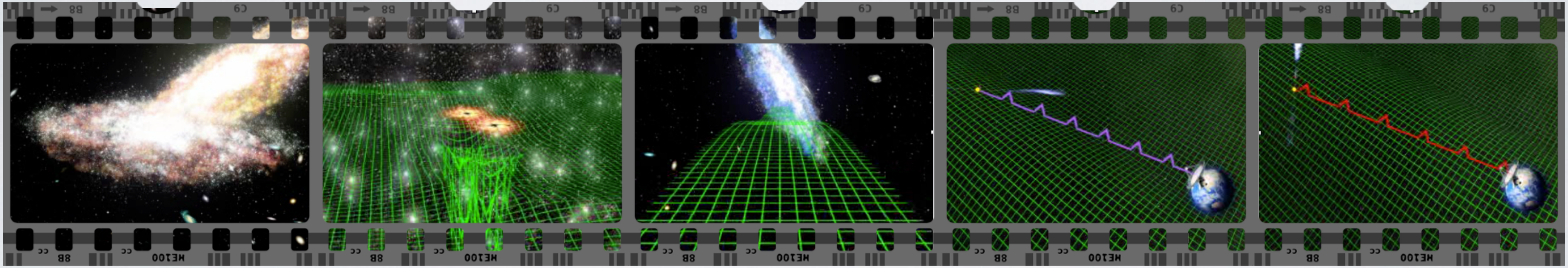




DETECTING GW WITH PULSARS

Basic idea: use the Earth-pulsar path as a Galaxy-sized arm of a cosmic detector on nHZ GWs from SMBHBs

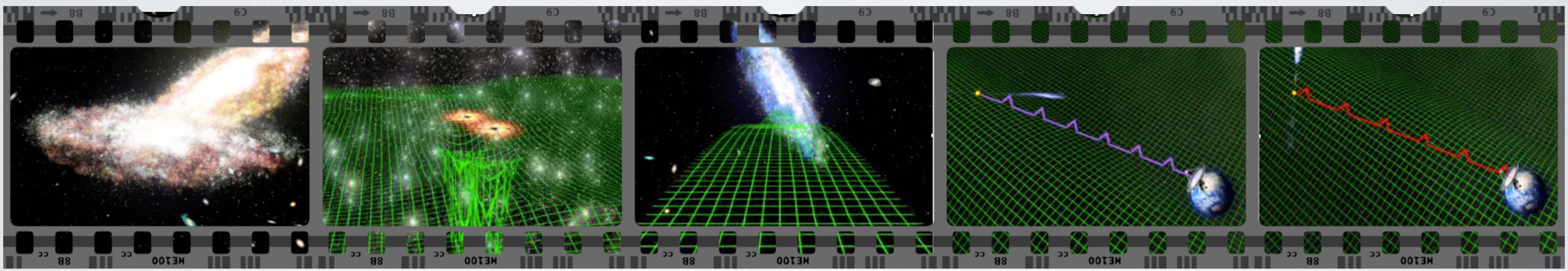


ATNF - John Rowe Animations

Perturbations in space-time can be detected in pulse times of arrival over a suitable long observation time span

DETECTING GW WITH PULSARS

Basic idea: use the Earth-pulsar path as a Galaxy-sized arm of a cosmic detector on nHZ GWs from SMBHBs



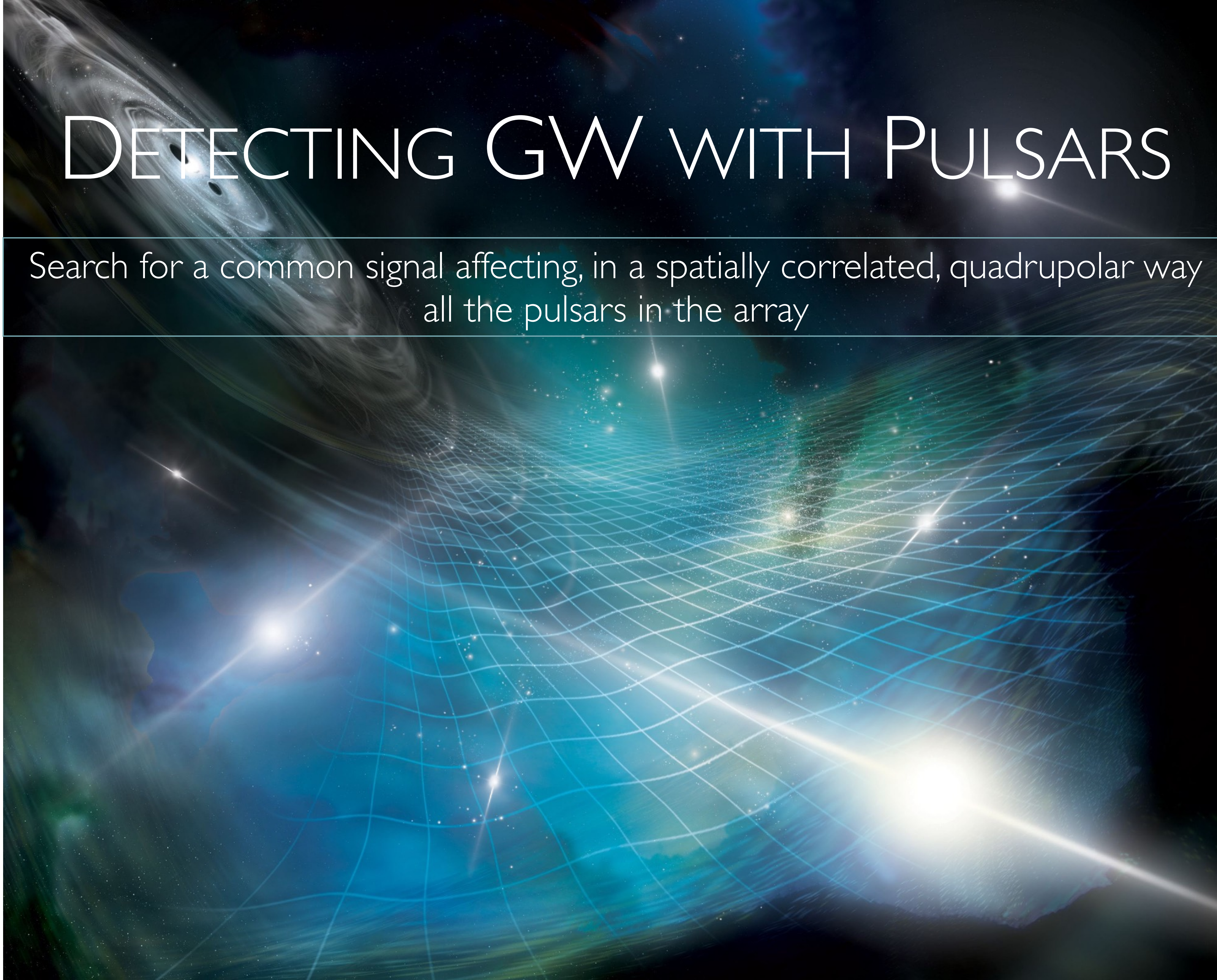
ATNF - John Rowe Animations

Perturbations in space-time can be detected in pulse times of arrival over a suitable long observation time span

A single pulsar is not enough -> Pulsar Timing Array

DETECTING GW WITH PULSARS

Search for a common signal affecting, in a spatially correlated, quadrupolar way all the pulsars in the array



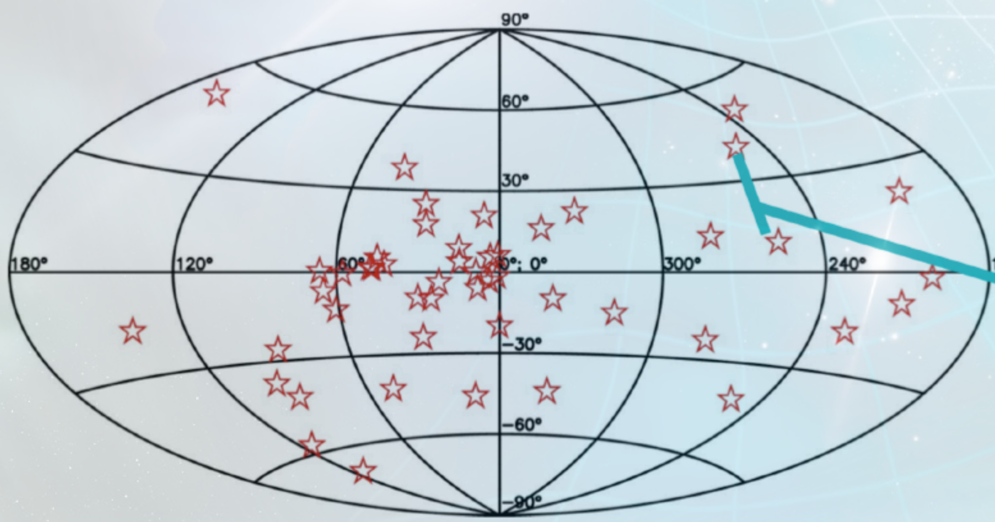
Detecting GW with Pulsars

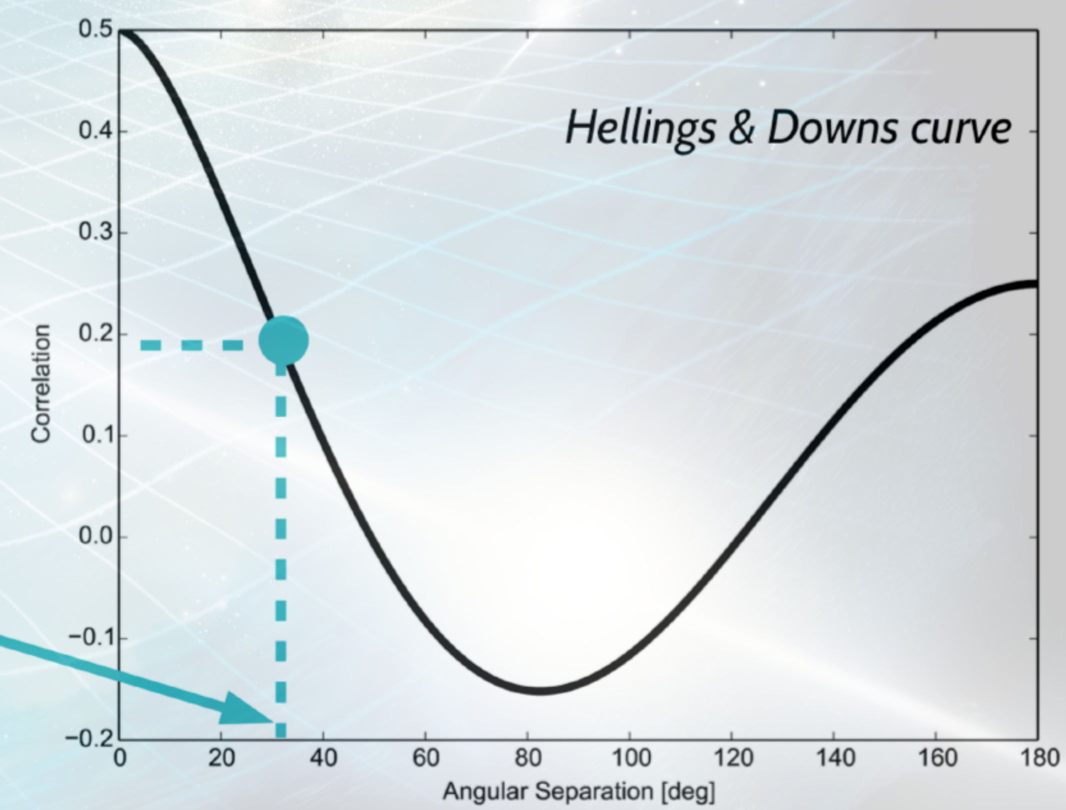
Search for a common signal affecting, in a spatially correlated, quadrupolar way all the pulsars in the array

Hellings and Downs (1983) derived an expression for the
angular correlation between pulsar timing residuals induced by a GWB

$$\zeta(\theta_{ij}) = \frac{3}{2} x \log(x) - \frac{x}{4} + \frac{1}{2}$$

$$x = [1 - \cos(\theta_{ij})]$$





Verbiest+2016

PTA Collaborations

PTA Collaborations

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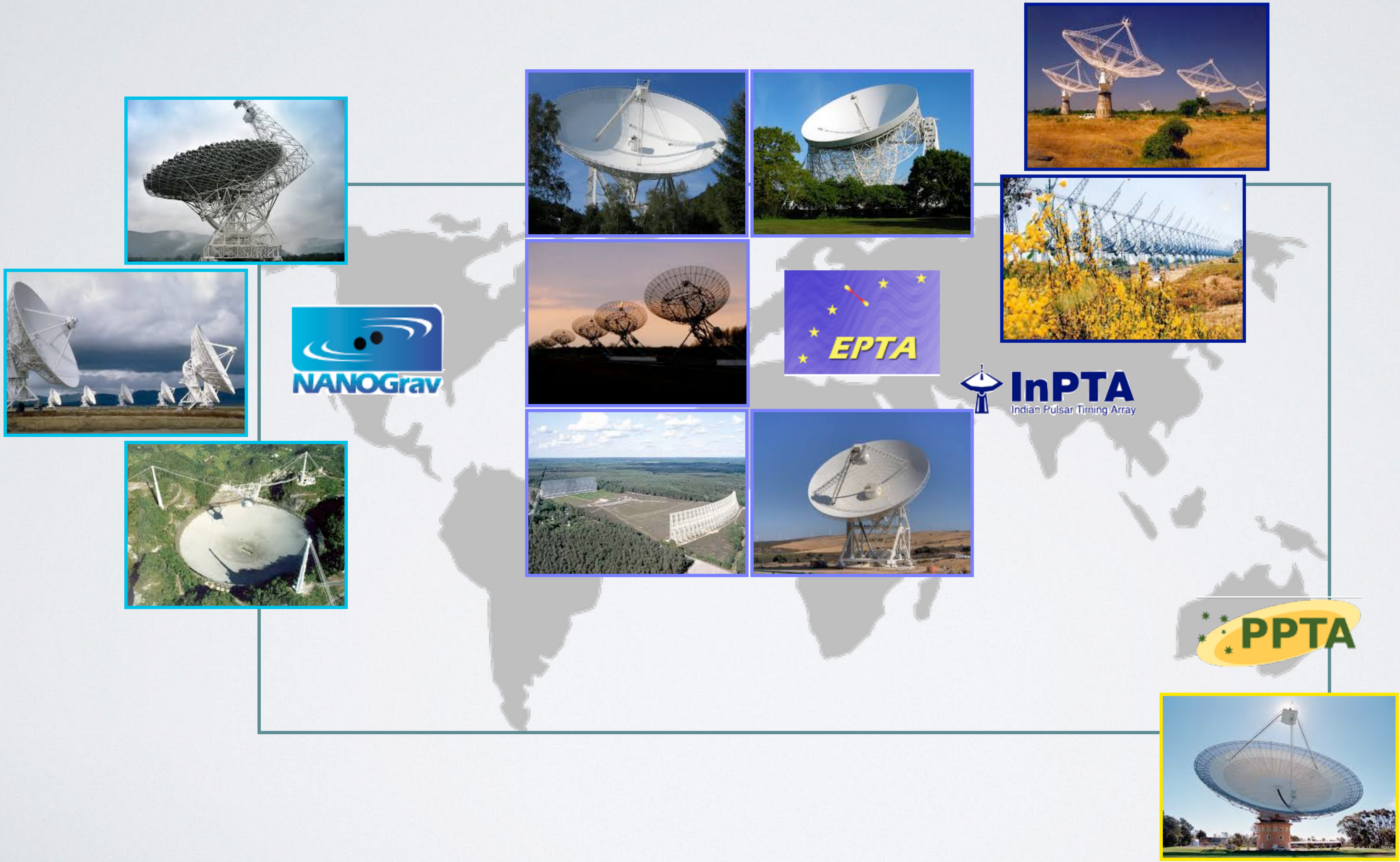

PTA Collaborations

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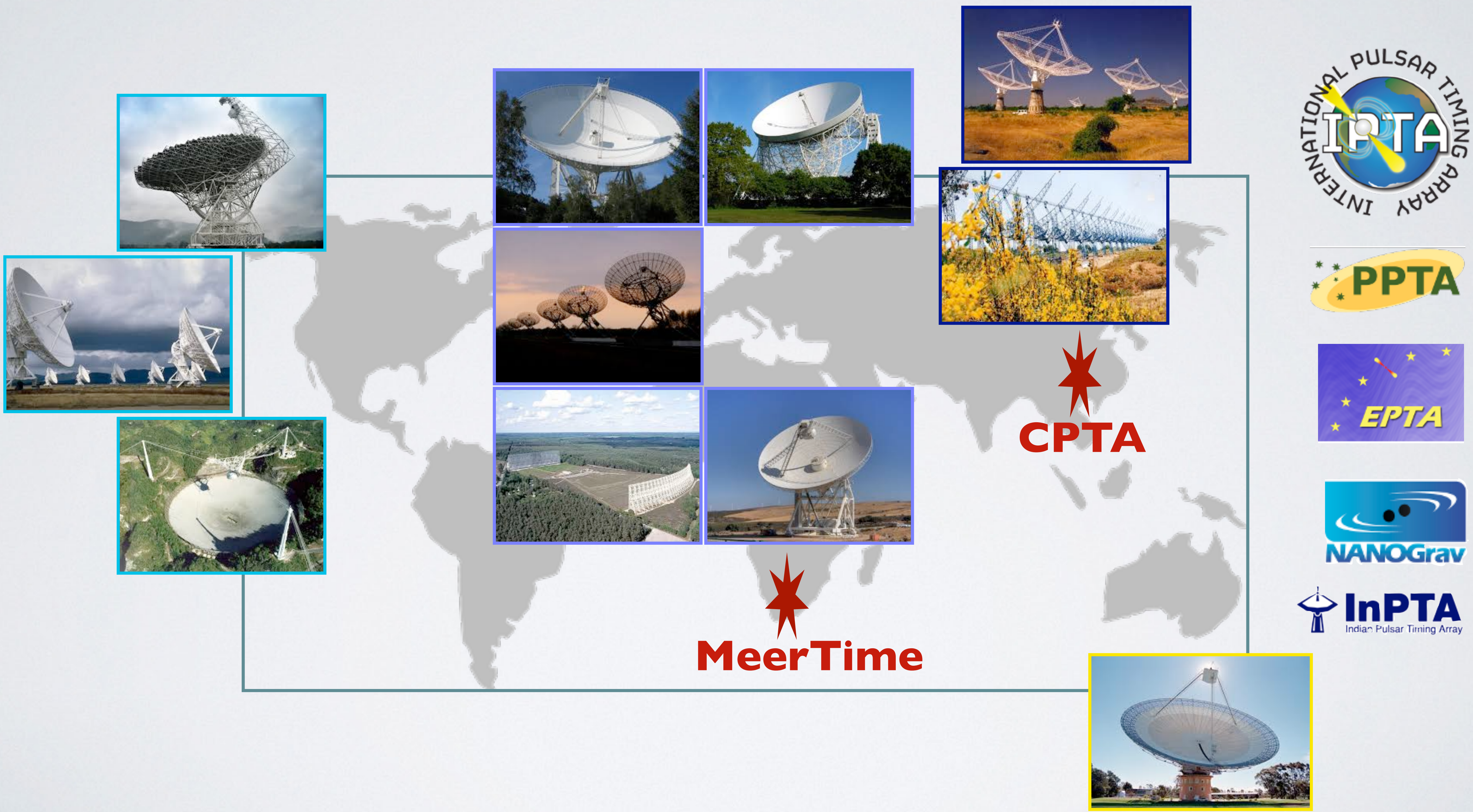
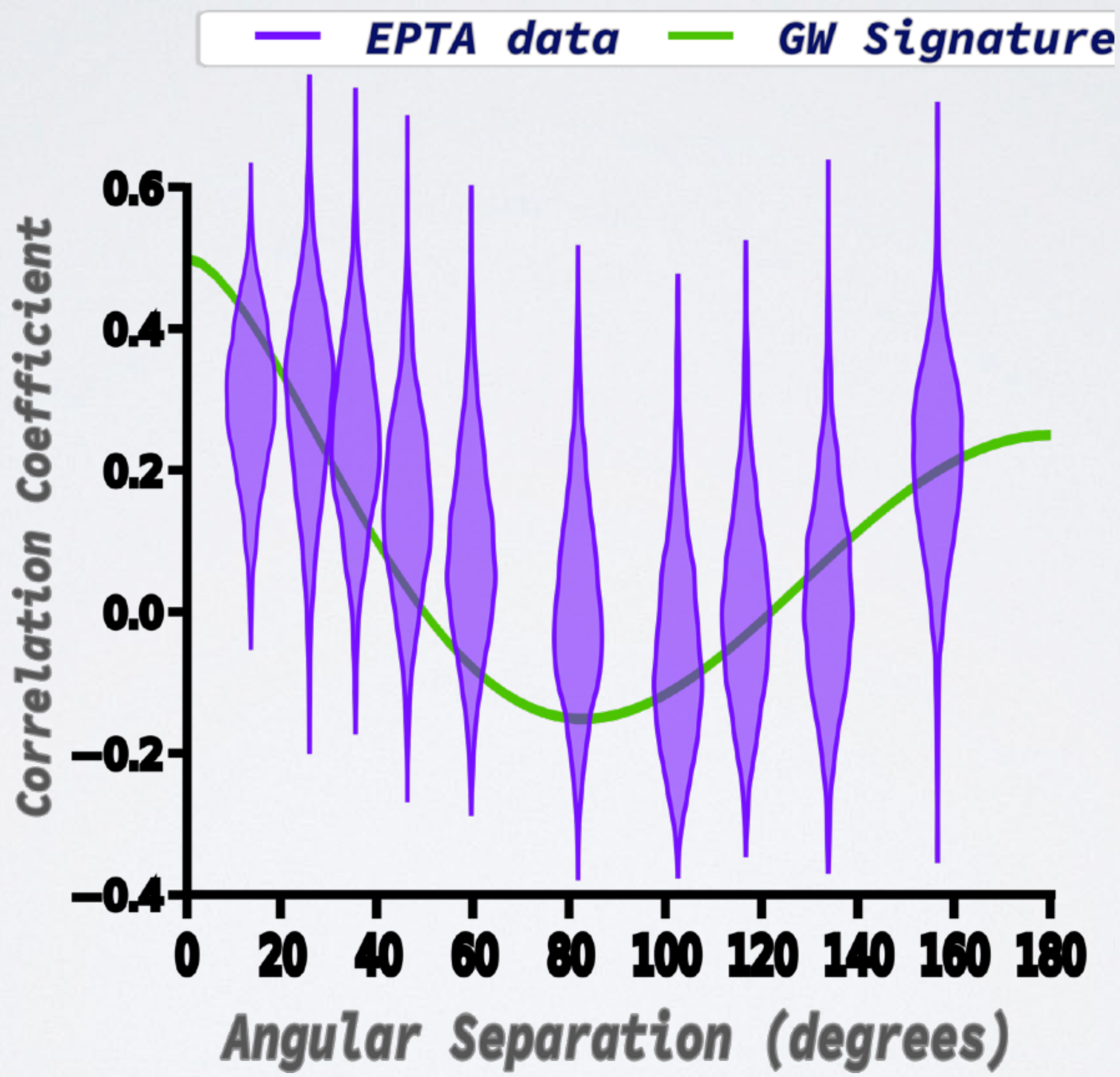


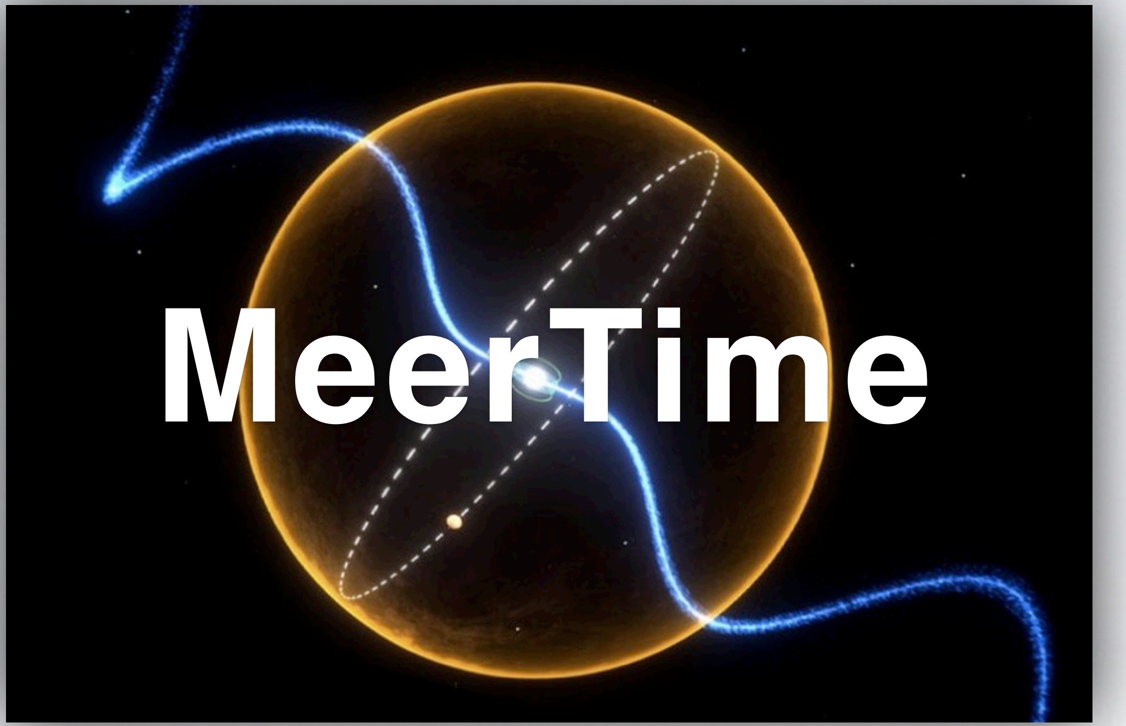
PTA RESULTS

PTA RESULTS



Antoniadis et al 2023

Pulsars with MeerKAT



Timing

TRAPUM

Transients and Pulsars with MeerKAT

Searching

Pulsars with MeerKAT

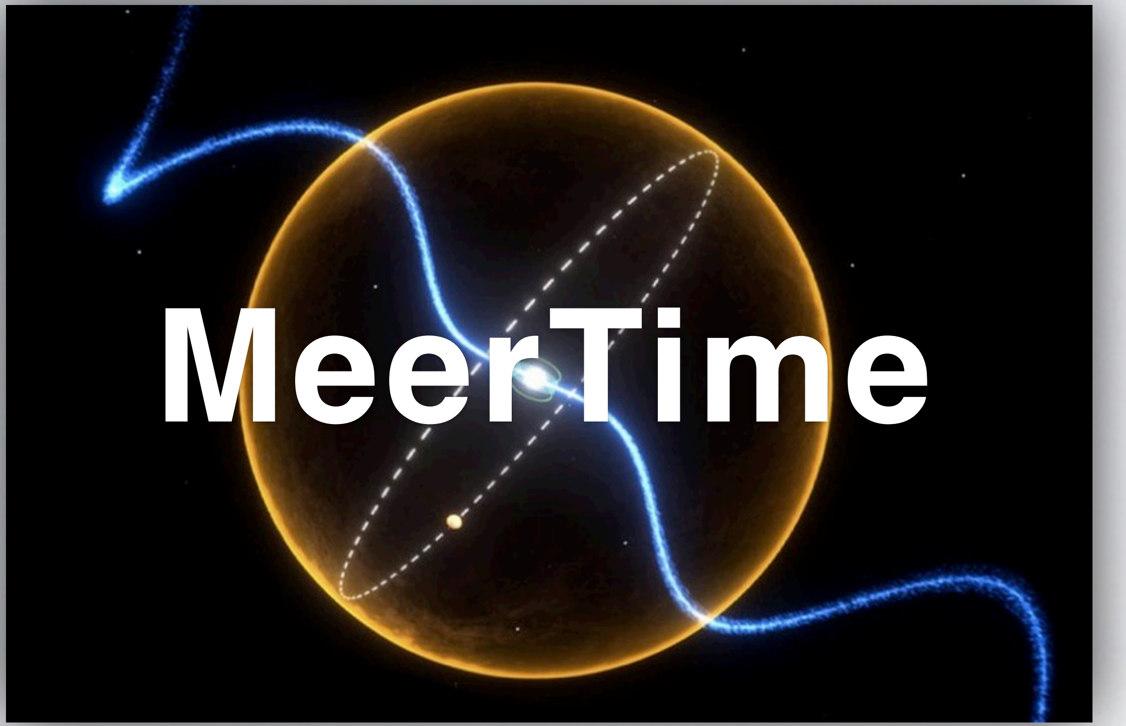
TRAPUM
Transients and Pulsars with MeerKAT

Timing

1. Relativistic and Binary Pulsars
2. PTA for GW detection
3. Globular Cluster Pulsars
4. The 1000 Pulsar Array

Searching

Pulsars with MeerKAT



TRAPUM
Transients and Pulsars with MeerKAT

Timing

1. Relativistic and Binary Pulsars
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Searching

1. SNRs,PWNe,TeV
2. Fermi un-ID sources
3. Globular Clusters
4. Nearby Galaxies
5. Transients (fly's eye+repeaters)

PULSARS WITH MEERKAT

TRAPUM

Transients and Pulsars with MeerKAT

TOTAL DISCOVERIES: 220

EXGAL: 14	**FERMI:** 36	**GC:** 87	**MMGPS-L:** 78	**MMGPS-S:** 3	**TEV/SNR /PWNE:** 2

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PULSARS WITH MEERKAT

TRAPUM Transients and Pulsars with MeerKAT

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GCs

TRAPUM+MeerTime discovered a pulsar with a companion in the NS-BH mass gap (Dutta et al. Science, in press)

Pulsars with MeerKAT

GCs

TRAPU[illegible]eerTime
discov[illegible]d a pul[illegible]r with
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Scie[illegible]e in [illegible]ress)

Pulsars with MeerKAT

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Double Pulsar

3 years of MeerKat rival 16 years results in NLO signal propagation effects (Hu et al 2022)

Pulsars with MeerKAT

GCs

TRAPU[illegible]eerTime discov[illegible]d a pul[illegible]r with a comp[illegible]an[illegible]he NS-BH mass ga[illegible]tta et al. Scie[illegible]e in [illegible]ress)

Double Pulsar

3 years of MeerKat rival 16 years results in NLO signal propagation effects (Hu et al 2022)

MeerKAT PTA

3.8 years of MeerKat already giving compelling results. In 2025 MK should account for 50% of IPTA sensitivity to GWs

Long Period pulsars at MWA

GLEAM-X J162759.5-523504

- P 18 min
- Highly linearly polarised
- L_radio > spindown energy
- Active 2 months in 2018
- Above the death-line

GPM J1839–10

- P 21 min
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- Active for at least 35 years
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Hurley-Walker et al 2022; 2023, Nature

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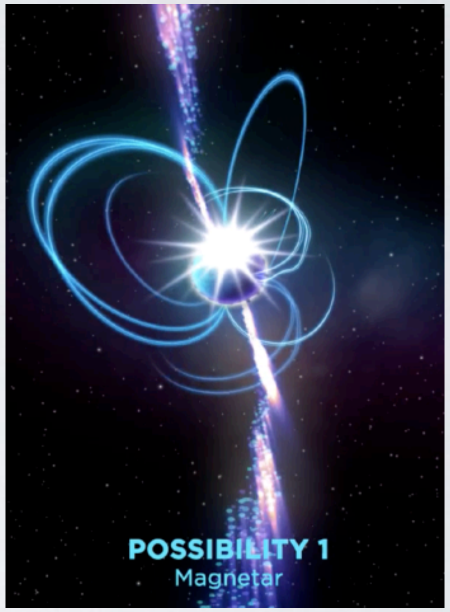

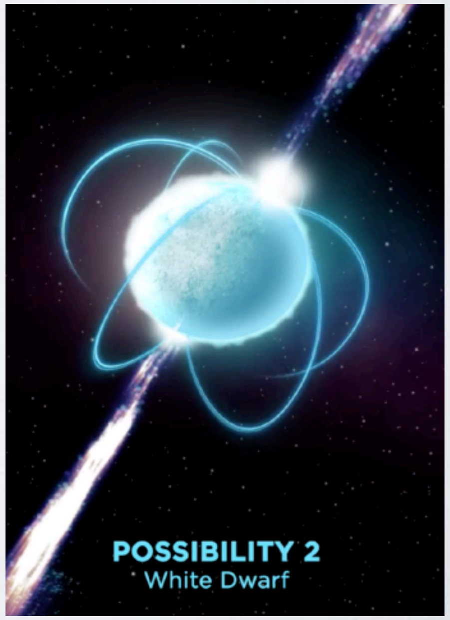

LONG PERIOD PULSARS AT MWA

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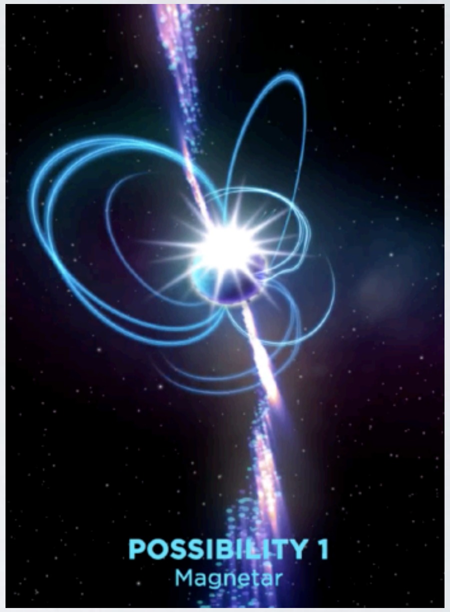

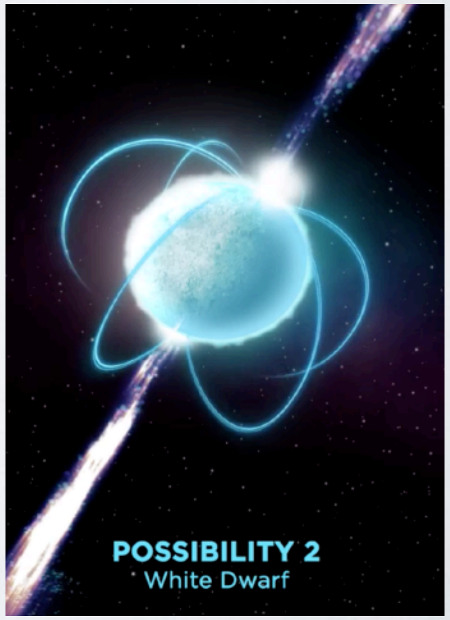

probe a previously unexplored transient-timescale parameter space

The role of the SKA

SKA can increase the scientific potential of pulsars by:

1) increasing the number of test objects

2) increasing the precision of the timing measurements

THE ROLE OF THE SKA

Search speed $\approx$ $(A_{eff}/T_{sys})^2\,\Omega$

SKA1: Multiplying a factor ≈ 3-4 the known population

SKA2: Multiplying a factor ≈ 10-12 the known population

3000 PSRs / 350 MSPs

↓

12000 PSRs / 1500 MSPs

—

20-30 relativistic PSRs

↓

100-200 rel PSRs

Timing quality $\sigma_{ToA} \approx T_{sys}/A_{eff}$

SKA1: Timing most of the targets a factor 5-10 better than now

SKA2: Timing the targets a factor 10-100 better than now

40 MSPs; few < 100 ns

↓

>100 MSPs; all < 100 ns

THE ROLE OF THE SKA

- Better constraint GR and alternative theories
- Find new exotic systems (MSP-MSP, MSP-BH; MSP-IMBH; PSR-SgrA*, triple systems...) to test extreme physics
- PTA studies of the GWB characteristics and detection of single sources with SKA-1, and full nHz GW astronomy of single sources and implied fundamental physics with SKA-2

Summary & Conclusions

- Pulsars are amazing laboratories
- PSRs studies will greatly advance thanks to the SKA
- SKA precursors and pathfinders are already giving great and unexpected results
- Italy is deeply involved in PSR projects within the SKA framework

We are looking forward to the SKA!

Thank you