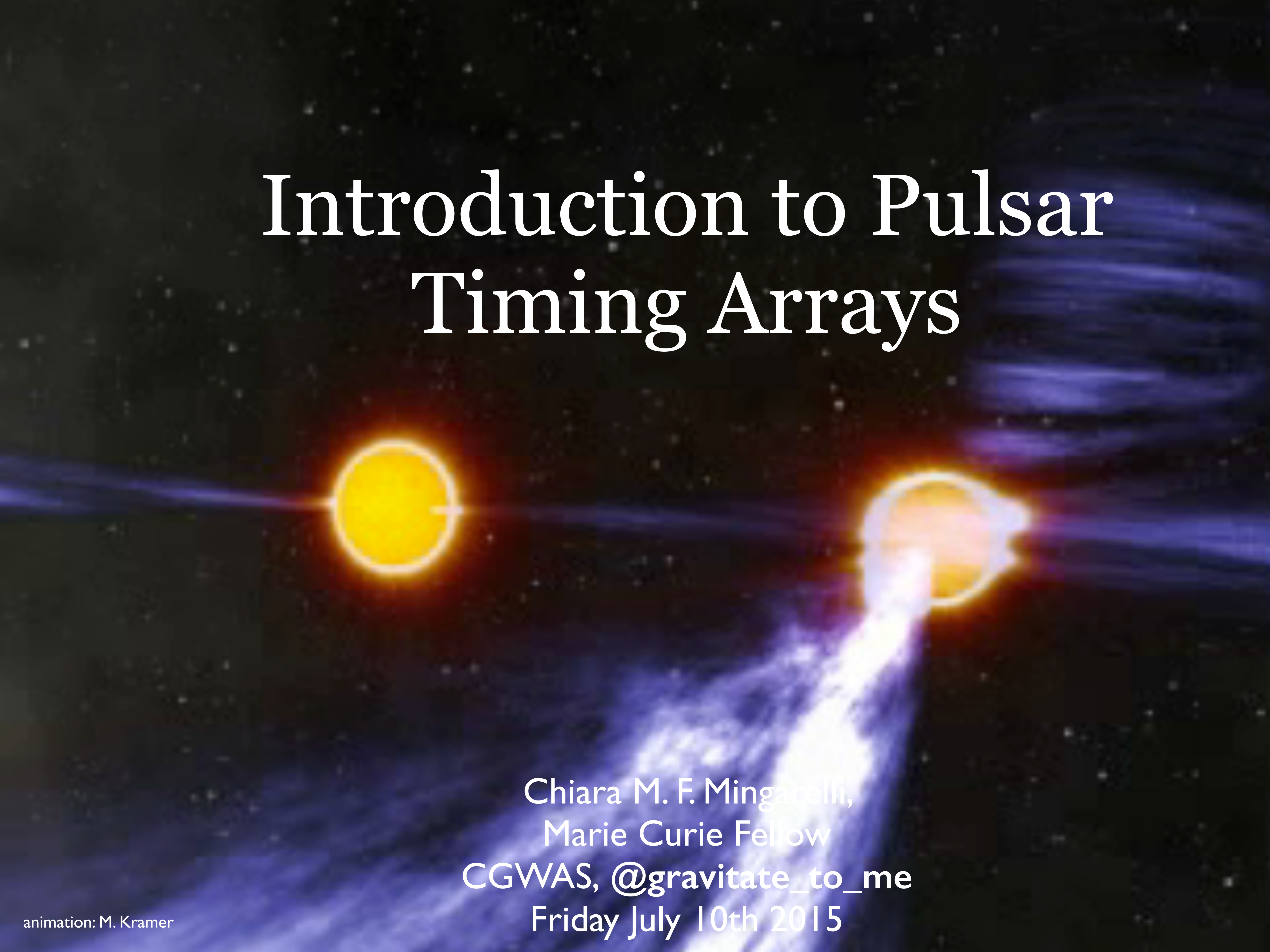
Introduction to Pulsar Timing Arrays

Chiara M. F. Mingarelli,
Marie Curie Fellow
CGWAS, @gravitate_to_me
Friday July 10th 2015



animation: M. Kramer

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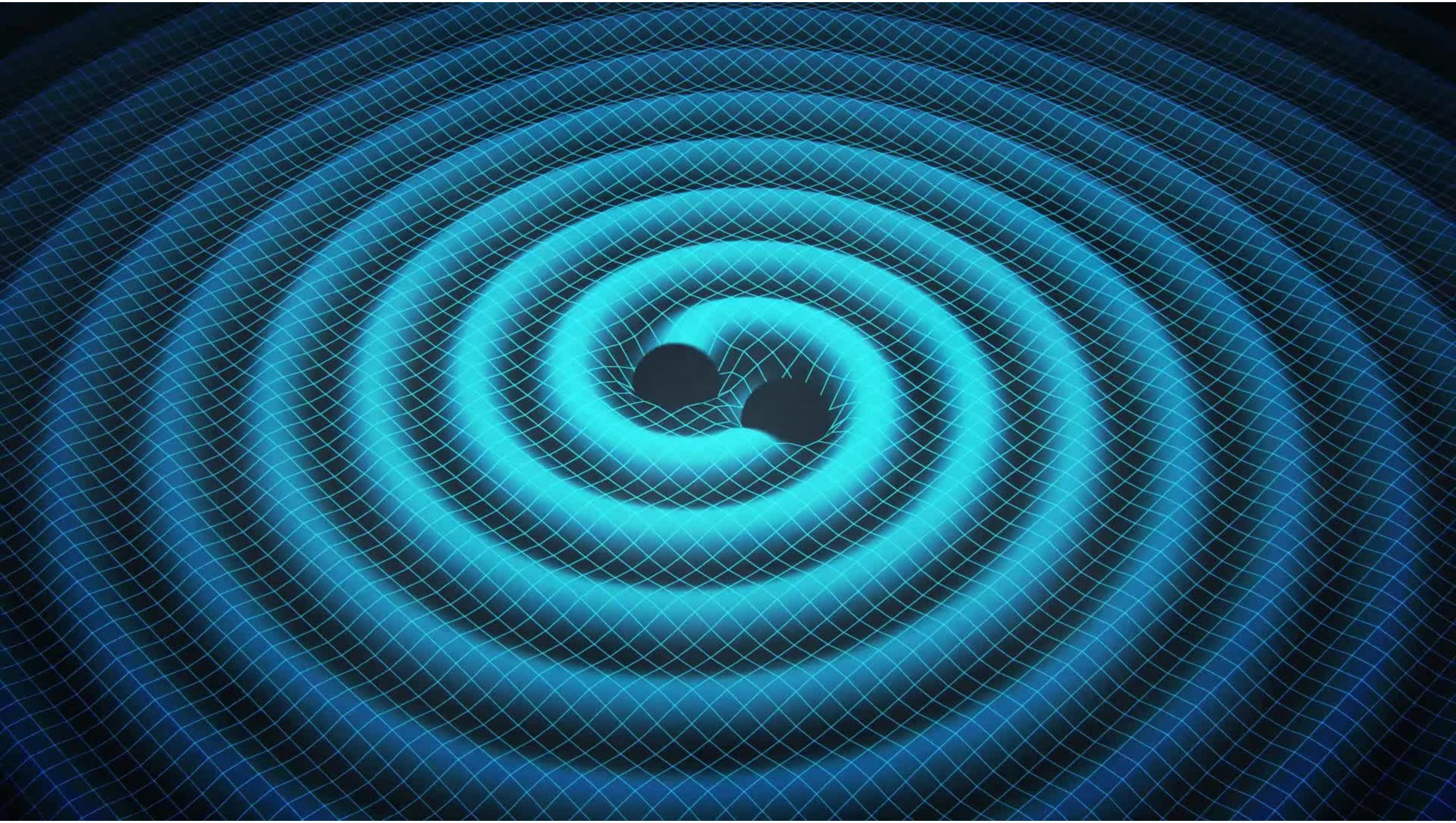
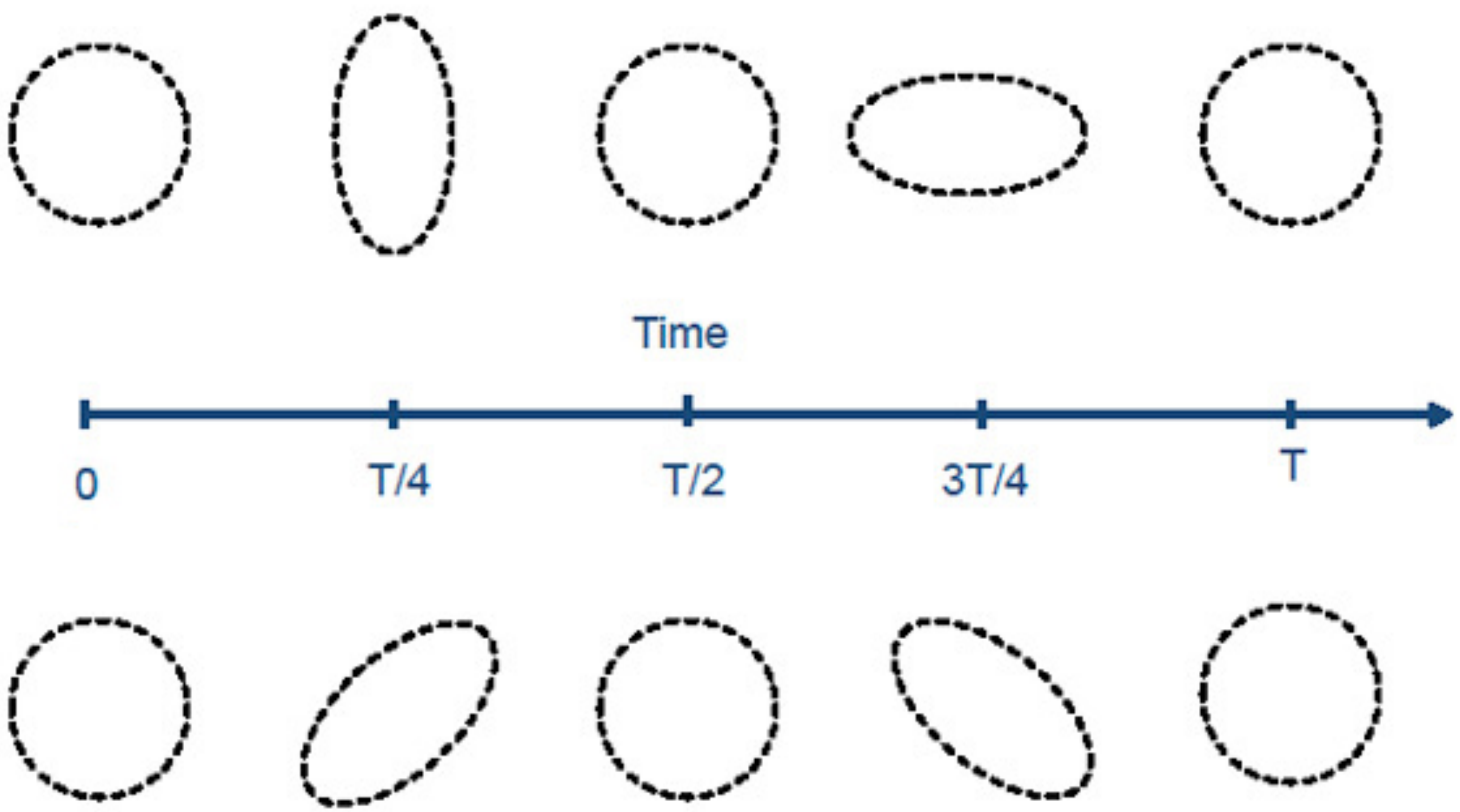
Gravitational Waves



Masses with varying quadrupole moments will emit GWs.

Gravitational Wave Strain

- **Dimensionless** quantity characterizing the deformation of space-time caused by a GW
- e.g. units of **metres/light** year or mm/km



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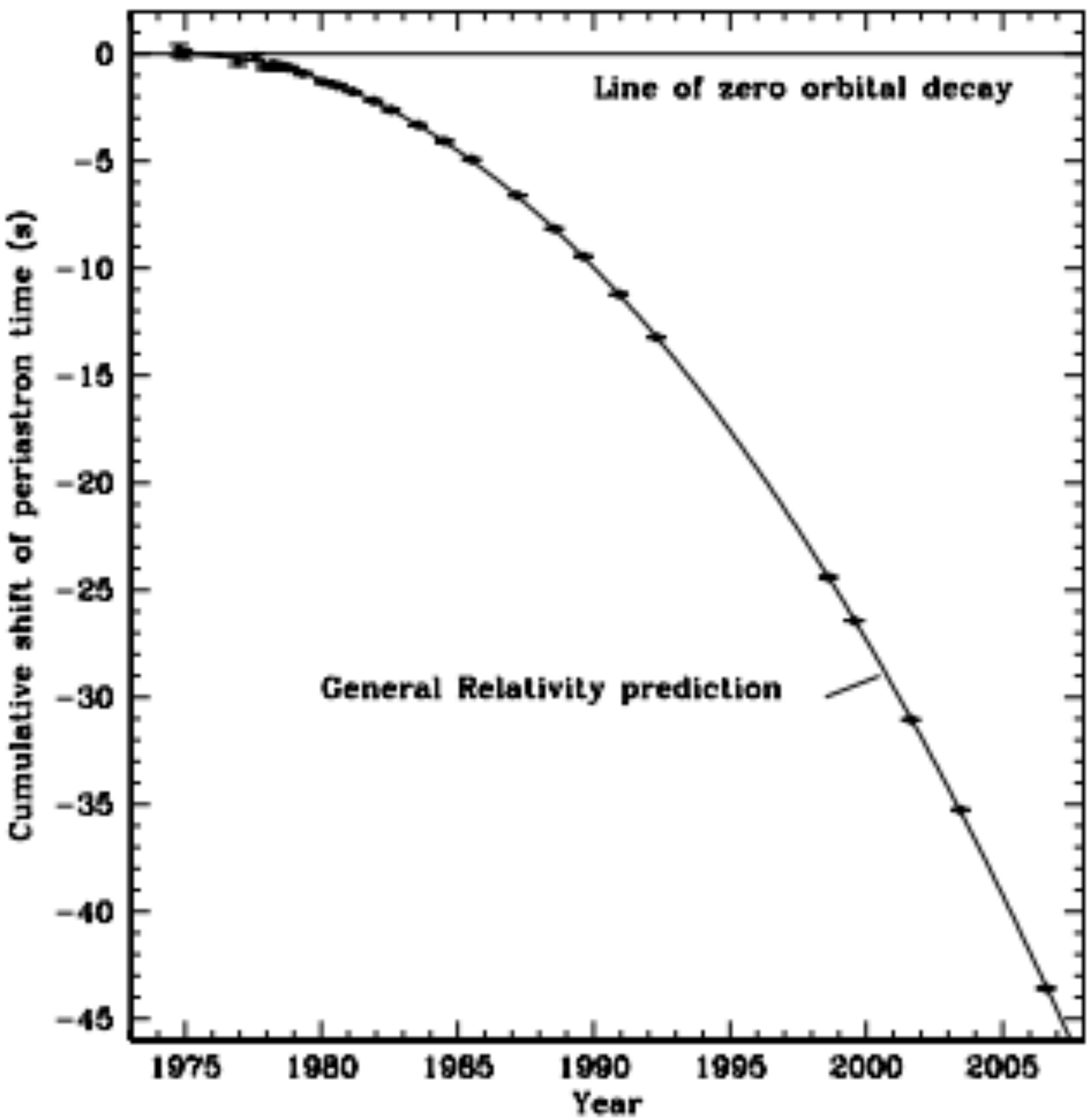
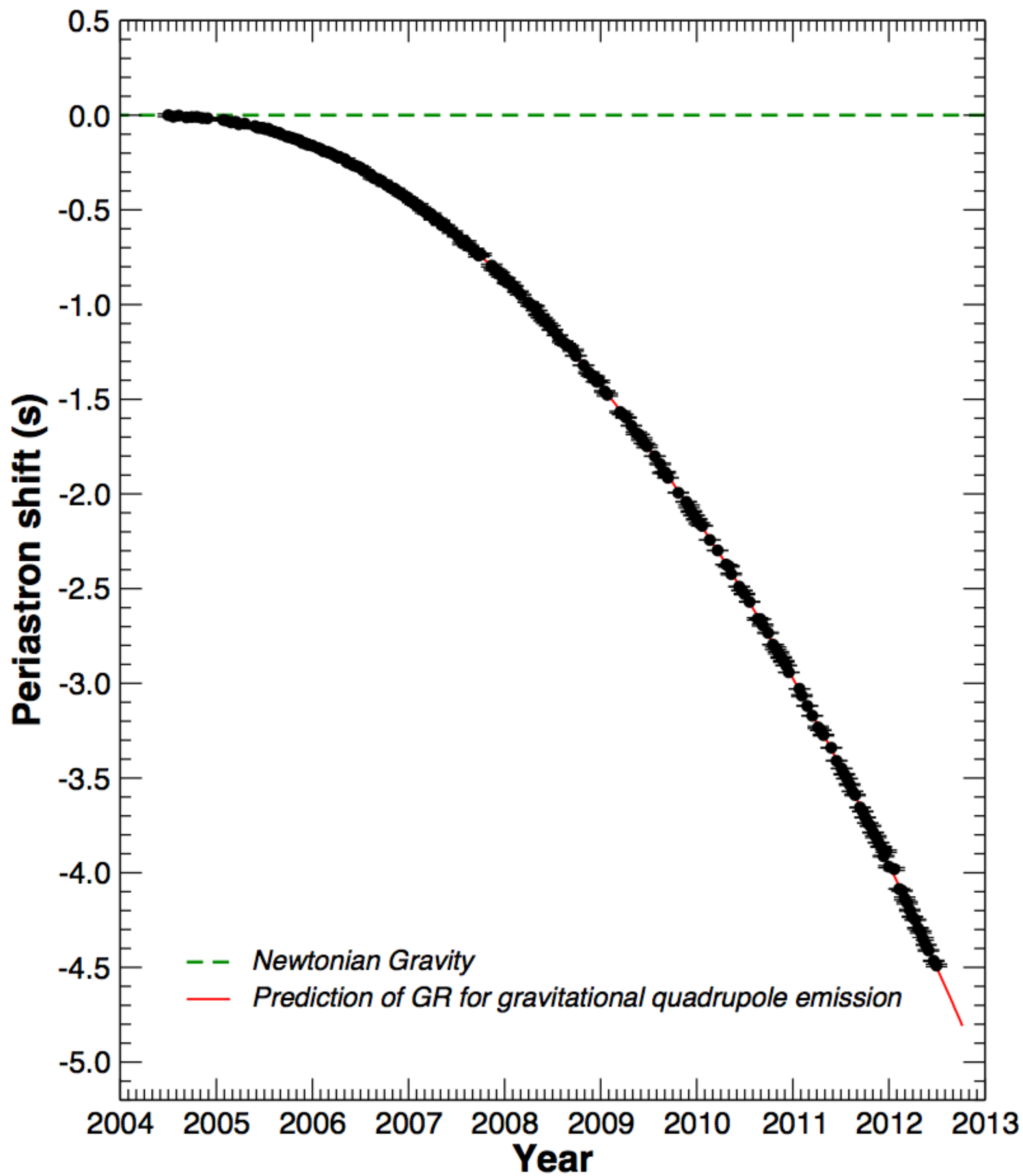
Evidence for Gravitational Waves



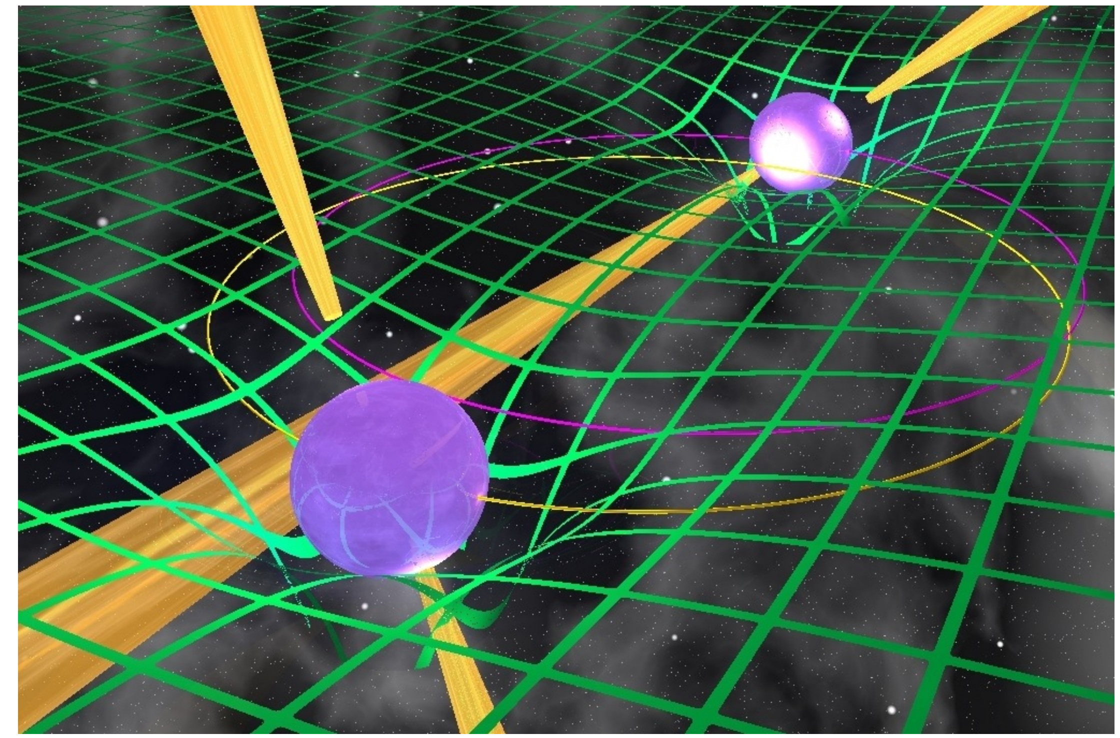
Hulse-Taylor Pulsar

Hulse & Taylor, 1975, ApJ, 195, L51
Weisberg, Nice, & Taylor, 2010, ApJ, 722, 1030

Evidence for Gravitational Waves



Kramer et al. in preparation



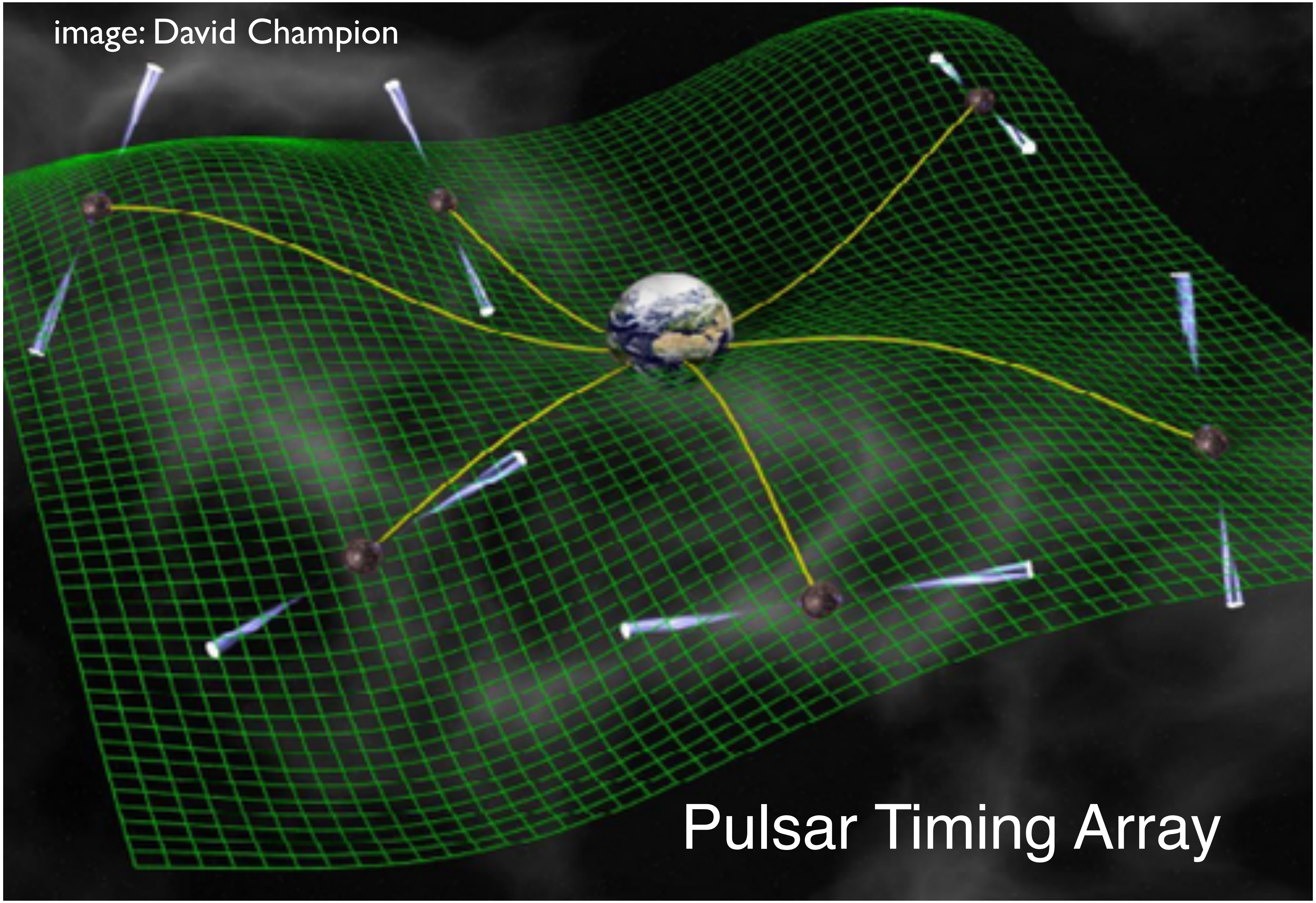
Double Pulsar 7 mm/day orbit shrinkage agrees to 0.1% with GR prediction!

Isn't this good enough?

Can detect GWs *directly* by observing actual change in light travel time between objects.
Allow us to test GR in new ways + study "dark" objects

Outline

- What is a pulsar timing array?
- How can use pulsar timing arrays to study GWs?
- What if GR isn't quite right?
- What if the background isn't isotropic?
- What can we learn from continuous GW detection?
- What can we say about cosmological models?
- What limits can we place on cosmic strings?

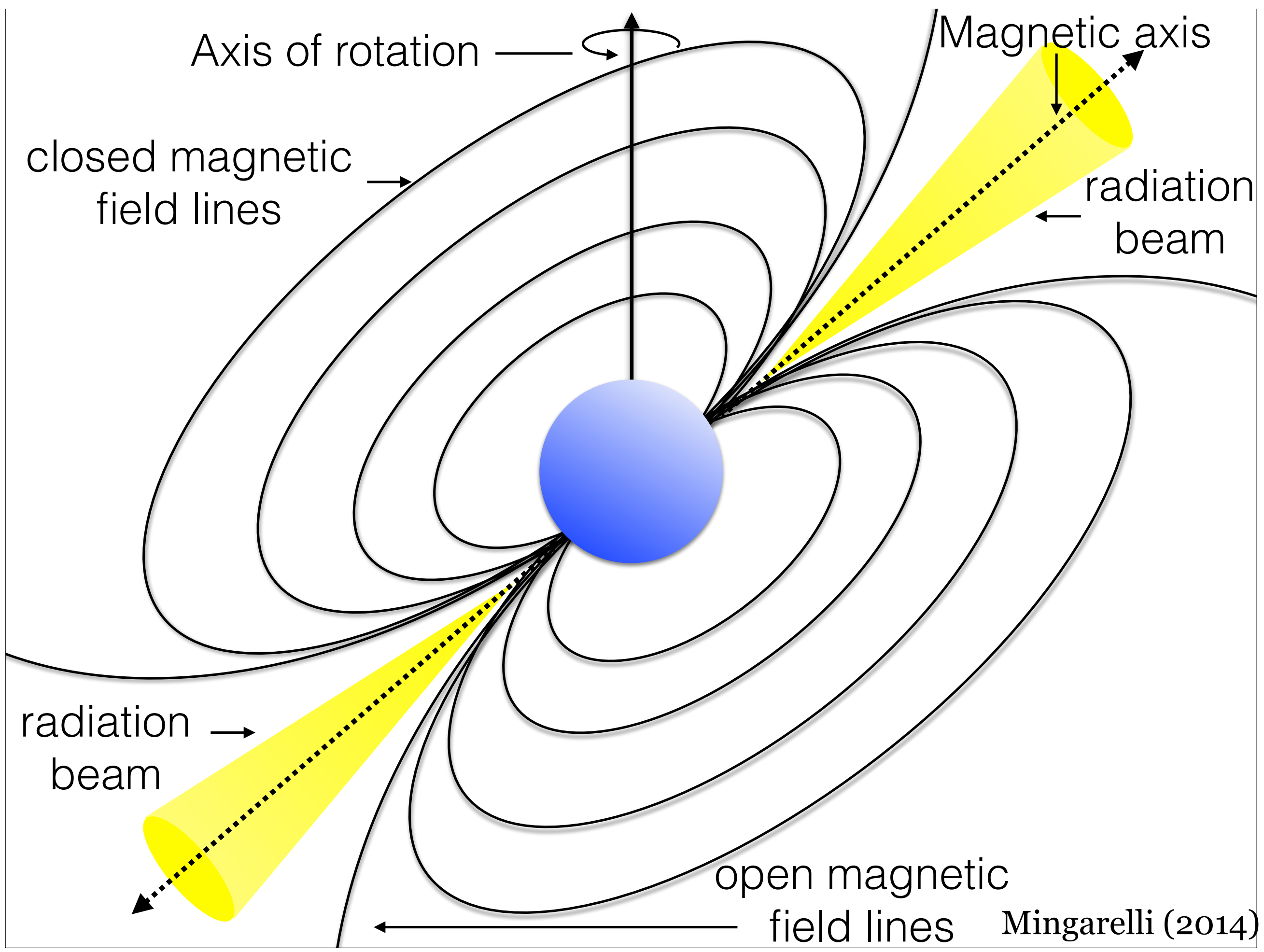


Galactic GW detector composed of pulsar array!

Each pulsar thousands of light years away.

What are pulsars?

Rotating neutron stars. They are compact, rapidly rotating, high magnetic field remnants of supernova explosions.



R ~ 10 km

M ~ 1.4 solar masses

P ~ 1.4 ms - 8.5 s

B ~ $10^8 – 10^{14}$ G

Pulsed emission detectable at radio, (optical), X-ray and gamma-ray energies.

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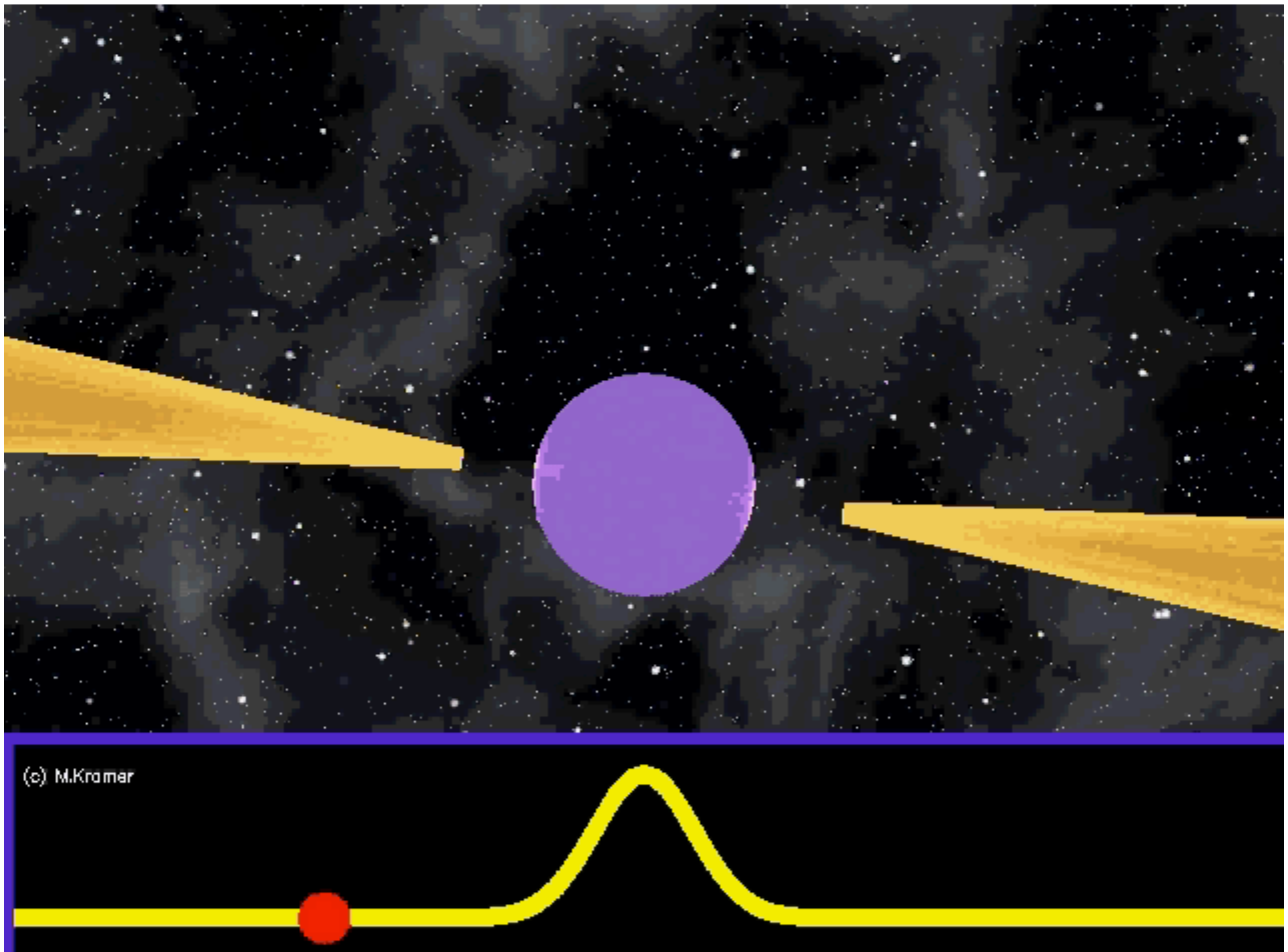

Vela
11 Hz

Crab
30 Hz

B1937+21
642 Hz

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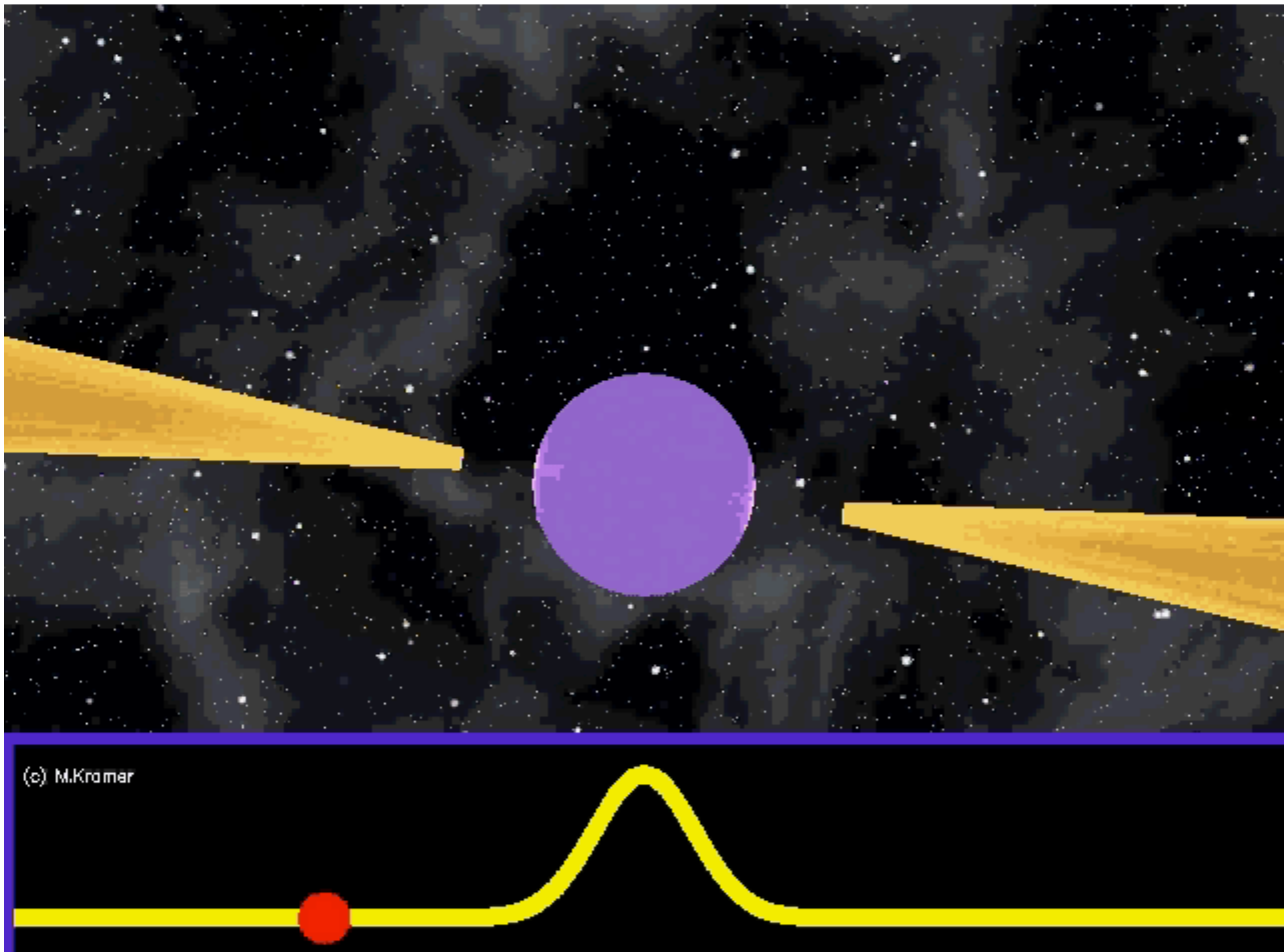

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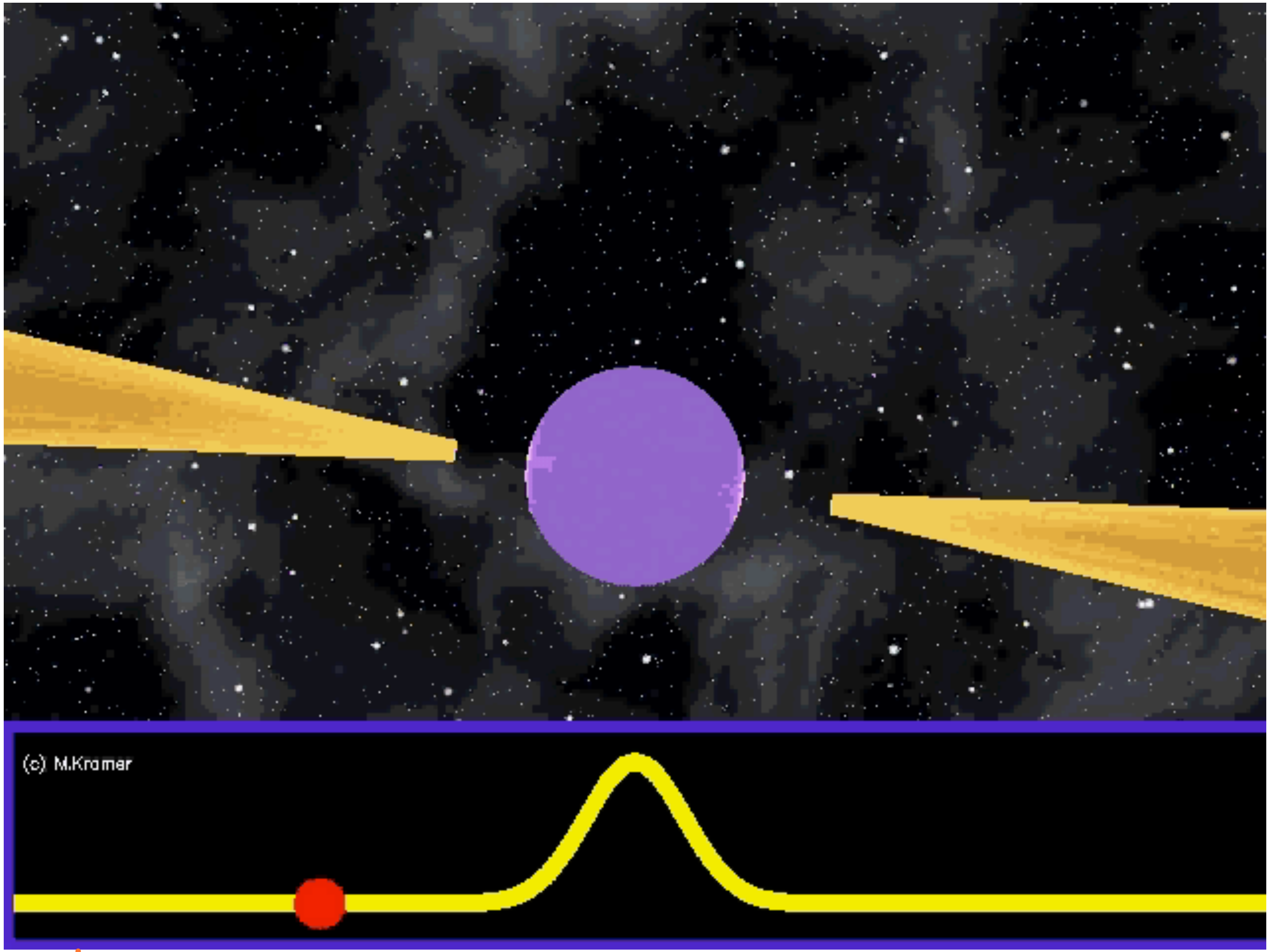

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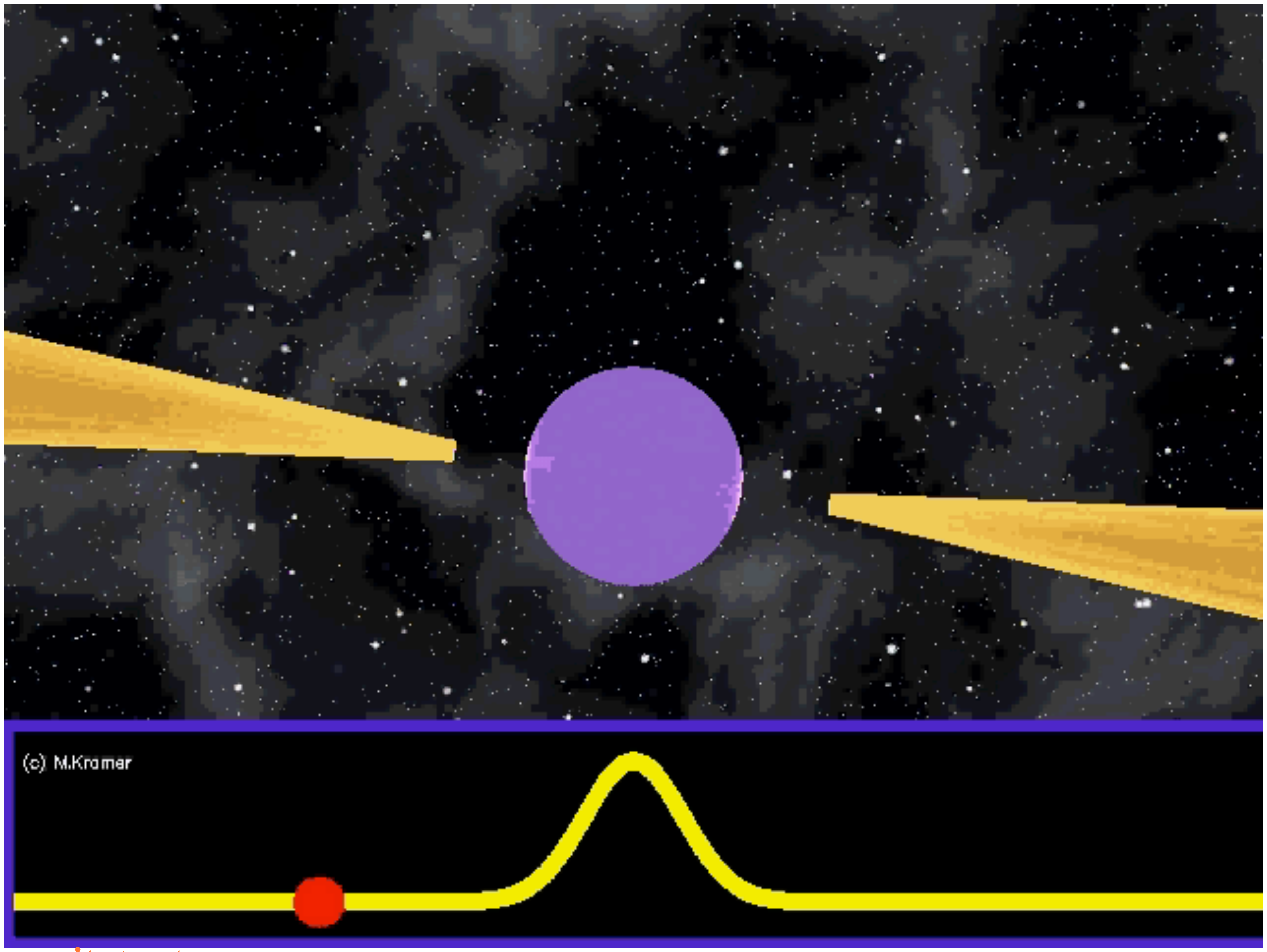

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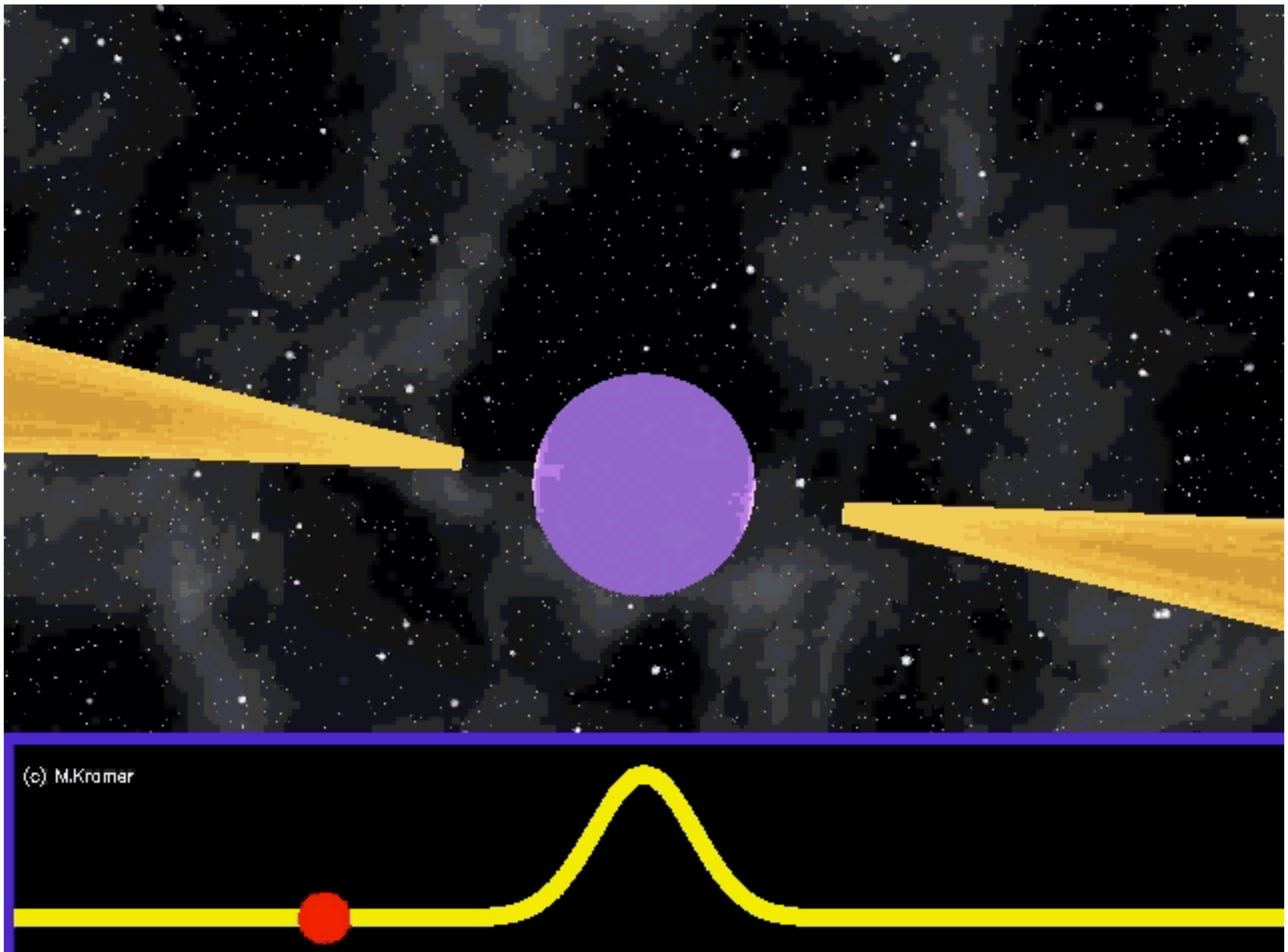

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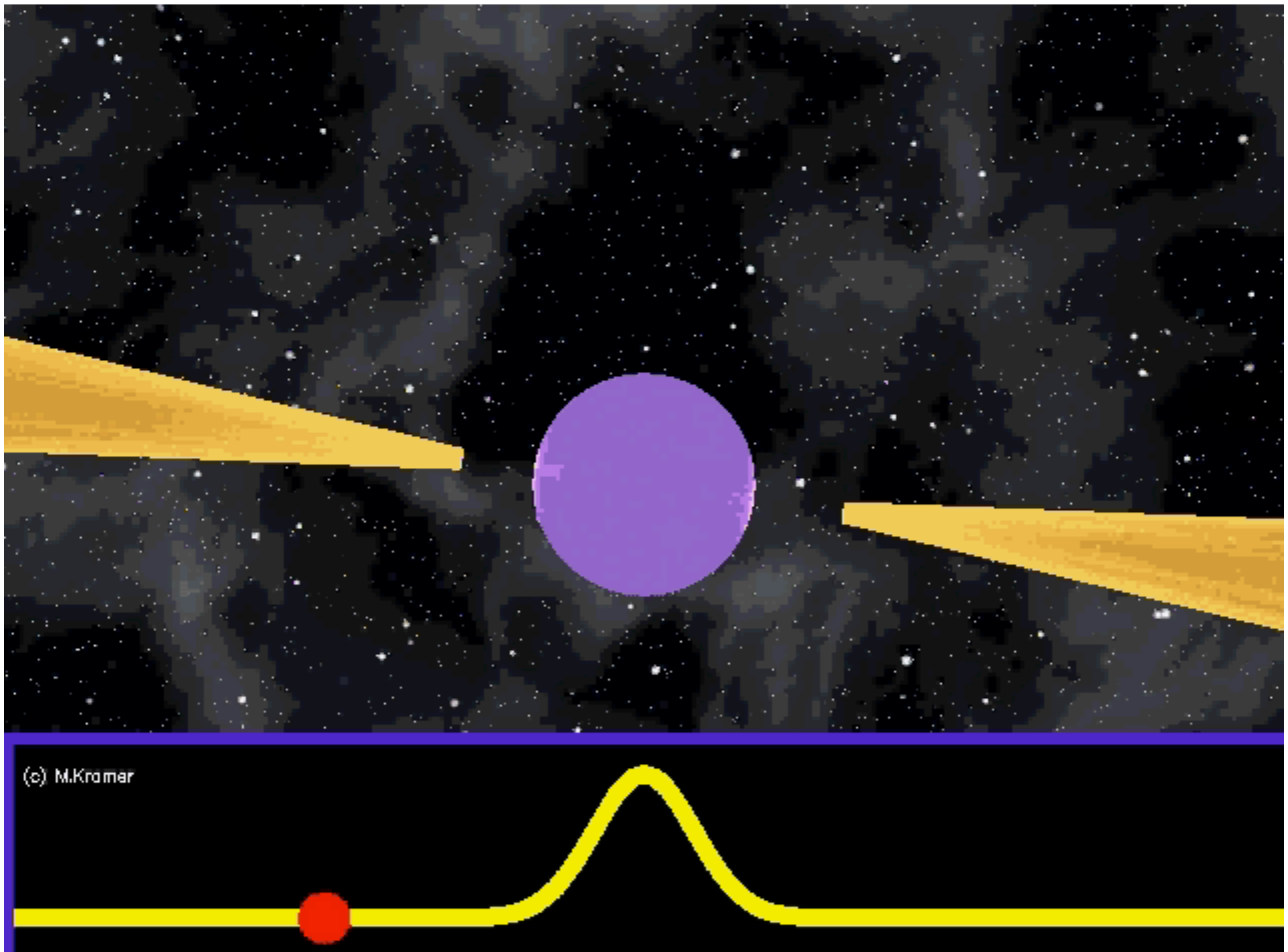

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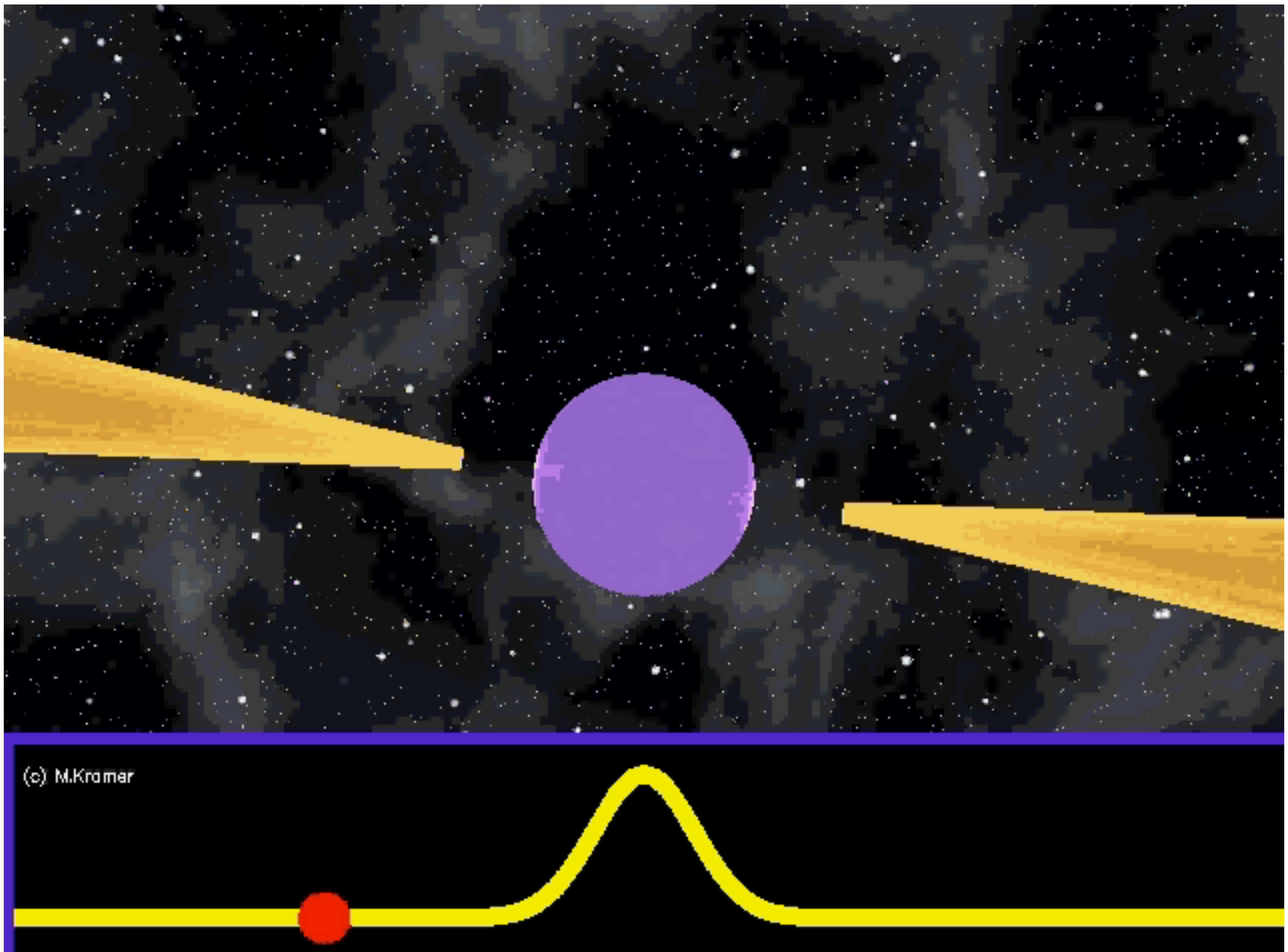

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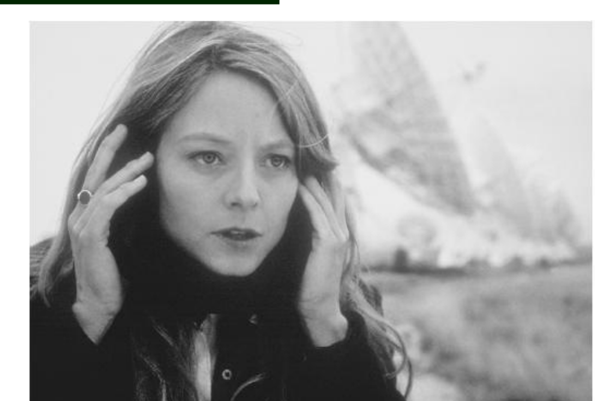

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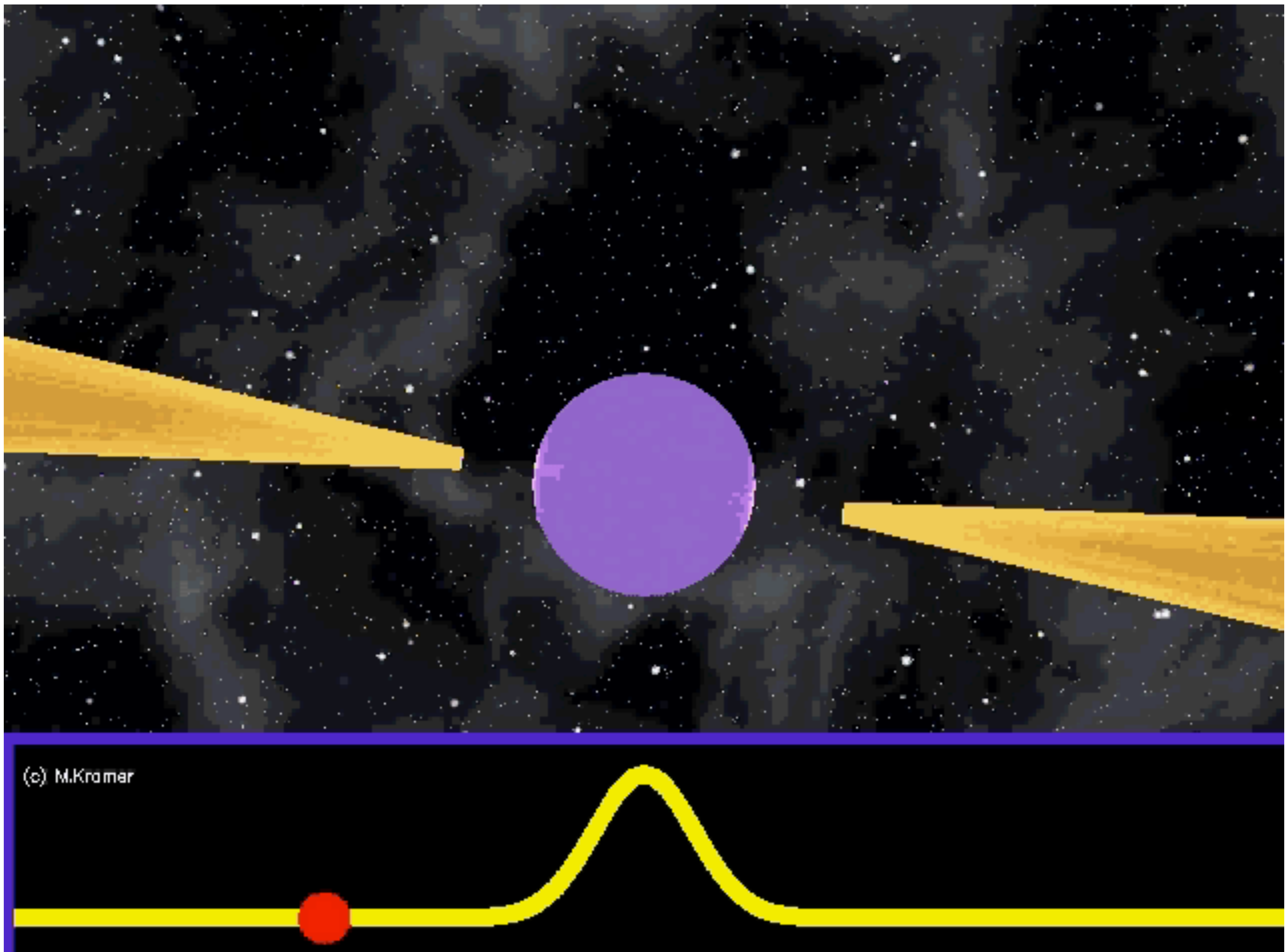

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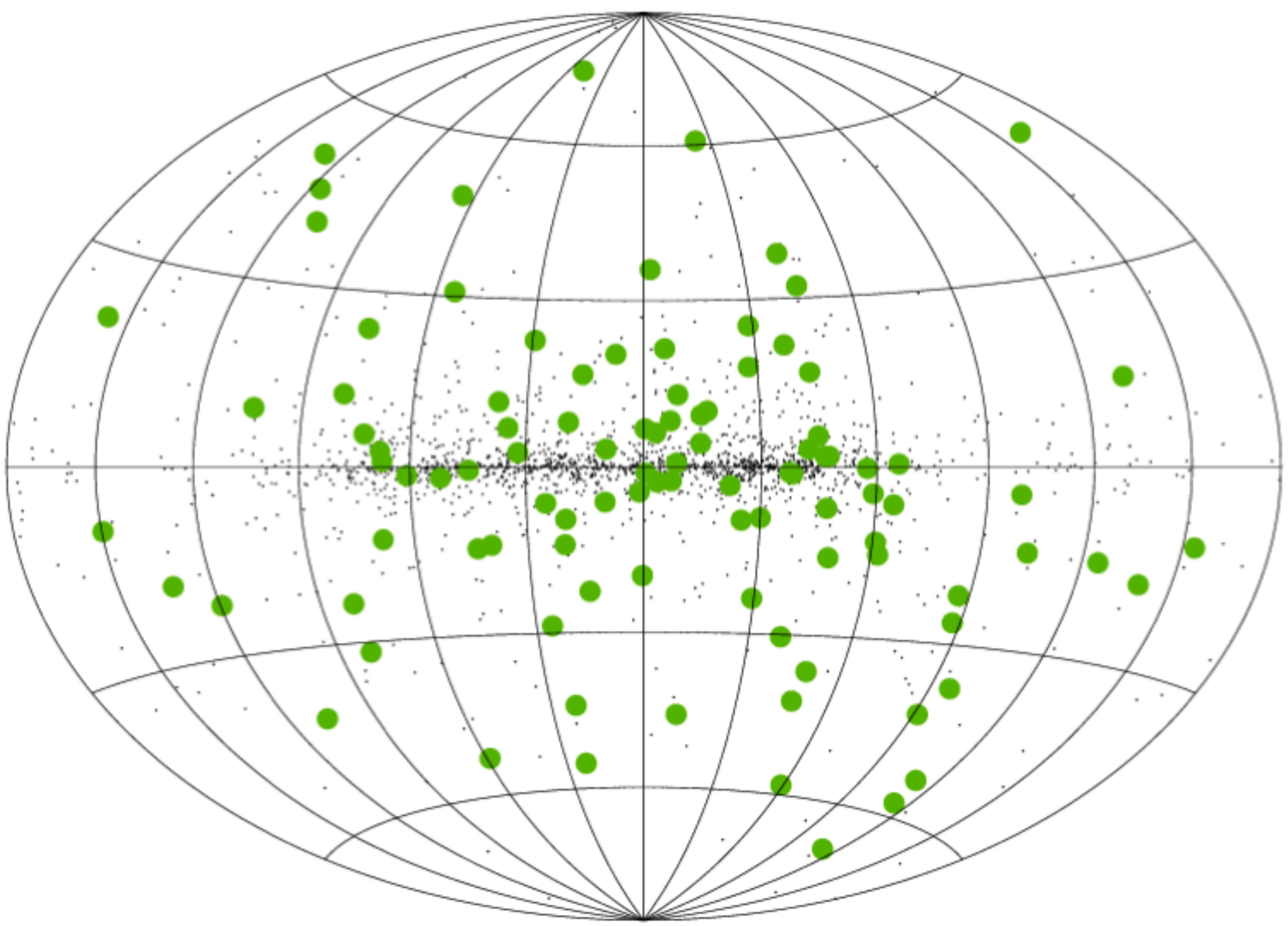
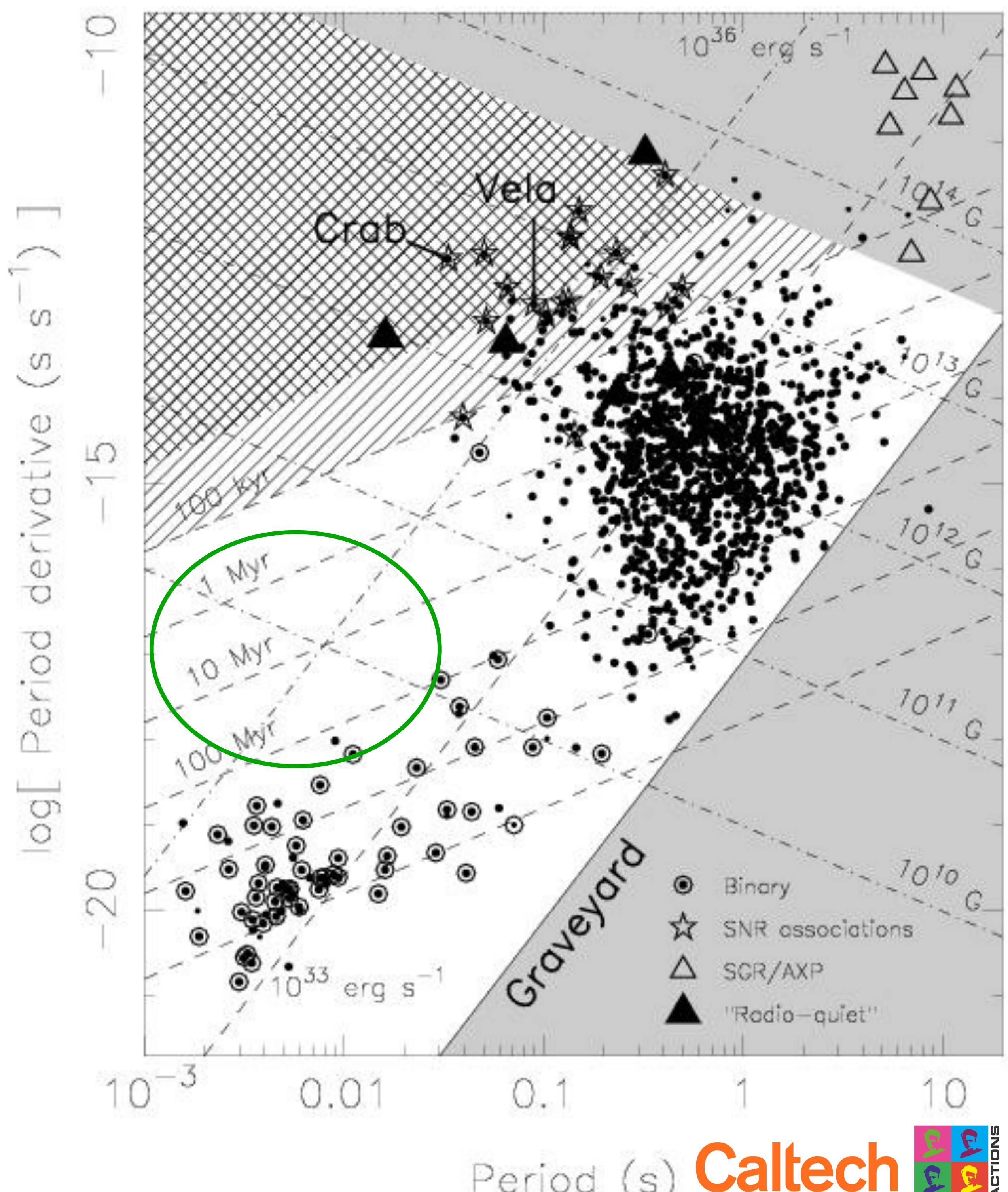
Millisecond Pulsars

2300 known pulsars, 230 MSPs (P < 20 ms)
Maybe 30,000 detectable!

Galactic MSPs are local (d ~ kly) and isotropically distributed.



$$\tau \propto P/\dot{P} \qquad B \propto \sqrt{P\dot{P}}$$



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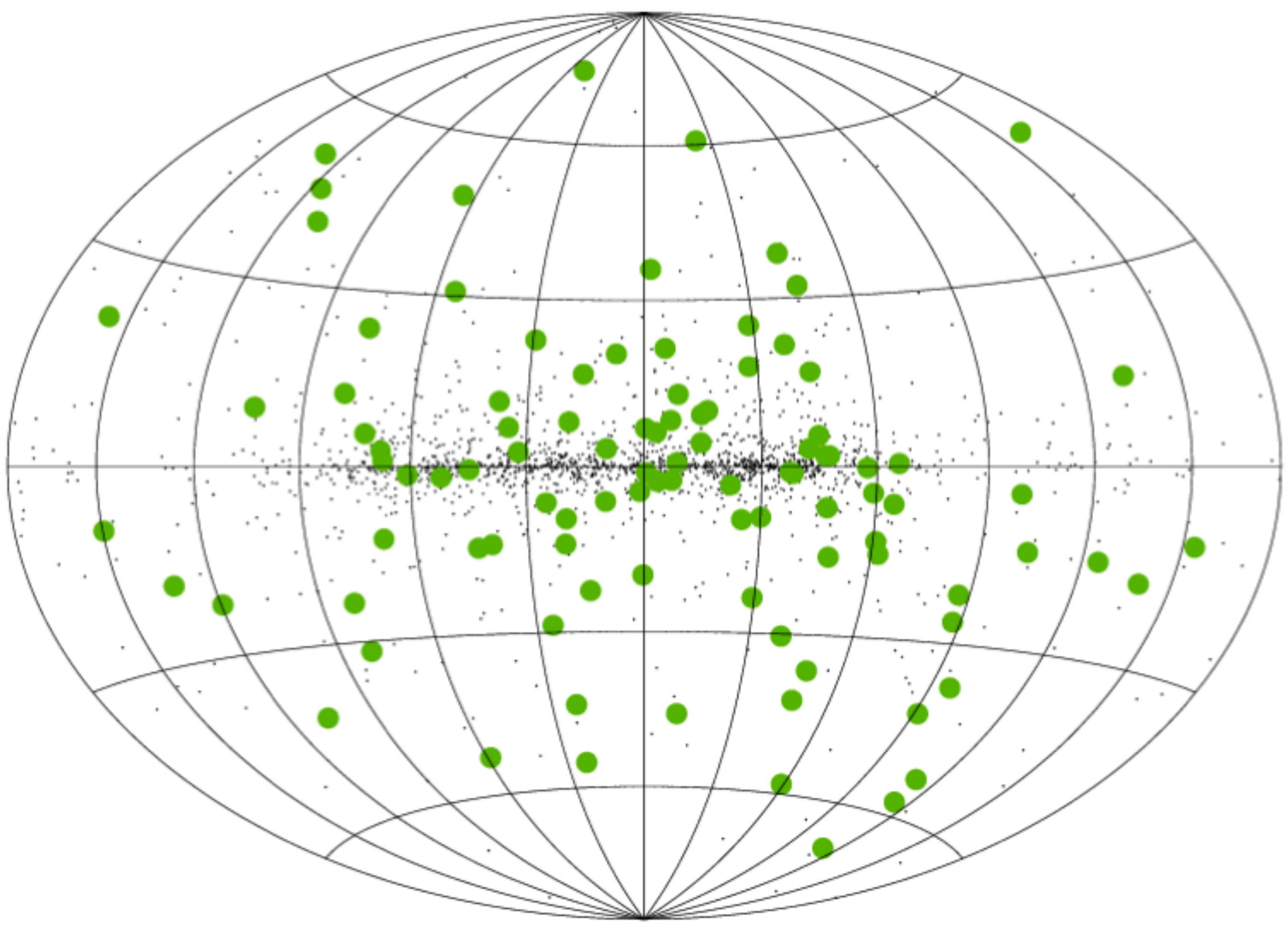
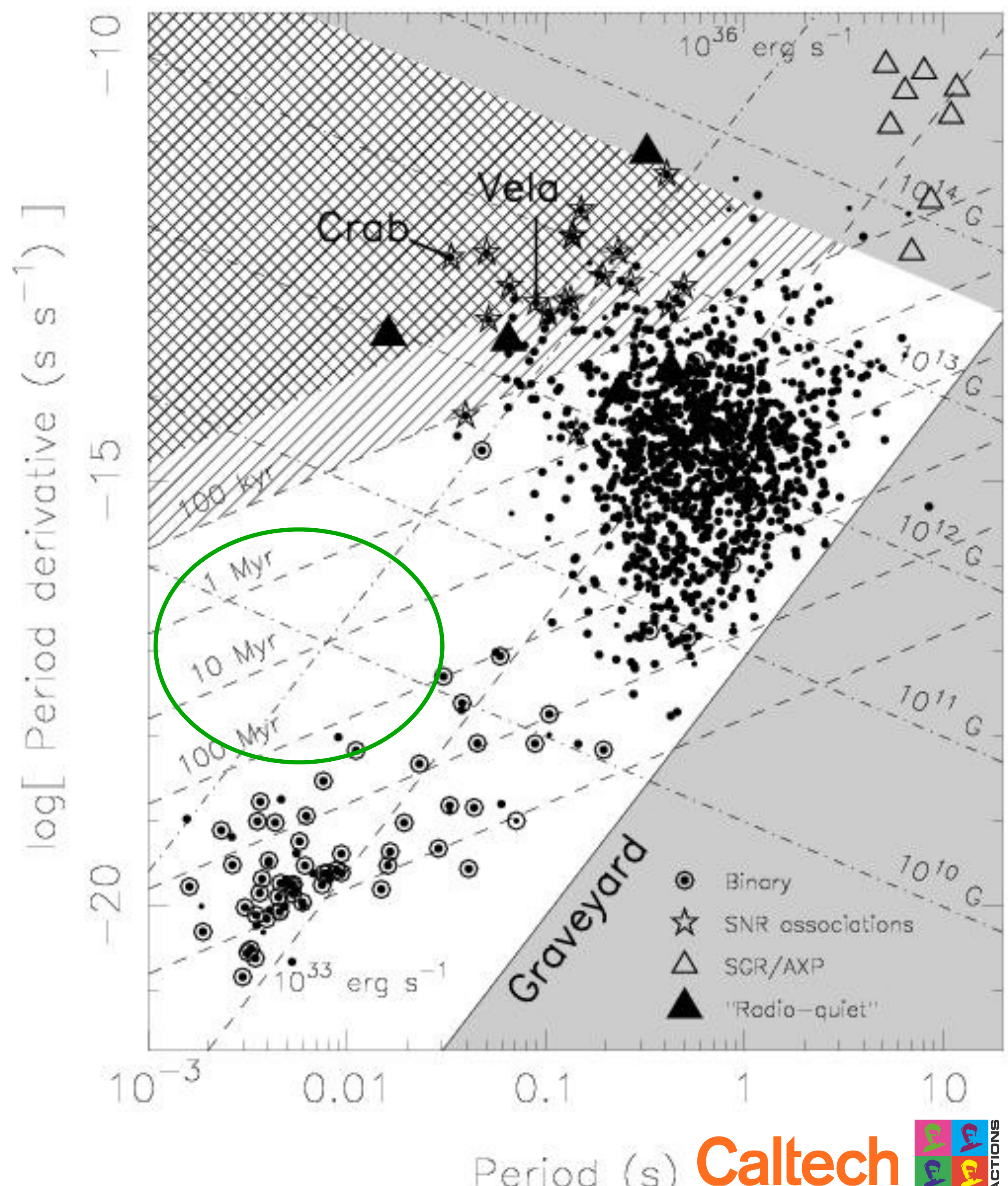


$$h \propto \delta t / T$$

$$\tau \propto P/\dot{P} \qquad B \propto \sqrt{P\dot{P}}$$



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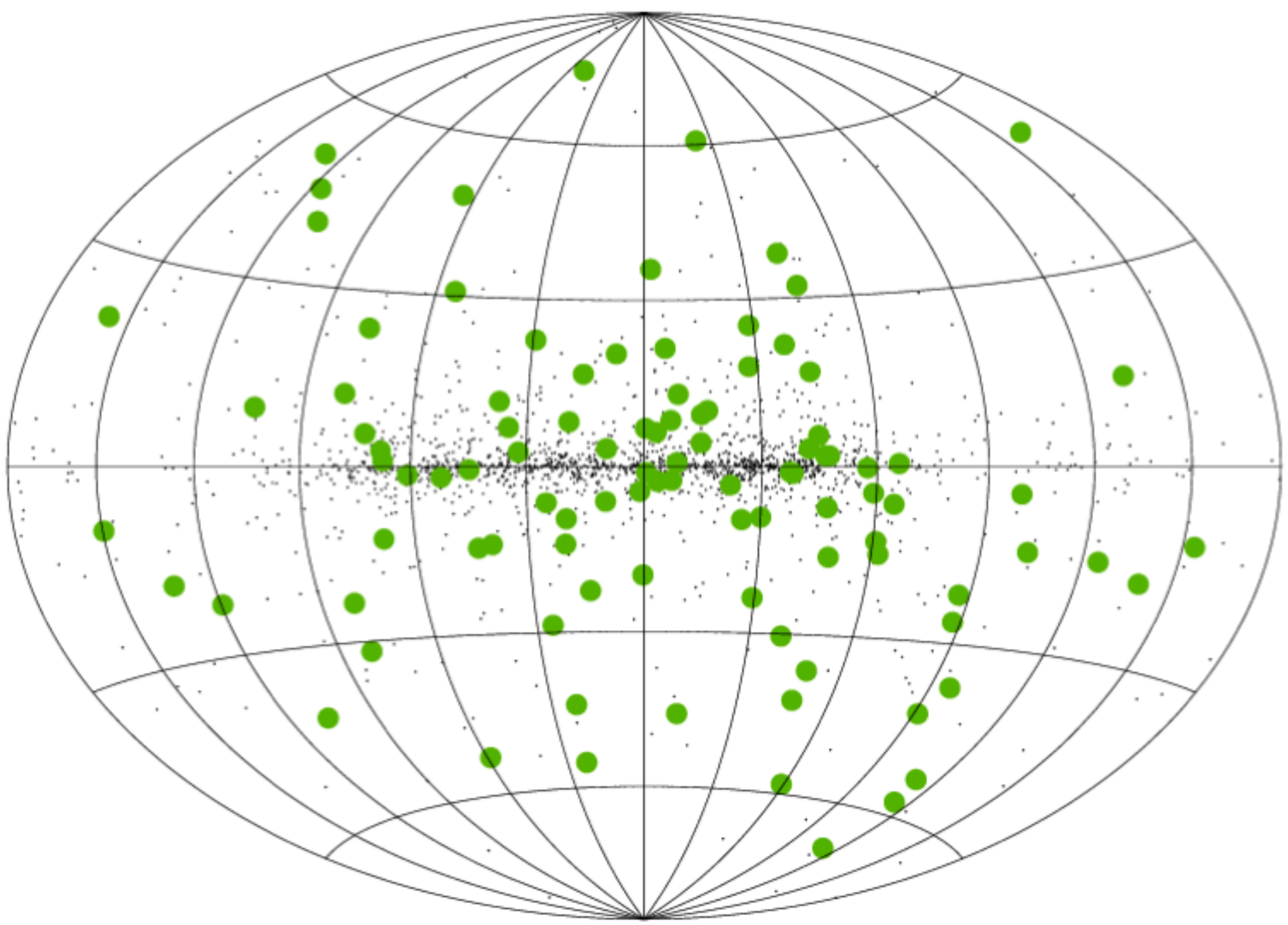
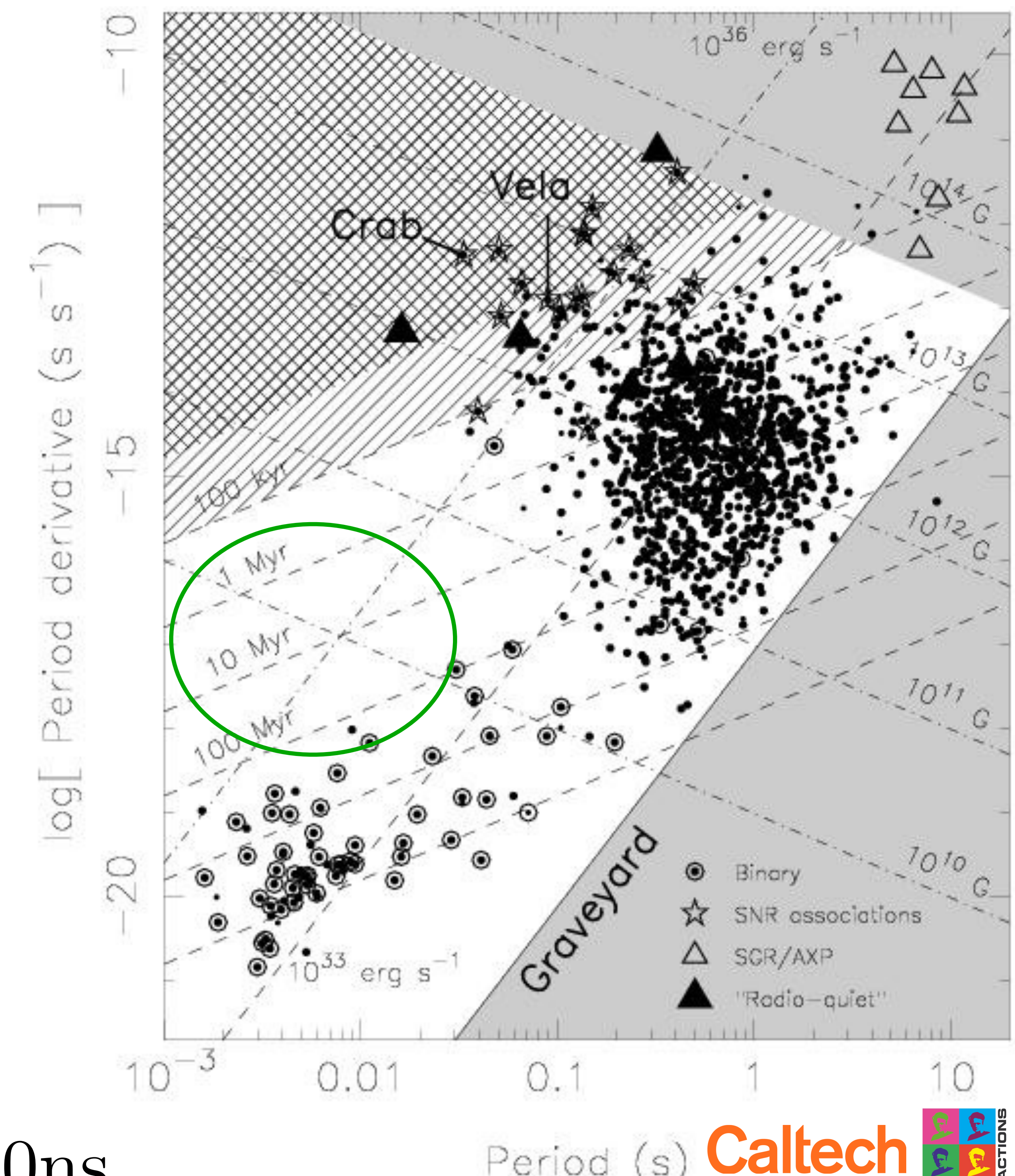


$$h \propto \delta t / T$$

$$\delta t \sim 10^{-15} 10\text{yrs} \sim 100\text{ns}$$

$$\tau \propto P/\dot{P} \qquad B \propto \sqrt{P\dot{P}}$$



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A Pulsar Timing Array

- Primary goal of PTAs is to detect a stochastic GW background.
- Currently 3 major PTAs: EPTA, Parkes PTA and NANOGrav.
- Together we form the IPTA: 40+ MSPs (and counting) and 8 radio telescopes

NANOGrav Intruments: Arecibo


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NANOGrav Experiment

100-m Green Bank Telescope, WV

300-m Arecibo Observatory
Arecibo, PR

We use large radio telescopes to observe lots of pulsars and search for tiny (but correlated!) perturbations on times of arrival due to GWs!

Pulsar Timing Array

Animation from John Rowe Animation/Australia Telescope National Facility, CSIRO

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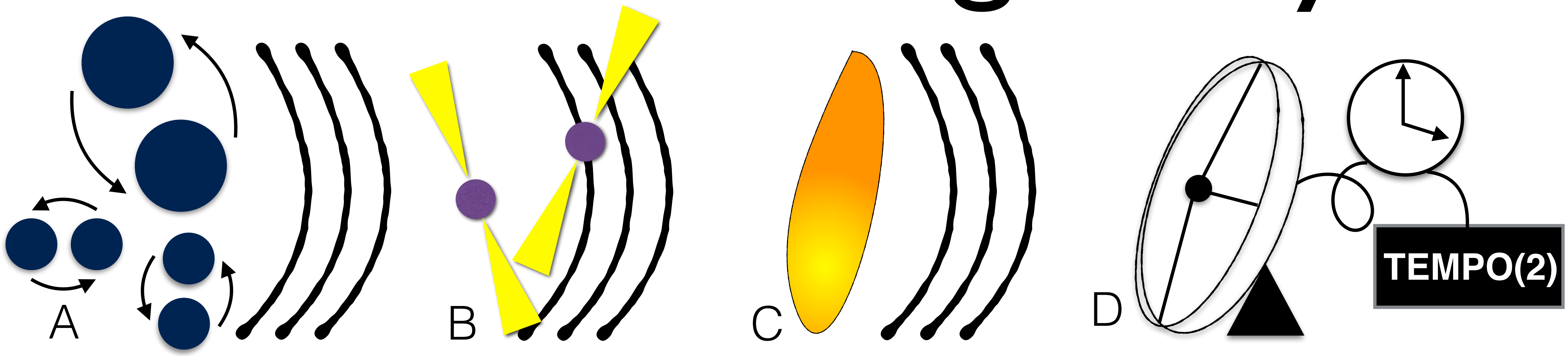

A: GWs from e.g. supermassive BH binaries (also cosmic strings)

B: GWs perturb space-time at the pulsars as they transit

C: ionized gas in the interstellar medium disperses & scatters the light from pulsars

D: GW perturb signals from all pulsars at Earth. Time of arrivals and residuals are calculated.

Science!

Gravitational Waves

Stochastic Background

Continuous Waves

Bursts

isotropic

anisotropic

detect or limit

memory

unmodeled

detect or limit

Science!

detect or limit

Funding

Outreach

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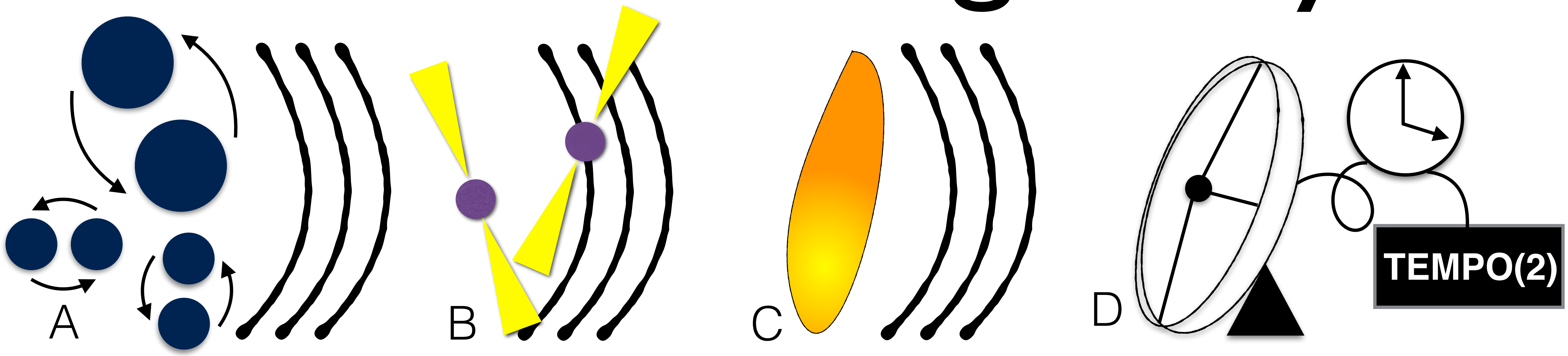
C. M. F. Mingarelli (2015)

Pulsar Timing Array



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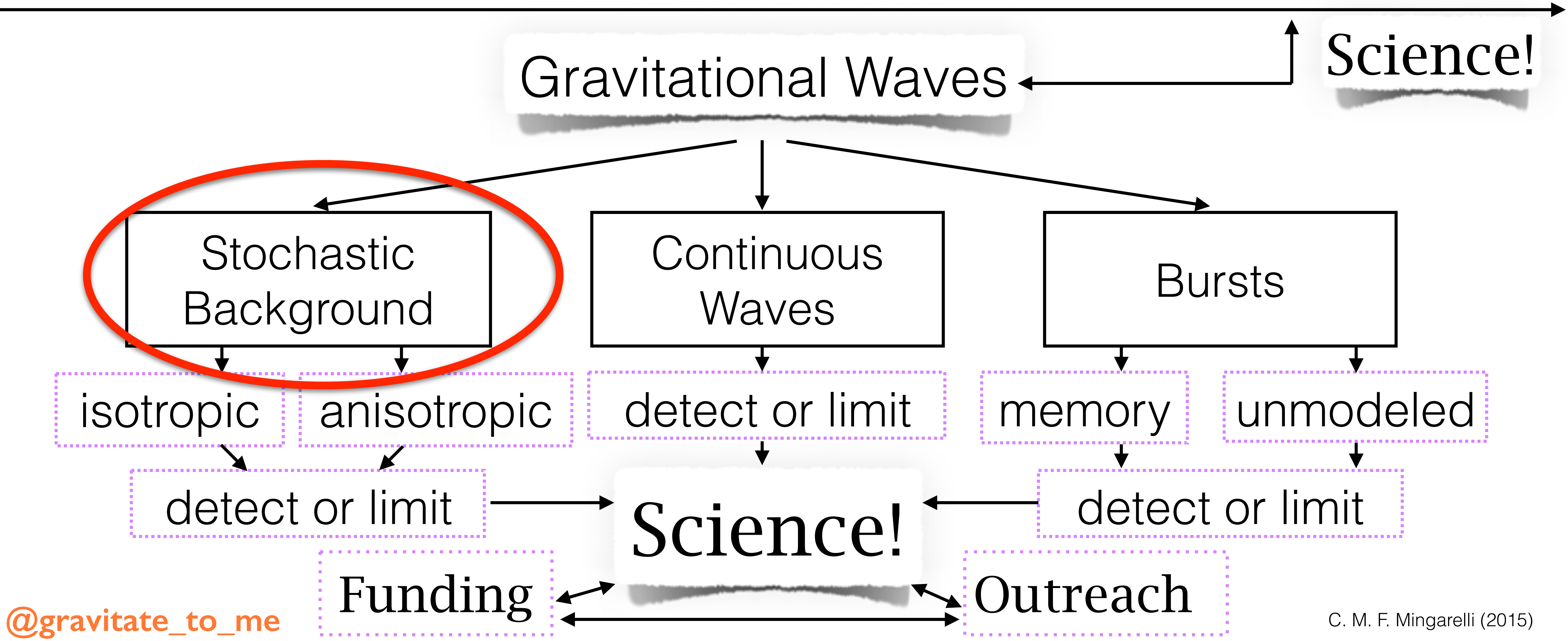

Pulsar Timing Array

- GW signal correlated between pulsars, pulsar noise is not.
- Sources include supermassive black hole binaries, cosmic strings and relic GWs from inflation.
- Frequency band defined by total observation time and cadence of observation: 1/10 yrs to 1/month, i.e. nanoHertz regime.

Stochastic Background

- Assuming *circular SMBH binaries* driven by GW emission only, can define a characteristic strain:

$$h_c^2 \sim f^{-4/3} \int\int dz d\mathcal{M} \frac{d^2 n}{dz d\mathcal{M}} \frac{1}{(1+z)^{1/3}} \mathcal{M}^{5/3}$$

$$h_c = A \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{-2/3} \qquad \Omega_{\mathrm{gw}}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2$$

Phinney (2001); Sesana(2012)

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number of mergers remnants per comoving volume

$$h_c = A \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{-2/3} \qquad \Omega_{\mathrm{gw}}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2$$

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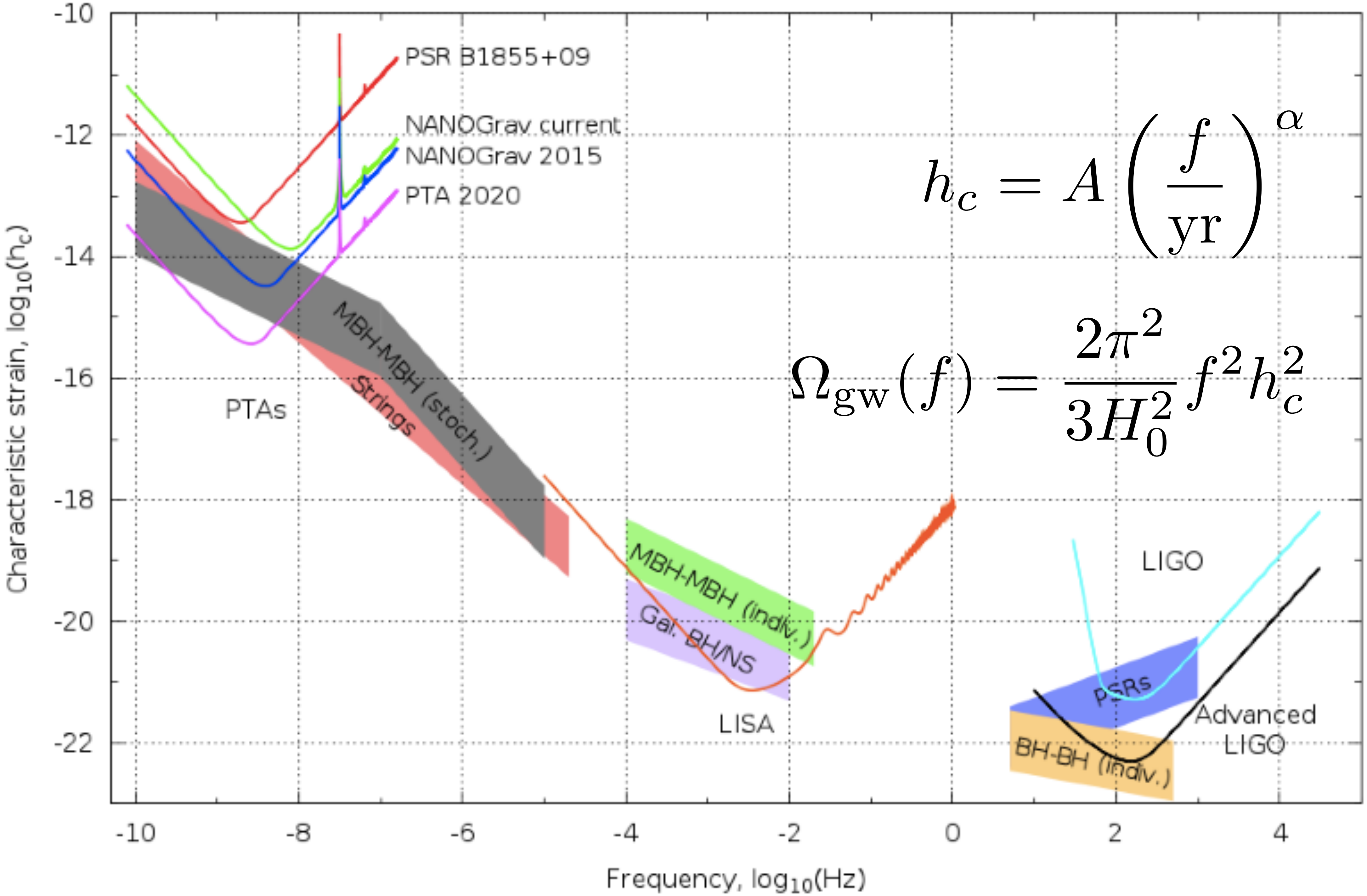
GW Landscape



$$h_c = A\left(\frac{f}{\mathrm{yr}}\right)^{\alpha}$$

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P. Demorest *et al.*, 2009

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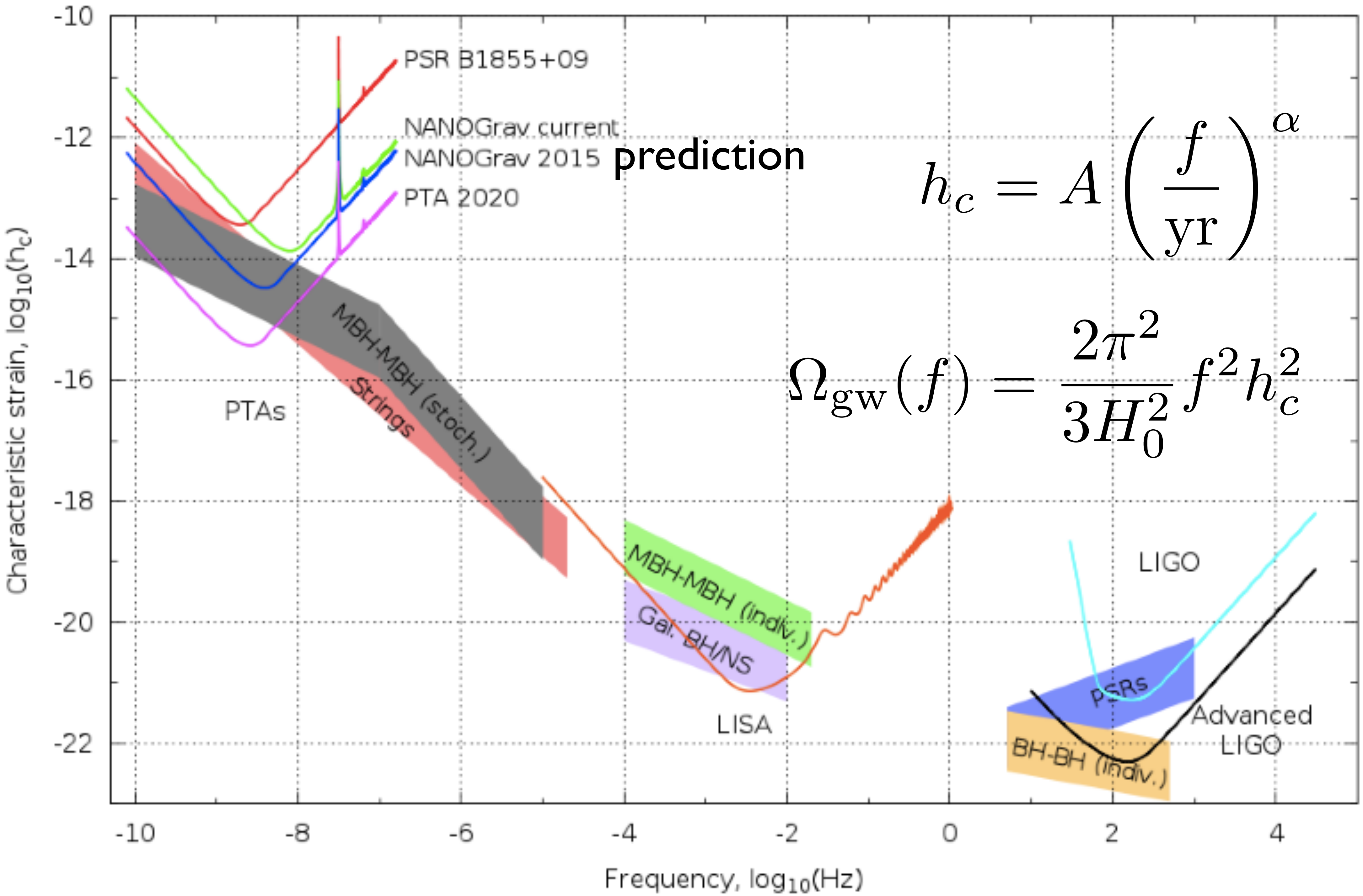

prediction

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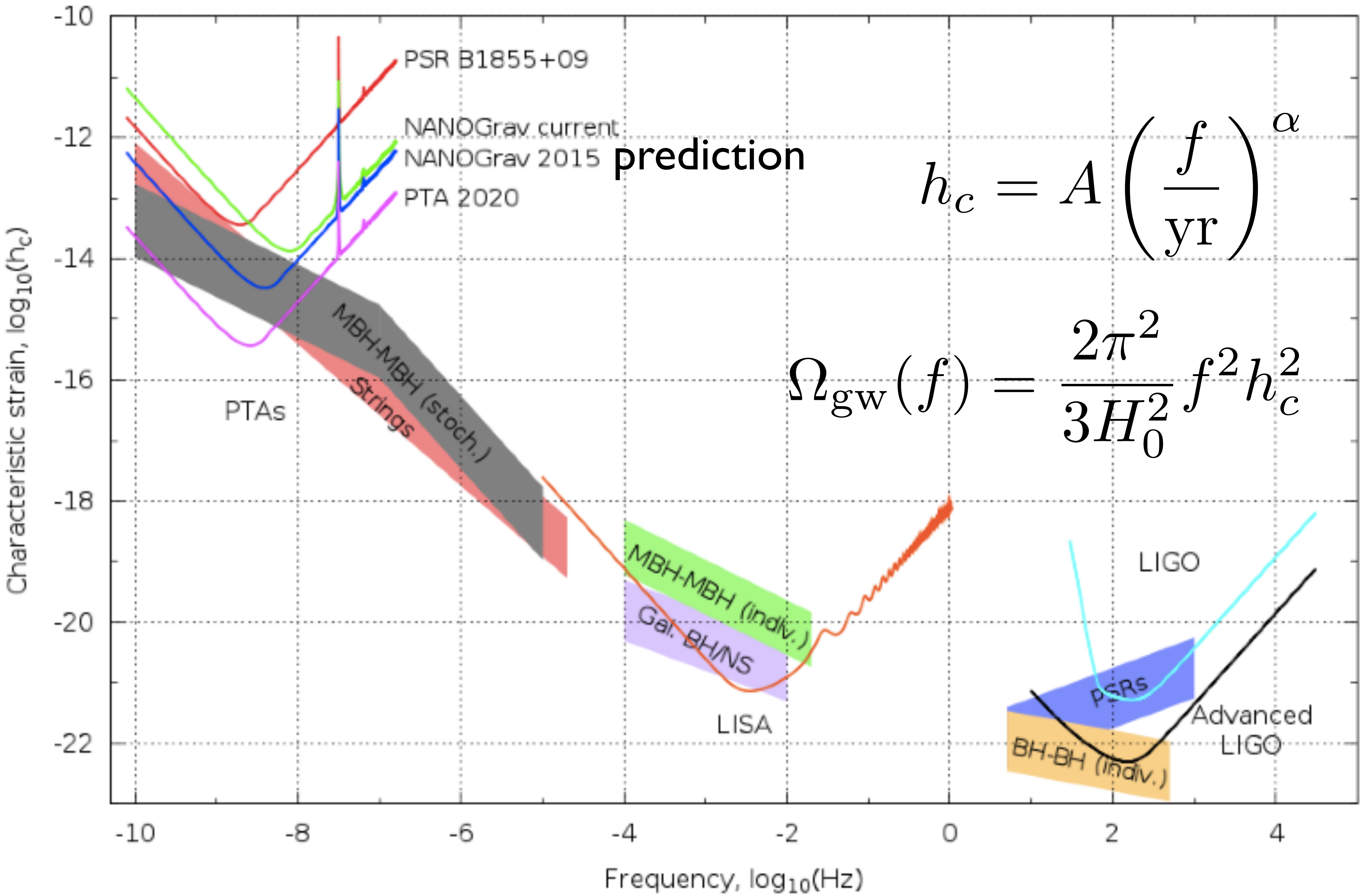

prediction

$$h_c = A \left(\frac{f}{\mathrm{yr}} \right)^{\alpha}$$

$\alpha = -2/3$

SMBHBs

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

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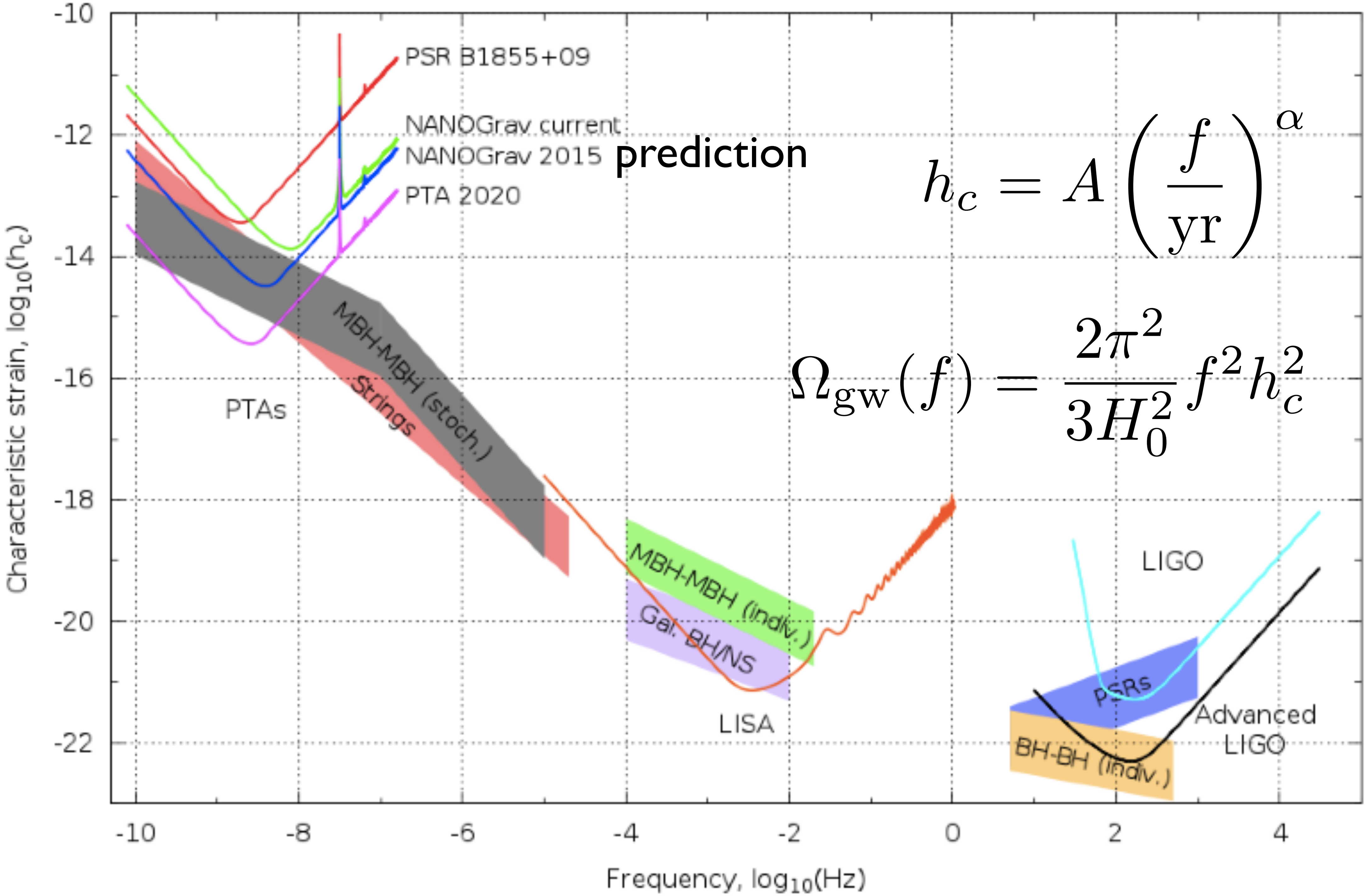

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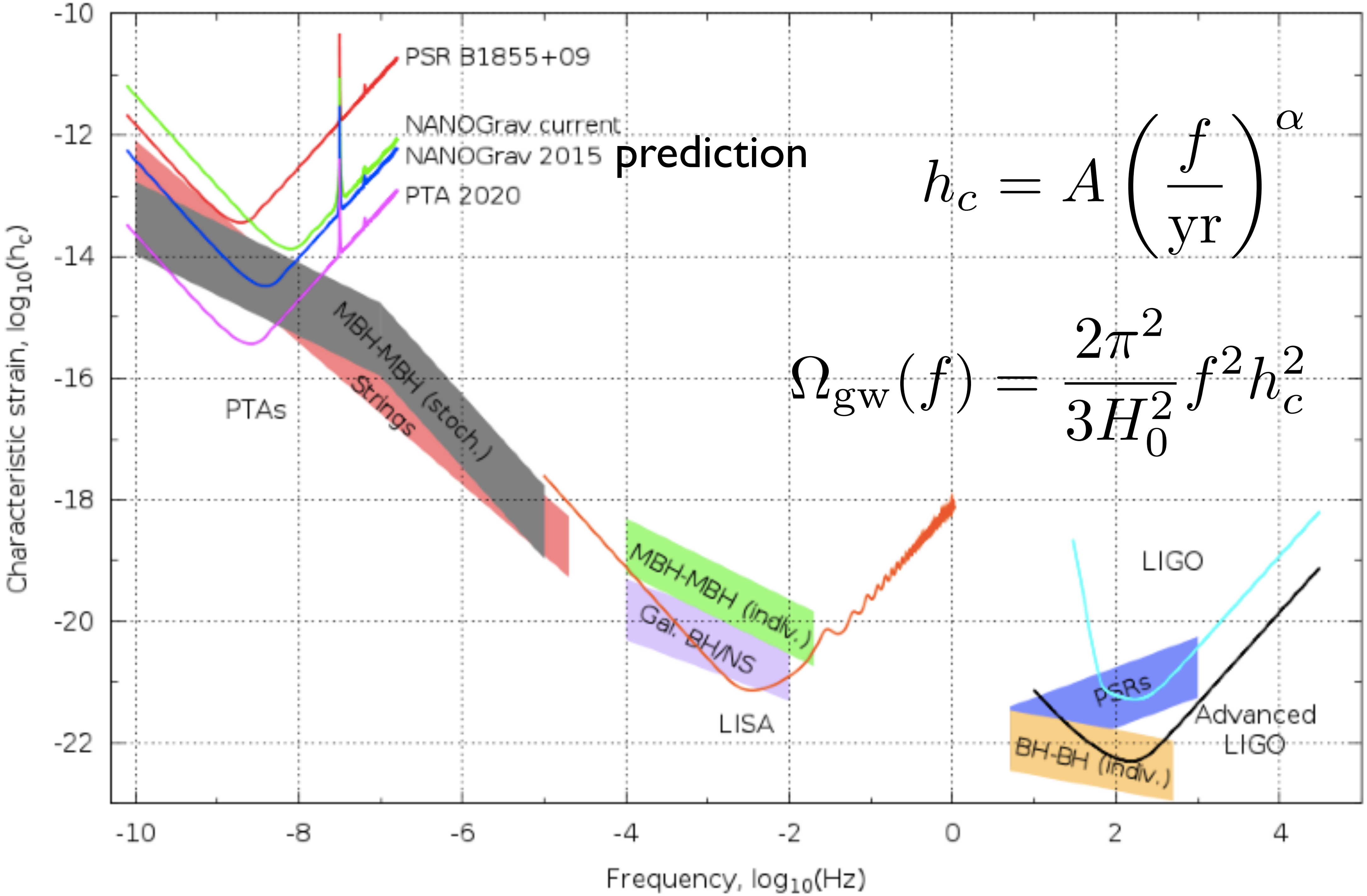
$$\Omega_{\mathrm{gw}}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2$$

$\alpha = -7/6$
Cosmic Strings

P. Demorest *et al.*, 2009

GW Landscape



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$\alpha = -2/3$
SMBHBs

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Cosmic Strings

$\alpha = -1$
Relics

P. Demorest *et al.*, 2009

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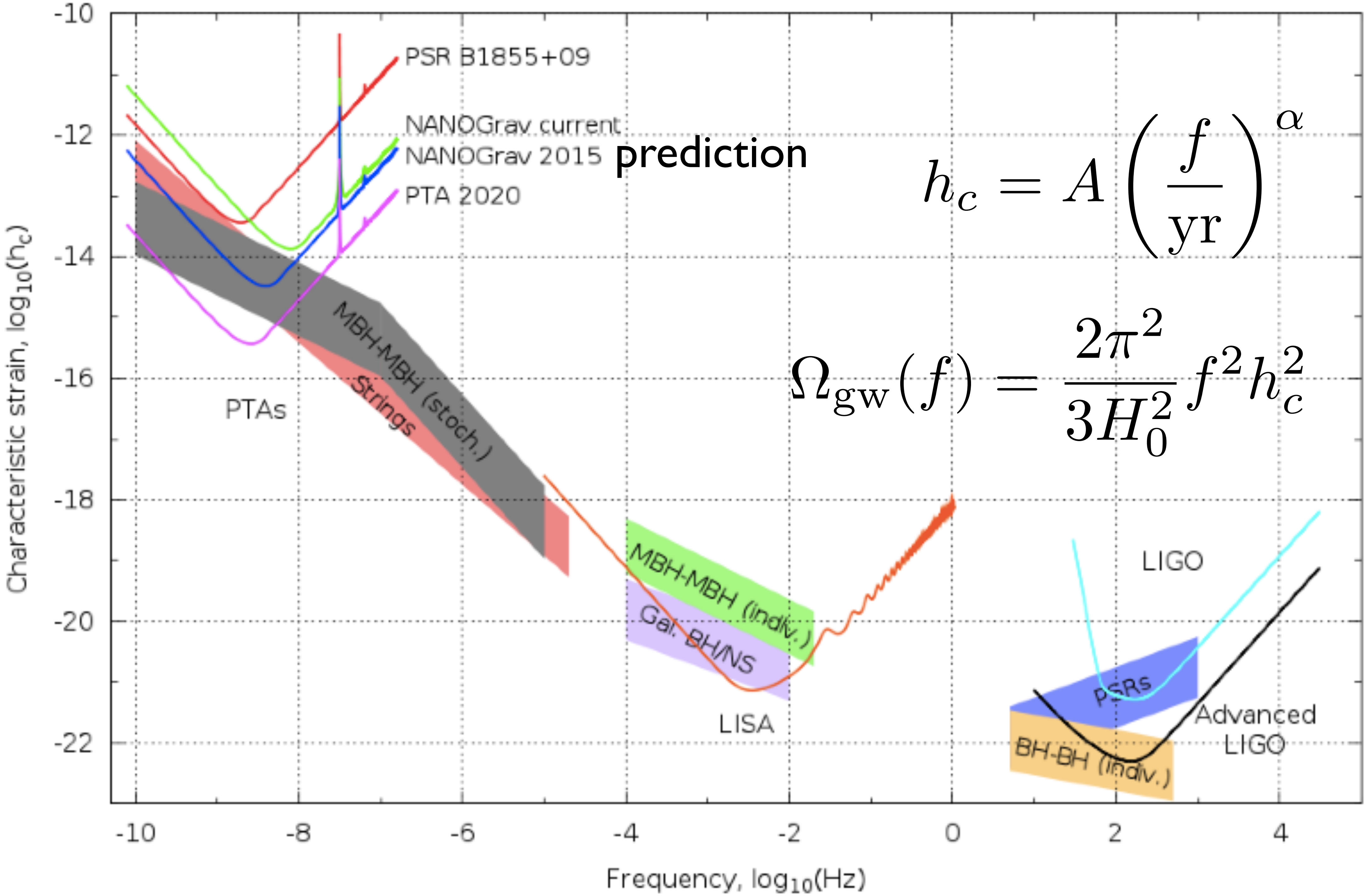

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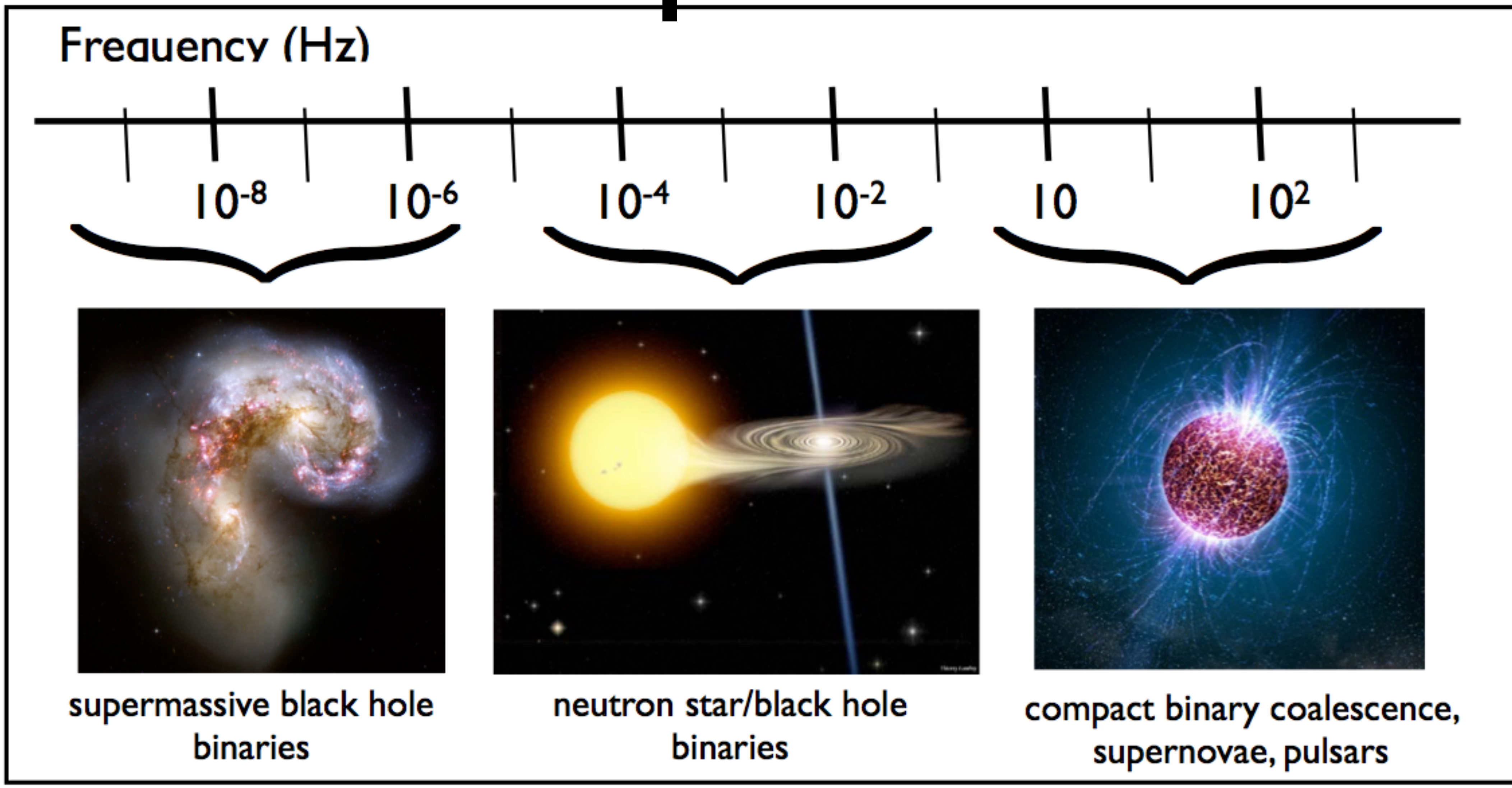
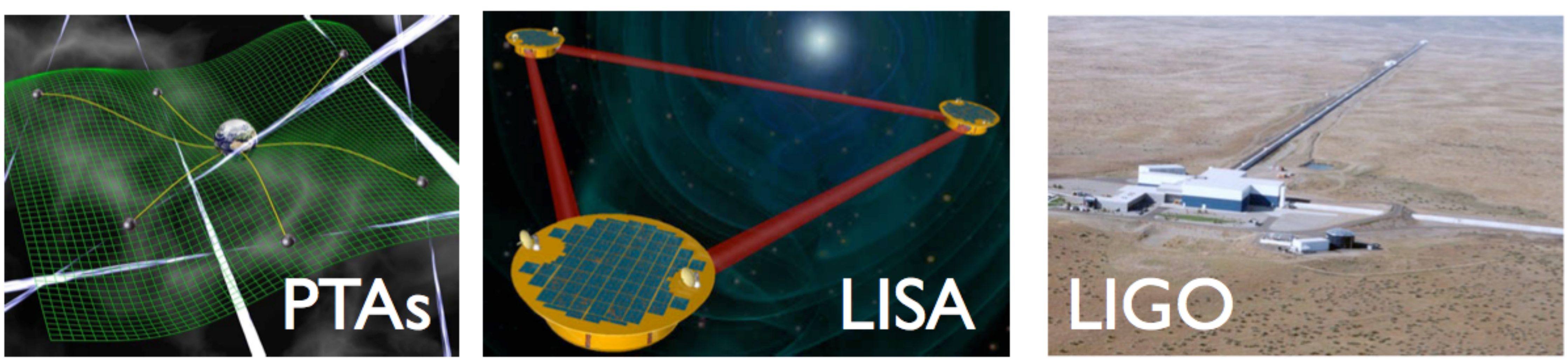
GW Experiments





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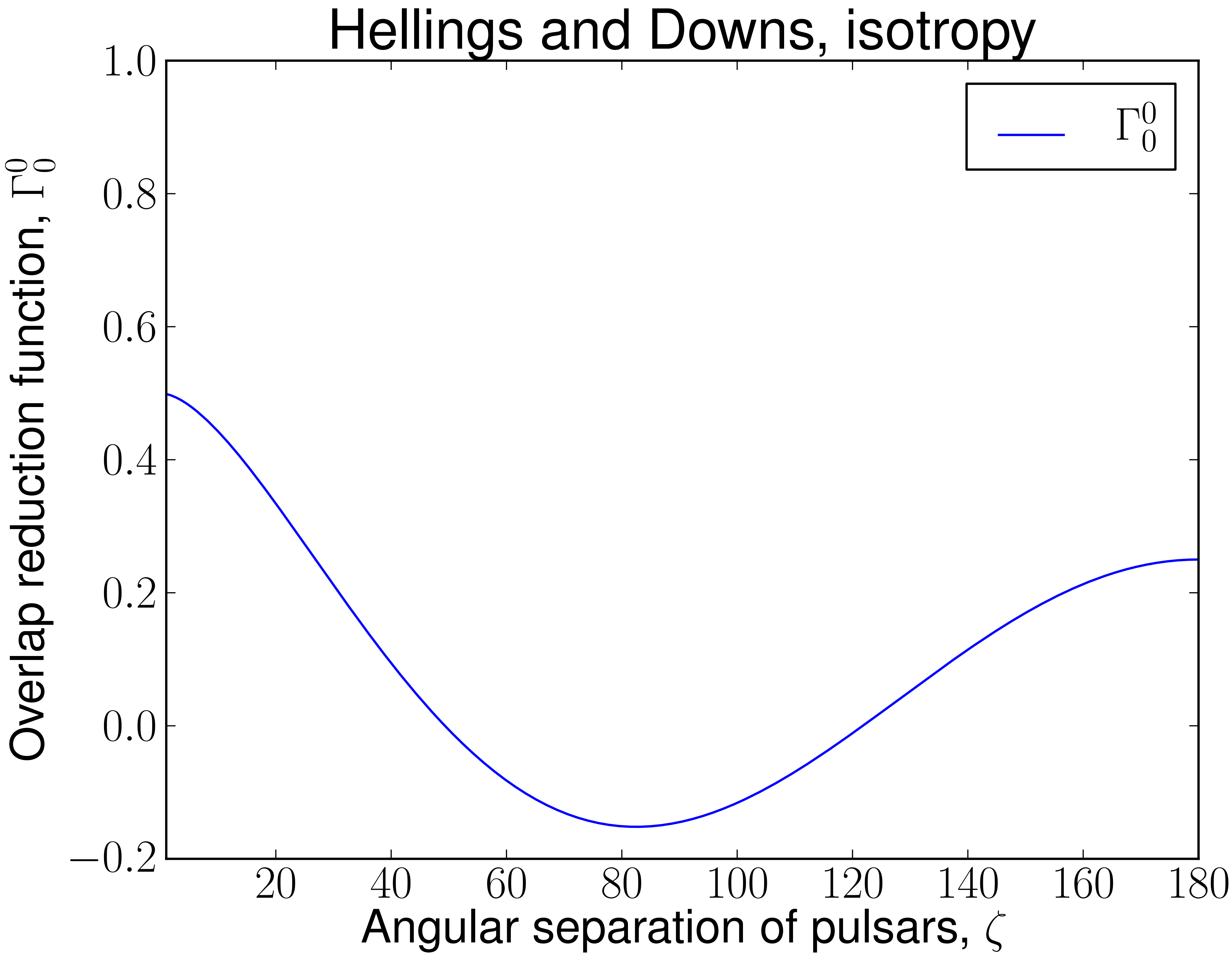
Look for characteristic correlation in residuals



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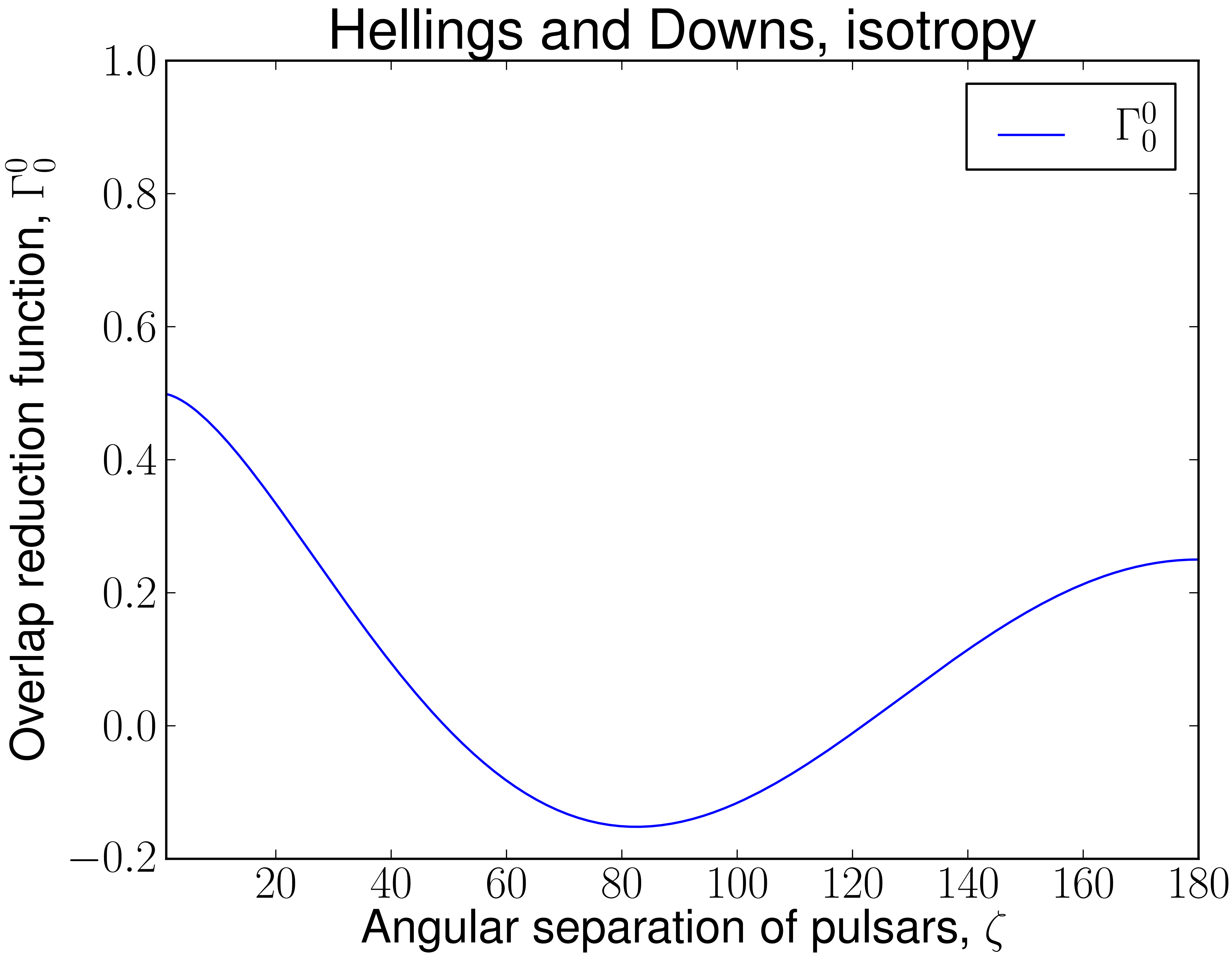

Overlap Reduction Function

For stochastic backgrounds

$$\langle r_{ai} r_{bj} \rangle \propto \, {}^{(ab)}\Gamma(f, \hat{\Omega}) \equiv \int_{S^2} d\hat{\Omega} P(\hat{\Omega}) \kappa_{ab}(f, \hat{\Omega}) F_a^A F_b^A$$

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residuals

Overlap Reduction Function

For stochastic backgrounds

antenna beam pattern

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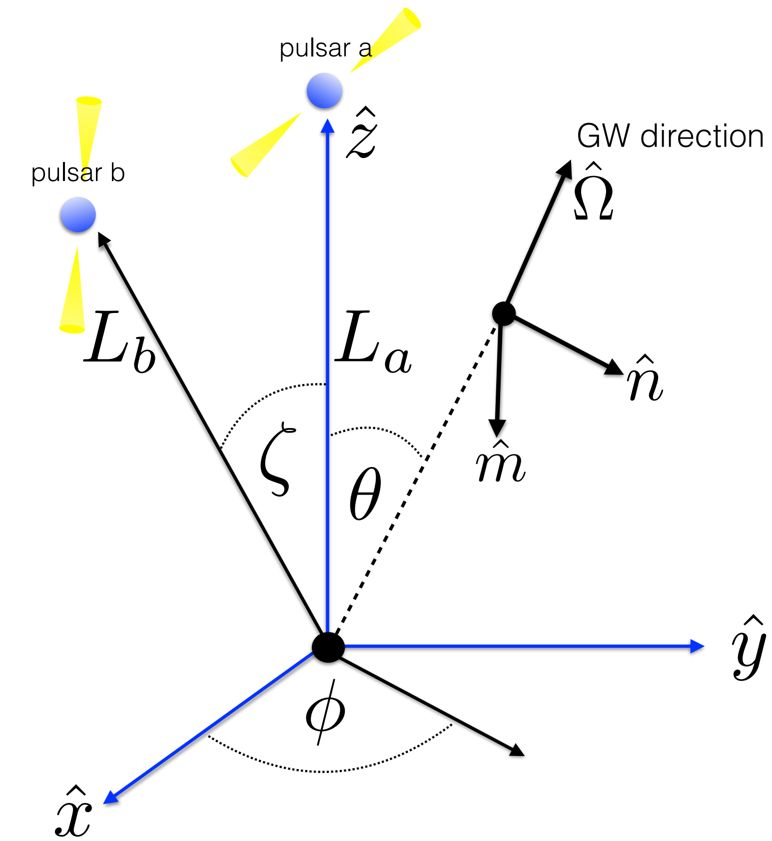

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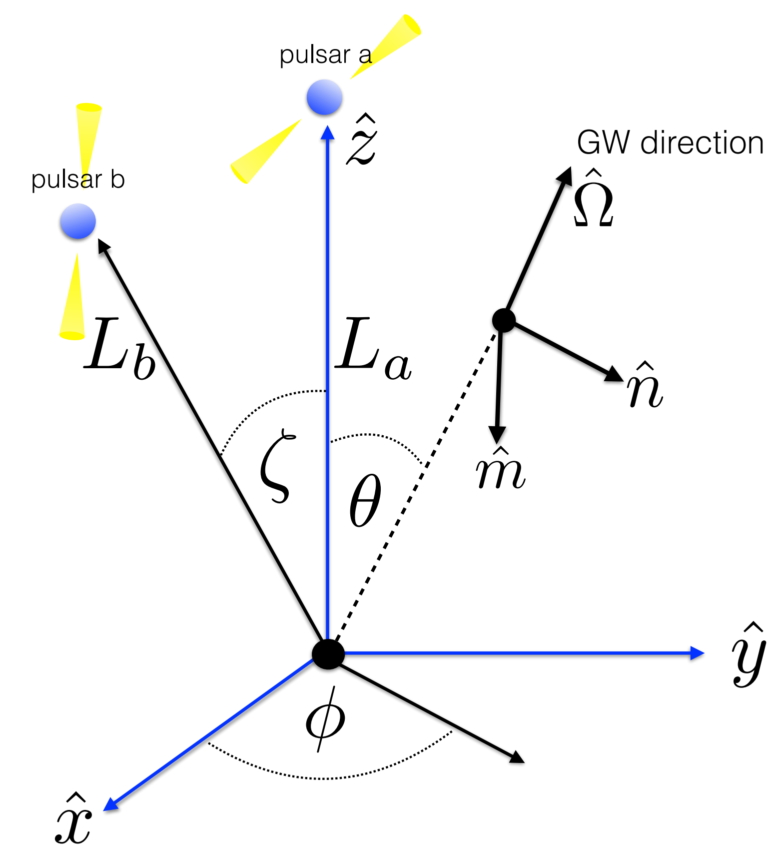
residuals

angular power distribution



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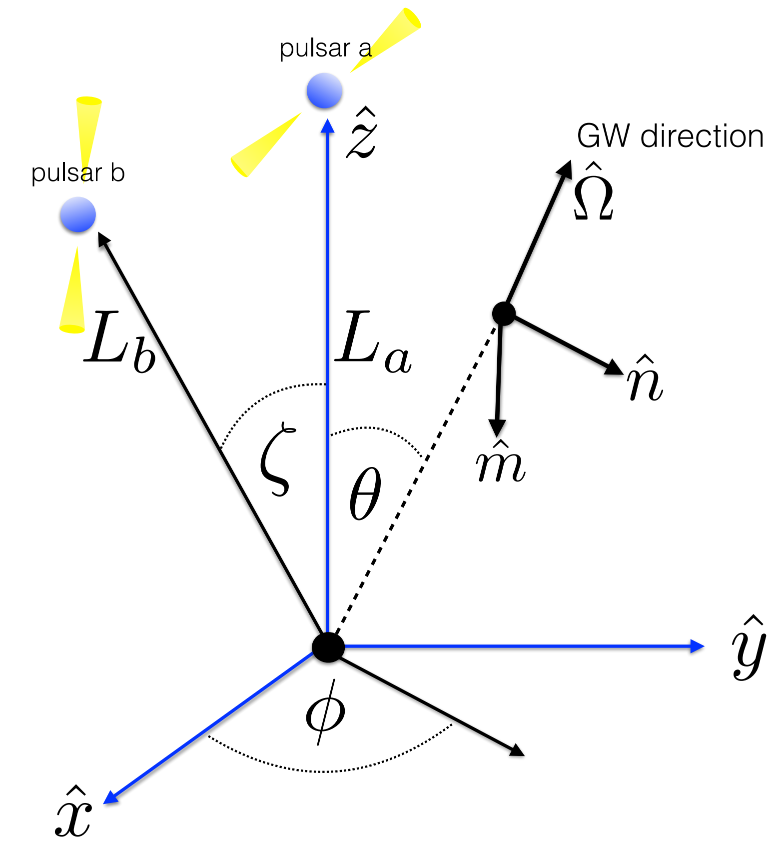

and

$$\kappa_{ab}(f, \hat{\Omega}) \equiv \left[1 - e^{i2\pi f L_a (1+\hat{\Omega}\cdot\hat{p}_a)}\right] \left[1 - e^{-i2\pi f L_b (1+\hat{\Omega}\cdot\hat{p}_b)}\right].$$

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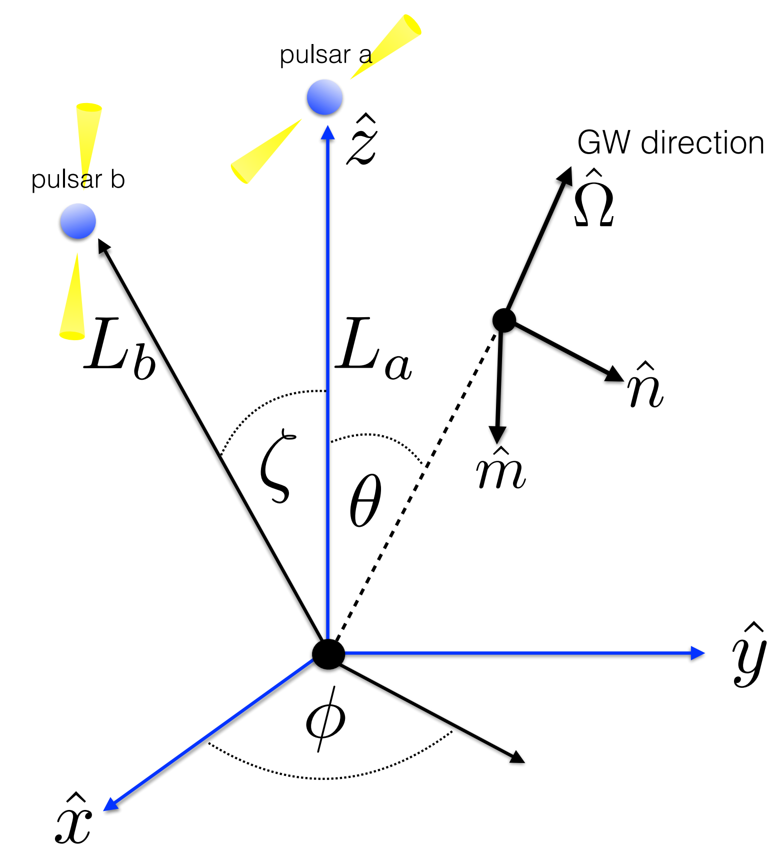

and

Earth term

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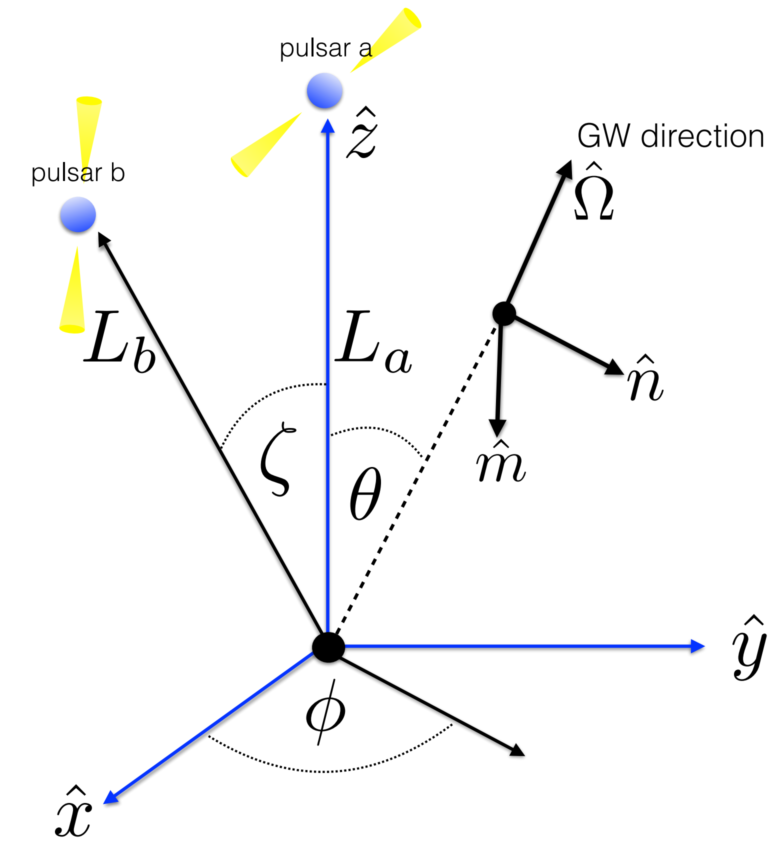
residuals

angular power distribution

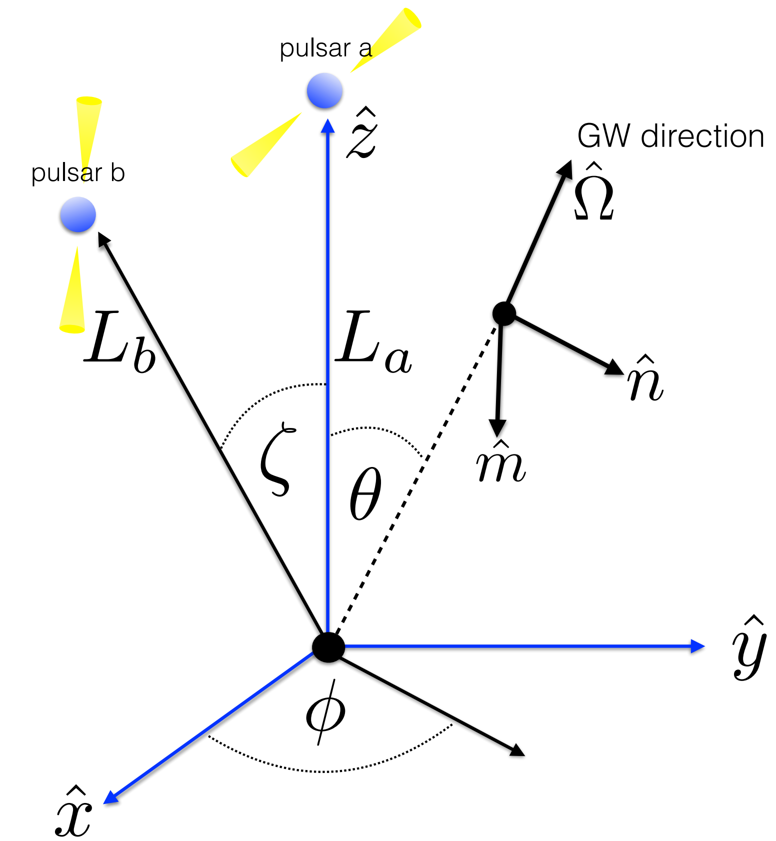


and

Earth term pulsar term

$$\kappa_{ab}(f, \hat{\Omega}) \equiv \left[1 - e^{i2\pi f L_a (1+\hat{\Omega}\cdot\hat{p}_a)}\right] \left[1 - e^{-i2\pi f L_b (1+\hat{\Omega}\cdot\hat{p}_b)}\right].$$

Overlap Reduction Function



For stochastic backgrounds

$$\langle r_{ai} r_{bj} \rangle \propto {}^{(ab)}\Gamma(f, \hat{\Omega}) \equiv \int_{S^2} d\hat{\Omega} P(\hat{\Omega}) \kappa_{ab}$$

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In the short wavelength approximation, fL >>1 and L_a=L_b so

$$\kappa_{ab} \approx 1 + \delta_{ab}$$

Outline

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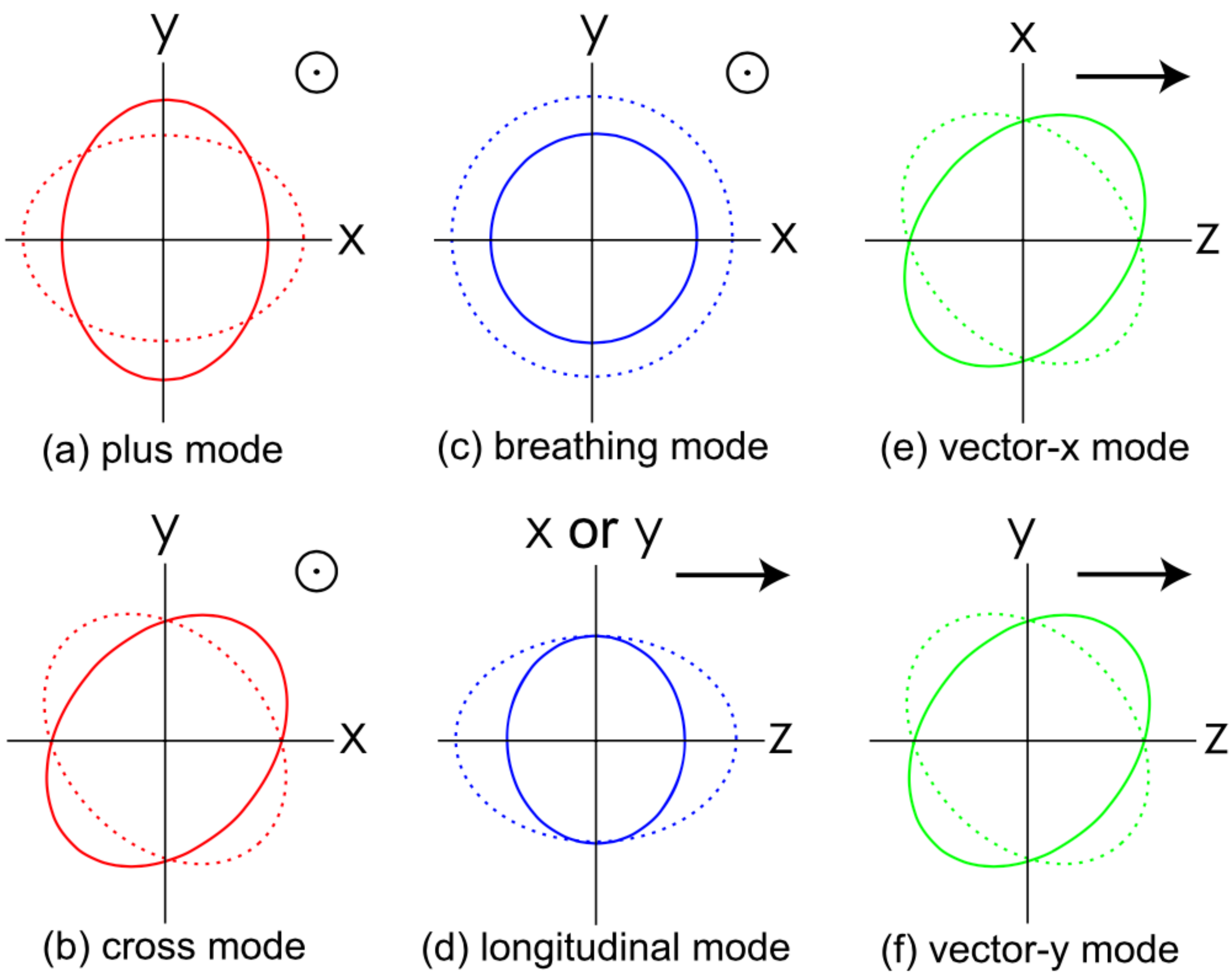
Tests of GR

- Recall Yanbei Chen's talk!
- Hellings and Downs overlap reduction function assumes General Relativity, and its 2 polarizing states, "+" and "x".
- Other theories of gravity allow for different polarization states, such as breathing modes, longitudinal modes and shear modes

GW Polarizations



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Sydney Chamberlin and Xavi Siemens, PRD 2012

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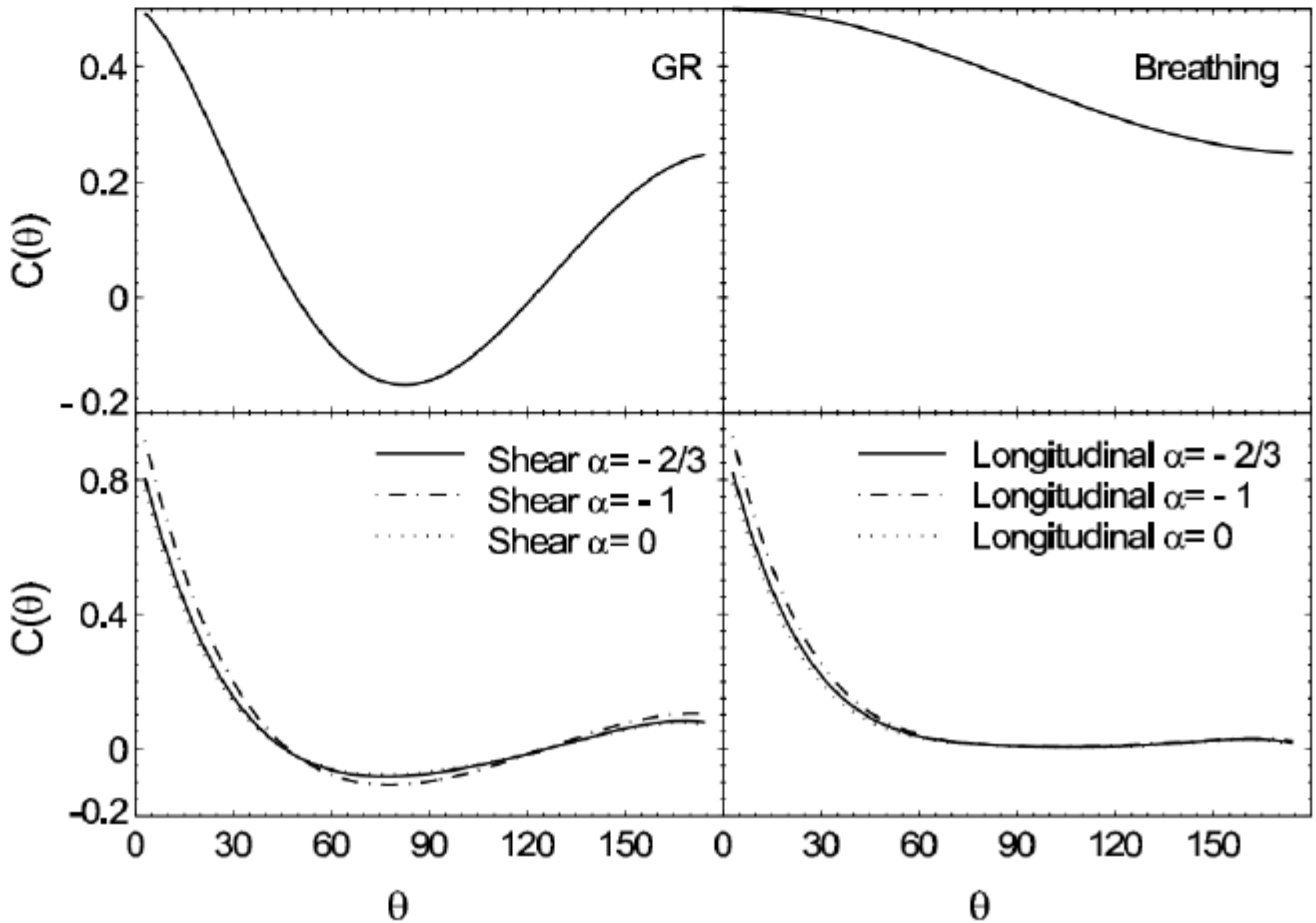
New correlation functions



 Lee et al. 2008, ApJ, 685, 1304

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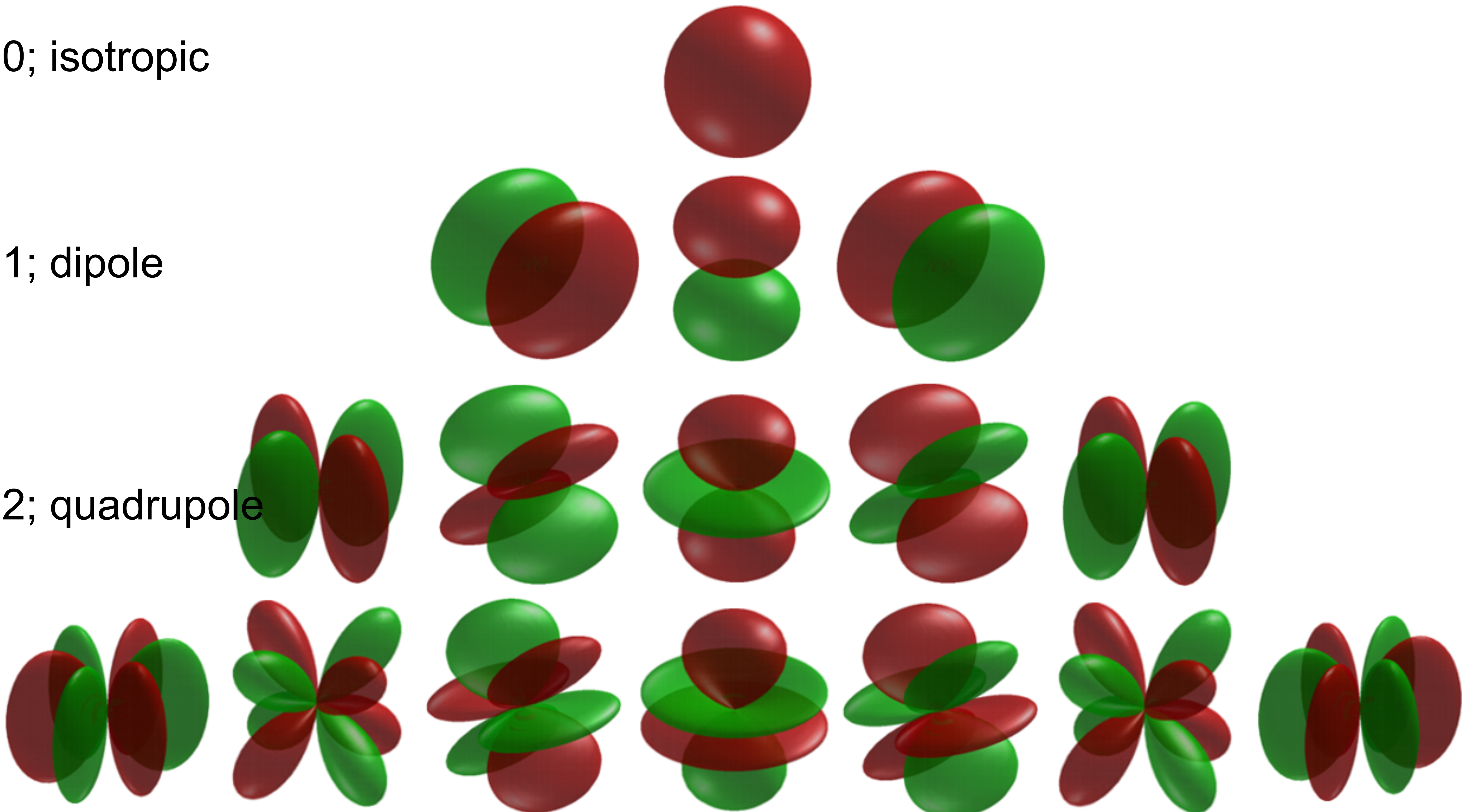
Spherical Harmonics

l=0; isotropic

l=1; dipole

l=2; quadrupole



Anisotropy

Anisotropy

$$\Gamma_{lm}^{(ab)}$$

Anisotropy

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GW Power

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$\boxed{\text{search for these}}$

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Mingarelli et al. (2013)

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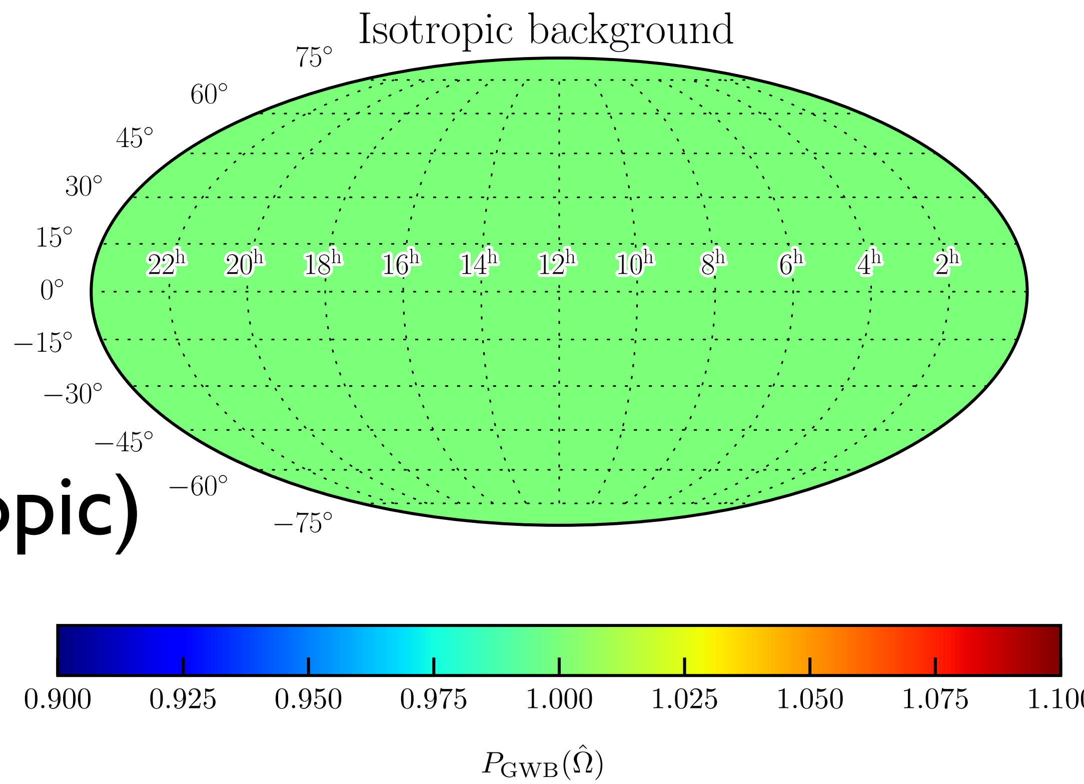
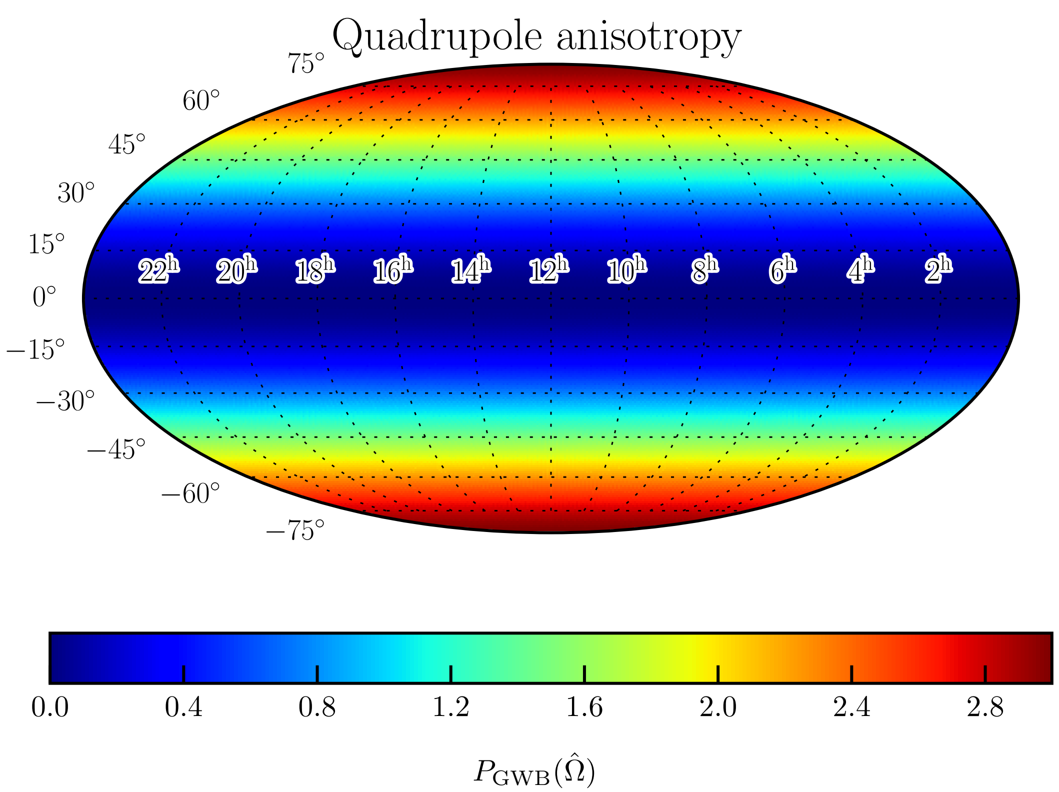
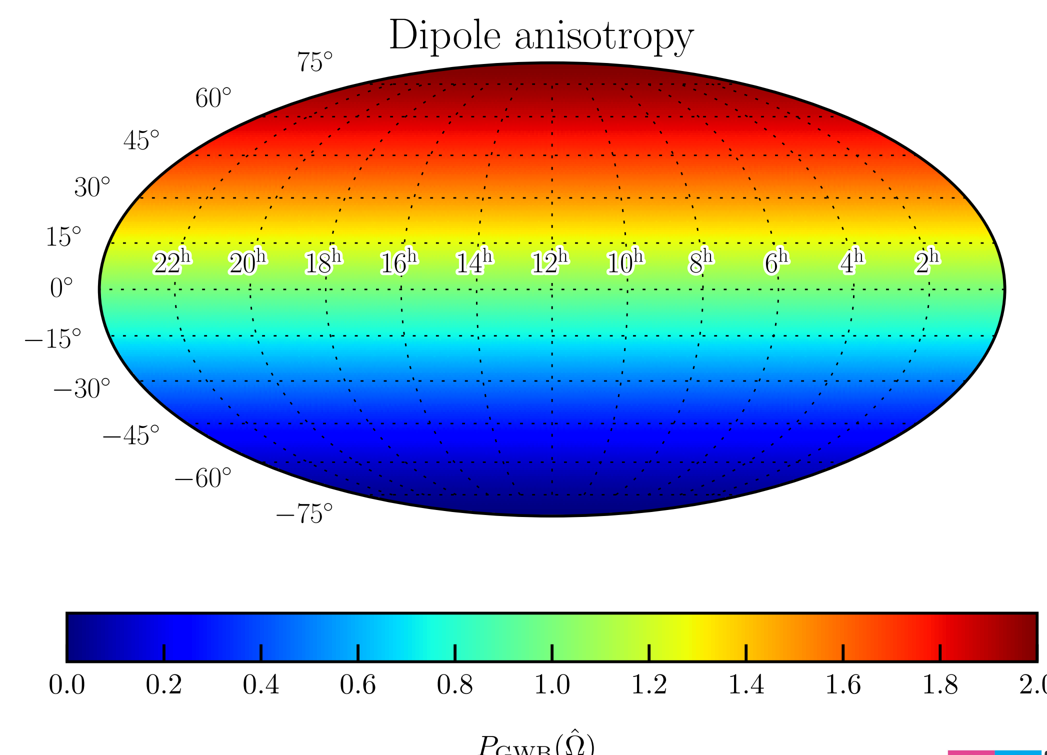
In terms of power on the sky



(also statistically isotropic)





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maps courtesy Stephen Taylor

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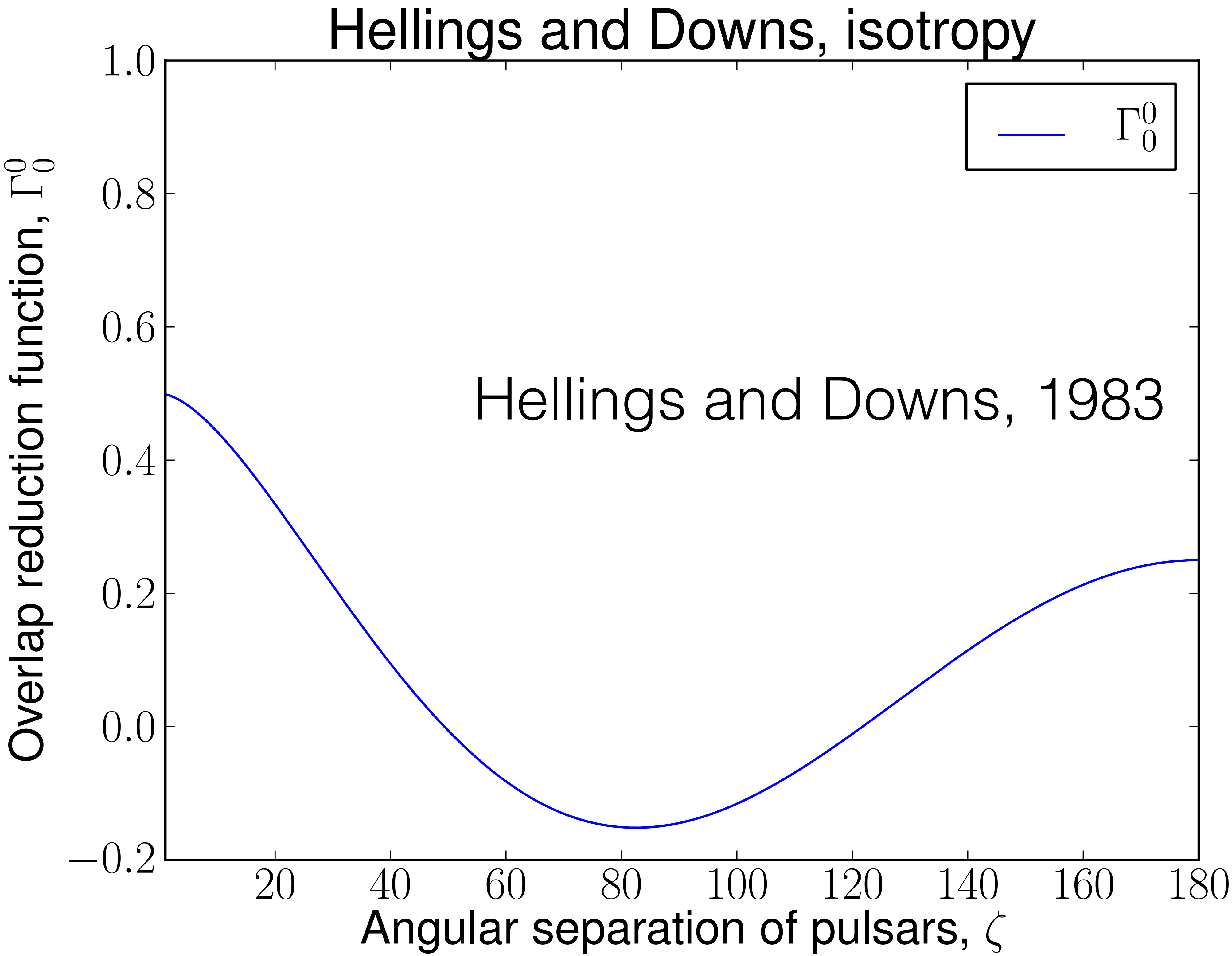

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Mingarelli et al. PRD **88**, 062005 (2013)

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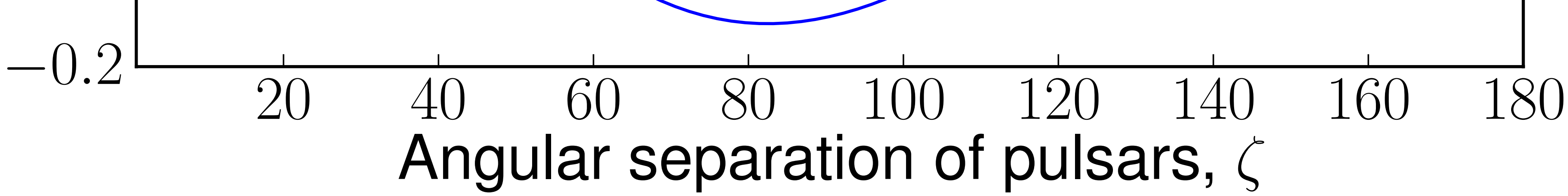

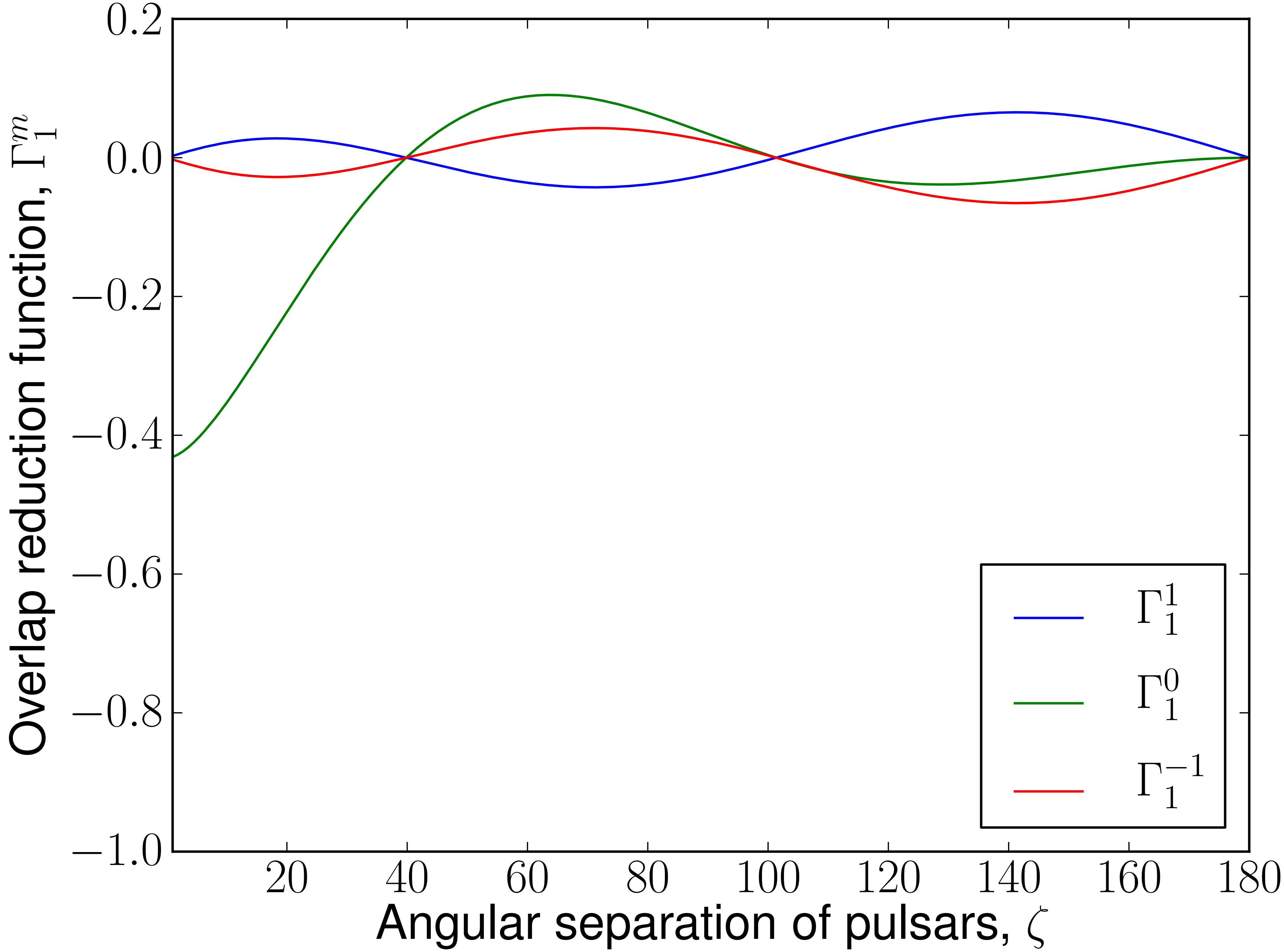

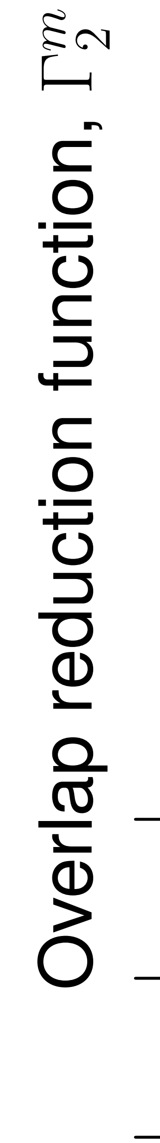

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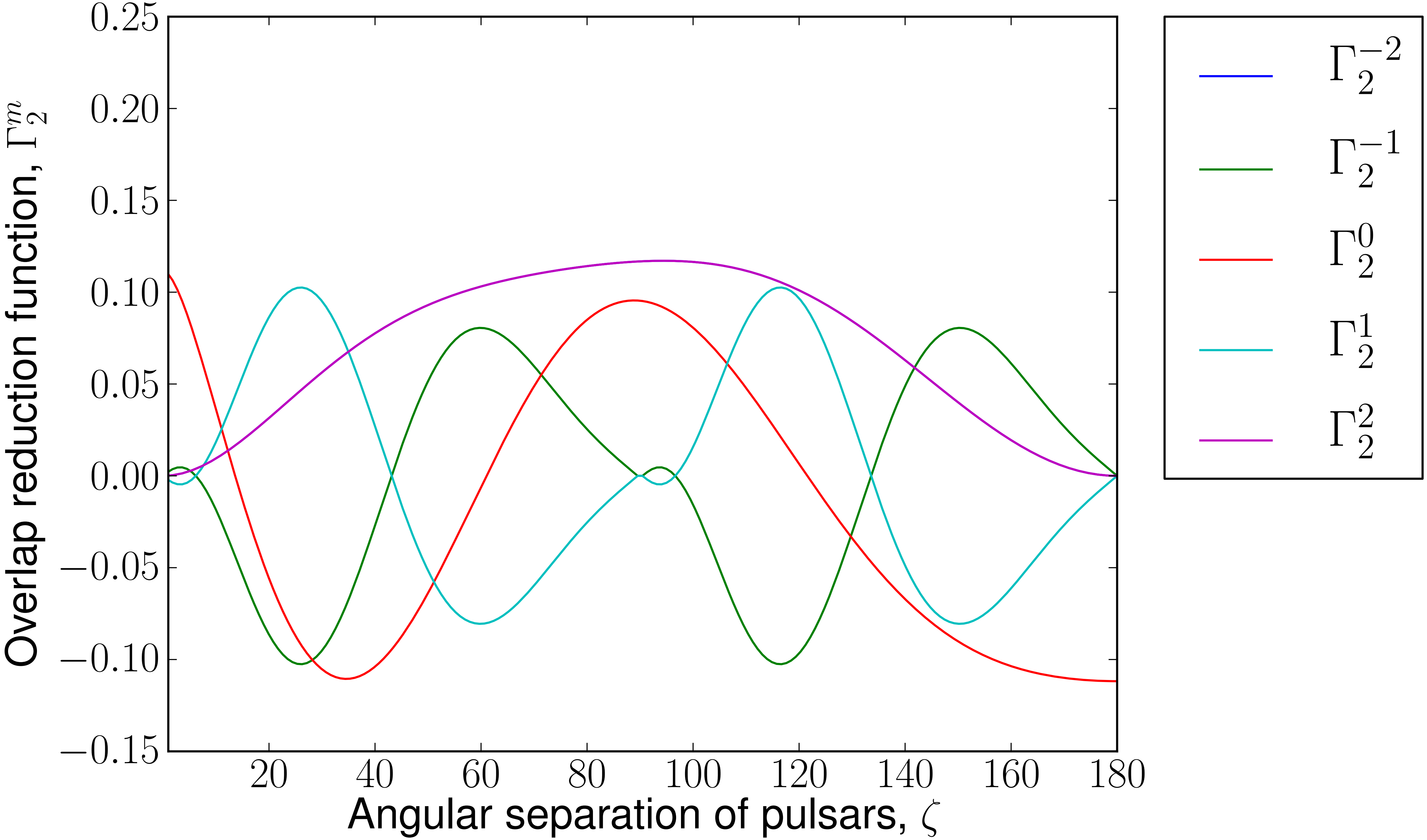

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Mingarelli et al. PRD **88**, 062005 (2013)

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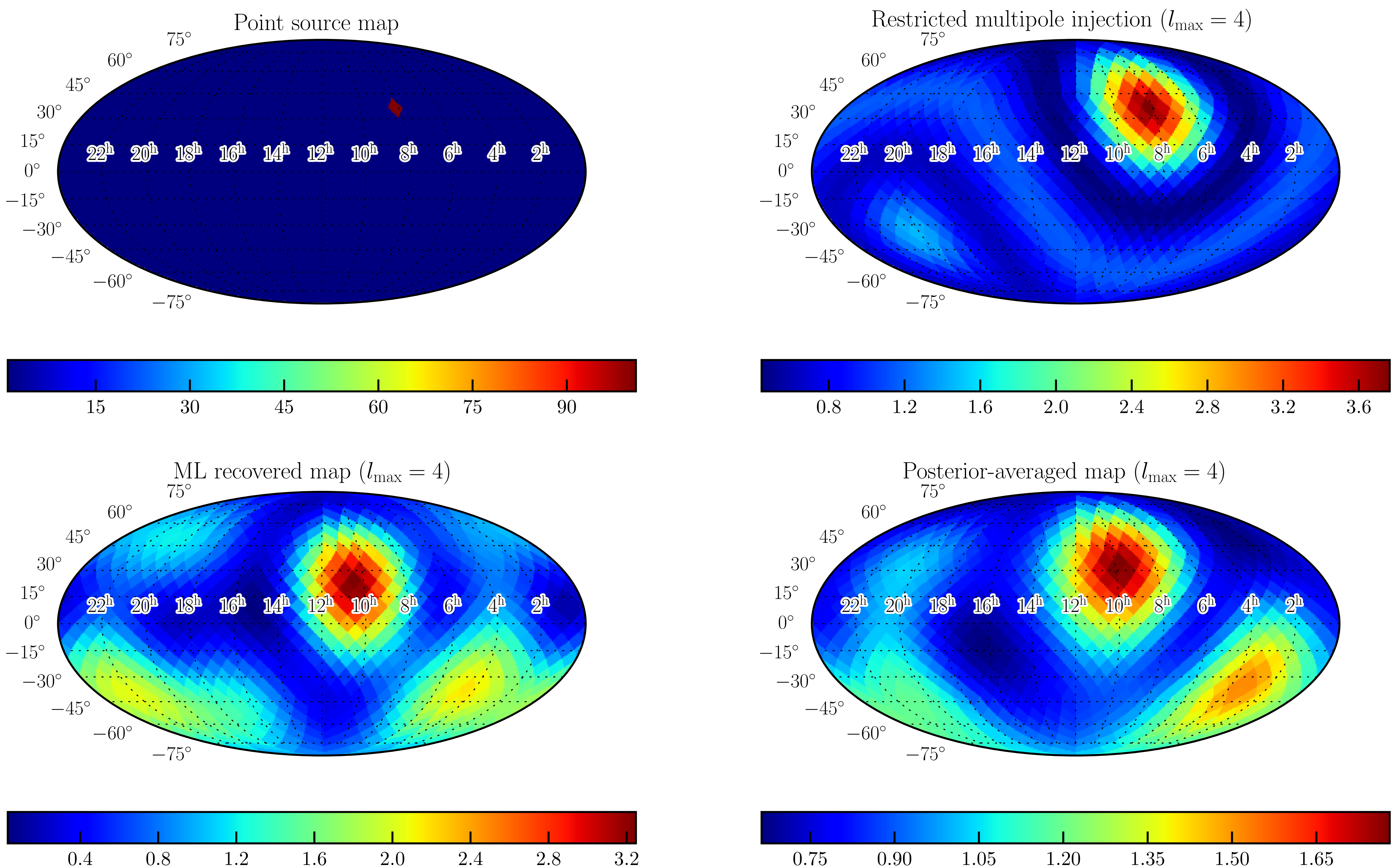
Inject & Recover



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Taylor, Mingarelli et al. PRL

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PRELIMINARY RESULTS

NANOGrav 9-yr dataset

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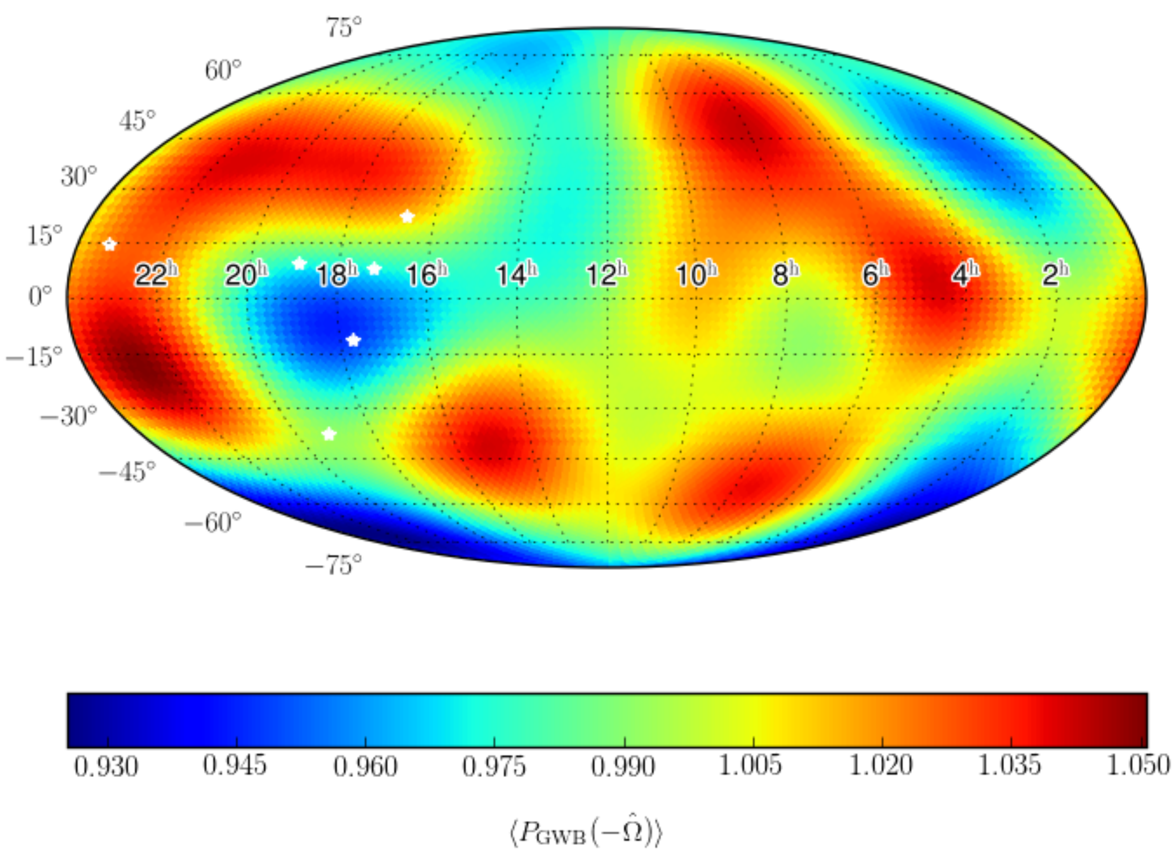

Power from full search

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PRELIMINARY RESULTS

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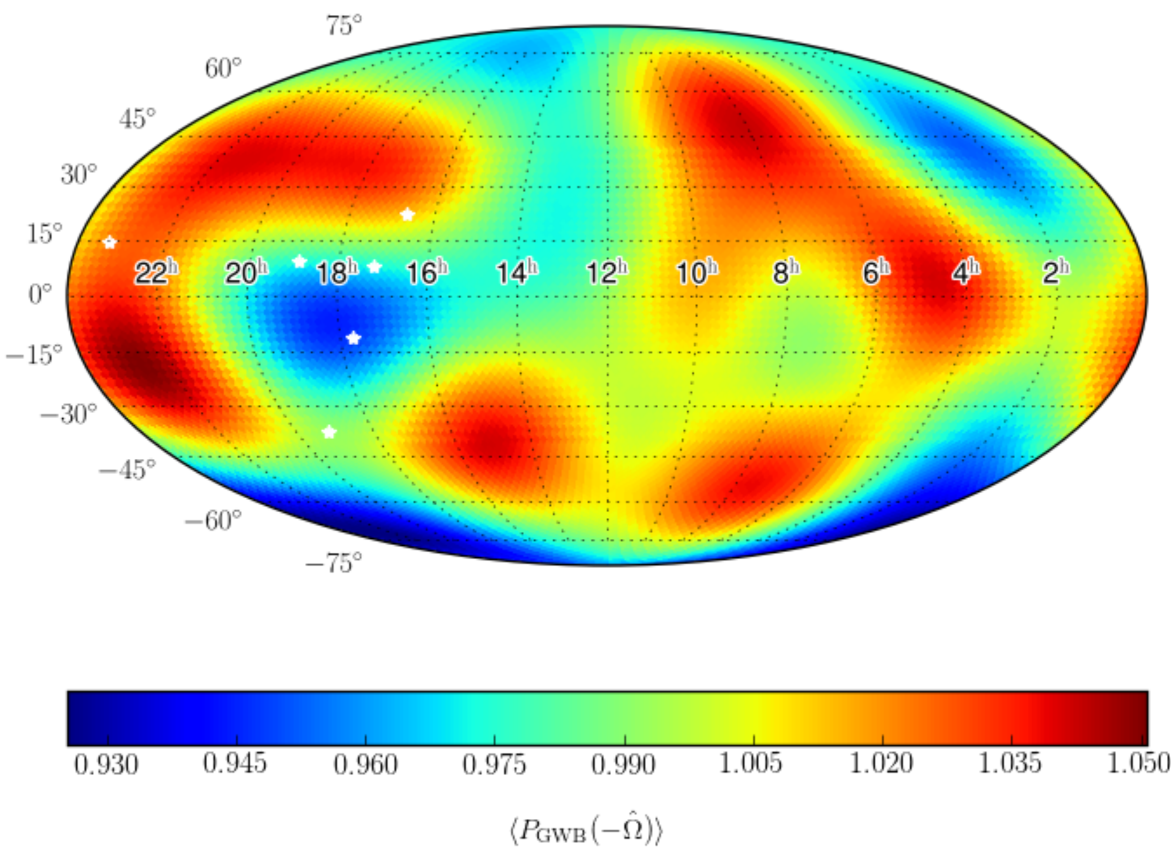

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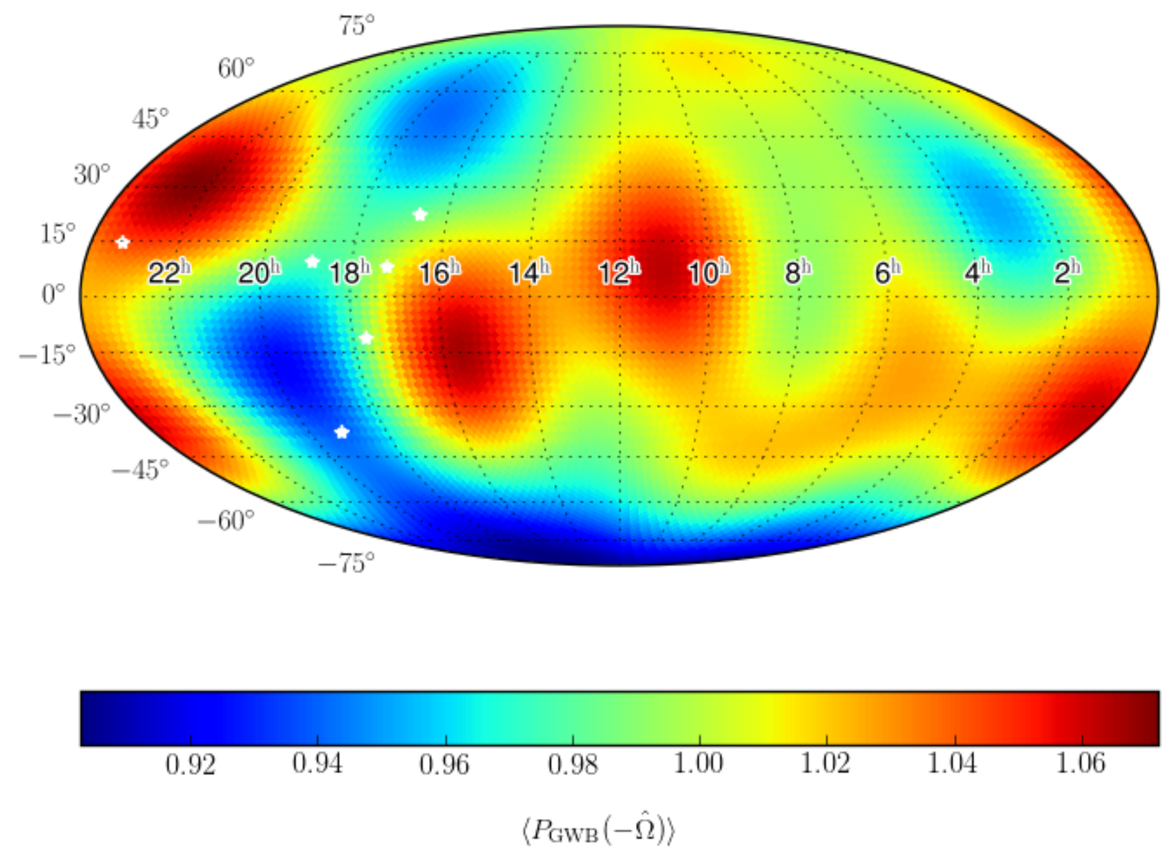

Prior (log likelihood=0)

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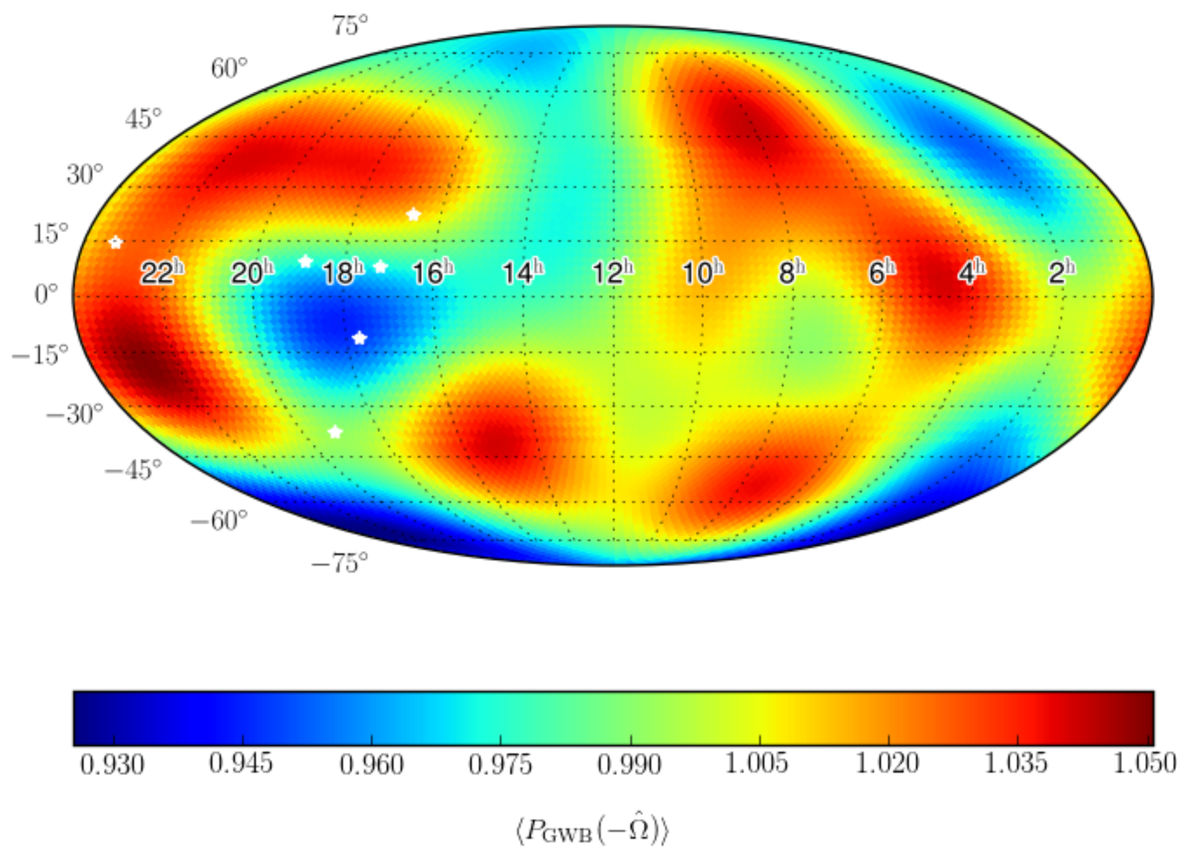

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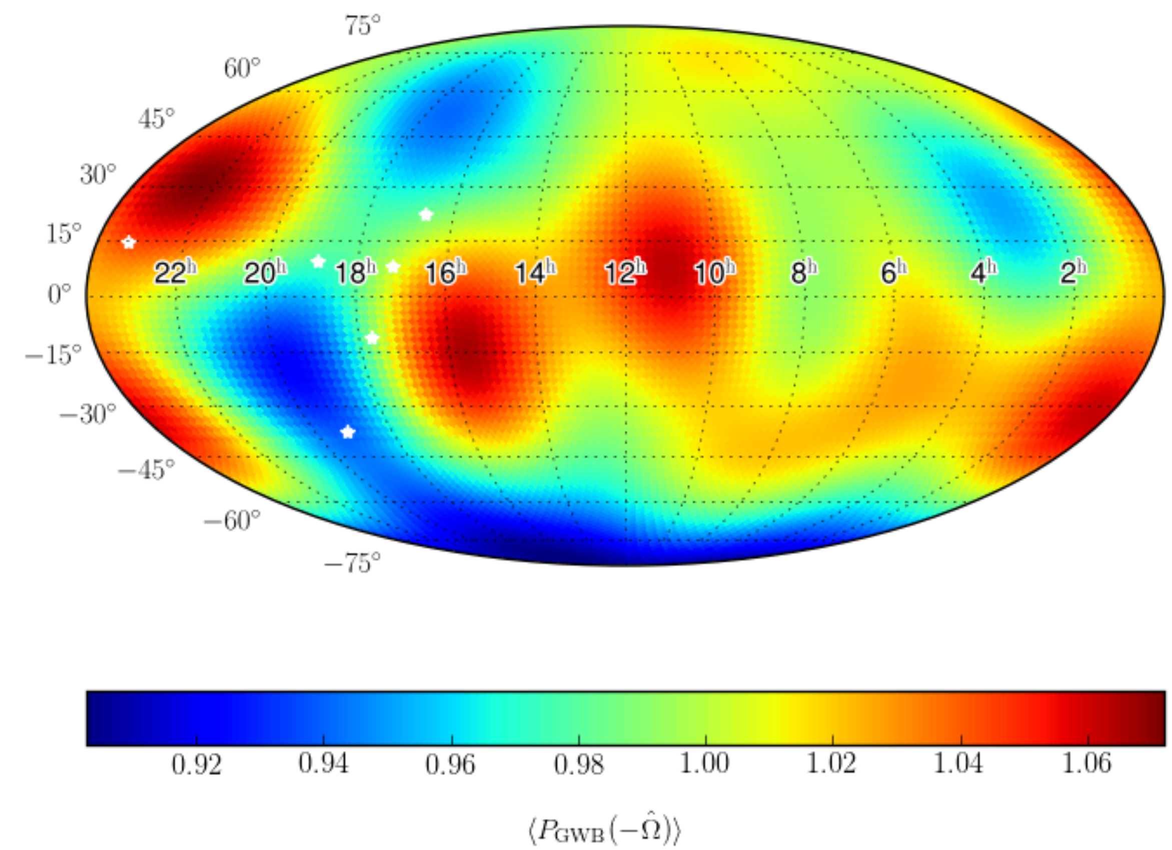

Prior (log likelihood=0)

Only 5% variation in power.. not significant

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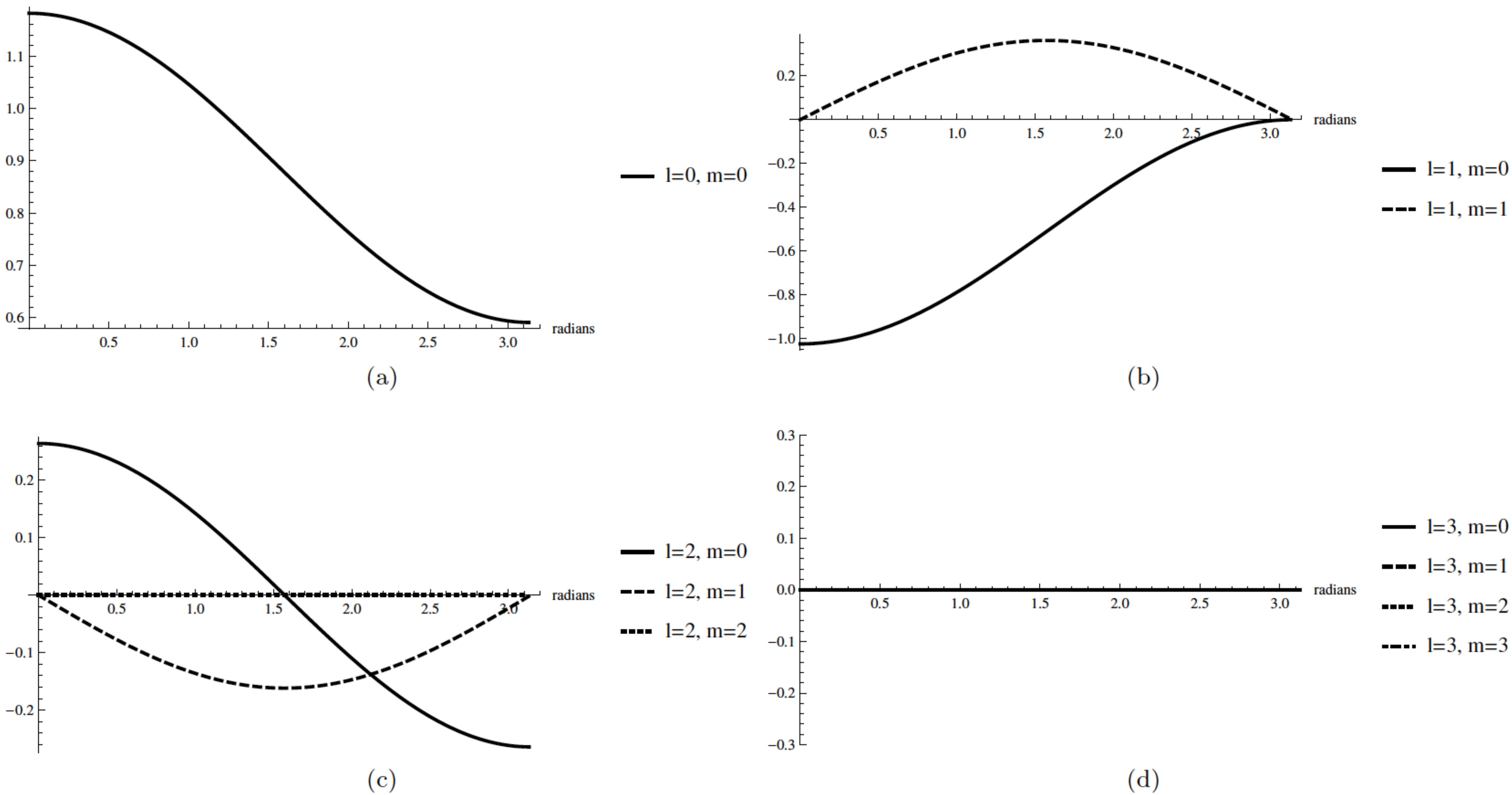
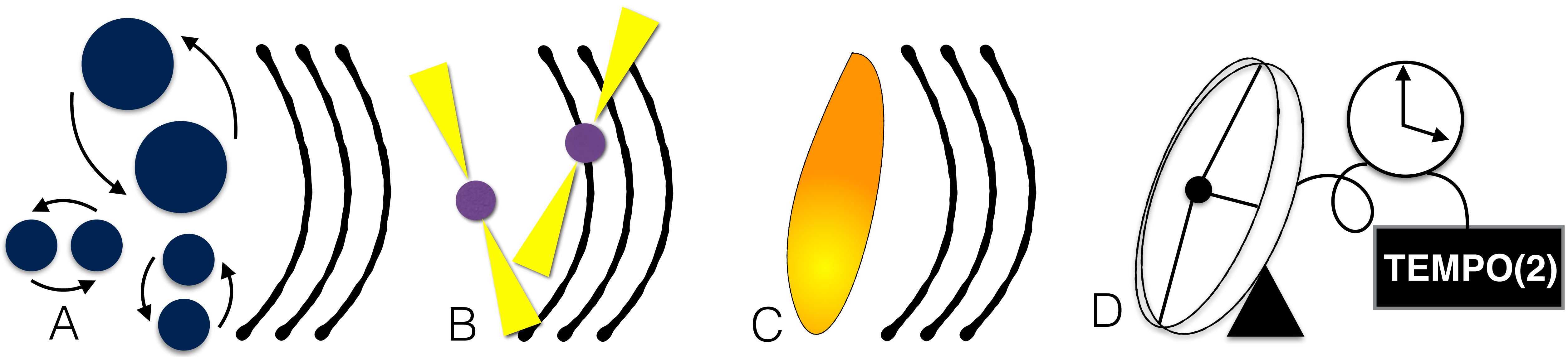
Anisotropic non-GR



Breathing mode overlap reduction function

Gair, Romano, Taylor 2015

Pulsar Timing Array



A: GWs from e.g. supermassive BH binaries (also cosmic strings)

B: GWs perturb space-time at the pulsars as they transit

C: ionized gas in the interstellar medium disperses & scatters the light from pulsars

D: GW perturb signals from all pulsars at Earth. Time of arrivals and residuals are calculated.

Science!

Gravitational Waves

Stochastic Background

- isotropic
- anisotropic
- detect or limit

Continuous Waves

- detect or limit

Bursts

- memory
- unmodeled
- detect or limit

Science!

Funding

Outreach

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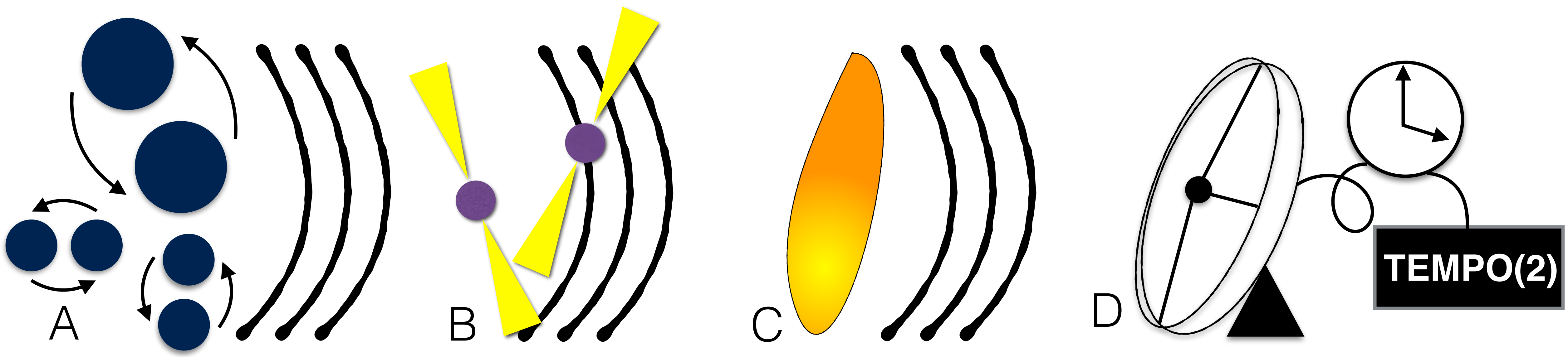

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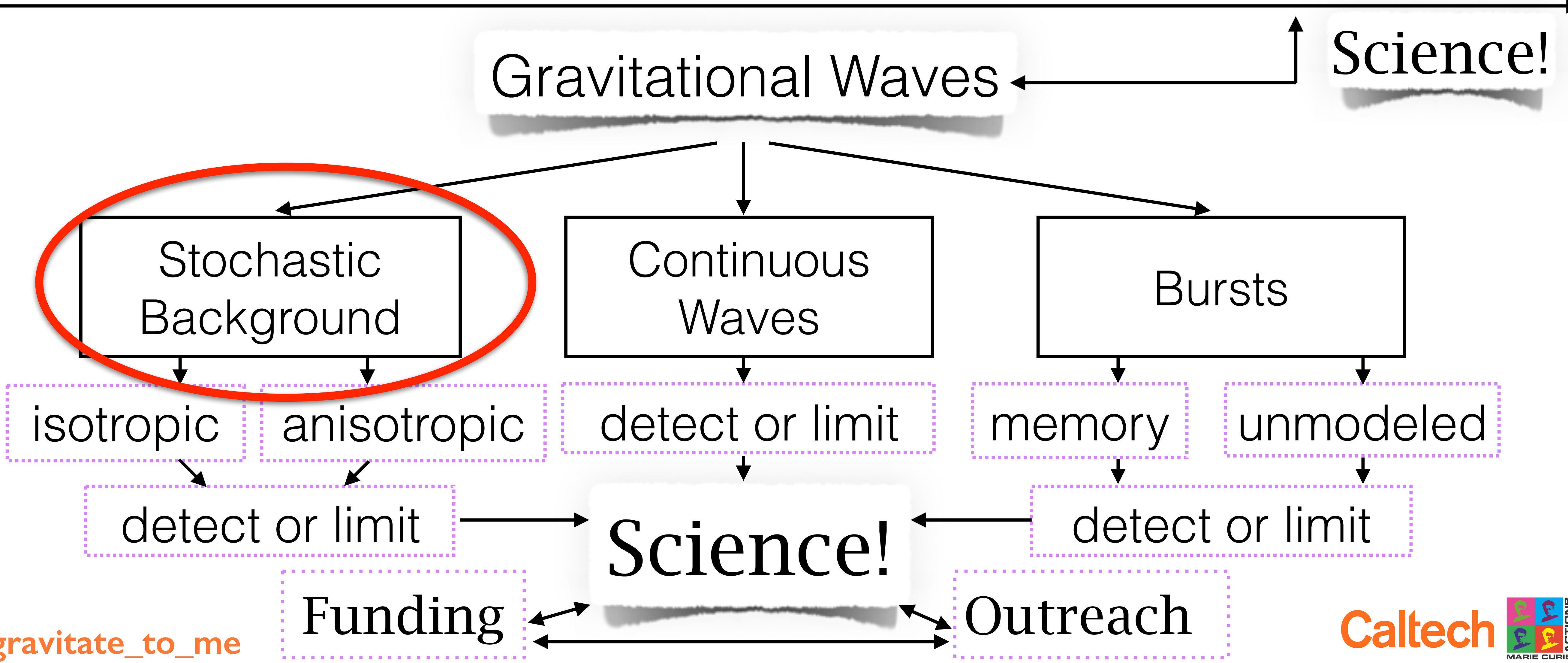

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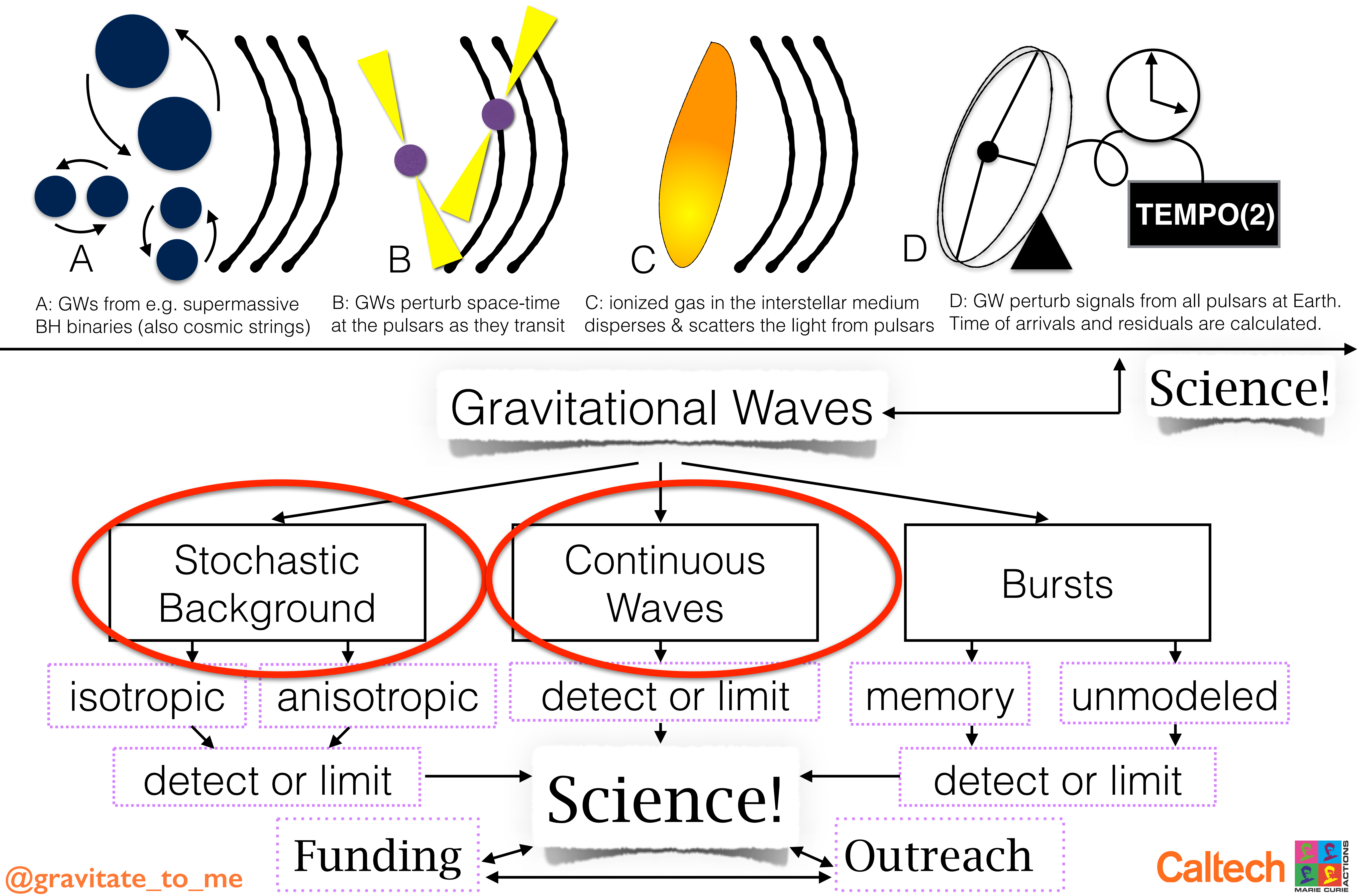

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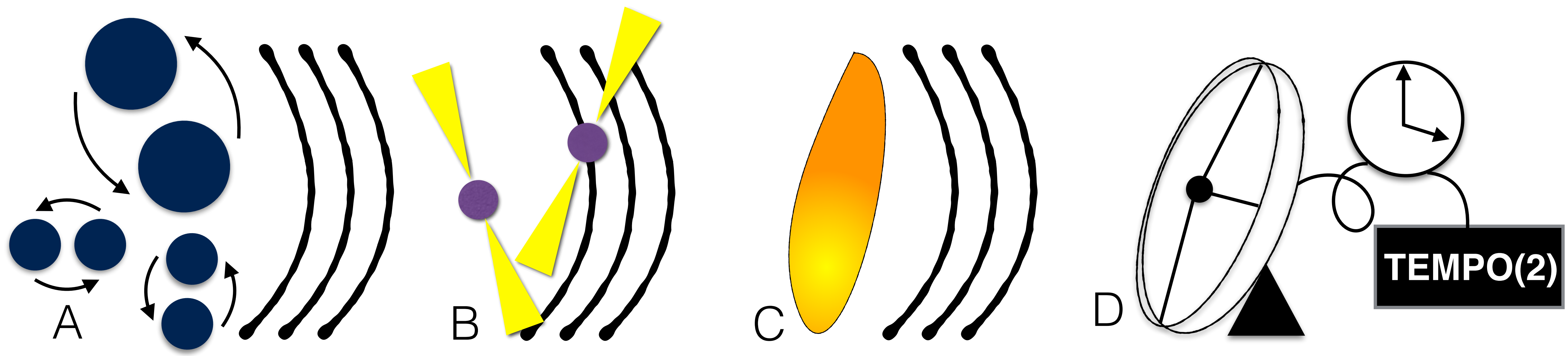

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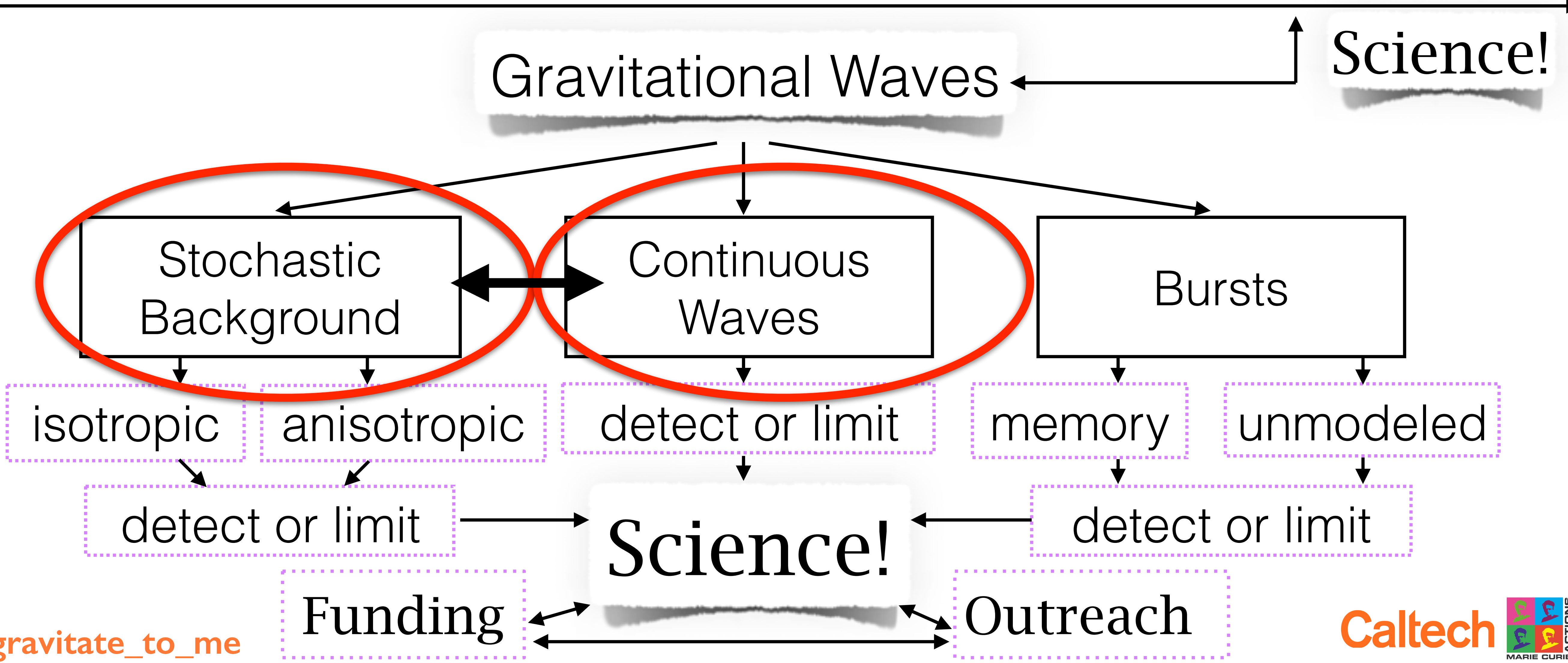

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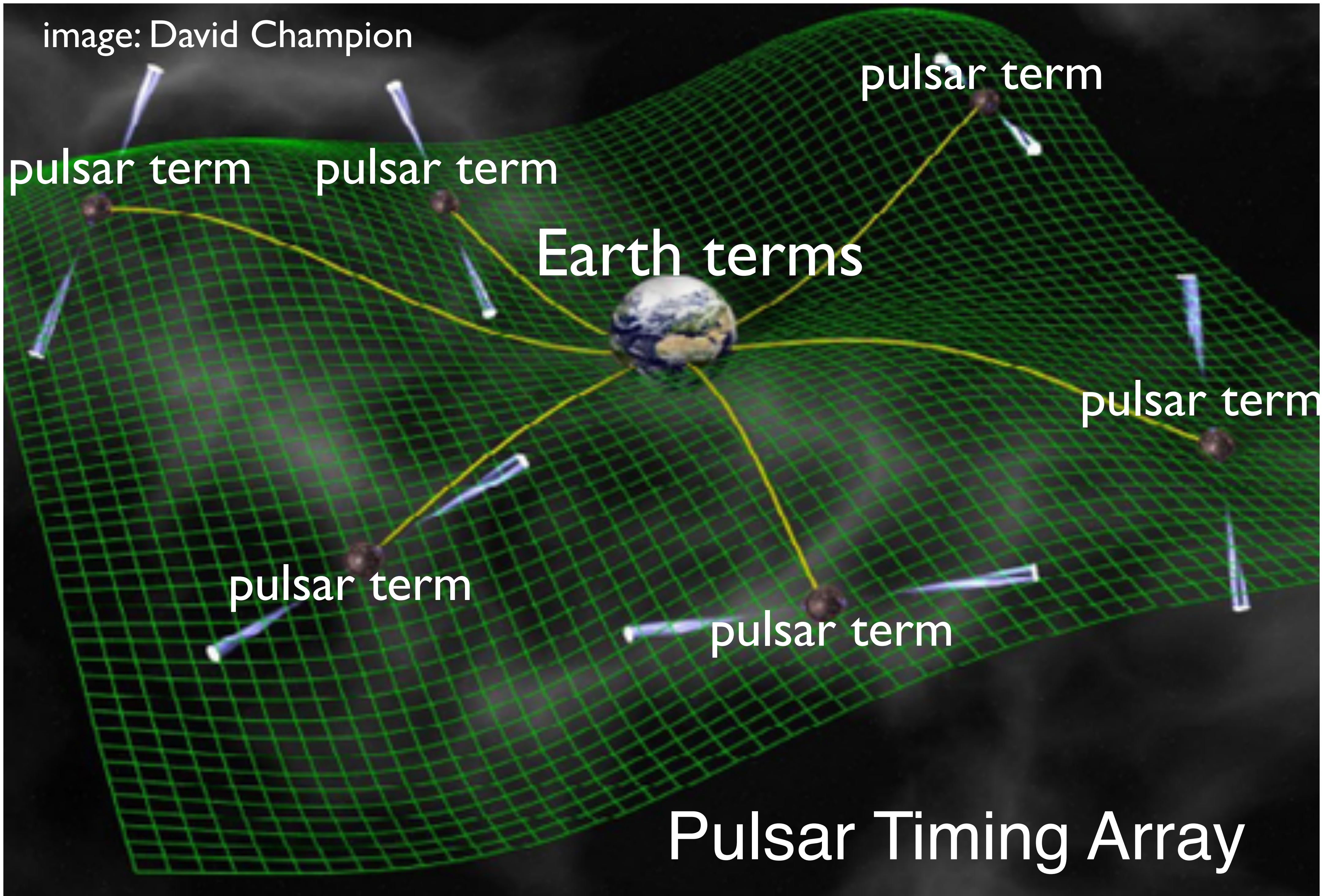
Astrophysics from Continuous GW Sources

General idea:

- Some sources may be sufficiently **close, high mass** to rise above the stochastic GW background, and become individually resolvable

- If the pulsar term is in a different frequency bin AND is resolvable, PTAs can be used as *time machines:* can measure evolution of SMBHBs

Pulsar Terms: all different



Typical parameters

- Expect to detect $10^8, 10^9 M_\odot$ SMBHBs that are still in the weak field adiabatic inspiral regime, separated by less than a parsec;

- Timescale for changes in orbit of SMBHB (in yrs):

$$f/\dot{f} = 1.6 \times 10^3 (\mathcal{M}/10^9\,M_\odot)^{-5/3} (f/50\,\mathrm{nHz})^{-8/3}$$

- Orbital period of the binary evolves over the light travel time between Earth and pulsar

$$\sim 3.3 \times 10^3\,(L_p(1 + \hat{\mathbf{\Omega}} \cdot \hat{\mathbf{p}})/\mathrm{kpc})\ \text{yrs}$$

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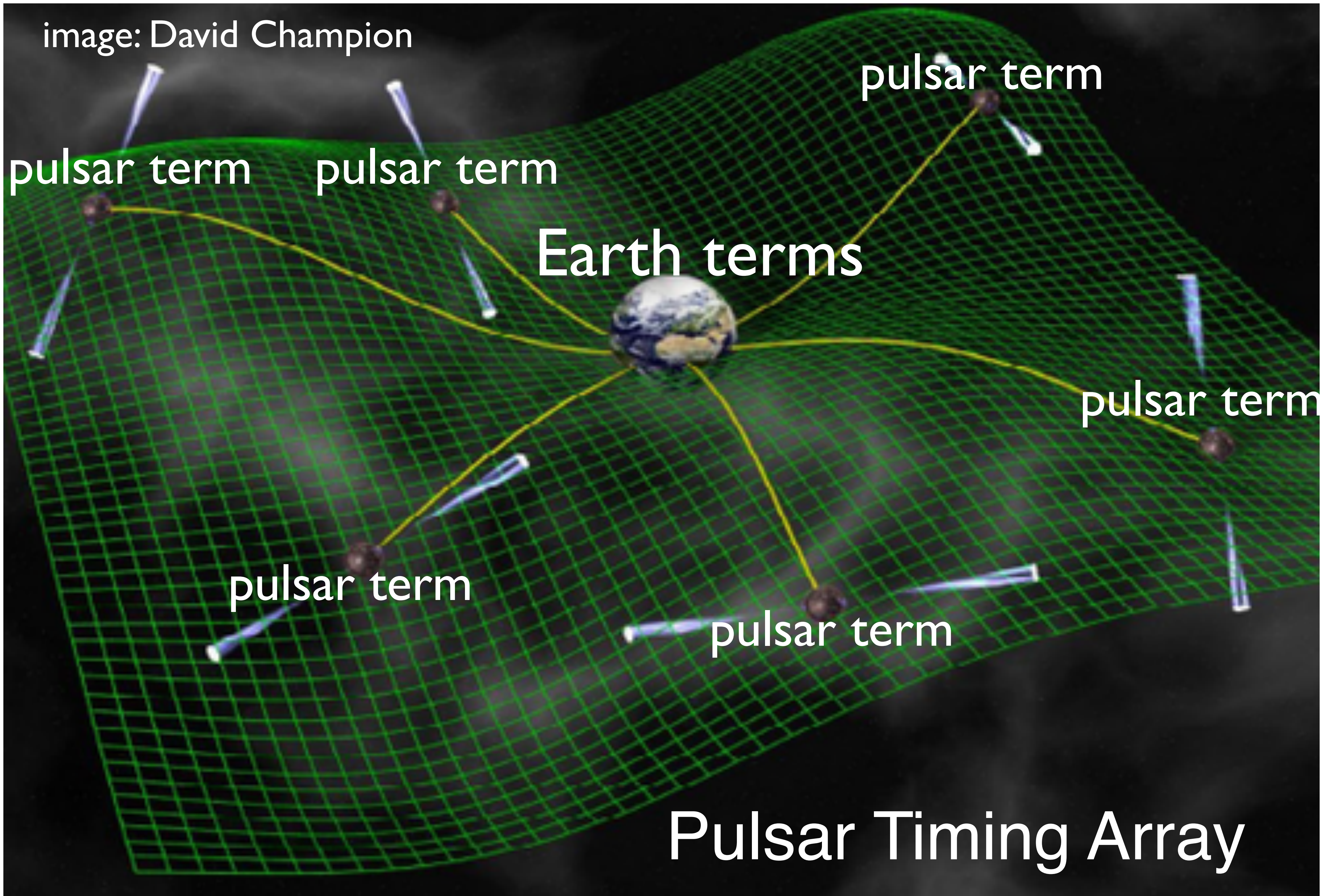

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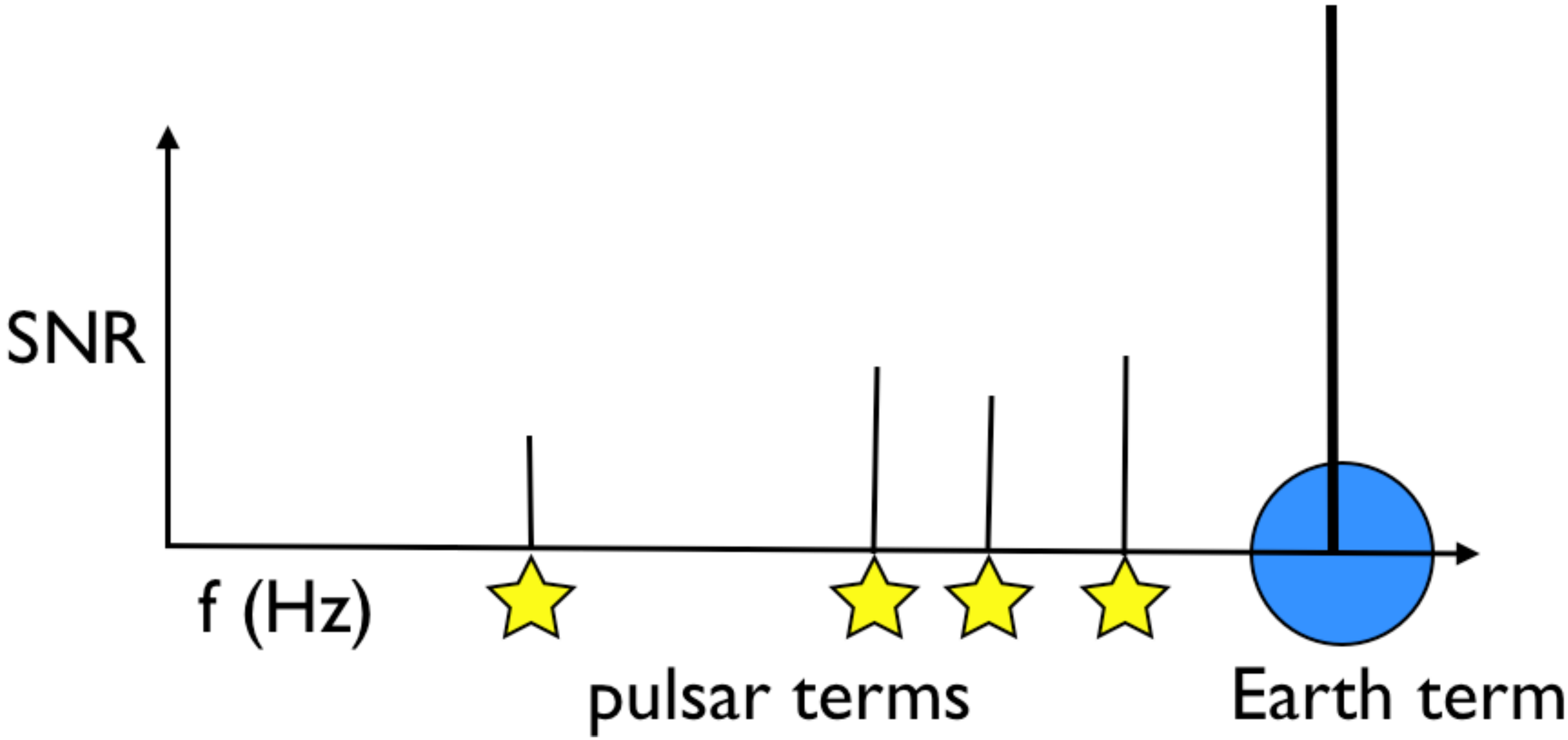
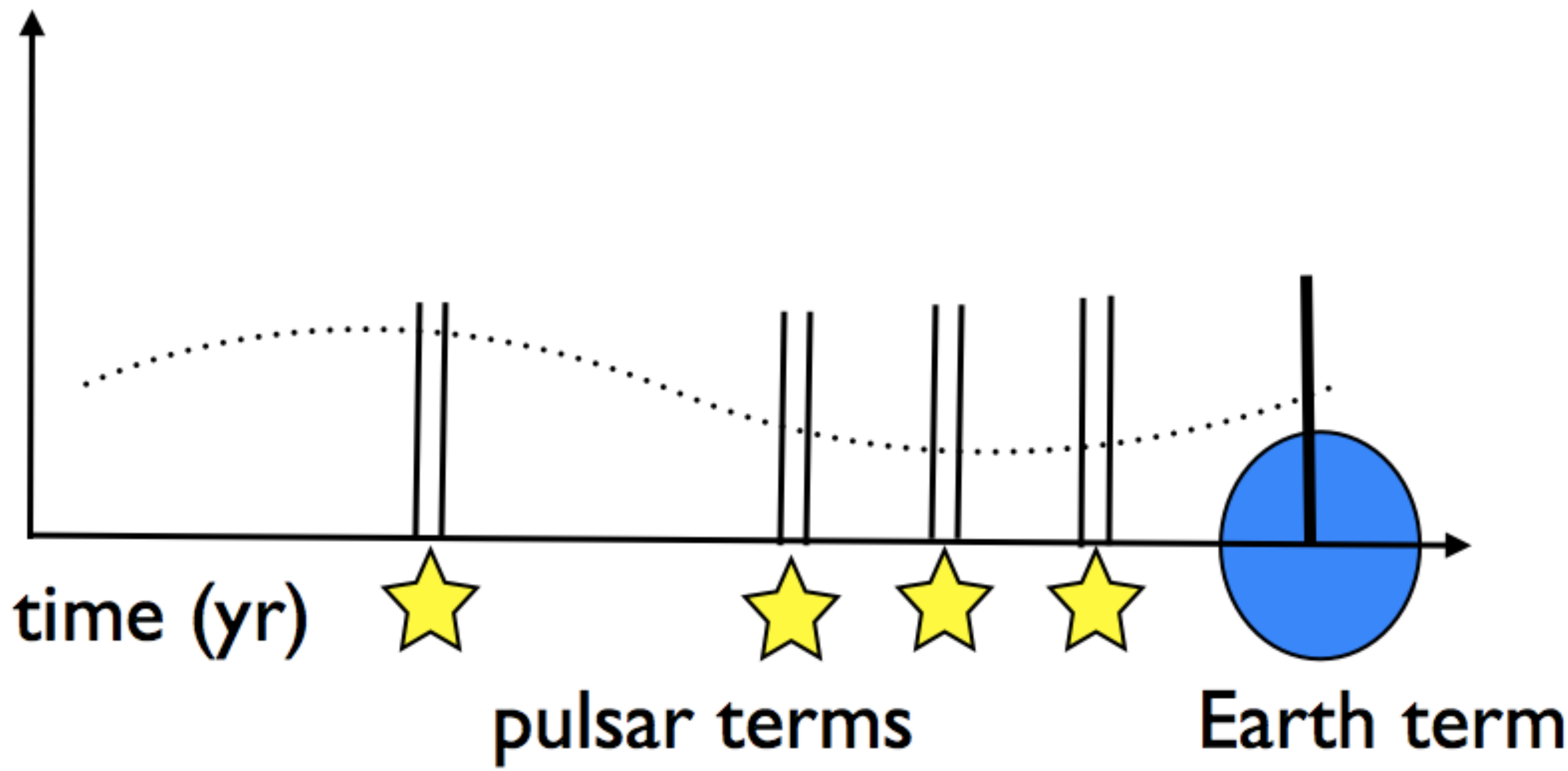
Pulsar Terms



Connect the dots...



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MARIE CURIE ACTIONS

Signals from precessing SMBHBs

- use “restricted” pN approximation: GW amplitude $A_{GW}(t)$ is taken at leading Newtonian order

- include modulation effects produced by spin-orbit coupling

- strain $h(t) = A_{\rm gw}(t) A_p(t) \cos[\Phi_{\rm gw}(t) + \varphi_p(t) + \varphi_T(t)]$

- physical parameters leave different observable signatures in h(t) and therefore in the TOAs

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Apostolatos+ (94)

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The spin leaves 3 distinctive imprints in the waveform:

1. alter the GW phase evolution through spin-orbit coupling at $p^{1.5}N$ order and higher
2. cause orbital plane to precess due to spin-orbit coupling an therefore induce amplitude and phase modulations in the waveform via and $A_p(t)$
3. through spin-orbit precession spins introduce a frame-dragging effect via

Apostolatos+ (94)

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3. through spin-orbit precession spins introduce a frame-dragging effect via $\varphi_T(t)$

Apostolatos+ (94)

post-Newtonian contributions to number of wave cycles

TABLE I. Frequency change Δf, total number of GW cycles, and individual contributions from the leading order terms in the pN expansion over the two relevant time scales—a 10 yr period starting at Earth and the time period $L_p(1 + \hat{\mathbf{\Omega}} \cdot \hat{\mathbf{p}})$ between the Earth and pulsar terms (hence the negative sign)—for selected values of $m_{1,2}$ and f_E.

m_1 ($M_\odot$)	m_2 ($M_\odot$)	f_E (nHz)	($v/c \times 10^{-2}$)	Time span	Δf (nHz)	Total	Newtonian	p^1N	$p^{1.5}$N	Spin orbit/β	p^2N
10^9	10^9	100	14.6	10 yr	3.22	32.1	31.7	0.9	−0.7	0.06	0.04
			9.6	−1 kpc	71.2	4305.1	4267.8	77.3	−45.8	3.6	2.2
		50	11.6	10 yr	0.24	15.8	15.7	0.3	−0.2	0.01	<0.01
			9.4	−1 kpc	23.1	3533.1	3504.8	53.5	−28.7	2.3	1.2
10^8	10^8	100	6.8	10 yr	0.07	31.6	31.4	0.2	−0.07	<0.01	<0.01
			6.4	−1 kpc	15.8	9396.3	9355.7	58.3	−19.9	1.6	0.5
		50	5.4	10 yr	0.005	15.8	15.7	0.06	−0.02	<0.01	<0.01
			5.3	−1 kpc	1.62	5061.4	5045.8	20.8	−5.8	0.5	0.1

Important to take spin into account

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Mingarelli et al., Phys.Rev.Lett. (2012)

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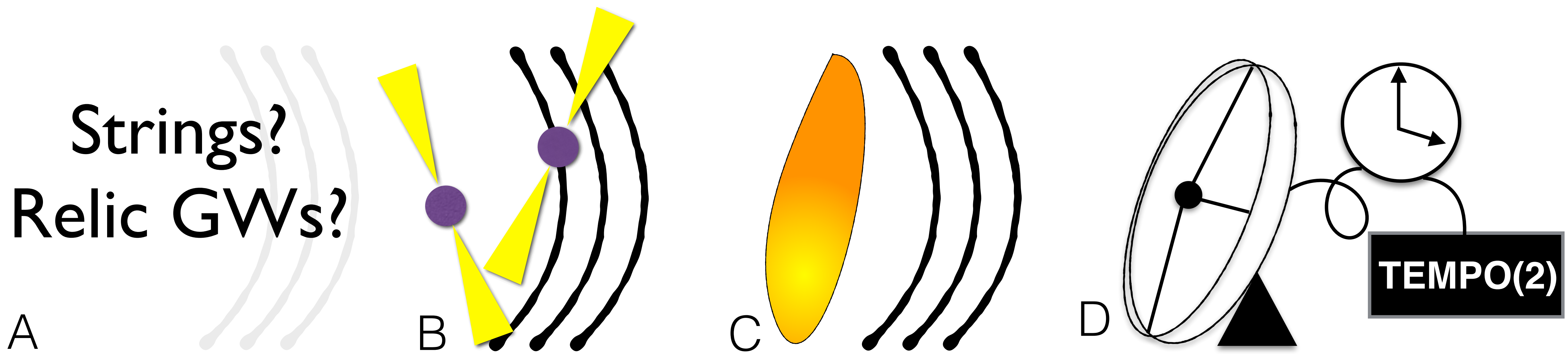
Pulsar Timing Array



A: GWs from e.g. supermassive BH binaries (also cosmic strings)

B: GWs perturb space-time at the pulsars as they transit

C: ionized gas in the interstellar medium disperses & scatters the light from pulsars

D: GW perturb signals from all pulsars at Earth. Time of arrivals and residuals are calculated.

Science!

Gravitational Waves

- Stochastic Background
  - isotropic
  - anisotropic
  - detect or limit
- Continuous Waves
  - detect or limit
- Bursts
  - memory
  - unmodeled
  - detect or limit

Science!

Funding

Outreach

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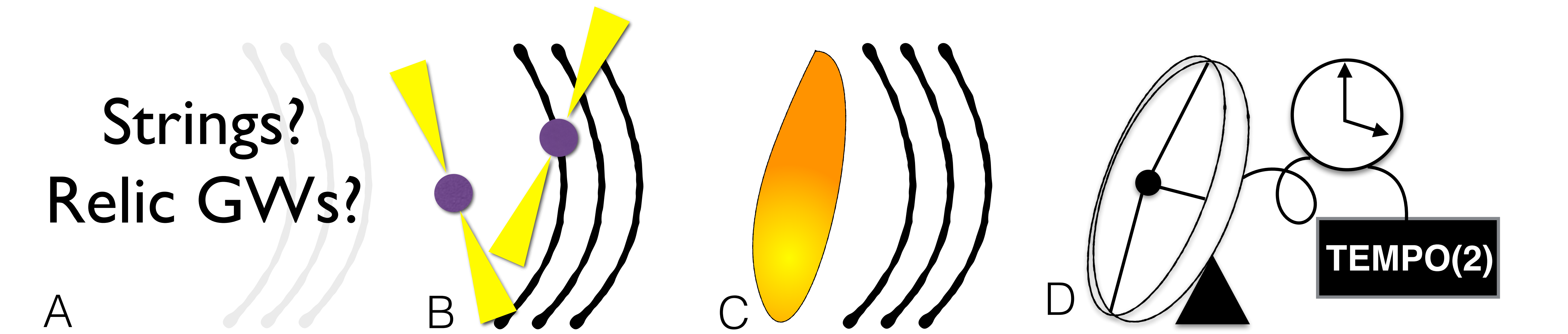
MARIE CURIE ACTIONS

Pulsar Timing Array



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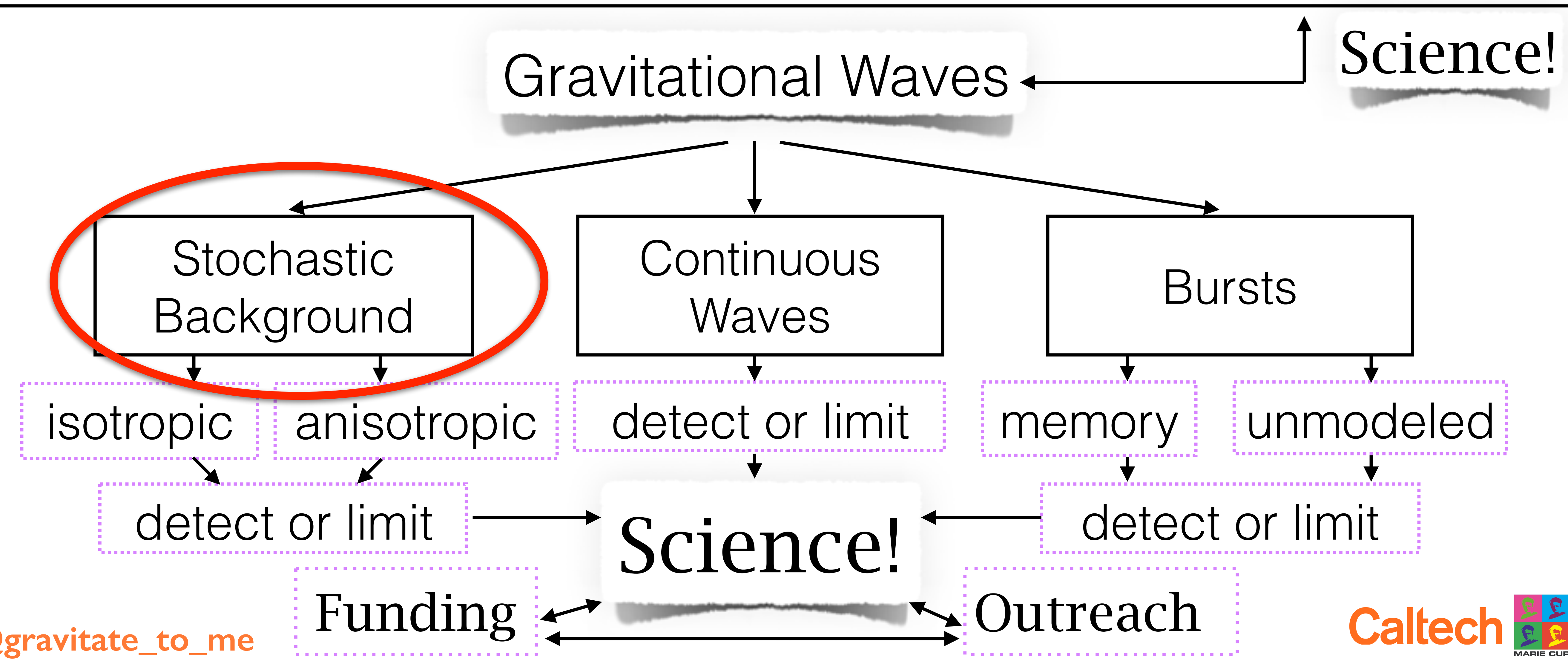

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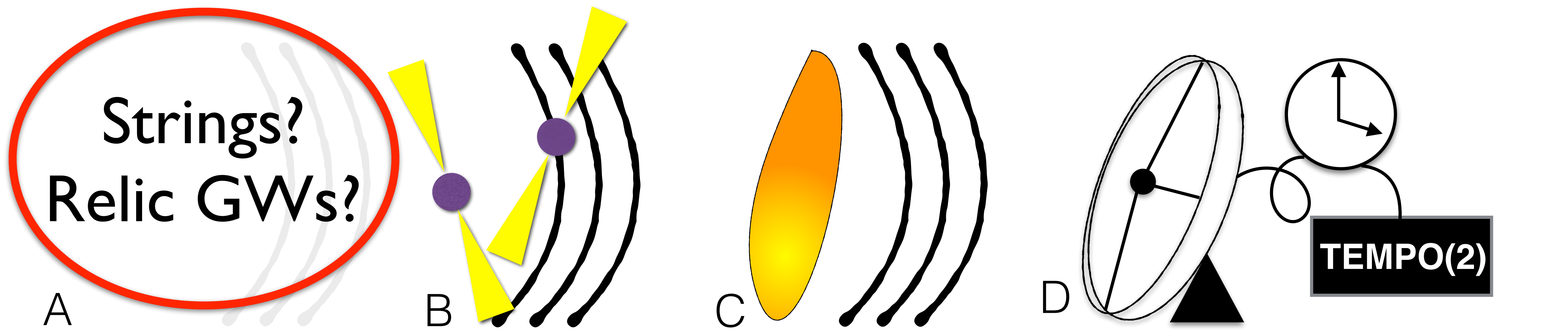

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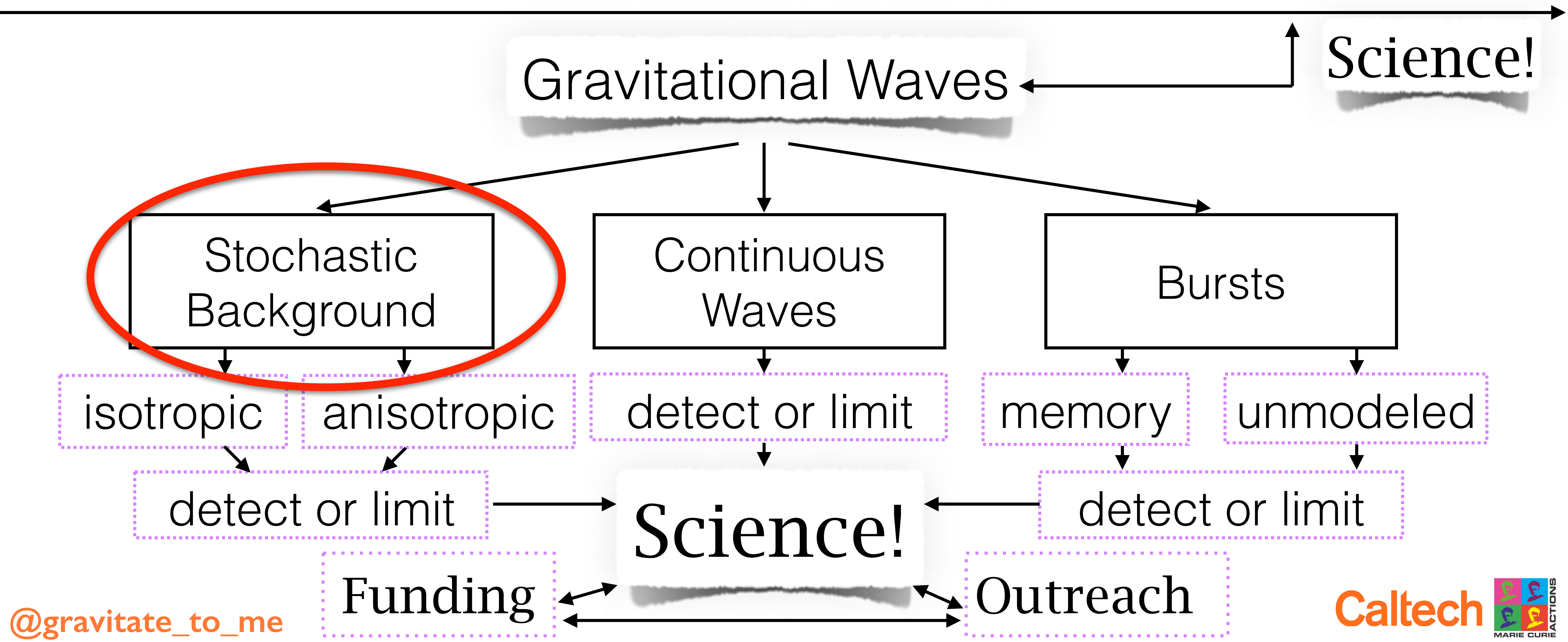

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Relic GW Background

- Quantum fluctuations of the gravitational field in the early Universe, amplified by inflation, are expected to produce a relic GWB
- At long wavelengths, GWs generated during inflationary epoch produce a characteristic signature in the polarization of the CMB radiation, as well as CMB temperature anisotropies

Relic GW Background

- At shorter wavelengths (PTA) this radiation manifests itself as a contribution to the present day energy density spectrum $\Omega_{\rm gw}(f)$
- GWB spectrum is directly related to the primordial tensor spectral index n_t and the equation of state of the early-Universe, and inflationary models, $n_t = -r/8$
- Assume end of inflation Universe enters radiation dominated era, w = 1/3, the spectrum of the background can be written as in Zhao et al. (2013):

$$\Omega_{\rm gw}^{\rm relic}(f) \approx 1.3 \times 10^{-16} 10^{10 n_t} \left(\frac{r}{0.12}\right) \left(\frac{f}{\rm yr^{-1}}\right)^{n_t} ,$$

EPTA Results

- Fix spectral index, vary noise parameters, find
  $\boxed{A < 1.4 \times 10^{-15} \text{ or } \Omega_{\rm gw}^{\rm relic}(f)h^2 < 1.2 \times 10^{-9}}$

Lentati et al. (including CMFM; 2015)

- Compare to BBN $\int \Omega_{\rm gw}(f)\mathrm{d}(\ln f) < 1.1 \times 10^{-5}(N_\nu - 3)$

Allen (1997), Maggiore (2000)

- CMB limits $h^2 \int \Omega_{\rm gw}(f)\mathrm{d}(\ln f) < 8.7 \times 10^{-6}$

Sendra, Smith (2012)

- LIGO, at f = 41.5-169.25 Hz $\Omega_{\rm gw}(f) = 5.6 \times 10^{-6}$

LIGO (2014)

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LIGO (2014)

NANOGrav results even more constraining, in prep

Outline

- What is a pulsar timing array?
- How can use pulsar timing arrays to study GWs?
- What if GR isn't quite right?
- What if the background isn't isotropic?
- What can we learn from continuous GW detection?
- What can we say about cosmological models?
- **What limits can we place on cosmic strings?**

Cosmic Strings

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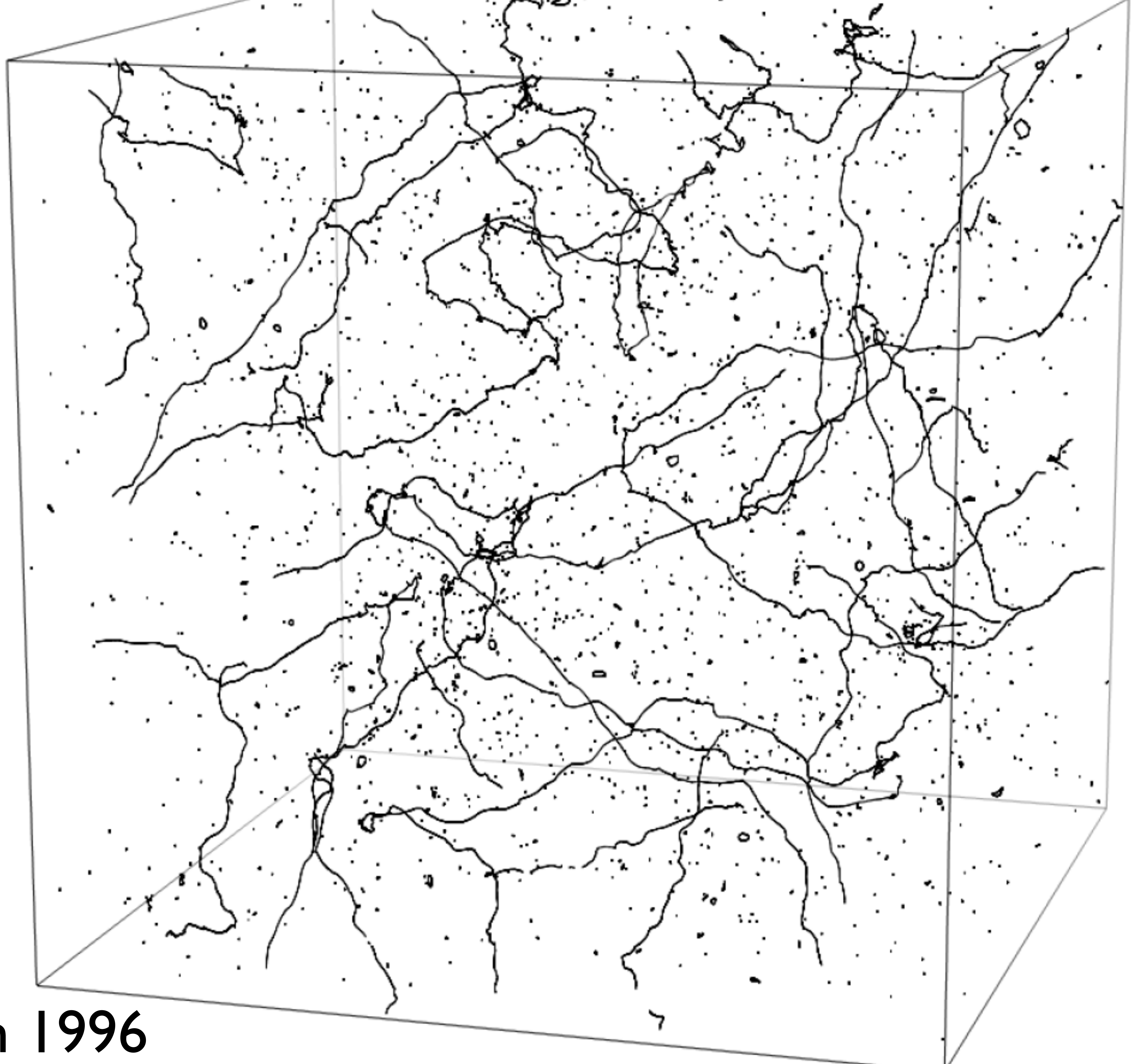
- Cosmic strings are one-dimensional topological defects created through spontaneous symmetry breaking during the various phase transitions in the early Universe.
- When two cosmic strings intersect, they ``intercommute" (exchange partners) with a characteristic probability, and form loops
- Loops decay via GW emission, creating background 10^{-16} Hz -10^{9} Hz, depending on size of loops created
- PTAs can probe the GW emission originating from loops decaying either in the matter era or in the radiation-to-matter era transition



Allen 1996

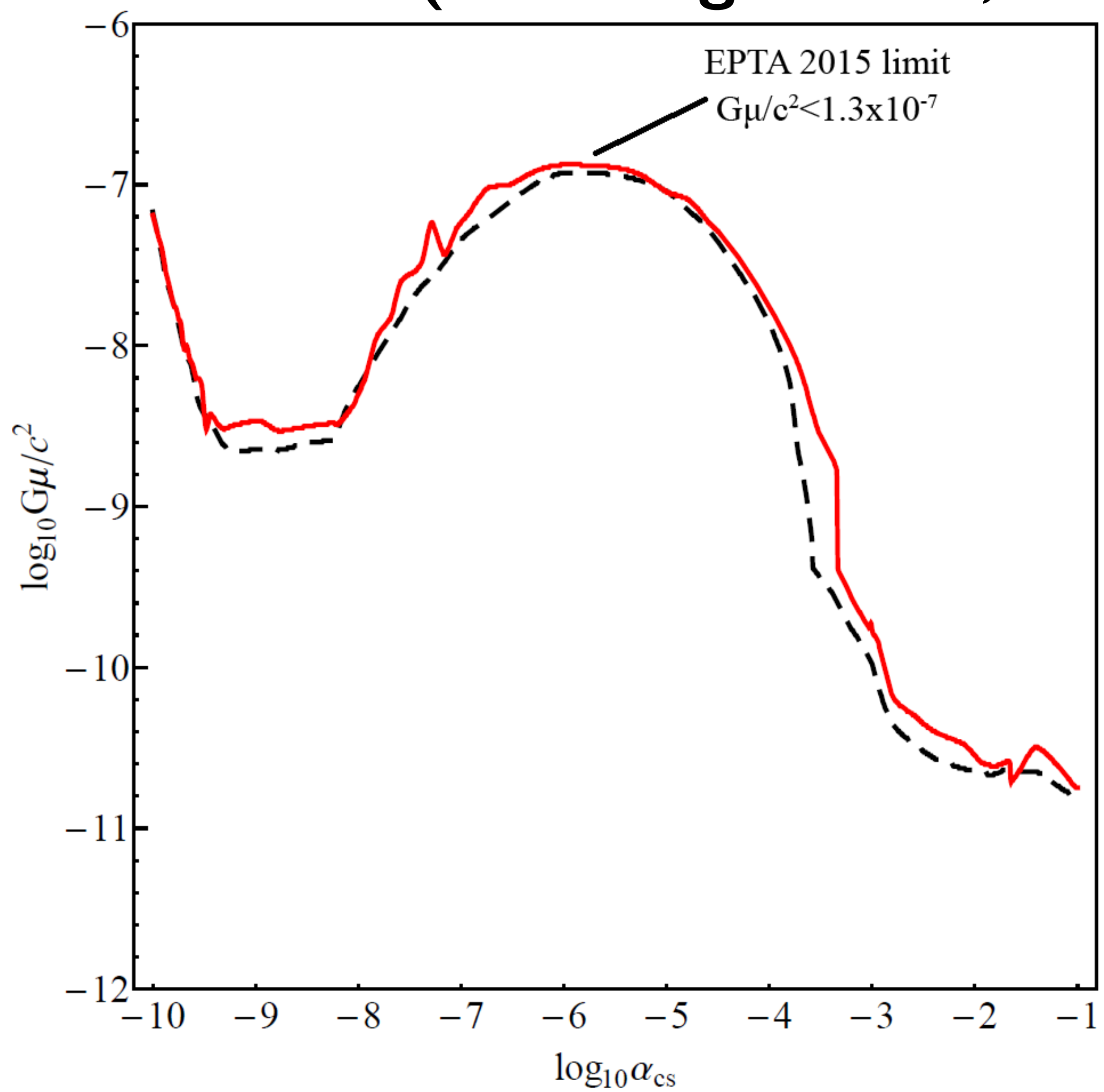
Cosmic String Limits

- Use spectra computed by Sanidas, Battye, Stappers (2012)
- Parameters are the string tension $G\mu/c^2$, the birth-scale of loops relative to the horizon α_{cs}, and the intercommutation probability, p
- *N*o assumption made concerning the dominant GW emission mechanism from the strings (i.e., kinks or cusps), which is modeled using two additional parameters, a spectral index, q, and a cut-off, n_* on the number of emission harmonics n

EPTA Results

Lentati et al. (including CMFM; 2015)

- Both the amplitude and spectral slope information of the GWB limits were used to construct the limits.
- Nambu-Goto (field theory strings) with p=1
- Equal to the best CMB limit by *Planck*+Atacama Cosmology Telescope+ SouthPoleTelescope
- GW limits subject to more uncertainties than CMB results, however, this constraint is independent of the values of the other model parameters

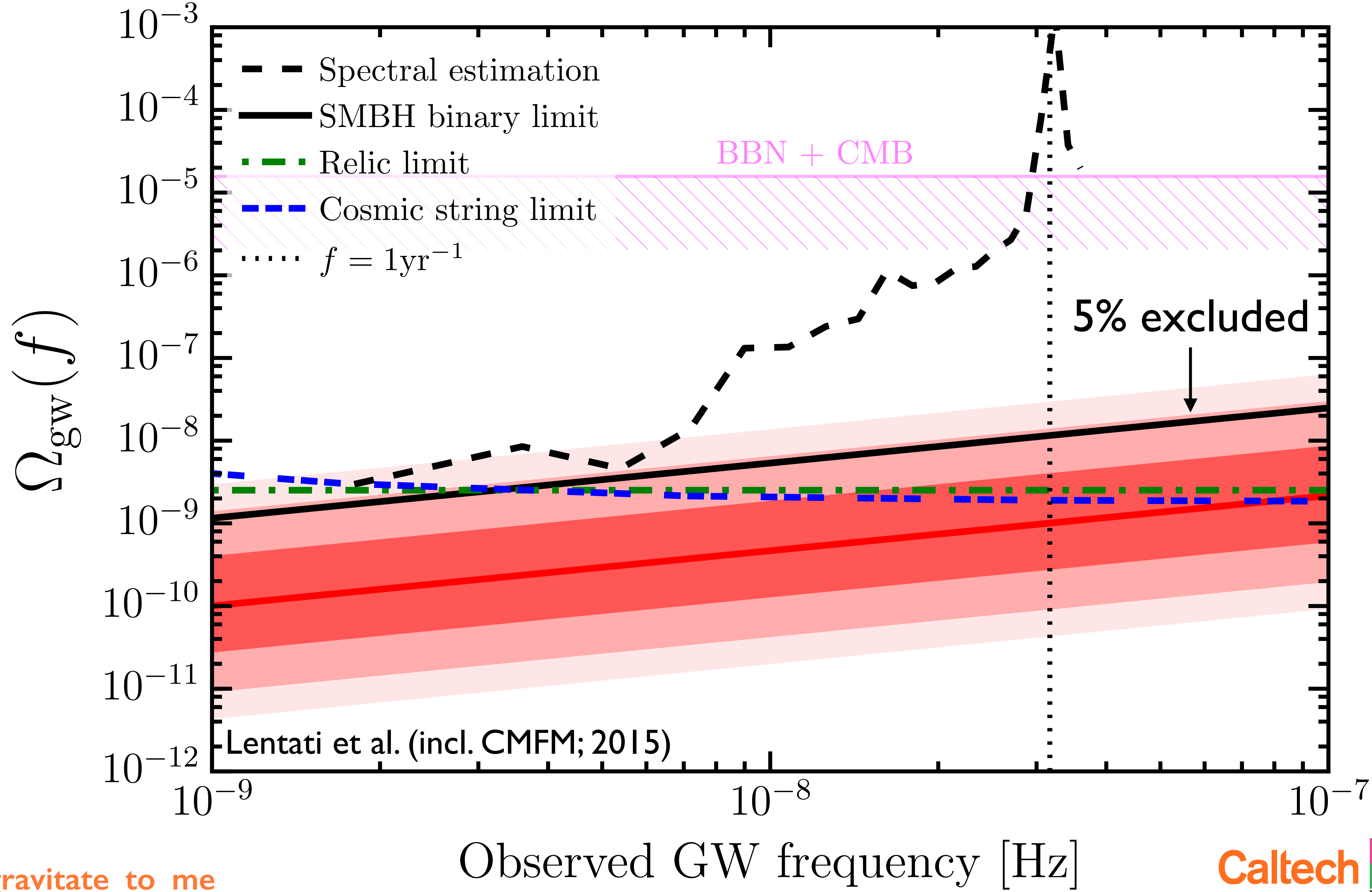


$$n_* = 1 \qquad -8 \lesssim \log_{10}\alpha_{\rm cs} \lesssim -3$$

EPTA Results

5% excluded

EPTA Results



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PTA Tasting Menu

- **PTAs are starting to rule out astrophysical models:**
  - galaxy mergers scenarios
- **PTAs can characterize the stochastic GWB on any angular scale:**
  - Can inject and recover anisotropic backgrounds
  - Use this to move from isotropic - single sources
- **Can use PTAs to test GR for isotropic and anisotropic GWBs**
- **Can eventually measure masses and spins of precessing SMBHBs**
- **PTAs may be able to constrain cosmological parameters**
- **PTAs can place stringent limits on cosmic string tension, which will continue to improve. Already as good as Planck!**

Thank You!

- A special thanks to the CGWAS coordinators, especially Patricia Schmidt
- Thank you to Maura McLaughlin and Justin Ellis for sharing some slides
- I acknowledge the support of a Marie Curie International Outgoing Fellowship within the 7th European Community Framework Program
- Thank you listeners for your attention and questions!
- Slides are online at www.chiaramingarelli.com