Exotica: Discovering new physics with gravitational waves

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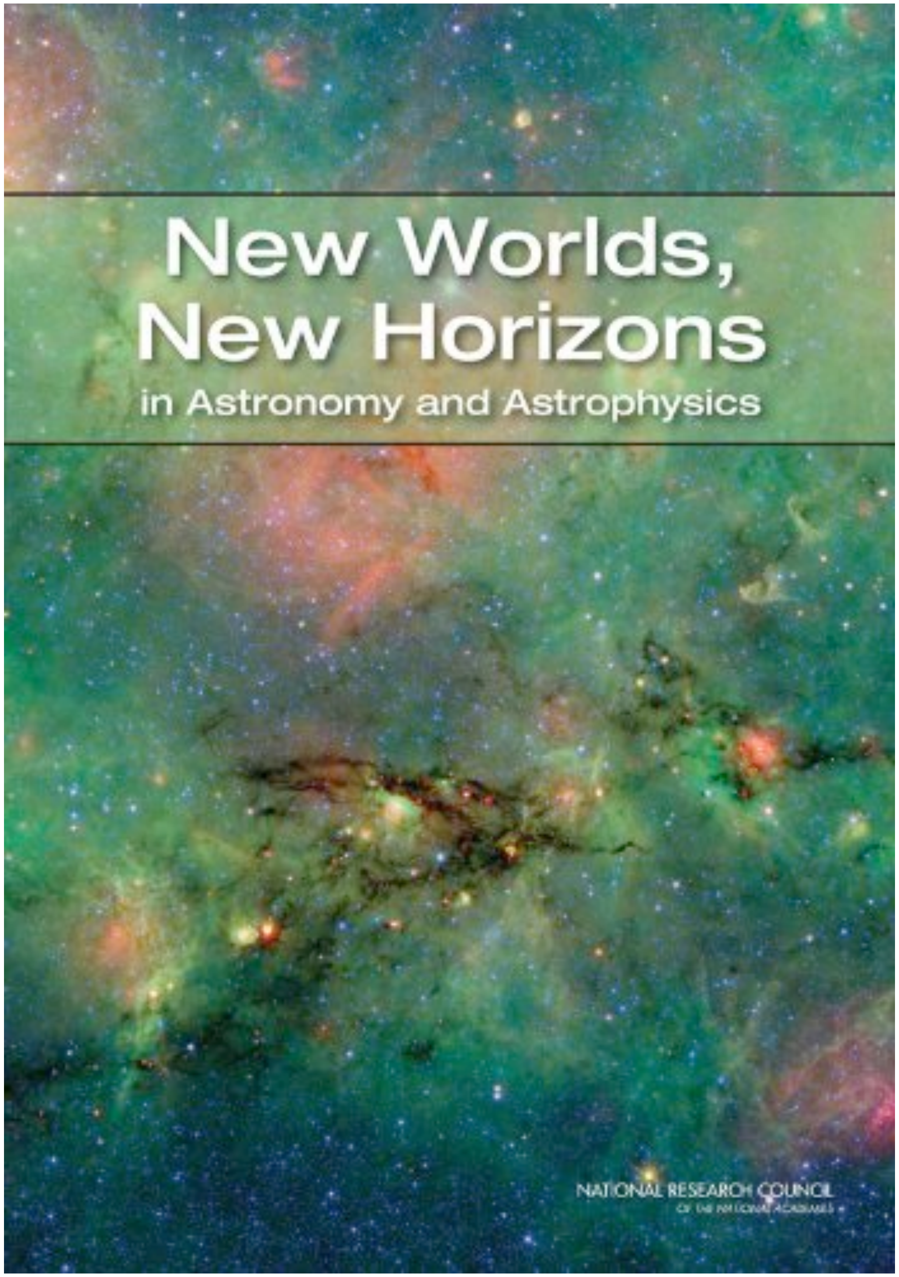
Montana State University



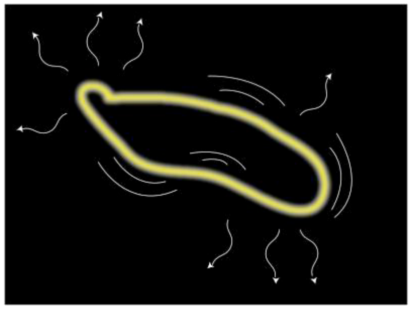
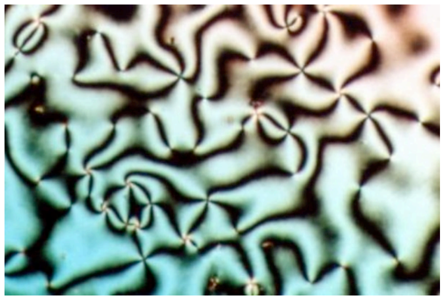
"It would be unprecedented in the history of astronomy if the gravitational radiation window being opened up by LISA does not reveal new, enigmatic sources"

Outline

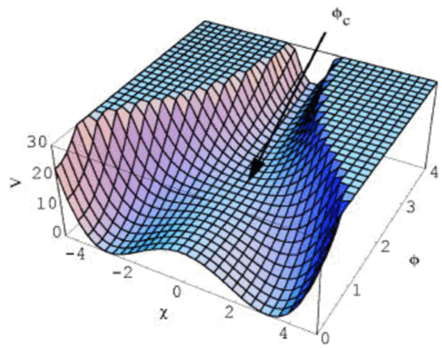
- Exotic sources of gravitational waves
- How to detect the unexpected?
- Testing General Relativity

Exotic Sources

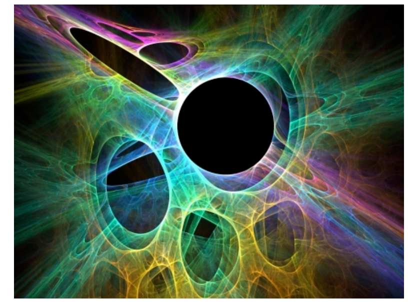
Imagined

Topological defects

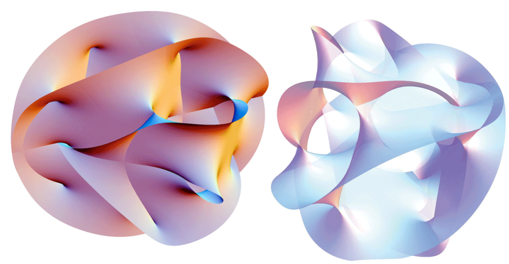


Pre-heating/Re-heating



Warped extra dimensions

Phase transitions- bubble nucleation,
cavitation, collisions



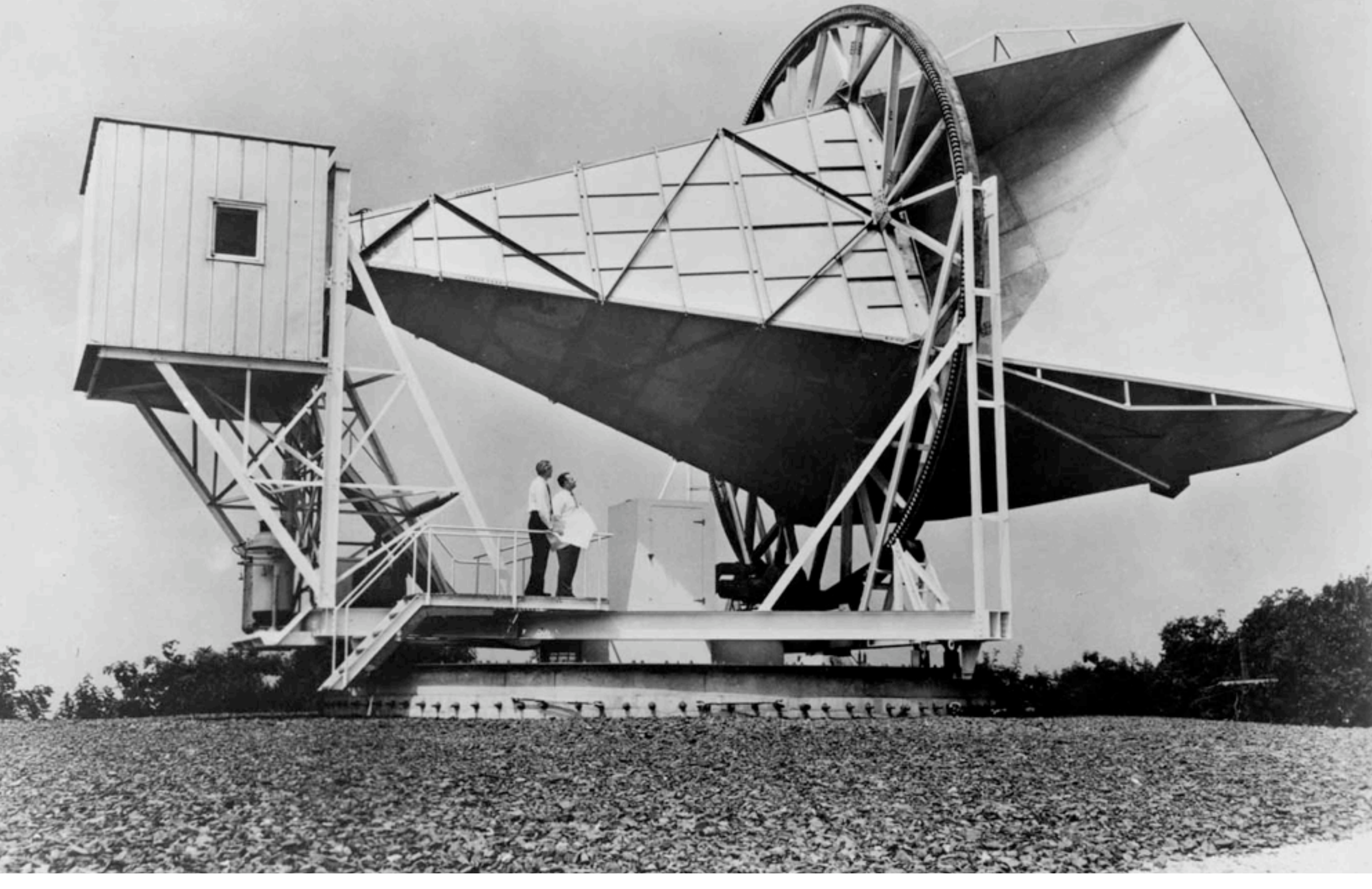
Braneworlds

Un-Imagined

Burst sources?

Detecting the Unmodeled and Unexpected

Is this a signal or an instrumental artifact?



Detecting the Unmodeled and Unexpected

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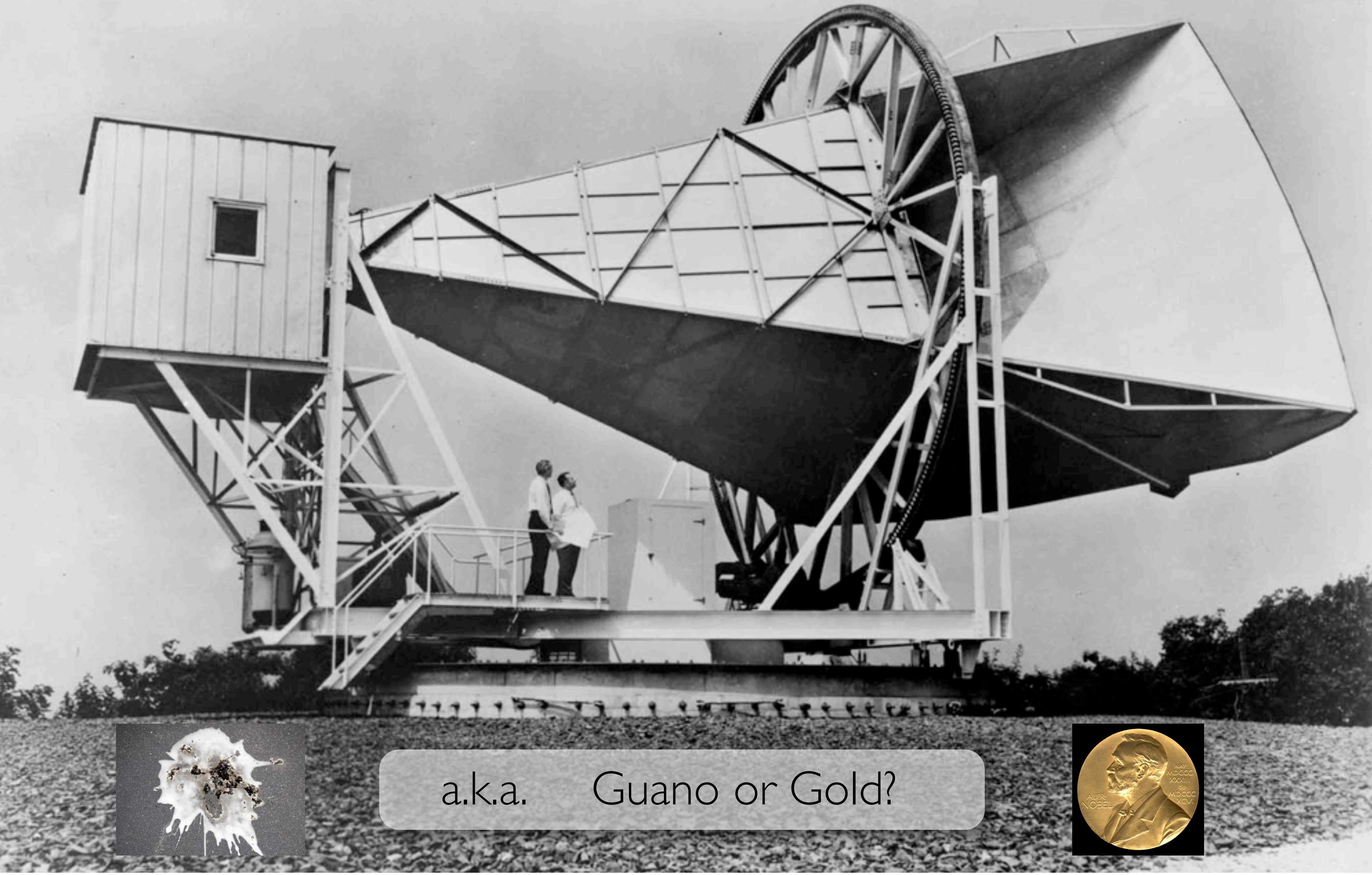
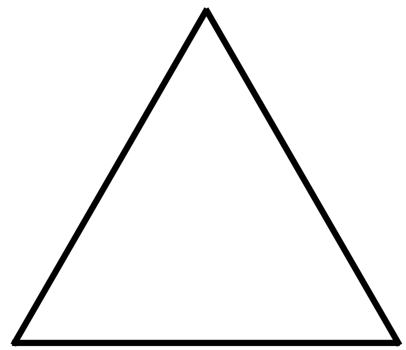


a.k.a. Guano or Gold?

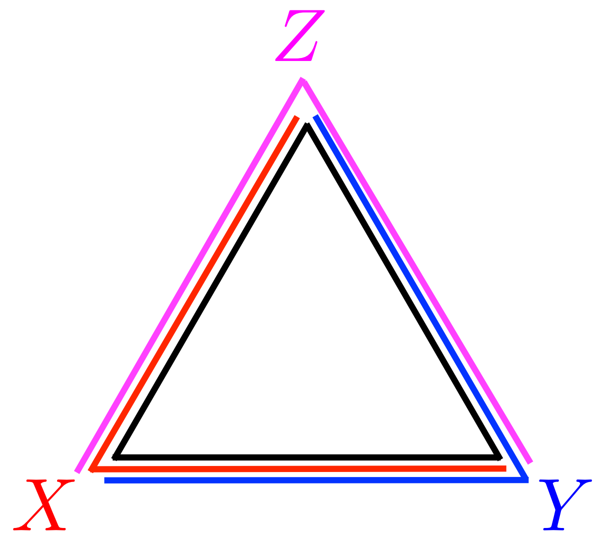
Exotica Detection

- Multiple channels for signal/noise separation
- Time delays for signal/noise separation
- Angular resolution & EM counterparts

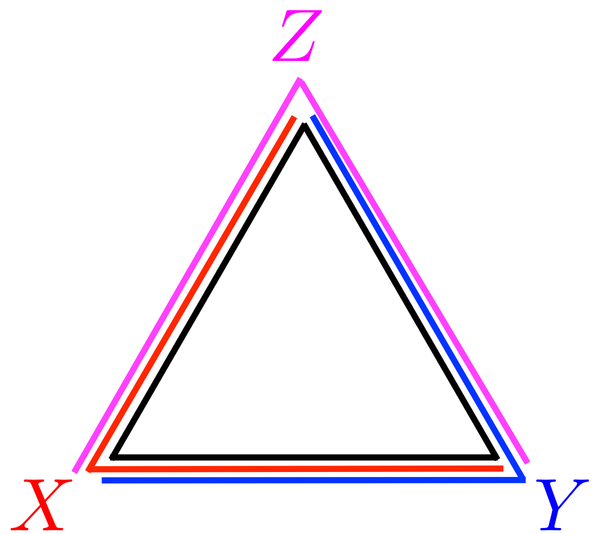
Three arms are better than two



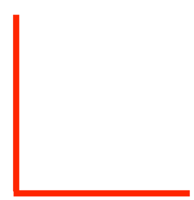
Three arms are better than two



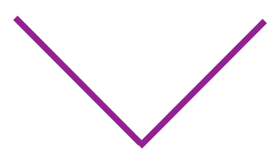
Three arms are better than two



$$S_+ = \frac{\sqrt{3}}{2}\, X \quad \Rightarrow$$



$$S_\times = \frac{1}{2}\,(X + 2Y) \quad \Rightarrow$$

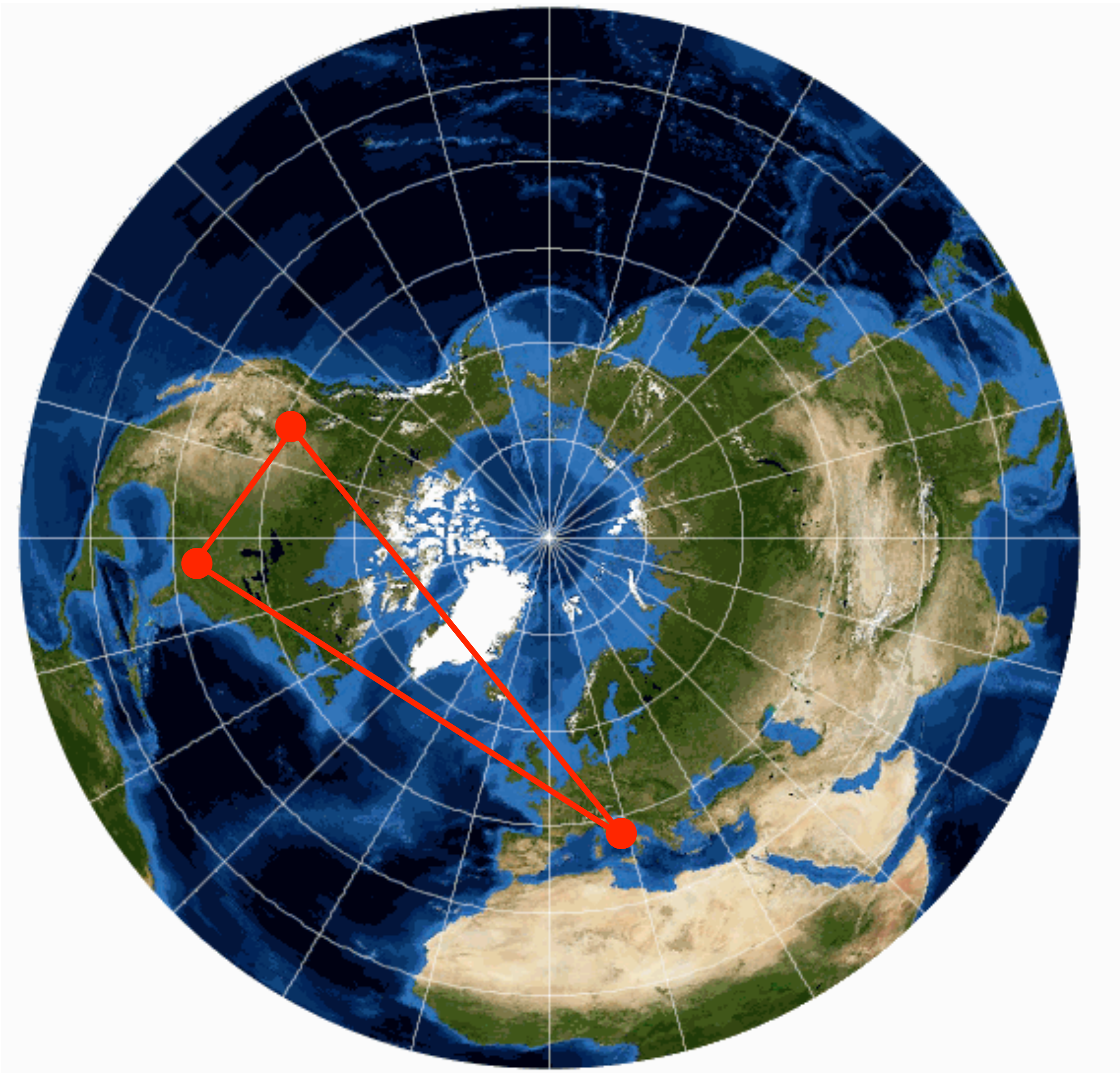


Instantaneous measurement of both polarization states and increased signal-to-noise

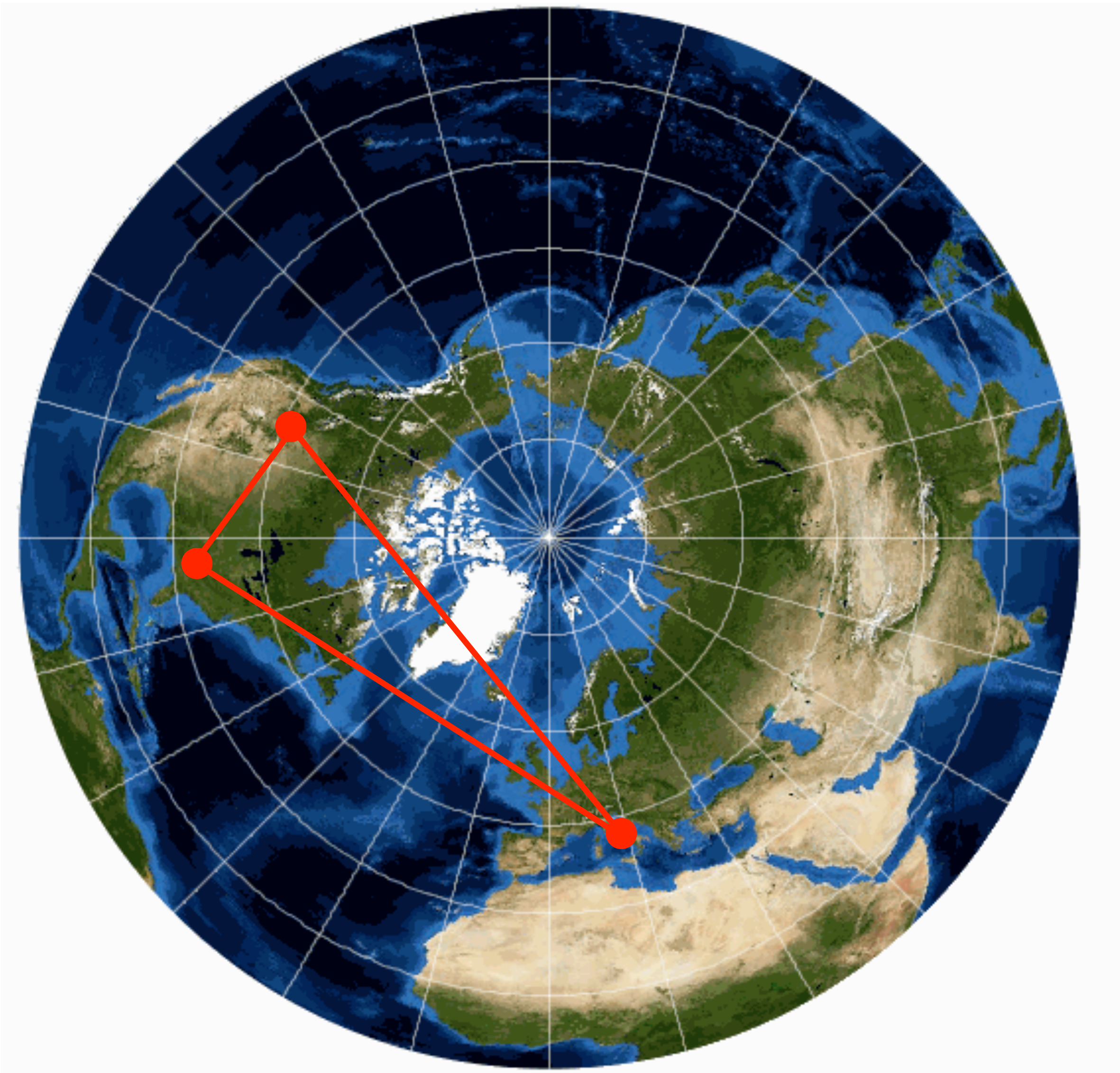
$$S_\odot = \frac{1}{3}\,(X + Y + Z) \quad \Rightarrow \quad \cdot$$

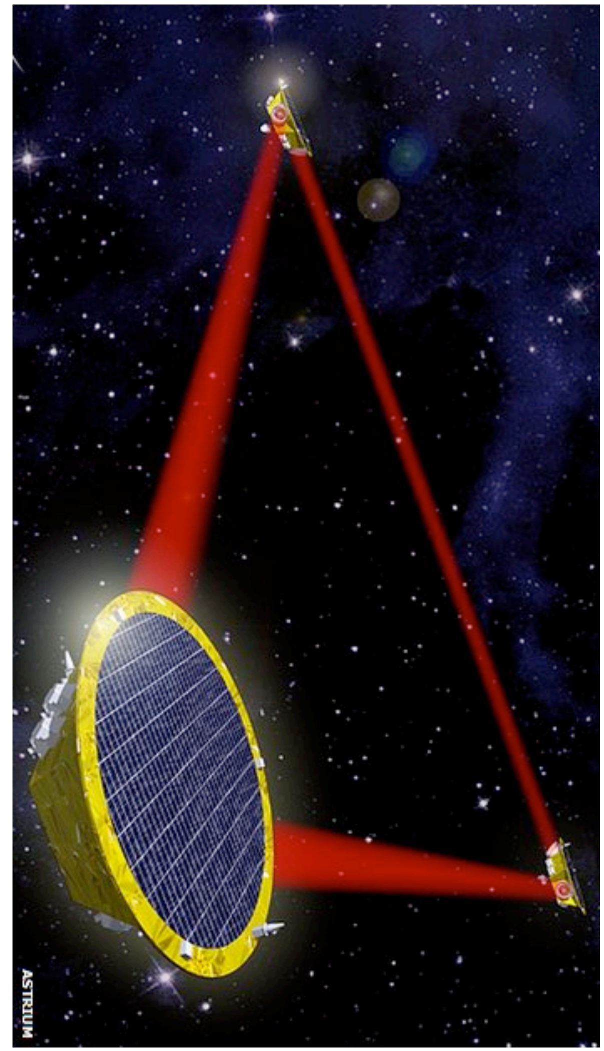
Null channel to monitor average low frequency instrument noise

Triangulation- Source Localization

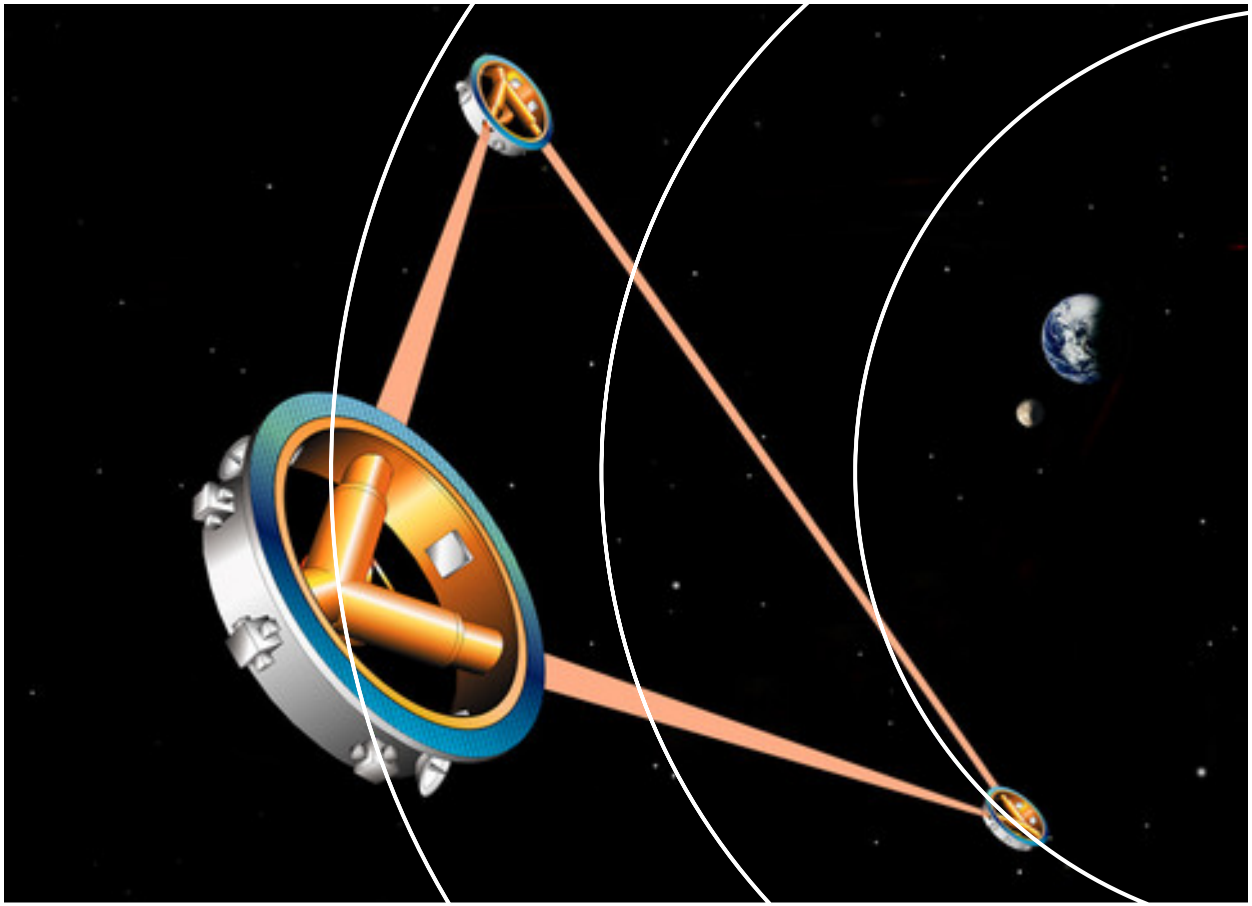


Triangulation- Source Localization





Separating Burst Signals from Noise



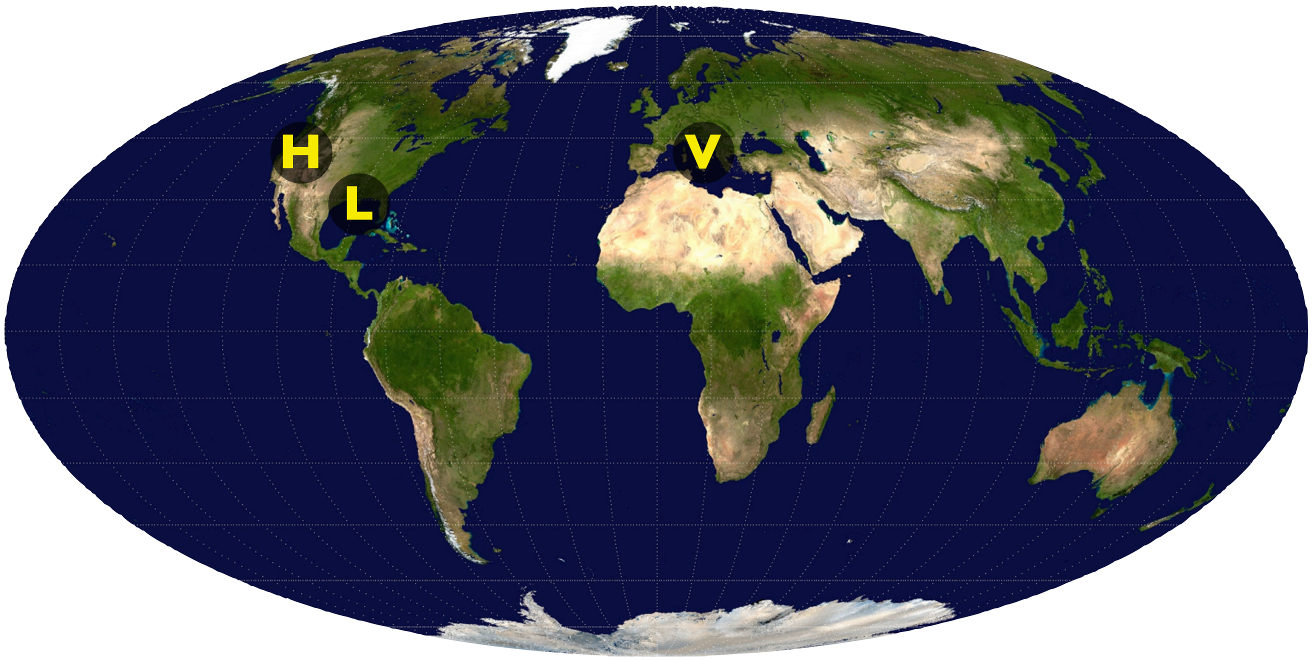
Noise delays

$$\Delta t = n \, \frac{L}{c}$$

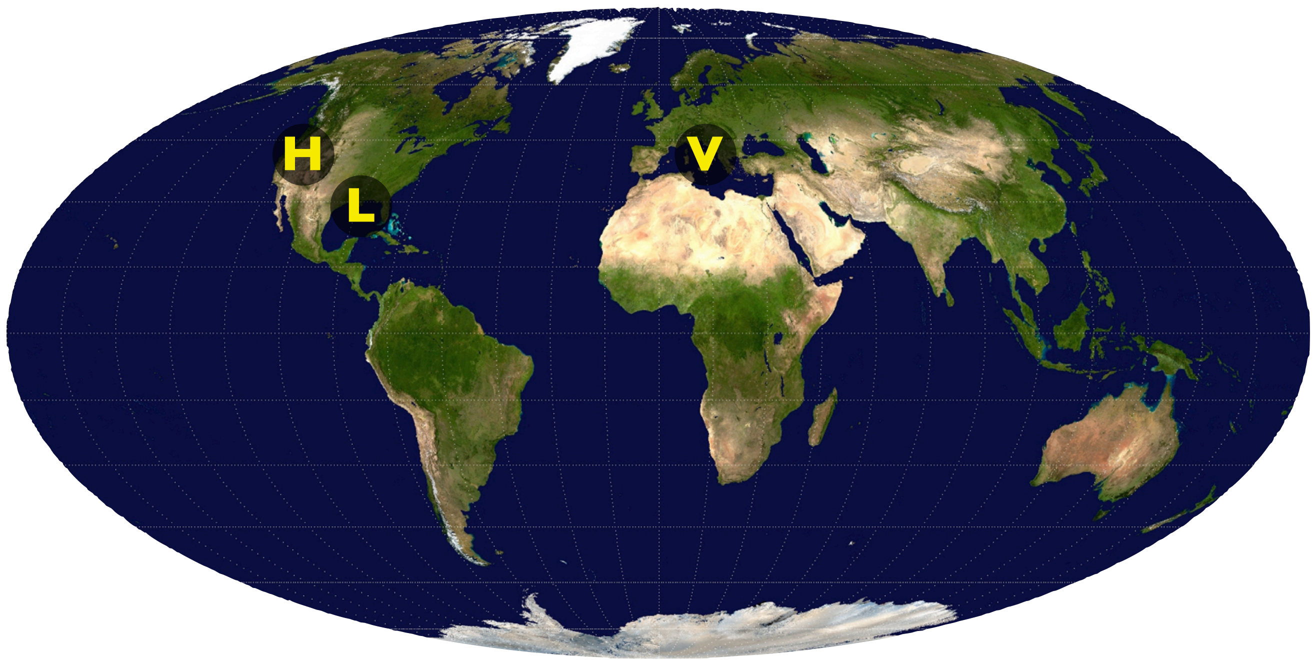
Signal delays

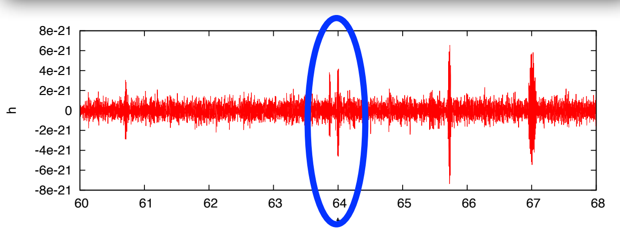
$$\Delta t = n \, \frac{L}{c} + \frac{\hat{k} \cdot \vec{L}}{c}$$

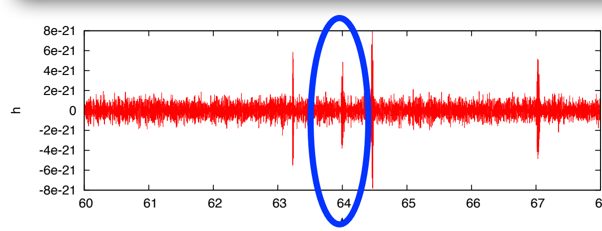
Separating Burst Signals from Noise: LIGO heritage

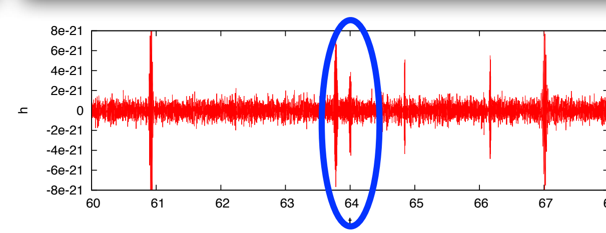


Separating Burst Signals from Noise: LIGO heritage









LIGO Burst reconstruction: BayesWave

(Mock LISA Data Challenge heritage here)

Bayeswave Burst Output page

Results for trigger at 1074003872

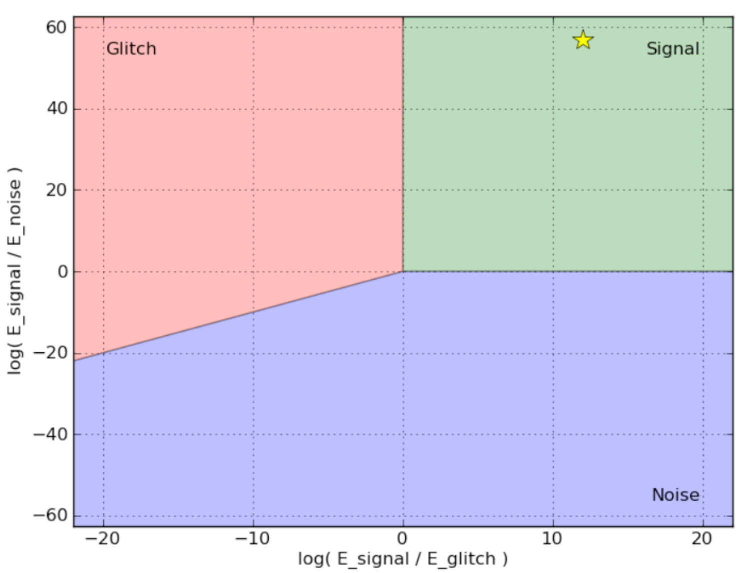
Detector names: H1 L1

Waveform type: Mueller

SNR: [16.782206953799999, 24.5957466029]

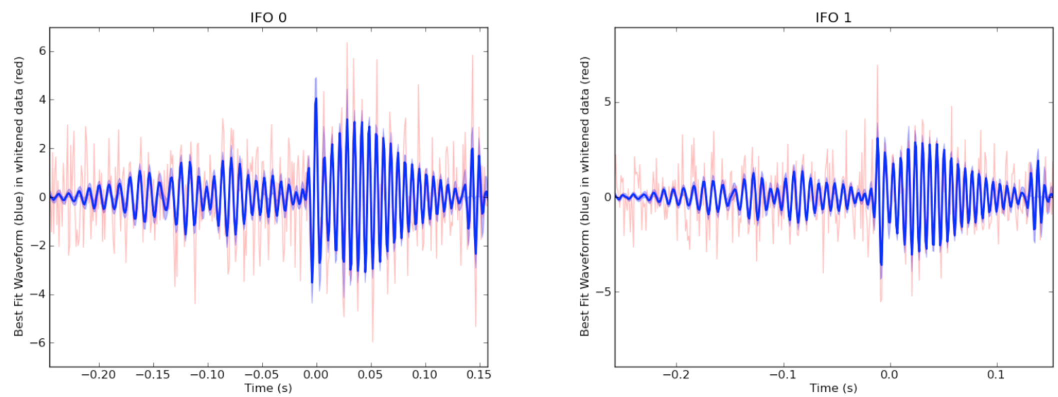
Evidence for Signal

log(Evidence_signal / Evidence_glitch) = 12.00
log(Evidence_signal / Evidence_noise) = 56.96

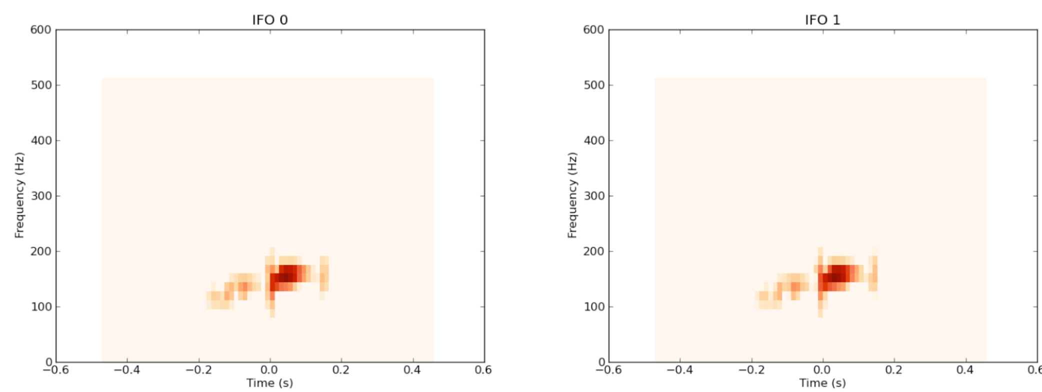


Median Signal Model Waveforms and 1-sigma Uncertainties

Reconstructed waveforms in whitened data. Red is data, blue is reconstructed waveform

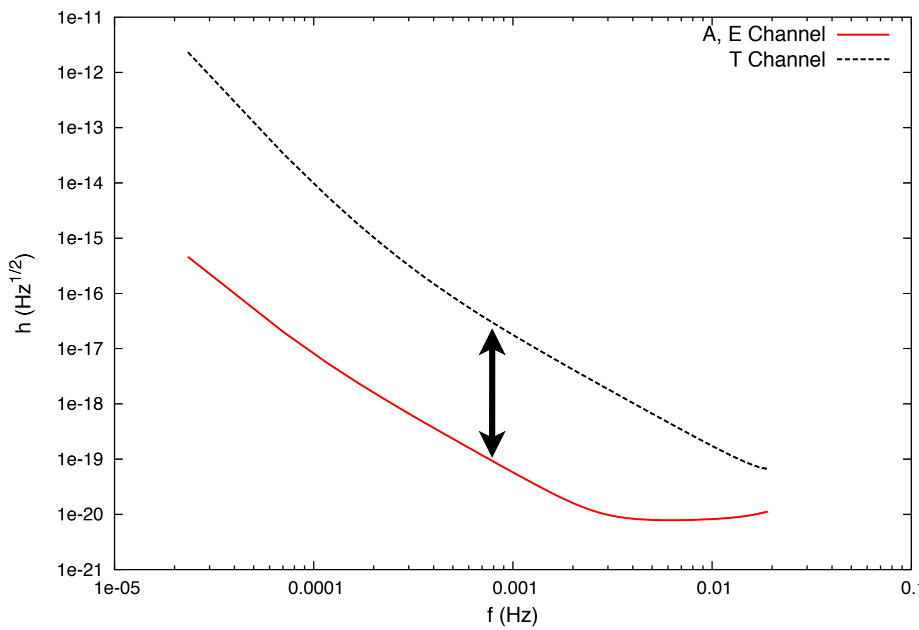


Spectrogram of median reconstructed signal model waveform

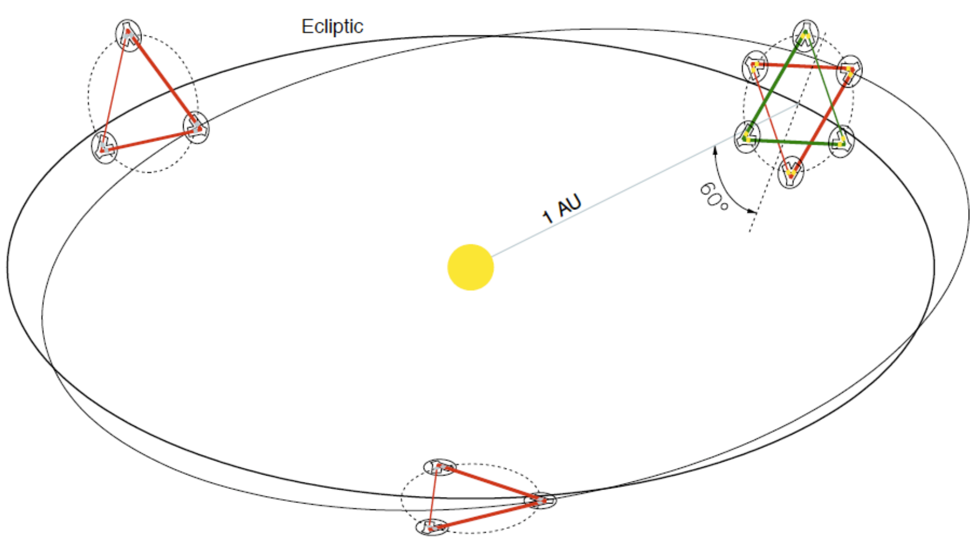


(Cornish & Littenberg 14)

Detecting a Stochastic Background

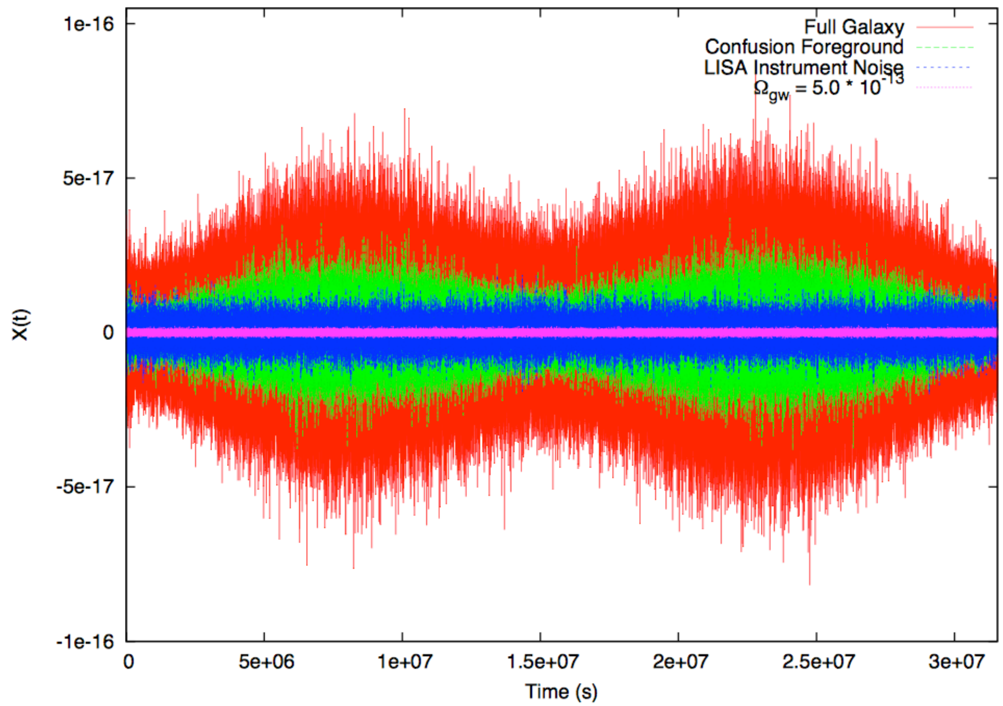


Lisa classic

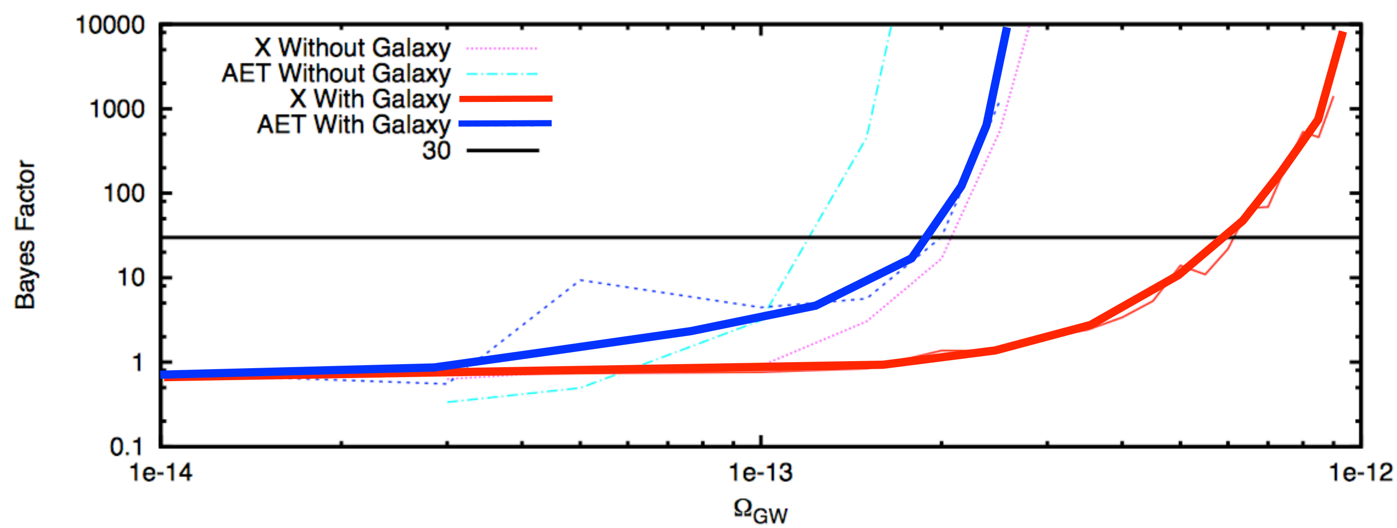


BBO

Detecting a Stochastic Background: (e)LISA

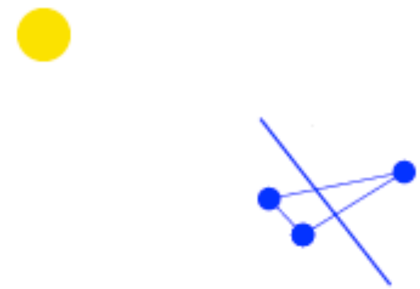


(Adams & Cornish 14)

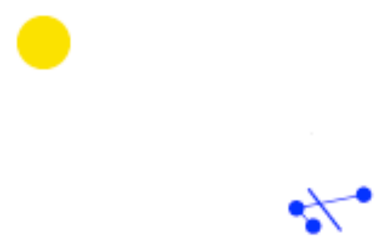


Burst detection with LISA/eLISA?

LISA

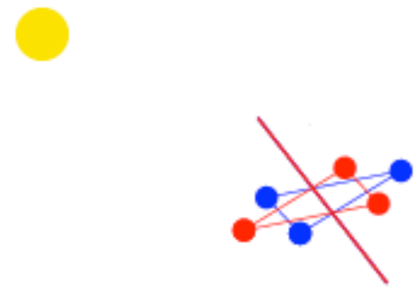


eLISA

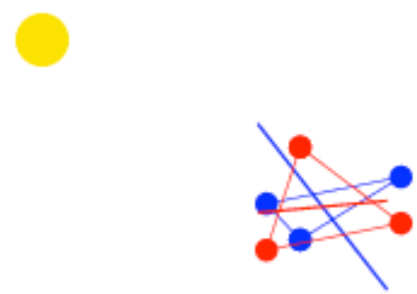


Up-scoping!

Cross

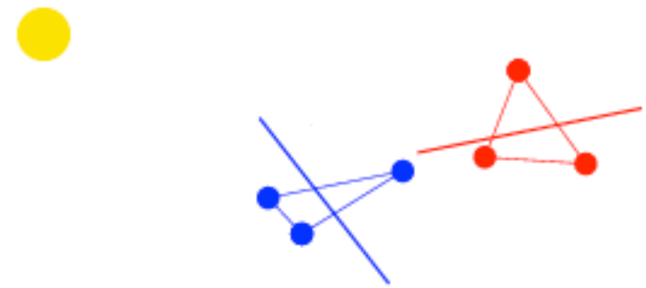


Flip

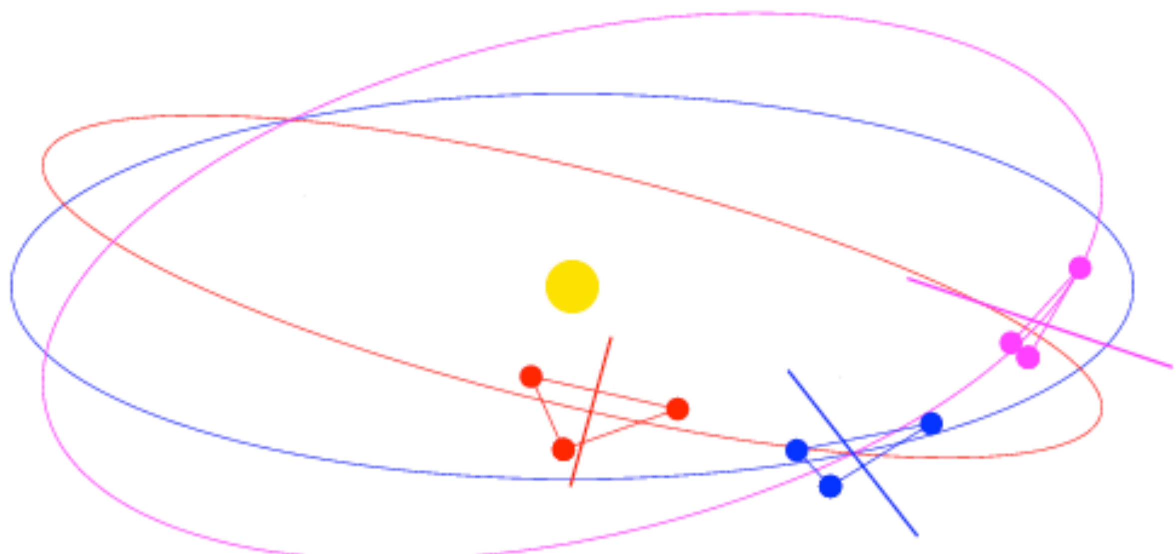


Up-scoping!

Dual

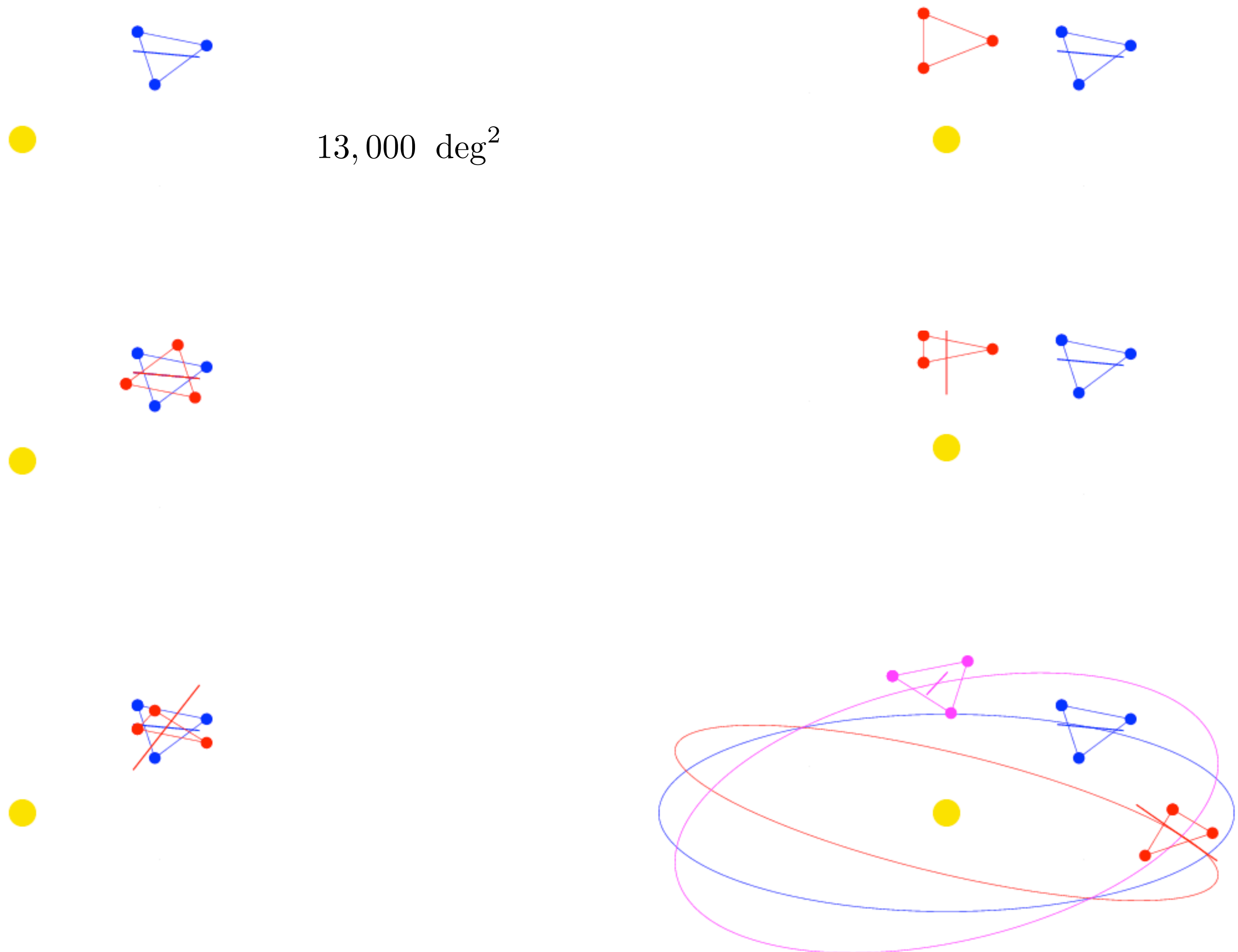


Trio



Burst Angular Resolution

$$f = 0.5 f_* \quad \text{SNR} = 100$$



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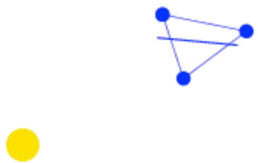
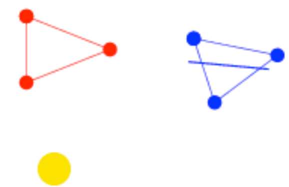
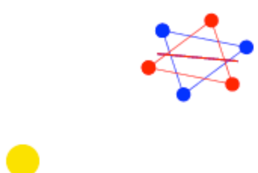
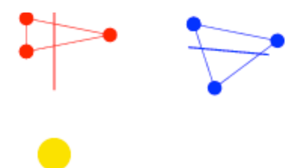


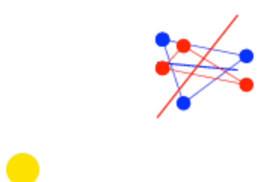
$13,000\ \ \mathrm{deg}^2$

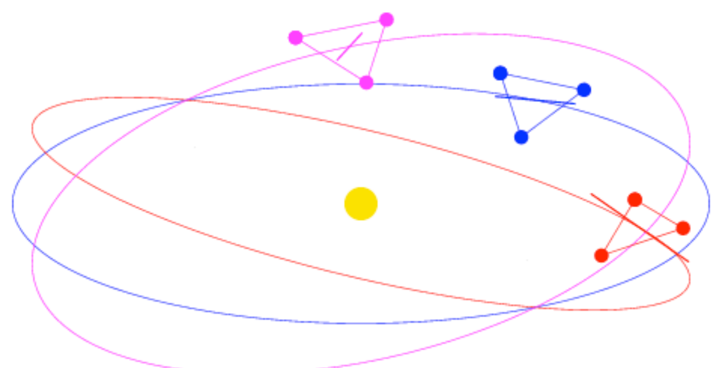




$300\ \ \mathrm{deg}^2$







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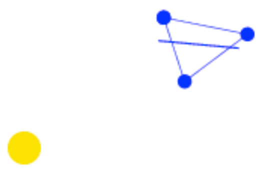

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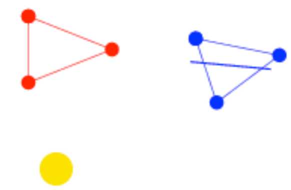

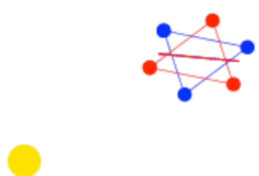

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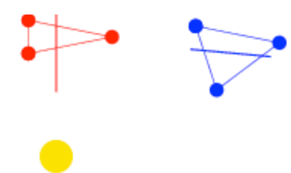
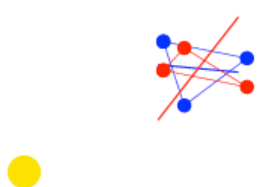
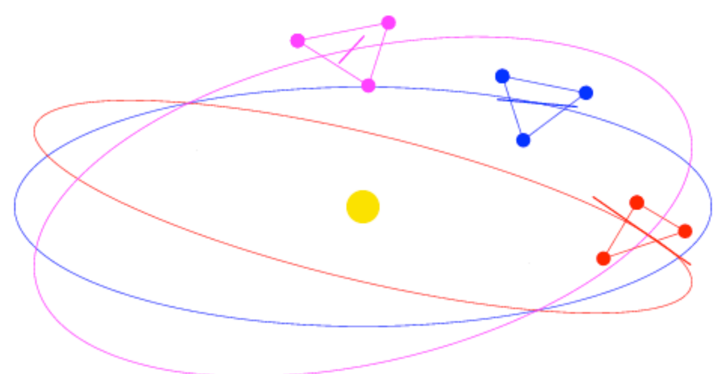




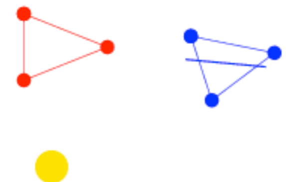
$3\ \ \mathrm{deg}^2$



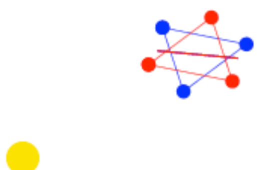
Burst Angular Resolution

$$f = 0.5 f_* \quad \mathrm{SNR} = 100$$

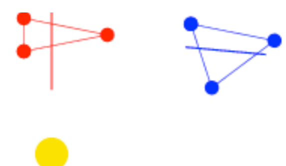
$13,000\ \deg^2$

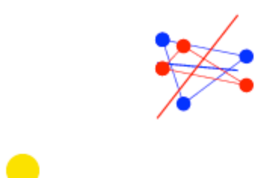


$0.8\ \deg^2$

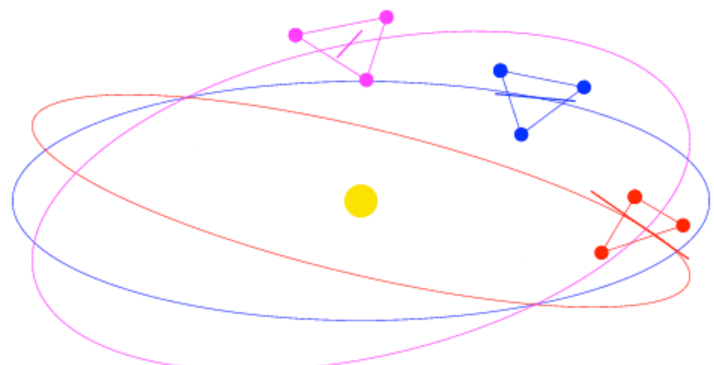


$300\ \deg^2$





$3\ \deg^2$



Burst Angular Resolution

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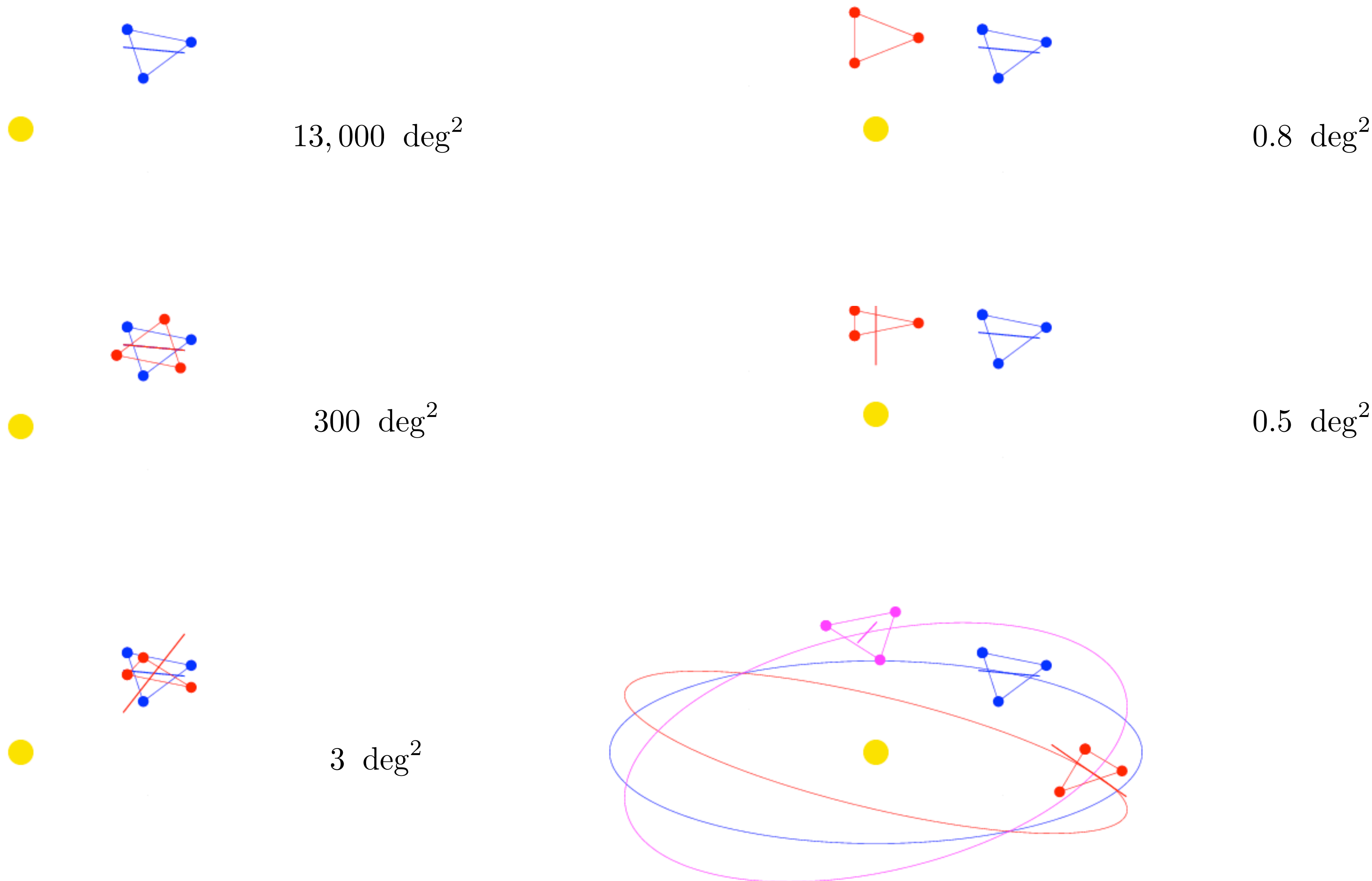

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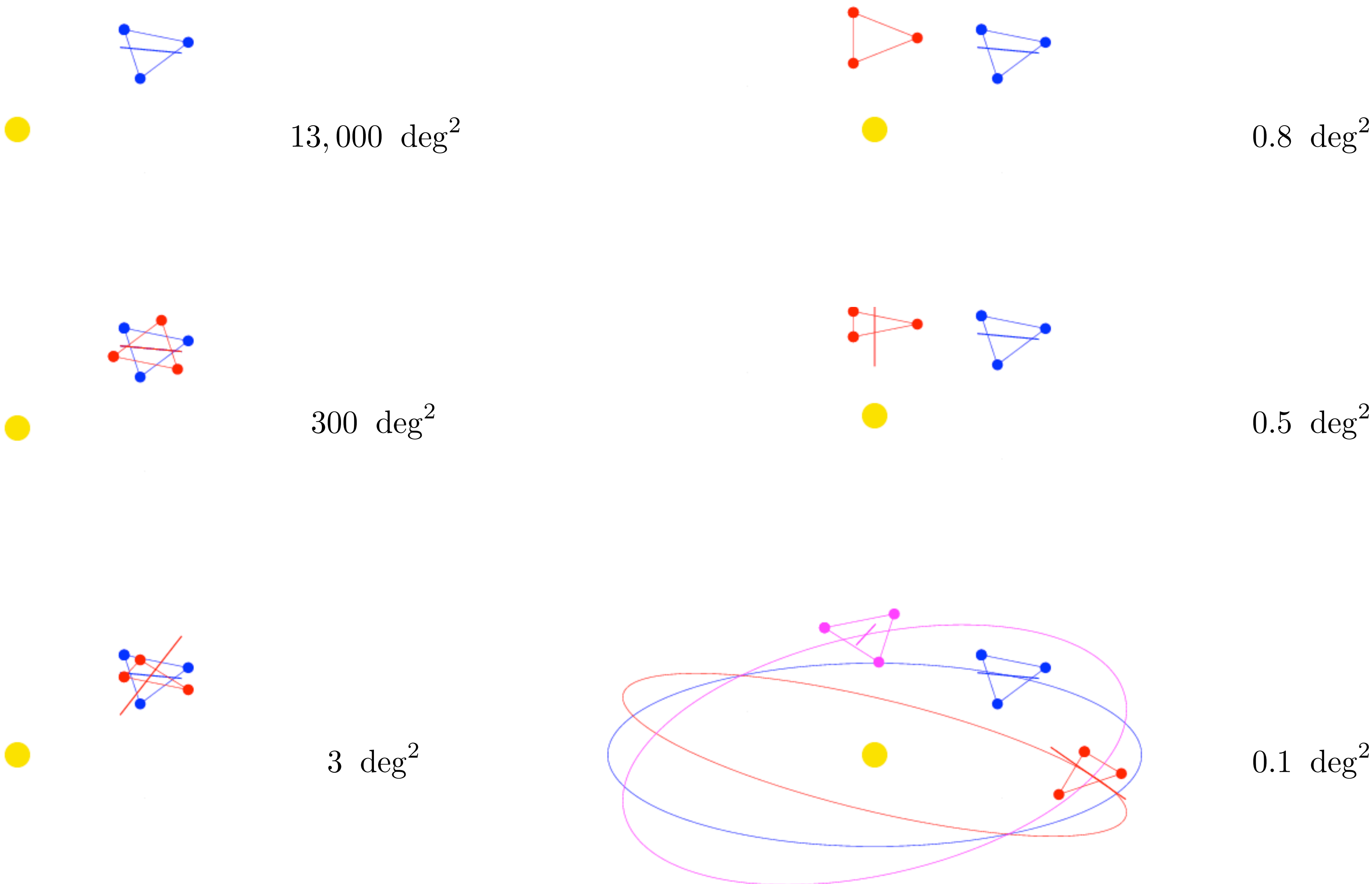
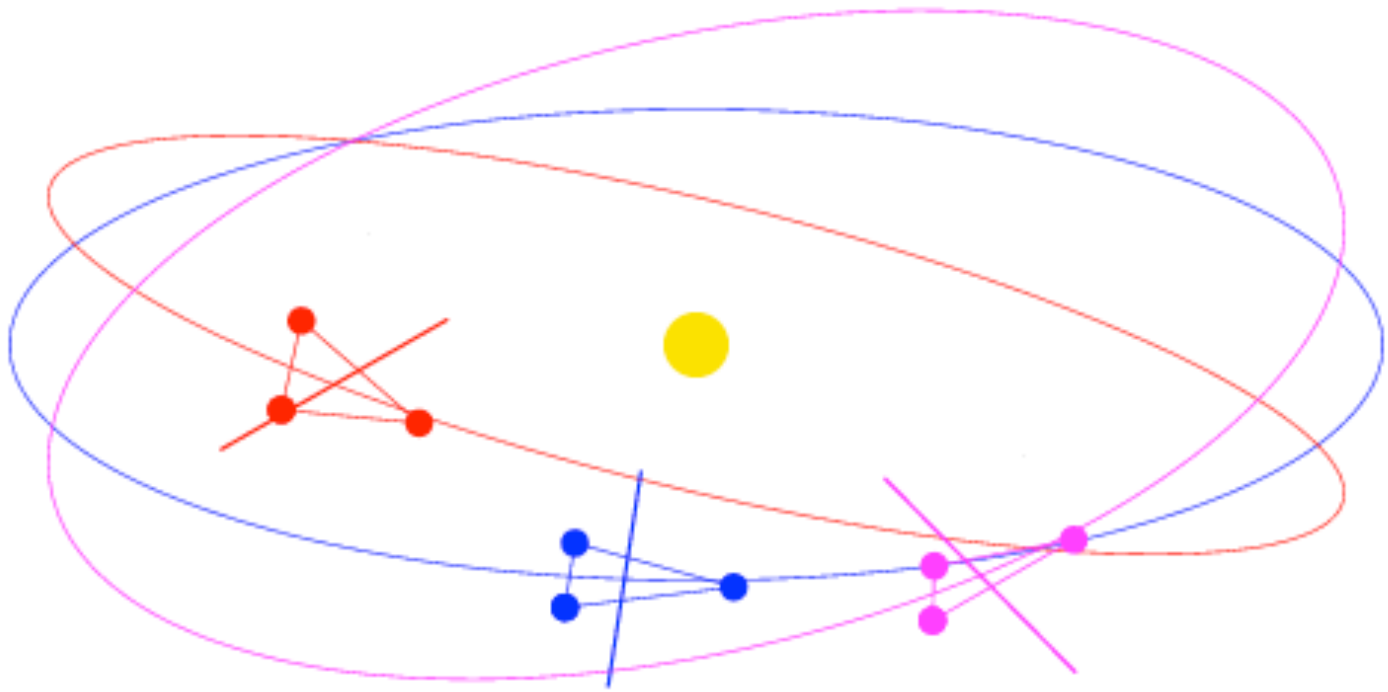
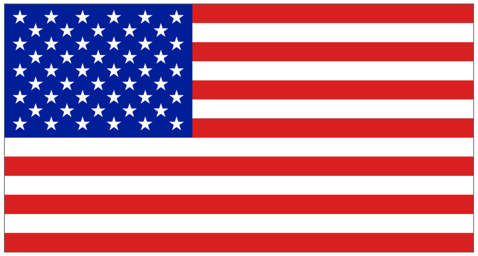
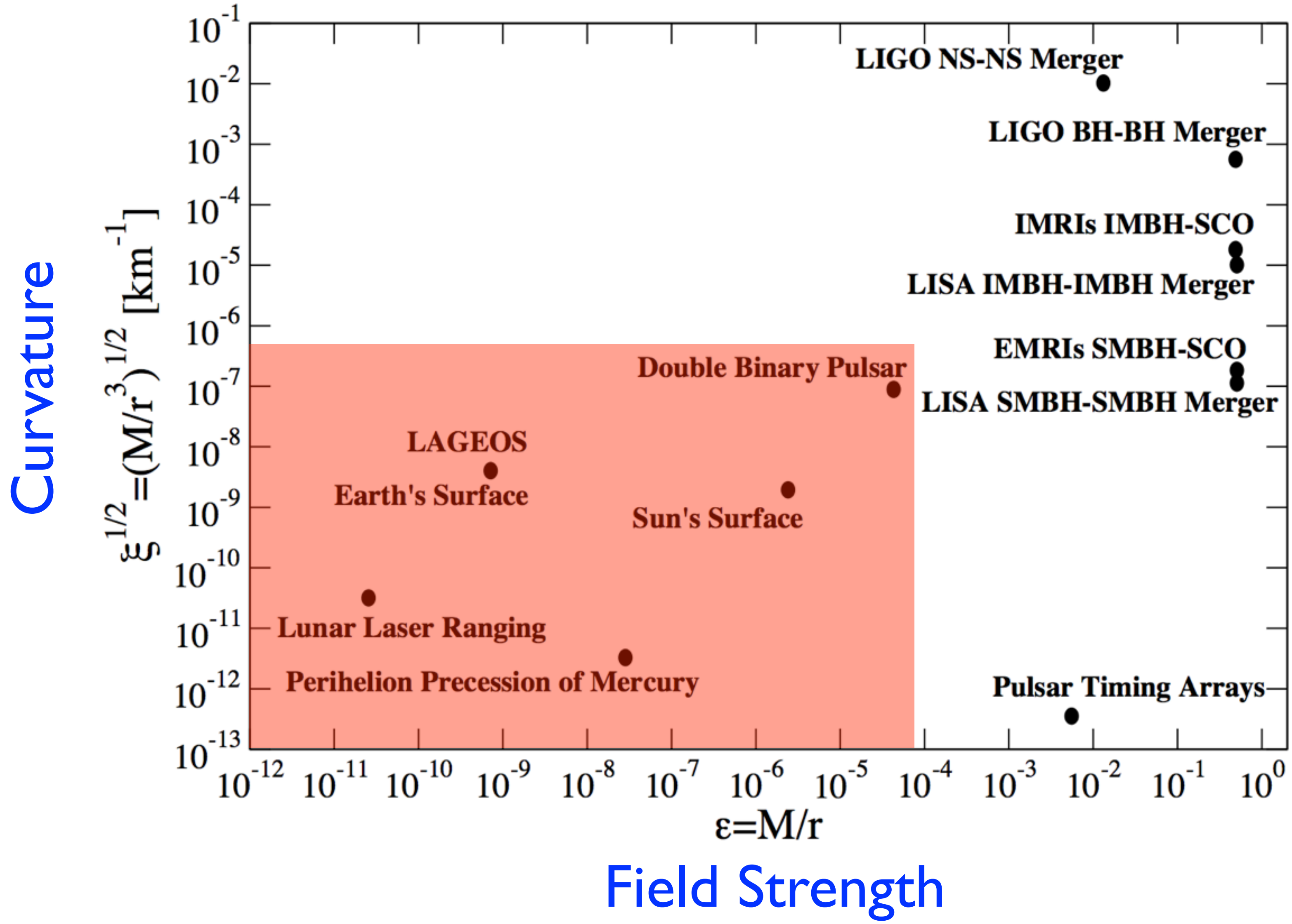


How to pay for it?





Tests of General Relativity



Will, Liv. Rev. 2005   Psaltis, Liv. Rev. 2008   Siemens & Yunes, Liv. Rev. 2012

Gravitational Wave Tests of General Relativity

- Internal (self consistency checks)
  - BH spectroscopy - ringdowns
  - BH mapping - EMRIs, IMRIs
- External (comparison to alternative theories)
  - Specific theories (e.g. scalar-tensor, Chern-Simons)
    - Polarization states
    - Graviton mass
  - Null tests, coherent residuals
  - Parameterized models (e.g. ppE)

Gravitational Wave Tests of General Relativity

Fitting Factor and Bayes Factor Related: $$\log \mathrm{BF} \simeq \frac{1}{2}(1 - \mathrm{FF}^2)\mathrm{SNR}^2$$

Cornish, Sampson, Yunes, Pretorius 2011

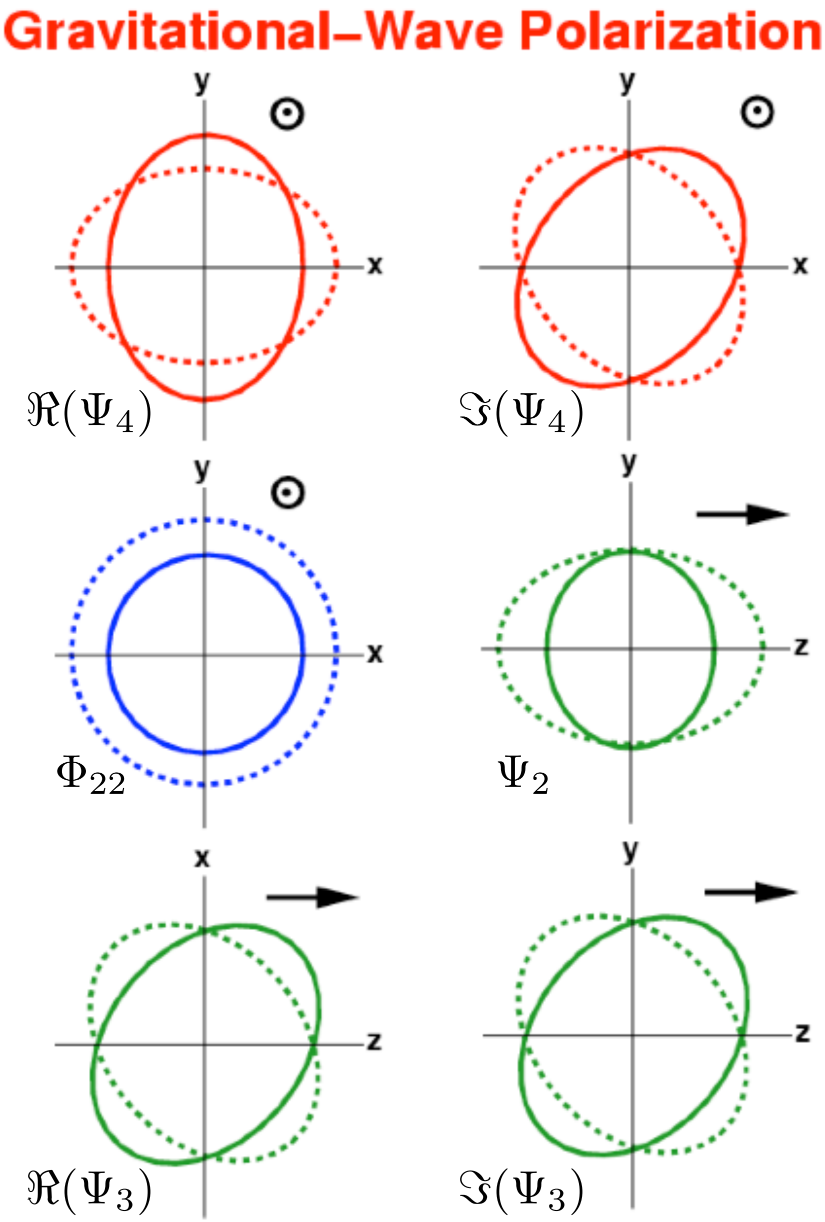
Mismatch and Bayes Factor Related: $$\Rightarrow \quad \mathrm{MM} \simeq \frac{\log \mathrm{BF}}{\mathrm{SNR}^2}$$

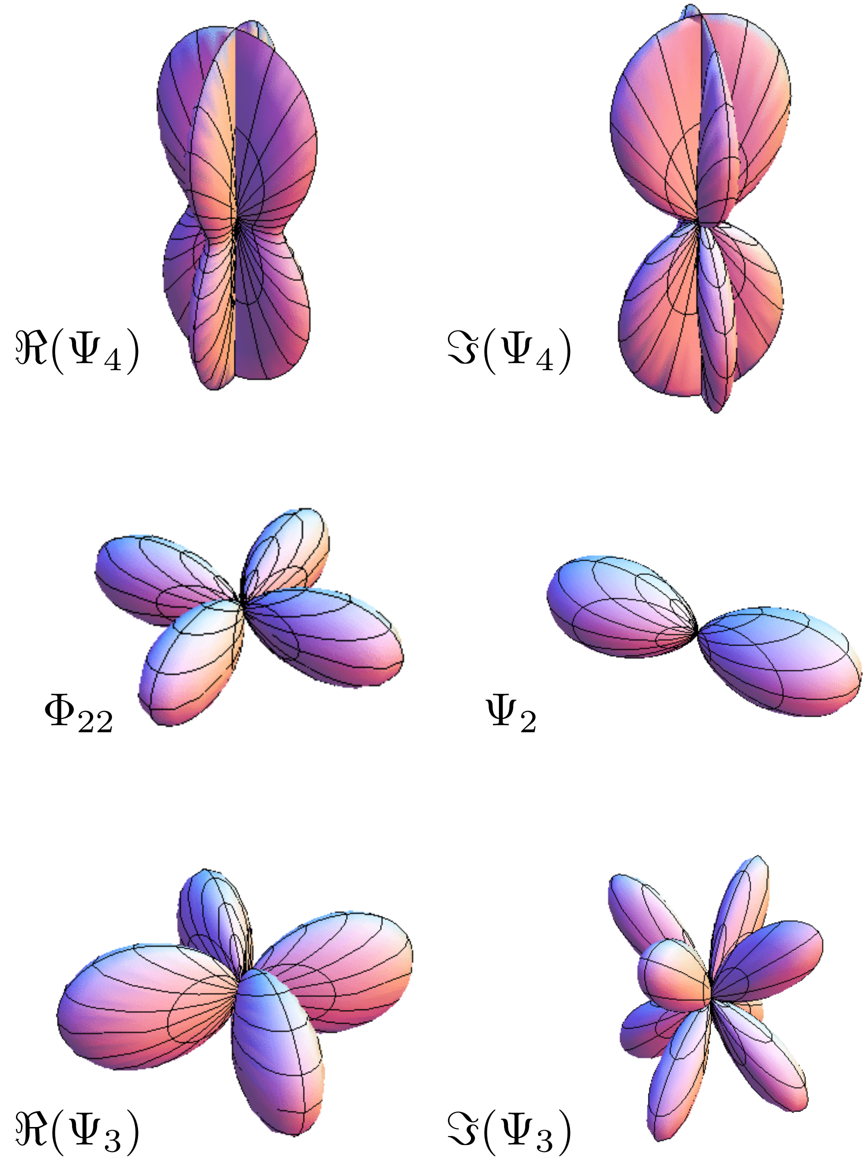
aLIGO detection with SNR = 10 — Can measure 10% departure from GR

LISA detection with SNR = 1000 — Can measure 0.001% departure from GR

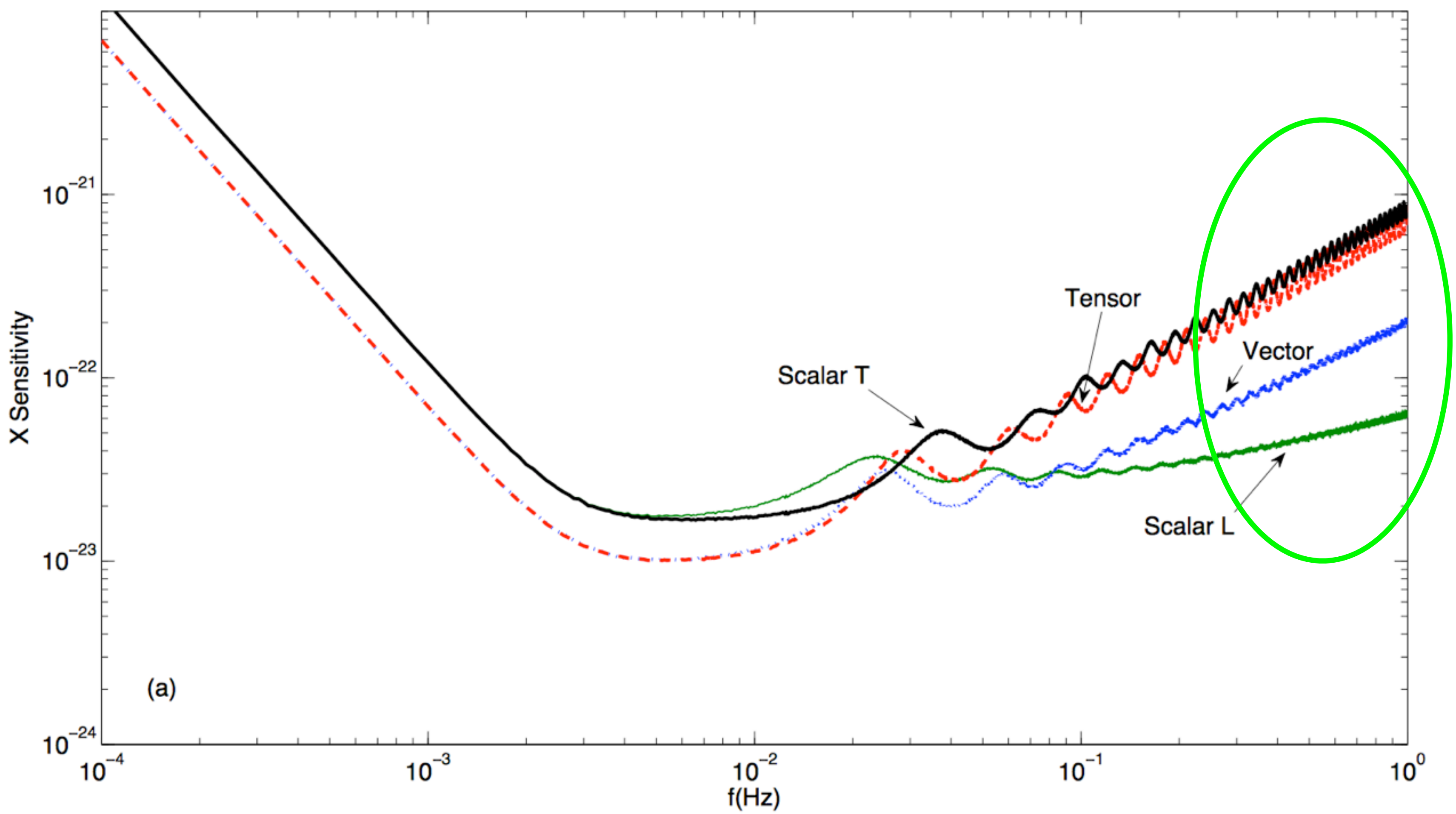
(> "4 sigma" detection)

Alternative Theories Predict Additional Polarization States





LISA sensitivity to alternative polarization states



[Tinto, da Silva Alves 2010]

Speed Gravity = Speed Light?

Massive Graviton	$v_g^2 = c^2(1 - (m_g/E_g)^2)$	
Dark Matter Emulators Desai, Kahya & Woodard 08	$v_g^2 > c^2$	(photons and gravitons "see" different metrics)
Braneworlds	$v_g^2 < c^2$	(gravitons propagate off the brane)

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Desai, Kahya & Woodard 08

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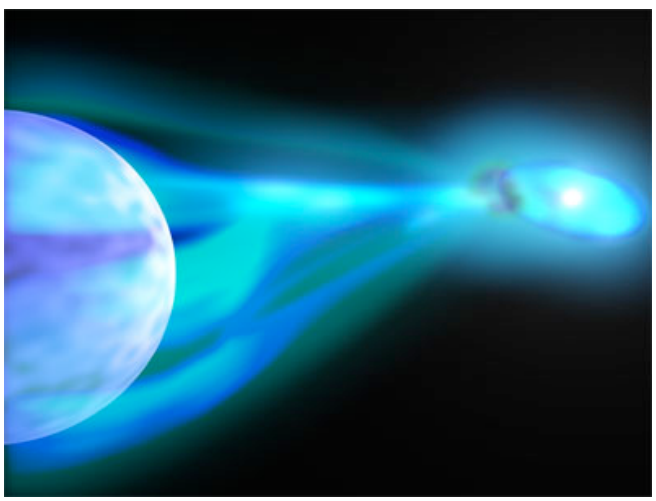

Optical Counterparts

Speed Gravity = Speed Light?

Massive Graviton $v_g^2 = c^2(1 - (m_g/E_g)^2)$

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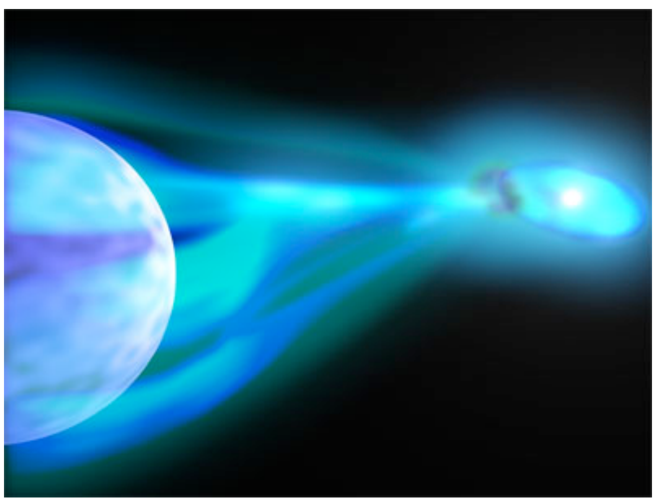
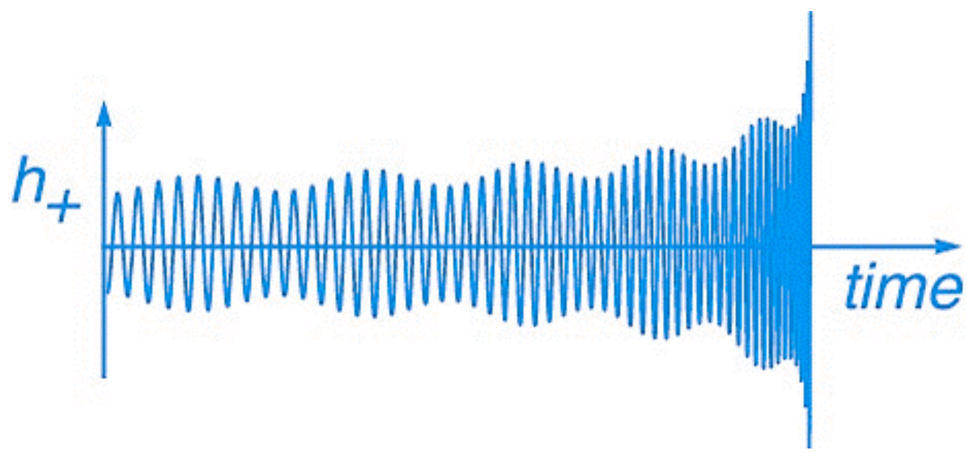
Desai, Kahya & Woodard 08

Braneworlds $v_g^2 < c^2$ (gravitons propagate off the brane)

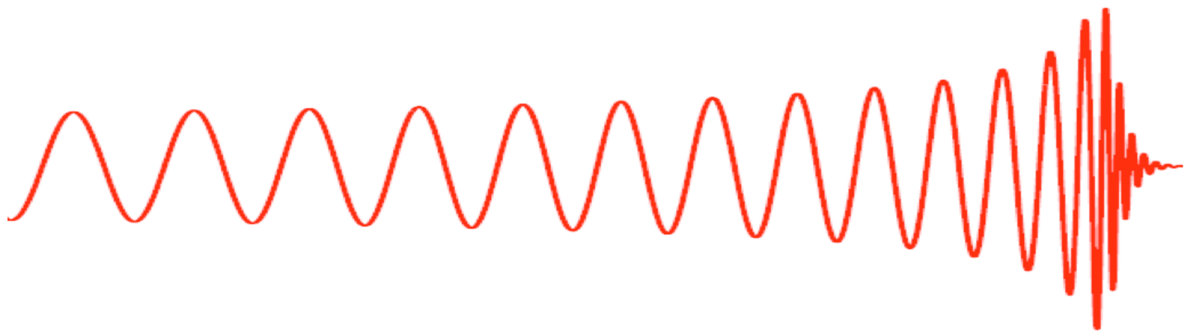


Optical Counterparts



Chirp "squeezing"

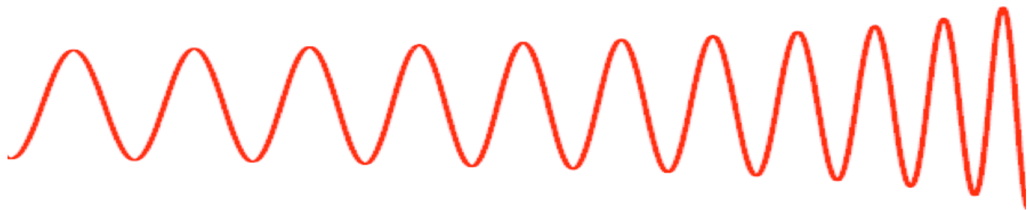
Post-Newtonian Waveforms



$h(t)$

$$h(f) = \mathcal{A}(f)\, e^{i\Psi(f)}$$

Post-Newtonian Waveforms

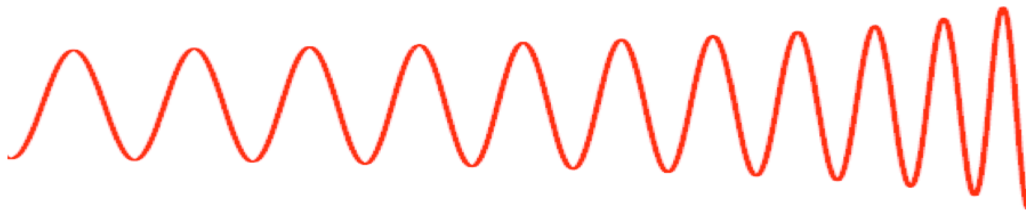


$h(t)$

$$h(f) = \mathcal{A}(f)\, e^{i\Psi(f)}$$

Leading order inspiral waveform $\quad u = (\pi \mathcal{M} f)^{1/3} \sim \frac{v}{c}$

Post-Newtonian Waveforms



$h(t)$

$$h(f) = \mathcal{A}(f)\, e^{i\Psi(f)}$$

Leading order inspiral waveform

$$u = (\pi \mathcal{M} f)^{1/3} \sim \frac{v}{c}$$

$$\mathcal{A}_{\rm GR}(f) = \frac{\mathcal{M}^2}{u^{7/2}} \frac{Q(\alpha, \delta, \psi, \iota)}{D_L}$$

$$\Psi_{\rm GR}(f) = 2\pi f t_c - \Phi_c - \pi/4 + \sum_{k=0} (\psi_k\, u^{k-5} + \psi_{lk}\, u^k \ln u)$$

Modified Waveforms

Variable G   Scalar Field

$$\Psi(f) = 2\pi f t_c - \Phi_c - \frac{\pi}{4} + \frac{3}{128}u^{-5}\Big[1 \quad -\frac{25}{1536}\dot{G}\mathcal{M}u^{-8} \quad -\frac{5}{84}\frac{S^2}{\omega_{\rm BD}}\eta^{3/5}u^{-2}$$

$$+\left(\frac{3715}{756}+\frac{55}{9}\eta\right)\eta^{-2/5}u^2 - 16\pi\eta^{-3/5}u^3 \quad -\frac{128}{3}\frac{\pi^2 D\mathcal{M}}{\lambda_g^2(1+z)}u^2 \quad + \ldots\Big]$$

Massive Graviton

$$\mathcal{A}(f) = \sqrt{\frac{5}{96}}\frac{\mathcal{M}^{5/6}}{D\,\pi^{2/3}}f^{-7/6}\left(1 \quad -\frac{5}{512}\dot{G}\mathcal{M}u^{-8} \quad + \left(\frac{743}{672}+\frac{11}{8}\eta\right)\eta^{-2/5}u^2 + \ldots\right)$$

Variable G

Parameterized Post Einsteinian

[Yunes-Pretorius '09]

$$h(f) = \mathcal{A}(f)\, e^{i\Psi(f)}$$

$$u = (\pi \mathcal{M} f)^{1/3}$$

$$\mathcal{A}(f) = \mathcal{A}_{\rm GR}(f)\,(1 + \alpha\, u^a)$$

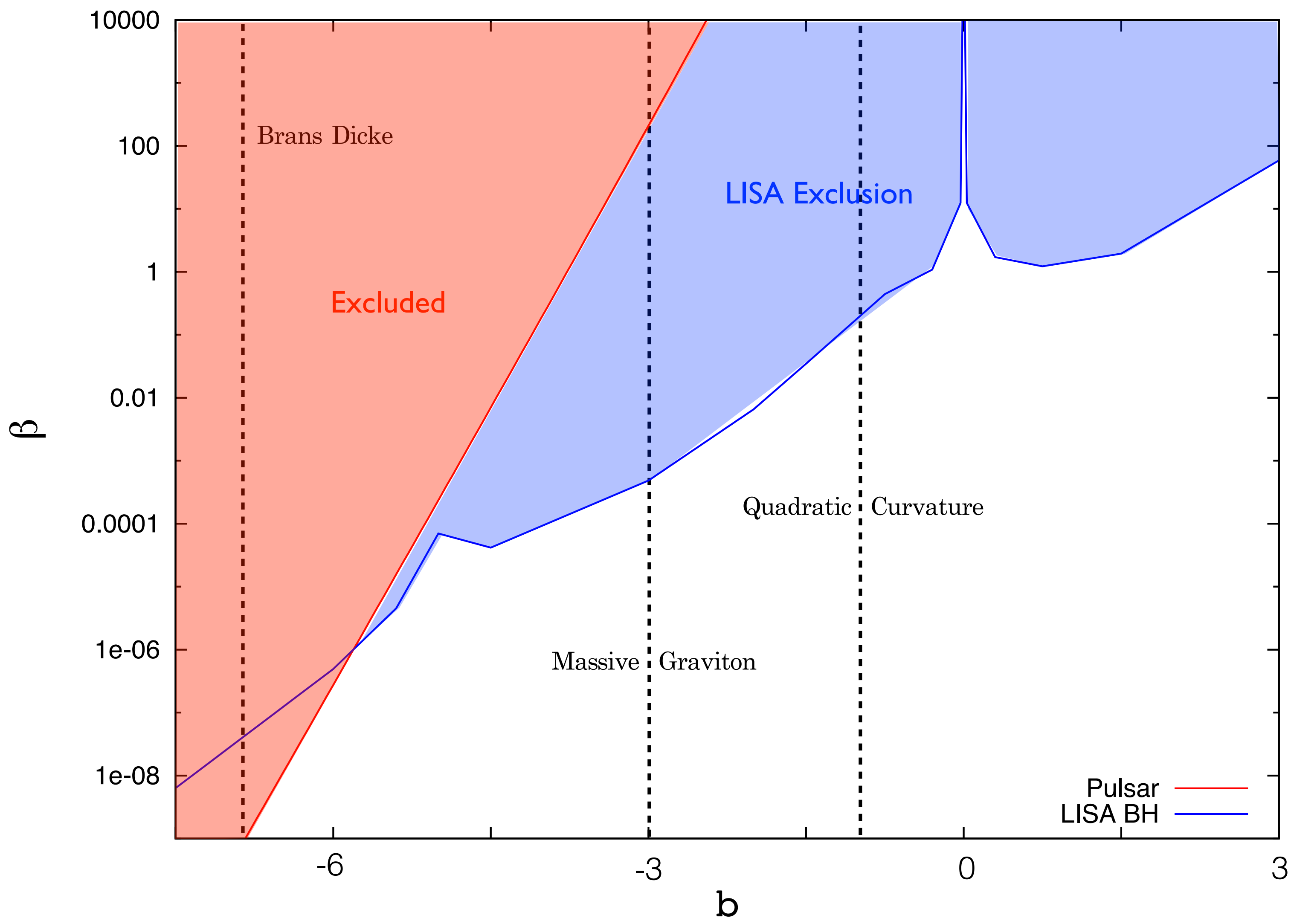
$$\Psi(f) = \Psi_{\rm GR}(f)\,\left(1 + \beta\, u^b\right)$$

Theory	α	a	β	b
General Relativity	0	-	0	-
Brans-Dicke	0	-	β	-7
Chern-Simons	α	1	0	-
Extra-Dimensions	0	-	β	-13
Qaudratic Curvature	0	-	β	-1
Variable G	α	-8	β	-13
Massive Graviton	0	-	β	-3

Covers almost all theories (certain massive scalar field and spontaneous scalarization scenarios are exceptions)

LISA vs. Current Pulsar Bounds

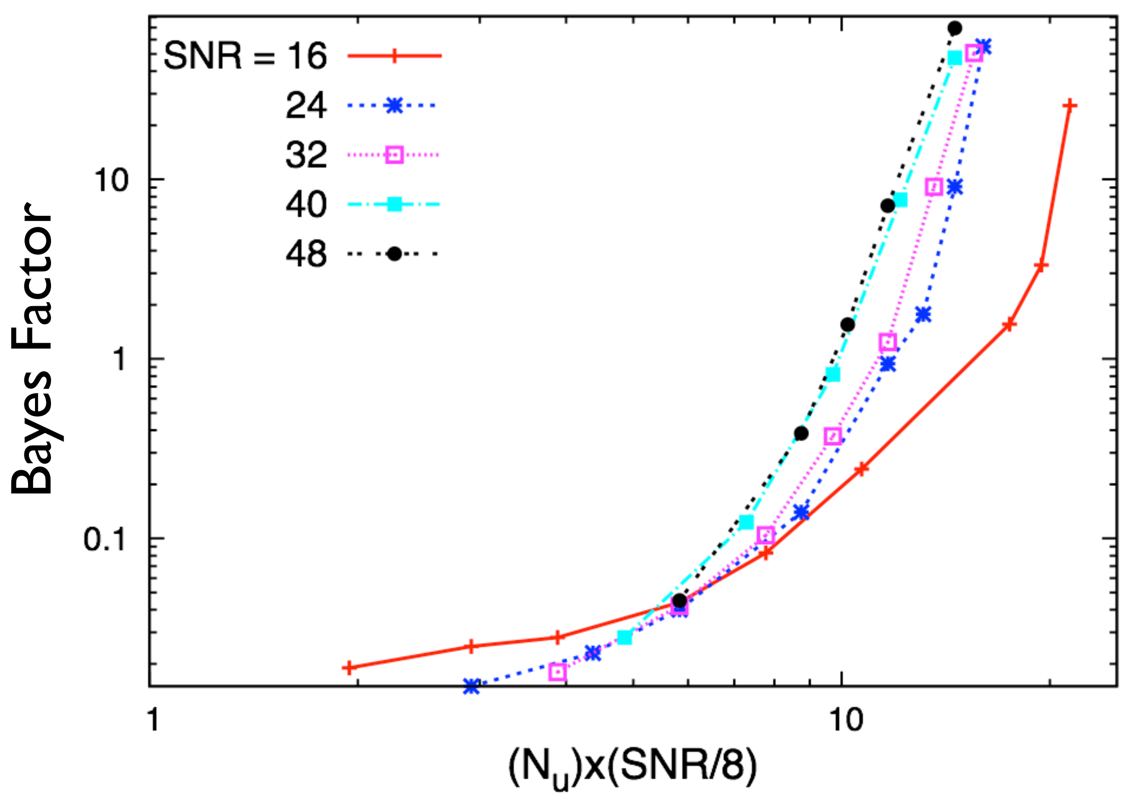
(Cornish, Sampson, Yunes & Pretorius 2011)



Back of the envelope bounds

Useful cycles $$\mathcal{N}_u = \left(\int_{F_{\min}}^{F_{\max}} \frac{df}{f}\frac{a^2(f)}{S_n(f)}\frac{d\phi}{2\pi df}\right)\left(\int_{F_{\min}}^{F_{\max}} \frac{df}{f}\frac{a^2(f)}{S_n(f)}\right)^{-1}$$

〔Damour, Iyer, Sathyaprakash '00〕

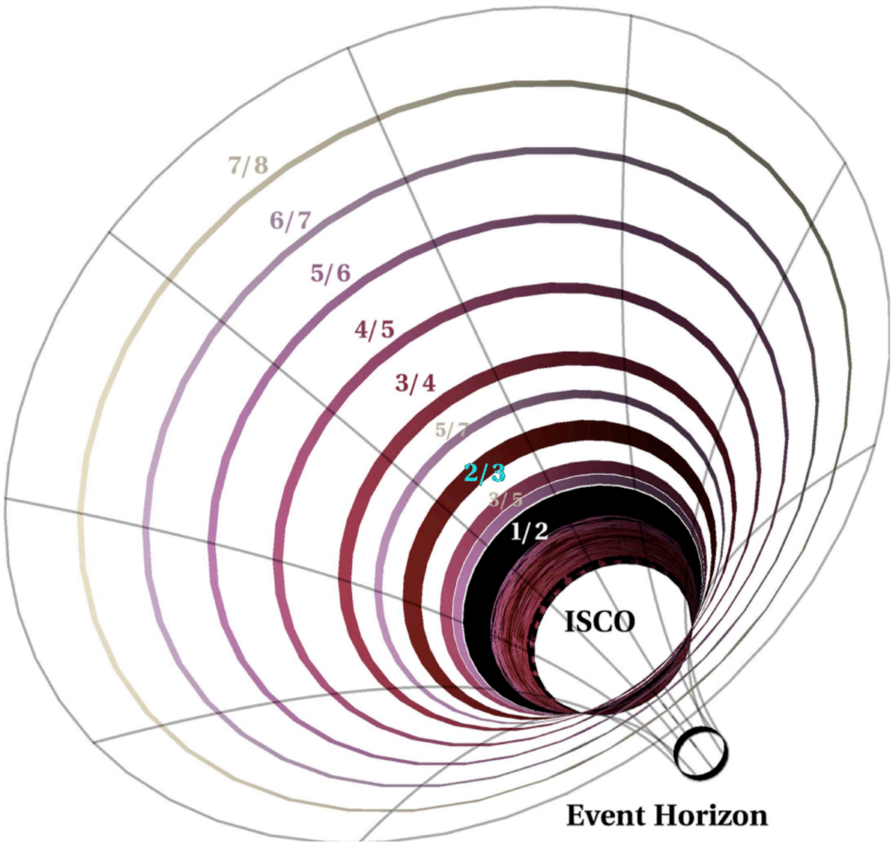


〔Sampson et al '14〕

Alternative Gravity Multipliers: Butterfly Effect

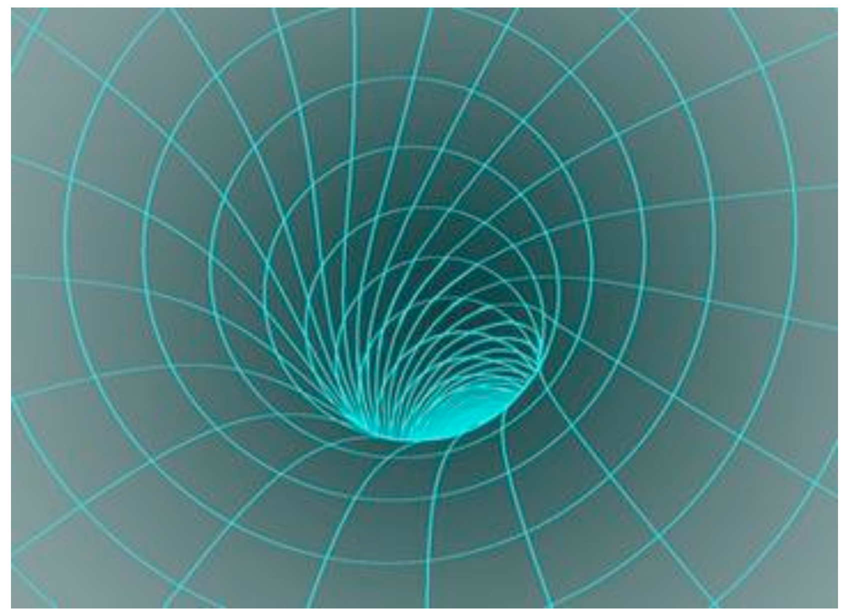
[Cornish ??]

EMRI resonances



[Brink, Geyer, Hinderer 13] [Ruangsri, Hughes 13]

Alternative Kerr Spacetimes



[Yagi, Yunes, Tanaka 12]