Multi-messenger science

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Aug 22, 2019

Summer Institute 2019

Lectures

- Day 1
  - Overview
  - Multi-messenger Science Introduction
  - Cosmic ray mystery / cosmic rays
  - Recent Breakthroughs in Multi-messenger Science
  - Outlook
- Day 2
  - Observatories for Multi-messenger astroparticle physics
  - High-energy Neutrinos and Multi-messenger Science
- Day 3
  - Real time / follow-up / Alert programs
  - Future perspectives

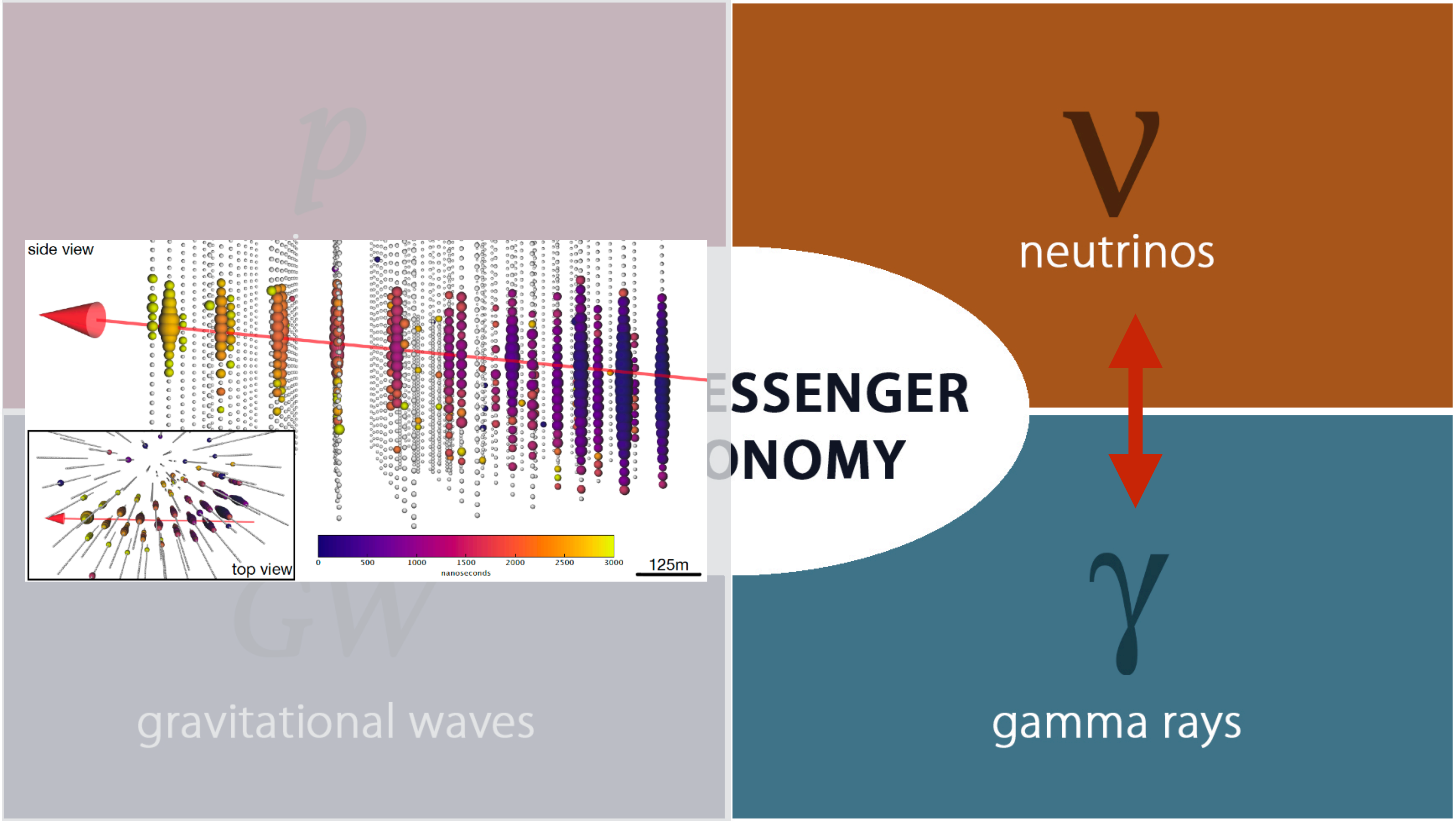
v3.2. 19.07.29

SI 2019 Schedule

	8/18 (Sun)	8/19 (Mon)	8/20 (Tue)	8/21 (Wed)	8/22 (Thu)	8/23 (Fri)	
9:00		D.L. - Morimitsu Tanimoto **[L] C. Rott 1**	D.L. - Ki-Young Choi **[L] M.Sasaki 1**	D.L. - Deog Ki Hong **[L] C. Shin 2**	D.L. - Koichi Hamaguchi **[L] T.Lin 3**	D.L. - Taichiro Kugo **[L] M. Sasaki 3**	9:00
10:00		D.L. - Morimitsu Tanimoto **[L] T. Lin 1**	D.L. - Ki-Young Choi **[L] T. Lin 2**	D.L. - Deog Ki Hong **[L] M. Sasaki 2**	D.L. - Koichi Hamaguchi **[L] C.Rott 3**	D.L. - Taichiro Kugo **[L] C. Shin 3**	10:00
11:00		Coffee	Coffee	Coffee	Coffee	Thanksgiving & Closing	11:00
		D.L. - X.G. He **[L] C.Shin 1**	D.L. - Matthew Baumgart **[L] C. Rott 2**	D.L. - Cheng Wei Chiang **[F] T.Kugo** **[F] Cologain**	D.L. - Seodong Shin **[F] YJKwon** **[F] X.G.He**		
12:00							12:00
12:30		Lunch	Lunch	Excursion	Lunch		12:30
16:00	Check-in & Welcoming	D.L. - Hyun Min Lee **[F] DKHong** **[F] Baumgart** **[F] JHyuck Park**	D.L. - Hyung Do Kim **[F] CWChiang** **[F-S] KBan, SMChoi** **[F] Y.Omura**		D.L. - Youngjoon Kwon **[F] Hamaguchi** **[F] JHSong** **[F] FPHuang**		16:00
17:30	Reception	Dinner	Dinner		Dinner		17:30
19:00		D.L. - Yuji Omura **[F] HDKim** **[F] SHYun**	**Parallel A, B**	Banquet	**Parallel C, D**		19:00
19:30	D.L. - Pyungwon Ko **[Colloquium 1]** **H.Murayama**						19:30
20:00		Coffee	**Poster Session**		**Poster Session**		20:00
21:00	Free discussion	D.L. - Pyungwon Ko **[Colloquium 2]** **H.Murayama**	Free discussion		Free discussion		21:00

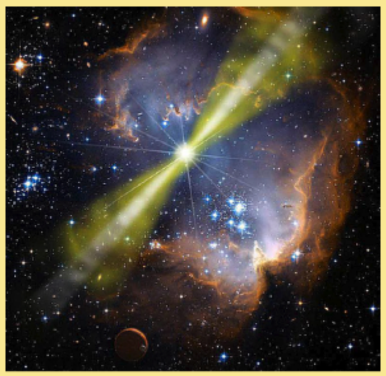
Multi-Messenger Astrophysics

Icecube-170922A and TXS 0506+056

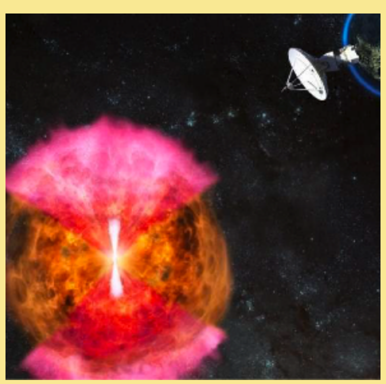


Potential extragalactic Sources

Explosions of massive stars



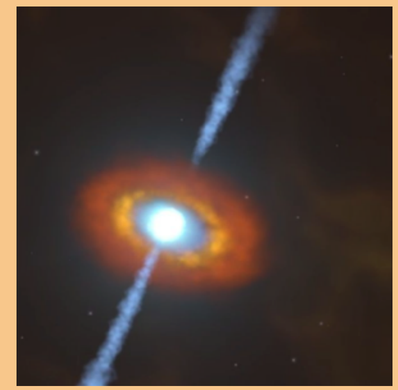
Gamma ray bursts (GRBs)



Choked GRBs

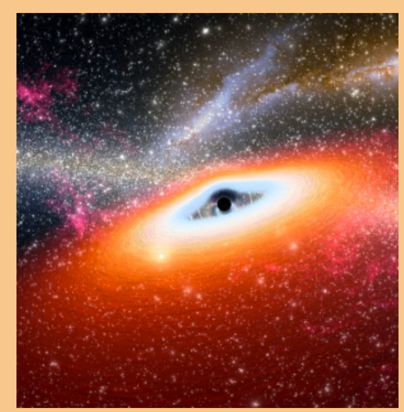
Supernovae IIn

Accreting supermassive black holes



Blazars

Tidal disruption events (TDEs)



Active Galactic Nuclei (AGN)

Calorimetric sources

Starburst galaxies

Clusters of Galaxies

seconds — weeks — month — continuous

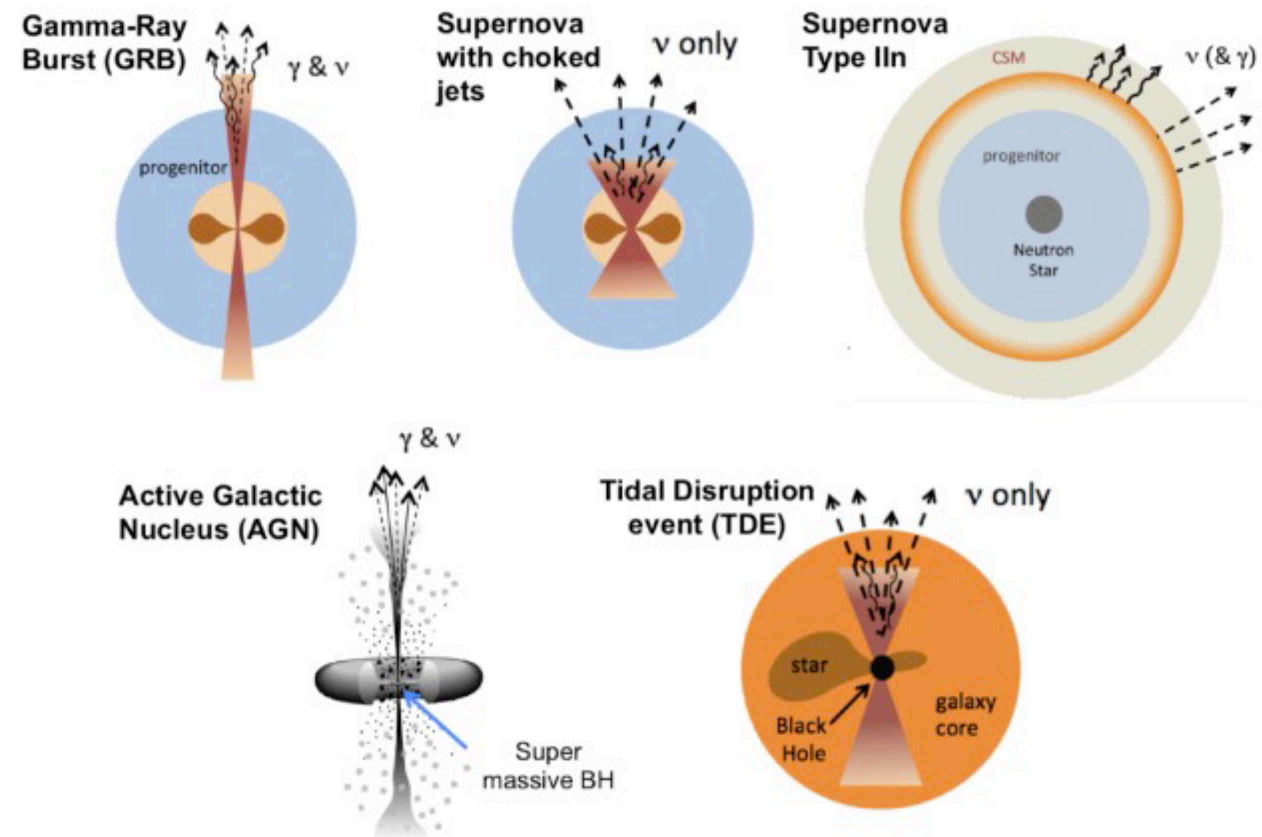
Electromagnetic emission of various sources

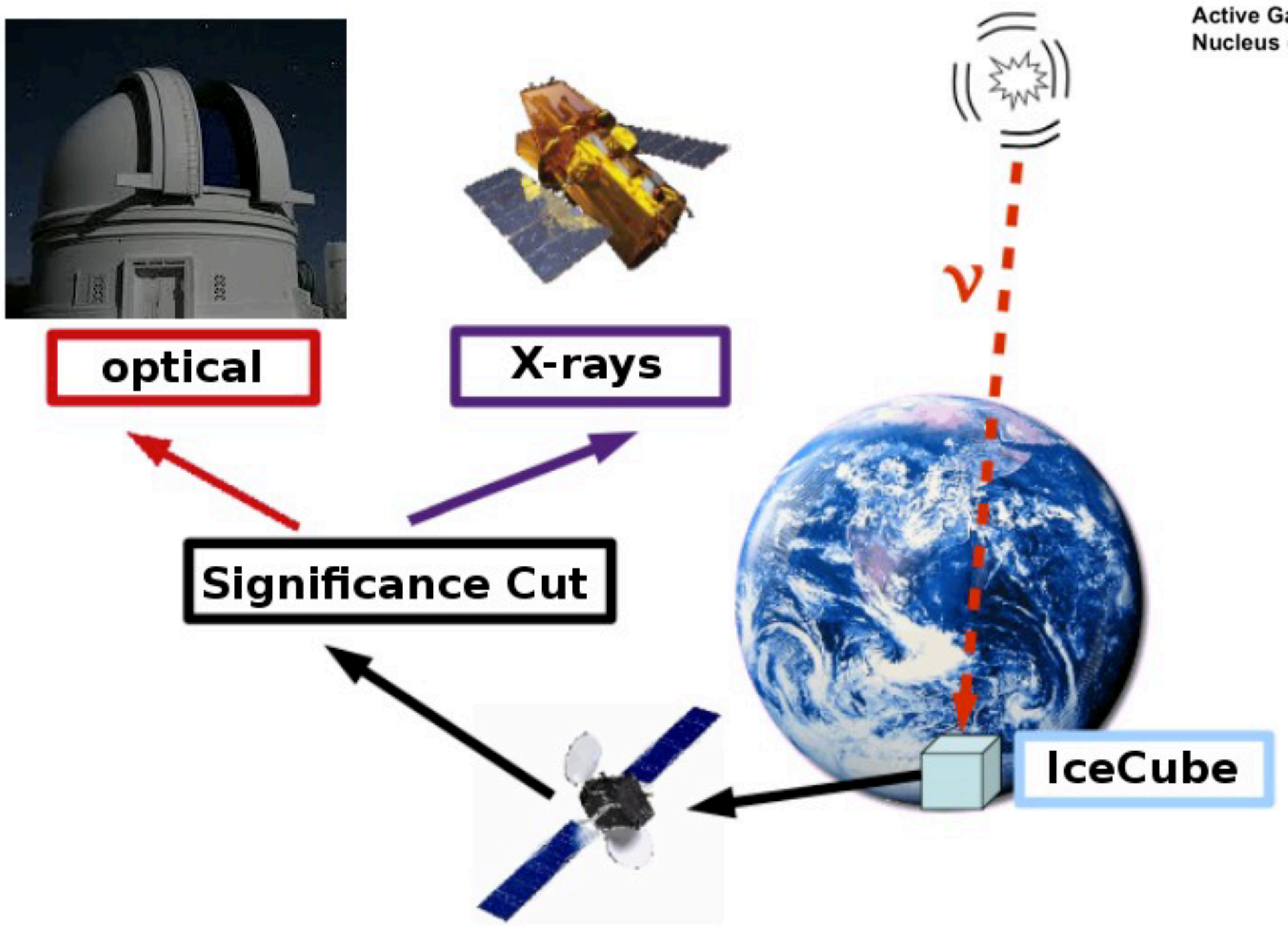
	Expected emission:	Opt. peak mag.:	Duration:
GRBs 	γ-rays, X-rays, UV, **optical** rarely: VHE γ-rays	-24th	~100 s
choked or II-GRBs 	**optical** maybe: γ-rays, X-rays, late radio	SN: -19th	ν: ~100 s em.: ~30 d
type IIn SNe 	**optical** rarely: γ-rays, X-rays	-18th (-21th if superl.)	~100 days
jetted TDEs 	**optical**, UV, X-rays	-20th	~100 days
blazars 	all wavelengths	-26th	minutes - months

Nora Linn Strotjohann | Optical emission from neutrino sources | 2019-05-21 | Page 14

Optical follow up (Neutrinos)

IceCube's optical follow up program

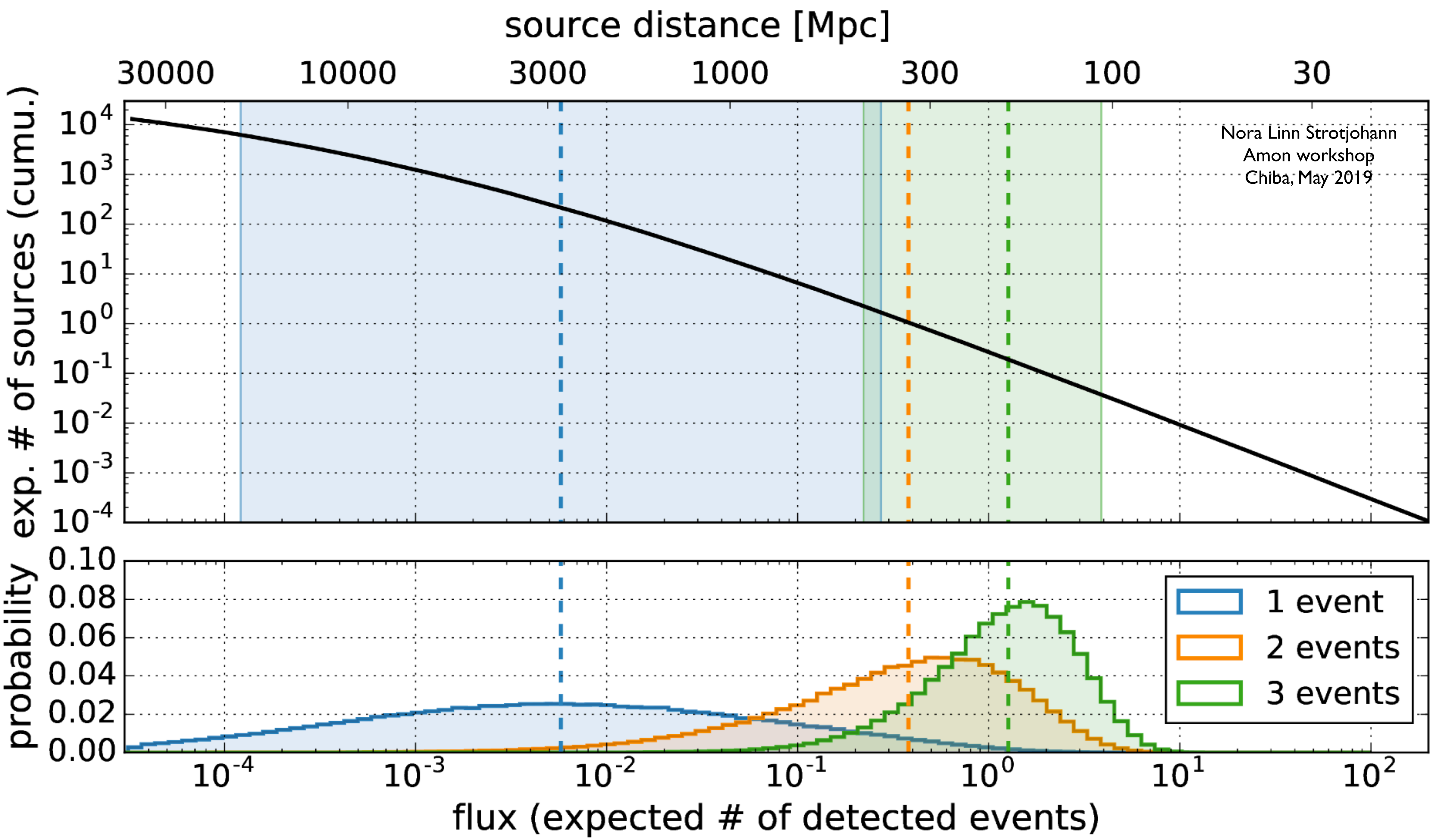




Selection criteria for optical and X-ray follow-up:
$\geq 2\ \nu_\mu$ in 100s and 3.5°

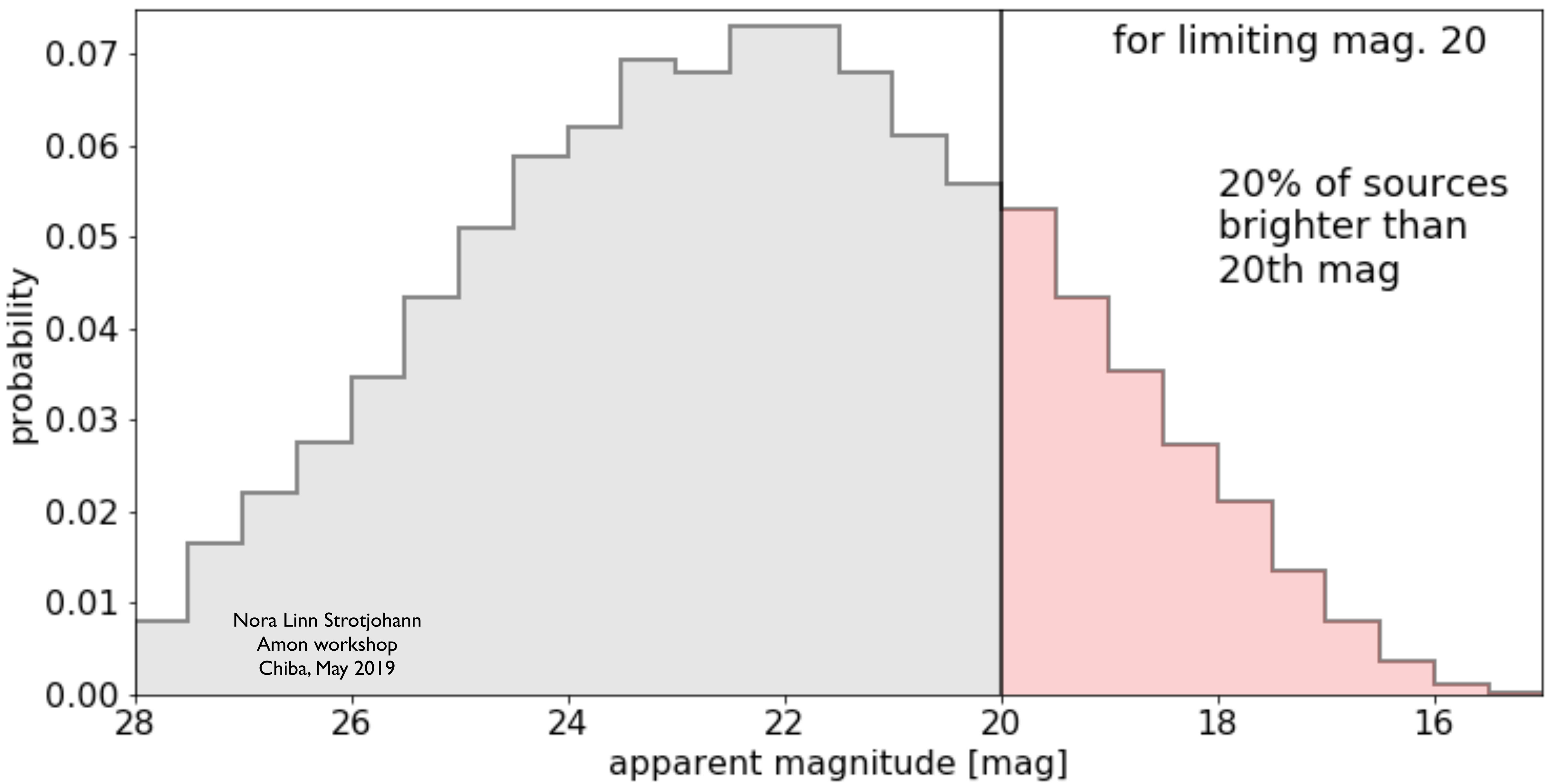
Distance of a neutrino source

- simulate a cosmic population of neutrino sources (in the example here no source evolution was used):
- Determine which sources are detected with 1, 2, or 3 events
  - → single events are most likely detected from distant sources

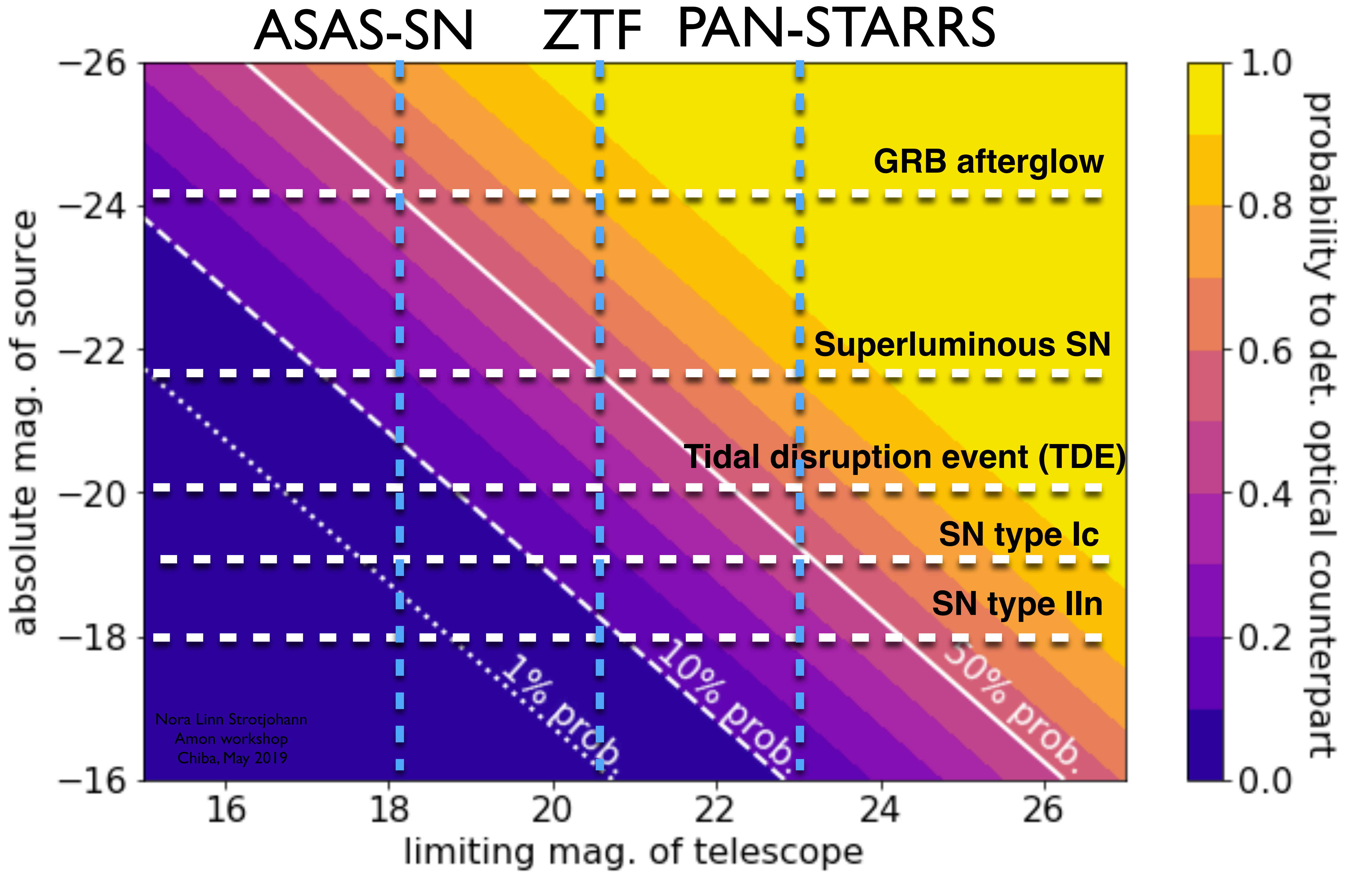


Magnitudes of sources detected with one event

- here for an absolute optical magnitude of -20
- most counterparts are close to the detection limit of a typical telescope

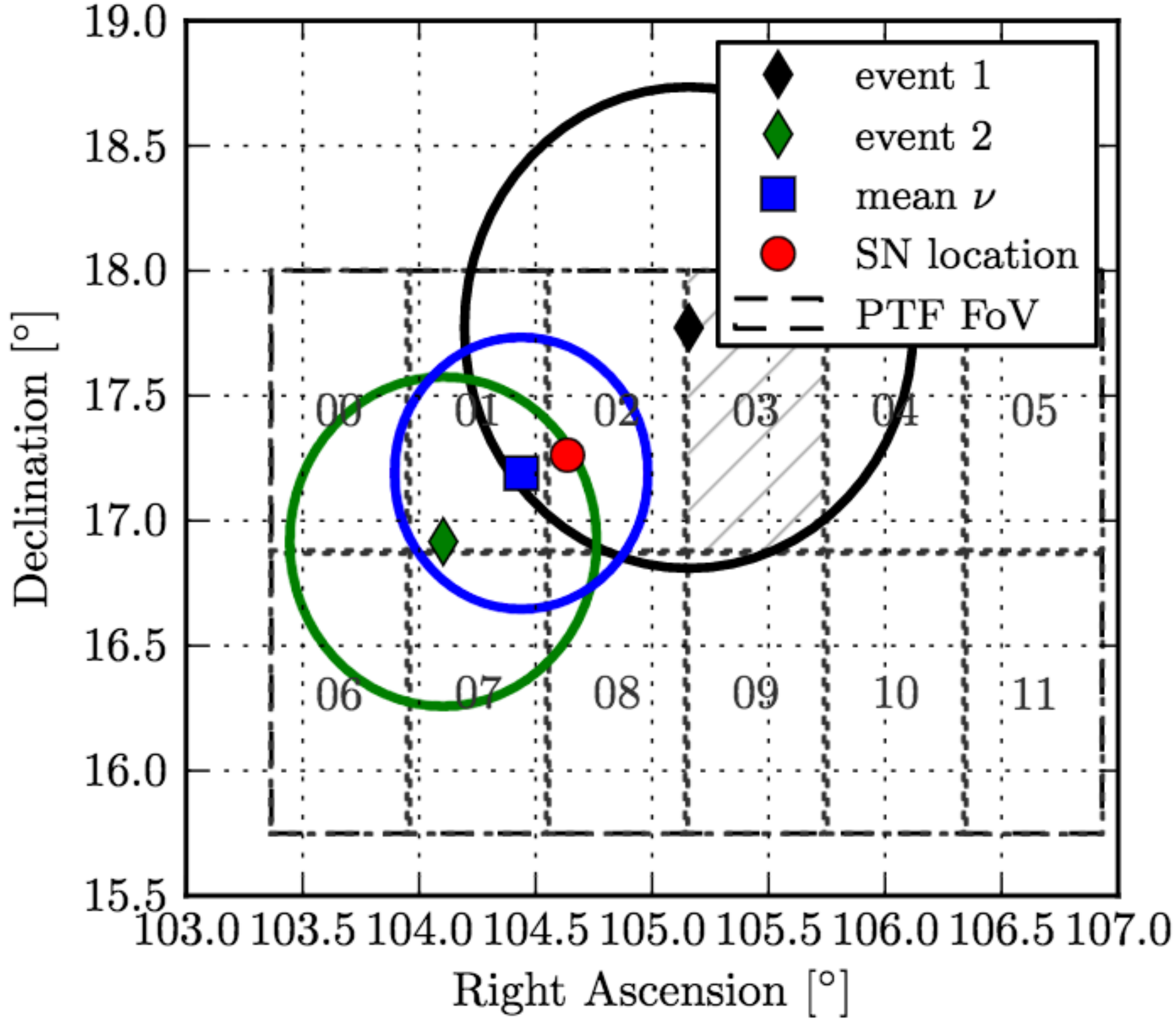


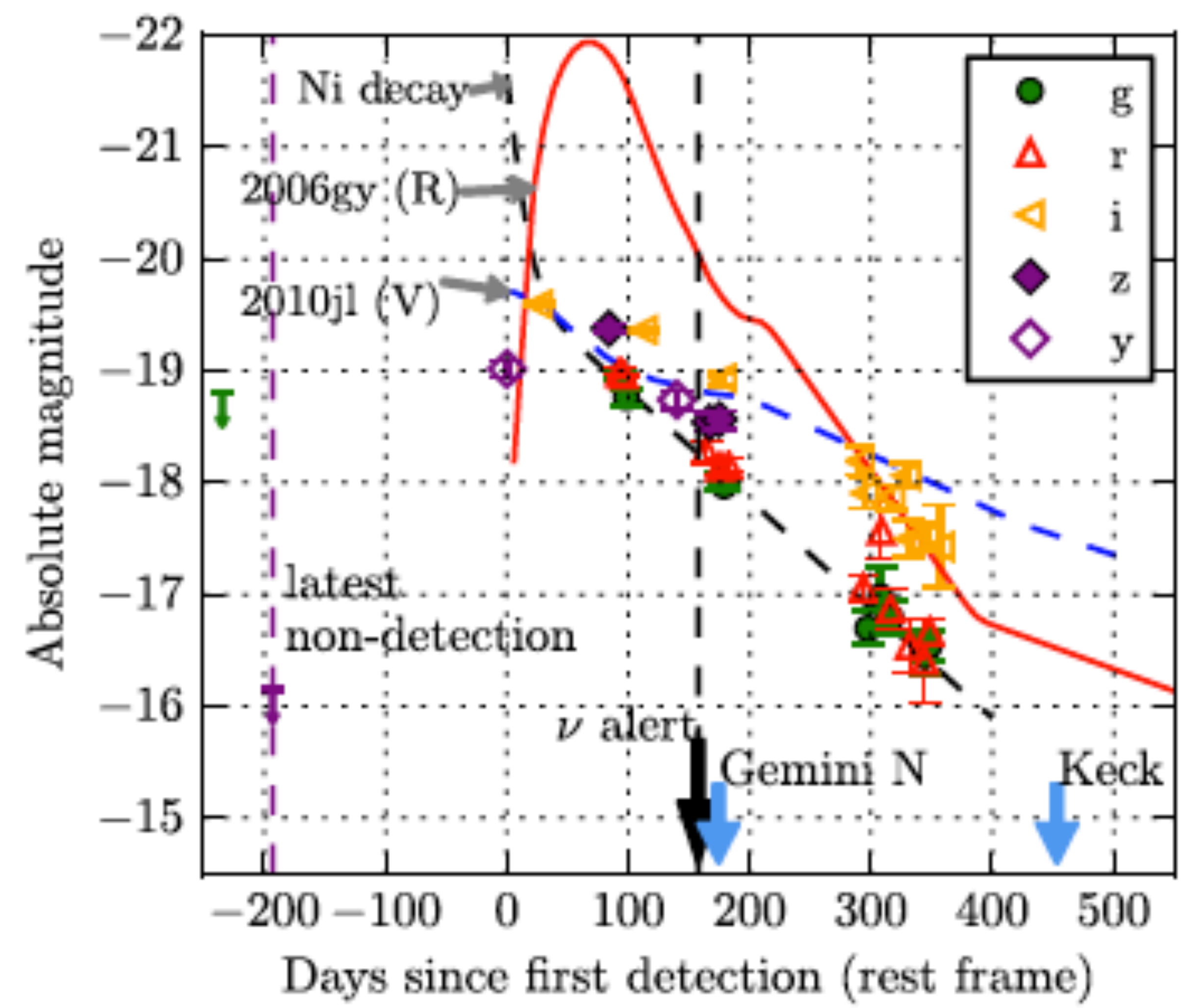
Follow up and detection probability



IceCube/PTF/Swift/Pan-STARRS Astrophys.J. 811 (2015) no.1, 52

Detection of a SN IIn in Optical Follow-up Observations of IceCube Neutrino Events





Optical Follow up resulted in the discovery of a Supernova Type IIn (z=0.0684) PTF12csy 0.2° away from the neutrino alert direction.

Causal connection is unlikely, explosion at least 158 days before neutrino observation

A posteriori significance of the detection is 2.2σ

Neutrino Triplet

IceCube arXiv:1702.06131v1

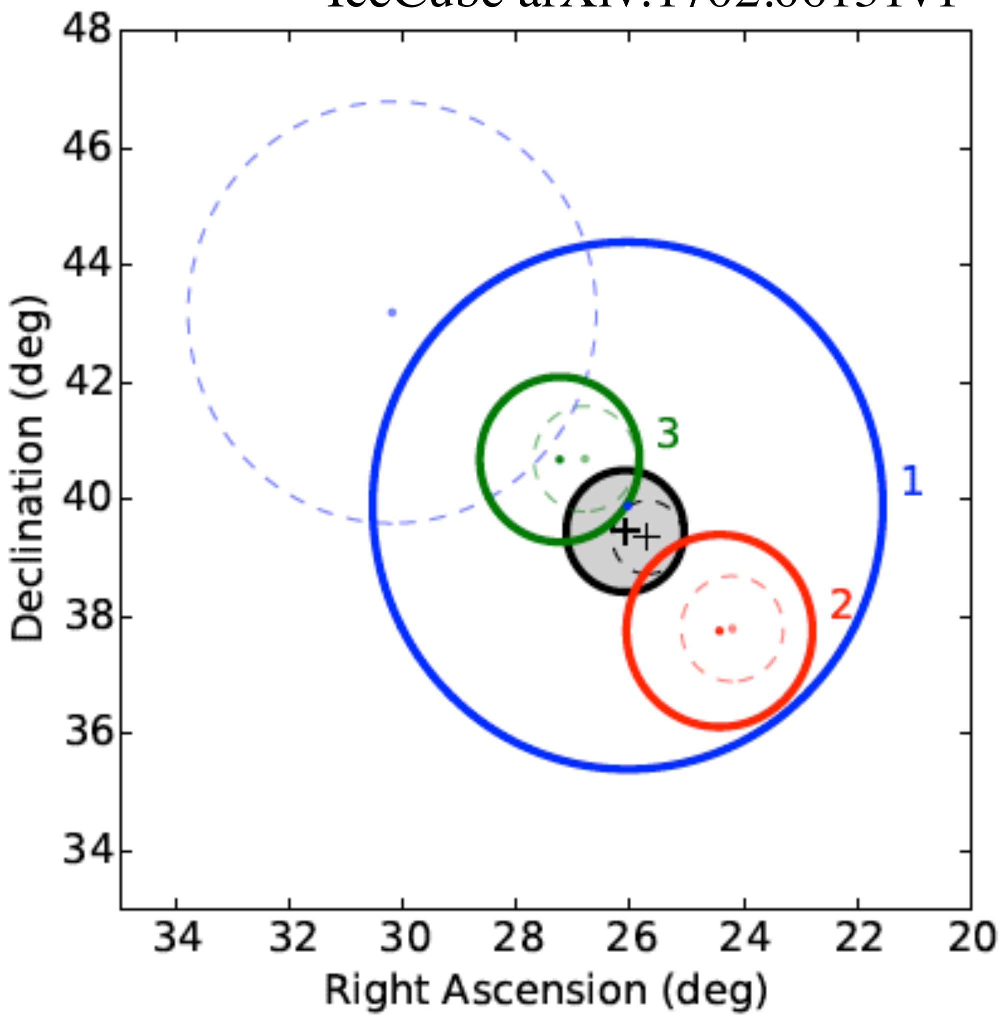


Fig. 1: Location of the three neutrino candidates in the triplet with their 50% error circles. The plus sign shows the combined direction and the shaded circle is the combined 50% error circle. The solid circles show the results of the MPE reconstruction which is as the default reconstruction in the following and the thin dashed circles correspond to the results of the Spline MPE reconstruction (compare Table 1).

IceCube arXiv:1702.06131v1

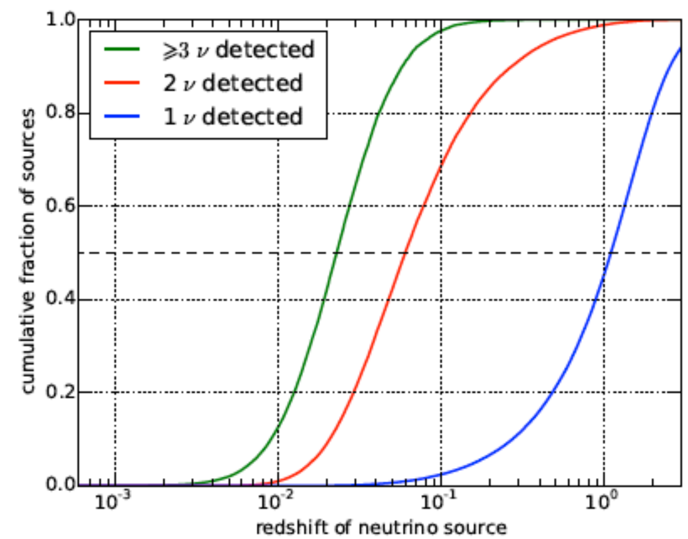
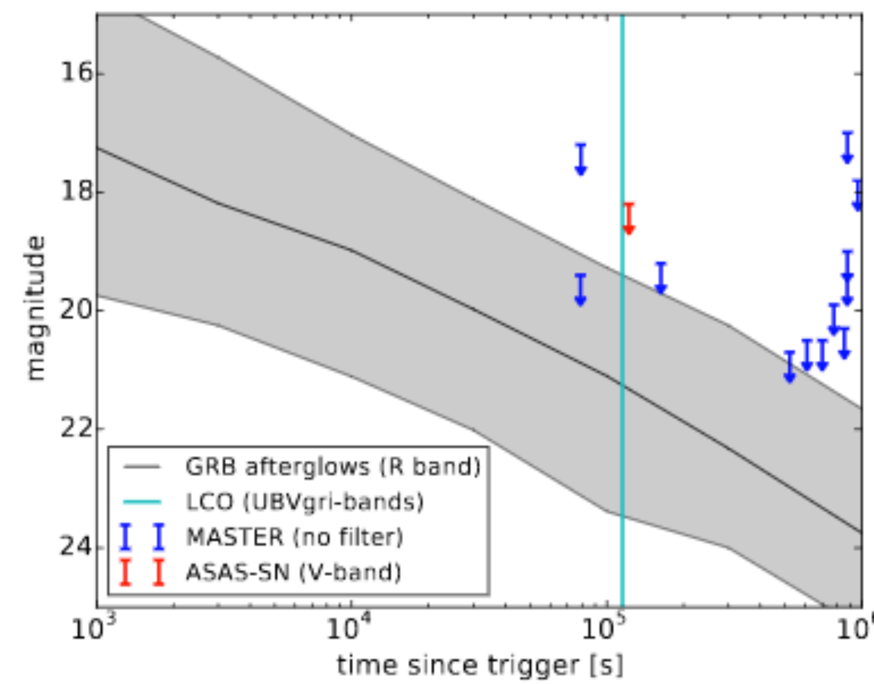


Fig. 8: Probability of detecting a neutrino source within a certain redshift. The figure was generated by simulating a population of transient neutrino sources with a density of $4 \times 10^{-6}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$ distributed in redshift according to the star-formation rate and normalized to produce the detected astrophysical neutrino flux. Sources detected with only one single neutrino are on average far away (median redshift of 1.1), while sources detected with three or more neutrinos must be located nearby.



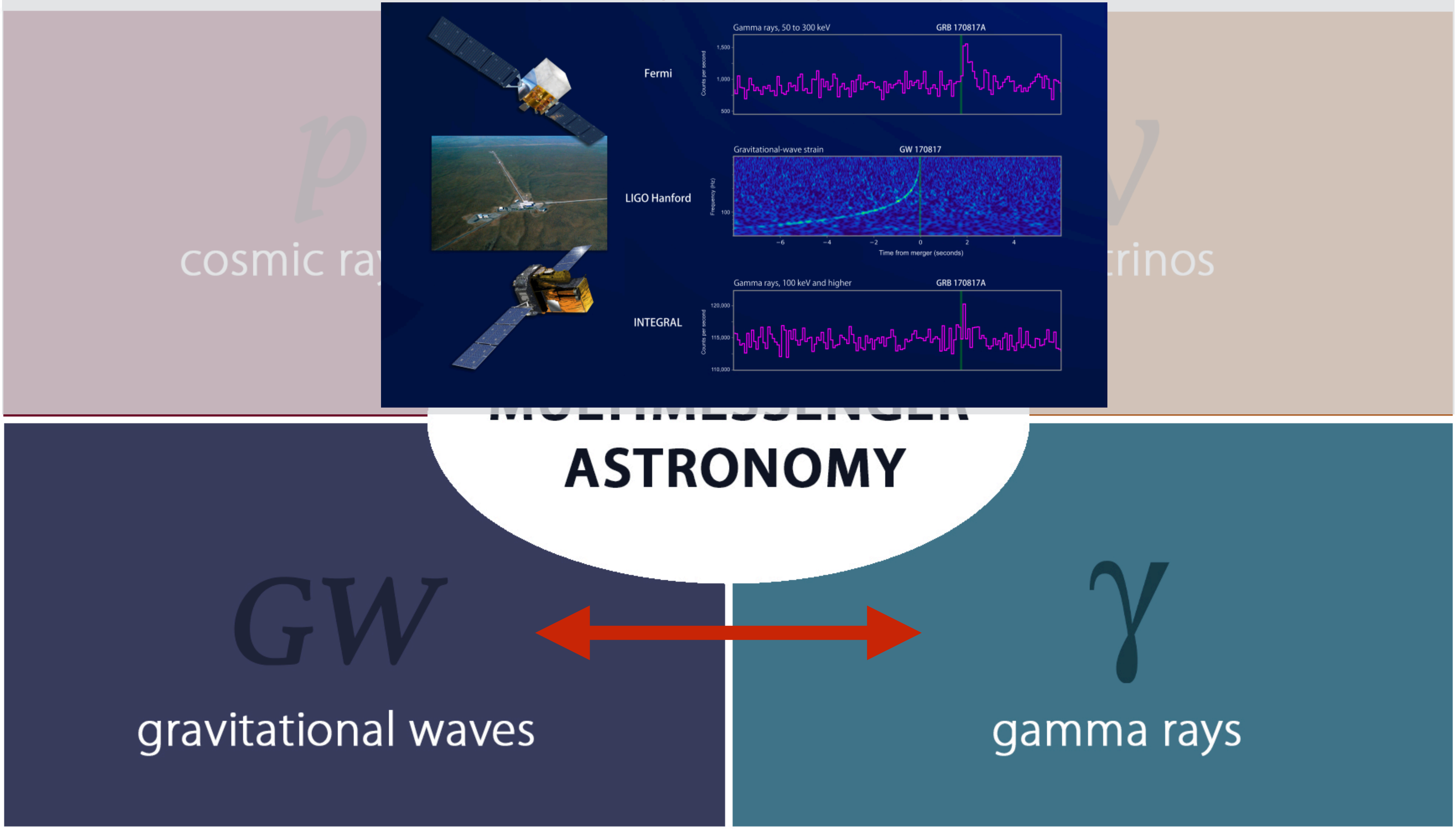
(b) Optical GRB light curves.

Observation of a neutrino triplet event, optical follow up was triggered, no likely counterparts observed.
(Random neutrino triplet events occur every 13.6yrs)

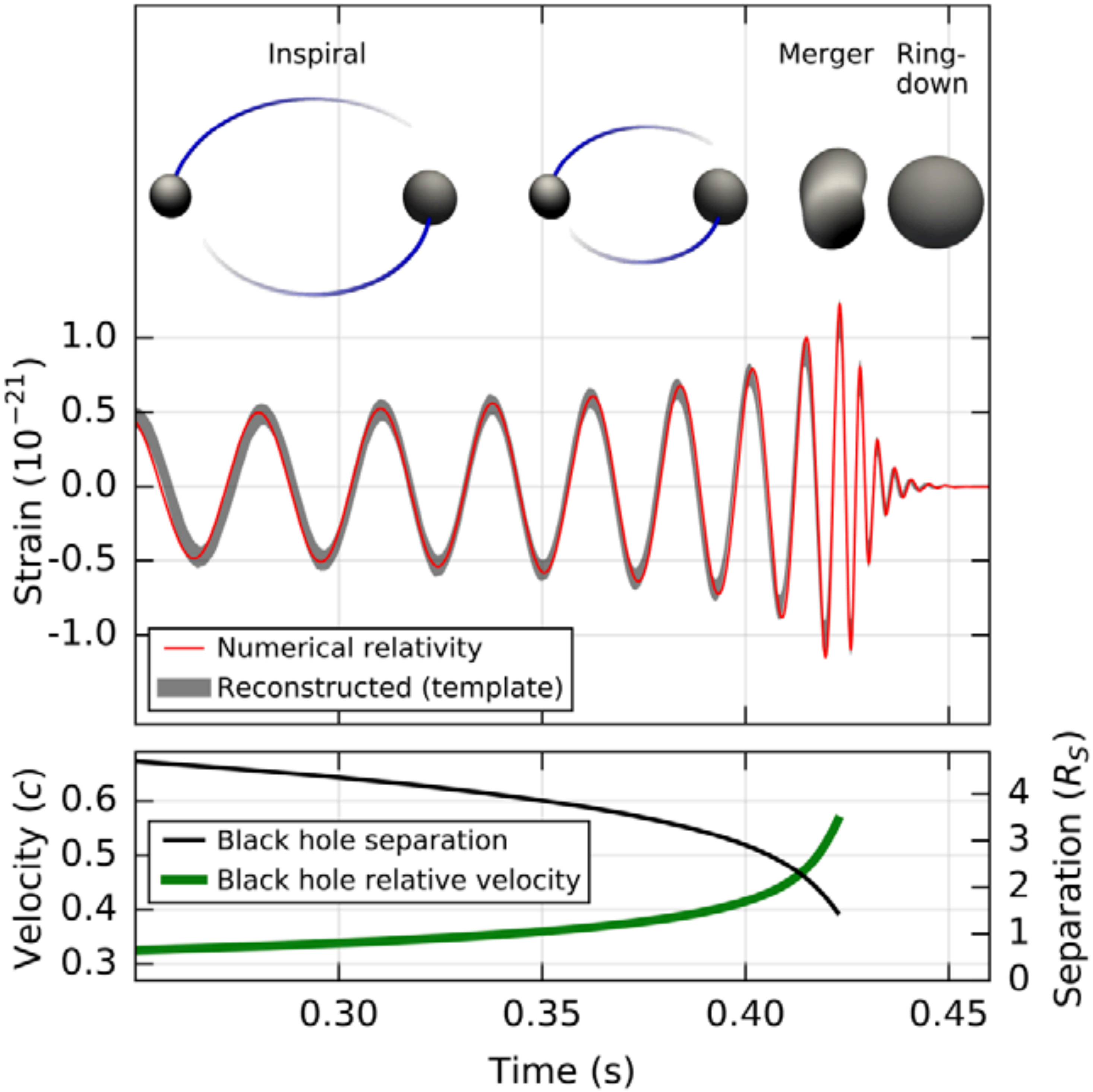
Graviational Wave Follow Ups

Multi-Messenger Astrophysics

GW170817 and GRB170817



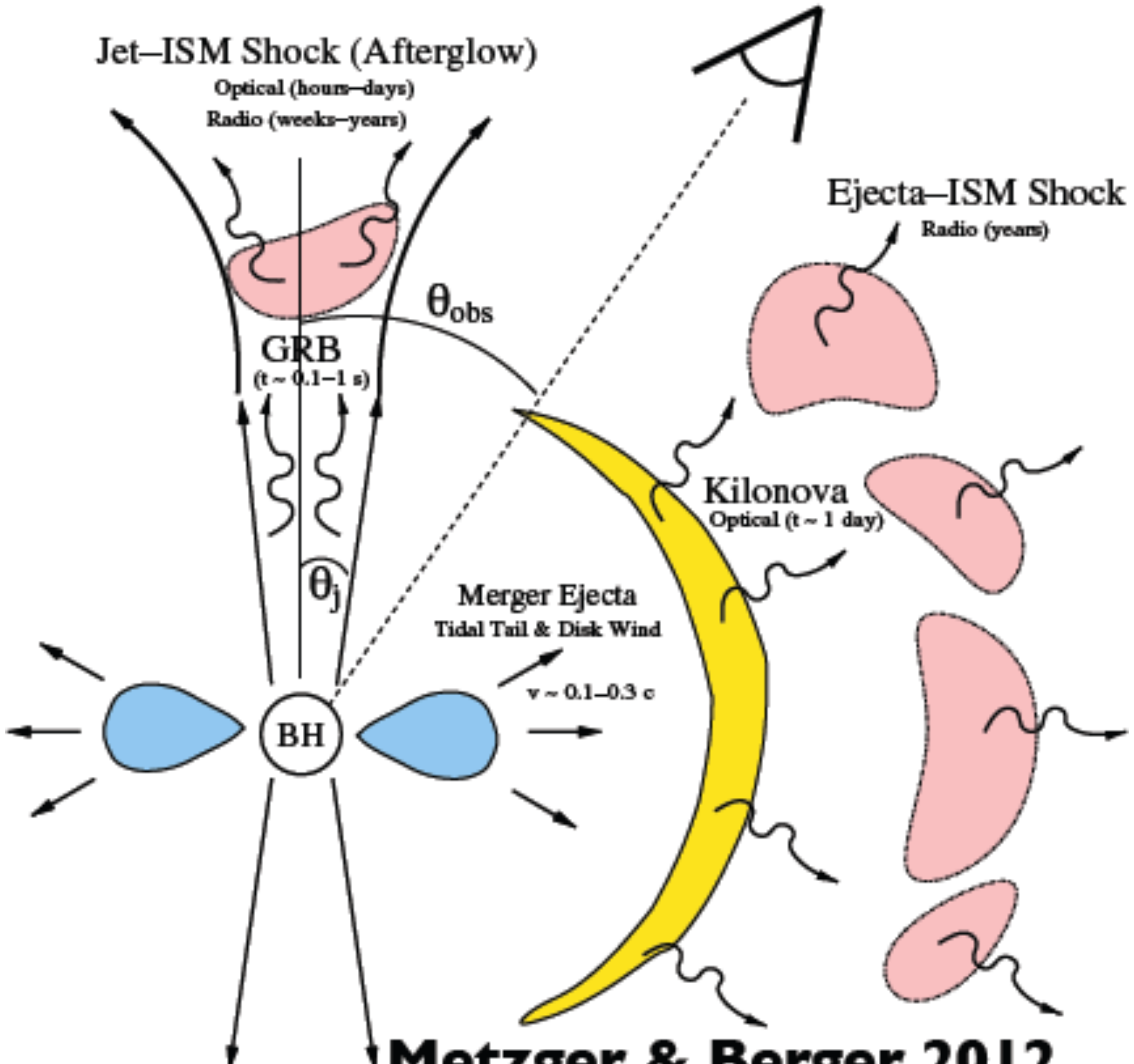
Era of GW astronomy



- The era of GW astronomy has started in 2015
  - GW150914 (BH-BH merger)
  - Nobel Prize 2017
- However, GW alone no accurate position
- Detection of counter part highly desired
  - Accurate position
  - Accurate redshift/distance
  - Astrophysical studies
    - Event classification
    - Search for new phenomena (e.g., kilonova)
    - Cosmological application

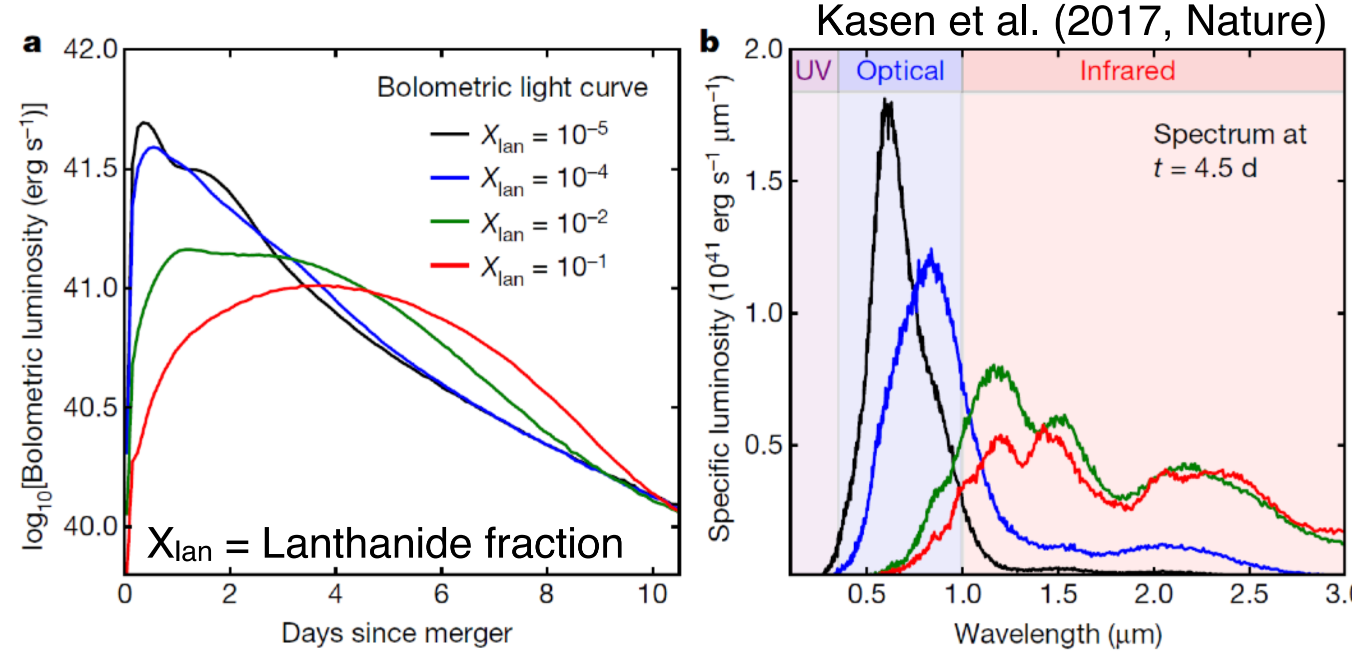
EM signatures from BNS merger

- EM signatures from NS-NS merger (BNS)
  - **On-axis** - short GRB (sGRB)
  - **Off-axis** - radio emissions
  - **Radioactive emission**
    - kilonova, macronova, …



Metzger & Berger 2012, ApJ, 746, 48

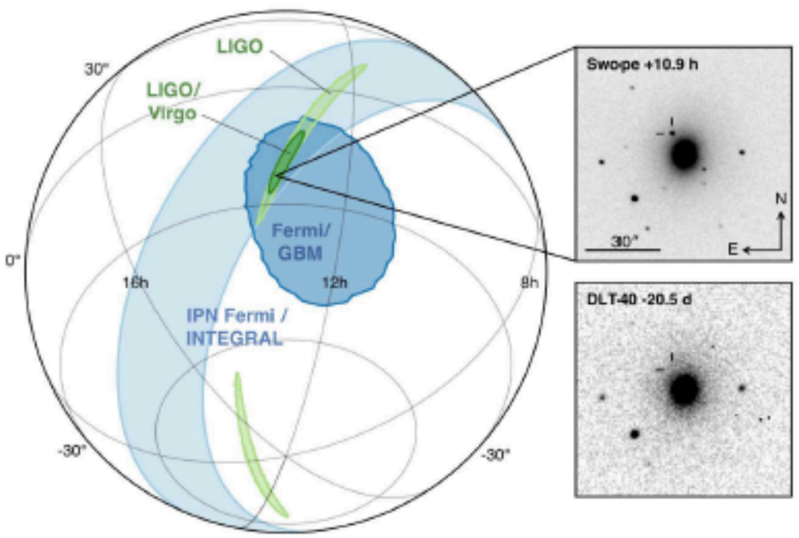
Kasen et al. (2017, Nature)



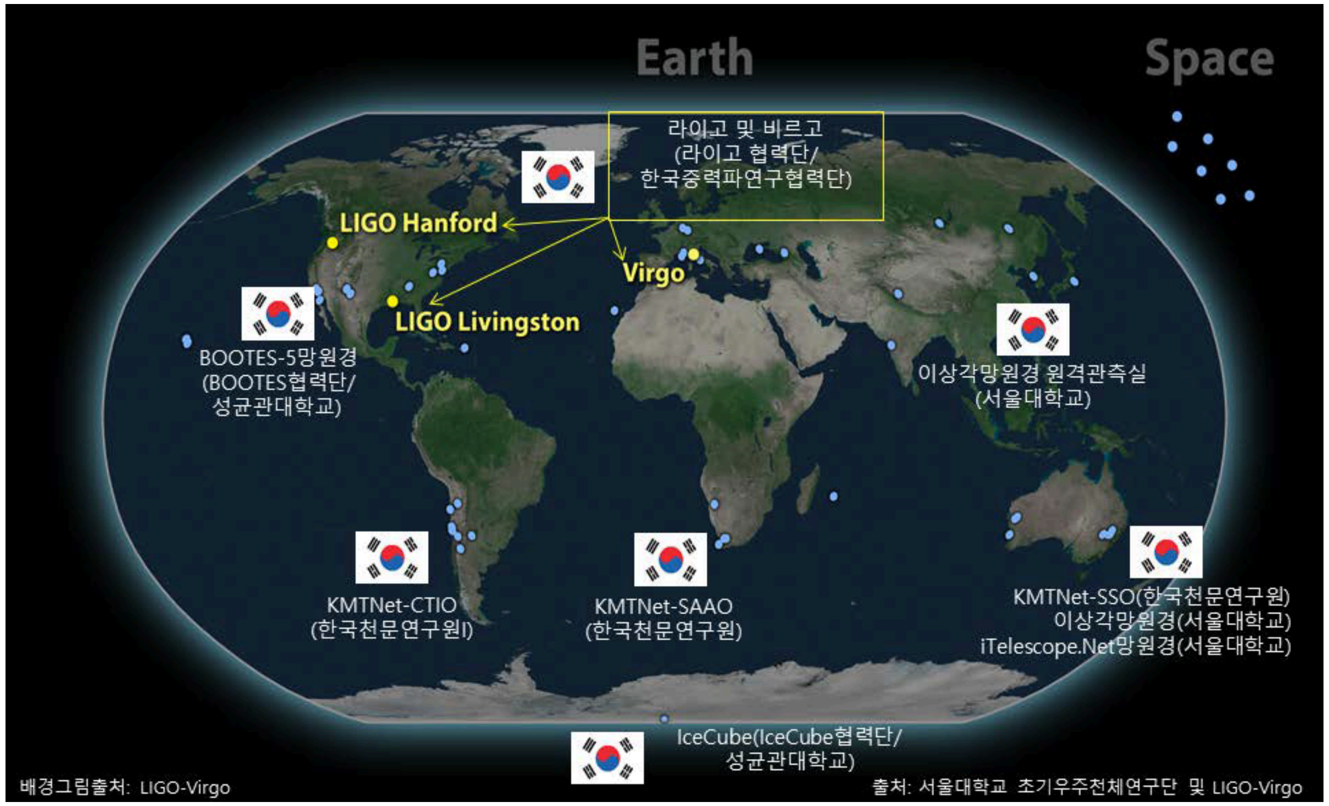
GW170817: NS-NS merger Optical counterpart discovery

GW170817

- 8 telescopes in Chile spotted GW counterpart at 11 hours after GW detection
- NGC 4993 at ~40 Mpc (RA:13h09m47s, Dec:-23d23m02s)



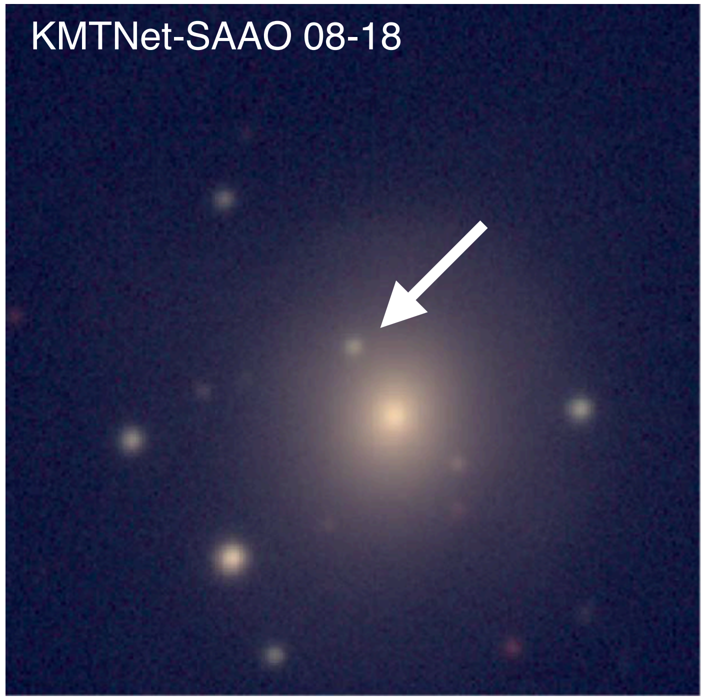
"MMA paper"
LIGO, Virgo,
Partner Astronomy Groups
2017, ApJL



- At 2017-8-18, about 21 hours after the GW detection, the GW EM counterpart was detected by LSGT (0.43m telescope!)

Lee Sang Gak Telescope
(Siding Spring Observatory)

Optical counterpart detection by LSGT



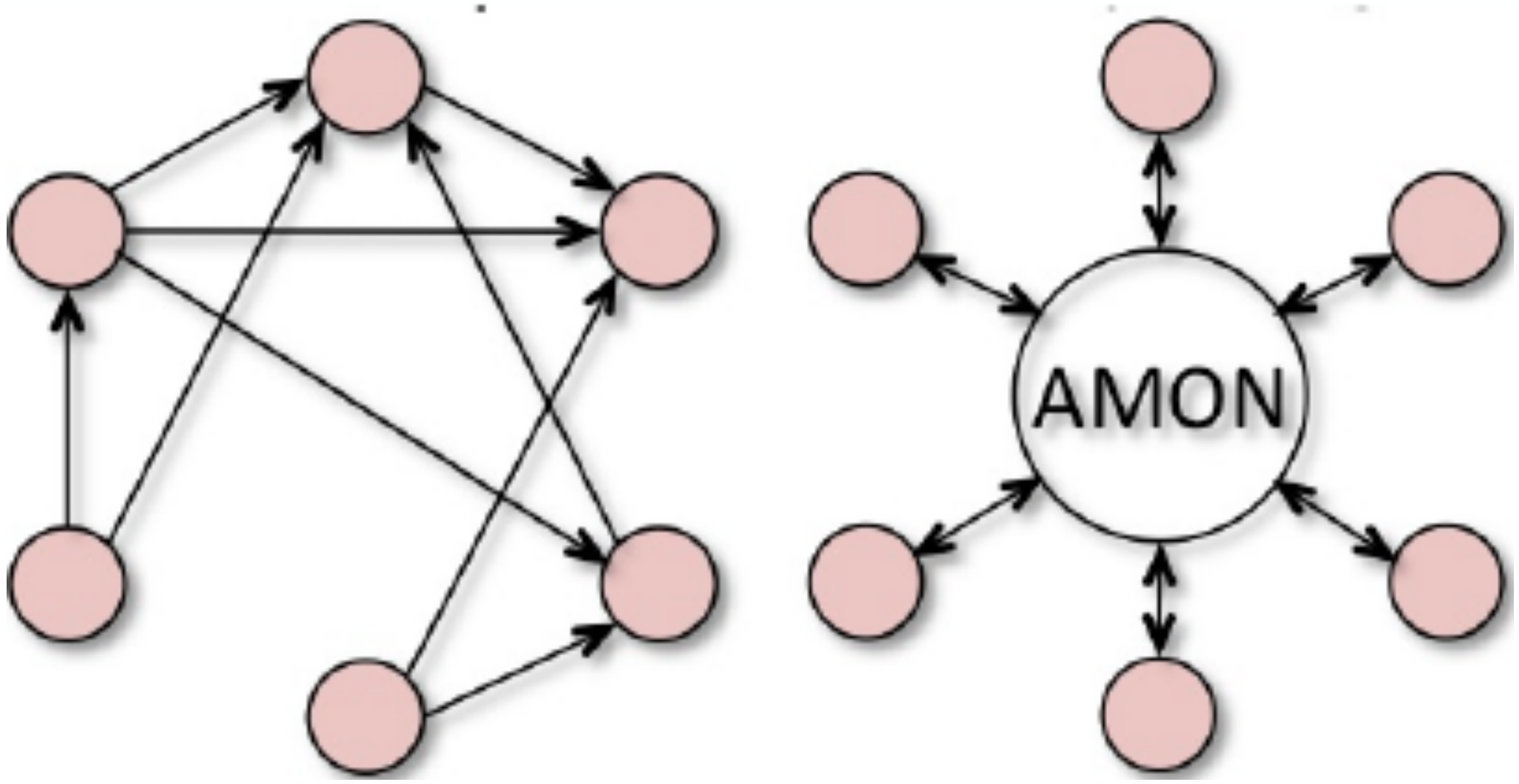
AMON

Astrophysical Multimessenger Observatory Network

http://www.amon.psu.edu/

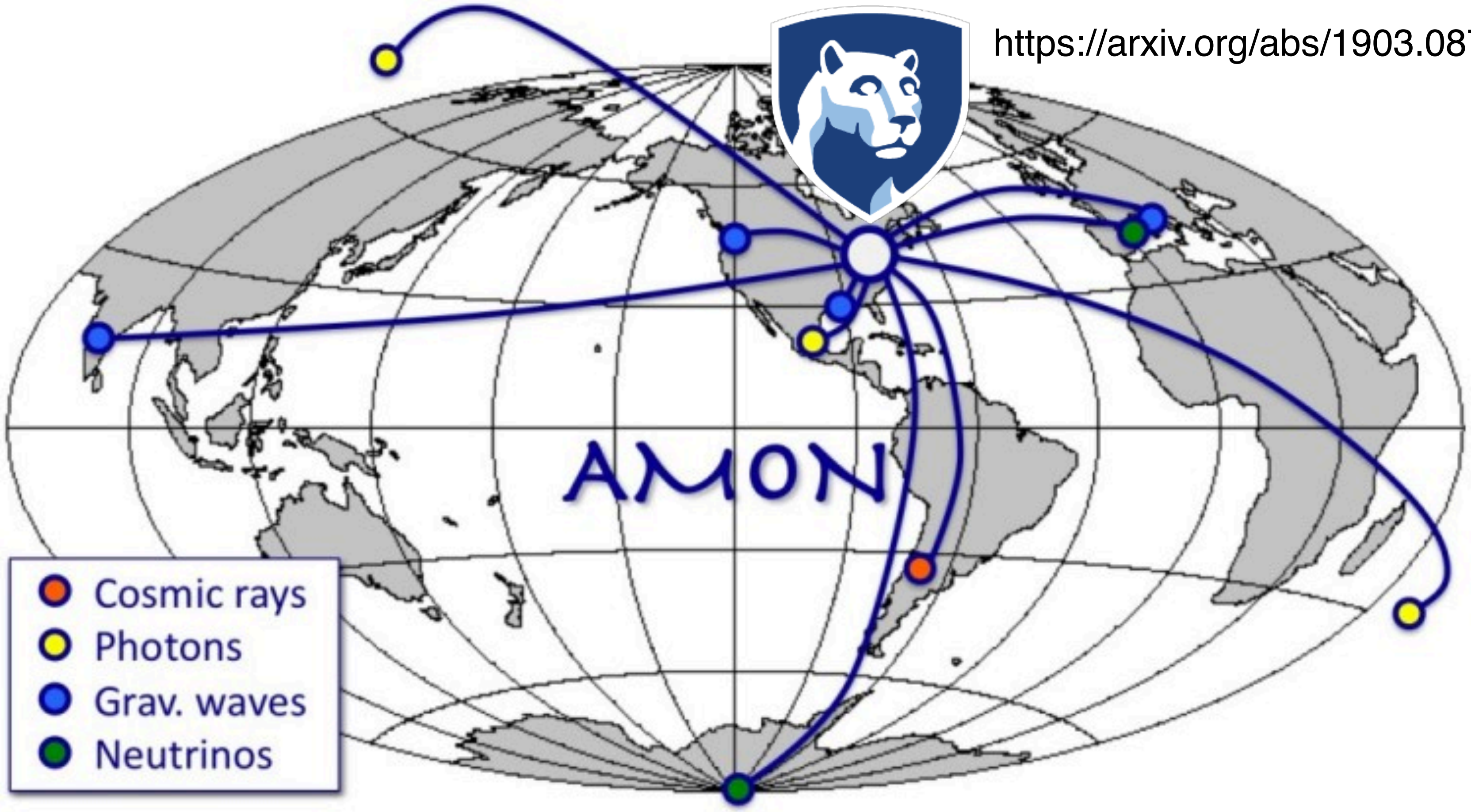
AMON Concept

Astrop.Phys. Vol. 45, 56–70, 2013



- Real-time and near real-time sharing of sub threshold data among multimessenger observatories
- Real-time and archival searches for any coincident (in time and space) signals.
- Prompt distribution of alerts for follow-up observations

AMON



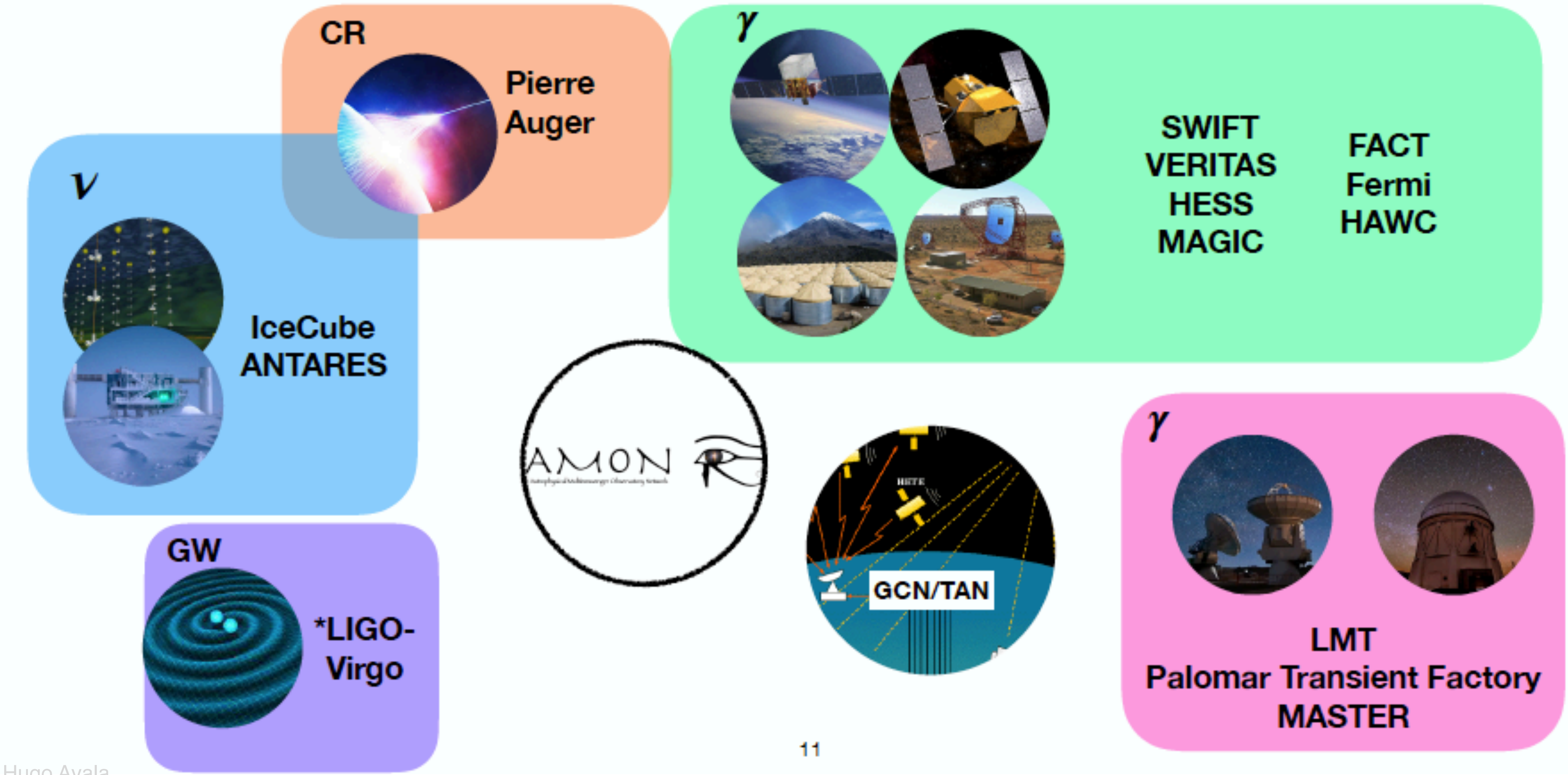
https://arxiv.org/abs/1903.08714

- AMON using sub-threshold data for multimessenger searches in real-time.
- AMON greatly simplifies multimessengers searches:
  - Common data format, transfer protocol, event database, MoUs.

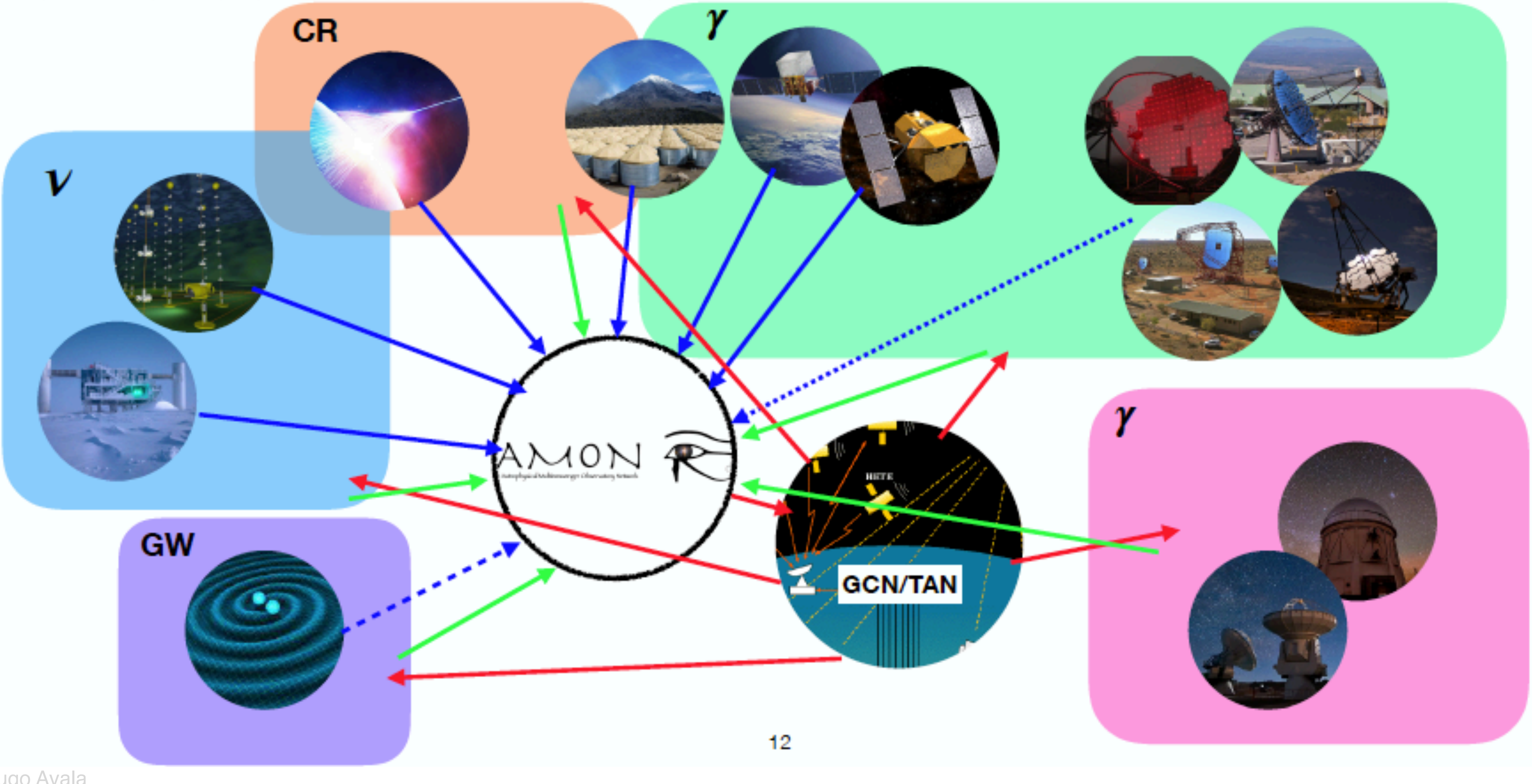
Astrophysical Multi-messenger Observatory Network (AMON)
Main idea: (Near) Real-time searches for transients to advance multimessenger astrophysics.

- Real-time coincidences:
  - Receive event data from different observatories and perform an immediate analysis
- Sub-threshold data:
  - Receive data that is below the detection threshold of an individual observatory
  - Careful coincident analysis can bring a sub-threshold event data into a possible detection

AMON members and prospective* members.

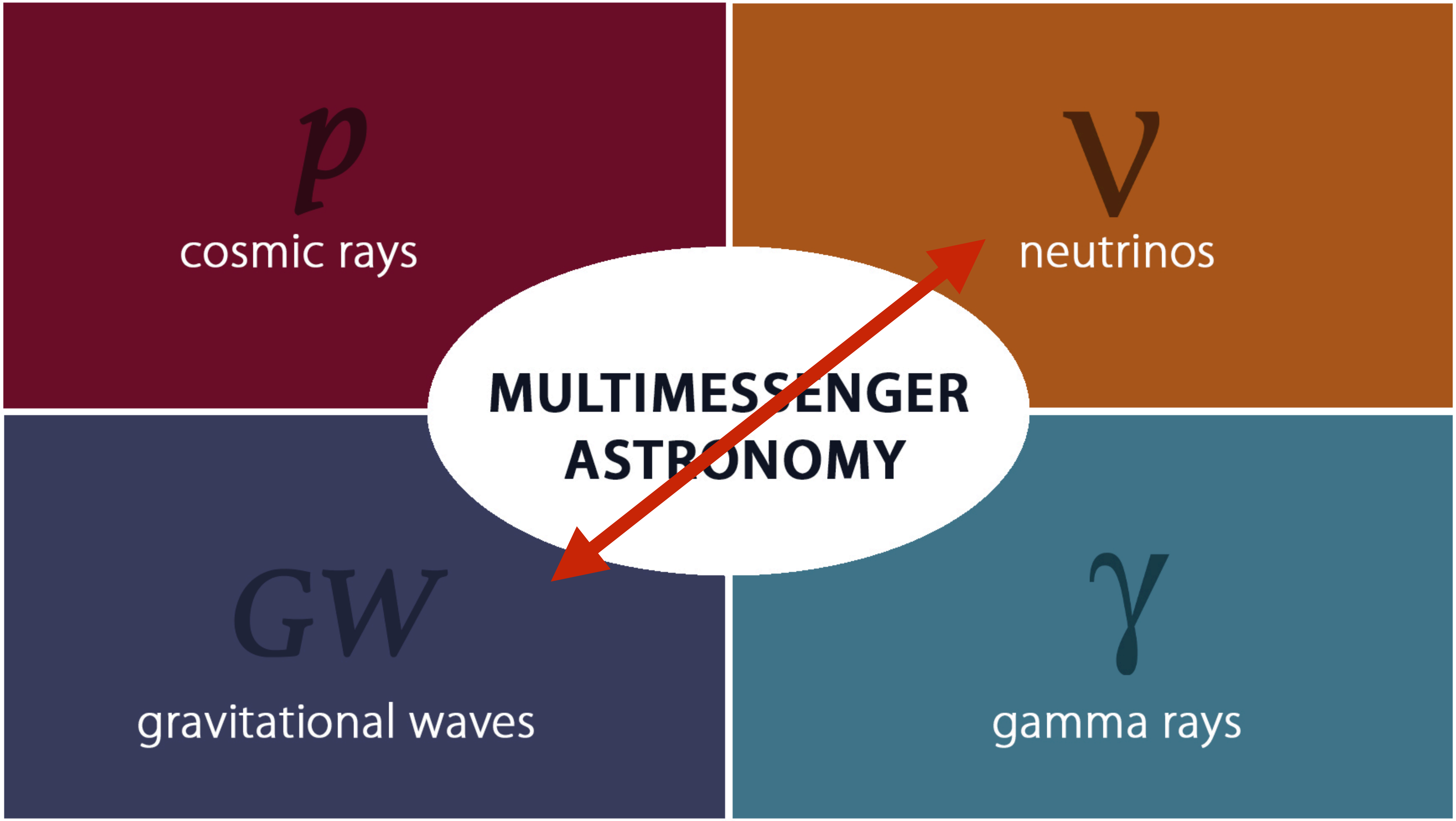


AMON receives sub-threshold data events and sends alerts to GCN/TAN which then are distributed to partner observatories/public. Interesting follow-ups are sent back to AMON and AMON then broadcasts alert revisions



GW+Neutrino ?

Multi-Messenger Astrophysics



The Astrophysical Journal Letters, 850:L35 (18pp), 2017 December 1 https://doi.org/10.3847/2041-8213/aa9aed

Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration, and LIGO Scientific Collaboration and Virgo Collaboration
(See the end matter for the full list of authors.)

Received 2017 October 15; revised 2017 November 9; accepted 2017 November 10; published 2017 November 29

Abstract

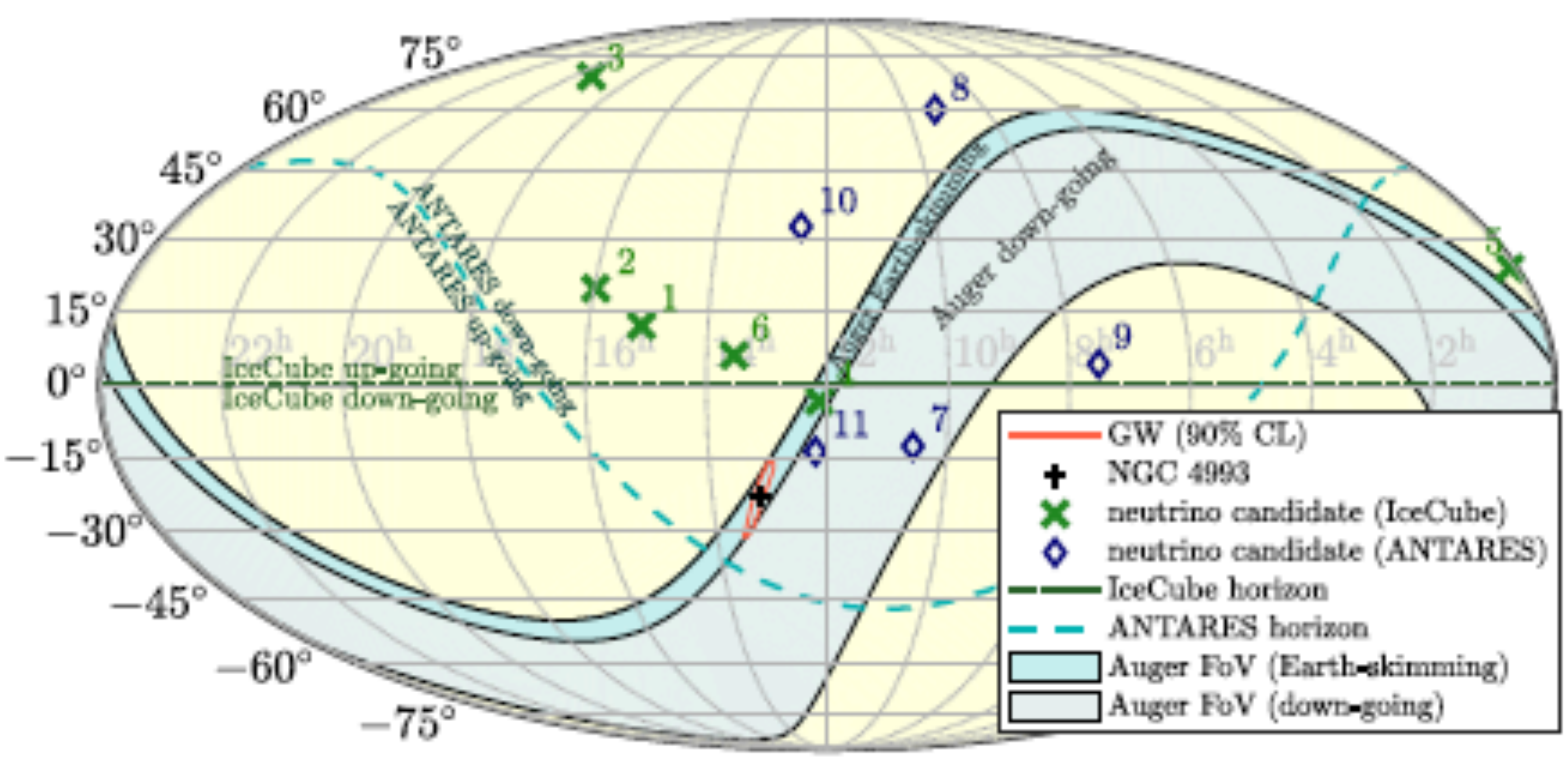
The Advanced LIGO and Advanced Virgo observatories recently discovered gravitational waves from a binary neutron star inspiral. A short gamma-ray burst (GRB) that followed the merger of this binary was also recorded by the *Fermi* Gamma-ray Burst Monitor (*Fermi*-GBM), and the Anti-Coincidence Shield for the Spectrometer for the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*), indicating particle acceleration by the source. The precise location of the event was determined by optical detections of emission following the merger. We searched for high-energy neutrinos from the merger in the GeV–EeV energy range using the ANTARES, IceCube, and Pierre Auger Observatories. No neutrinos directionally coincident with the source were detected within ±500 s around the merger time. Additionally, no MeV neutrino burst signal was detected coincident with the merger. We further carried out an extended search in the direction of the source for high-energy neutrinos within the 14 day period following the merger, but found no evidence of emission. We used these results to probe dissipation mechanisms in relativistic outflows driven by the binary neutron star merger. The non-detection is consistent with model predictions of short GRBs observed at a large off-axis angle.

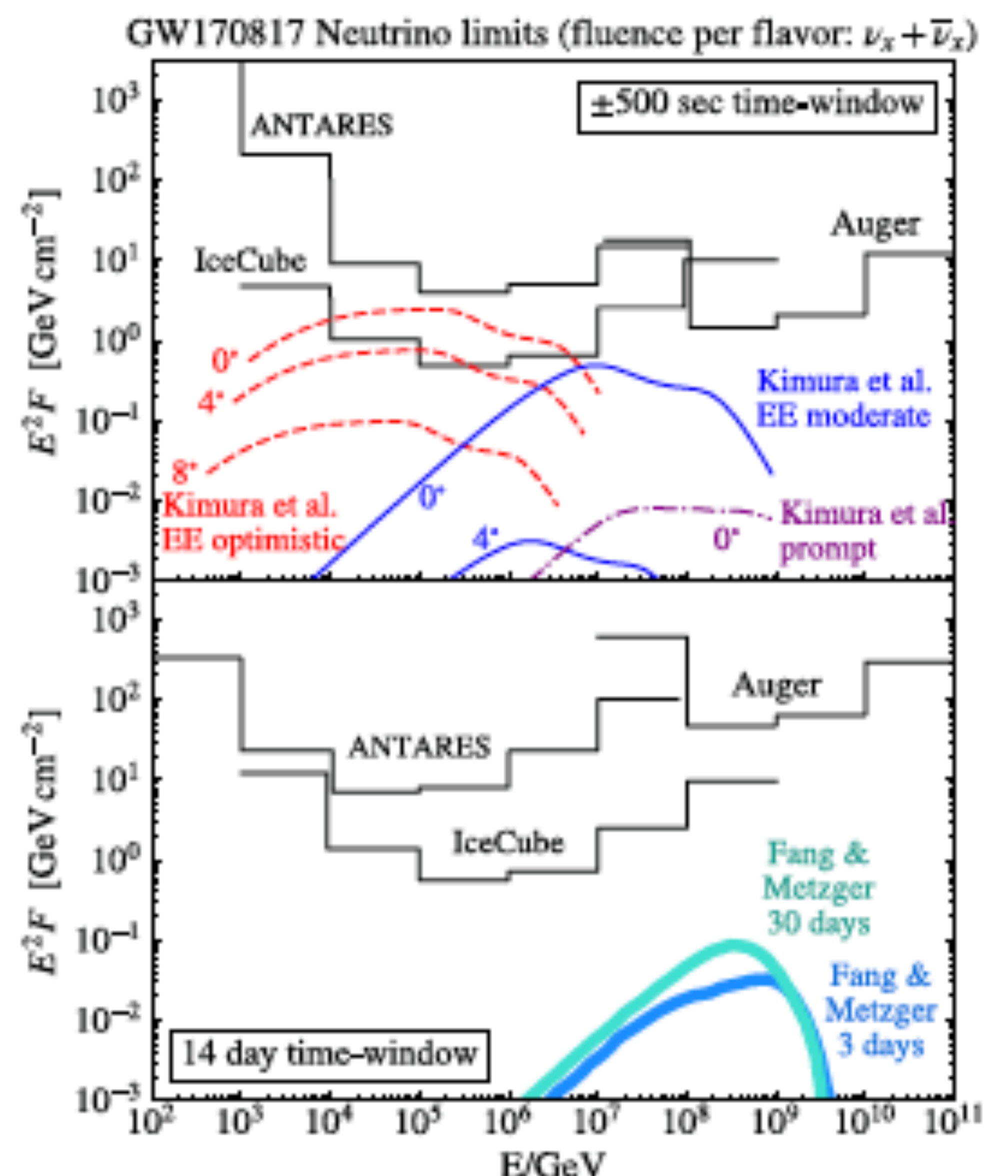
Gravitational Waves

GW170817

- binary neutron star inspiral
- followed by short GRB (observed by Fermi-GBM)

Imre Bartos Neutrino 2018





- Search within 1000 s and 2-week time windows (model motivated).
- Complementary sensitivity from the three detectors.
- No significant coincident detection.
- On-axis emission could have produced detectable emission in some models.

ANTARES, IceCube, Auger, LIGO, Virgo 2017

Recent events

- Neutrino observed in coincidence with Gravitational wave ! … but significance from this event alone is not very high

TITLE: GCN CIRCULAR
NUMBER: 25192
SUBJECT: LIGO/Virgo S190728q: One neutrino candidate from IceCube search
DATE: 19/07/28 10:06:18 GMT
FROM: Raamis Hussain at IceCube <raamis.hussain@icecube.wisc.edu>

IceCube Collaboration (http://icecube.wisc.edu/) reports:

A search for track-like muon neutrino events detected by IceCube consistent with the sky localization of gravitational-wave candidate S190728q in a time range of 1000 seconds [1] centered on the alert event time (2019-07-28 06:36:50.529 UTC to 2019-07-28 06:53:30.529 UTC) has been performed. During this time period IceCube was collecting good quality data. The search is a maximum likelihood analysis which searches for a generic point-like neutrino source coincident with the given GW skymap [2].

One track-like event is found in spatial and temporal coincidence with the gravitational-wave candidate S190728q calculated from the map circulated in the 4-Initial notice. This represents an overall p-value of 0.03 (1.84 sigma).

An earlier search (GCN 25185) based on preliminary information of S190728q yielded no significant p-values for the worse GW localization [3].

Properties of the coincident events are shown below.

dt	ra (deg)	dec (deg)	Angular Uncertainty(deg)	p-value(generic transient)
-360	312.87	5.85	4.81	0.039

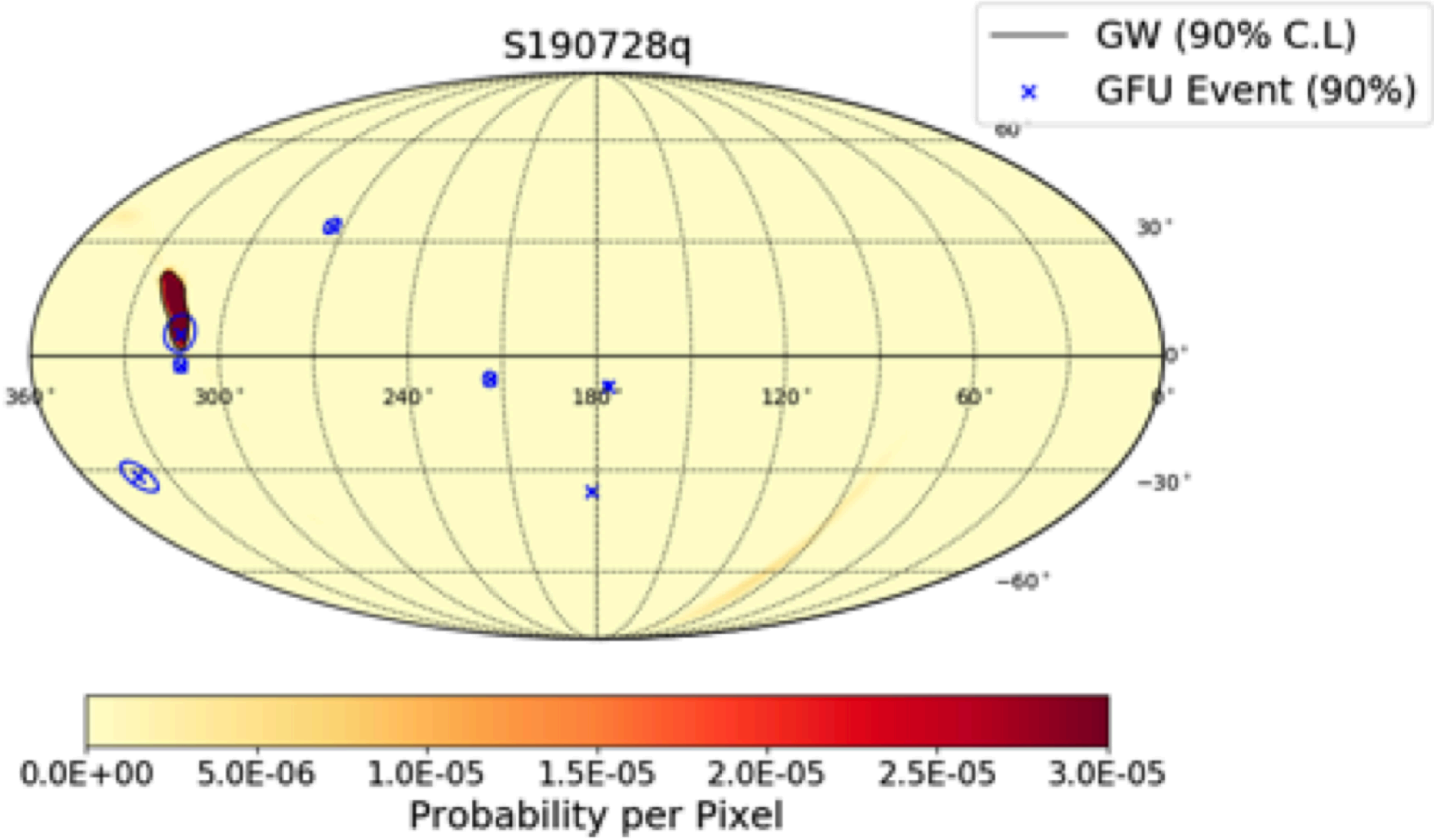
where:
dt = Time offset (sec) of track event with respect to GW trigger.
Angular uncertainty = Angular uncertainty of track event: the radius of a circle representing 90% CL containment by area.
p-value = the p-value for this specific track event
RA & Dec = Right ascension and declination in degrees quoted in J2000 epoch

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica. The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu

[1] Baret et al., Astroparticle Physics 35, 1 (2011)
[2] Braun et al., Astroparticle Physics 29, 299 (2008)
[3] GCN 25185: https://gcn.gsfc.nasa.gov/gcn3/25185.gcn3

https://gcn.gsfc.nasa.gov/gcn3/25192.gcn3

Gravitational Waves Follow Up

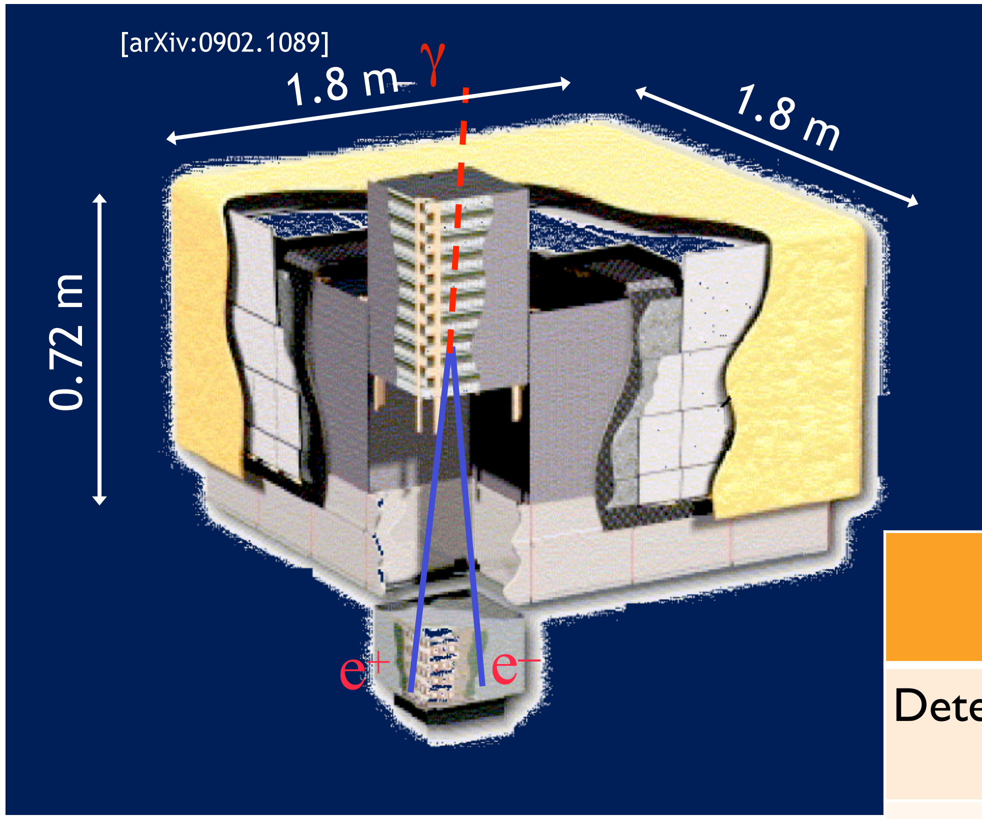


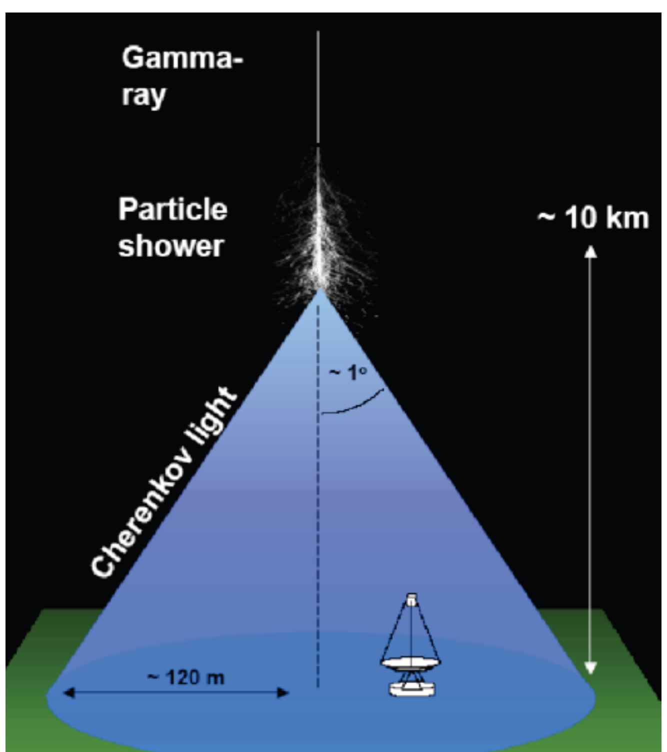
https://gcn.gsfc.nasa.gov/gcn3/25192.gcn3

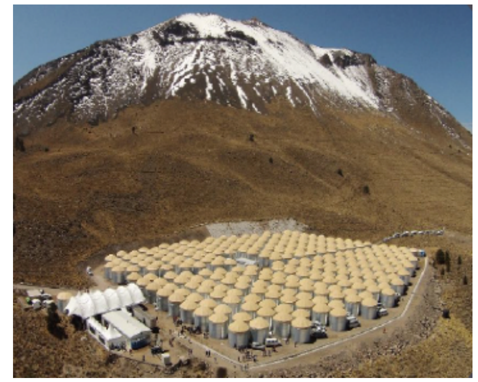
dt	RA (deg)	Dec (deg)	Angular uncertainty (deg)	P-value (Bayesian)	P-value (generic transient)
-360s	312.87	5.85	4.81	0.010 (2.33 σ)	0.016 (2.21 σ)

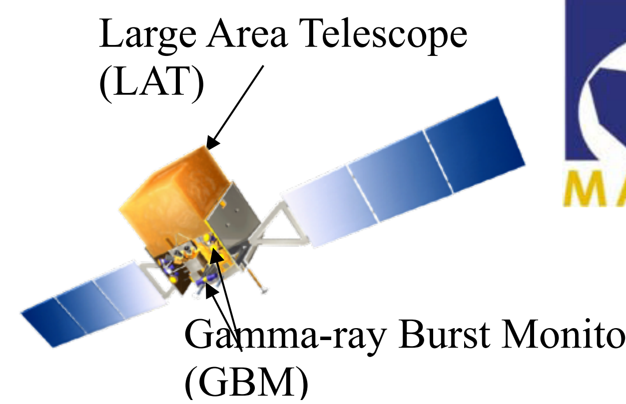
Gamma-ray observatories

gamma-rays









MAGIC

VERITAS

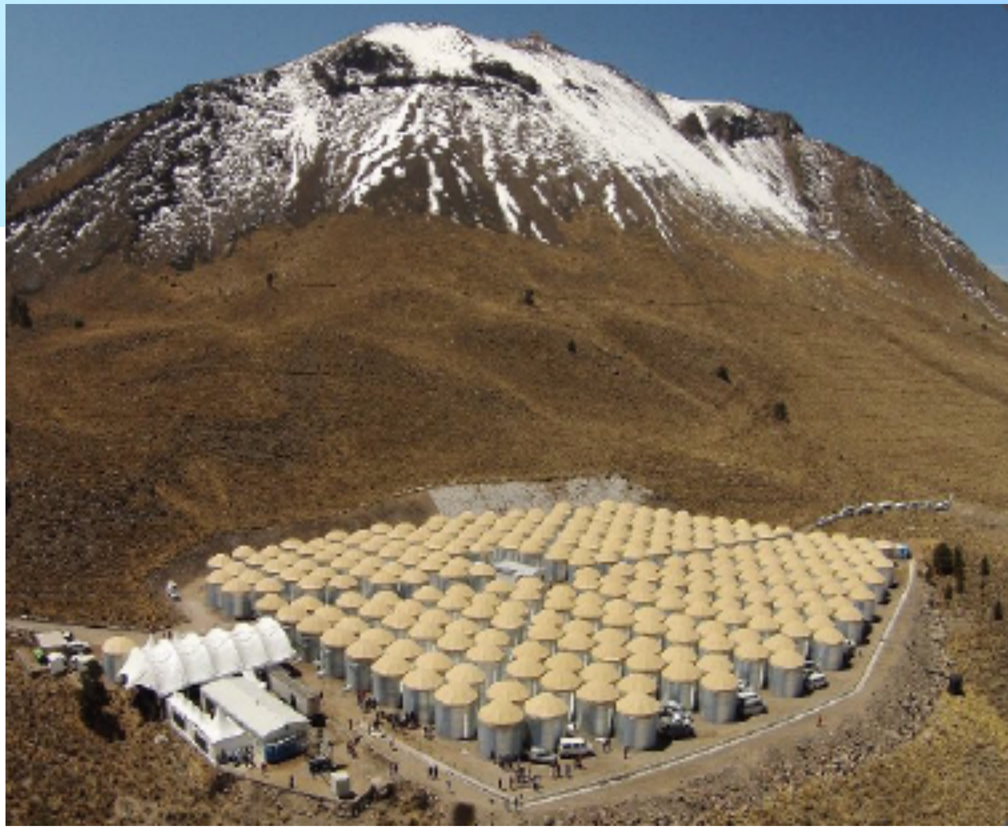
	High Altitude Water Cherenkov	Fermi-LAT	Imaging Air Cherenkov Telescopes
Detection Method	Water-cherenkov surface em-shower	Pair conversion	Cherenkov light from particle shower
Effective Area	0.1km^2 (above 10TeV)	1m^2	~400-500m^2
Field of View (FOV)	2sr (coverage 8sr)	2.5sr	3.5° - 5.0°
Duty cycle	~100%	~100%	~15-10%
Energy range	100GeV - 100TeV	20MeV - 300GeV	>100GeV
Energy resolution	<50%(@10TeV)	4% (@5GeV) 2% (@200GeV)	10% - 20%
Angular resolution	~0.1° (@100TeV) ~0.5° (@1TeV) ~2.0°(@100GeV)	~0.1° (@10GeV) ~3.5°(@100MeV)	0.1° at 100 GeV

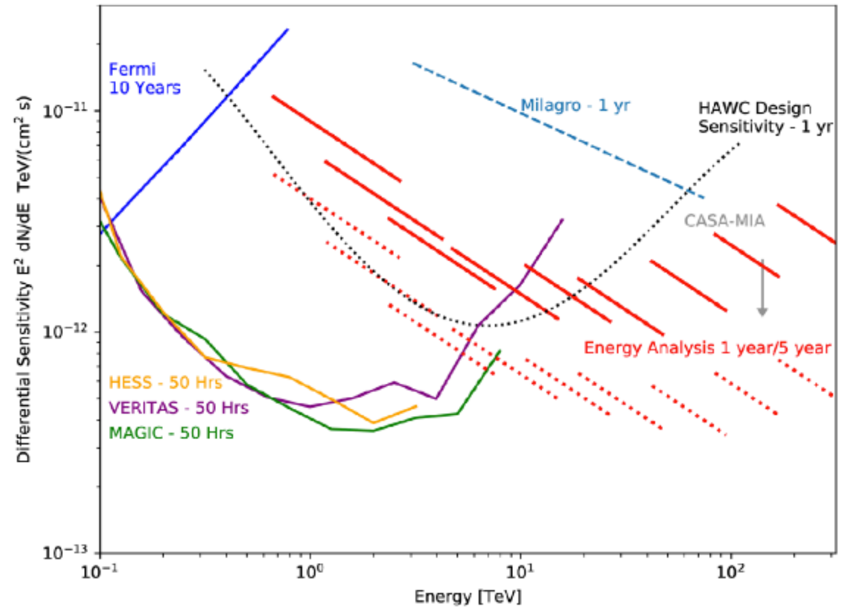
large FOV — pointed observations

continuous operations

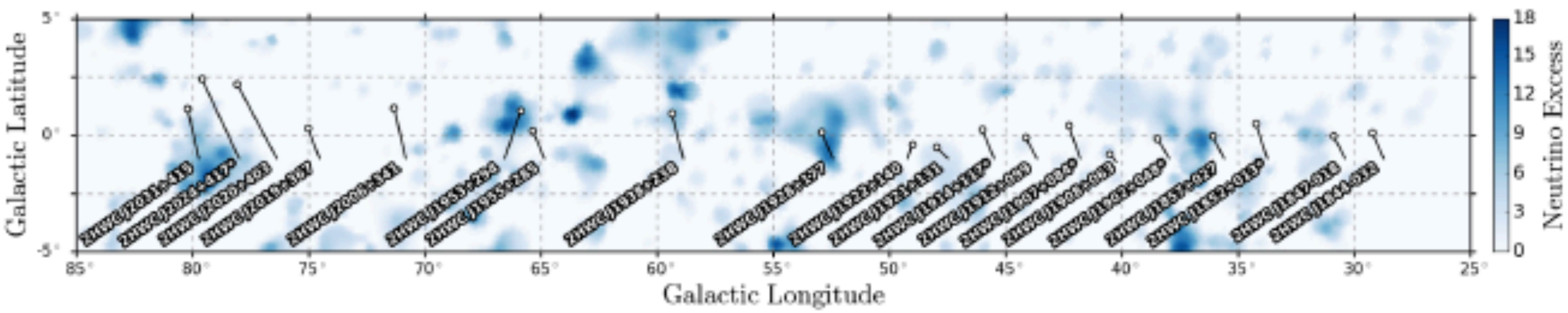
Gamma-ray continuous

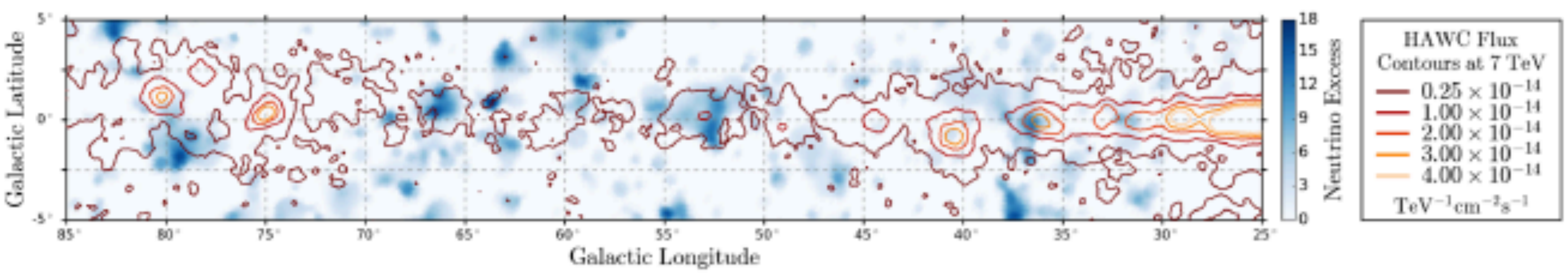
HAWC Sources

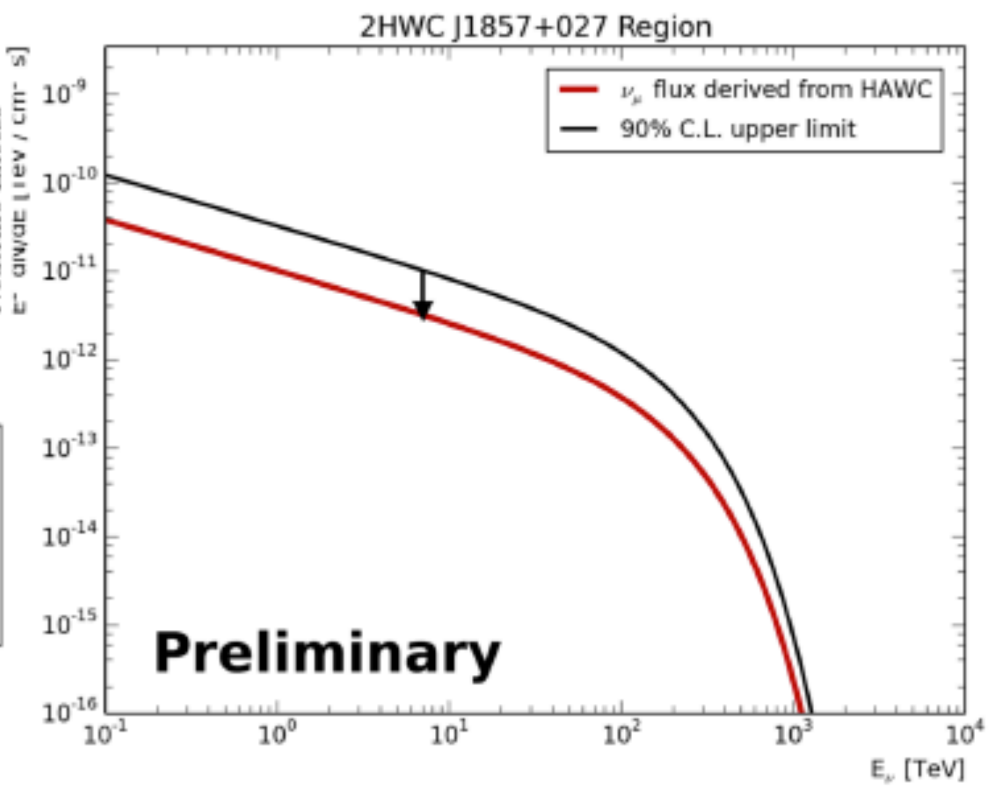




A. Kheirandish NU6b





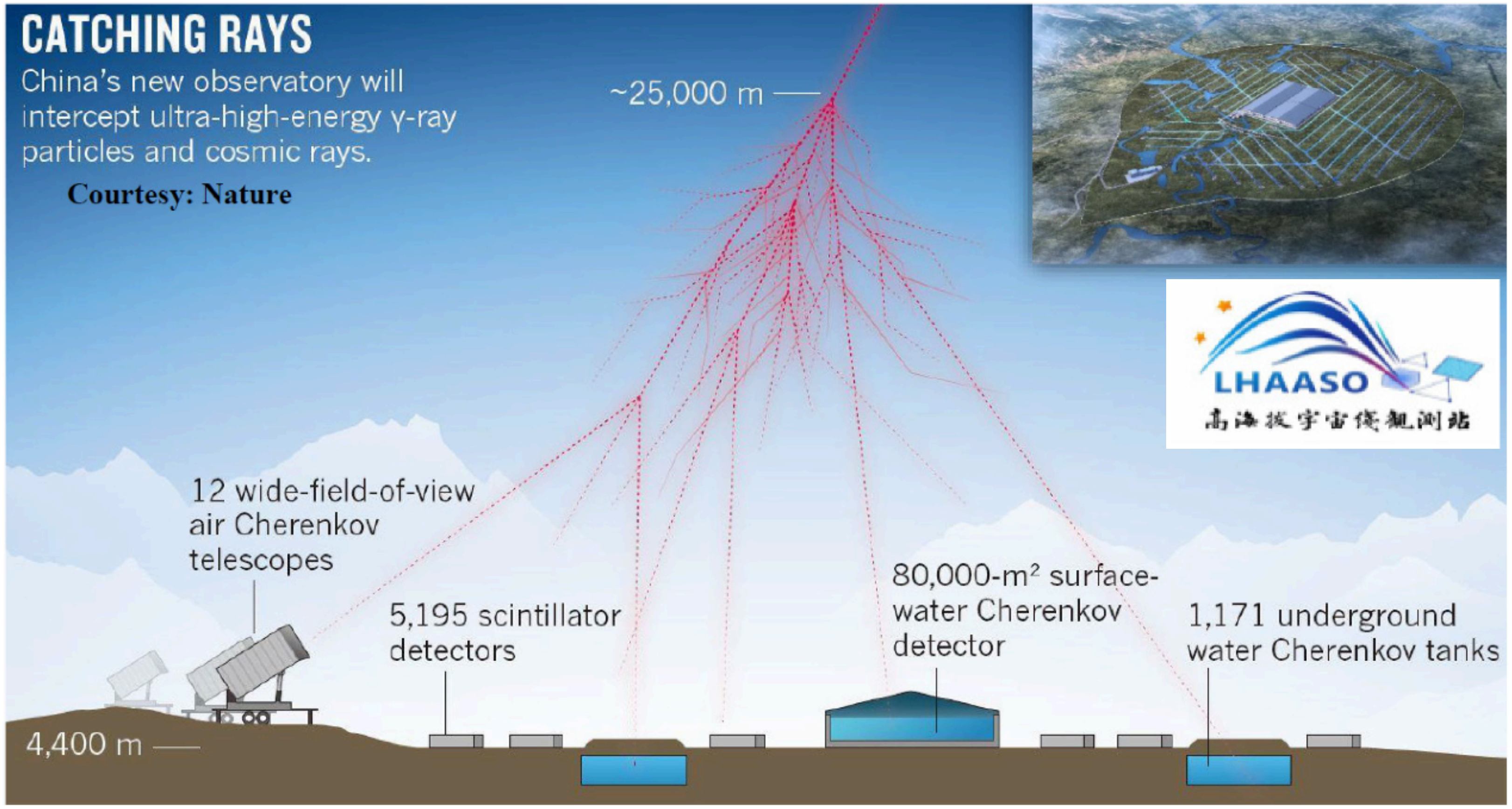


Stacked search for neutrino emission from HAWC 2HWC catalog

Template analysis for neutrino emission from Galactic plane and certain source regions

Most significant result is for J1857+027 (p value 0.02 before trials correction)

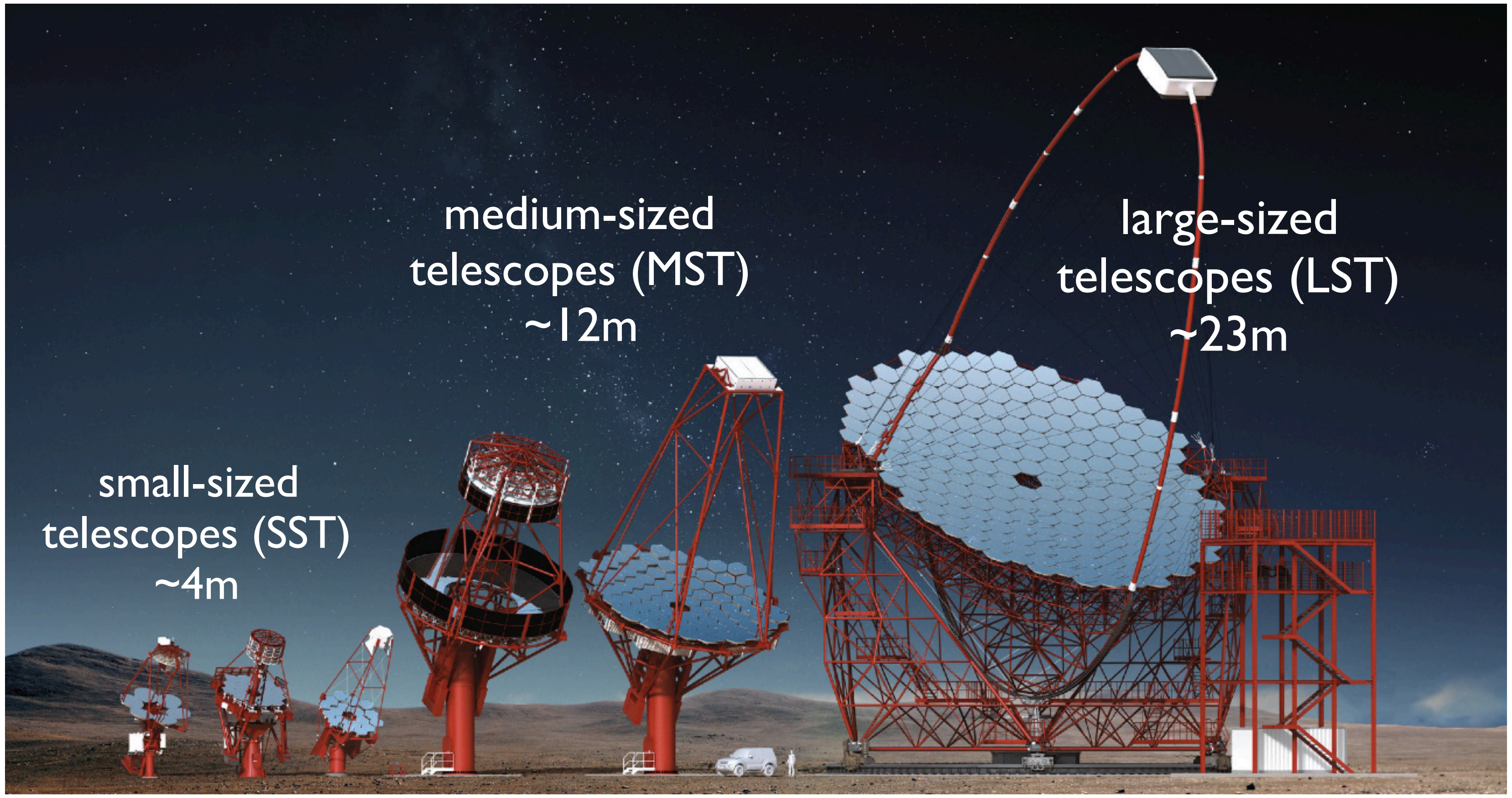
LHAASO



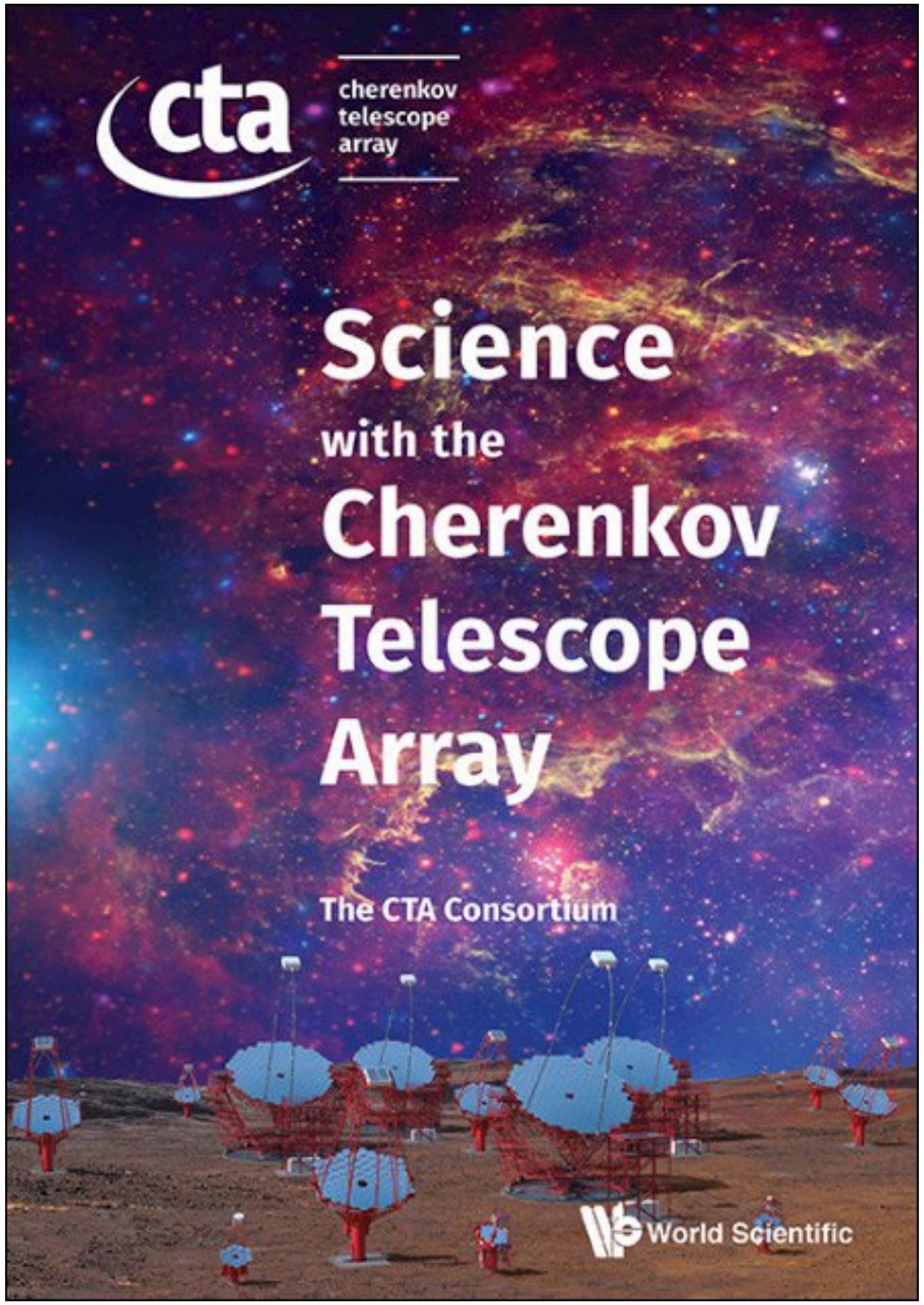
LHAASO –a one km² multi-hybrid detector in China

- Deployments on-going
- First detectors operating
- Construction completion in 2021

Gamma-ray pointed

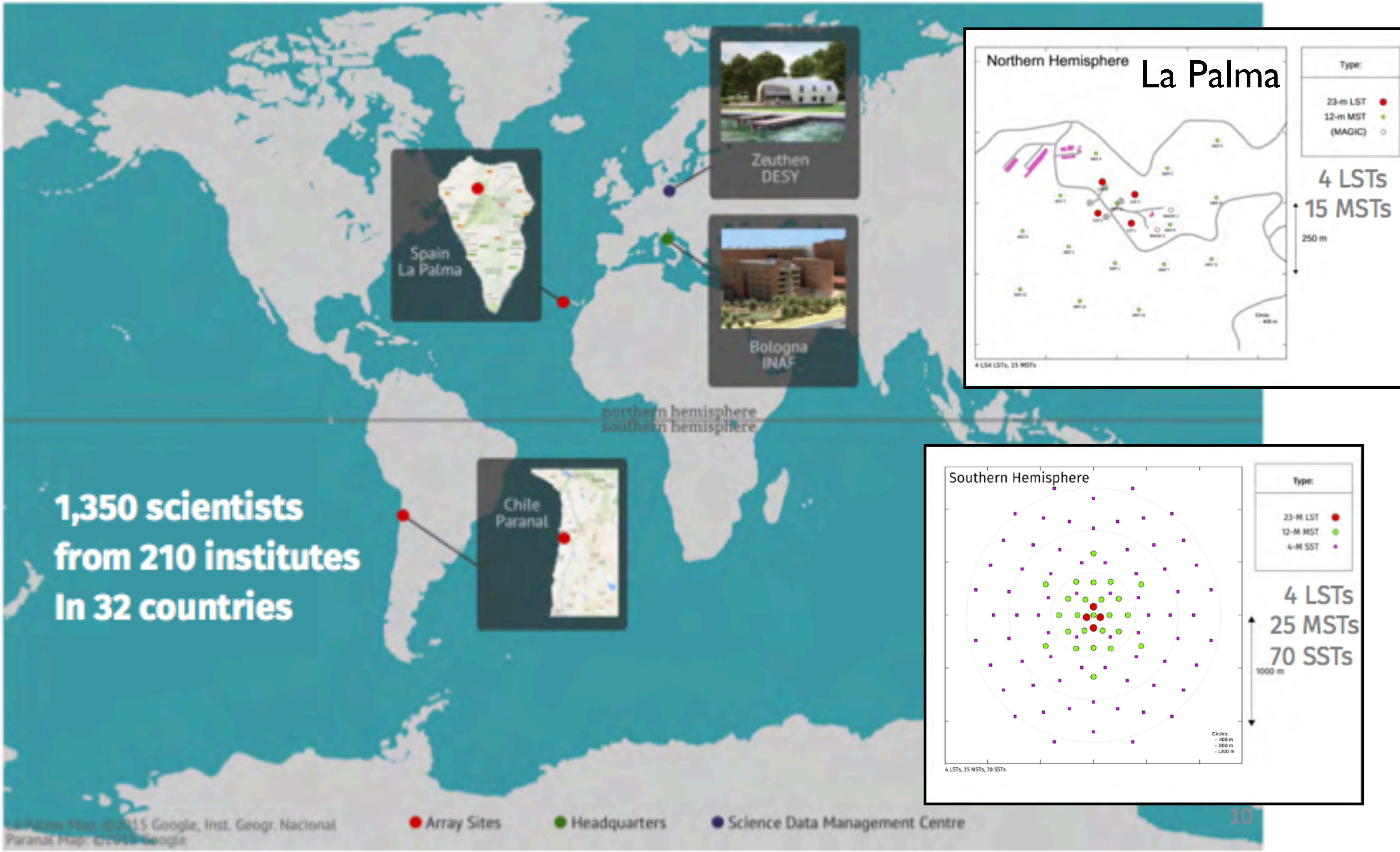


- Two sides:
  - Southern side 4km² coverage (SST+MST+LST)
  - Northern side 0.4km² coverage (MST+LST)
- CTA Schedule
  - 2018 - Host sites agreements finalized
  - 2020 First Pre-production telescopes on Site
  - 2022 Begin of Observatory Operations
  - 2025 Construction Project Completion

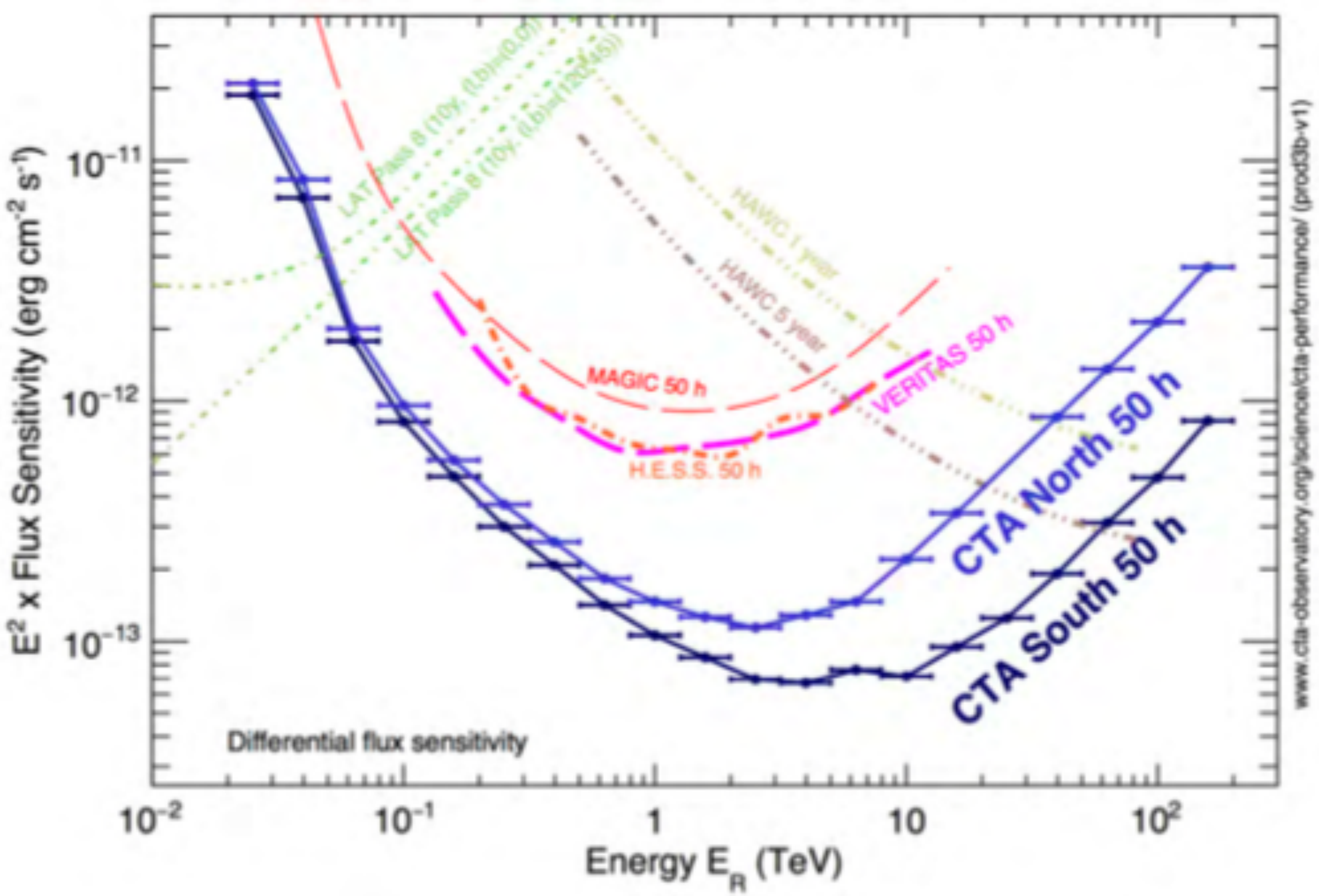


arXiv:1709.07997

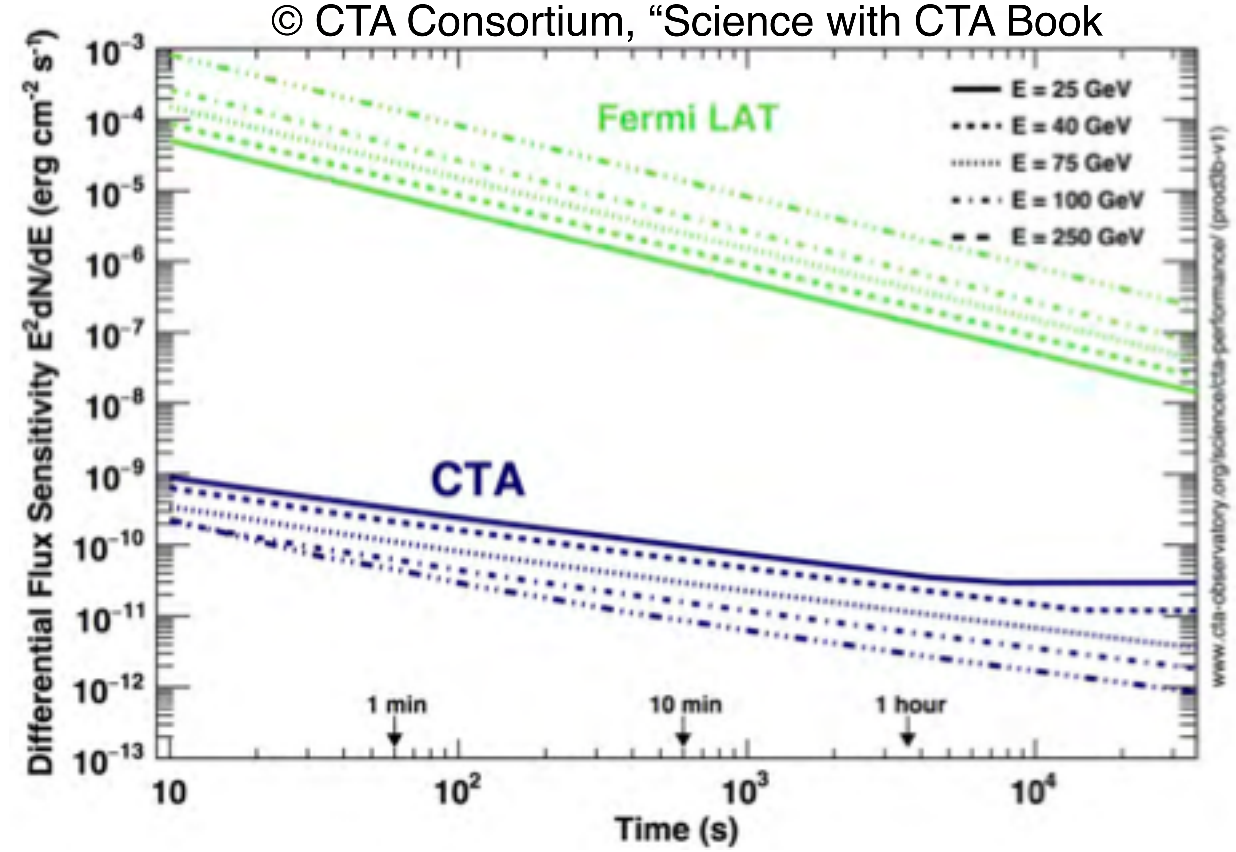
Cherenkov Telescope Array (CTA)



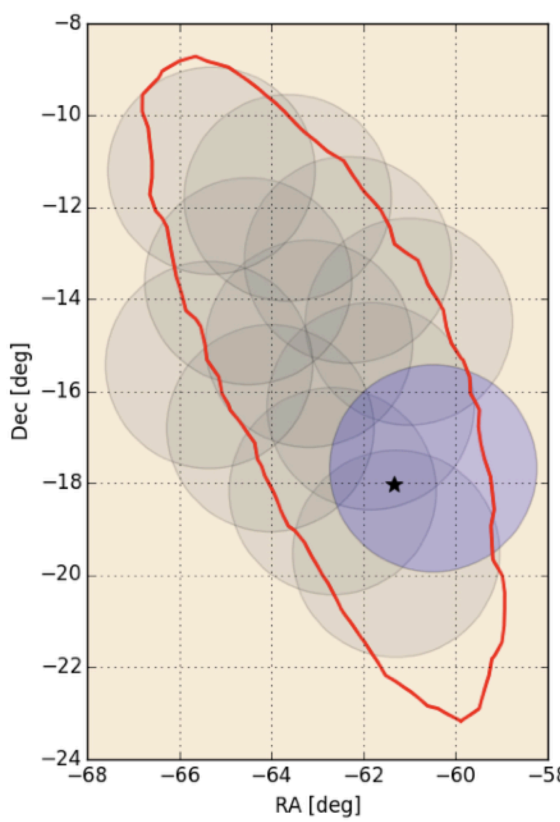
CTA Sensitivity and Multimessenger program



© CTA Consortium, "Science with CTA Book



- Accessible energy range from below 100 GeV to above 100 TeV
- A factor of 5-20x improvement in differential sensitivity relative to current IACTS
- 8° FOV in survey mode for extended objects
- Transients - Limited FOV dependent on external triggers
  - Fast slewing of the LST telescopes (~20s) and coverage or both hemispheres

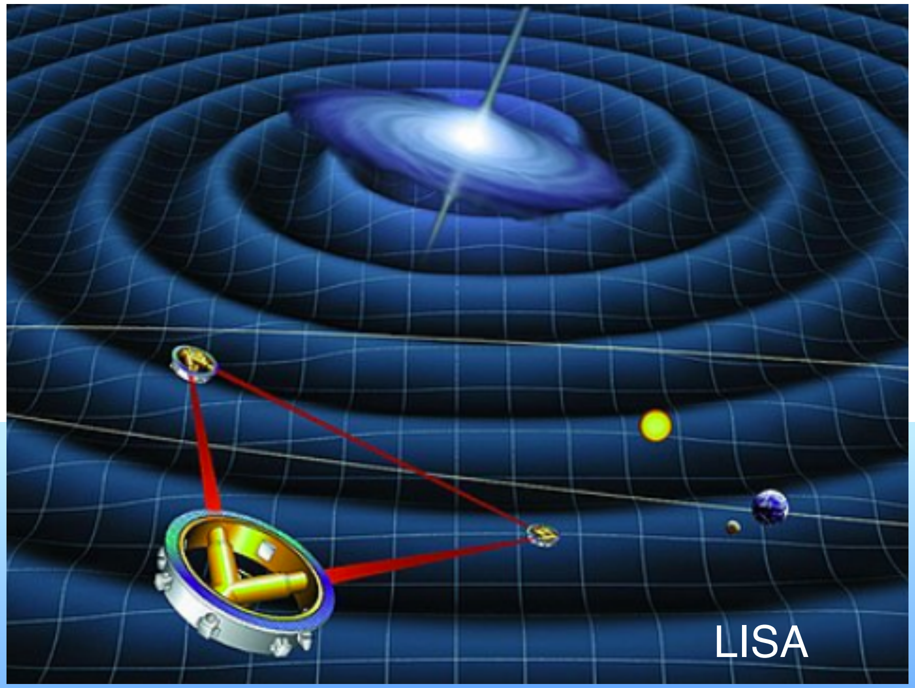


CTA Follow-up strategy of GW sky localisation region

arXiv:1801.05167

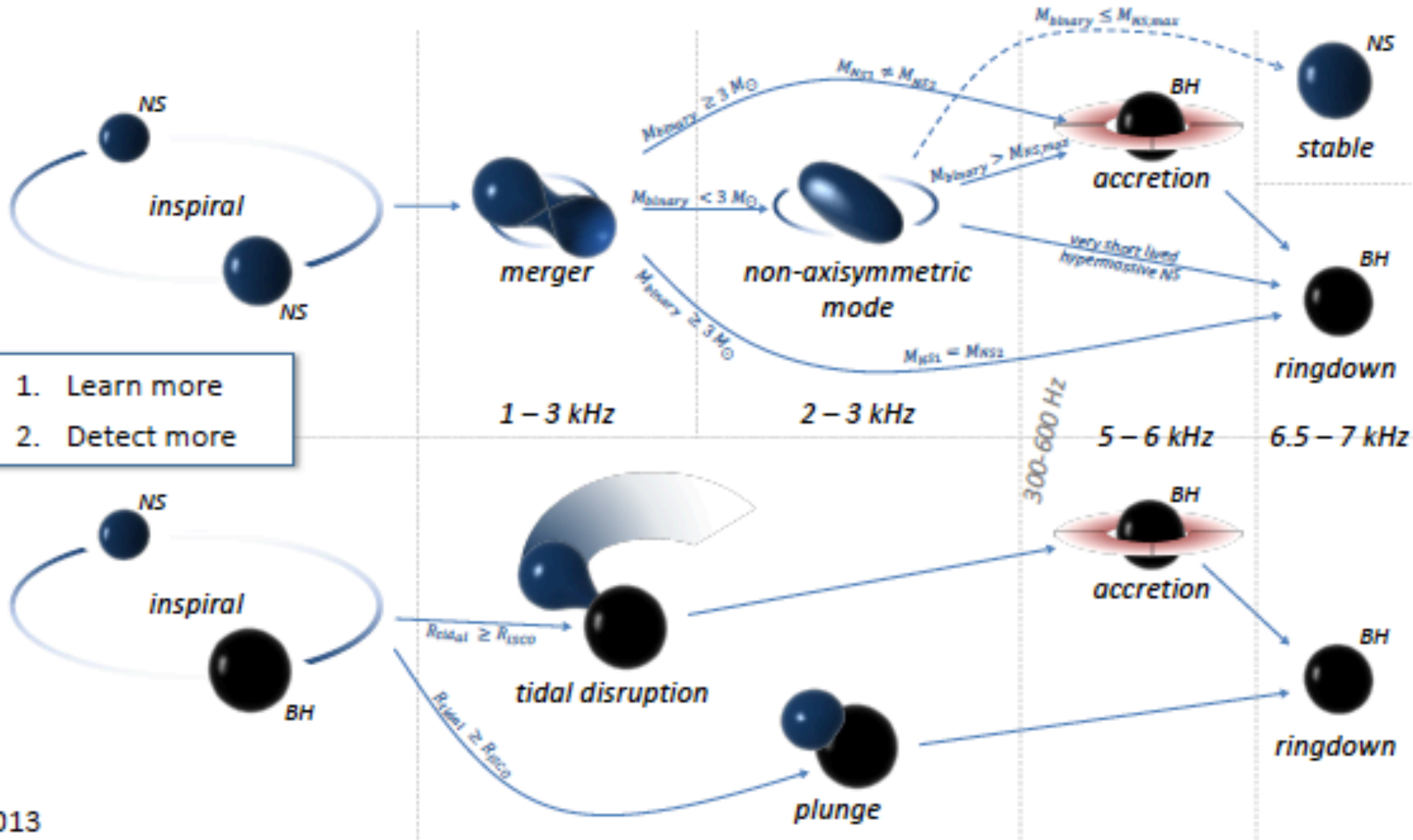
Band or Messenger	Astrophysical Probes	Galactic Plane Survey	LMC & SFRs	CRs & Diffuse Emission	Galactic Transients	Starburst & Galaxy Clusters	GRBs	AGNs	Radio Galaxies	Redshifts	GWs & Neutrinos
Radio	Particle and magnetic-field density probe. Transients. Pulsar timing.	✔	✔	✔	✔	✔	✔	✔	✔		✔
(Sub)Millimetre	Interstellar gas mapping. Matter ionisation levels. High-res interferometry.	✔	✔	✔		✔		✔	✔		
IR/Optical	Thermal emission. Variable non-thermal emission. Polarisation.	✔	✔	✔	✔	✔		✔	✔	✔	
Transient Factories	Wide-field monitoring & transients detection. Multi-messenger follow-ups.						✔	✔			✔
X-rays	Accretion and outflows. Particle acceleration. Plasma properties.	✔	✔	✔	✔	✔	✔	✔	✔		✔
MeV-GeV Gamma-rays	High-energy transients. Pion-decay signature. Inverse-Compton process	✔	✔	✔	✔	✔	✔	✔			✔
Other VHE	Particle detectors for 100% duty cycle monitoring of TeV sky.	✔	✔	✔		✔		✔			
Neutrinos	Probe of cosmic-ray acceleration sites. Probe of PeV energy processes.			✔			✔	✔			✔
Gravitational Waves	Mergers of compact objects (Neutron Stars). Gamma-ray Bursts.						✔				✔

Figure 3: Matrix of CTA Science Cases and associated MWL / multi-messenger synergies. The science cases listed refer to the core science programme of CTA, to be developed within the Consortium proprietary time. Some comments on the astrophysical capabilities from each band are also added. Ticks marked in red are to indicate the principal synergies of each science case.



Gravitational Waves

Compact binary mergers

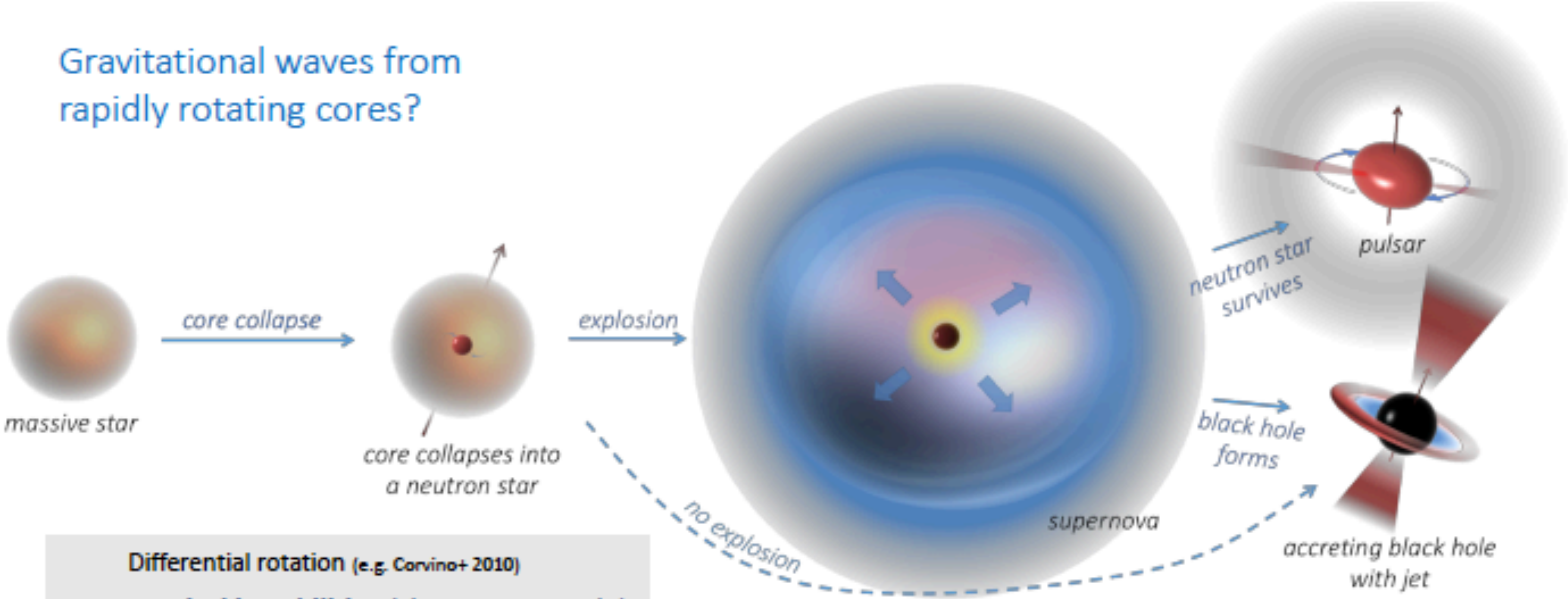


Goals:
1. Learn more
2. Detect more

Bartos+ 2013

Stellar core collapse

Gravitational waves from rapidly rotating cores?

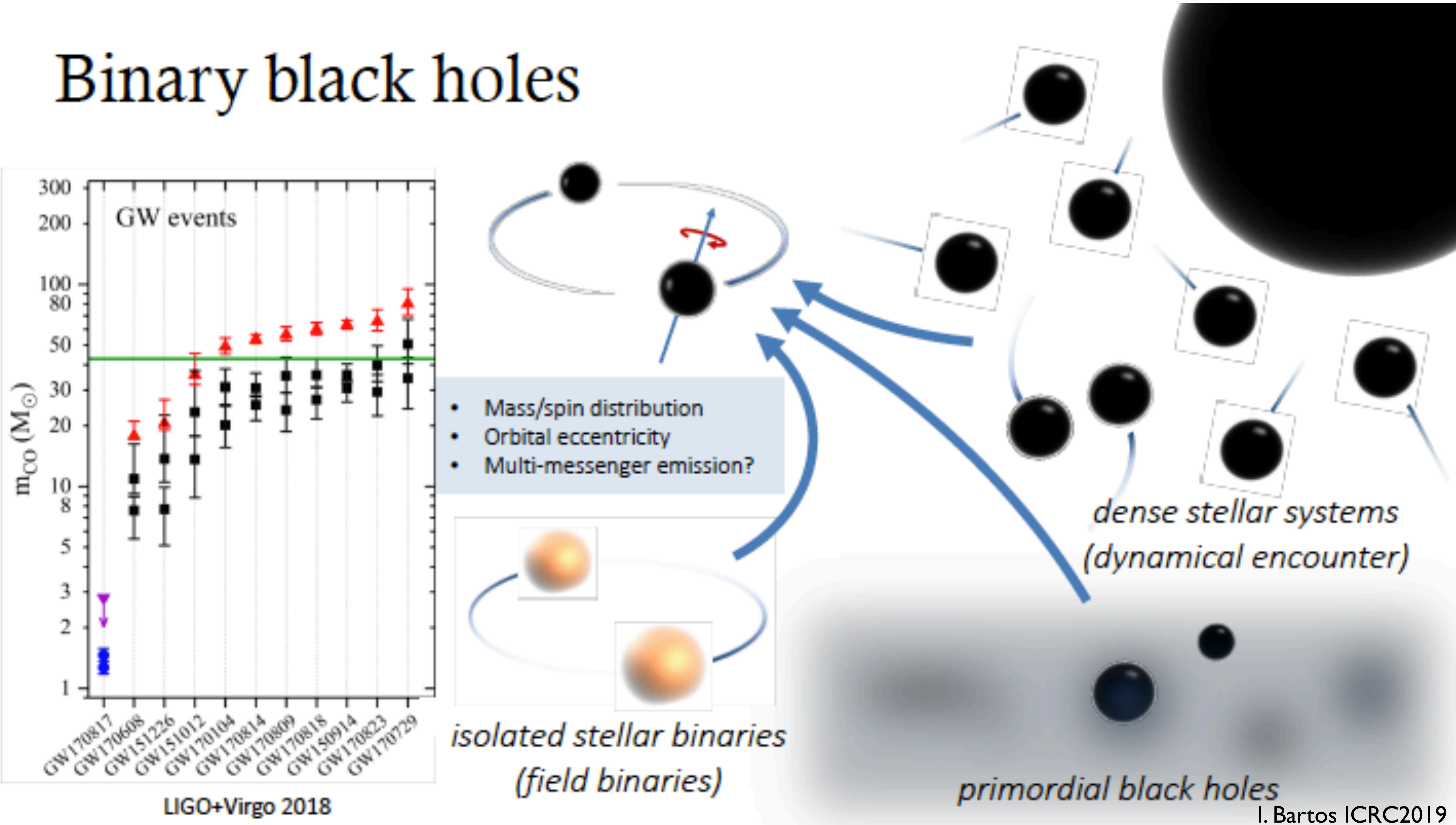


Differential rotation (e.g. Corvino+ 2010)

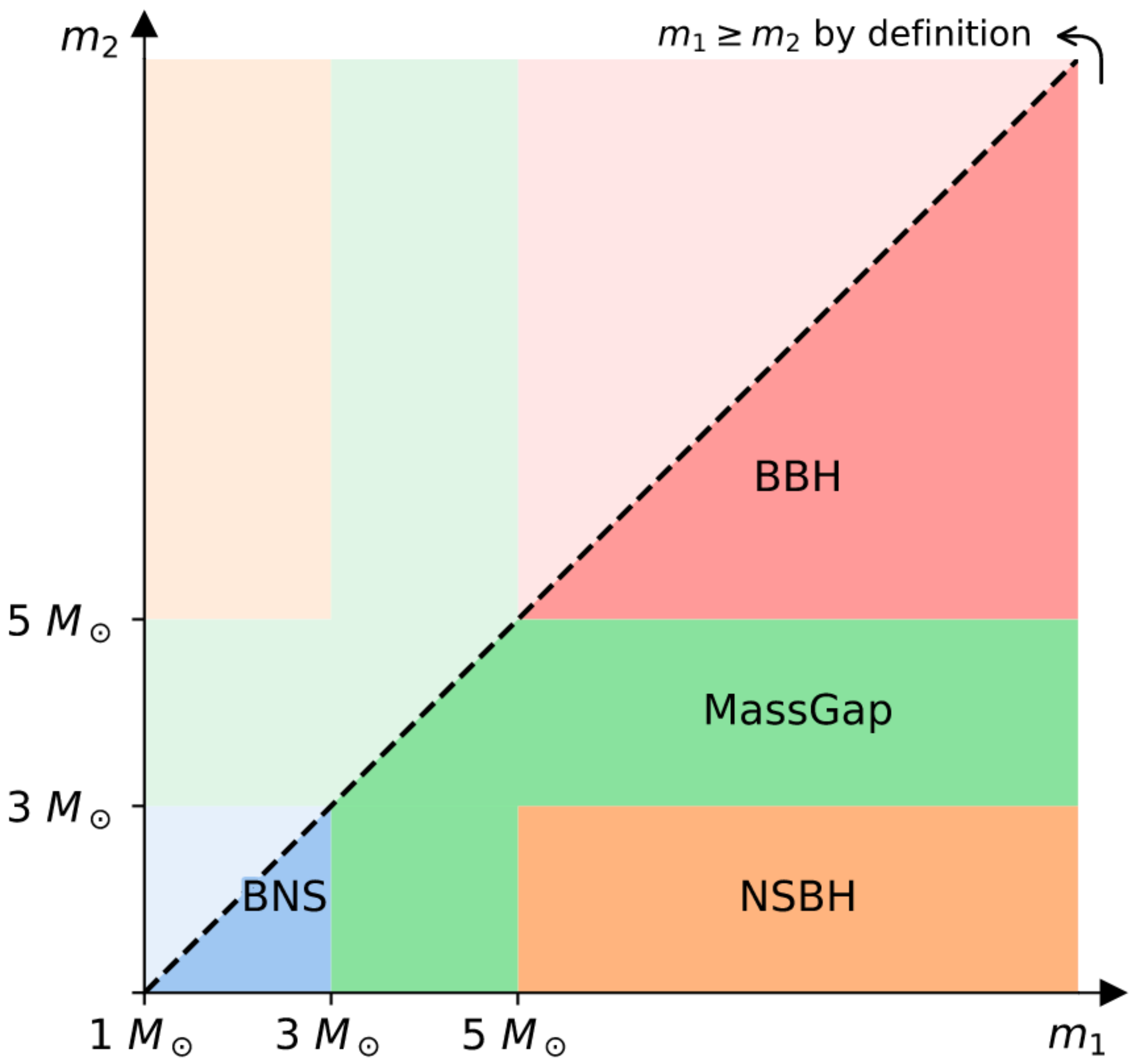
- **Dynamical instabilities** *(shorter time scale)*
- **Secular instabilities** *(longer time scale)*
- **Magnetic distortion**

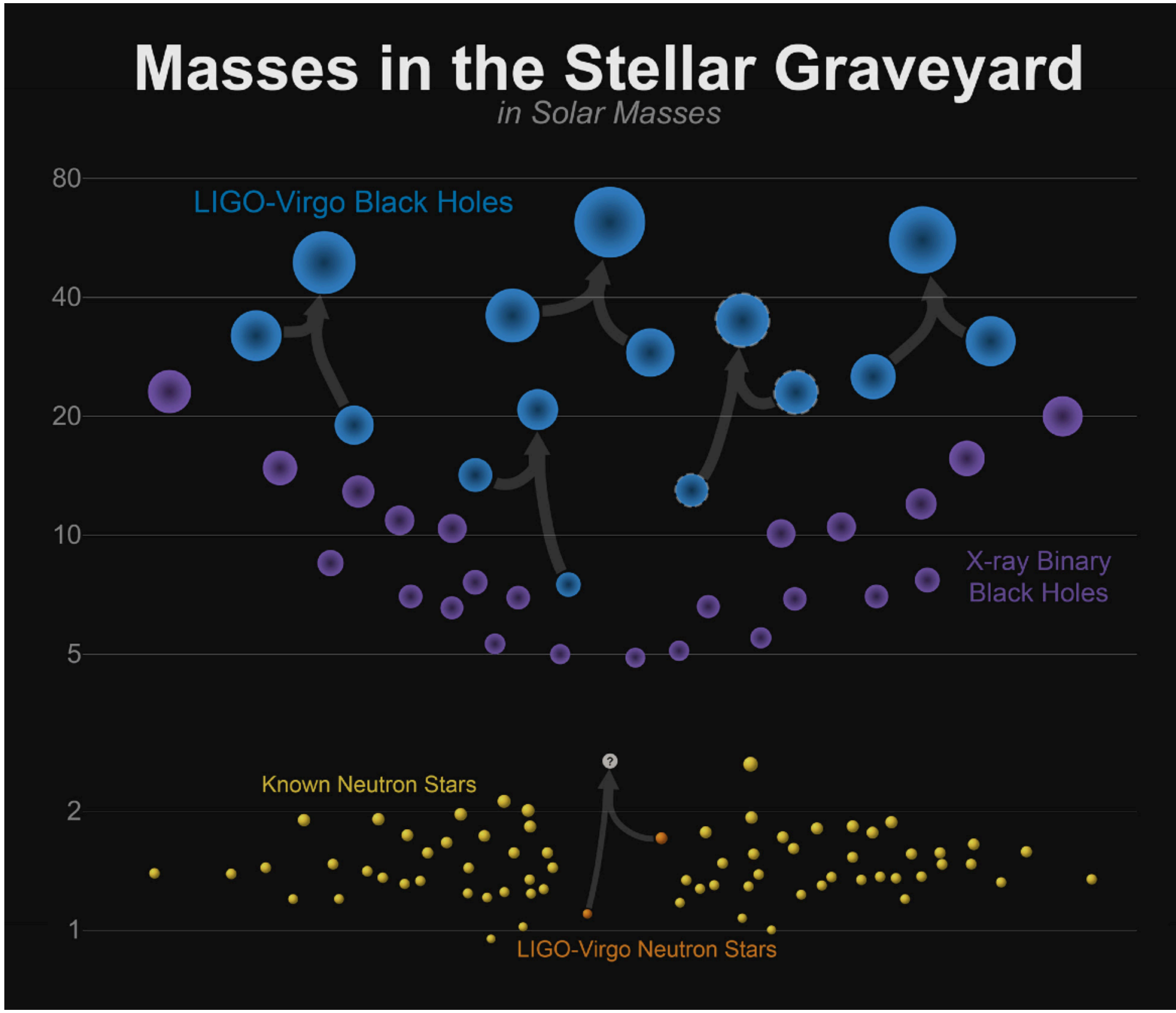
Fallback accretion? *(Piro & Thrane, 2012)*

I. Bartos ICRC2019



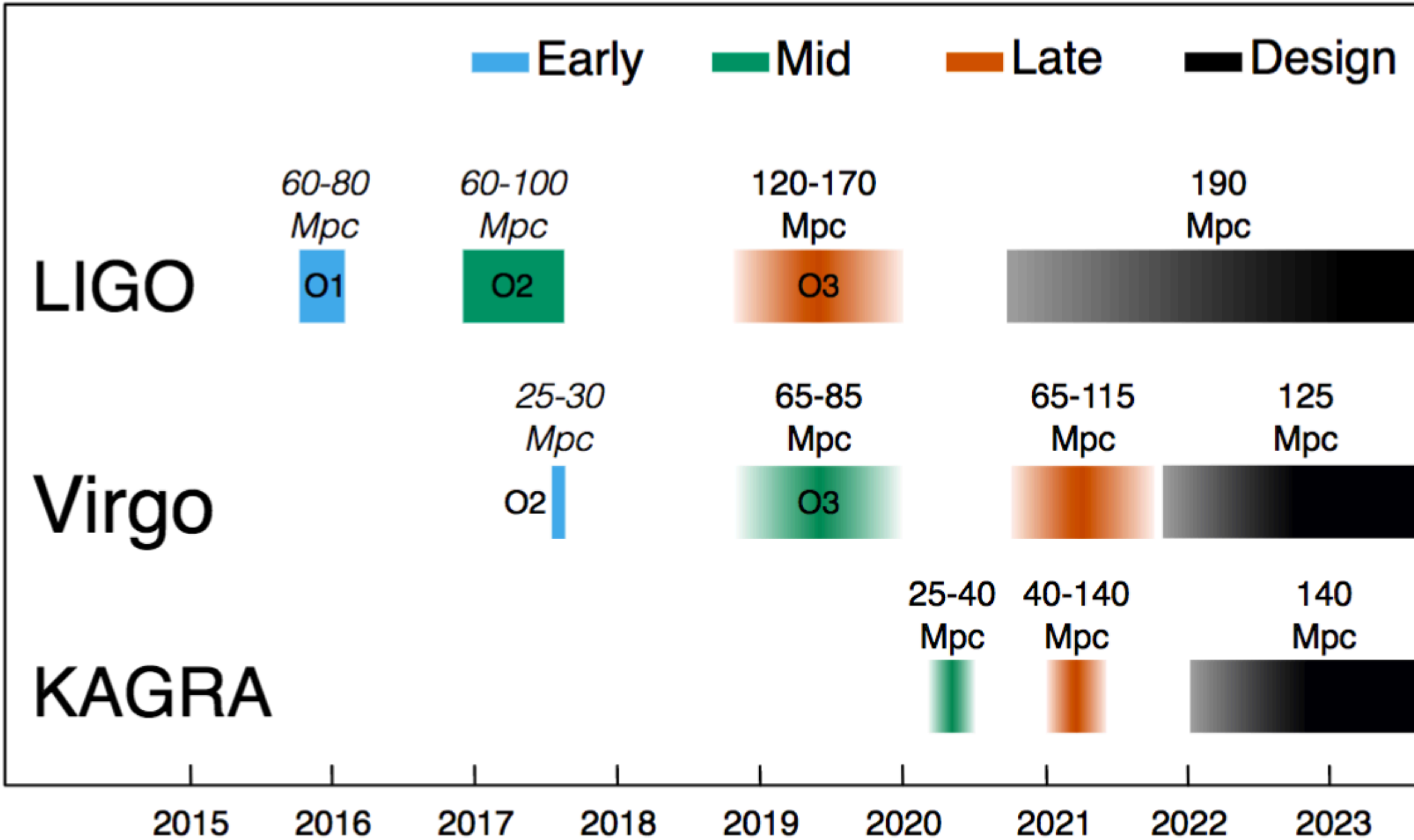
- Mass/spin distribution
- Orbital eccentricity
- Multi-messenger emission?



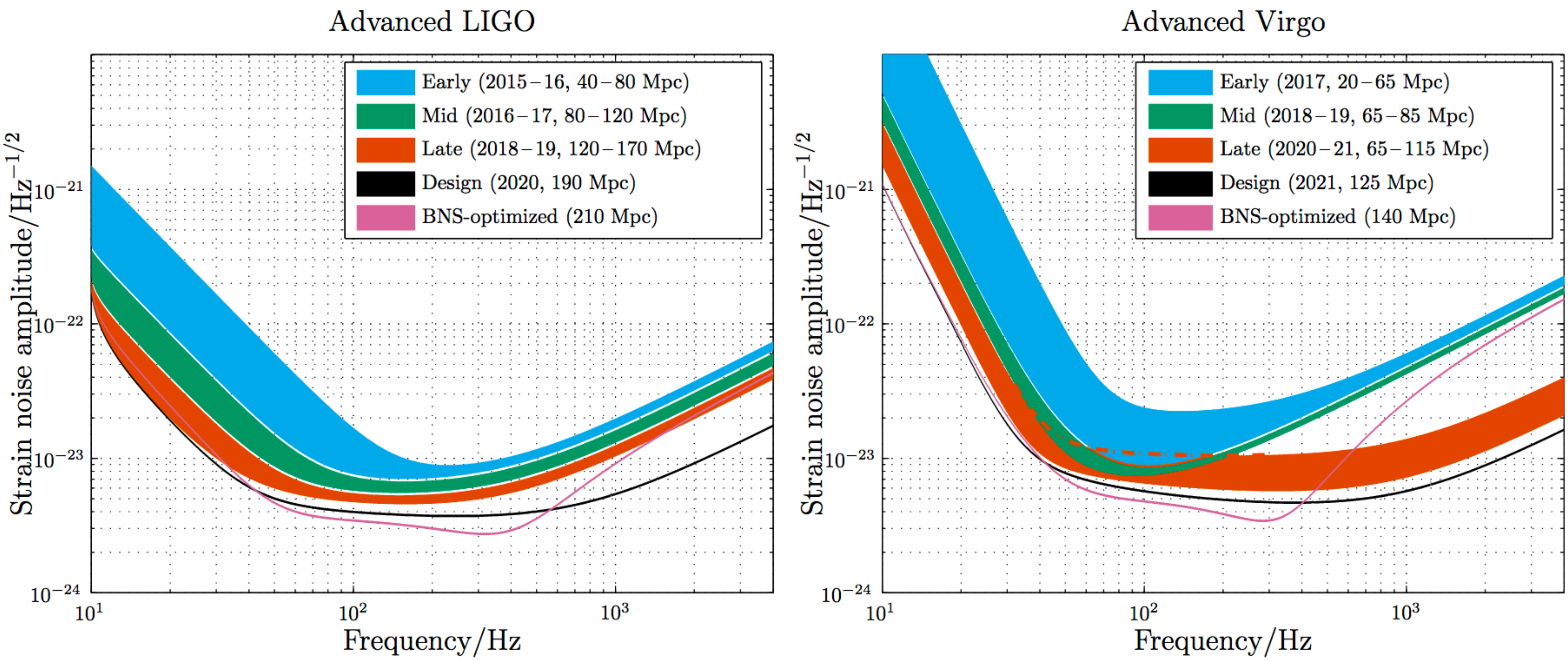


https://emfollow.docs.ligo.org/userguide/content.html

The next few years

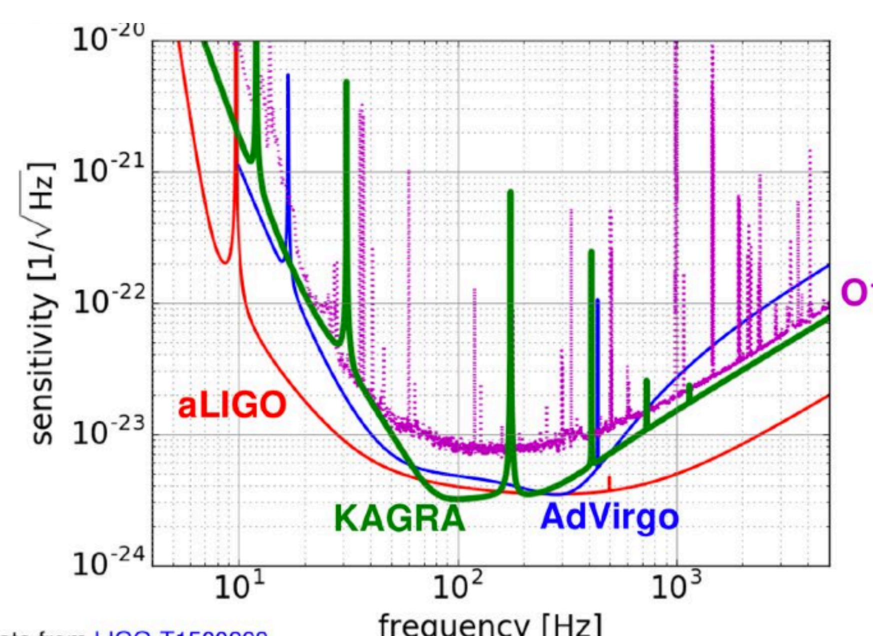


Current and upcoming science runs



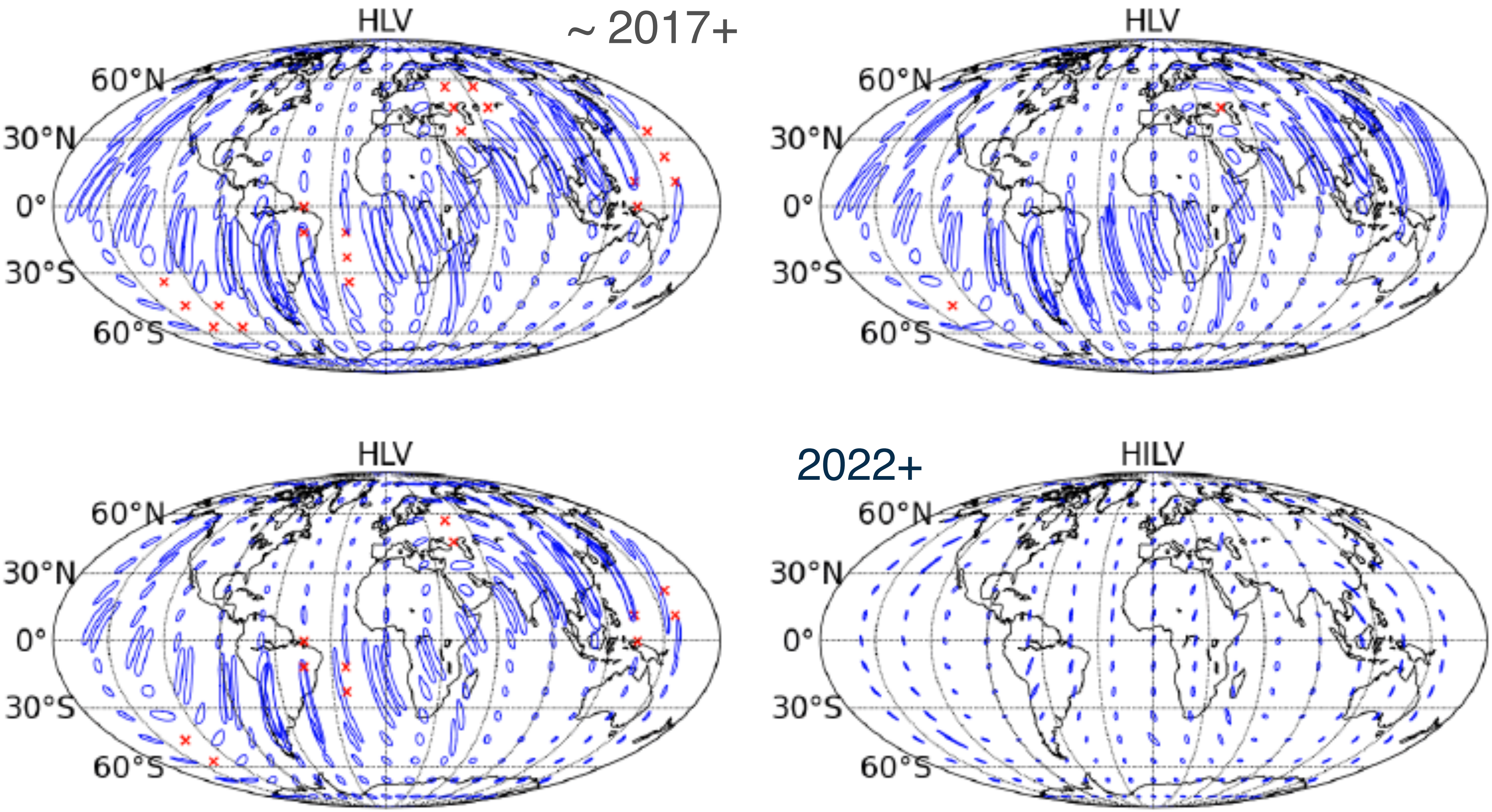
3km Cryogenic Laser Interferometer

1000m under the mountain summit
358m above sea level



Spectra data from LIGO-T1500293

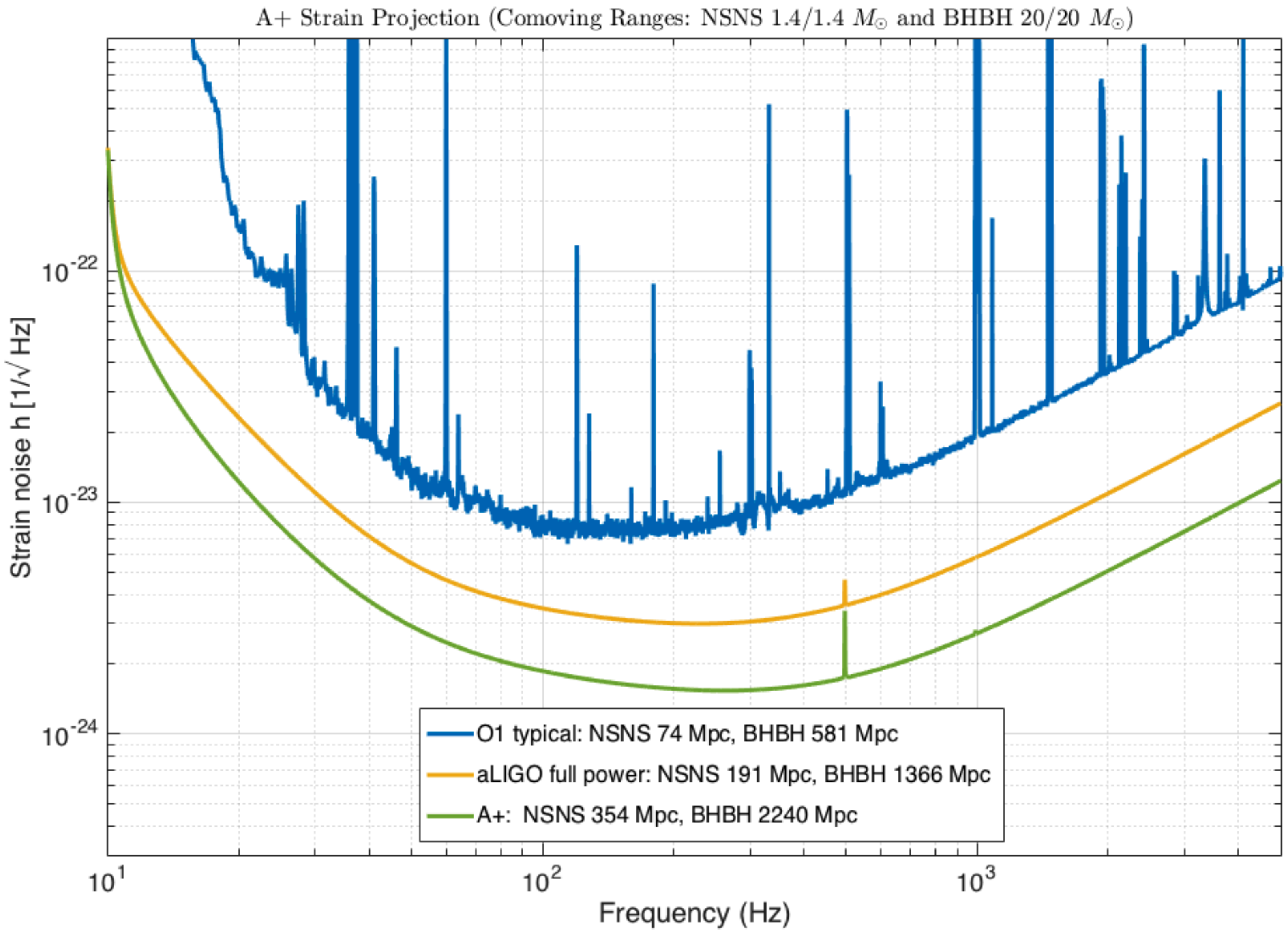
LIGO India



HLV
~ 2017+
60°N
30°N
0°
30°S
60°S
HLV
60°N
30°N
0°
30°S
60°S
HLV
60°N
30°N
0°
30°S
60°S
2022+
HILV
60°N
30°N
0°
30°S
60°S

‘A+’ aLIGO mid scale upgrade

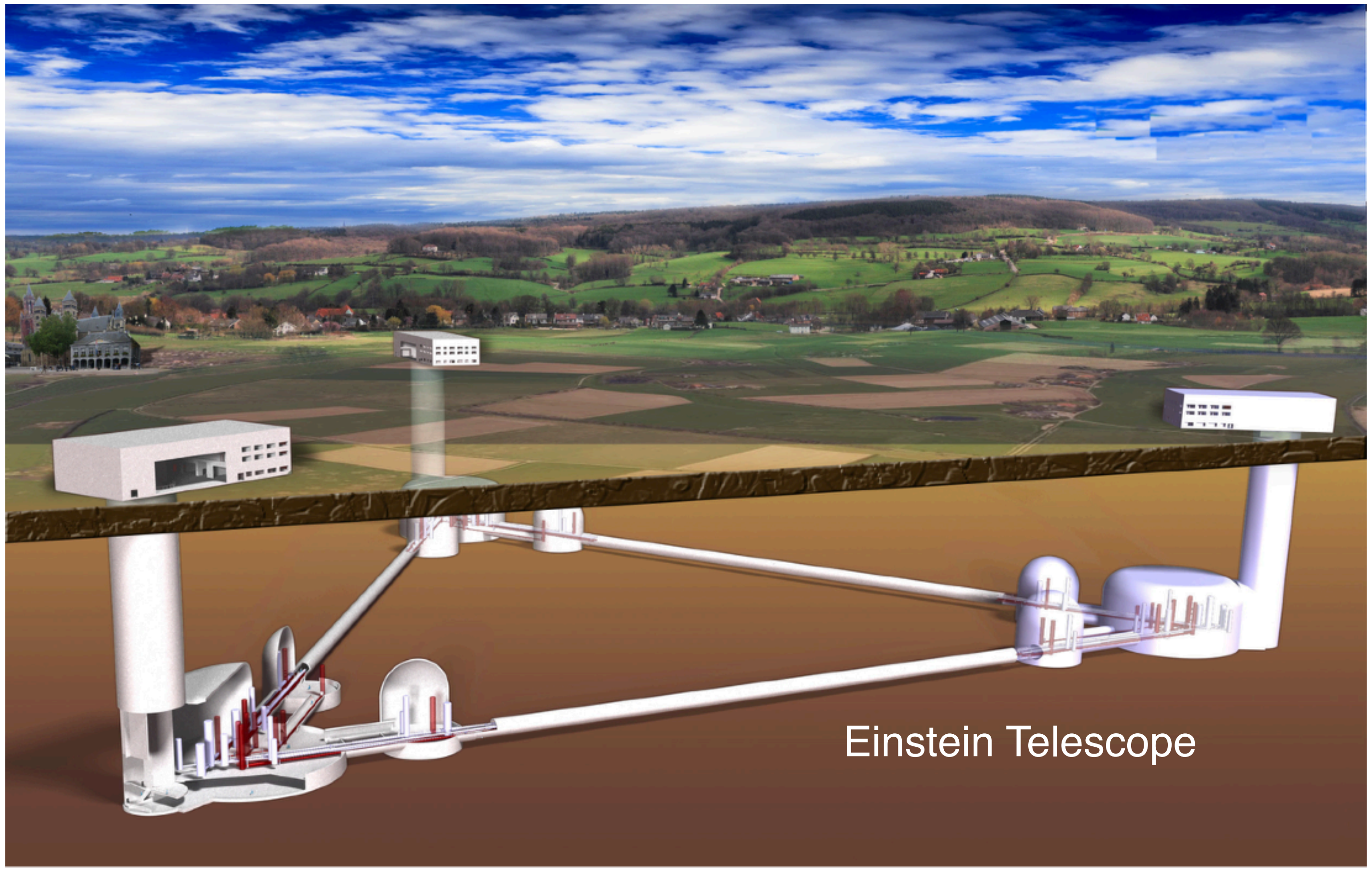
- Upgrade to aLIGO that leverages existing technology and infrastructure, with minimal new investment and moderate risk
- Target: average 1.7x increase in range over aLIGO
  - ~ 5x greater event rate than Advanced LIGO
  - ~ 40 times greater than current Advanced LIGO sensitivity
- Stepping stone to future detector technologies
- Two year down time; back online by 2023

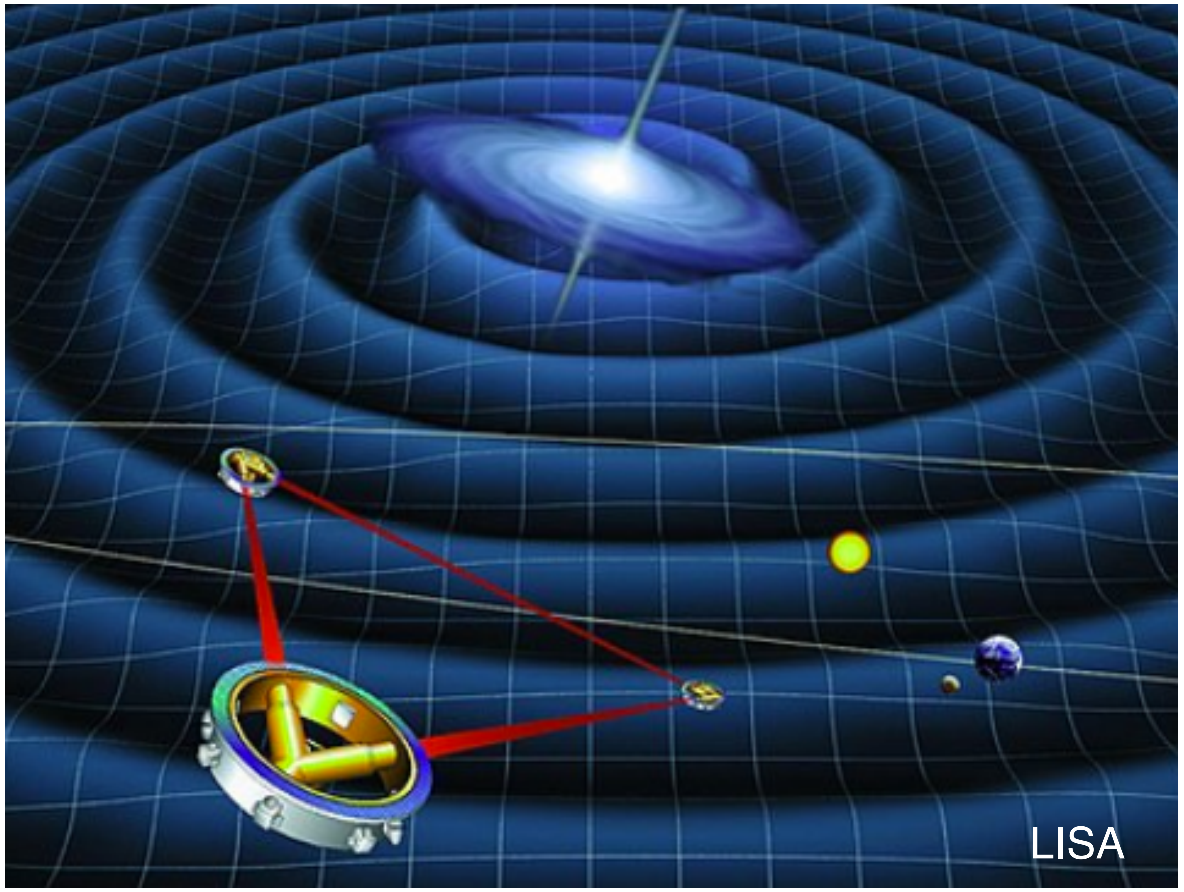


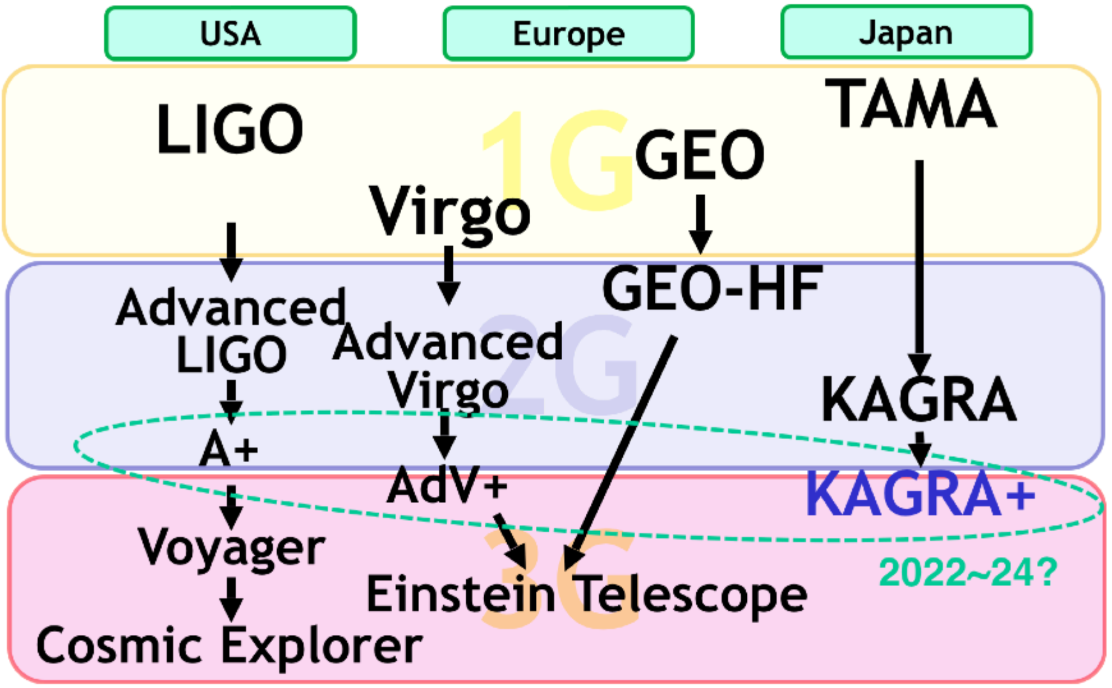
A+ key parameters

12 dB injected squeezing
15% readout loss
100 m filter cavity (FC)
20 ppm round trip FC loss
Coating Thermal Noise half of aLIGO

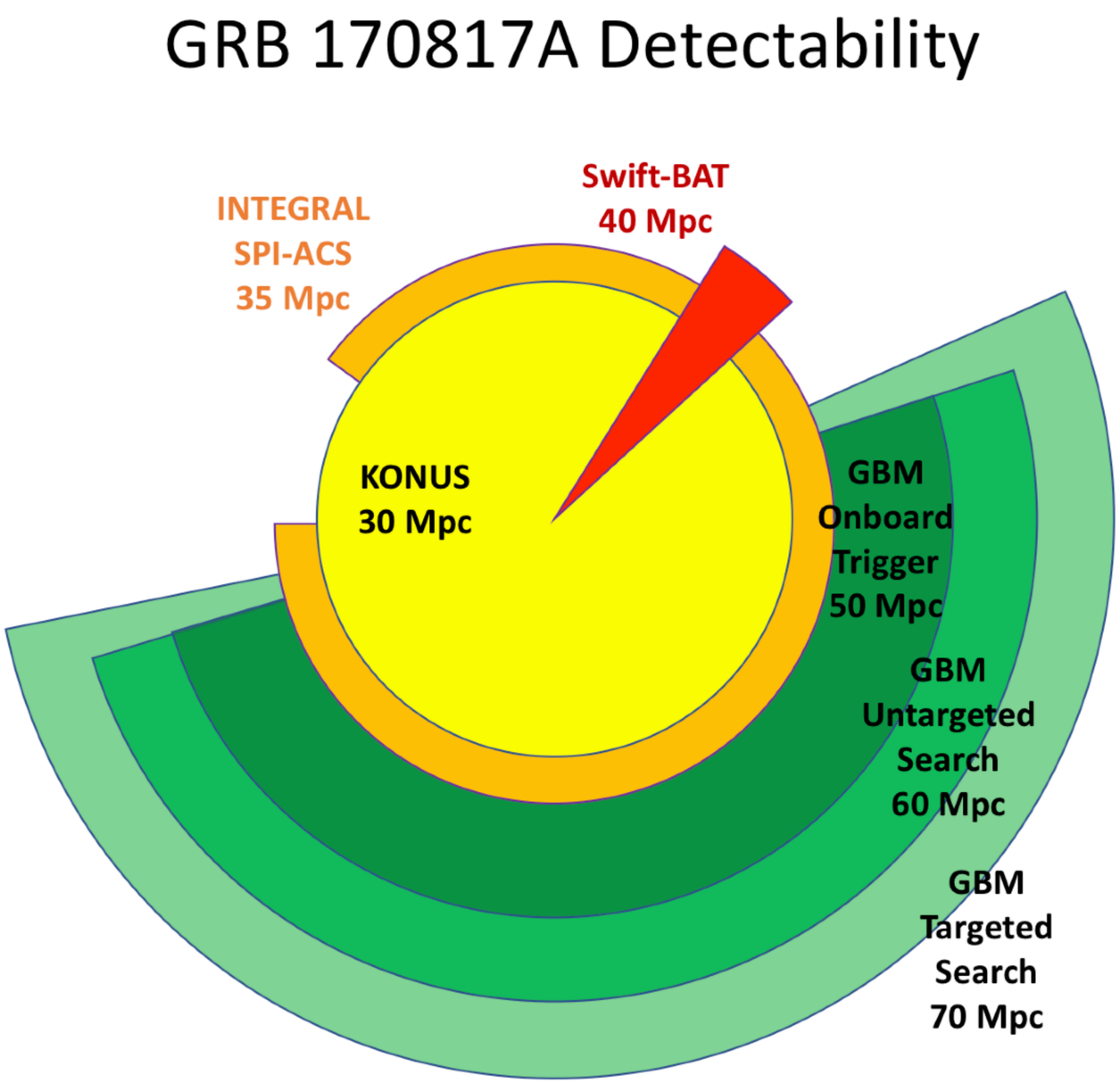
Further future







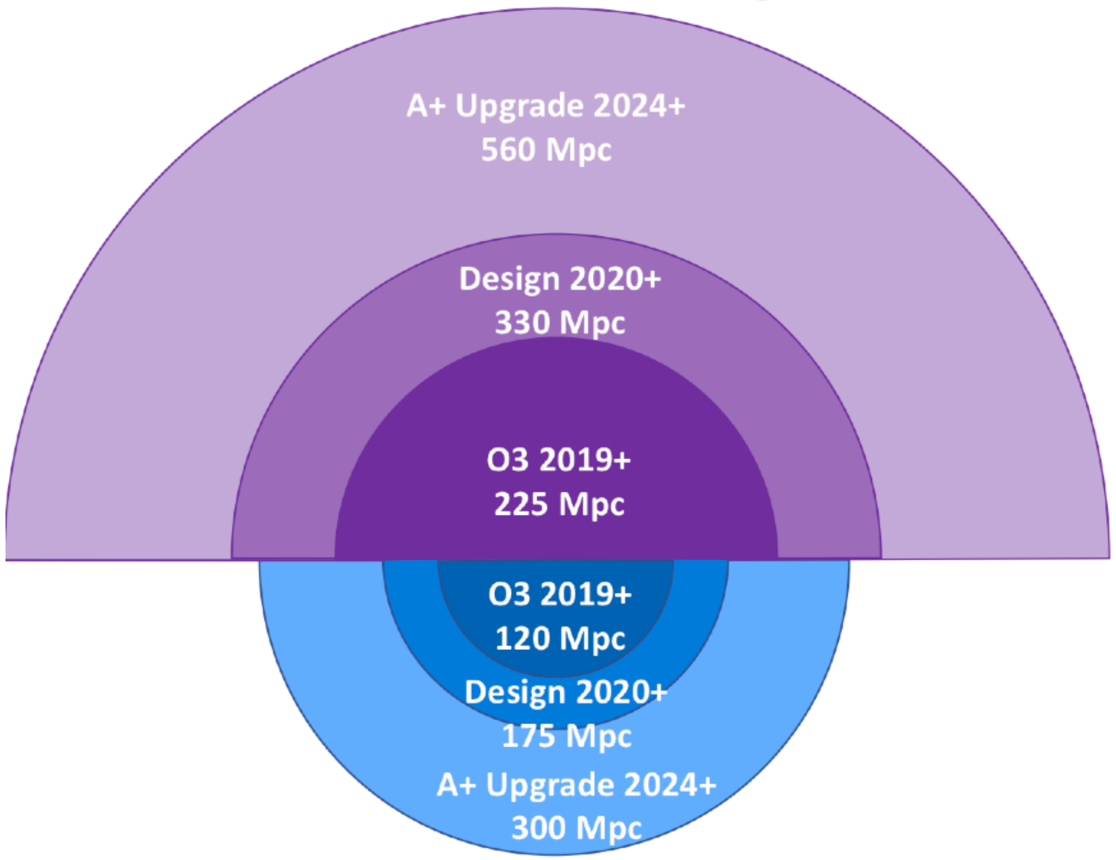
GRB+GW Prospects



- Was GRB 170817A lucky?
- Is there a huge population of faint nearby sGRBs?
- How well can the current fleet of GRB instruments do?
- How can we do better?

GW+GRB

GW+GBM Range



GW Range

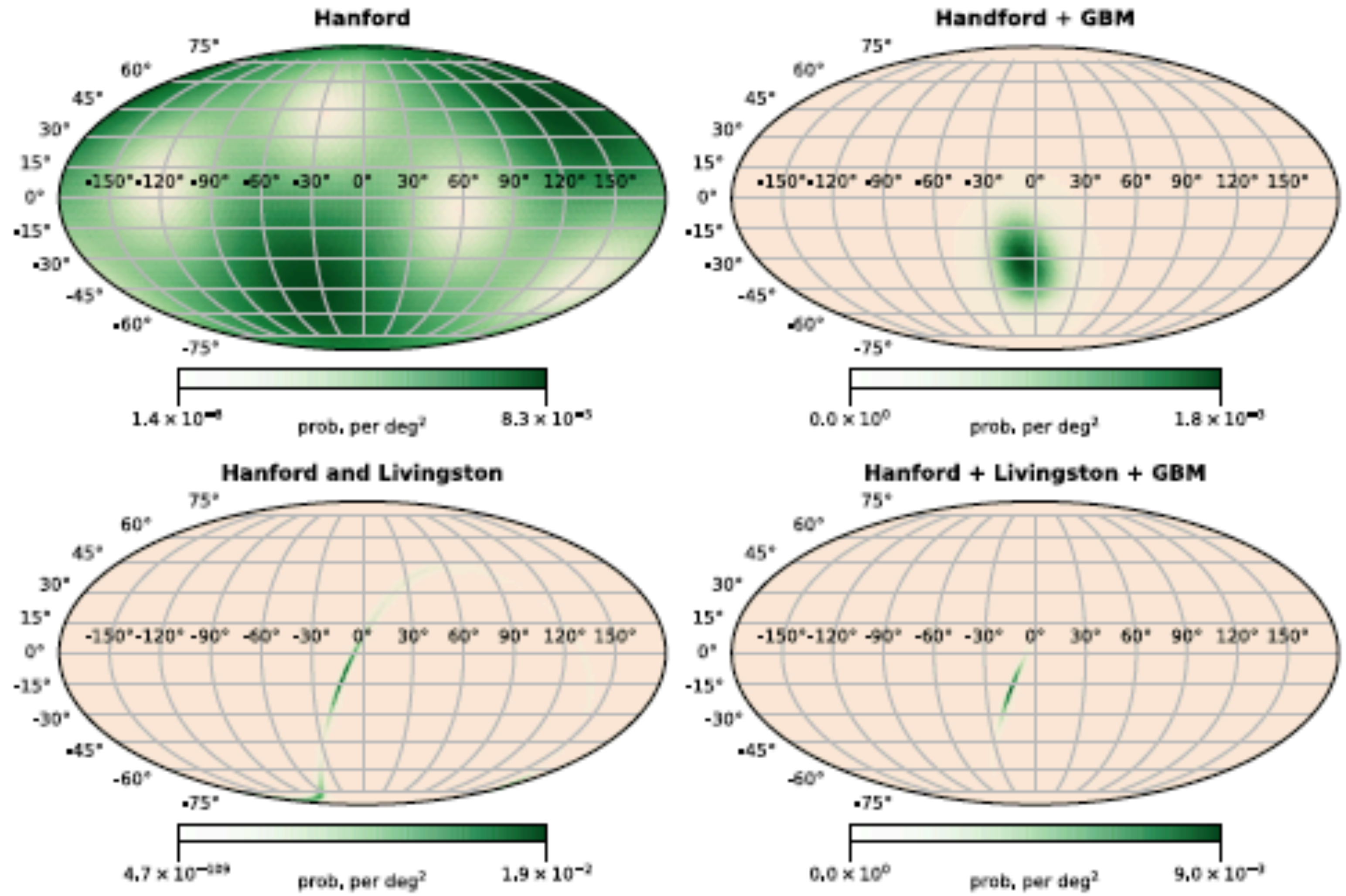
Instrument	Year	Frequency Range	BNS Range	BNS Rates (1/year)
GEO600	1995-	~150-3000 Hz		
Advanced LIGO	2015-	~20-1000 Hz	173 Mpc	0 (O1; 2015-2016)
Advanced Virgo	2016-	~20-1000 Hz	125 Mpc	1 (O2; 2017-2018)
KAGRA	2019+	~20-700 Hz	140 Mpc	4-80 (2020+)
LIGO-India	2024+	~20-1000 Hz	173 Mpc	11-180 (2024+)
Advanced LIGO+	2025+	~20-1000 Hz	325 Mpc	>100
Advanced Virgo+	2025+	~20-1000 Hz	215 Mpc	
LIGO Voyager	2028+	~10-5,000 Hz	~1 Gpc	>1,000

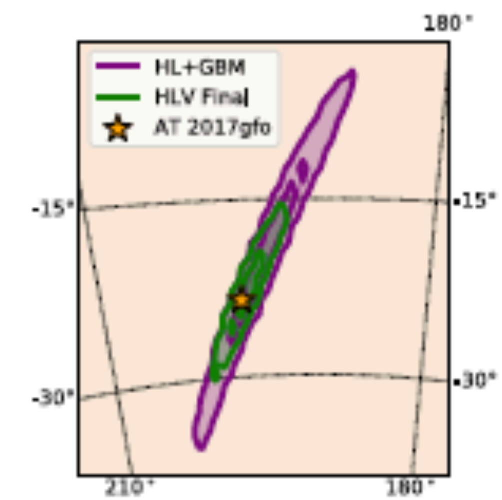
Burns et al. 2019 (arXiv:1903.04472)

- Coincident GRB provides more than astrophysics, but also joint localization and detection, increasing capability
- On-axis events have stronger GW signals
- GRB provides trigger time and rough sky localization, allows GW search window to be smaller, and therefore more sensitive given trials

Gravitational Wave Counterparts

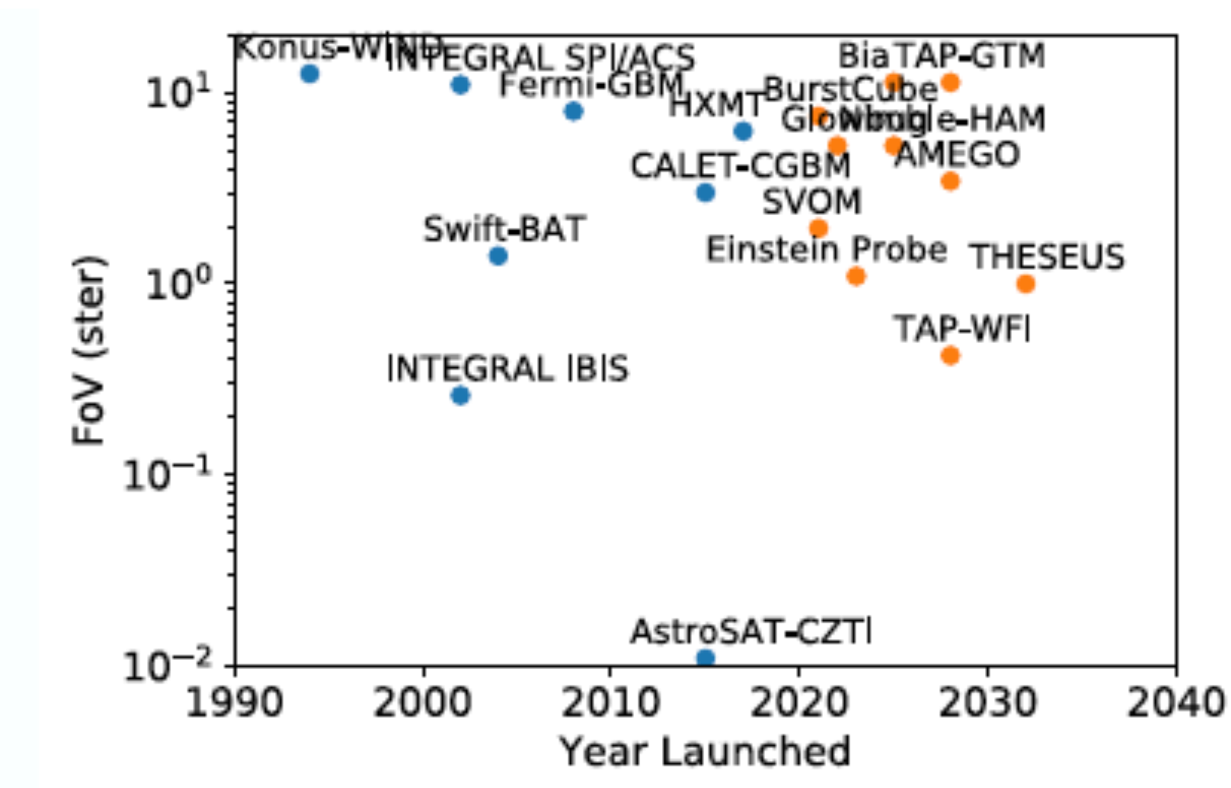
- Gamma-ray GRB localization in addition with interferometry in GW network helps fast localization
- Especially important for 1 or 2 interferometer localizations
- GBM localization provided within seconds of detection
- Joint localizations with LIGO are on-going and provided automatically in O3

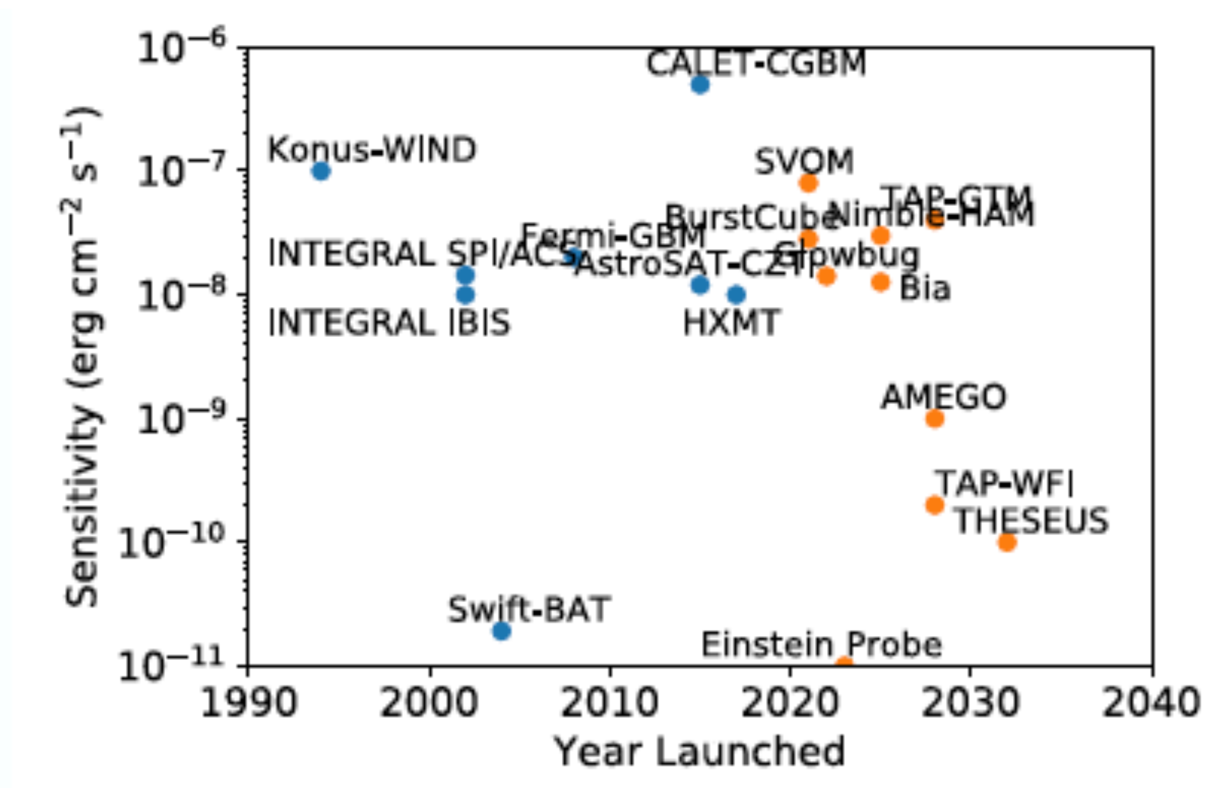




Status of the Current GRB-detecting Fleet

	Year Launched	Energy Coverage	Field of View x Duty Cycle (% of sky)	sGRB Rate (yr^{-1})
KONUS-Wind	1994	20 keV - 15 MeV	95%	18
INTEGRAL SPI/ACS	2002	80 kev - 10 MeV	100%	~30
Swift-BAT	2004	15-150 keV	15%	10
Fermi-LAT	2008	30 MeV - >300 GeV	20%	~1
Fermi-GBM	2008	8 keV - 40 MeV	60%	40-80
CALET-CGBM	2014	7 keV - 20 MeV	25%	~3-6
AstroSat-CZTI	2015	10-150 keV	1%	~3
Insight-HXMT	2017	0.2-3 MeV	60%	~5-10
Other gamma-ray monitors that are part of IPN: Odyssey, Messenger				





Desired for Next generation GRB detectors

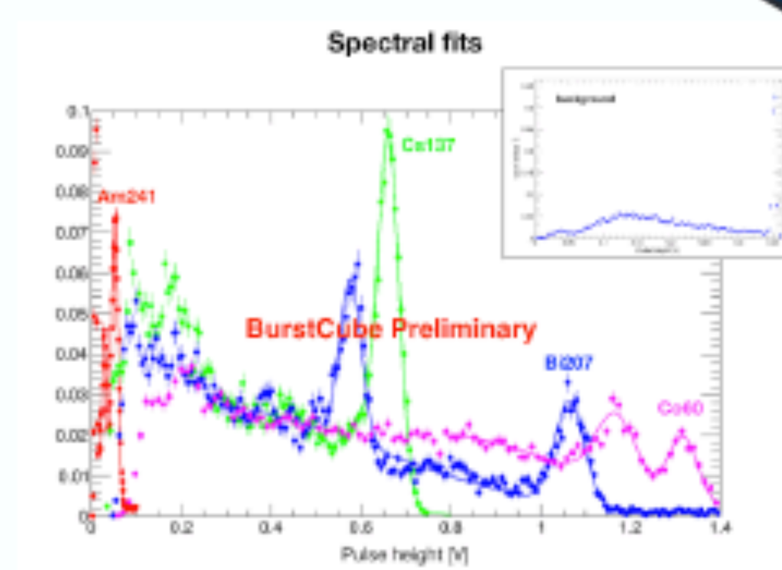
- Capabilities needed for GW-GRB science in the next decade?
  - All-sky coverage
  - Sensitivity to weak GRBs
  - Rapid notification
  - degree-scale (or better) localizations
  - Wide gamma-ray energy band
  - Rapid multi-wavelength follow-up observations
- Considerations
  - all on one platform or distributed
  - dedicated GRB mission or broadly capable

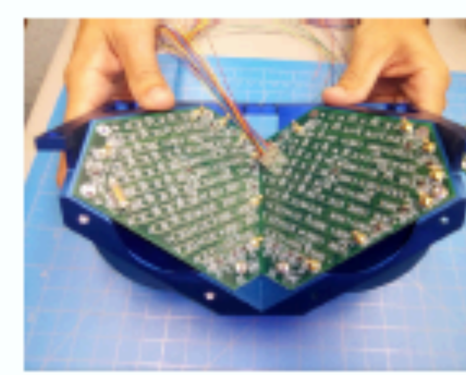
BurstCube

PI: Jeremy Perkins (NASA/GSFC)

Judy Racusin @ The New Era of Multi-Messenger Astrophysics, Groningen, March 26-30, 2019

- 6U CubeSat currently in design and prototyping phase
- Instrument:
  - Four 9 cm diameter CsI scintillating crystals read out by low-power SiPM arrays
  - Energy band 30-1000 keV
- Rapid Communications - will send GRB alerts and localization to community within minutes
- Complement existing GRB-detecting instruments
- Launch ready in late-2021
- 6 month mission, 1 year goal





AMEGO - All-sky Medium Energy Gamma-ray Observatory

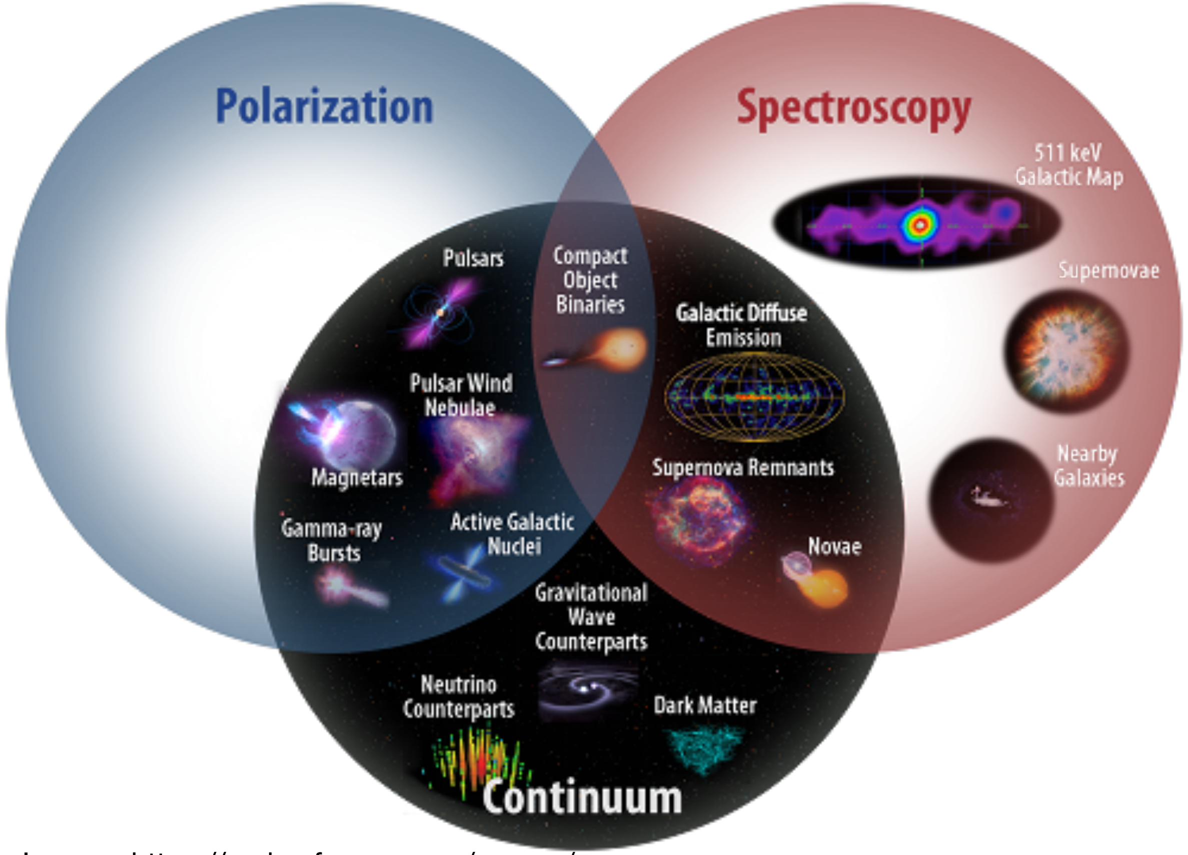
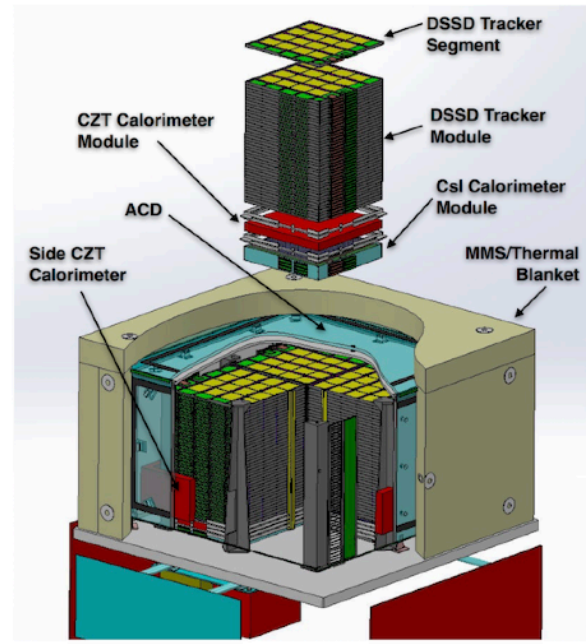
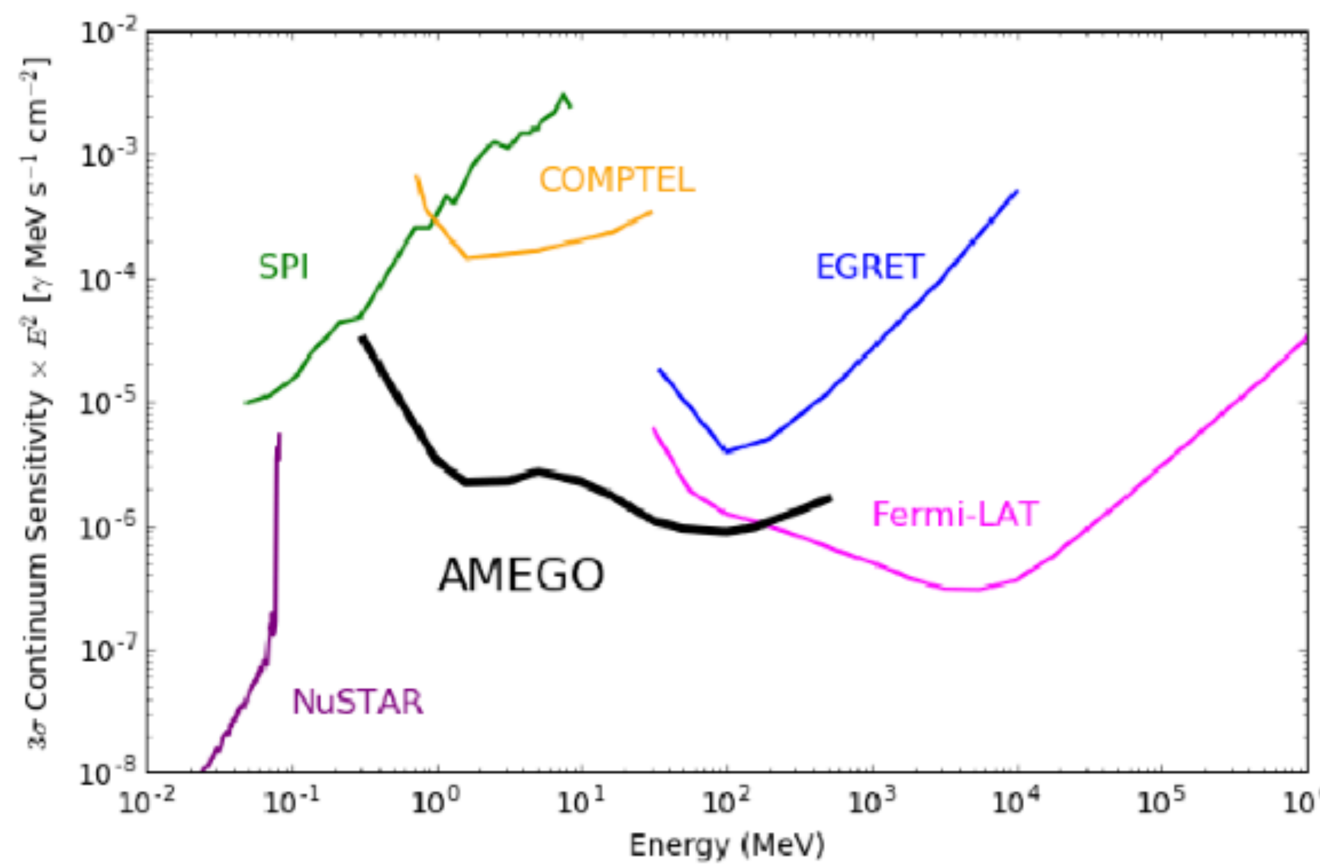


Image - https://asd.gsfc.nasa.gov/amego/



- Double-sided silicon strip tracker, CZT & CsI calorimeters, ACD
- Compton & Pair Telescope viewing ~20% of sky surveying entire sky over 2 orbits (like Fermi-LAT)
- Many sources have peak spectra in MeV band (AGN, pulsars, GRBs) – sensitive instrument needed to understand emission processes
- If GW-GRBs are under-luminous, AMEGO will be far more sensitive than scintillator instruments
- Launch in late 2020's
- 5 year mission (10 year goal)

- Probe Concept: 2020 NASA Astrophysics Decadal Review
- Energy Range: 200 keV to 10 GeV
- Observing strategy: survey (80% sky/orbit, ~2.5 sr FoV)



https://asd.gsfc.nasa.gov/amego/


Astro 2020
Board on Physics and Astronomy
Space Studies Board

- Conducted by The National Academies of Sciences, Engineering, and Medicine
  - Private, nonprofit institutions that provide independent advice to the nation on pressing science issues.
- All 3 agencies (NASA, NSF, and DOE) & the National Academies want to see ambitious programs backed by strong science cases

Task highlights:

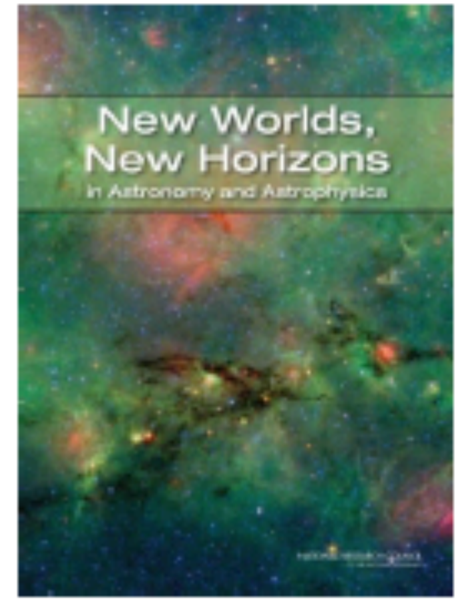
- Review current state of astronomy and astrophysics
- Identify compelling science challenges for future
- *Develop research strategy to advance scientific frontiers in 2022-2032*
  - Recommend and rank high priority activities
  - Consider international and private landscape
  - Consider timing, cost, and risk
- Develop decision rules for robust program
- Assess the state of the profession
  - Provide specific, actionable and practical recommendations

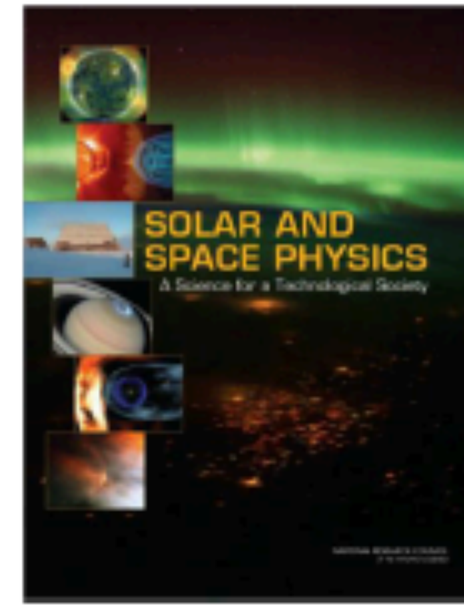
What is a Decadal Survey

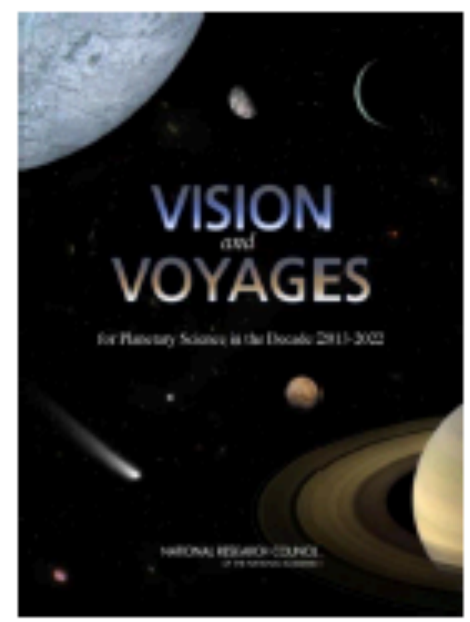
- **Undertaken by the National Academies of Sciences, Engineering, and Medicine for NASA, NSF and DOE and led by community members** who analyze and prioritize science questions for the next decade.

- **Provides prioritized recommendations** for government investment in research and facilities, including space and ground-based activities.

- **Required by US Congress** under the 2005 and 2008 NASA Authorization Acts, including an evaluation of risks/budgets for major missions. Also reaffirmed in NASA Transition Authorization Act of 2017.







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Survey Scope

- Ground and space-based observations, theory, computation, lab astrophysics
- Ground-based solar astronomy
- Gravitational-wave observations related to astronomy and astrophysics
- Multi-messenger astronomy and astrophysics
- Exoplanets & Astrobiology
  - Informed by recent NAS studies: *Exoplanet Science Strategy* and *Astrobiology Strategy for the Search for Life*
- Consider implementation and scope of WFIRST, Athena, LISA
  - Need not be ranked
- Excluded: direct dark matter detection, microgravity research, fundamental physics, projects under construction (JWST, DKIST, LSST, DESI)

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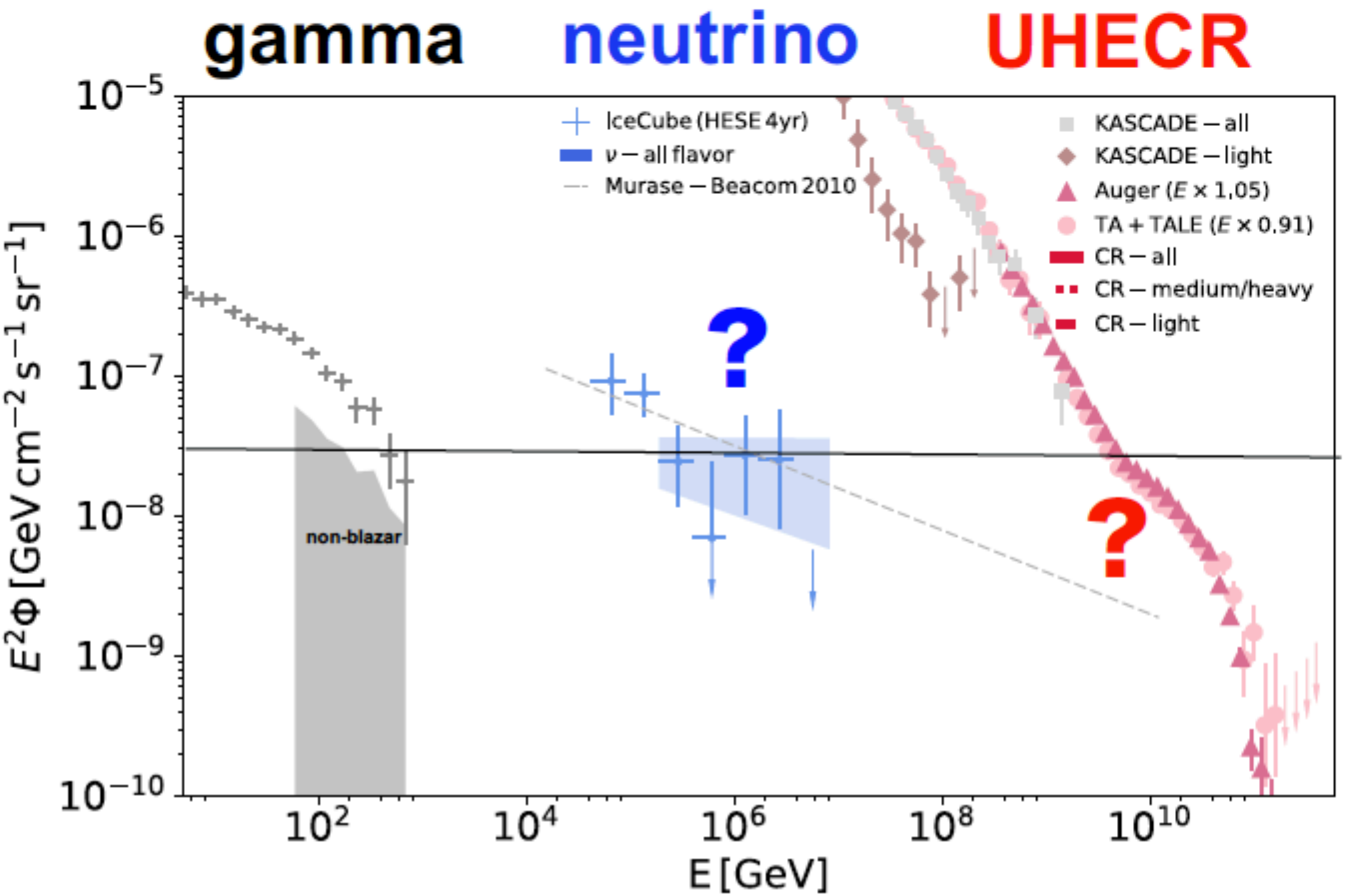
Astro2020 - Decadal Survey Timeline

Time	Activity
End of November 2018	Co-Chairs Announced (Fiona Harrison,Rob Kennicutt)
Spring 2019	Survey committee identified & appointed
Late Spring 2019	Panels formed
Late CY2019	Panel deliberations
Spring / Summer 2020	Survey deliberations and report writing
Early 2021	Release of public report

- 12 Panels (including Particle Astrophysics and Gravitation)
- 590 white submissions
  - available at www.nas.edu/astro2020 / https://baas.aas.org/community/astro2020-science-white-papers/

Multi-Messenger Connection among High-Energy Cosmic Particles

Combined picture



Astrophysical Explanations

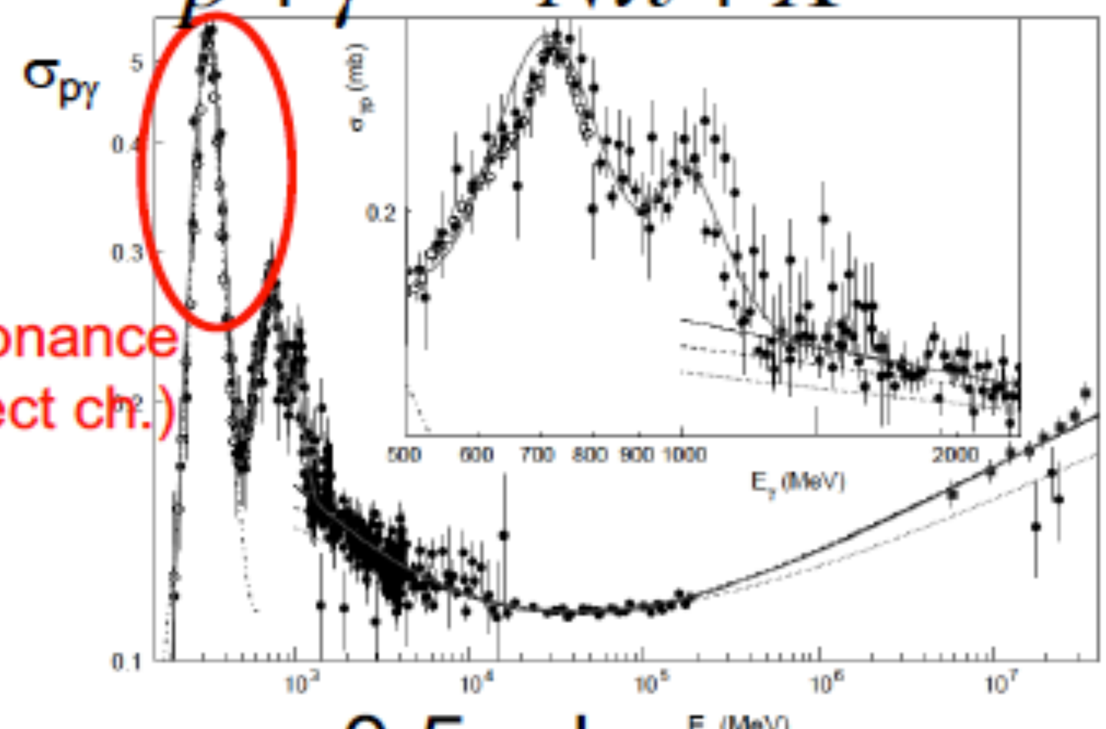
$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Cosmic-ray Accelerators (ex. UHECR candidate sources)

Active galactic nuclei

γ-ray burst

$$p + \gamma \rightarrow N\pi + X$$



$\sigma_{p\gamma} \sim \alpha \sigma_{pp} \sim 0.5$ mb

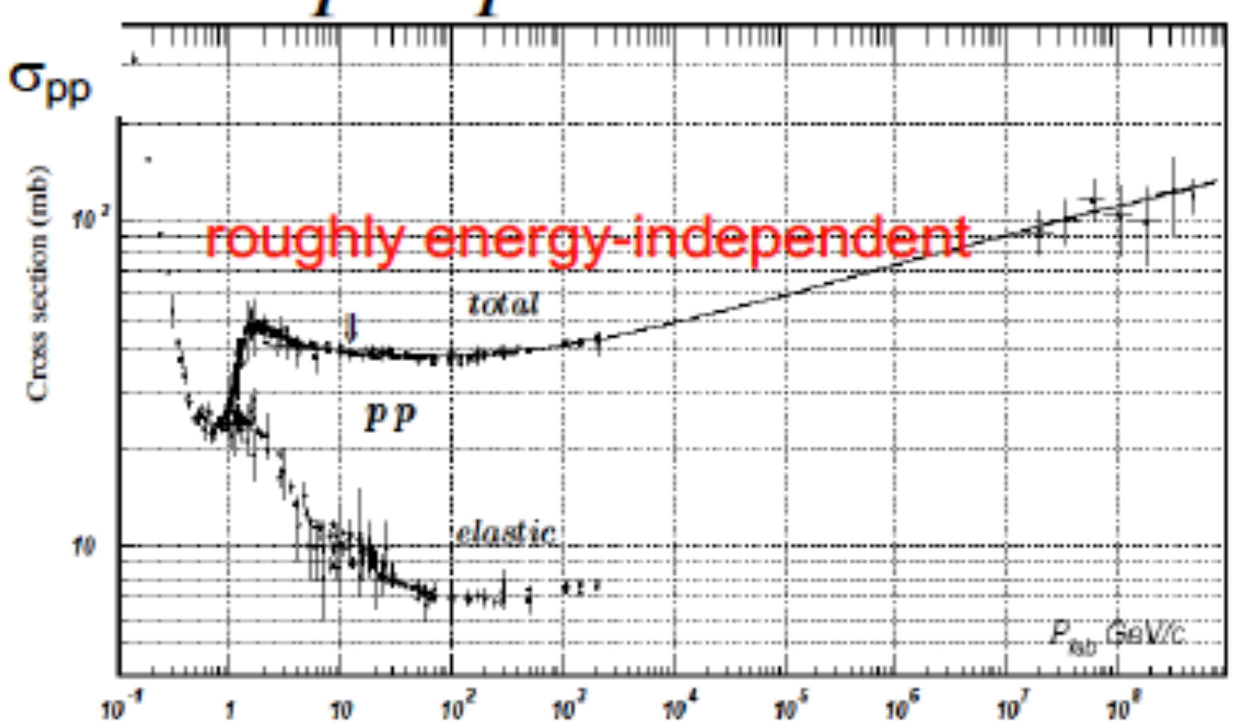
$\varepsilon'_p \varepsilon'_\gamma \sim (0.34\ \mathrm{GeV})(m_p/2) \sim 0.16\ \mathrm{GeV}^2$

Cosmic-ray Reservoirs

Starburst galaxy

Galaxy group/cluster

$$p + p \rightarrow N\pi + X$$

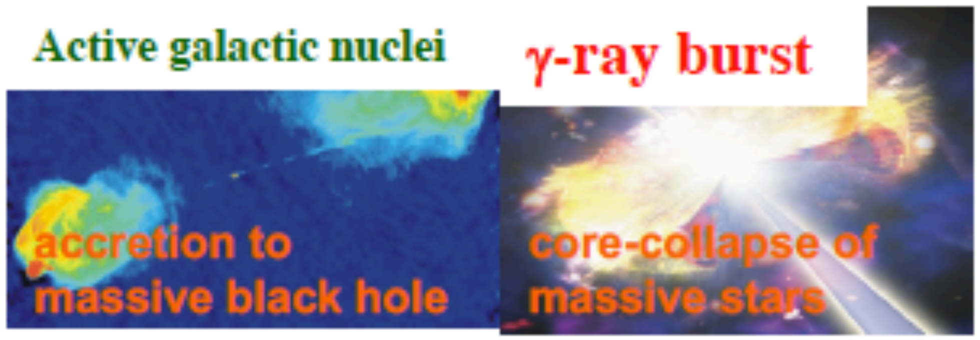


$\sigma_{pp} \sim 30$ mb

Astrophysical Explanations

$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Cosmic-ray Accelerators (ex. UHECR candidate sources)	Cosmic-ray Reservoirs



Accelerators:

$$p + \gamma \rightarrow N\pi + X$$

$\pi^{\pm}:\pi^{0} \sim 1:1$

$\rightarrow E_\gamma^2\, \Phi_\gamma \sim (4/3)\, E_\nu^2\, \Phi_\nu$

Reservoirs:

$$p + p \rightarrow N\pi + X$$

$\pi^{\pm}:\pi^{0} \sim 2:1$

$\rightarrow E_\gamma^2\, \Phi_\gamma \sim (2/3)\, E_\nu^2\, \Phi_\nu$

$$\pi^0 \rightarrow \gamma + \gamma$$

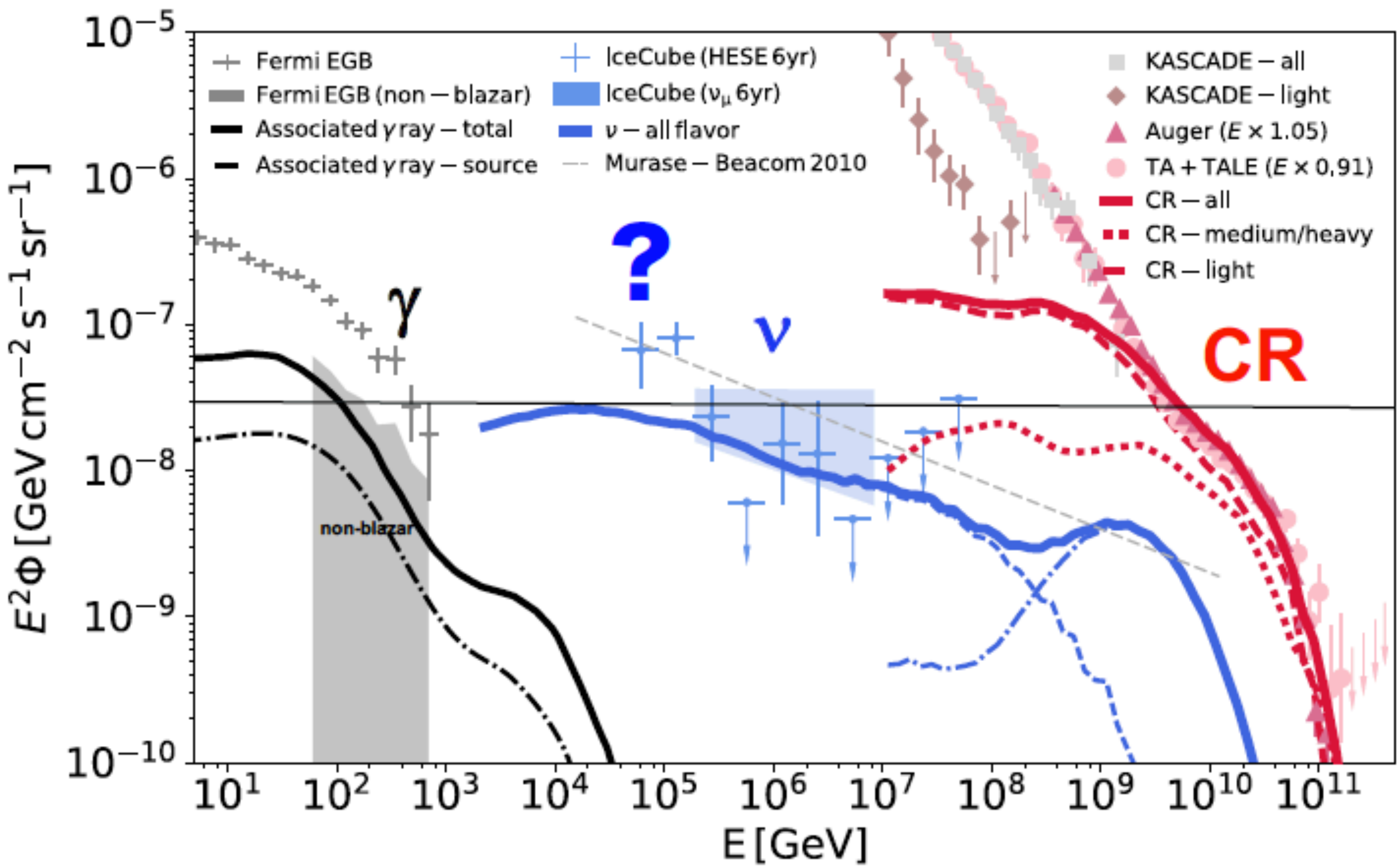
>TeV γ rays interact with CMB & extragalactic background light (EBL)

$$\gamma + \gamma_{CMB/EBL} \rightarrow e^+ + e^-$$

ex. $\lambda_{\gamma\gamma}$(TeV) ~ 300 Mpc
$\lambda_{\gamma\gamma}$(PeV) ~ 10 kpc ~ distance to Gal. Center

Cosmic Particle Unification?

AGN embedded in large scale structures (Fang & KM Nature Phys 18)



Conclusions

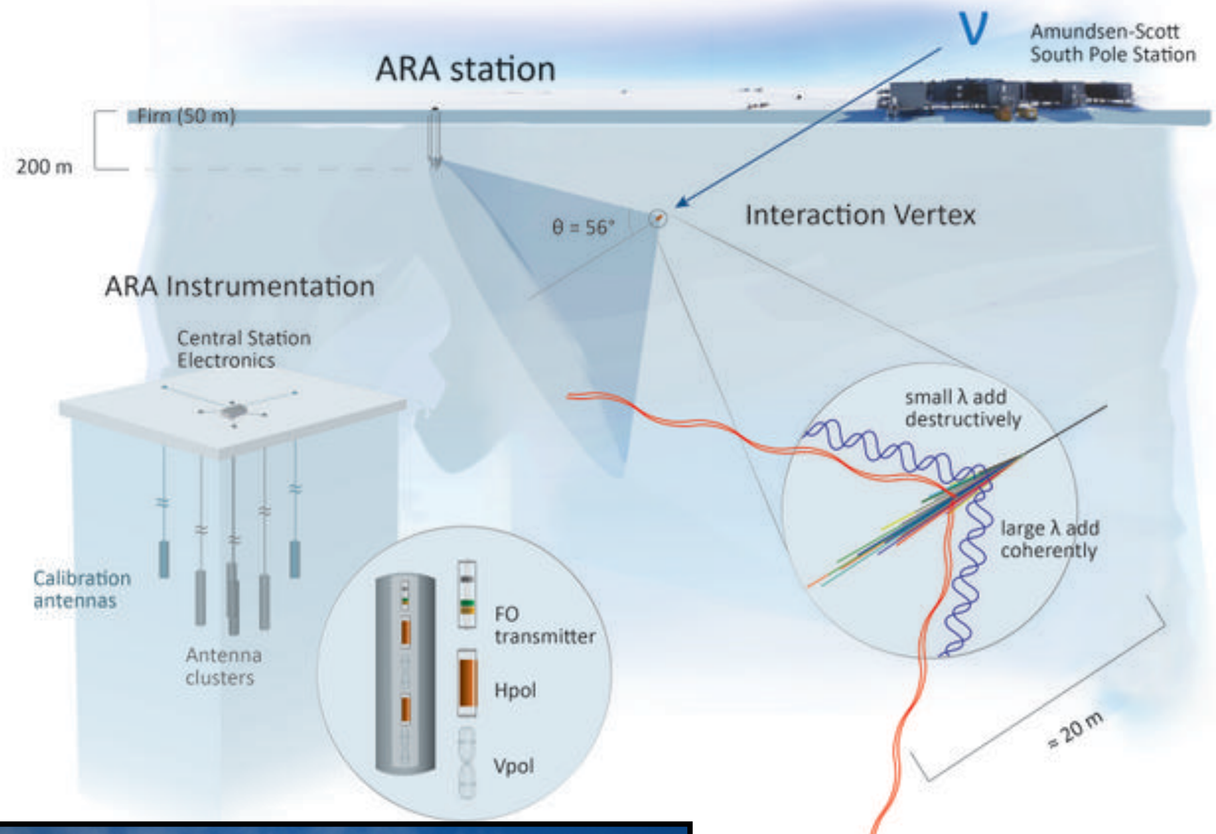
- Multi-messenger astroparticle physics a vibrant new field
- Can observe the Universe in fundamentally new ways
- New instrumentation will continue to drive discoveries
- Big data and model building challenges ahead … making sense of all the data

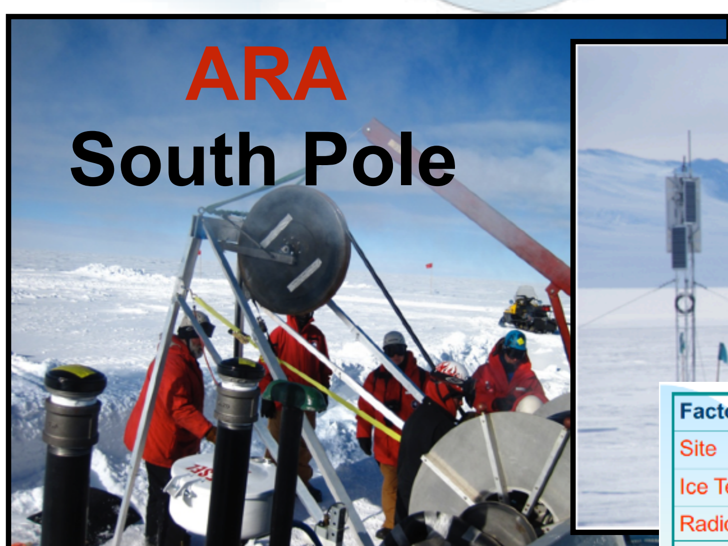
Backup

Radio Detection of Neutrinos

Two classic approaches

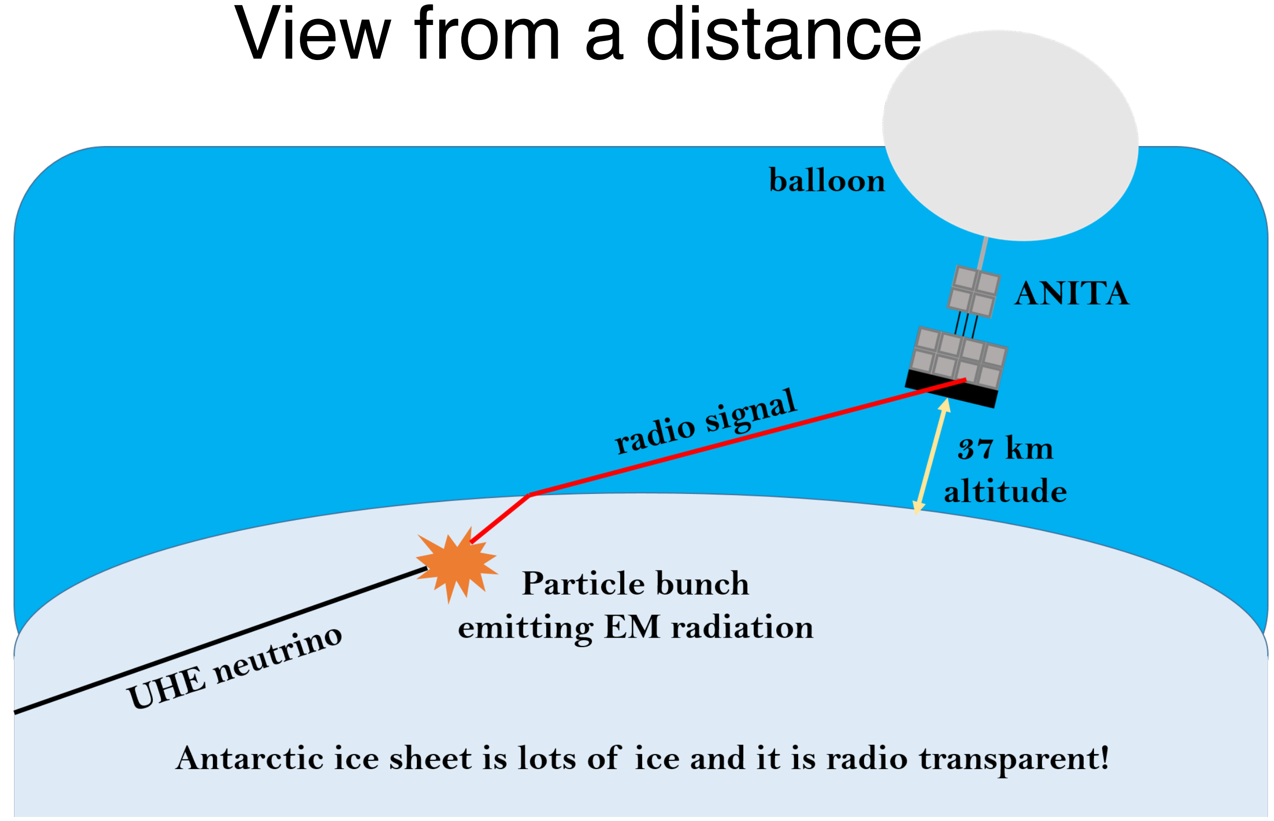
Instrument the ice





Factor	ARA	ARIANNA
Site	South Pole	Ross Ice Shelf
Ice Temperature	Colder	Warmer
Radio Atten. Length	820 m (avg.)	400 m (avg.)
Antenna Deployment	200 m deep narrow borehole	Surface
Acceptance	Horizontal	Horizontal + Downgoing
Anthropogenic Noise	South Pole Station	Little
Logistics	South Pole Station, 2800 m elevation Winter power	Green Field Site Near sea level Winter wind (maybe)
Surface Temperature	-20 to -40^{0}C	Surface temp ~0 ^{0}C

View from a distance



Graphic: Oindree Banerjee

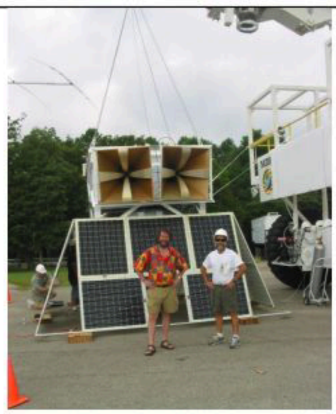
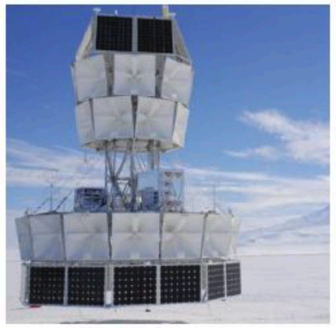
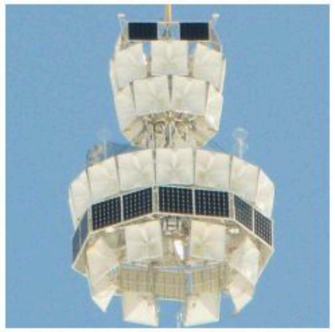
- RICE (Radio Ice Cherenkov Experiment) 1995-2012
  - Dave Besson, Ilya Kravchenko, *et al.*
  - Antennas deployed along strings of AMANDA
  - ~100-200 m depth
- World's best limits for one decade for 50 PeV-1 EeV

Pure ice is low-loss for radio:
field attenuation lengths ~1 km

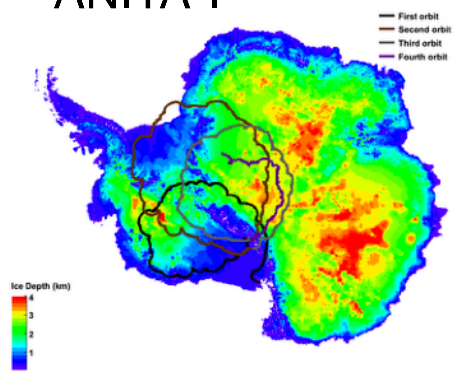
ANITA - ANtarctic Impulsive Transient Antenna

ANITA

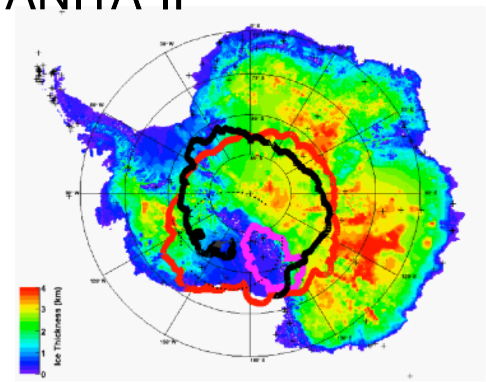
- ANtarctic Impulsive Transient Antenna
  - NASA ultralong duration balloon experiment
- Seeking radio signals from earth-skimming UHE neutrinos
- To this date, 4 flights

ANITA-Lite	ANITA-I	ANITA-II	**ANITA-III**	ANITA-IV
				
2003-2004	2006-2007	2008-2009	2014-2015	2016
18 days, 2 antennas	35 days, 32 antennas	30 days, 40 antennas	22 days, 48 antennas	29 days, 48 antennas
Piggy-back on TIGER	Multi-band, Pol-independent trigger	Multi-band, VPol trigger	Full-band HPol + VPol trigger	Full-band, Lin-Pol trigger
Analyzed	Analyzed	Analyzed	**Recently analyzed**	Analysis Ongoing

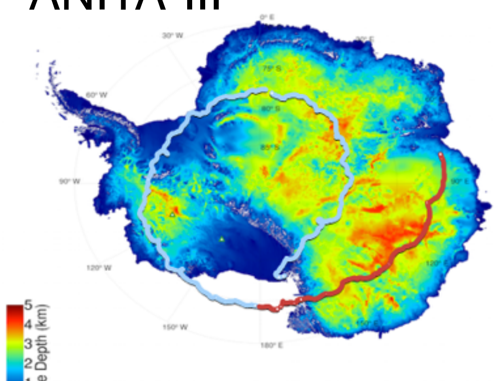
ANITA-I



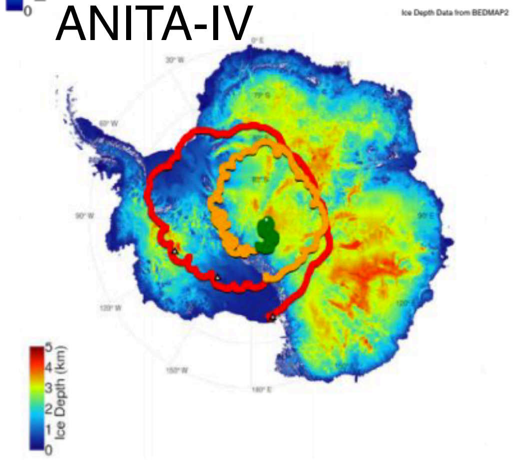
ANITA-II



ANITA-III

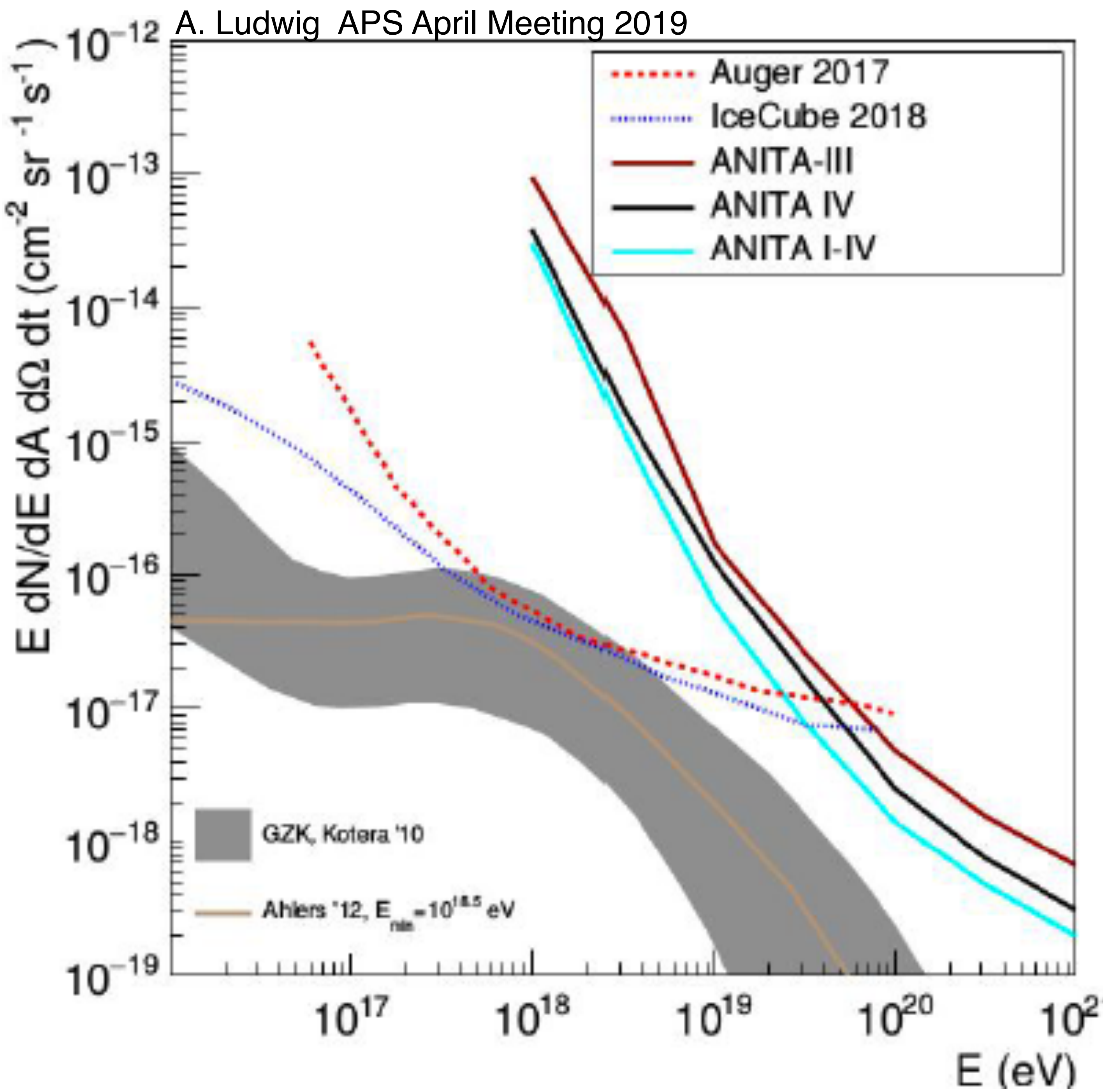


ANITA-IV



Current limits

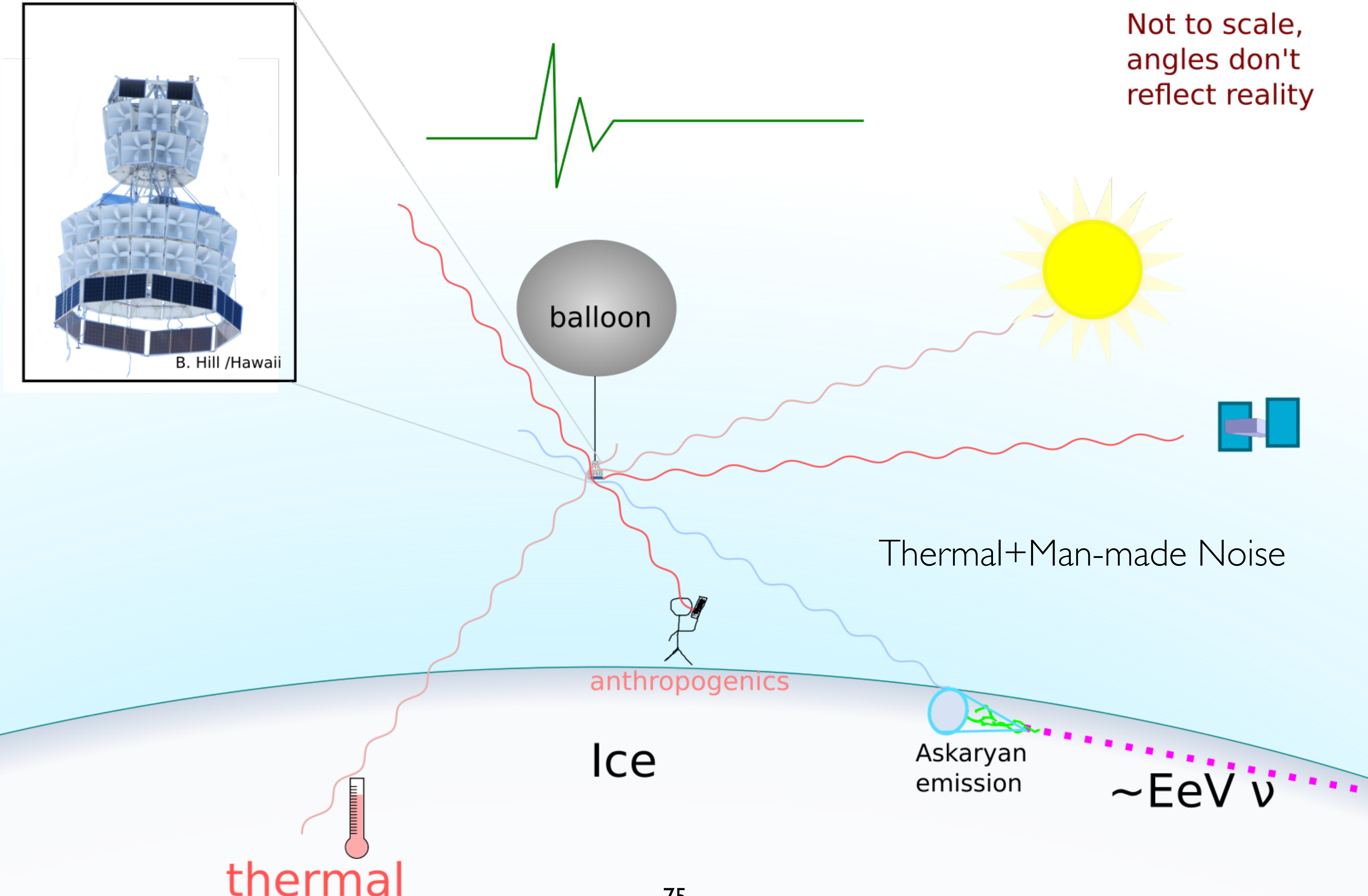
- ANITA (4 flights)
- IceCube
  - Tracks or cascades with very high light output
- Auger
  - Showers emerging from the Earth
  - Near-vertical & deeply interacting high-angle
- Current Limits touch on some GZK predictions
  - All protons
  - Favorable evolution



A. Ludwig APS April Meeting 2019

M. G. Aartsen et al., PRL117, 241101 (2016);
A. Aab et al., Phys. Rev. D91, 092008 (2015);
P. W. Gorham et al., Phys. Rev. D85, 049901 (2012)

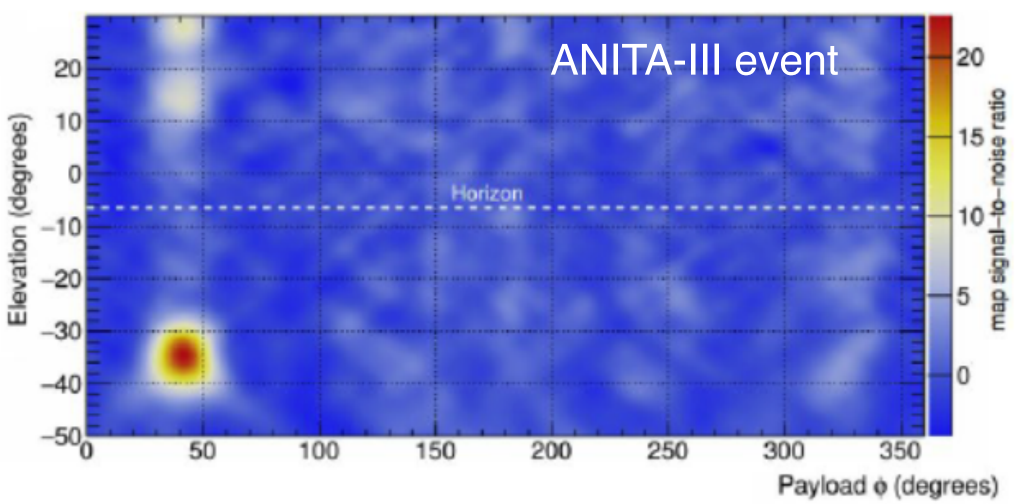
ANITA-III Diffuse (Askaryan Neutrino Search)

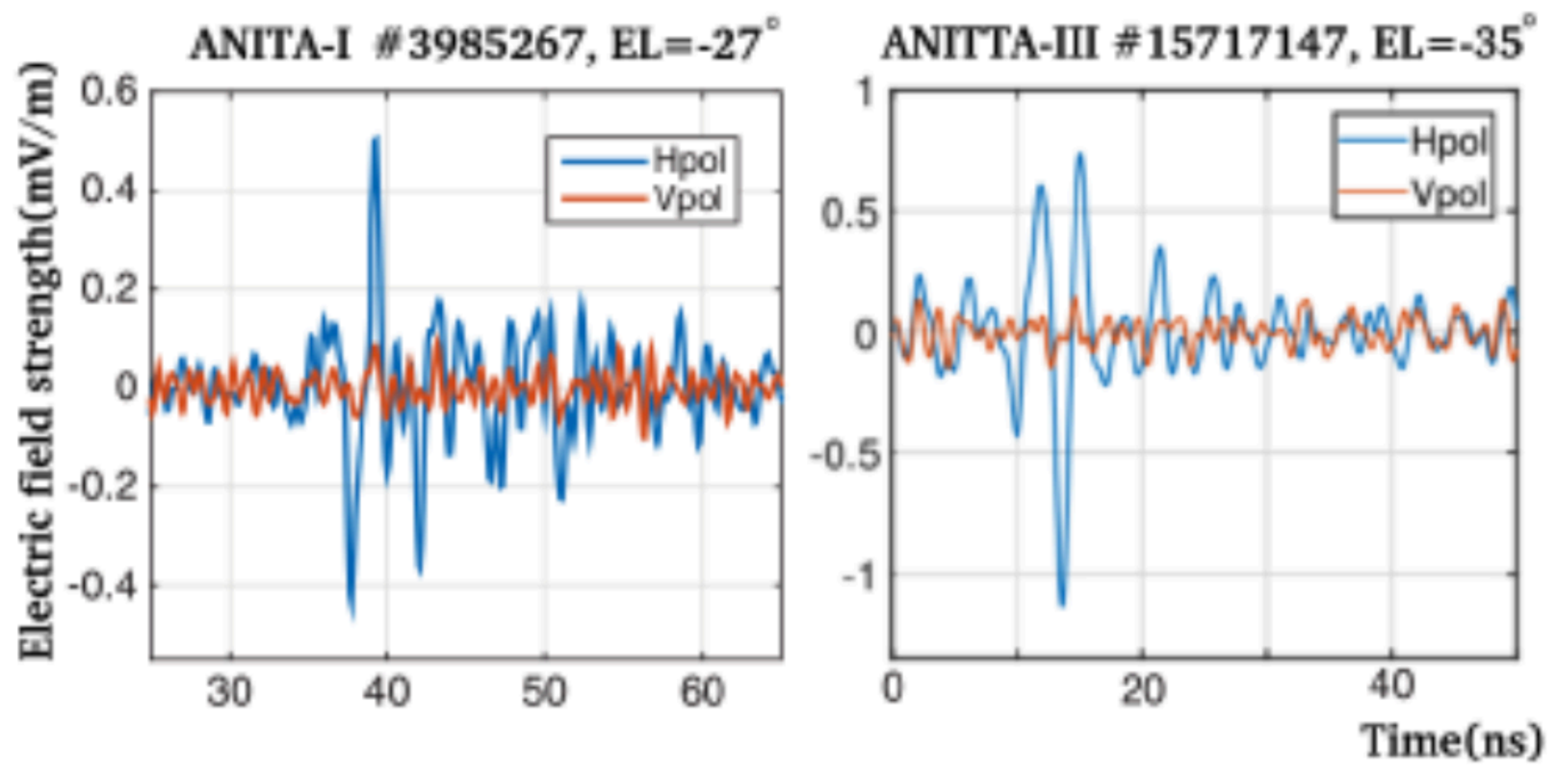


Romero-Wolf et al Phys.Rev. D99 (2019) no.6, 063011 (arXiv:1811.07261)

ANITA Anomalous Events

- ANITA-I event reported in P. Gorham et al. [ANITA Collaboration], Phys. Rev. Lett. 117, 071101 (2016).
- ANITA-III event reported in P. Gorham et al. [ANITA Collaboration], Phys. Rev. Lett. 121, 161102 (2018).





	ANITA-I: Event 3,985,267	ANITA-III: Event 15,717,147
Payload Elevation Angle	-27.4° ± 0.3°	-35.0° ± 0.3°
Payload Azimuth Angle	159.6° ± 0.7°	61.4° ± 0.7°
Payload Altitude	35.029 km	35.861 km
Ice Thickness	3.53 km	3.22 km
Magnetic Field Strength at 0-km	49.9892 μT	60.0783 μT
Magnetic Field I	-68.24265°	-77.4927°
Magnetic Field D	-38.5059°	-155.6842°
Peak Hpol Electric Field Strength	0.77 mV/m	1.1 mV/m
Air shower energy	0.6 ± 0.4 EeV	$0.6^{+0.3}_{-0.2}$ EeV

- Two anomalous events observed
- Mostly H-pol
- Consistent with UHECR signature but clearly up-going (emerging from ice)

ANITA Anomalous Events

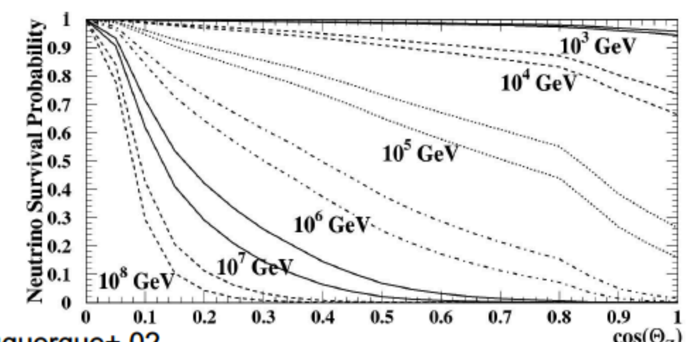
Fox et al (2019)

TABLE I. Properties of the ANITA Anomalous Events

Property	AAE 061228	AAE 141220
Flight & Event	ANITA-I #3985267	ANITA-III #15717147
Date & Time (UTC)	2006-12-28 00:33:20	2014-12-20 08:33:22.5
Equatorial coordinates (J2000)	R.A. 282°.14064, Dec. +20°.33043	R.A. 50°.78203, Dec. +38°.65498
Energy $\varepsilon_{\rm cr}$	0.6 ± 0.4 EeV	$0.56^{+0.30}_{-0.20}$ EeV
Zenith angle z'/z	117°.4 / 116°.8 ± 0°.3	125°.0 / 124°.5 ± 0°.3
Earth chord length ℓ	5740 ± 60 km	7210 ± 55 km
Mean interaction length for $\varepsilon_\nu = 1$ EeV	290 km	265 km
$p_{\rm SM}(\varepsilon_\tau > 0.1\,{\rm EeV})$ for $\varepsilon_\nu = 1$ EeV	4.4×10^{-7}	3.2×10^{-8}
$p_{\rm SM}(z > z_{\rm obs})$ for $\varepsilon_\nu = 1$ EeV, $\varepsilon_\tau > 0.1$ EeV	6.7×10^{-5}	3.8×10^{-6}
n_τ(1–10 PeV) : n_τ(10–100 PeV) : n_τ(> 0.1 EeV)	34 : 35 : 1	270 : 120 : 1

- Emerged from the Earth at ~27 degrees below the horizon
- Earth chord length 5740 km (~15 interaction lengths for incoming EeV neutrino)

- Emerged from the Earth at ~35 degrees below the horizon
- Earth chord length 7210 km (~27 interaction lengths for incoming EeV neutrino)



Albuquerque+ 02

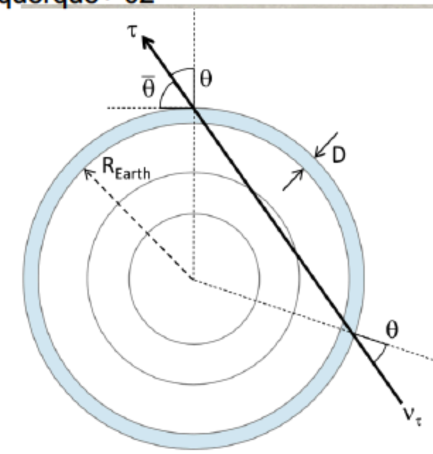
K. Murase LHC-Results Forum 2019

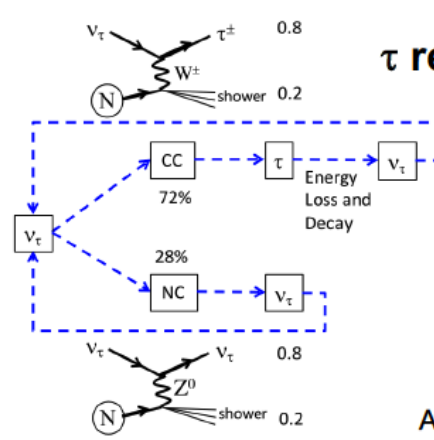
$\sigma_{\nu N}$~10^{-32} cm2 @ EeV

ρ_{Earth}~5.5 g cm-3

chord length~7300km

-> $\tau_{\nu N}$~60 >> 1





τ regeneration

NuTauSim

Alvarez-Muniz+ 08

New Physics Implications

Standard model explanation can be excluded (if we consider the ANITA signals as real)

- Inconsistency with energy and zenith angle of events
- Inconsistency with observed astrophysical neutrino flux by IceCube

- SUSY (Long-lived particles) - NLSP stau / NLSP bino / CHAMPS / sphaleron configurations
  - Long-lived stau (Fox et al 2018, Collins et al 2018, Anchordoqui & Antoniadis 2018, … Albuquerque 2004/2007)
- Leptoquarks
  - Chauhan & Mohanty 2018
- Dark matter related models
  - Heurtier et al 2019, Anchordoqui et al. 2018
- Sterile neutrinos
  - Cherry & Shoemaker 2018, Huang 2018

Connolly et al
arXiv:1807.08892

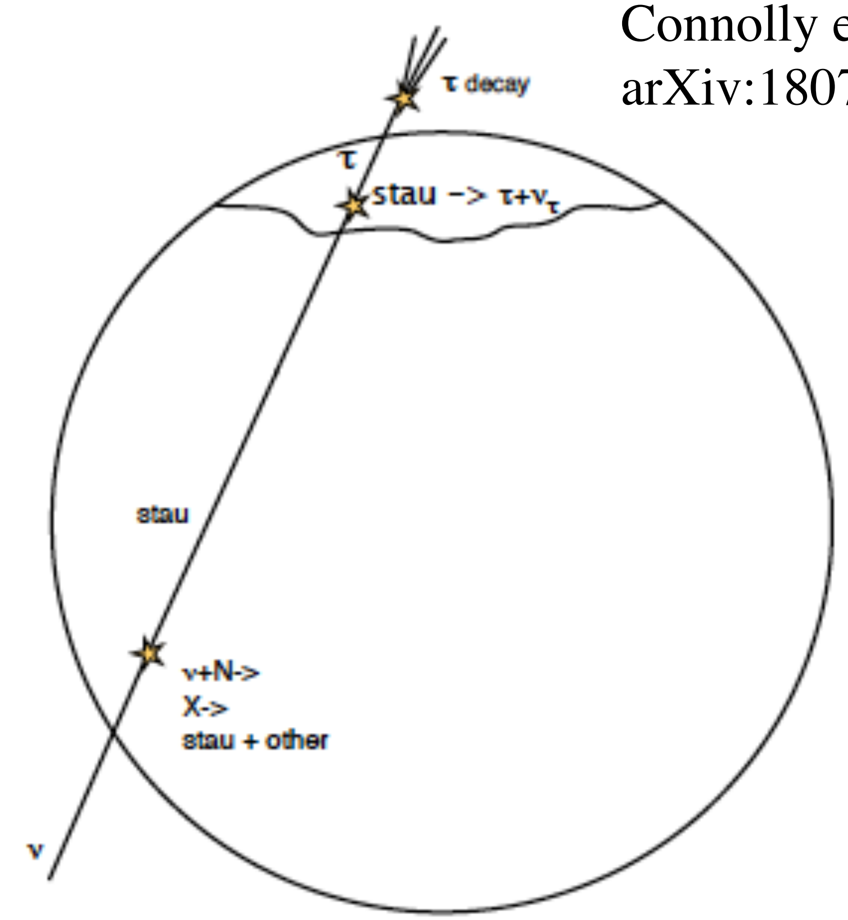


Figure 2: Sketch of the signature being considered here. Although the figure shows one stau being produced in the νN interaction, a stau pair could be produced instead, doubling the probability of detection.

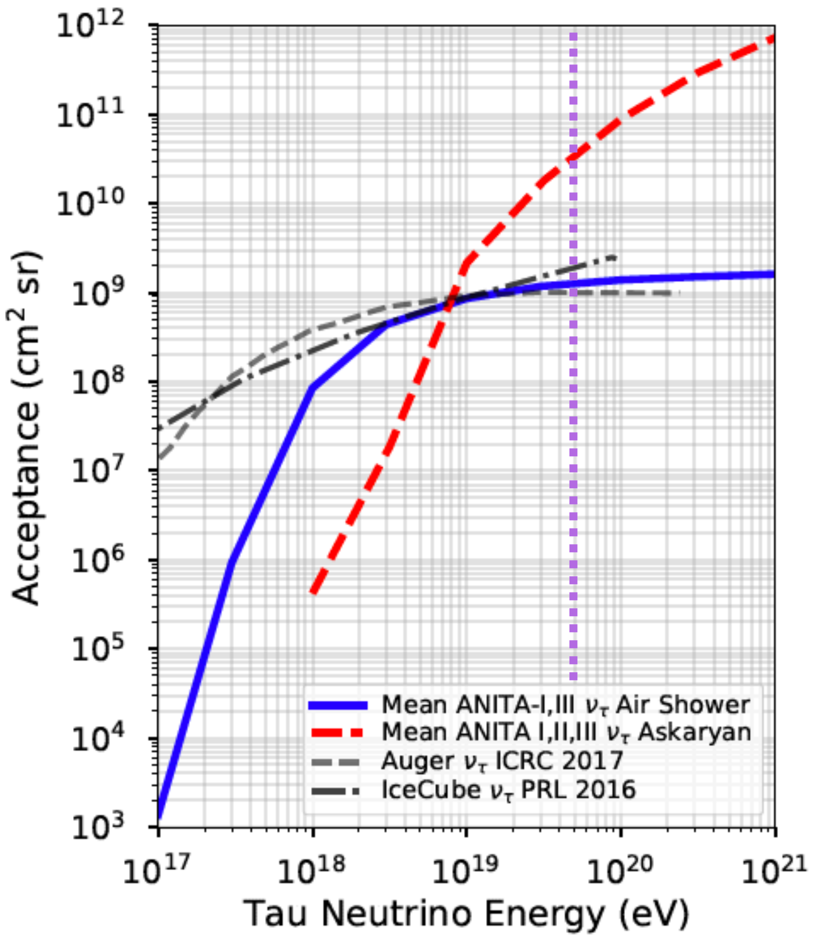
Unexpected backgrounds ?

- Double reflection by crevasses?
- Anthropogenic backgrounds
- Coherent transition radiation (de Vries & Prohira 2019)
- Other unknown backgrounds ?

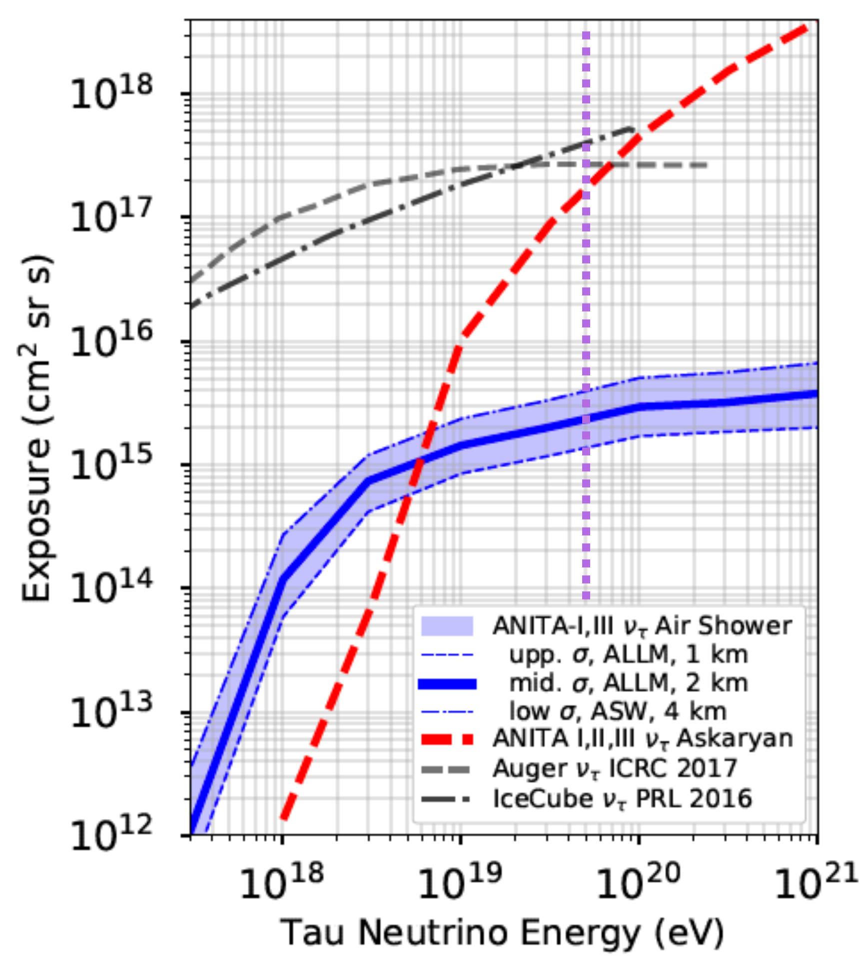
IceCube data appears inconsistent with these events

Romero-Wolf et al Phys.Rev. D99 (2019) no.6, 063011
(arXiv:1811.07261)

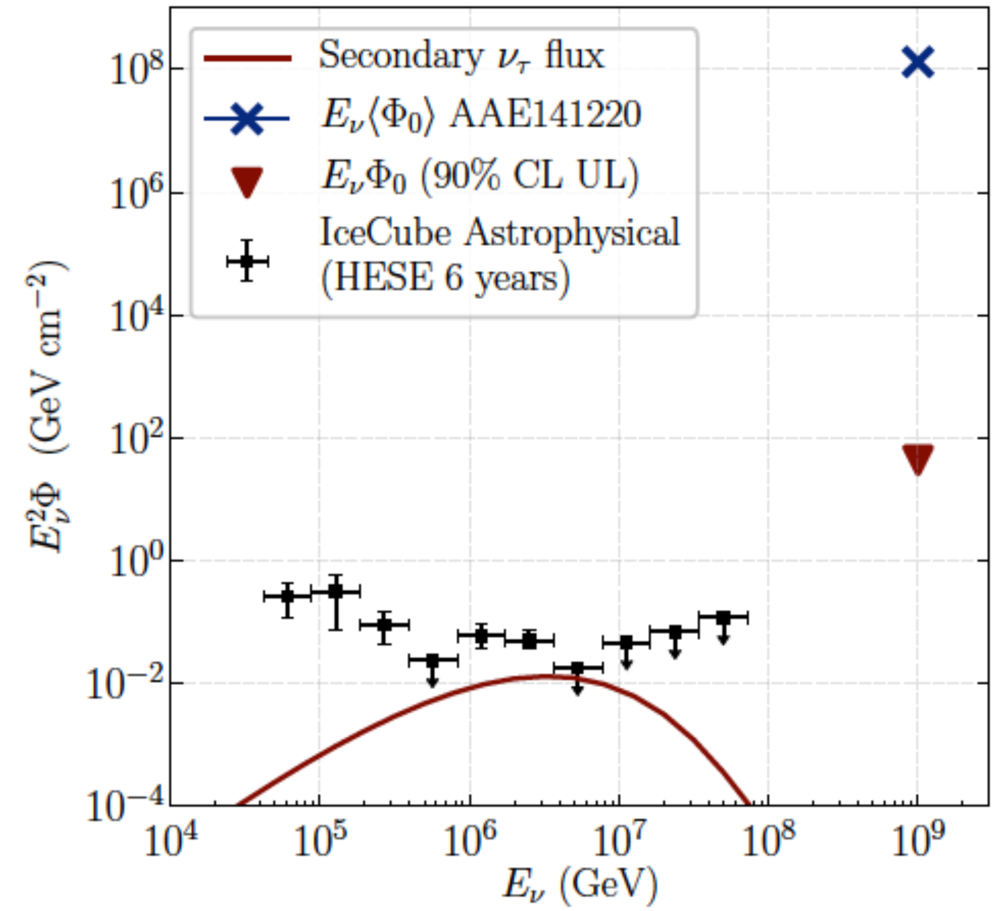
Consistency among experiments



Romero-Wolf et al. (2018)



Safa et al. PoS(ICRC2019)995



- Many more events in IceCube & Auger data expected for E<$10^{19.5}$ eV … but not reported
- Any flux from the direction of the ANITA events should be accompanied by secondary tau-neutrinos detectable at IceCube
- Maximum allowed secondary flux at IceCube at 10^6 inconsistent with ANITA event
- (Kistler & Laha PRL 120 (2018) no.24, 241105 - very high-energy tau tracks)

IceCube data inconsistent with the anomalous ANITA events