Title: The Multi-Messenger Milky Way

Speakers: Sarah Gossan

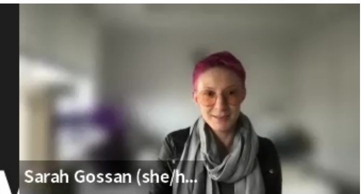
Series: Strong Gravity

Date: December 02, 2021 - 1:00 PM

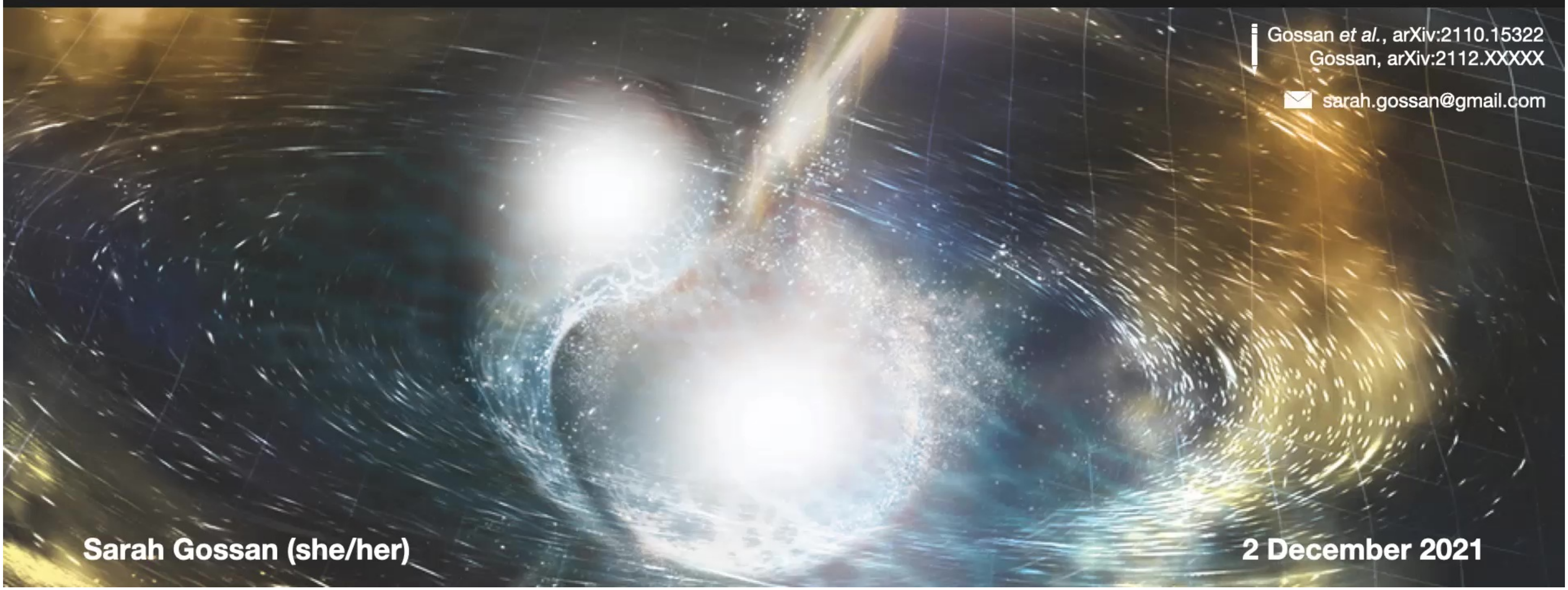
URL: https://pirsa.org/21120008

Abstract: The era of multi-messenger astronomy is well and truly upon us, with 90 compact binaries observed since the Advanced LIGO detectors saw first light in 2015. Despite our very own cosmic backyard, the Milky Way, being ripe with prospective sources for ground-based gravitational wave detectors, the closest source detected thus far (GW170817, the famed binary neutron star merger) was at a distance of 40 Mpc. In this talk, I will outline a number of prospective Galactic multi-messenger sources, and discuss several ways in which their detection over the next twenty years can be improved through both experimental and analytical techniques.

Zoom Link: https://pitp.zoom.us/j/93664322641?pwd=VUoxbmFGZE1KczJ1RU1MR09TQ05Ldz09

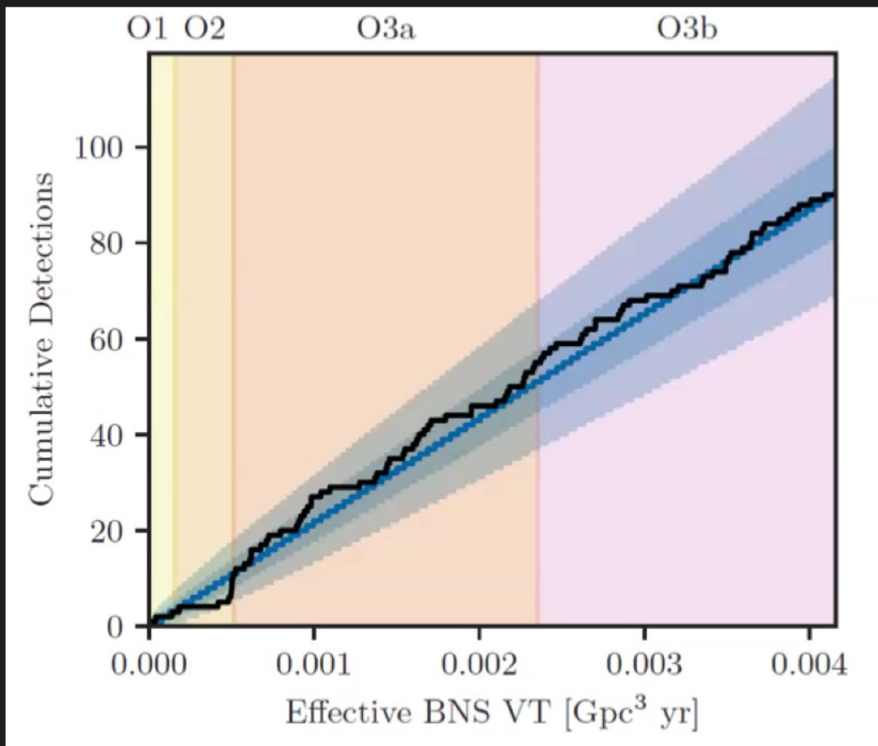


Exploring the Multi-Messenger Milky Way



The story so far

Since Advanced LIGO saw `first light' in 2015:



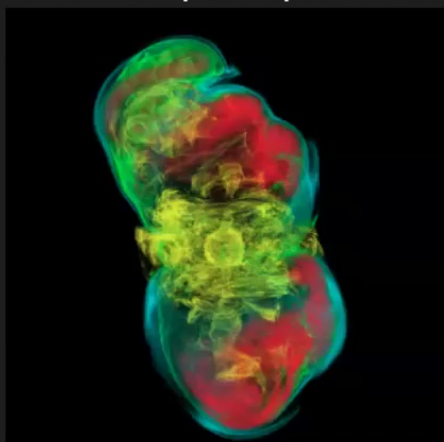
Credit: LIGO-Virgo Collaboration

Credit: The SXS Project

Credit: U. of Warwick/M. Garlick

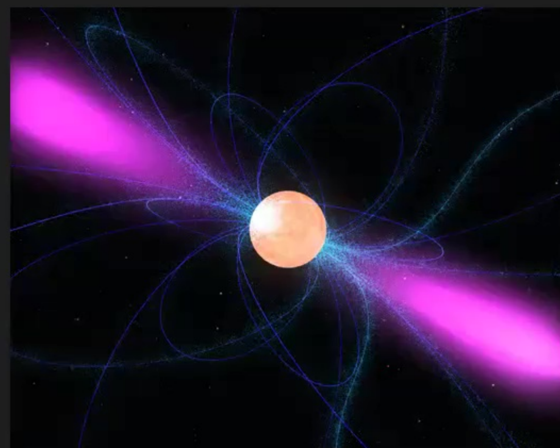
The Galactic GW Zoo

Core-collapse supernovae



Credit: P. Mösta/S. Richers/Caltech

Pulsars

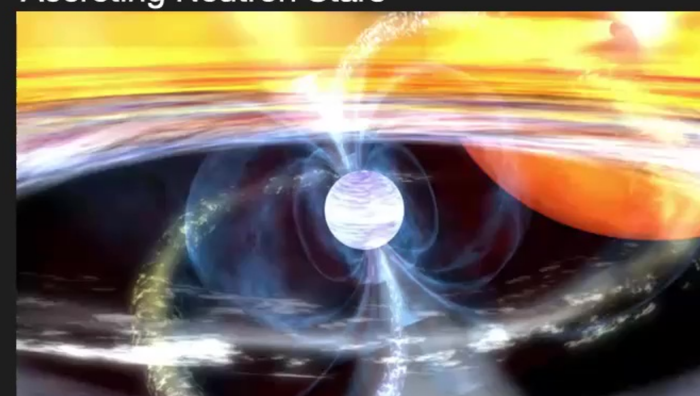


Credit: NASA

Thorne-Zytkow objects

Credit: Astronomy magazine

Accreting Neutron Stars



Credit: NASA / GSFC SVS / Dana Berry

Compact binaries

Credit: M. Weiss

A tangent: observable gravitational wave

Polarization-averaged signal-to-noise ratio (SNR) in a single detector

$$\langle \rho^2 \rangle \propto P(\theta, \phi) \int_0^\infty \mathrm{d}f \, \frac{|\tilde{h}(f)|^2}{S_h(f)}$$

GW emission **in Fourier domain**

$$|\tilde{h}(f)|^2 = |\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2$$

Polarization-averaged antenna power of the detector

Power spectral density (PSD) of detector noise

Observed SNR dependent on: **(1) Signal strength**

(2) Detector sensitivity

- **(a) Noise floor**
- **(b) Antenna power**

(3) Ability to recover signal from noise

Why haven't we detected Galactic GWs

1. Weaker gravitational wave emission than compact binaries

   Can we build new, more sensitive detectors?

Observed SNR

(1) Signal strength

(2) Detector sensitivity

(a) Noise floor

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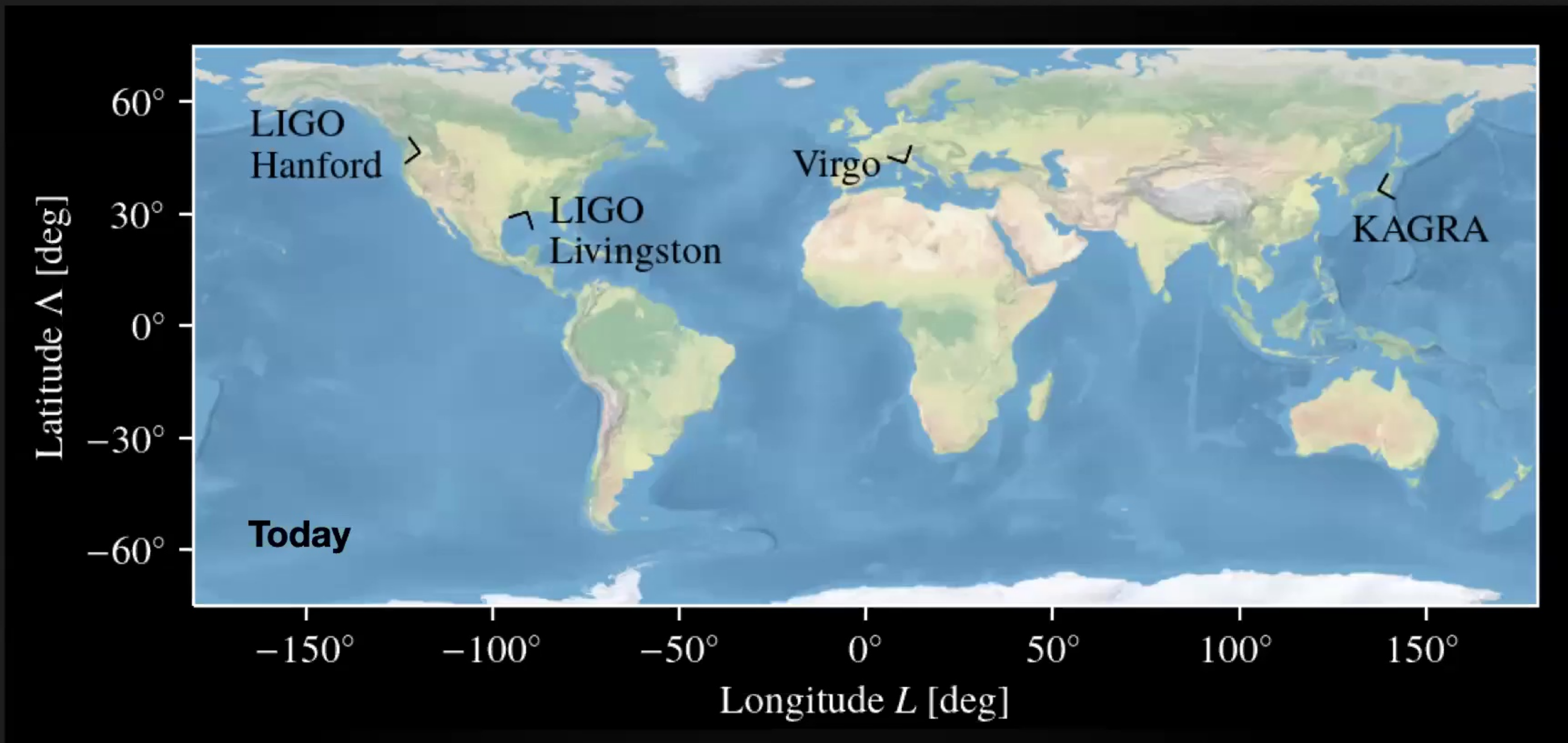
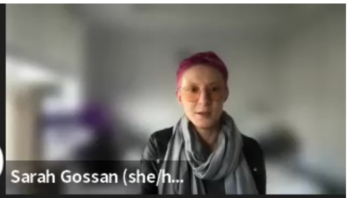
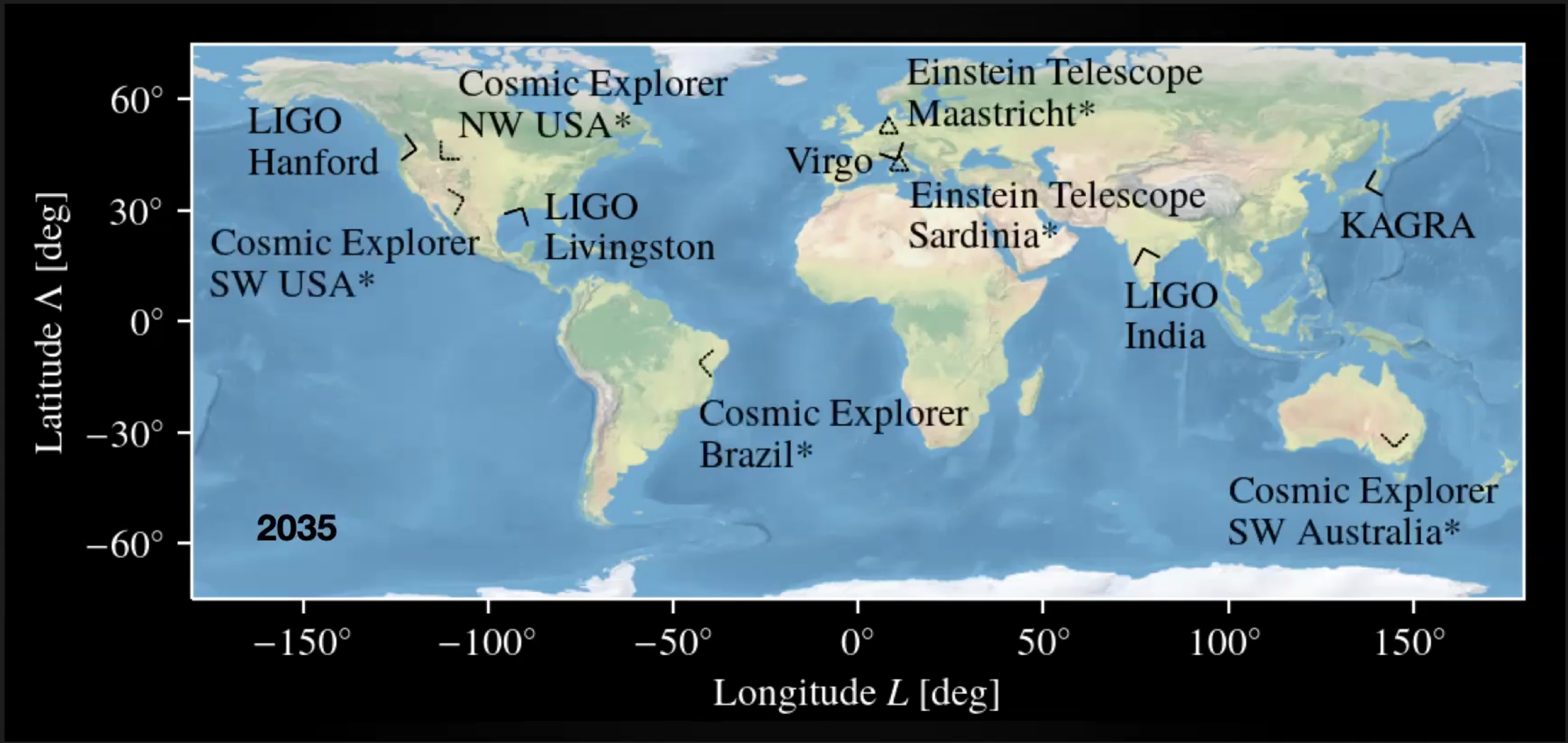
A Global GW Detection Network: 2G to

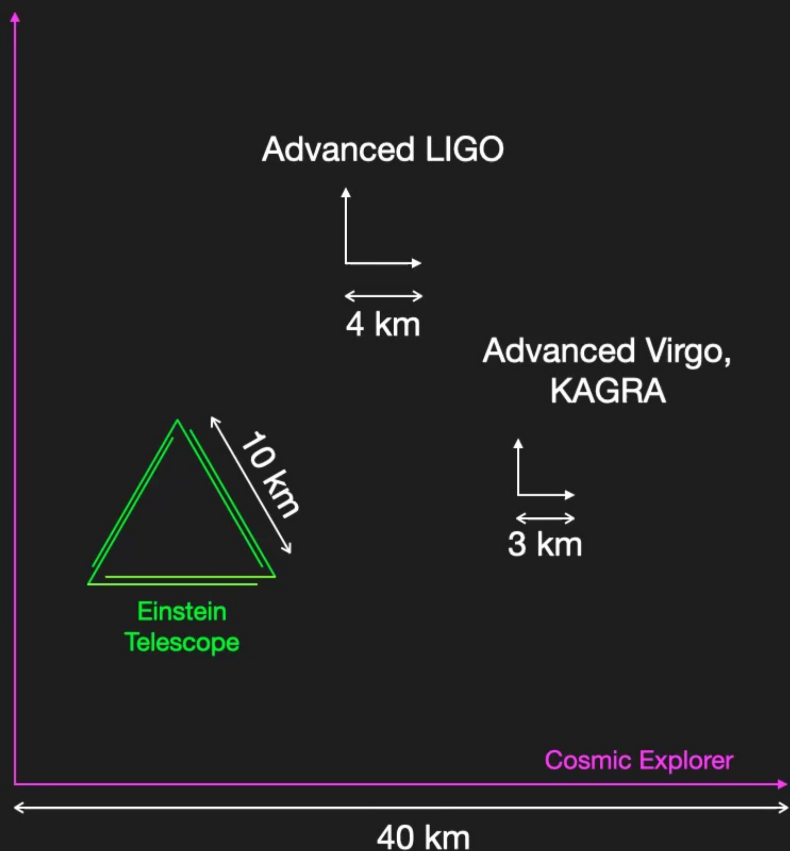


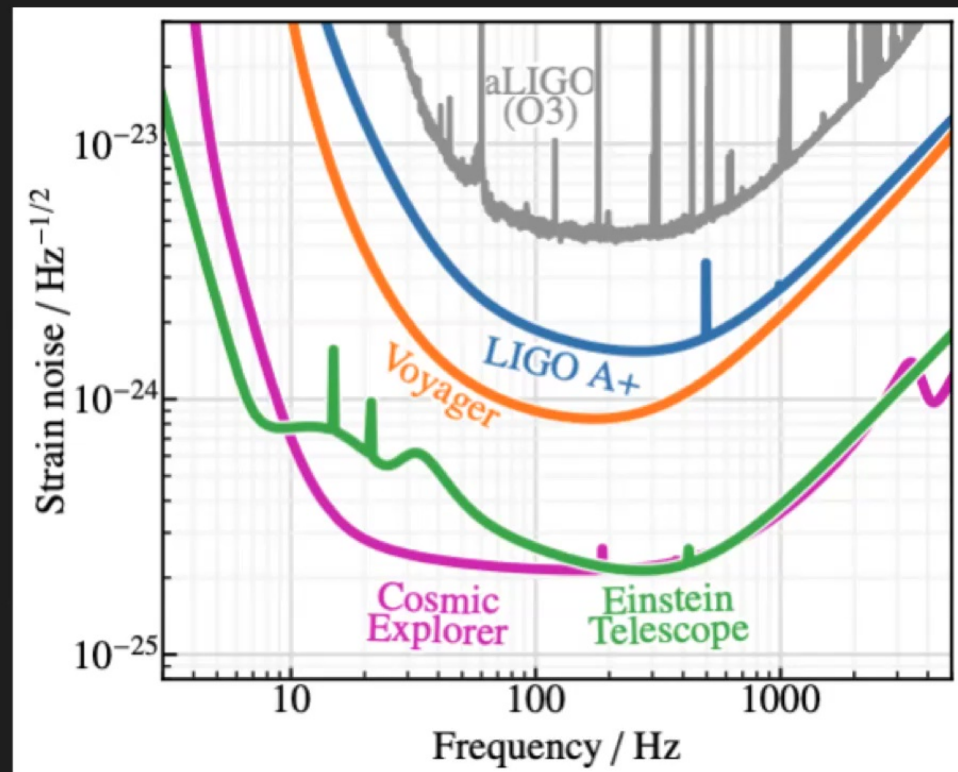
A Global GW Detection Network: 2G to

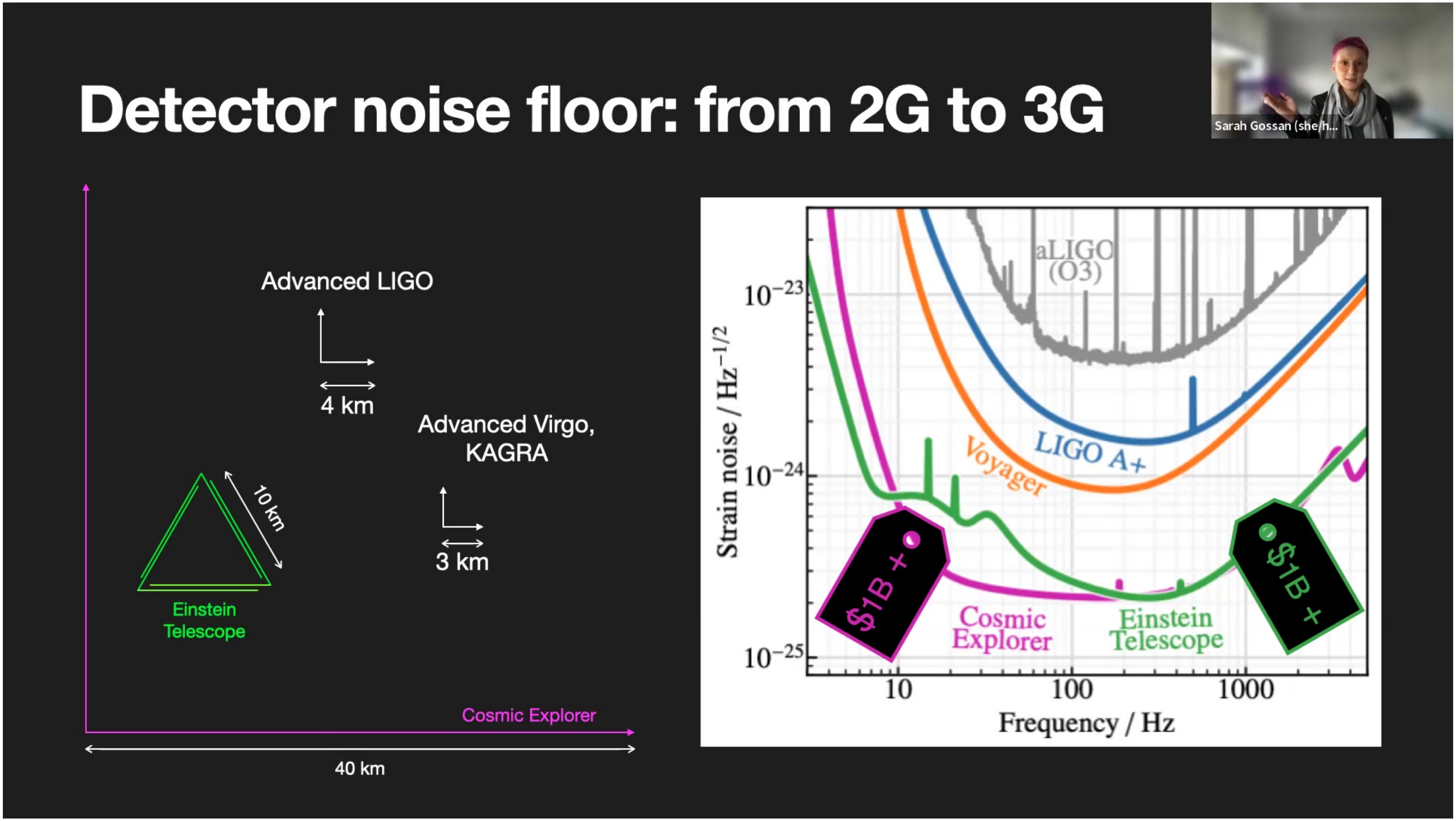




Detector noise floor: from 2G to 3G







Detector noise floor: from 2G to 3G
Sarah Gossan (she/h...
Advanced LIGO
4 km
Advanced Virgo, KAGRA
3 km
10 km
Einstein Telescope
Cosmic Explorer
40 km
aLIGO (O3)
LIGO A+
Voyager
Cosmic Explorer
Einstein Telescope
$1B +
$1B +
Strain noise / Hz$^{-1/2}$
10^{-23}
10^{-24}
10^{-25}
10
100
1000
Frequency / Hz

Why haven't we detected Galactic GWs yet?

1. Weaker gravitational wave emission than compact binaries

   Can we build new, more sensitive detectors?

   Sure, but $$$$$$$$$$

Observed SNR

(1) Signal strength

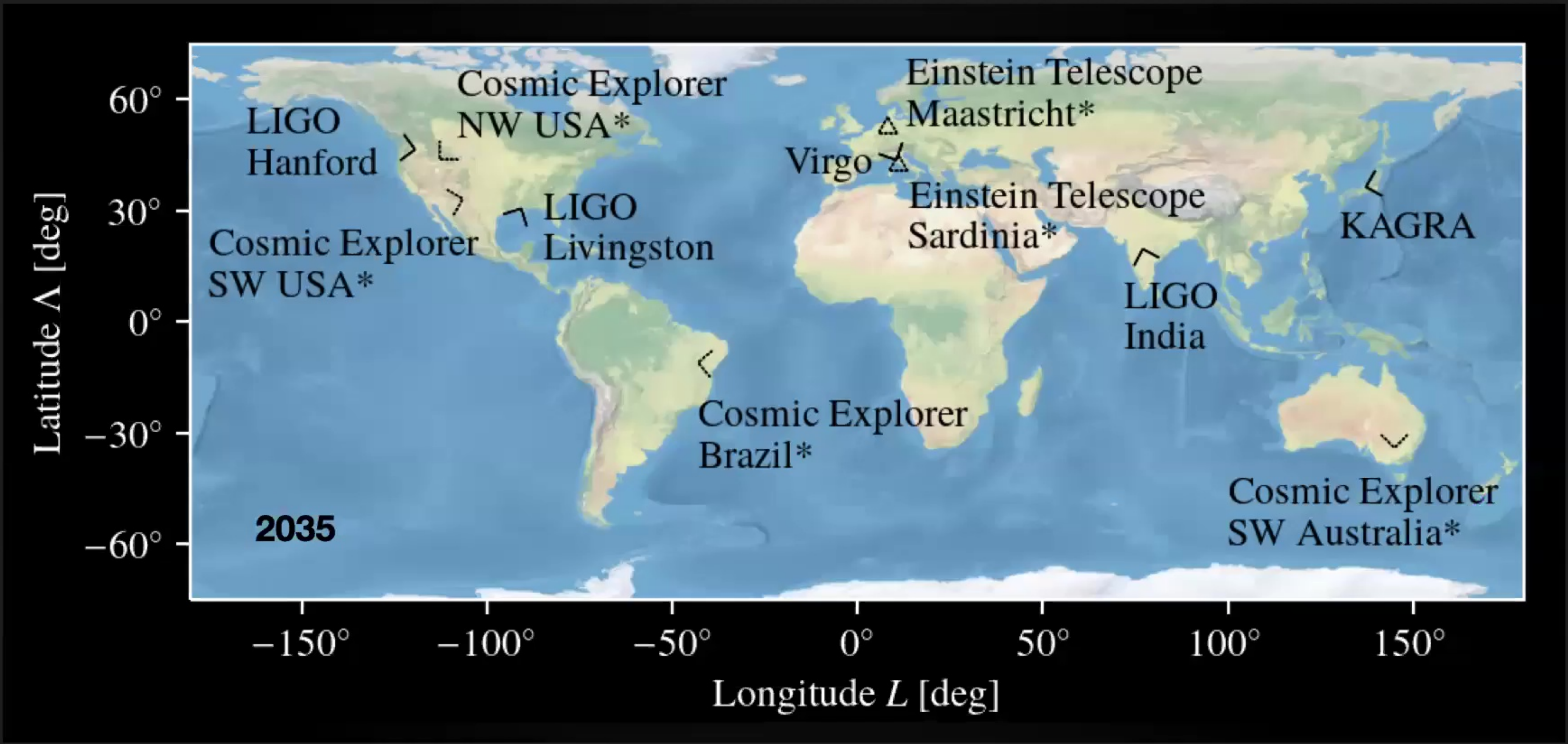
(2) Detector sensitivity

(a) Noise floor

(b) Antenna power

(3) Ability to recover signal from noise

A Global GW Detection Network: 2G to 3G



Why haven't we detected Galactic GWs

1. Weaker gravitational wave emission than compact binaries

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2. Sources not isotropically distributed across the sky

Observed SNR

(1) Signal strength

(2) Detector sensitivity
   (a) Noise floor
   (b) Antenna power

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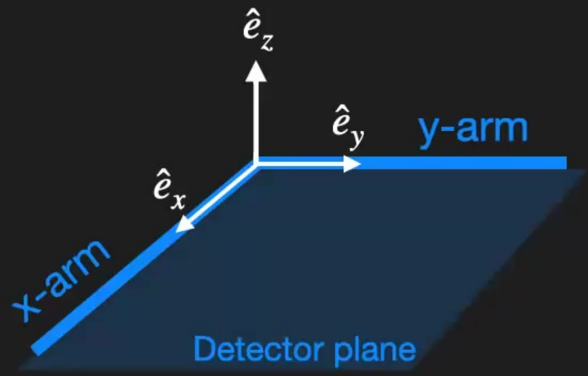
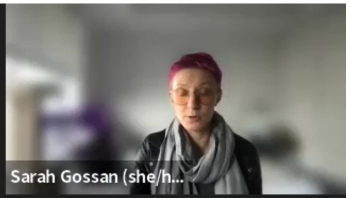
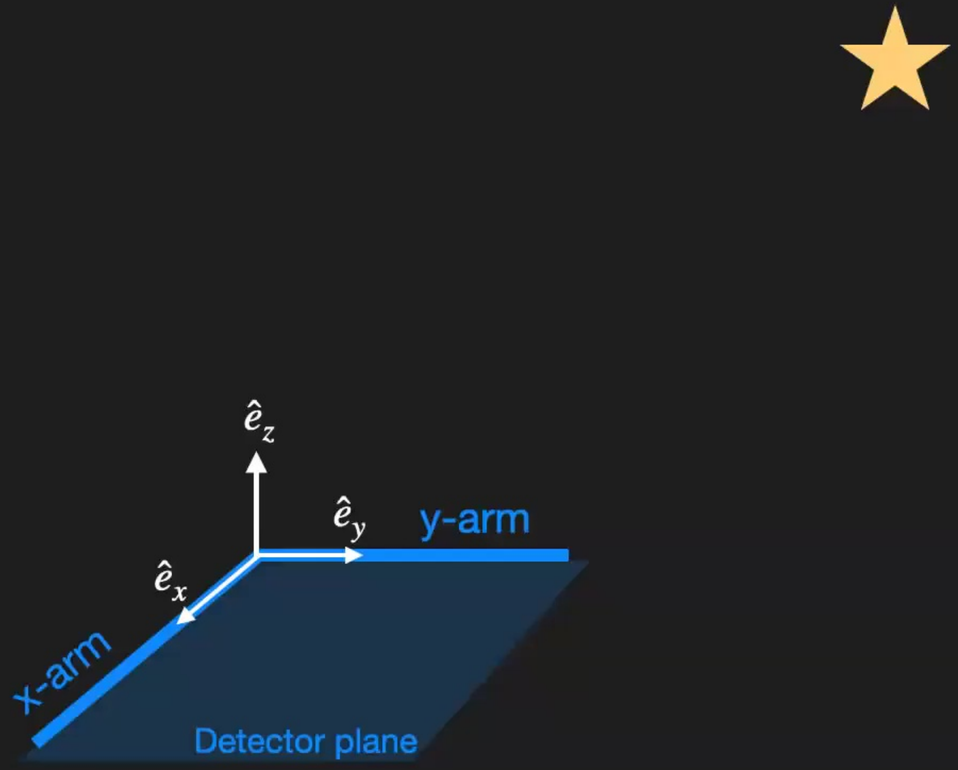
Detector Frame

Detector Frame

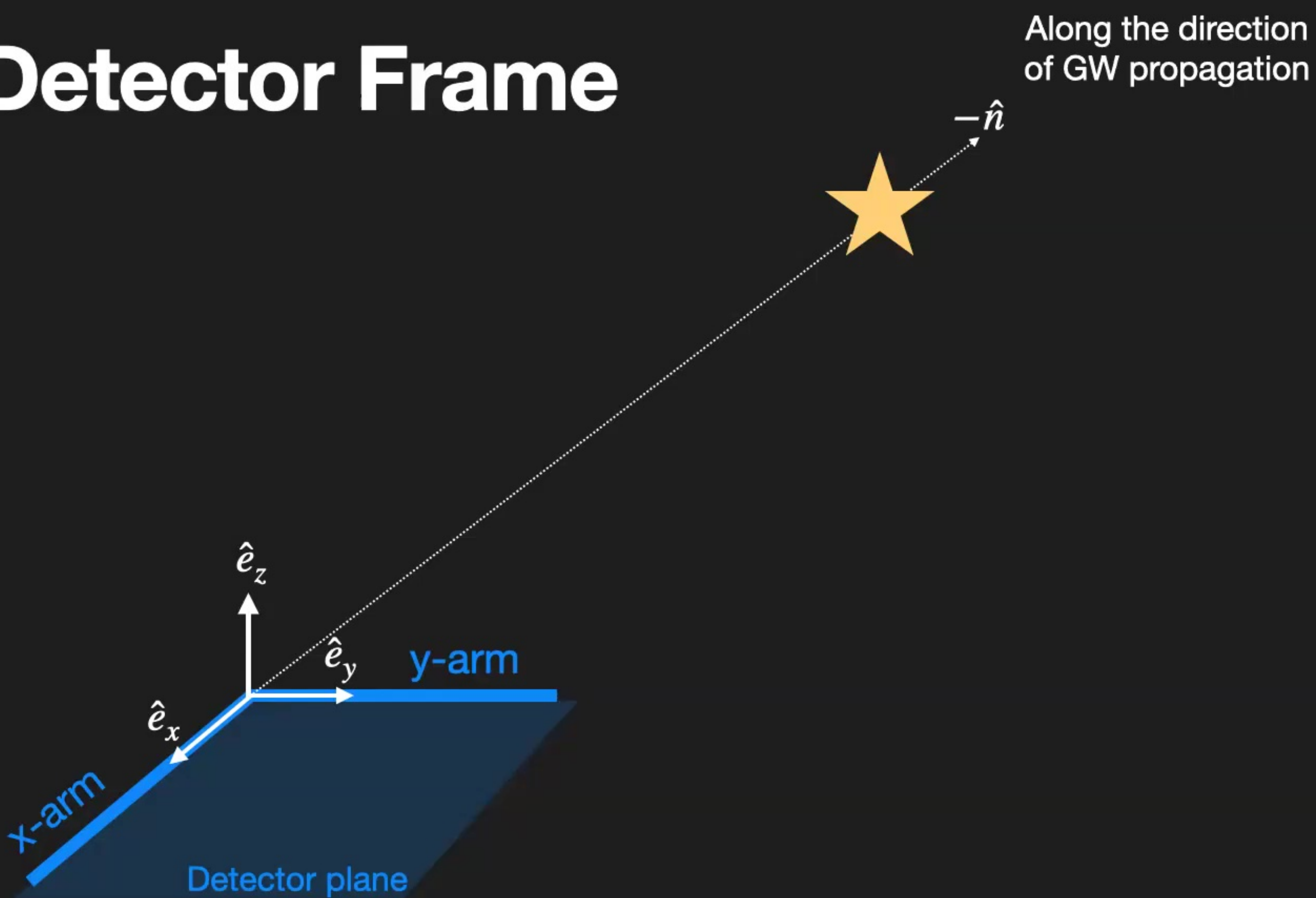


Detector Frame

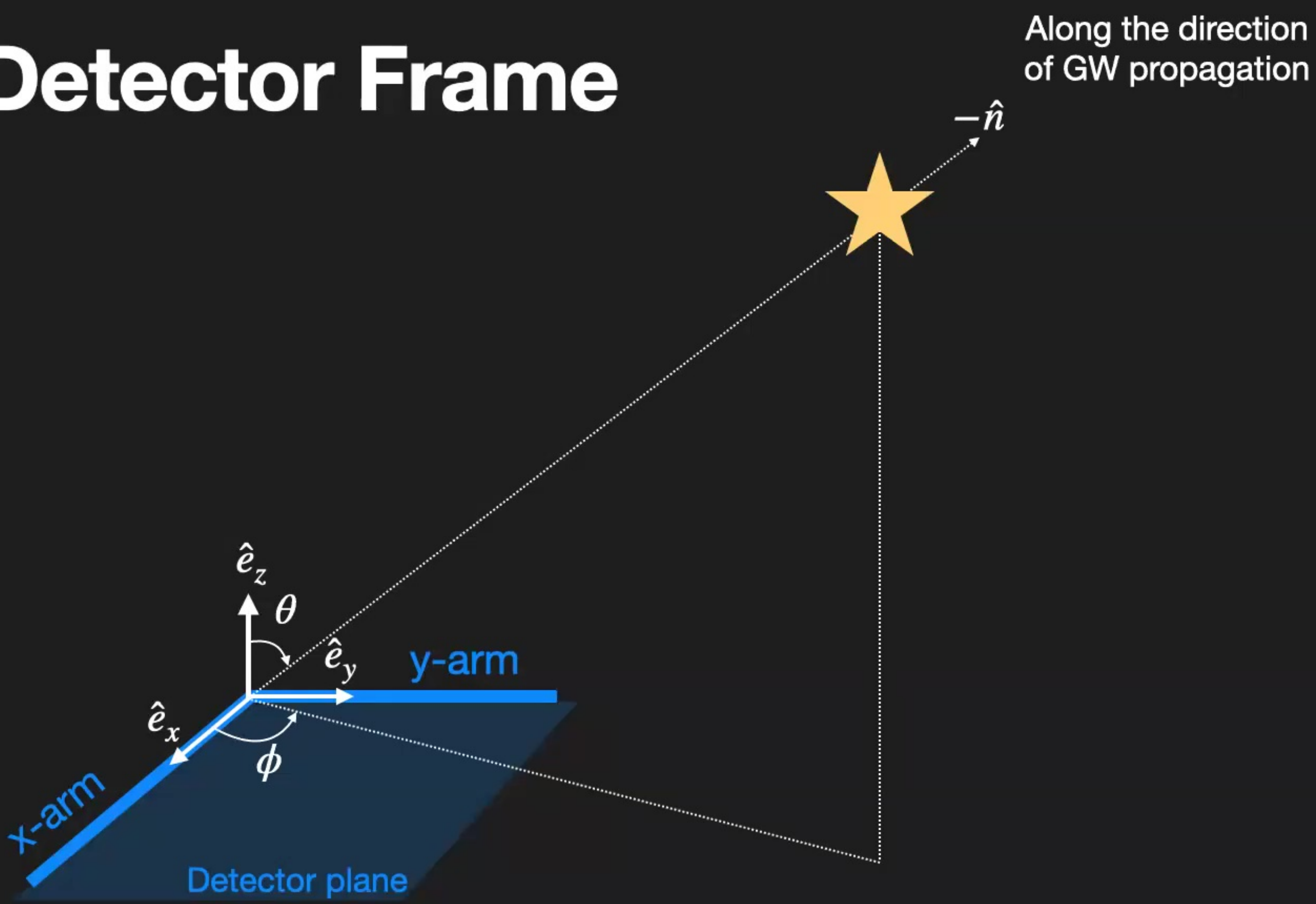




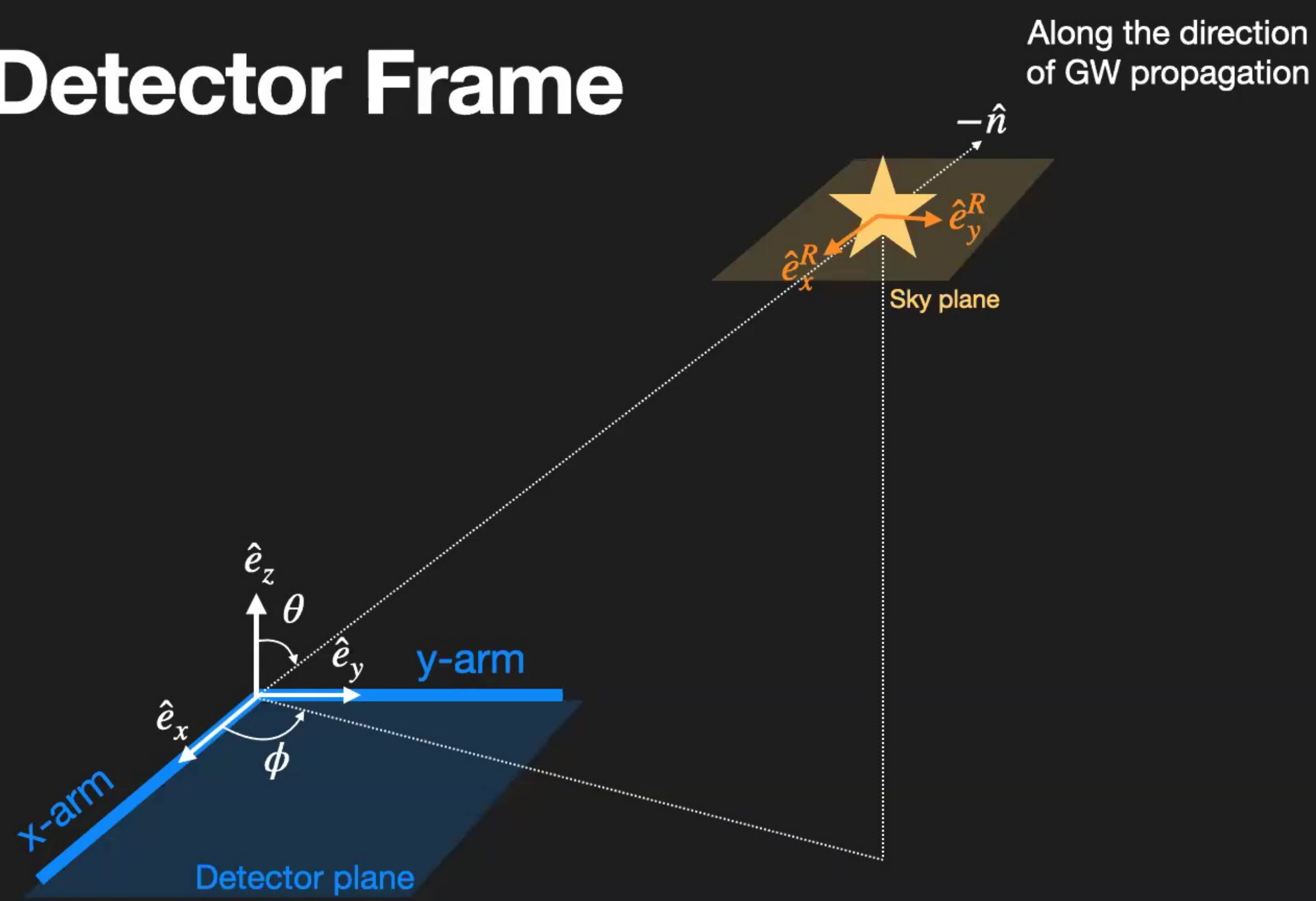
Detector Frame



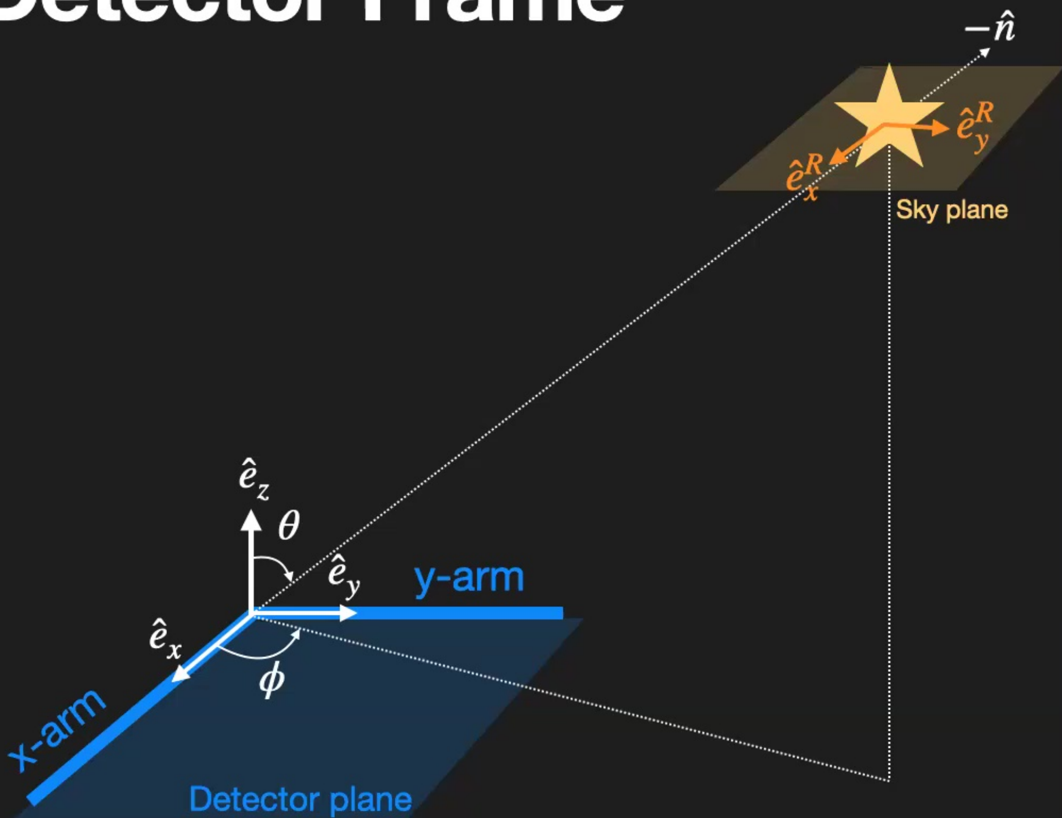
Detector Frame



Detector Frame

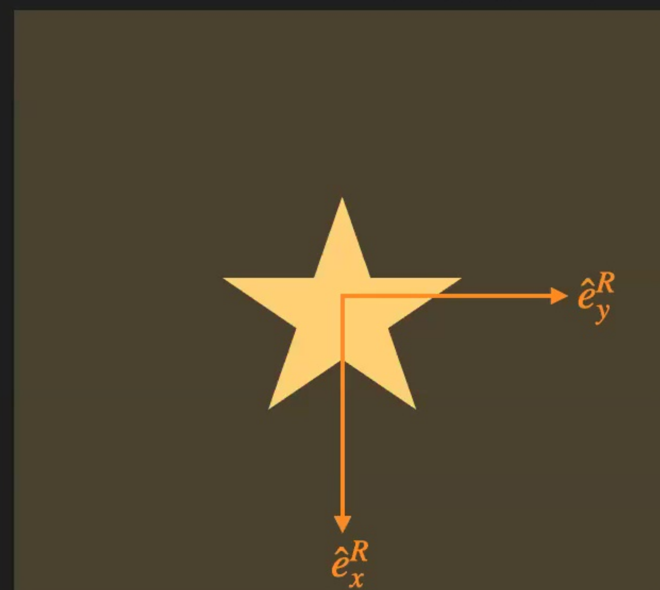


Detector Frame

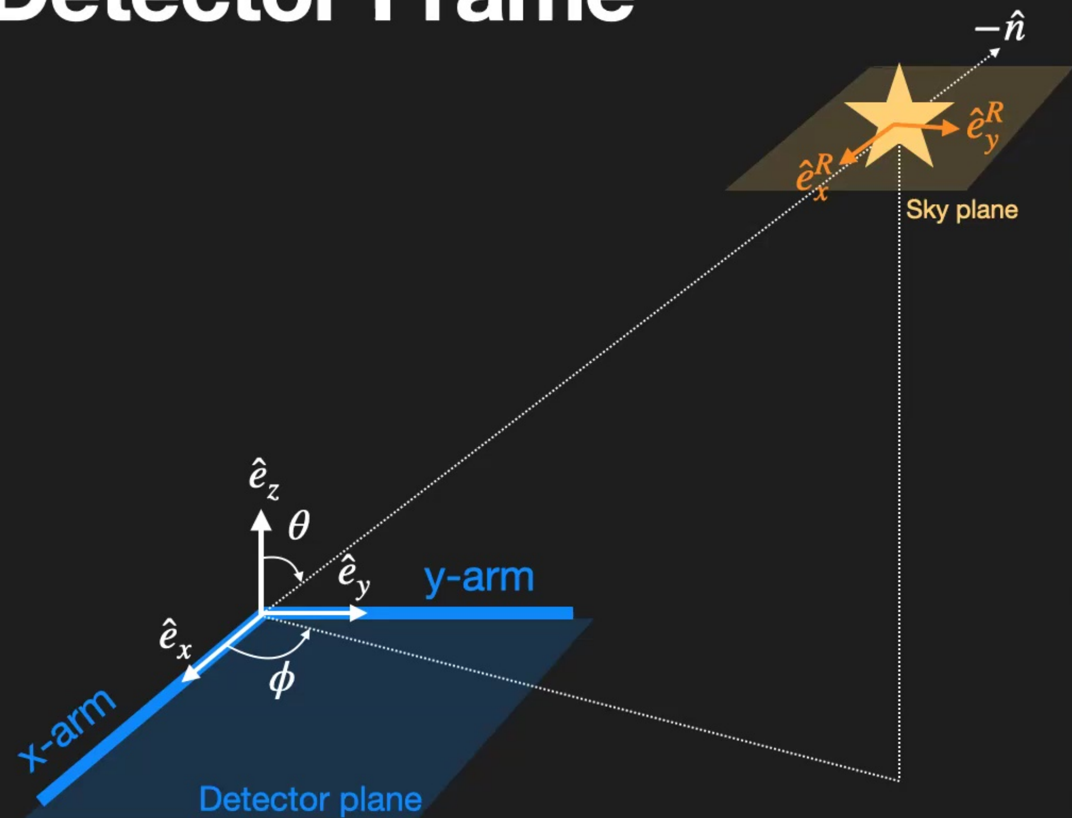


Along the direction
of GW propagation

$-\hat{n}$ out of the screen



Detector Frame



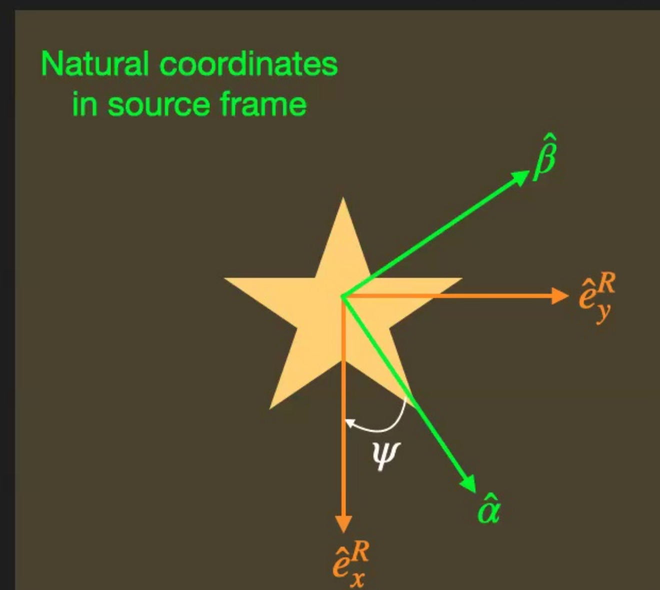
Along the direction
of GW propagation

θ Co-

ϕ Azi

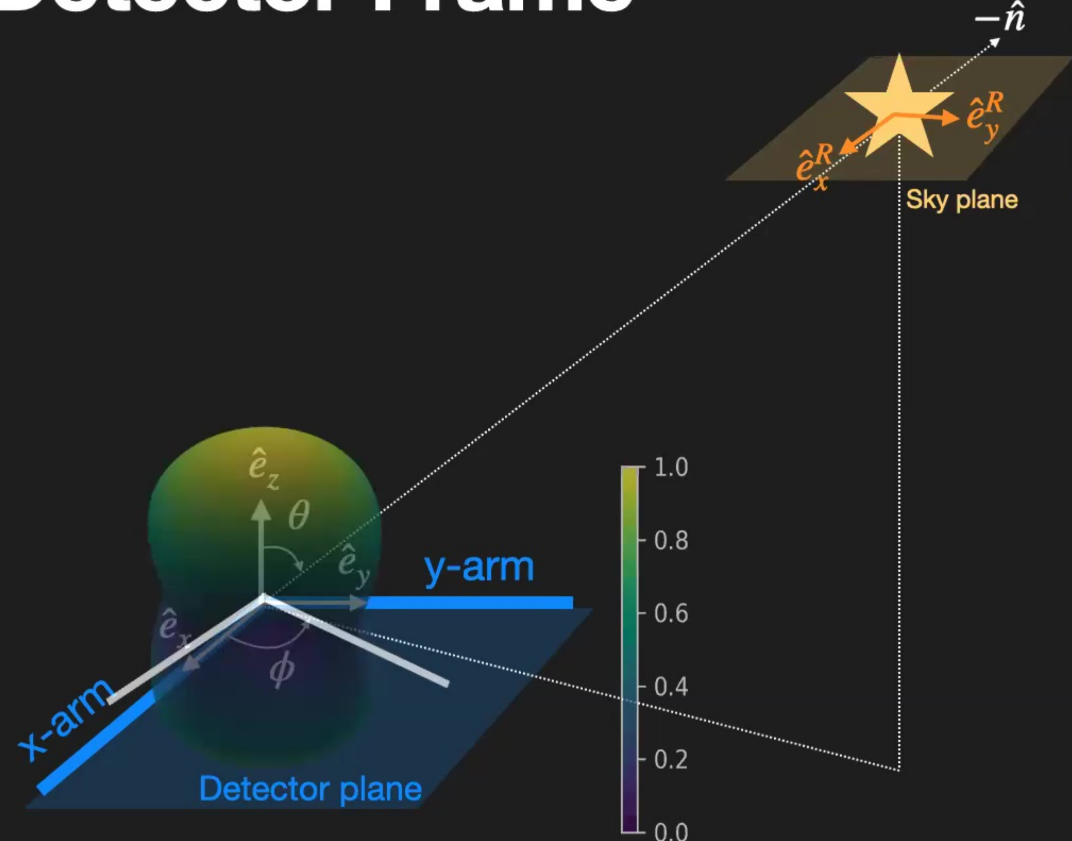
ψ Polarisation angle

$-\hat{n}$ out of the screen



Detector Frame

Along the direction
of GW propagation



θ Co-

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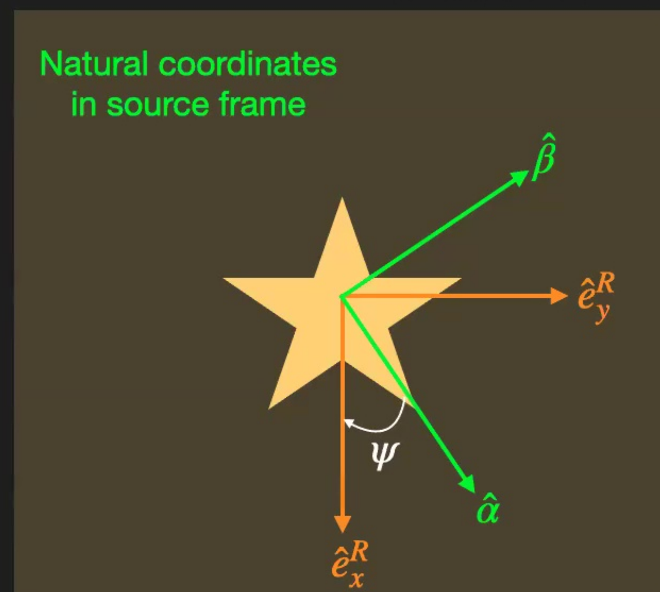


Celestial frame

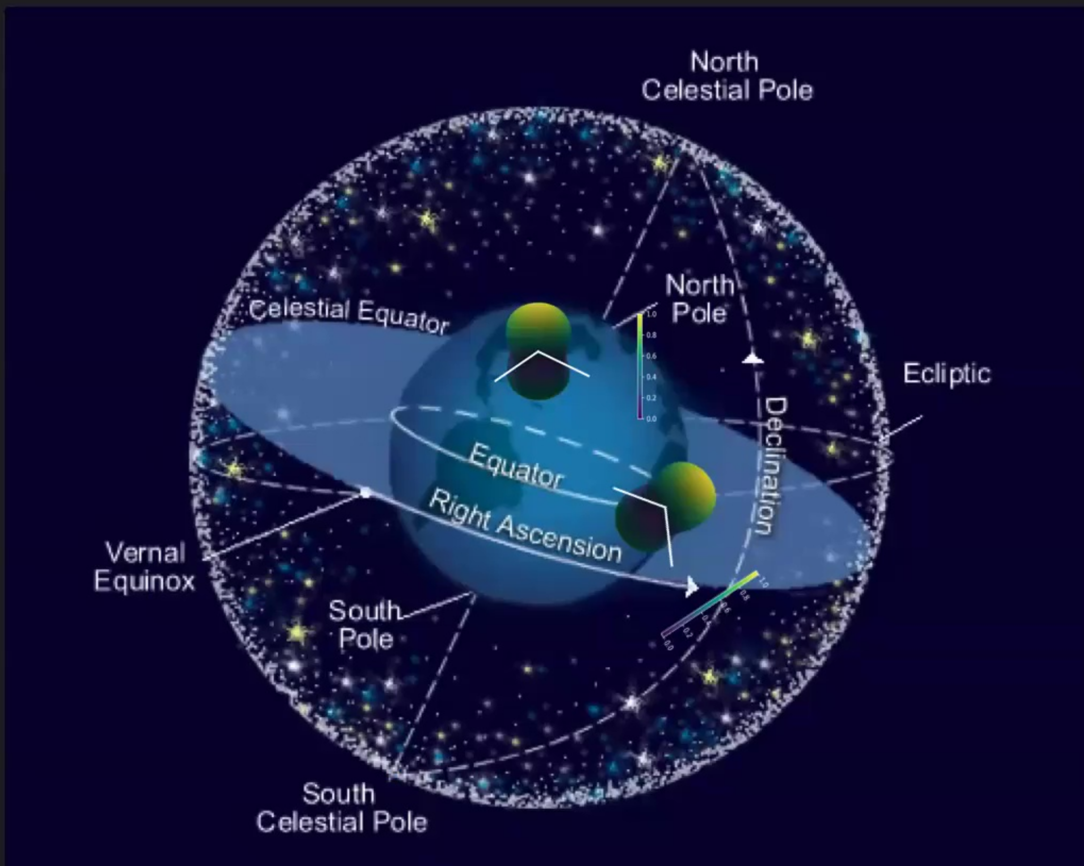
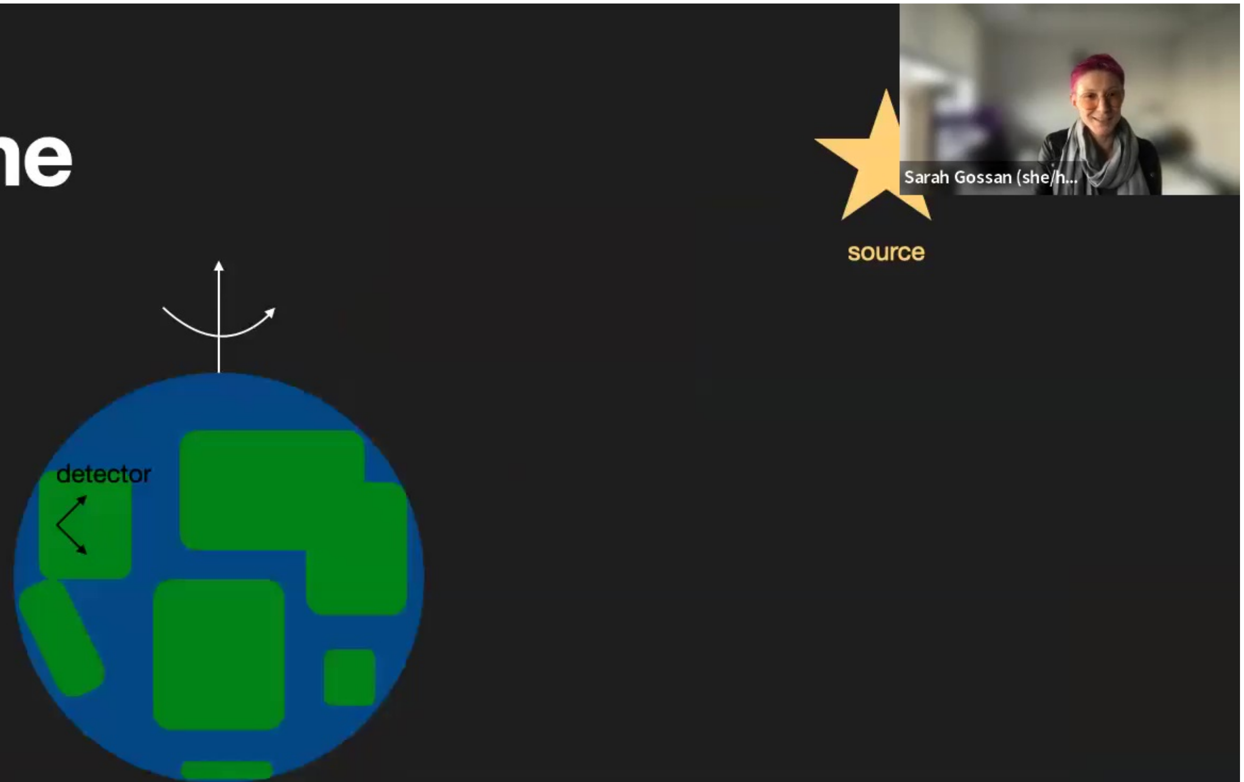


Image underlay credit: Lunar and Planetary Institute

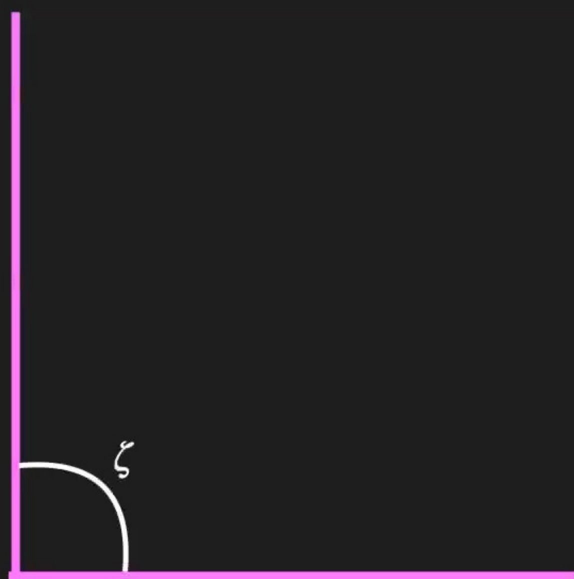
Right ascension $\alpha = \phi - \mathrm{GMST}(t)$

Declination $\delta = \pi/2 - \theta$

Earth-Fixed Frame



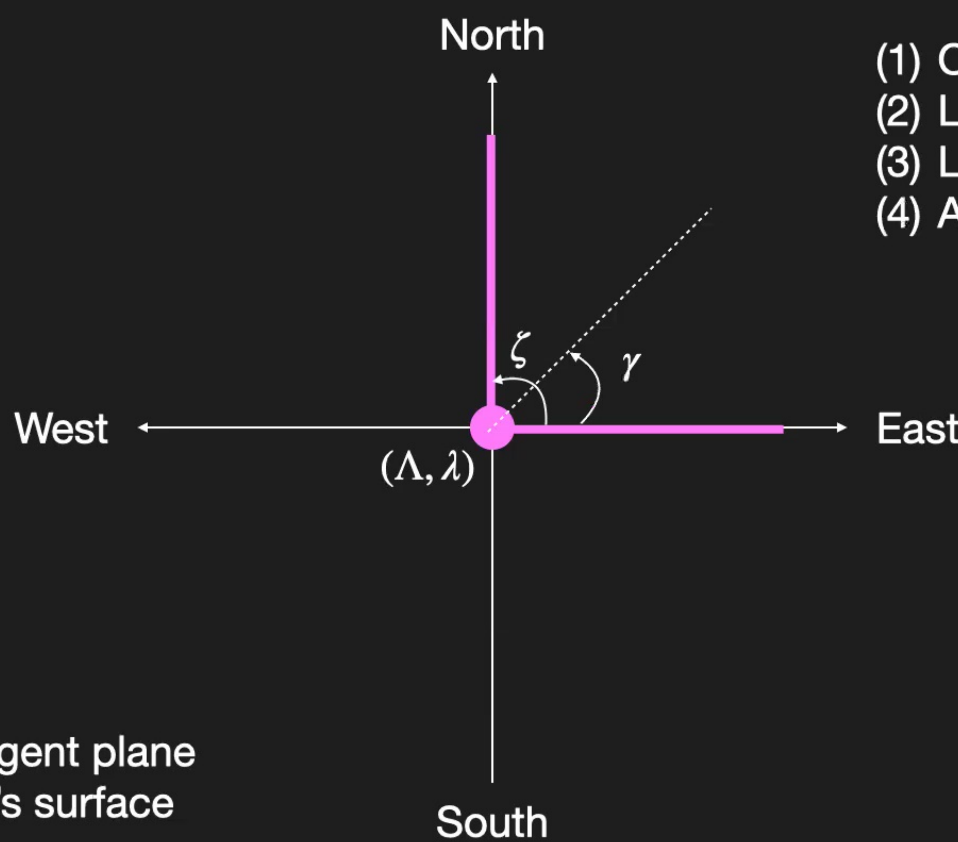
Characterising detector geometry



(1) Opening angle ζ

Characterising detector geometry

(1) Opening angle ζ
(2) Latitude of detector vertex Λ
(3) Longitude of detector vertex λ
(4) Arm bisector angle γ

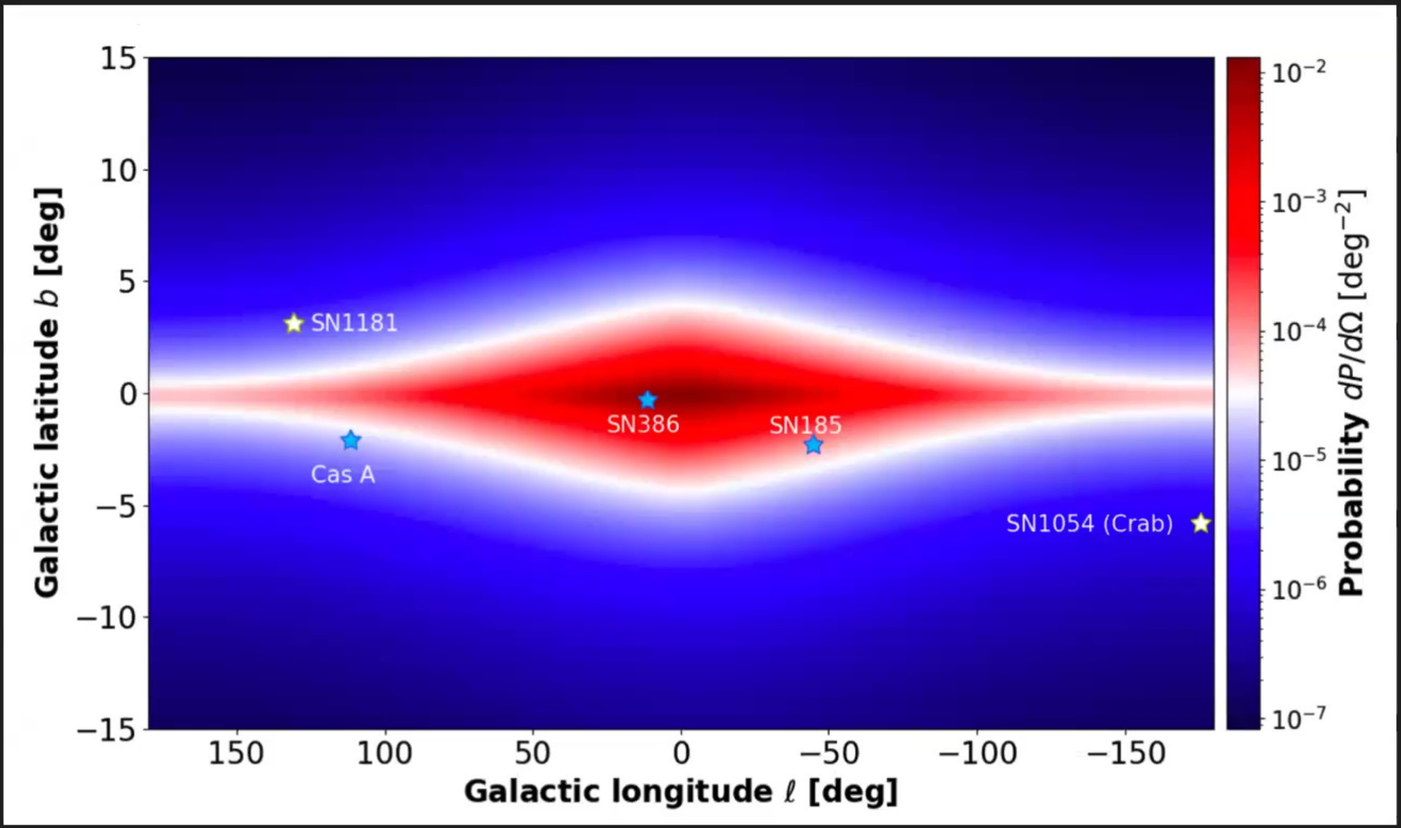


Local tangent plane
to Earth's surface

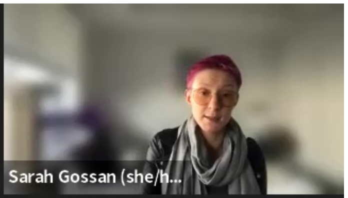
Detector-Source Geometry in Earth-Fixed

- Can compute polarisation-averaged antenna power at time t for any detector using
    - Detector placement: $(\zeta, \Lambda, \lambda, \gamma)$
    - Source position: (α, δ)
- For Galactic sources, how does this vary with detector placement?

Galactic distribution of sources



Adams *et al.* (2013), Murphey *et al.* (2021)



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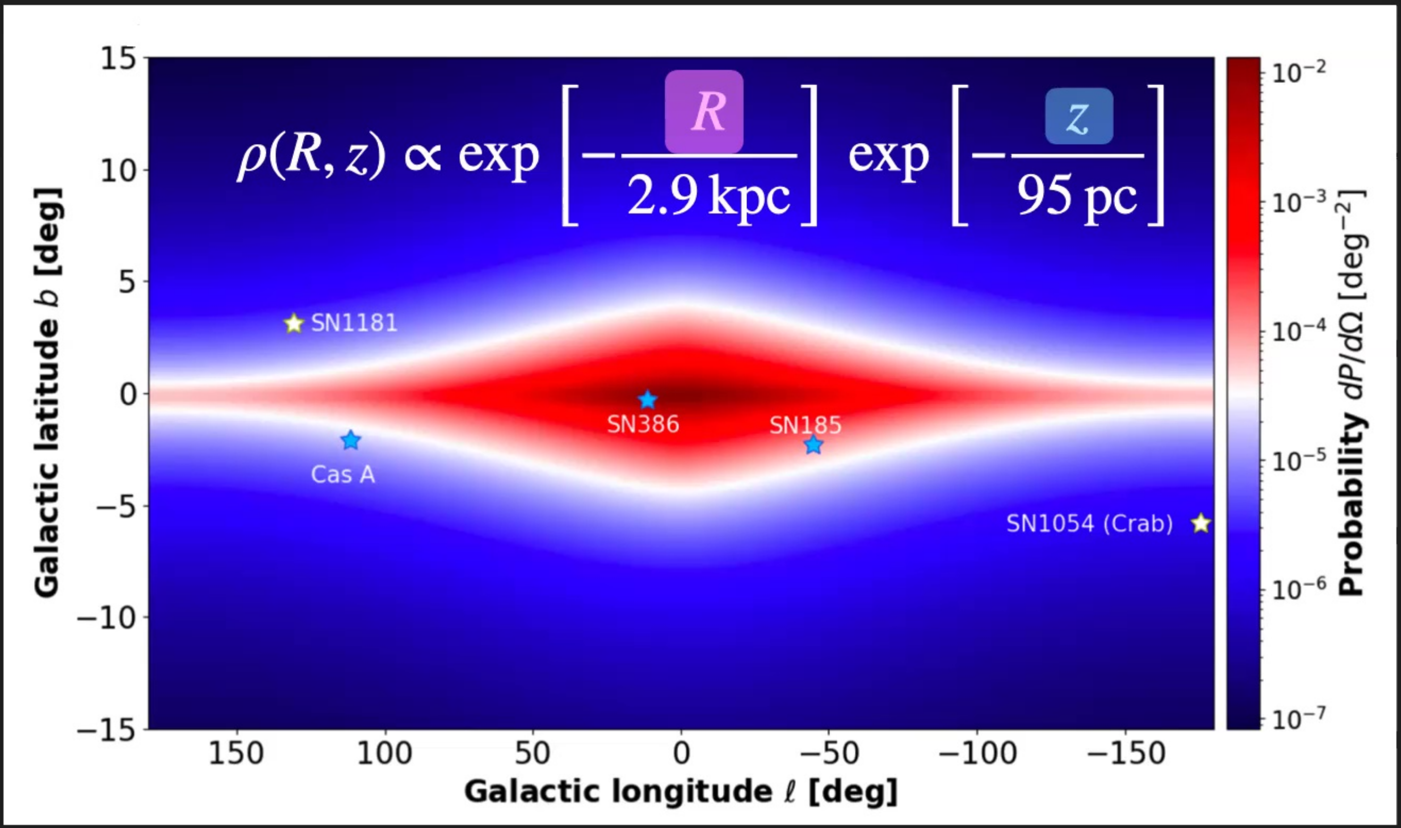

R: Distance from Galactic centre [kpc]

z: Distance above Galactic plane [pc]

Adams *et al.* (2013), Murphey *et al.* (2021)

Detector-Source Geometry in Earth-Fixed

- Can compute polarisation-averaged antenna power at time t for any detector using
    - Detector placement: $(\zeta, \Lambda, \lambda, \gamma)$
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- For Galactic sources, how does this vary with detector placement?
    - Galactic centre
    - Averaged over the Milky Way

Detector-Source Geometry in Earth-Fixed

- Can compute polarisation-averaged antenna power at time t for any detector using
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    - Source position: (α, δ)
- For Galactic sources, how does this vary with detector placement?
    - Galactic centre
    - Averaged over the Milky Way
- Figure of merit?

A new figure of merit

Normalised, polarisation-averaged antenna power

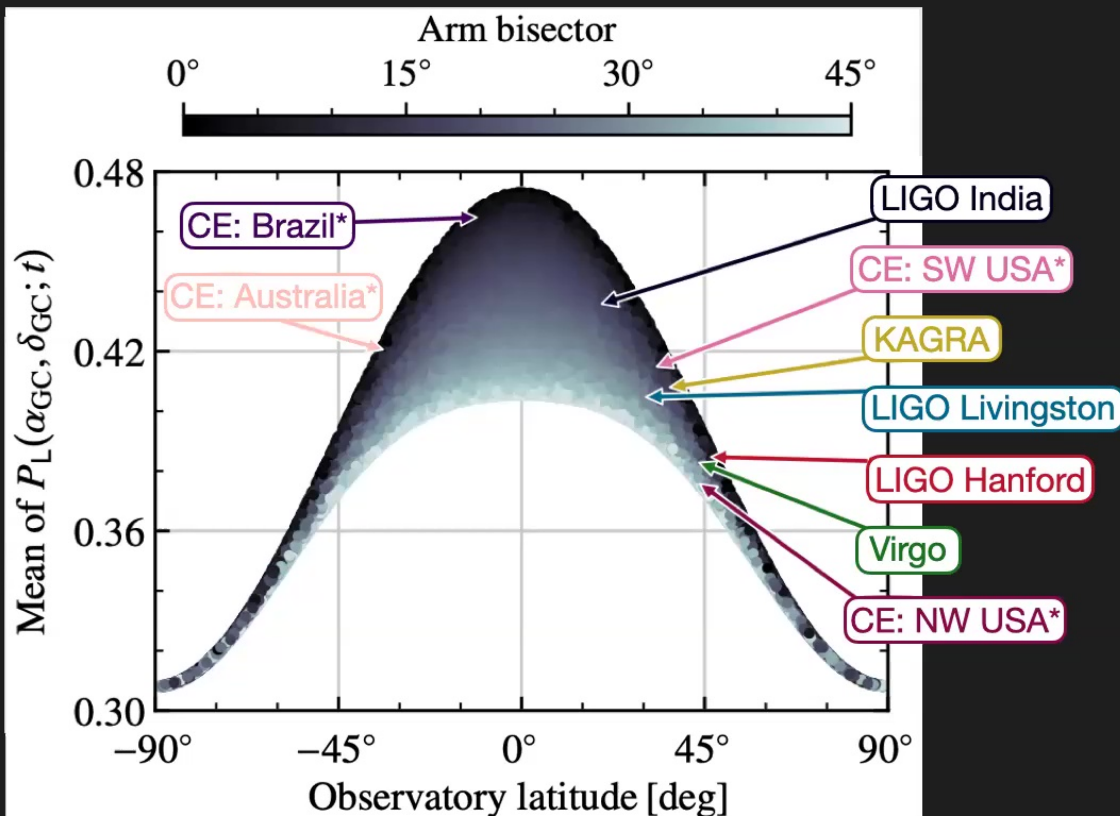
$P_{\mathrm{L}}(\alpha_{\mathrm{GC}}, \delta_{\mathrm{GC}}; t)$ —Antenna power for source at Galactic centre for a given L-shaped detector as a function of time

$\langle P_{\mathrm{L}}(t) \rangle_{\mathrm{MW}}$ — Antenna power averaged over a population of sources distributed across the Milky Way for a given L-shaped detector as a function of time

$P_{\triangle}(\alpha_{\mathrm{GC}}, \delta_{\mathrm{GC}}; t)$ — Antenna power for source at the Galactic centre for a given triangle-shaped detector as a function of time

$\langle P_{\triangle}(t) \rangle_{\mathrm{MW}}$ — Antenna power averaged over a population of sources distributed across the Milky Way for a given triangle-shaped detector as a function of time

Optimal single detector placement: CE



Gossan+2021, arXiv:2110.15322

30,000 randomly distributed observatories

Fixed

Type of detector: L-shaped, CE-like

Source position: Galactic centre

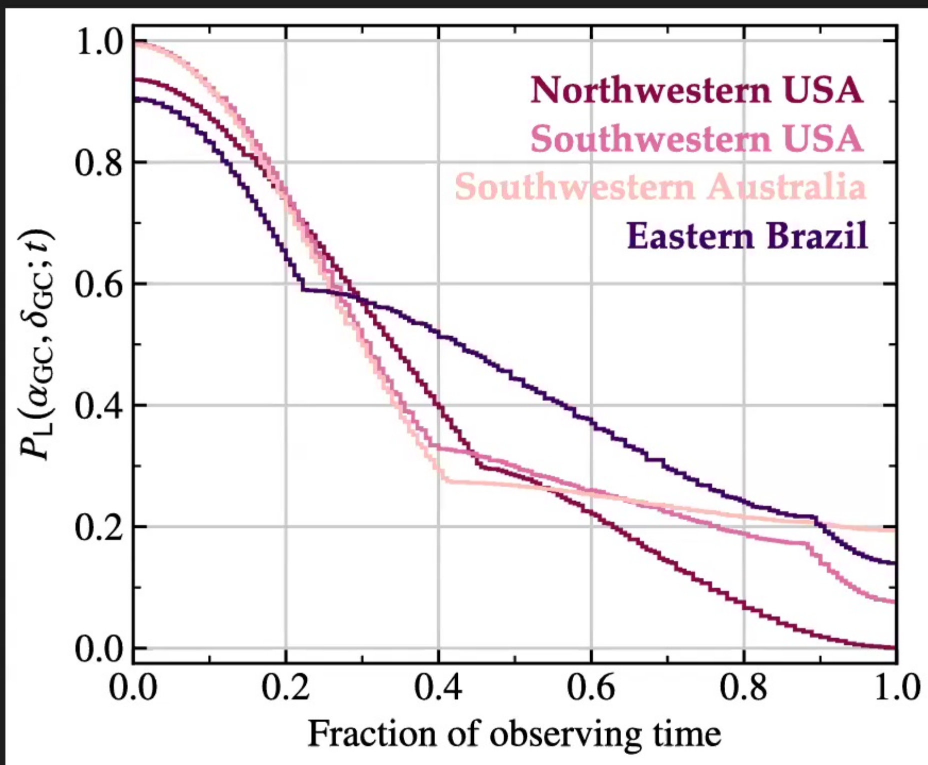
Varied

Detector placement:

- Latitude of detector vertex
- Longitude of detector vertex
- Angle of detector arms bisector

Time: Average taken over one sidereal day

Optimal single detector placement: CE



Gossan+2021, arXiv:2110.15322

Fixed

Type of detector: L-shaped, CE-like

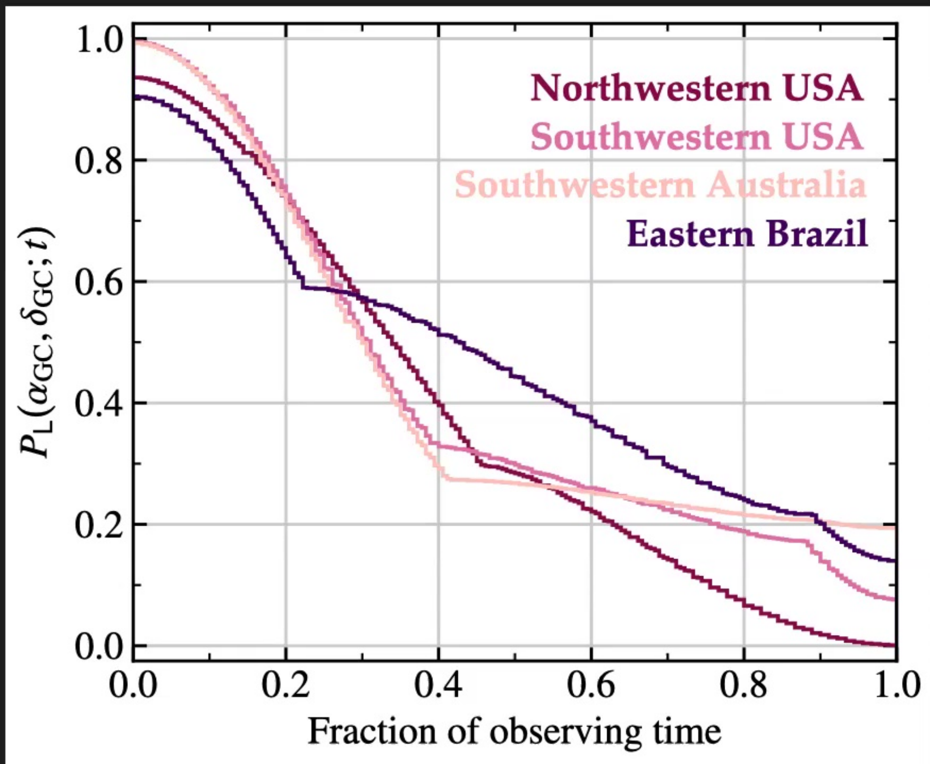
Source position: Galactic centre

Varied

Detector placement:
Four proposed site locations and orientations

Time:
Cumulative power over the sidereal day

Optimal single detector placement: CE



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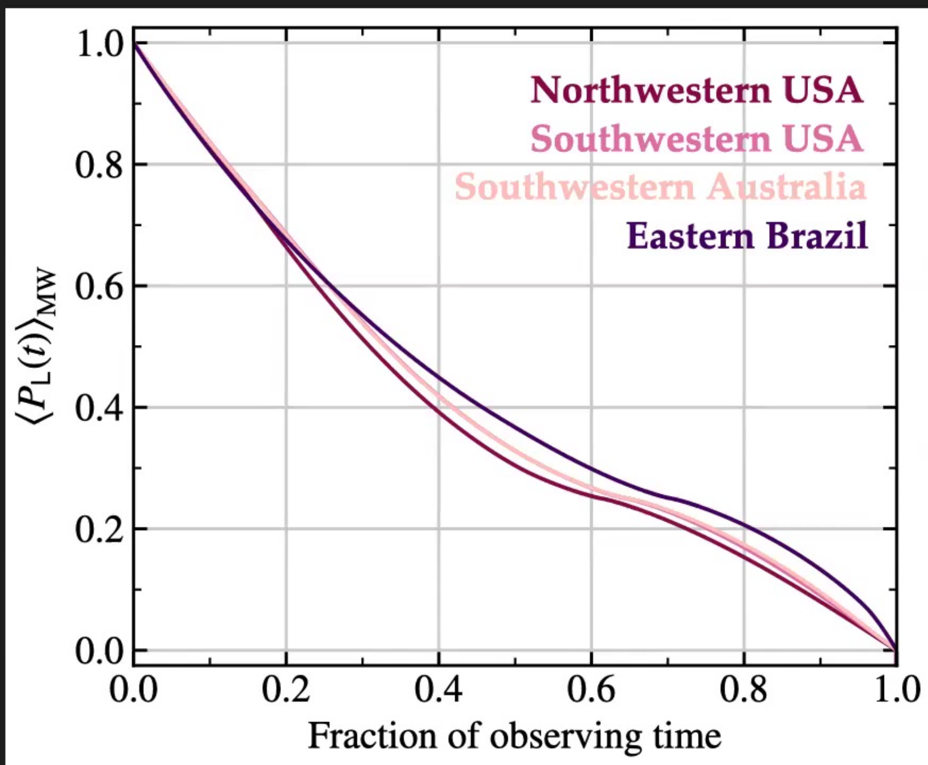


Gossan+2021, arXiv:2110.15322

Fixed

Type of detector: L-shaped, CE-like

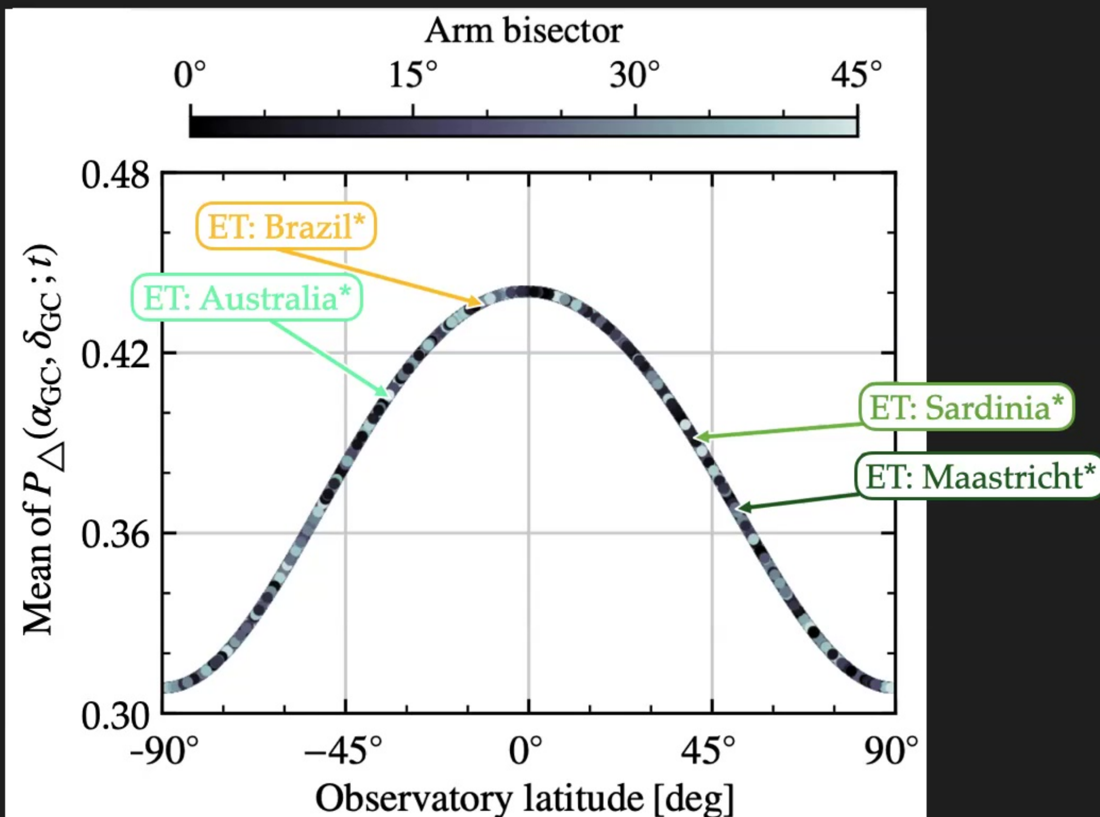
Varied

Detector placement:
Four proposed site locations and orientations

Source position:
Average over Galactic distribution

Time:
Cumulative power over the sidereal day

Optimal single detector placement: ET



Gossan+2021, arXiv:2110.15322

30,000 randomly distributed observatories

Fixed

Type of detector: △-shaped, ET-like

Source position: Galactic centre

Varied

Detector placement:

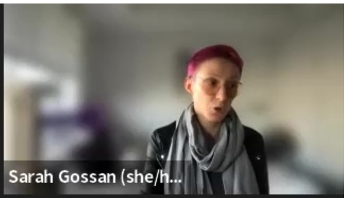
Latitude of detector vertex

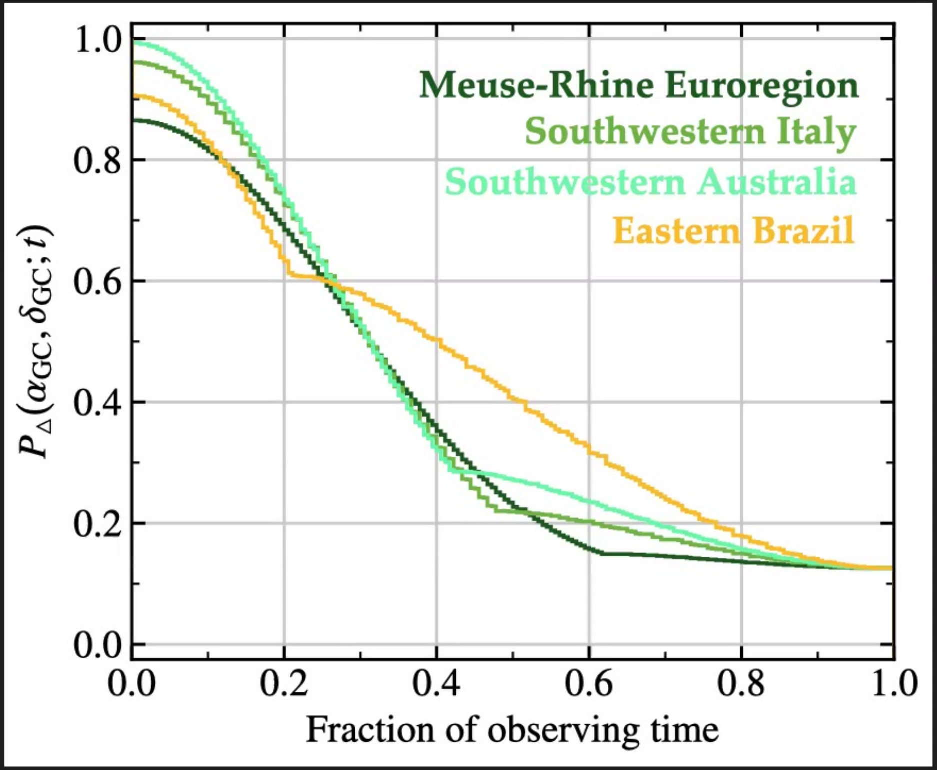
Longitude of detector vertex

Angle of detector arms bisector

Time: Average taken over one sidereal day

Optimal single detector placement: ET





Gossan+2021, arXiv:2110.15322

Fixed

Type of detector: △-shaped, ET-like

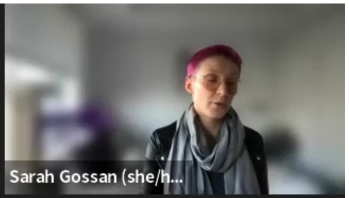
Varied

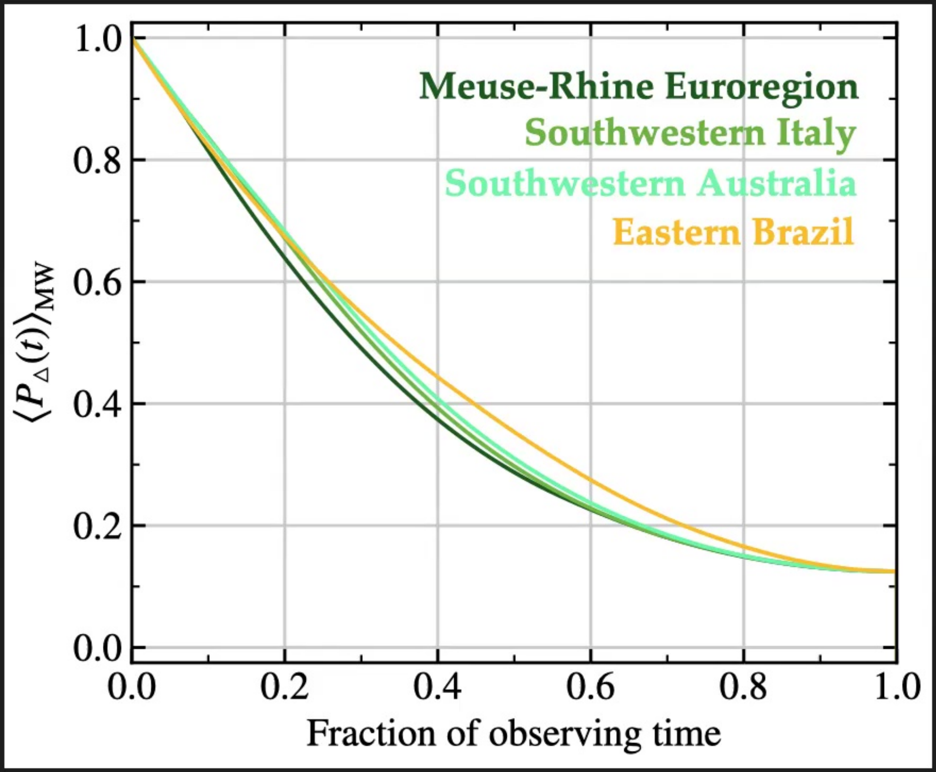
Detector placement:
Four proposed site locations and orientations

Source position:
Average over Galactic distribution

Time:
Cumulative power over the sidereal day

Optimal single detector placement: ET





Gossan+2021, arXiv:2110.15322

Fixed

Type of detector: △-shaped, ET-like

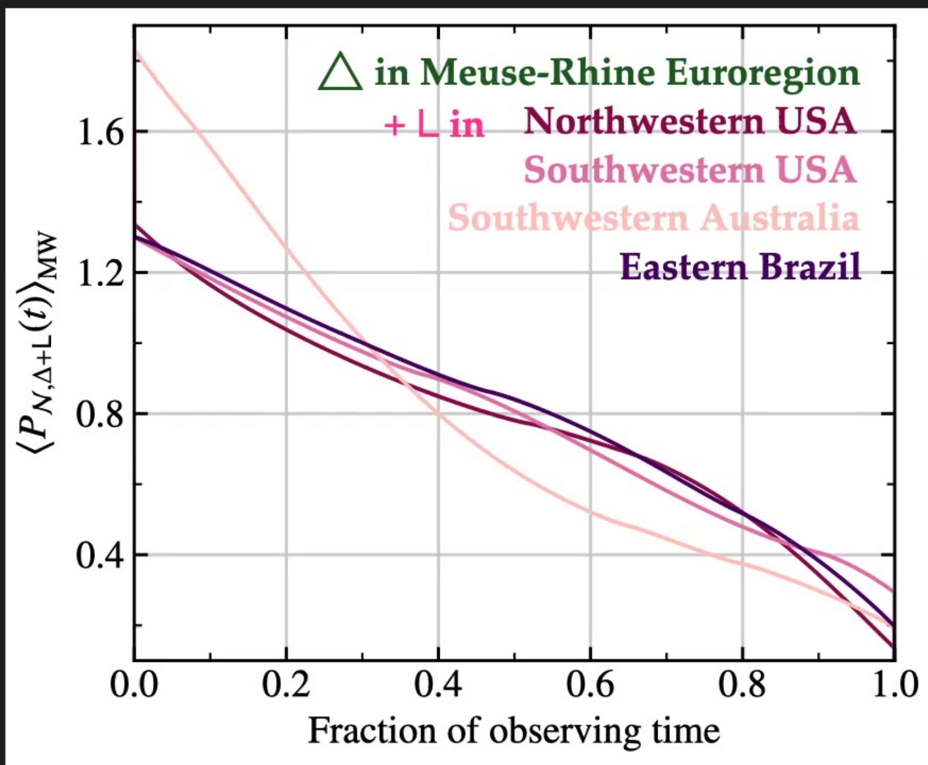
Varied

Detector placement:
Four proposed site locations and orientations

Source position:
Average over Galactic distribution

Time:
Cumulative power over the sidereal day

Optimal two detector placement: ET +



Gossan+2021, arXiv:2110.15322

Fixed

Type of detector:

One △-shaped, ET-like in Maastricht

One L-shaped, CE-like

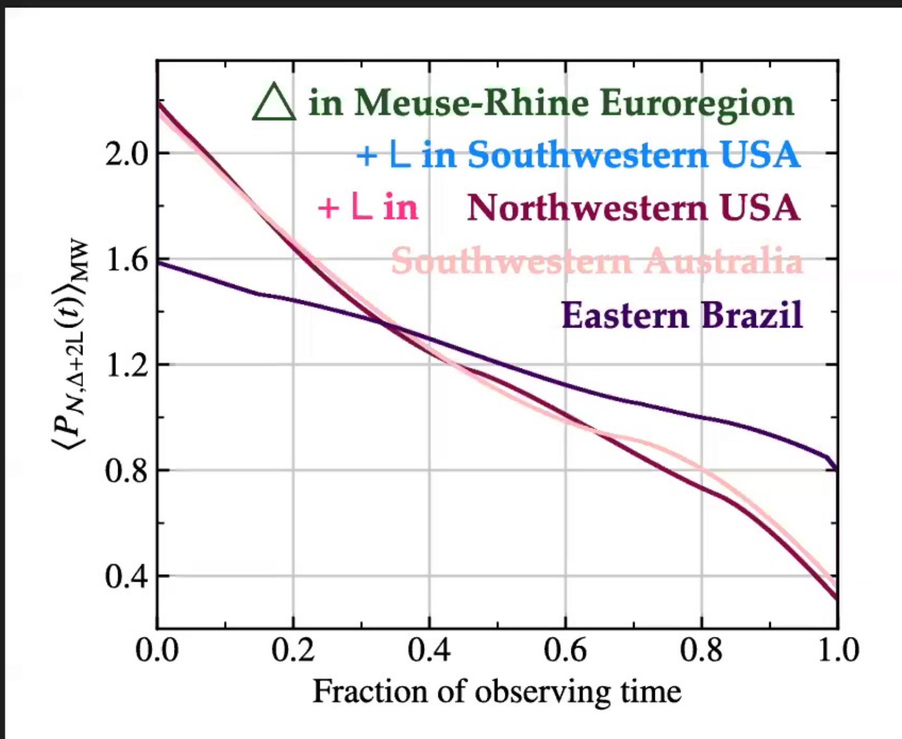
Varied

Detector placement:
Four proposed site locations and orientations for L-shaped detector

Source position:
Averaged over Galactic distribution

Time:
Cumulative power over the sidereal day

Optimal three detector placement: ET -



Gossan+2021, arXiv:2110.15322

Fixed

Type of detector:

One △-shaped, ET-like in Maastricht

Two L-shaped, CE-like - one in SW USA

Varied

Detector placement:

Three proposed site locations and orientations for L-shaped detector

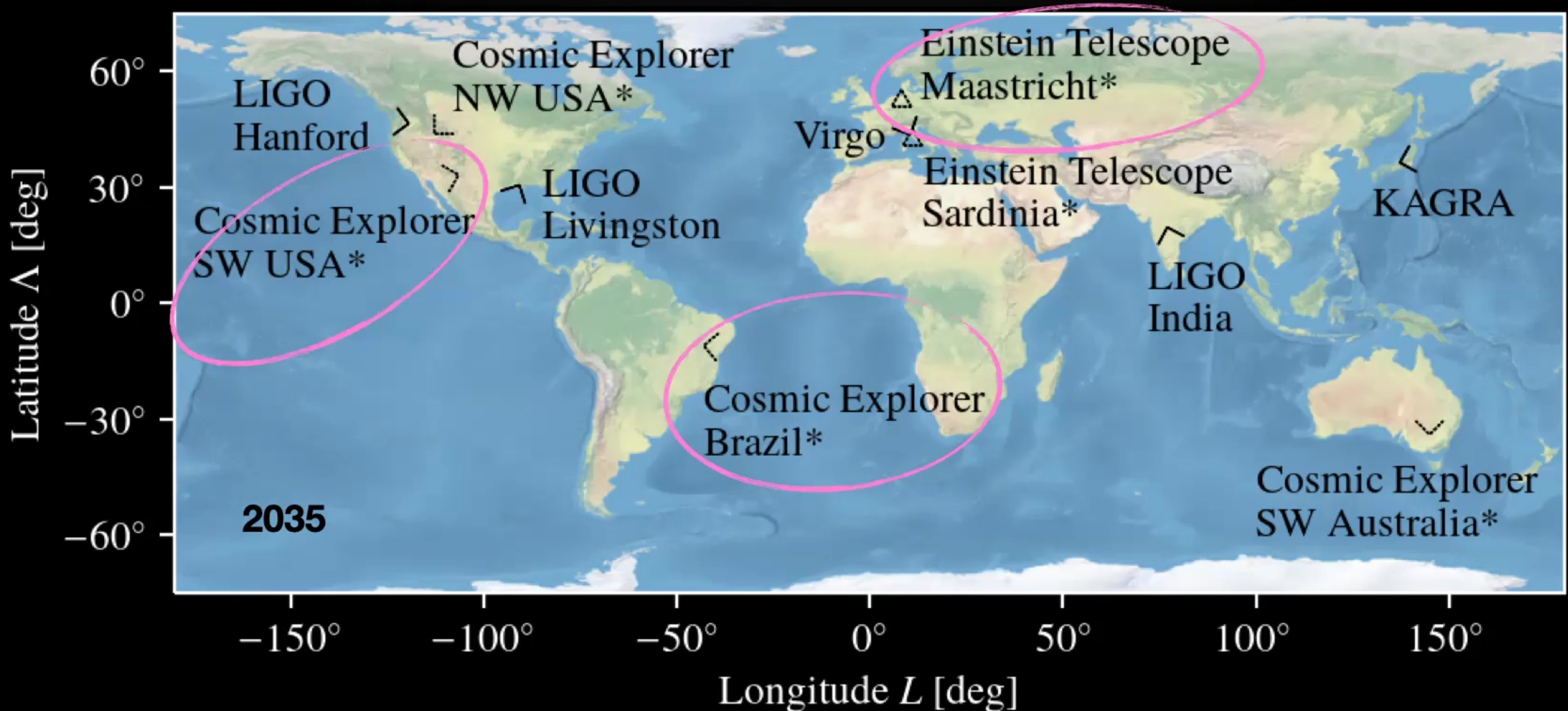
Source position:

Average over Galactic distribution

Time:

Cumulative power over the sidereal day

Our dream network for Galactic Scienc



Why haven't we detected Galactic GWs

1. Weaker gravitational wave emission than compact binaries

   Can we build new, more sensitive detectors?

   Sure, but $$$$$$$$$$

2. Sources not isotropically distributed across the sky

   Can we place detectors to be more sensitive to the Milky Way?

   Yes! Place equatorially for up to 50% more antenna power

Observed SNR

(1) Signal strength

(2) Detector sensitivity

(a) Noise floor

(b) Antenna power

(3) Ability to recover signal from noise

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3. Waveform morphology poorly modelled

Observed SNR

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(2) Detector sensitivity

- (a) Noise floor
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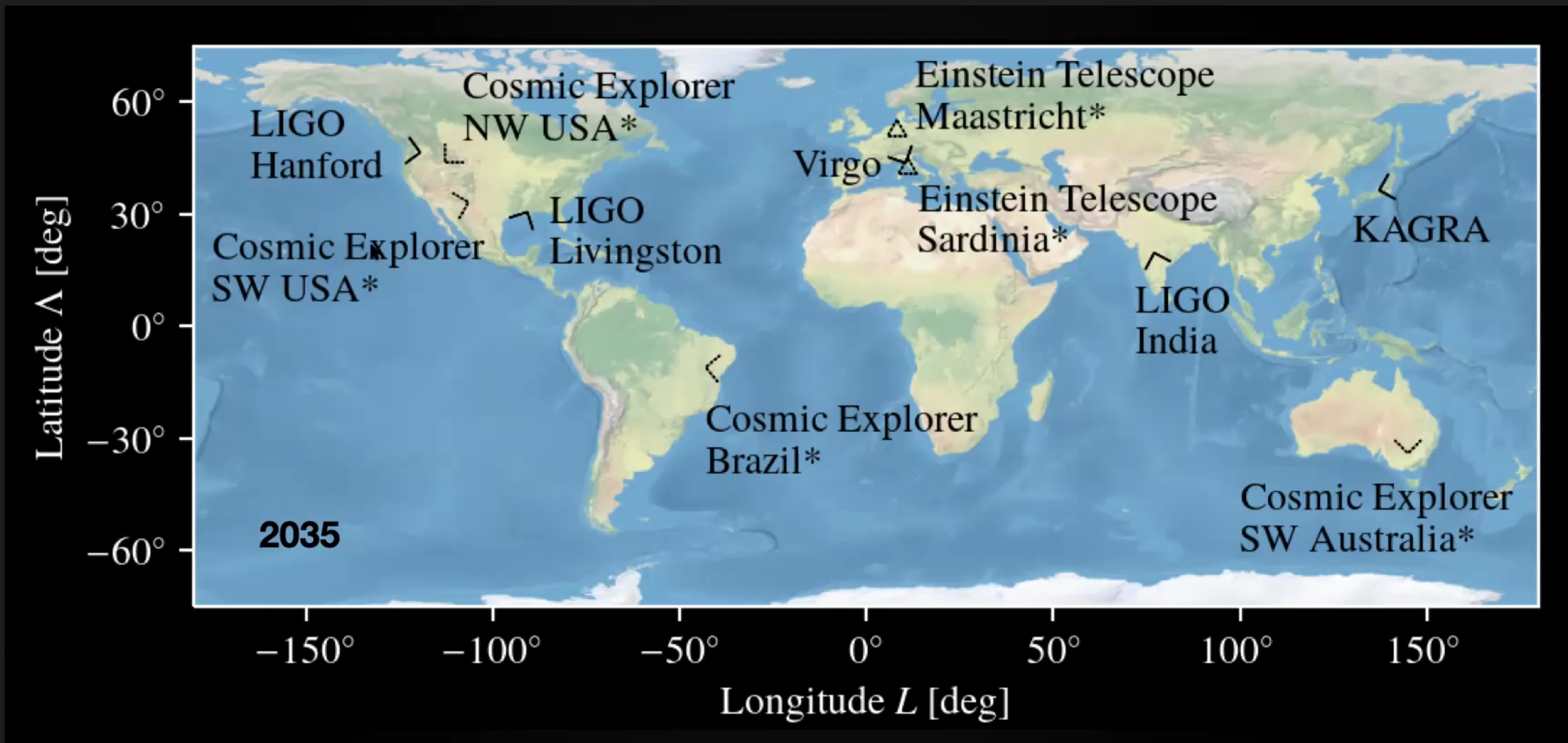
(3) Ability to recover signal from noise

Our dream network for Galactic Scienc



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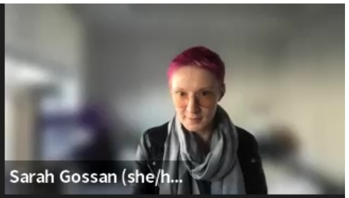

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3. Waveform morphology poorly modelled

   Can we improve signal recovery using source properties?

Observed SNR

(1) Signal strength

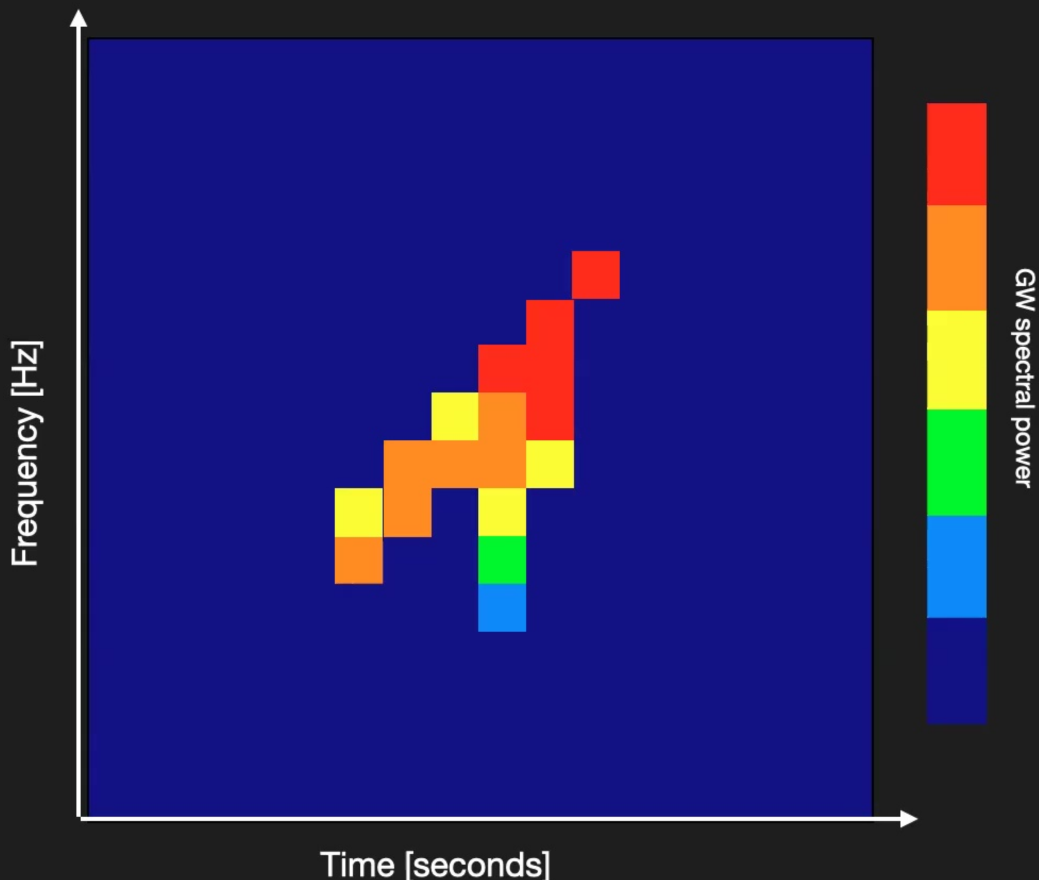
(2) Detector sensitivity

(a) Noise floor

(b) Antenna power

(3) Ability to recover signal from noise

Gravitational wave detection — excess-



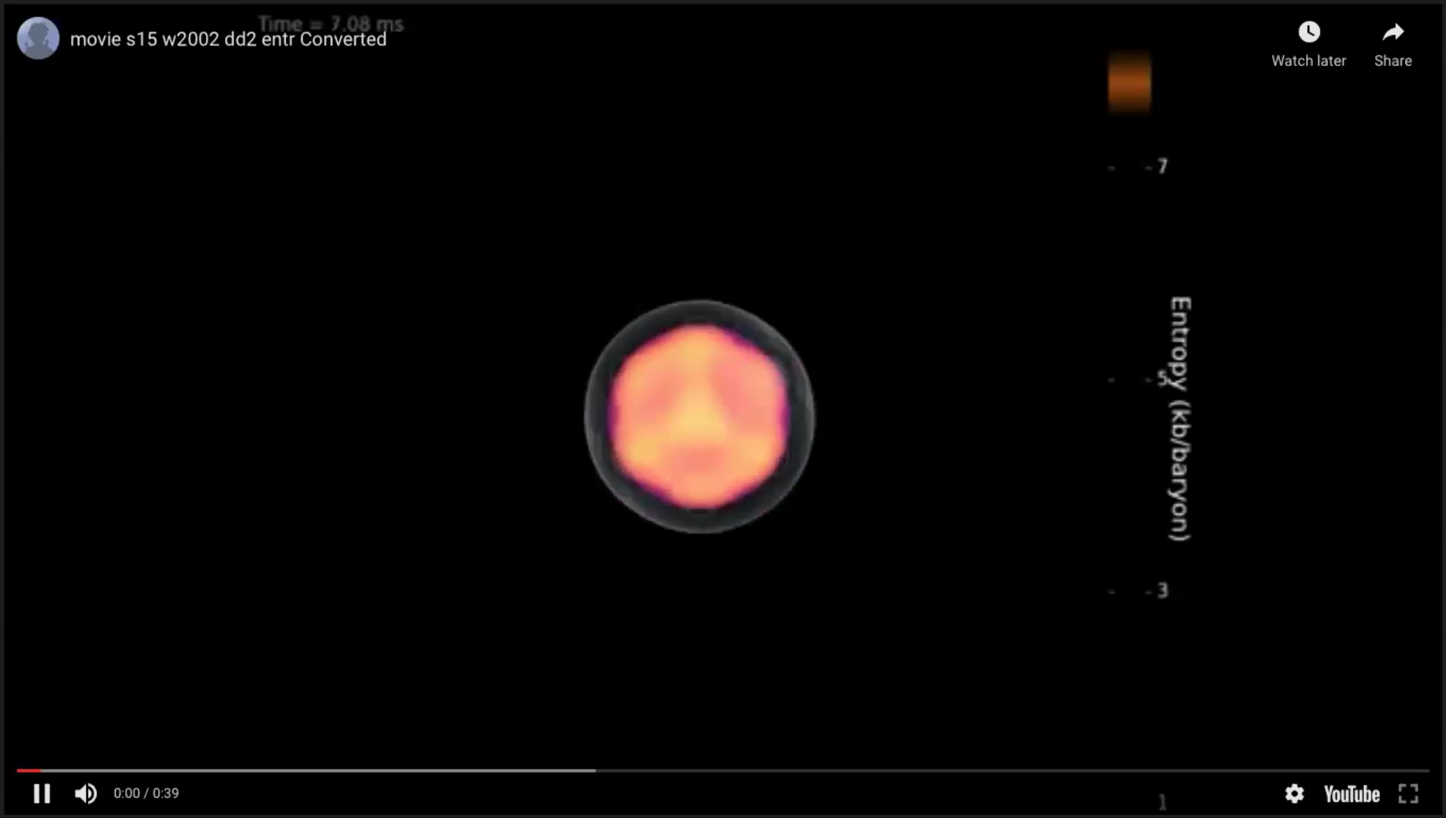
Assumptions:
(1) Limited only to the time and frequency band of the search area

Pros:
(1) Very little knowledge of signal morphology required

(2) Uses set of basis functions (e.g. sine-Gaussians) look for excess power in time-frequency space

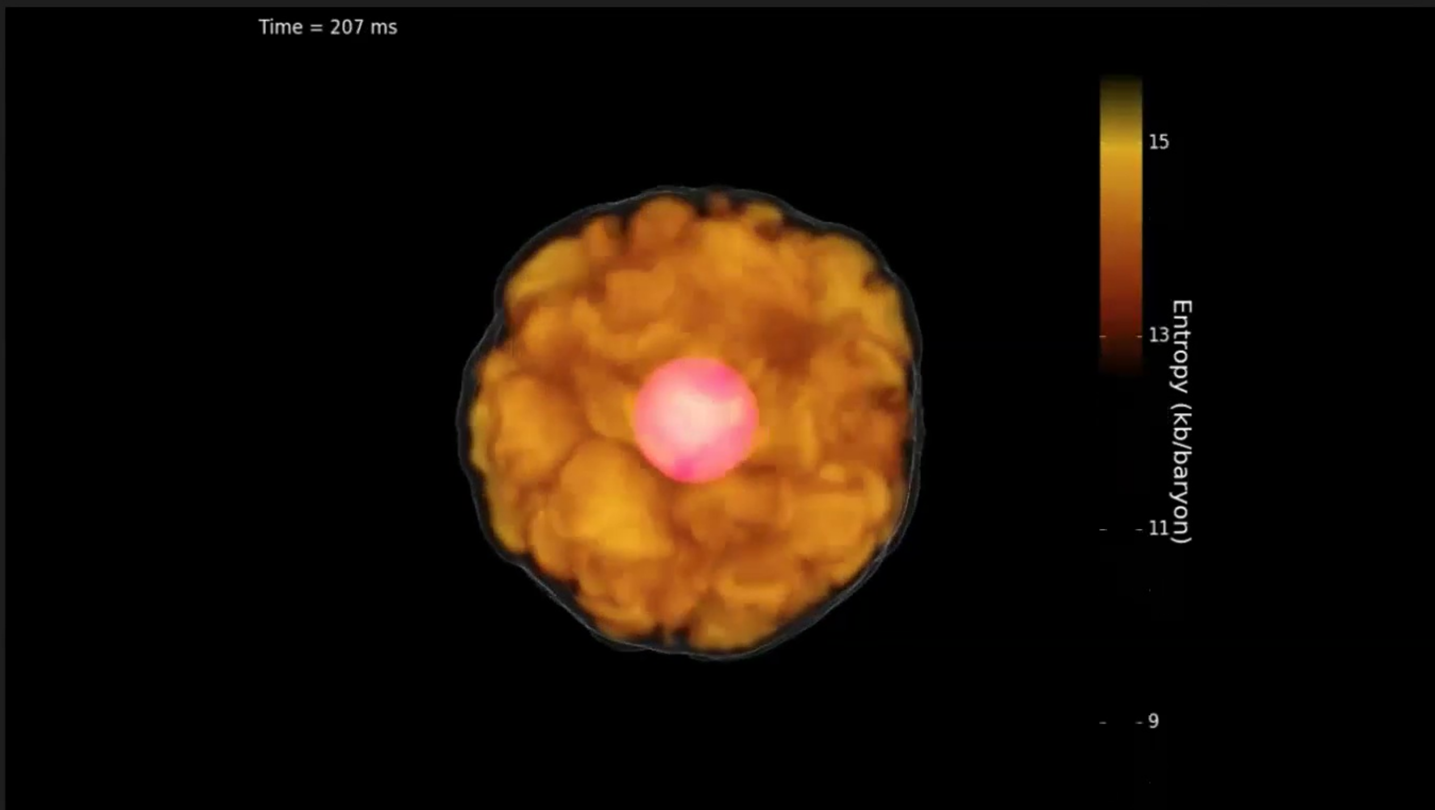
Cons:
Far less sensitive than matched-filter search

Case study: Core-collapse supernovae



Credit:
Kuo-Chuan Pan

Case study: Core-collapse supernovae



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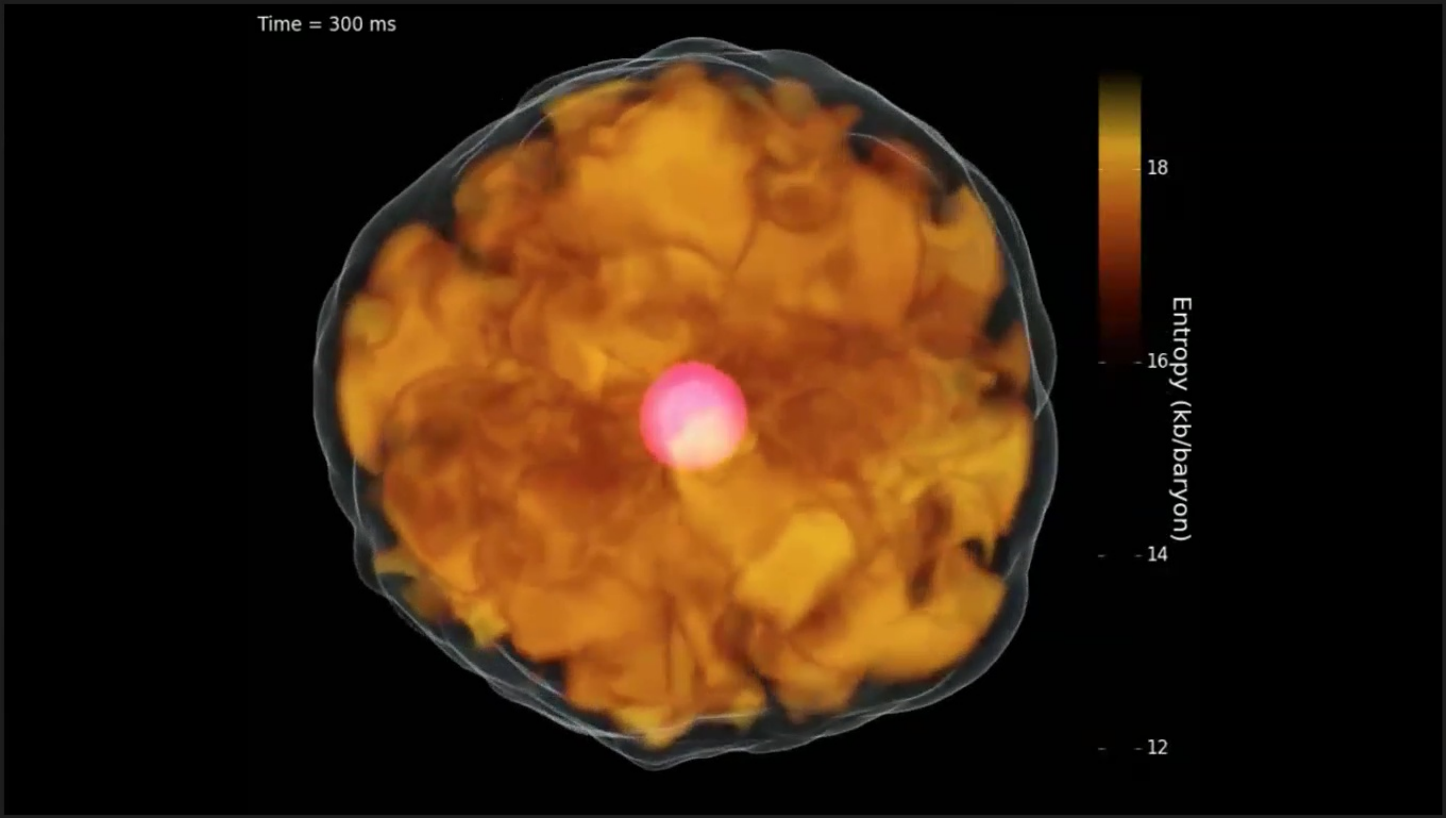

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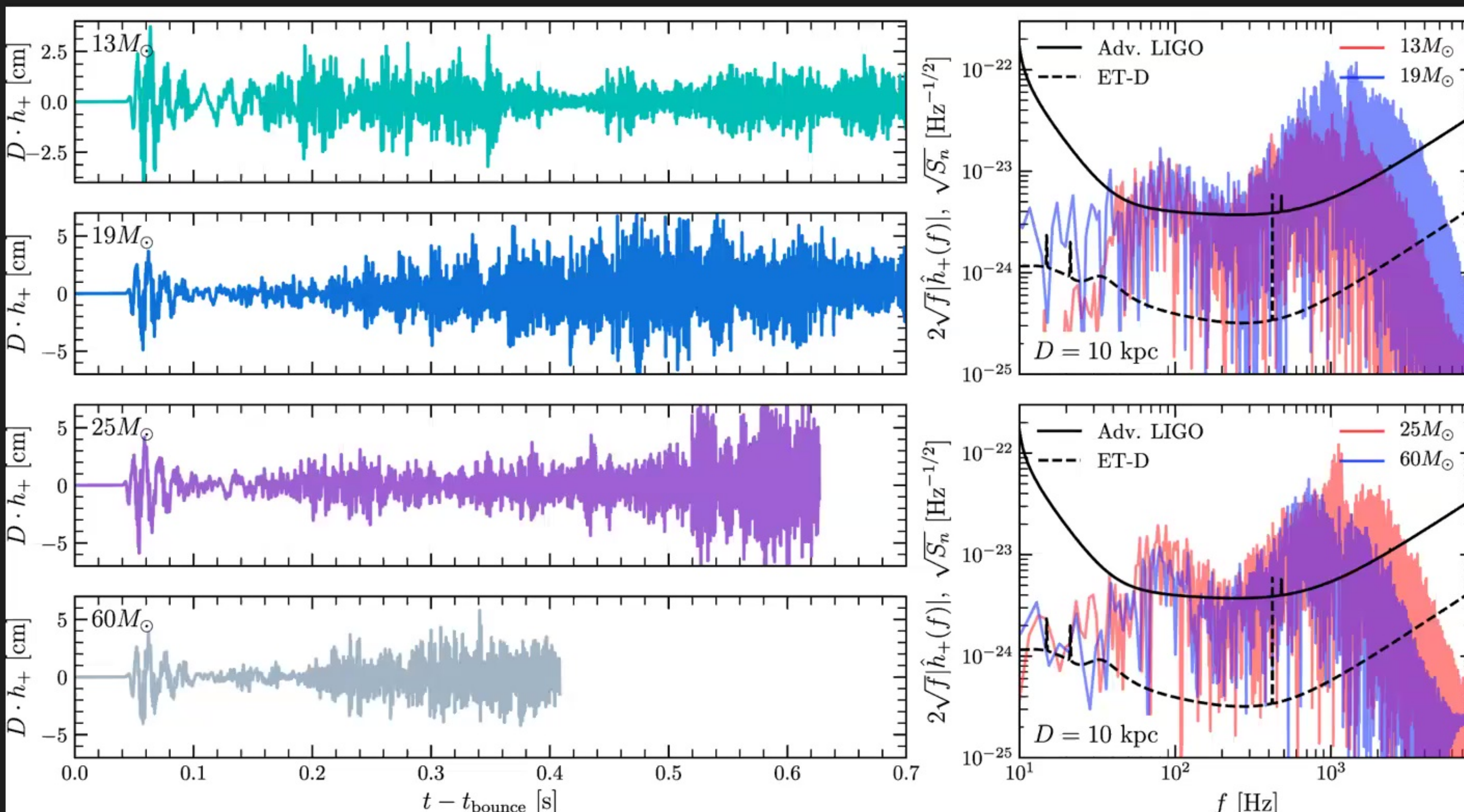


Image credit: Radice *et al.* (2019)

Case study: Core-collapse supernovae

Per **Gossan *et al.*** **(2016), arXiv:1511.02836**

Three-detector network at design sensitivity
(LIGO Hanford, LIGO Livingston, Advanced Virgo)

Distance where 90% of injected signals are recovered,
false alarm probability of 0.1%:

Garden-variety supernovae: ~1-4 kpc

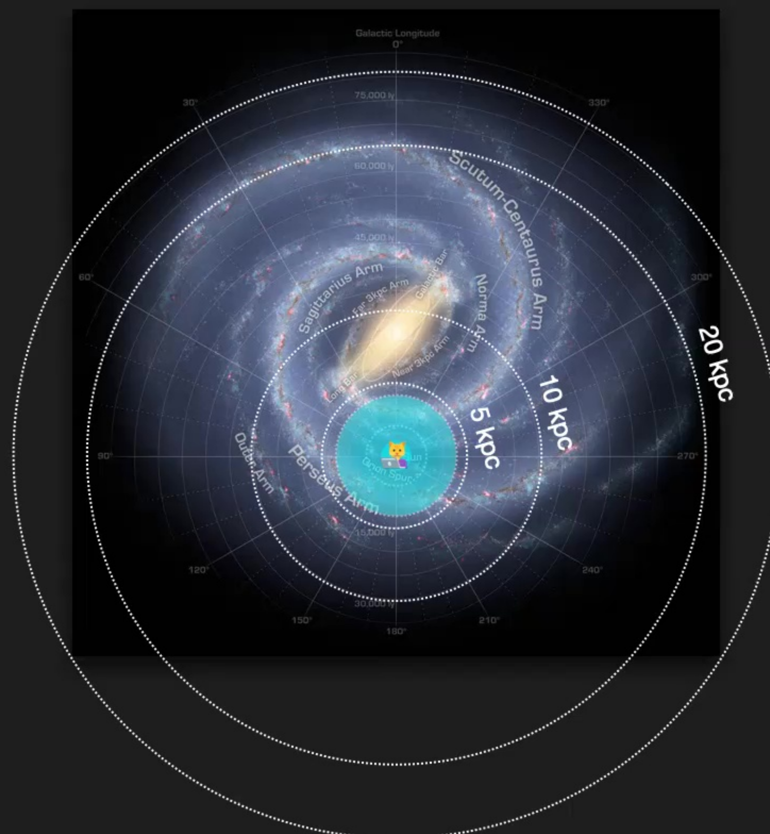
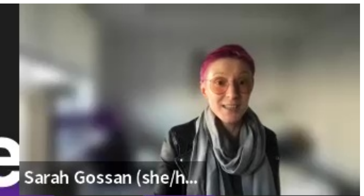


Image underlay credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Case study: Core-collapse supernovae



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Rapidly rotating progenitor (<1% of CCSNe): ~ 5-45 kpc

Order of magnitude LESS than matched-filter
SNR estimates……

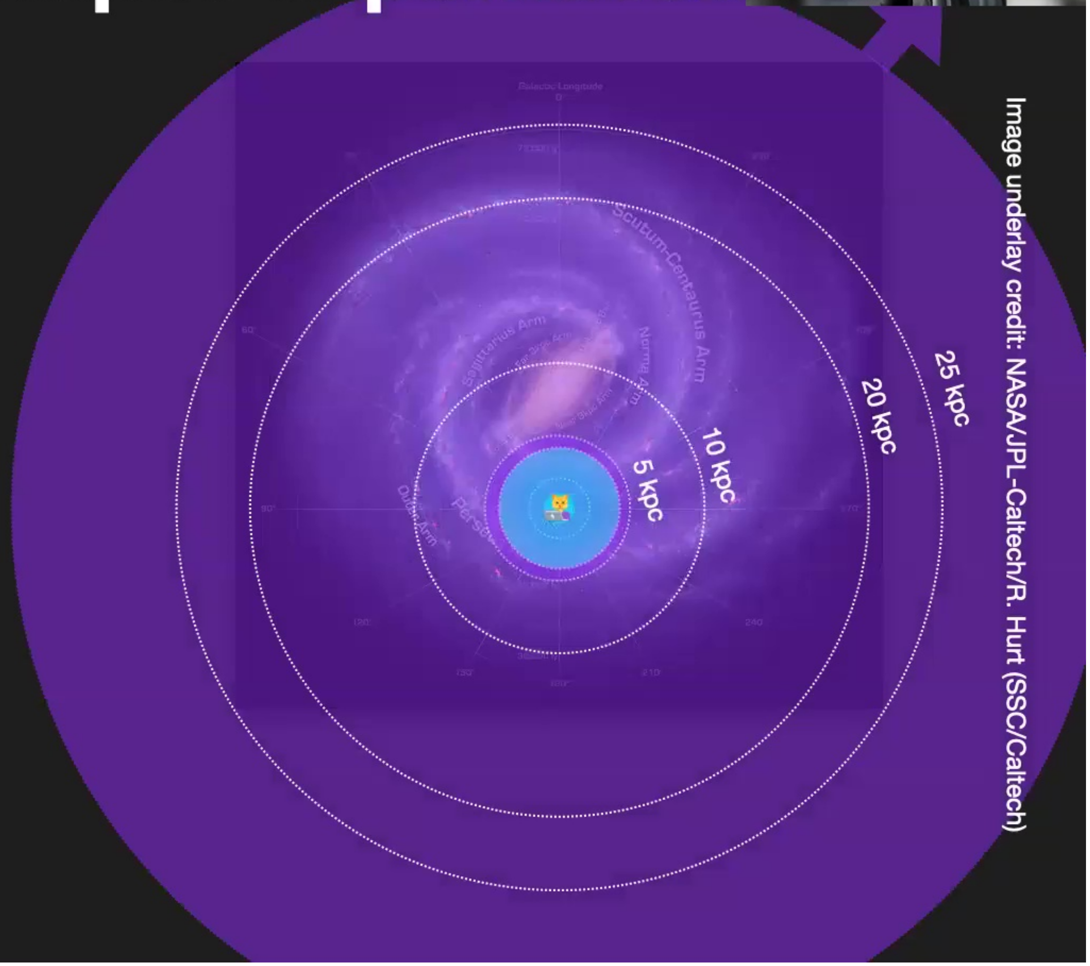


Image underlay credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Case study: Core-collapse supernovae

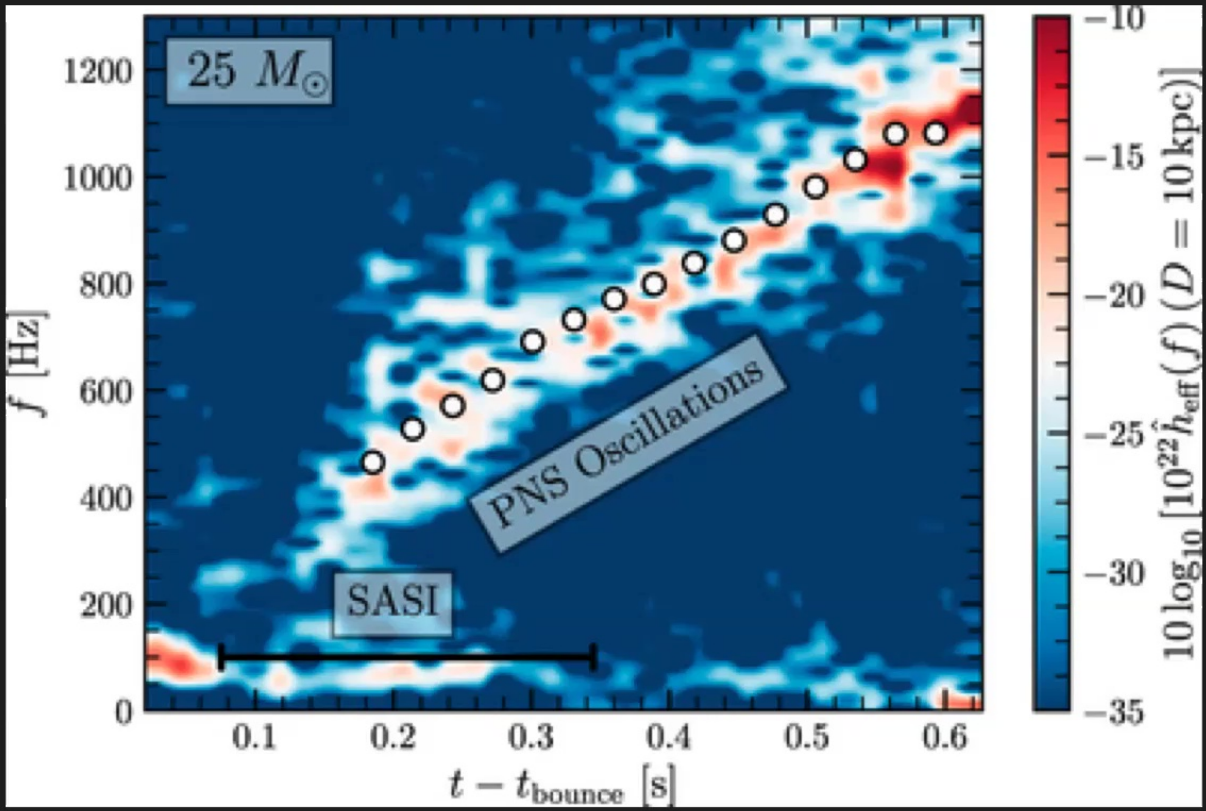


Image credit: Radice *et al.* (2019)

Sarah Gossan (she/h...

Case study: Core-collapse supernovae

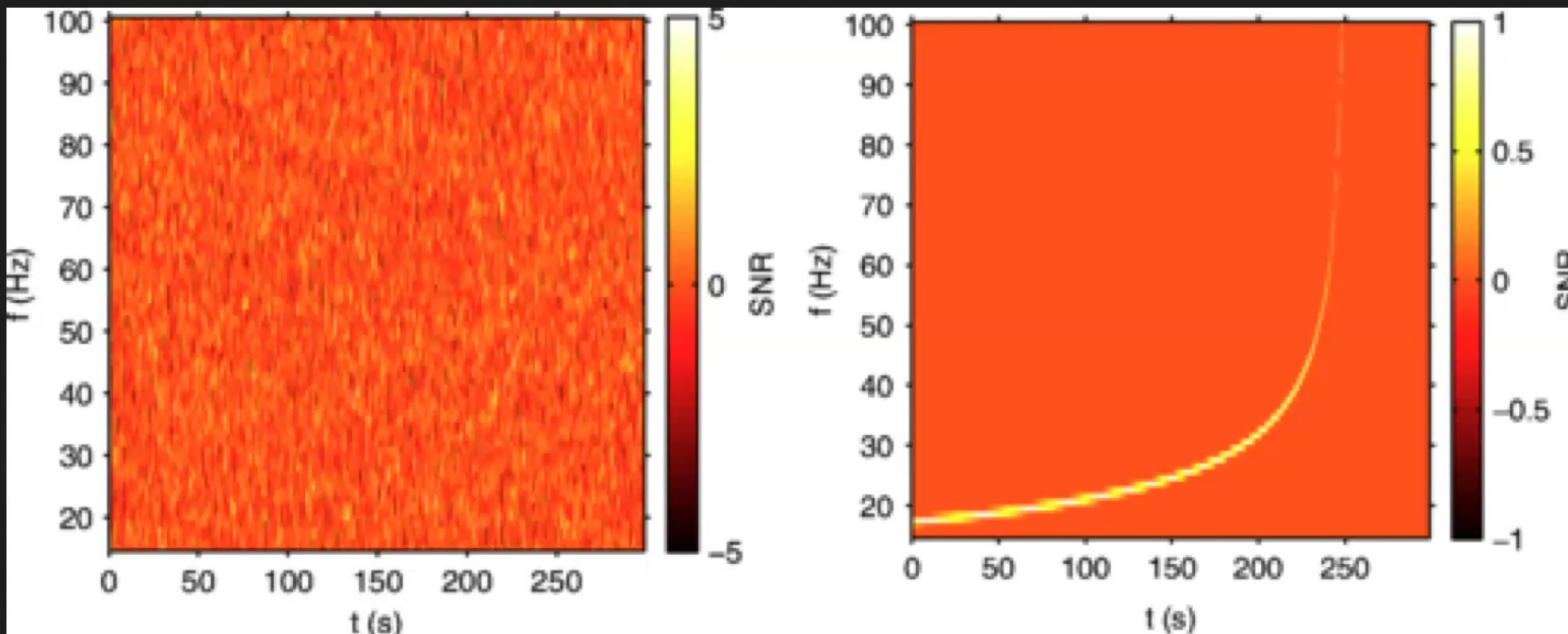
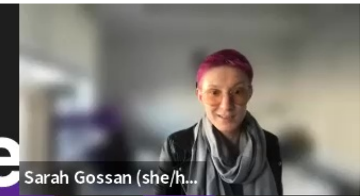


Image Credit: Coughlin *et al.* (2014) Phys. Rev. D **90**, 083005

Time for something new?

Case study: Core-collapse supernovae



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Order of magnitude LESS than matched-filter SNR estimates……

Can and MUST do better

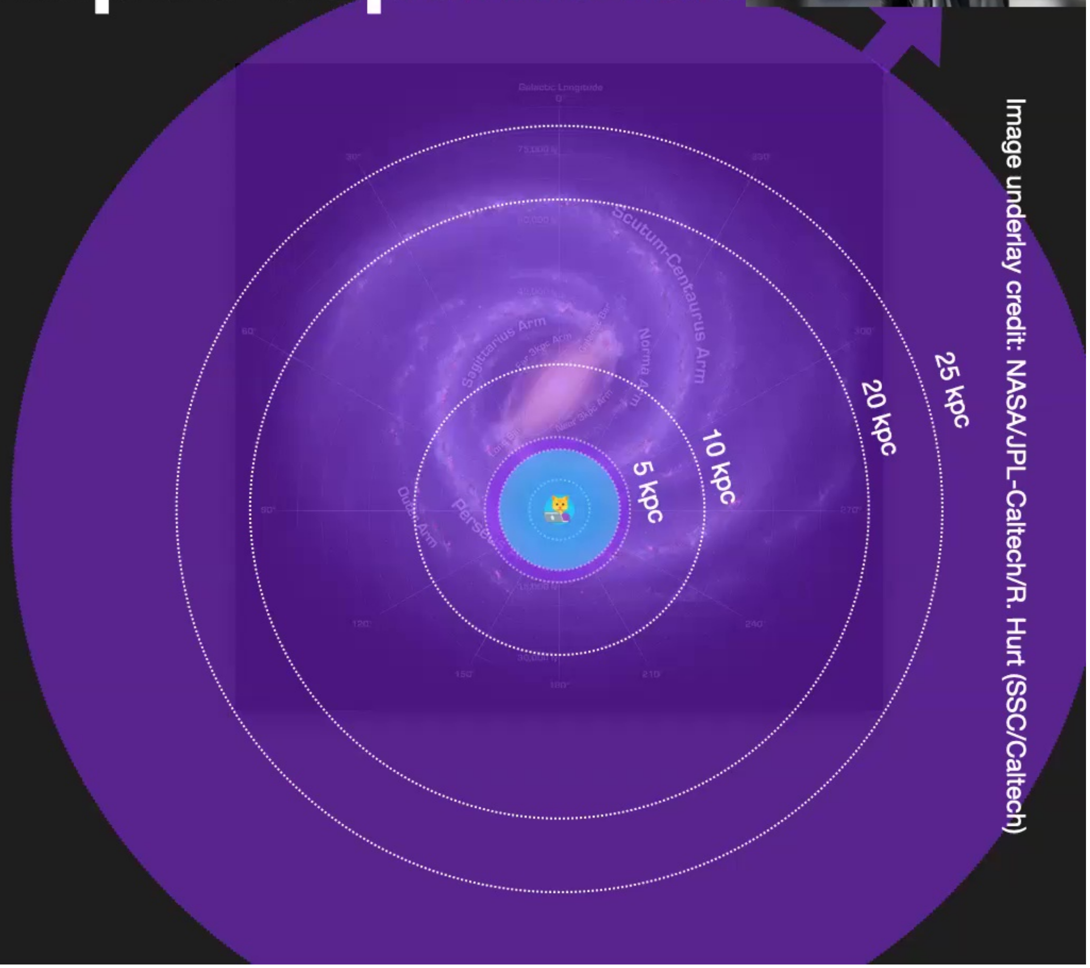

Image underlay credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Why haven't we detected Galactic GWs

1. Weaker gravitational wave emission than compact binaries

   Can we build new, more sensitive detectors?

   Sure, but $$$$$$$$$$

2. Sources not isotropically distributed across the sky

   Can we place detectors to be more sensitive to the Milky Way?

   Yes! Place equatorially for up to 50% more antenna power

3. Waveform morphology poorly modelled

   Can we improve signal recovery using source properties?

   Work in progress — but we really need to!

Observed SNR

(1) Signal strength

(2) Detector sensitivity

(a) Noise floor

(b) Antenna power

(3) Ability to recover signal from noise

In summary..

- Era of multi-messenger astronomy is upon us, but no Galactic GW seen yet!
- Can we improve detection prospects? YES!
    - Build more detectors
    - Place new detectors for maximal antenna sensitivity to Galactic source population (equatorially located)
    - Improve search sensitivity with tailored analysis tools based on source physics
- Do cool science! 💥