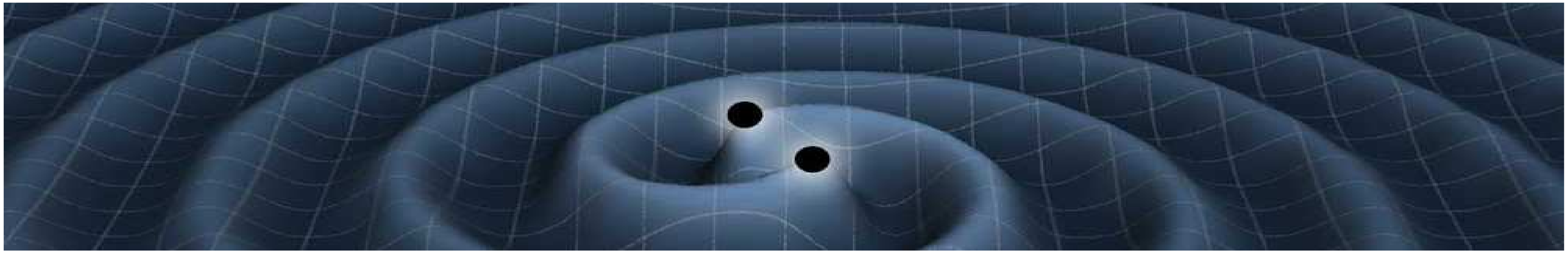
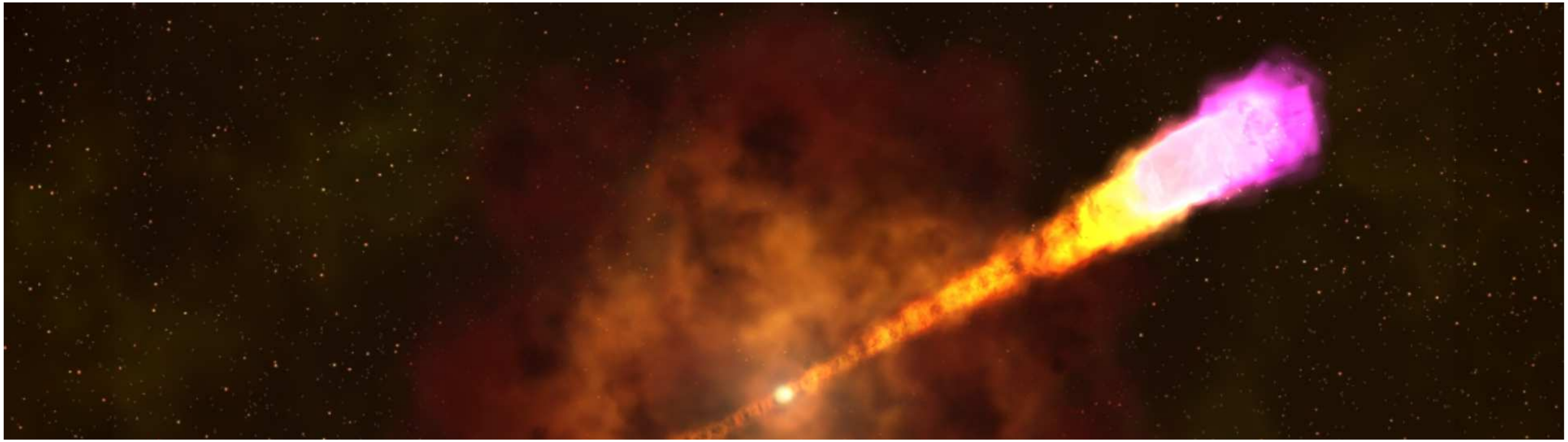


High-energy electromagnetic follow-up of GW transient events

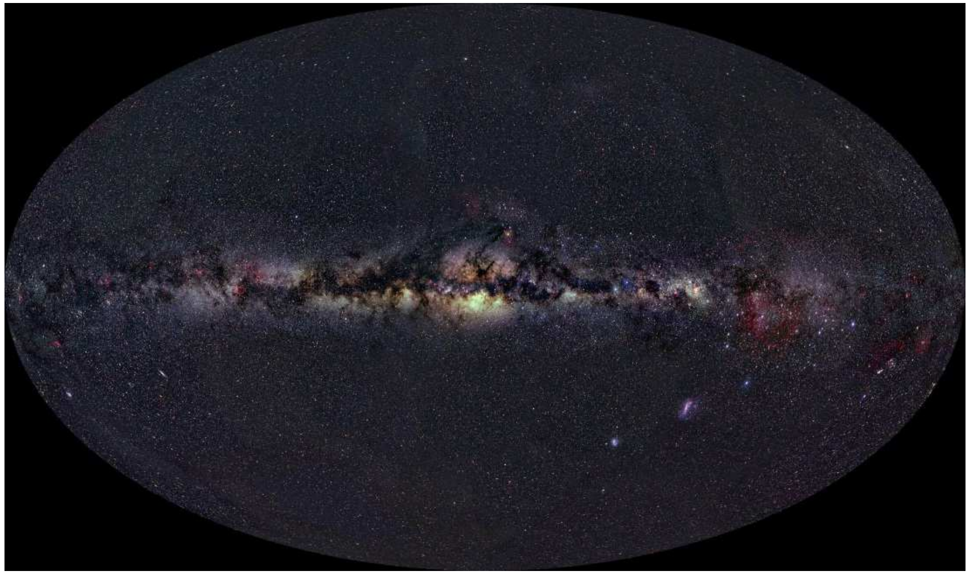
Massimiliano Razzano, Barbara Patricelli
University of Pisa & INFN-Pisa
In collaboration with G. Cella, M. Branchesi, E. Pian, A. Stamerra

TAUP 2015 (Turin, 8 Sep 2015)

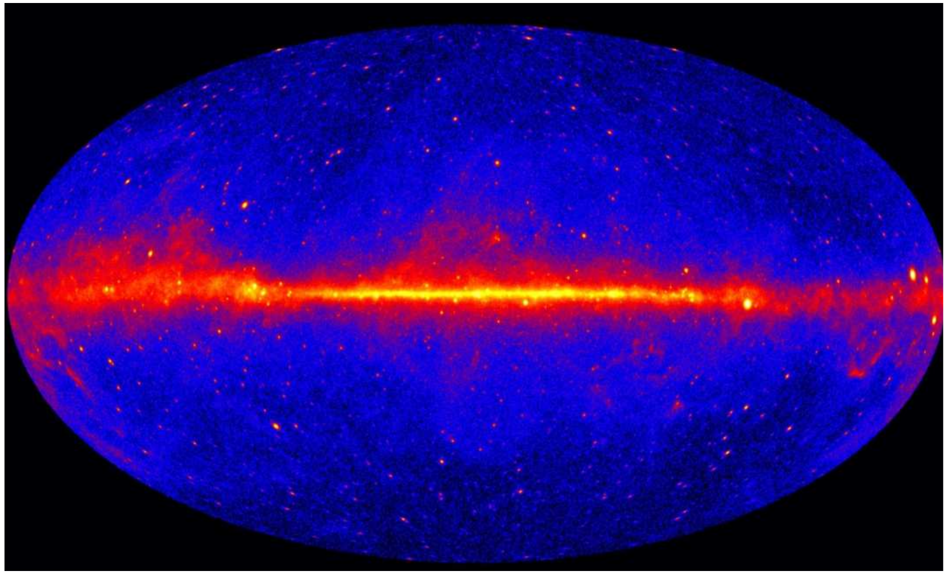


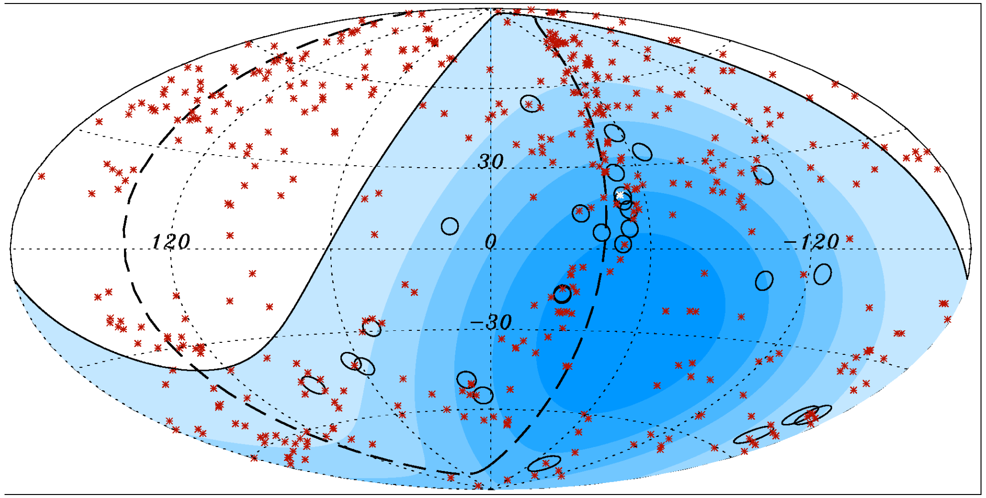
A multi-messenger sky

Optical (APOD)

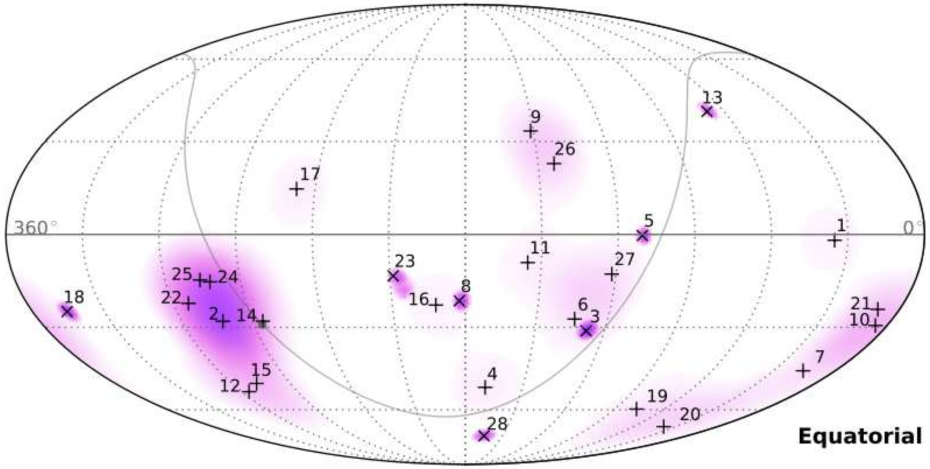


Gamma rays > 0.1 GeV (Fermi-LAT, 2013)





Cosmic rays > 57 Eev (Auger, 2007)



Neutrinos > 30 Tev (Icecube, 2013)

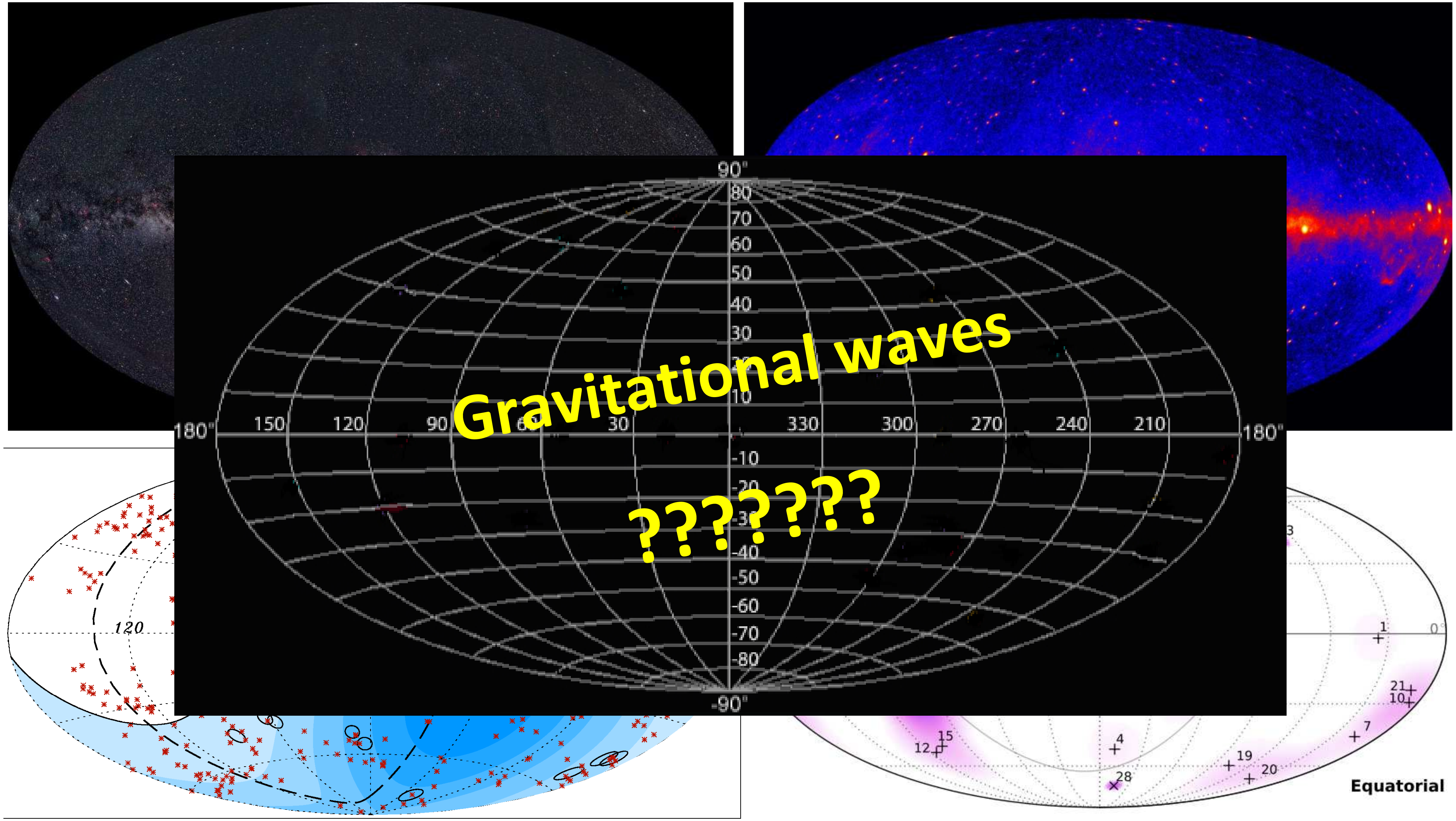
*

M. Razzano

A multi-messenger sky

Optical (APOD)

Gamma rays > 0.1 GeV (Fermi-LAT, 2013)



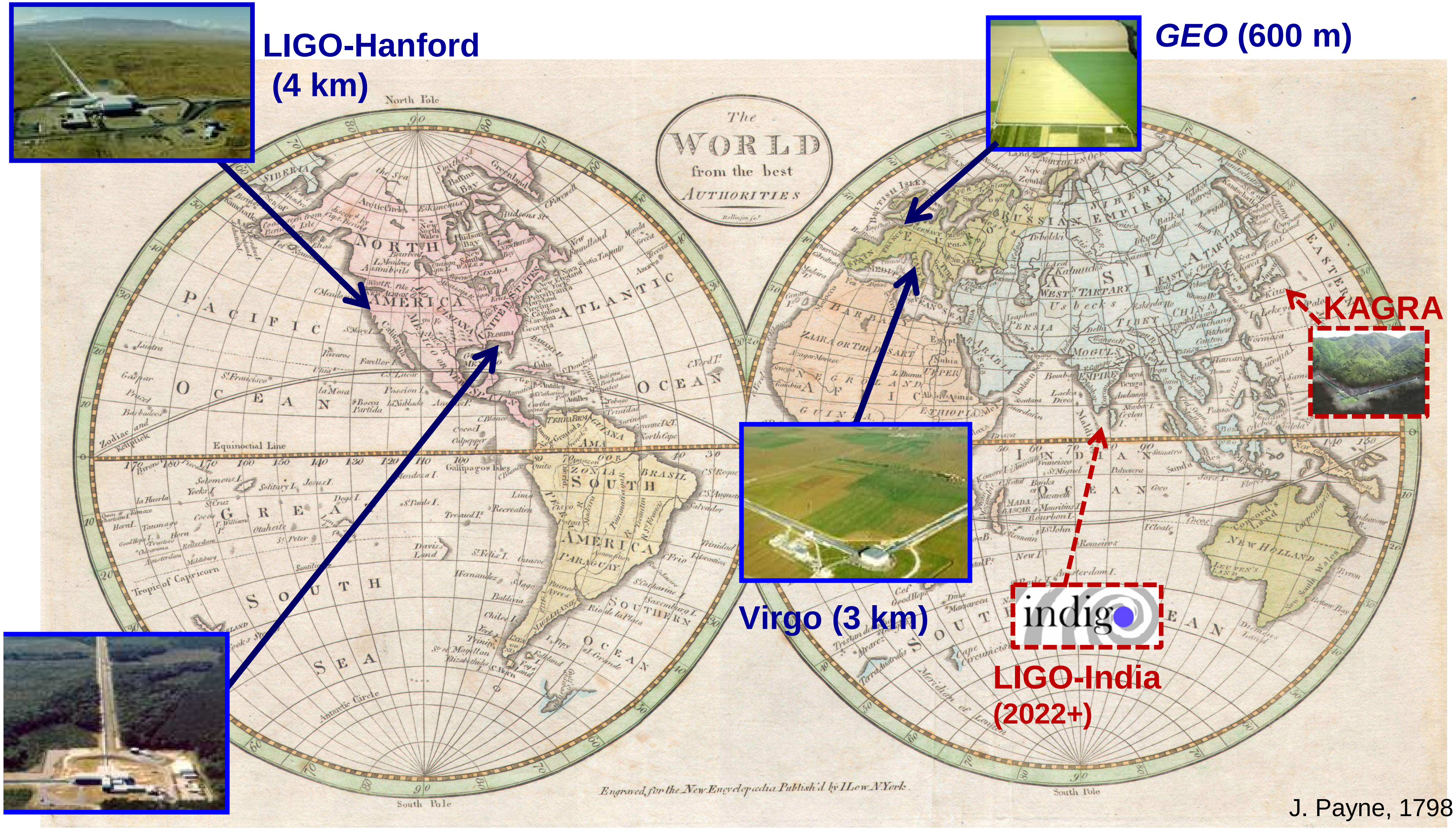
Cosmic rays > 57 Eev (Auger, 2007)

Neutrinos > 30 Tev (Icecube, 2013)

*

M. Razzano

The new era of Advanced GW detectors



LIGO-Hanford
(4 km)

***GEO* (600 m)**

KAGRA

Virgo (3 km)

LIGO-India
(2022+)

LIGO-Livingston
(4 km)

J. Payne, 1798

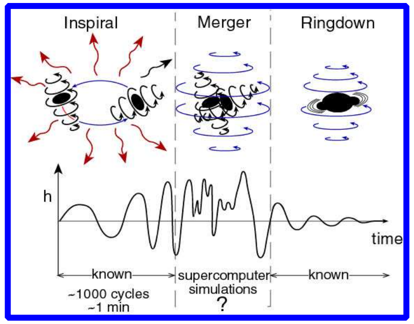
Advanced LIGO Advanced Virgo
First joint runs in 2016

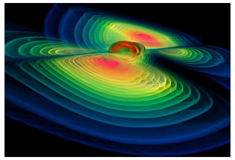
Expected GW sources detectable by LIGO/Virgo

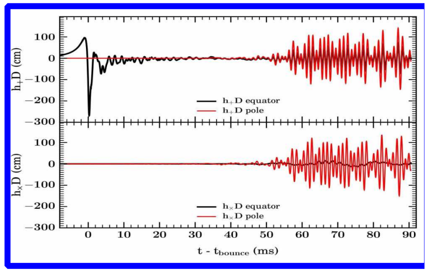
Transients

- **Coalescence of compact binary systems (NSs and/or BHs)**
  - Known waveform (template banks)
  - $E_{gw} \sim 10^{-2}\ Mc^2$

- **Core-collapse of massive stars**
  - Uncertain waveform
  - $E_{gw} \sim 10^{-8} - 10^{-4}\ Mc^2$





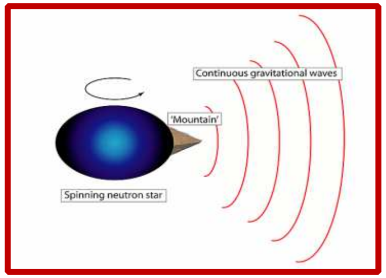


Ott, C. 2009

Non transients

- **Rotating neutron stars**
  - Quadrupole emission from star's asymmetry
  - Continuous and Periodic

- **Stochastic background**
  - Superposition of many signals (mergers, cosmological, etc)
  - Low frequency



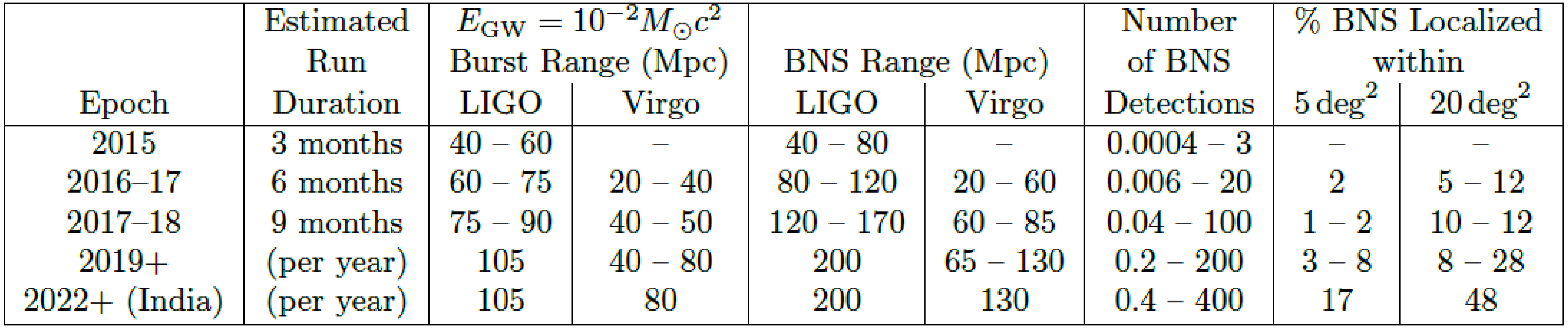
Mergers of compact objects

- **Best candidates for the first GW detection in the Advanced Era**
- **However, large uncertanties on the rates of these events**

Plausible observing scenario

LSC & Virgo collaboration
arXiv:1304.0670

aLIGO/Virgo Range | **Rate** | **Localization**



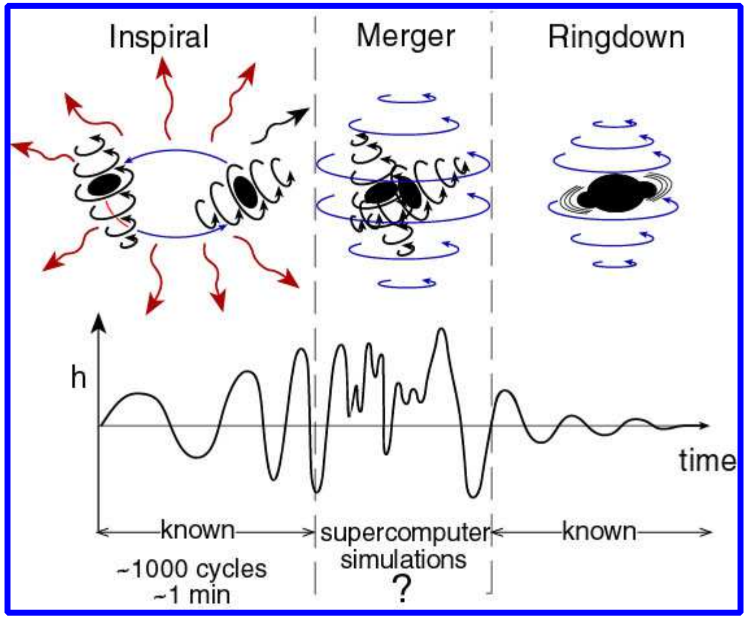
	Estimated Run	$E_{\mathrm{GW}} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS	% BNS Localized within	
Epoch	Duration	LIGO	Virgo	LIGO	Virgo	Detections	5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 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

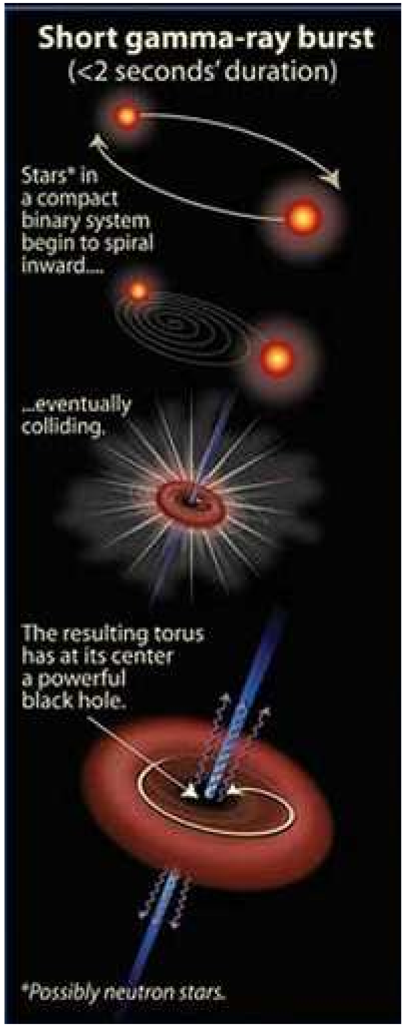
The GRB connection

- **Short GRBs (<2 s) are believed to be associated with mergers**

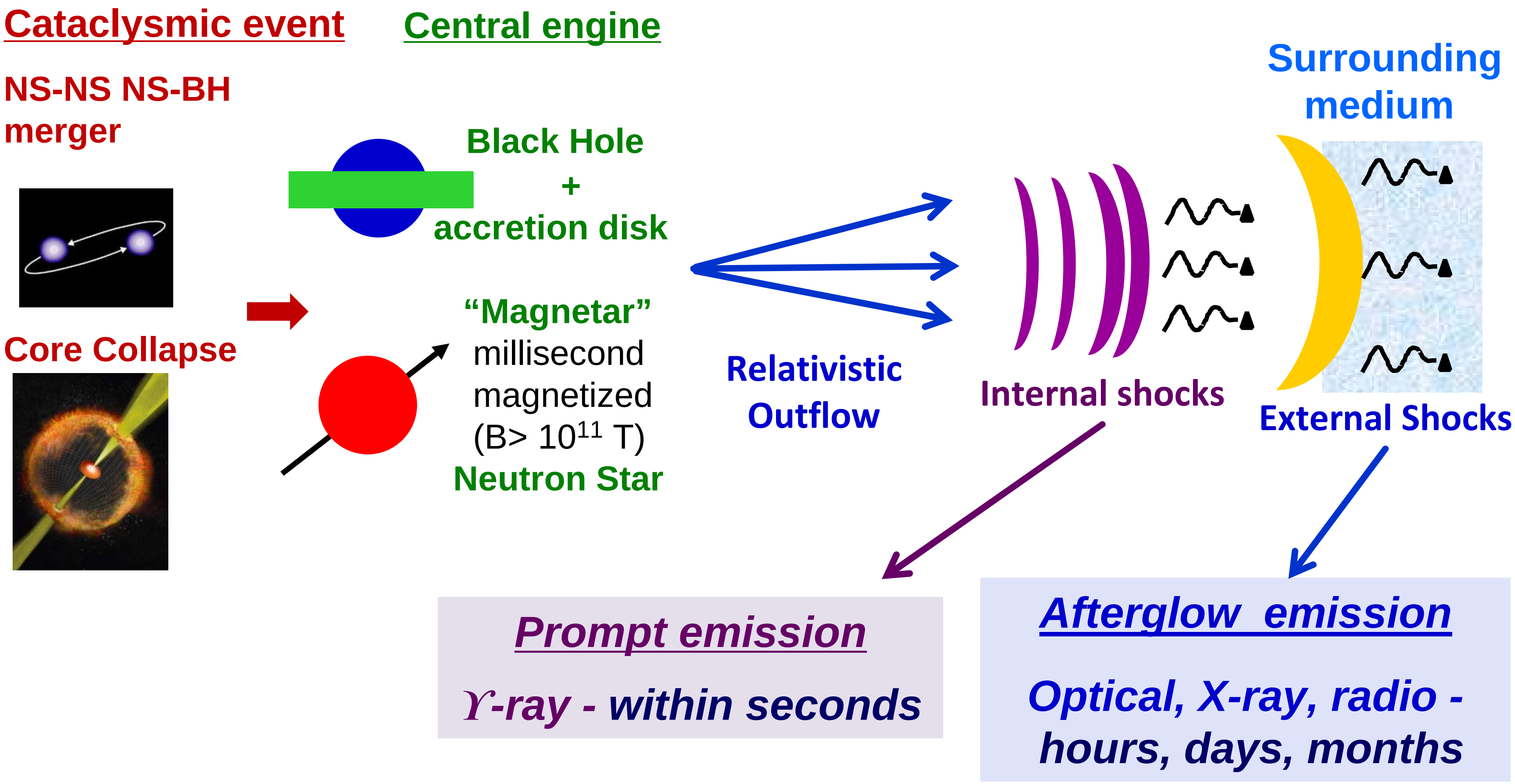
- **Long are associated with core-collapse**
  - But not covered here ☹

- **EM follow-up observations are key to test this association!**





The Fireball Model for GRBs



Cataclysmic event

NS-NS NS-BH merger

Core Collapse

Central engine

Black Hole + accretion disk

“Magnetar” millisecond magnetized (B> 10^{11} T) **Neutron Star**

Relativistic Outflow

Internal shocks

Surrounding medium

External Shocks

Prompt emission

ϒ-ray - within seconds

Afterglow emission

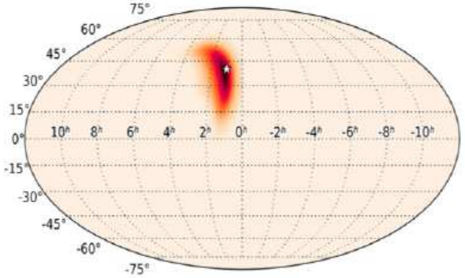
Optical, X-ray, radio - hours, days, months

The role of EM follow-up

Key tool to

- **better understand the physics of compact objects**
- **unveil the nature of short GRB progenitors**

GW alert → **Sky localization** → **EM follow-up**



Latency to generate GW alerts with sky localization: few – tens minutes

→ EM observations mainly of the afterglow emission

GW Localization uncertainties within 10-100 sq deg

→ Wide field of view (FOV) EM detectors are needed

→ High-Energy (X, gamma) very well suited (large FOVs + spectral coverage)

The question

NASA

“How can high-energy observatories
contribute to the EM follow-up campaigns?”

Short answer:

> “Sure, Fermi, Swift are helpful because of large FOVs, spectral coverage and continuous monitoring”

Long answer:

> “We need some more detailed study, and some simulations”

The Fermi Large Area Telescope

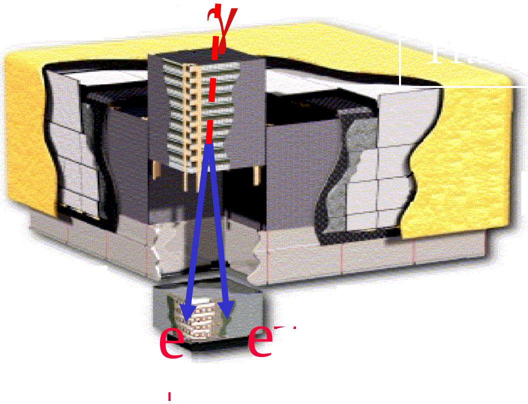
Credit: http://fermi.gsfc.nasa.gov/

Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors (8 keV - 30 MeV)

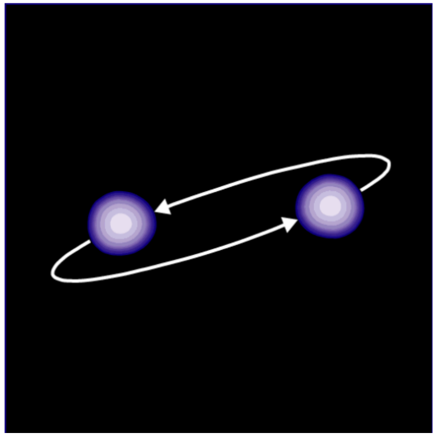
Large Area Telescope (LAT)
20 MeV - 300 GeV

LAT features

- **Huge field of view (~2.4 sr)**
  - **20% of the sky at any moment**
  - **Full sky in 3 hrs**
  - **Cover large GW error boxes**
- **Large effective area**
  - **Detect faint sources**
- **Accurate localization (r_{68}~0.8° @10GeV)**
  - **Refine localization of GW events**
  - **Alerts & follow-up**



Step 1:
simulating the mergers



NASA

- Milky way-like galaxies dominating the Local Universe
- $\rho_{galaxies}$ =0.0116 Mpc^{-3} (Kopparapu et al. 2006)
- Simulated galaxies uniformly distributed in volume
- Merging systems:
  - www.syntheticuniverse.org (Dominik et al. 2012)
  - NS-NS, $Z=Z_{sol}$ and $Z=0.1xZ_{sol}$
  - “Standard model”
- Merger rates: 23.5 Myr^{-1} ($Z=Z_{sol}$) and 8.1 Myr^{-1} ($Z=0.1xZ_{sol}$)
  - (Dominik et al. 2012)

- 1000 realizations (each one for a 1-year observing period)

Step 2:
Simulating the GW emission & detection

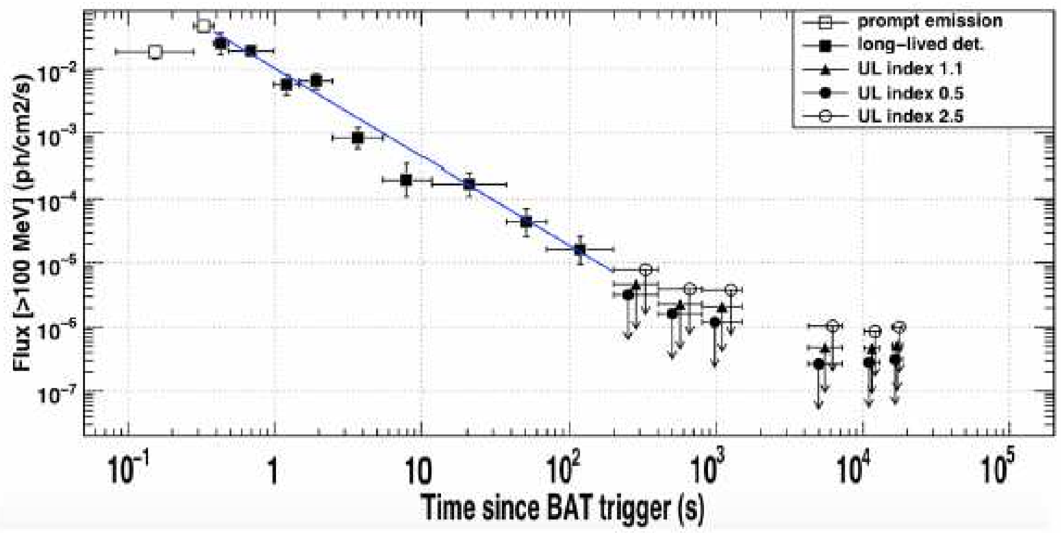
NASA

- **GW signals**
  - Each NS-NS merging system has the same sky position of the host galaxy, and a random inclination of the orbital plane
  - Non-spinning systems
  - TaylorT4 waveforms (Buonanno et al. 2009)

- **GW detection**
  - Detector configurations (aLIGO and AdV): 2016-2017 and 2019+ (design), Aasi et al. 2013
  - Matched filtering technique (Wainstein 1962)
  - Trigger: at least 2 detectors
  - Combined detector SNR threshold: 12
  - GW localization with BAYESTAR (Singer et al. 2014)
  - Independent duty cycle of each interferometer: 100 % and 80 %

Step 3:
Simulating the EM emission (sGRB)

- **Each merger has an associated GRB**
  - GRB 090510 as a prototype:
  - Only short GRB with extended HE (>4 GeV) emission (up to 200 s), seen from the LAT (Ackermann et al. 2010, De Pasquale et al. 2010)
  - Power-law decay light curve (index 1.38)
  - Power-law spectrum (Γ = 2.1)



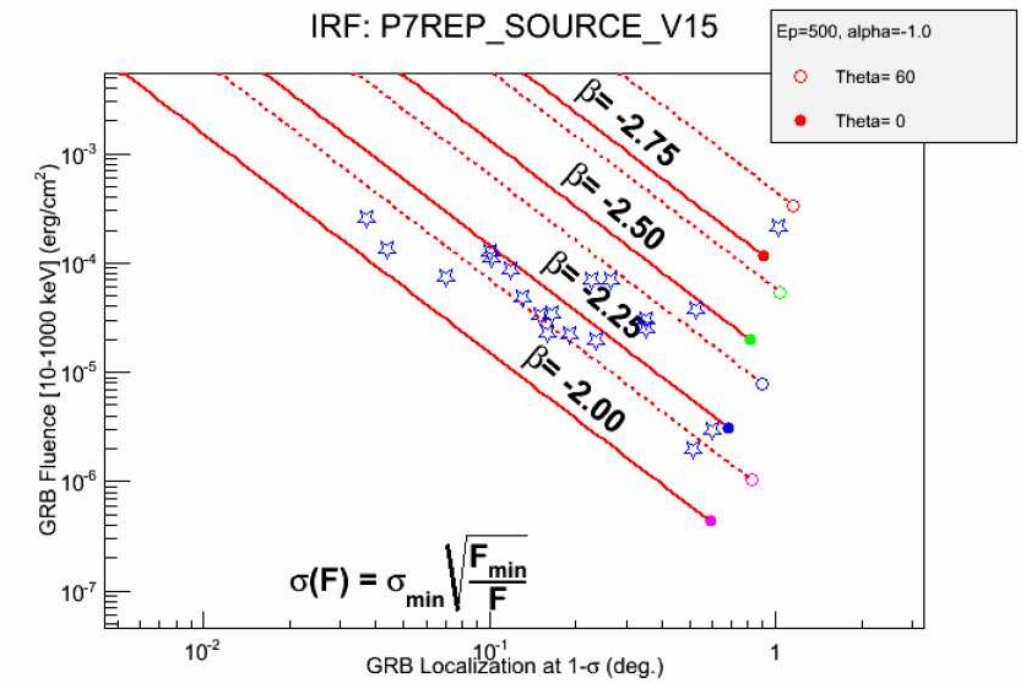
Step 3:
Simulating the EM emission (sGRB)

- **Basic assumptions:**

  - All the merging NS-NS systems progenitors of short GRBs.
  - The total EM energy emitted in rays is: 10^{49} - 10^{53} erg.
  - Same temporal decay and spectrum of GRB 090510.
  - GRB 090510 is an on-axis GRB (θ=0).
  - To correct for θ, we consider a simplified model of a moving point source $\gamma = 100$ (see e.g. Granot et al. 2002).

Step 3:
Simulating the EM emission (sGRB)

- We re-scaled the HE flux of GRB 090510 above 100 MeV (effects of distances, total energies, and inclination angles of the progenitors)
- We did a comparison with the Fermi-LAT sensitivity (rescaled to >100 MeV)



- Calculate integration time t_f needed for the simulated GRBs to have a fuence equal above LAT threshold
- Sensitivity corresponding to 1° for θ=0°

http://www.slac.stanford.edu/exp/glast/groups/canda/archive/p7rep v15/lat Performance.htm

First results: GW detection and localization (2016-17)

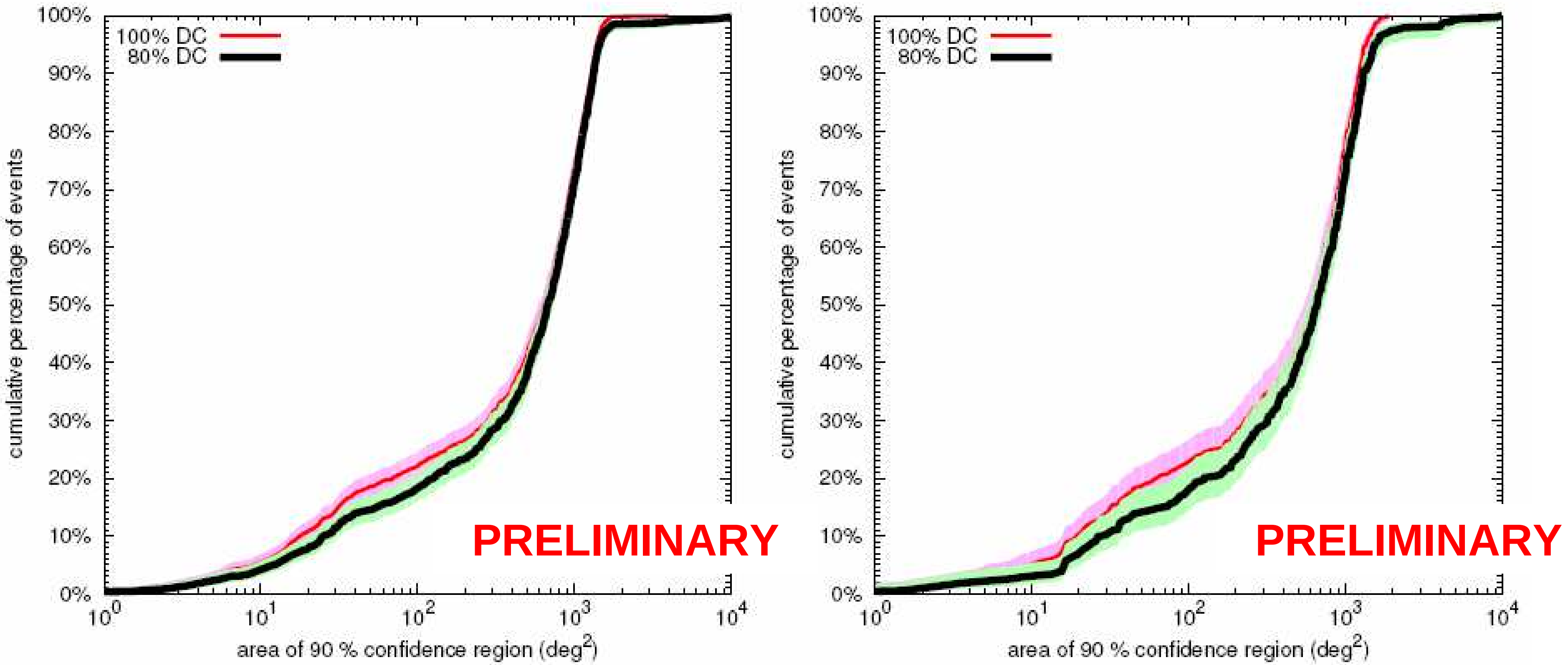
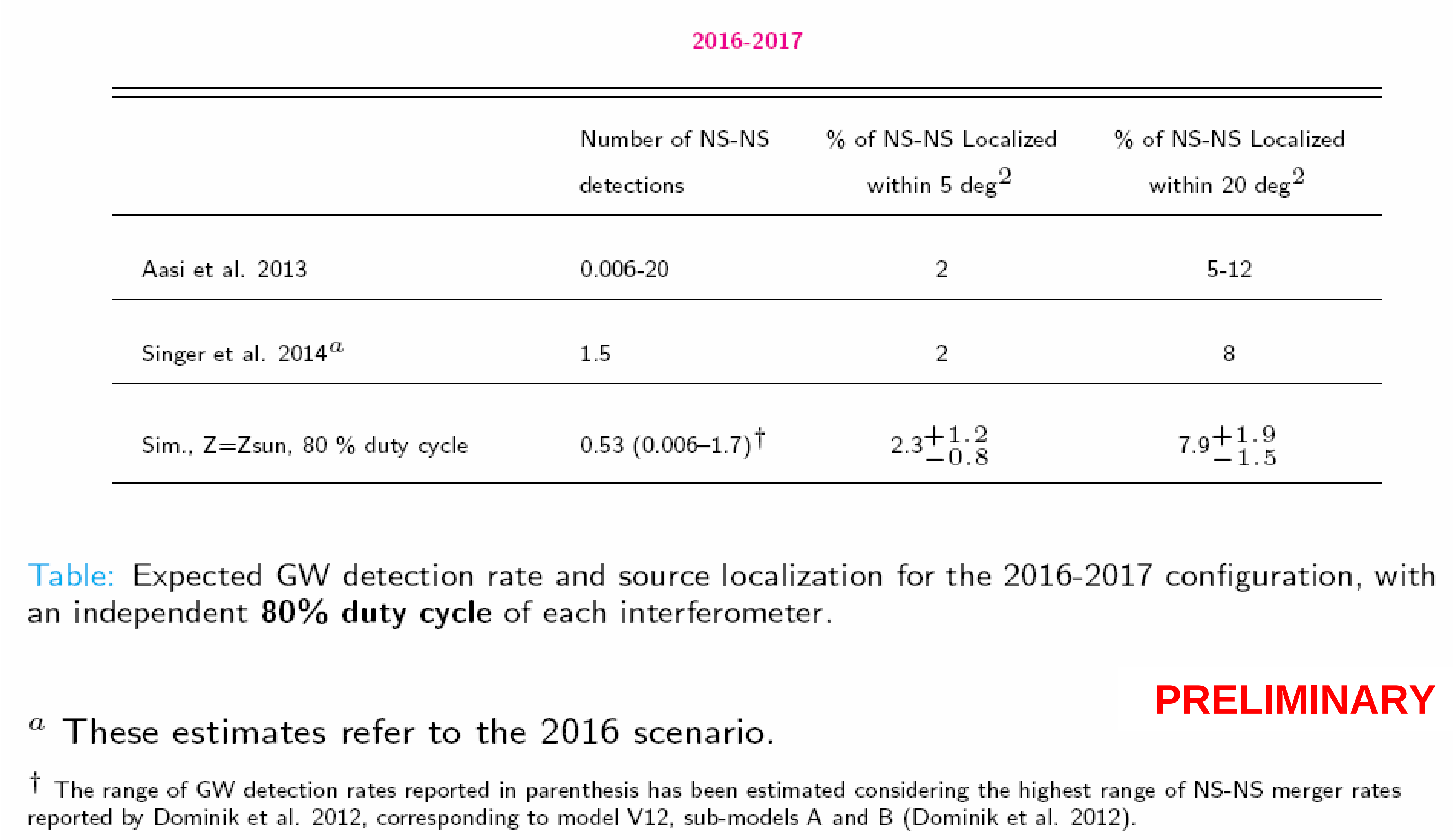


Figure: Cumulative histograms of sky localization areas for NS-NS systems at solar metallicity (left) and sub-solar metallicity (right), for the 2016-2017 configuration of the interferometers.

First results: GW detection and localization (2016-17)



2016-2017

	Number of NS-NS detections	% of NS-NS Localized within 5 deg^2	% of NS-NS Localized within 20 deg^2
Aasi et al. 2013	0.006-20	2	5-12
Singer et al. 2014[a]	1.5	2	8
Sim., Z=Zsun, 80 % duty cycle	0.53 (0.006–1.7)[†]	$2.3^{+1.2}_{-0.8}$	$7.9^{+1.9}_{-1.5}$

Table: Expected GW detection rate and source localization for the 2016-2017 configuration, with an independent **80% duty cycle** of each interferometer.

PRELIMINARY

[a] These estimates refer to the 2016 scenario.

[†] The range of GW detection rates reported in parenthesis has been estimated considering the highest range of NS-NS merger rates reported by Dominik et al. 2012, corresponding to model V12, sub-models A and B (Dominik et al. 2012).

First results: GW detection and localization (Design configuration, 2019+)

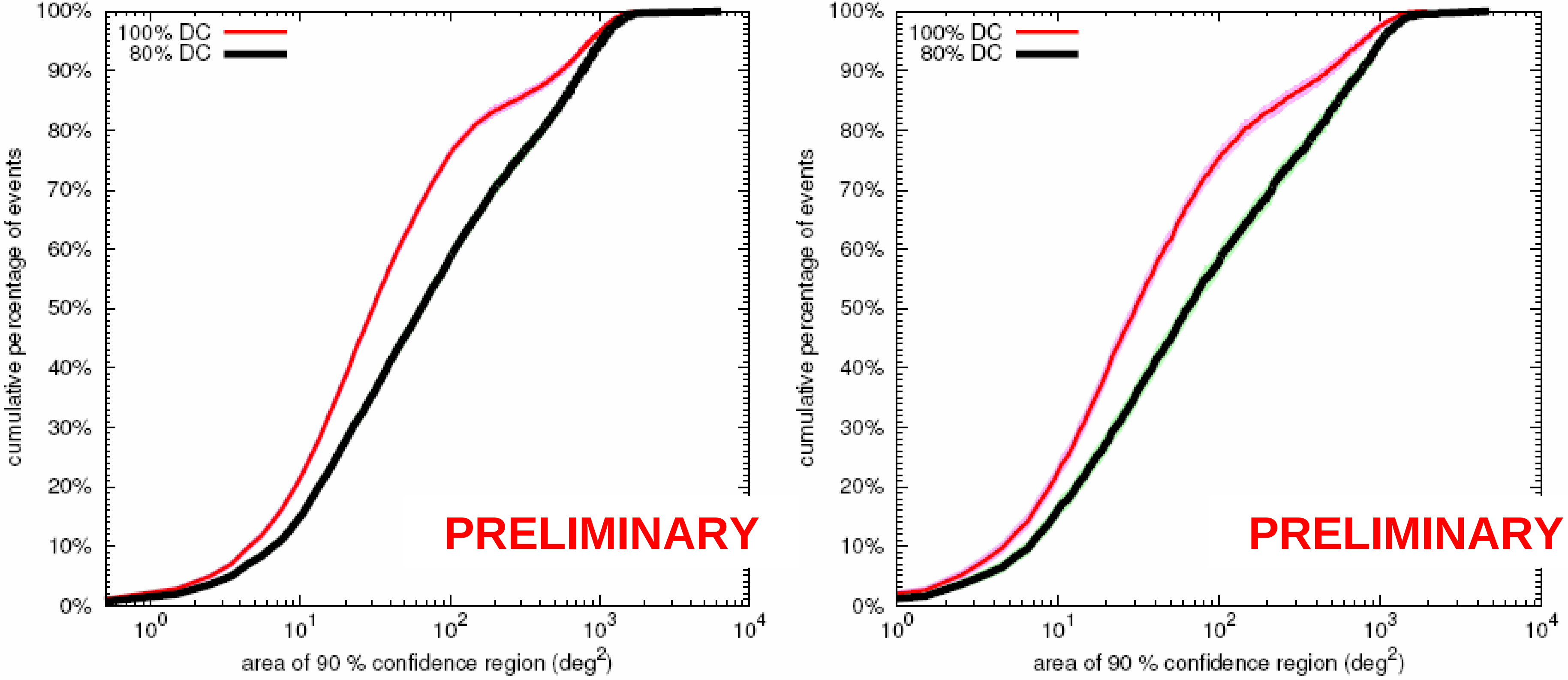
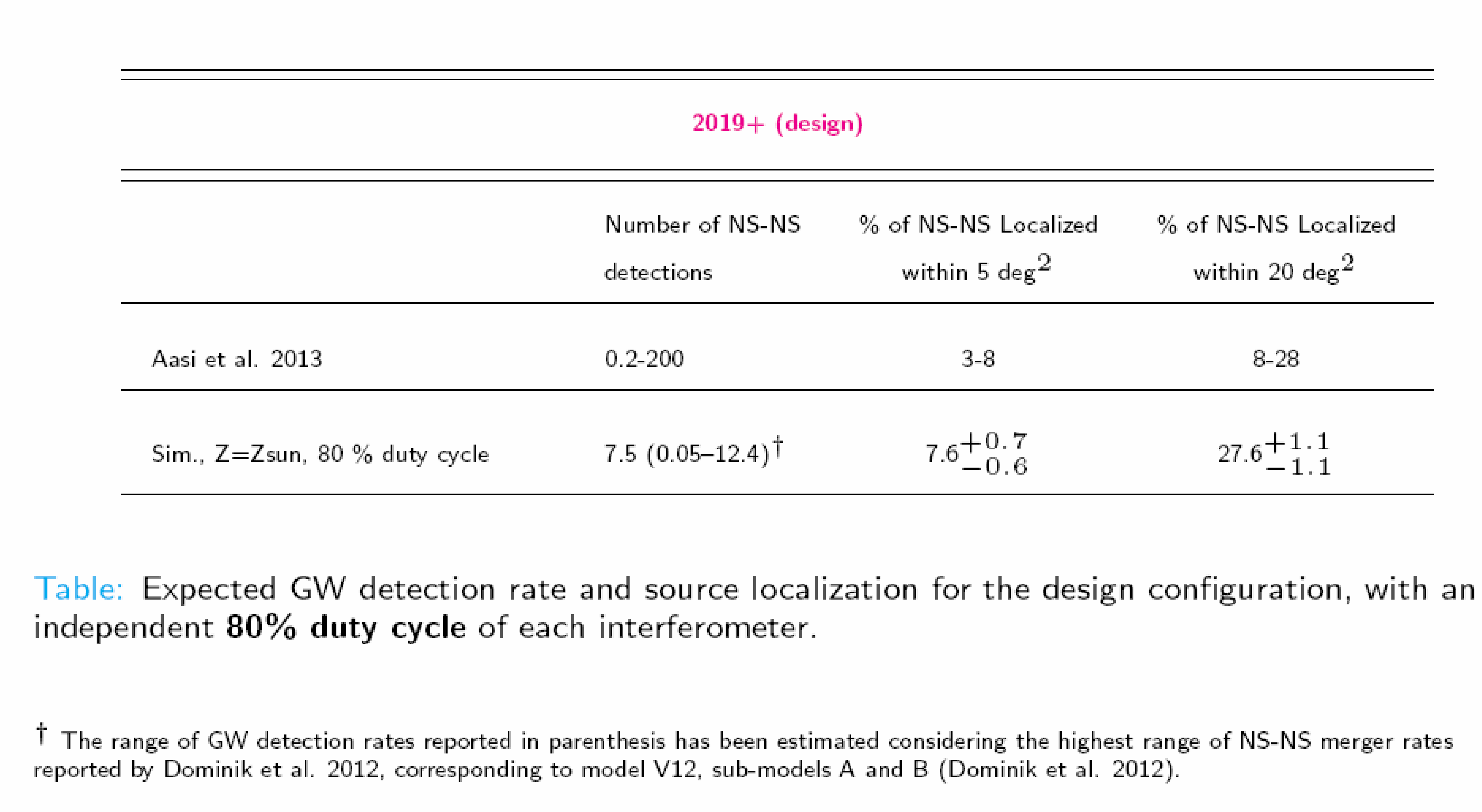


Figure: Cumulative histograms of sky localization areas for NS-NS systems at solar metallicity (left) and sub-solar metallicity (right), for the design configuration of the interferometers.

First results: GW detection and localization (Design configuration, 2019+)



2019+ (design)

	Number of NS-NS detections	% of NS-NS Localized within 5 deg^2	% of NS-NS Localized within 20 deg^2
Aasi et al. 2013	0.2-200	3-8	8-28
Sim., Z=Zsun, 80 % duty cycle	7.5 (0.05–12.4)[†]	$7.6^{+0.7}_{-0.6}$	$27.6^{+1.1}_{-1.1}$

Table: Expected GW detection rate and source localization for the design configuration, with an independent **80% duty cycle** of each interferometer.

[†] The range of GW detection rates reported in parenthesis has been estimated considering the highest range of NS-NS merger rates reported by Dominik et al. 2012, corresponding to model V12, sub-models A and B (Dominik et al. 2012).

PRELIMINARY

First results: EM gamma-ray detections (Design configuration, 2019+)

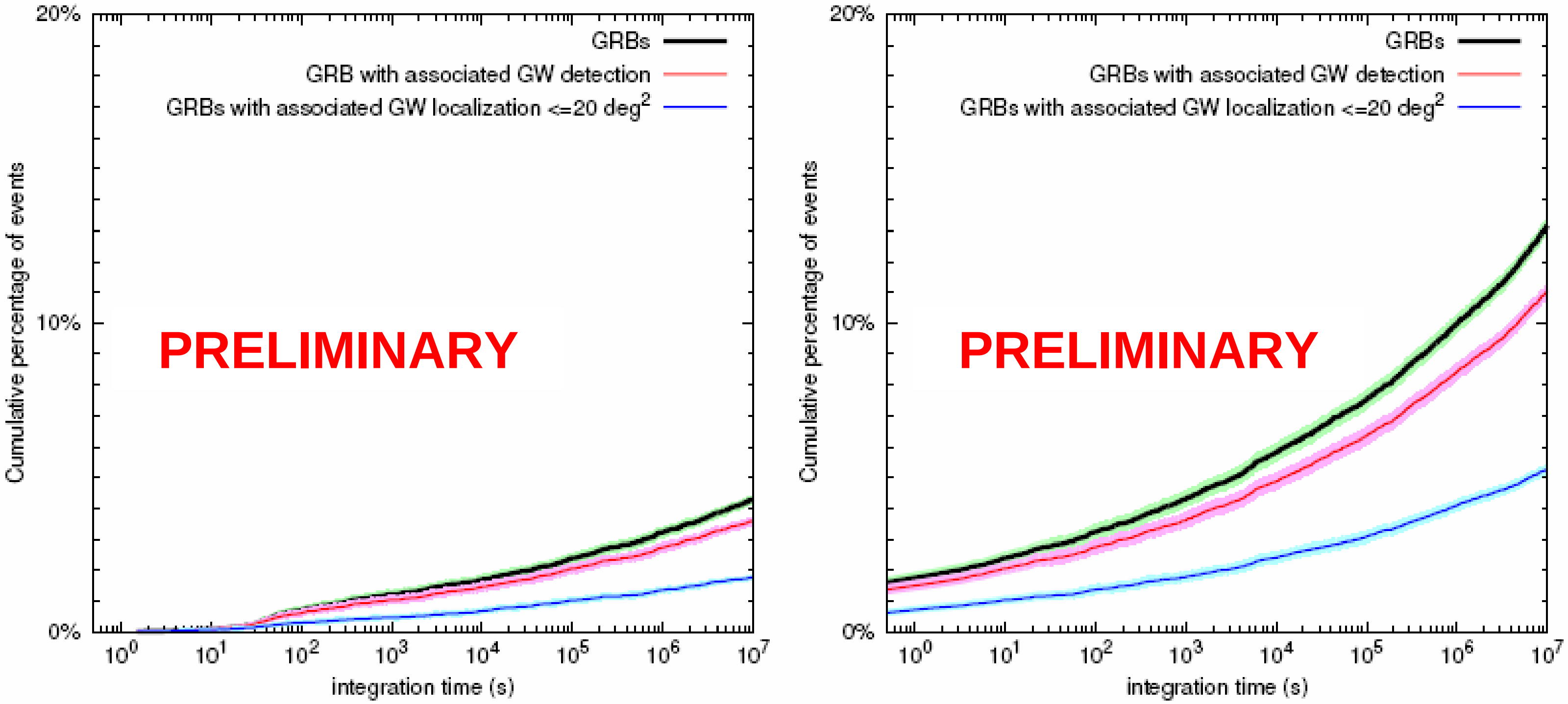
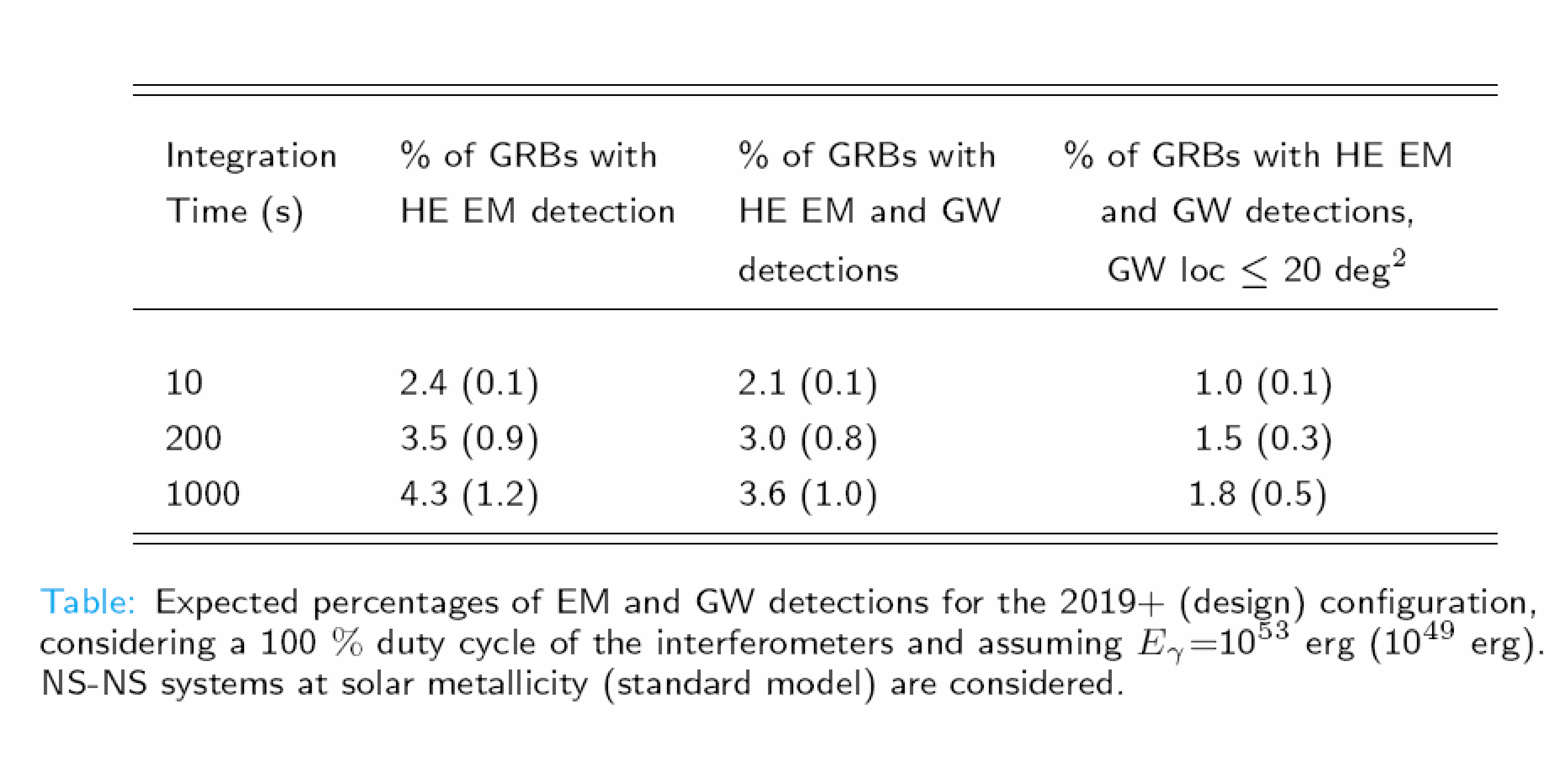


Figure: Left: cumulative histogram of the integration time needed for the simulated GRBs (in red), for the simulated GRBs with associated GW detection (in black) and with a sky localization ≤ 20 deg^2 (in blue) to be detected by the LAT. We assume $E_\gamma = 10^{49}$ erg and, for the GW detections, we consider the design scenario and a 100 $\%$ duty cycle of each interferometer. NS-NS systems at solar metallicity (standard model) are considered. Right: same as left, but we assume $E_\gamma = 10^{53}$ erg.

First results: EM gamma-ray detections (Design configuration, 2019+)



Integration Time (s)	% of GRBs with HE EM detection	% of GRBs with HE EM and GW detections	% of GRBs with HE EM and GW detections, GW loc $\lesssim$ 20 deg^2
10	2.4 (0.1)	2.1 (0.1)	1.0 (0.1)
200	3.5 (0.9)	3.0 (0.8)	1.5 (0.3)
1000	4.3 (1.2)	3.6 (1.0)	1.8 (0.5)

Table: Expected percentages of EM and GW detections for the 2019+ (design) configuration, considering a 100 % duty cycle of the interferometers and assuming $E_\gamma = 10^{53}$ erg (10^{49} erg). NS-NS systems at solar metallicity (standard model) are considered.

PRELIMINARY

Conclusions (and next steps)

- The era of Advanced GW detectors is coming (very) soon!
- We have estimated the GW detection rates and sky localizations for NS-NS mergers
- Results consistent with those in literature
- We have presented estimates of the joint gamma-ray EM and GW detection rates with *Fermi*-LAT

- Next steps
  - Investigation of the optimal HE EM follow-up strategies
  - Extension with other models by Dominik et al. 2012
  - Extension to NS-BH binaries
  - Extension to other observatories (e.g. ACTs, Swift, etc)