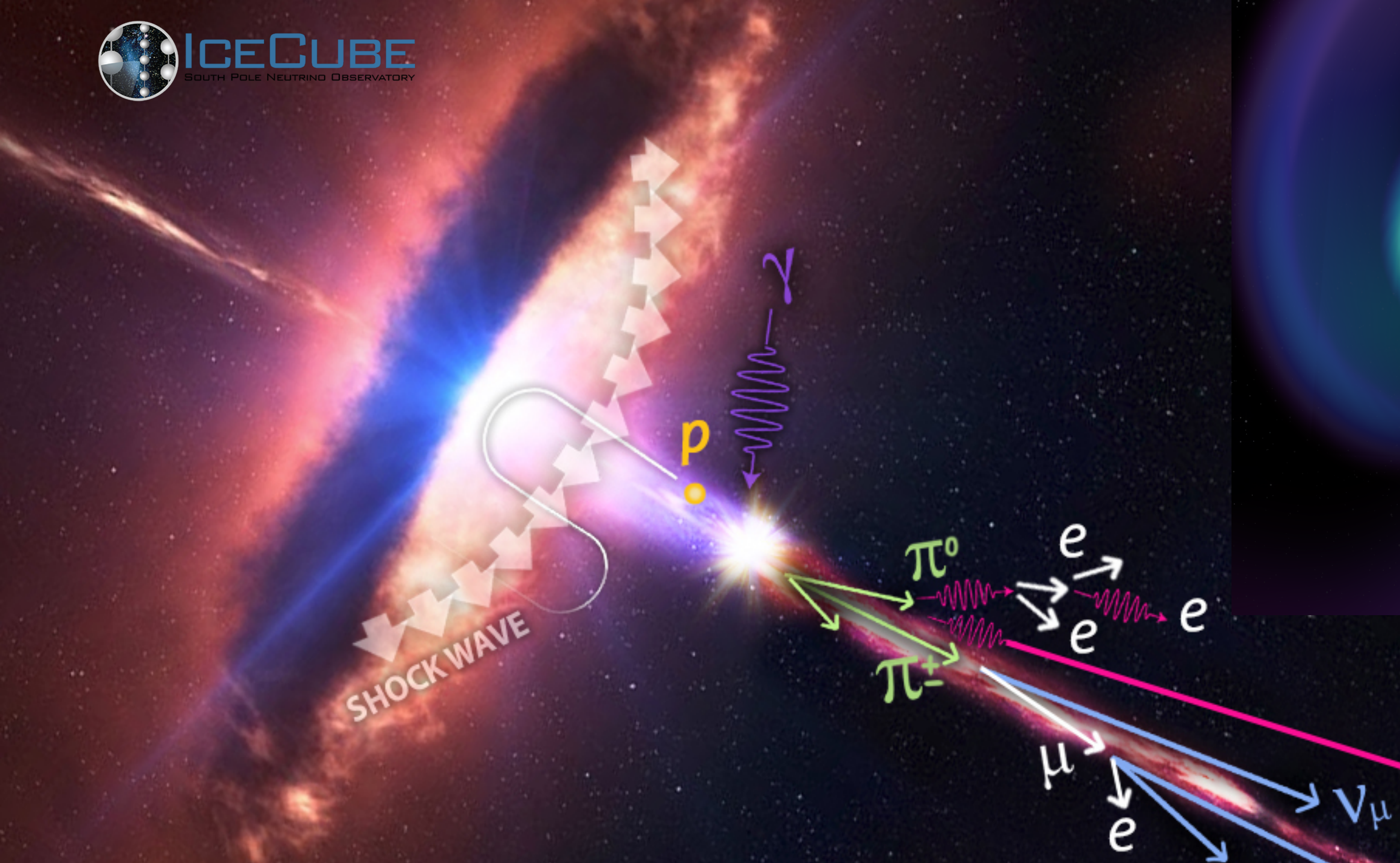
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

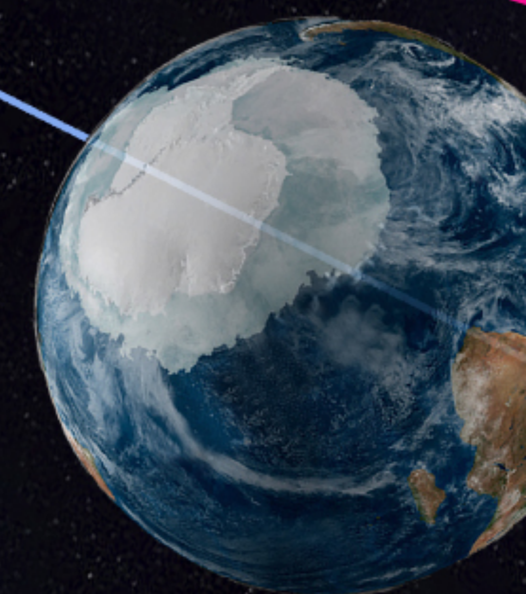
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



Azadeh Keivani
Columbia University

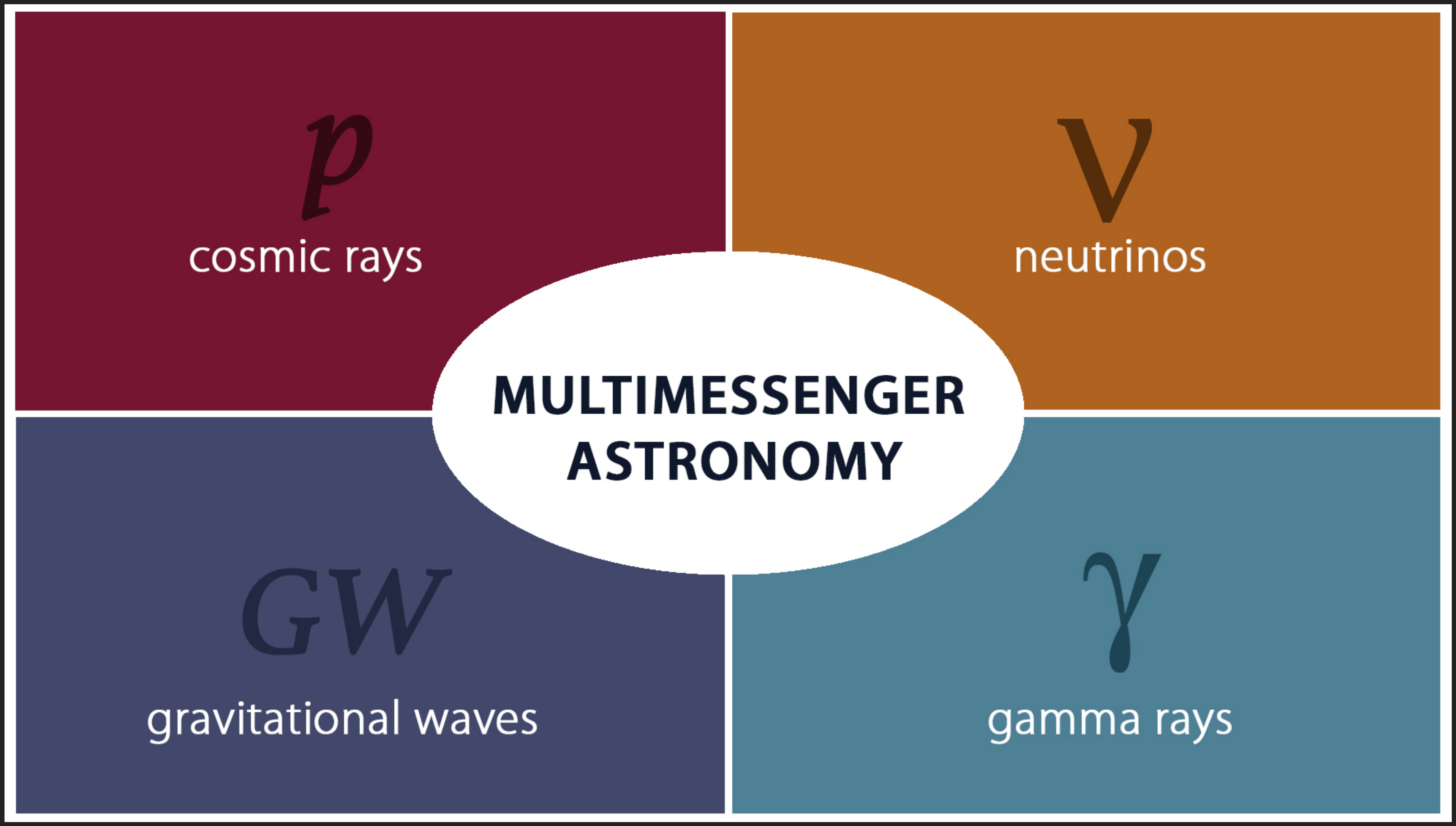
On behalf of the IceCube Collaboration

Multi-Messenger Gravitational Wave + High-Energy Neutrino Searches with LIGO, Virgo, and IceCube



ICRC 2019
Madison, WI

Multi-Messenger Astrophysics



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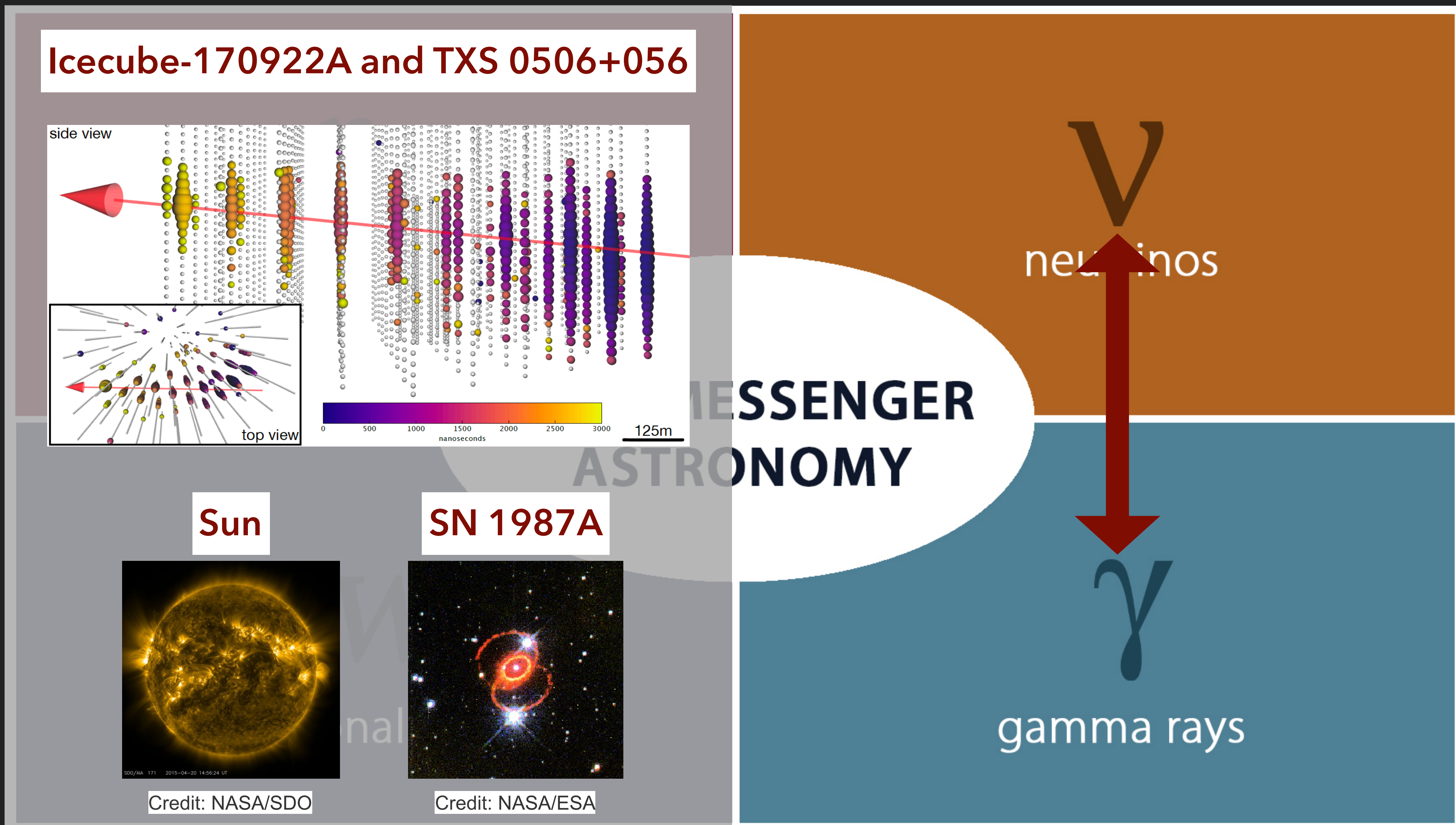

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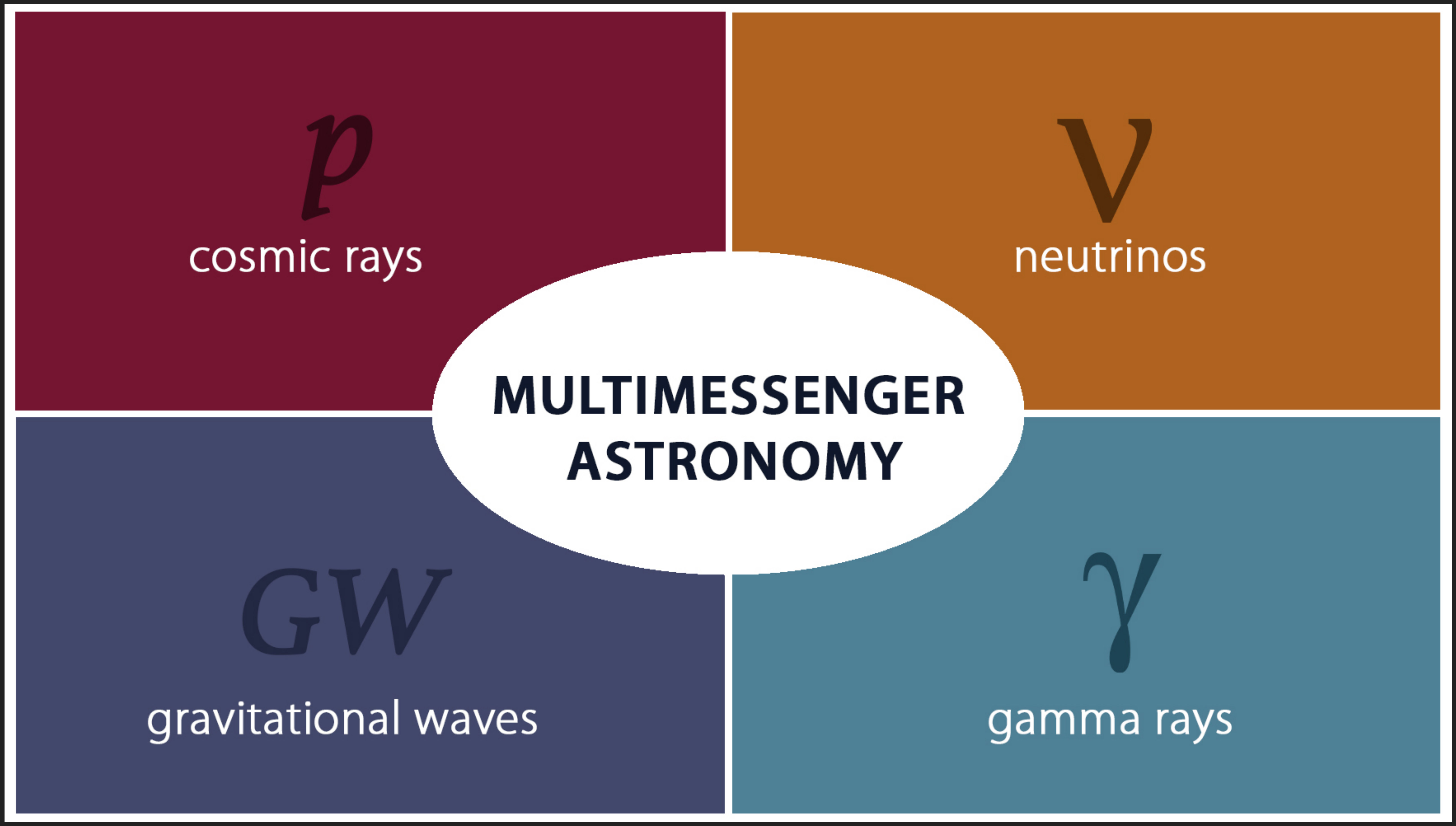

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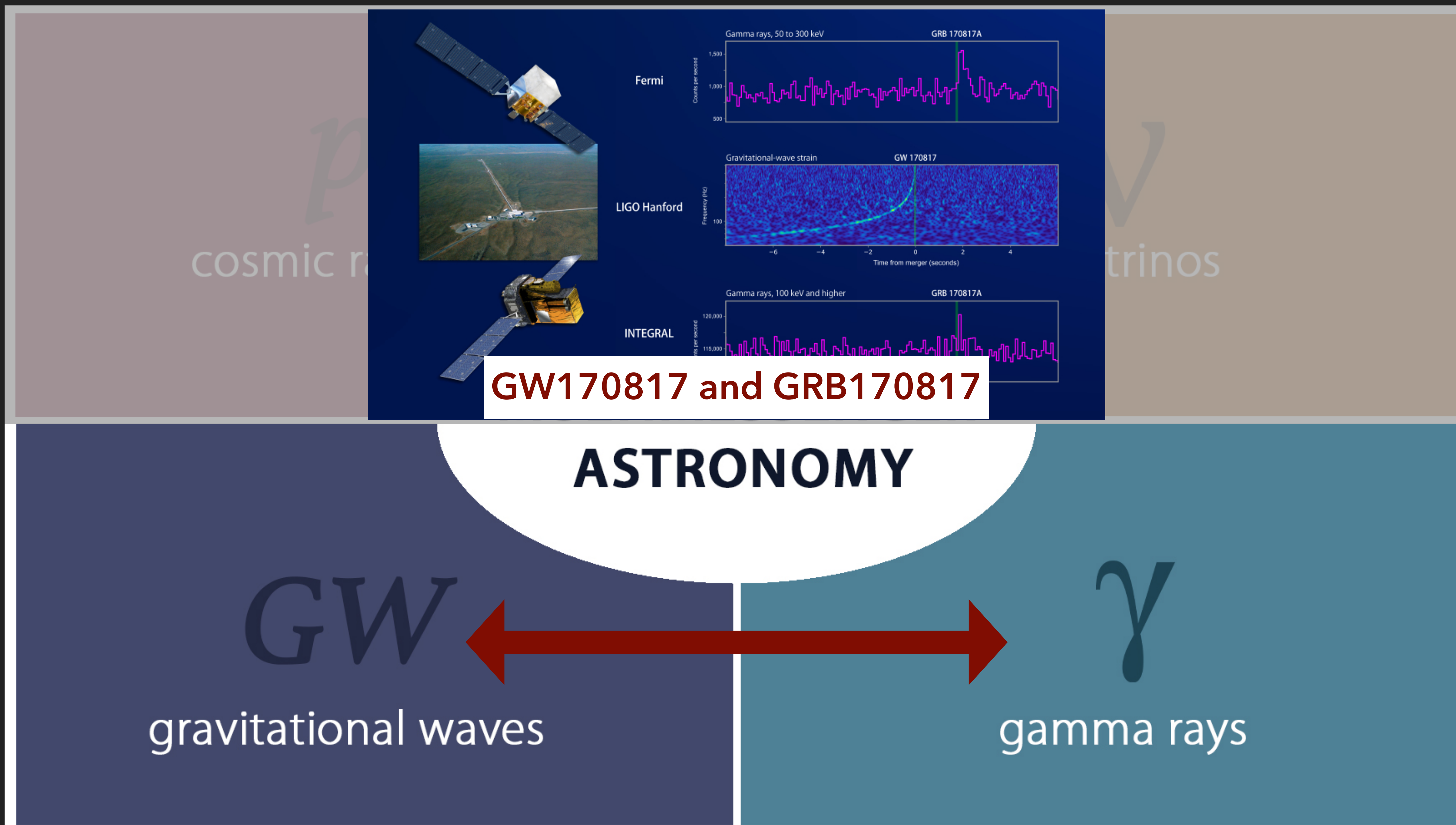

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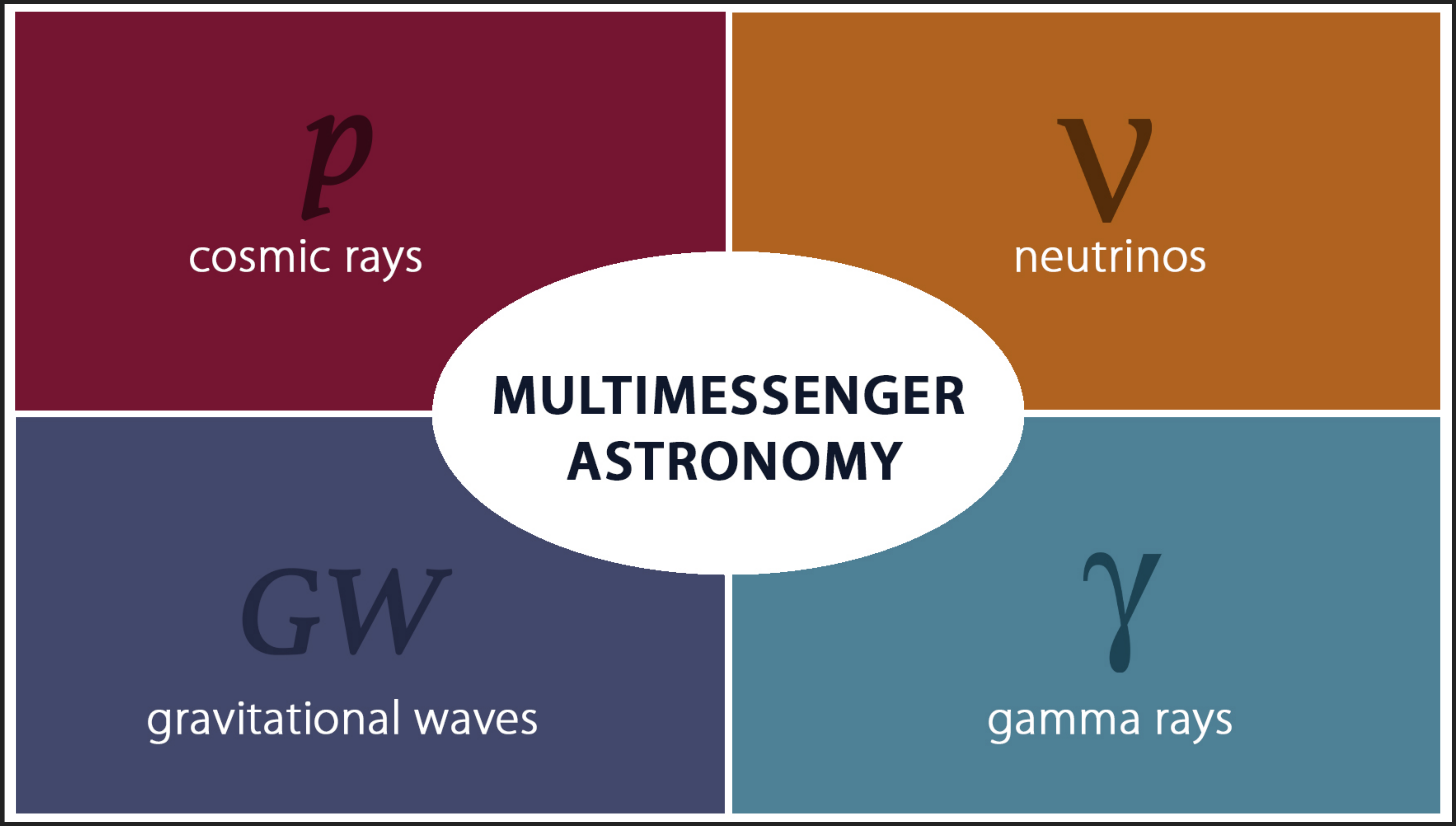

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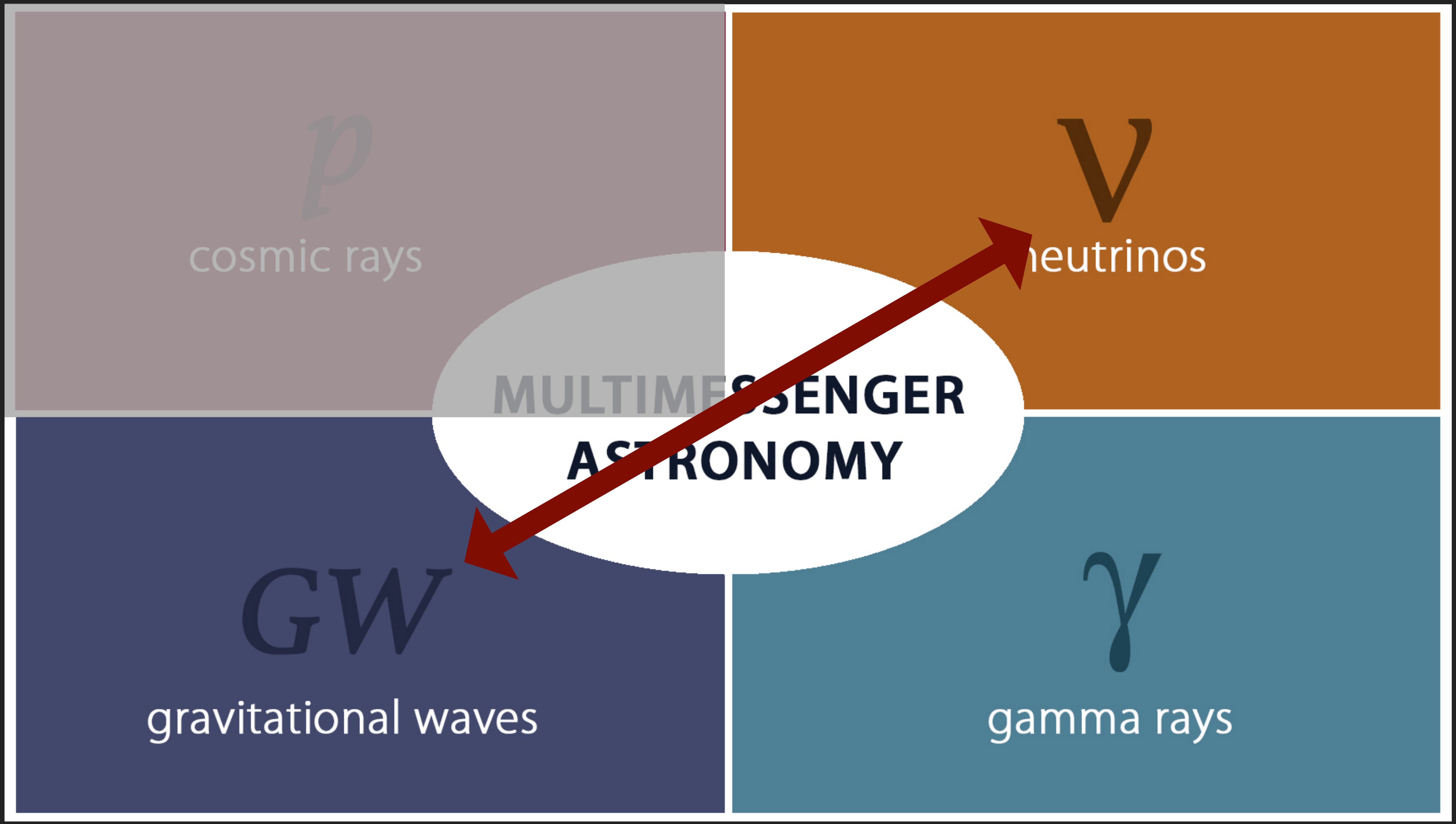

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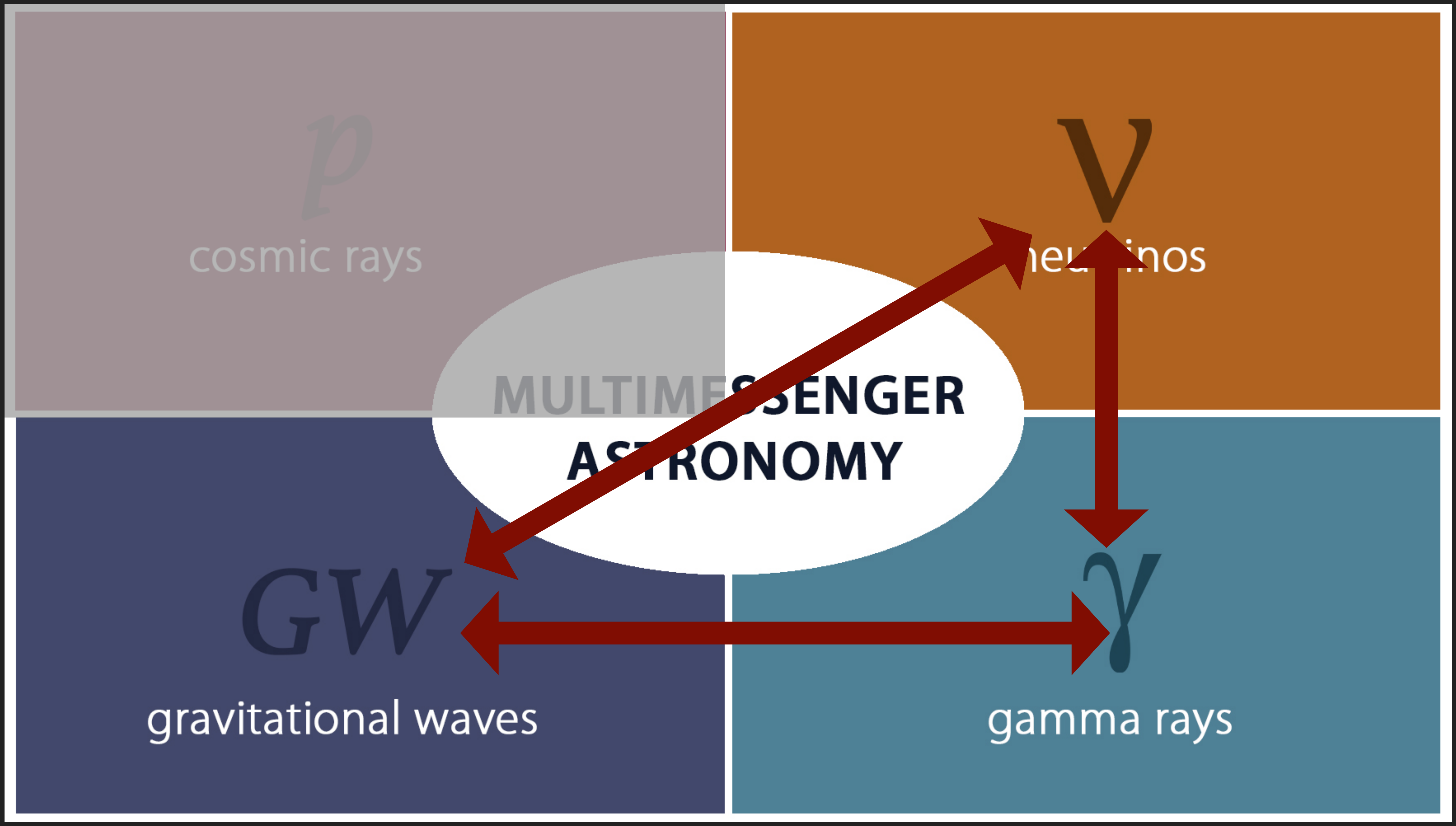
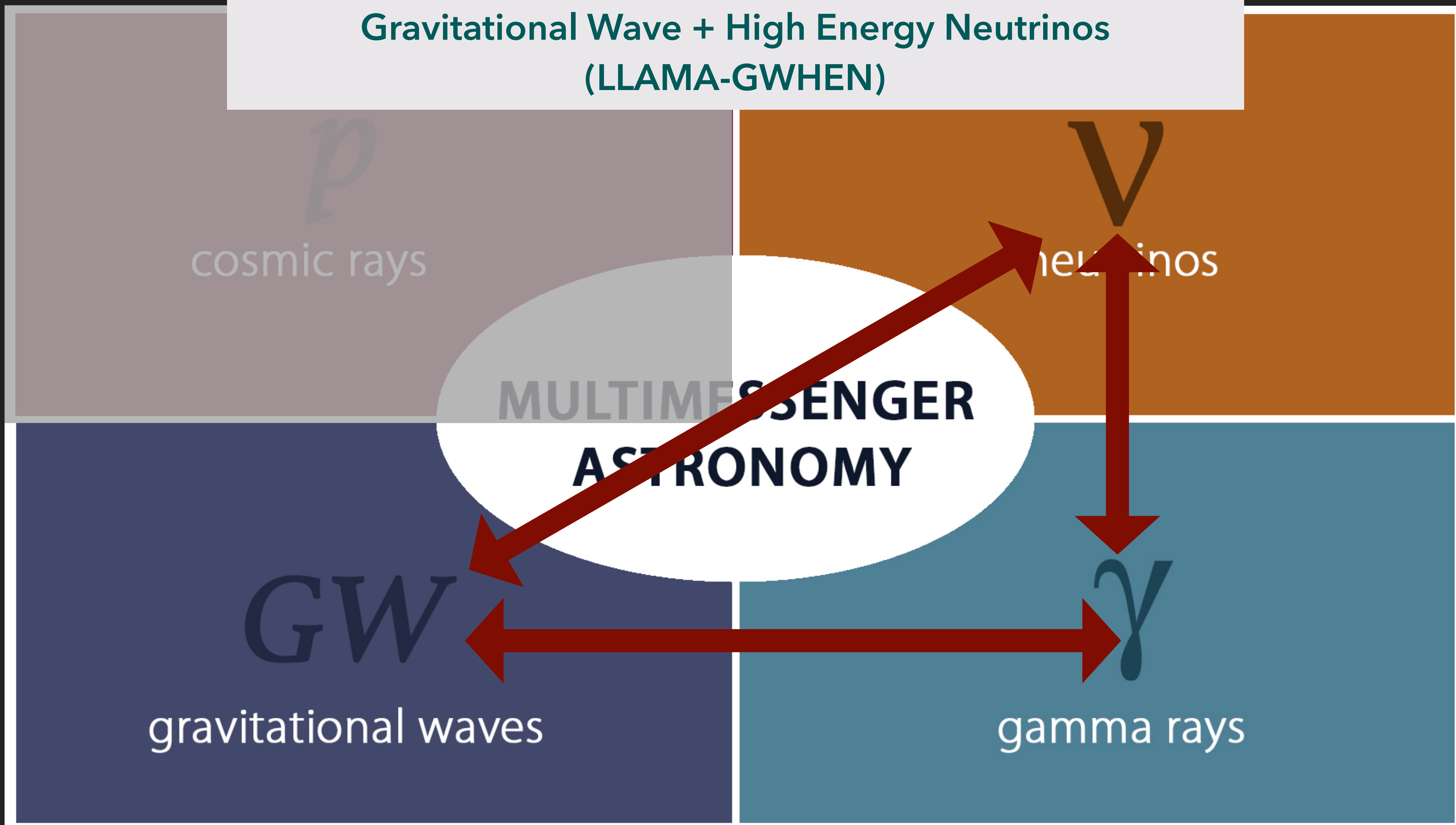


Multi-Messenger Astrophysics

Low-Latency Algorithm for Multi-messenger Astrophysics
Gravitational Wave + High Energy Neutrinos
(LLAMA-GWHEN)



Gravitational Waves and High-Energy Neutrinos

We search for common sources of gravitational waves (GWs) and high-energy neutrinos (HENs) in **realtime/low-latency!**

No astrophysical source has yet been observed simultaneously with both messengers!

PoS 930

S. Countryman, AK, I. Bartos, et al (2019) arXiv:1901.05486

I. Bartos, D. Veske, AK, et al (2019) arXiv:1810.11467

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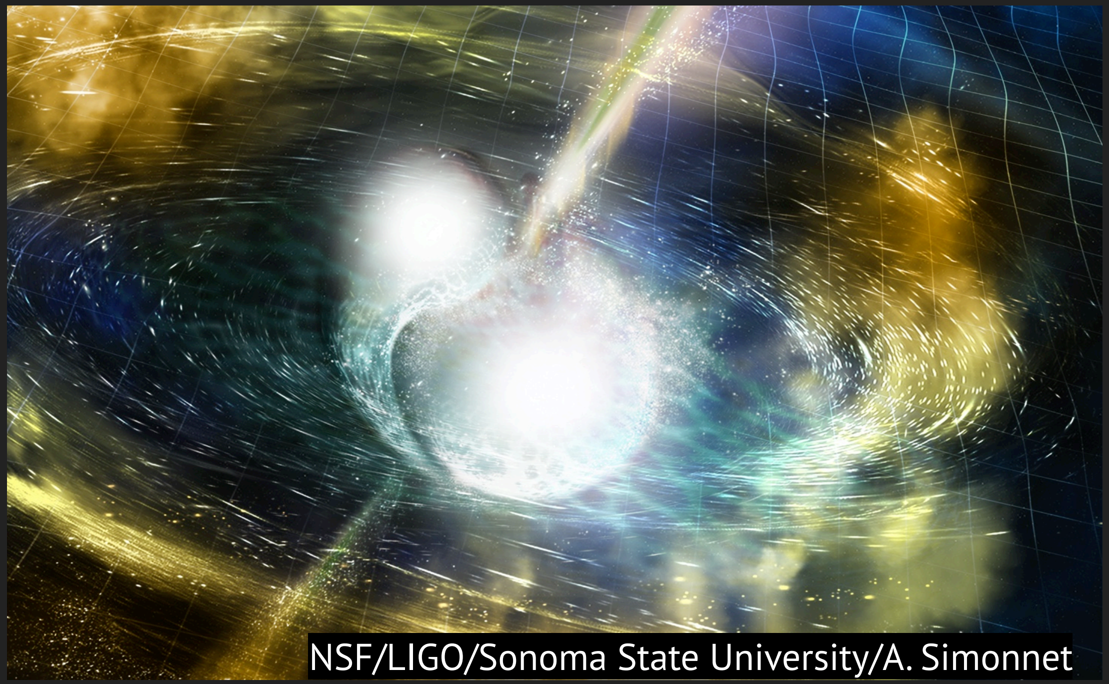
Note: There is another parallel search in IceCube using a transient likelihood analysis!

PoS 918

Talk by Raamis Hussain
NU9d

Candidate Sources

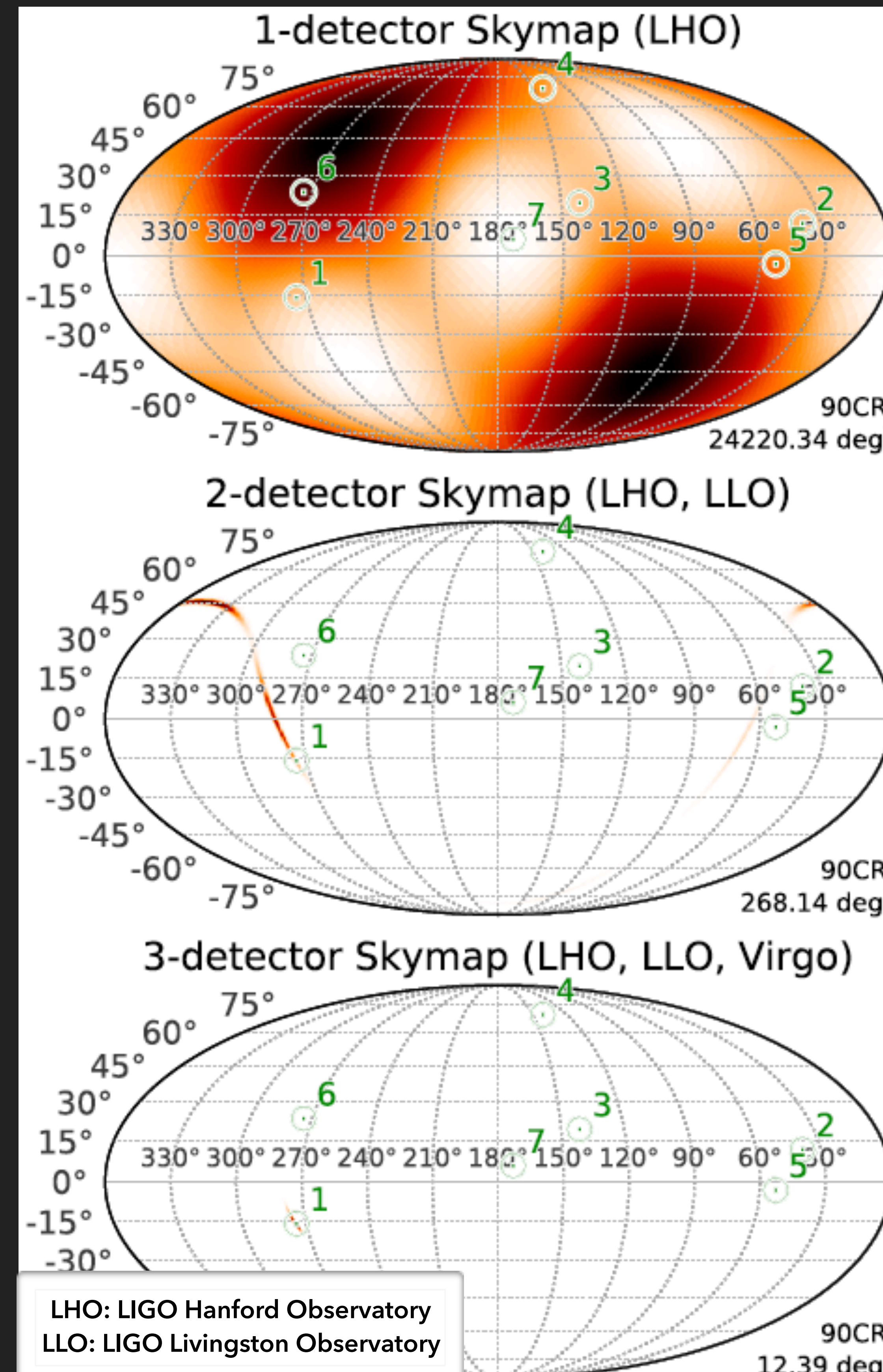
- Several sources proposed:
  - Binary neutron star (BNS) merger
  - Neutron star – black hole merger
  - Core-collapse supernova
  - Gamma-ray burst (GRB)
  - Soft gamma repeater
  - …



- The most promising:
  Short GRBs associated with BNS mergers
- Create relativistic outflows producing HENs
- Revealing unknown sources

Advantages of GW+HEN search

- **Improved localization:**
  - GW area size (10s-1000s deg²) a limiting factor for EM follow-up efforts
  - Neutrinos (0.5 deg²)
- **Sub-threshold search:**
  - Events with low significances standalone
  - Joint GW+HEN event: higher significance
  - Further follow-up observations increase discovery potential
- **Astrophysical information:**
  - E.g. prior distance distribution
  - Enhance sensitivity
- **Higher event rate:**
  - Automation is needed



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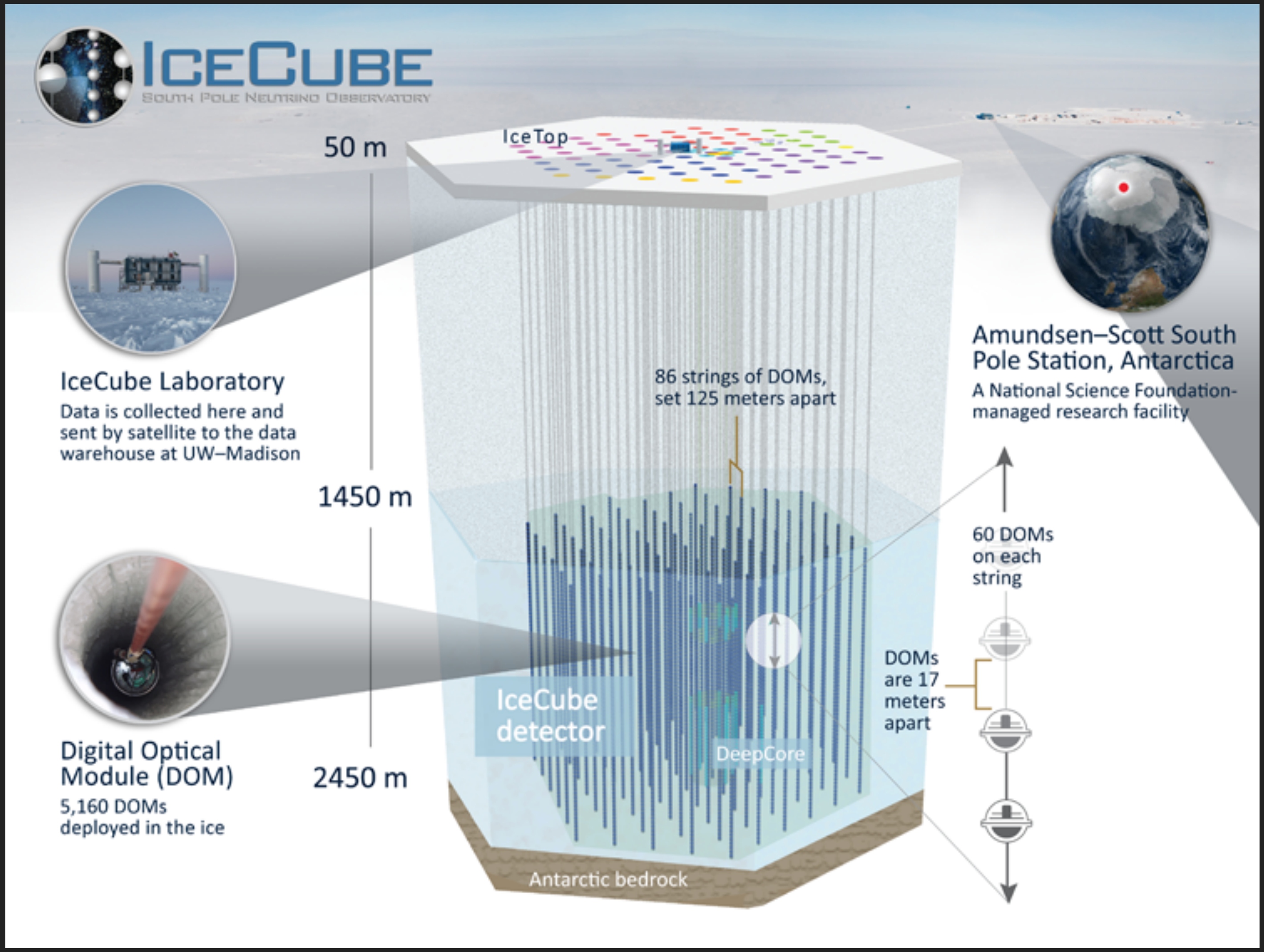
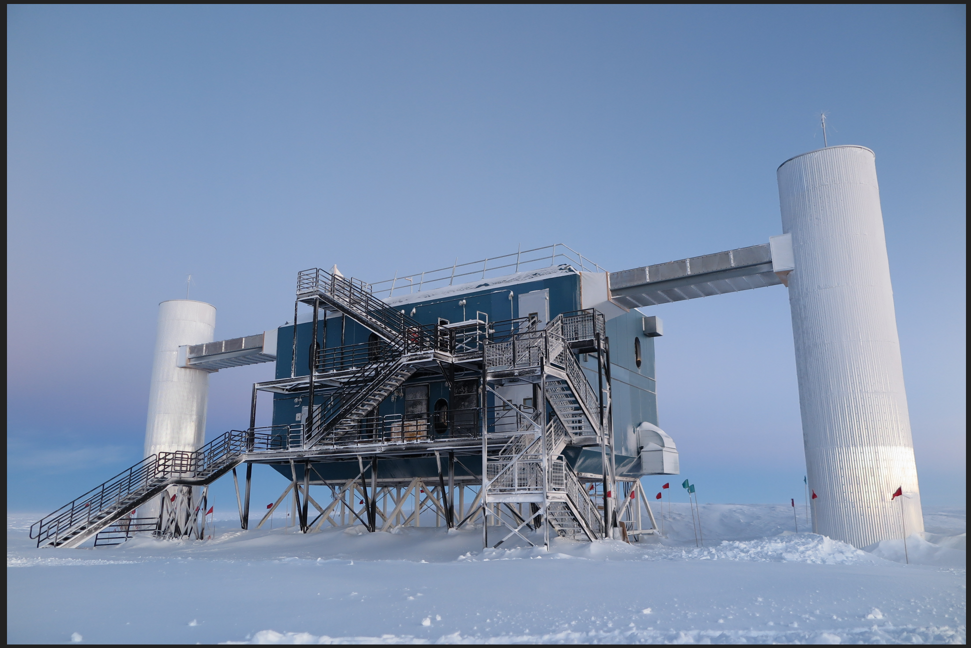


★IceCube Neutrino Observatory is a Gigaton detector at the South Pole designed to detect cosmic neutrinos!



★LIGO/Virgo observatories designed to detect cosmic gravitational waves by measuring the ripples in spacetime.

GW+HEN event significance

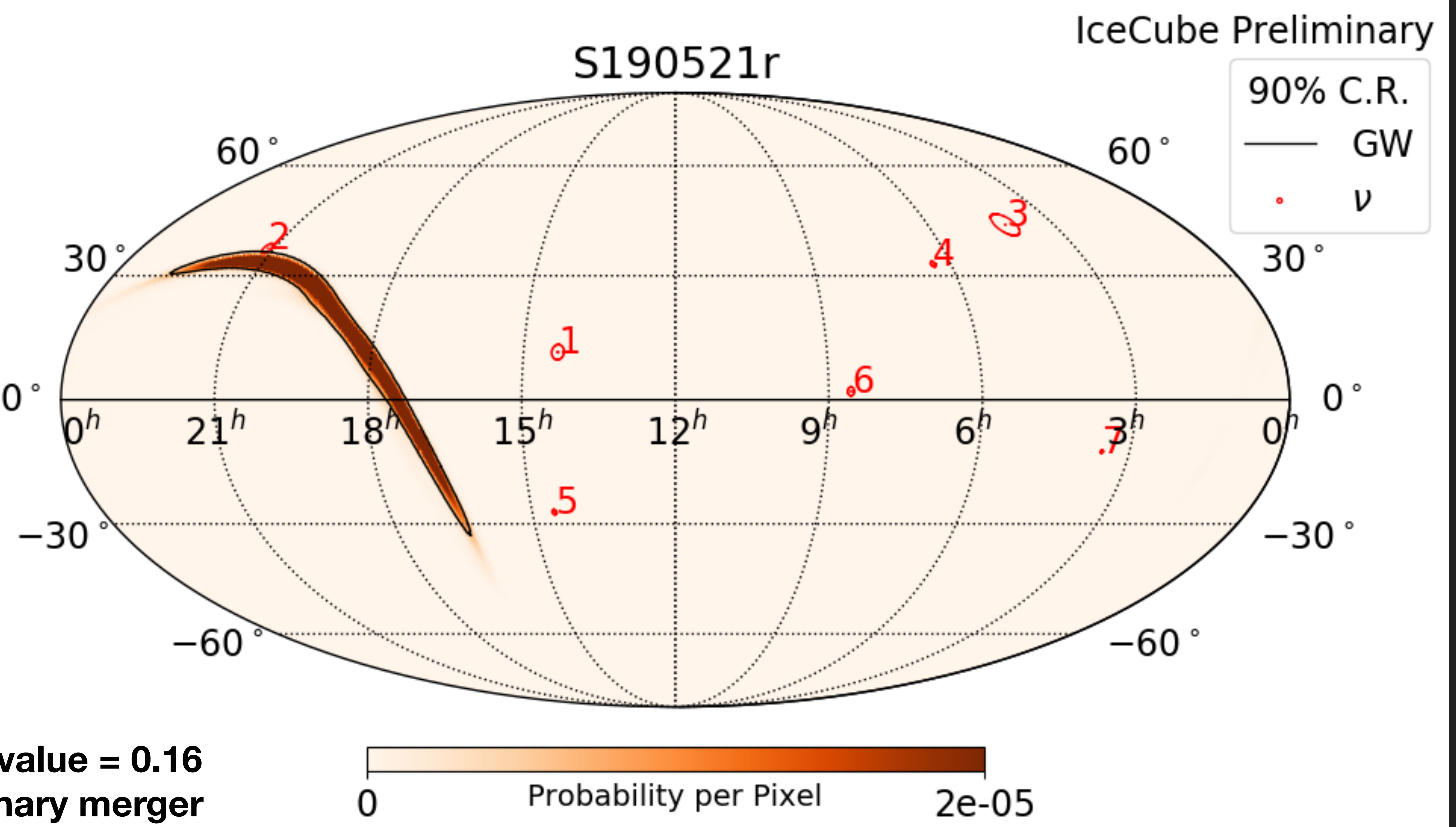
- Test Statistic (TS) based on astrophysical priors and detector characteristics (empirical)
- Define whether a GWHEN correlated signal is:
  - Real event (P_{signal})
  - Chance coincidence of background GW and background neutrino (P_{null})
  - Chance coincidence of astrophysical GW and background neutrino or vice versa ($P_{coincidence}$)
- Calculate p-values using Bayesian odds ratio as TS

$$\mathrm{TS} = \frac{P_{signal}}{P_{null} + P_{coincidence}}$$

I. Bartos, D. Veske, AK, et al (2019) arXiv:1810.11467

O3 event example: S190521r

An example of our internal analysis



P-value = 0.16
Binary merger

Results during O3 so far

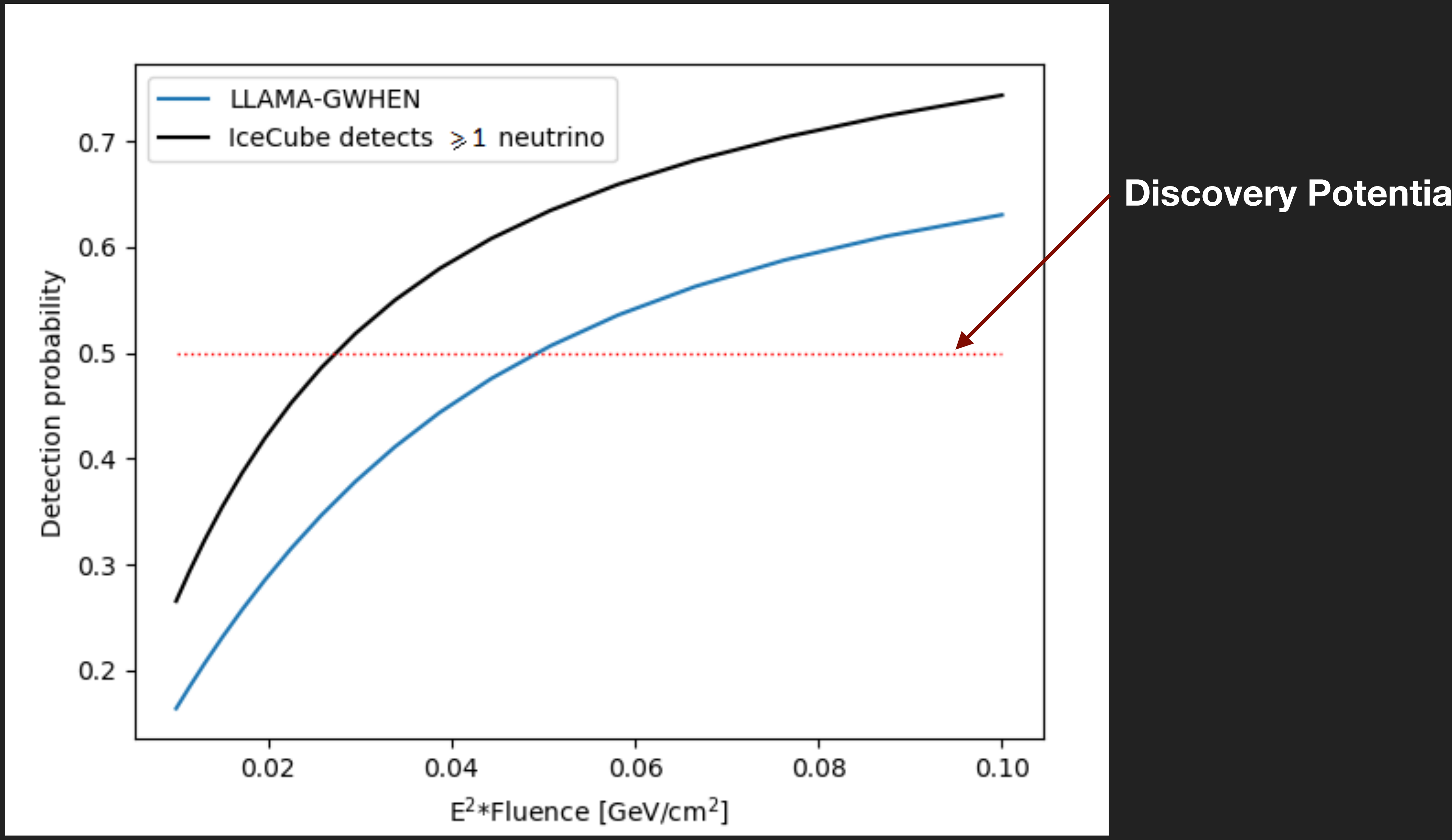
No.	GW event	Possible Source (probability)	p-value (binary merger)
1	S190408an	BBH (>99%)	0.15
2	S190412m	BBH (>99%)	0.83
3	S190421ar	BBH (97%), Trs (3%)	0.62
4	S190425z	BNS (>99%)	—
5	S190426c	BNS (49%), NSBH (13%), Trs (14%), MG (24%)	—
6	S190503bf	BBH (96%), MG (3%)	0.29
7	S190510g	BNS (42%), Trs (58%)	—
8	S190512at	BBH (99%), Trs (1%)	0.51
9	S190513bm	BBH (94%), MG (5%)	0.74
10	S190517h	BBH (98%), MG (2%)	0.12
11	S190519bj	BBH (96%), Trs (4%)	0.16
12	S190521g	BBH (97%), Trs (3%)	0.19
13	S190521r	BBH (>99%)	0.16
14	S190602aq	BBH (>99%)	0.13
15	S190630ag	BBH (94%), MG (5%), NSBH (<1%), Trs (<1%),	0.23
16	S190701ah	BBH (93%), Trs (7%)	0.20
17	S190706ai	BBH (>99%)	0.77
18	S190707q	BBH (>99%)	0.49
19	S190718y	BNS (2%), Trs (98%)	0.13
20	S190720a	BBH (>99%)	0.75
21	S190727h	BBH (92%), Trs (5%), MG (3%)	0.45

P-values for BNS events being revisited

BBH: Binary Black Hole
BNS: Binary Neutron Star
Trs: Terrestrial
MG: MassGap
NSBH: Neutron Star - Black Hole

Discovery Potential

- Discovery potential of the LLAMA search for GWHEN events vs ν fluence
- Fluence = 0.049 GeV/cm^2
  (detected with 50%, averaged of the entire sky)
- E^{-2} energy spectrum

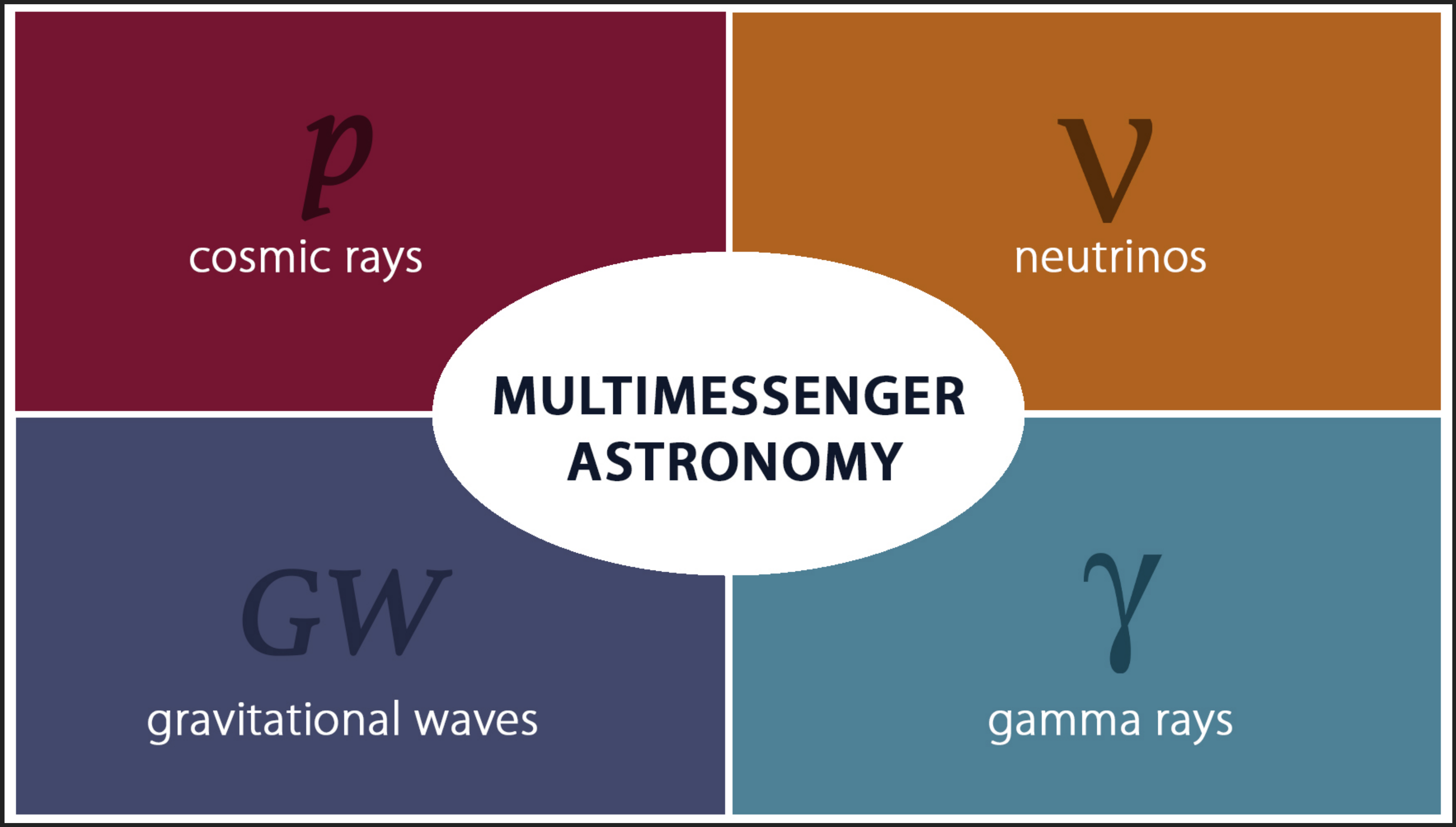


GCN Circular Content

- Send out GCN Circulars of follow-up results of any GW event
  Median latency relative to the GCN notices: 67±33* minutes!
- Two methods/hypotheses tested and reported in IceCube
  (one is LLAMA-GWHEN)
- In case of p-value < 1%, distribute information:
  - Time differences
  - Direction
  - Angular error
  - Number of neutrinos
  - P-values of both analyses
- Possible revisions
  (due to improved GW or HEN localization)
- Potential retractions
  (due to a retraction of one of the input triggers)

* 95% CI

Thank you!


p
cosmic rays
ν
neutrinos
MULTIMESSENGER
ASTRONOMY
GW
gravitational waves
γ
gamma rays

Back-Ups

Data Stream

- GW triggers:
  LIGO/Virgo significant candidate events generated by detection pipelines (cWB, GstLAL, PyCBC, etc.)
  stored on GraceDB including skymaps
- Pull data from GraceDB
  (currently only public alerts)
- IceCube triggers:
  Gamma-ray Follow-Up (GFU) stream
- Pull data from IceCube's GFU API
- LLAMA-GWHEN runs the analysis
- Produce joint skymap and significance
- Prepare a GCN Circular draft