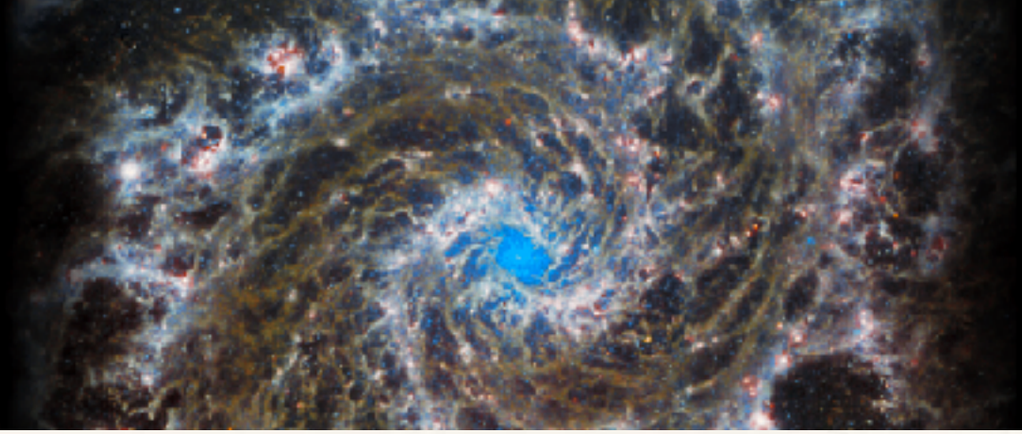
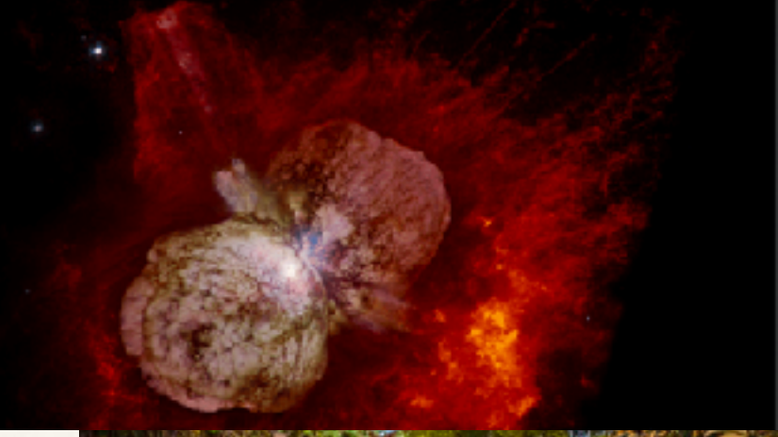
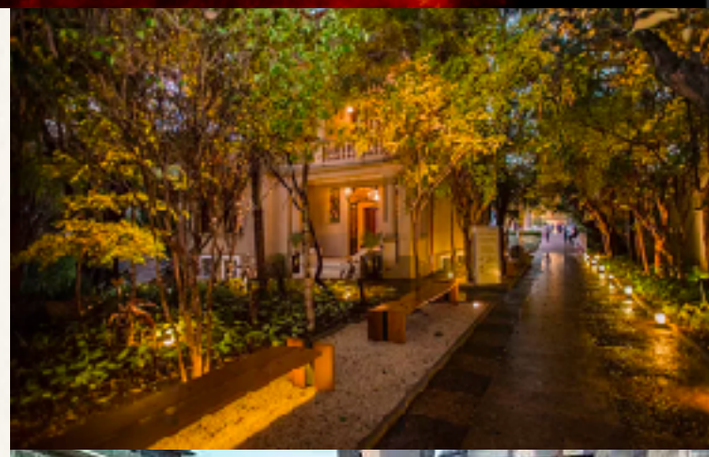



Principia Program on Multi-Messenger Astrophysics

May 22 - June 16, 2023

- *New physics with multi-messenger observations; main theoretical challenges and key experiments/instruments of the next decade*



São Paulo Advanced School on Multi-Messenger Astrophysics

May 29 - June 7, 2023

- *Training the next generation of researchers in multi-messenger areas*

LOC: **Raul Abramo** (Coordinator; USP, Physics); **Ivone Albuquerque** (USP, Physics); **Rita de Cássia dos Anjos** (UFPR); **Enrico Bertuzzo** (USP, Physics); **Rodrigo Nemmen** (USP, Astronomy); **Orlando L. G. Peres** (Unicamp, Physics); **Edivaldo M. Santos** (USP, Physics); **L. Vitor de Souza** (USP/SC, Physics); **Riccardo Sturani** (UNESP, Physics)

Motivations for the Principia Program on Multi-Messenger Astrophysics

- **Fast-growing** field worldwide
- Opportunities for **discoveries** and **new physics**
- New instruments, new experiments, **new data — new theories**?
- Combination of **different data sets** & physical observables
- Increasing need for **coordination** between different instruments/experiments
- Trend for **larger, transnational efforts** present challenges & opportunities
- The importance of **networks**
- How to **train a new generation** of physicists & astronomers?

Motivations for the Principia Program on Multi-Messenger Astrophysics

- **Not a "pipe dream" anymore:**
  - Diffuse astrophysical neutrinos detected by IceCube
  - Gravitational waves detected by LIGO/Virgo
  - Joint detections of GWs and photons (Kilonova)
  - Joint detections of neutrinos and photons (Supernova 1987a, blazar TXS 0506+056)
- **With MM observations, "*astrophysics is fundamental physics*" (2203.10074)**

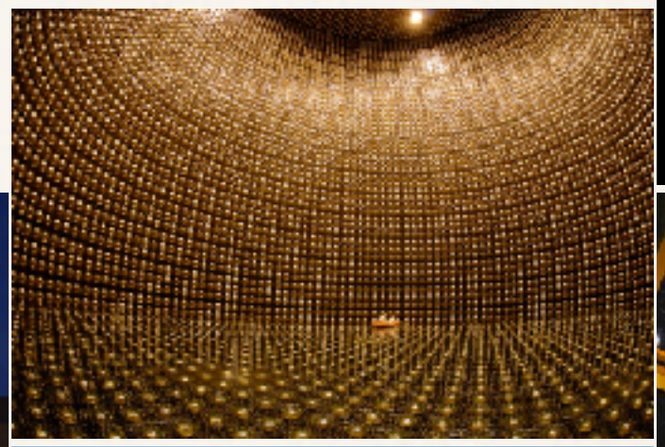
Goals of the Program

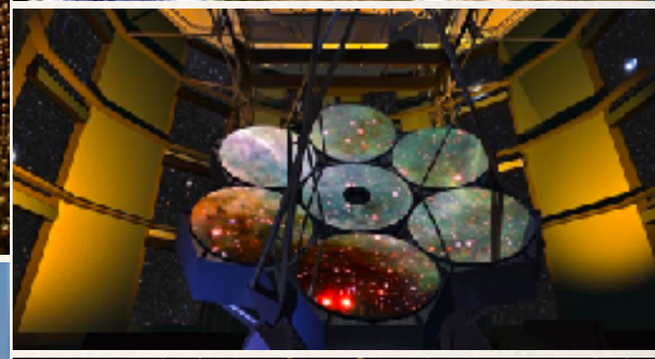
- Identify **key areas of fundamental physics** that may be impacted
- Focus on main **new experimental efforts** that look promising, and how **local instrumentation expertise** could help us become part of those collaborations
- Prepare and support local research community to **meet these challenges**
- Come up with medium- and long-term **plans**
- Produce a **record** of the conclusions of the Program

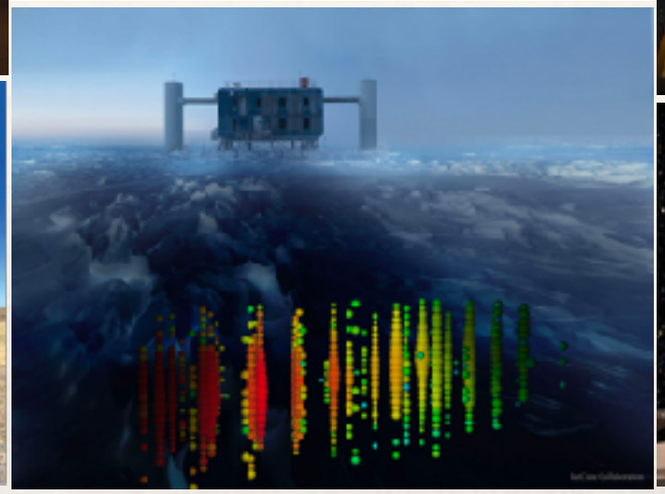
Key messengers and their detectors (as of today)

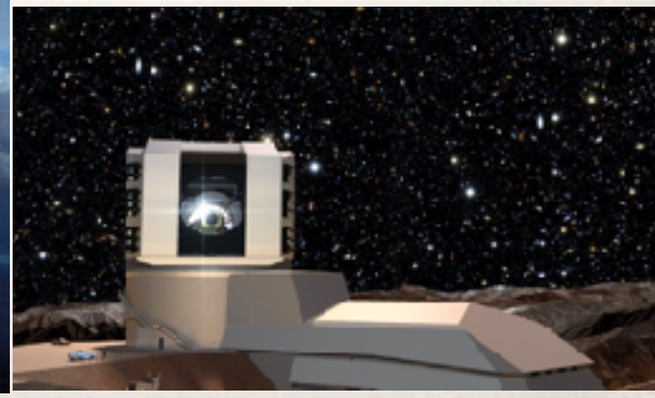
EM waves/photons

Neutrinos

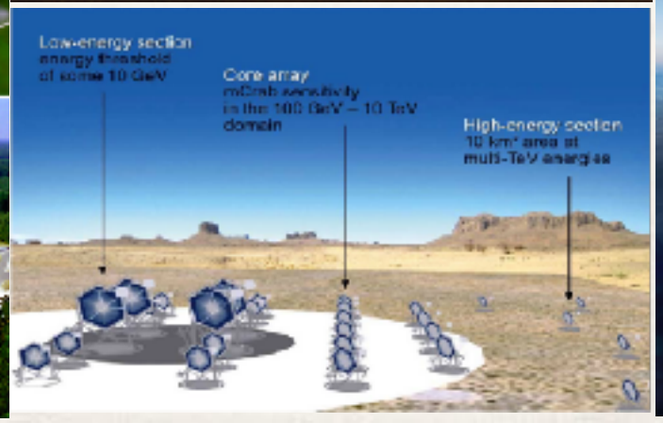








Cosmic rays



Gravity waves

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Principia Program on Multi-Messenger Astrophysics

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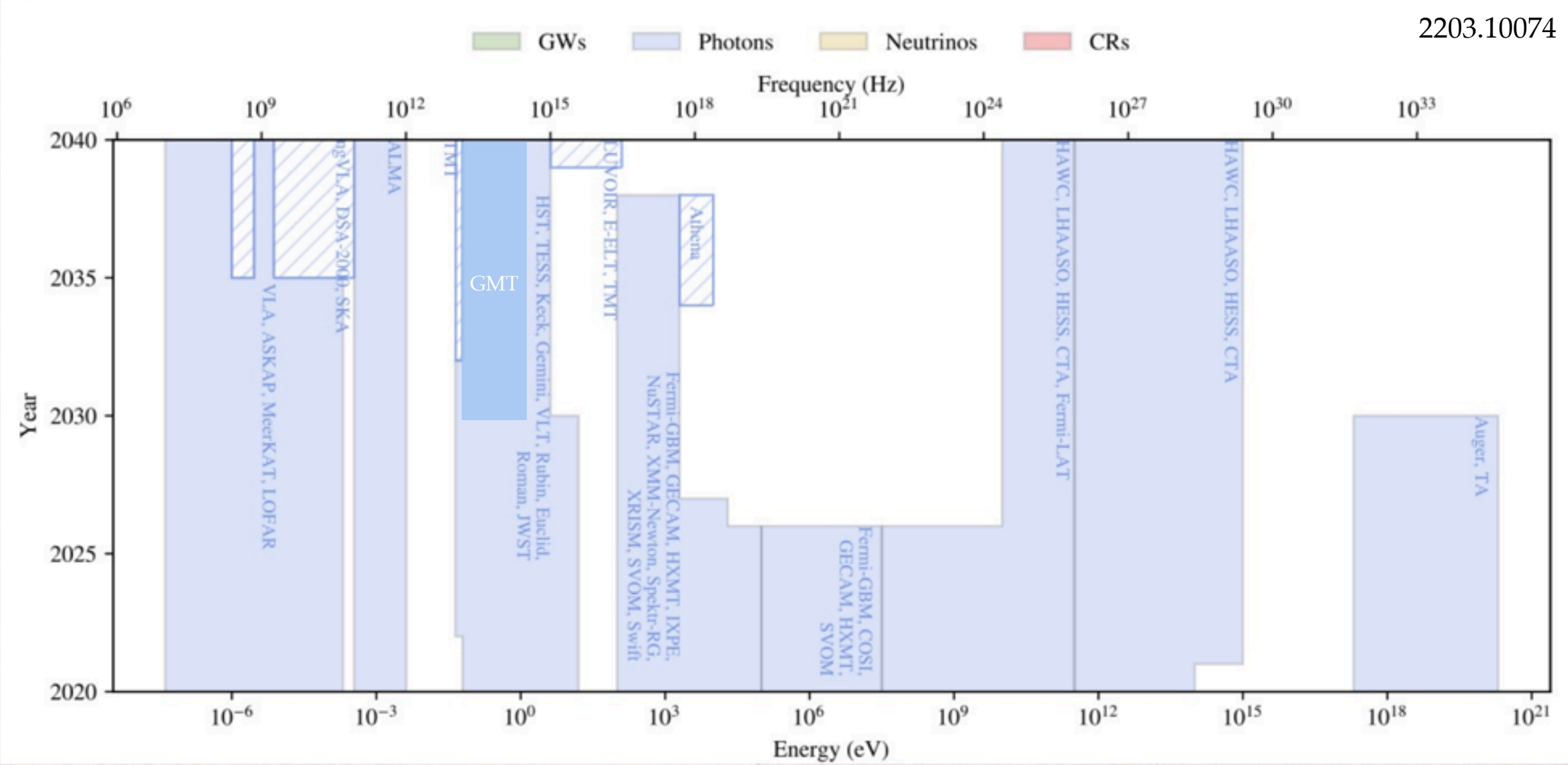
Facilities: past & present

	EM	HEN	UHECR	GW
Current	Swift satellite: EAT 15-150keV; XRT 0.2-10keV; UVOT 170-560nm Fermi satellite: LAT 20 MeV-300 GeV; GBM 10keV-25MeV HAWC (North -ground air shower array): 0.3-100 TeV MAGIC, HESS, VERITAS ground IACTs: 150 GeV-30 TeV ZTF, ASAS-SN ground surveys, optical, near-IR LOFAR: ground array transient survey, radio	ICECUBE Ice Cherenkov array: Gton array TeV-100 PeV, Deep Core 10-300 GeV ANTARES water Cherenkov array: 50 kton, TeV-10 PeV, Super-K water Cherenkov array: 50 kton, 4.5MeV-1 TeV ANITA balloon radio array: 10^{17} - 10^{20} eV	AUGER extensive air shower array: 3,000 km², 1600 tanks, 27 air fluor. tel., 10^{17}-10^{21}eV TA extensive air shower array: 760 km² surface tanks + air fluor. tel., 10^{17}-10^{21}eV	LIGO, 2x4 km GW ground interferometer: ~10-10^{3} Hz. (~1-100 M_{sun} equal mass binaries) VIRGO 2x3 km GW ground interferometer: ~10-10^{3} Hz. (~1-100 M_{sun} equal mass binaries) Pulsar Timing Array radio interferometer, NANOGrav: (10^{9}-10^{7} M_{sun} equal mass binaries)
In construction	SVOM satellite (~2021): [illegible] GLOWBUG, space-iss (~2023): [illegible] Einstein Probe satellite (late 2022) Large FoV 0.5-5 keV Time-Domain Explorer GECAM satellite (mid-2020s) All-sky, 6 keV-5 MeV GWcounterpart eROSITA, satellite (~2020): All-sky transient survey, 0.3-10 keV LHAASO ground air shower array (~2022) 100GeV - 1 PeV LSGT ground survey (~2022) optical, near-IR SKA ground array survey (~2022) Radio interferometer CTA ground IACT arrays, (~2025?): LST 20-150GV, 40 MST 0.5-10TeV, 70 SST 5-300TeV	ICECUBE upgrade (~2021): PINGU 7 new strings, 5-20 GeV KM3NeT water Cherenkov array (~2024?) 4-8 Gton TeV-10 PeV. ORCA 1-20GeV. ARCA 0.1TeV-100PeV Baikal GVD water Cherenkov array (~>2024?) 2 Gton, 5 TeV-10 PeV, Hyper-K water Cherenkov array (~>2026) 1 Mton, 1 MeV- 1 TeV	AUGER, Prime: Add 1500 surface scintillators, 10^{17}-10^{21} eV LHAASO ground air shower array (~>2023?) 100GeV – 1 PeV TAx4 (4 times previous area, ~>2023?): ~3,000 km² - 10^{17}-10^{21}eV	LIGO, A+ upgrade (2023): (increase previous detection distance by x2) KAGRA 2x3 km GW underground interf. (~2022): ~10-10^{3} Hz. (~1-100 M_{sun} equal mass binaries) LIGO-India 2x4 km GW ground interf.(~2024): ~10-10^{3} Hz. (~1-100 M_{sun} equal mass binaries) Pulsar Timing Array radio interf. (>2020), PPTA, EPTA: (10^{6}-10^{7} M_{sun} equal mass binaries) eLISA, 3x2.5x10^{6} km (~>2030s) GW space interferometer: ~10^{-4}-10^{-1} Hz. (~10^{5}-10^{7} M_{sun} equal mass binaries)
Proposed	ISS-TAO, space-SS (~2023?) GIM 10keV-1 MeV, ULTRASAT satellite (~2023?) 50cm UV telescope, 250-280nm AMEGO satellite (~>2030s?): 300 keV-10 GeV HAWC Southern hemisphere (~>2030s?): 4xNorth size, higher altitude, 0.1-100 TeV TMT, ELT, GMT (~>2025-30) 30 m class O/IR ground-based telescopes	ICECUBE Gen-2 (~>2030s?): PINGU 1-20 GeV High Energy extension <100 PeV ARIANNA ice radio array (~>2025-30s?): 10^{17} - 10^{20} eV ARA/RNO ice radio array (~>2025-30s?): 10^{17} - 10^{20} eV GRAND ground det. array (~>2030s?): 10^{17} - 10^{21} eV	K-EUSO, space-ISS (~>2023-25?): UV tel. det. of exersive air showers 10^{17} - 10^{21} eV POEMMA satellite array (~>2030s?): UV telescope det., 10^{17} - 10^{20} eV GRAND ground det. array (~>2030s?): 10^{17} - 10^{21} eV TRINITY ground radio array (~>2030s?): UV telescope det., $10^{16.5}$ - 10^{18} eV	LIGO Voyager upgrade (~>mid-2020s) (DNS range up to 700-1,000 Mpc) Cosmic Explorer, 2x40 km (~>2030s) GW ground interferometer: ~10-10^{3} Hz. (~1-100 M_{sun} equal mass binaries) Einstein Telescope, 3x10 km (~>2030s) GW underground interferometer: ~10-10^{3} Hz. (~1-100 M_{sun} equal mass binaries)

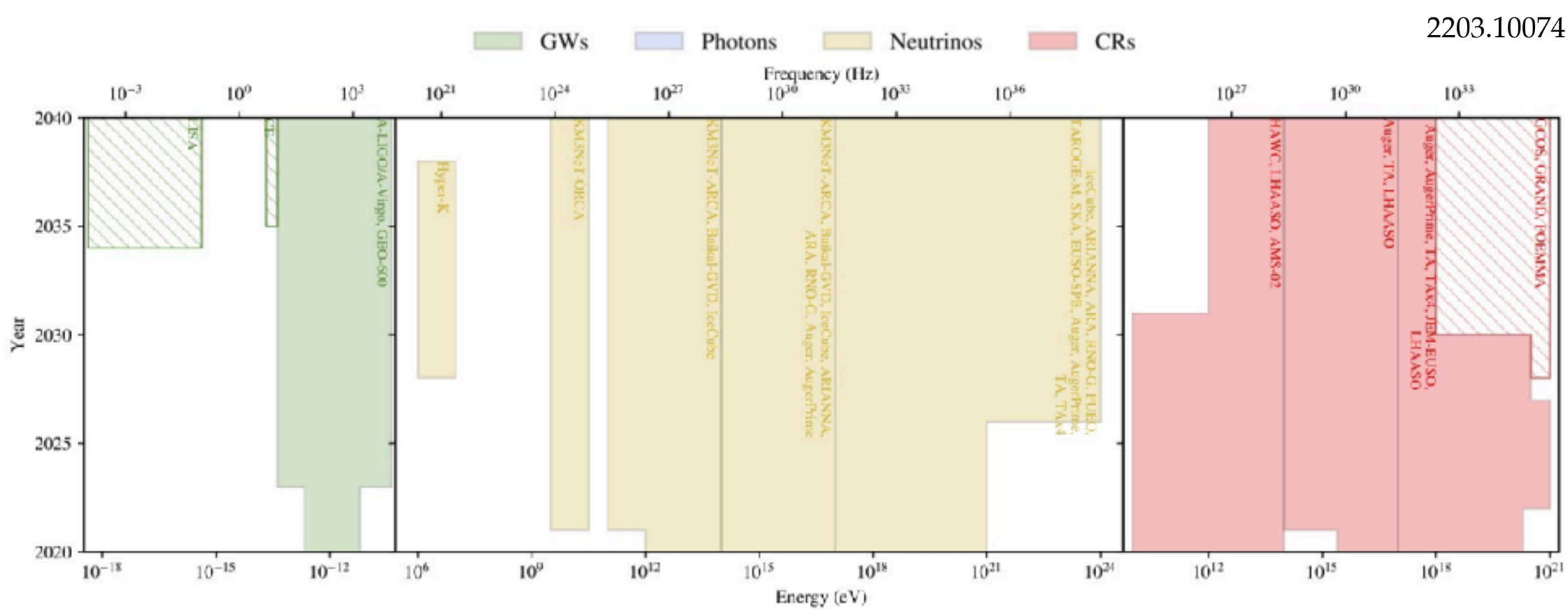
1906.10212

Facilities: past & present



Facilities: past & present

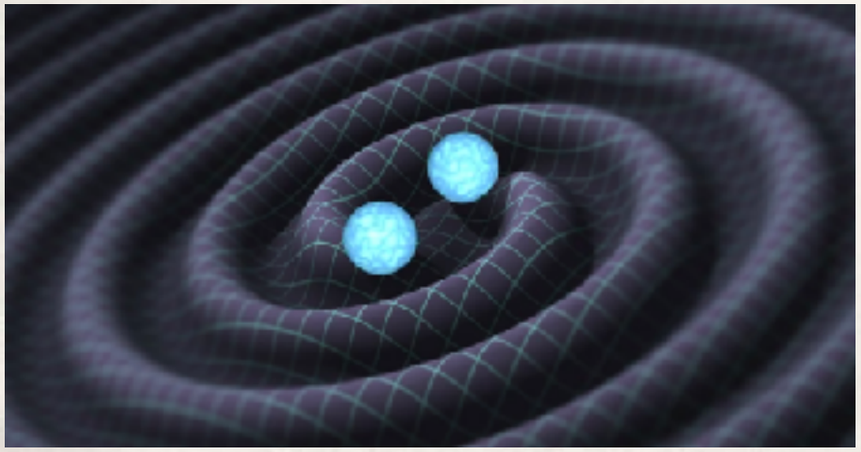
2203.10074



Main candidates for astrophysical emitters/progenitors

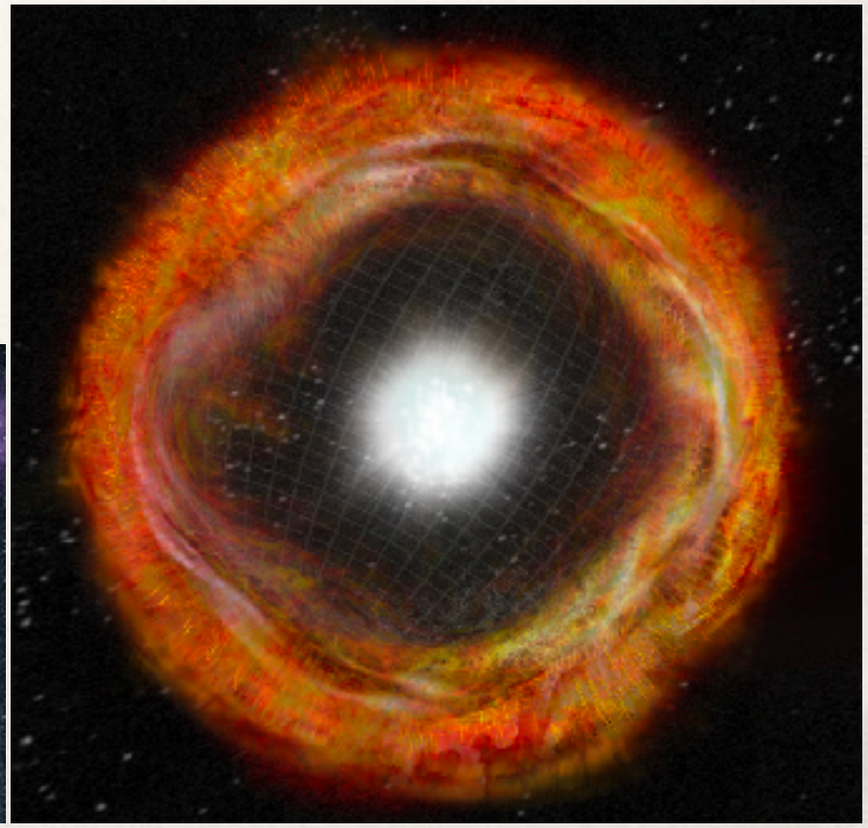
- But we should expect to discover new phenomena

Mergers of compact objects (BHs/NSs)



Active galactic nuclei (esp. quasars/blazars)

Supernovas



Multi-messenger aspect

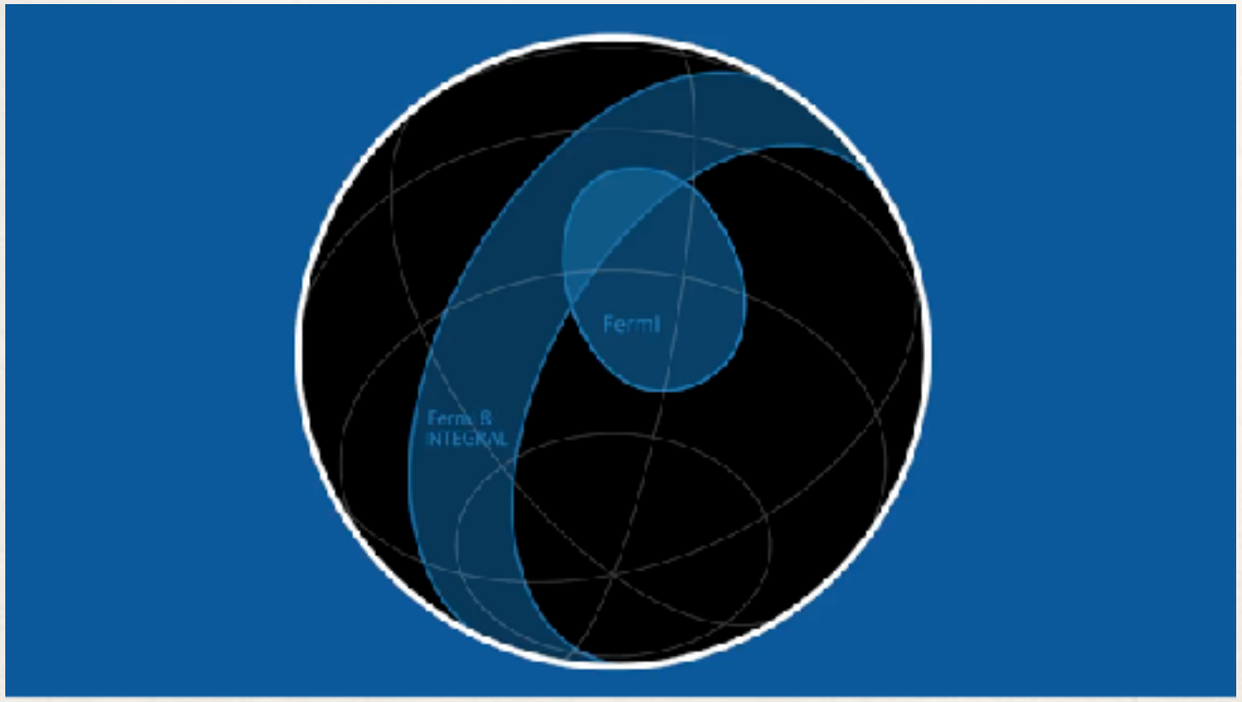
- Two or more messengers from the same sources
- **Coincidence** in time or space — or, even better, **both**
- **Complementarity** between probes of physical mechanisms behind emissions

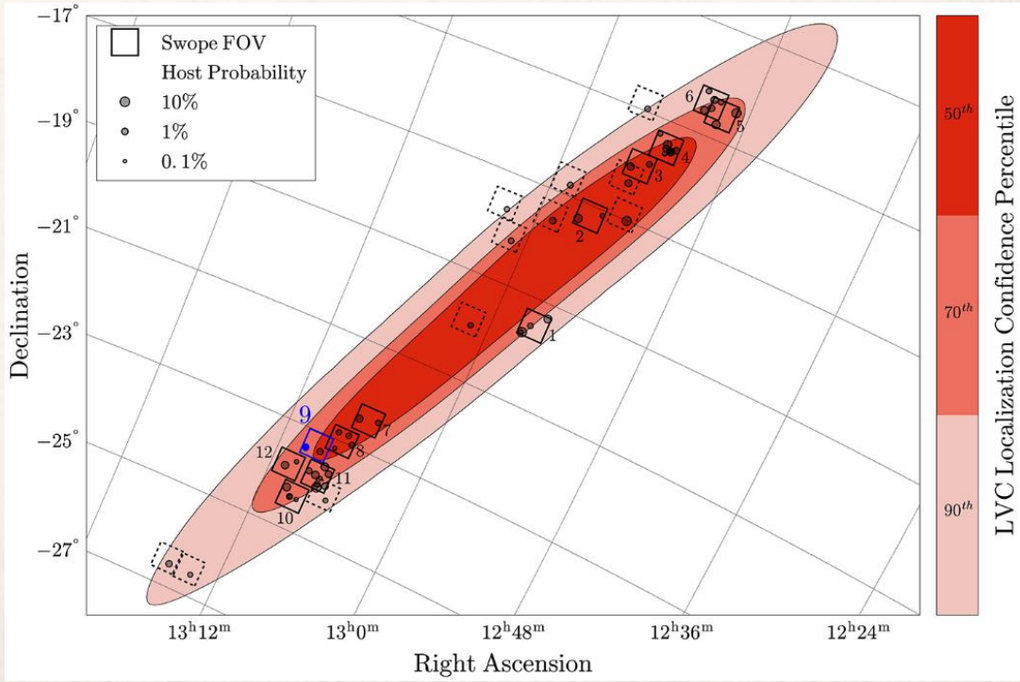
Keys for future MM efforts

- Larger fields of view
- Better directional resolution for tracing events
- Greater time domain discrimination
- Greater depth/sensitivity
- Tools to identify events on top of backgrounds/foregrounds
- Better coordination between instruments

The obvious example: GW170817

- LIGO & Fermi-GBM both critical for **zooming into the area** for the candidate
- SWOPE Supernova Survey had **previously mapped** the nearby galaxies in that area
- Their survey uses two small (1m) **wide FoV** (30'x30') telescopes (@California and @Chile)

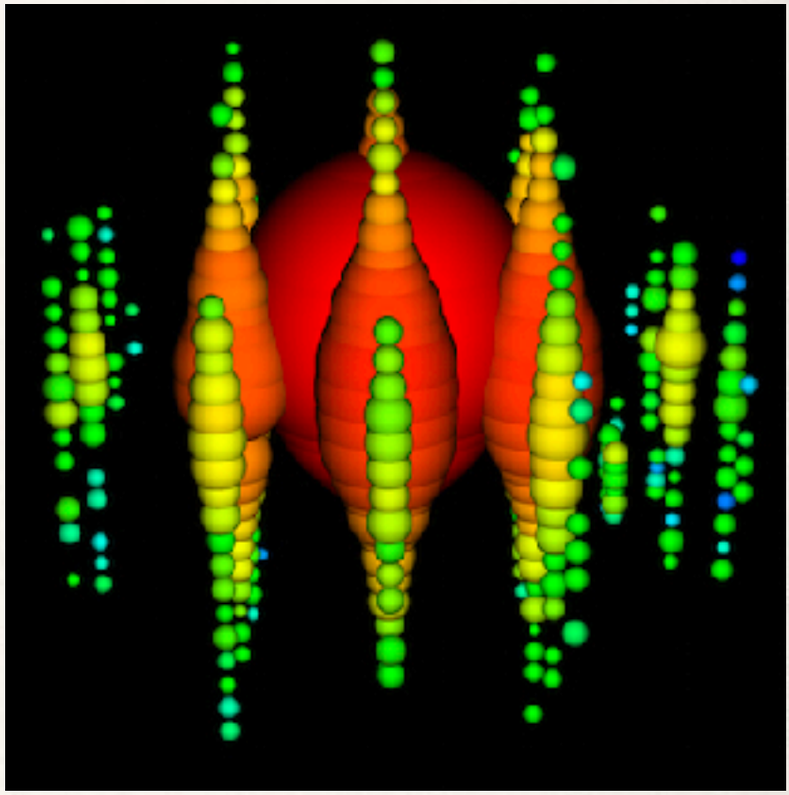


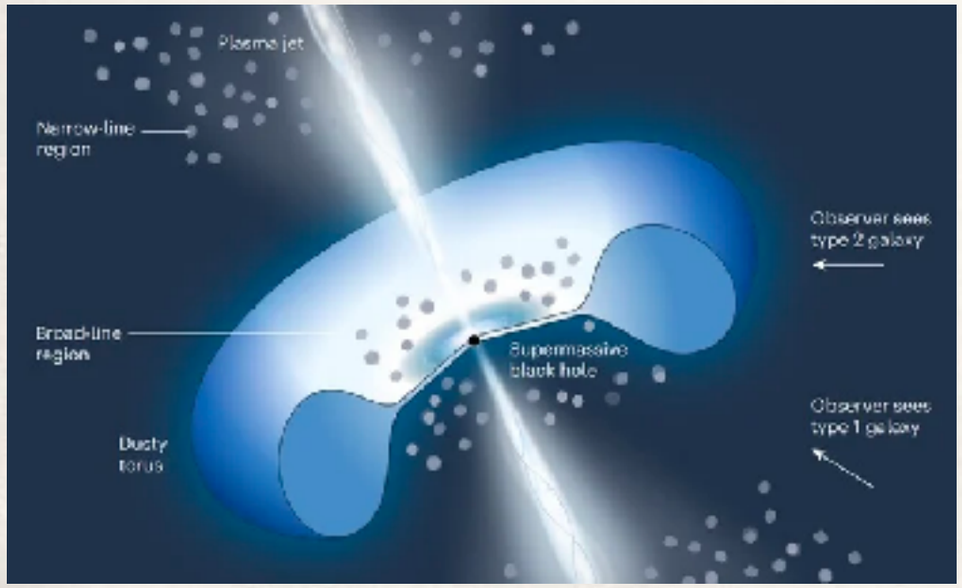


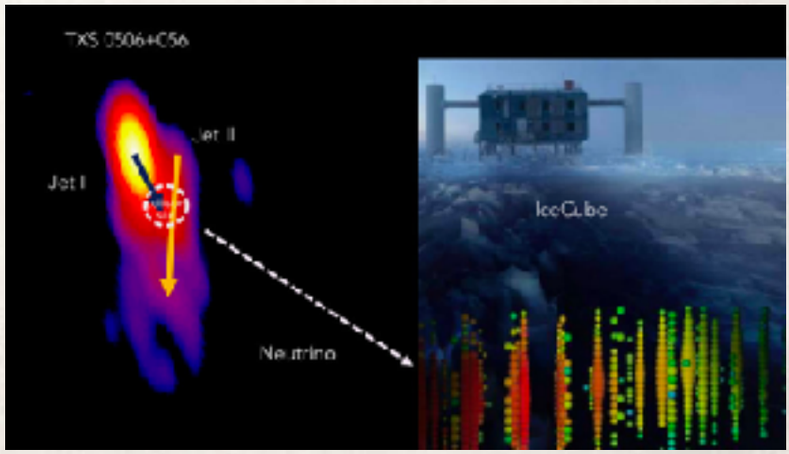
Coulter et al., Science 2017

But what are we still missing?

- Mechanisms for γ-ray emissions in **Kilonovas**?
- Where did “Bert”, “Ernie" and “Big Bird” (**~PeV neutrinos**) come from? Could it be a blazar, like TXS 0506+056…?
- Still not clear what are the **progenitors** of most **HECRs**
- What are the acceleration mechanisms **deep** inside AGNs?
- What are the **sources of γ-ray bursts** and **fast radio bursts**?



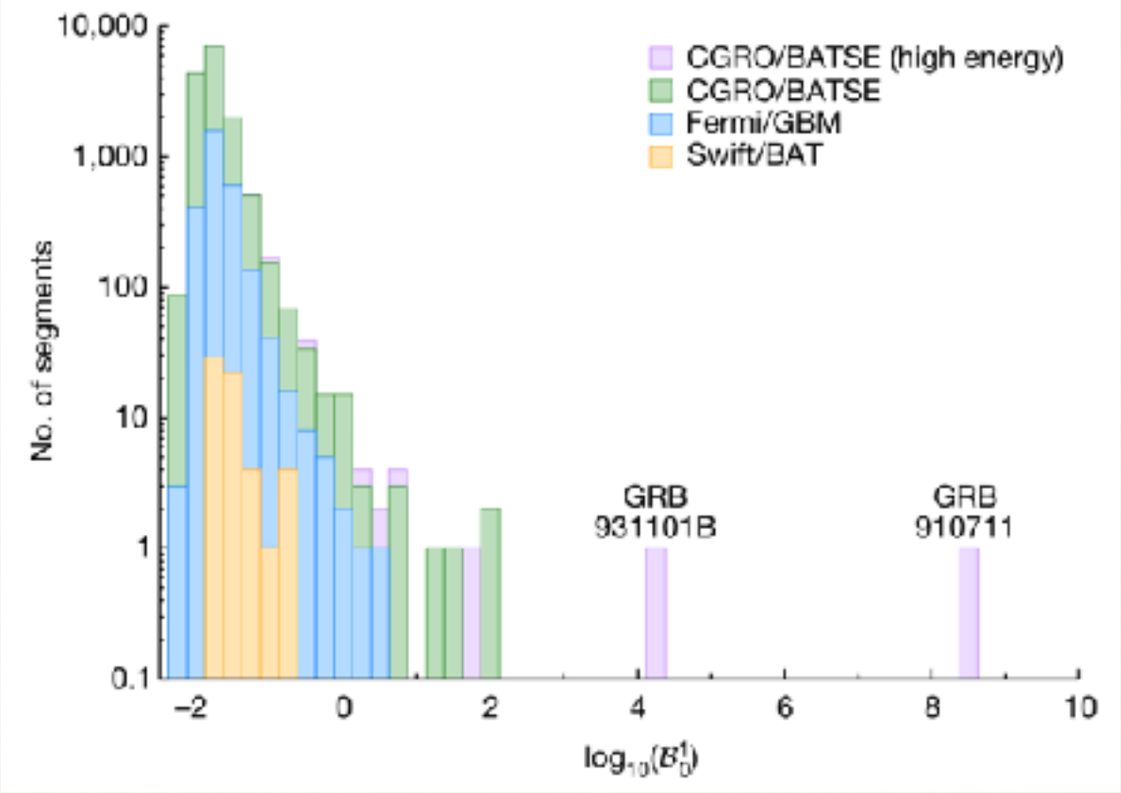




What else could we possibly find?

An interesting example:

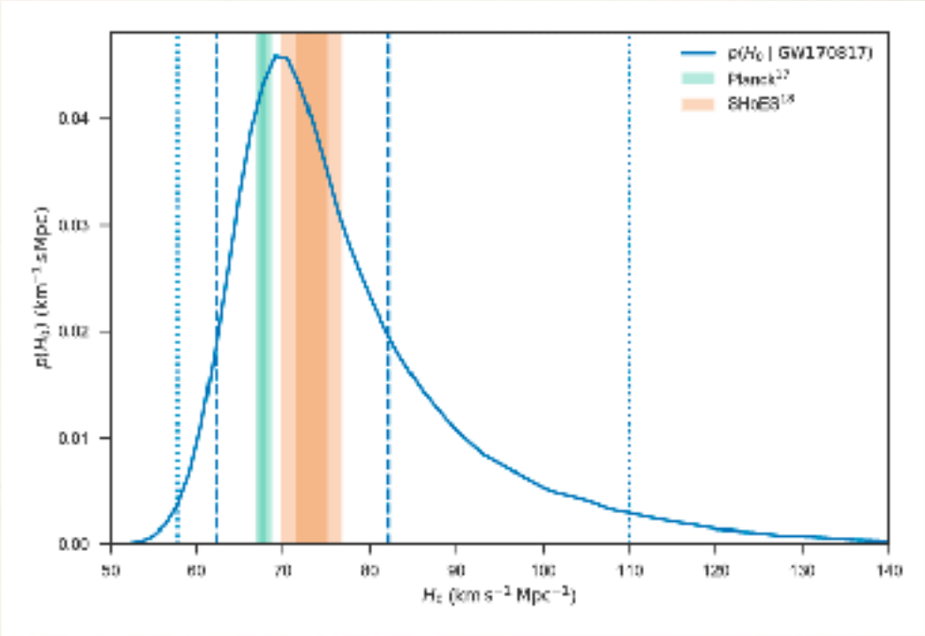
- Presently there are no γ-ray instruments with good **time-domain** capabilities
- BATSE **was** able to resolve γ-ray detections in real time, but it died in ~2000
- Cecilia Chirenti et al. analyzed archival data from BATSE looking for the "quasi-periodic" signals characteristic of mergers of compact objects (NS-NS, BH-NS).
- They found **two good candidates!** (See talk by Cecilia on Wednesday)

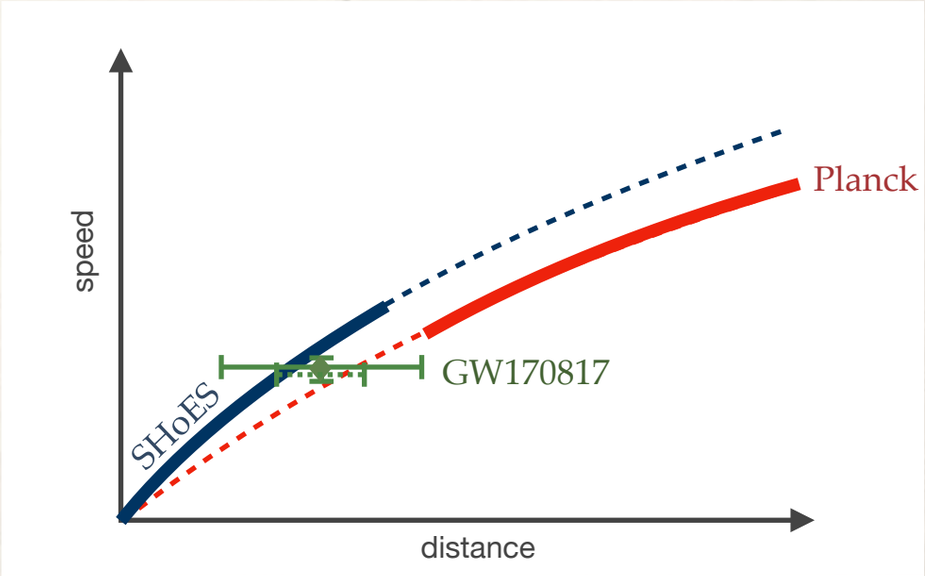


Chirenti et al., Nature 2023

And, of course, we need to talk about H_0...

- The "tension" between local/late measurements (SHoES) and early measurements (Planck) is at $\sim 5\ \sigma$:
  - Local/late: $H_0 = 73.4^{+0.99}_{-1.22}$ km s^{-1} Mpc^{-1} (Riess et al. 2022, Scolnic et al. 2022)
  - Early: $H_0 = (67.4 \pm 0.5)$ km s^{-1} Mpc^{-1} (Aghanim et al. 2018)
- NS-NS and NS-BH mergers are probably the **ultimate standard candles**
- It may be possible to improve the constraints on the inclination angle of the merger through γ-ray (Guidorzi et al., ApJ 2017) or radio observations (Hotokezaka et al., Nature Astron. 2019)



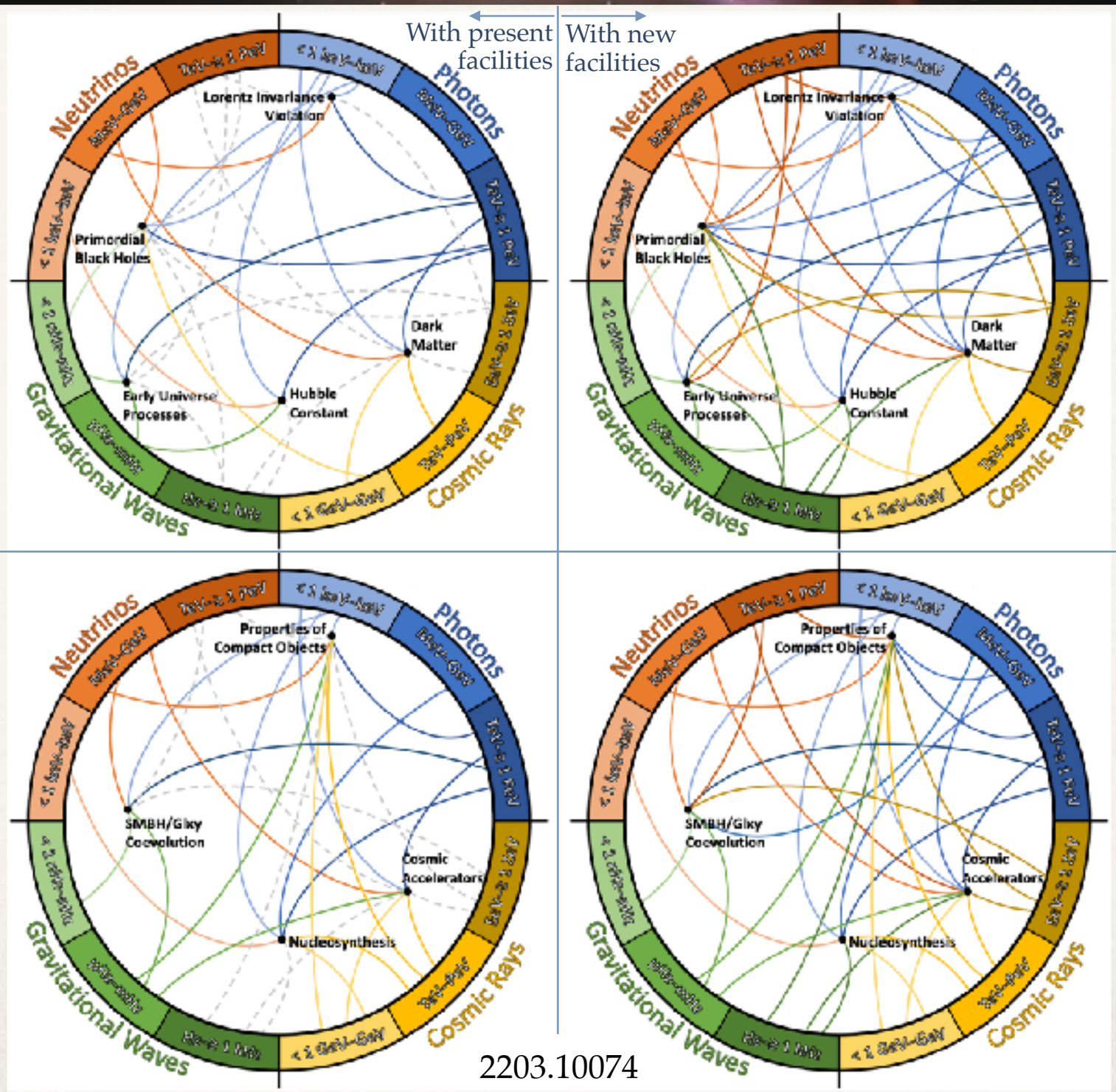


Principia Program on Multi-Messenger Astrophysics

With present facilities | With new facilities

Fundamental physics questions

Astrophysical sources



2203.10074

Principia Program on Multi-Messenger Astrophysics

Participants

Day		22/05	23/05	24/05	25/05	26/05	27/05	28/05		29/05	30/05	31/05	01/06	02/06	03/06		04/06	05/06	06/06	07/06	08/06	09/06	10/06	11/06		12/06	13/06	14/06	15/06	16/06
Weekday		Mon	Tue	Wed	Thu	Fri	Sat	Sun		Mon	Tue	Wed	Thu	Fri	Sat		Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun		Mon	Tue	Wed	Thu	Fri
Program		X	X	X	X	X				X	X	X	X	X				X	X	X	HOLIDAY!	HOLIDAY!	HOLIDAY!	HOLIDAY!		X	X	X	X	X
Aviv School										X	X	X	X	A			X	X	X	X	HOLIDAY!	HOLIDAY!	HOLIDAY!	HOLIDAY!						
	Offices Week #1								Offices Week #2	X	X	X	X	A		Offices Week #3	X	X	X	X	HOLIDAY!	HOLIDAY!	HOLIDAY!	HOLIDAY!	Offices Week #4					
Raul Abramo	4	X	X	X	X	X			4	X	X	X	X	X		4	X	X	X	X					4	X	X	X	X	X
Mario Diaz	3	X	X	X	X	X			3	X	X	X																		
Rita de Cássia	4	X	X	X	X	X			4	X	X	X																		
Martin Makler	1	X	X	X	X	X			1	X	X	X																		
Miguel Quartin	1	X	X	X	X	X																			4	X	X	X	X	X
Peter Tinyakov	2	X	X	X	X	X																								
Maria Ioana Codrina	2	X	X	X	X	X																								
Juan Estrada	1	X	X	X	X	X																								
Carlos Henrique Coimbra	4	X	X	X	X	X			4	X	X	X	X	X																
Edivaldo Moura Santos	1	T	X	T	T	X			1	T	X	T	X	M		4	X	T	X	T					4	T	X	T	X	T
Enrico Berluzzo	4	X	X			X			4	X	X			X		4	X	X							4	X	X	X	X	X
Riccardo Sturani	3	X	X	X	X	X			3	X	X	X	X	X		4	X	X	X	X					4	X	X	X	X	X
Brian Reville	3			X	X	X			2	X	X	X																		
Vitor de Souza	2	X	X	X					4	X	X	X													4	X	X	X		
Irene di Palma	2					X			3	X	X	X	X	X																
Orlando Peres	4					X										4	X	X	X	X								X	X	X
Aion Viana									2	X	X	X	X	X																
Emille Ishida									1	X	X	X	X	X																
Alicia López Cramos									2	X	X	X	X	X		2	X	X	X	X										
Ivone Albuquerque													I					X	I	X					2	X	I	X		
Carlos Argüelles Delgado																1	X	X	X	X					1	X	X			
Armen Esmaili																	X	X	X	X					1	X	X	X	X	X
Zoltan Haiman																3		X	X	X					3	X	X	X		
João Coelho																									2	X	X	X	X	X
Rodrigo Nemmen																									3	X	X	X	X	X
Pedro de Holanda																									4	X	X	X	X	X

Offices

Week #1: May 22-26

#4 Raul, Miguel, Rita, Carlos, Enrico, Ulisses	#3 Brian, Mario, Riccardo	#2 Peter, Maris & Vitor	#1 Juan, Edivaldo & Martin
	Common area		

But… feel free to tweak with these arrangements

Offices

Week # 2: May 29-June 2 (Program + School)

#4 Raul, Rita, Carlos, Enrico, Vitor & Ulisses	#3 Mario, Riccardo, Irene	#2 Brian, Aion & Alicia	#1 Edivaldo, Martin & Emille
	Common area		

Offices

Week # 3: June 4-June 7 (Program + School)

#4 Raul, Edivaldo, Enrico, Riccardo, Orlando	#3 Zoltan	#2 Alicia	#1 Carlos
	Common area		

Offices

Week # 4: June 12-June 16

#4 Raul, Miguel, Edivaldo, Enrico, Riccardo, Vitor	#3 Zoltan & Rodrigo	#2 Ivone & João	#1 Carlos & Arman
	Common area		

Principia Program on Multi-Messenger Astrophysics

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Week #1

	Mon (22/5)	Tue (23/5)	Wed (24/5)	Thu (25/5)	Fri (26/5)
9:30-11:00	Welcome & summary of the goals of the Programme Chairs: **Raul & Vitor**	Open time	Invited talks 9:30 **Isabela S. de Matos**: *Testing gravity on cosmological scales with gravitational waves* 10:15 Rogemar **Riffel**: *Active Galactic Nuclei in Multimessengers*	2-3 short talks/reviews	2-3 short talks/reviews
11:00-11:30	Coffee	Coffee	Invited talks 11:00 **Cecilia Chirenti**: *Gamma ray bursts, (hypermassive) neutron stars and gravitational waves*	Coffee	Coffee
11:30-12:30	Short talks/reviews: Riccardo, Vitor, Rita	2-3 short talks/reviews: Ioana, Martin	Invited talks 11:45 **Rogério Rosenfeld**: *Cosmology with Rubin Observatory's LSST: Challenges and Opportunities*	Review of MMA challenges & opportunities in light of local community strengths **Chairs: Riccardo & Rita**	**Round table**: key challenges, experiments & instruments, ranked in 2D: science relevance v. feasibility in next 10 years **Chairs: Martin & Irene**
12:30-14:30	**Lunch**	Lunch	Lunch	Lunch	**Lunch**
14:30-16:00	MMA challenges & opportunities of next 10 years **Chairs: Martin & Peter**	Open time	Invited talks 14:30 **Valerio Marra**: *A roadmap for cosmological inference using dark sirens and LSST observations* 15:15 **Clecio de Bom**:	Open time	Open time
16:00-16:30	Coffee	Coffee	Coffee	Coffee	Coffee
16:30-17:30	Focus discussion: GWs and MMA **Chairs: Riccardo & Mario**	**Focus discussion:** Strengths and weaknesses of the local community **Chairs: Miguel & Edivaldo**	Focus discussion: Cosmic Rays, Gamma-ray Astronomy & MMA **Chairs: Ioana & Vitor**	Long-term future, "blue sky" ideas **Chairs: Brian & Mario**	Wrap up of 1st week: executive summary of main conclusions. **Social gathering at end of the day in the rooftop lounge**

Auditório Boulevard

Sala da Escola de Talentos (ET)

Principia Program on Multi-Messenger Astrophysics

Week # 2

	Mon (29/5)	Tue (30/5)	Wed (31/5)	Thu (1/6)	Fri (2/6)
9:30-10:00 **10:00-11:00**	Registration Welcome, Local Information, School Organization	**Brian Reville** *Particle Acceleration and Radiation Processes* **Lecture 1**	**Brian Reville** *Particle Acceleration and Radiation Processes* **Lecture 2**	**Irene di Palma** *Gravitational Waves* **Lecture 4**	**Visit to Sirius (LNLS, CNPEM)**
11:00-11:30	**Coffee**	**Coffee**	**Coffee**	**Coffee**	**Bus leaves Flat Universe at 11 am, arrives at LNLS at 12:30.**
11:30-13:00	**Alicia López Óramas** *Gamma-Ray Astrophysics* **Lecture 1**	**Irene di Palma** *Gravitational Waves* **Lecture 2**	**Irene di Palma** *Gravitational Waves* **Lecture 3**	**Emille Ishida** *Using machine learning to find astronomical transients*	**Visit to Sirius (LNLS, CNPEM)**
13:00-14:30	**Lunch**	**Lunch**	**Lunch**	**Lunch**	**Visit to Sirius (LNLS, CNPEM)**
14:30-16:00	**Irene di Palma** *Gravitational Waves* **Lecture 1**	**Alicia López Óramas** *Gamma-Ray Astrophysics* **Lecture 2**	**Alicia López Óramas** *Gamma-Ray Astrophysics* **Lecture 3**	**Hands-on sessions**	**Visit to Sirius (LNLS, CNPEM)**
16:00-16:30	**Coffee**	**Coffee**	**Coffee**	**Coffee**	**Visit to Sirius (LNLS, CNPEM)**
16:30-17:30	**Martin Makler** *Strong gravitational lensing of supernovas, gravitational waves and other sources*	**Mario Diaz** *A Brief History of Gravitational Waves: From Denial to Multimessenger Astrophysics*	**Aion Viana** *Dark Matter searches in the multi-messenger era*	**Student seminars - Session 1: posters & short talks (5 mins)** **Social gathering at end of the day in the rooftop lounge**	**Visit to Sirius (LNLS, CNPEM): bus leaves lab at 5pm, arrives on Flat Universe at 6:30pm**

Principia Program: focus groups and discussions between participants and lecturers of the School

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Week # 3

	Sun (4/6)	Mon (5/6)	Tue (6/6)	Wed (7/6)
9:30-11:00	Free time	**Carlos Arguelles Delgado** *High-energy Neutrino Astrophysics* **Lecture 2**	**Carlos Arguelles Delgado** *High-energy Neutrino Astrophysics* **Lecture 3**	**Zoltan Haiman** *The astrophysics of black hole mergers* **Lecture 3**
11:00-11:30	Coffee	Coffee	Coffee	Coffee
11:30-13:00	**Carlos Arguelles Delgado** *High-energy Neutrino Astrophysics* **Lecture 1**	**Riccardo Sturani** *Special topics Lecture 7*	**Zoltan Haiman** *The astrophysics of black hole mergers* **Lecture 2**	**Carlos Arguelles Delgado** *High-energy Neutrino Astrophysics* **Lecture 4**
13:00-14:30	Lunch	Lunch	Lunch	Lunch
14:30-16:00	**Edivaldo Moura Santos** *AGN population studies using gamma rays*	**Ivone Albuquerque** *Searching for light dark matter*	**Enrico Bertuzzo** *The Dark Matter model landscape*	**Final discussion session and wrap-up of the School**
16:00-16:30	Coffee	Coffee	Coffee	**Free time + possible extra student talks**
16:30-17:30	**Arman Esmaili** Special topics Lecture 6	**Zoltan Haiman** *The astrophysics of black hole mergers* **Lecture 1**	**Student seminars - Session 2: posters & short talks (5 mins)**	**Cocktail in the rooftop lounge**

Principia Program: focus groups and discussions between participants and lecturers of the School; review previous discussions and results; start preparation of the draft of the White Paper.

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Week # 4

	Mon (12/6)	Tue (13/6)	Wed (14/6)	Thu (15/6)	Fri (16/6)
9:30-10:30	Executive summary of previous weeks; goals of the Program; drafting skeleton for White Paper for Brazilian community & funding agencies **Chairs: Raul & Riccardo**	Focus discussion: neutrinos, dark matter searches & MMA **Chairs: Juan & Carlos A.-D.**	Focus discussion: optical/infrared astronomy & MMA **Chairs: Miguel & Rodrigo**	Review of progress on white paper and adherence to goals of the Program, then moving on to splinter groups **Chairs: Edivaldo & Orlando**	**Wrap-up of Program: main conclusions, key areas & opportunities**
10:30-11:00	Coffee	Coffee	Coffee	Coffee	Coffee
11:00-12:30	2 short talks + discussion: MMA and dark matter. **Chairs: Ivone & Enrico**	2 short talks + discussion: MMA and optical/infrared astronomy. **Chairs: Rodrigo & Zoltan**	General discussion to organize the drafting of the white paper, then moving on to splinter groups **Chairs: Raul & Riccardo**	Splinter groups; drafting white paper	**Discussion about the status of the White Paper; open issues, strong/weak areas**
12:30-14:30	Lunch	Lunch	Lunch	Lunch	Lunch
14:30-16:00	Open time	Meetings with industry, engineers and other partners for development of instrumentation: 2 short talks + discussion	Splinter groups; drafting white paper	Splinter groups; drafting white paper	Free
16:00-16:30	Coffee	Coffee	Coffee	Coffee	Coffee
16:30-18:00	2 short talks + discussion: MMA and neutrinos. **Chairs: Pedro & Arman**	Meetings with industry, engineers and other partners for development of instrumentation: 2 short talks + discussion	Splinter groups; drafting white paper; brief progress report at the end of the day.	Splinter groups; drafting white paper; brief progress report at the end of the day. **Social event at end of the day at the rooftop lounge**	Free

Auditório Boulevard

Sala da Escola de Talentos (ET)