Status and Prospects for Gravitational Wave Physics and Astronomy

V. Kalogera, T. Prince, R. Weiss

Board on Physics and Astronomy
National Academies
Washington DC, April 25, 2015

Outline

- Overview of field and Ground-based Science

  — Vicky Kalogera

- Pulsar Timing and Space-based Science & Detectors

  — Tom Prince

- Evolution of Ground-based Detectors

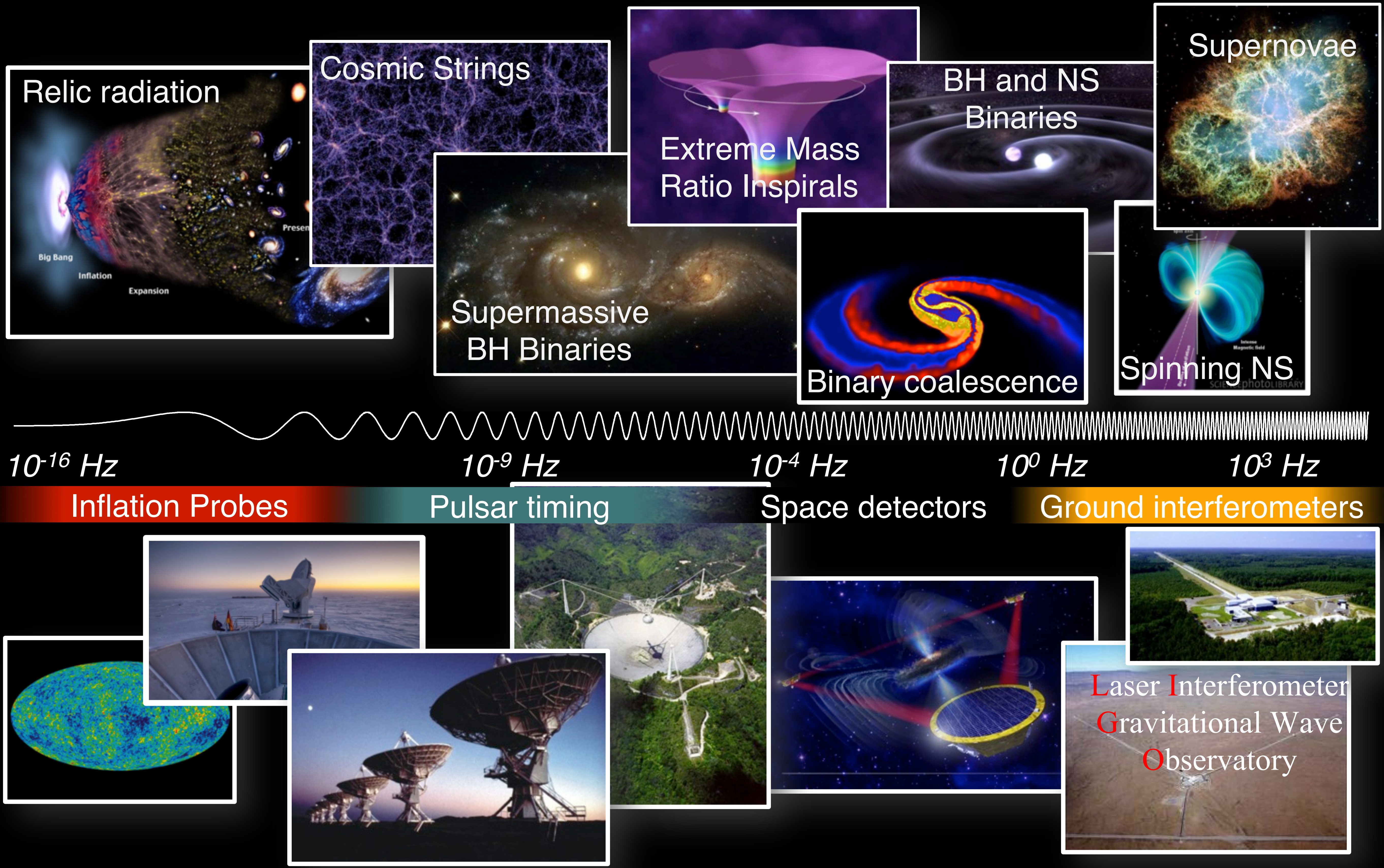
  — Rai Weiss

- Request of Board on Physics and Astronomy

  NRC Study of long-term directions

  for ground-based detectors and science

The Gravitational Wave Spectrum



Relic radiation

Cosmic Strings

Supermassive BH Binaries

Extreme Mass Ratio Inspirals

BH and NS Binaries

Binary coalescence

Supernovae

Spinning NS

10^{-16} Hz

10^{-9} Hz

10^{-4} Hz

10^{0} Hz

10^{3} Hz

Inflation Probes

Pulsar timing

Space detectors

Ground interferometers

Laser Interferometer Gravitational Wave Observatory

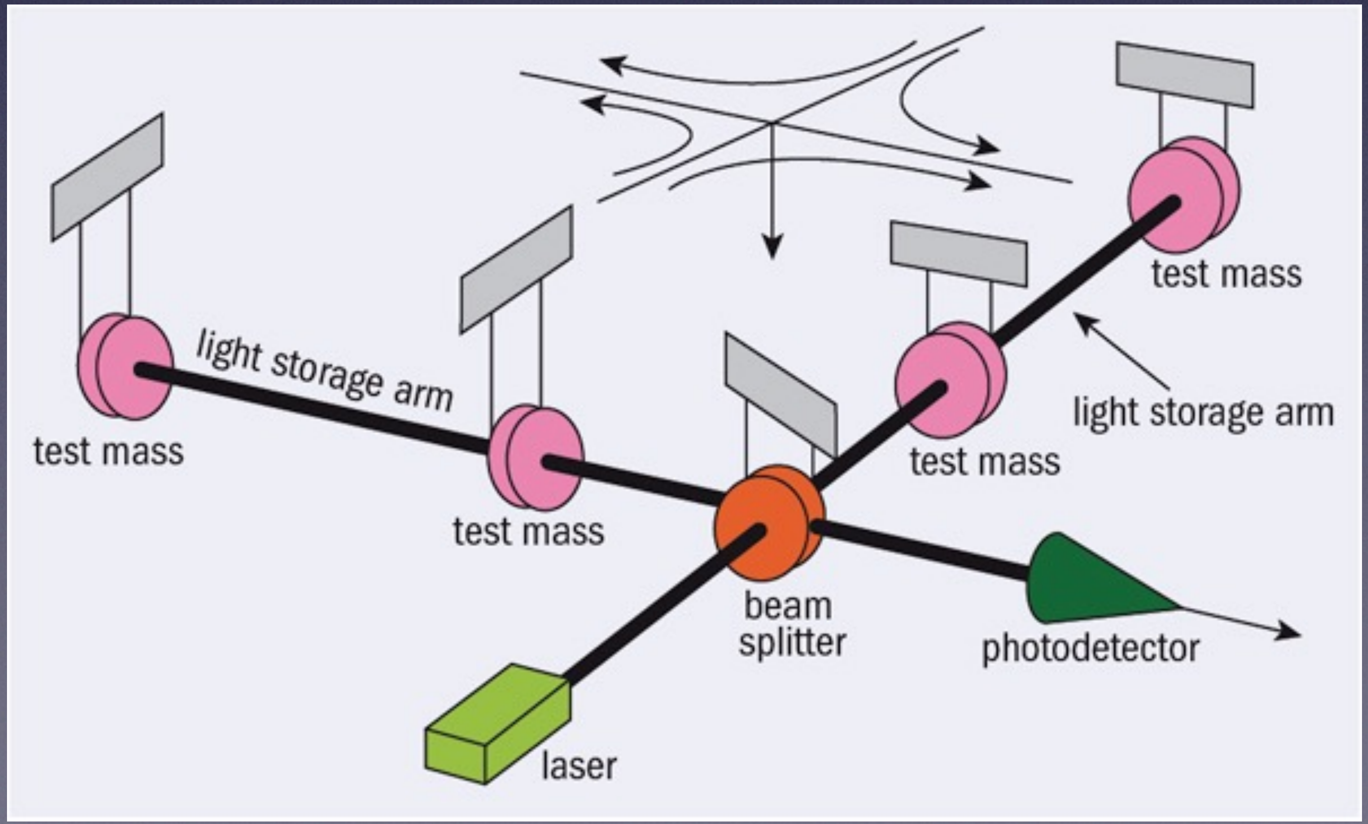
Slide: Matt Evans (MIT)

LIGO - Virgo Detector Network

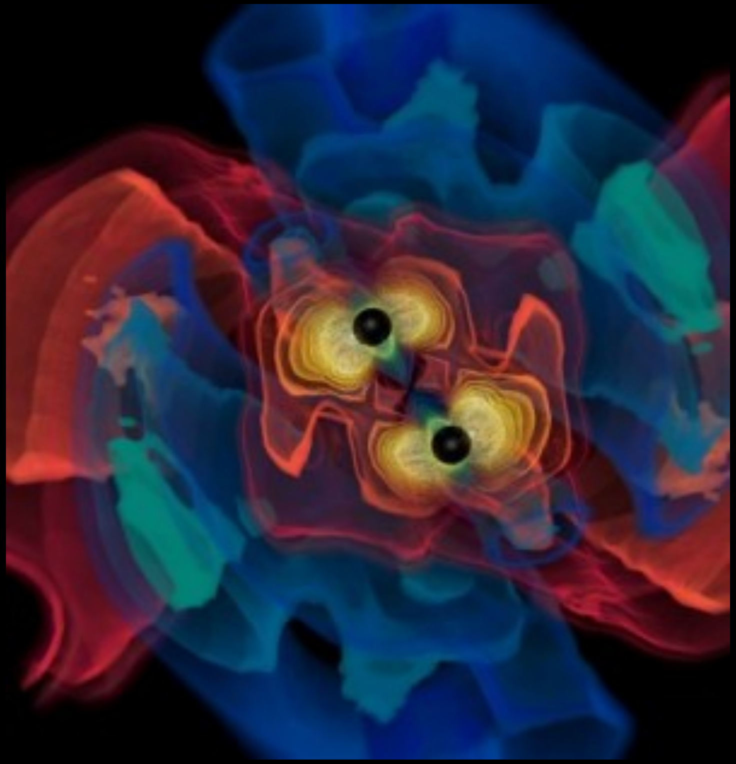
LIGO-Hanford
(H1)

LIGO-Livingston
(L1)

Virgo-Pisa
(V1)



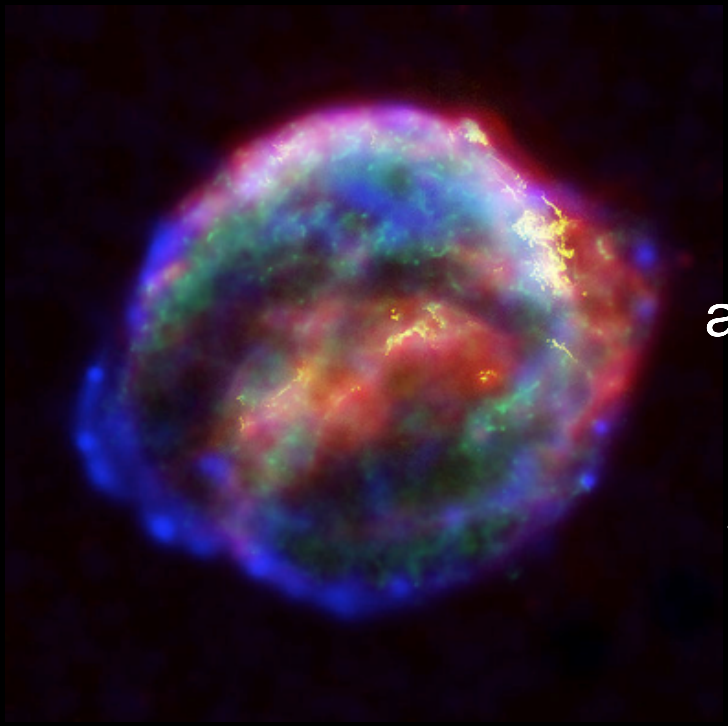
Astrophysical Targets for Ground-based Detectors



Credit: AEI, CCT, LSU

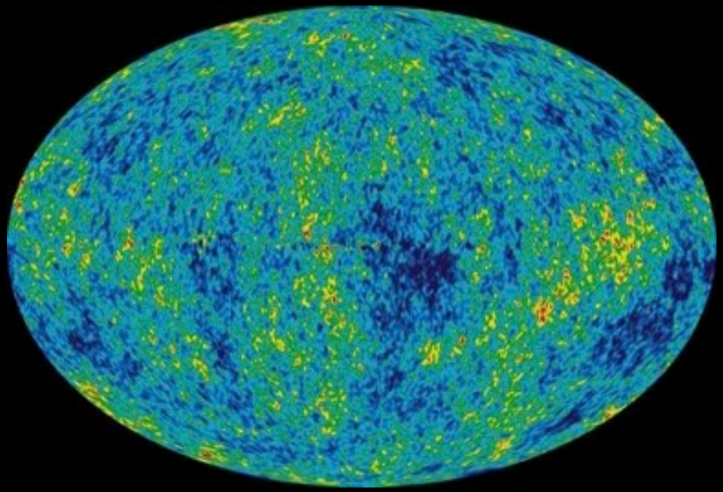
Coalescing Binary Systems

- Well-modelled
- Neutron stars, low mass black holes, and NS/BS systems



'Bursts'

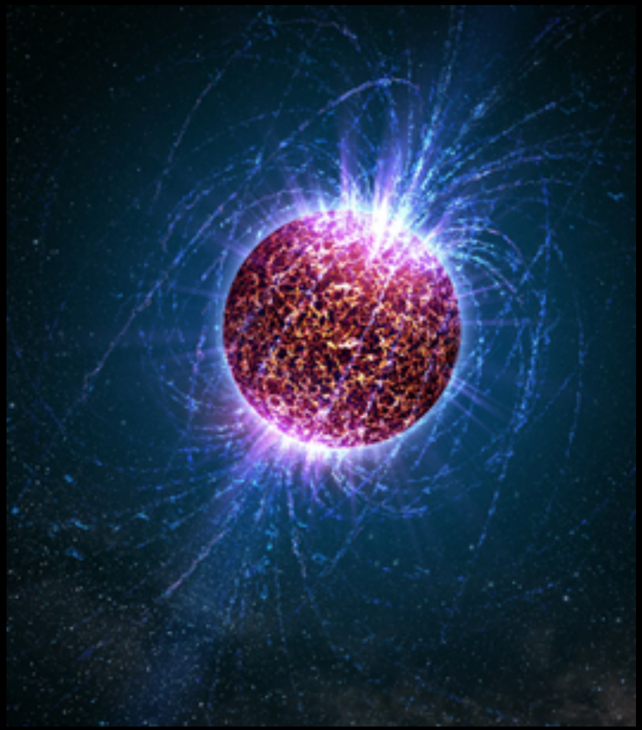
- Unmodelled
- galactic asymmetric core collapse supernovae
- cosmic strings
- ???



NASA/WMAP Science Team

Stochastic GWs

- Noise
- Incoherent background from primordial GWs or an ensemble of unphased sources
- primordial GWs unlikely to detect, but can bound in the 10-10000 Hz range



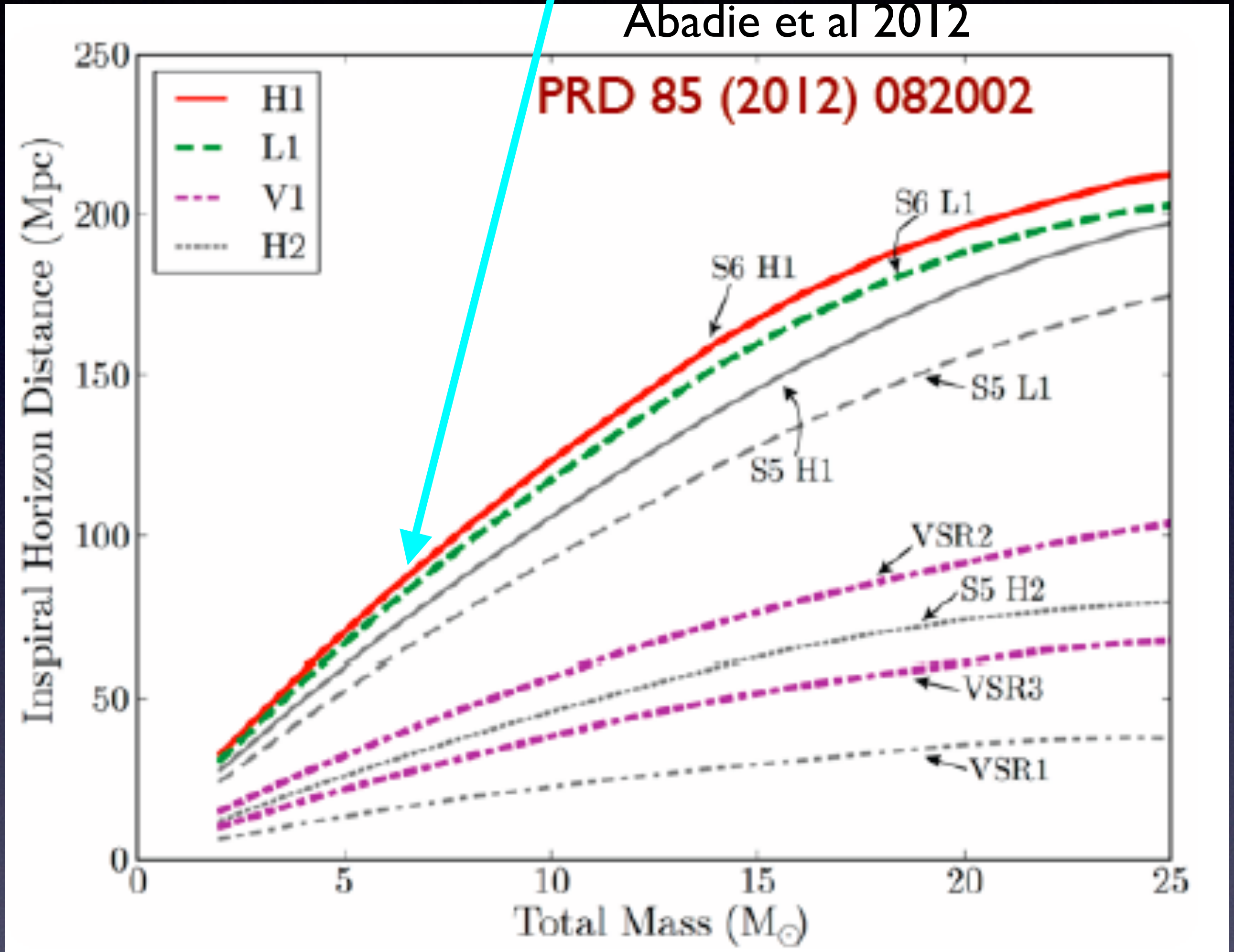
Casey Reed, Penn State

Continuous Sources

- Essentially Monotone
- Spinning neutron stars
- probe crustal deformations, equation of state, 'quarki-ness'

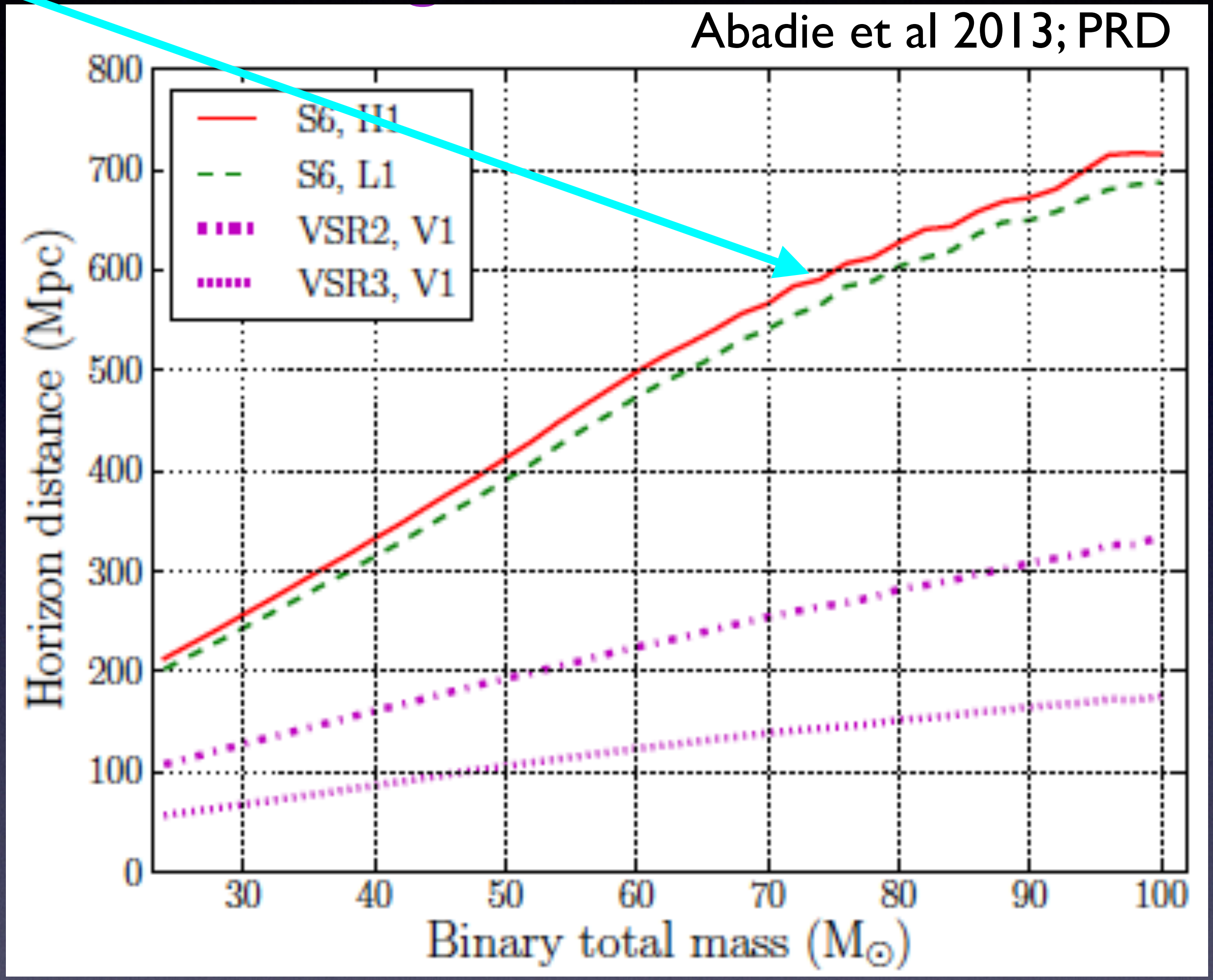
slide: D. Shoemaker

Initial LIGO Science Reach



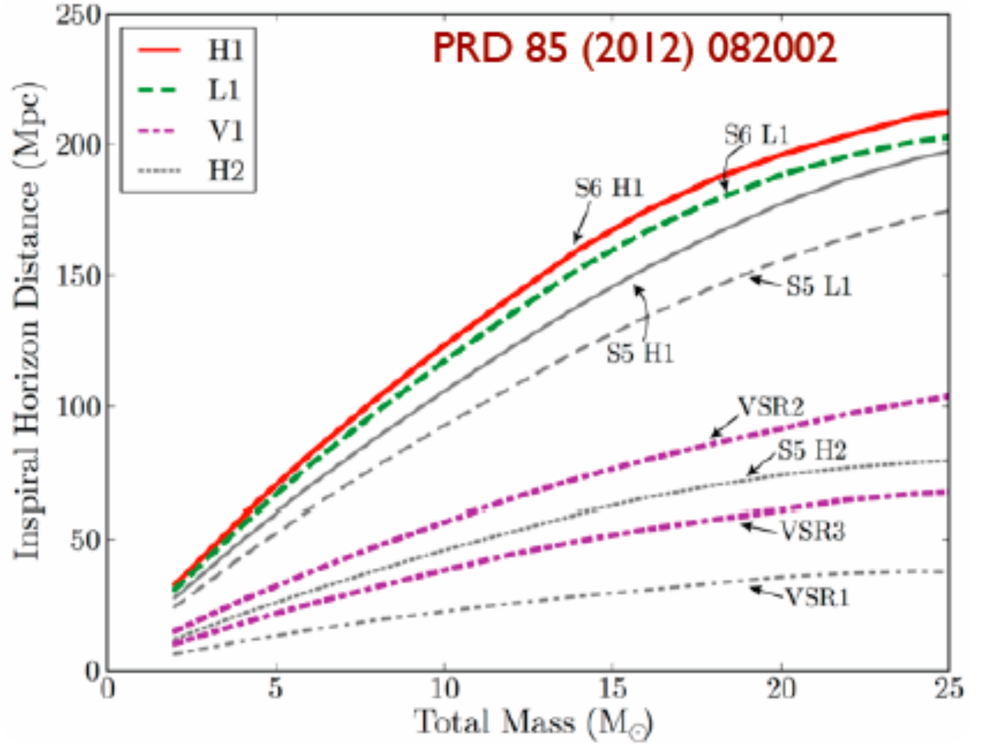
Abadie et al 2012

PRD 85 (2012) 082002

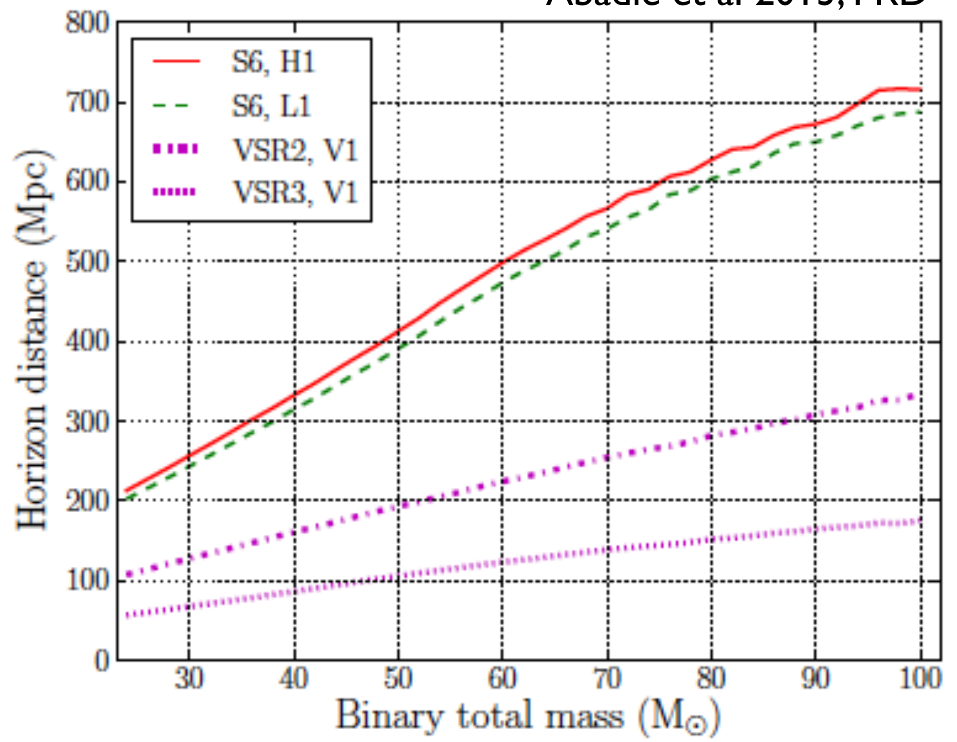


Abadie et al 2013; PRD

Initial LIGO Science Reach

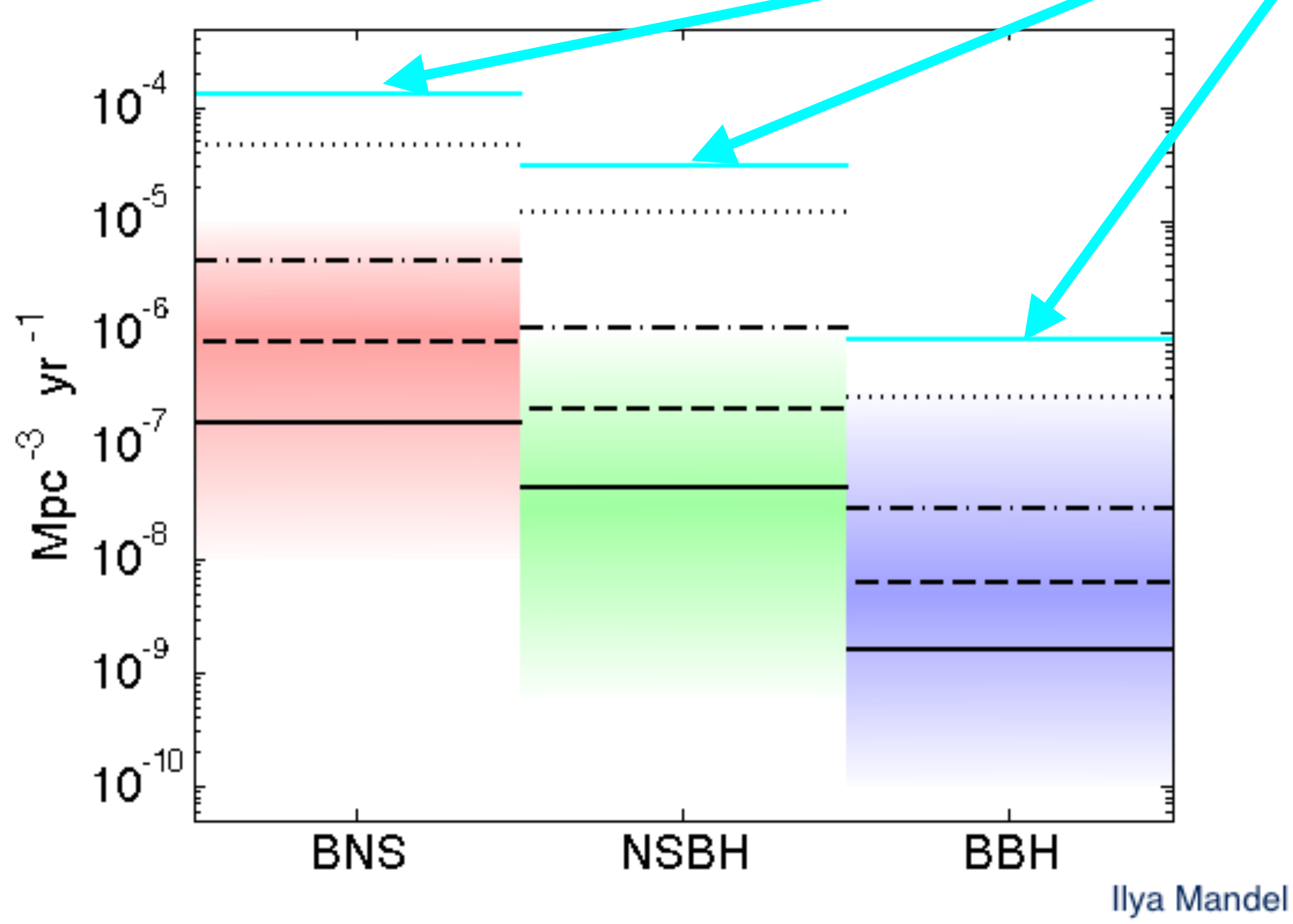


Abadie et al 2012



Abadie et al 2013; PRD

Rates Upper Limits



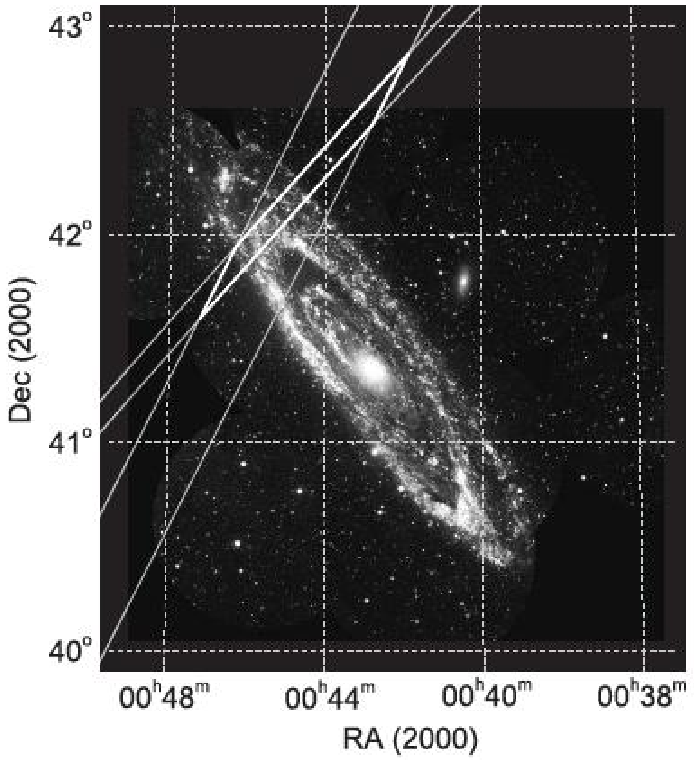
Abadie et al. 2010 & Abadie et al. 2012

Just factor of ~2 off astrophysical predictions for BH-BH

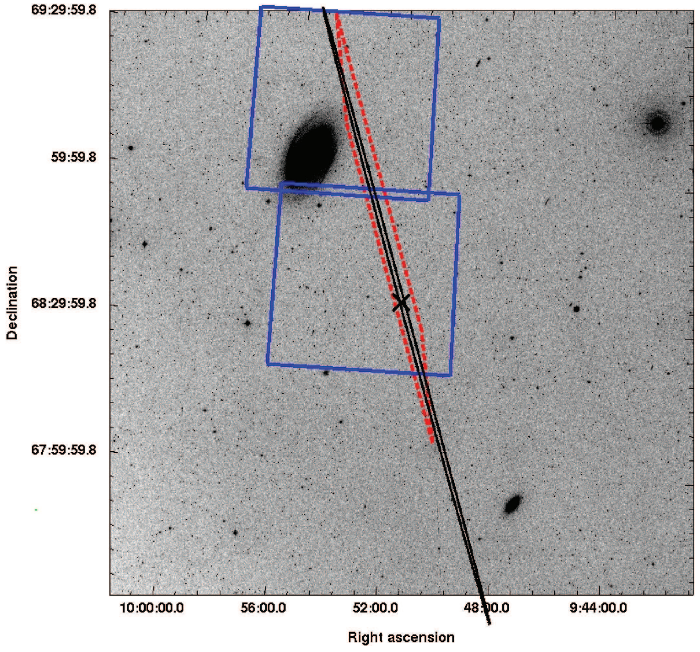
Follow-up of 2 close short GRBs

Abbott et al. 2008 & Abadie et al. 2012b

GRB070201 error box (Mazets et al., 2008)



GRB051103 error box (Hurley et al., 2010)



Binary Coalescence in M31 & M81 excluded at > 98% CL

GRB origin constraints:

- Neutron Star Quake in M31/M81

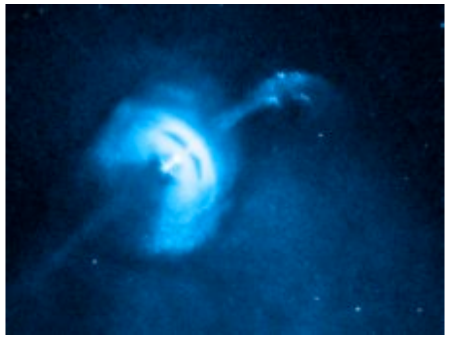
OR

- Binary Coalescence @distance > 3.5-5Mpc

Other Science Highlights

Continuous Wave Sources

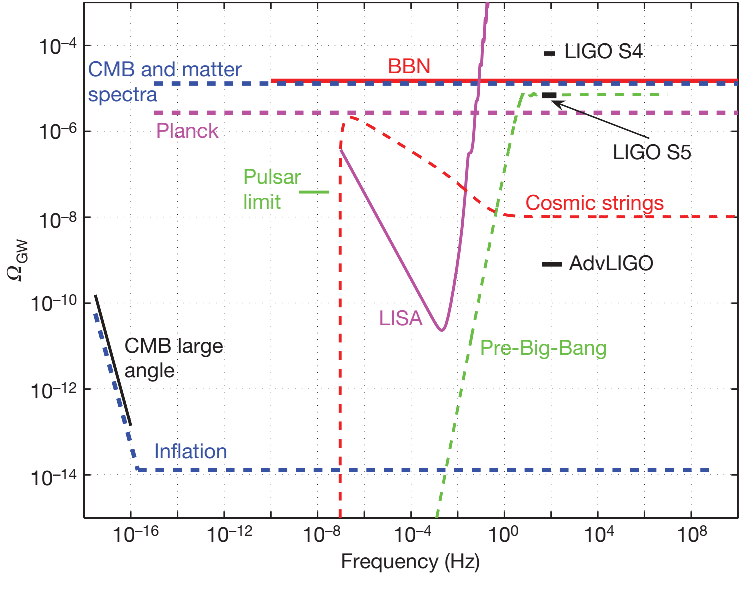
Upper limits on GW emissions from Crab and Vela pulsars - $\varepsilon < 1.8 \times 10^{-4}$



Abbott et al. 2010

Abadie et al. 2011

Stochastic Backgrounds



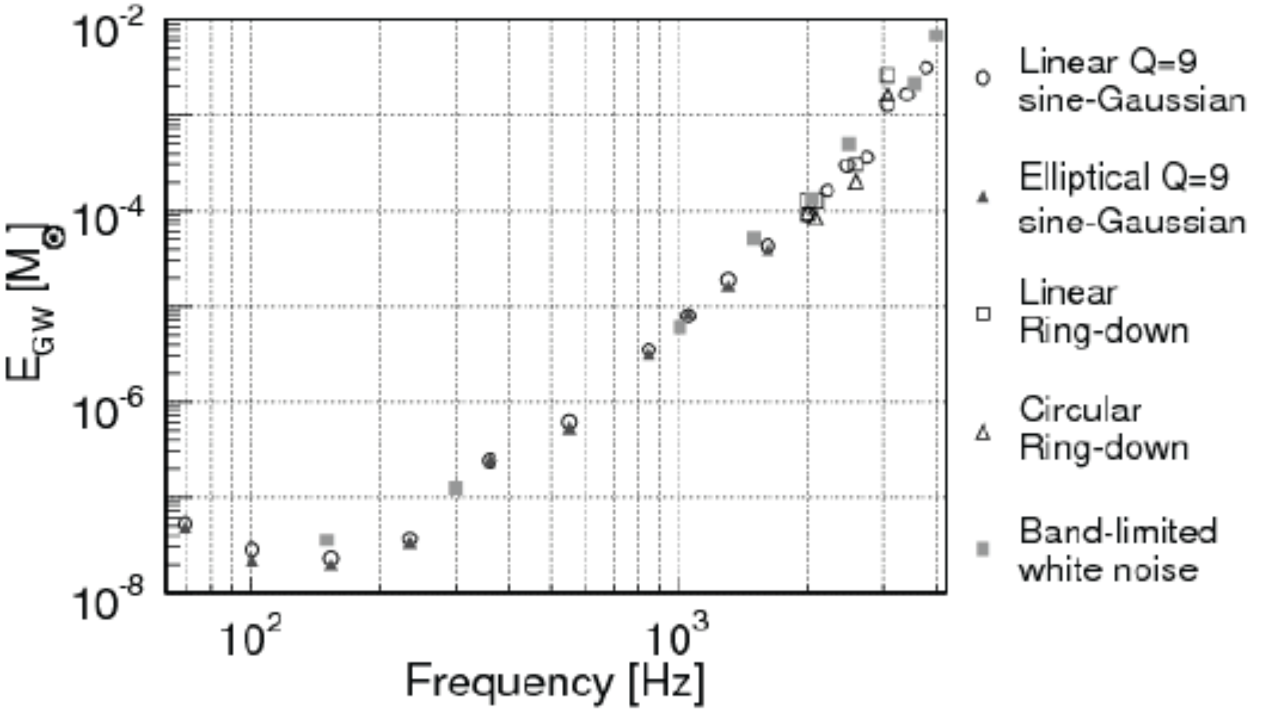
below BBN

Abbott et al. 2009

Bursts

Upper limit on GW energy emitted by generic sources at 10 kpc

Abadie et al. 2012



Upper Limits on

1000's of magnetar bursts

Abadie et al. 2011

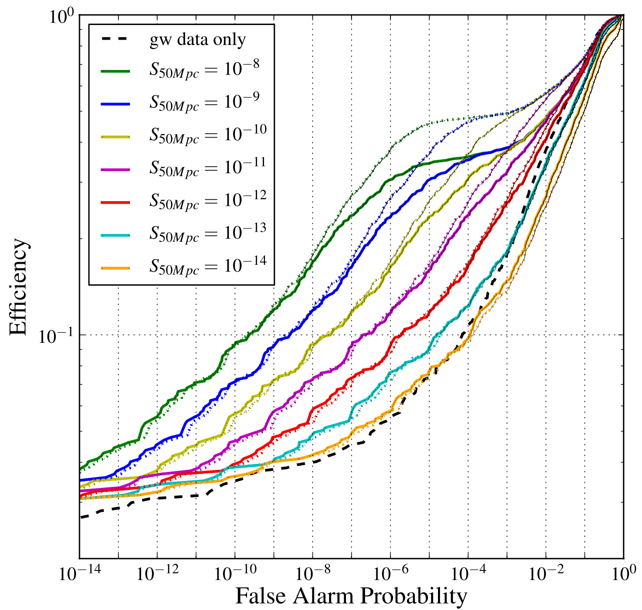
100's of gamma-ray bursts

Abadie et al. 2012

Multi-Messenger Highlights

Gamma Rays

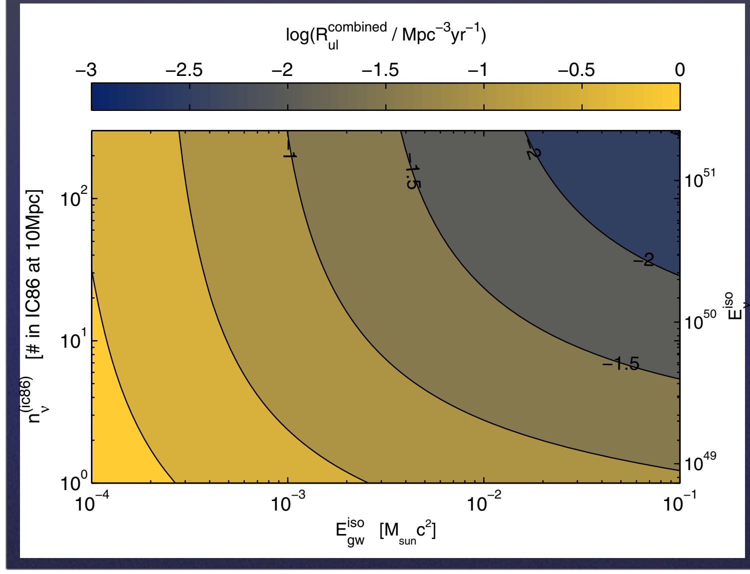
Evans et al. 2012



Swift follow-up within 12 hr

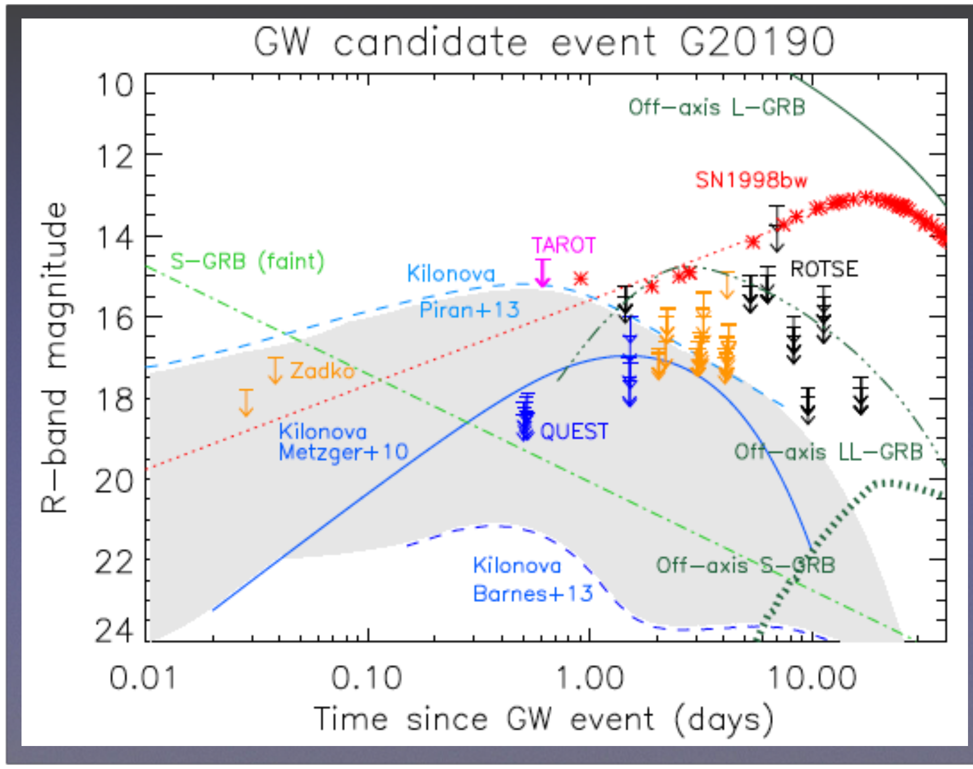
Neutrinos

Aartsen et al. 2014



Icecube-LIGO coherent analysis

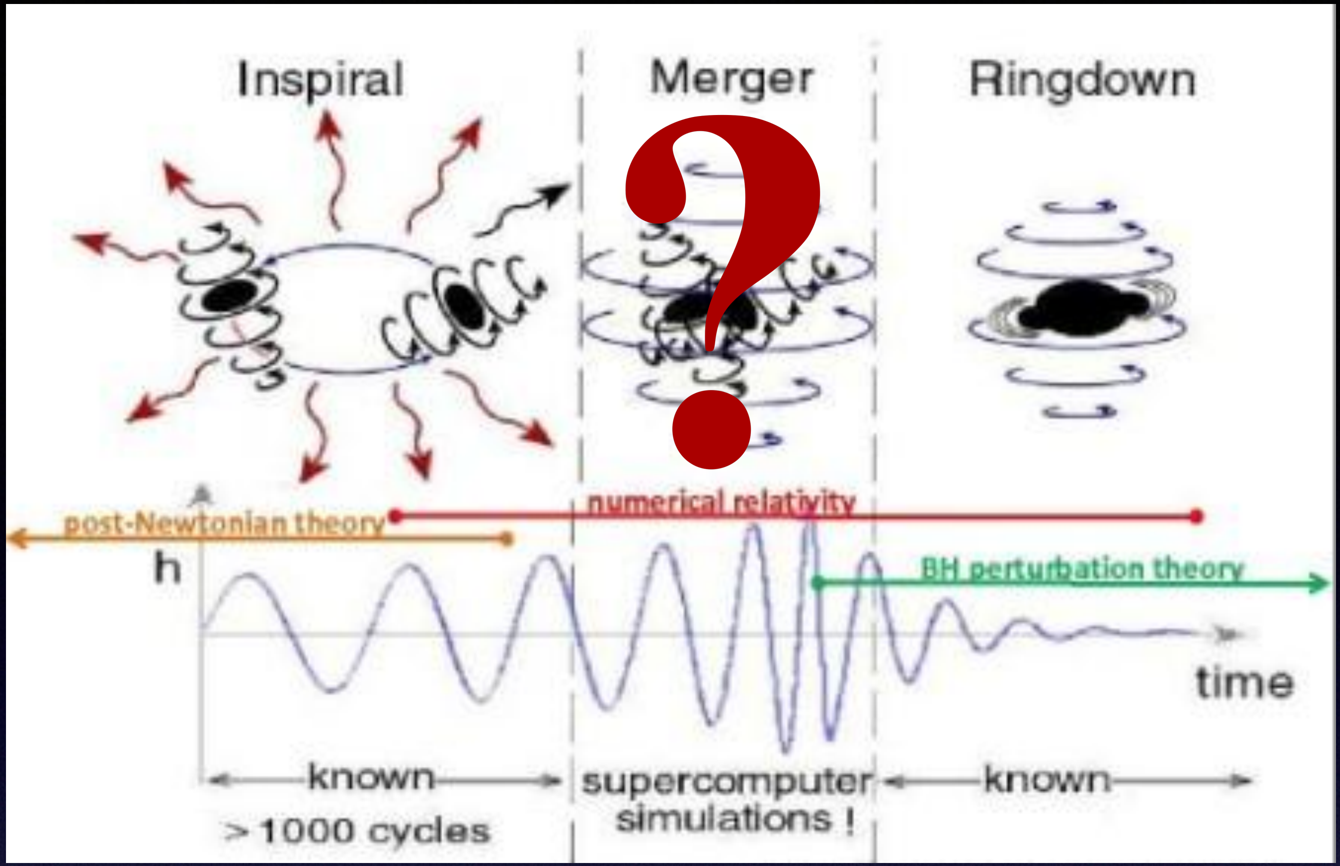
Optical



- 5 telescopes
- as soon as 40min out to ~10d
- transient models excluded

On the way to
Advanced LIGO …

Major Progress
in Theory and Data Analysis



Numerical Relativity Breakthroughs!

Pretorius 2005
Campaneli et al. 2006
Baker et al. 2006

100's of NR waveforms

Mroue
et al. 2013

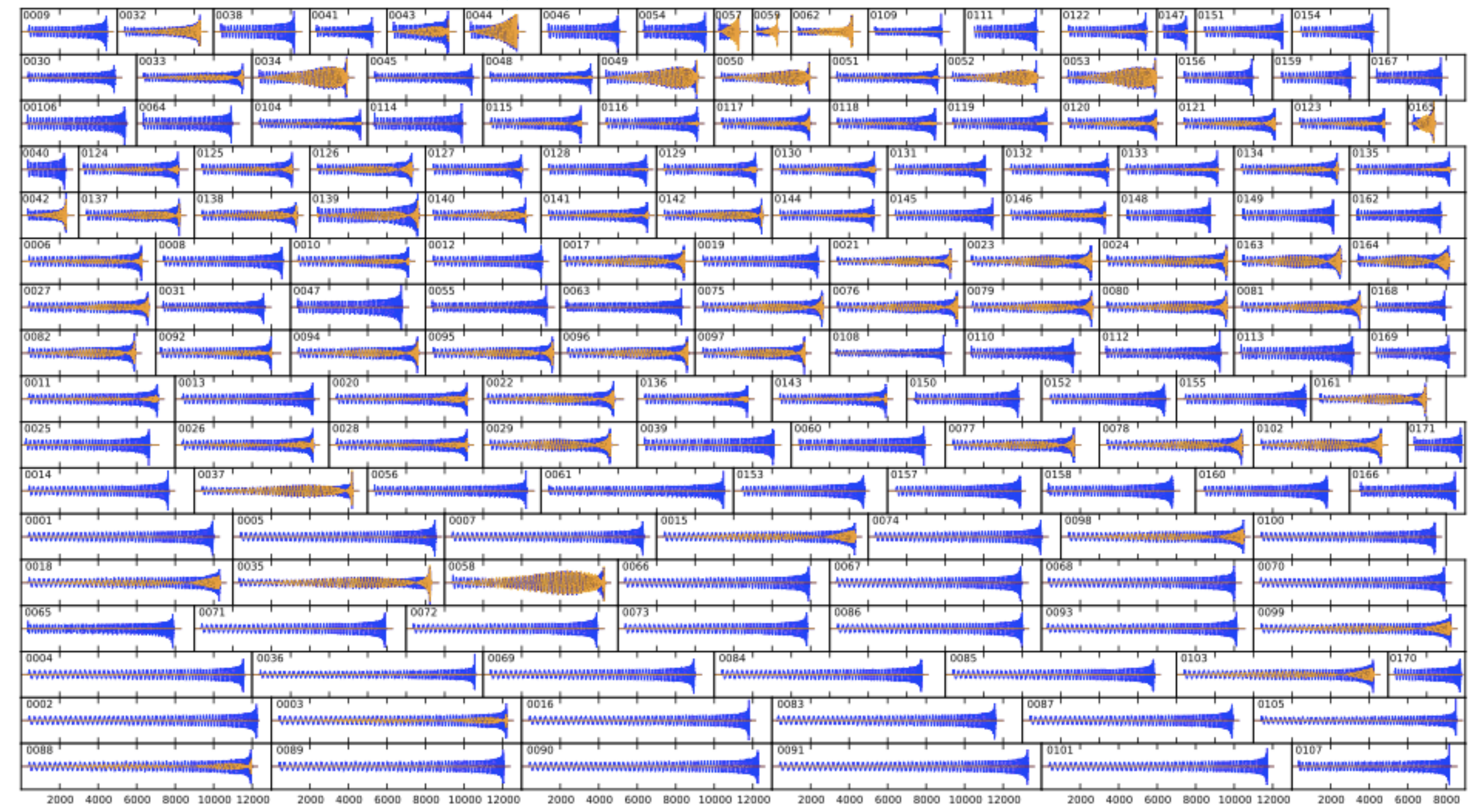


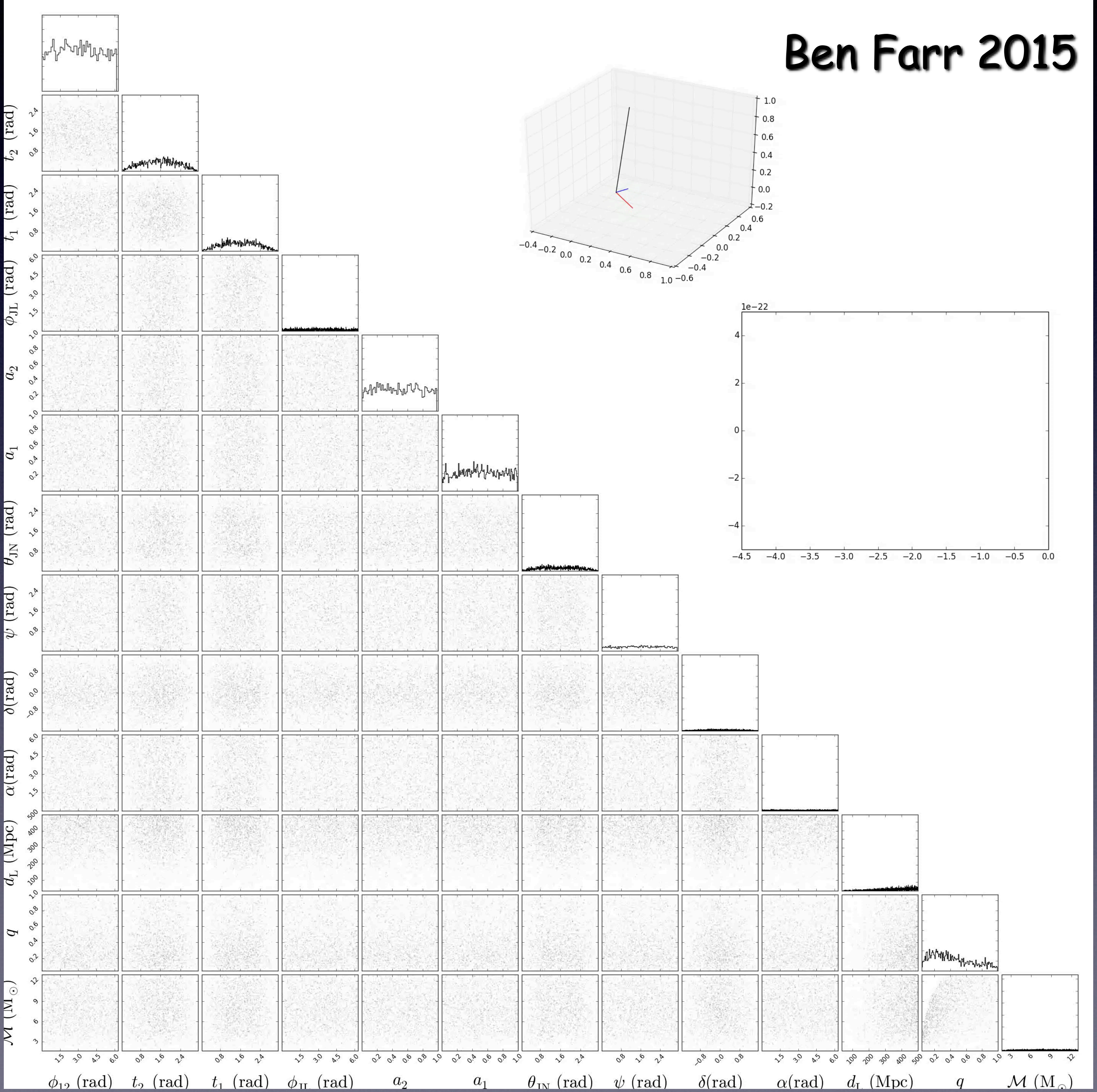
FIG. 3. Waveform polarizations h_+ (blue) and $h_\times$ (orange) in a sky direction parallel to the initial orbital plane of each simulation. All plots have the same horizontal scale, with each tick representing a time interval of $2000M$ (equal to 0.2 s for a $20M_\odot$ BBH).

MAJOR REMAINING CHALLENGE:

High-Fidelity, Fast
Inspiral+Merger+Ringdown
with Full
double-spin Precession
across all source parameters

! do not exist !

Gravitational-Wave Astrophysics:
The parameter estimation era


Ben Farr 2015

BH spin
cannot be ignored

Great Need for:

- Fast Waveforms

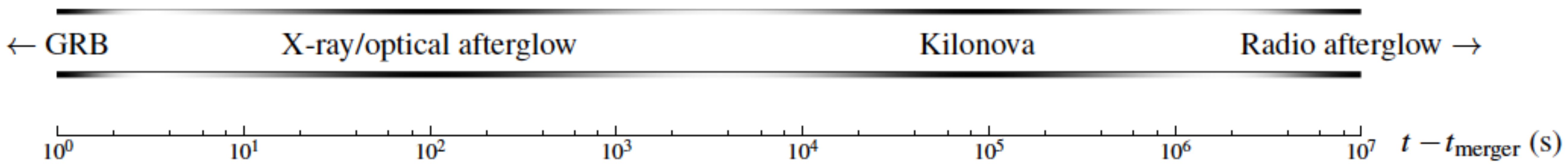
- Smart Sampling
in highly structured
15-dimensional space

Tremendous speed progress:
from months to days/hours
and soon to just minutes

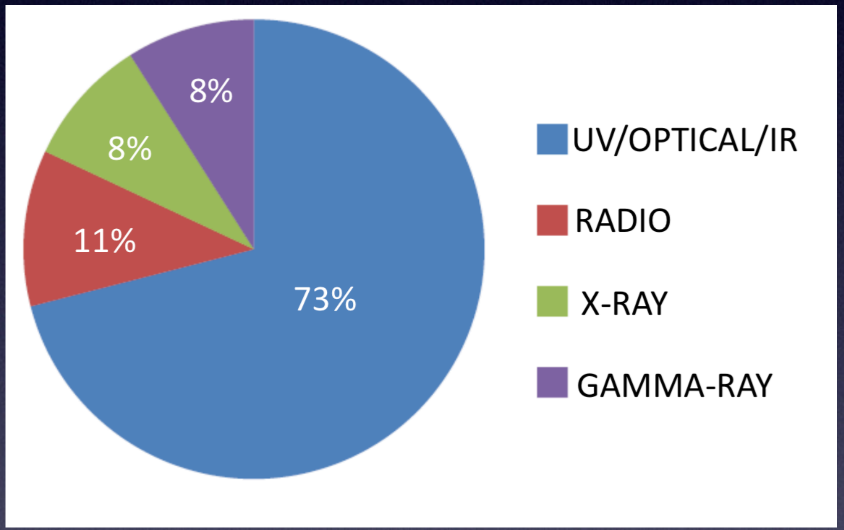
Multi-Messenger Searches

Binary Inspirals and Mergers
Supernova Explosions
Other Burst Signals

Multi-Messenger Searches



Expected EM signals following binary NS inspirals



LIGO-EM official partnerships

75 MOUs signed already

full EM coverage: from radio to gamma-ray

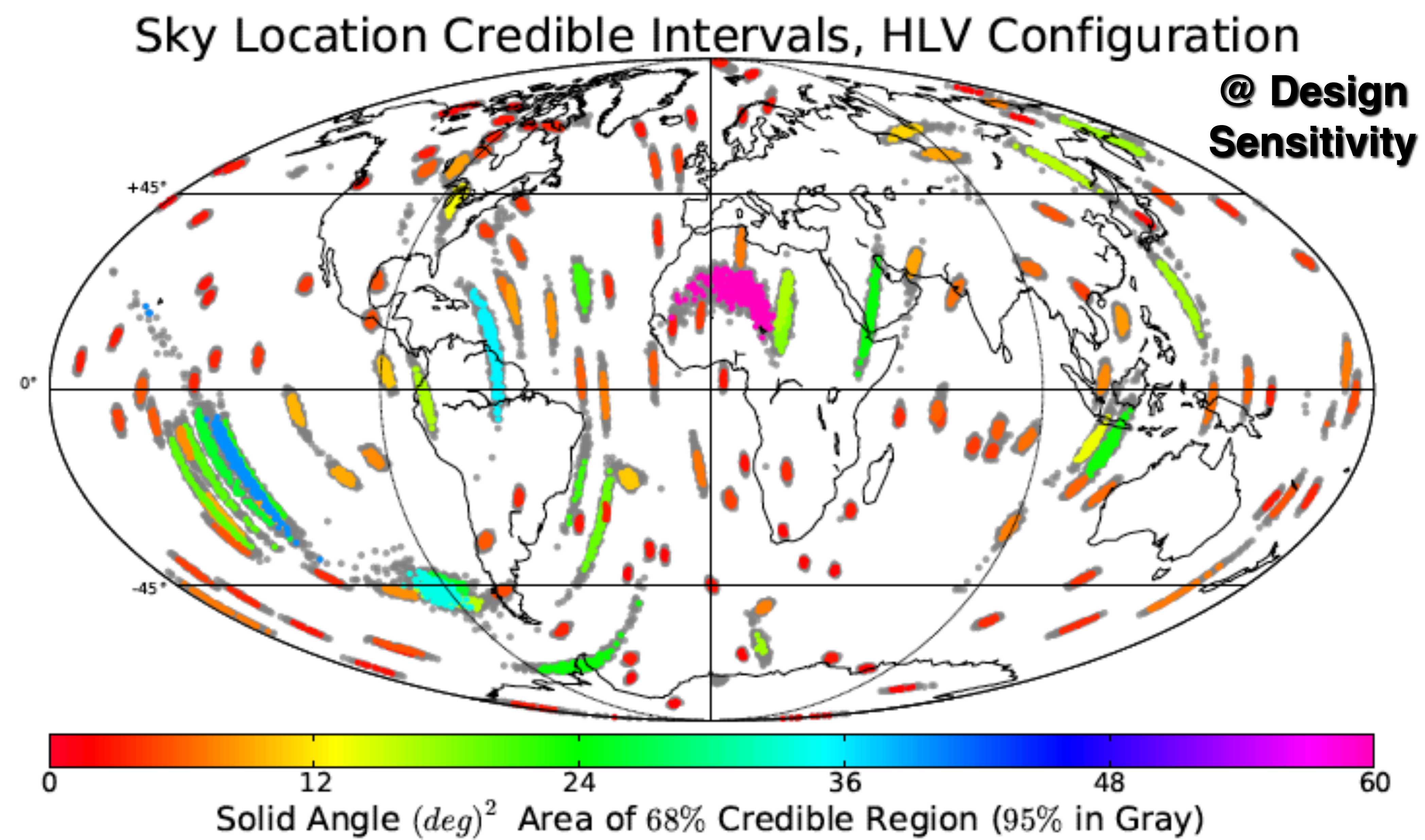
Follow-up will start already with LIGO-O1, Fall 2015

major challenge:

sky localizations of 100's of square degrees initially

Localization:
NS-NS Inspiral at high SNR

Rodriguez et al 2014



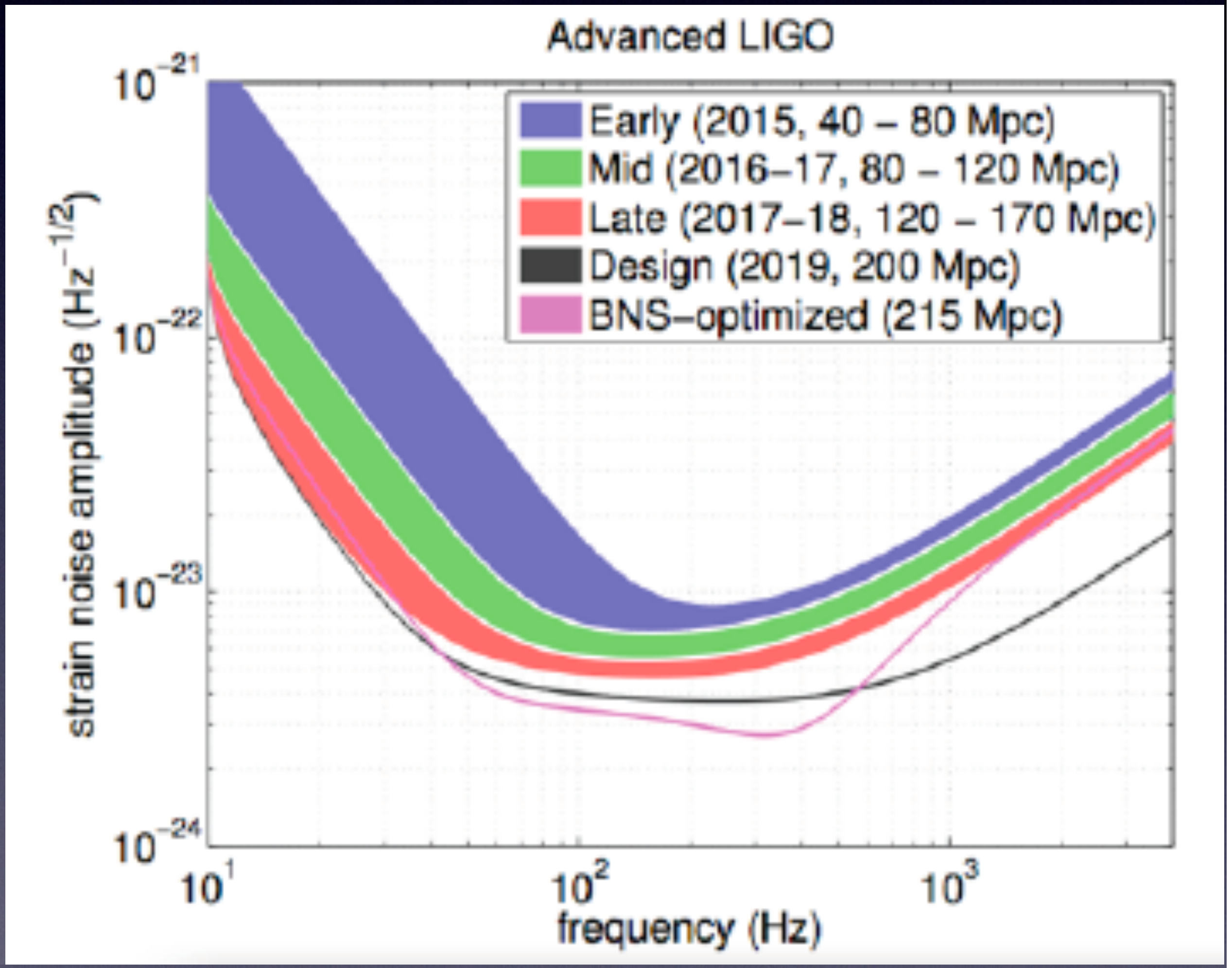
at 95% CL
median error
~ 10 deg^2

for distributed
SNR

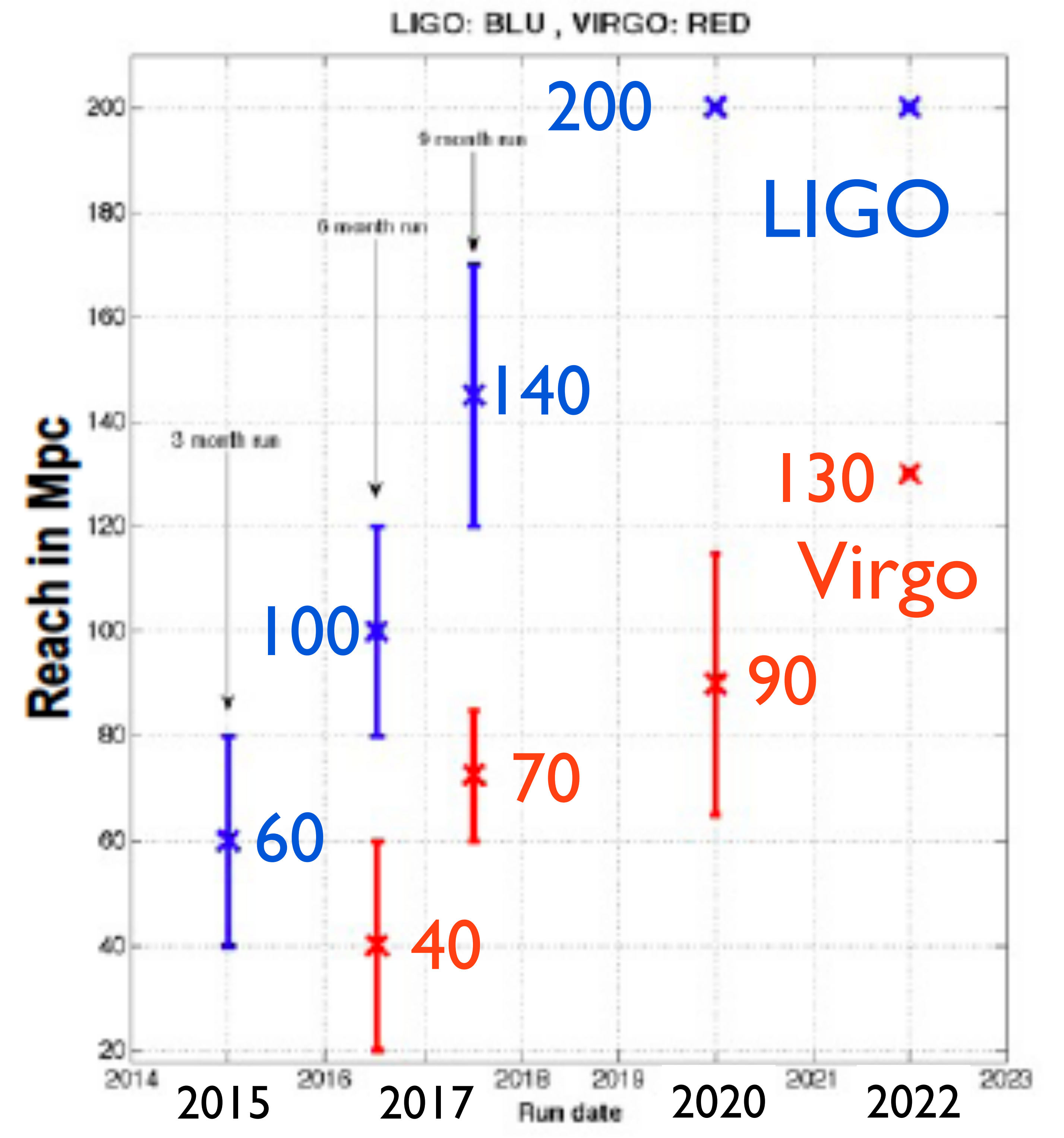
40% of
error boxes
> 100 deg^2

Current Science Plan for Advanced Detectors

Aasi et al 2013; arXiv: 1304.0670



NS-NS Reach in Mpc

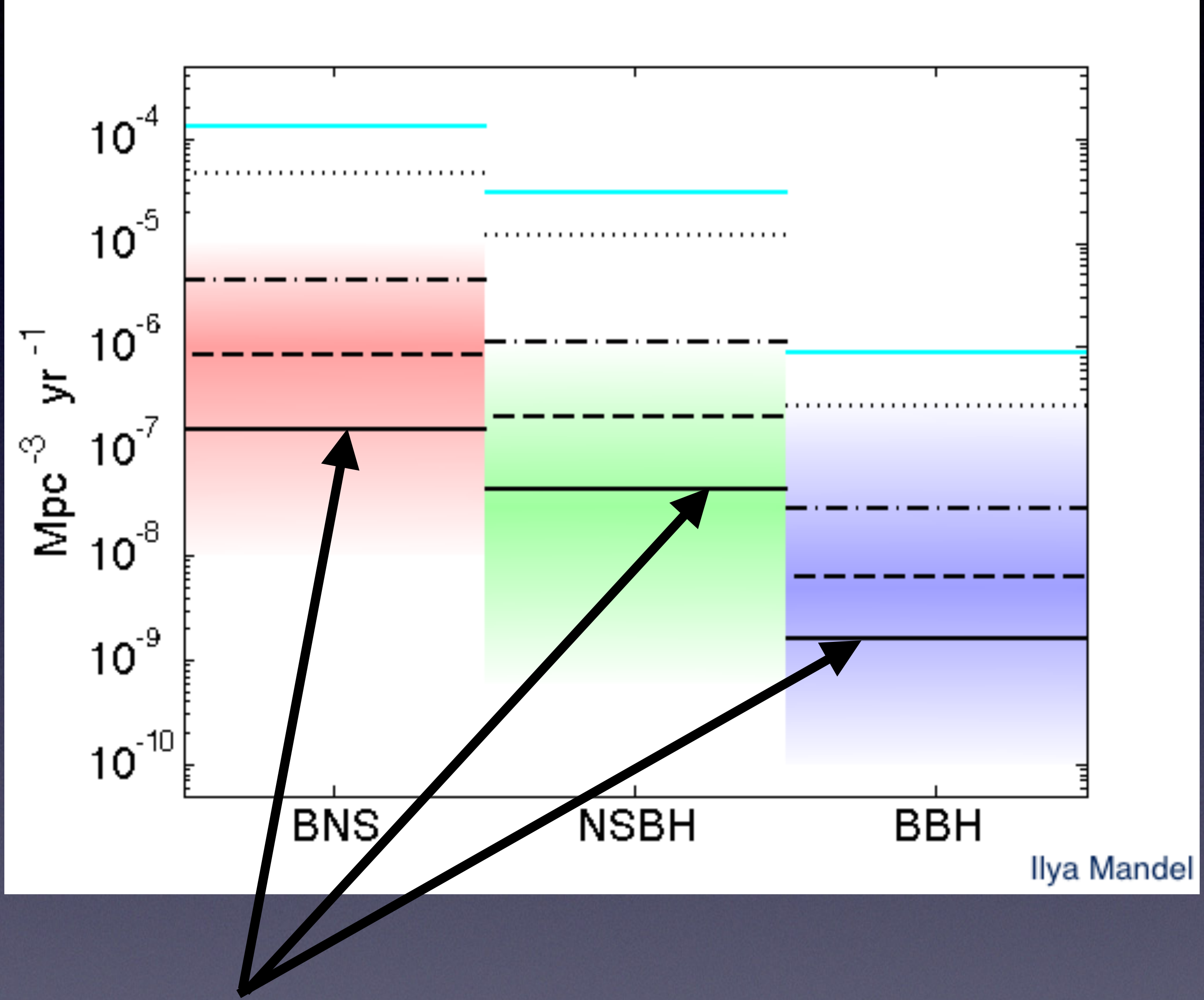


BH-BH Reach:

out to z~2 for 150Msun

out to 1,000Msun

Advanced Expectations by 2020 ?
Binary Merger Rates



Ilya Mandel

Best expected Upper Limits
from Advanced
LIGO - Virgo

Abadie et al. 2010 & Abadie et al. 2012

AdLIGO Design Sensitivity	**Low** (per yr)	**"Realistic"** (per yr)	**High** (per yr)
NS-NS	**0.4**	**40**	**400**
NS-BH	**0.2**	**10**	**300**
BH-BH	**0.4**	**20**	**1000**

How many coincident
with short Gamma Ray Bursts?
only ~ 0.5 - 2 / yr

Science to still reach out for post-Advanced-LIGO

- large samples of high-SNR GW-GRB events for precision cosmology
- large samples of high-SNR BH-BH mergers to test strong-field GR
- high-SNR detection to nail the NS EOS

—> tidal/merger effects - supernovae - pulsars

- nail the origin of short GRBs
- constrain the supernova and/or magnetar mechanisms
- definitively assess the existence of IMBH
- measure reliably the maximum NS mass
- nail the BH mass spectrum out to 1,000's of solar masses
- uncover the origin of BH spins
- quantify the relative BH-BH pops from dense clusters or the field
- best constrain the evolution processes of stellar binaries

What is needed for post-AdLIGO Science?

- Deep GW observations: out to redshifts of 3–5
- Broadband GW observations: out to about 5 kHz
- Comparable detector in southern-most location

Some words of caution:

Wright 2015

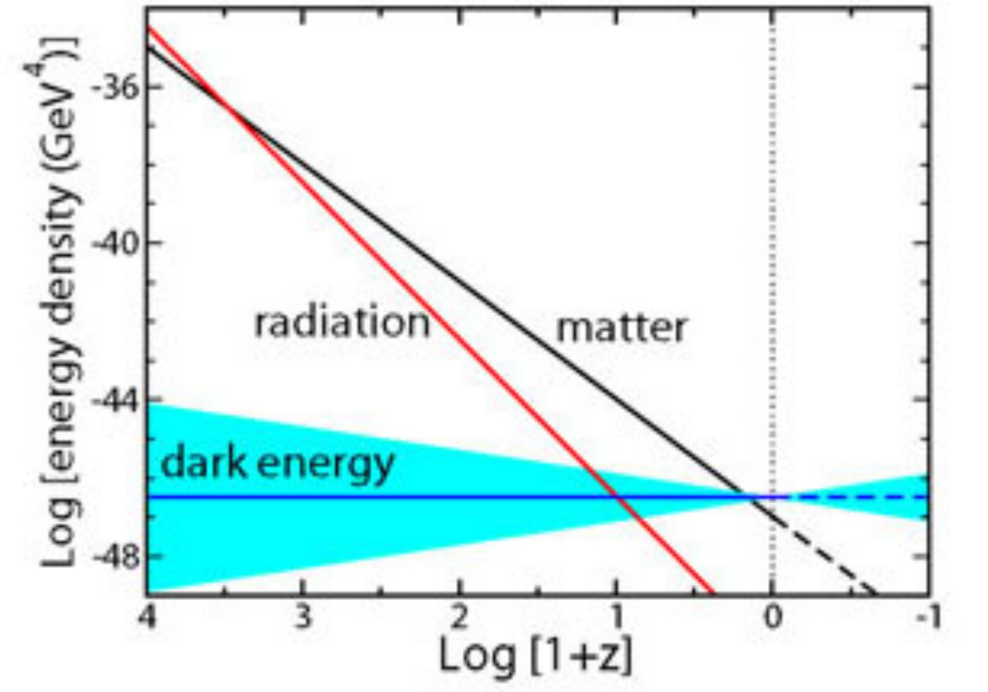
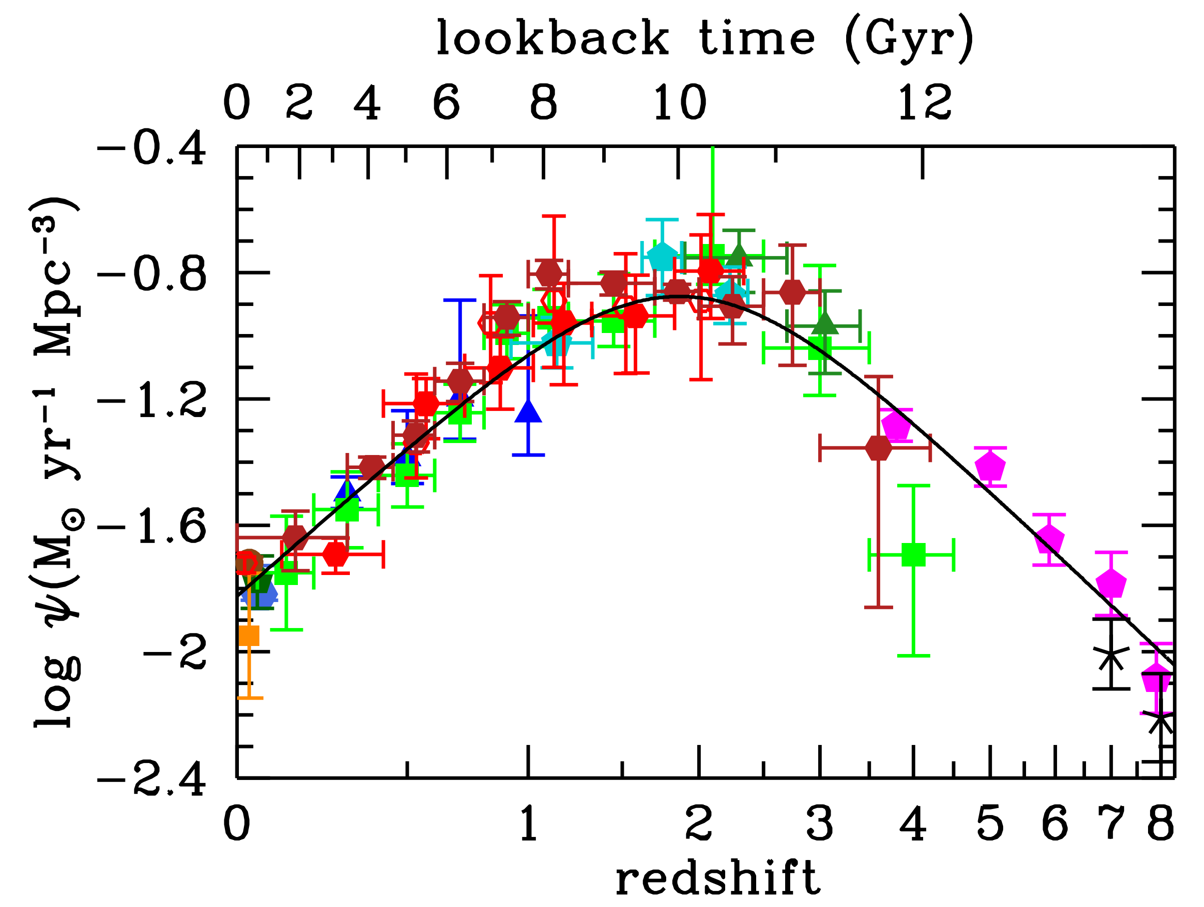


Figure 1. Evolution of radiation, matter, and dark energy densities with redshift. For dark energy, the band represents w = -1 ± 0.2.

Madau & Dickinson 2015

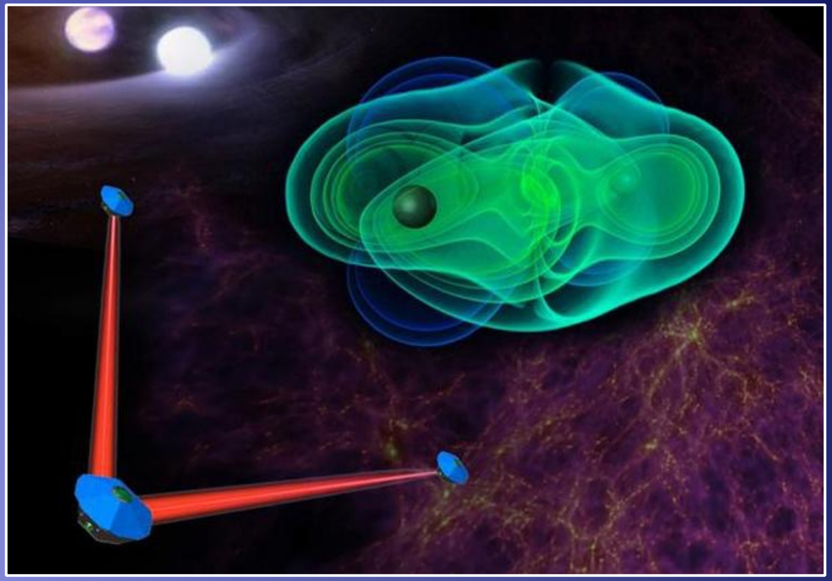


Pulsar Timing and
Space-based Science & Detectors

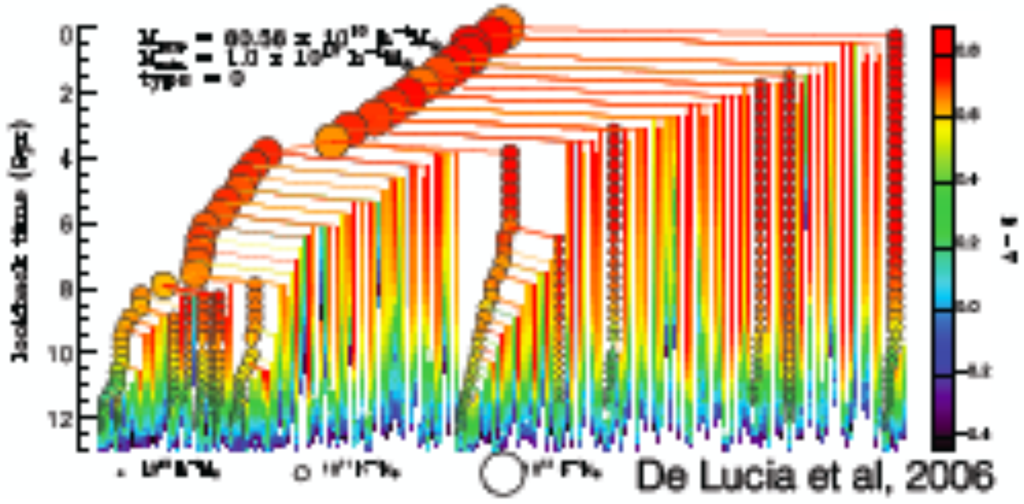
Tom Prince

Low-Frequency GW

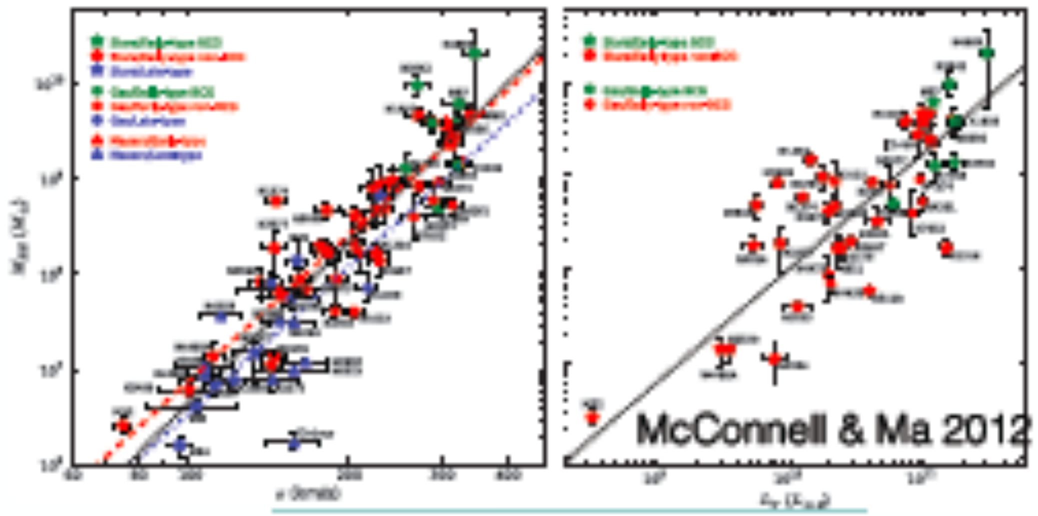
- Two categories: space-based and pulsar timing
  - Pulsar timing: 1 – 100 nHz
  - Space-based: 0.1 – 100 mHz
- Major science objectives
  - Massive BH mergers
  - Supermassive BH binaries
  - Capture of compact objects by BHs in centers of galaxies
  - Ultra-compact binaries in the Galaxy
  - Cosmic GW background
  - Tests of GR



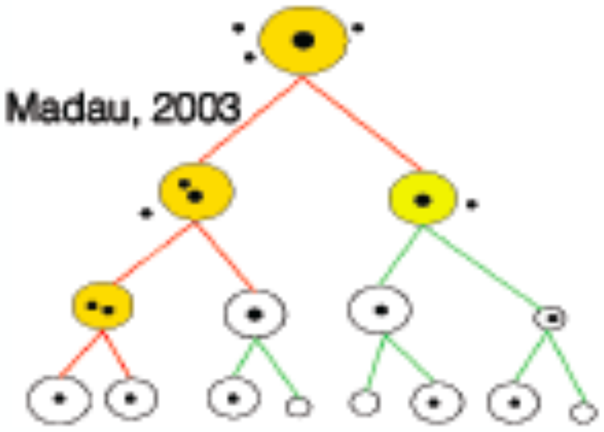
Massive Black Hole Binaries/Mergers: A Strong Source of Low-Frequency GW



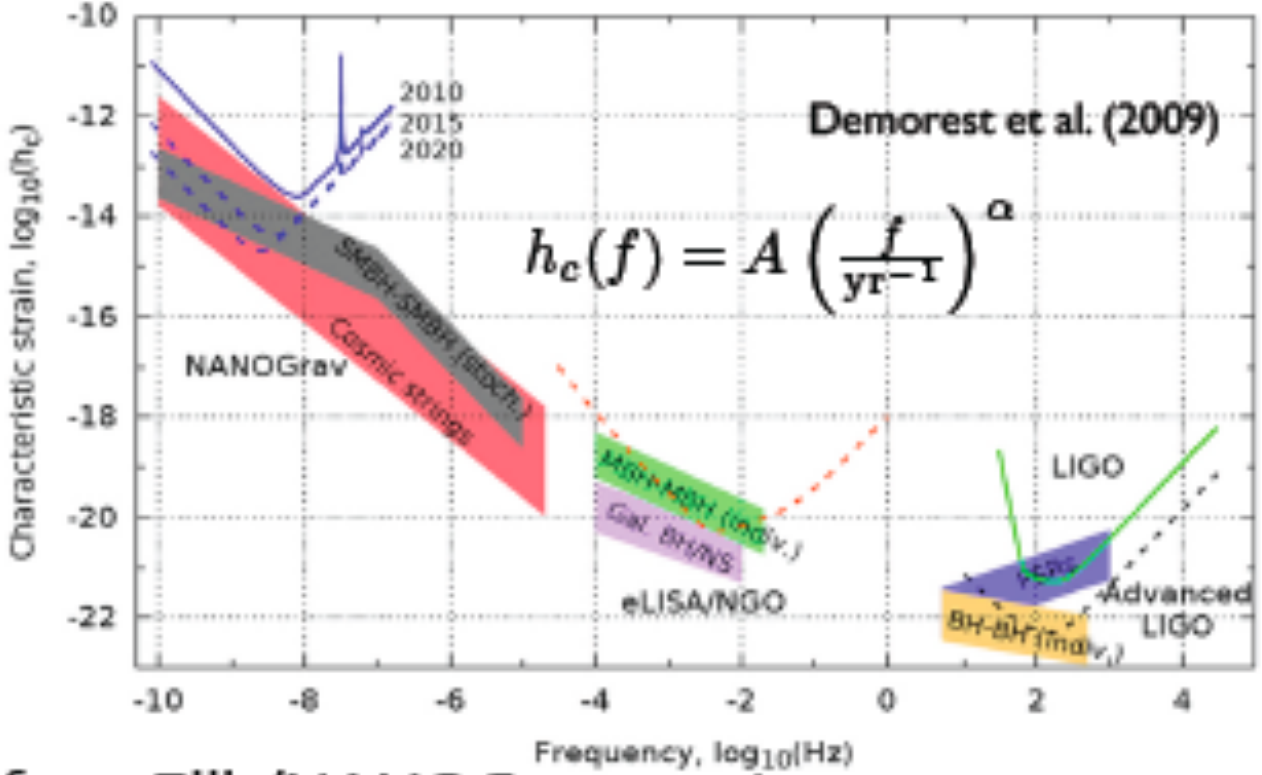
De Lucia et al, 2006



McConnell & Ma 2012

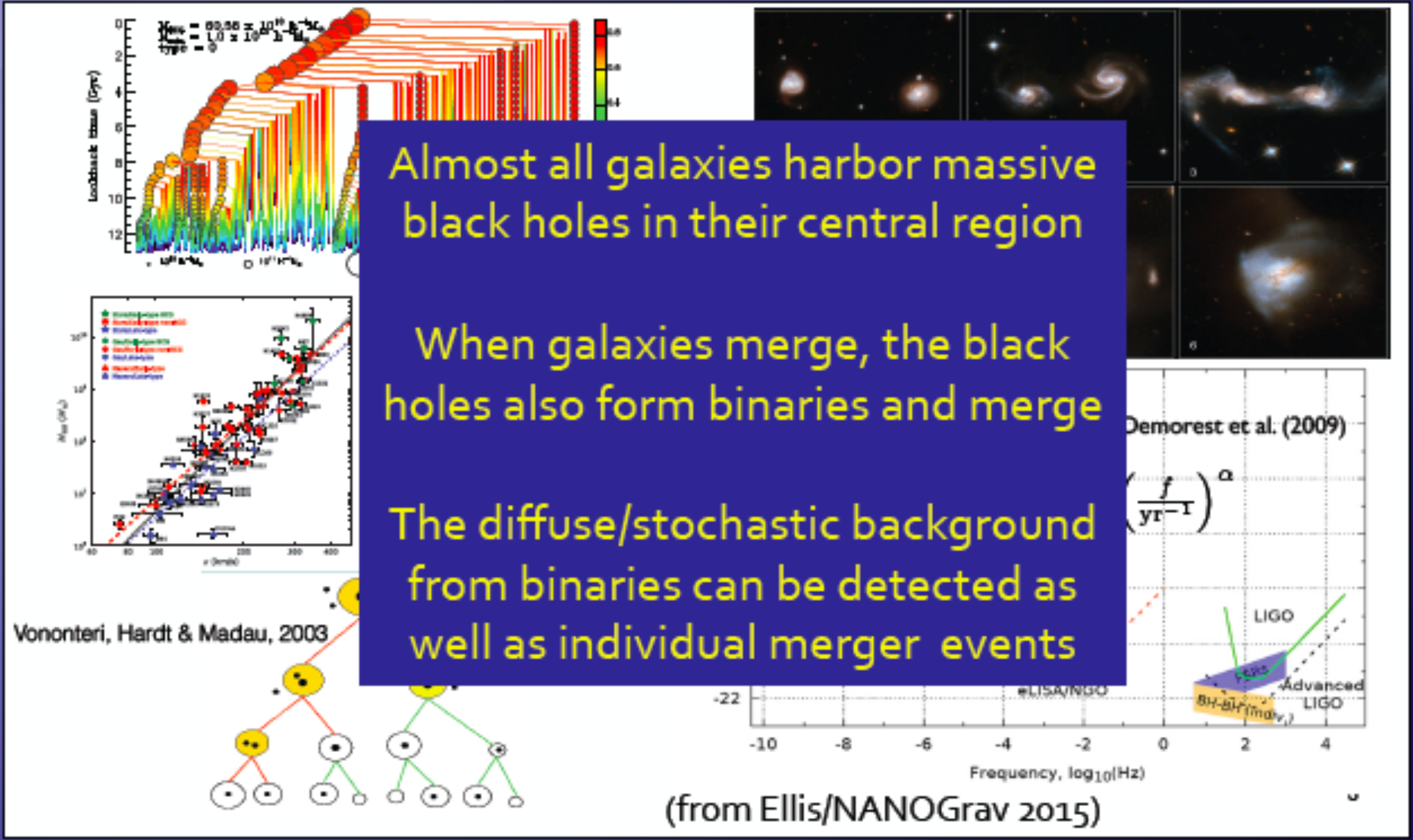


Vononteri, Hardt & Madau, 2003



(from Ellis/NANOGrav 2015)

Massive Black Hole Mergers:
A Strong Source of Low-Frequency GW



Vononteri, Hardt & Madau, 2003

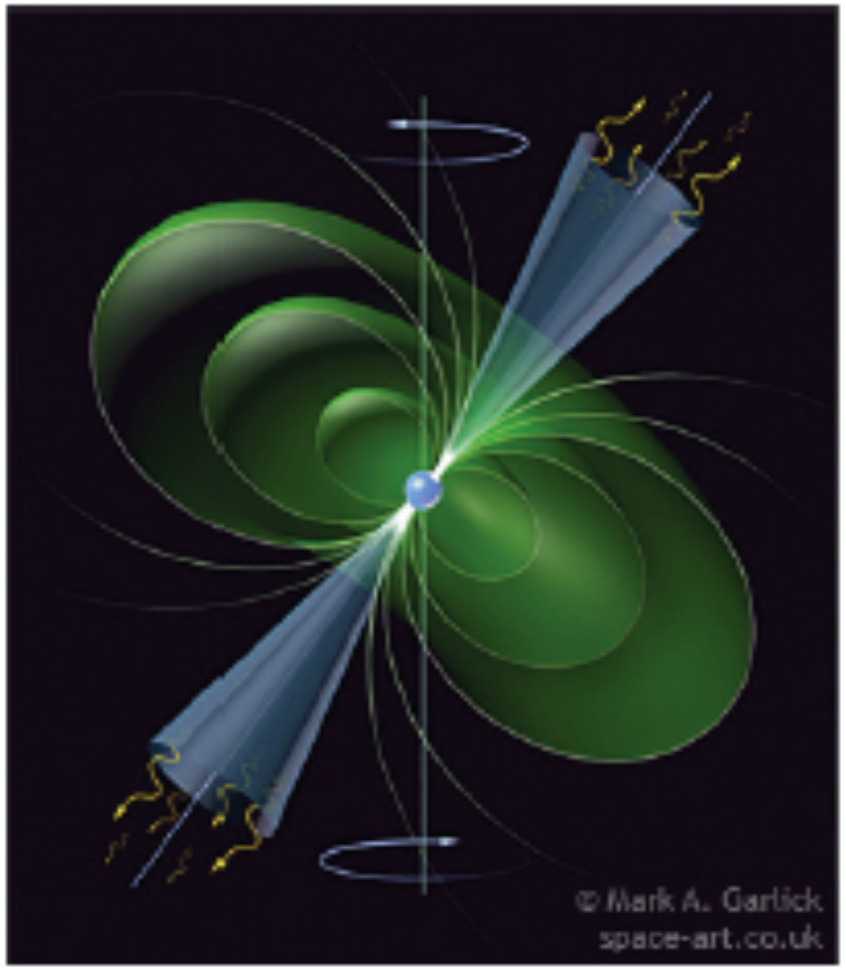
Almost all galaxies harbor massive black holes in their central region

When galaxies merge, the black holes also form binaries and merge

The diffuse/stochastic background from binaries can be detected as well as individual merger events

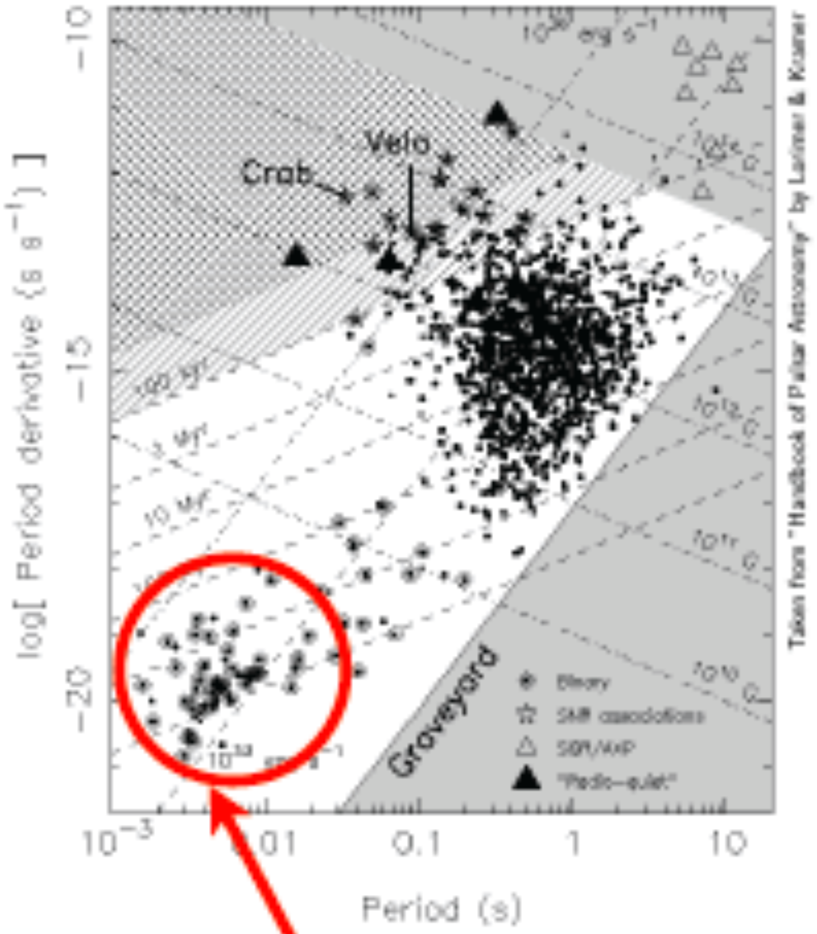
(from Ellis/NANOGrav 2015)

Pulsar Timing Preliminaries

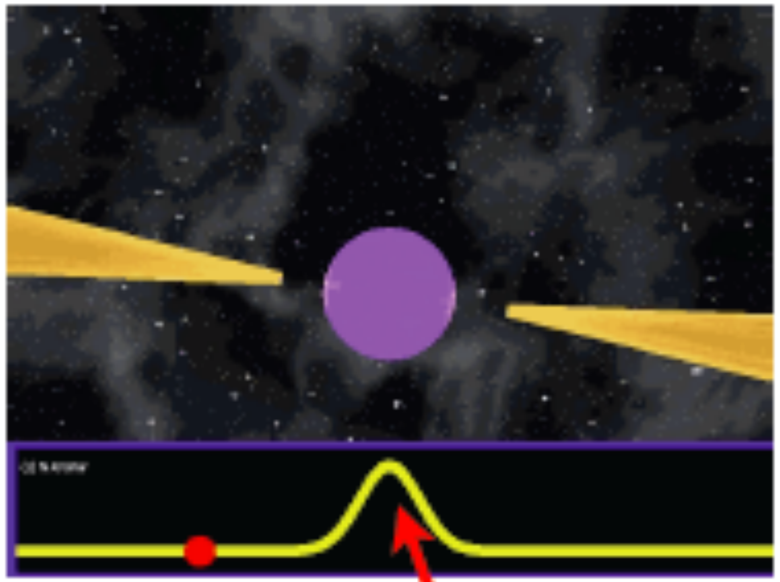


© Mark A. Garlick
space-art.co.uk

Highly magnetized rotating neutron star

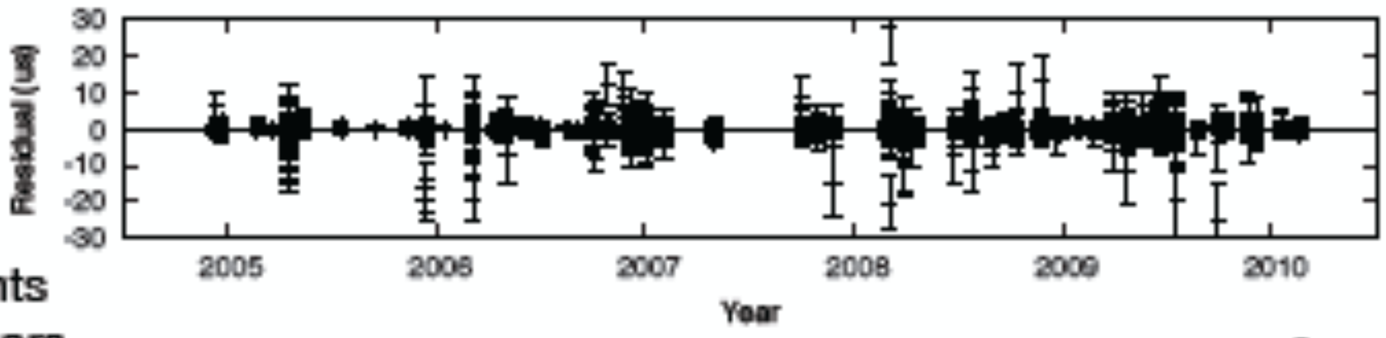


Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer



time-of-arrival (TOA)

Extremely stable clocks



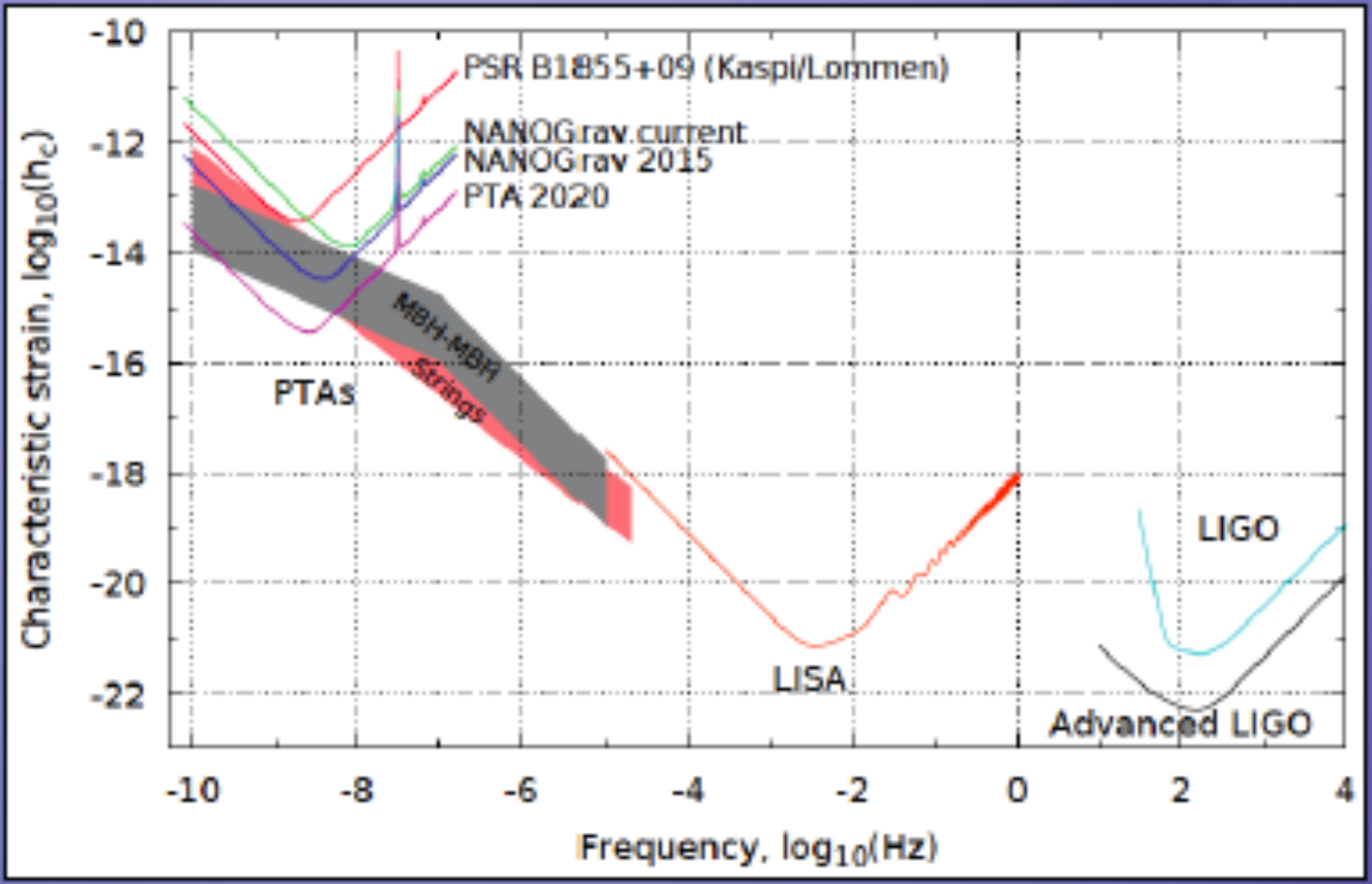
$$\delta t = t_{\mathrm{measured}} - t_{\mathrm{model}}$$

Pulsar Timing "Residual"

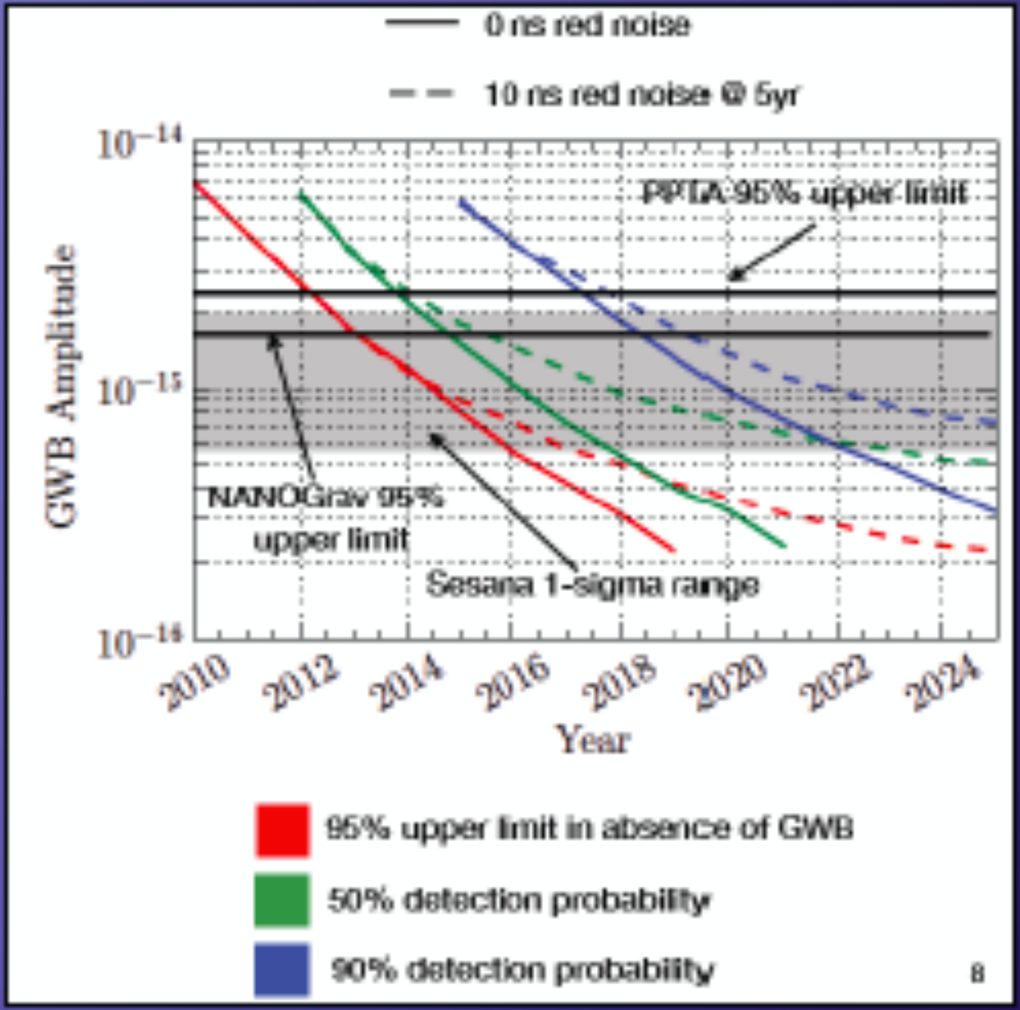
Measured Pulse time-of-arrival (TOA)

Model that accounts for many delay factors but not GWs

Stochastic Background from Supermassive Black Hole Binaries – PTA Limits



NANOGRAV white paper (2009)



Ellis+15

NANOGrav on track with anticipated sensitivity improvements. Already placing constraints on stochastic background from massive black hole merger

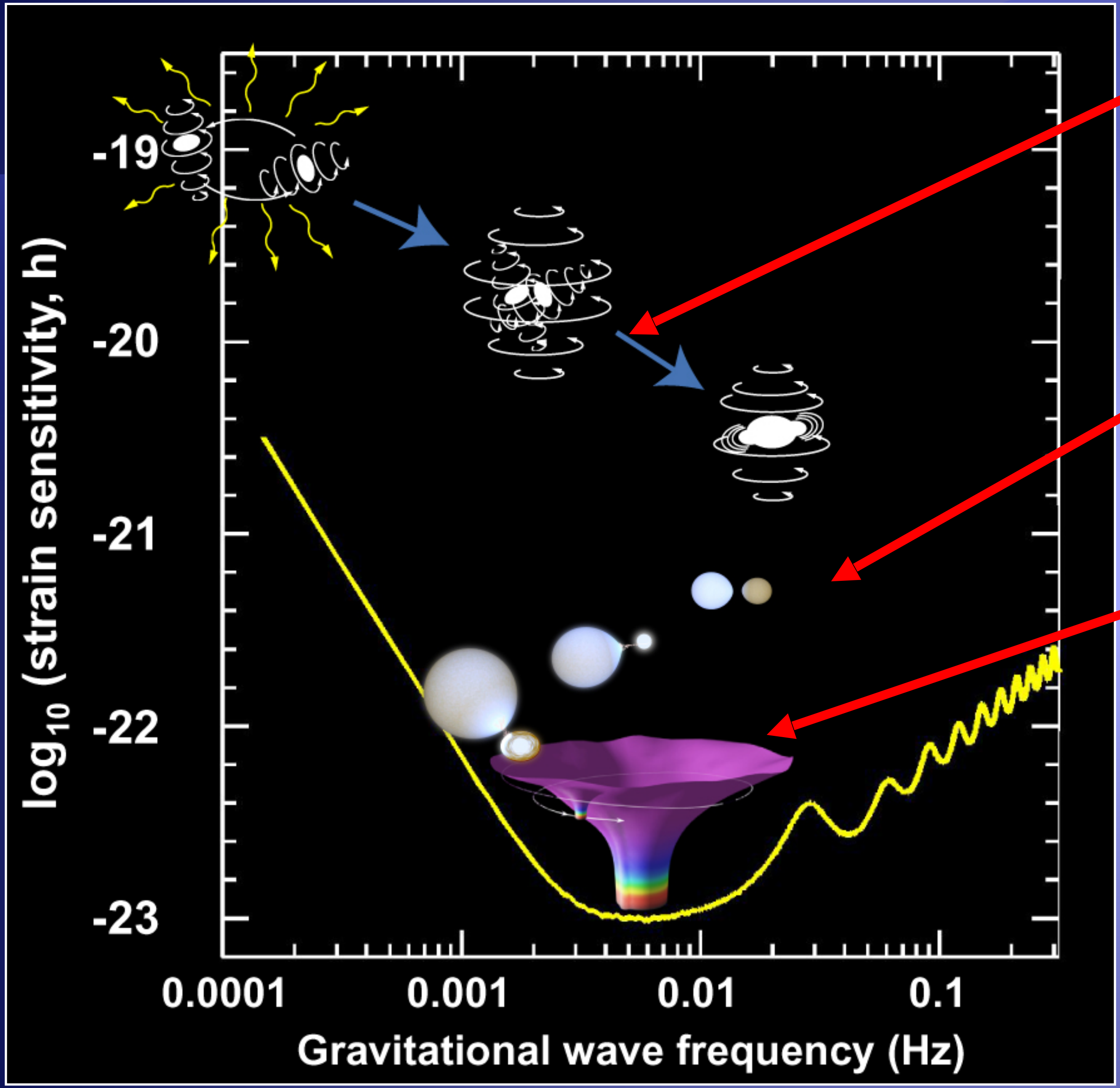
PTA: Pulsar Timing Array
NANOGrav: The North American Nanohertz Observatory for Gravitational Waves

Status: GW from Pulsar Timing

- Recommended as Mid-scale (MSIP) candidate project in Astro2010 decadal review
- Principal US effort: NANOGrav
  - Member of the International Pulsar Timing Array along with EPTA (Europe) and PPTA (Australia)
- Recent (3/31/15) $14.5M NSF award to NANOGrav for Physics Frontier Center -- very positive step
  - Combines NSF MSIP and PFC programs
  - Siemens (UWM, PI/Director) and McLaughlin (WVU,Co-PI/Director)
  - Active work underway to add pulsars to the array, increase observation time, and improve GW limits

(T. Prince communicated with Siemens, McLaughlin, and other members of US NANOGrav community e.g. Lazio, Ellis,…)

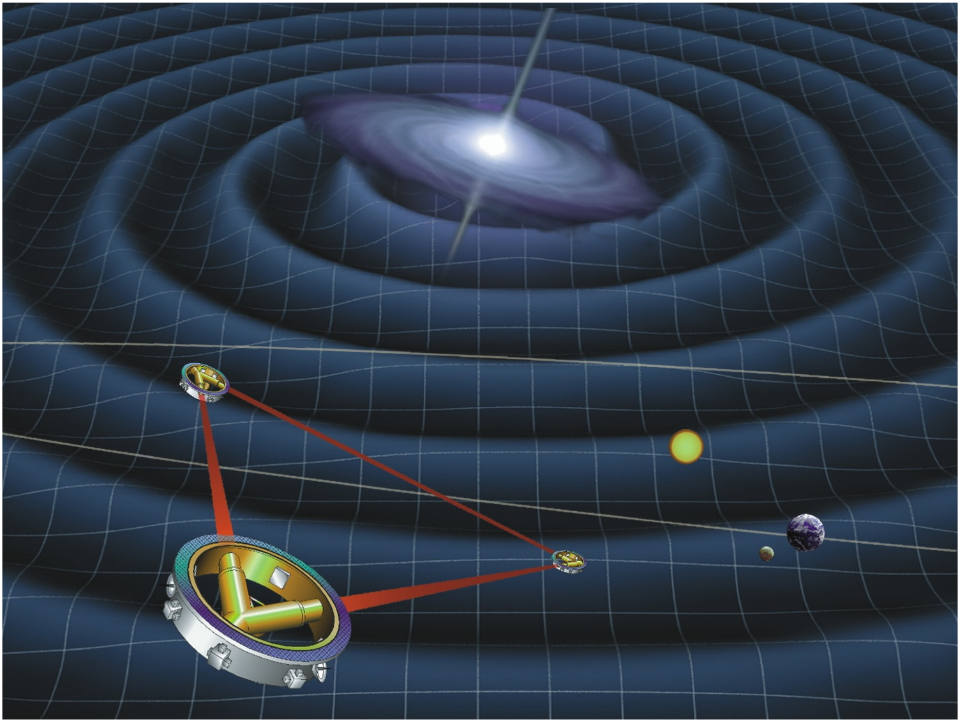
Space-Based GW with a LISA Mission



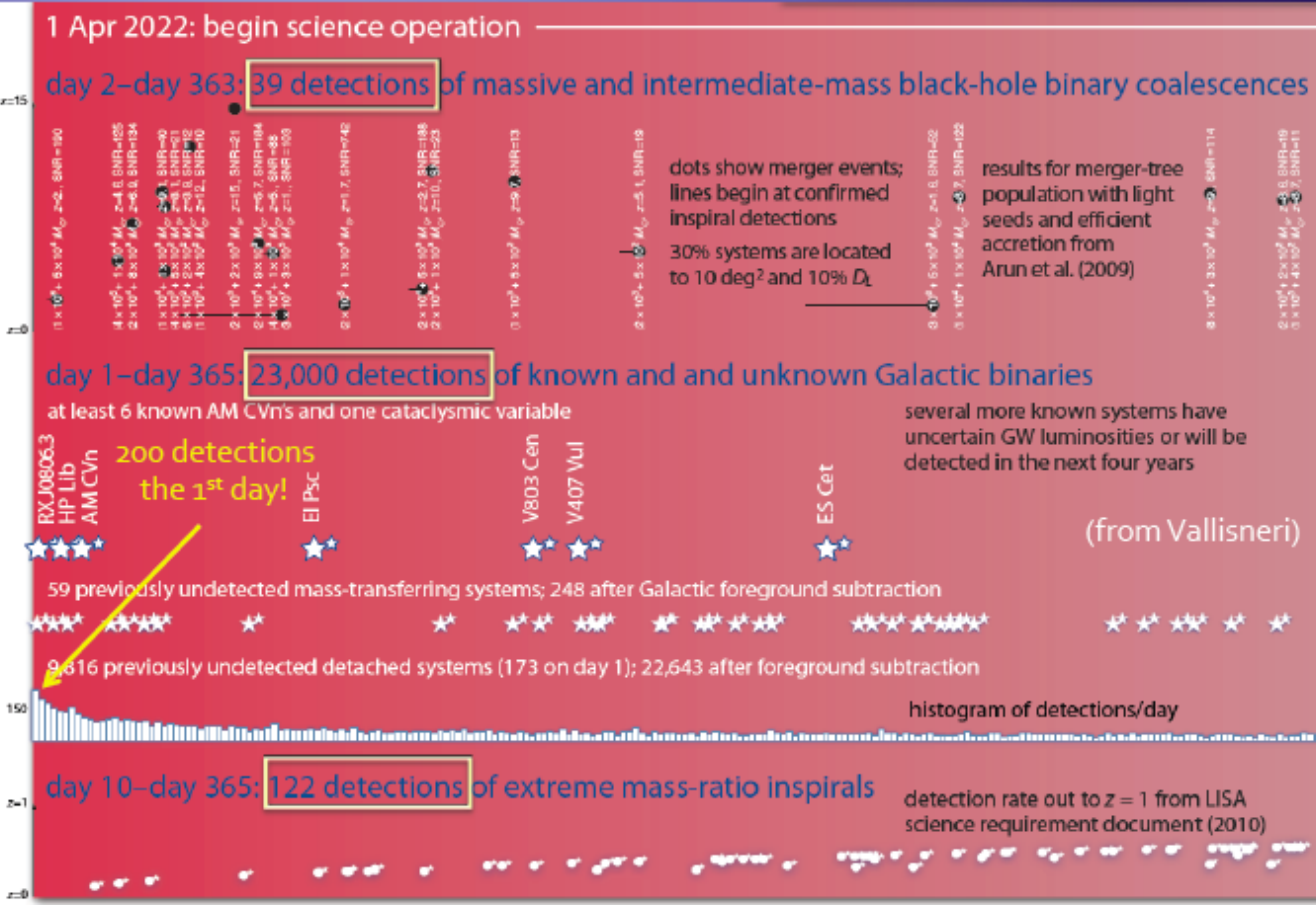
Massive Black Hole Mergers (~tens to hundreds)

Ultra-Compact Binaries (~thousands)

Capture of stellar-mass black holes by massive BHs in normal galactic nuclei (~hundreds)



The First Year in the Life of LISA: A Realistic Simulation



1 Apr 2022: begin science operation

day 2–day 363: 39 detections of massive and intermediate-mass black-hole binary coalescences

dots show merger events; lines begin at confirmed inspiral detections

30% systems are located to 10 deg² and 10% D_L

results for merger-tree population with light seeds and efficient accretion from Arun et al. (2009)

day 1–day 365: 23,000 detections of known and and unknown Galactic binaries

at least 6 known AM CVn's and one cataclysmic variable

several more known systems have uncertain GW luminosities or will be detected in the next four years

200 detections the 1st day!

(from Vallisneri)

59 previously undetected mass-transferring systems; 248 after Galactic foreground subtraction

9,816 previously undetected detached systems (173 on day 1); 22,643 after foreground subtraction

histogram of detections/day

day 10–day 365: 122 detections of extreme mass-ratio inspirals

detection rate out to $z = 1$ from LISA science requirement document (2010)

Status: Space-based GW

LISA Pathfinder
(ESA launch 2015)

- Laser Interferometer Space Antenna (LISA)
  - One of only two missions recommended for flight during this decade by Astro2010 decadal review
    - Funds not available due to JWST overruns
  - ESA has chosen a GW mission (L3) [for ***2034***]
- Discussion with Paul Hertz (April 7, 2015)
  - Current NASA plan is to partner with ESA on eLISA
  - Science case will need to be made to Astro2020
  - NASA will be open to decadal recommendations about US role in space-based GW, taking into account developments in Europe and elsewhere

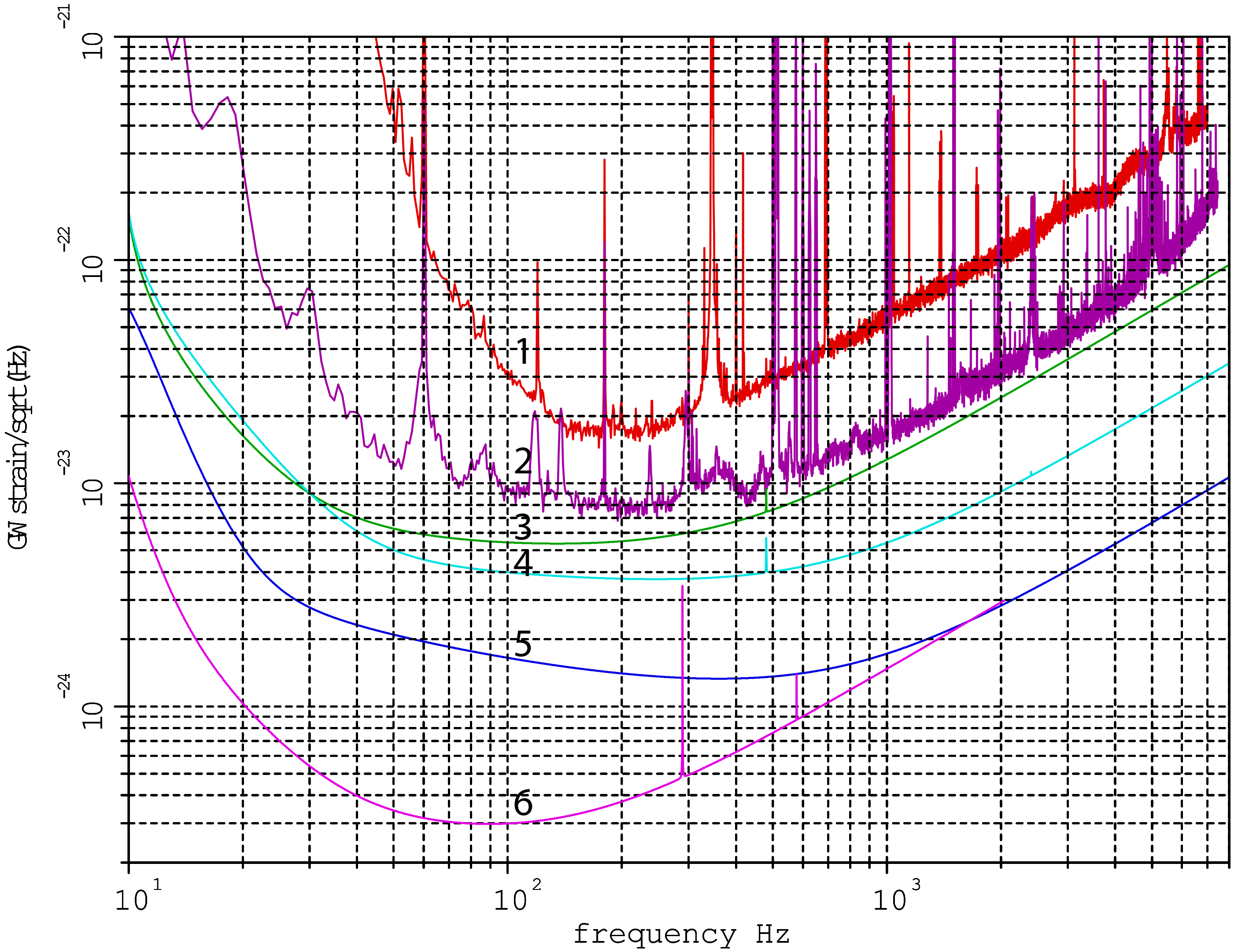
(T. Prince also communicated with Conklin, Cornish, Mueller, Stebbins -- leaders of US space-based GW community)

Evolution of Ground-based Detectors

Near and Long-term Goals

Rai Weiss

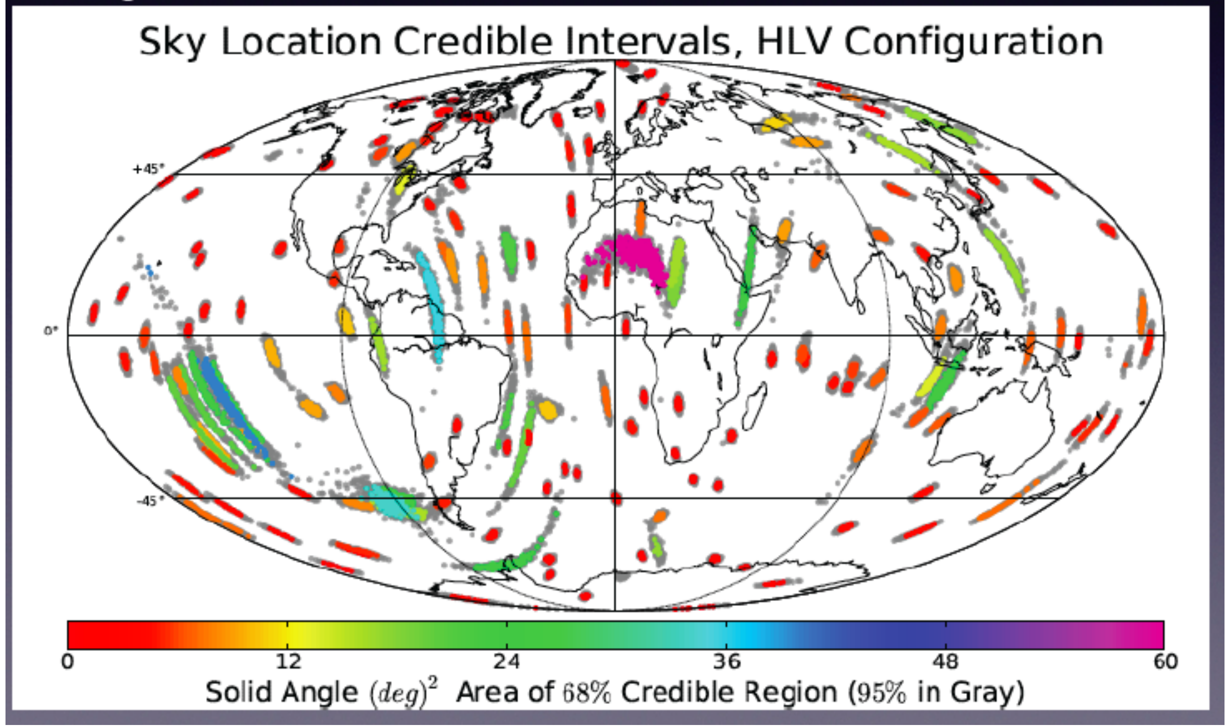
Interferometer evolution



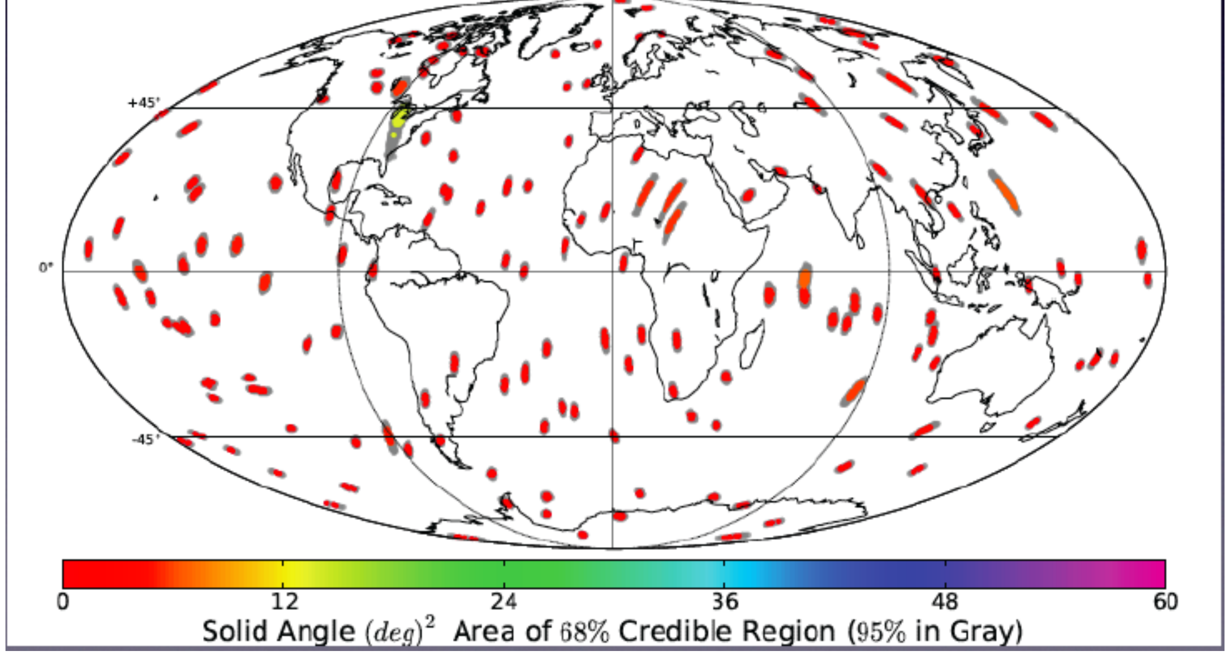
1 LHO enhanced LIGO NS/NS 15Mpc
2 LLO advanced LIGO today 67Mpc
3 Advanced LIGO low power 150Mpc
4 Advanced LIGO high power 190Mpc
5 Example "Voyager" 600Mpc 10db squeezing, 160kg test masses
6 Example "Explorer" z~2 40Km, 5db squeezing, 40kg test masses

Rodriguez et al 2014

Sky Location Credible Intervals, HLV Configuration



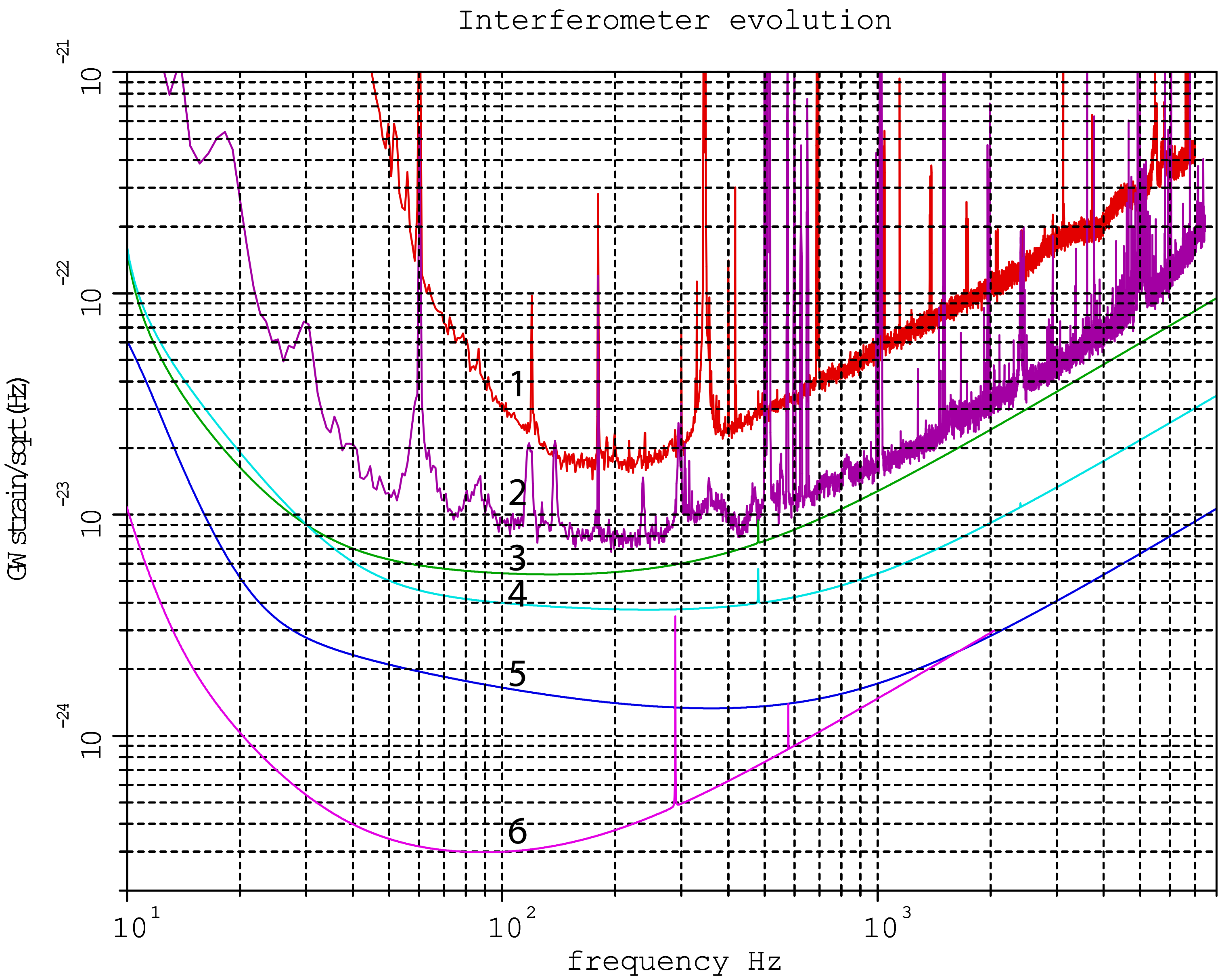
Sky Location Credible Intervals, HLVI Configuration



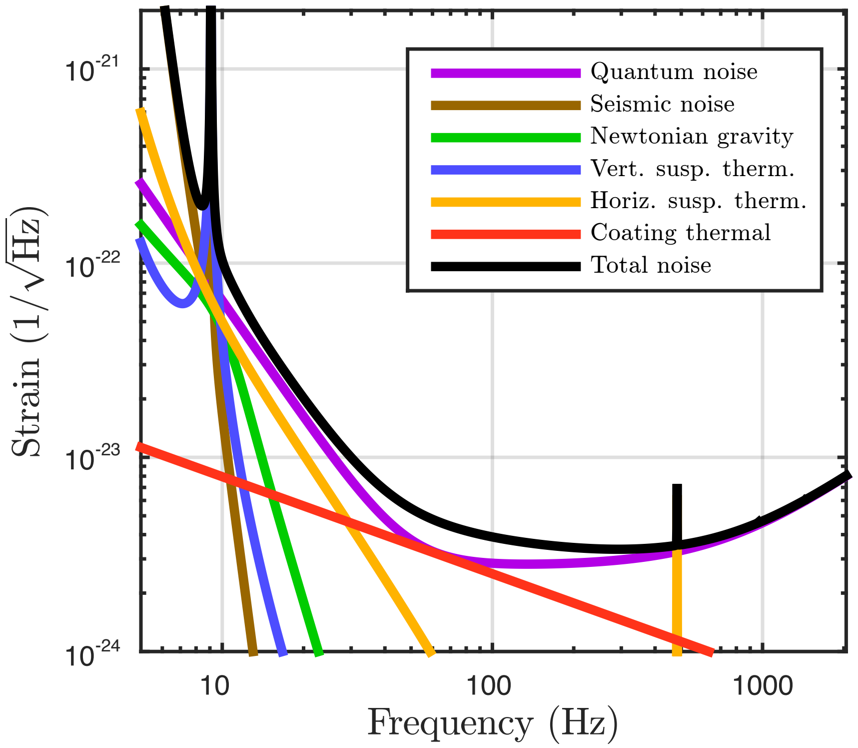
NS/NS coalescence localization errors
for two networks

Proposed run schedule

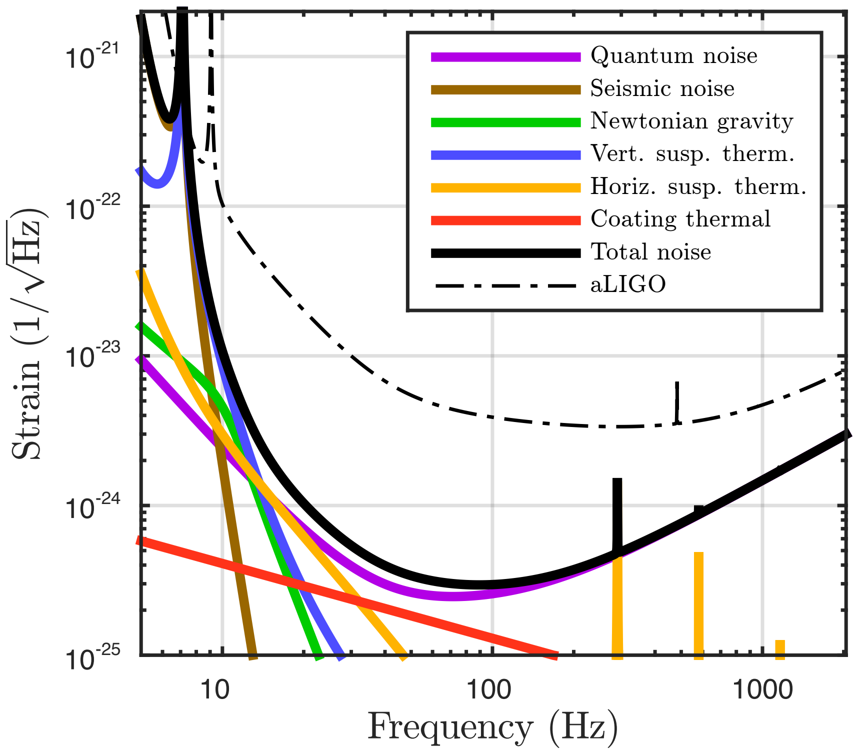
	Estimated Run	$E_{\rm GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS	% BNS Localized within	
Epoch	Duration	LIGO	Virgo	LIGO	Virgo	Detections	5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48



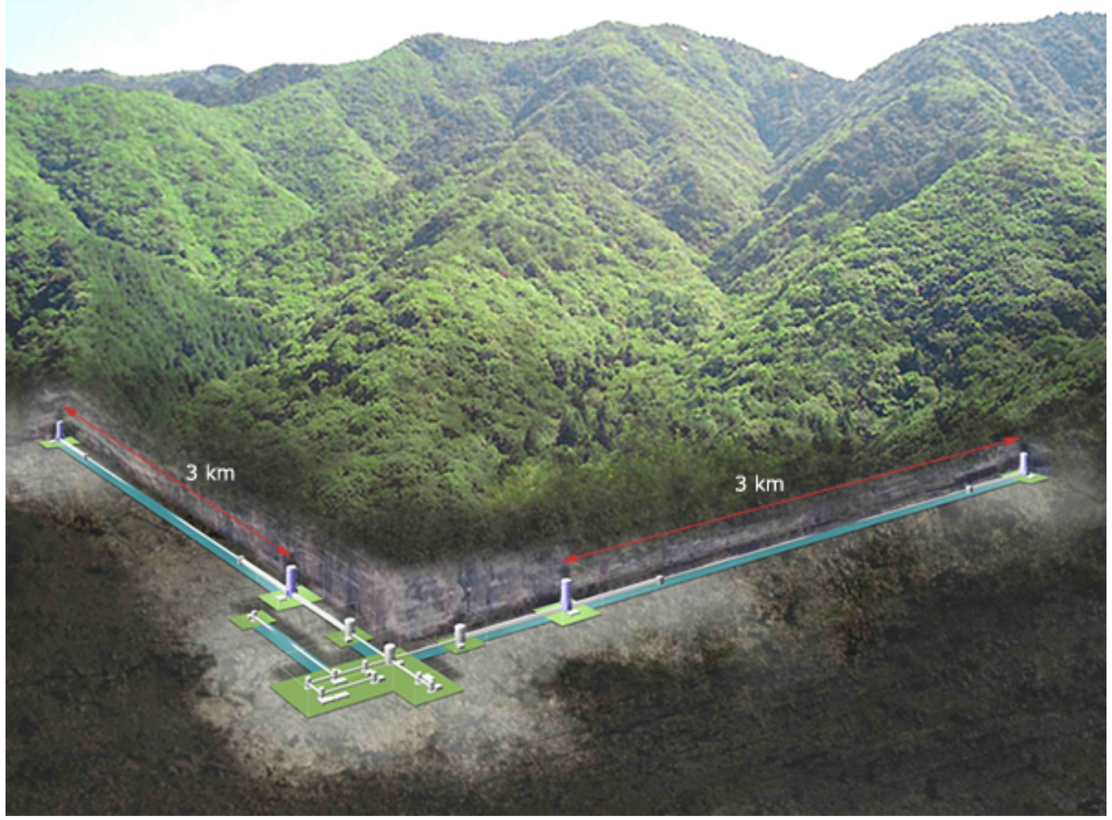
1 LHO enhanced LIGO NS/NS 15Mpc
2 LLO advanced LIGO today 67Mpc
3 Advanced LIGO low power 150Mpc
4 Advanced LIGO high power 190Mpc
5 Example "Voyager" 600Mpc 10db squeezing, 160kg test masses
6 Example "Explorer" z~2 40Km, 5db squeezing, 40kg test masses



Advanced LIGO high power noise budget

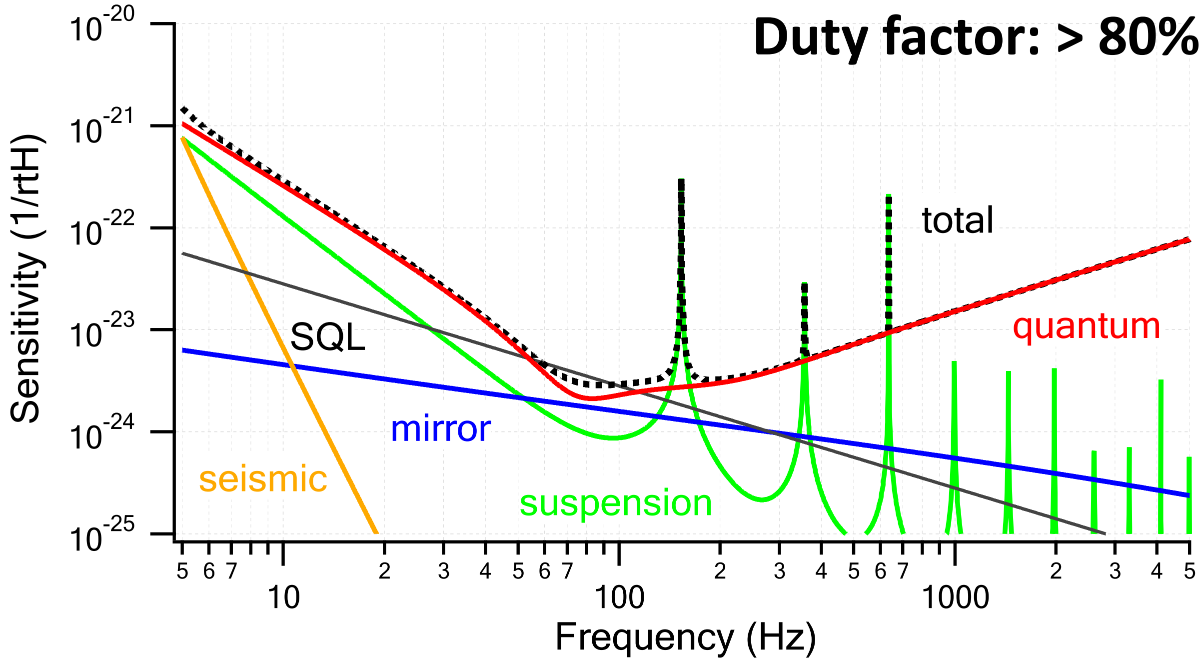


Example Explorer 40km noise budget

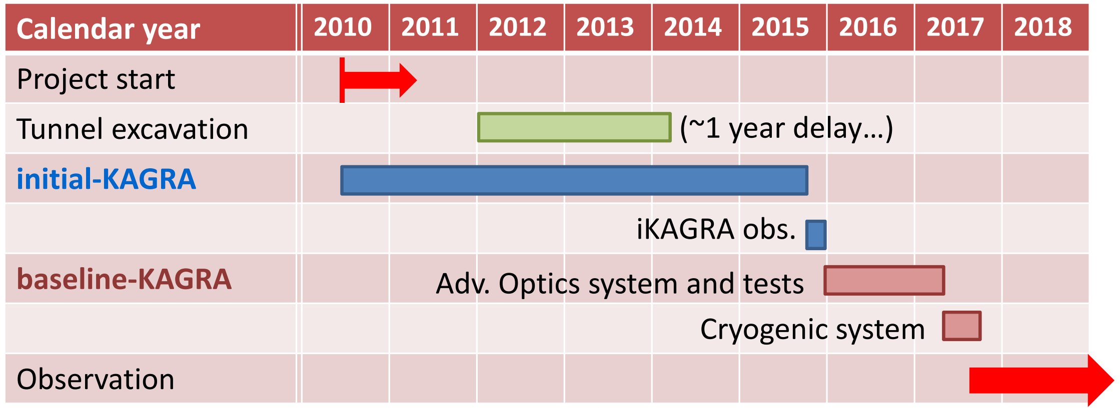


Kagra: cryogenic interferometer
in Kamioka Mine, Japan
S. Kawamura (2014)

Target Sensitivity of KAGRA

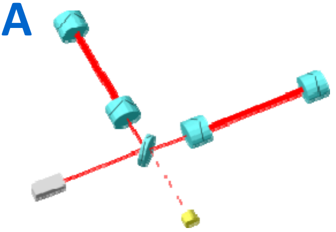


Schedule of KAGRA



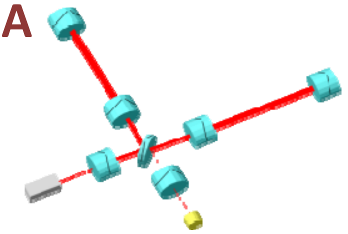
Calendar year	2010	2011	2012	2013	2014	2015	2016	2017	2018
Project start	➡								
Tunnel excavation			🟩	🟩	(~1 year delay…)				
initial-KAGRA	🟦	🟦	🟦	🟦	🟦	🟦			
					iKAGRA obs.	🟦			
baseline-KAGRA						Adv. Optics system and tests	🟥		
							Cryogenic system	🟥	
Observation								➡	➡

iKAGRA

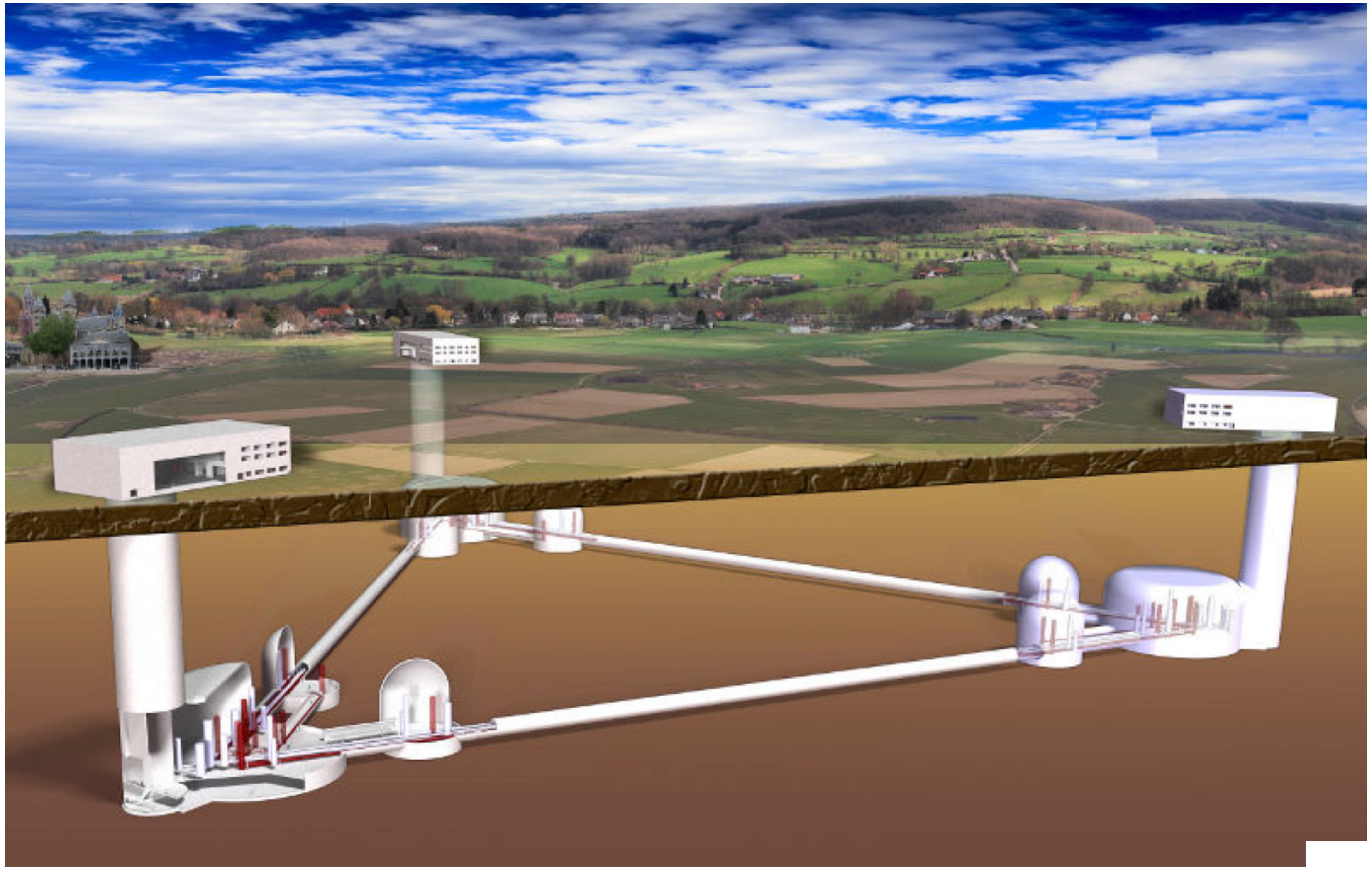


- Fabry-Perot Michelson interferometer
- Room temperature
- Simple seismic isolation system

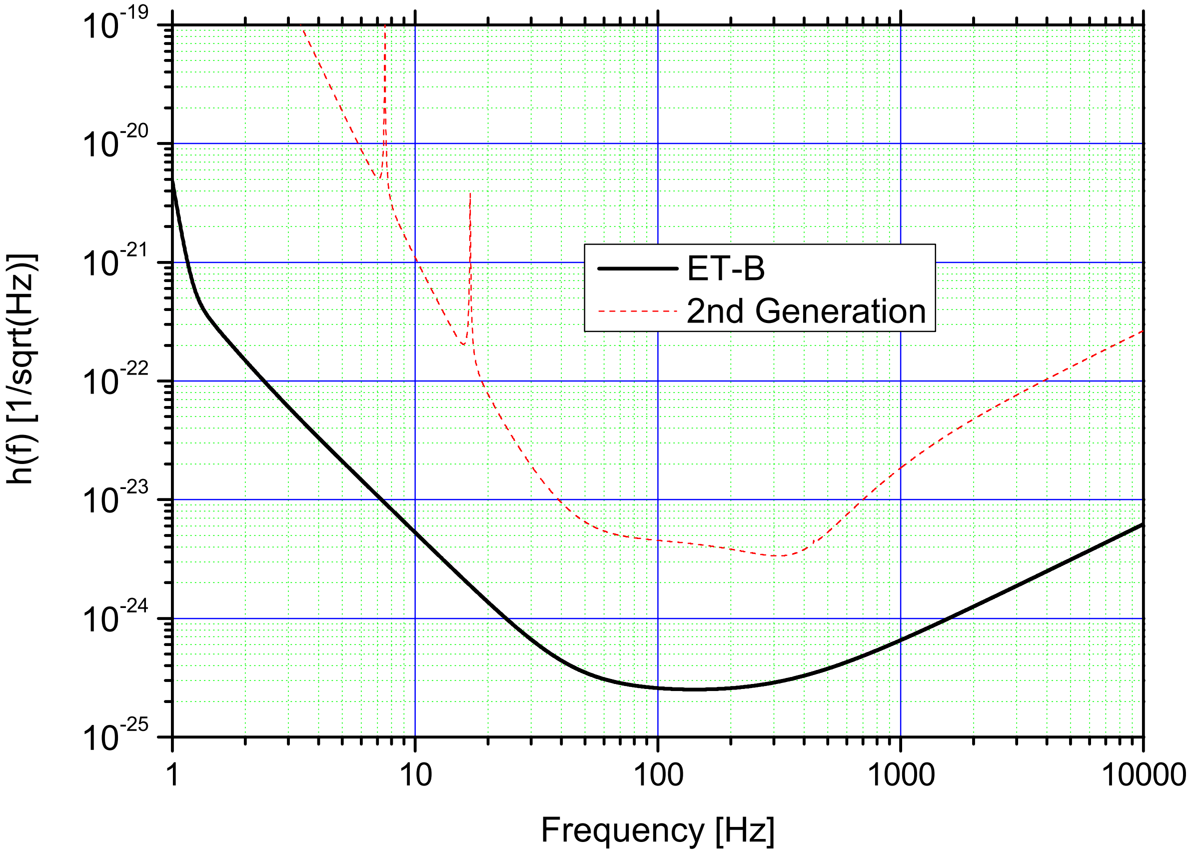
bKAGRA



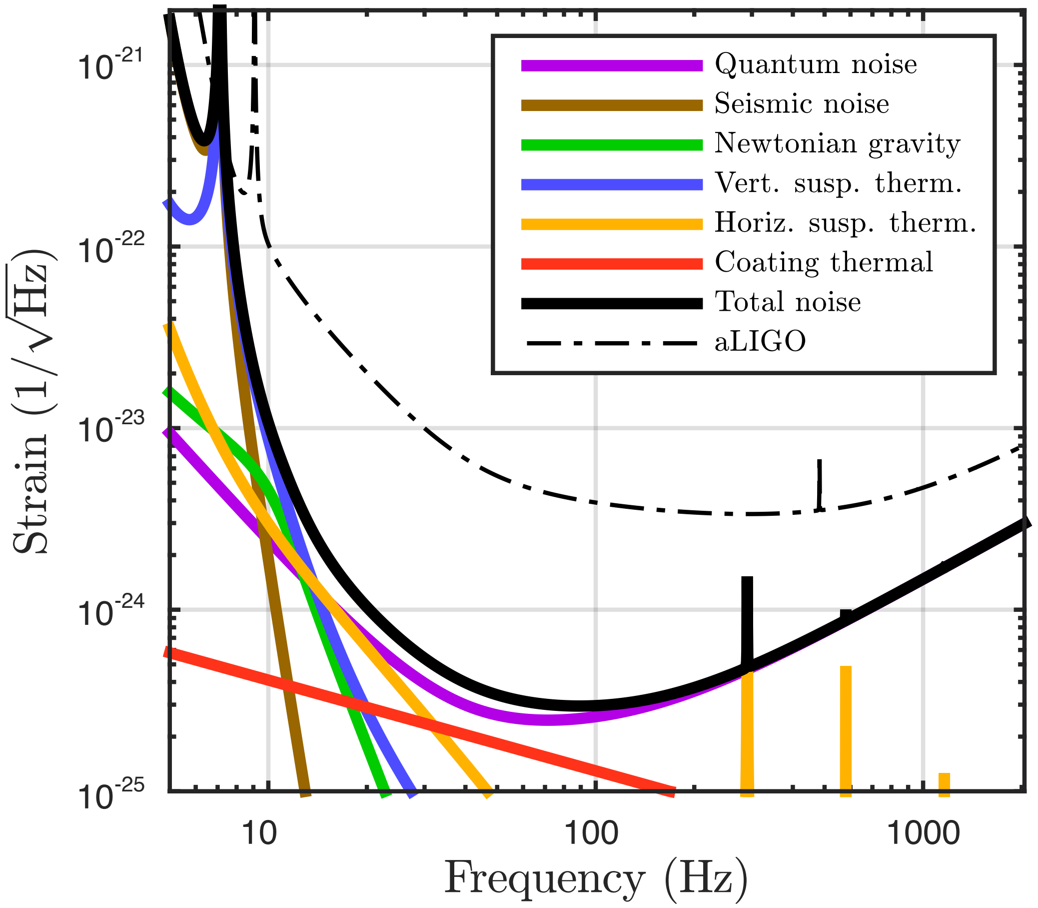
- Resonant sideband extraction
- Cryogenic temperature
- Advanced seismic isolation system



Einstein Gravitational Wave Observatory Study (M.Puntoro 2010)



Example Explorer 40km noise budget



Near and long-term goals

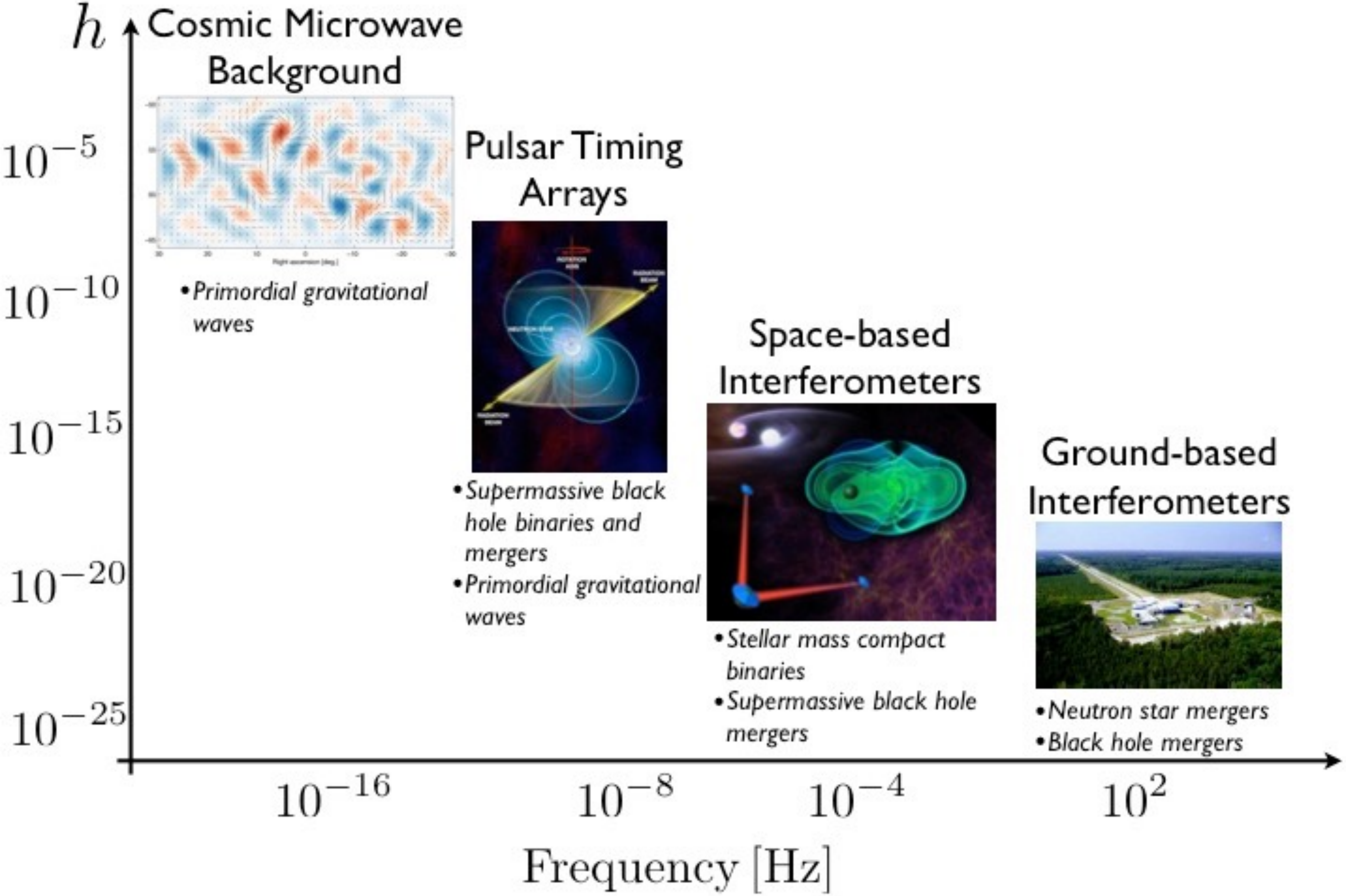
- CMB polarization
  - NT: Ground and balloon based
    - Increased sky and wavelength coverage
    - Angular scales as large as 10 degrees with polarization modulators
    - Large format detector arrays BLIP limited by CMB
  - LT: Space based: Inflation Probe (CMBPol)
- Pulsar timing
  - NT: continued access to telescope time (GBT and Arecibo), continued funding for observations and algorithm development
  - LT: SKA or other advanced facilities with increased pulsar timing & search capabilities
- Space
  - NT: NASA funding of technology development commensurate with future strong role in LISA-like mission (lasers, telescopes, thrusters, analysis…)
  - NT: NASA support of LISA science community in advance of Astro2020 -- currently almost no NASA science funding – not commensurate with strong science support for LISA from Astro2010
  - LT: Strong US role in future LISA-like space mission
- Ground
  - NT: Operate and improve Advanced LIGO
  - NT&LT: increase the network
  - LT: new detectors/configurations & science reach (needs study)

Request of BPA

- An NRC study about the future directions of ground-based gravitational-wave research
- Why now:
  - The possibility of detections in the next few years
  - The long development times for the technology
  - Scientific input on technical and scientific tradeoffs
  - Continuity for the strong technical and experimental physics groups now in the field

Extra Slides

Gravitational wave spectrum



Cosmic Microwave Background

- *Primordial gravitational waves*

Pulsar Timing Arrays

- *Supermassive black hole binaries and mergers*
- *Primordial gravitational waves*

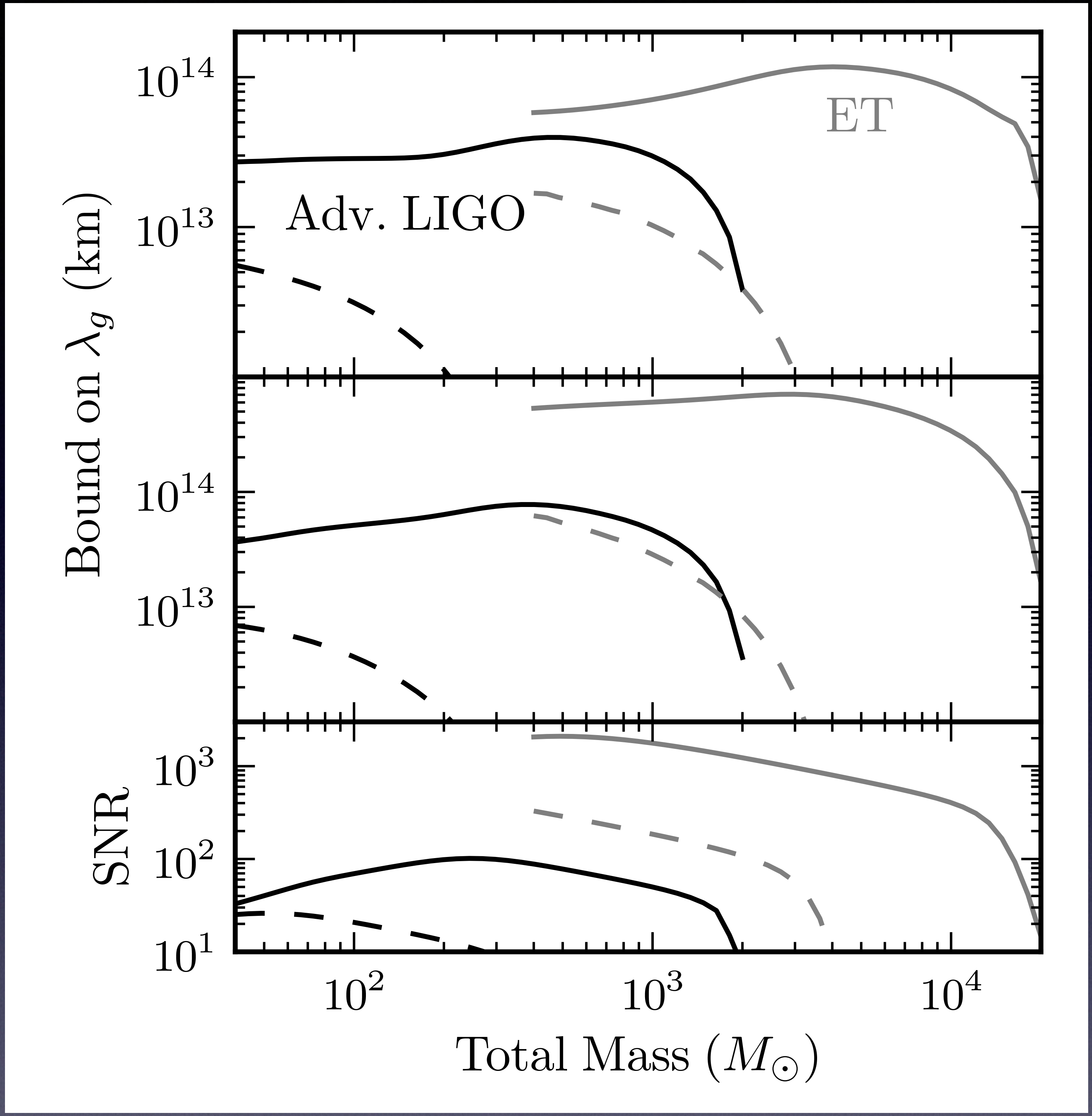
Space-based Interferometers

- *Stellar mass compact binaries*
- *Supermassive black hole mergers*

Ground-based Interferometers

- *Neutron star mergers*
- *Black hole mergers*

Keppel & Ajith 2010



GR tests: graviton mass

Solar System Limit:
2.8x10^12 km

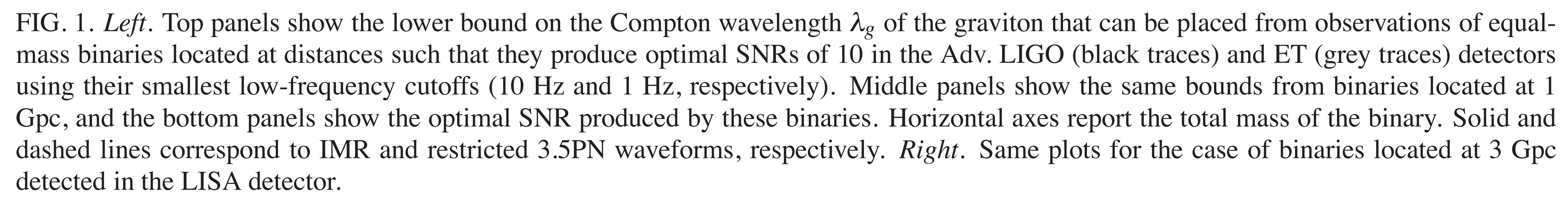
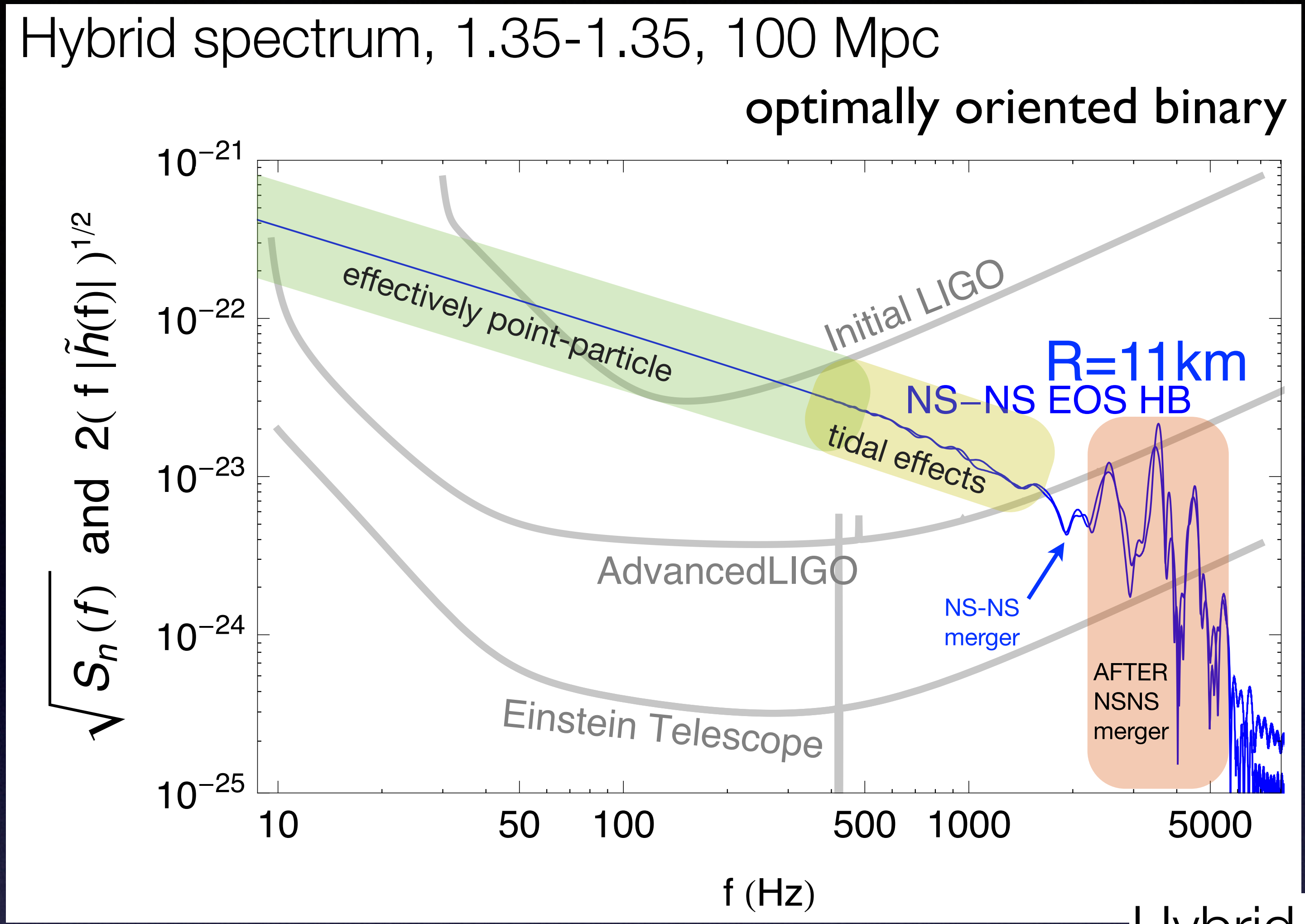
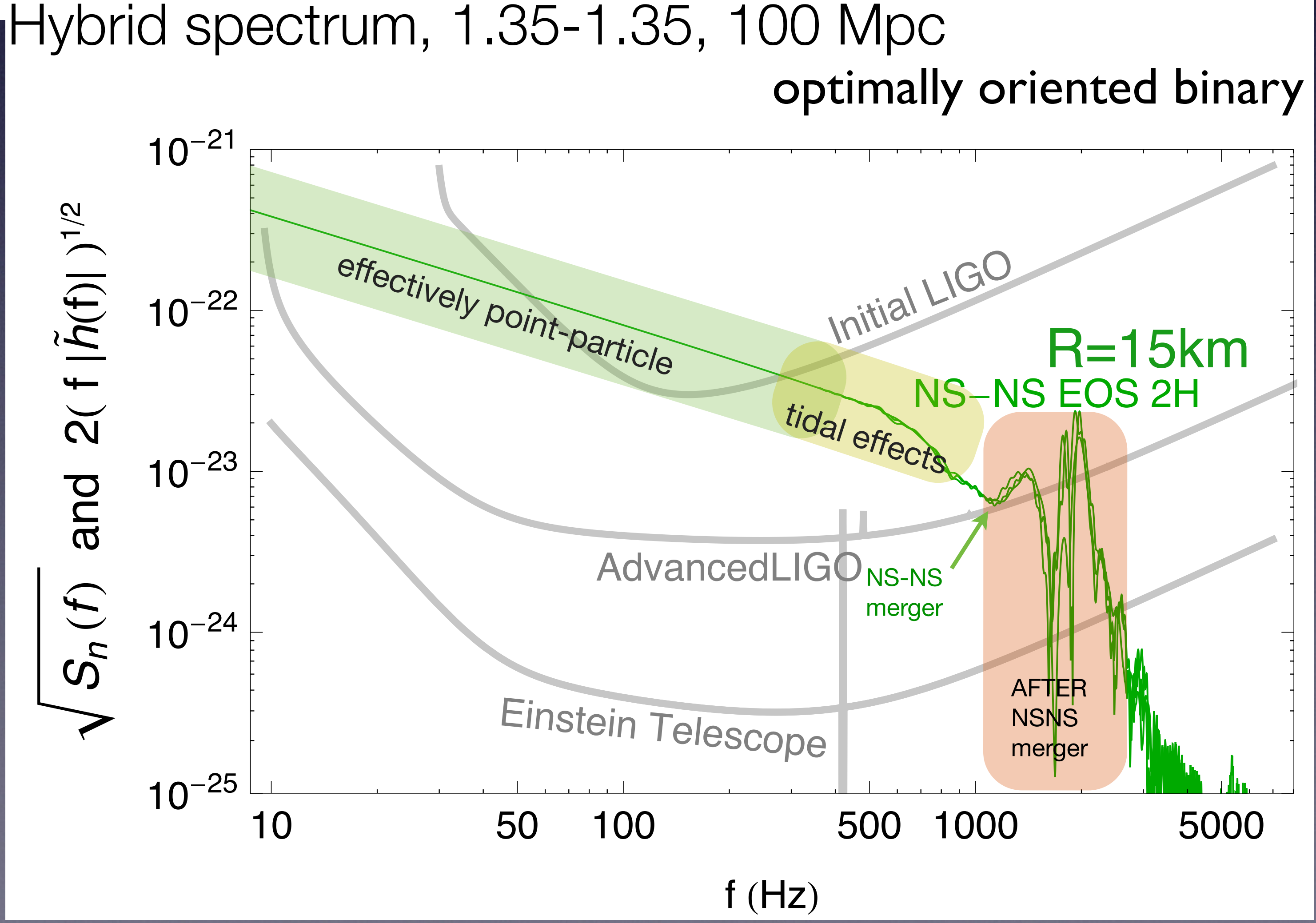


FIG. 1. *Left*. Top panels show the lower bound on the Compton wavelength λ_g of the graviton that can be placed from observations of equal-mass binaries located at distances such that they produce optimal SNRs of 10 in the Adv. LIGO (black traces) and ET (grey traces) detectors using their smallest low-frequency cutoffs (10 Hz and 1 Hz, respectively). Middle panels show the same bounds from binaries located at 1 Gpc, and the bottom panels show the optimal SNR produced by these binaries. Horizontal axes report the total mass of the binary. Solid and dashed lines correspond to IMR and restricted 3.5PN waveforms, respectively. *Right*. Same plots for the case of binaries located at 3 Gpc detected in the LISA detector.

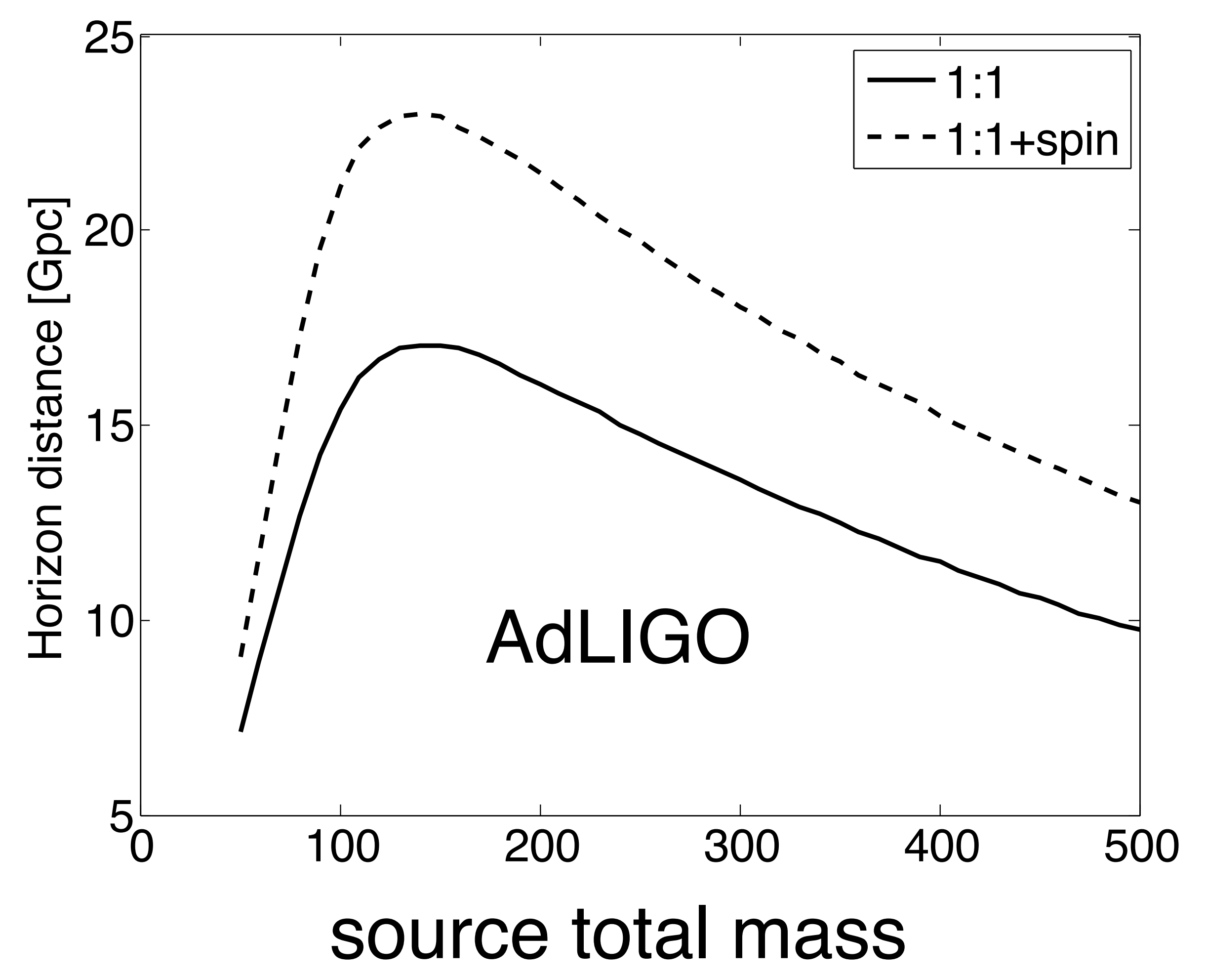
Jocelyn Read 2015

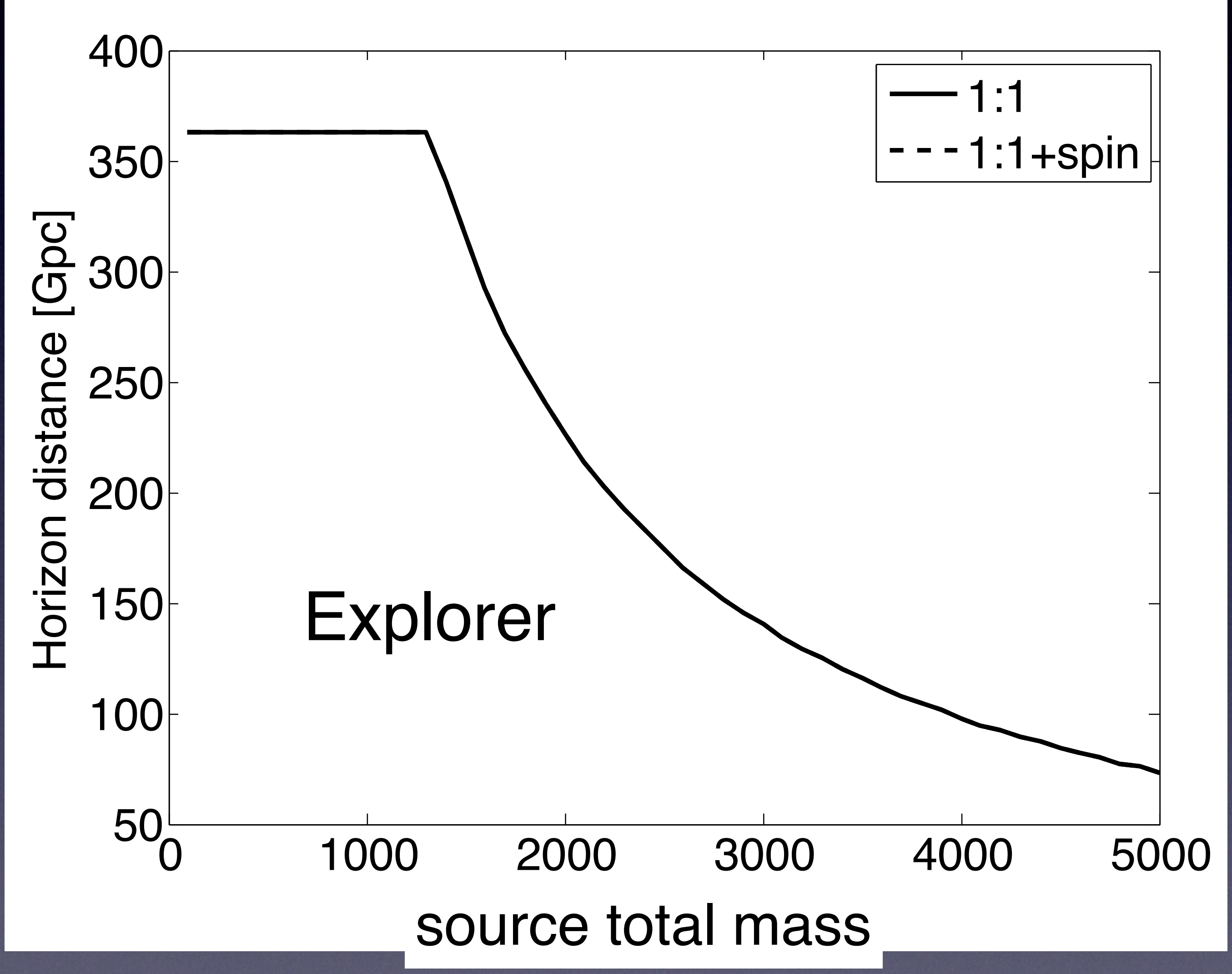




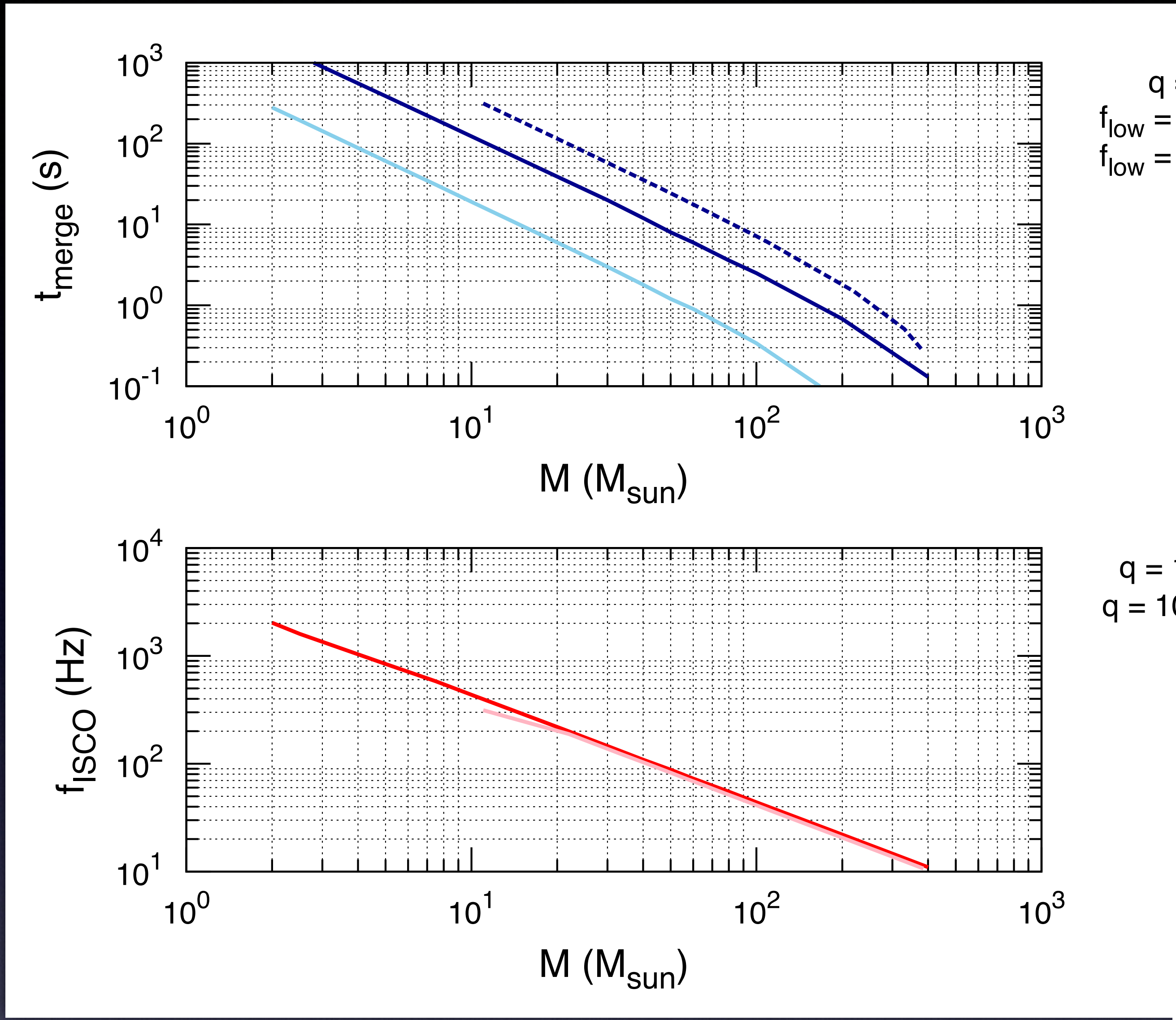
Sensitivity to Intermediate-Mass BHs

Mandel 2015

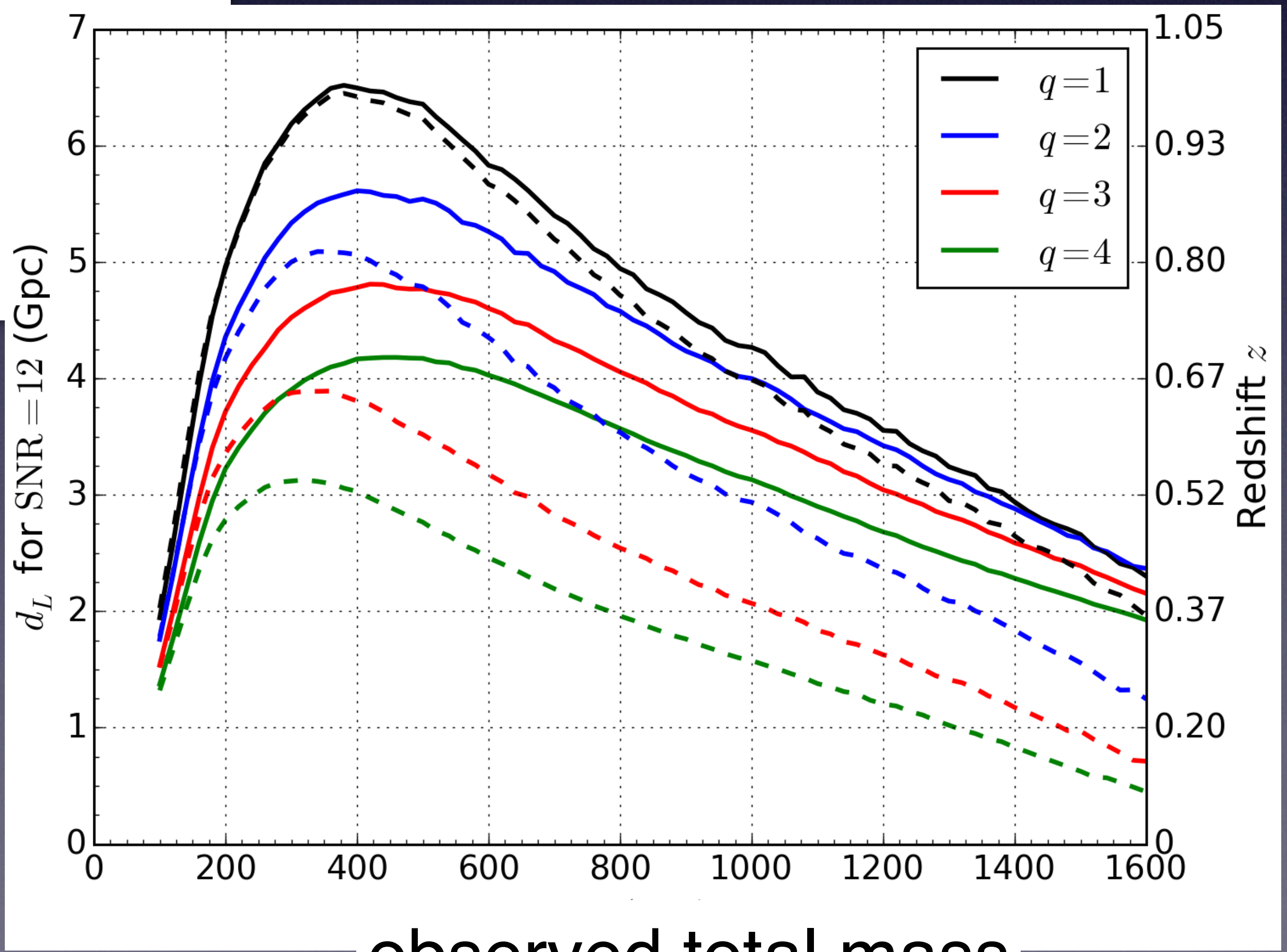




Littenberg 2015

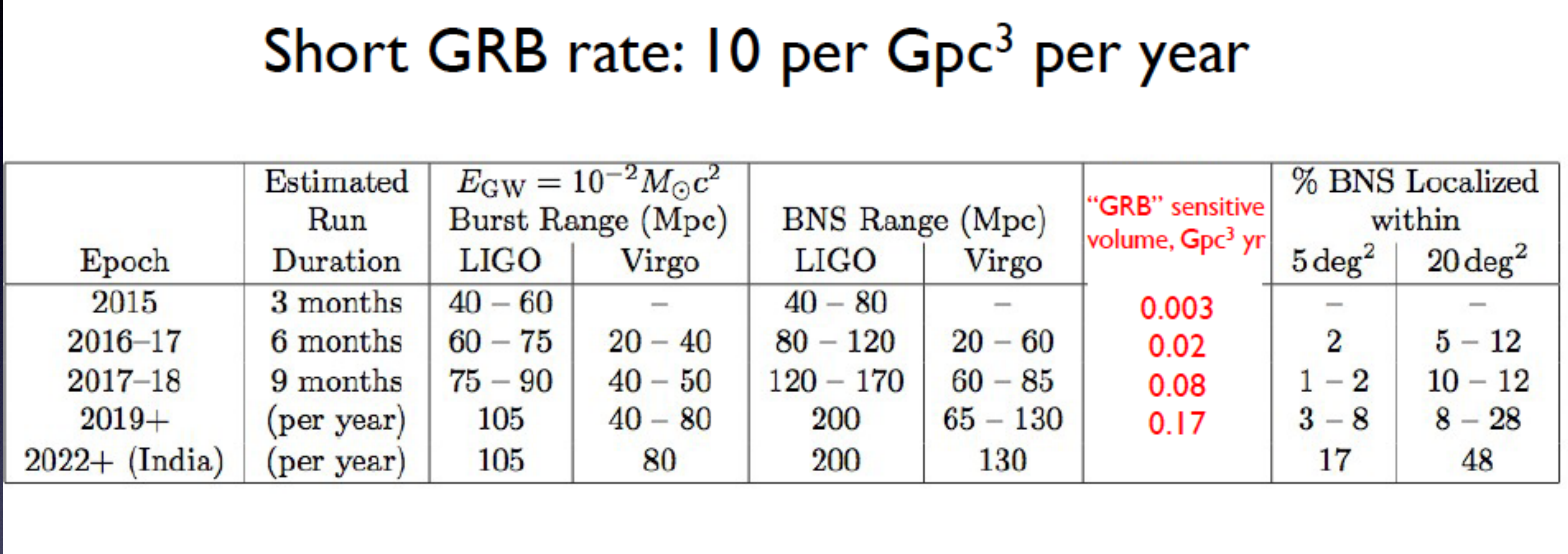


Graff et al. 2015



observed total mass

Mandel 2014

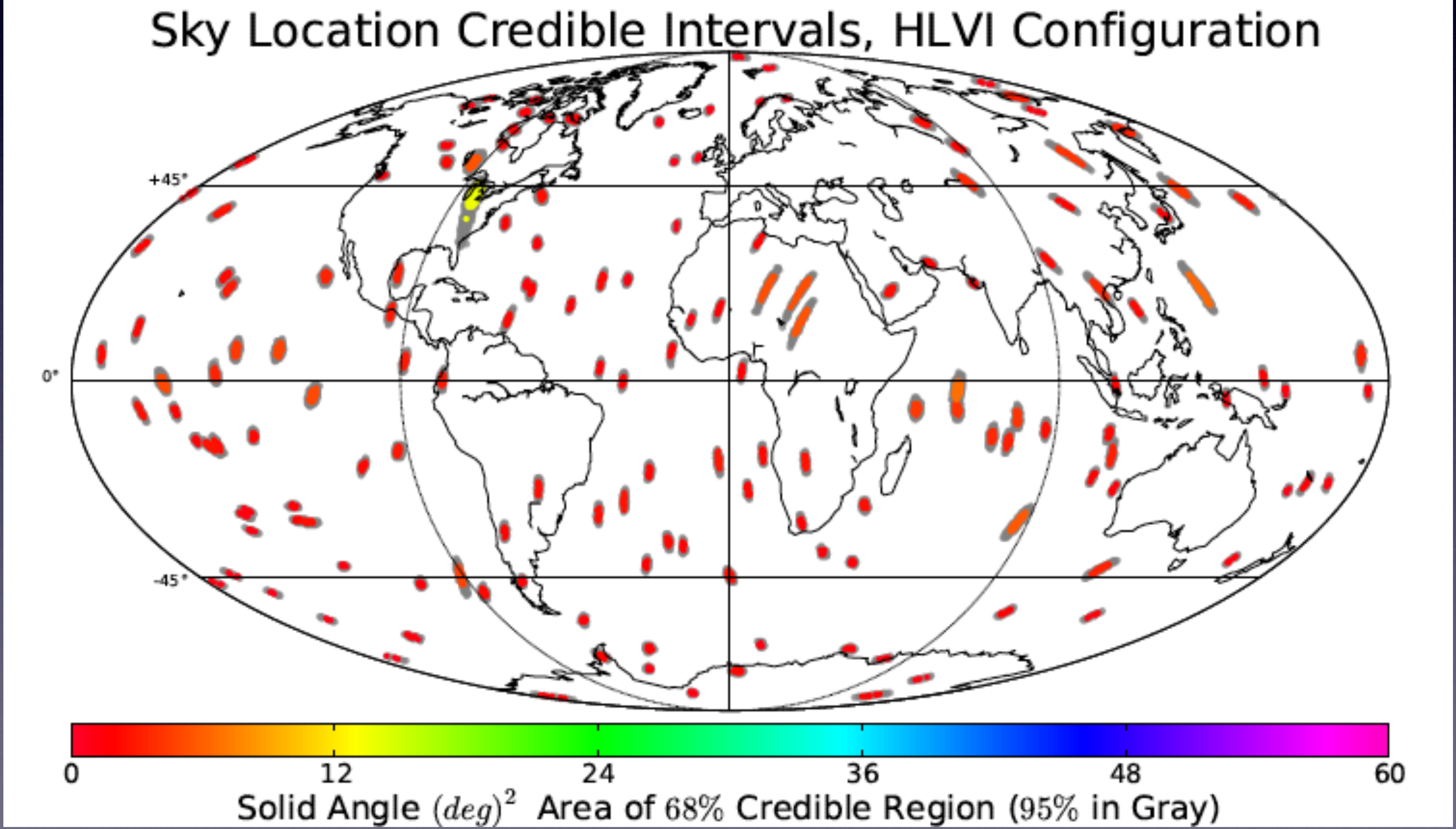


Short GRB rate: 10 per Gpc^3 per year

Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		"GRB" sensitive volume, Gpc^3 yr	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.003	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.02	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.08	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.17	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130		17	48

Localization:
NS-NS Inspiral

Rodriguez et al 2014



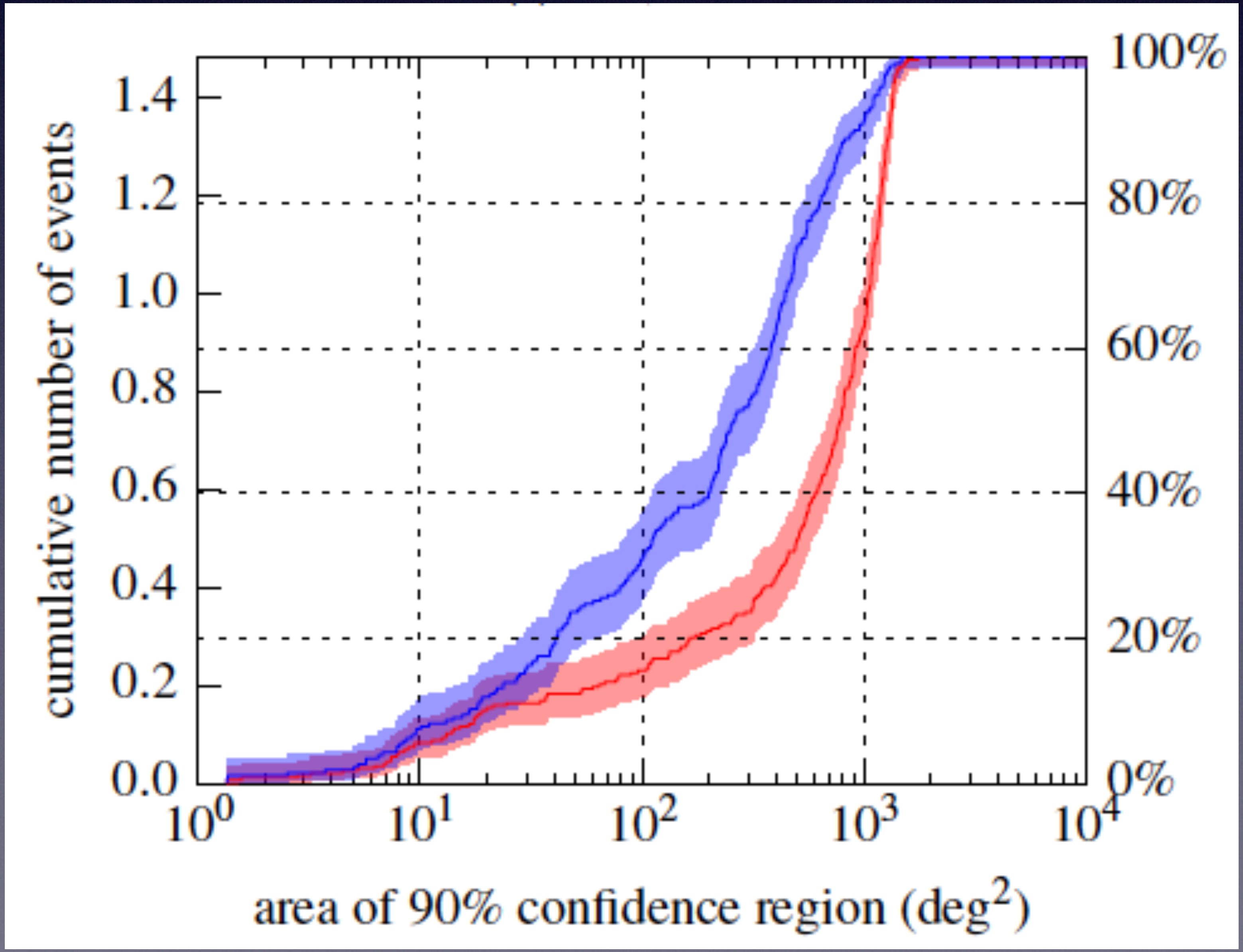
with
INDIGO

at 95% CL
median
error of
~ 5 deg^2

Localization:
NS-NS Inspiral

What about the Ad run in 2016?

Singer et al 2014



3 detectors:
2 LIGO & Virgo
(V less sensitive by ~3)

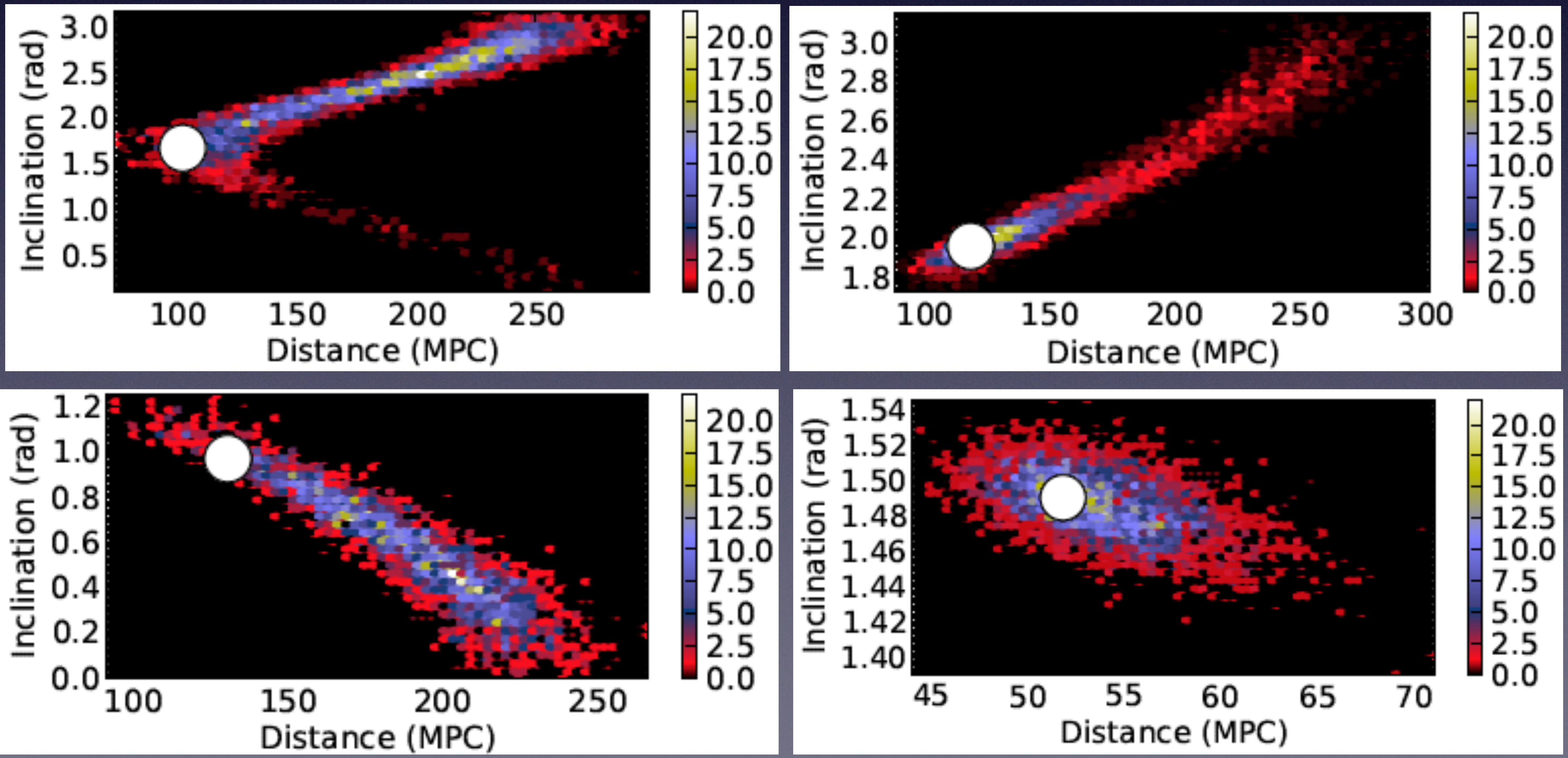
BayesPE
decreases median area
by ~3-5

can account for
non-detection in Virgo

Physical Parameter Estimation: NS-NS Inspiral

What about distance, masses, binary inclination?

only with BayesPE

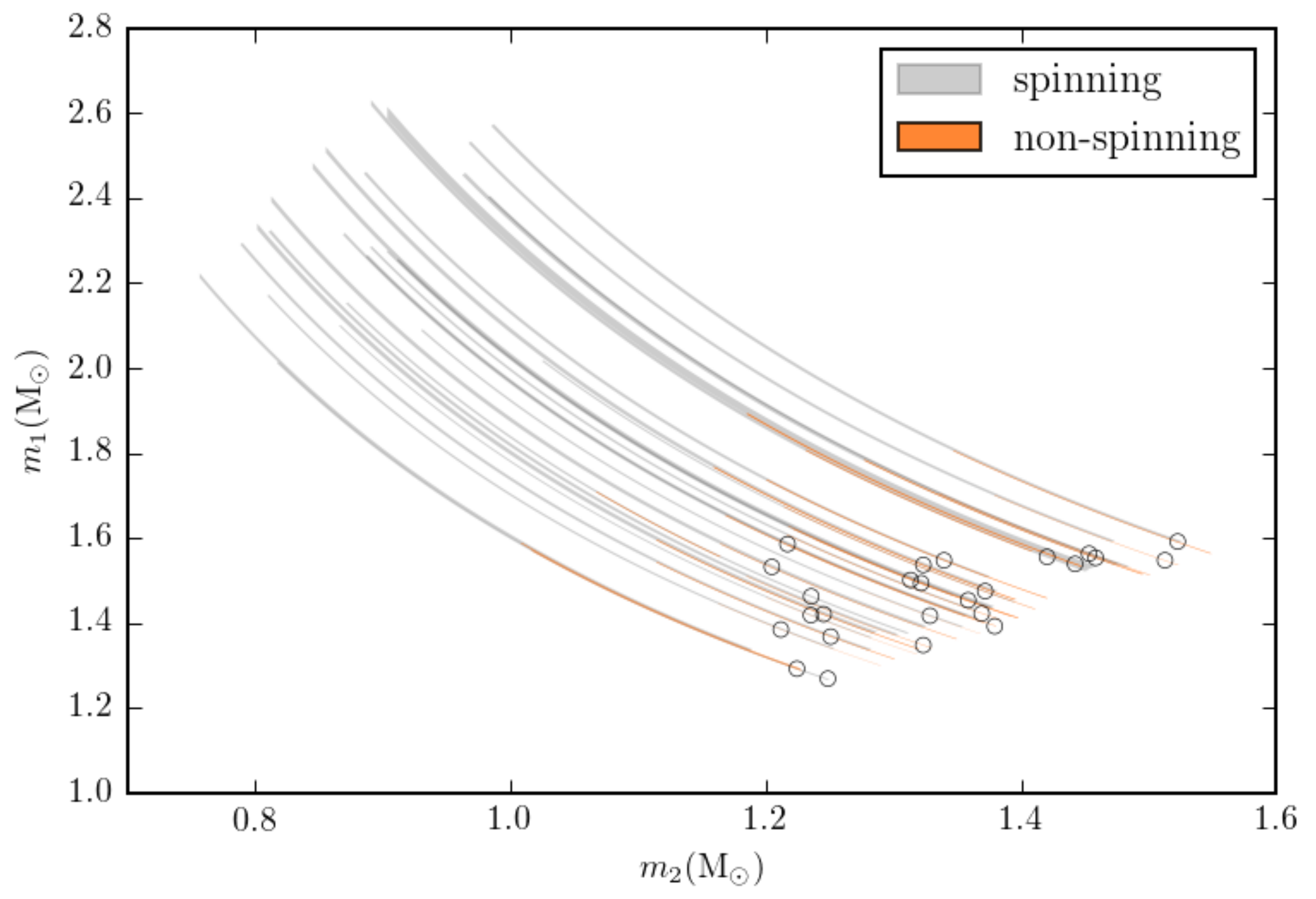


typically within factor of ~2

if only we knew inclination

Physical Parameter Estimation: NS-NS Inspiral

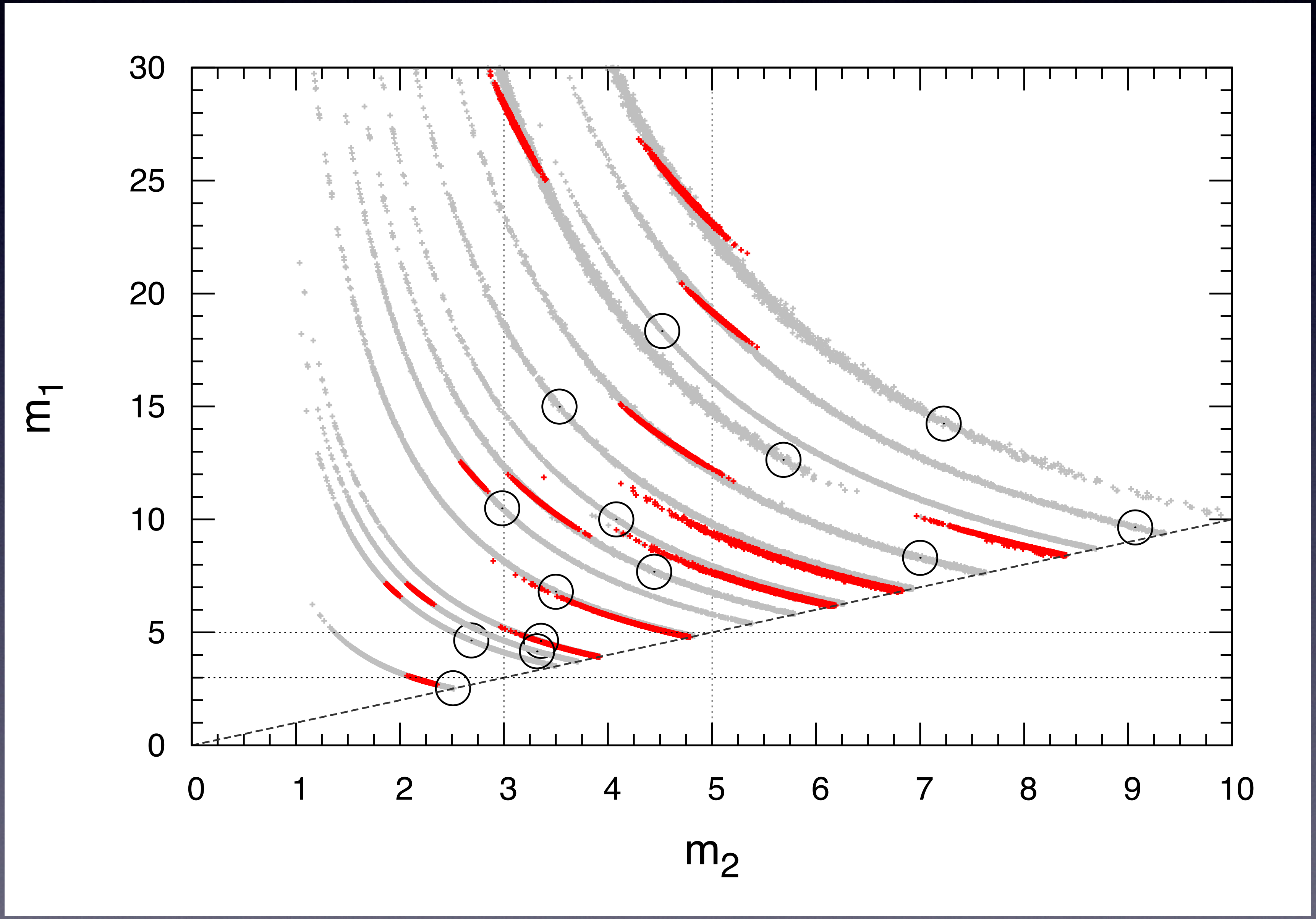
Farr et al 2015



allowing for spin increases mass errors to ~50%

Individual Mass Recovery: NS-BH and BH-BH Inspiral

Littenberg et al 2015

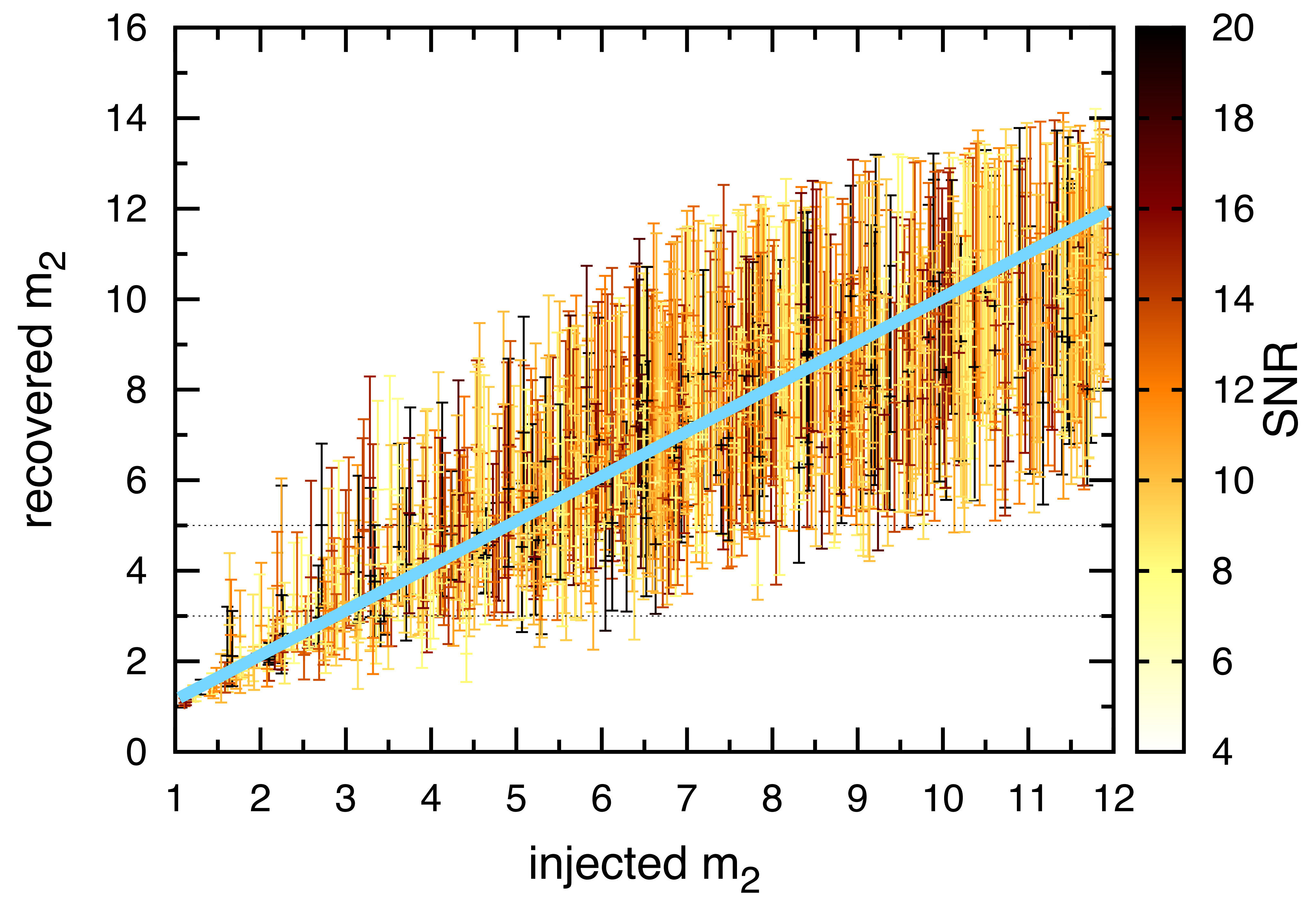


Mass errors increase when freedom of spin is accounted for

but is also becomes correct!

Individual Mass Recovery: NS-BH and BH-BH Inspiral

Littenberg et al 2015

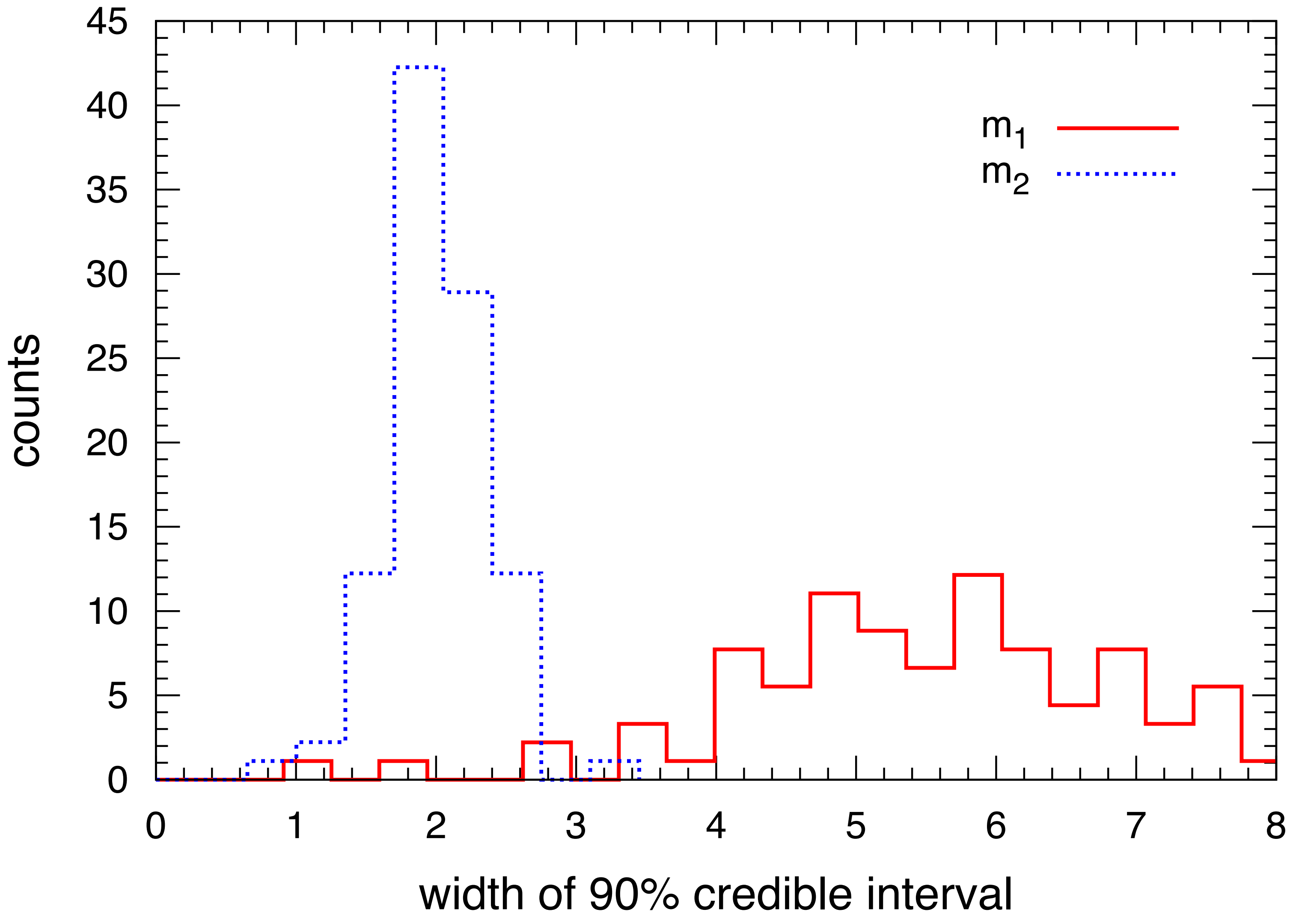


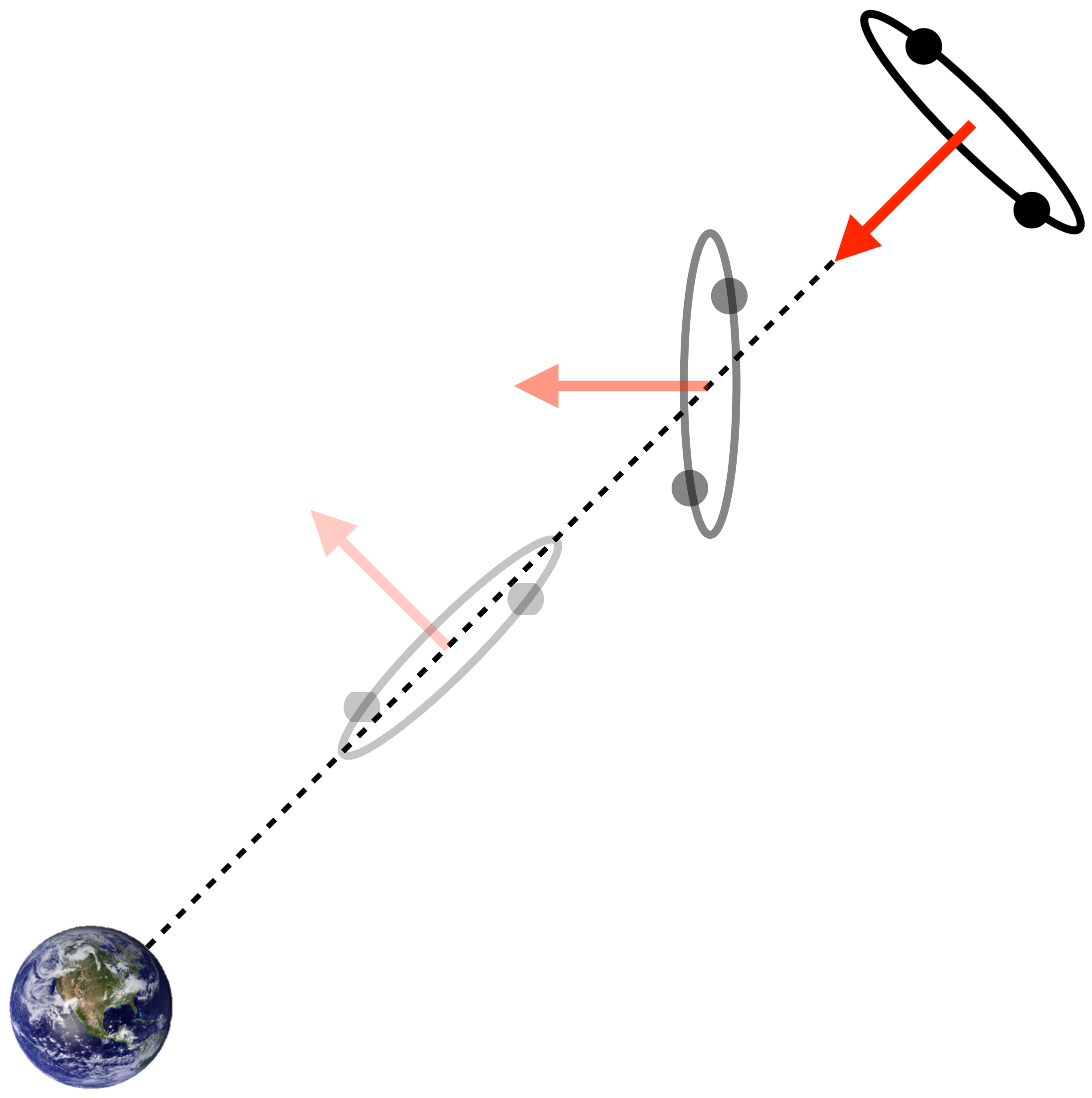
Can we tell a NS-BH from a BH-BH ?

Yes, if
$m_2 < 1.5\ M_{sun}$
or
$m_2 > 6\ M_{sun}$

Is there anything in the Mass Gap?

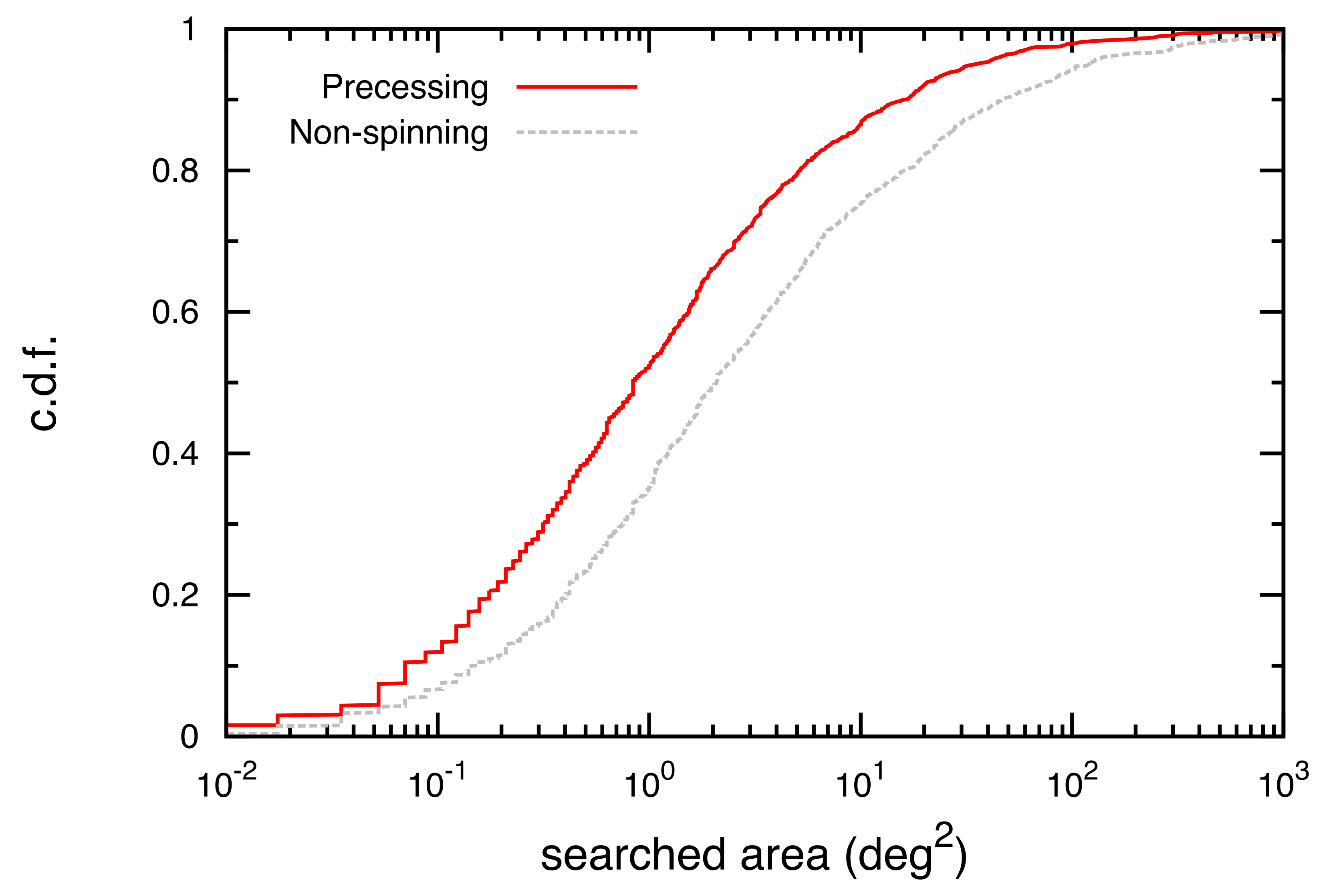
1. Source-by-source, when are component masses constrained to be within [3,5] M_{sun}?





Errors in component masses are typically larger than the gap

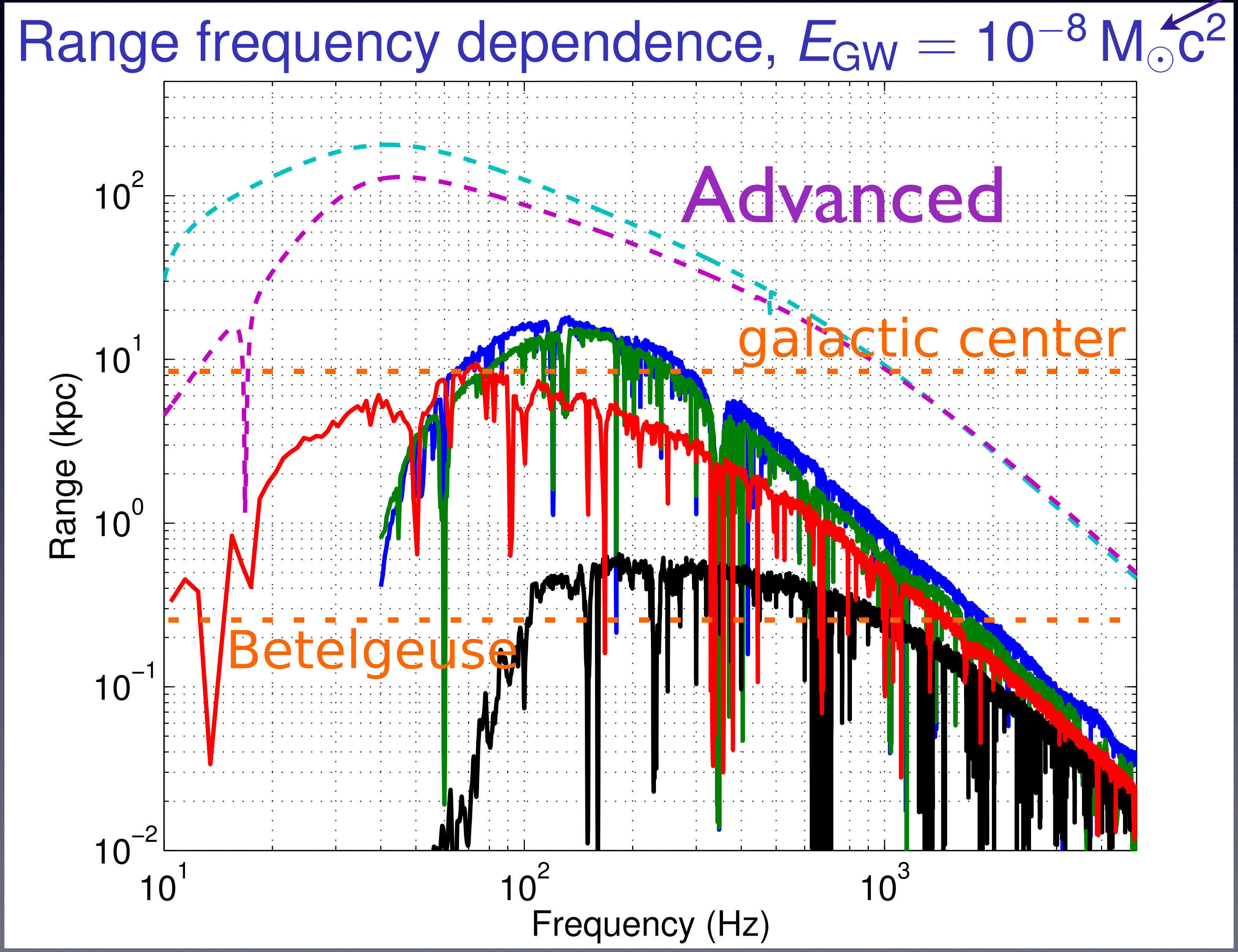
Littenberg et al 2015



Sky Localization improves when spin is accounted for

Expectations for Advanced Searches of Generic Bursts

M. Was (priv. comm.)



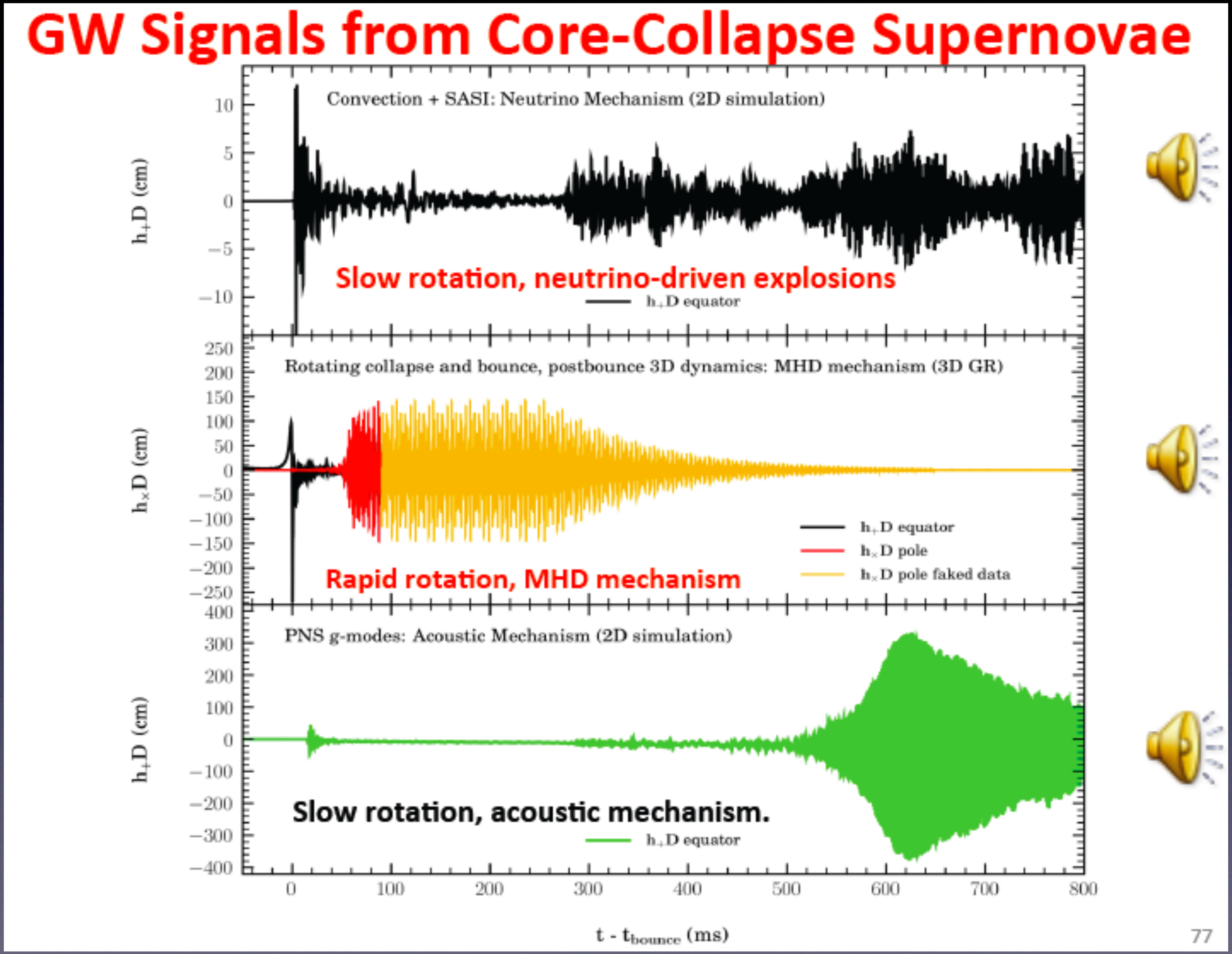
good rule of thumb?

Could GW emission efficiency be frequency dependent?

2015 AdLIGO
2 detectors

Ben Farr

Christian Ott (priv. communication)



GW Signals from Core-Collapse Supernovae

Convection + SASI: Neutrino Mechanism (2D simulation)

Slow rotation, neutrino-driven explosions

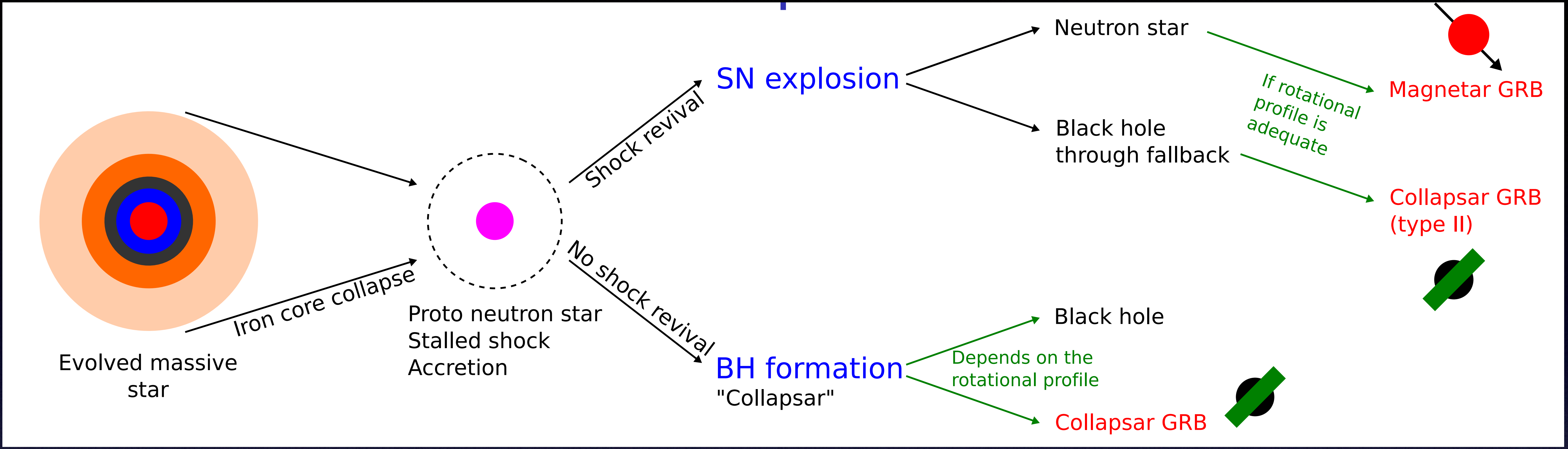
Rotating collapse and bounce, postbounce 3D dynamics: MHD mechanism (3D GR)

Rapid rotation, MHD mechanism

PNS g-modes: Acoustic Mechanism (2D simulation)

Slow rotation, acoustic mechanism.

Christian Ott (priv. communication)



Evolved massive star

Iron core collapse

Proto neutron star
Stalled shock
Accretion

Shock revival

No shock revival

SN explosion

Neutron star

Black hole
through fallback

If rotational profile is adequate

Magnetar GRB

Collapsar GRB
(type II)

BH formation
"Collapsar"

Black hole

Depends on the rotational profile

Collapsar GRB

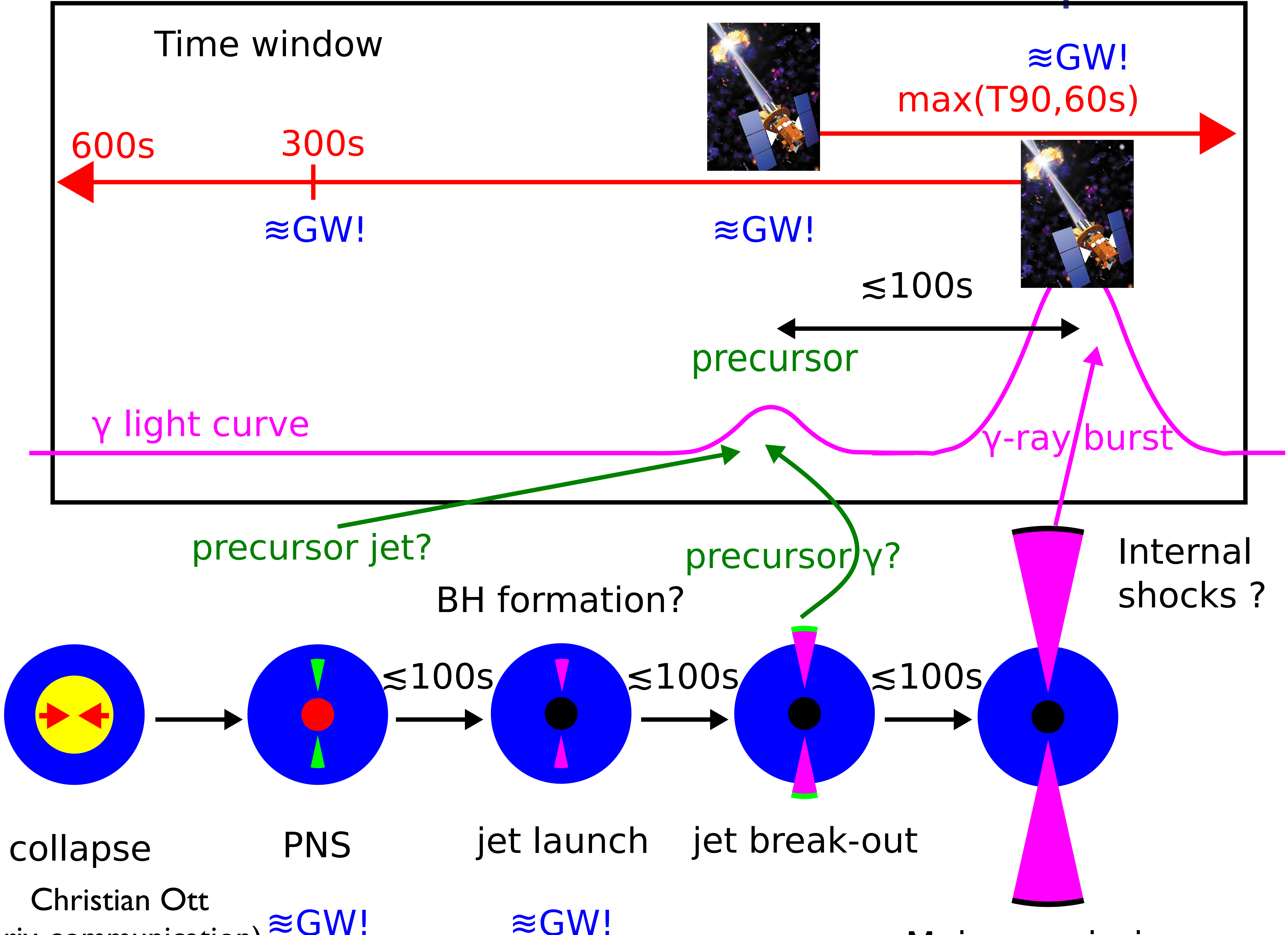
- Magnetar central engine / Proto neutron star
  - bar mode instability in the star (Shibata et al., 2003)
  - neutron star core fragmentation (Davies et al., 2002; Kobayashi and Mészáros, 2003)
- Black hole and accretion disk
  - Disk fragmentation (Piro and Pfahl, 2007)
  - Disk precession (Romero et al., 2010)

⇒ circular polarization along rotation axis

⇒ Emitted GW energy $\lesssim 10^{-2} M_\odot c^2$

- Other emission mechanism but no prospects for extra-galactic reach
  - Out of frequency band (Neutrino, normal modes, ...)
  - Too small amplitude (Core bounce, SASI, ...)

GW vs GRB time of arrival - stellar collapse



Time window

≋GW!

max(T90,60s)

600s

300s

≋GW!

≋GW!

≲100s

precursor

γ light curve

γ-ray burst

precursor jet?

precursor γ?

BH formation?

Internal shocks ?

≲100s

≲100s

≲100s

collapse

PNS

jet launch

jet break-out

Main γ emission

≋GW!

≋GW!

Christian Ott
(priv. communication)