Science Results and Plans for S5

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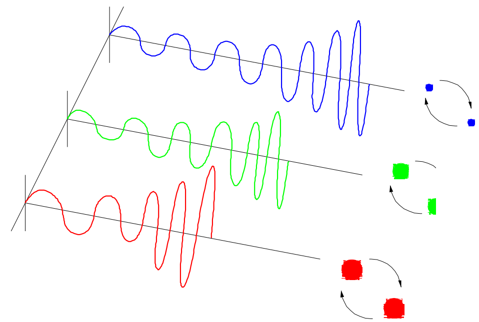
LIGO Scientific Collaboration

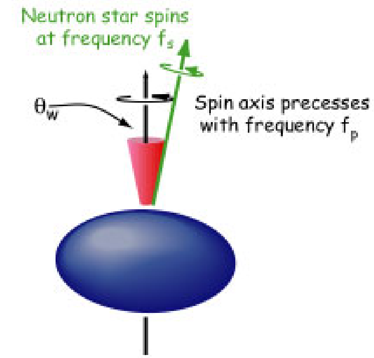
Science Goals

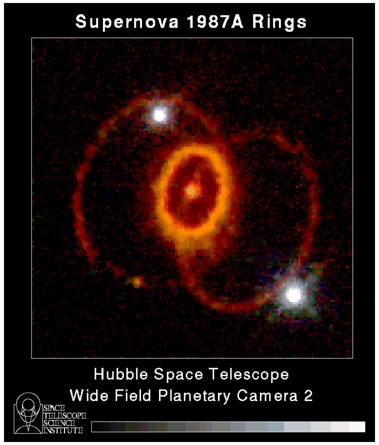
- Direct verification of two of most dramatic predictions of Einstein's general relativity
  - » Existence of gravitational waves
  - » Direct observation of black holes
- Physics
  - » Detailed tests of properties of gravitational waves including speed, polarization, strength, graviton mass, ...
  - » Probe strong field gravity around black holes and in the early universe
  - » Probe the neutron star equation of state
- Astronomy
  - » By performing routine astronomical observations, understand compact binary populations, rates of supernovae explosions, test gamma-ray burst models
- LIGO provides a new window on the Universe

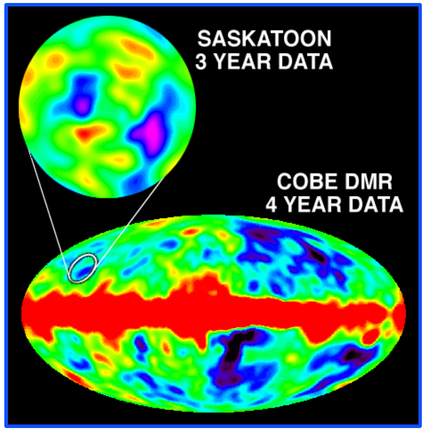
Astrophysical Sources of Gravitational Waves

- Compact binary systems
  - » Black holes and neutron stars
  - » Inspiral and merger
  - » Probe internal structure, populations, and spacetime geometry
- Spinning neutron stars
  - » LMXBs, known & unknown pulsars
  - » Probe internal structure and populations
- Neutron star birth
  - » Tumbling and/or convection
  - » Correlations with EM observations
- Stochastic background
  - » Big bang & other early universe
  - » Background of GW bursts



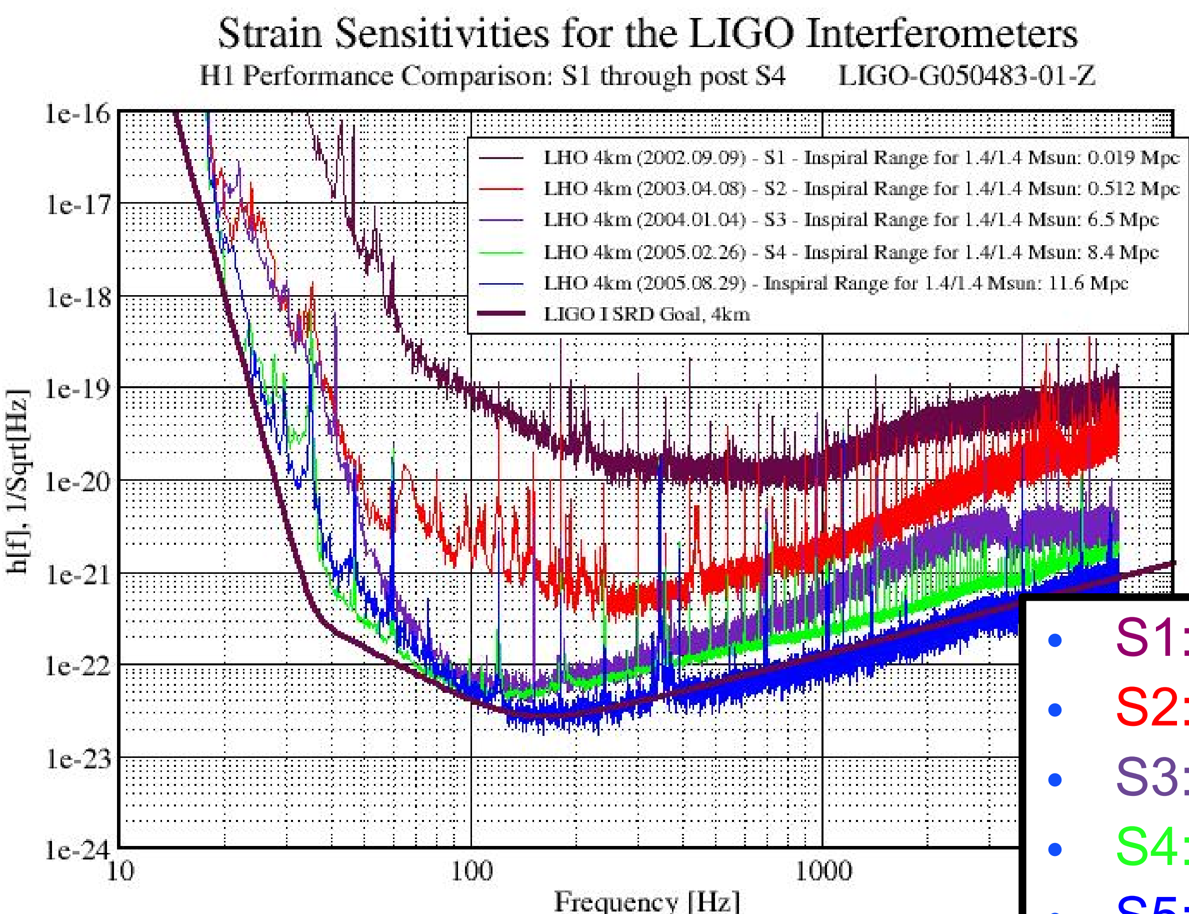






LIGO

History of science runs



- S1: 23 Aug – 9 Sep ‘02
- S2: 14 Feb – 14 Apr ‘03
- S3: 31 Oct ‘03 – 9 Jan ‘04
- S4: 22 Feb – 23 Mar ‘05
- S5: 4 Nov ‘05 ....

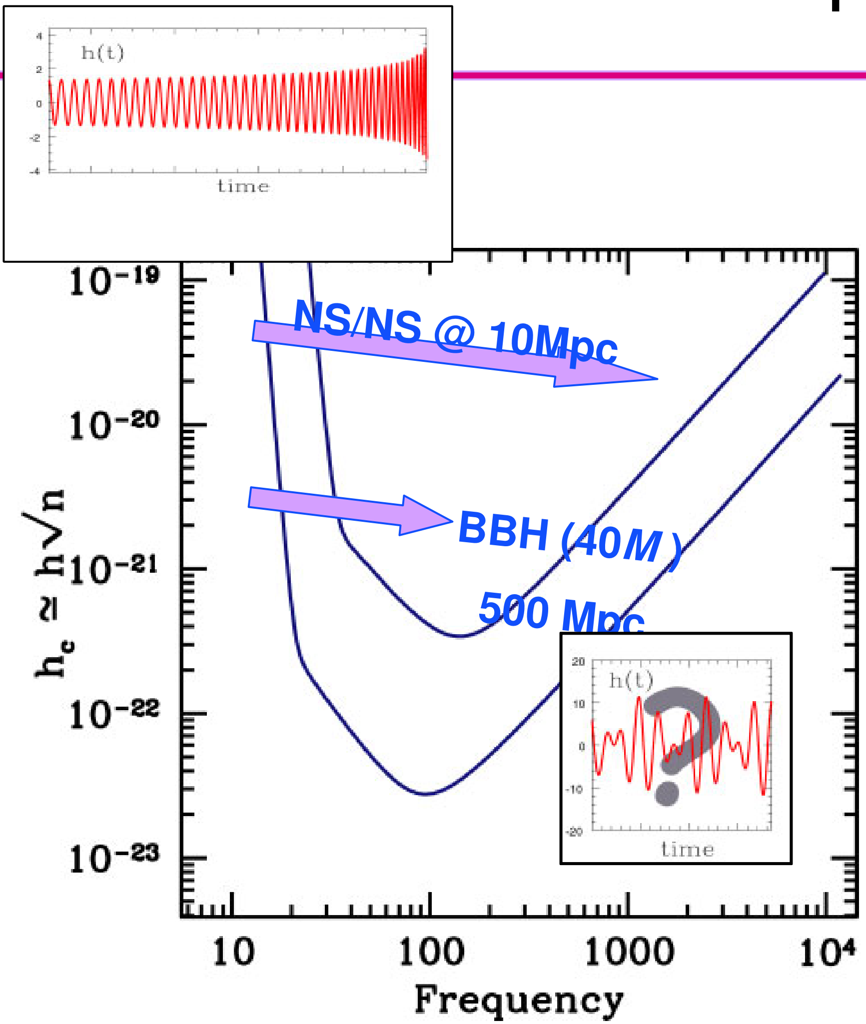
Observational papers

1. Neutron Star Binaries: *Phys. Rev. D* **69**, 122001 (2004)
2. Stochastic Background: *Phys. Rev. D* **69**, 122004 (2004)
3. Bursts: *Phys. Rev. D* **69**, 102001 (2004)
4. PSR J1939+2134: *Phys. Rev. D* **69**, 082004 (2004)
5. 28 Pulsars: *PRL* **94**, 181103 (2005)
6. GRB030329: *Phys. Rev. D* **72**, 042002 (2005)
7. Bursts: *Phys. Rev. D* **72**, 062001 (2005)
8. Neutron Star Binaries*: Phys. Rev. D in press, gr-qc/0505041*
9. Primordial Black Holes: *Phys. Rev. D* in press, gr-qc/0505042
10. Bursts using LIGO+TAMA: *Phys. Rev. D* in press, gr-qc/0507081
11. Unknown pulsars: *Phys. Rev. D* in press, gr-qc/0508065
12. Binary Black Holes: gr-qc/0509129
13. Stochastic: *PRL* in press, astro-ph/0507254
14. Bursts: Class Quantum Grav.

....many others in preparation....

....plus too many technical publications to list....

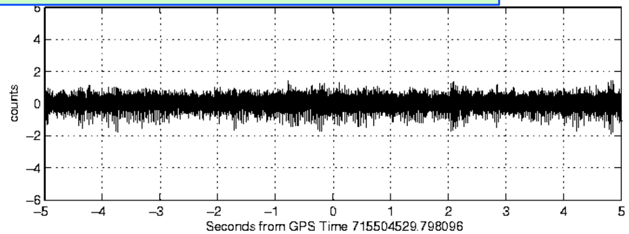
Inspiral and Merger of Compact Binaries



- LIGO is sensitive to:
  - » Gravitational waves from binary systems containing neutron stars & stellar mass black holes
  - » Last several minutes of inspiral driven by GW emission
  - » Clean systems, accurate modeling shows that GW's depend on masses/spins only
- Binary Neutron Star Rates
  - » Theoretical estimates give upper bound of 1/3yr for LIGO S5
- Binary Black Hole Rates
  - » Theoretical estimates give upper bound of 1/yr for LIGO S5

Matched filtering

GW Channel
+ simulated inspiral



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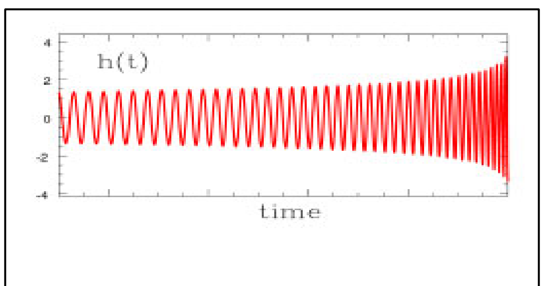
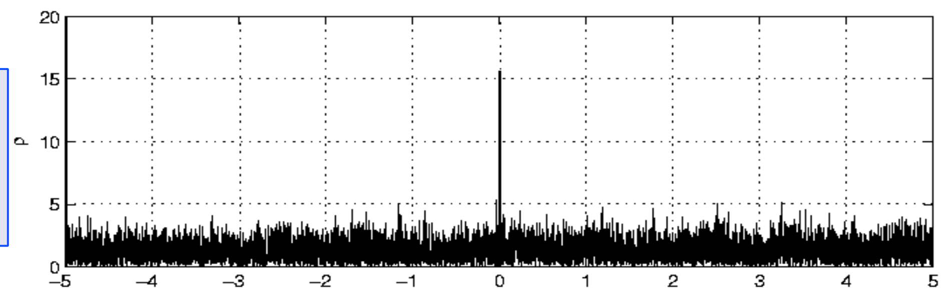
Filter to suppress
high/low freq

☆



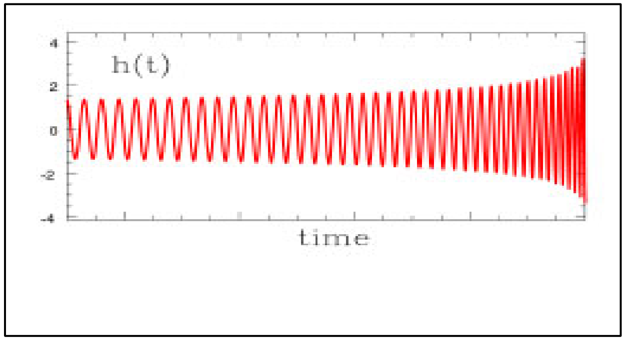
SNR



Coalescence Time

How to detect inspiral waves

- Use template based matched filtering algorithm
- Search for non-spinning binaries
  - » 2.0 post-Newtonian waveforms

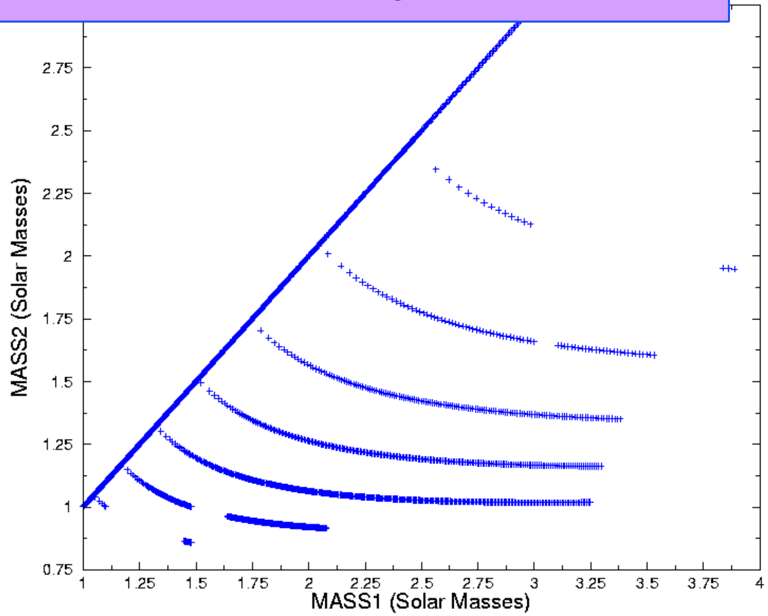


$$s(t) = (1\text{Mpc}/D) \times [\,\sin(a)\, h^{I}_{s}\,(t-t0) + \cos(a)\, h^{I}_{c}\,(t-t0)]$$

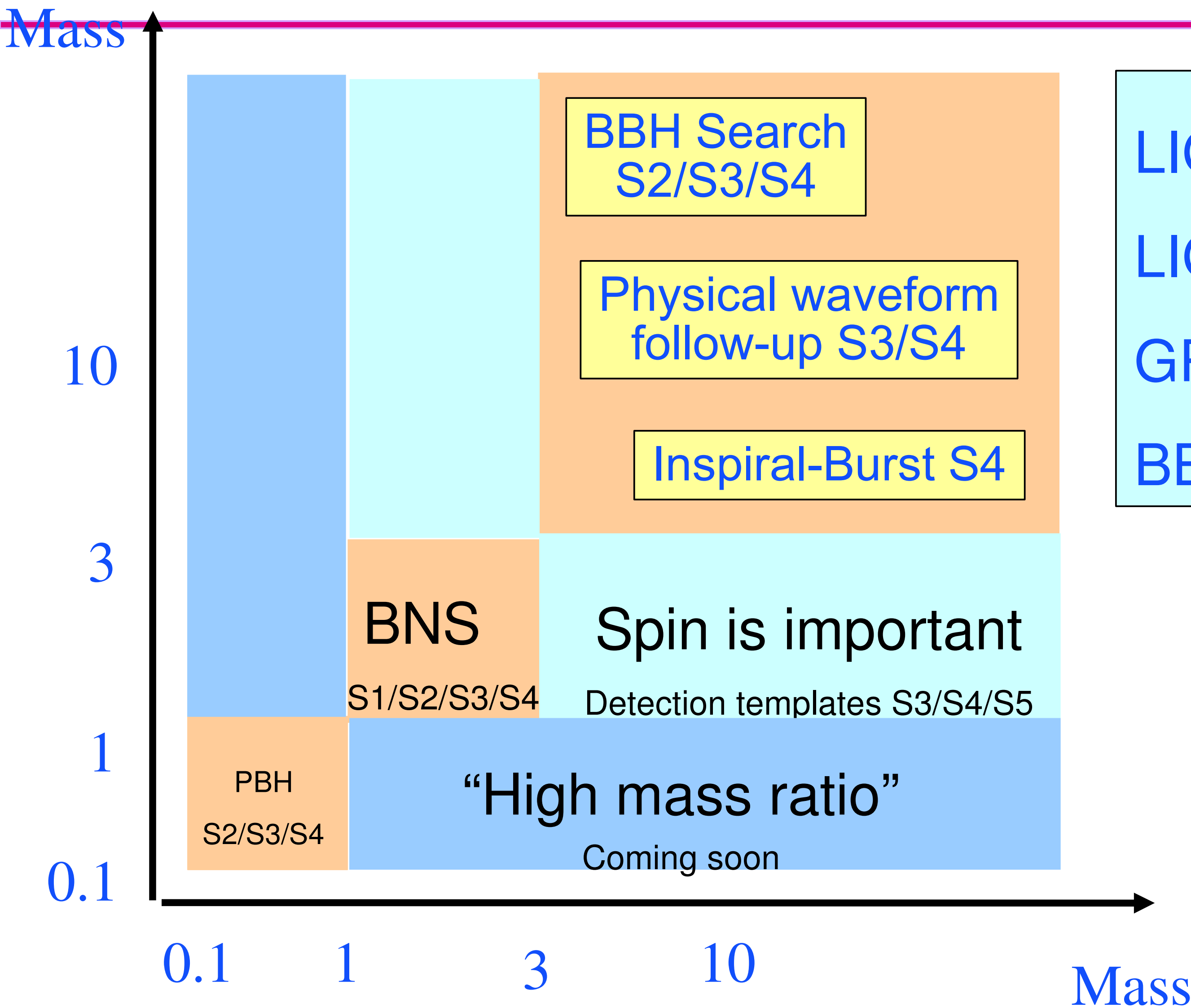
- D: effective distance; a: phase

Discrete set of templates labeled by I=(m1, m2)

- » 1.0 Msun < m1, m2 < 3.0 Msun



Active Inspiral Searches



LIGO-Virgo analysis

LIGO-TAMA analysis

GRB Coincidence

BBH follow up

LIGO

Binary Neutron Star Search:

LSC

LIGO S5 Range

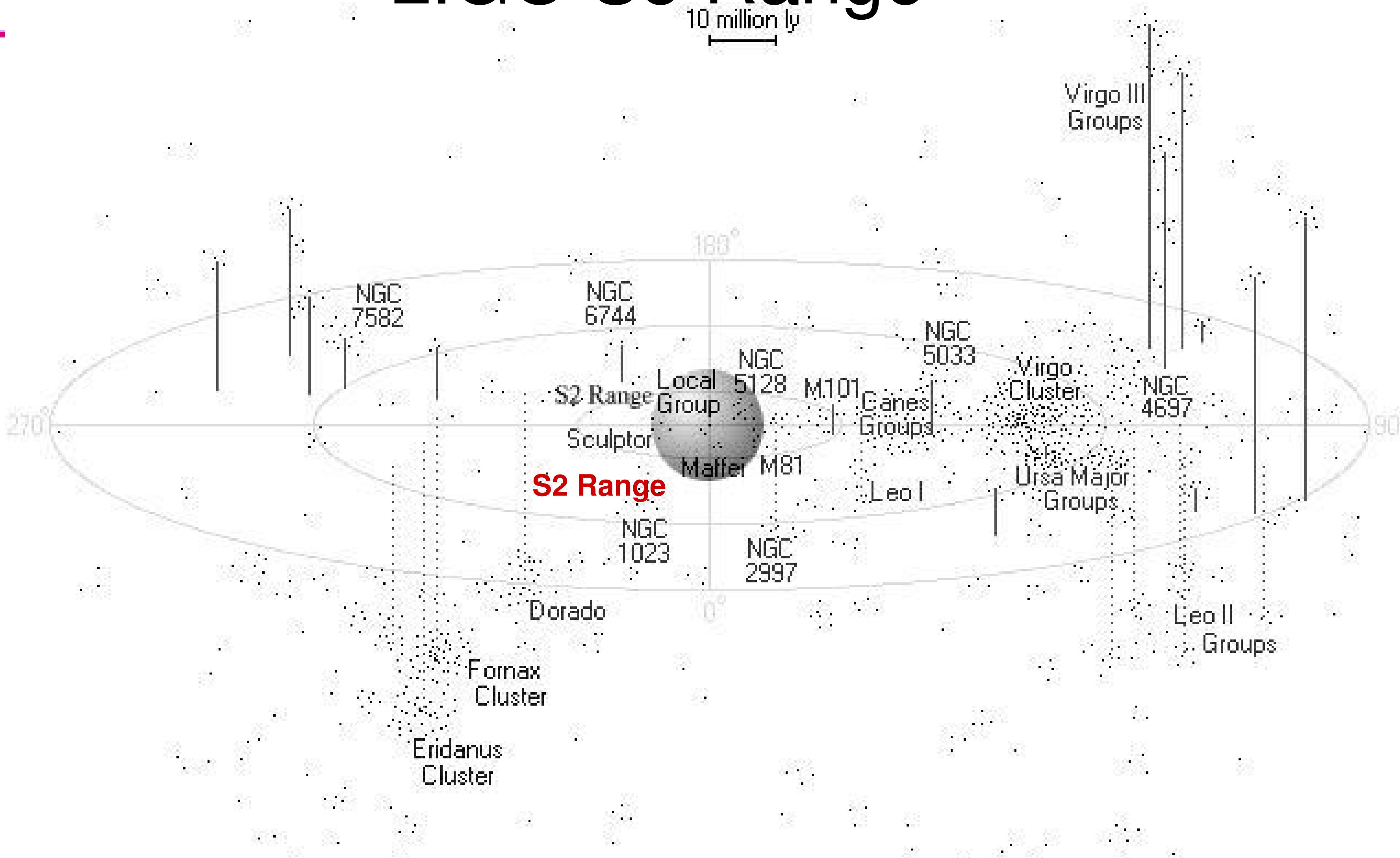
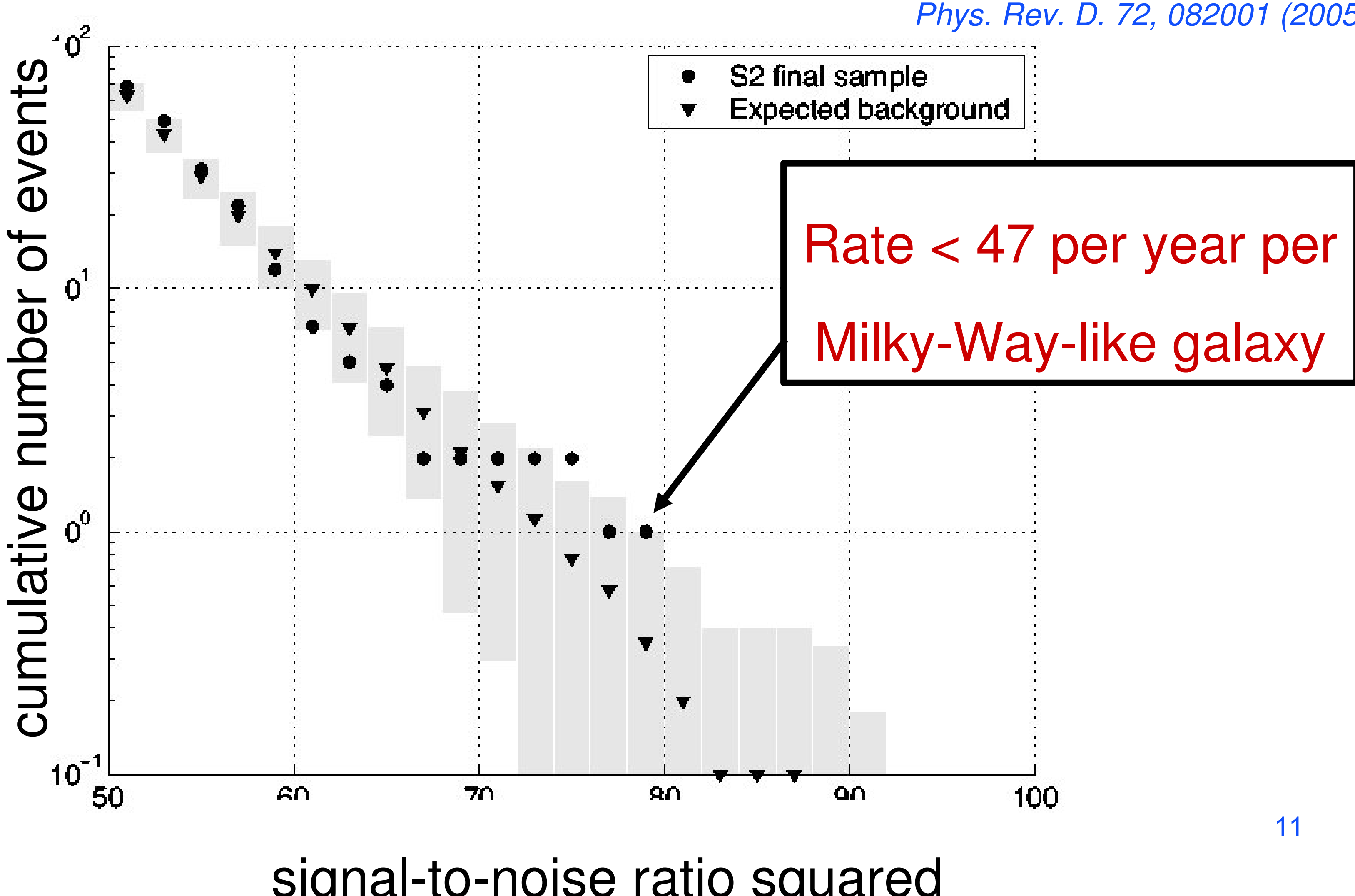


Image: R. Powell

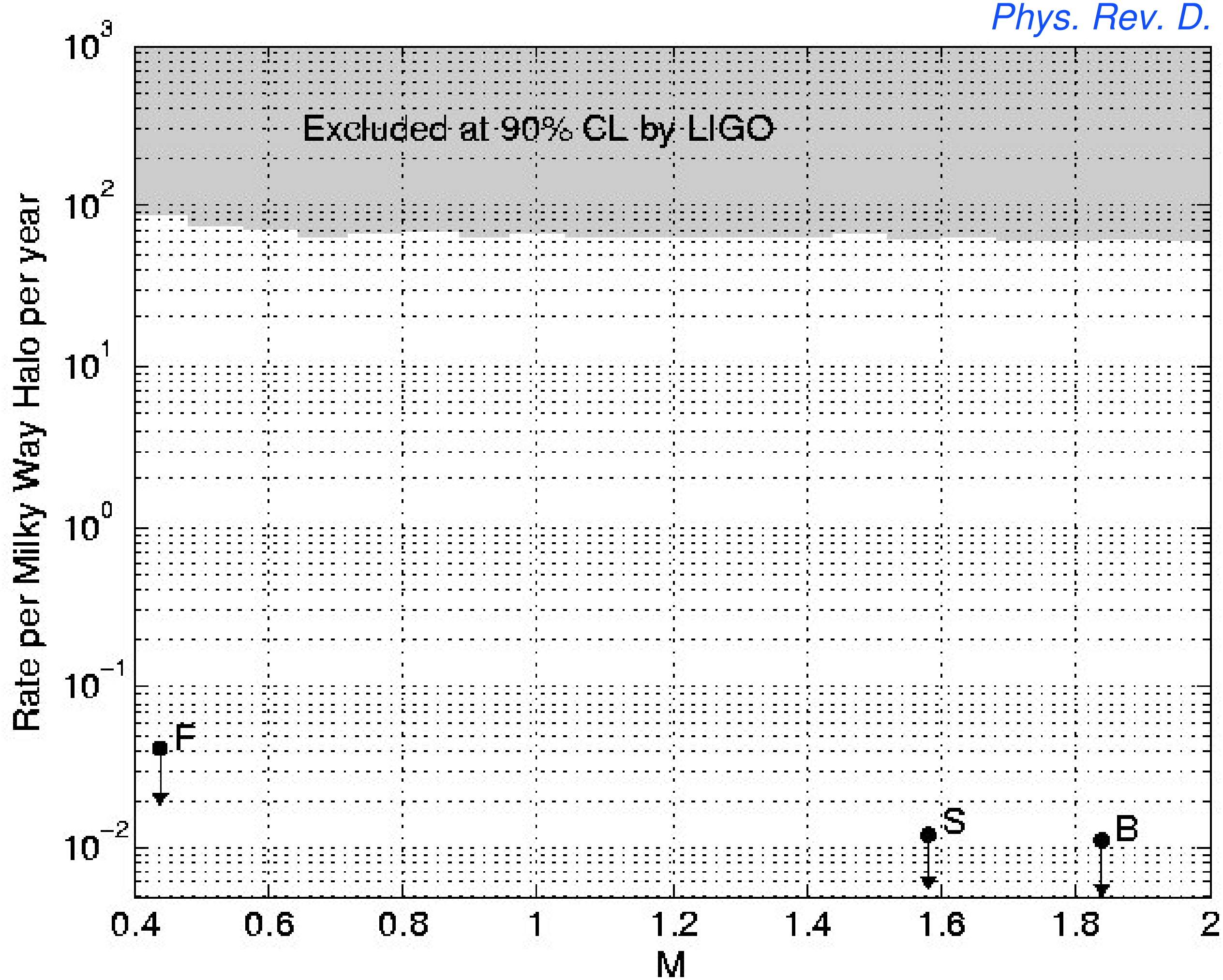
Binary Neutron Star Search Results (S2)

Phys. Rev. D. 72, 082001 (2005)



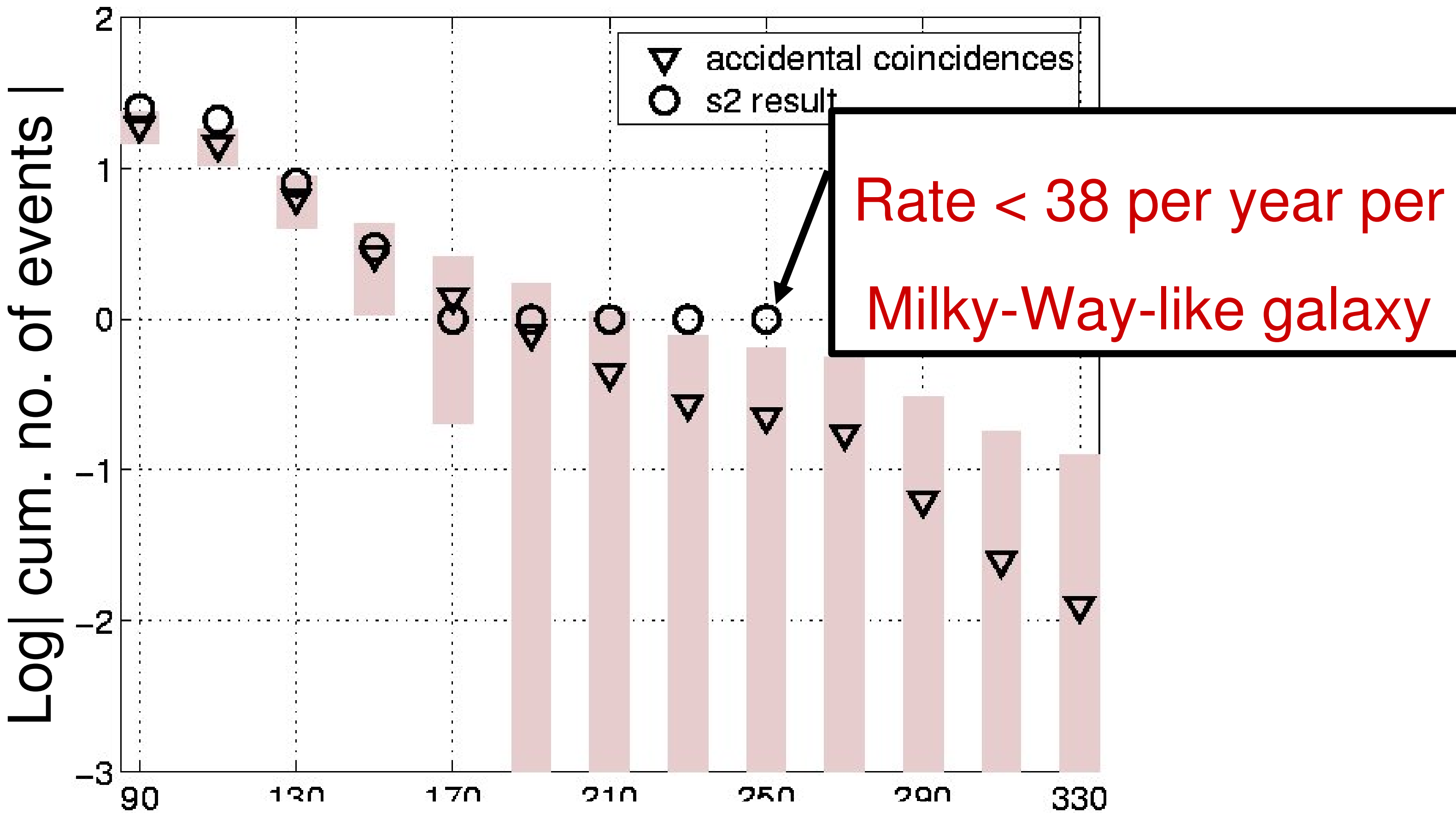
Search for Primordial Black Hole Binaries (S2)

Phys. Rev. D. 72, 082002 (2005)



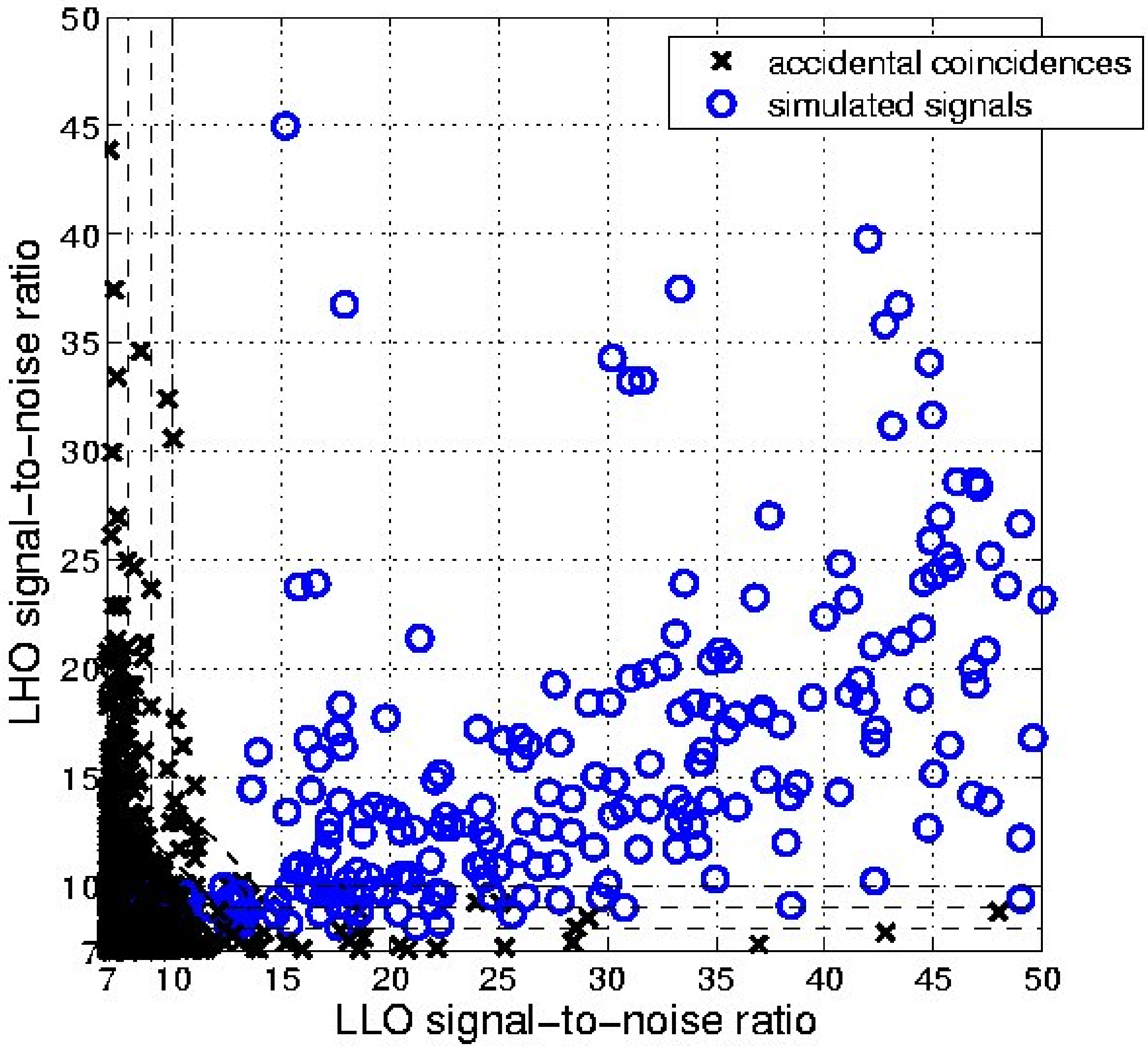
Binary Black Hole Search (S2)

Submitted to Phys. Rev. D., gr-qc/0509129



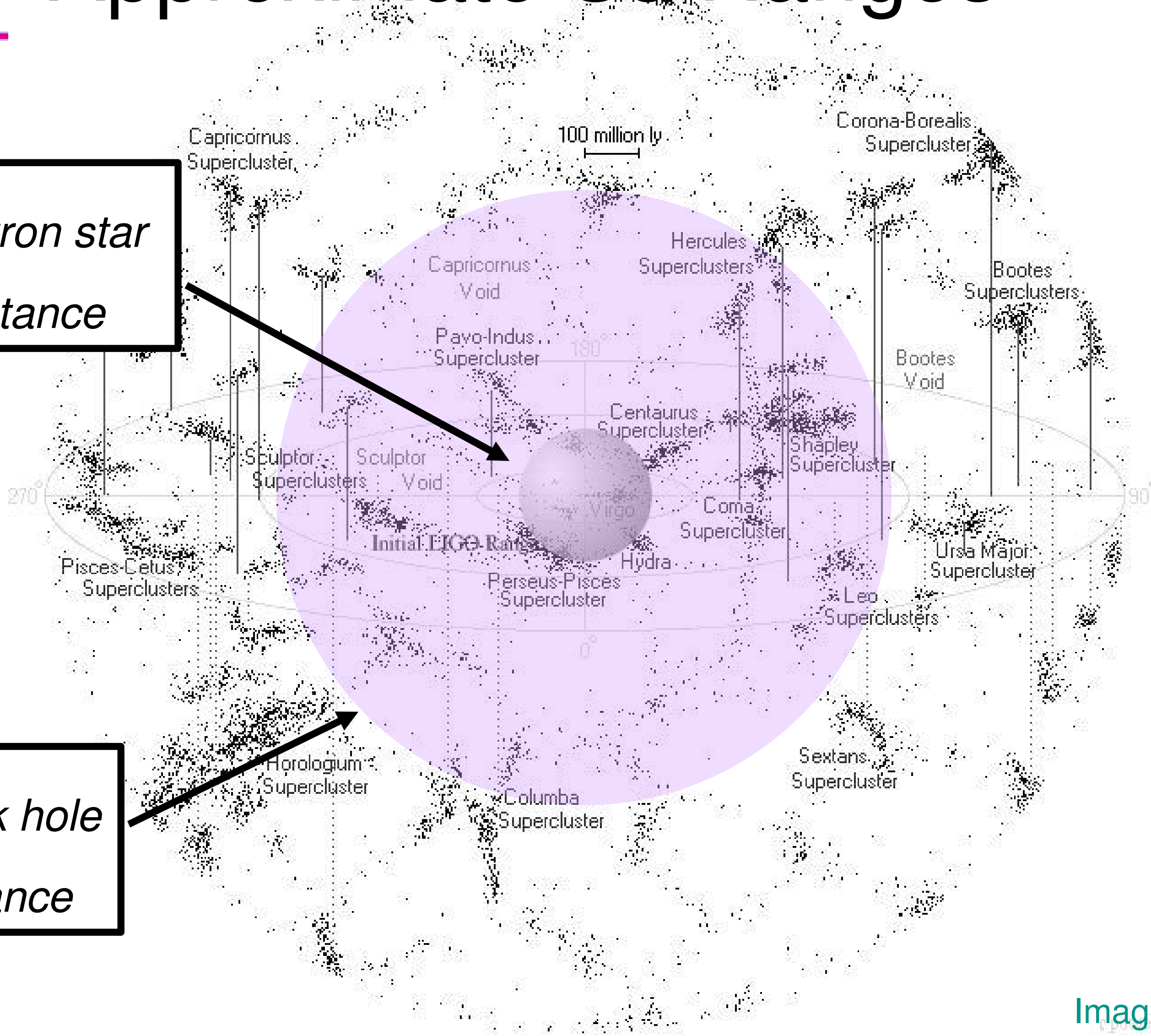
signal-to-noise ratio squared

How would we do at detection?



Binary Inspiral Searches: Approximate S5 Ranges

binary neutron star max. distance

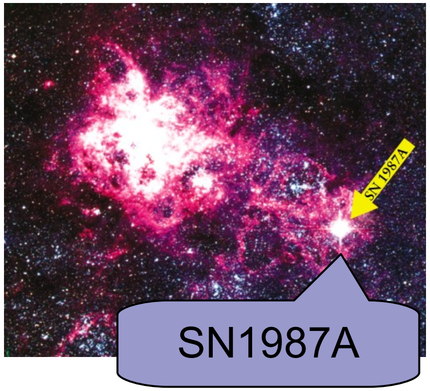


binary black hole max. distance

Image: R. Powell

Burst Sources

- General Properties
  - » Duration << observation time
- Promise
  - » Unexpected sources and serendipity
  - » Search techniques must use minimal information
- Examples
  - » Black hole and neutron star merger
  - » Supernovae & gamma-ray bursters
  - » Instabilities in nascent neutron stars
  - » Kinks and cusps on cosmic strings



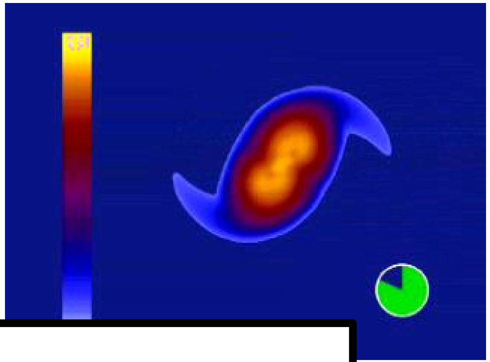


Image: Baumgarte,Shapiro, Shibata

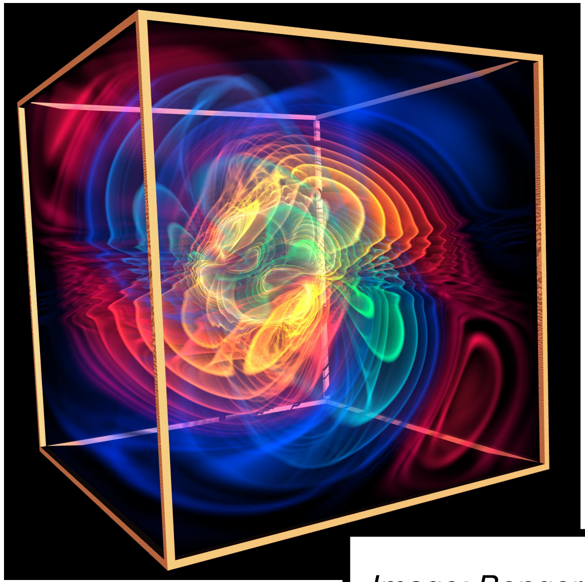


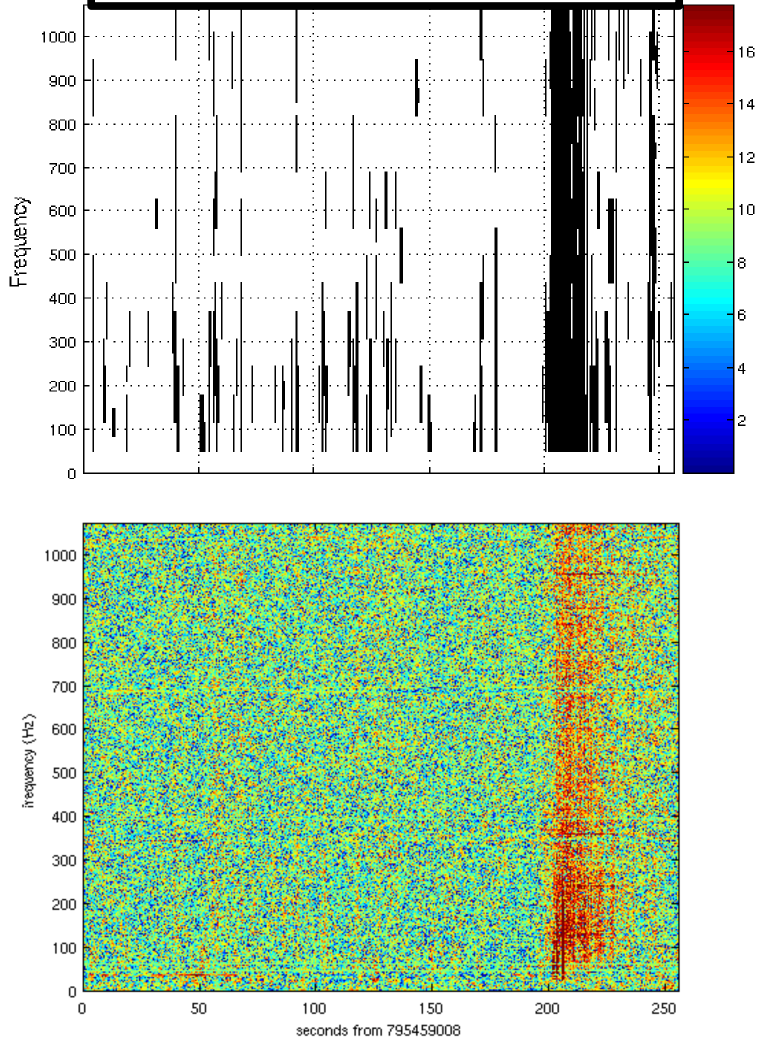
Image: Benger

Burst Group Activities

- Search for bursts of unknown origin/waveform
  - » Generate event triggers for each instrument
  - » Veto triggers due to instrumental artifacts
  - » Determine upper limit on rate as function of strain
  - » Monte Carlo by simulated injections of astrophysical motivated signals and other model burst waveforms
- Ongoing activities
  - » Search for bursts associated with GRB's and other EM triggers
  - » Untriggered searches by broad range of methods (cast wide net)
  - » Inpiral-burst-ringdown coincidence searches
  - » Cosmic string burst search
- Other Activities:
  - » LIGO-TAMA Joint Analysis of S2 Data (complete)
  - » LIGO-VIRGO Working Group

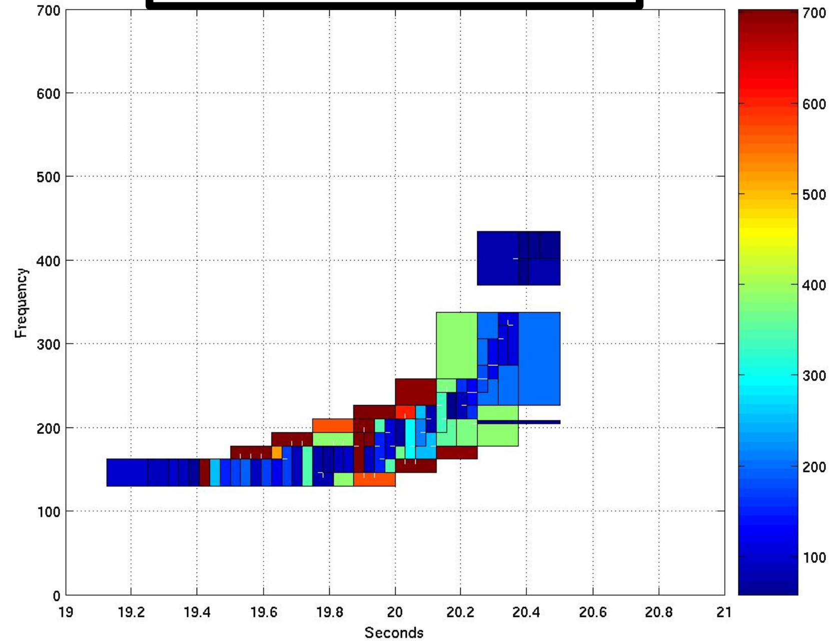
Search Method: Time-frequency decompositions

Noise event: triggers and spectrogram



Requires coincidence between at least two interferometers & detailed examination of instrumental & environmental behavior

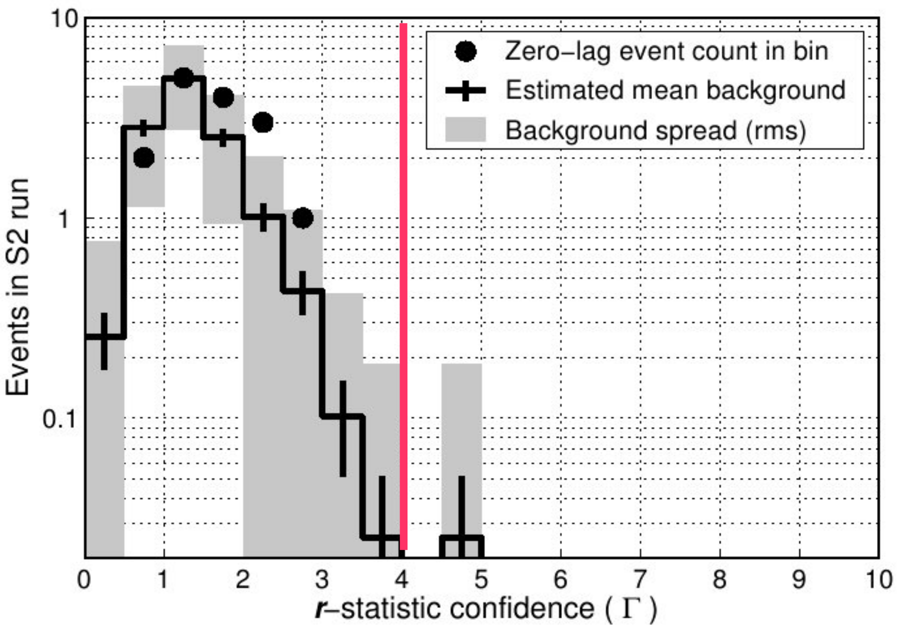
Simulated injection in hardware



LIGO

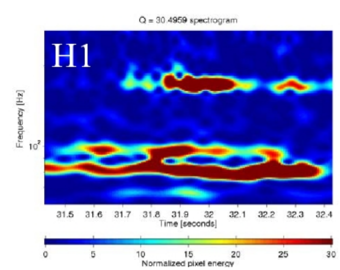
Burst search results

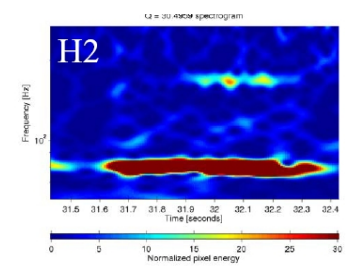
Phys. Rev. D. 72, 062001 (2005)

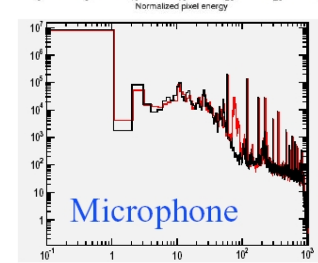


- Raw results are reported
- Interpreted upper limit on representative waveform families is also report ......

- Burst search triggers
  - » Blind search procedure provide list of coincident triggers
  - » Auxiliary and environmental channels provide important information which can veto a trigger – very important to burst searches.
  - » Example:

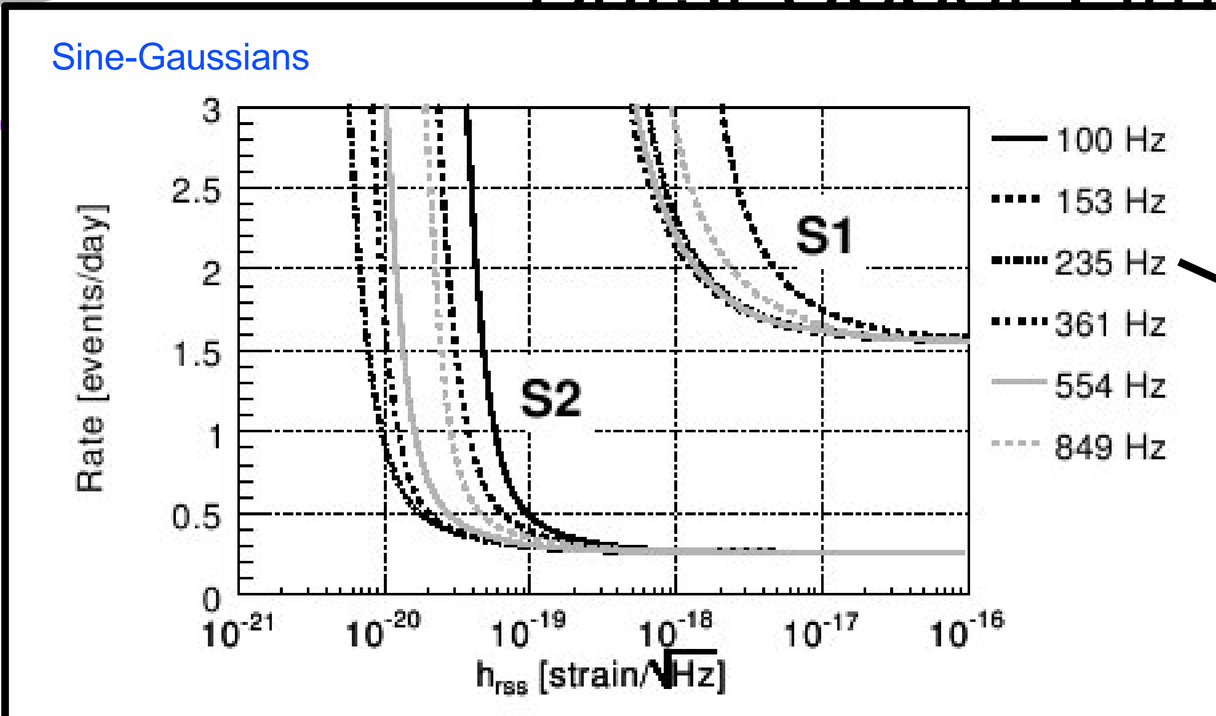


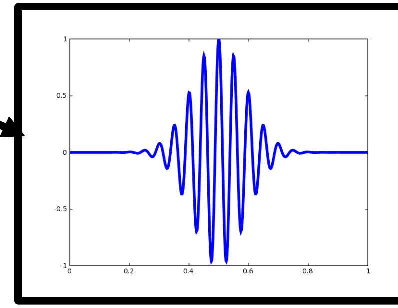


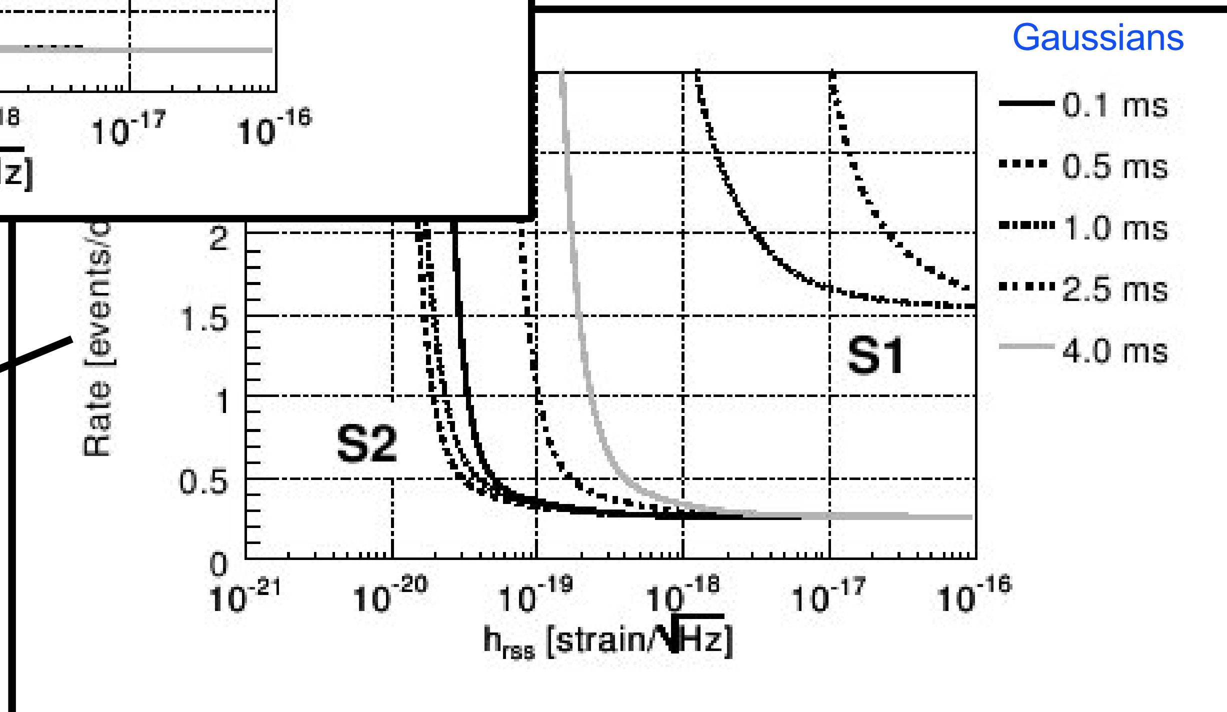


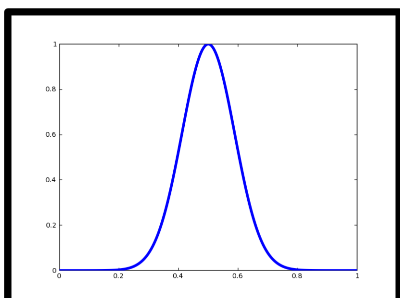
Burst Upper Limit

Phys. Rev. D. 72, 062001 (2005)



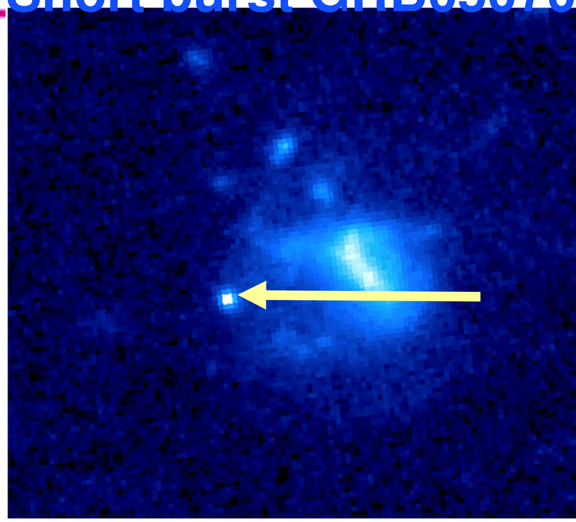






Gamma-ray bursts: short and long

Short burst GRB050709

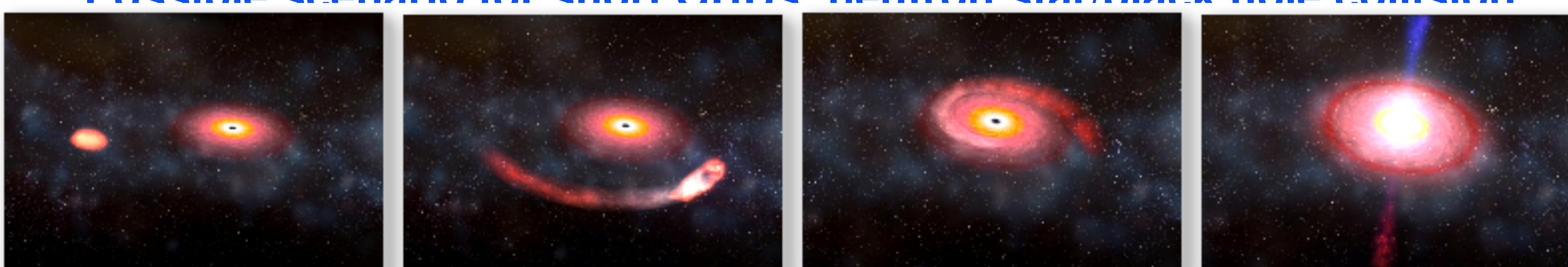


HST Image Credit: Derek Fox

Long burst GRB030329

NASA Image

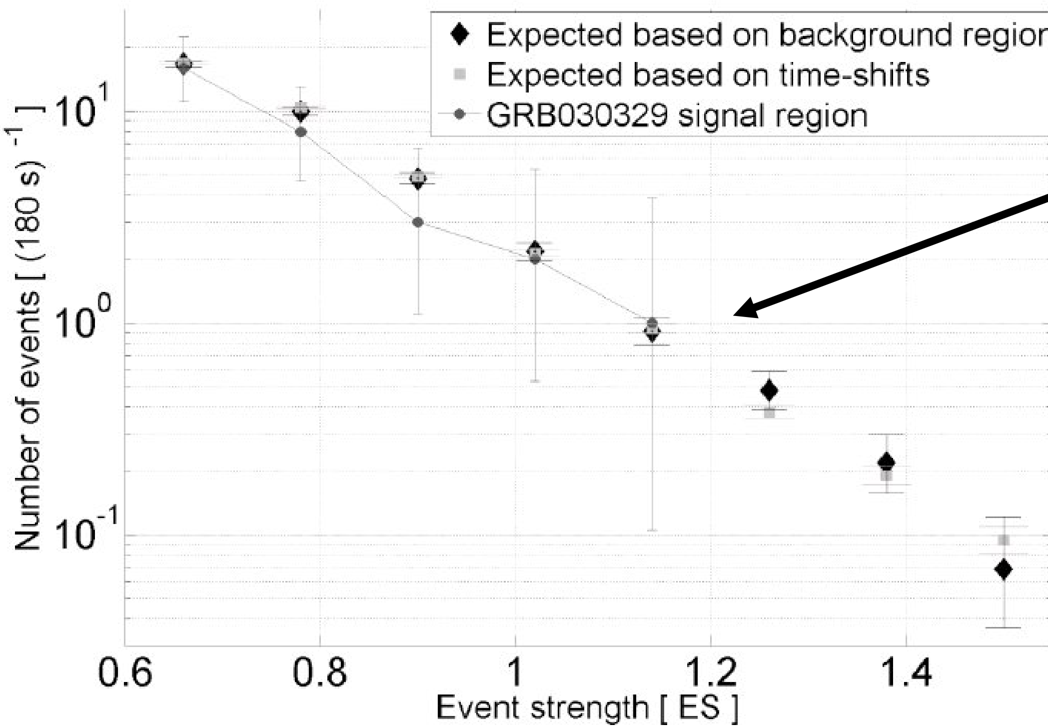
Possible scenario for short GRBs: neutron star/black hole collision



Credit: Dana Berry/NASA

Triggered search around GRB030329

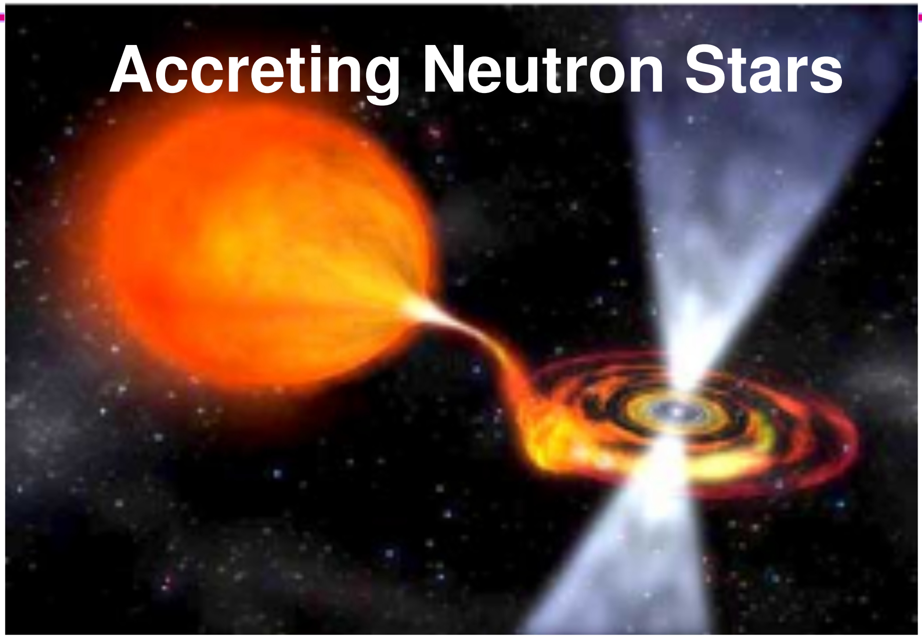
*Physical Review D **72** 042002 (2005)*



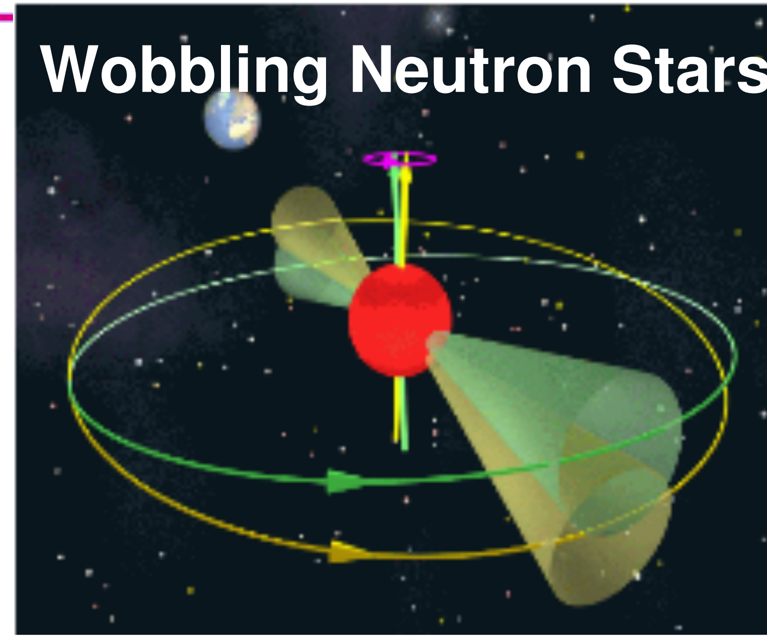
Root sum square sensitivity < 6×10^{-21}

- Cross-correlate data around time of GRB trigger
- Estimate background from off-source times around GRB
- Estimate background from time-slides
- S3/S4 analysis will cover ~20-30 GRB's

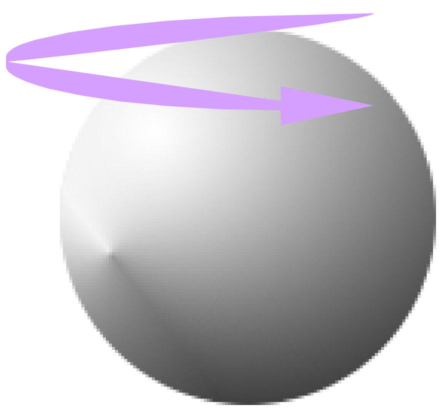
Continuous wave searches: target sources



Credit: Dana Berry/NASA



Credit: M. Kramer



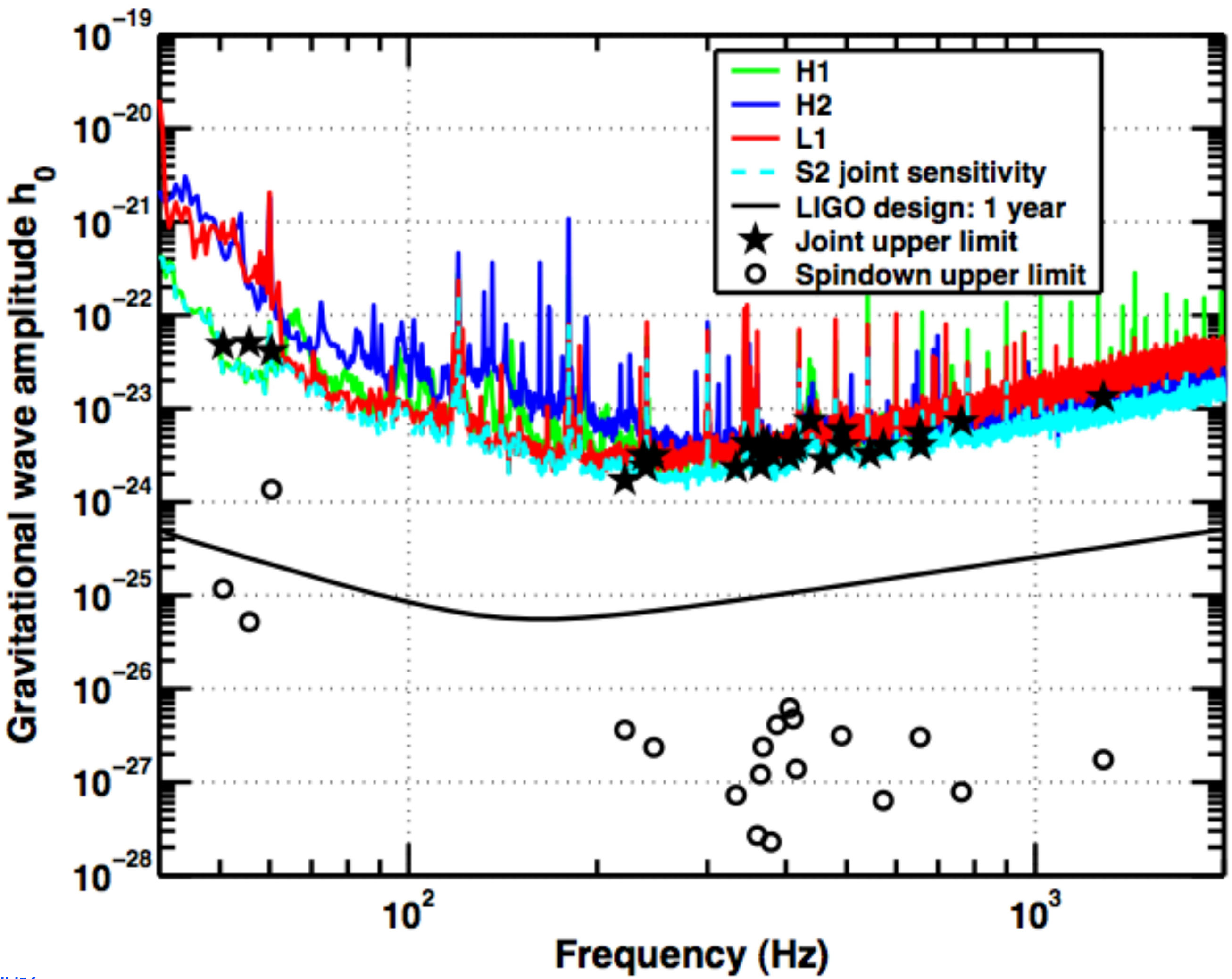
Bumpy Neutron Star

Continuous Wave Group Activities

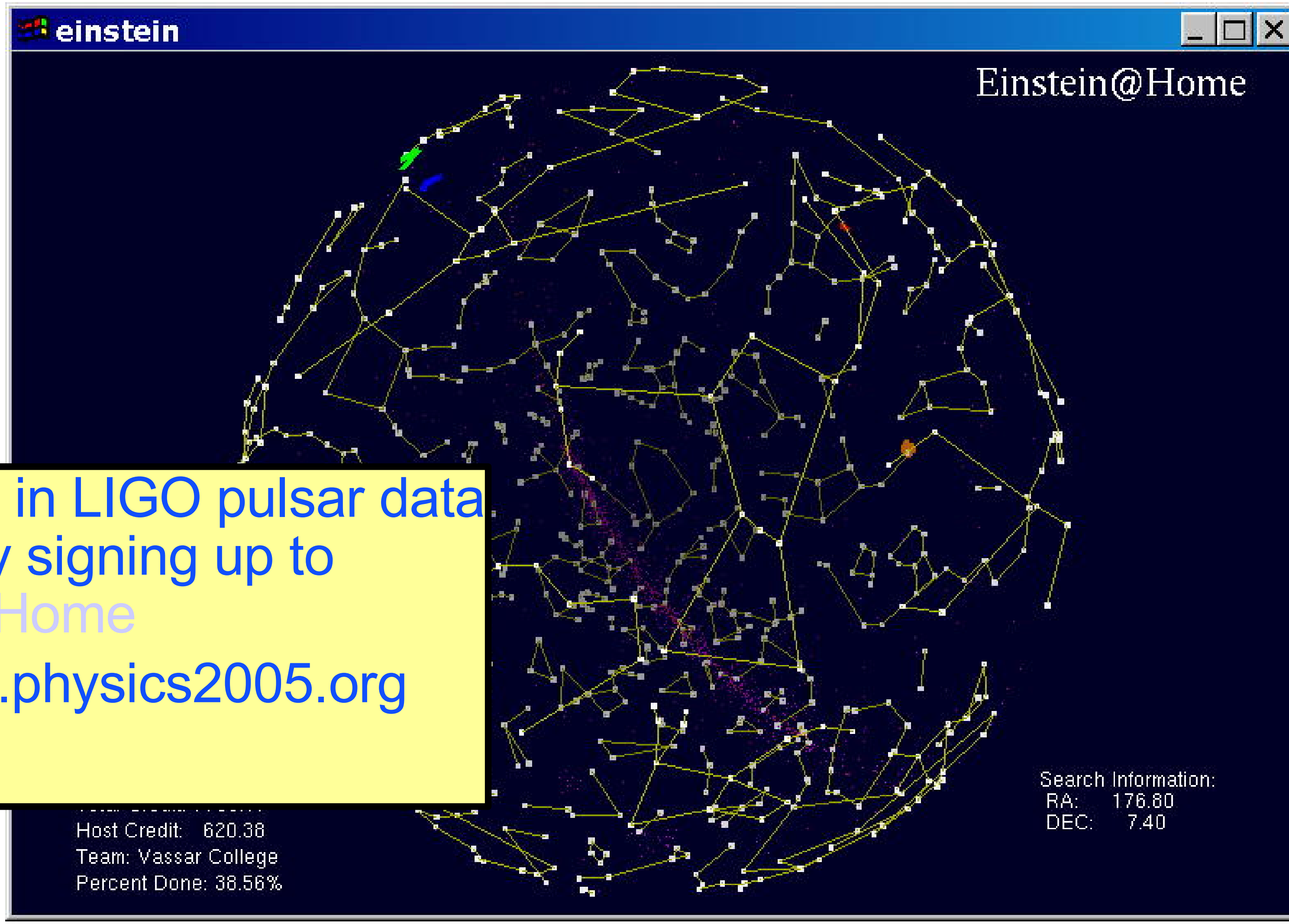
- Known pulsar searches
  - » Catalog of known pulsars
  - » Heterodyne narrow BW folding data
  - » Coherent frequency domain search using Hough transform
- All sky unbiased
  - » Sum short power spectra (no doppler correction)
- Wide area search
  - » Hierarchical Hough transform code is under development
  - » Demodulation is functioning and used in known pulsar search
  - » Demodulation points on sky under control
  - » Efficient positioning of spindown/sky points under development

Search for Known Pulsars

Physical Review Letters ***94*** *181103 (2005)*

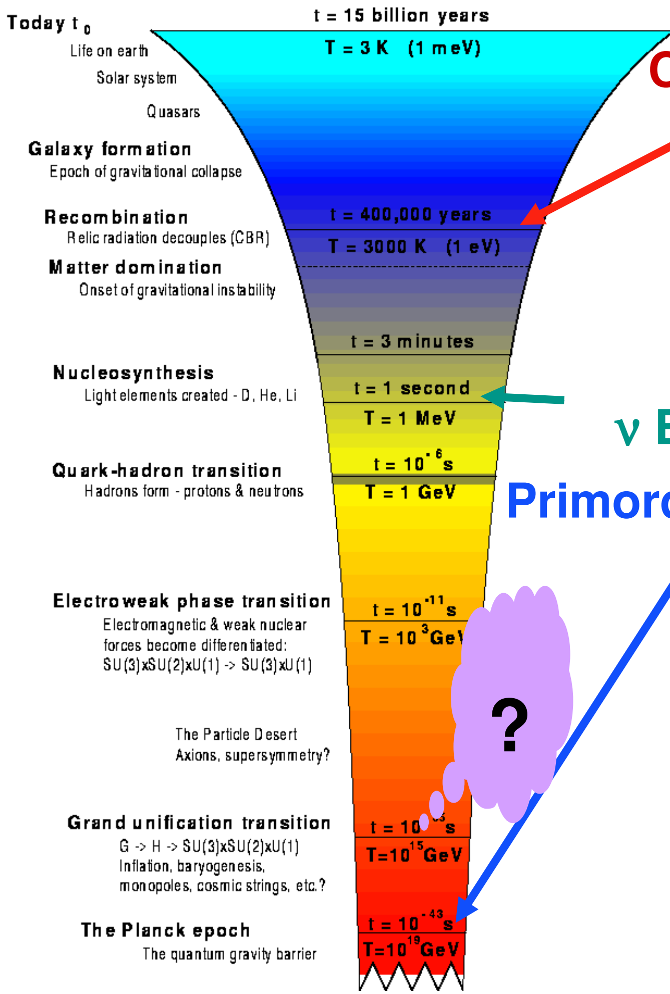


Einstein@Home

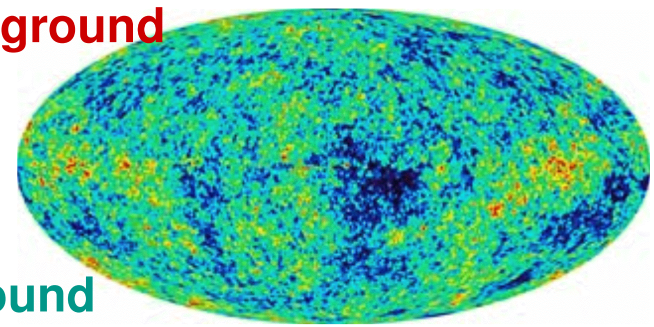


- Participate in LIGO pulsar data analysis by signing up to Einstein@Home
- http://www.physics2005.org

Probing the early Universe

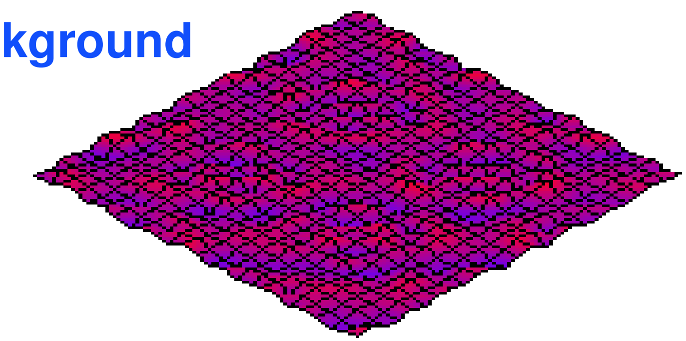


Cosmic Microwave Background



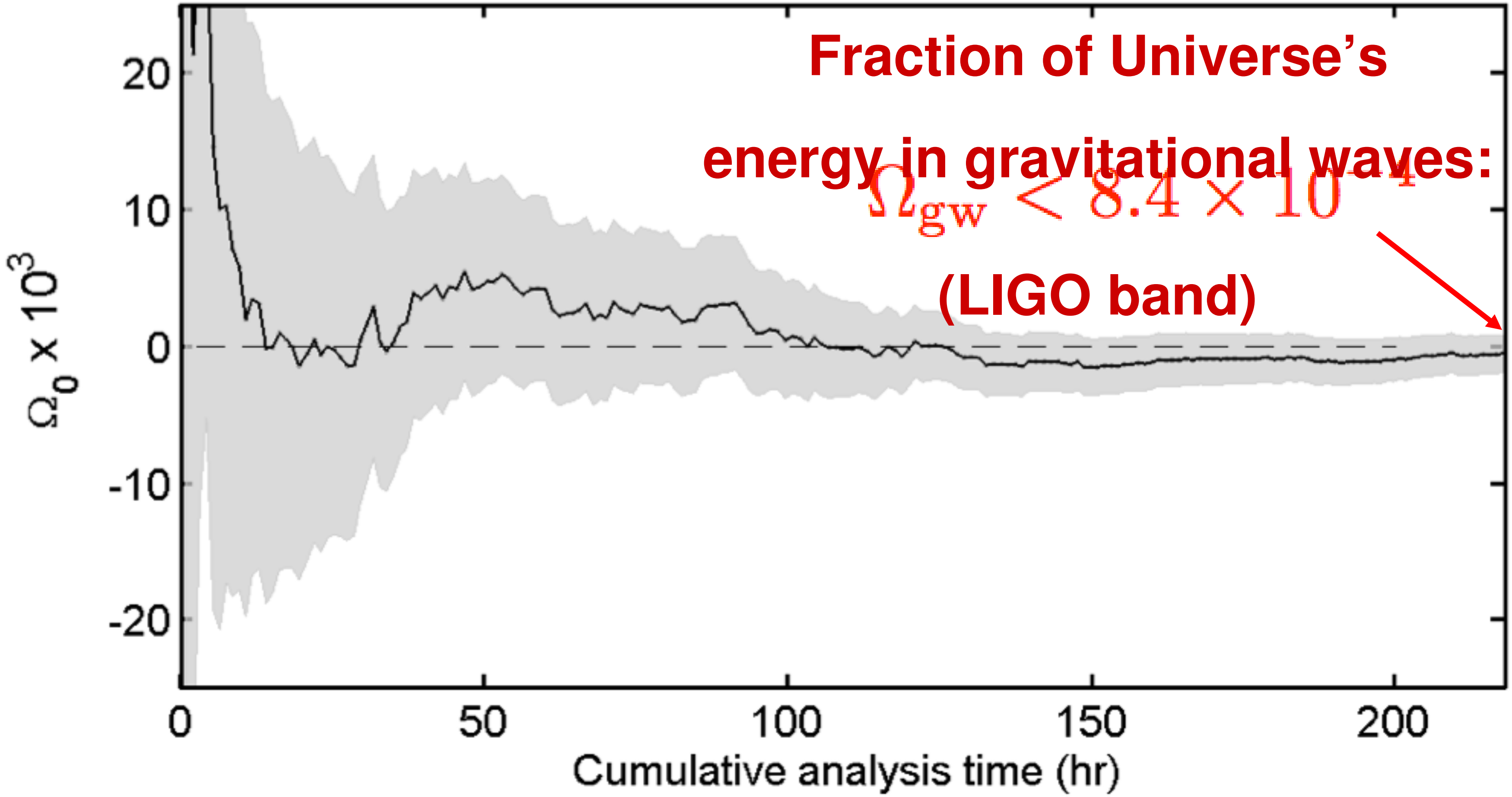
ν Background

Primordial Gravitational-Wave Background



Stochastic Background Search (S3)

Physical Review Letters, In Press



Fraction of Universe's energy in gravitational waves: $\Omega_{gw} < 8.4 \times 10^{-4}$ **(LIGO band)**

Observational Constraints

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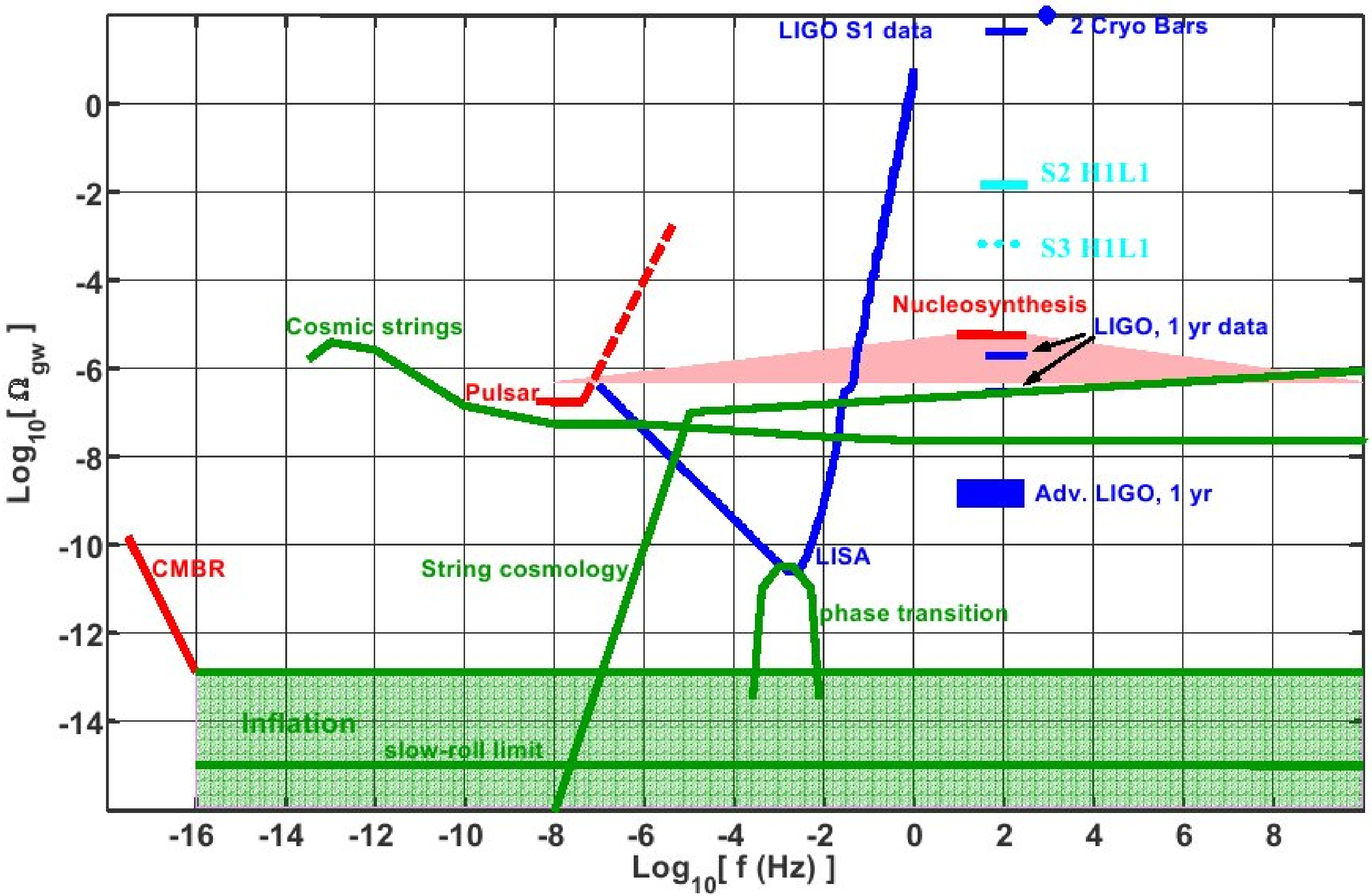

S5 Plans: Inspiral Searches

- The following searches will be "fast-tracked"
  - » Binary Neutron Star Search
  - » Binary Black Hole Search
- Targets for the analysis:
  - » First stage triggers generated in real time at LHO, LLO and by GEO using Onasys
  - » Trigger summaries available via DMT monitor in control room
  - » Latency on this will be about 10 minutes
  - » Coincidence and chi-squared test performed at central location with latency of about 1-2 hours
  - » Background estimation automatically handled in coincidence step
  - » Injection runs running side-by side with main searches
  - » Coherent follow up of candidates with latency of 1-2 hours
  - » Group will follow up accidentals

S5 Plans: Burst Searches

- Searches that will be fast-tracked
  - » Prompt follow up in the gravitational-wave channel of GRB and other astronomical triggers
  - » All-sky, all-times search (untriggered searches)
    - – Online “high threshold” search, gold plated event detection search or upper limit
    - – Offline deeper search
    - – Distributional analysis
  - » Prompt (minutes, hours) detector characterization
    - – Establish data quality
    - – Event-by-event vetoes
    - – Establish criteria for detection confidence
    - – Support online “high threshold” search
    - – Characterize outliers in near real-time

S5 Plans: Continuous Wave Searches

- Following searches that can be “fast-tracked” , but ***not*** online
  - » Time-domain searches for known objects
    - – Updates ~ 1/month
  - » Incoherent methods
    - – Blind all-sky,wide-band searches. Monthly results for internal consumption.
    - – But deeper searches will not be available on this time scale
- Online daily fast scan of data without Doppler modulation correction. Computational cost negligible.
- Goal: deepest, blind, wide-band search : hierarchical also with. Einstein@Home

S5 Plans: Stochastic Searches

- Search that will be “fast-tracked”
  - » Accumulated sensitivity calculated on weekly basis
  - » GPS times that fail sigma ratio cut (-> stationarity)
  - » Long-term coherence calculations (weekly)
  - » Fast-track: H1-L1 isotropic search (6 months)
- Possible bottle necks:
  - » Statistically significant H1-L1 correlation!!