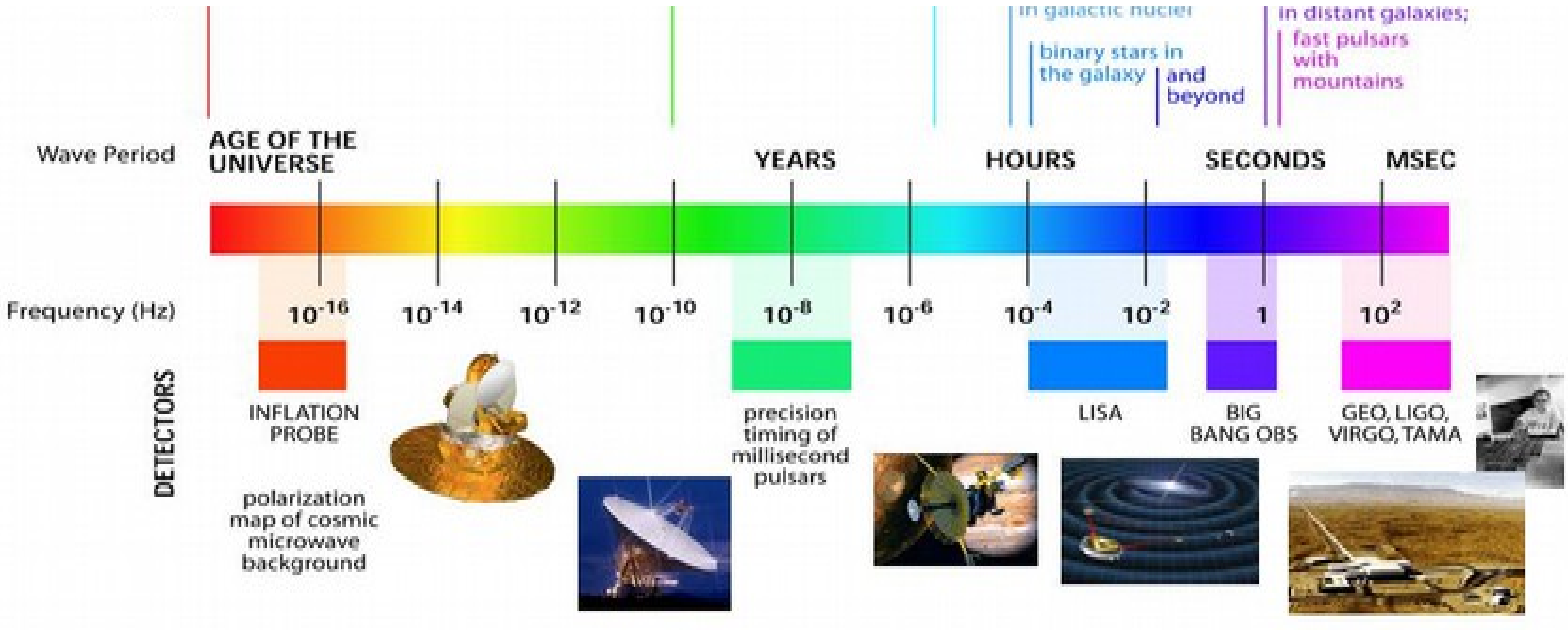
Outline

- **LIGO and Virgo detectors**
  - Brief introduction and current status
    (will hear much more with David Schoemaker's presentation)
  - Searching for GW transients
- **GW and multimessenger astrophysics**
  - **Why?** Scientific motivations
    - Connection to Gamma-ray bursts
  - **How?** Coordination for joint observations
    - Externally triggered GW searches
    - Electromagnetic follow-up of GW events




Gravitational wave spectrum



European Pulsar Timing Array

Pulsar Timing

nHz

eLISA & LISA Pathfinder

Space-based interferometers

mHz

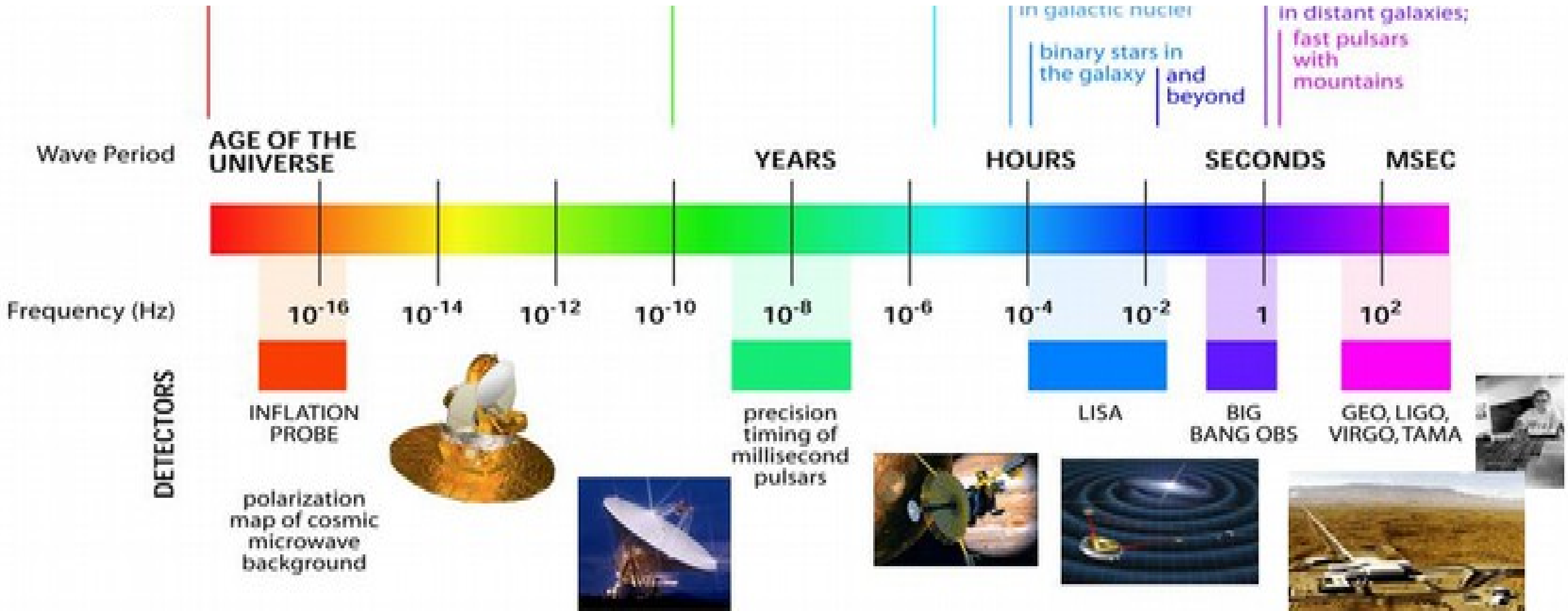
Advanced Virgo/LIGO

Ground-based interferometers

100 Hz

$10^6 M_\odot$

Gravitational wave spectrum



Size of the source

$$R \sim 2GM/c^2$$

sets the scale over which
the source's dynamics varies

$$f_{GW} \propto \sqrt{GM/R^3}$$

$$M = \frac{1}{4\sqrt{2}\pi} \frac{c^3}{G f_{GW}}$$

European Pulsar Timing Array

nHz

$10^{12} M_\odot$
Super-massive black-holes (high-end)

eLISA & LISA Pathfinder

mHz

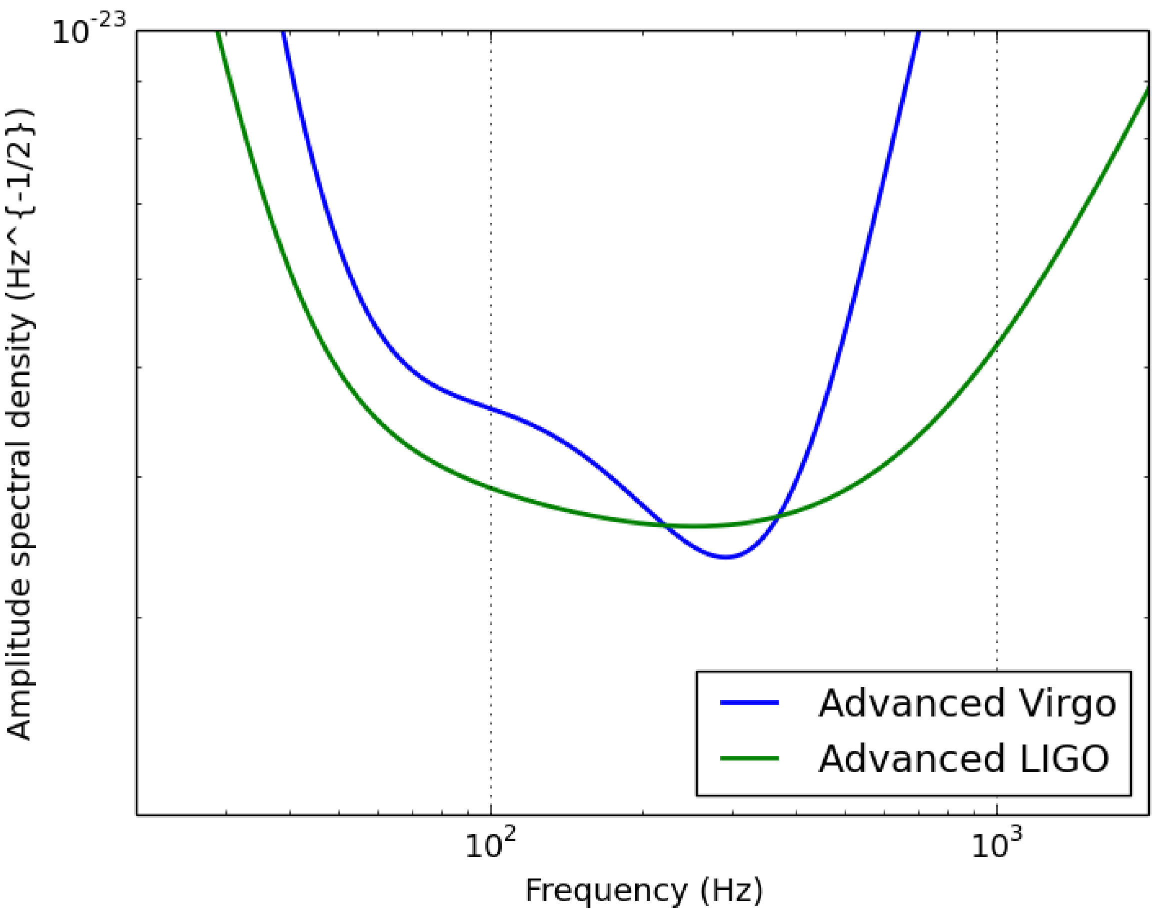
$10^6 M_\odot$
Super-massive black-holes (low-end)

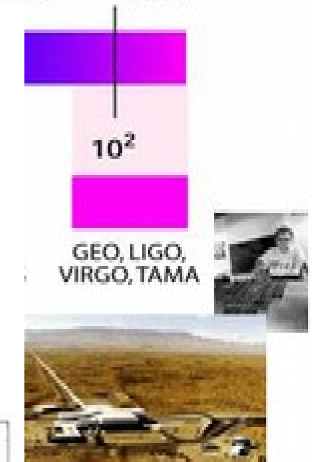
Advanced Virgo/LIGO

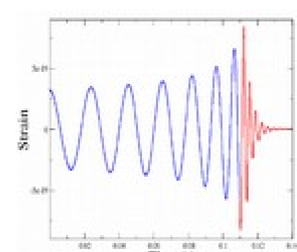
100 Hz

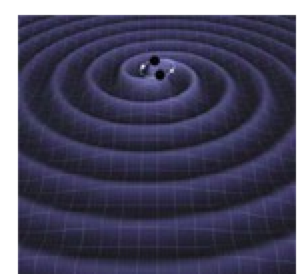
Stellar-mass
Black-holes and neutron stars

Gravitational wave spectrum







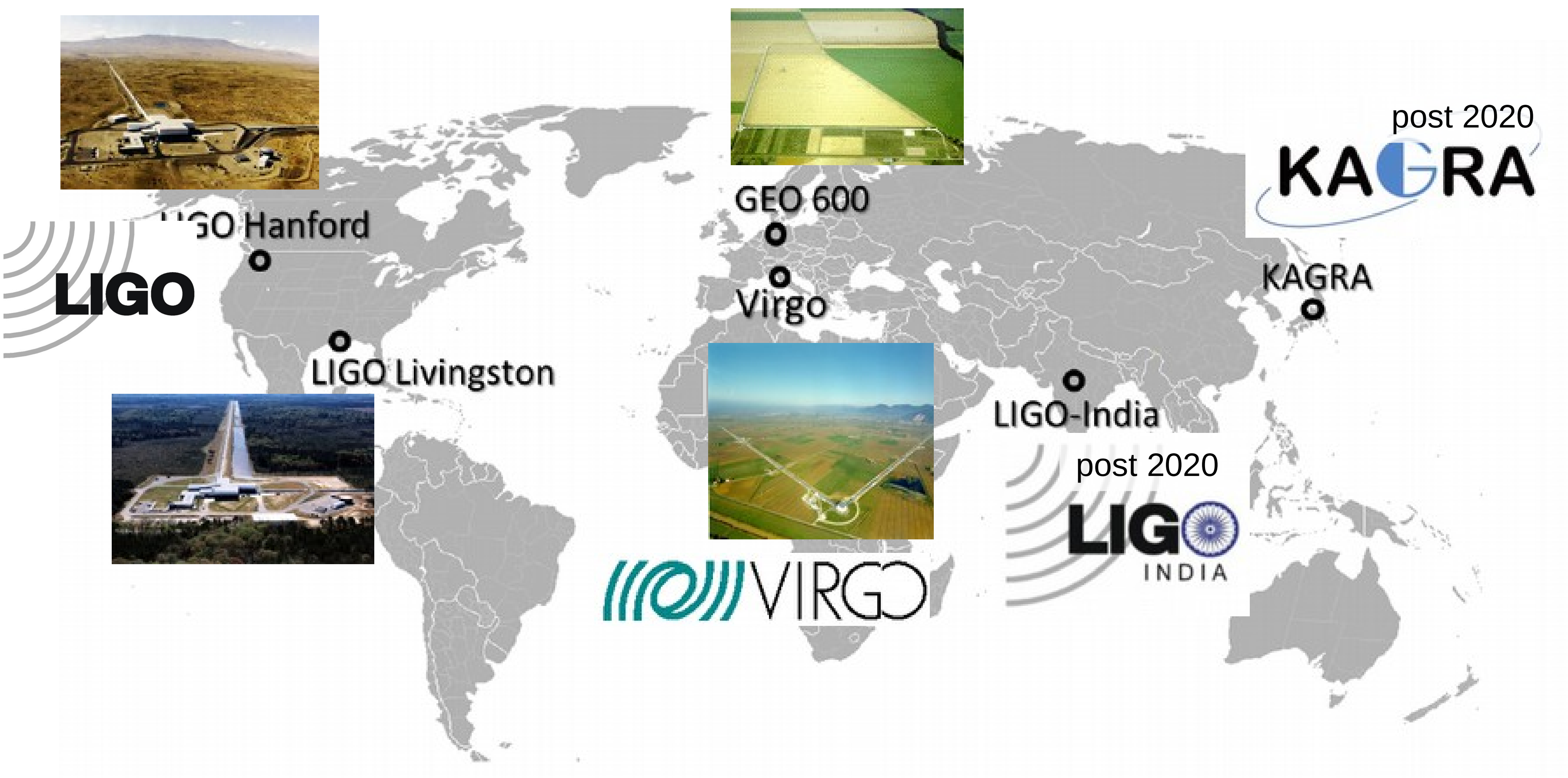


Advanced Virgo/LIGO

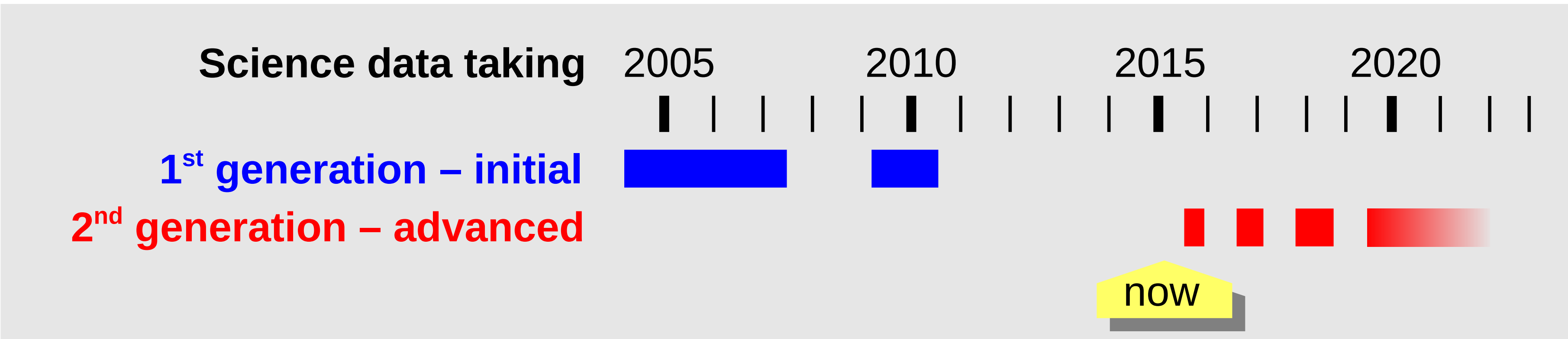
100 Hz

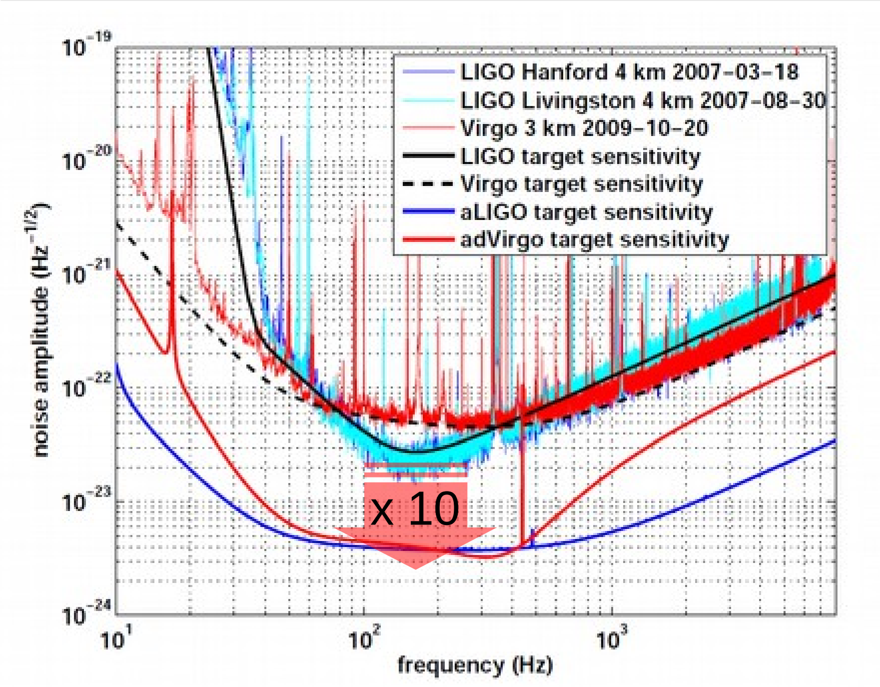
Stellar-mass
Black-holes and neutron stars

GW detectors in the world



GW detectors: status and timeline





1^{st} generation – initial

3 joint LIGO – Virgo science runs
~2 yrs total, target sensitivity reached
40 papers on transient & continuous sources

horizon = detection distance to coalescing binaries of neutron stars

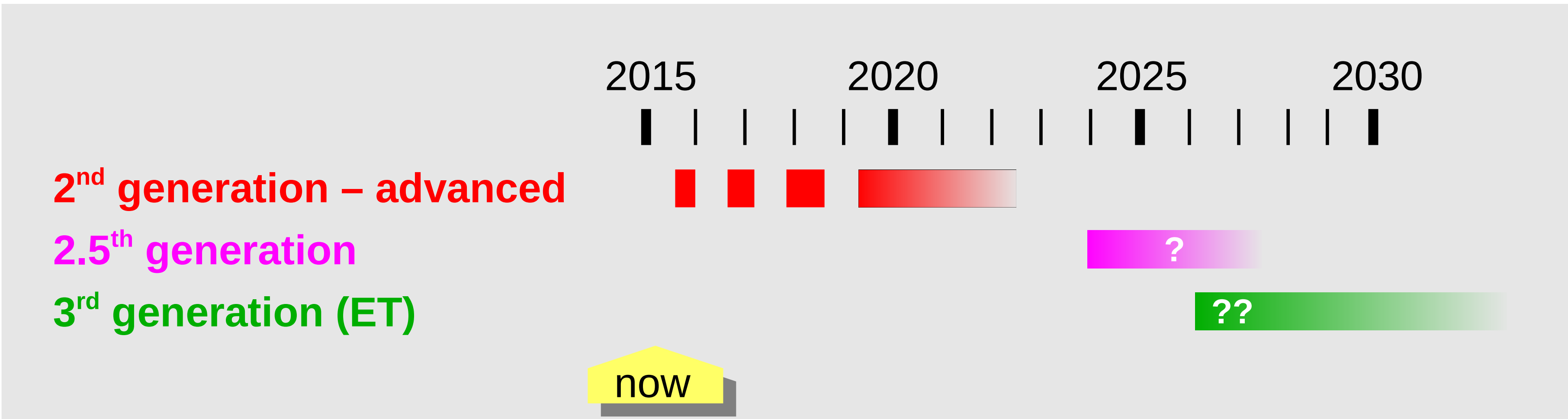
Initial: LIGO ~ 40 Mpc Virgo ~ 20 Mpc

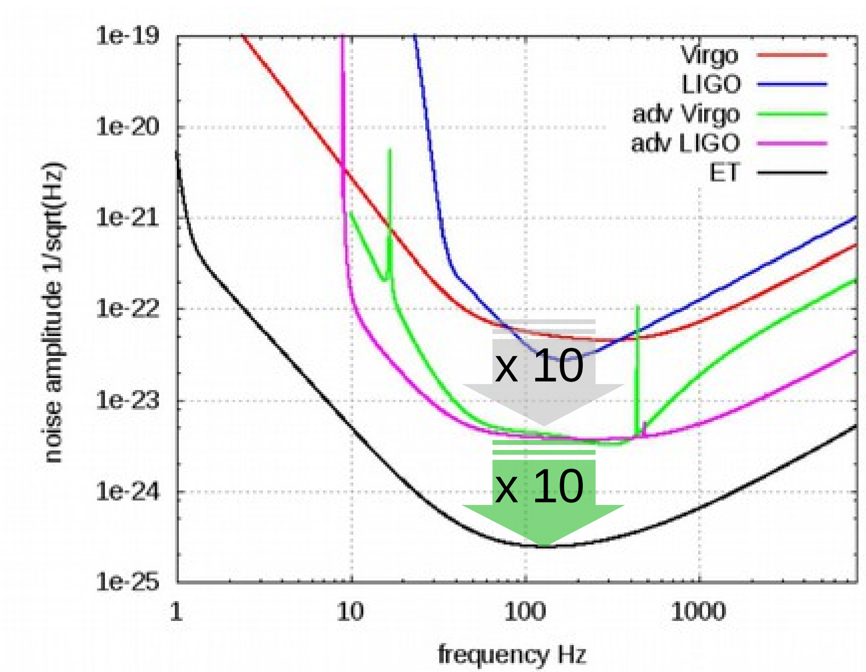
2^{nd} generation – advanced

Improvement x 10 – # of events x 1000

Adv: LIGO ~ 450 Mpc Virgo ~ 320 Mpc

Future GW detectors





2.5th generation – "enhanced"

Same infrastructure as 2nd generation
Improvement x 3 – # of events x 30

BNS 1.4 x 1.4 M_{sun}: 600 Mpc, z~.15

NS-BH 1.4 x 10 M_{sun}: 1.2 Gpc, z~.25

3rd generation (Einstein Telescope)

FP7 concept study
New infrastructure (underground, long arms)
Improvement x 10 – # of events x 1000

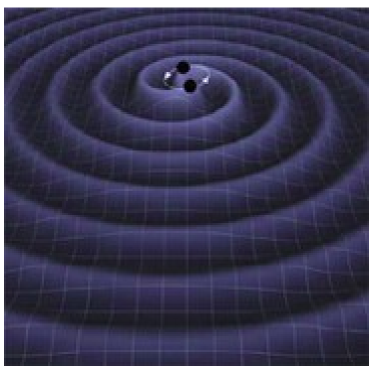
BNS 1.4 x 1.4 M_{sun}: 2 Gpc, z~.4

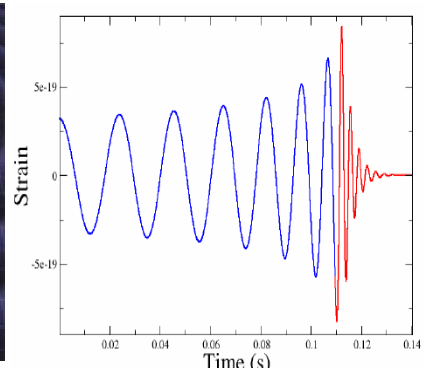
NS-BH 1.4 x 10 M_{sun}: 4 Gpc, z~.6

Searches for GW transient sources

Searches for GW transient sources

- **GW data streams are analyzed jointly**
  - Initially LIGO Hanford+Livingston and Virgo; later others too
- **Two main types** of transient searches



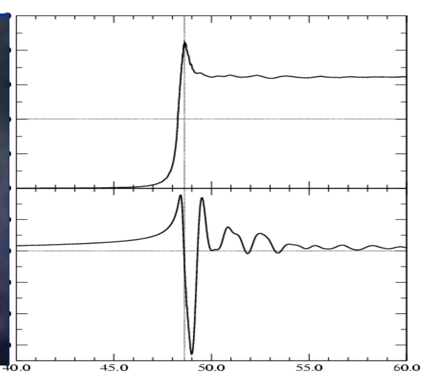


Compact Binary Coalescence (CBC)

Known waveform → **Matched filtering**

Require **consistency with waveform morphology**

Correlation with templates for a range of component masses and spins



Unmodelled GW Burst $\lesssim$ 10 sec duration

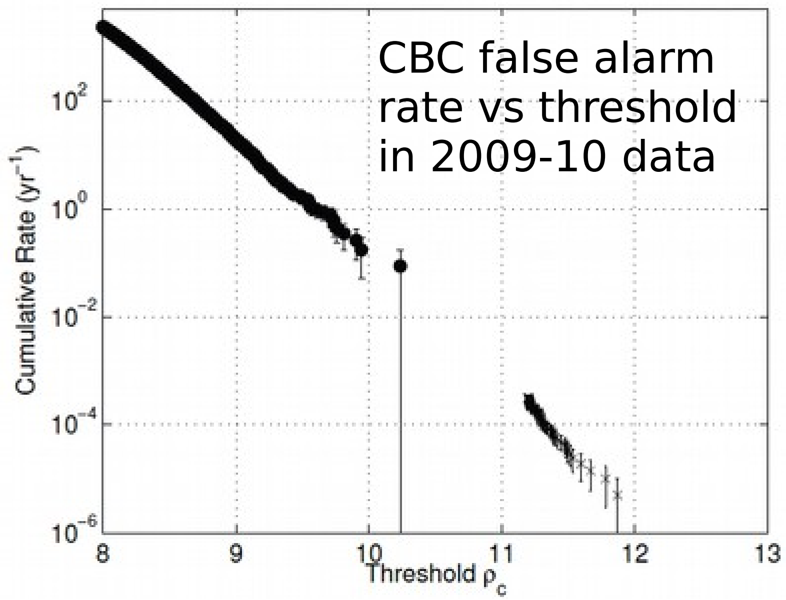
Arbitrary waveform → **Excess power**

Excess power in time-frequency representation.

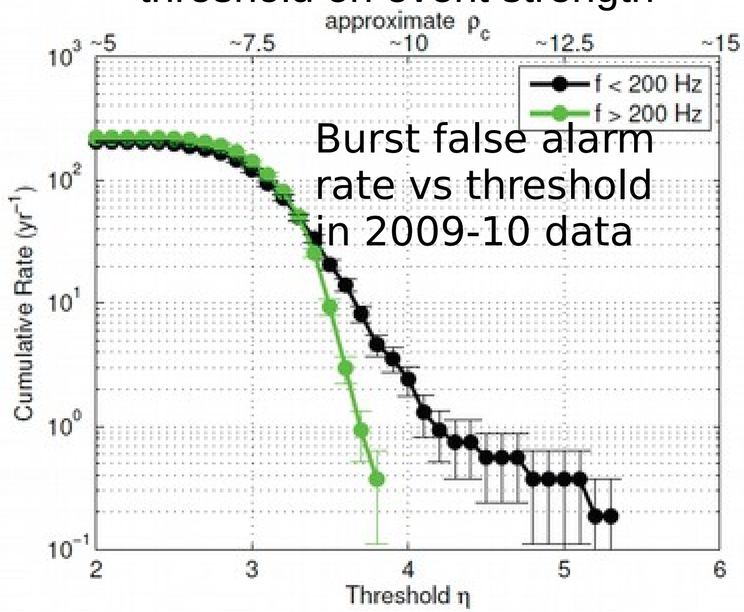
Require **coherent signals** in detectors

Event strength characterized by detection statistics ρ (scale as SNR) obtained from data

Background estimation and significance



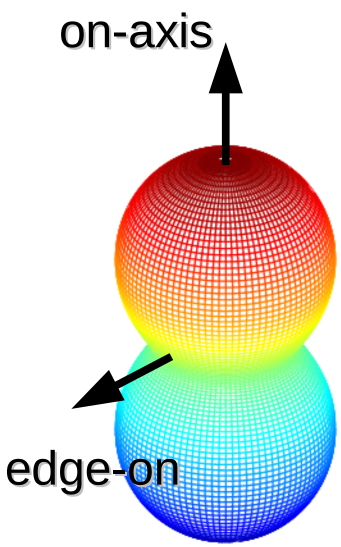
threshold on event strength



- Real noise is **non-Gaussian**
  - "**Glitches**" limit sensitivity
  - Data quality is crucial
    - ✔ Exclude events from known bad times
  - Cannot be modeled accurately
- Estimate **false alarm rate** = *rate of as loud background trigger*
  - **Time slide experiments**: time-shift data streams with **non-physical delays** and repeat analysis
  - **CBC**: thank to consistency tests, the background rate falls rapidly
  - **Bursts**: noise artifacts have a greater impact, especially at lower freq.

GW and multimessenger astrophysics

GW and multimessenger astrophysics



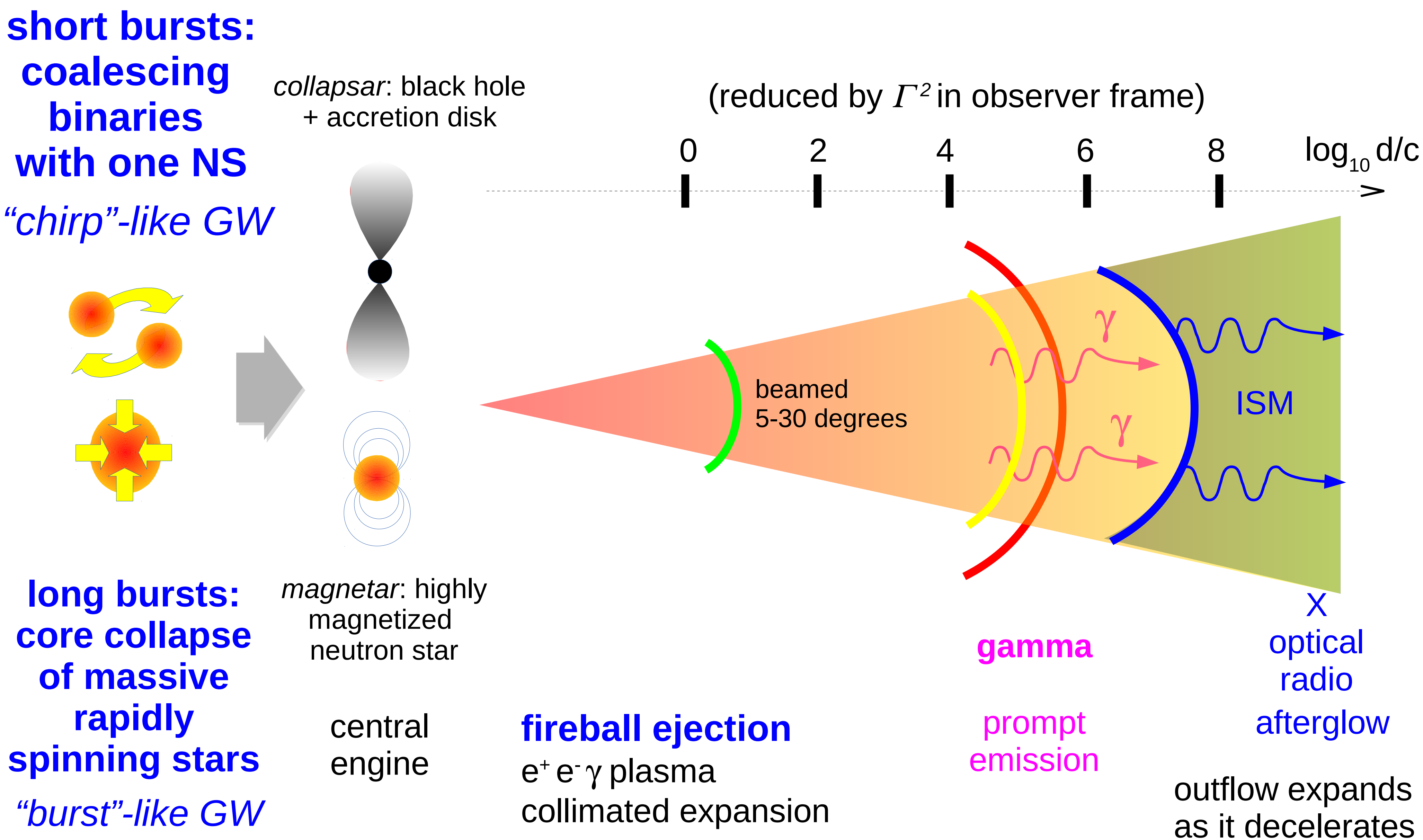
- **GW transient sources** are **highly energetic** astrophysical events and must be **relatively close** to be detected by LIGO and Virgo
  - GW emission is **weakly beamed**
- They will likely release **other types of radiations** (electromagnetic and neutrinos)

Order-of-magnitude estimate – back of the envelop

1% of rest mass released in GW during a stellar-mass merger
Assume 1% of this amount is released into EM radiation
in **few seconds**
over the **entire EM spectrum** up to γ-rays (3 x 10^{20} Hz, MeV)
if source at 100 Mpc, **flux density at Earth is 50 mJy, 12 mag_{AB}**

BUT source is very dense (opaque to EM).

Gamma-ray bursts

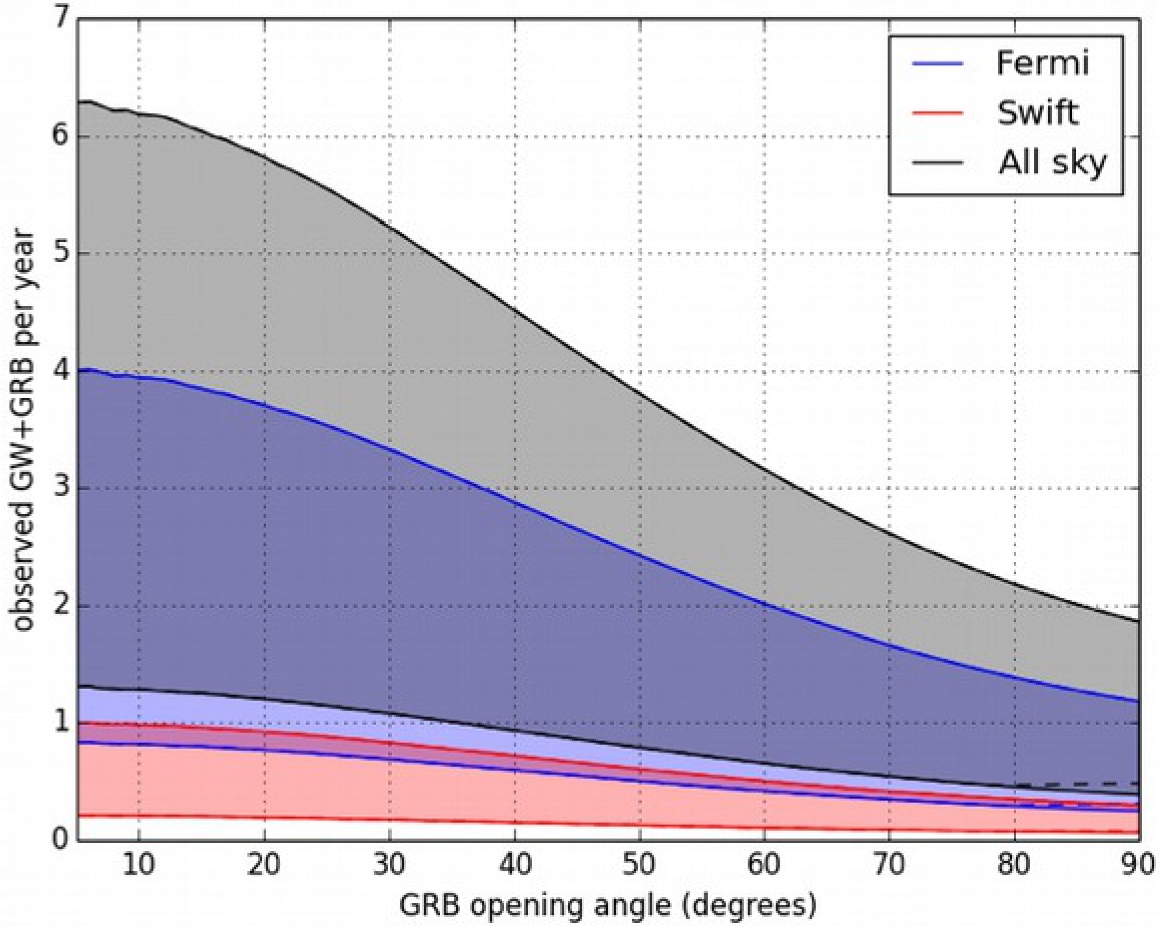


GW observability of short GRBs

- Best candidate for joint GW-EM observation
- Population of short GRBs
  - Current: Fermi/GBM, Swift/BAT, IPN
    Future mission: SVOM (China/France) 2021
  - *~50* short GRB/yr, *<z> ~ 0.5*
  - Uncertain beaming: jet opening angle ~10 degrees?
  - Rate ~ *8-30 /Gpc^3/yr* [Guetta & Piran, 2006]
- Prospect for joint EM-GW observation
  - GRB080905A, z=0.12 D~550 Mpc [Clark et al., 1409.8149]

    NS-NS: SNR=7.7 (FAR 1%). NS-BH: detected

GW observability of short GRBs



Few events/yr in LIGO/Virgo horizon distance

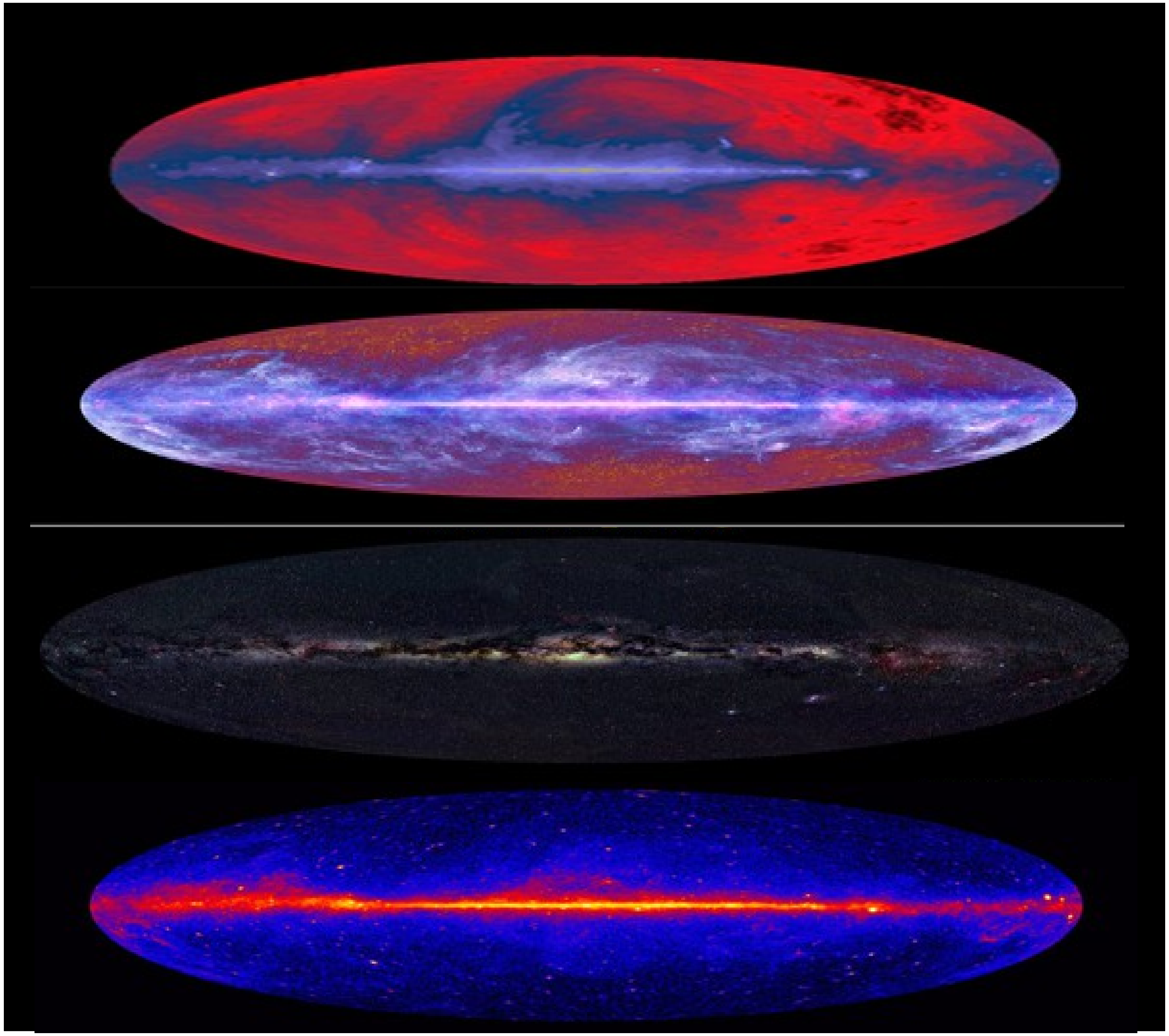
Clark et al., 1409.8149

Motivations for multimessenger astrophysics

- Confirm the **astrophysical nature** of the observed GW event
- Allow **deeper searches** for weak GW signals
- Get a **more complete picture** of the source
  - Follow the successes of **multiwavelength astrophysics ♦**
  - **GW: bulk motion** – global source dynamics
  - **EM:** thermal emission at the surface, particule acceleration
  - **Neutrino**: radioactive decay, hadron acceleration
- **Better constraints** on the source physics
  - Assess source energetics – what are the driving physical processes?

Coordinated observations are required

Multiwavelength astrophysics



Radio
charge/plasma oscillation
Interstellar medium – cold gas

Micro-wave
plasma oscil./molecule rotation
Interstellar medium – dust

Infra-red/Visible
Molecular electron excitation
Surface of stars

X-rays/Gamma-rays
Radioactive decay, pair production
Supernova, BH accretion

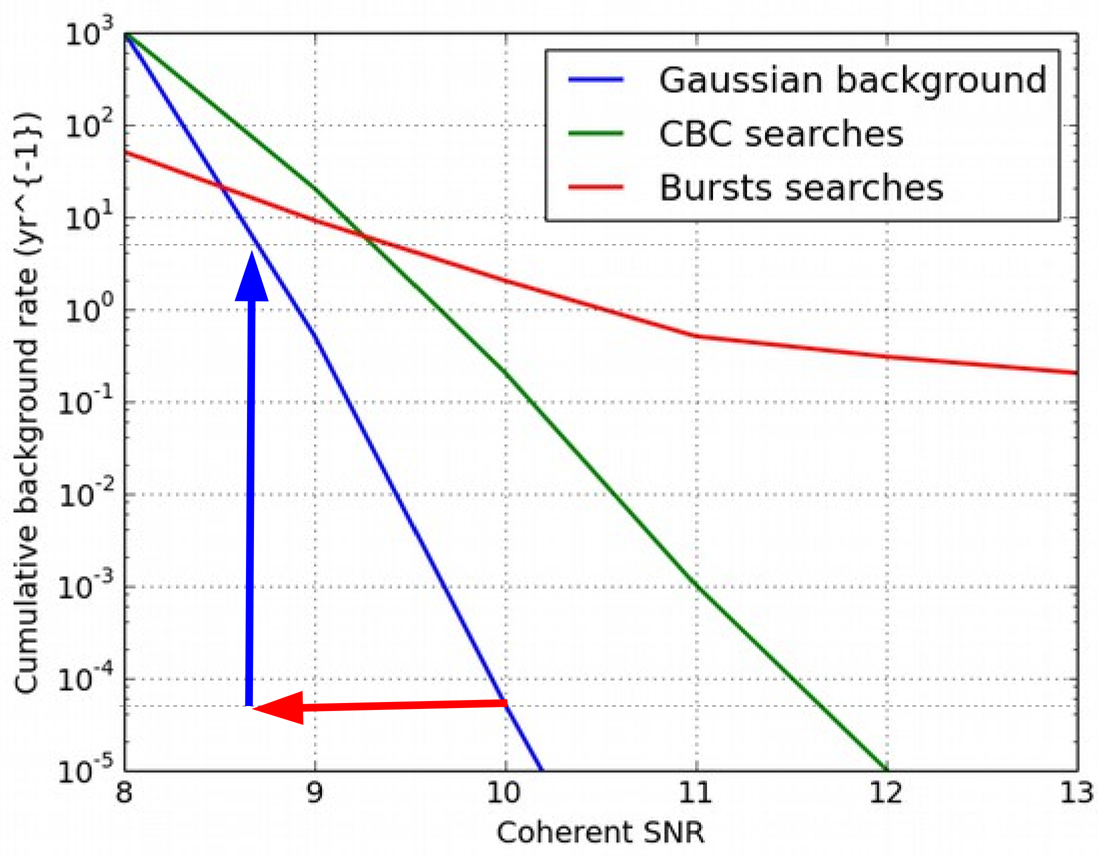
Physics corresponding to emitted frequency in the source frame
Can be redshifted in observer frame – cosmology or relativistic jet

Different strategies for joint observations (1)

- Deep GW searches **triggered by astrophysical alerts**
  - e.g., process all GCN & SNEWS notices with few days latency
- **Electromagnetic follow-up** of GW alerts
  - e.g., seek a counterpart (for ex., GRB afterglow)
- Off-line joint **coincidence with other astrophysical events** (possibly sub-threshold)
  - e.g., high-energy neutrinos

Deep targeted GW searches (1)

- Astrophysical trigger provides time and direction
  - **reduction of the search parameter space** → gain in sensitivity



Event localized in a time window of **few minutes** during a science run of **few months**

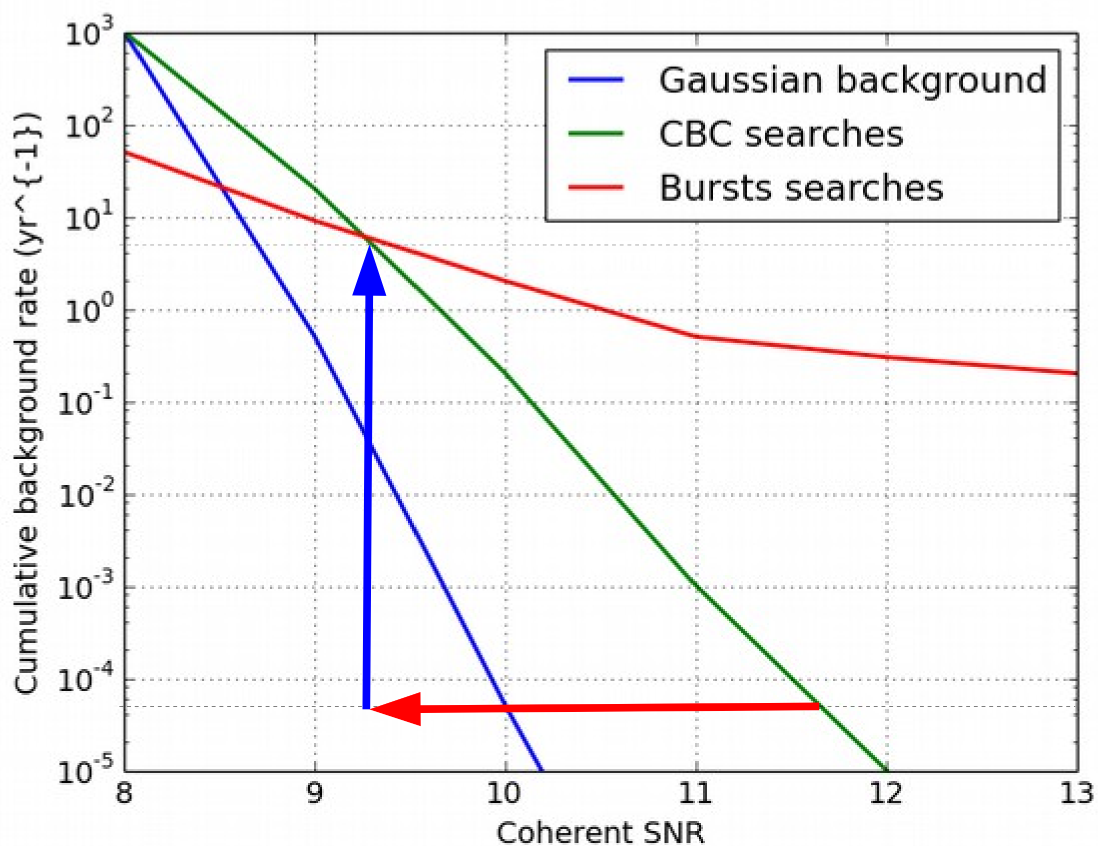
Reduction ~ 10^{-5}

Sensitivity gain: 15 % (amplitude)
50 % (volume)

M Was et al, 2013

Deep targeted GW searches (2)

- Astrophysical trigger provides time and direction
  - **reduction of the search parameter space** → gain in sensitivity



M Was et al, 2013

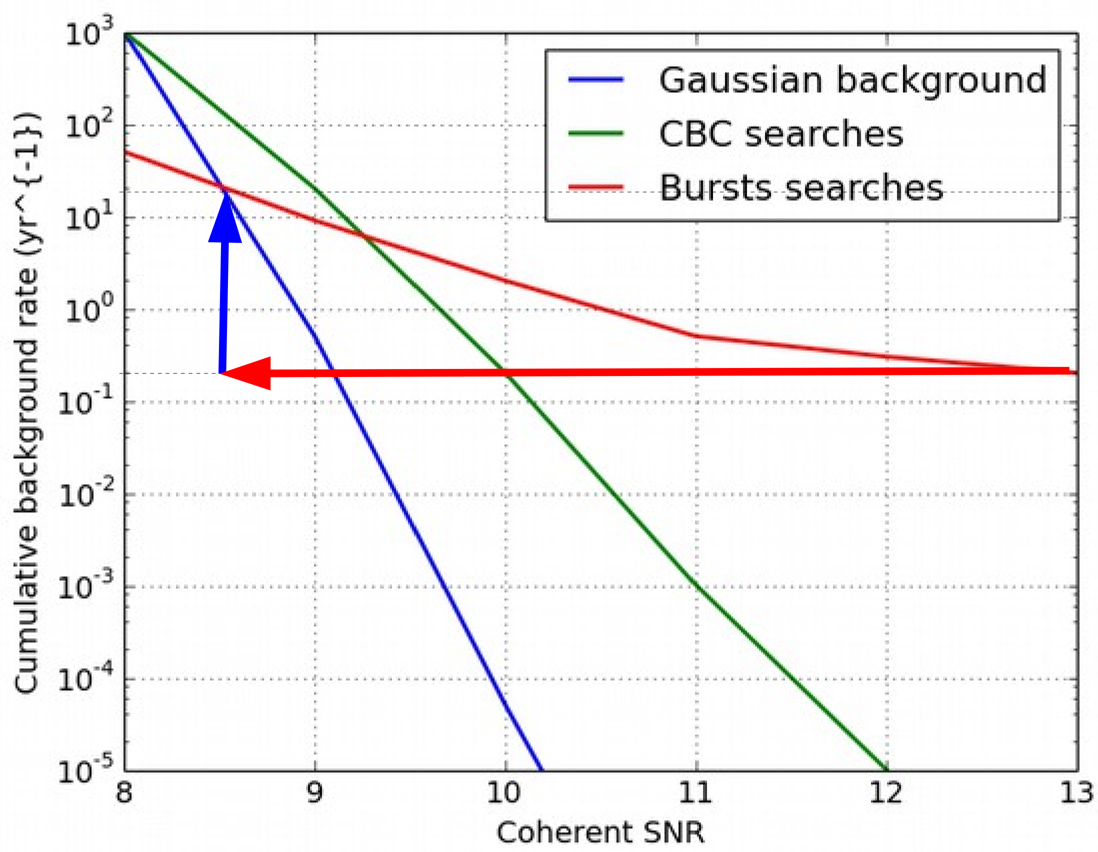
Event localized in a time window of **few minutes** during a science run of **few months**

Reduction ~ 10^{-5}

Sensitivity gain: 20 % (amplitude)
70 % (volume)

Deep targeted GW searches (3)

- Astrophysical trigger provides time and direction
  - **reduction of the search parameter space** → gain in sensitivity



Event localized in a time window of **1 day** during a science run of **few months**

Reduction ~ 10^{-2}

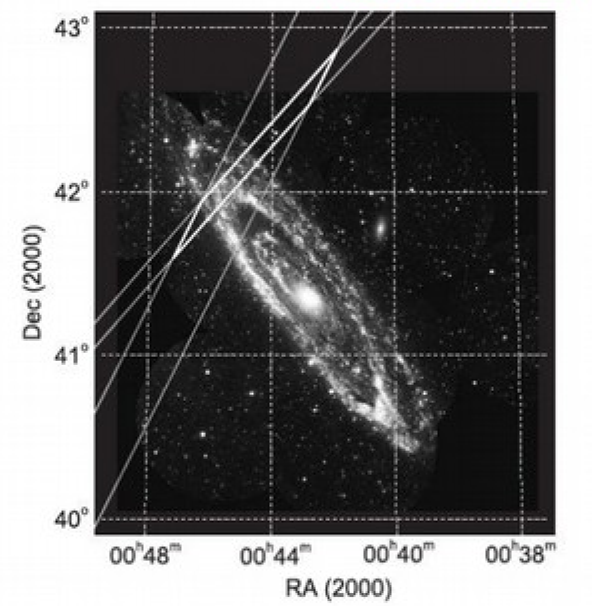
Sensitivity gain: 60 % (amplitude)
x 4 (volume)

M Was et al, 2013

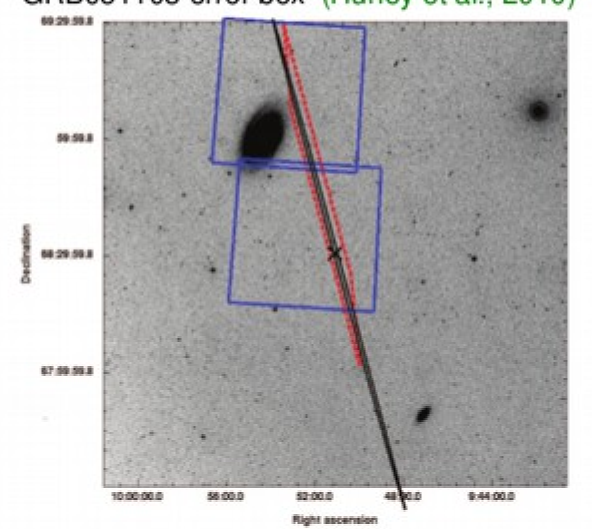
GRB070201 & GRB051103

- Short bursts, potentially close-by
  - GRB070201: error box overlap with **M31 (770 kpc)**
  - GRB051103: error box overlap with **M81 (3.6 Mpc)**
- No GW detection
  - GW data **exclude a local binary coalescence** with high confidence
- Data compatible with
  - Giant flare from Soft Gamma Repeater in M31/M81
  - Binary coalescence behind M31/M81

GRB070201 error box (Mazets et al., 2008)



GRB051103 error box (Hurley et al., 2010)



Different strategies for joint observations (2)

- Deep GW searches **triggered by astrophysical alerts**
  - e.g., process all GCN & SNEWS notices with few days latency
- **Electromagnetic follow-up** of GW alerts
  - e.g., seek a counterpart (for ex., GRB afterglow)
- Off-line joint **coincidence with other astrophysical events** (possibly sub-threshold)
  - e.g., high-energy neutrinos

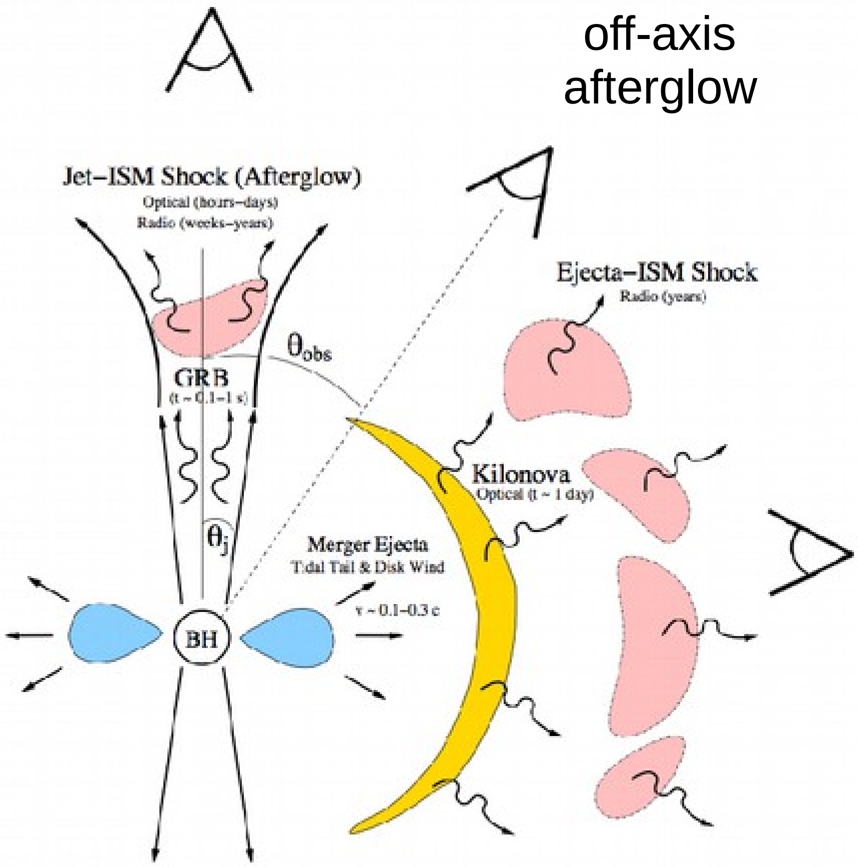
Potential EM counterparts to GW

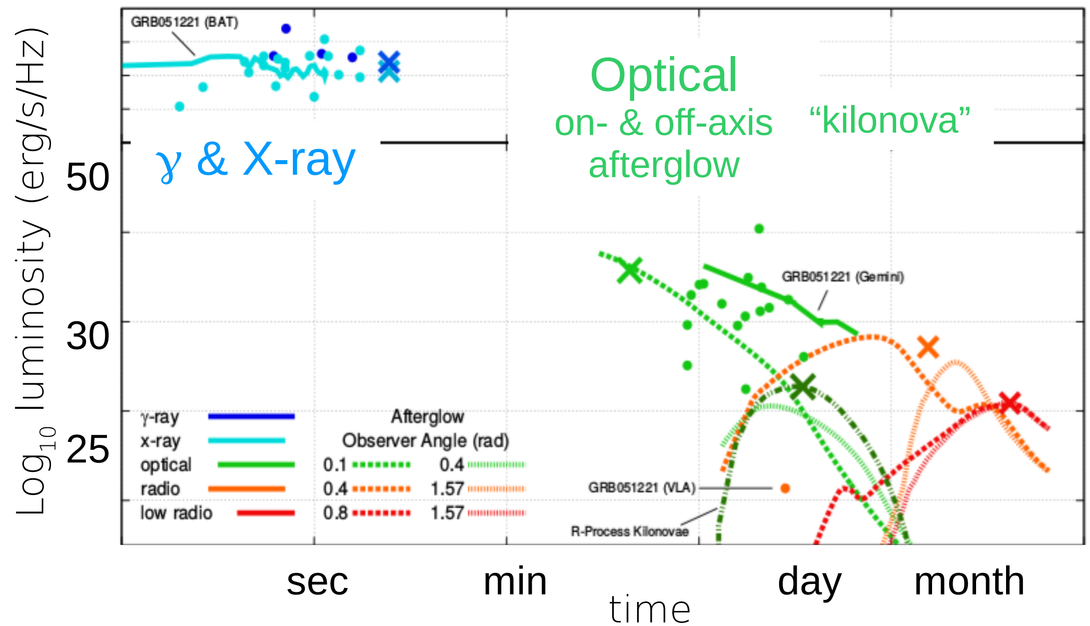
Example of short hard burst

Prompt burst & on-axis afterglow

Bright but beamed

off-axis afterglow





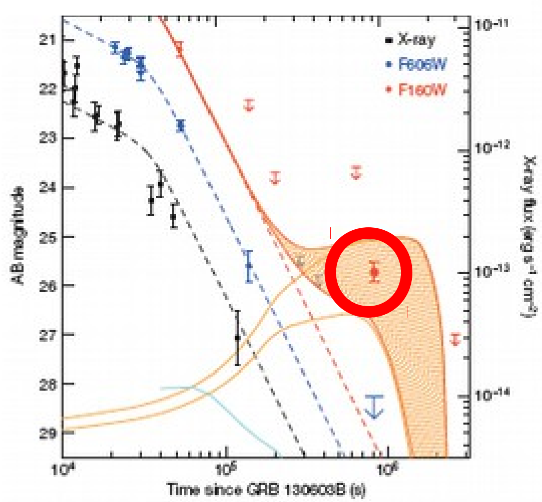
"kilonova"

Isotropic but dim

Optical transient due to **decay of heavy elements in ejecta (r-process)**

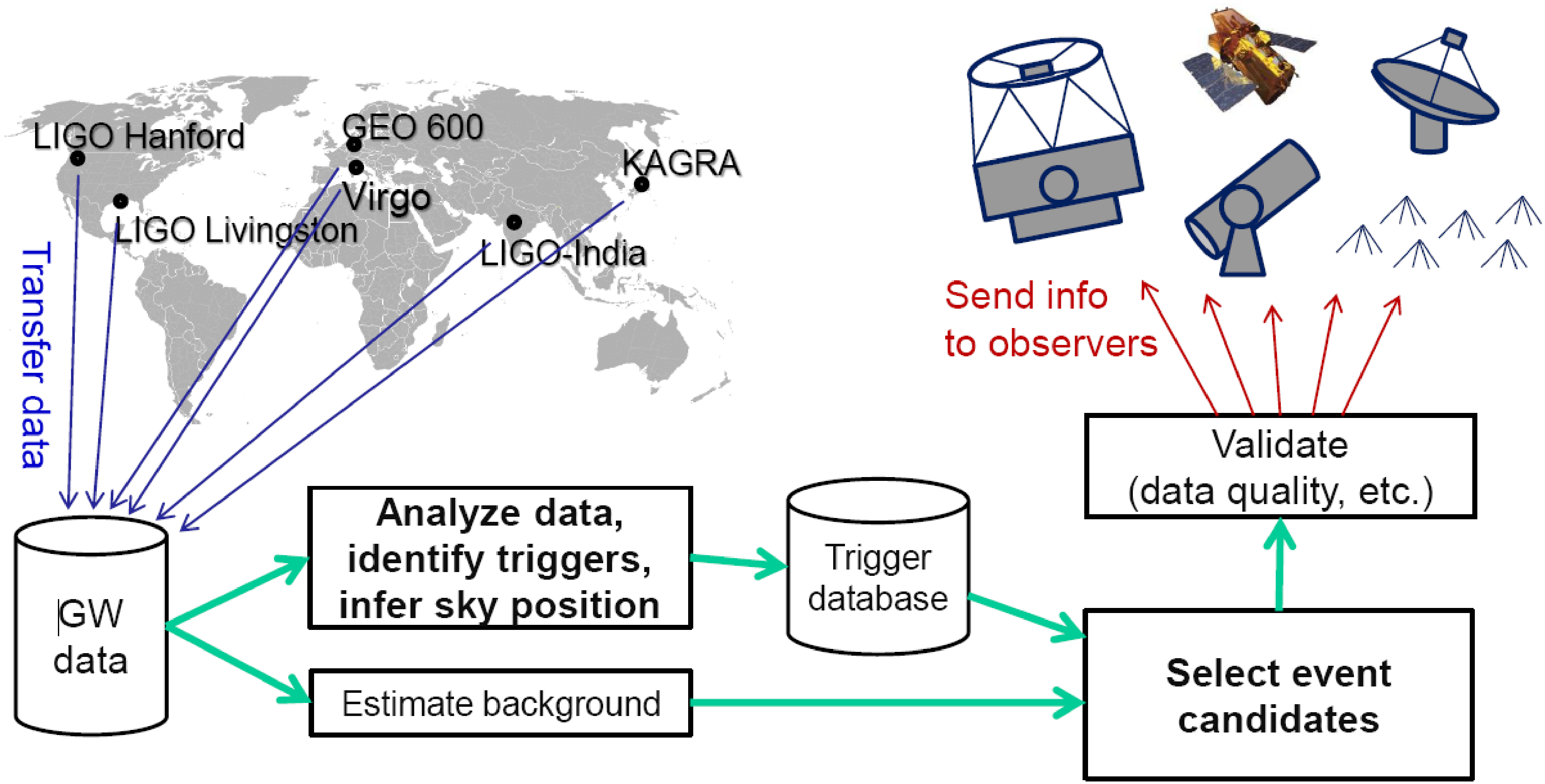
May be important sites for the **production of heavy elements**

1st candidate? GRB130603B



Courtesy of B. Metzger and Kelley et al, arXiv:1209.3027

LIGO-Virgo GW alert system

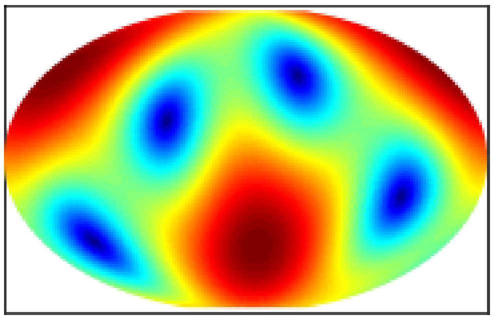


Identify significant transients worth following up

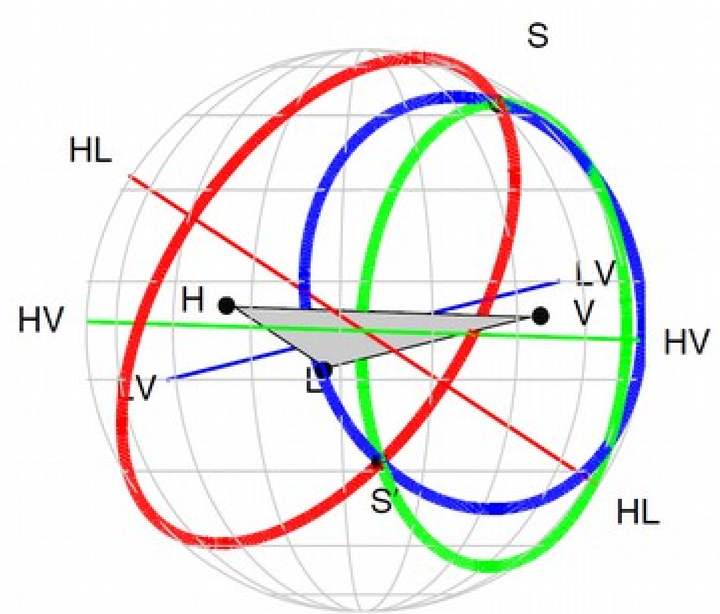
Distribute alerts to observing partners within 5-10 mins

Source direction reconstruction

Antenna beam pattern
Virgo



$$(F_+^2 + F_\times^2)^{1/2}$$

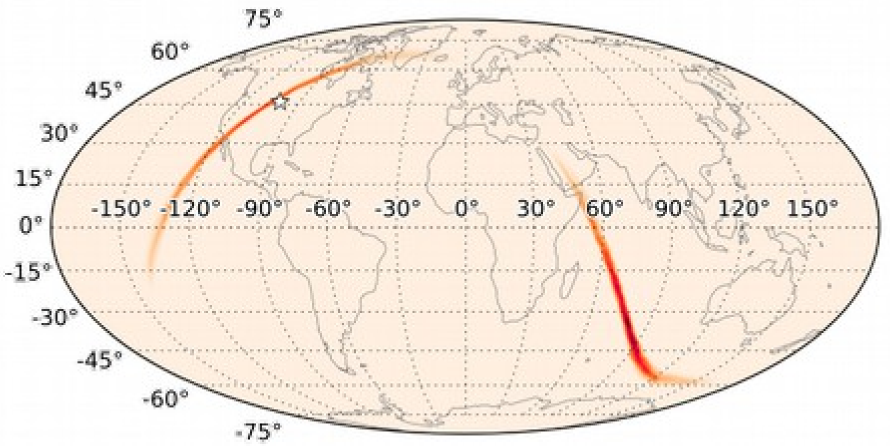


- Each detector have a broad antenna beam pattern (**non directional**)
- Basic localization principle: **triangulation from times of flight**
  - Two detectors localize to a ring in the sky
  - Three detectors to two points, etc.
  - Leading order approx.: gives a rule of thumb for localization accuracy but it is pessimitic
- Amplitude & phase measured at each detector allow **coherent analysis**
  - **Posterior probability skymap** from Bayesian full-scale parameter estimation obtained within hours
  - **Fast reconstruction from simplified model within minutes**

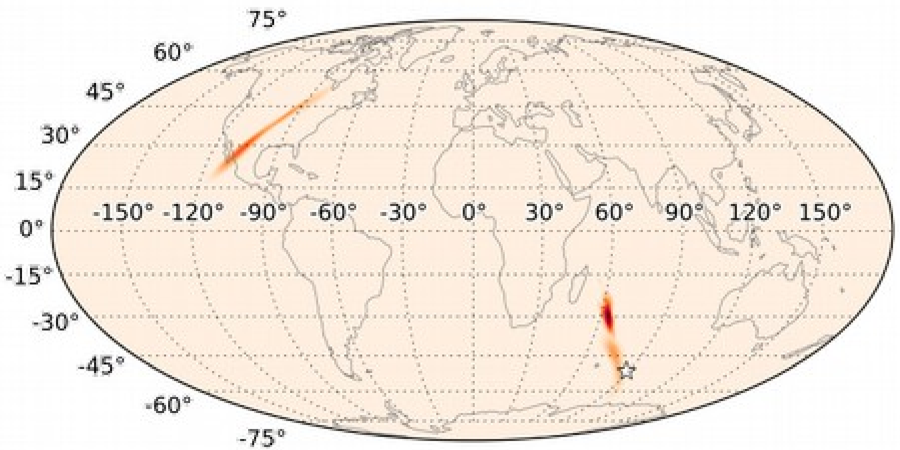
Error on sky localization

- **Reconstructed sky regions are large**!
  - Assuming pretty loud event with SNR = 12, FAR ~ 10^{-2} /yr
  - Credible region at 90 % level is **500 square degrees with 2 LIGO**
  - Reduces to **200 square degrees with Virgo**
  - **Multi-modal** posterior distribution ("banana" islands)
  - Coverage of GW error box is **challenging**!

LIGO-only 2015

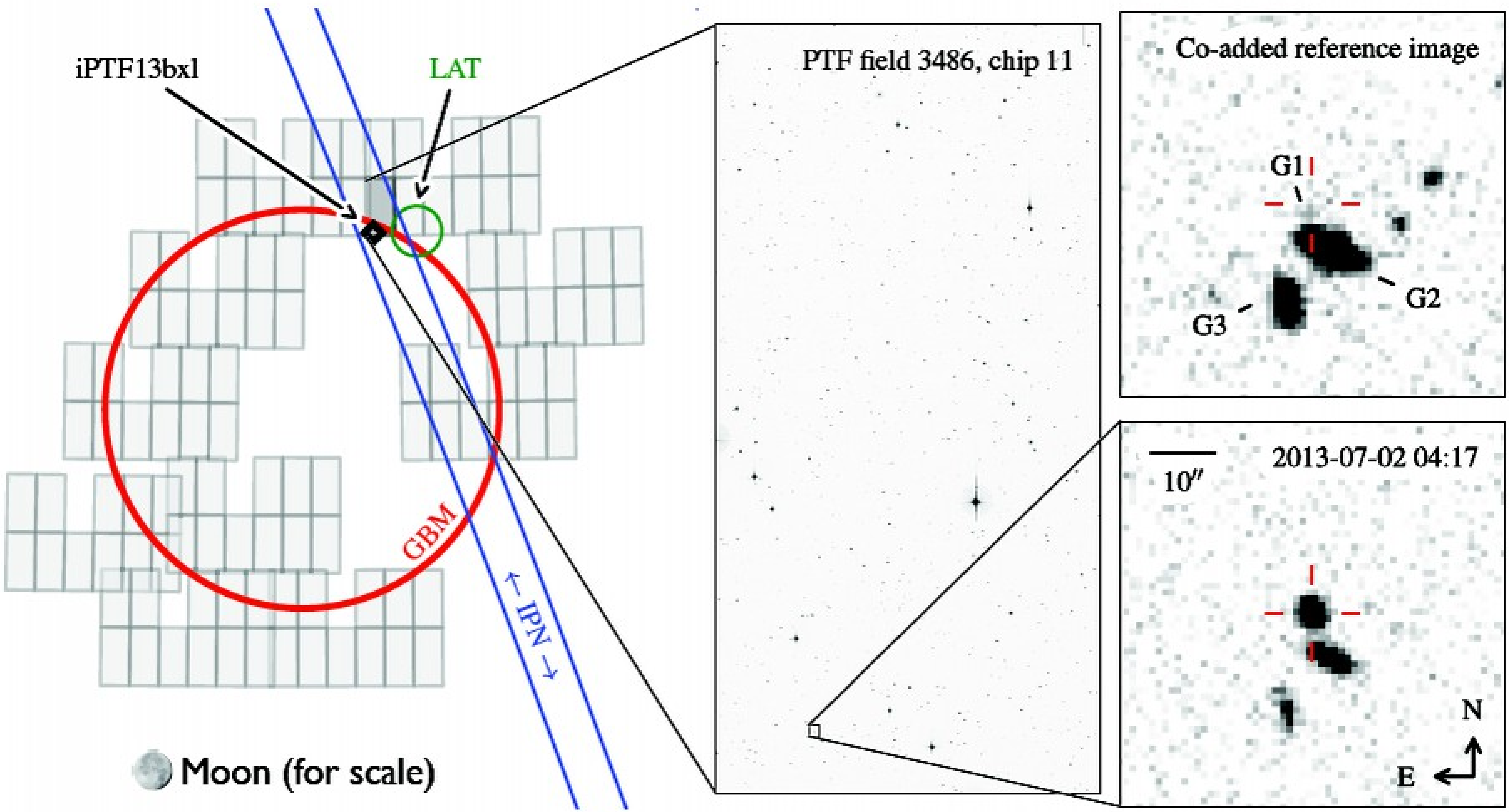


LIGO-Virgo 2016-17



Singer et al., ApJ795, 105 (2014) arXiv:1404.5623 http://www.ligo.org/scientists/first2years

Discovery & redshift of a GBM GRB in 71 deg^2



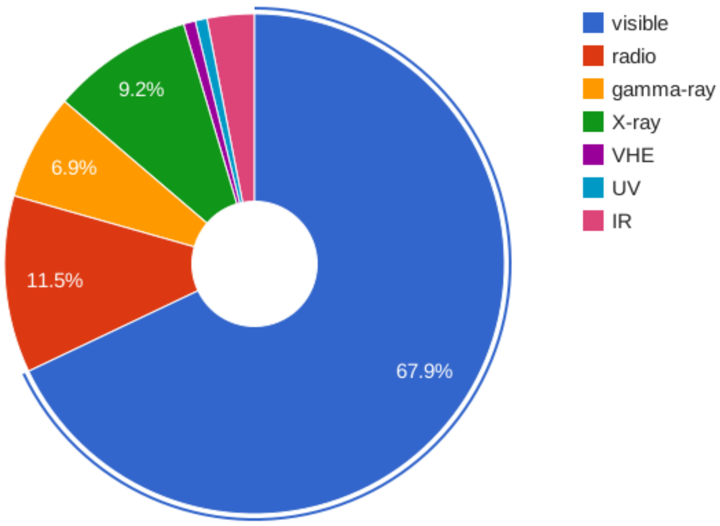
=SN2013dx

Singer et al.(2013, 2013, ApJL 776:34)

http://dx.doi.org/10.1088/2041-8205/776/2/L34

LIGO-Virgo EM follow-up program

- Plan for public release **after first 4 detections**
- Two open calls for partnerships for early period
  - Alerts will be sent through **private GCN network**
  - Signed agreements with **70 groups worldwide**
  - ~500 astronomers, 150 instruments, 10 space observatories
  - From radio to gamma-rays



Enabling EM follow-up (1)

GraceDB – Gravitational Wave Candidate Event DB

HOME | SEARCH | CREATE | REPORTS | RSS | LATEST | OPTIONS
AUTHENTICATED AS: ERIC CHASSANDE-MOTTIN

Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	FAR (Hz)	Links	UTC Submitted
G158249		CBC	MBTAOnline		H1,L1	1117621400.2060	1.372e-06	Data	2015-06-06 10:24:49 UTC

Coinc Tables

End Time	1117621400.2060
Total Mass	9.2271
Chirp Mass	3.0849
SNR	13.6718
False Alarm Probability	

Single Inspiral Tables

IFO	L1	H1
Channel		
End Time	1117621400.219121932	1117621400.206010103
Template Duration	None	None
Effective Distance	177.7525	459.68568
COA Phase	-0.2746053	-1.0825006
Mass 1	7.365417	7.365417
Mass 2	1.861673	1.861673
η	0.16105389	0.16105389
F Final	None	None
SNR	12.637432	5.2167654
χ^2	None	None
χ^2 DOF	None	None
spin1z	-0.2383012	-0.2383012
spin2z	0.0005419254	0.0005419254

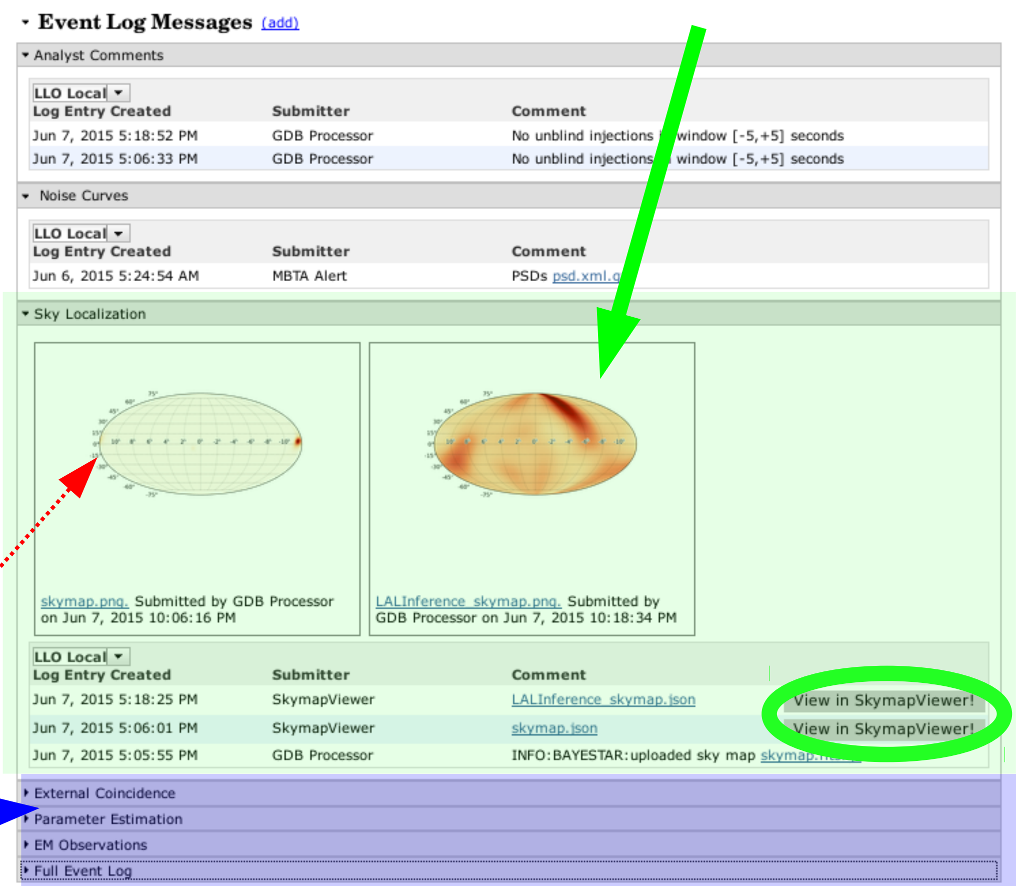
Neighbors [-5,+5]

No neighbors in range.

Low latency analysis
Preliminary alert in 3-5 mins

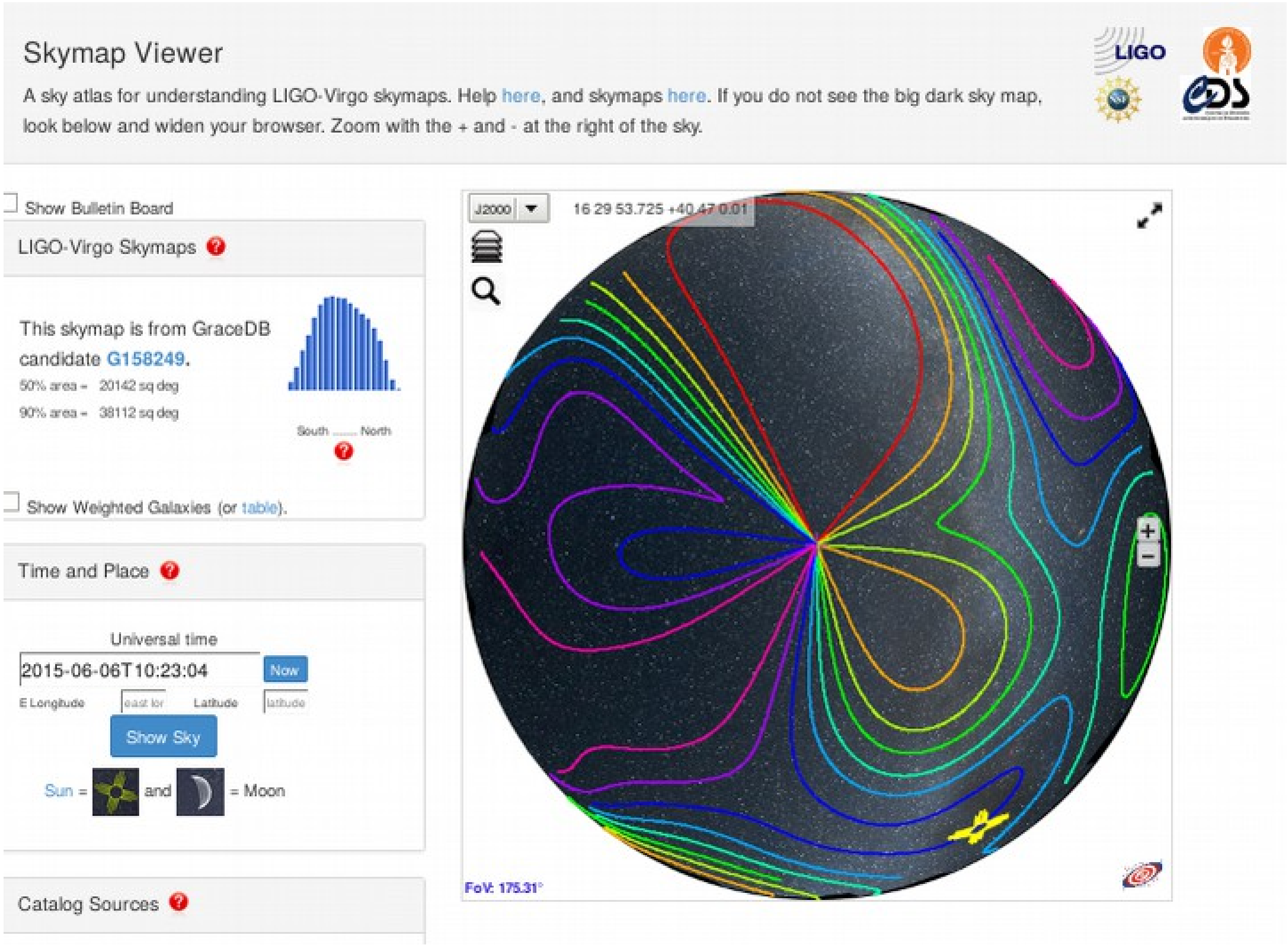
Rapid preliminary sky position
Initial alert issued in 5-10 mins

Detailed analysis: Bayesian parameter estimation
Alert updates or retraction within hours



Coincident astrophysical event or EM follow-up observations

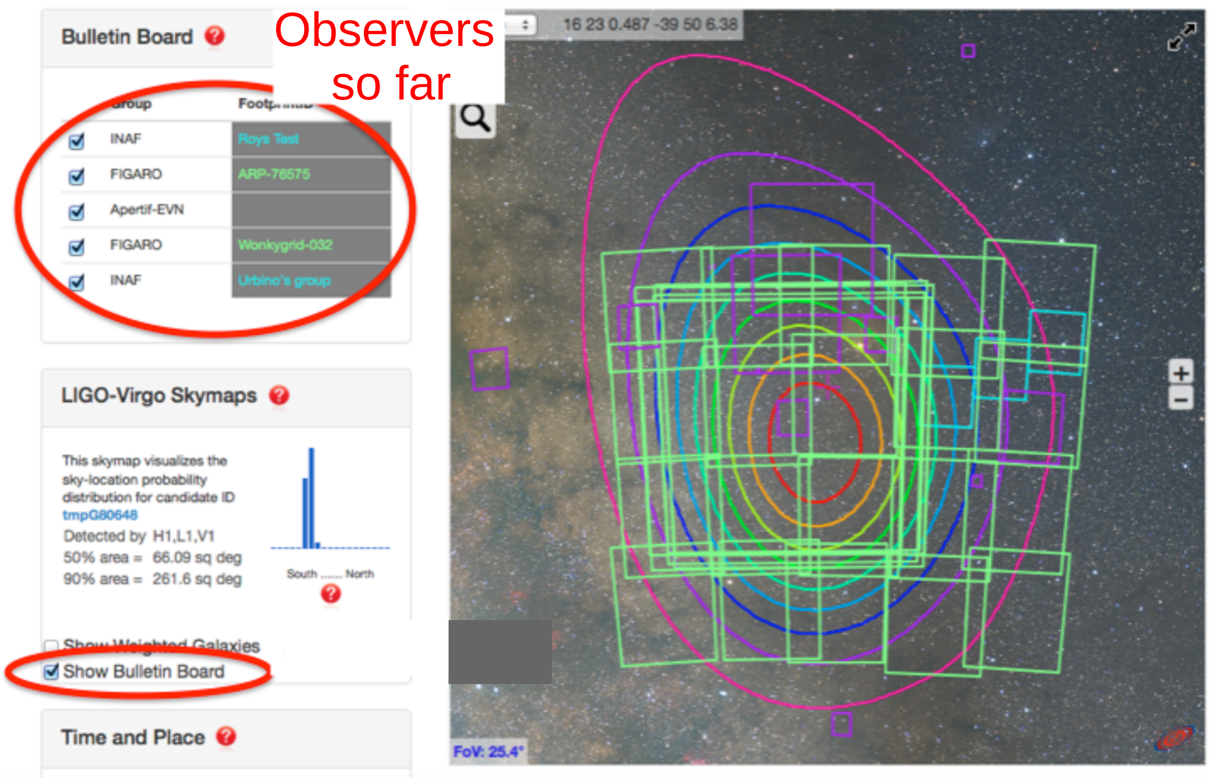
Enabling EM follow-up (2)



Enabling EM follow-up (3)

Tools which allow cooperation to maximize error box coverage

- Don't observe what is already covered → collect **footprints of the observed fields**
- Hierarchical follow-up: shallow wide-field to deep narrow-field telescopes → **share candidates**



Summary

- **Advanced detectors close to first light**
- **Synergy between GW observations and high-energy astrophysics**
  - Potential for a wealth of new science!
  - GW are crucial for GRB science
    - Association between **short GRB and BNS/BH-NS**
    - **Beaming** (ratio of GW events observed vs non-observed in γ-rays)
  - GRB may impact GW science
    - **Deeper searches** (+50 % observable volume)
    - Speed of GWs relative to c with 10^{-16} accuracy (10 s over 1.2 Gyr travel time)
  - In the longer term
    - Cosmography with "*standard sirens*"?

      D_L from GW, *z* from EM (host identification)

      → H_0 to 10-30 % with ~10 short GRBs [Nissanke et al, 1307.2638]