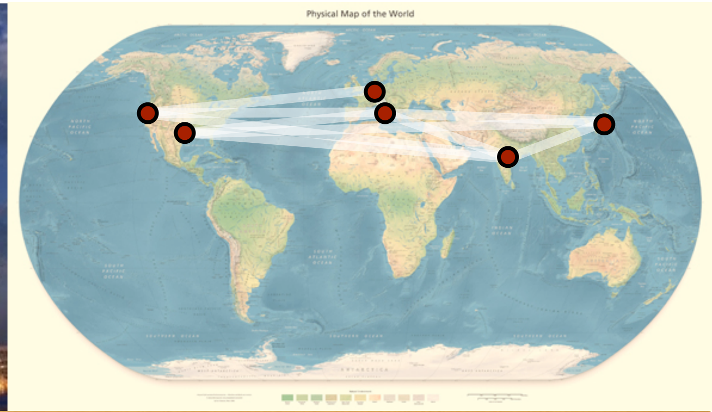


Gravitational Wave Astronomy in the next Decade

Bernard Schutz
MPI Gravitational Physics (Albert Einstein Institute), Germany
and Cardiff University, Wales

Gravitational Waves ~1963

- GW detection is not on the agenda at the First Texas Symposium. But its origins are in the same period.

Theory

- 1955: Einstein dies, believing GWs probably not real!
- 1955-7: Work by Goldberg, Weber & Wheeler, Pirani, others give convincing arguments about reality.
- 1957-mid '60s: Energy in GWs understood, GW generation begins to come under control.

Observation

- 1960: Weber embarks on GW detection with first bar detector.
- He considered interferometry but rejects it because technology was not ready.
- Late '60s: Weber claims GW detections. Within 5 years this claim is no longer accepted.

Gravitational Waves ~1963

- GW detection is not on the agenda at the First Texas Symposium. But its origins are in the same period.

Theory

- 1955: Einstein dies, believing GWs probably not real!
- 195 We others give convincing arguments about reality.
- 1957-mid '60s: Energy in GWs understood, GW generation begins to come under control.

Observation

- 1960: Weber embarks on GW detection with first bar
- metry but rejects it because technology was not ready.
- Late '60s: Weber claims GW detections. Within 5 years this claim is no longer accepted.

First clean observational evidence:
J Taylor at 1978 Texas Symposium (Munich)!

From Weber to LIGO

- From 1970s to 1990s, interferometer groups developed technology using prototypes. Bars gradually became obsolete.
- Theoretical studies showed that supernovae are not promising sources (target for bars) but compact-object binaries (NS-NS, BH-BH) are very promising (require broadband interferometers for detection). pN binary theory had to be worked out!
- LIGO, VIRGO, GEO600 2015-10 were the first instruments to reach a "plausible" detection sensitivity. But they did not get lucky.
- Advanced LIGO and VIRGO will reach a "probable" detection sensitivity 2016-18.
- From Weber's bars ($h \sim 10^{-16}$) to Advanced LIGO ($h \sim 10^{-22}$) is a reach improvement of 10^6, equivalent to increasing the diameter of a telescope by the same factor. Field has progressed by roughly a factor of 10 each decade.
    - *If one's eye has a 7 mm pupil, this would scale it up to a telescope diameter of 7 km!*
- But our little 7 mm eyes *see* stars at night. aLIGO is only just at that threshold!
- Remarkably, four different technologies are now moving in parallel toward GW detection in four different frequency bands: LIGO, eLISA, pulsar timing, CMB.

LIGO 1992 vs 2013

How does LIGO's 1992 "definition" paper (Abramovici et al, *Science* **256**, 325-333) compare to sensitivity and rate predictions today (LV "Observing Scenarios" paper arXiv:1304.0670, subm. *Liv Rev Relativity*).

1992	2013
LIGO's first detector system might see gravitational waves, and the advanced detectors discussed above are highly likely to see them. Success will probably come between the first-detector level and the advanced level, that is, a few years after LIGO goes into operation.	Initial detectors made no detections; advanced detectors very likely to do so.
The uncertainty in the waves' strength arises solely from the uncertain distance to the nearest such sources. The observed statistics of binary neutron stars in our own galaxy, extrapolated to include distant galaxies, give a best estimate (*32, 33*) of 200 Mpc (650 million light years) for the distance to which LIGO must look to see three neutron star inspirals per year. Further anal-	Advanced detectors will increase sensitivity in stages. By 2019 the mean range should be 200 Mpc and the expected number of binary neutron star detections will be 0.2-200 per year, with a best estimate of 40 per year.

LIGO 1992 vs 2013

How does LIGO's 1992 "definition" paper (Abramovici et al, *Science* **256**, 325-333) compare to sensitivity and rate predictions today (LV "Observing Scenarios" paper arXiv:1304.0670, subm. *Liv Rev Relativity*).

1992

LIGO's first detector system might see gravitational waves, and the advanced detectors discussed above are highly likely to see them. Success ... the first-detect... level, that is, a... into operation.

The uncertainty in the waves' strength arises solely from the uncertain distance to the nearest such sources. The observed statistics of binary neutron stars in our own galaxy, extrapolated to include distant galaxies, give a best estimate (32, 33) of 200 Mpc (650 million light years) for the distance to which LIGO must look to see three neutron star inspirals per year. Further anal-

2013

- Initial detectors made no detections; advanced detectors

But: Initial estimates of the timescale to build LIGO were too optimistic. Reasons: complex technology, slower pace of funding.

- Advanced detectors will increase sensitivity in stages. By 2019 the mean range should be 200 Mpc and the expected number of binary neutron star detections will be 0.2-200 per year, with a best estimate of 40 per year.

LIGO 1992 vs 2013

How does LIGO's 1992 "definition" paper (Abramovici et al, *Science* **256**, 325-333) compare to sensitivity and rate predictions today (LV "Observing Scenarios" paper arXiv:1304.0670, subm. *Liv Rev Relativity*).

1992

LIGO's first detector system might see gravitational waves, and the advanced detectors discussed above are highly likely to **see** them. Success will probably come between the first-detector level and the advanced level, that is, a few years after LIGO goes into operation.

The uncertainty in the waves' strength arises solely from the uncertain distance to the nearest such sources. The observed statistics of binary neutron stars in our own galaxy, extrapolated to include distant galaxies, give a best estimate (*32, 33*) of 200 Mpc (650 million light years) for the distance to which LIGO must look to **see** three neutron star inspirals per year. Further anal-

2013

- Initial detectors made no detections; advanced detectors very likely to do so.
- Advanced detectors will increase sensitivity in stages. By 2019 the mean range should be 200 Mpc and the expected number of binary neutron star detections will be 0.2-200 per year, with a best estimate of 40 per year.

The GW Paradigm

- Over the last 10 years we have begun to understand GW astronomy using a paradigm of "listening" rather than "seeing".
- Detectors are like microphones: essentially omni-directional.
- Information is mainly in the **phase** of the waveform, not its spectrum.
- GWs, like sound, penetrate where light cannot, so they can reveal dark or obscured systems.

Now: the Current IFO network

All GW projects cooperate and pool data. Demanded by the science: reliability, sky position, polarization, ...

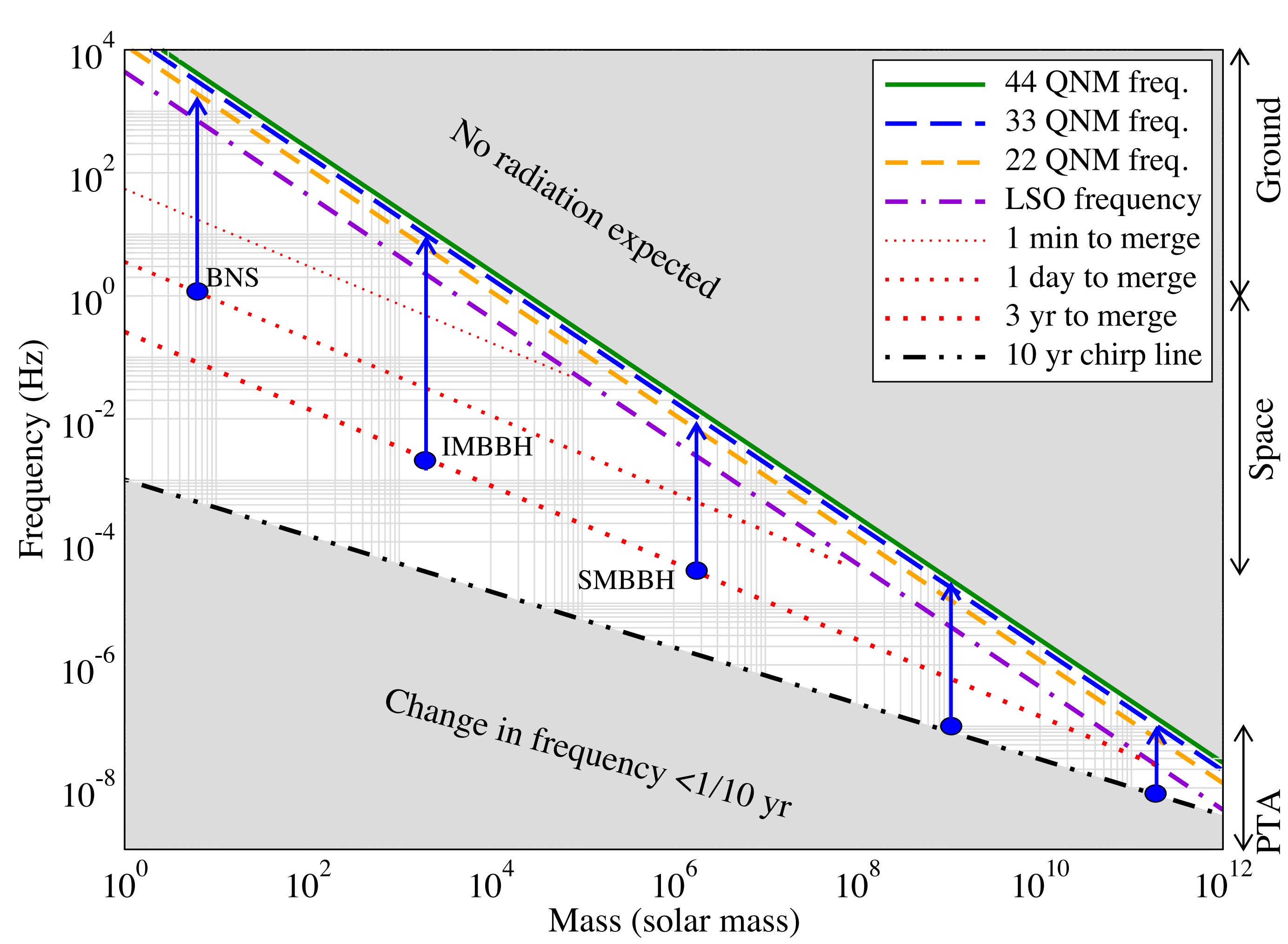
Inherent danger in such a monopoly, so L-V collaboration takes elaborate steps for quality control.

Answer in the long run is open data.

First-generation IFOs

- Observing by LIGO, Virgo, GEO600 2005-2010 has laid foundations for success with Advanced Detectors:
  - Demonstration that large IFOs can be controlled with duty cycle ~ 70%.
  - Organizing data analysis teams, proving of data analysis algorithms, verifying code, establishing the results review process, agreeing detection criteria, even writing a specimen paper.
  - Development in GEO600 of Advanced technologies: monolithic suspensions, high-power lasers, signal recycling, squeezed light.
  - Significant upper limits on GW pulsars (Crab, Vela), stochastic background radiation, compact binary coalescence.

The GW Spectrum



(B. S. Sathyaprakash)

Binaries with LIGO-Virgo

- Binaries in 100 Hz band all merge within a few minutes
  - BNS: best estimate rate 40/yr at 200 Mpc
  - BBH: very uncertain, rate maybe 50% of BNS
  - NS-BH: maybe rare?
- Initial detectors have set upper limits
  - BNS: none to 20 Mpc, rate < 1.3×10^{-4} Mpc^{-1} yr^{-1}; for Adv LIGO ~ 10^3 yr^{-1}. [*Phys. Rev. D* **85**, 082002 (2012)]
  - BBH: none to 300 Mpc, rate < 3.3×10^{-7} Mpc^{-1} yr^{-1}; for Adv LIGO ~ 10^3 yr^{-1}. [*Phys. Rev. D* **87**, 022002 (2013)]

GW Pulsars with LIGO-Virgo

- Spinning NSs are long-lived, so GWs must be weak. Need to integrate months of data.
- Searches for known pulsars use radio timing. See arXiv: 1309.4027.
  - Crab: $h < 2.3\text{x}10^{-25}$, $(\mathrm{d}E/\mathrm{d}t)_{\mathrm{GW}} < 0.01\ (\mathrm{d}E/\mathrm{d}t)_{\mathrm{tot}}$
  - Vela: $h < 1.1\text{x}10^{-24}$, $(\mathrm{d}E/\mathrm{d}t)_{\mathrm{GW}} < 0.1\ (\mathrm{d}E/\mathrm{d}t)_{\mathrm{tot}}$
- All-sky searches (Einstein@Home): no detections, limits around $h = 10^{-24}$, depends on f. [*Phys. Rev. D* **87**, 042001 (2013)].
- The limits for known pulsars typically constrain ellipticity around spin axis to $\varepsilon < 10^{-6}$ or even smaller. Neutron stars are spherical at the 1 cm level!!

Burst searches w LIGO-Virgo

- There have been many searches with data 2005-10:
  - Untriggered all-sky searches set upper limits around 10^{-21} in 1 year: *Phys. Rev. D* **85**, 122007 (2012).
  - Searches triggered by gamma-ray bursts have found no GW counterparts. See arXiv:1309.6160, *Astrophys. J.* **760** (2012) 12, *Astrophys. J.* **755** (2012) 2.
  - Swift did searches triggered by GW candidate events, also with no positives: *Astrophys. J. Suppl.* **203** (2012) 28
  - Searches for coincidences between GW and neutrino events with Antares: *JCAP* **1306** (2013) 008.
  - Searches for optical counterparts to GW candidate events: arXiv: 1310.2314, *Astron. Astrophys.* **541** (2012) A155
- These have prepared software, techniques, protocols for searches with advanced detectors.

Other LIGO-Virgo Searches

- Many other searches have been performed:
  - Stochastic background (isotropic and directed)
  - Cosmic strings
  - GWs from pulsar glitches (NS ringdown modes)
  - GWs from pulsars near Galactic Center
  - Ringdowns of black holes

Einstein@Home Finds Radio and Gamma-ray Pulsars

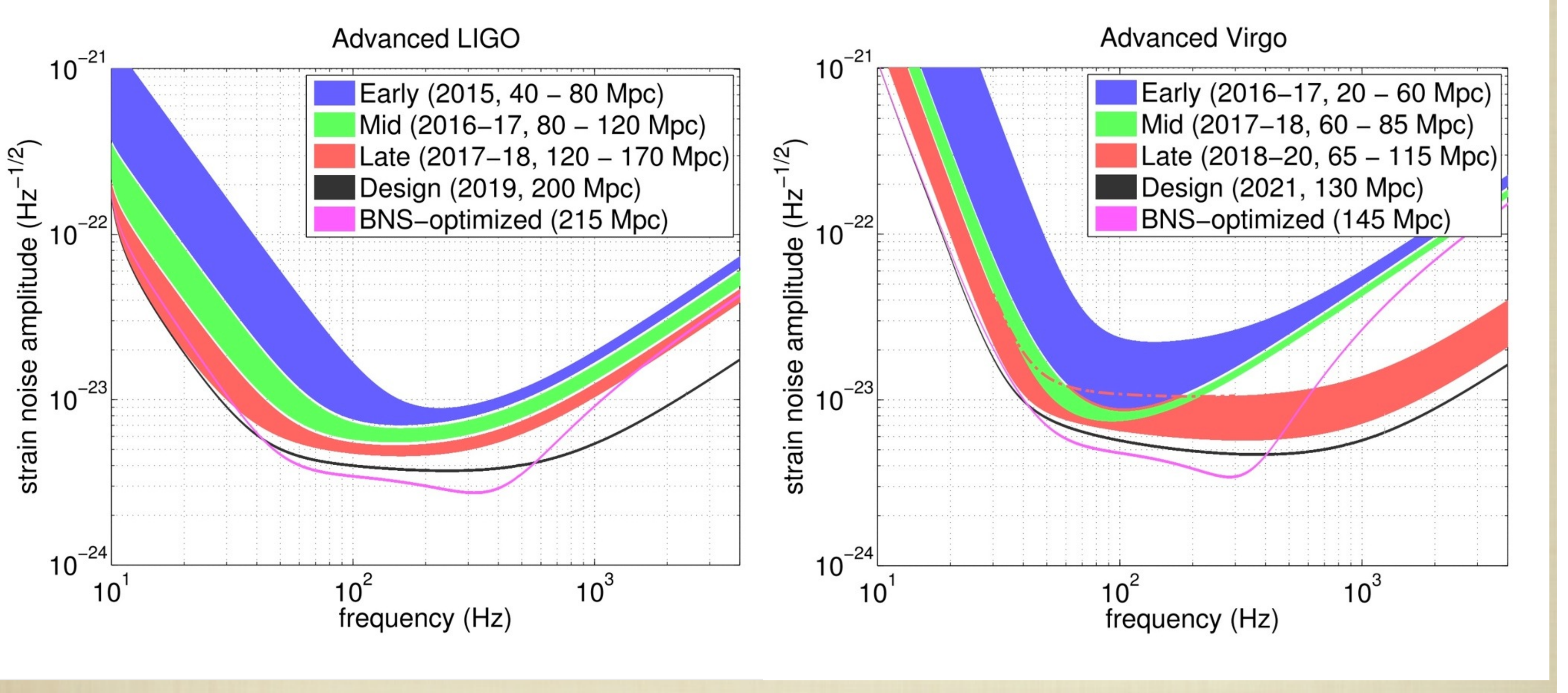
- Volunteer computing system Einstein@Home delivers 470 Tflops continuously.
- GW software was developed for deep searches for periodic signals.
- Bruce Allen and team (AEI) applying similar techniques and finding pulsars in data from Aricebo [*Astrophys. J. Lett.* **732**, L1 (2011)] and Fermi/LAT [*Astrophys. J. Lett.* **779**, L11 (2013)].
- Recent Parkes analysis found 24 pulsars, including 6 in binaries [*Astrophys. J.* **774**, 93 (2013)].

Advanced Detector Observing

- From 2015 onward, LIGO will have periods of observing alternating with periods of improving sensitivity.
- Intensive preparations in the collaboration to prepare for low-latency analysis and data releases.
- If all goes well and the “best estimate” rates are correct, first detection should happen 2016-17.
- Multimessenger should be a feature of the observing scenario from the start. L-V has had meetings in Amsterdam and Chicago to initiate collaborations with EM and neutrino observers.

Projected progress

arXiv:1304.0670



Ranges are polarization- and antenna-pattern-averaged detection distance for NS-NS binary coalescence.

First science with aLIGO

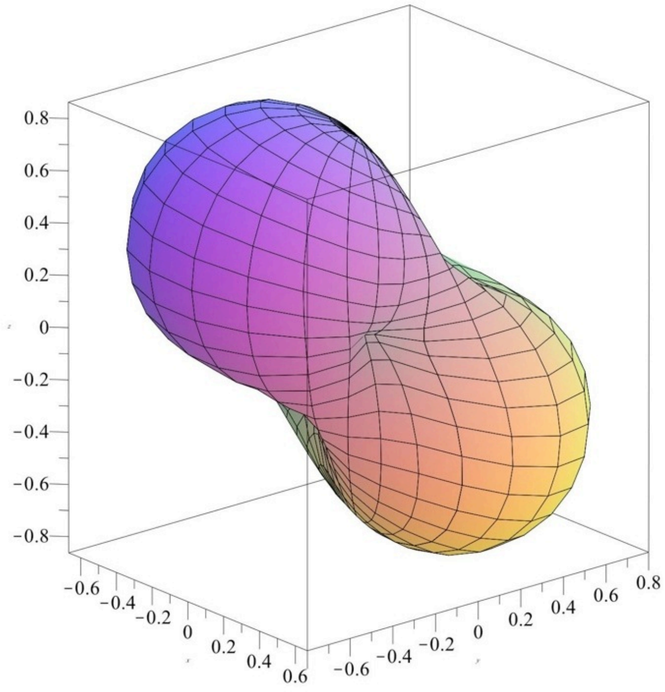
- When the aLIGO range reaches 120 Mpc, the “best estimate” NS-NS merger rate (*CQG* **27**, 173001, 2010) suggests a detection rate of 4 per year. This could happen in 2016 but more likely 2017. The real rate might be as low as 0.04 per year or as high as 40 per year.
- The first NS-NS detections will be intensively followed up by EM observatories looking for afterglows, but if AdV is not observing, or has lower sensitivity, then error box is very big. About 1 in 30 detections is expected to be associated with a detected gamma-ray burst (depends on beam-width of gamma burst).
- BH-BH merger rate more uncertain, but “expected” rate is about 50% of NS-NS rate.
- The network SNR threshold for these detections should be about 12. Median SNR will be 1.3 times this ~ 15 $\Rightarrow$ typical parameters measured to 7% accuracy.
- Standard sirens: distance to binaries to ±7% if position error is reduced by ID.
- After the first 4 confirmed events, LIGO will begin releasing alerts (including data) on all strong candidates.

New detectors

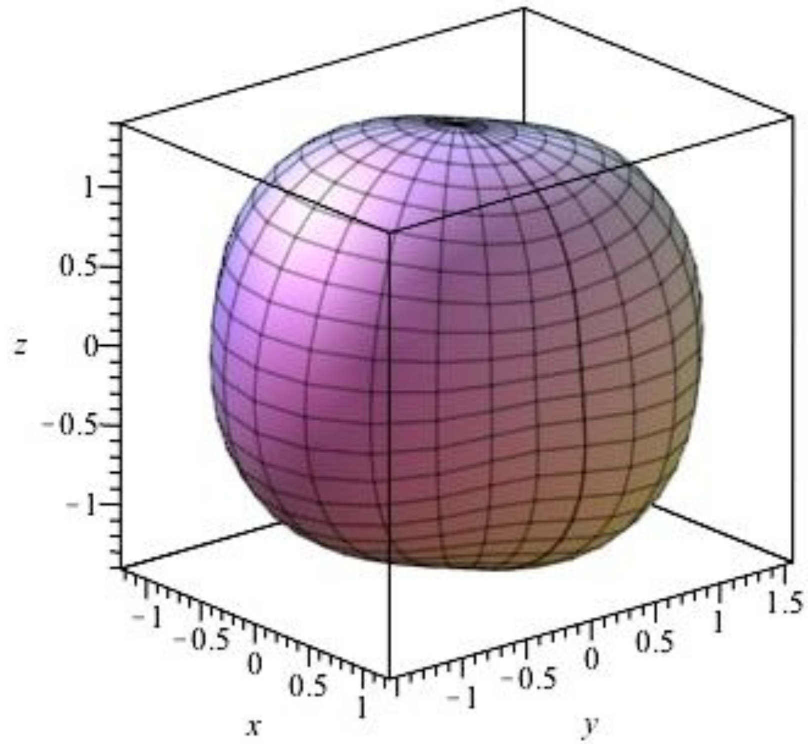
- KAGRA (**KA**mioka **GRA**vitational wave detector, Japan) plans a very short iKAGRA observing run in 2015 at low sensitivity. But it projects it will reach full advanced-level sensitivity by 2018.
  - With KAGRA, network will have better position-finding, more sky coverage.
- LIGO-India expecting approval, but recent financial restrictions in India will stretch out the time-line. Full aLIGO sensitivity not before 2020.
  - With LIGO-India the network will have an isotropic antenna pattern and much better duty cycle.
- GEO-HF will be competitive with aLIGO at $f \sim 1$ kHz until the final sensitivity upgrade of aLIGO uses its full laser power ~2019.

Expanded IFO network 2020+

An Isotropic Network

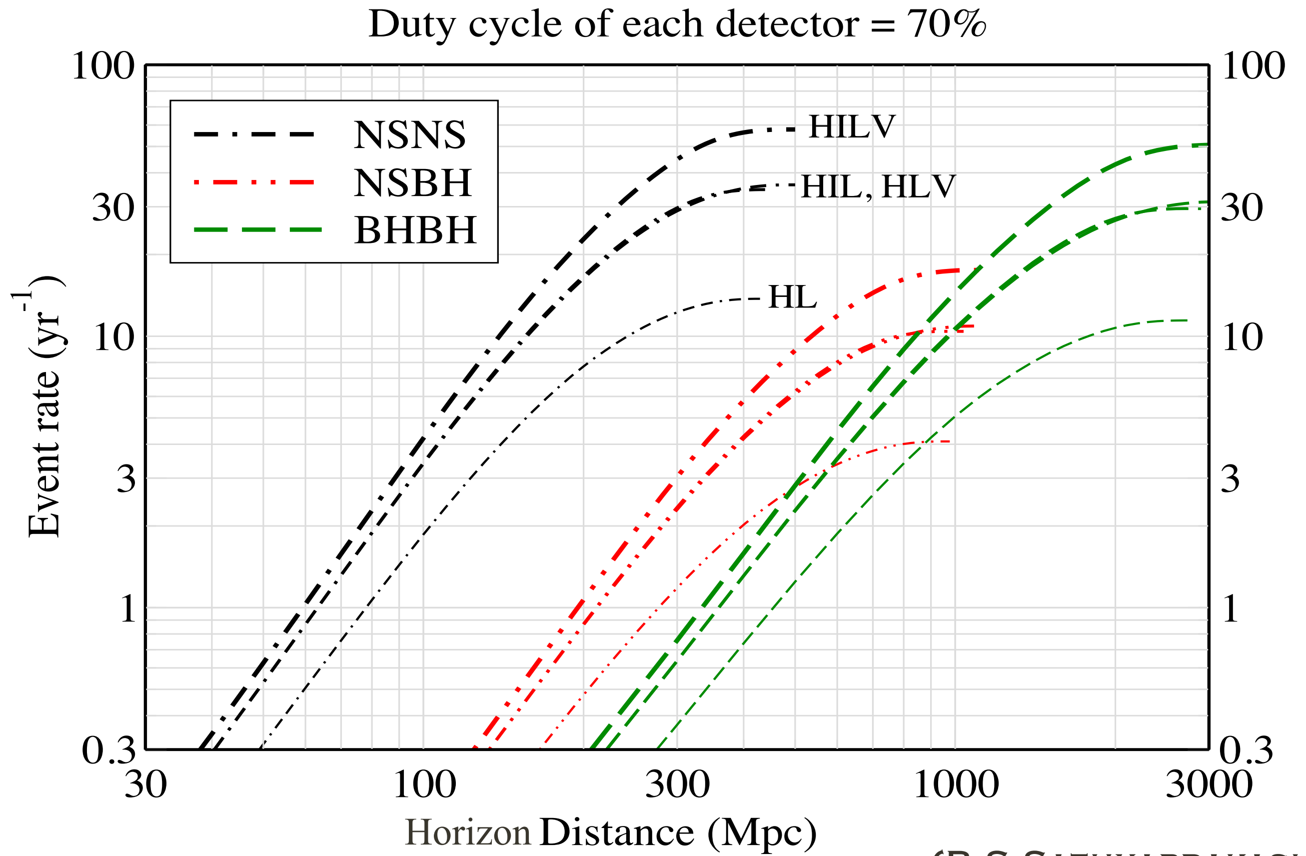


LIGO-Virgo



5 IFOs

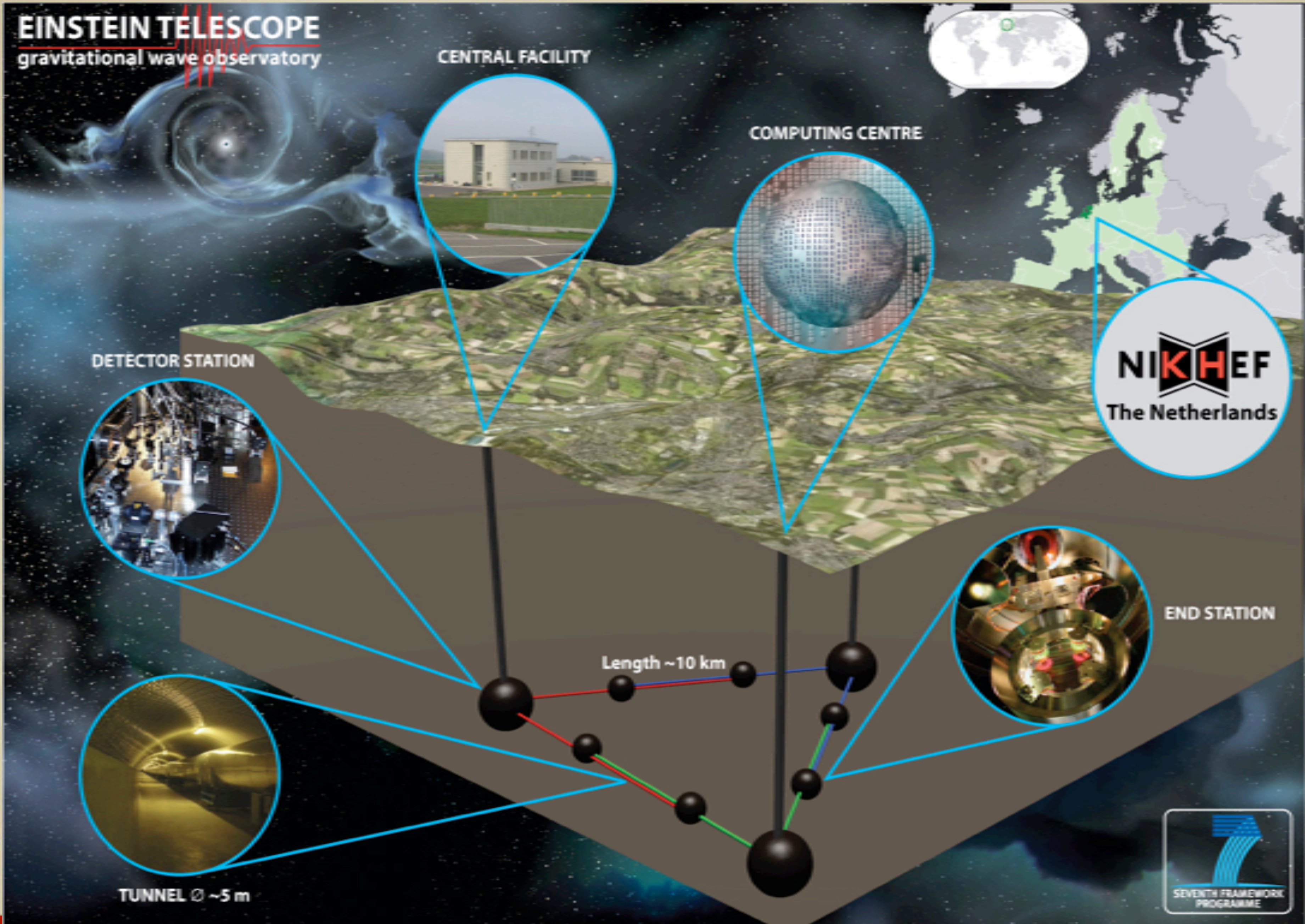
Expected Event Rate



(B S Sathyaprakash)

Science with the full network

- With 5 detectors, NS-NS event rate ~100 per year. Loudest SNR per year ~ 50.
  - *Nuclear physics:* The strongest events constrain NS EOS.
  - *GR Tests:* cosmic censorship, non-GR propagation (v<c, birefringence).
  - *Statistics:* M, J for NSs and BHs in binaries.
  - *Hubble constant:* With 50 NS-NS merger events, network could determine H_0 to better than 1% (statistical errors, no prior IDs needed). But controlling systematics (calibration) will be hard. This is a local value, out to $z \sim 0.05$.
  - *Discovery space:* Network has 3 *null streams* to veto glitches, making searches for unmodelled bursts more sensitive.
  - *Stochastic background:* The 2 LIGO IFOs will reach $\Omega_{gw} \sim 10^{-9}$. Possible sources: GUTs phase transition, cosmic strings, non-standard inflation.
- After 2020, aLIGO and AdV may begin to upgrade again, to "2.5G" sensitivity. Factors of 2-5 are possible in range improvements.


EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
NIKHEF
The Netherlands
END STATION
Length ~10 km
TUNNEL ∅ ~5 m
SEVENTH FRAMEWORK PROGRAMME

Einstein Telescope

- Advanced LIGO & Virgo are the first detection instruments. Real GW astronomy will need more sensitivity, greater range.

- The ET design study, funded by the EU, led to a feasible plan for a 3G detector.

- With two such detectors on the globe, and with 2.5G Advanced detectors still operating, the network could essentially detect all the NS-NS events in the universe.

- Europeans are now preparing a further study proposal for ET. Funding will not be approved before first LIGO detections. Construction would start 2020's, first operation before 2030.

LISA, eLISA and LPF

- mHz band is richest of all. Massive black hole binary mergers out to $z = 20$ or more trace the weaving of the cosmic web. Stringent tests of GR from EMRIs. mHz data stream will be full of overlapping detectable signals.
- The withdrawal of NASA from LISA in 2011 led to a descoping of the mission (only two arms with links, forming only one interferometer), and new competitions for ESA's large mission launches L1, L2, L3.
- ESA has assigned the L3 launch slot in 2034-6 to eLISA. It wanted to wait to make sure LISA Pathfinder is successful, so did not want to allocate L2 (2028).
- LISA Pathfinder launch expected mid-2015.
- ESA will consider minor partnerships with NASA, possibly China. This could roll back the descoping and produce essentially the original LISA science. It might also bring the launch forward in time.

LISA, eLISA and LPF

- mHz band is richest of all. Massive black hole binary mergers out to $z = 20$ or more trace the weaving of the cosmic web. Stringent tests of GR from EMRIs. mHz data stream will be full of overlapping detectable signals.
- The withdrawal of NASA from LISA in 2011 led to a descoping of the mission (only two arms with links, forming only one interferometer), and nev
- ESA … wait to ma … L2 (20
- LIS
- ESA will consider minor partnerships with NASA, possibly China. This could roll back the descoping and produce essentially the original LISA science. It might also bring the launch forward in time.

The eLISA whitepaper is arXiv:1305.5720.
There is a website for the proposal:
http://www.elisascience.org.
Please visit it and sign up as a supporter:
community numbers are being watched by ESA!

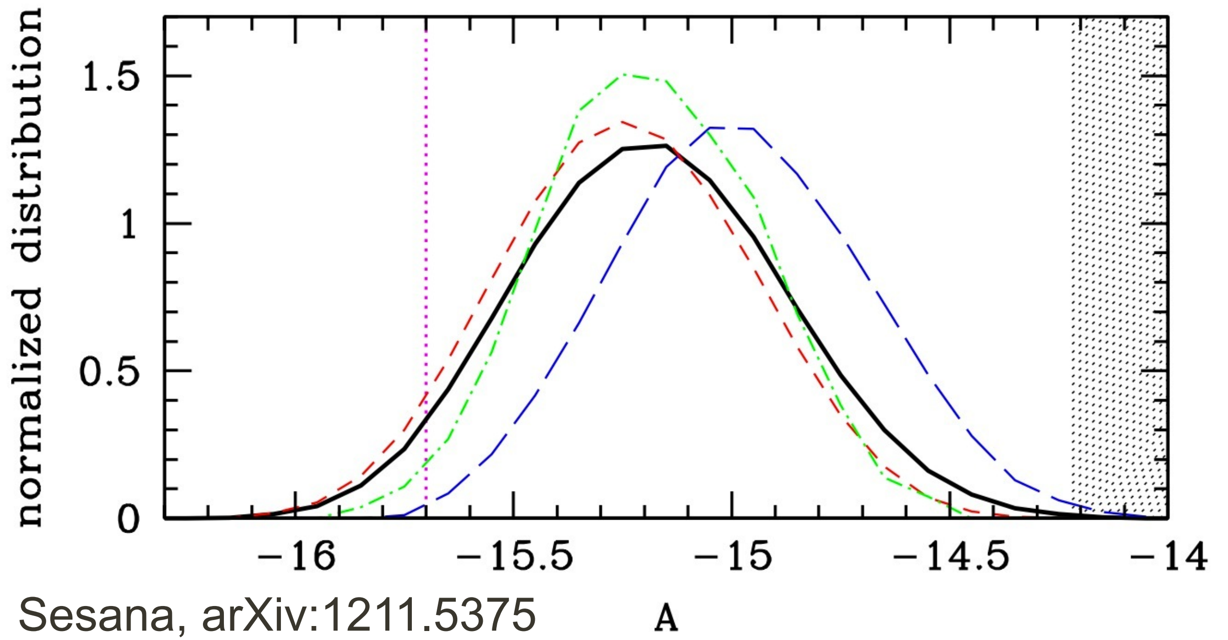
Pulsar Timing Arrays

- The three PTA projects in Australia, Europe, and N America are making rapid progress pooling their data and getting more observing time for the stablest millisecond pulsars.
- Their sensitivity is already beginning to constrain the most optimistic predictions of the level of a stochastic background (of astrophysical origin) at nHz frequencies due to binary SMBHs (McWilliams et al, arXiv1211.4590)
- SKA (2020+) will take PT to a new level: individual SMBH binaries will be identified.

GW amplitude pdf based on large ensemble of evolutionary models.

Shaded: current PTA limits.

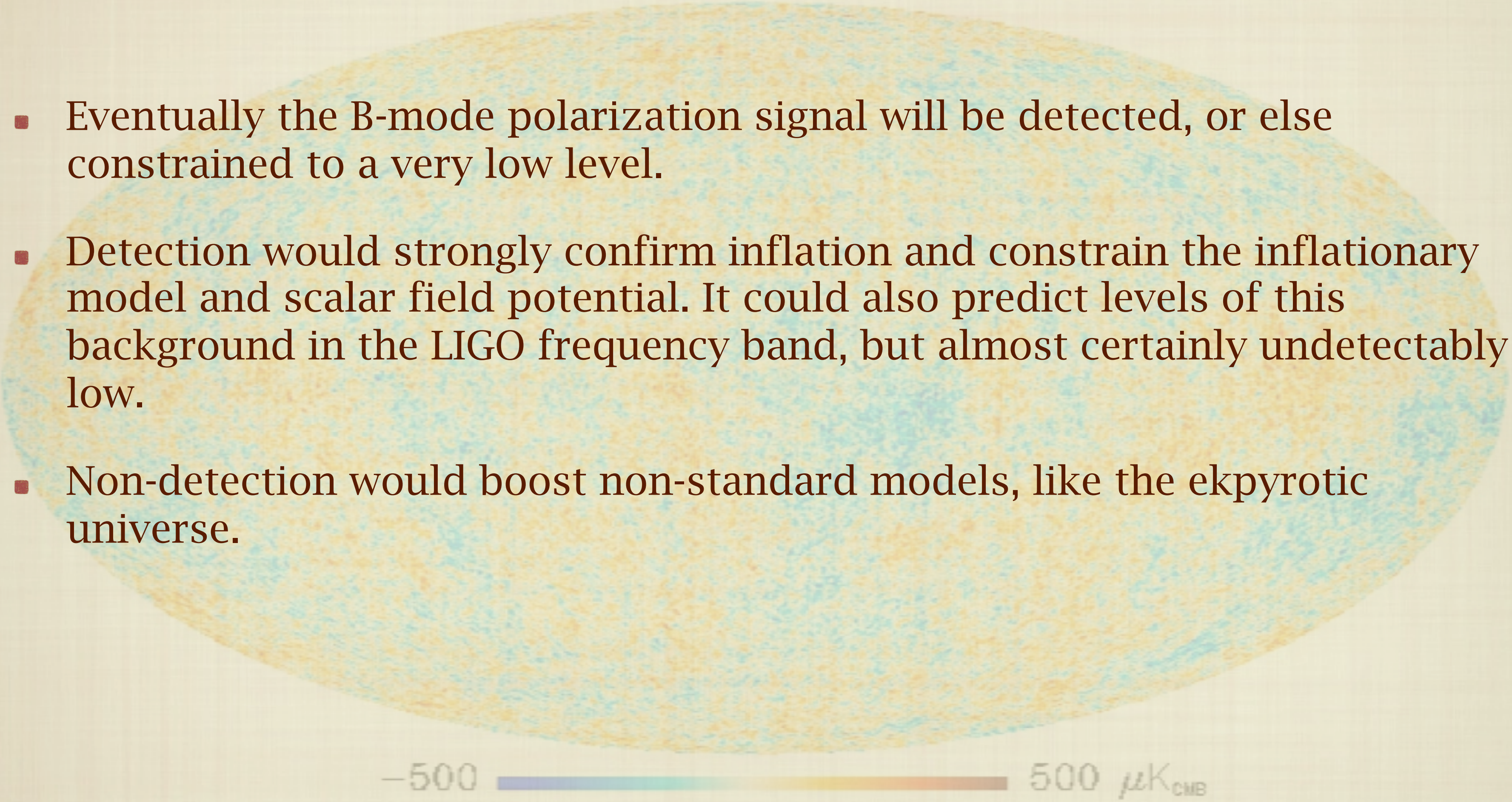
Black: PTA with 20 MSPs for 10 years.



Sesana, arXiv:1211.5375

CMB polarization signal

- Eventually the B-mode polarization signal will be detected, or else constrained to a very low level.
- Detection would strongly confirm inflation and constrain the inflationary model and scalar field potential. It could also predict levels of this background in the LIGO frequency band, but almost certainly undetectably low.
- Non-detection would boost non-standard models, like the ekpyrotic universe.



My 2015-25 Crystal Ball

- 2015: Advanced LIGO upgrade finishes, commissioning and science runs alternate until full sensitivity 2019.
- 2015+: PTAs pool data, increase number of MSPs.
- 2015: iKAGRA science run.
- 2015: LISA Pathfinder launched.
- 2016-20: eLISA design finalized with input from LPF.
- 2016: Advanced Virgo upgrade finishes, Virgo joins LIGO science runs in 2017.
- 2016-18: Advanced LIGO makes its first detection: NS-NS.
- 2017-22: Pulsar timing arrays get first nHz detection.
- 2017-22: First CMB measurement of Ω_{gw} at z ~ 1000.
- 2018: KAGRA joins Advanced detector network.
- 2020: ET approved in Europe, construction begins 2025.
- 2020-22: LIGO-India joins Advanced detector network.
- 2020+: Advanced detectors upgrade to 2.5G sensitivity, PTAs study individual SMBH binary systems.

Verifying Expectations

Pop of mergers: NS-NS, BH-BH (< 100 $M_\odot$) Assoc. w GRBs. Poss GWPSR.

Population of SMBHS at 10^9 $M_\odot$

Confirm inflation, restrict models

More events, identifications. Hubble const measured to 1%

GWPSRs, stochastic, cosmic strings, unexpected events all more likely.

Discovery Space