LIGO-Virgo Searches for Periodic Gravitational Waves from Rapidly Rotating Neutron Stars

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on behalf of the LIGO Scientific Collaboration
and the Virgo Collaboration
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Outline

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Gravitational Waves from Neutron Stars

- Focus on observation of GW from NS w/ground-based detectors

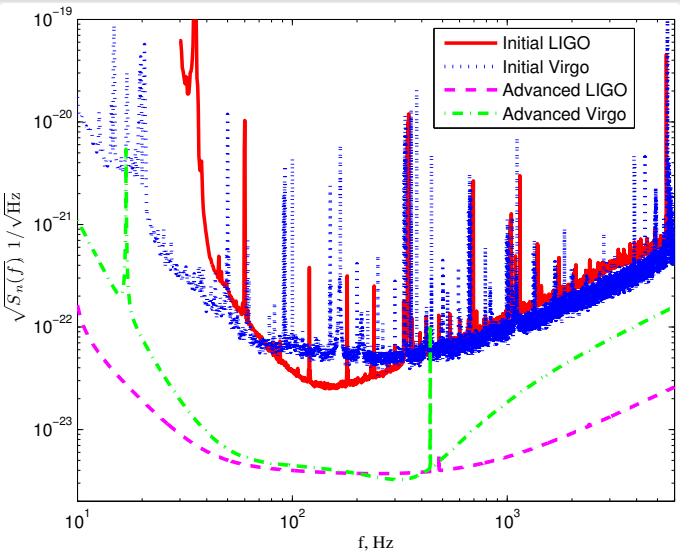
$$10\,\mathrm{Hz} \lesssim f_{\mathrm{gw}} \lesssim 4000\,\mathrm{Hz}$$

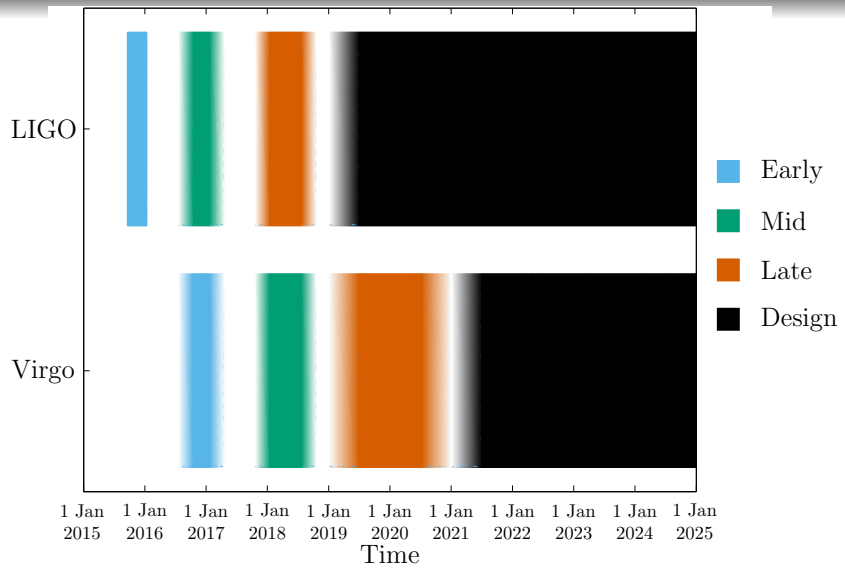
(**NOT** use of Pulsar Timing Array as nanohertz GW detector)

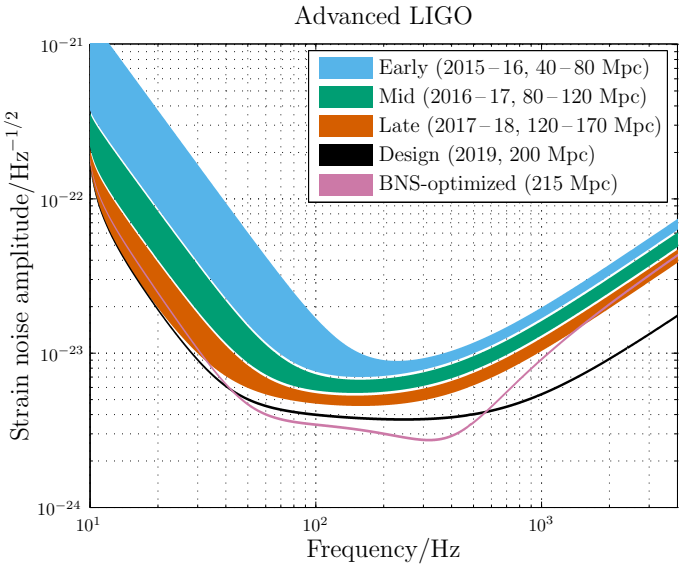
- Two kinds of GW from neutron stars:
  - Transient signal from binary inspiral (or glitch): talk by Anuradha Gupta
  - ☞ Long-lived periodic signal from rapid rotation ($P \lesssim 0.2\,\mathrm{s}$)
    Continuous Wave ("CW")
- Generations of ground-based interferometric GW detectors
  - Initial detector era: null results & upper limits
    - Initial LIGO 2002-2010; design sensitivity from 2006
    - Initial Virgo 2007-2011; design sensitivity from 2010
  - Advanced detector era: $10\times$ improvement in design sens
    - Advanced LIGO from 2015; design sens expected 2019
    - Advanced Virgo from 2016? design sens expected 2021
    - KAGRA & LIGO India in construction & planning stages

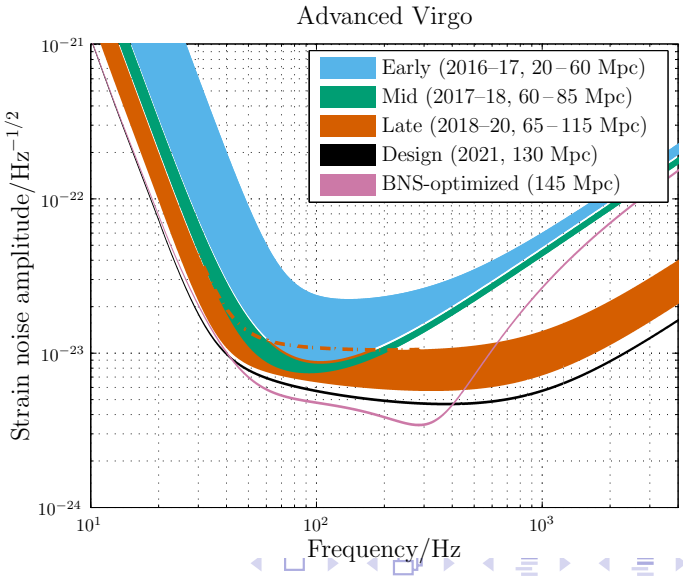
Advanced Detector Timeline

LVC, arXiv:1304.0670









Periodic GW Sources

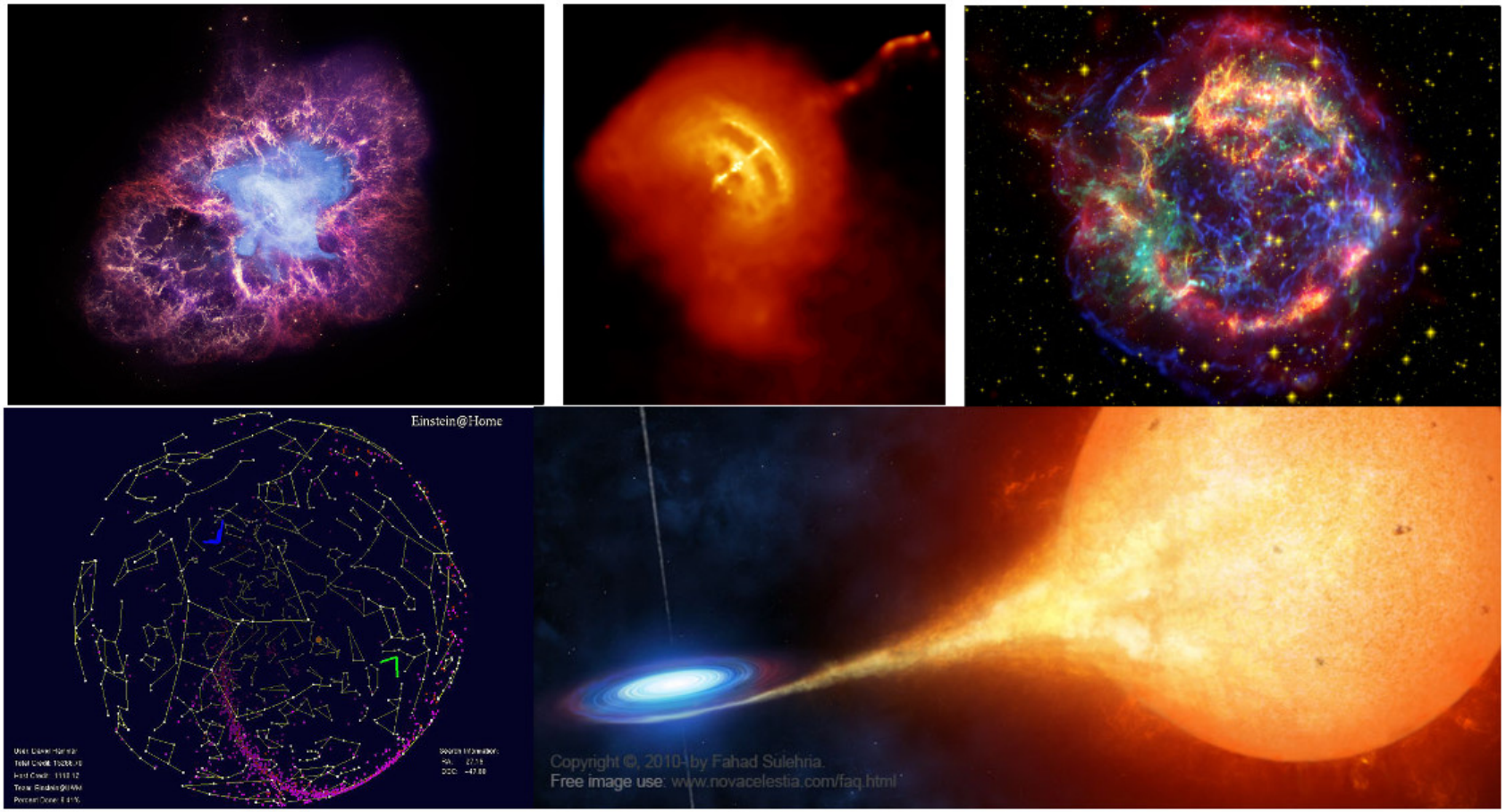


Image Credits (clockwise): Hubble/Chandra; Chandra; Spitzer/Hubble/Chandra; Fahad Sulehria, http://www.novacelestia.com/; http://www.einsteinathome.org/

Continuous Wave Signals

- Rotating NS w/deformation or long-lived oscillation emits nearly sinusoidal signal; two polarization states

$$h_+ = h_0 \frac{1+\cos^2\iota}{2}\cos\Phi(\tau(t)) \qquad h_\times = h_0 \cos\iota \sin\Phi(\tau(t))$$

  - $\Phi(\tau) \equiv$ phase evolution in inertial frame: f, $\dot{f}$, $\ddot{f}$, ...
  - $\tau(t) \equiv$ Doppler modulation from detector motion (& binary orbit)

  Note since gravity couples so weakly, only have to worry about lowest harmonic; No complicated "pulse profile"
- Don't need to search over amplitude params (extrinsic)
  $h_0 = \frac{4\pi^2 G|I_{xx}-I_{yy}|f_{gw}^2}{c^4 d}$, spin orientation ($\iota$, ψ), ϕ_0
  (can analytically maximize likelihood over them)
- Templates parameterized by phase params (intrinsic)
  f, $\dot{f}$, sky position (α, δ), orbital params (if NS in binary)

  Broad antenna pattern; sky position primarily from Doppler modulation

Computing Cost Motivates Search Strategies

All-sky coherent search of full phase param space infeasible:
# of templates skyrockets w/increasing integration time
E.g, for all-sky search with one spindown,

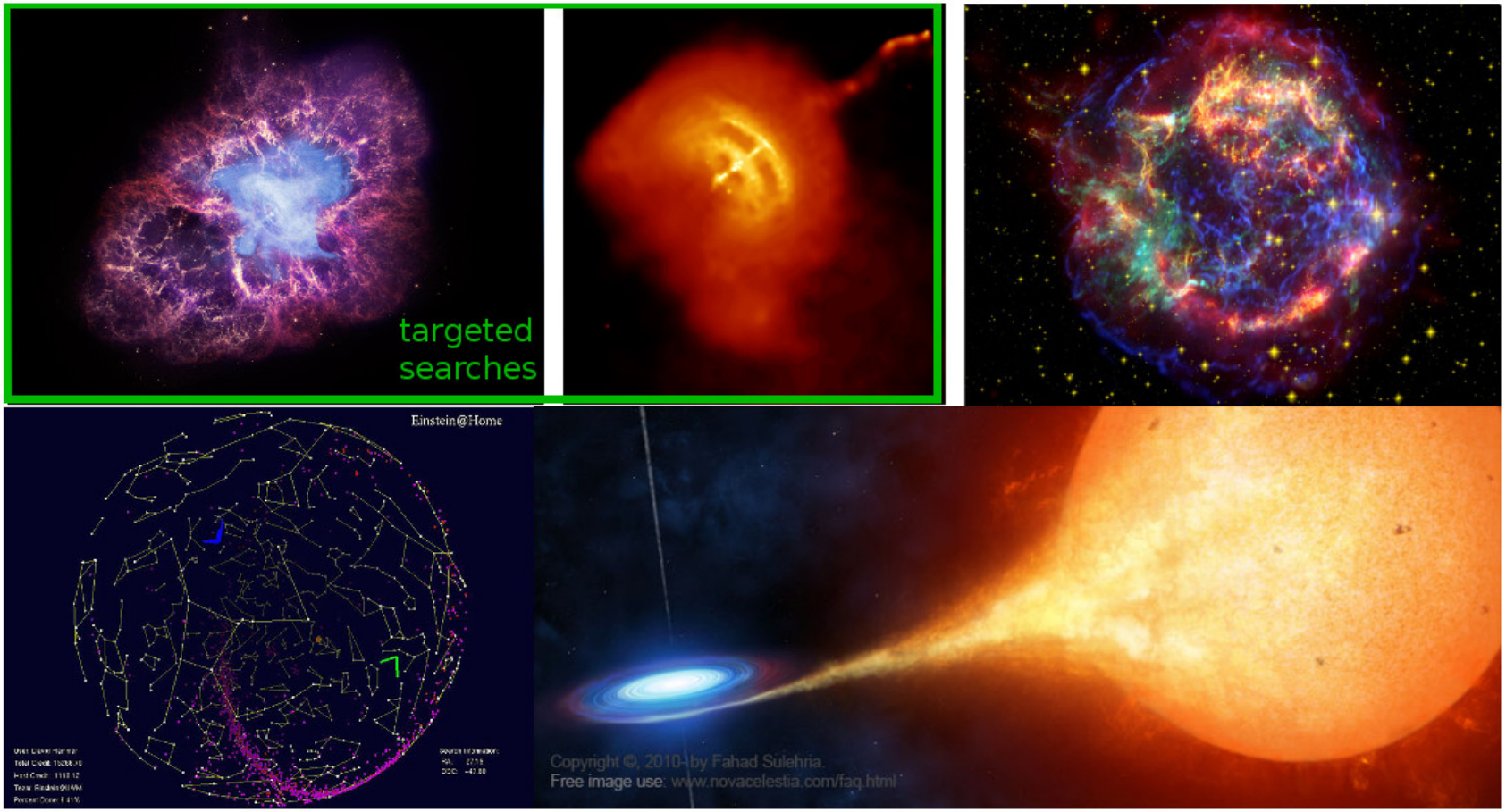
$$N_{\text{tmplts}} \sim \frac{1}{\Delta f}\frac{1}{\Delta \dot{f}}\frac{1}{\Delta \text{sky}} \sim T \cdot T^2 \cdot (fT)^2 \propto T^5$$

Different strategies depending on knowledge of object:

- Known pulsars: all phase parameters known,
  can do fully coherent **Targeted Search**
  Note $f_{\text{gw}} = 2f_{\text{rot}}$ for triaxial ellipsoid rotating about principal axis
- Unknown objects: need to use semi-coherent methods for
  Blind Search
- Known objects not seen as pulsars
  (e.g., SN remnants, LMXBs): can do **Directed Search**
  but need to cope w/uncertain remaining phase parameters

Outline

Periodic GW Sources – Known Pulsars



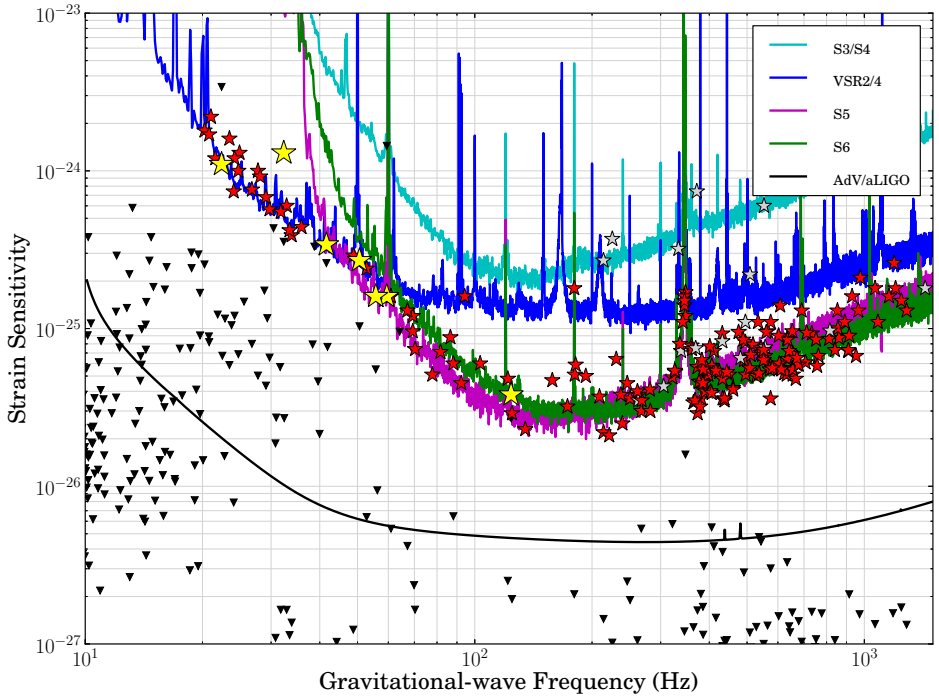
LSC-Virgo Targeted CW Searches

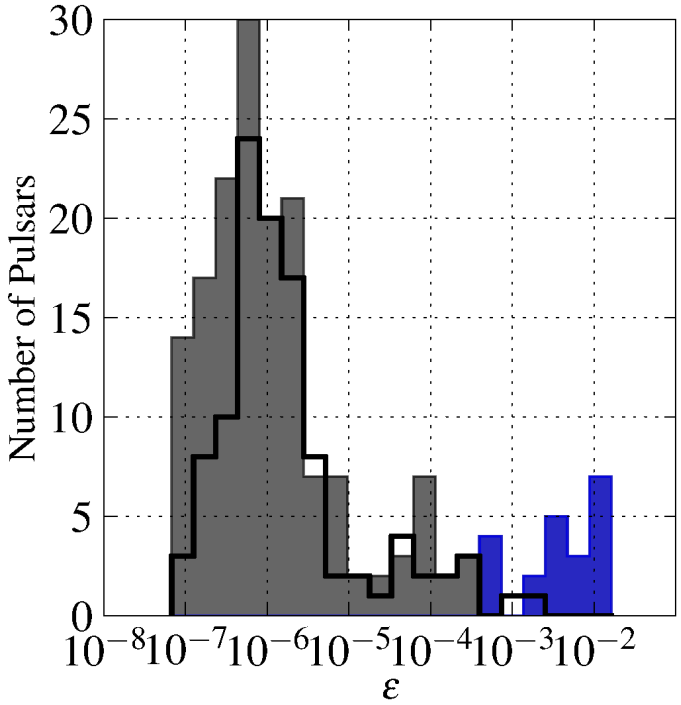
1. "Setting upper limits on the strength of periodic gravitational waves from PSR J1939+2134 using the first science data from the GEO 600 and LIGO detectors."
2. "Limits on gravitational wave emission from selected pulsars using LIGO data."
3. "Upper Limits on Gravitational Wave Emission from 78 Radio Pulsars."
4. "Beating the spin-down limit on gravitational wave emission from the Crab pulsar"
5. "Searches for gravitational waves from known pulsars with S5 LIGO data"
6. "Beating the spin-down limit on gravitational wave emission from the Vela pulsar"
7. "Gravitational-waves from known pulsars: results from the initial detector era"
8. "Narrow-band search of continuous gravitational-wave signals from Crab and Vela pulsars in Virgo VSR4 data"

Pulsar ephemeris means phase model known

☞ Searches not computationally bound

Known pulsar upper limits from initial detector era

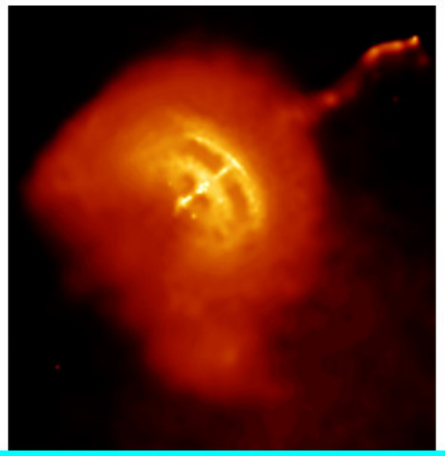


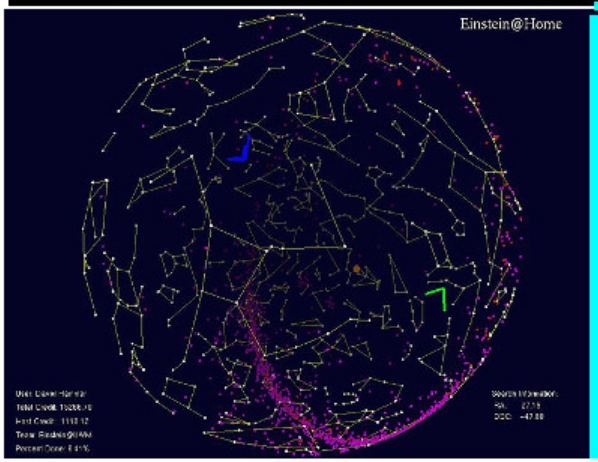


LVC, arXiv:1309.4027; *ApJ* **785**, 119 (2014)

$$h_0 = \frac{4\pi^2 G \varepsilon I_{zz} f_{gw}^2}{c^4 d}; \qquad \varepsilon = |I_{xx} - I_{yy}| / I_{zz}$$

Periodic GW Sources – Known Neutron Stars





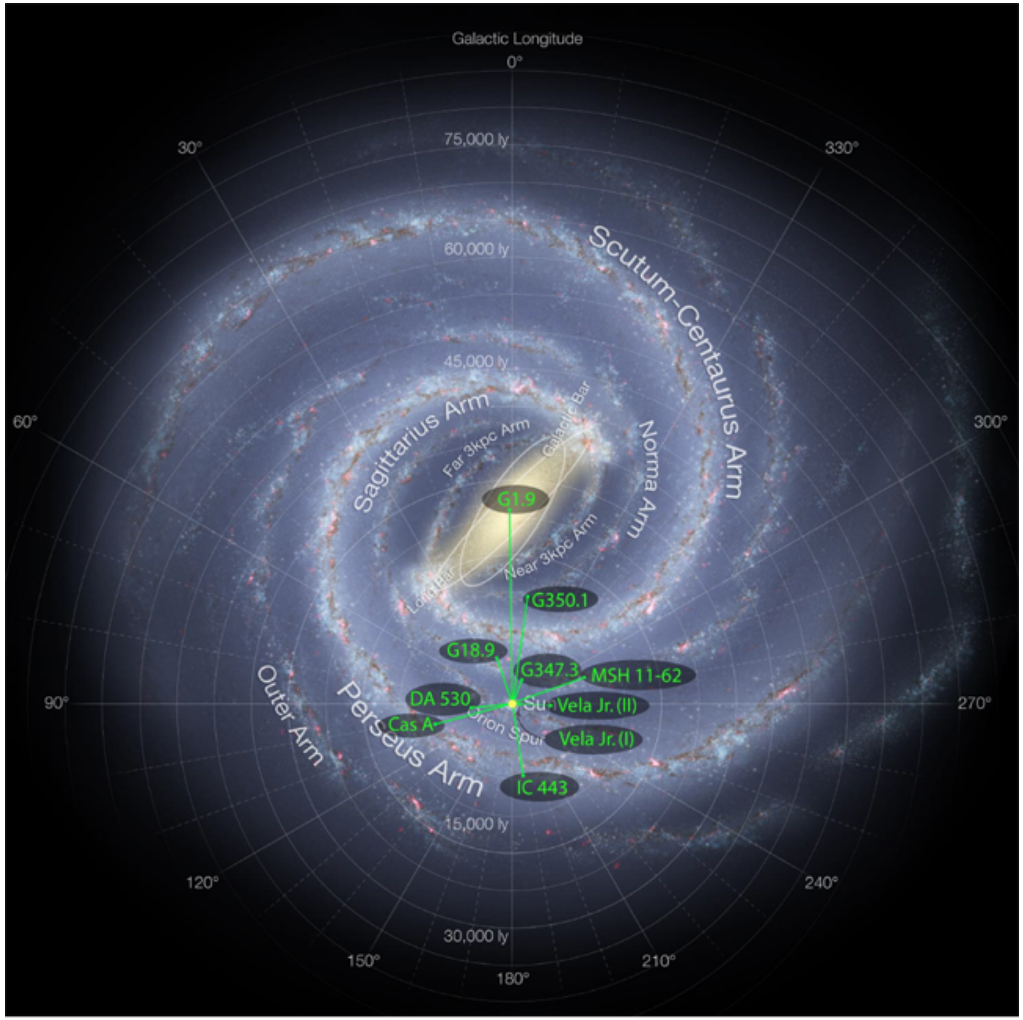
LSC-Virgo Directed CW Searches

1. "Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1: results from the second LIGO science run."
2. "Upper limit map of a background of gravitational waves."
3. "First search for gravitational waves from the youngest known neutron star"
4. "A directed search for continuous Gravitational Waves from the Galactic Center"
5. "Directional limits on persistent gravitational waves using LIGO S5 science data"
6. "A directed search for gravitational waves from Scorpius X-1 with initial LIGO"
7. "Searches for continuous gravitational waves from nine young supernova remnants"

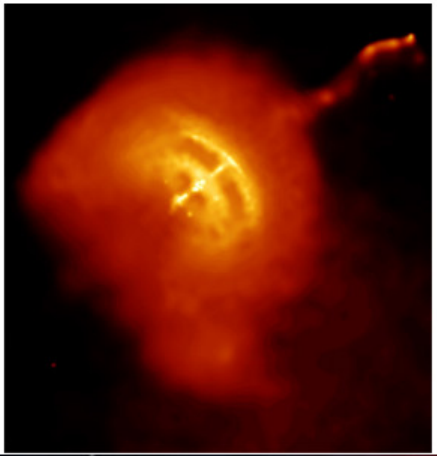
Sco X-1, SN Remnants, Galactic Center

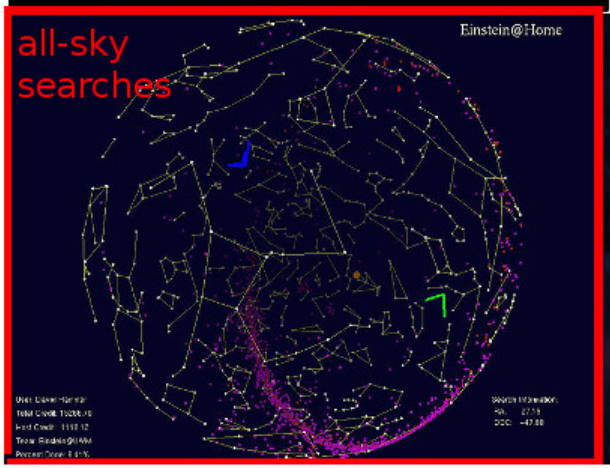
Directed Searches in Supernova Remnants

LVC, arXiv:1412.5942; *ApJ* **813**, 39 (2015)



Periodic GW Sources – Unknown Neutron Stars

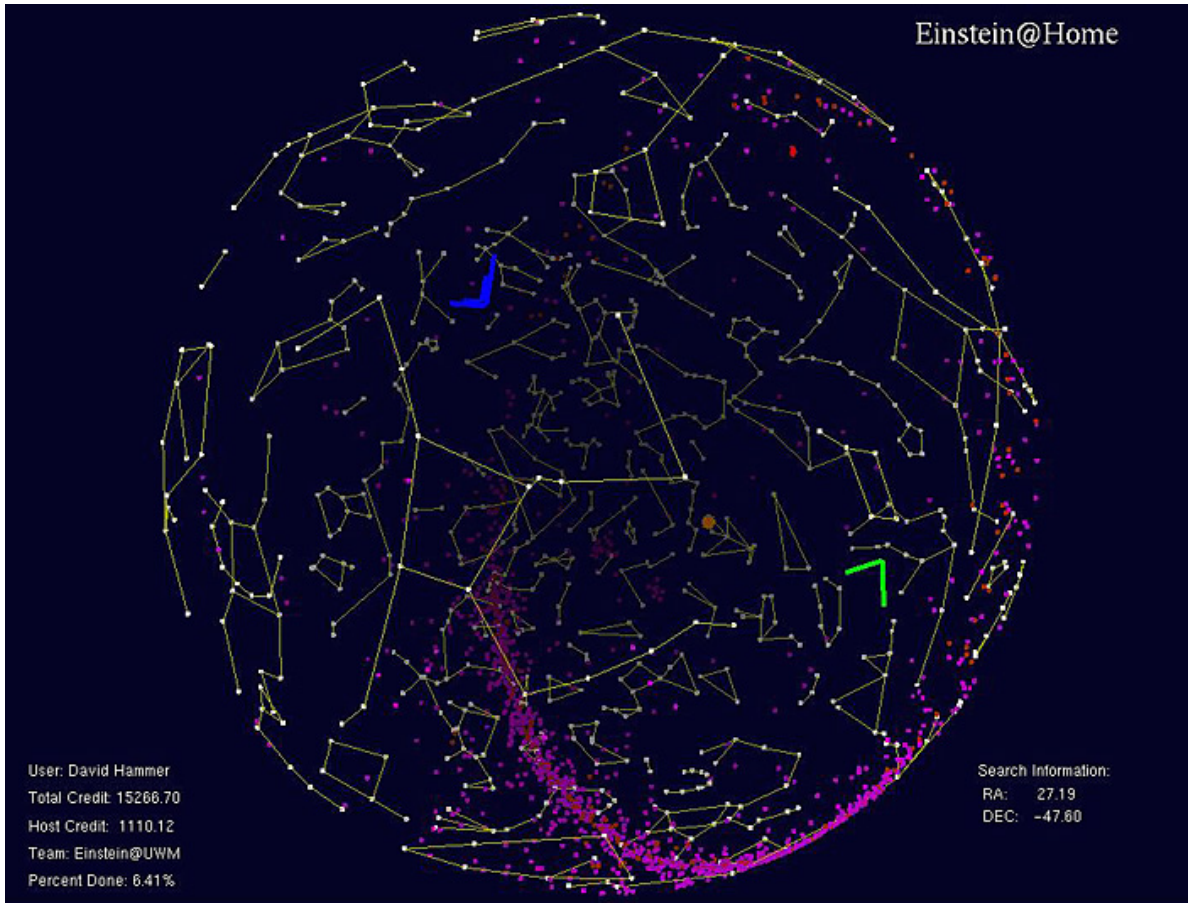




LSC-Virgo Blind CW Searches

1. "First all-sky upper limits from LIGO on the strength of periodic gravitational waves using the Hough transform."
2. "Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1: results from the second LIGO science run."
3. "All-sky search for periodic gravitational waves in LIGO S4 data"
4. "The Einstein@Home search for periodic gravitational waves in LIGO S4 data"
5. "All-sky LIGO Search for Periodic Gravitational Waves in the Early S5 Data"
6. "Einstein@Home search for periodic gravitational waves in early S5 LIGO data"
7. "All-sky search for periodic gravitational waves in the full S5 LIGO data"
8. "Einstein@Home all-sky search for periodic gravitational waves in LIGO S5 data"
9. "Application of a Hough search for continuous gravitational waves on data from the 5th LIGO science run"
10. "Implementation of an F-statistic all-sky search for continuous gravitational waves in Virgo VSR1 data"
11. "First all-sky search for continuous gravitational waves from unknown sources in binary systems."
12. "A search of the Orion spur for continuous gravitational waves using a "loosely coherent" algorithm on data from LIGO interferometers"
13. "First low frequency all-sky search for continuous gravitational wave signals"

One All-Sky Tool: Einstein@Home

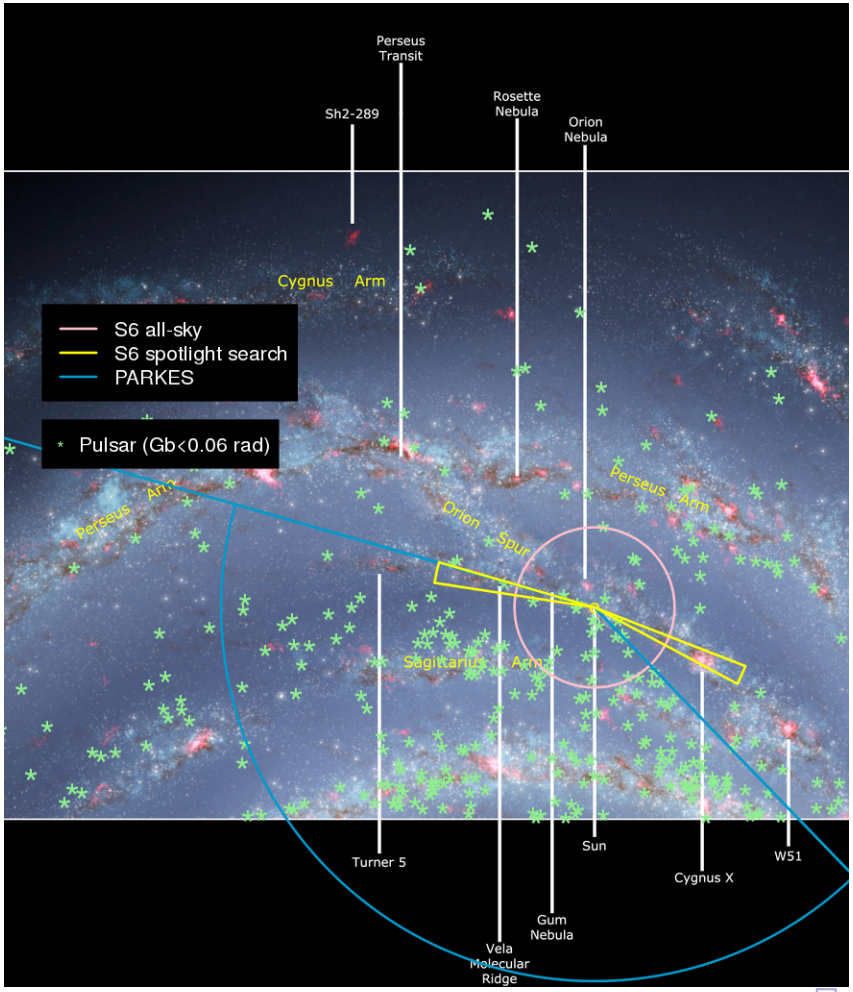


Volunteer distributed computing project

Also used to search radio & gamma-ray data for binary pulsars

Blind "Spotlight" Search

LVC arXiv:1510.03474
Blind but not all-sky; focus on Orion spur

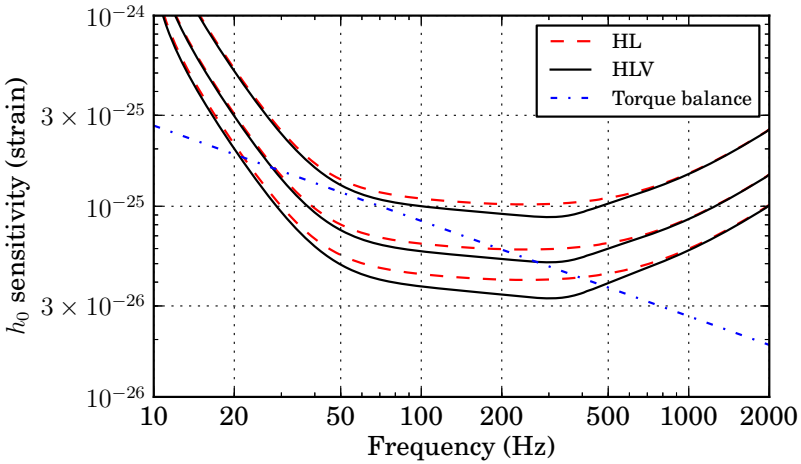


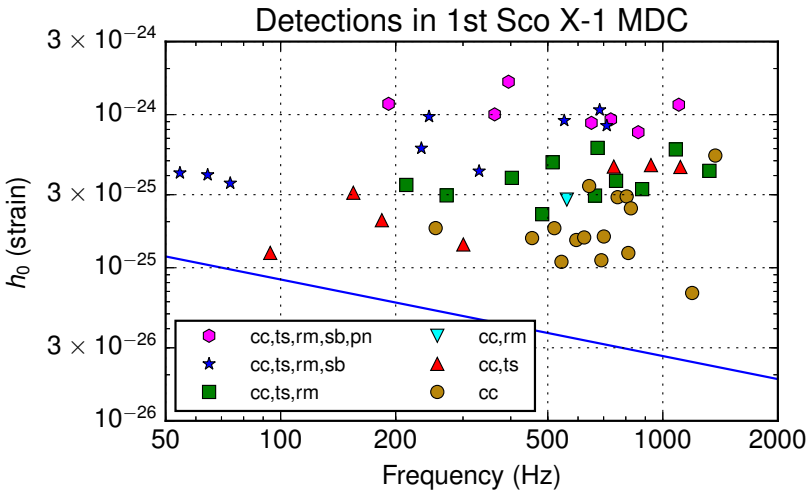
Outline

Plans for Advanced Detector Era

- Search plans in LVC Data Analysis White Paper LIGO-T1500055
- Targeted searches for known pulsars (radio, X-ray, γ-ray)
  Depends on ephemeris from electromagnetic observations
  Benefits to AMXP searches from ASTROSAT: Arunava Mukherjee's talk
- Directed searches for SN remnants and LMXBs
  Cas A, Sco X-1 & J1751-305 highest priority
- All-sky searches w/LVC clusters & Einstein@Home

Prospects for Sco X-1 w/Advanced Detectors





Whelan et al arXiv:1504.05890; *PRD* **91**, 102005 (2015)
Messenger et al arXiv:1504.05889; *PRD* **92**, 023006 (2015)
Leaci & Prix arXiv:1502.00914; *PRD* **91**, 102003 (2015)