Astronomy's "Next Big Thing:" What can we expect from direct gravitational-wave observations?

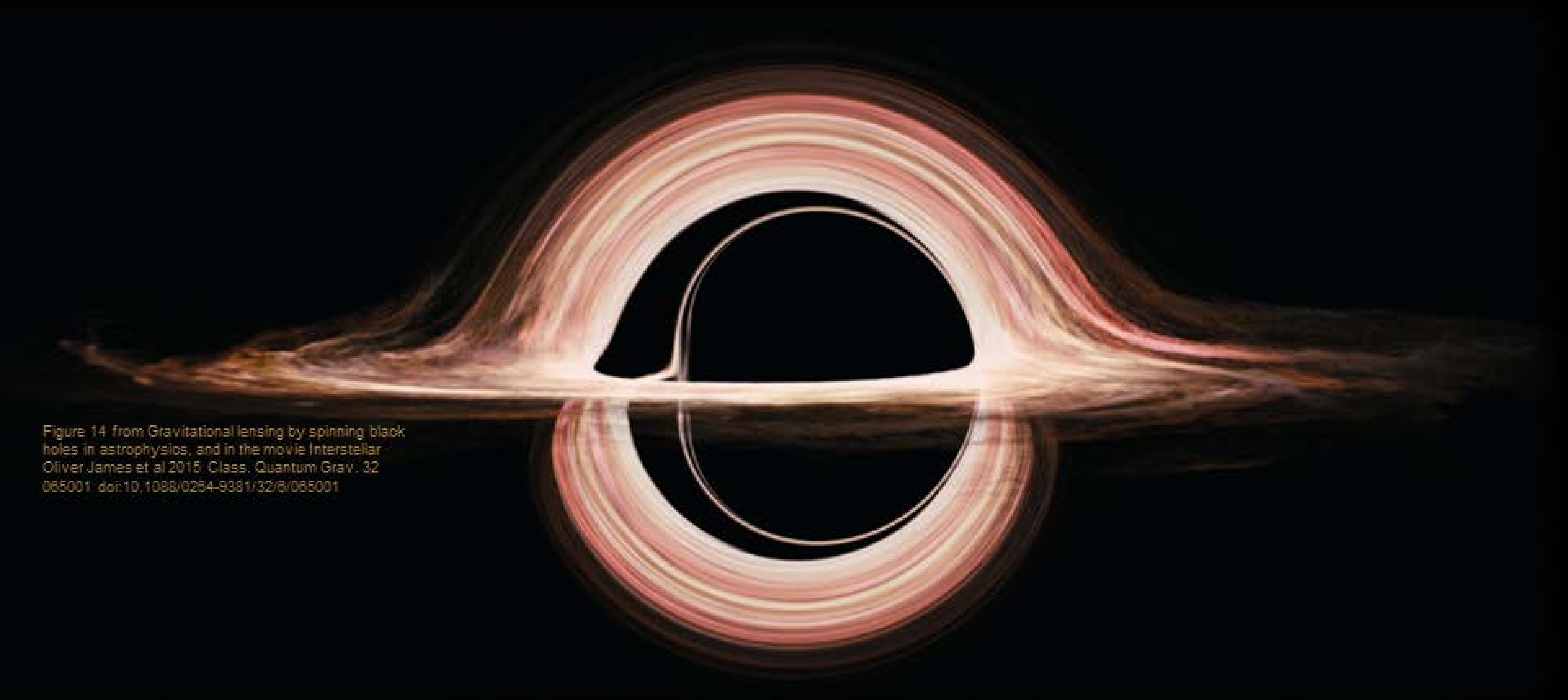


Figure 14 from Gravitational lensing by spinning black holes in astrophysics, and in the movie Interstellar Oliver James et al 2015 Class. Quantum Grav. 32 065001 doi:10.1088/0264-9381/32/6/065001

G
E
Co

Szabolcs Marka, Imre Bartos, Zsuzsa Marka

Columbia Experimental Gravity Group

Columbia University in the City of New York,

2017

Worldwide reach of the LIGO Scientific Collaboration

TRINITY UNIVERSITY
UNIVERSITY OF MARYLAND
Andrews University
WASHINGTON STATE UNIVERSITY
CALIFORNIA STATE UNIVERSITY FULLERTON
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE
SONOMA STATE UNIVERSITY
indigo
MONTCLAIR STATE UNIVERSITY
University of Glasgow
Australian National University
WHITMAN COLLEGE
AMERICAN UNIVERSITY
UNIVERSITY OF THE WEST of SCOTLAND UWS
TEXAS TECH UNIVERSITY
清華大学 Tsinghua University
R·I·T
Max Planck Institute for Gravitational Physics ALBERT EINSTEIN INSTITUTE
UNIVERSITY OF STRATHCLYDE
MICHIGAN
Università degli Studi del Sannio
CITA ICAT
NASA GODDARD SPACE FLIGHT CENTER
ICTP SAIFR
THE UNIVERSITY OF WESTERN AUSTRALIA
PAH
ACU
UNIVERSITY OF CAMBRIDGE
MONASH University
SOUTHERN UNIVERSITY
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK
THE UNIVERSITY OF CHICAGO
MONTANA STATE UNIVERSITY
THE UNIVERSITY OF ADELAIDE AUSTRALIA
THE UNIVERSITY of MISSISSIPPI
Caltech
UNIVERSITY OF MINNESOTA
UNIVERSITY OF BIRMINGHAM
THE UNIVERSITY OF MELBOURNE
UIB Universitat de les Illes Balears
UNIVERSITY OF WASHINGTON
GEO 600
UTRGV
UNIVERSITY of WISCONSIN UWMILWAUKEE
SYRACUSE UNIVERSITY FOUNDED AD 1870
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
Northwestern
MONASH University
INPE
UF UNIVERSITY of FLORIDA
Georgia Institute of Technology
Korean Gravitational-Wave Group
LSU LOUISIANA STATE UNIVERSITY
ACIGA
University of Southampton
CHARLES STURT UNIVERSITY
EMBRY-RIDDLE AERONAUTICAL UNIVERSITY
Leibniz Universität Hannover
PennState
Science & Technology Facilities Council Rutherford Appleton Laboratory

The New York Times
Clinton Paints Sanders Plans As Unrealistic
New Lines of Attack at Milwaukee Debate
WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT
A RIPPLE IN SPACE-TIME
An Echo of Black Holes Colliding a Billion Light-Years Away
Long in Clinton's Corner, Blacks Notice Sanders
Last Occupier In Rural Oregon Is Coaxed Out
The Washington Post
ara
ara.cat
El metro finalment arriba avui a l'aeroport
La L9 recorre 20 quilòmetres, ha costat 2.899 milions i s'ha fet en 13
DESCOBRIMENT
CNN
U.S. | Crime + Justice | Energy + Environment | Extreme Weather | Space + Science
Gravitational waves op
the universe,' scientists
By Todd Leopold, CNN
Updated 1:28 PM ET, Thu February 11, 2016 | Video Source: CNN
"This has been the top story on both the domestic and international site!"
USA TODAY WEEKEND
FEBRUARY 12
GRAVITATIONAL WAVES CONFIRMED
'A WHOLE NEW WINDOW ON THE UNIVERSE'
IN NEWS
Discovery affirms Einstein theory
Gravitational waves Einstein foresaw are detected
THE MONITO
FRIDAY, FEBRUARY 12, 2016
SERVING THE RIO GRANDE VALLEY SINCE 1909
Collaboration proves Einstein correct
Texas A
regents a
$40M fa
Die Presse
SEIT 1848
Jetzt sehen wir Einsteins Wellen
MOST EMAILED
MOST VIEWED
RECOMMENDED FOR YOU
1. OUT THERE
Gravitational Waves Detected, Confirming Einstein's Theory
2. CHARLES M. BLOW
Stop Bernie-Splaining to Black Voters
3. NICHOLAS KRISTOF
The G.O.P. Created Donald Trump

https://writescience.wordpress.com/tag/gravitational-waves/

1916:

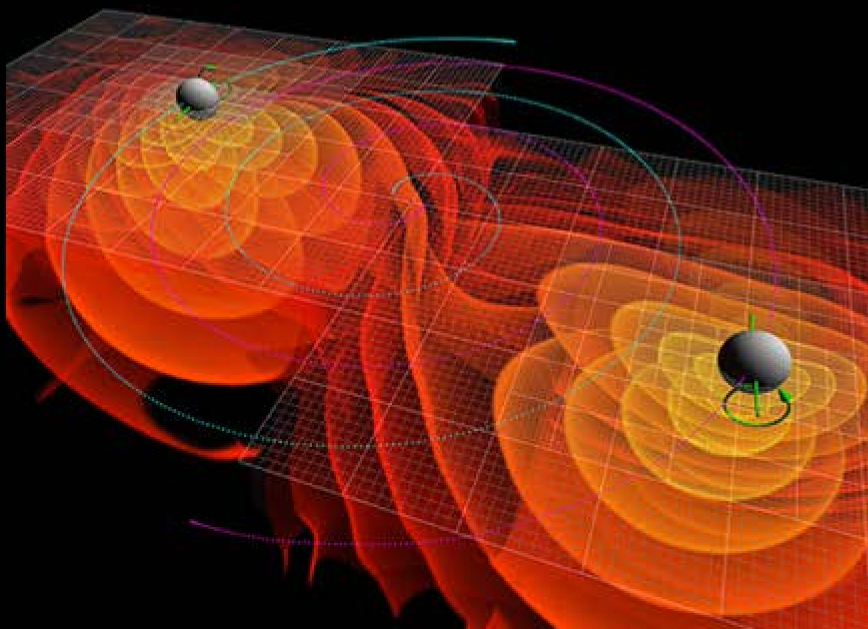
Thanks to D.Shoemaker, S.Larson, and LSC

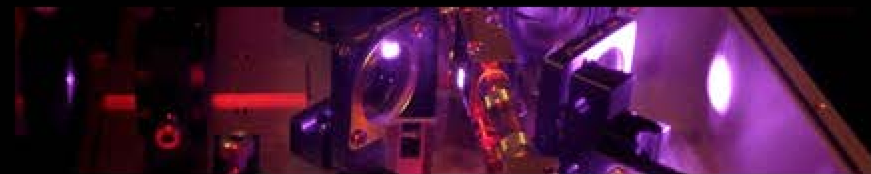
Gravitational waves

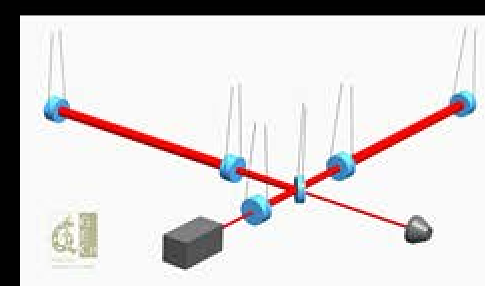
Typical signal at Earth: $h \sim 10^{-21}$!

0.000000000000000000001

~ a millionth of a Cent on $17,749,226,163,000 !

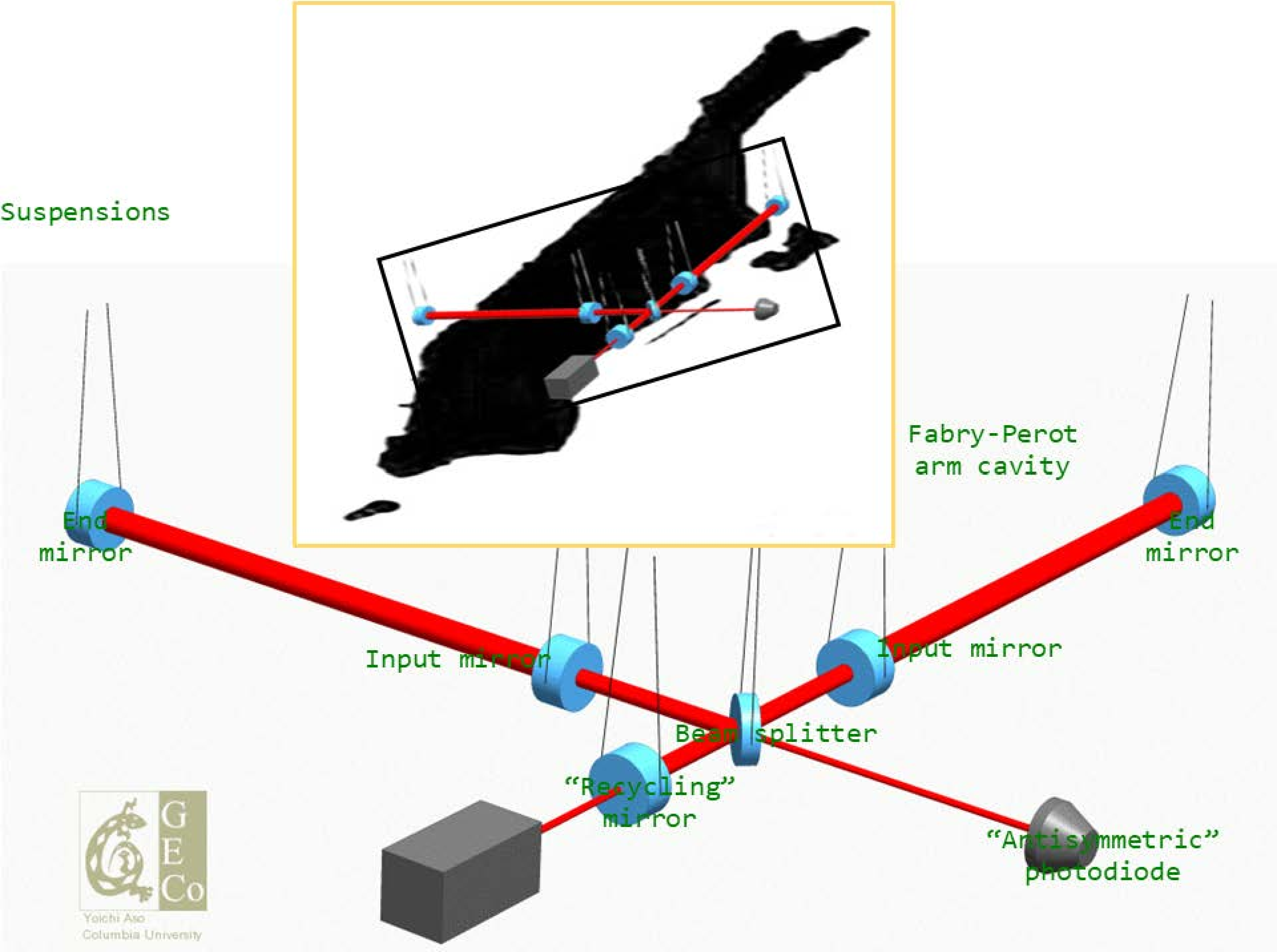






Big Unknowns:

- How is the hidden life of married Black Holes?
- Was Einstein right about Gravity?
- Where did we come from? What is the history of the accelerating expansion of the Universe?
- …


Suspensions
Fabry-Perot
arm cavity
End
mirror
End
mirror
Input mirror
Input mirror
Beam splitter
“Recycling”
mirror
“Antisymmetric”
photodiode
GECo
Yoichi Aso
Columbia University

1956 : Gedanken experiment using interferometry to detect GWs:
F.A.E. Pirani, Acta Phys. Polon. 15, 389 (1956)
(predates invention of laser by 4 years!)

1963: Laser interferometry for gravitational-wave detection mentioned as theoretical possibility (Gerstenstein and Pustovoit 1963 Sov. Phys.–JETP 16 433)

1971:

Photon-Noise-Limited Laser Transducer for Gravitational Antenna

Thanks to D.Shoemaker, and LSC

G. E. Moss, L. R. Miller, and R. L. Forward

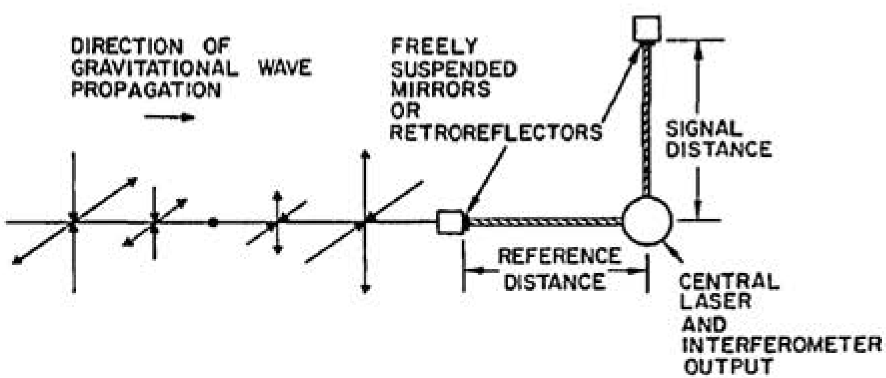


Fig. 1. Right angle interferometer antenna. The reference distance is not changed by gravitational radiation in the direction of propagation shown.

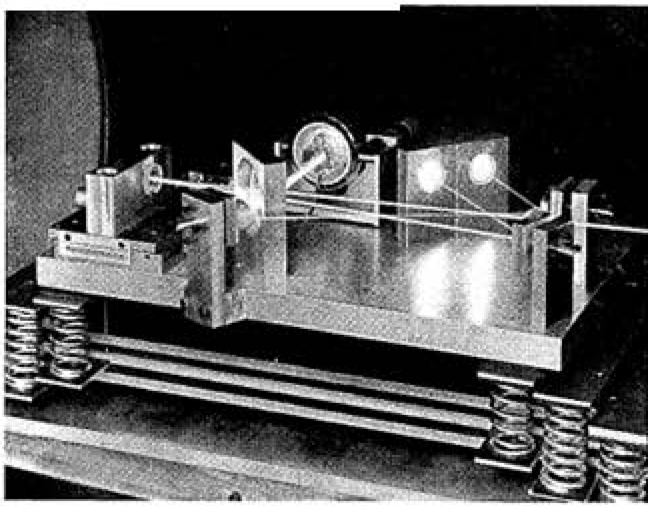


Fig. 4. Photograph of interferometer setup on 3-Hz isolation suspension.

Late 1960s-1972: Rai Weiss of MIT was teaching a course on GR in the late ‘60s… Wanted a good homework problem for the students… Why not ask them to work out how to use laser interferometry to detect gravitational waves?...Weiss wrote the instruction book LIGO have been following ever since…

QUARTERLY PROGRESS REPORT

No. 105

APRIL 15, 1972

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

RESEARCH LABORATORY OF ELECTRONICS

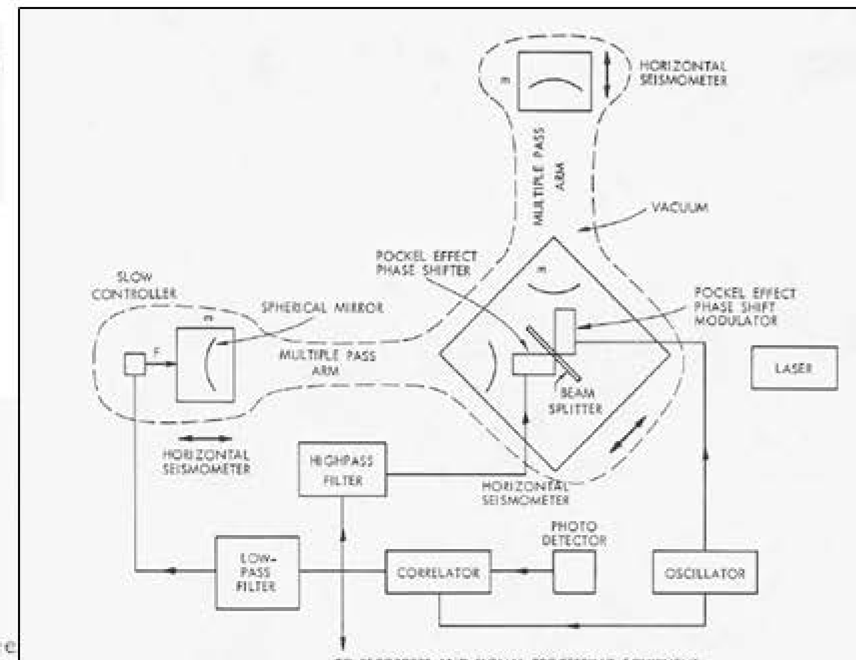
CAMBRIDGE, MASSACHUSETTS 02139

(V. GRAVITATION RESEARCH)

B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

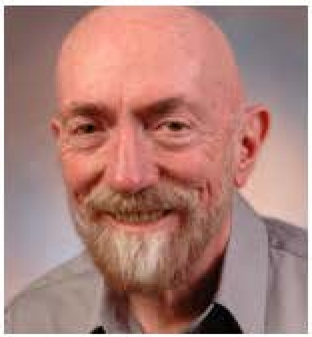
1. Introduction

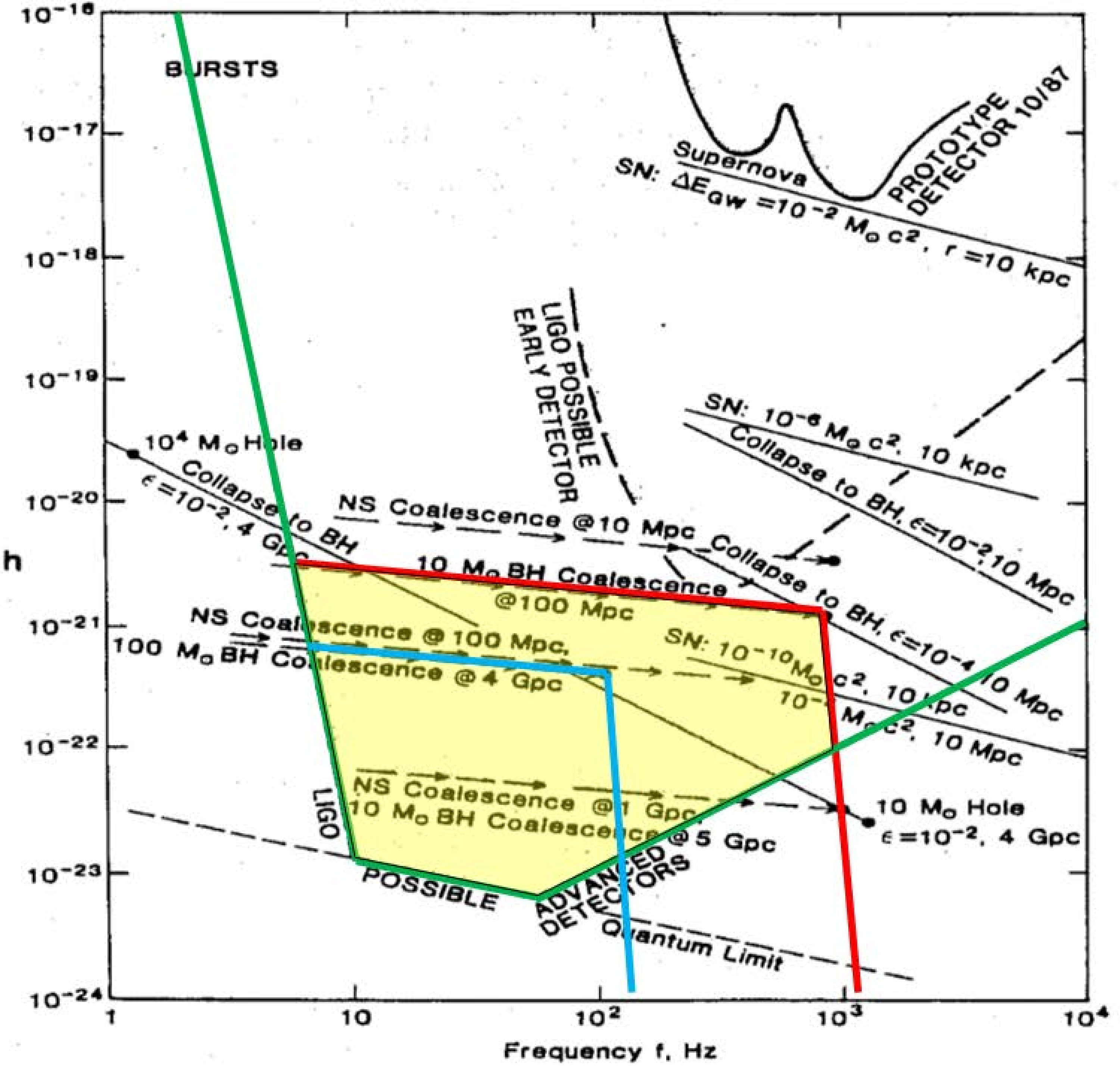
The prediction of gravitational radiation that travels at the speed of light has bee

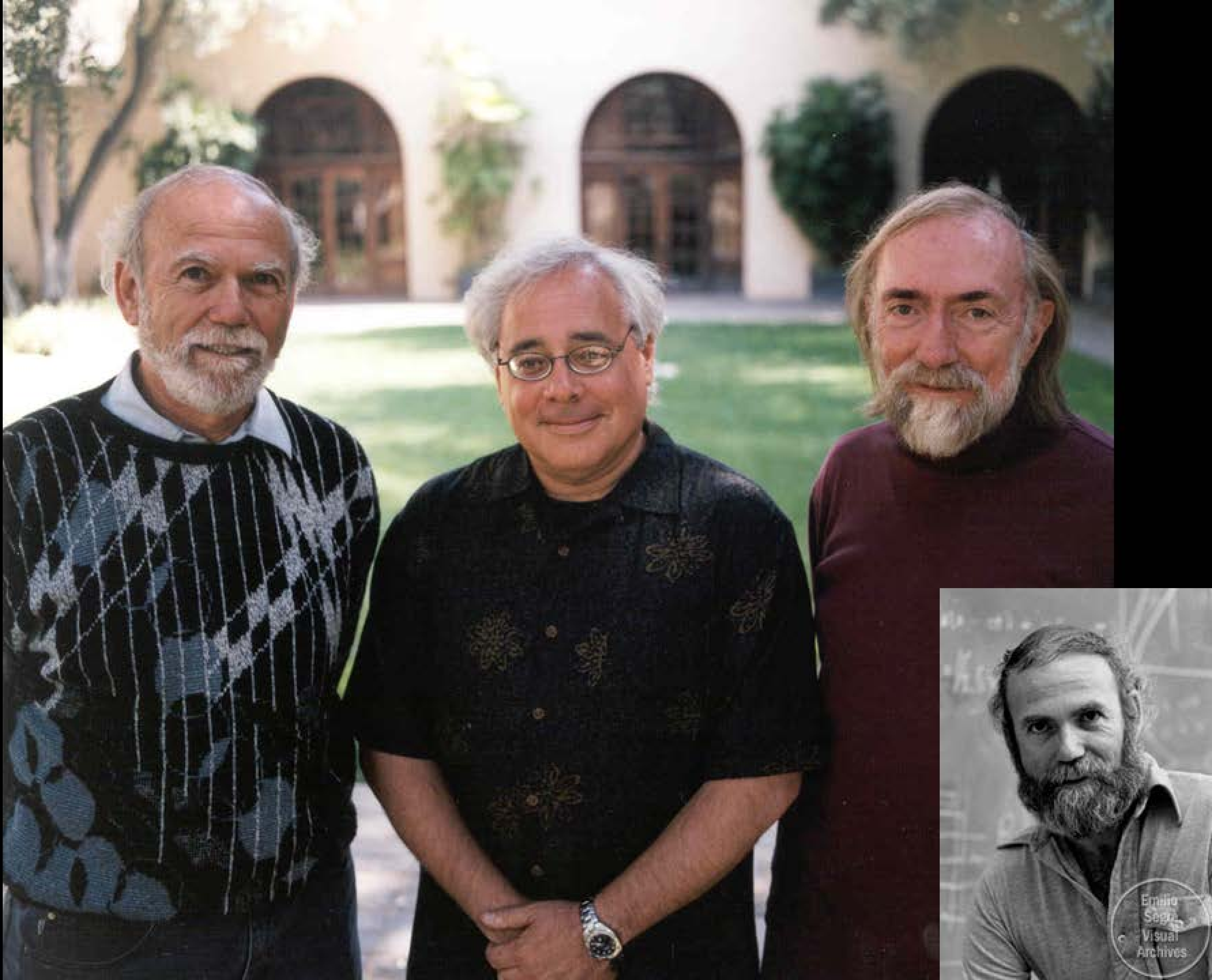


Thanks to D.Shoemaker, S.Larson, and LSC

Rochus Vogt, Ron Drever, Kip Thorne, Rai Weiss, 1987







Credit: Caltech

aLIGO's path through the decades:

1990-2000: R&D, meetings
1999: White Paper with conceptual design

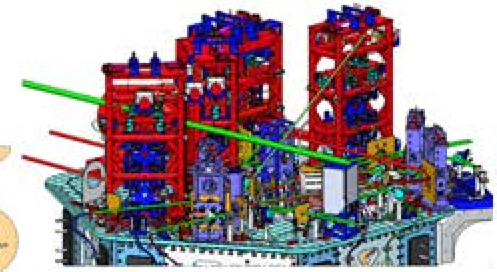
2000-2004: Prototyping, modeling, applying
(Note: this how where the LIGO Scientific Collaboration took form, to focus the community – City-States morph into Unions of LIGO, GEO, Virgo, KAGRA, ACIGA)

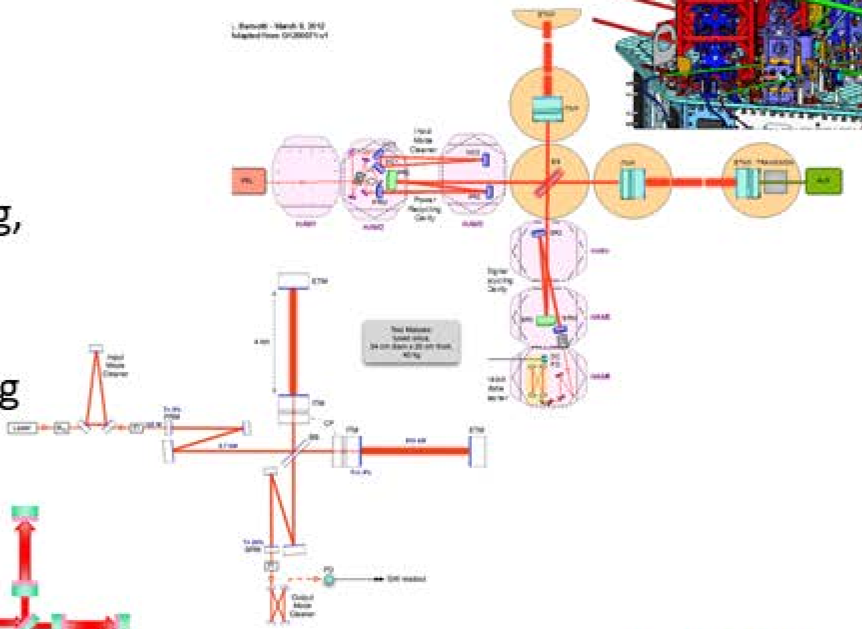
2006: Funding for 2008 start
2005-2008: Engineering, 1st articles, procurements

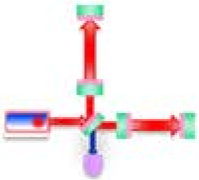
2008-2012: Building, de-installing, cleaning, installing

2013-2015: Installing, testing, documenting
2015? Astrophysics

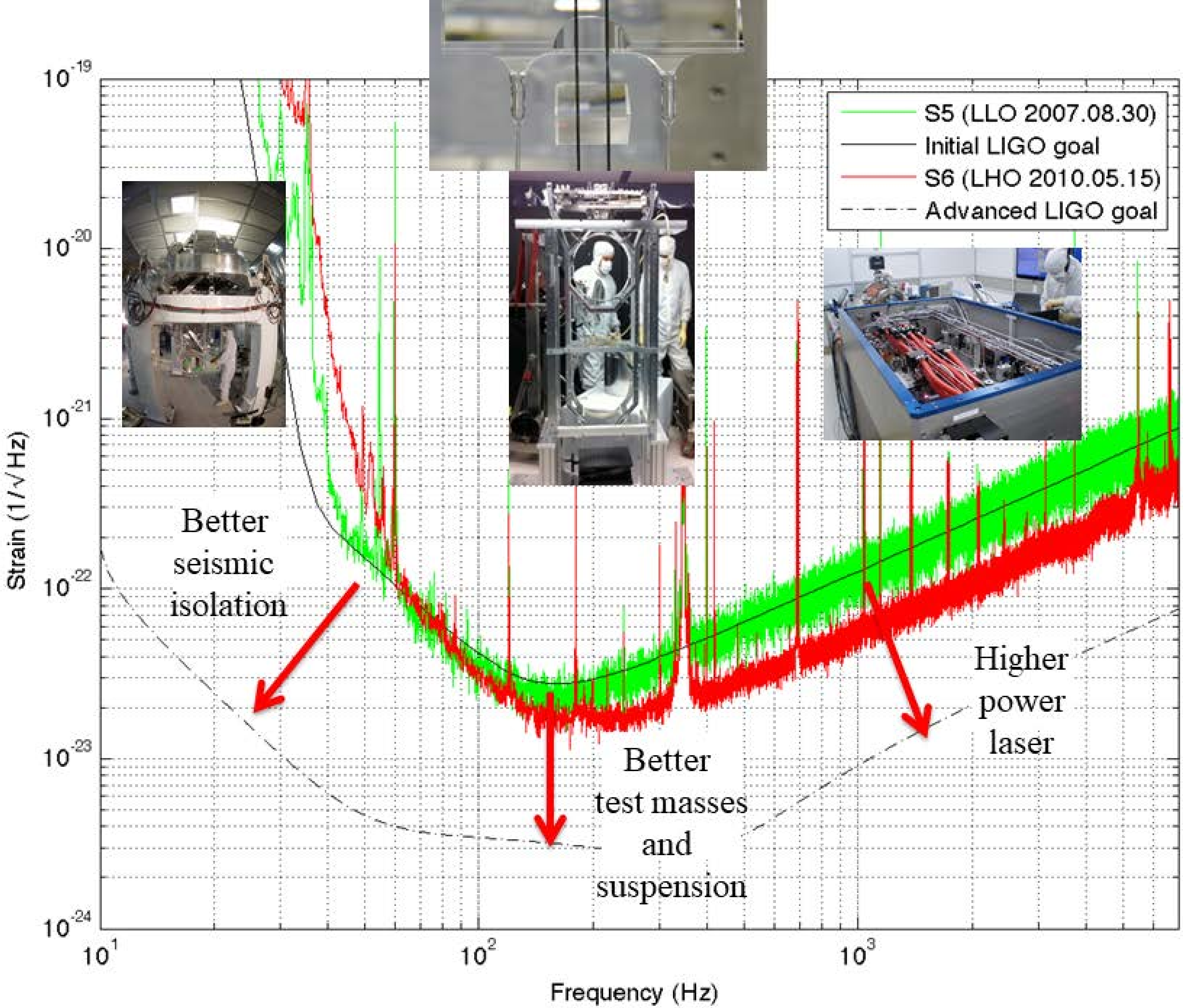
So, about 20 years from ripe R&D to fruition…
(similar to Initial LIGO)
Sobering for the next generation –
need the conceptual design soon!



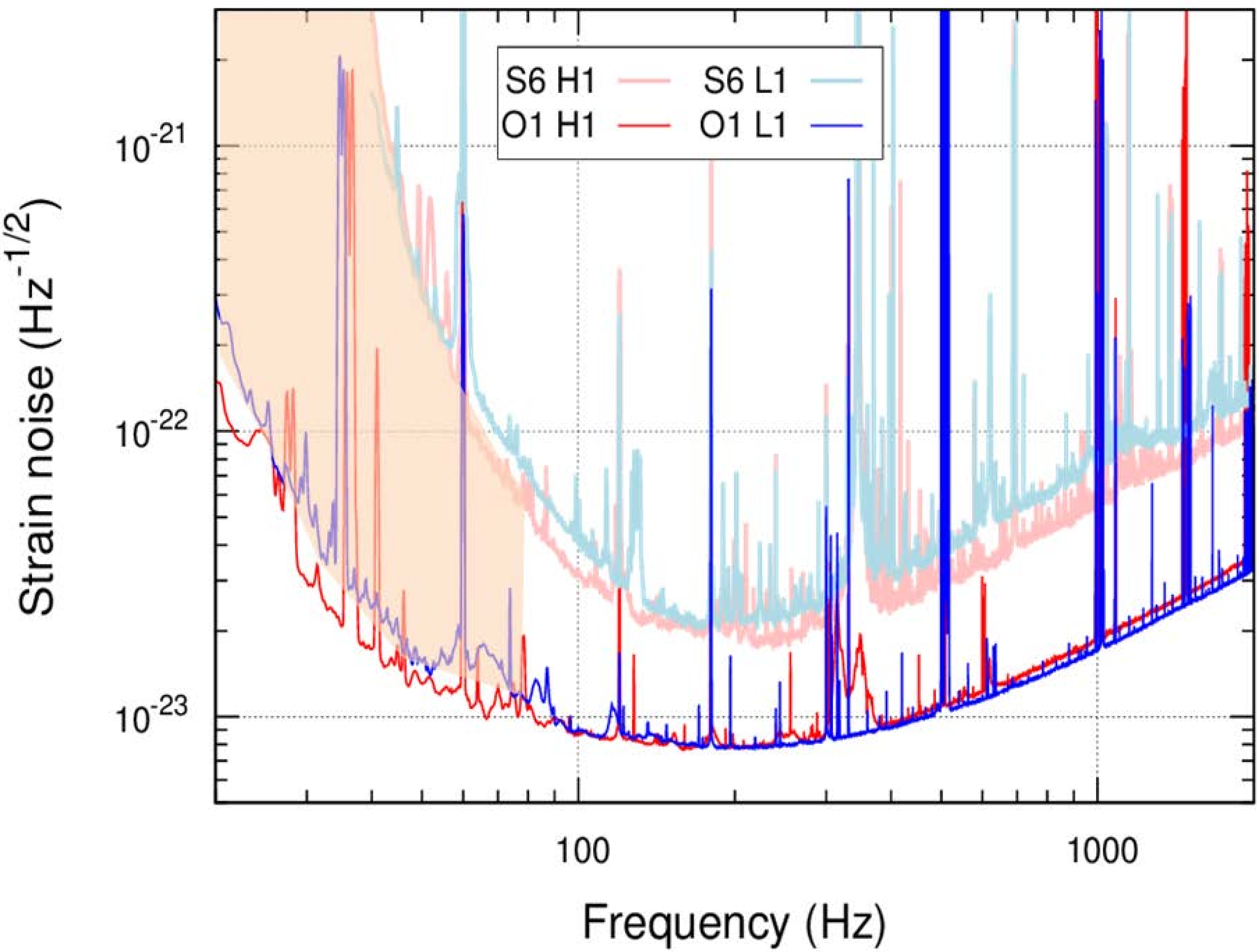




Thanks to D.Shoemaker and LSC



Courtesy of LIGO and LSC



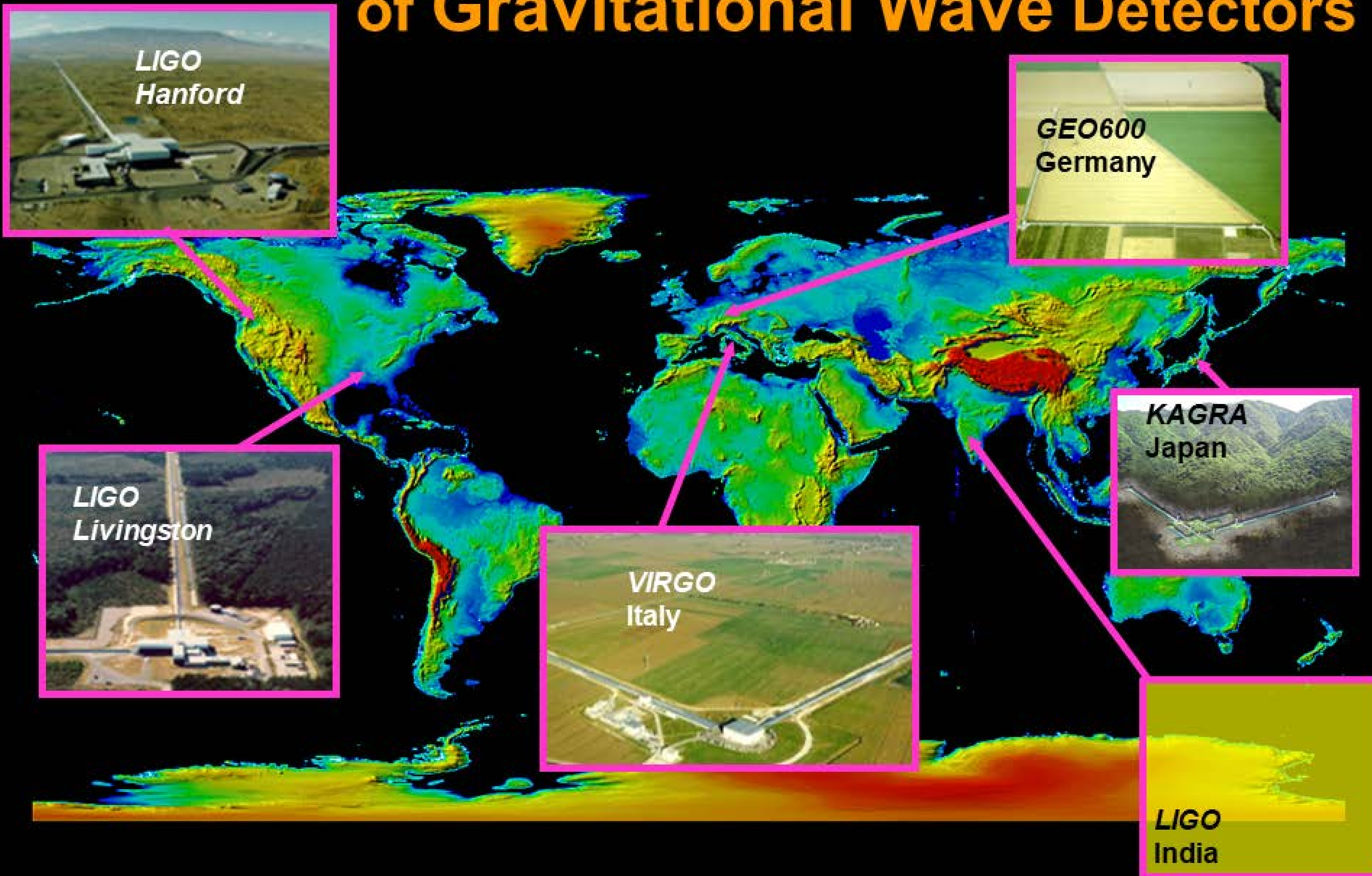
S6 H1
S6 L1
O1 H1
O1 L1
Strain noise (Hz^-1/2)
10^-21
10^-22
10^-23
100
1000
Frequency (Hz)

Exciting Exploratory Science !

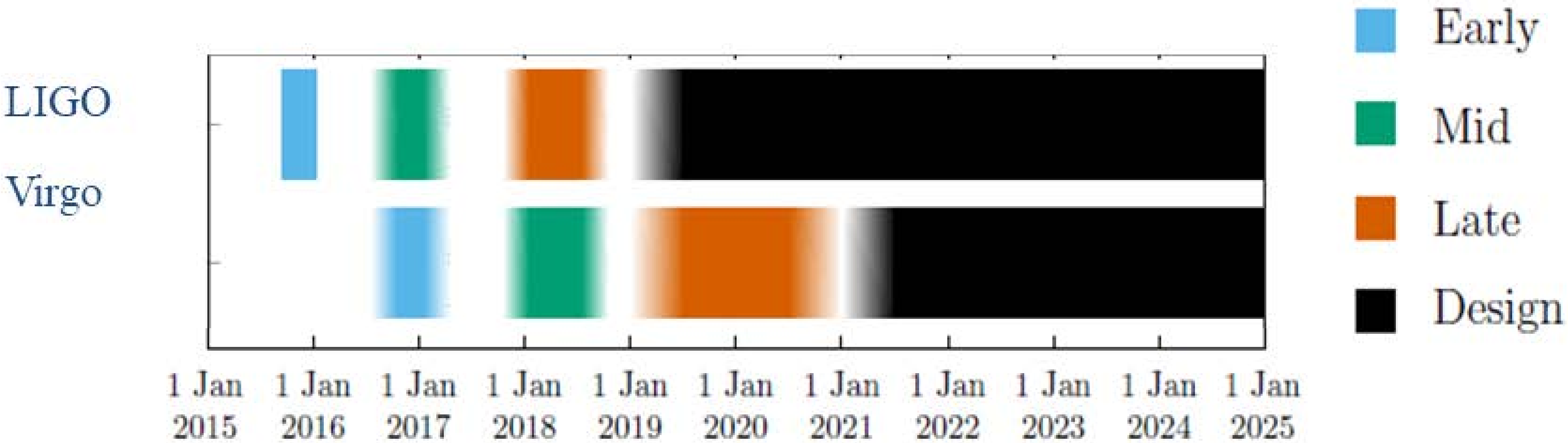
Advanced LIGO Hanford, WA

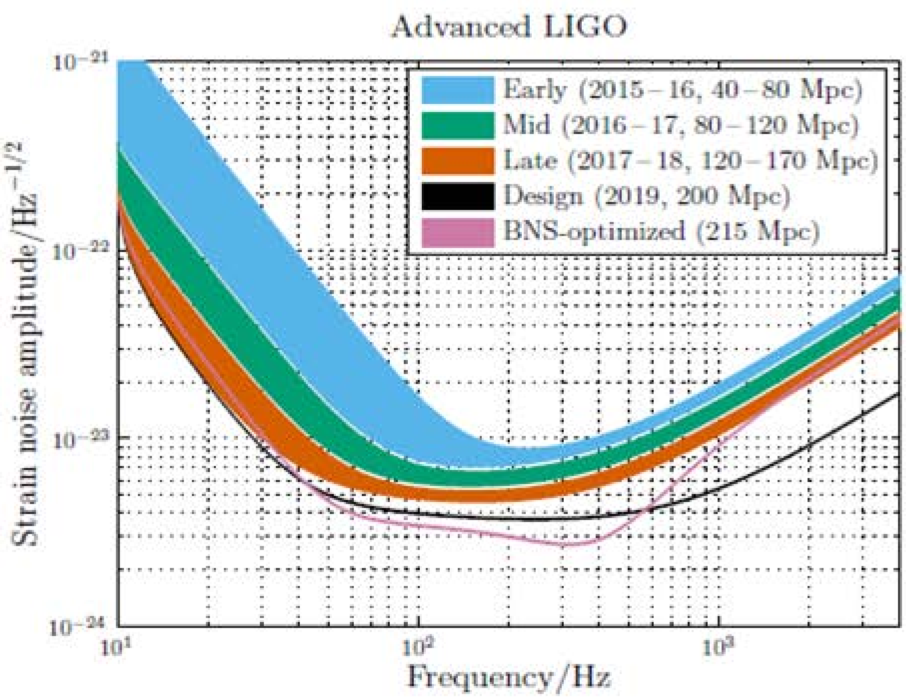
LIGO Livingston, LA

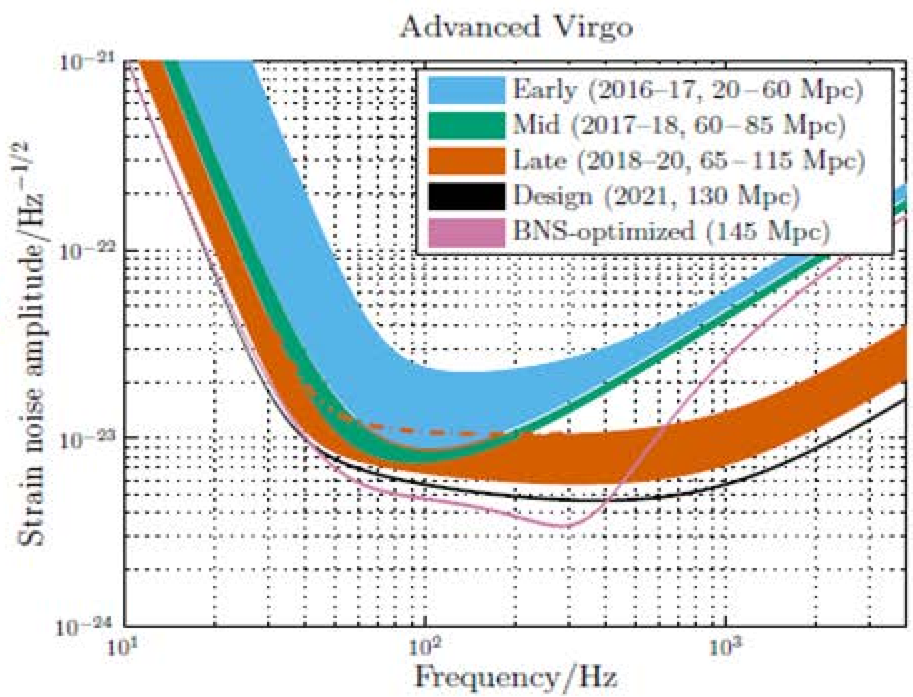
The Global Network of Gravitational Wave Detectors



Advanced Detector Evolution

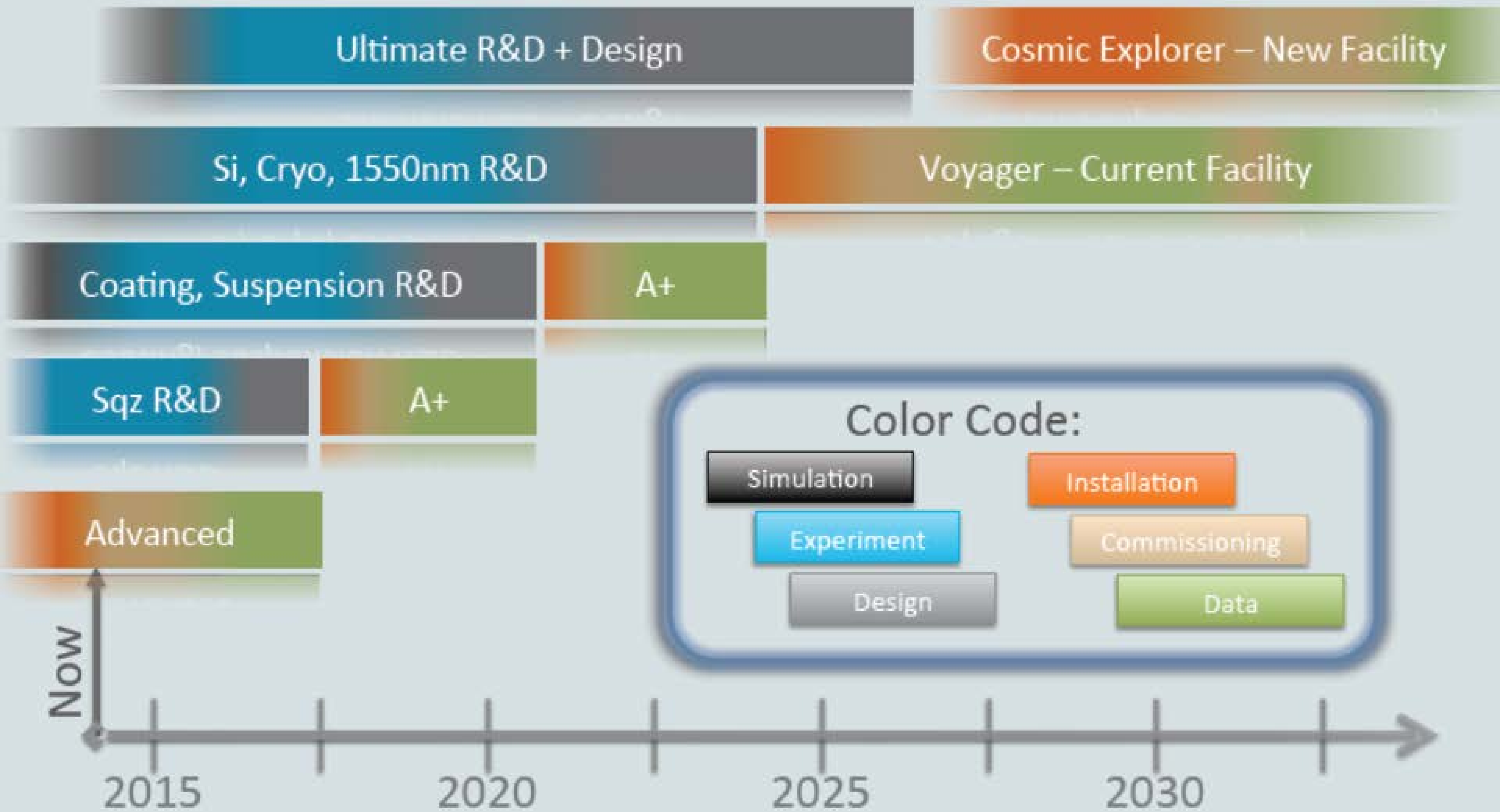






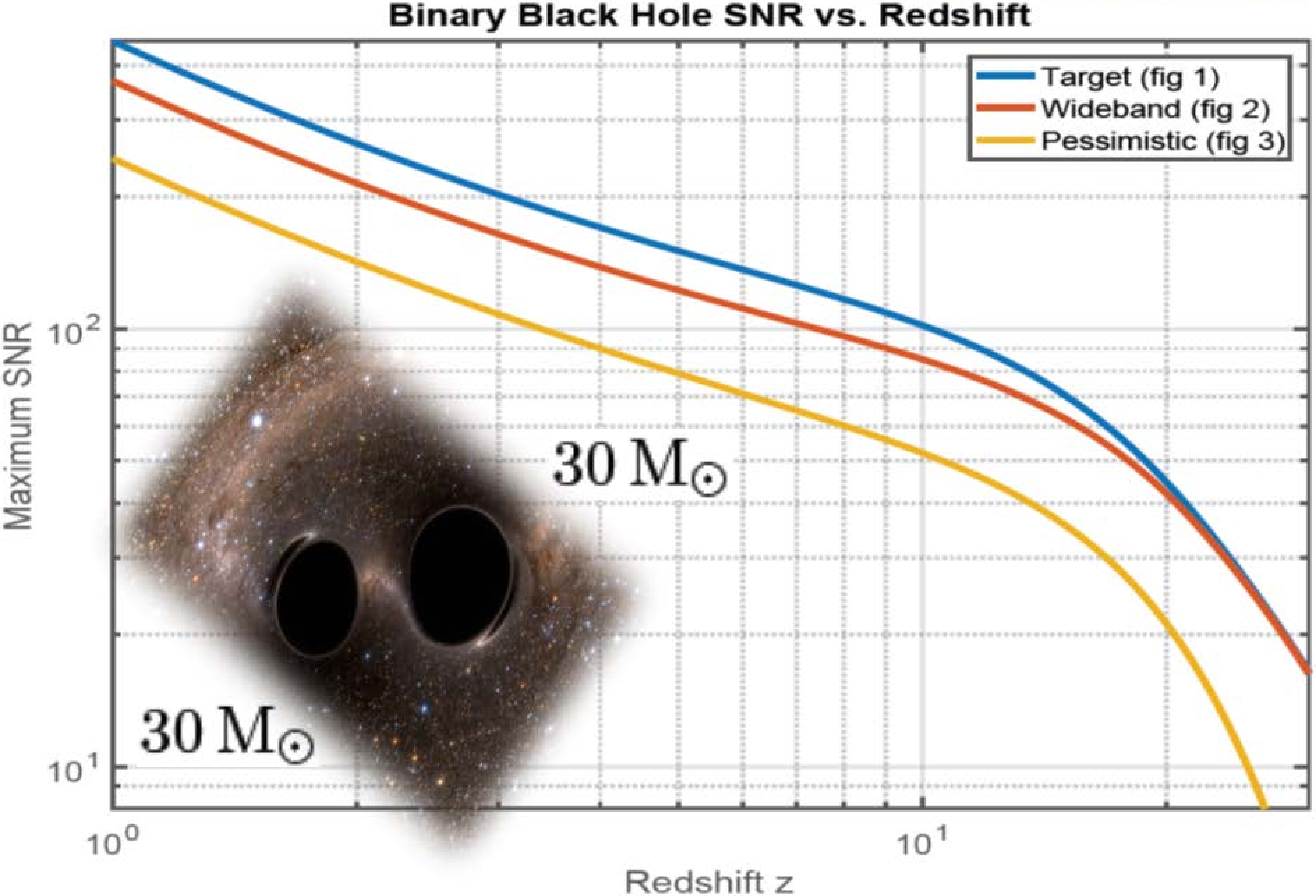
Credit: Stan Whitcomb, Living Rev. Relativity 19 (2016), 1

LIGO Upgrade Timeline



Cosmic Explorer – The current endpoint of foresight and technology

Abbott et al. 2017, CQGra, 34, 044001 https://arxiv.org/abs/1607.08697



Cosmic Explorer – The current endpoint of foresight and technology

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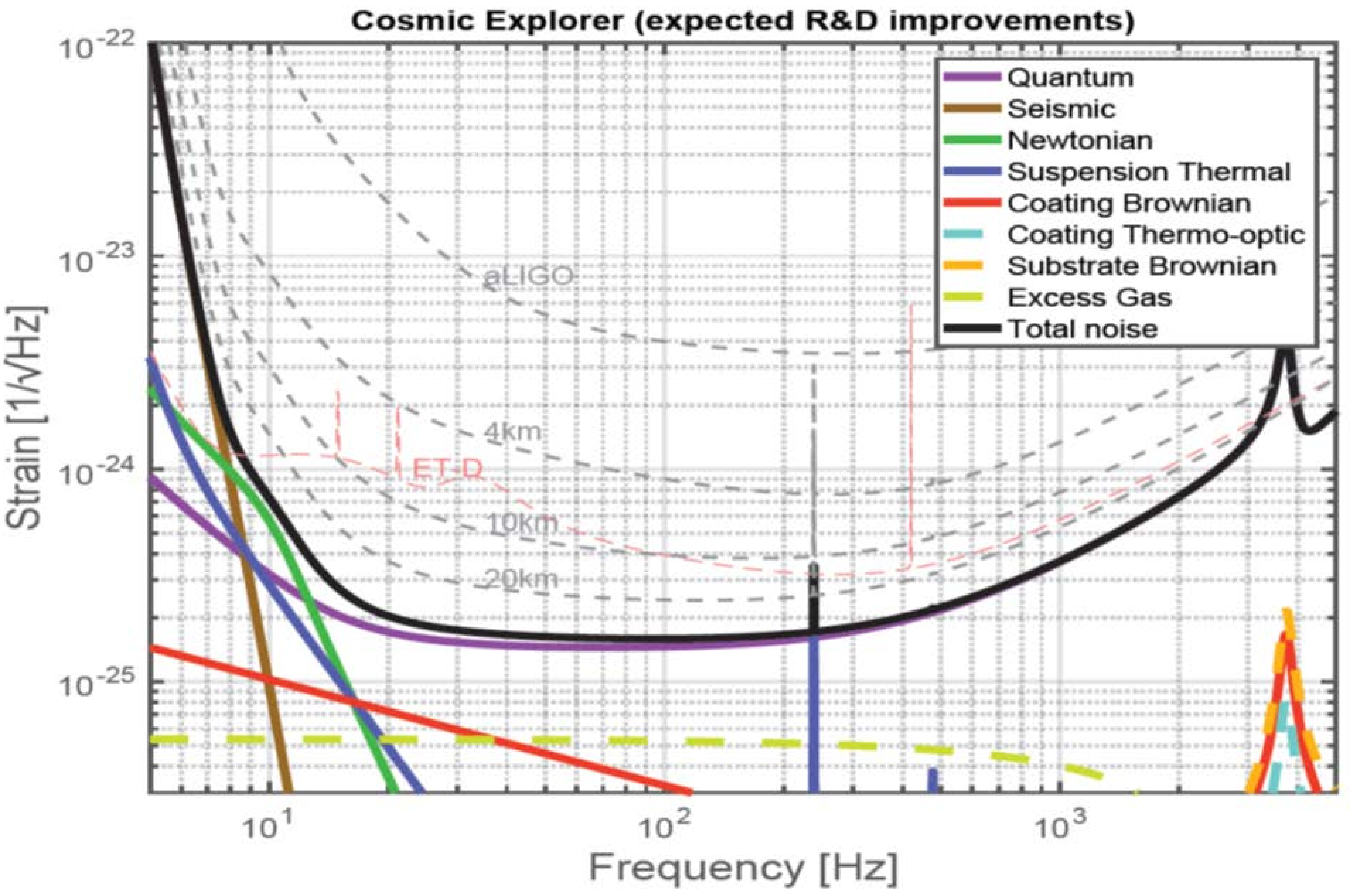
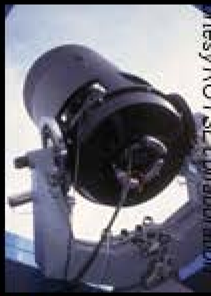


Basic Glossary: Multimessenger Approaches

"Multi-messenger astrophysics": connecting different kinds of observations of the same astrophysical event or system

---

"Follow-Up" strategy:

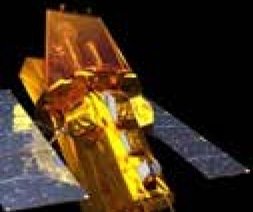


GW
Data

Flow of trigger information →

Telescopes, Satellites or other external entities

"ExtTrig" strategy:



Telescopes, Satellites or other external entities

Flow of trigger information →

GW
Search

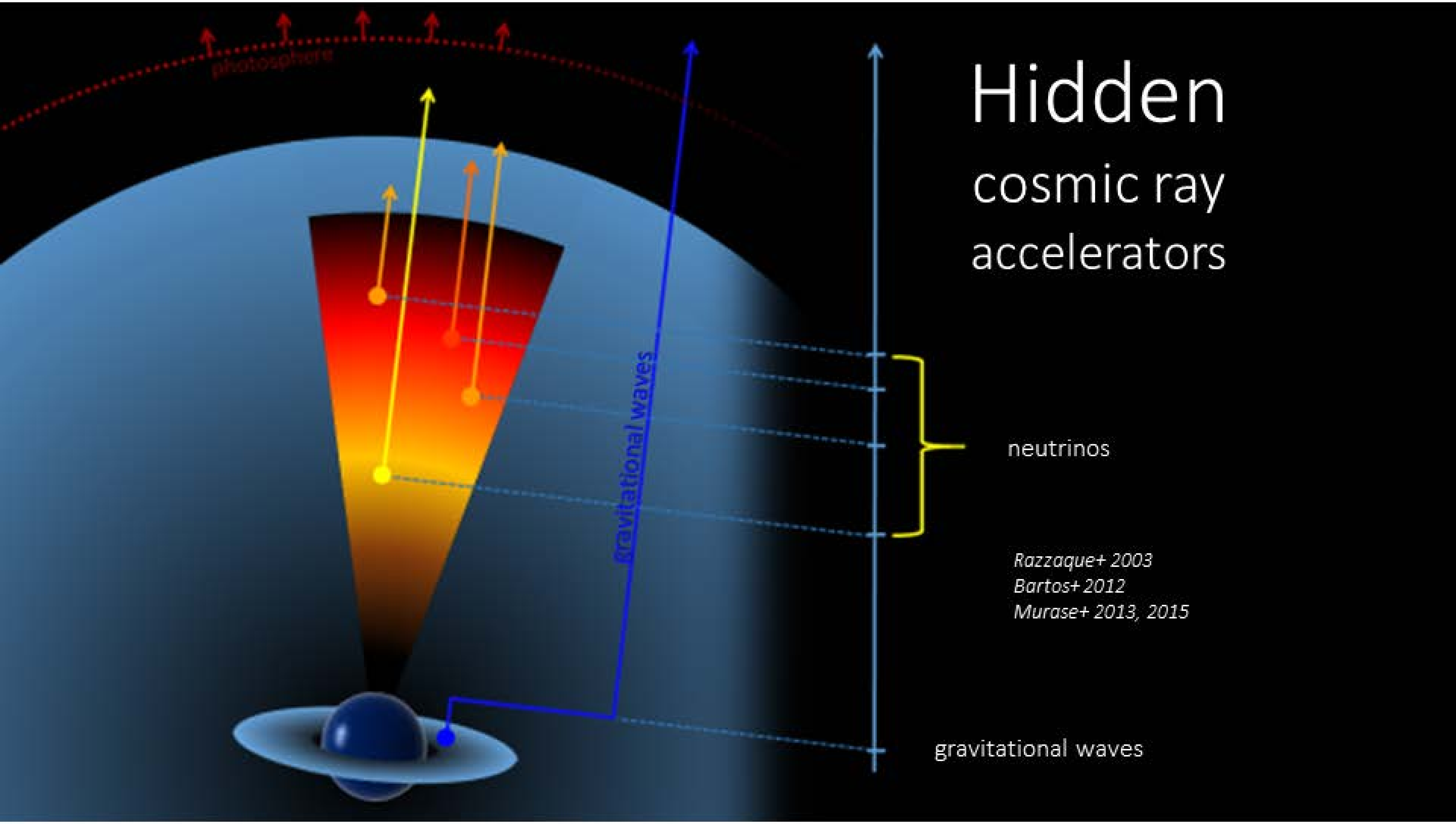
Transient Multimessenger Astrophysics with GWs

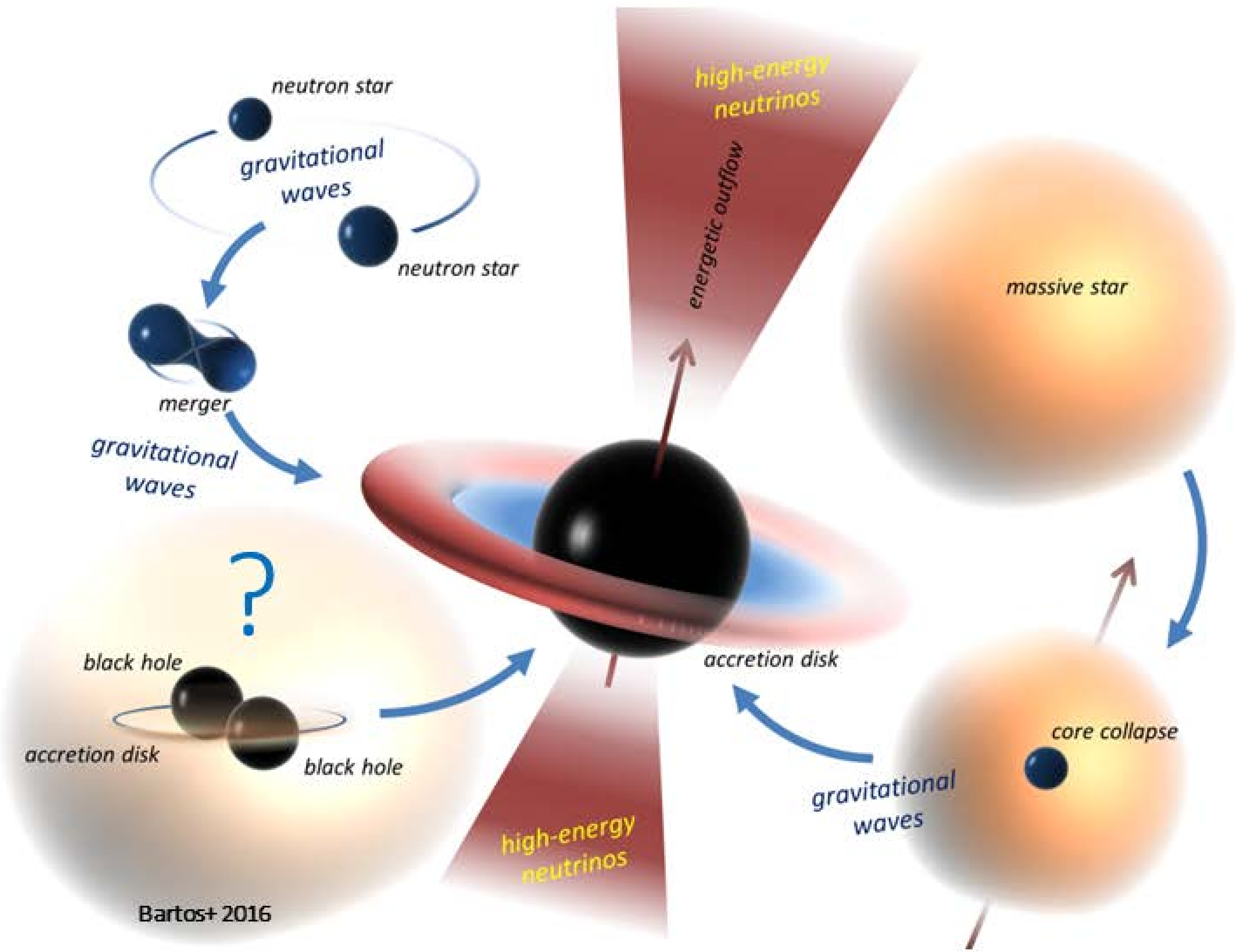
» Gamma-ray transients (GRBs, SGRs)
» Optical transients
» Neutrino events
» Radio transients
» X-ray transients
» …

Image credit: Zsuzsa Marka – GWDAW12

- Correlation in time
- Correlation in direction
- Information on the source properties, host galaxy, distance
- …

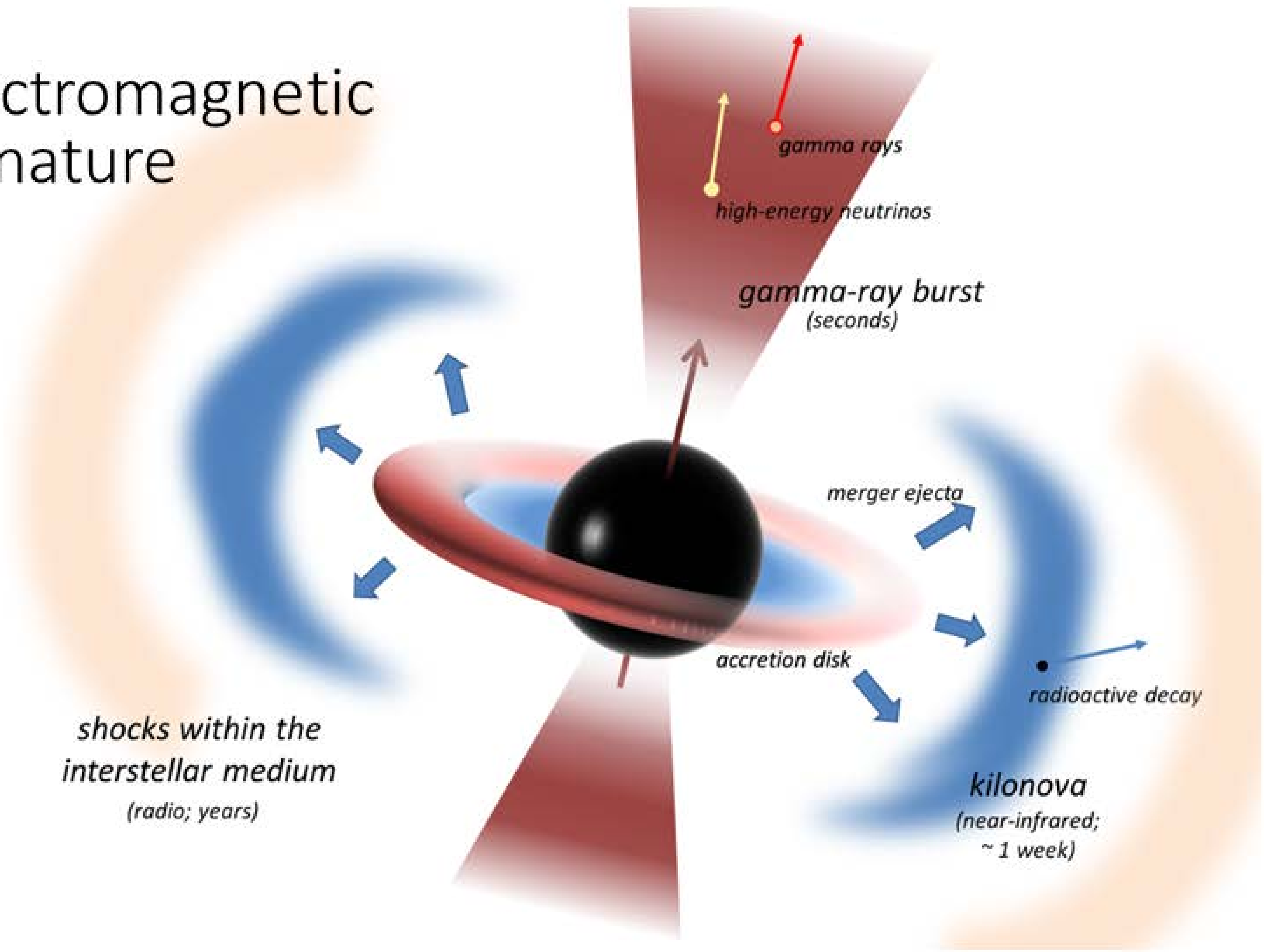
✓ Confident detection of GWs.
✓ Better background rejection $\Rightarrow$ Higher sensitivity to GW signals.
✓ More information about the source/engine.
✓ Measurements made possible through coincident detection.


Hidden
cosmic ray
accelerators
photosphere
gravitational waves
neutrinos
Razzaque+ 2003
Bartos+ 2012
Murase+ 2013, 2015
gravitational waves



neutron star
gravitational
waves
neutron star
merger
gravitational
waves
?
black hole
accretion disk
black hole
Bartos+ 2016
high-energy
neutrinos
energetic outflow
accretion disk
high-energy
neutrinos
massive star
core collapse
gravitational
waves

electromagnetic signature

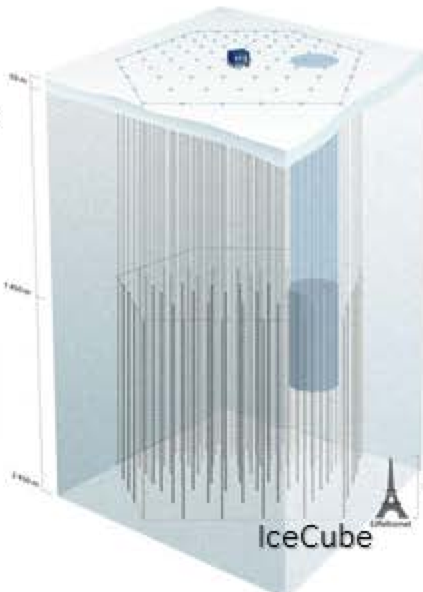


LIGO
LIGO
(neutrino)
VIRGO
(neutrin
IceCube
Arctic Ocean
Beaufort Sea
Baffin Bay
Greenland Sea
Kara Sea
Laptev Sea
East Siberian Sea
Barents Sea
Norwegian Sea
Hudson Bay
Labrador Sea
Gulf of Alaska
Sea of Okhotsk
Bering Sea
North Pacific Ocean
North Atlantic Ocean
North Pacific Ocean
East China Sea
Caribbean Sea
Arabian Sea
Bay of Bengal
South China Sea
South Atlantic Ocean
Indian Ocean
Coral Sea
South Pacific Ocean
Tasman Sea

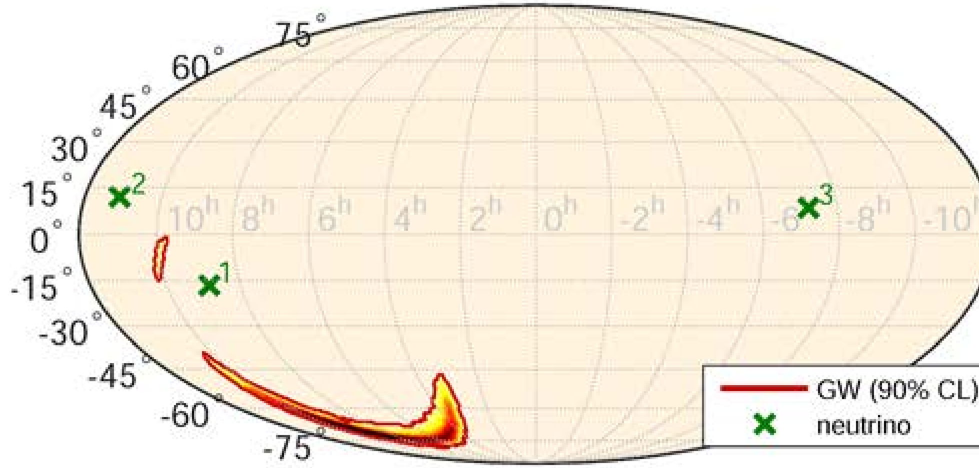
neutrino counterpart for gravitational waves

Super-Kamiokande

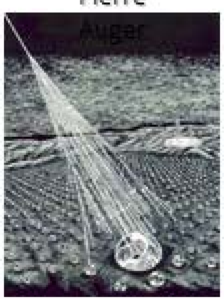
Abe+ ApJL 2016



IceCube



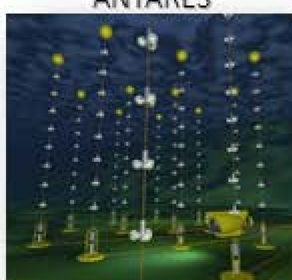
Pierre Auger



KamLAND

KamLAND 2016 (1606.07155)

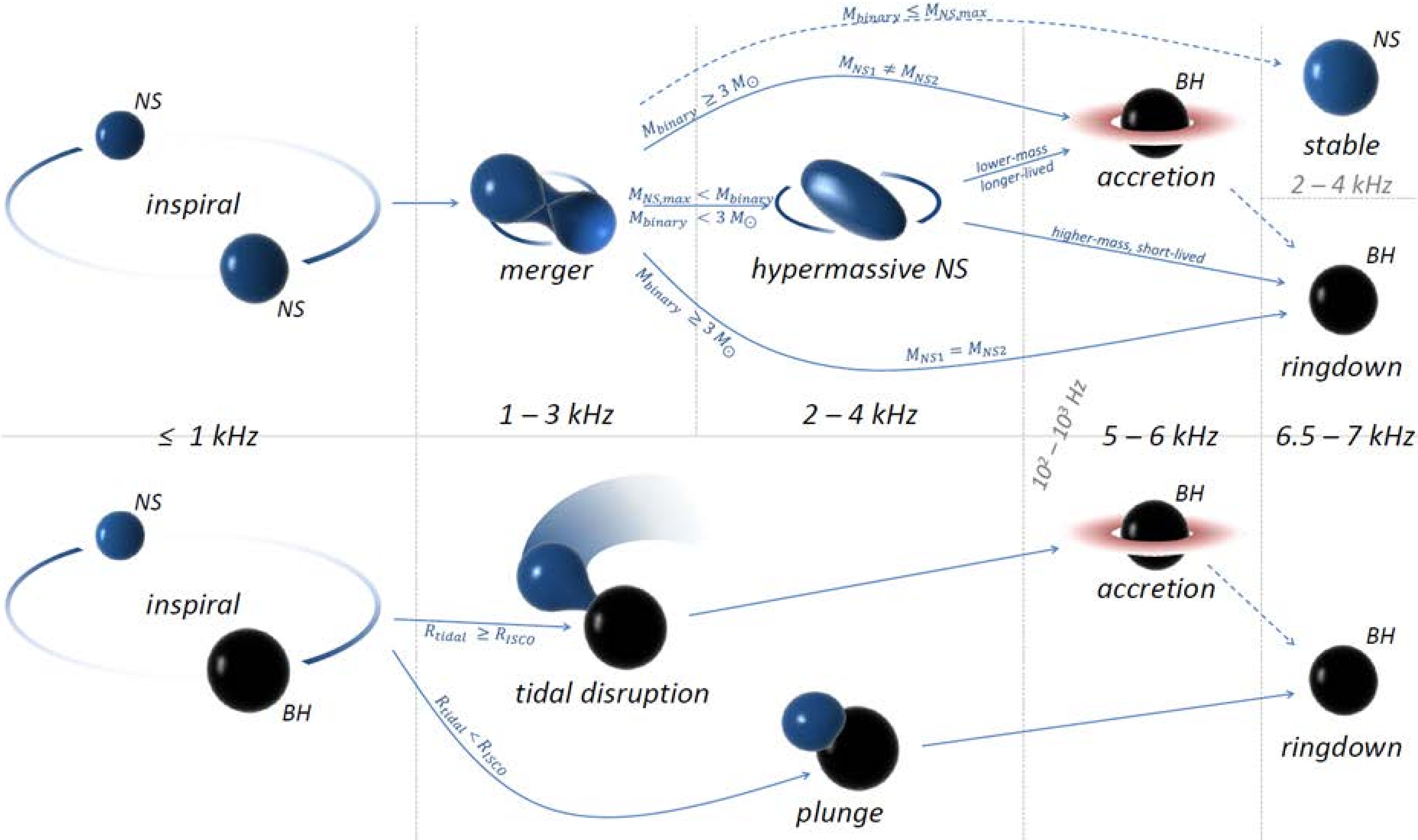
ANTARES



#	ΔT [s]	RA [h]	Dec [°]	σ_μ^{rec} [°]	E_μ^{rec} [TeV]	fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%

ANTARES+IceCube+LIGO+Virgo PRD 2016 (1602.05411)

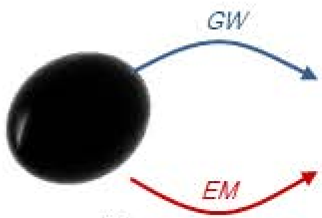
GWs FROM COMPACT BINARIES



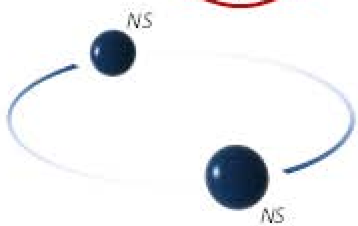
Bartos, Brady, Marka CQG 2013

science targets

PHYSICS

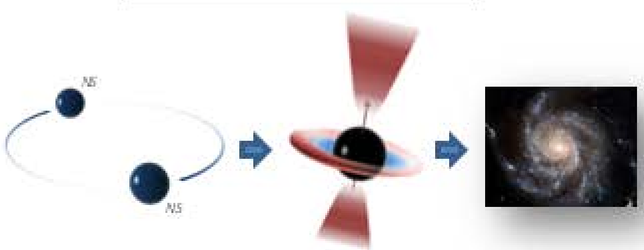


speed of gravity



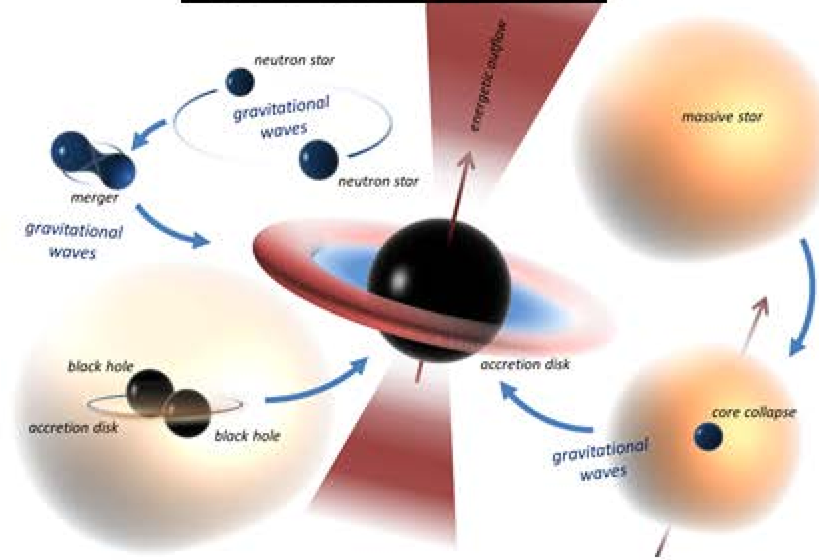
Equation of state of supranuclear matter

COSMOLOGY

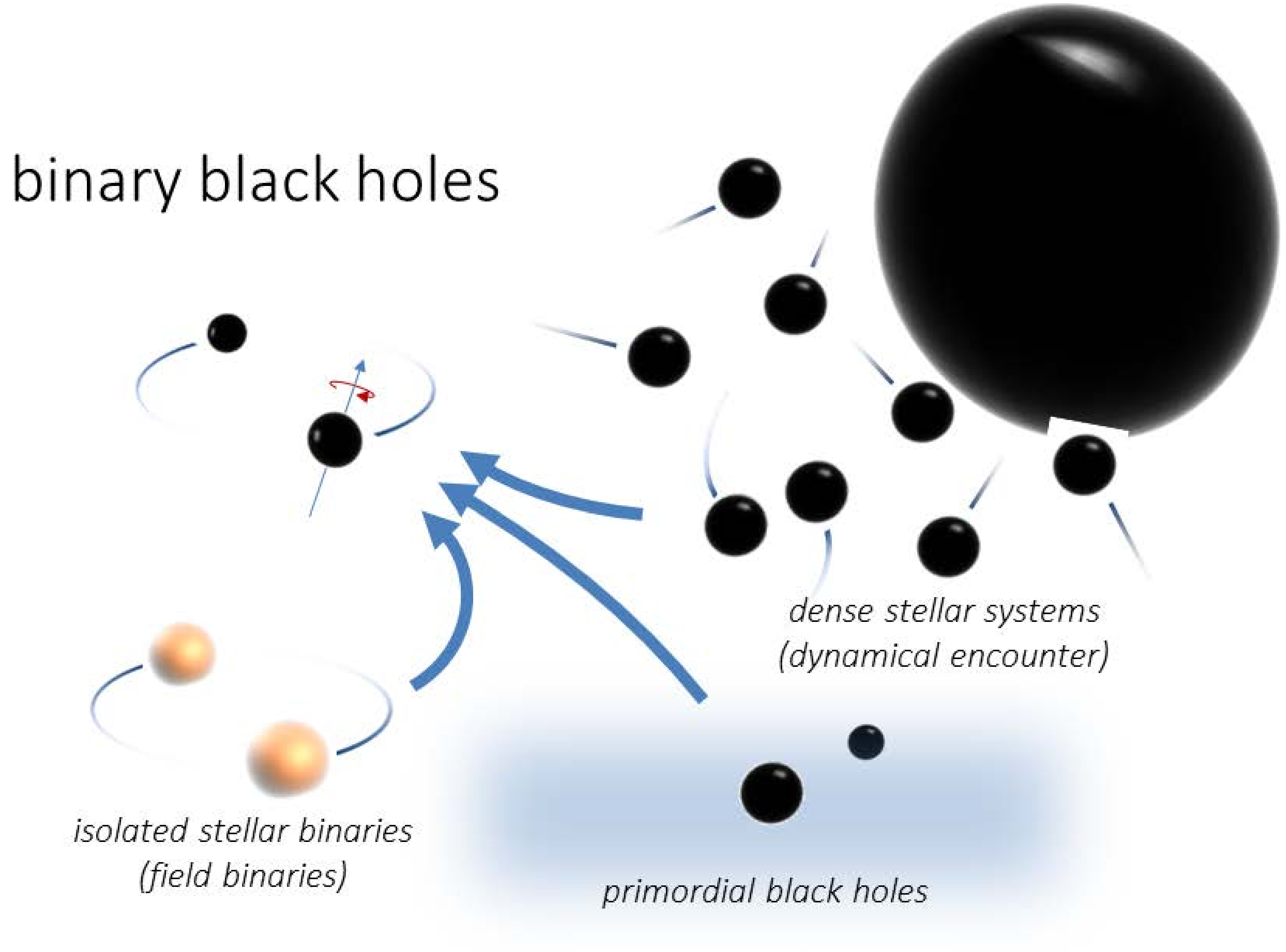


Alternative distance ladder

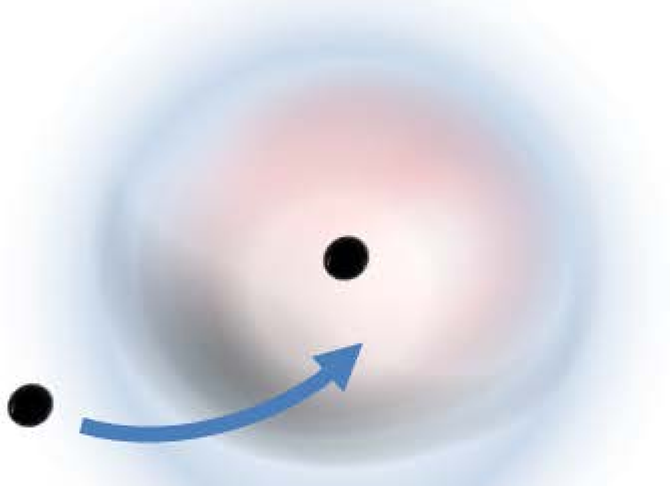
ASTROPHYSICS



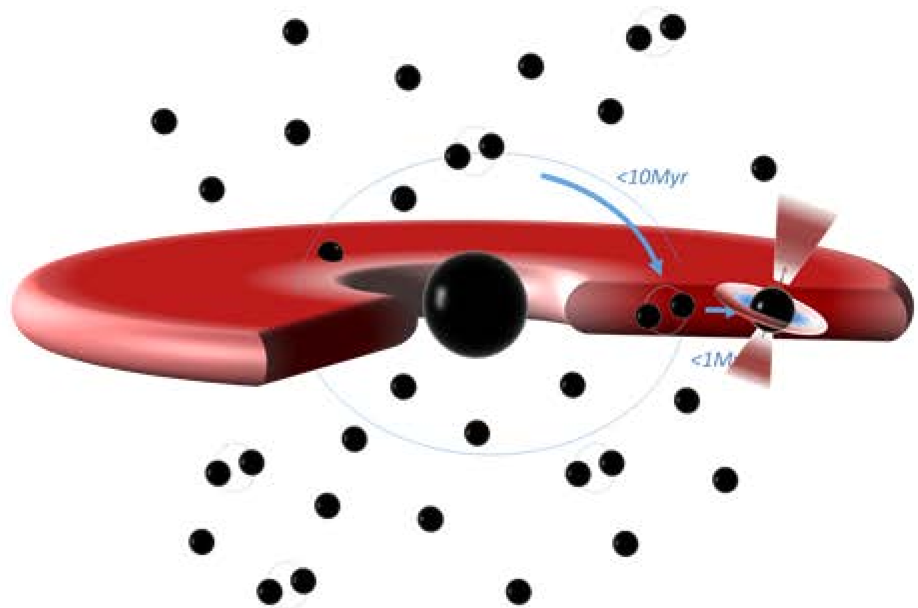
- *Black hole accretion*
- *Binary formation channels*
- *High-energy particle acceleration*
- *Stellar core collapse*
- *...*


binary black holes
dense stellar systems
(dynamical encounter)
isolated stellar binaries
(field binaries)
primordial black holes

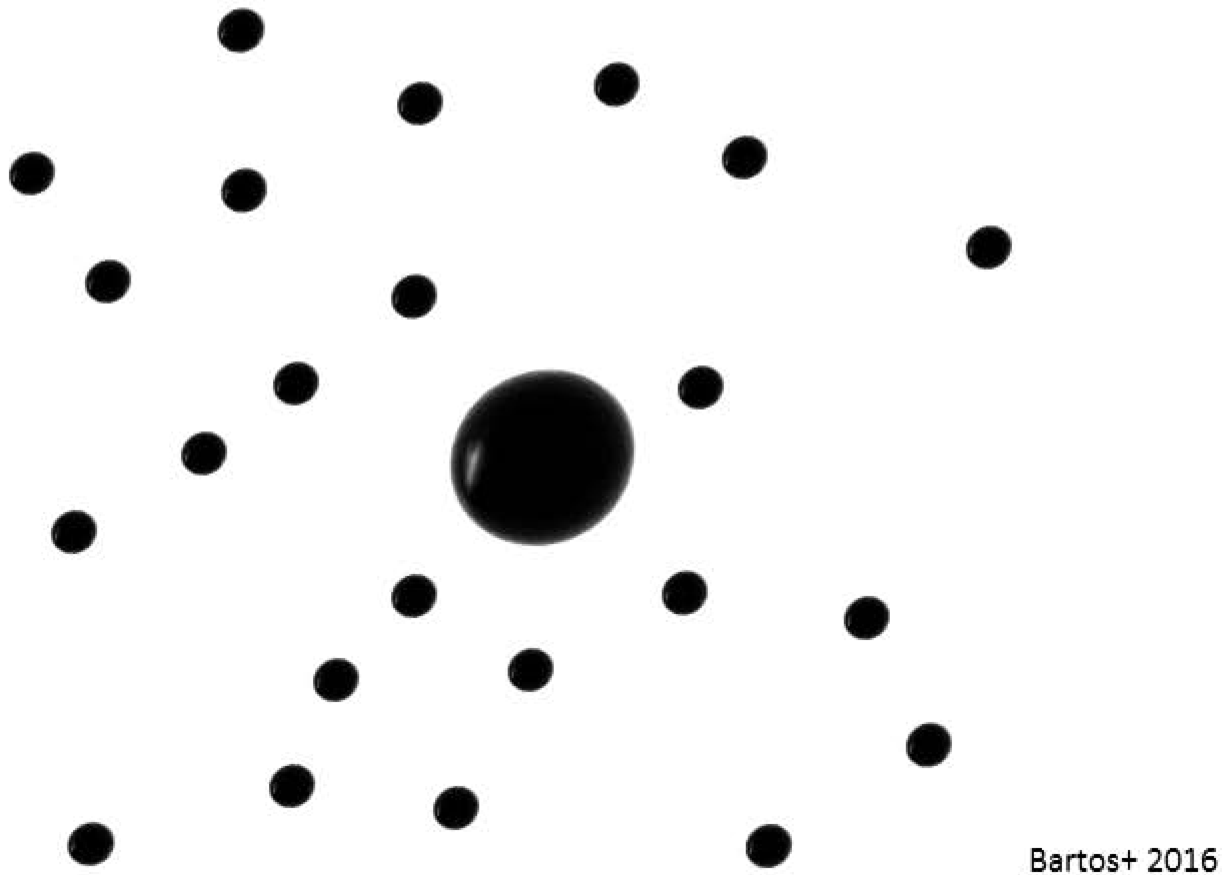
possible source of dense environment



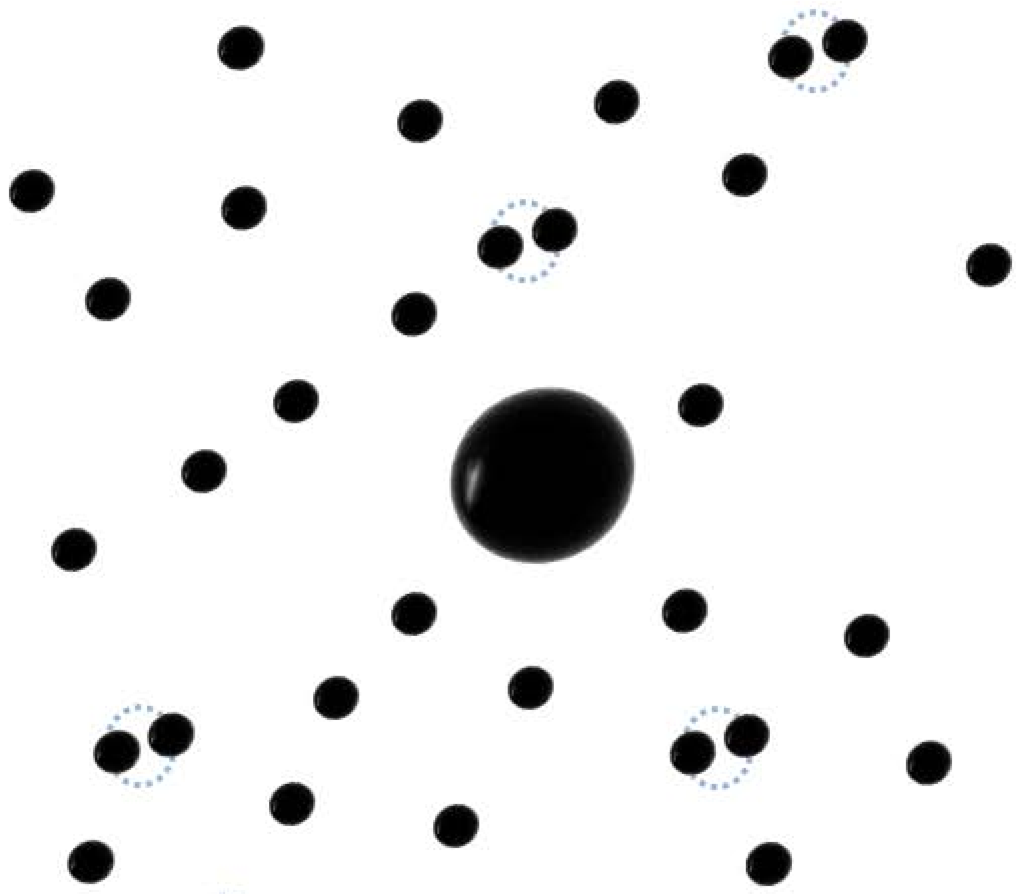
Gas remains from stellar progenitor
(Perna+ 2016, Mink+ 2017)



Black holes AGN disks
(Bartos+ 2017, Stone+ 2017)

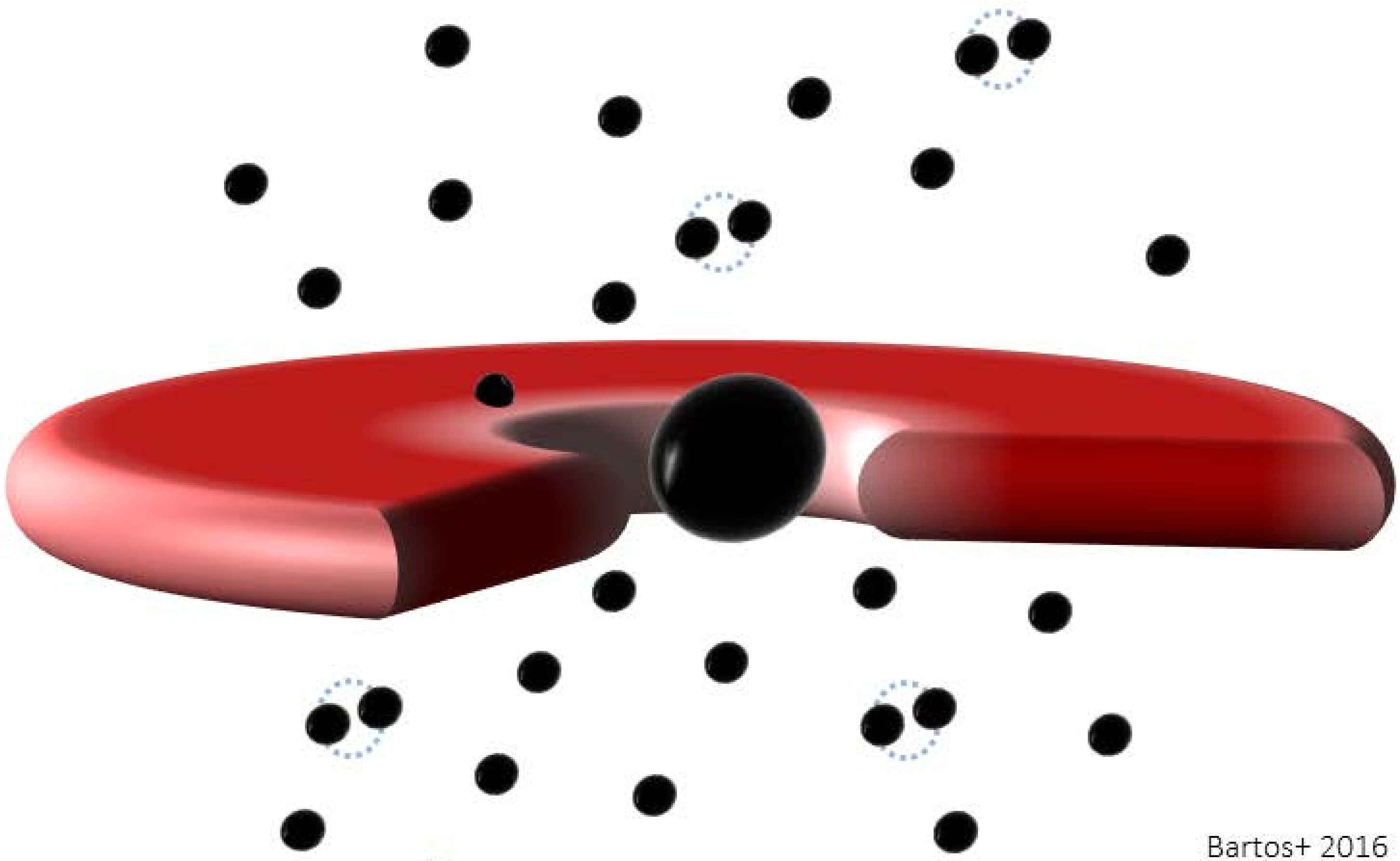


Galactic centers may harbor thousands of stellar mass black holes within the inner parsec (Morris 1993, O'Leary+ 2009).

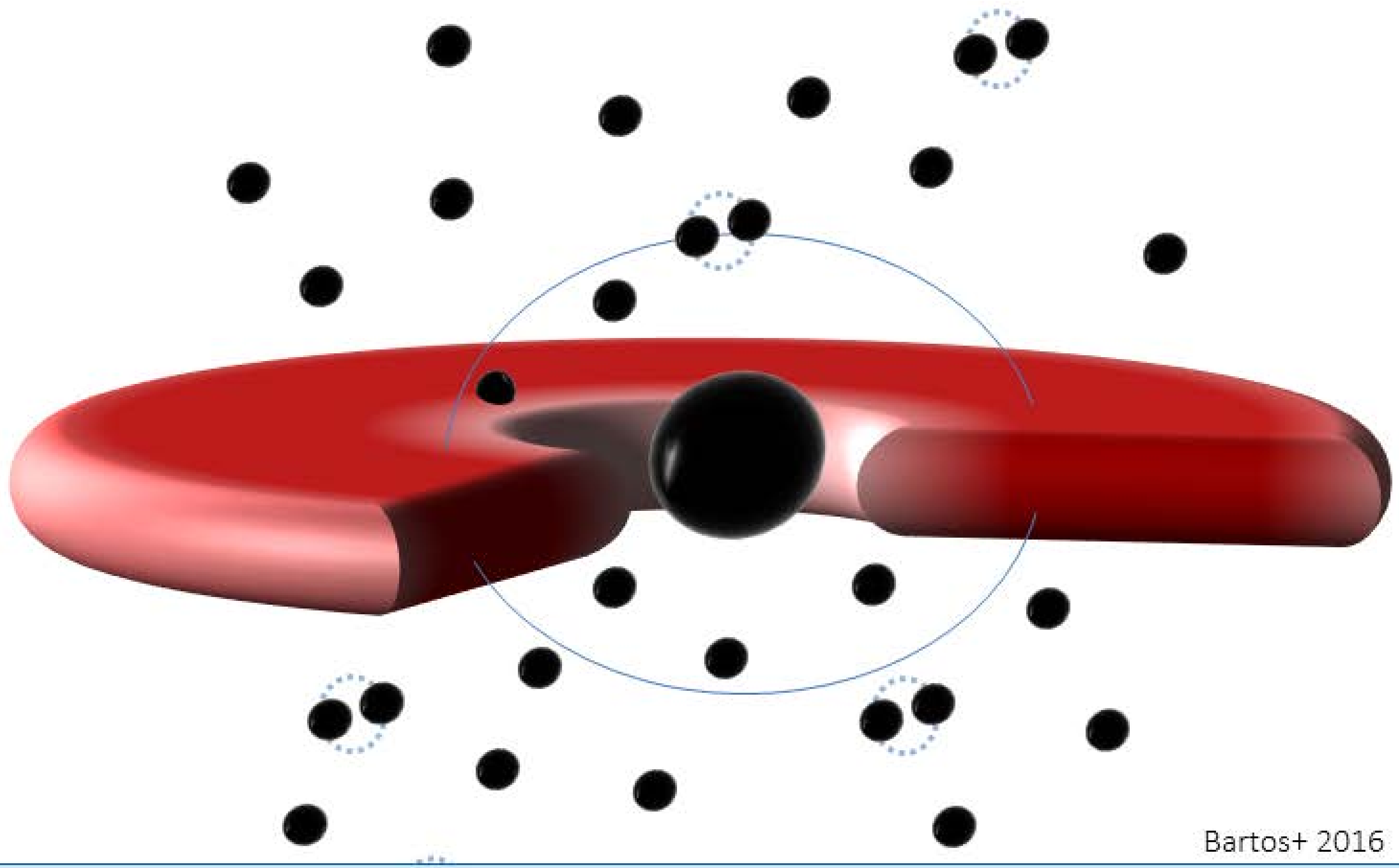


Bartos+ 2016

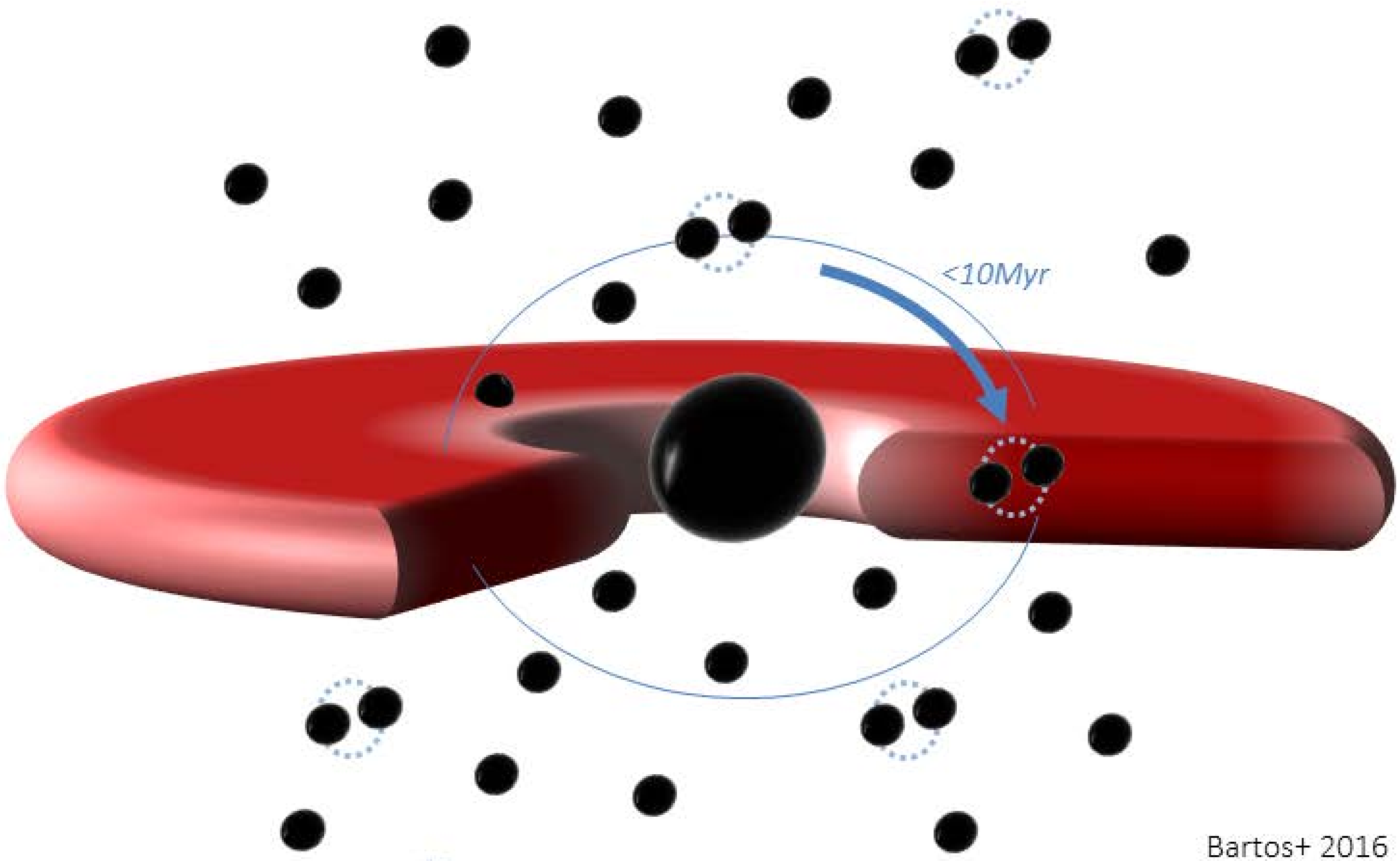
A fraction of black holes may be in binaries (30%; Pfuhl 2014).



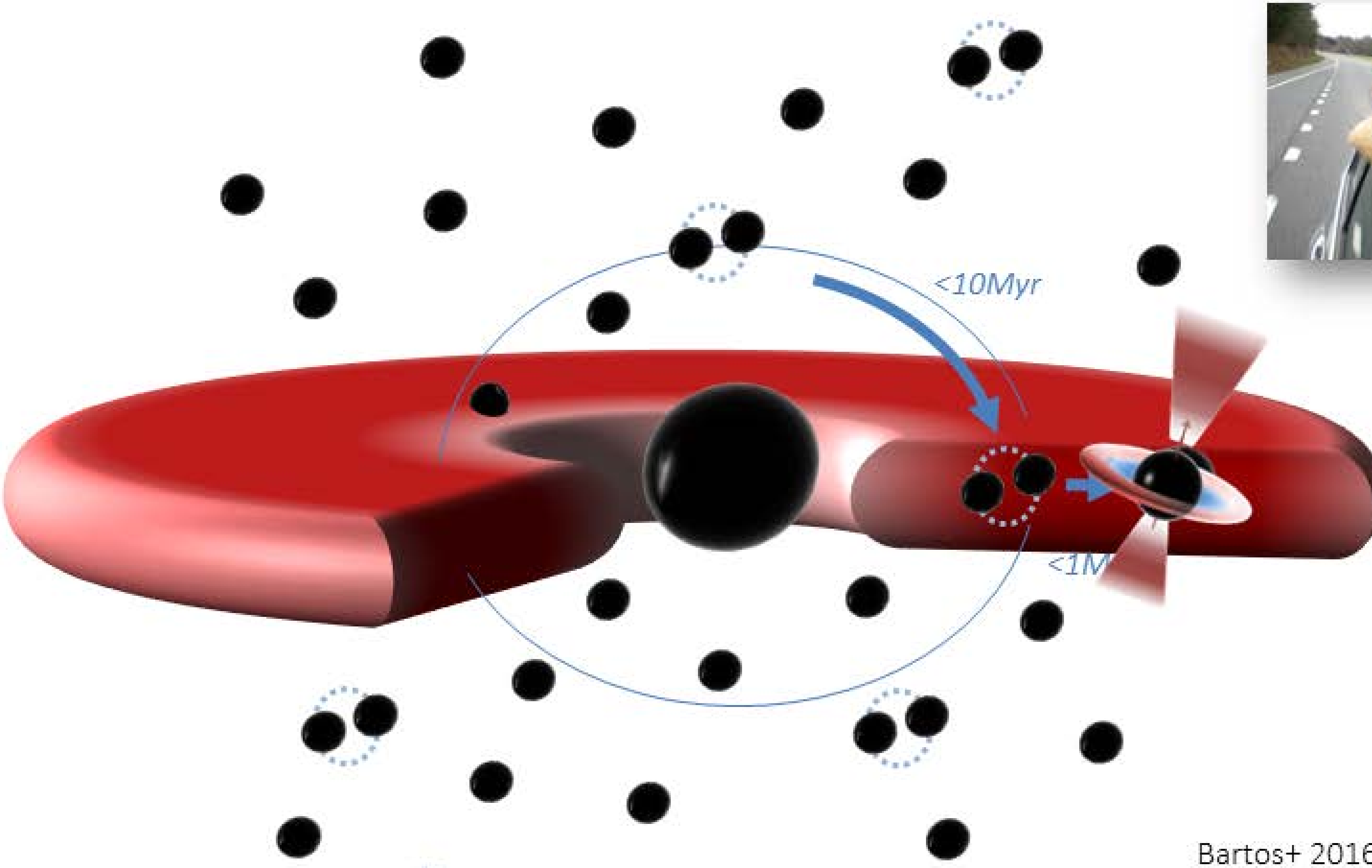
Some galactic centers accrete large amounts of gas (active galactic nuclei).



Binaries migrate into the disk...

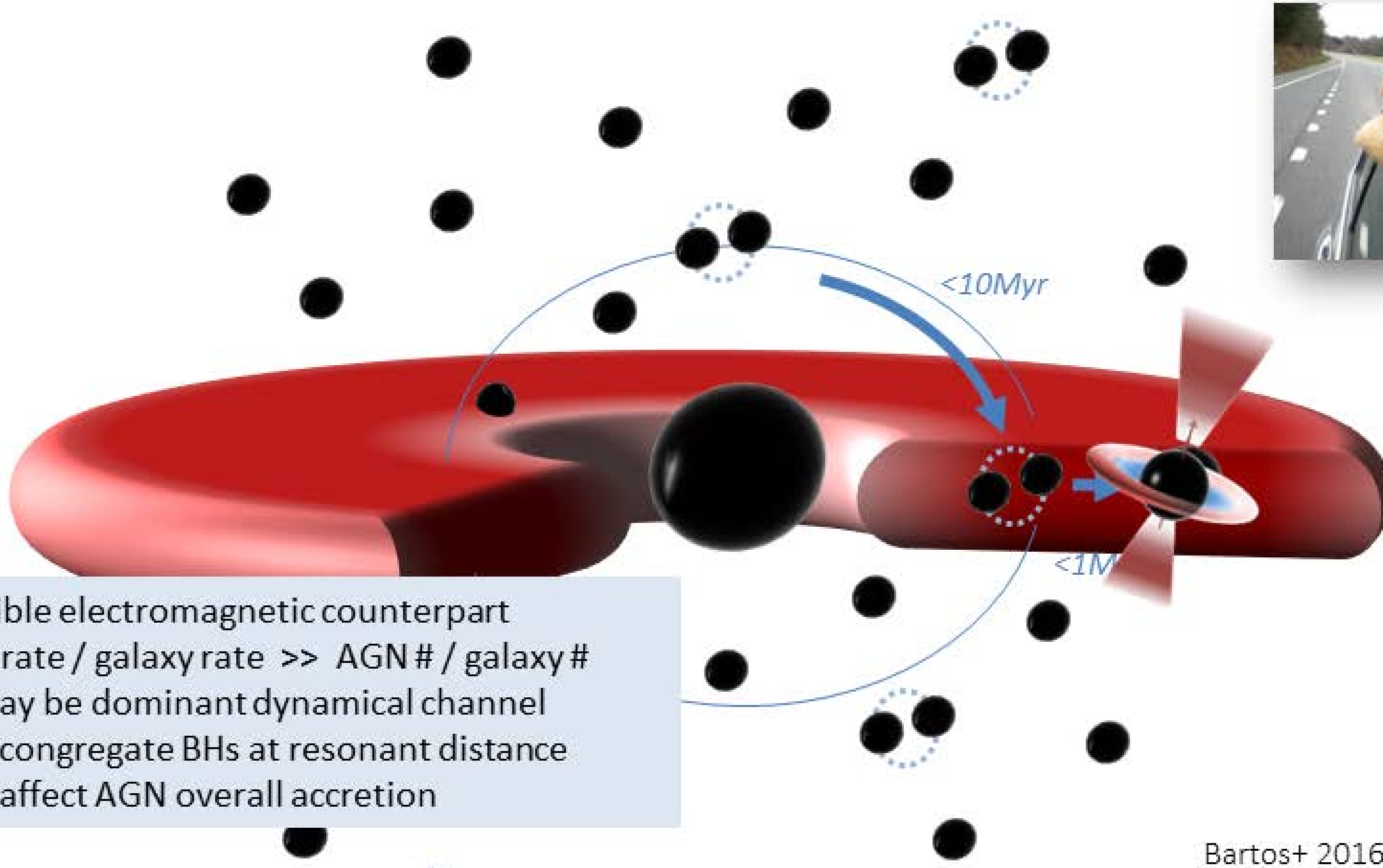


Binaries migrate into the disk…



Bartos+ 2016

…and then rapidly inspiral via dynamical friction.



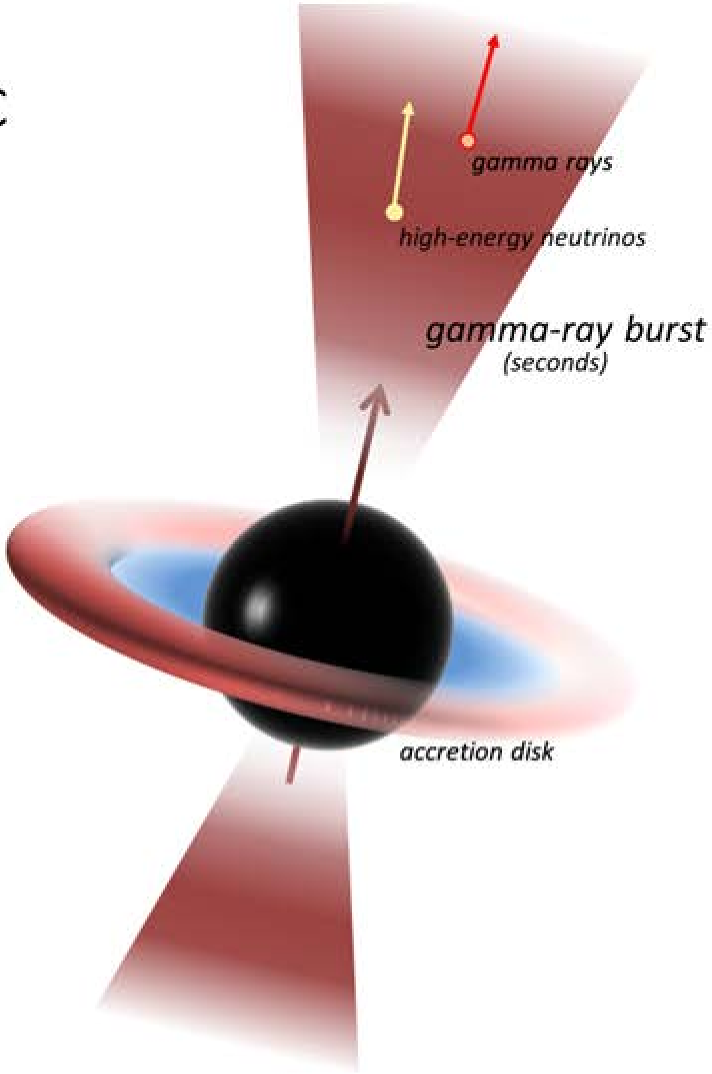
- Possible electromagnetic counterpart
- AGN rate / galaxy rate >> AGN # / galaxy #
  → may be dominant dynamical channel
- May congregate BHs at resonant distance
- May affect AGN overall accretion

Bartos+ 2016

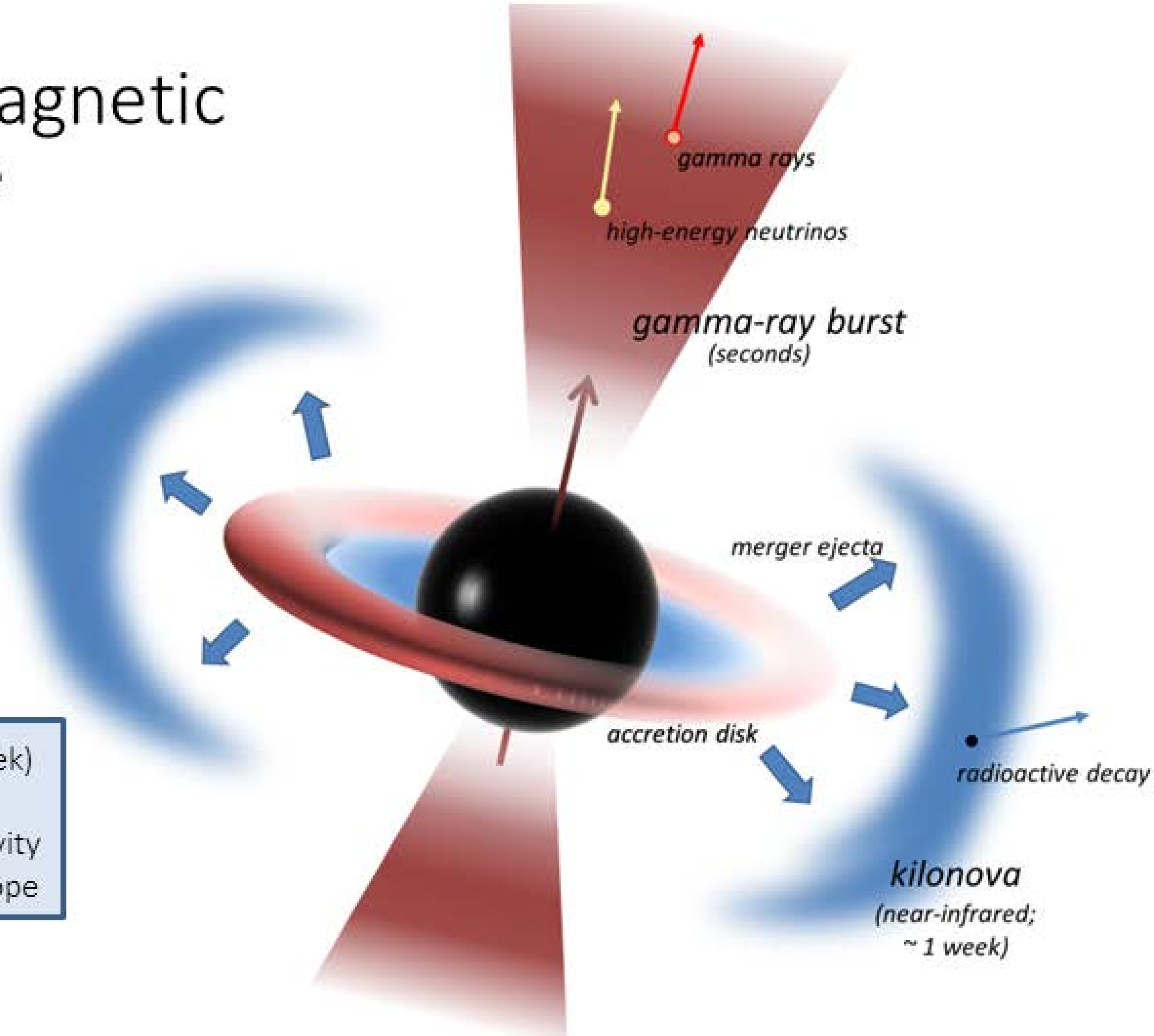
…and then rapidly inspiral via dynamical friction.

electromagnetic signature

- Beamed
- Good gamma-ray FoV (Fermi GBM: 64%; LAT: 20%; Swift BAT: 16%; XRT: 0%)
- Gamma-ray long term?
- Follow-up difficult (limited localization)



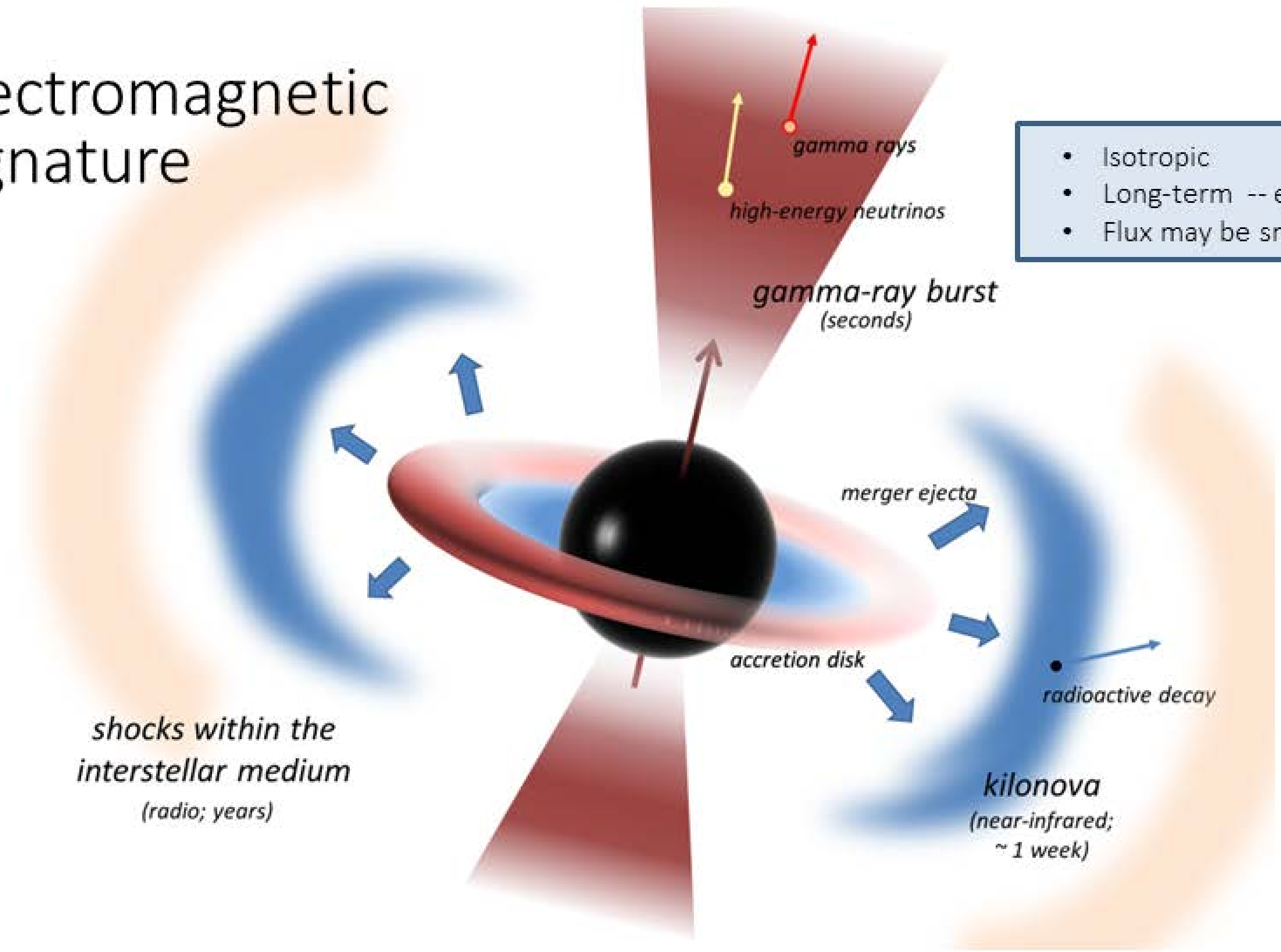
electromagnetic signature



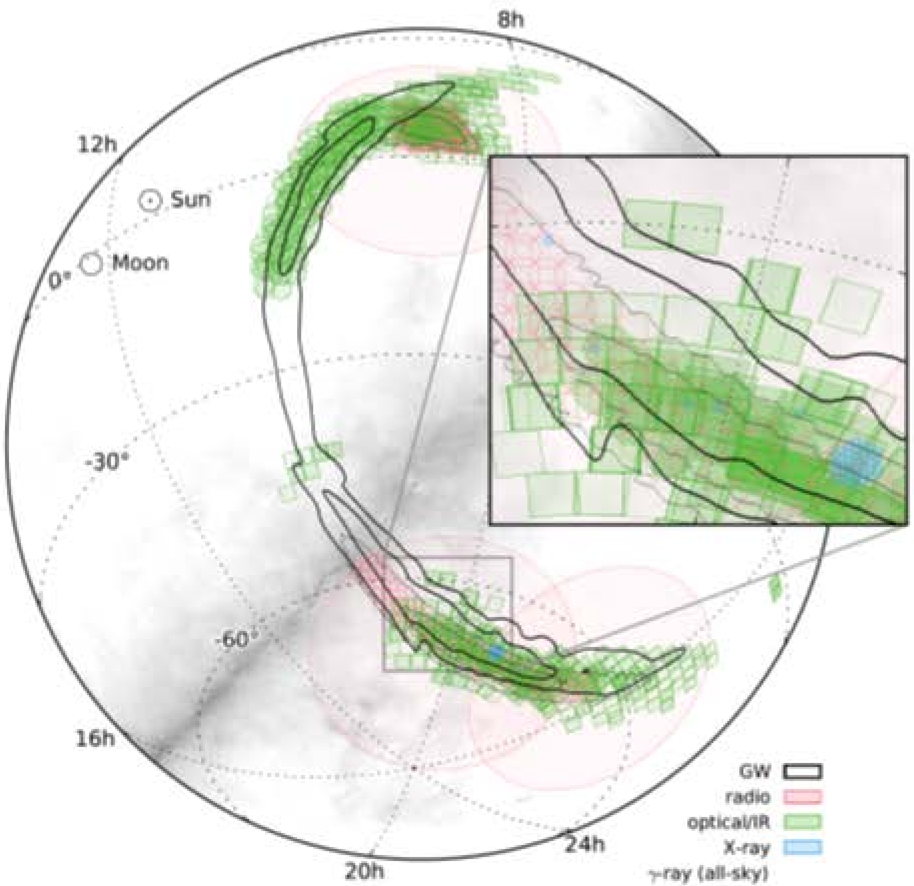
- Good time frame (~week)
- Isotropic
- Limited IR FoV / sensitivity
- → not for every telescope

electromagnetic signature

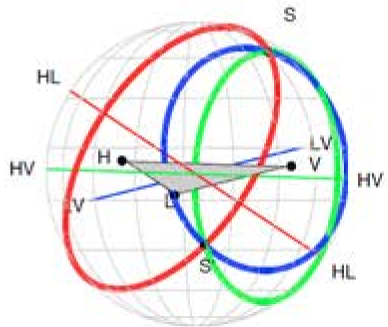
- Isotropic
- Long-term -- easy follow-up
- Flux may be small?



localization



Abbott et al. 2016 (1602.08492)

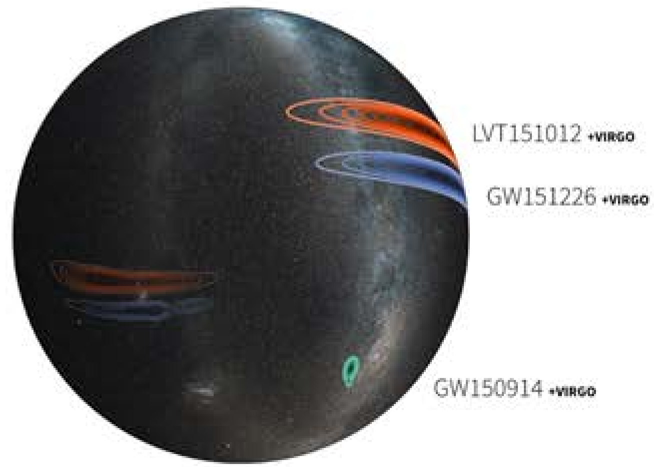


Chatterji+ PRD 2006

- 100-1000 deg^2
- Improves with more detectors
- Difficult to cover for many optical observatories
- Significant transient foreground (SNe)
- 1/month FAR LIGO triggers

MORE DETECTORS NEEDED

Actual estimates



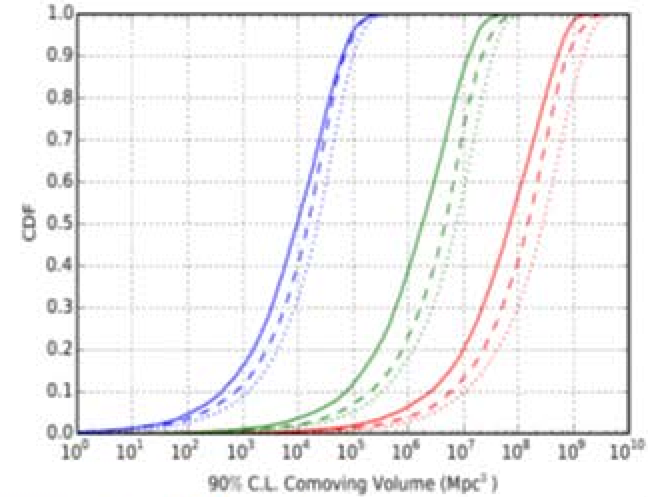
Simulated estimates with Virgo

3-D projection of the Milky Way onto a transparent globe shows the probable locations of confirmed detections GW150914 (green), and GW151226 (blue), and the candidate LVT151012 (red). The outer contour for each represents the 90 percent confidence region while the innermost contour is the 10 percent region. Image credit: LIGO/Axel Mellinger.

GW localization alone can probe origin

<u>What if we have no other information than GW?</u>

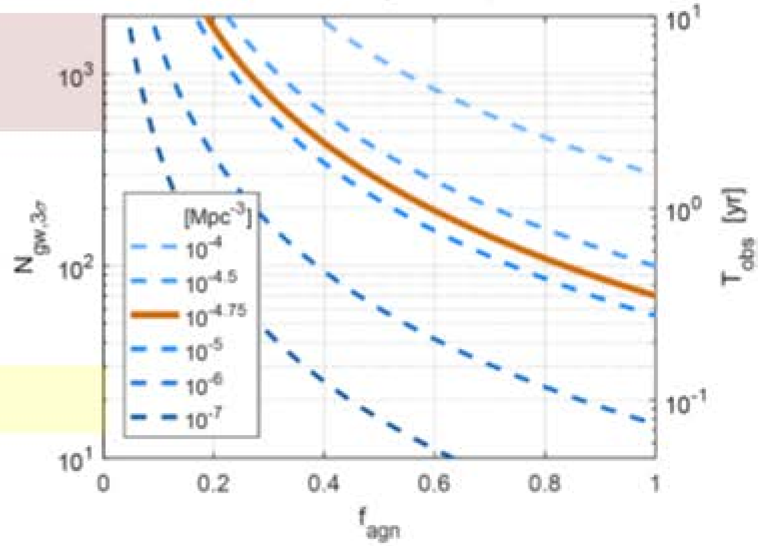
Spatial correlation can be enough for rare source types



Even fractional contributions to the total BBH merger rate can be established (>~20%) in ~few years

Understanding expected formation rate's dependence on galaxy properties can be game changer

Need more complete & deeper host catalogs

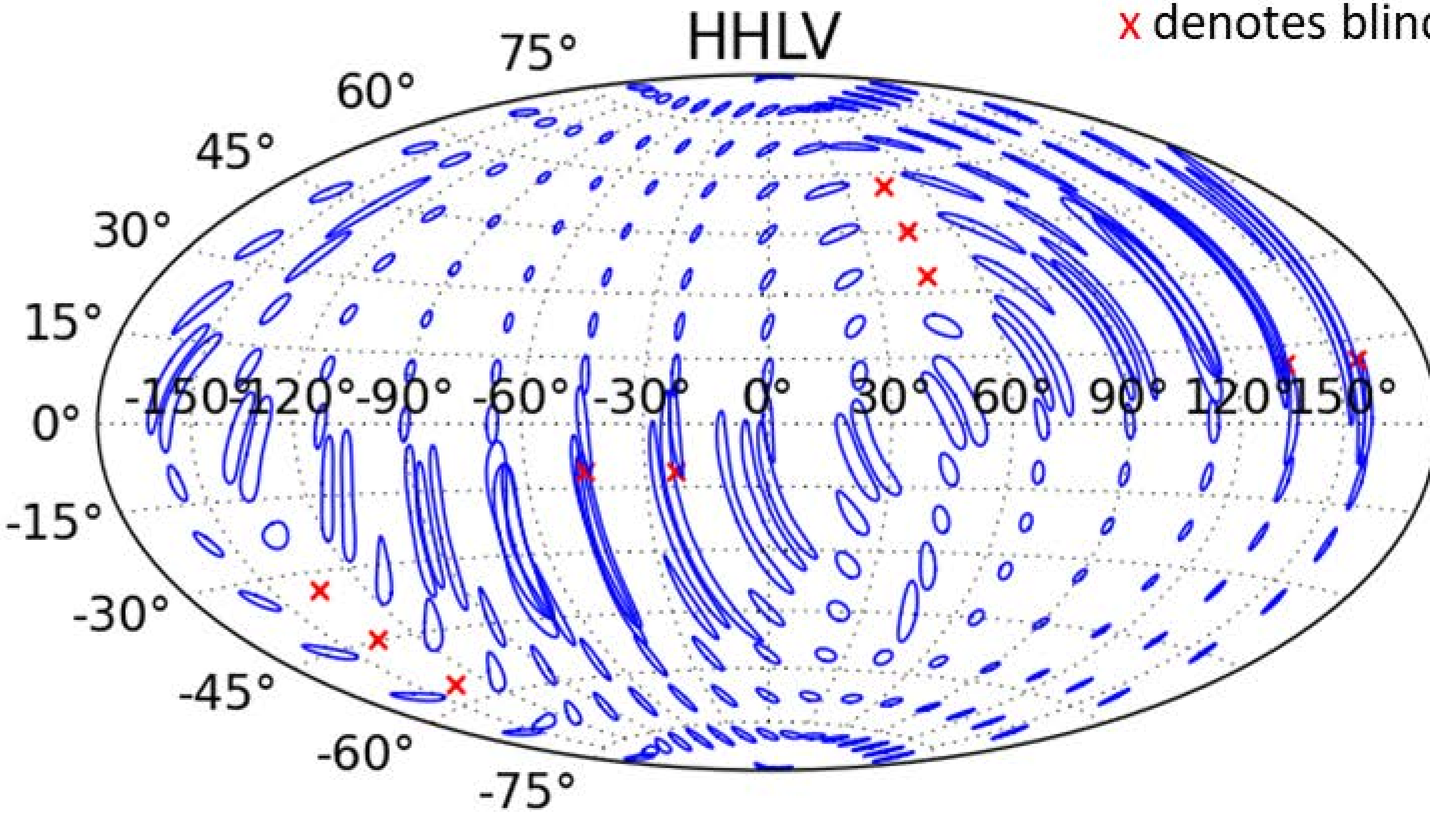


Bartos, Haiman, Marka, Metzger, Stone, Marka 2017

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo

3 site network

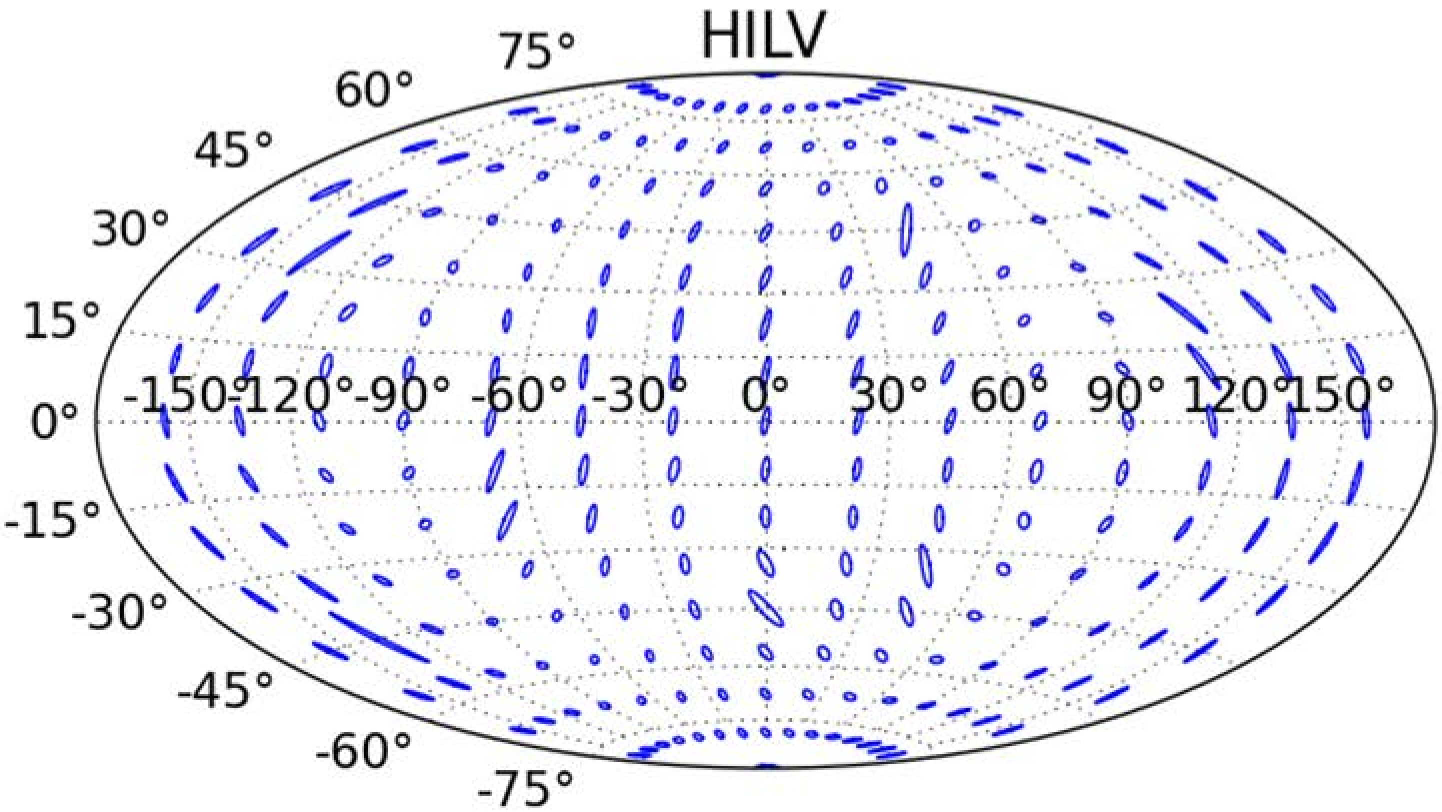
x denotes blind spots



S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

Localization: Hanford-Livingston-Virgo-India

4 site network

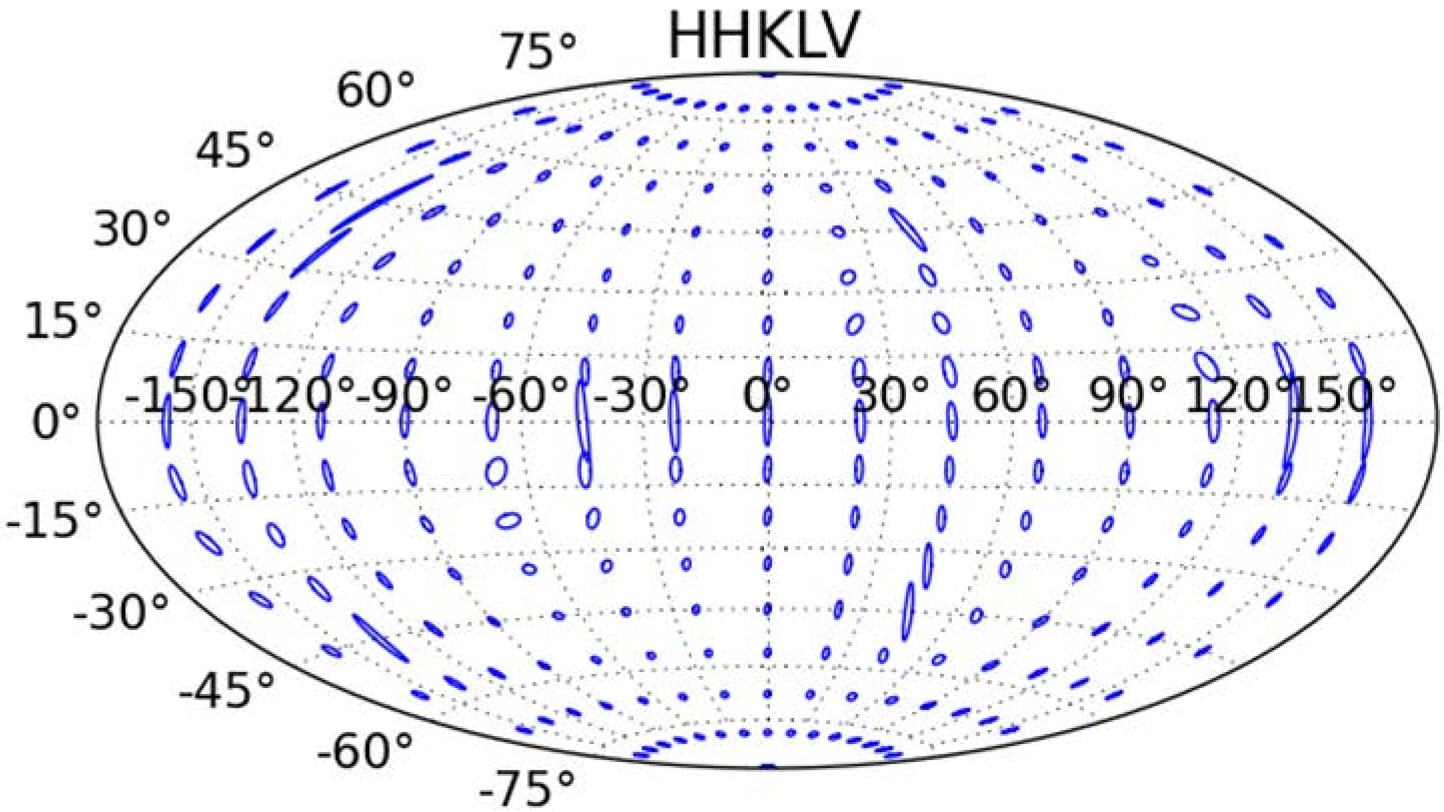


S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

Courtesy of David Reitze , Caltech and LSC

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo-KAGRA

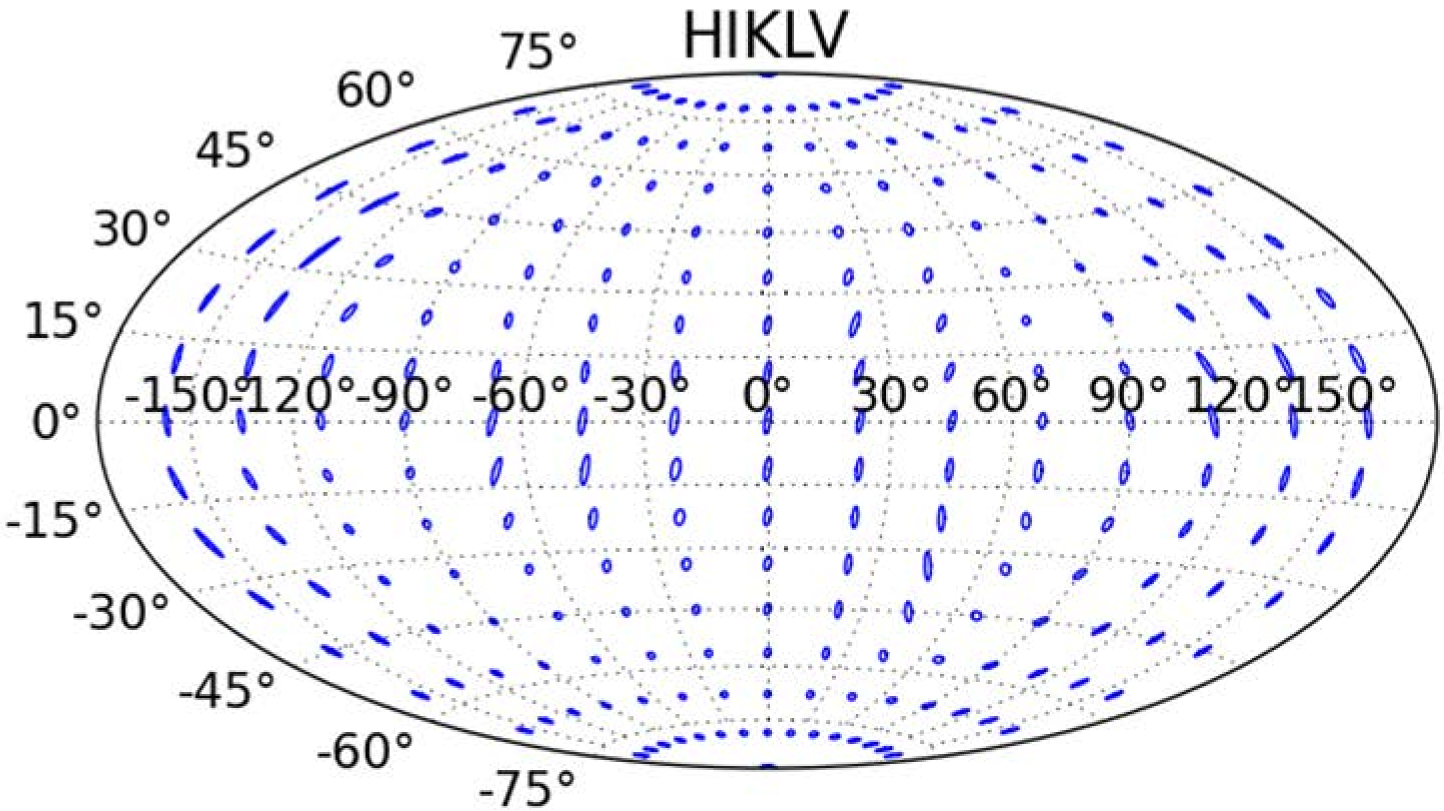
4 site network



S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

ary Neutron Star Merger Localization: Hanford-Livingston-Virgo-India-KAGRA

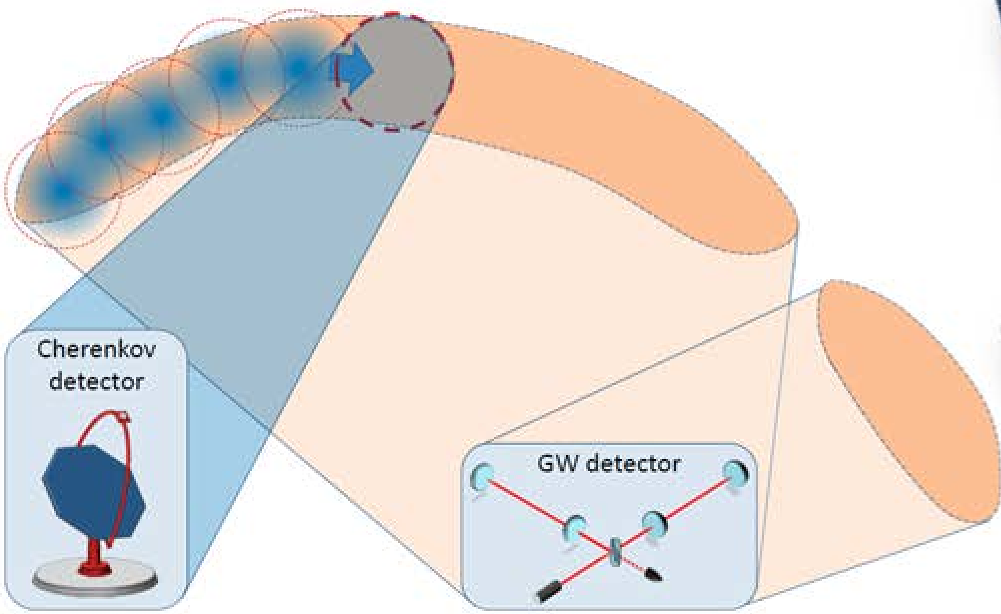
5 site network



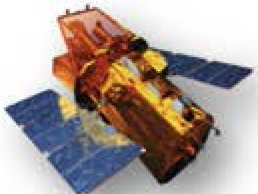
S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

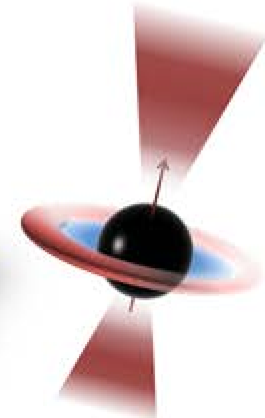
high-energy emission --- early targeting

- Gamma-ray bursts – all-sky observation
- GeV photons --- large FoV telescopes with quick response (CTA from 2018+)
- Beaming is not good.

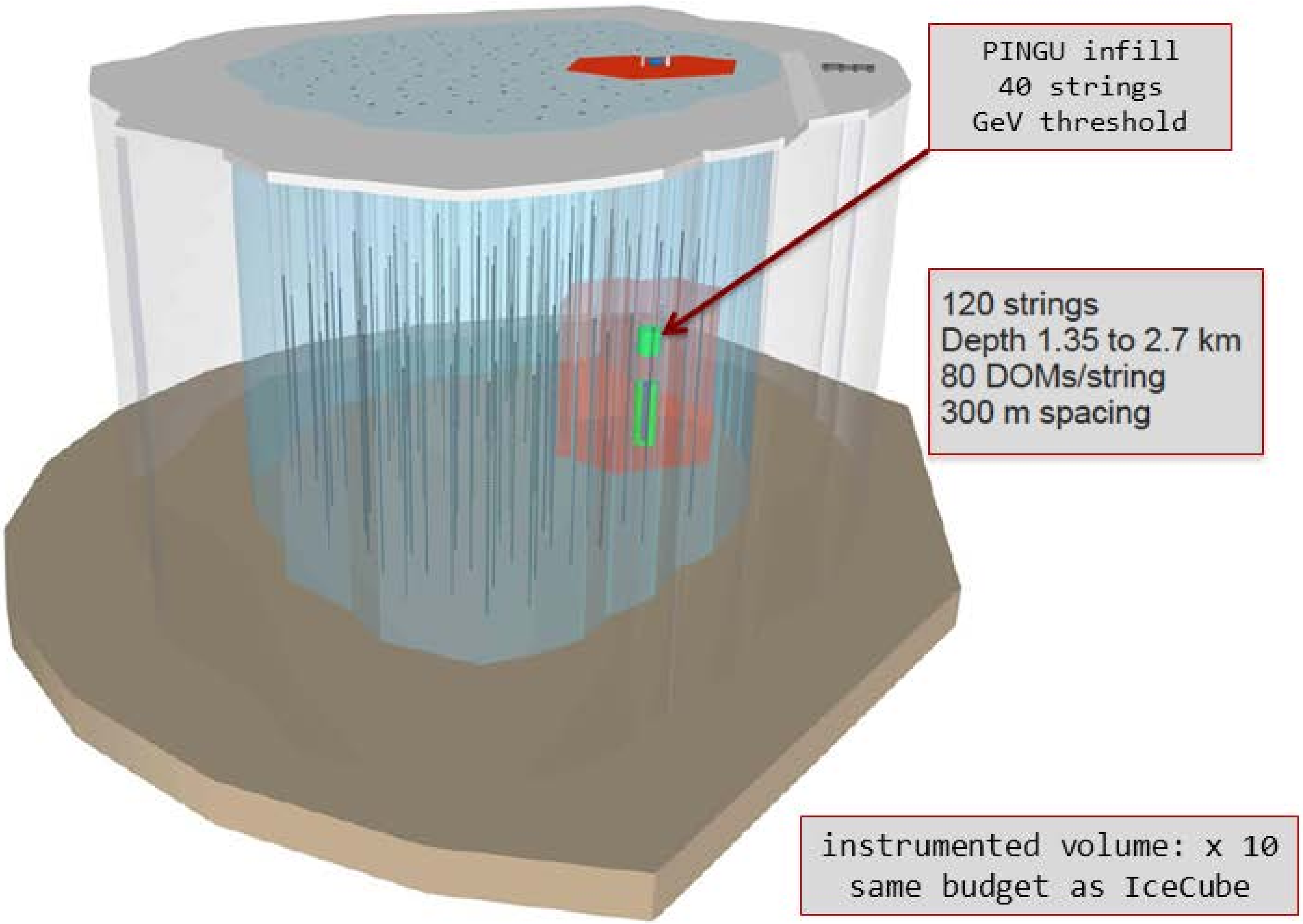


Bartos+ MNRAS 2014





beyond IceCube



LSST

✓ 35 m² collecting area
(~ all kilonovae)

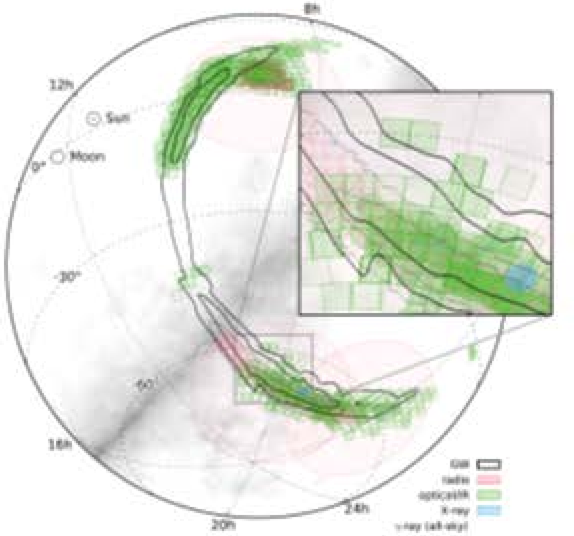
✓ Scans the entire available sky every few nights

✓ NIR sensitive

Complete in 2022
(we'll have many detections by then)

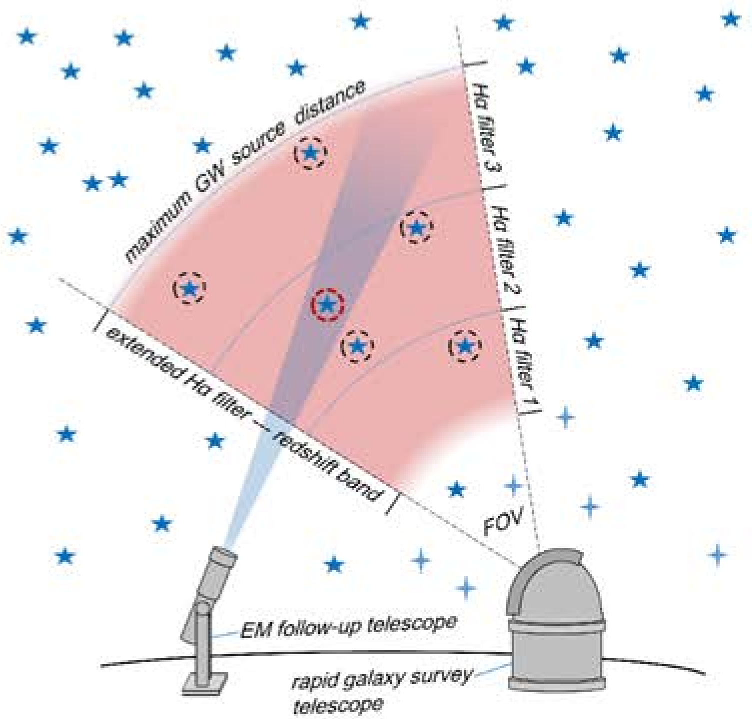
Huge foreground

Galaxy Catalogs *(on the fly?)*



- Benefits
  - Target for small FoV telescopes (e.g. Swift-XRT)
  - Decrease false positive rate (abundant transients)
- Current catalogs are not complete
  - GWGC, GLADE, CLU (~40% complete @ 200Mpc)
- Not clear what the good prior is for galaxies (Berger 2014)

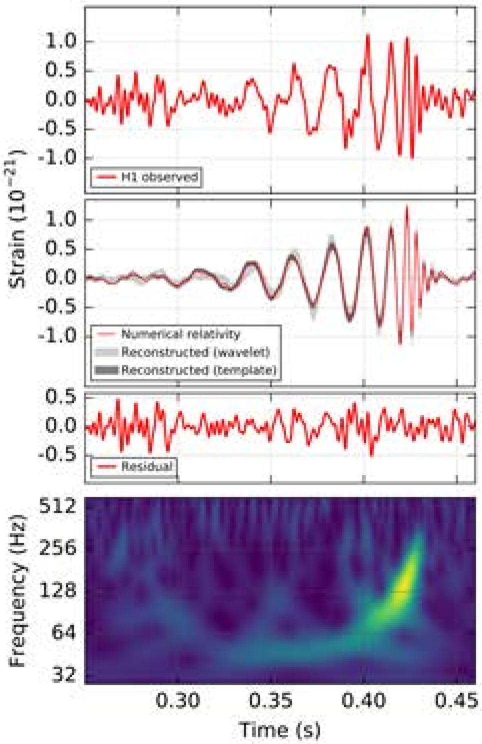
- Option: ToO cataloging (Bartos, Crotts, Marka 2015)
  - ✓ 1 week
  - ✓ 200-500 Mpc
  - ✓ 100 deg^2
  - ✓ Meter class telescopes work.



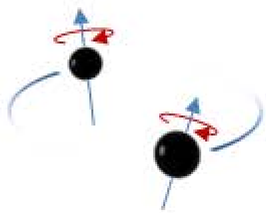
Using galaxies is "essentially" multimessenger by itself.

(Bartos, Crotts, Marka ApJ Lett. 2015)

Other way to increase detection rate: improve GW searches



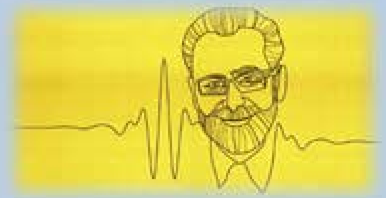
- **Matched filter technique** using numerical+analytical waveforms. O(10^5) templates.



15 (+2) parameters
masses (2)
distance (1)
direction (2)
orientation (2)
spin (6)
time (1)
phase (1)
+ eccentricity (2)

- **Development**:
  - Eccentricity, perpendicular spin
  - neutron Star tidal deformation
  - detector characterization
  - **Relax model-based restrictions**

Disruption: astrophysical information



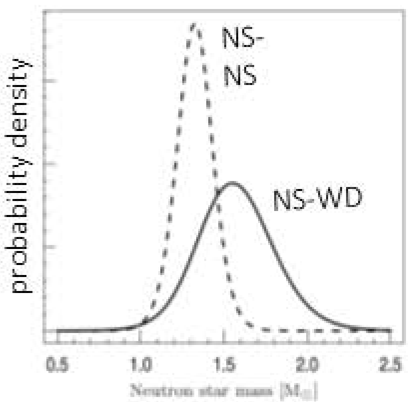
Yves Meyer
(Abel Prize)

neutron star mass distribution

- possible mass range: $\approx 1M_{\odot} - 3M_{\odot}$
- NS-NS observed in very narrow mass range: $M_{NS} = 1.33 \pm 0.11$
- Sensitive distance (ρ_{th}) depends on trial factor (N_{trial}):

$$\rho_{\rm th} \approx \sqrt{2\ln(\mathcal{N}_{\rm trial}/{\rm FAP})}$$

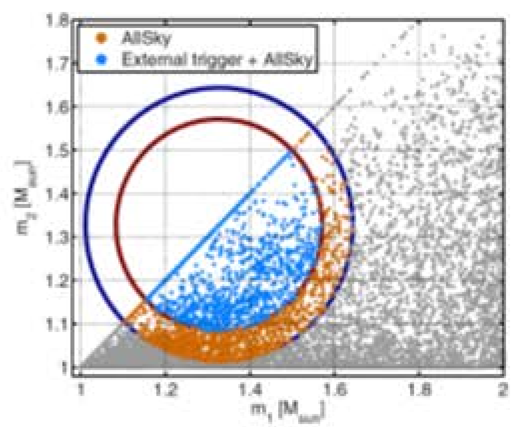
- Detection rate strongly depends on : $\mathcal{R} \propto \rho_{\rm th}^{-3}$

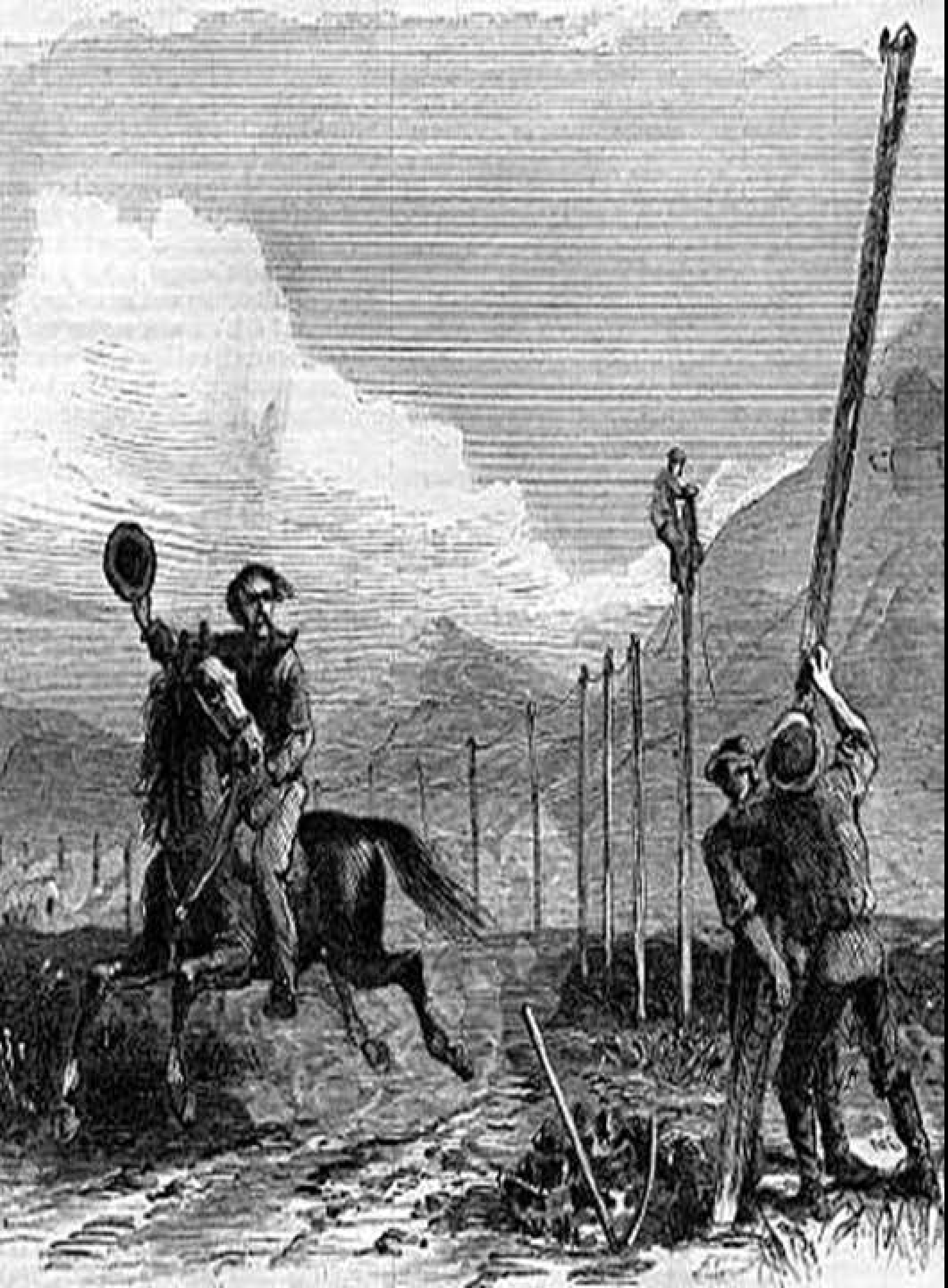


Improvement for optimal size or weighted template bank

- All-sky:
  15%
- *Multimessenger:*
  60%

Bartos & Marka PRL 2015





Pioneering fields of science often have more questions than answers…

Marka, 2010, http://iopscience.iop.org/1742-6596/243/1/012001/pdf/1742-6596_243_1_012001.pdf

Open Questions for Multimessenger Observations with Gravitational Wave Detectors? Oh… YES !

1. What is the speed of gravitational waves, subluminal or superluminal?
2. Does Einstein's theory of general relativity remain valid in the strong field regime?
3. Does gravity violate parity?
4. Is there a new length scale beyond which general relativity is modified?
5. Which alternative gravity theories can be excluded experimentally?
6. How often can an unidentified electromagnetic transient be explained by a gravitational wave emitter?
7. Is there a high redshift population of intermediate mass black holes?
8. Can gravitational waves help in explaining the origin of Ultra-Luminous X-ray binaries?
9. Can we search for new physics in the ultra-weak field regime?
10. Can a massive graviton serve as a cold-dark-matter candidate ?
11. What fraction of the cosmic source's energy is emitted in the form of gravitational waves?

Marka, 2010, http://iopscience.iop.org/1742-6596/243/1/012001/pdf/1742-6596_243_1_012001.pdf

Open Questions for Multimessenger Observations with Gravitational Wave Detectors? Oh… YES !

12. Can gravitational wave detectors provide an early warning to electromagnetic observers to allow the detection of early light curves ?

13. Do gravitational measurements of distance agree with the concordance cosmology?

14. What is the mass spectrum and spin distribution of black holes ?

15. Are there extra gravitational wave polarizations?

16. Is there a significant non-axisymmetric crust or core dynamics associated with SGRs?

Marka, 2010, http://iopscience.iop.org/1742-6596/243/1/012001/pdf/1742-6596_243_1_012001.pdf

Open Questions for Multimessenger Observations with Gravitational Wave Detectors? Oh… YES !

17. What is the precise origin of SGR flares ? (e.g., What is the mechanism for GW and EM emission and how are they correlated?)
18. Is there a fundamental difference between giant and common SGRs?
19. Do quark stars exist?
20. Can we exclude or confirm some of the SGR models?
21. What is the origin of pulsar glitches?
22. What is the composition and structure of neutron stars and their cores?
23. What is the tallest mountain that can be supported by neutron stars?
24. Can we use GW-EM observations to guide or EM+null GW results to distinguish the local extragalactic SGR contributions from the short GRB population?

Marka, 2010, http://iopscience.iop.org/1742-6596/243/1/012001/pdf/1742-6596_243_1_012001.pdf

Open Questions for Multimessenger Observations with Gravitational Wave Detectors? Oh… YES !

25. What is the nature of gravitational collapse?
26. What is the relationship between the supernova progenitor and remnant (e.g., final mass and spin)?
27. If the supernova remnant is not a black hole, how does it behave? (e.g., a transient hypermassive remnant with unstable modes or collapse to a BH?)
28. What happens in a core collapse supernova before the light and neutrinos escape?
29. What is the delay in between neutrinos and gravitational waves in a core collapse supernovae?
30. What is the role of anisotropic neutrino emission in supernovae?
31. What is the mass of a neutrino?
32. Can we see core collapse supernovae in gravitational waves that are not visible in neutrinos?
33. Is there an electromagnetically hidden population of core collapse events?
34. How many dynamical scenarios are associated with core collapse supernovae? Can we distinguish between them?
35. Can pulsar birth kicks result in detectable gravitational waves?

Marka, 2010, http://iopscience.iop.org/1742-6596/243/1/012001/pdf/1742-6596_243_1_012001.pdf

Open Questions for Multimessenger Observations with Gravitational Wave Detectors? Oh… YES !

25. What is the time delay between the electromagnetic brightening and the core collapse of a supernova?
26. What are the properties of the core collapse supernova progenitor?
36. What is the role of the rotation and magnetic fields in stellar core collapse?

37. What is the origin of long and short GRBs? What is the precise dynamics of each GRB engine?
38. Is there any longer-lasting central engine left over from the GRB explosion, and what's its nature?
39. Are there electromagnetically hidden populations of GRBs?
40. Does the hypothesized low luminosity GRB population exist?
41. Can we have direct inferences on the GRB jet parameters from gravitational waves?
42. Can we estimate properties of the nuclear equation state using short GRBs?
43. Can we relate the luminosity distribution of GRBs to beaming and the central engine mechanism?

Marka, 2010, http://iopscience.iop.org/1742-6596/243/1/012001/pdf/1742-6596_243_1_012001.pdf

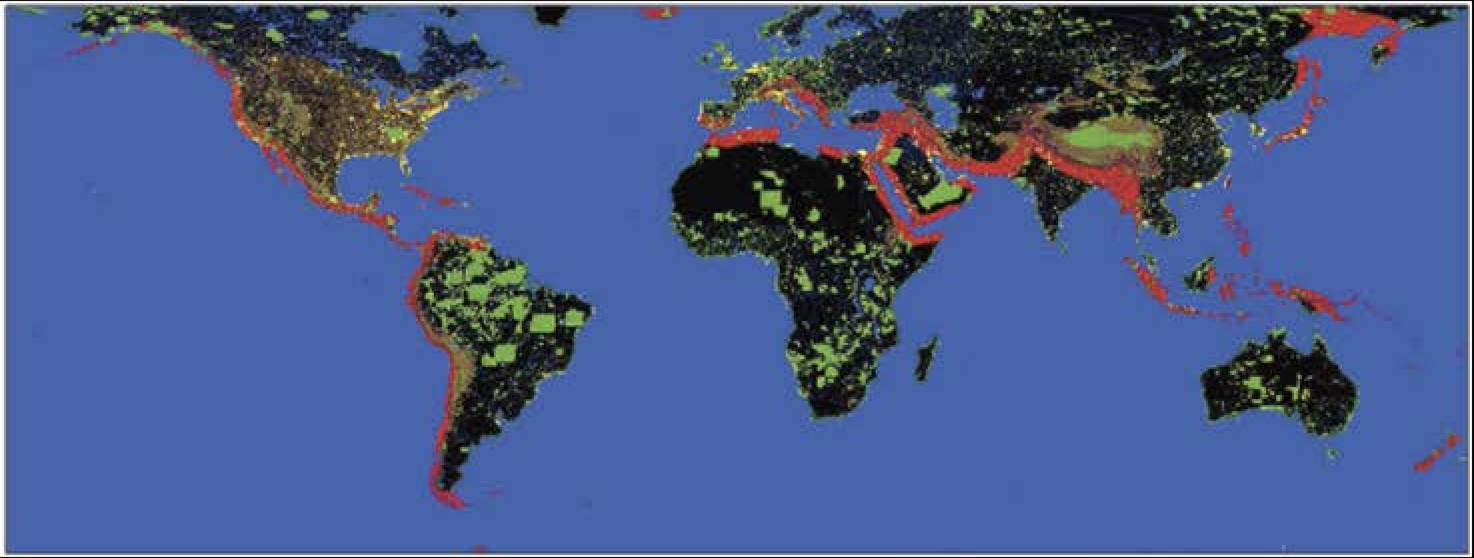
Open Questions for Multimessenger Observations with Gravitational Wave Detectors? Oh… YES !

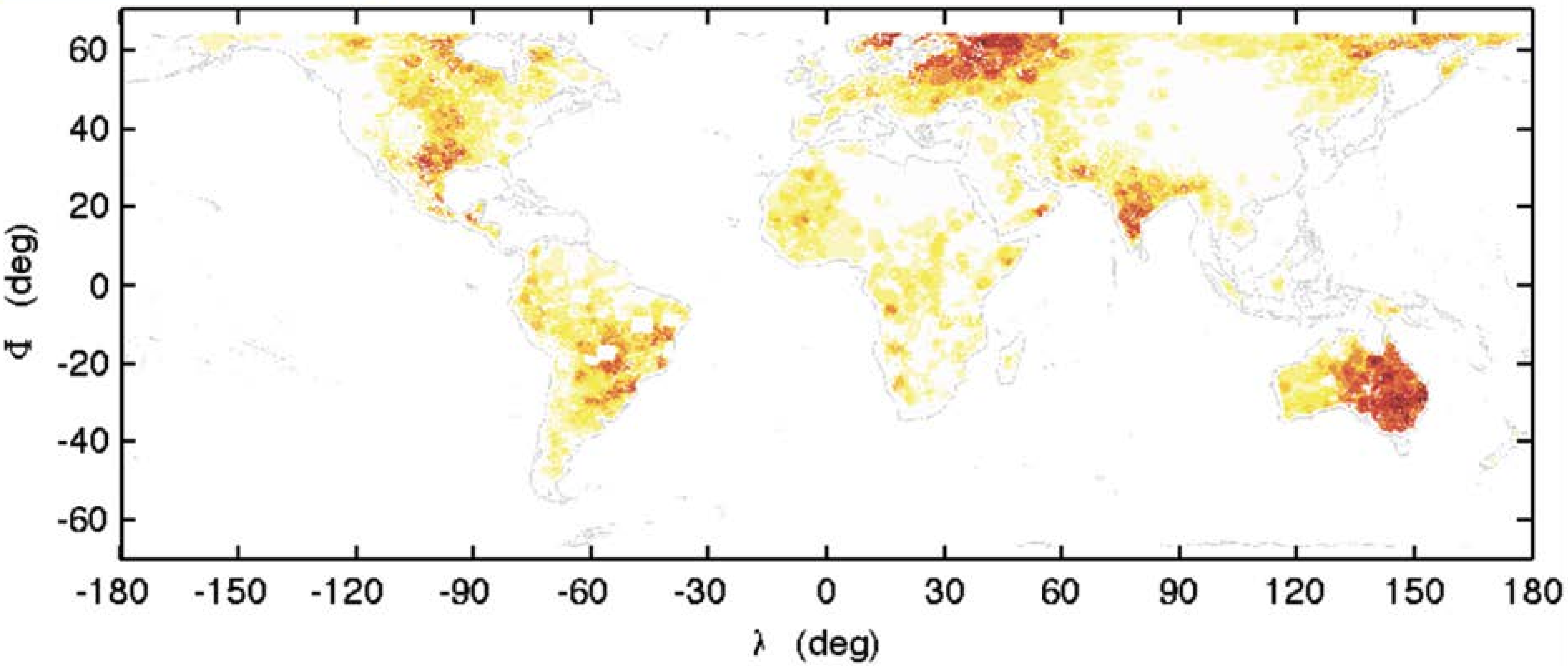
25. What is the relationship between the parameters of a compact binary system and it's electromagnetic and neutrino emission?
26. What GRB progenitor models can we confirm or reject?
27. Are there other (sub)classes of GRBs? Do choked GRBs exist? What is the origin of choked GRBs? Cosmic population of choked GRBs?
44. What are the engines producing high energy neutrino and gravitational wave emission together?
45. What is the dynamics/energetics of joint high energy neutrino and gravitational wave emitters?
46. What is the electromagnetic emission of binary neutron star coalescence?
47. What is the electromagnetic emission of a neutron star-black hole coalescence?
48. Is there any electromagnetic emission from binary black hole coalescence?
49. What is the nature of XRFs and their relationship to long GRBs?
50. Is it possible to construct a competitive Hubble diagram based on gravitational wave standard sirens?
51. …

… and dozens(???) of other exciting questions are waiting to be answered by the community!

Global Optimization for Future Gravitational Wave Detectors' Sites

Class. Quantum Grav., (2014)





Takeaway

Multimessenger-gravitational wave astrophysics:

- ✓ More information is more science.

Gravitational-wave detectors:

- ✓ Rapidly expanding horizon (eventually >1 detection/week)
- ✓ Substantial multimessenger effort underway

Road ahead:

- ✓ Initially binary black holes → multimessenger?
- ✓ New, large-scale observatories (LSST, CTA, JWST, SKA, ...)
- ✓ Localization / host galaxy catalogs
- ✓ Astrophysical information → GW searches


NSF
Questions?