Multi-Messenger Astronomy with Rubin Telescope

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INAF

Time Line

2019 named "Legacy Survey of Space and Time" of the "Vera C. Rubin Observatory"

2025 System First Light ⇨ commissioning and science verification

2-3 months after System First Light ⇨ First data preview release (DP1)

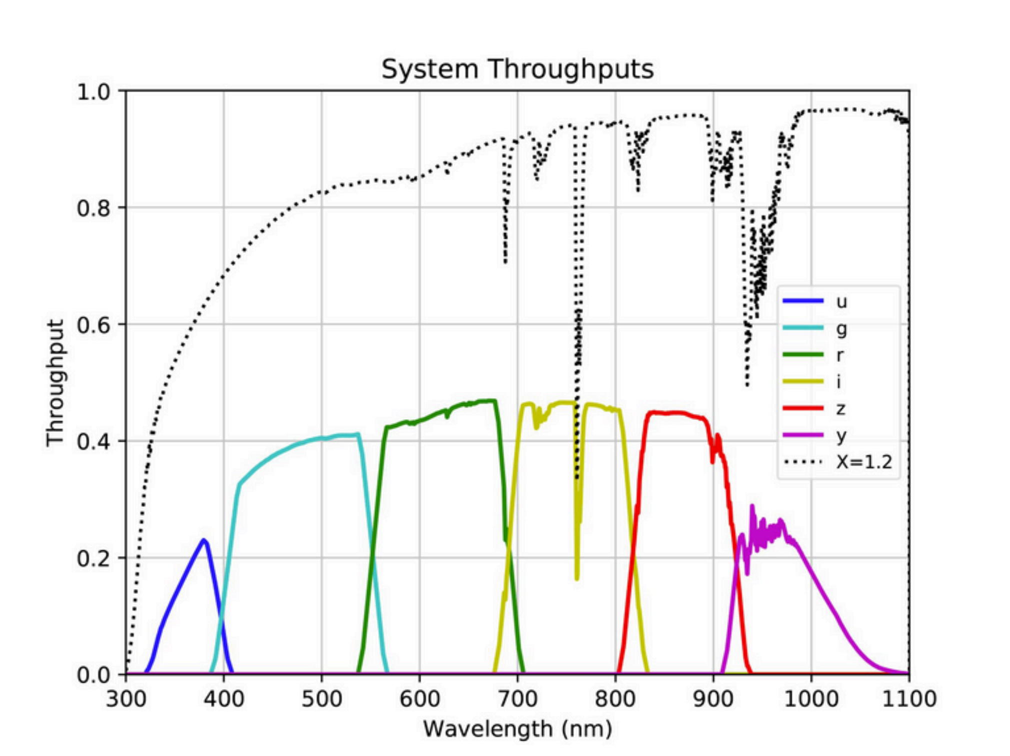
4-7 months after System First Light ⇨ LSST Survey start

9-12 months after System First Light ⇨ Data Preview 2 (DP2)

12-14 months after LSST Survey ⇨ Data Release 1 (DR1)

(Monthly updates on https://www.lsst.org/about/project-status)

Rubin telescope: some key numbers



Nightly data size: 20 TB/night

Final database size (DR11) : 15 PB

Number of objects (full survey, DR11): 20B galaxies

17B resolved stars

6M orbits of solar system bodies

Primary mirror diameter : 8.4 m

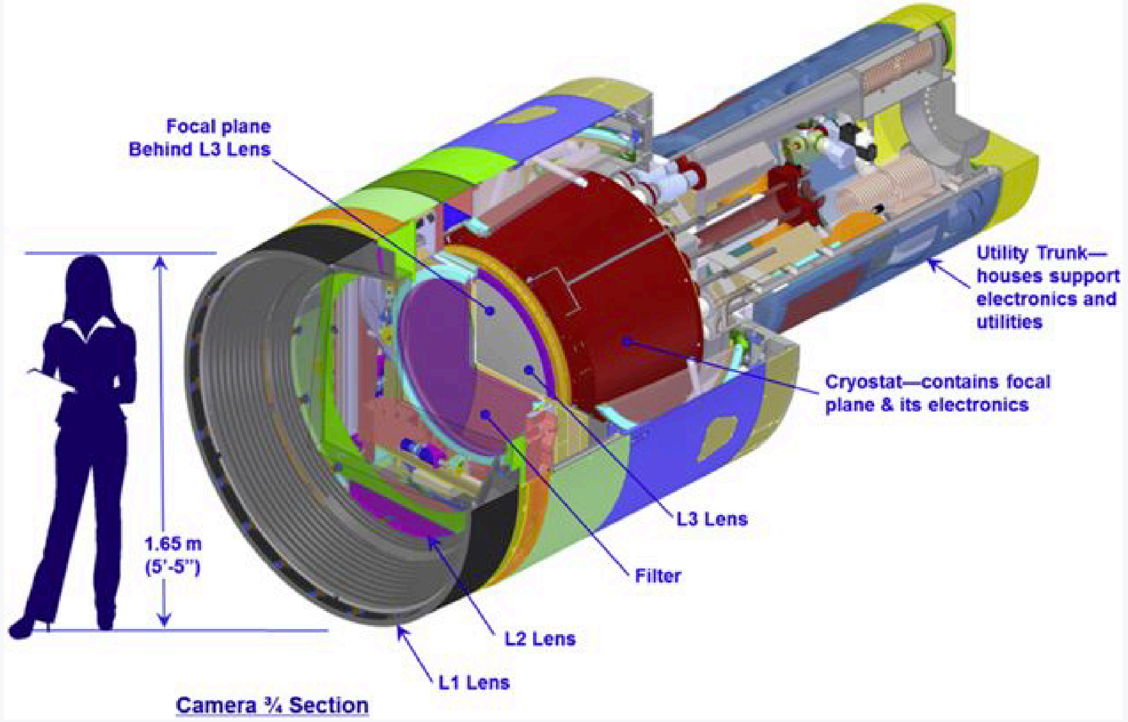
Field of View : 9.6 square degrees

Focal plane : 189 4kx4k science CCD chips, 0.2 arcsec/pixel

Survey duration : 10 years

Number of visits: ~2.1 million

Six filters: u g r i z y



Ivezic et al. (2019, ApJ, 873, 111)

Survey Cadence

Observing strategy still to be finalised according to inputs from the scientific community

(see ApJ Supplement Series focus issue on Rubin LSST Survey Strategy Optimization)

Wide Fast Deep (WFD)

main survey - about 20000 deg^2 ~90% of time 2-3 visits of the same field in the same night, then after ~3 days when all filters are considered (after 1-3 weeks in the same filter)

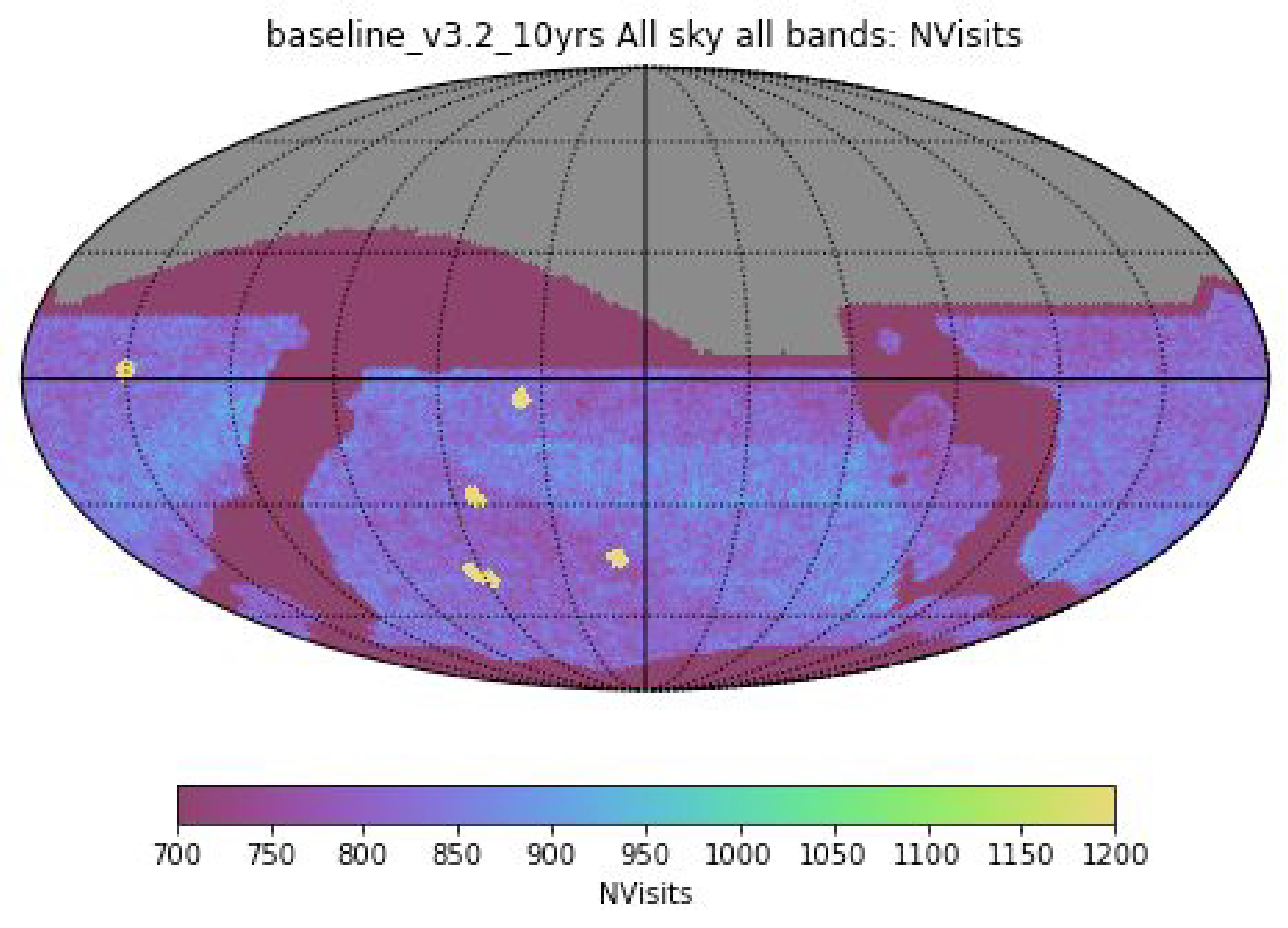
Deep Drilling fields (DDF)

~7% of time; 5 fields (1 double), 9.6 deg^2 each

Near-Sun Twilight Microsurvey

~1% of time, early microsurvey to improve recovery of interior-to-Earth asteroids

Possible other mini/micro surveys



Survey Depth

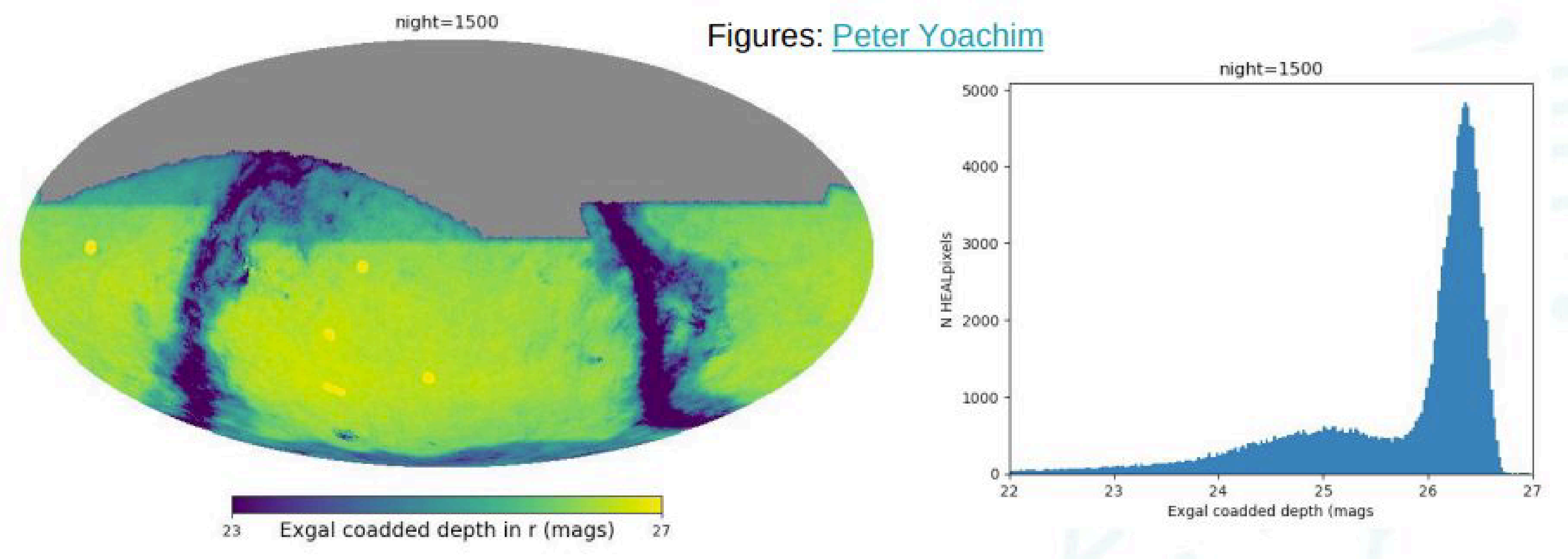
Single image 5σ depths in u, g, r, i, z, y:
23.9, 25.0, 24.7, 24.0, 23.3, 22.1

Wide Fast Deep (WFD)

10 yr coadded image stack 5σ depths in u, g, r, i, z, y:
26.1, 27.4, 27.5, 26.8, 26.1, 24.9

Deep Drilling Fields (DDFs)

10 yr coadded image stack 5σ depths in u, g, r, i, z, y:
28-28.5, 28.7, 28.9, 28.4, 28.0, 27.0



From Buchanan 2023 and Mendoza 2023 - presentations at the 2023 Project & Community Workshop

Target of opportunity observations with Rubin

(less than 3% of survey time)

1. **Gravitational Waves and Multi-Messenger Astronomy**

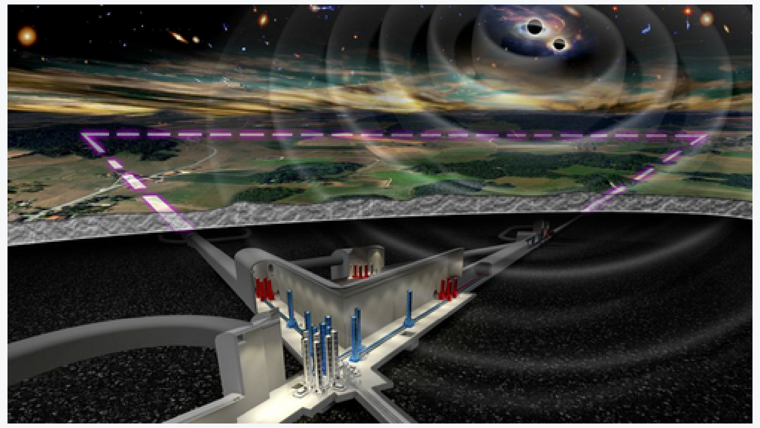
2. **High-Energy Neutrinos**

3. **Galactic Supernova**

4. **Small PHA Potential Impactor**

KM3NeT, Mediterranean Sea

Virgo, Italy



Einstein Telescope

LIGO, USA

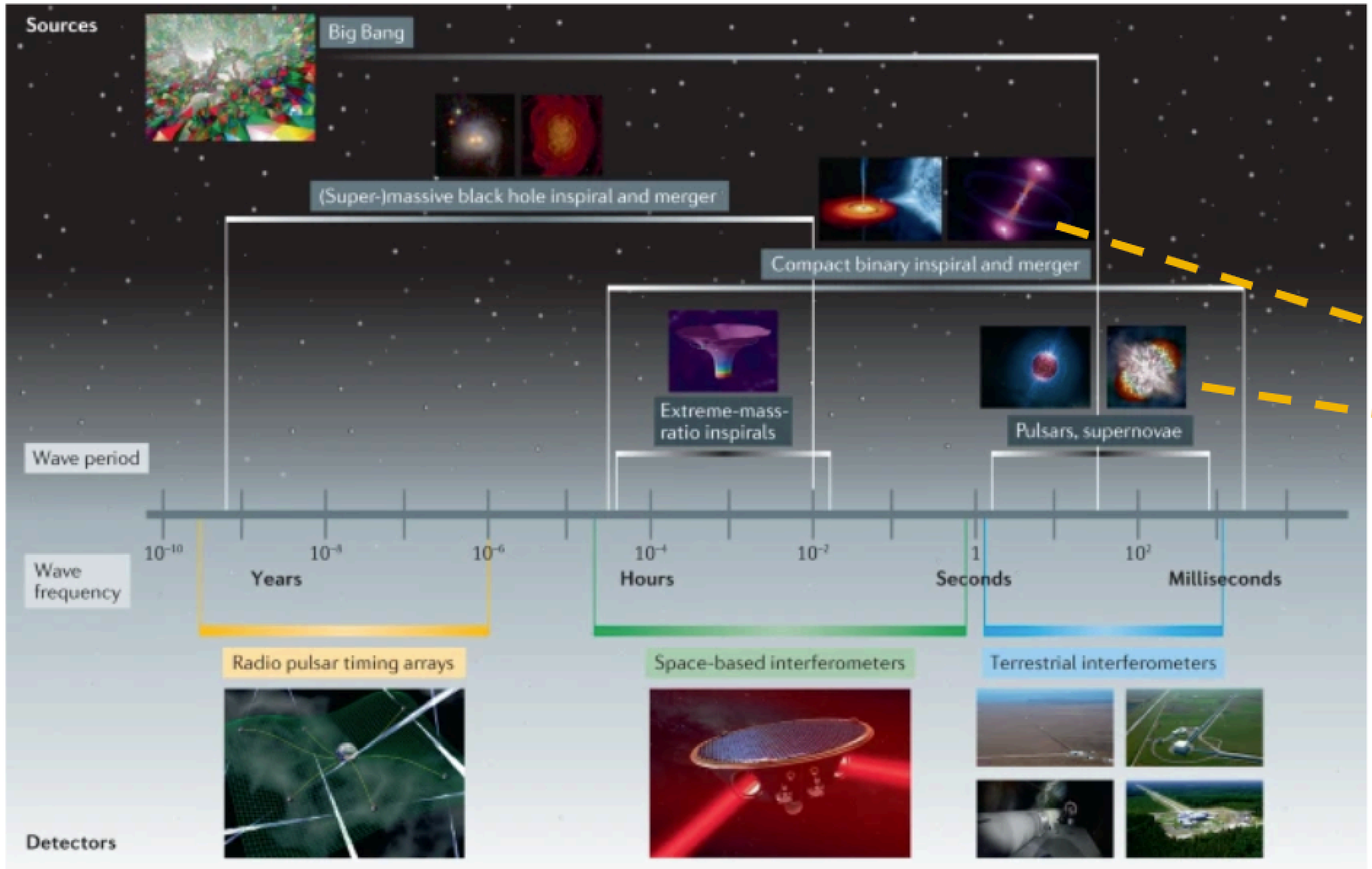
IceCube, South Pole


Up to 10 million alerts, 20 TB of data...every night!
Science Collaborations (SCs)
Galaxies
Stars, Milky Way & Local Volume
Solar System
Dark Energy
Active Galactic Nuclei
Transient/Variable Stars
Strong Lensing
Informatics & Statistics

WHY RUBIN

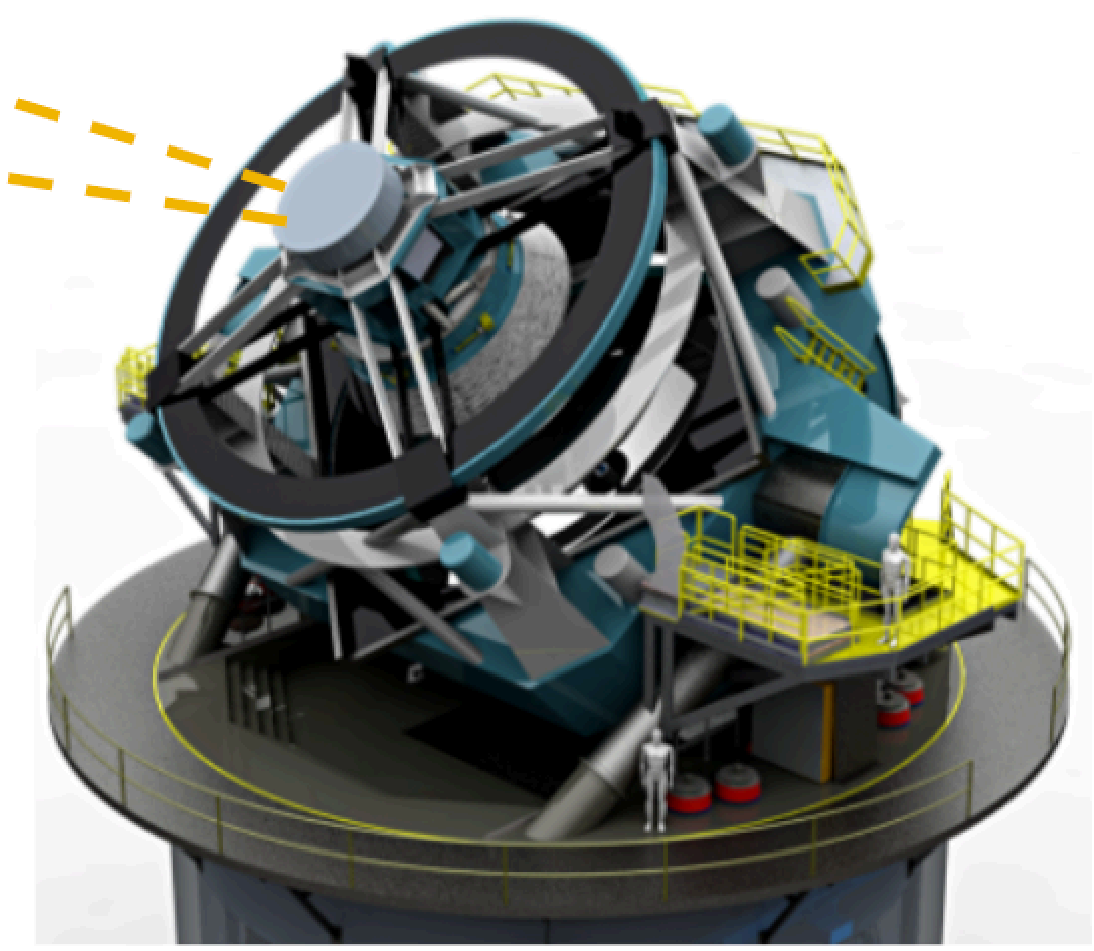
Rubin TVS - Multi-wavelength and GW follow-up sub-group

coordinator: Raffaella Margutti, Berkley, USA



Gravitational-wave physics and astronomy in the 2020s and 2030s, Nature Reviews Physics

- **Rubin as a (ToO) follow-up machine** -> sources from GW detectors
- **Rubin as a discovery machine** -> follow-up from other facilities

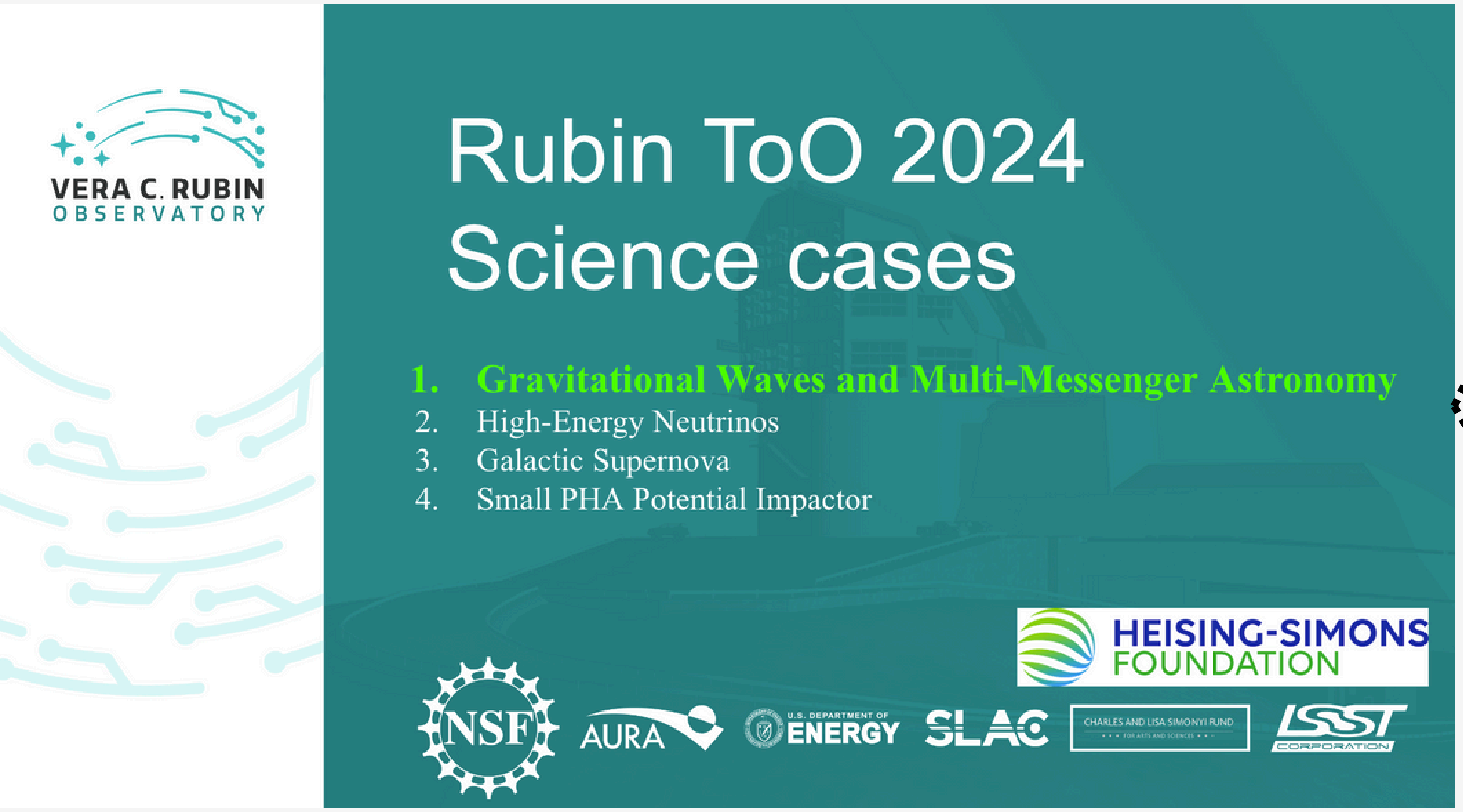


(Key Challenge: Limited resources for multi-wave follow-up vs. number of LSST transients)

WHY RUBIN

Rubin as a (ToO) follow-up machine

Multi-Messenger Astronomy: Gravitational Waves Science Case Motivation



April, 18 2024: report sent to the SCOC (Survey Cadence Optimization Committee)

1. Gravitational Waves and Multi-Messenger Astronomy

Binary Neutron Star Mergers and Neutron Star - Black Hole Mergers

Science case leads: Silvia Piranomonte, Stephen Smartt

Gravitationally lensed Binary Neutron Star mergers

Science case lead: Graham Smith

Black Hole-Black Hole Mergers

Science case lead: Antonella Palmese

Unidentified GW Sources

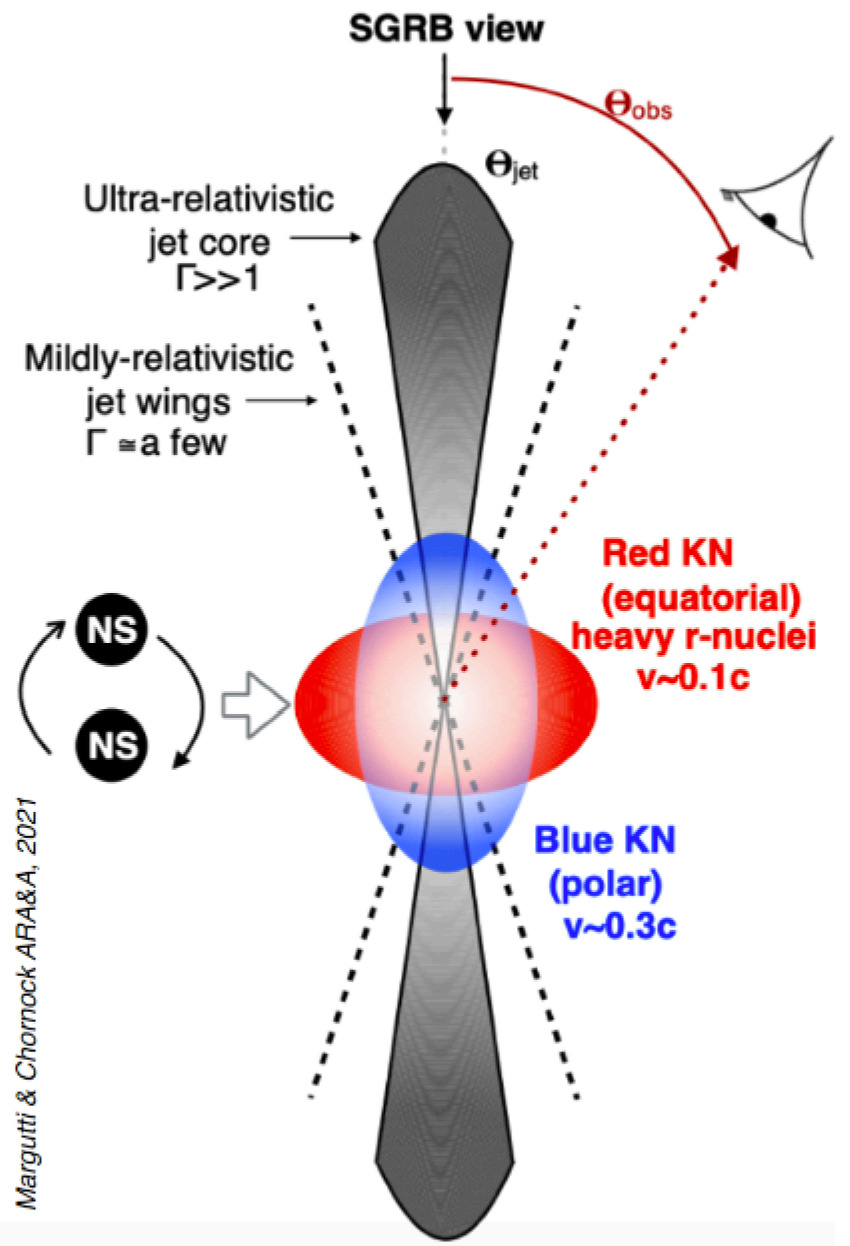
Science case lead: Ryan Chornock

Emerging Ideas Science Case: Gravitationally lensed Gamma-Ray Bursts and their afterglows

Science case lead: Graham Smith

WHY RUBIN

NS-NS / NS-BH mergers: what do we expect to see ?



(the merger scenarios lead to the a central engine (rapidly accreting BH surrounded by a massive disc able to launch a jet)

★ Collimated EM emission from **Short GRBs**

Brief, intense flash of gamma-ray radiation with a detectable X-ray/UV/**OPTICAL**/IR/radio counterpart (afterglow)

Fast: from few ms to hundreds of s
Energetic: 10–7 - 10–3 erg cm–2
Bright: 10–8 - 10–4 erg cm–2 s–1

★ Optical/NIR isotropic emissions: **Kilonova**

r-process

⇩

Nucleosynthesis of heavy nuclei

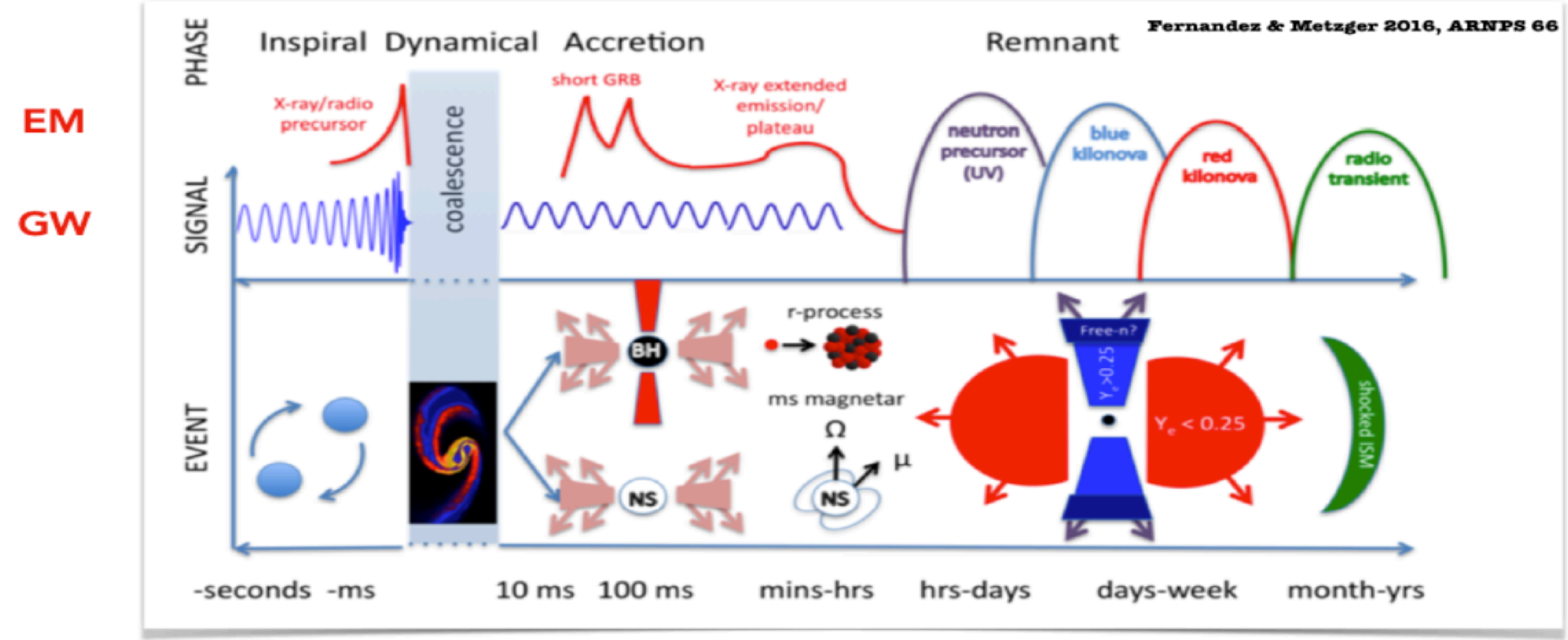
⇩

Radioactive decay of heavy elements

WHY RUBIN

NS-NS / NS-BH mergers: what do we expect to see?

NS-NS NS-BH Merger: a global picture



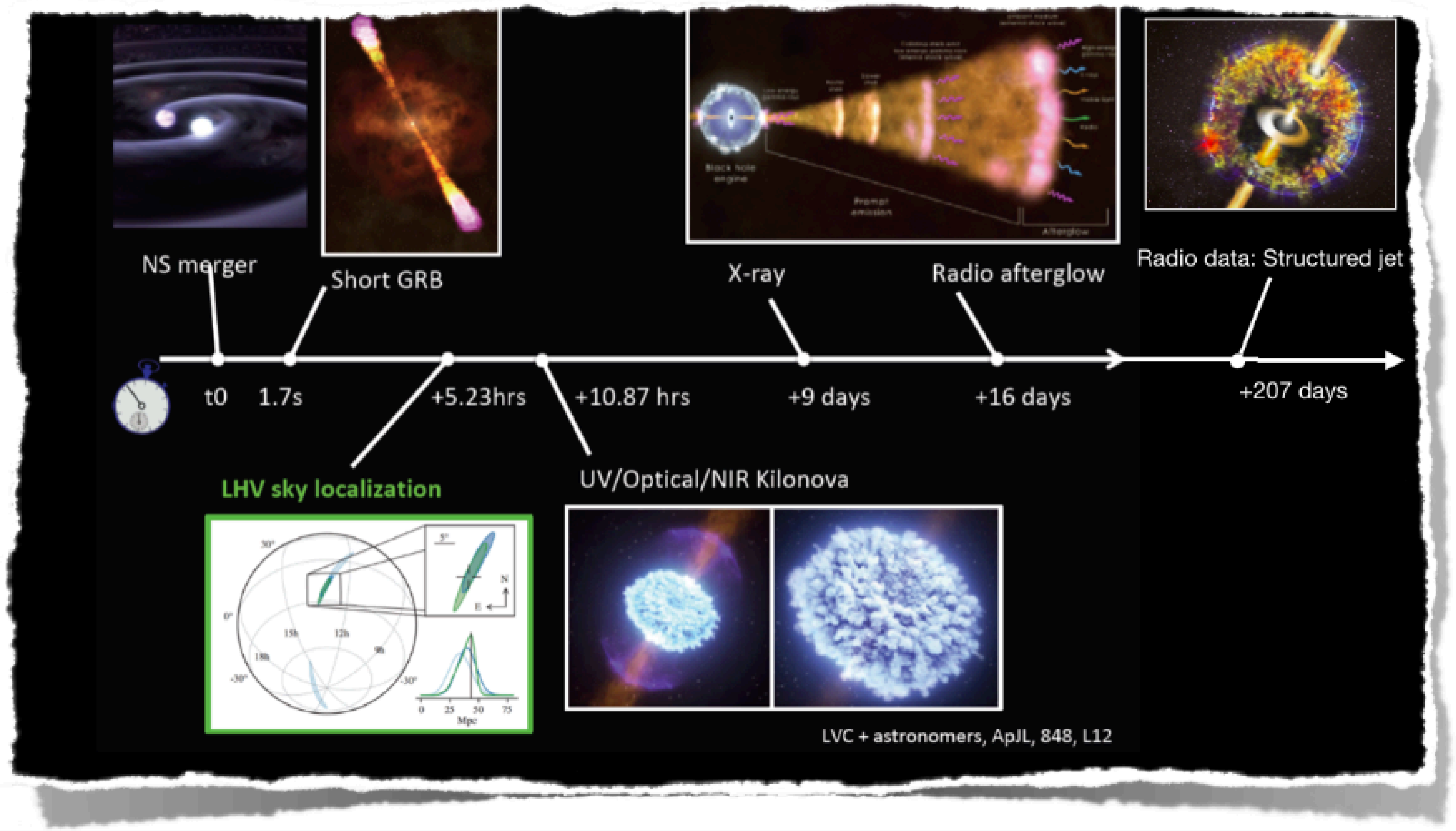
Request for network of multi-wavelenght observatories which **cover huge region** of the sky, **get on target promptly**, **repeat** observations over different timescales and **go deep**

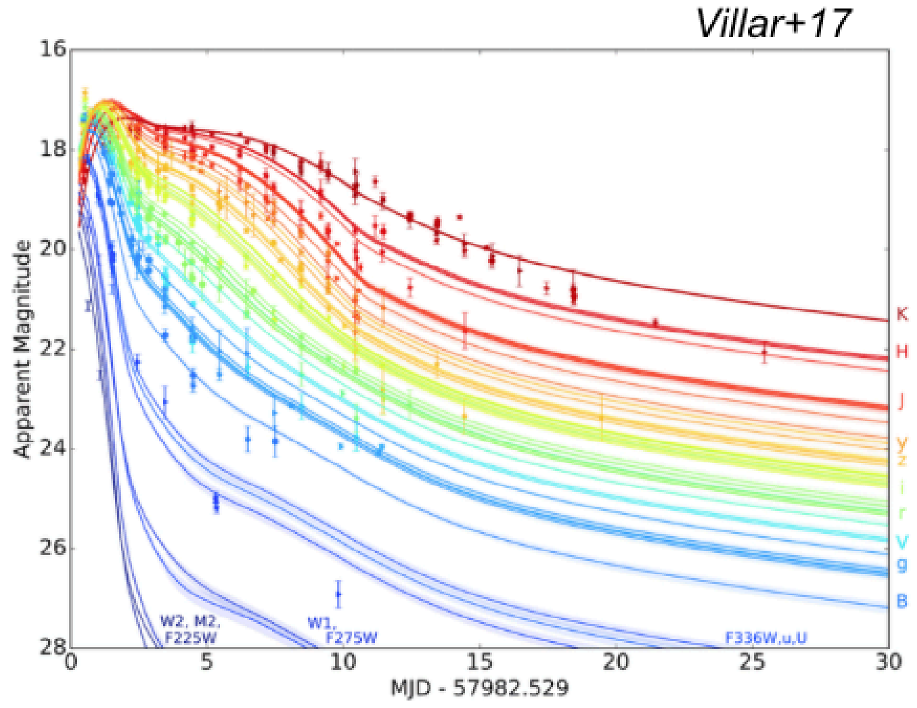
WHY RUBIN

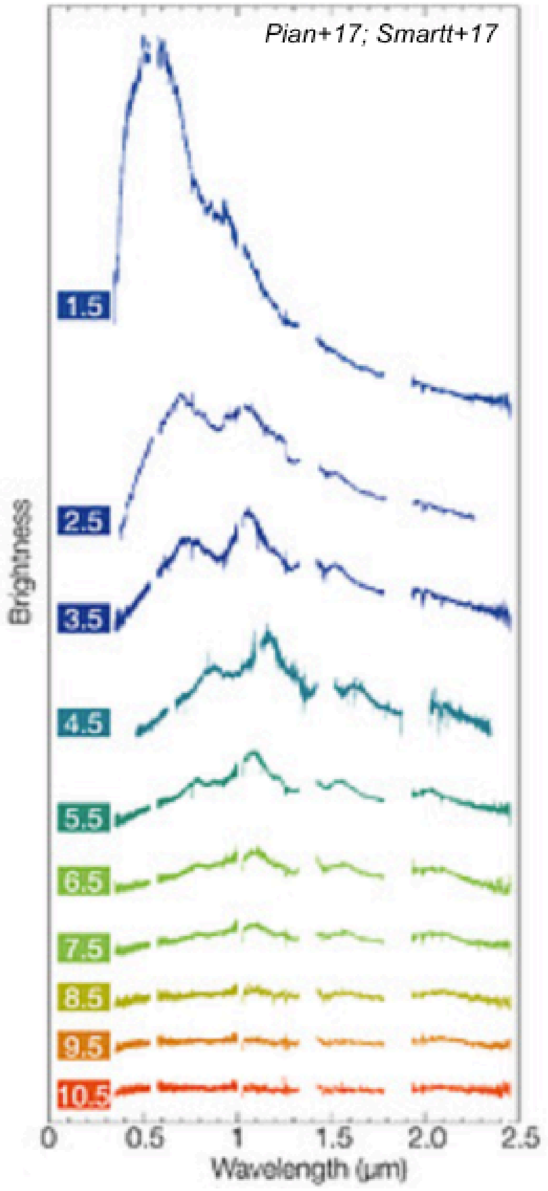
NS-NS / NS-BH mergers: what do we expect to see?

GW170817 - GRB170817: the game changer

We have seen the light !!





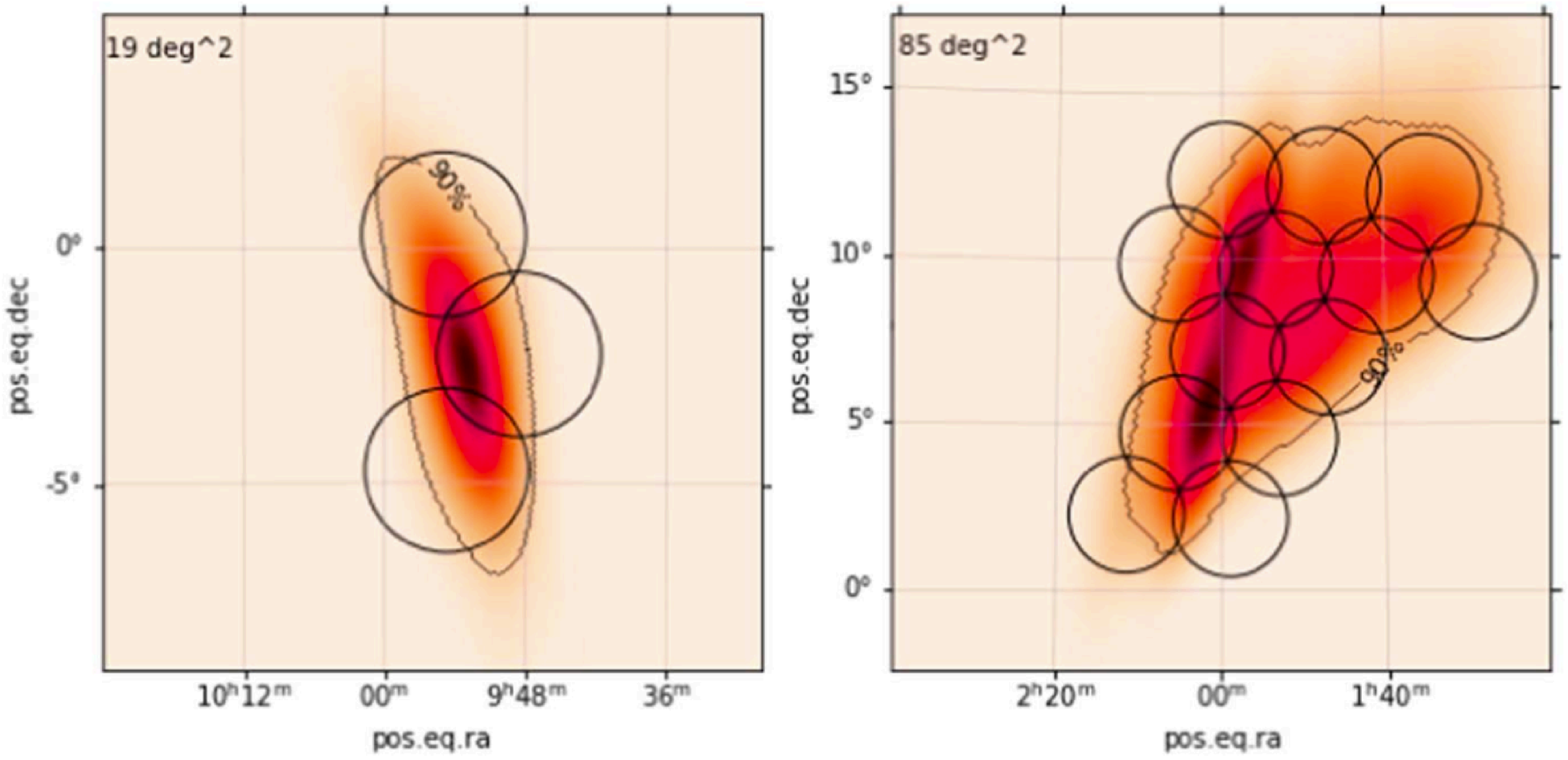


WHY RUBIN

Follow-up strategy (not an easy game)

large sky maps, faint targets

Rubin tiling of simulated GW skymaps for NS–NS mergers



Sky maps from GW detections can be 100s to 1000s square degrees.

We will limit ourselves to, roughly, **Ω** ≲ 100 square degrees

We will (still) need a large field of view for efficient observations

COVER HUGE REGION

Andreoni et al. 2022

Justification for the use of Rubin

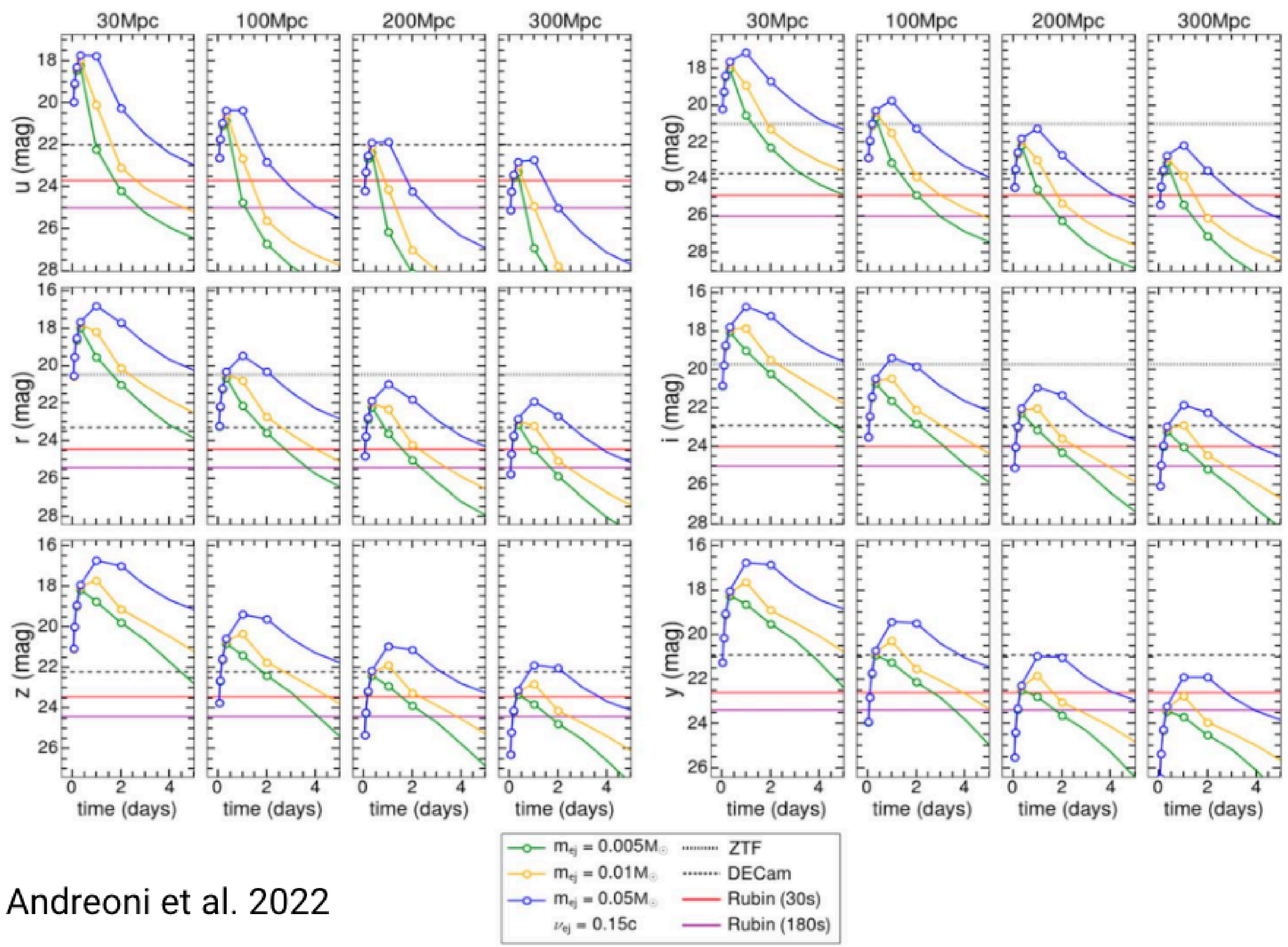
Filter	Depth (AB mag)			*M* (350 Mpc)			*M* (700 Mpc)			Exptime (sec)		
u	24.9	24.7	23.9	-12.8	-13.1	-13.8	-14.4	-14.6	-15.3	180	- 120	- 30
g	26.0	25.8	25.0	-11.7	-12.0	-12.7	-13.3	-13.5	-14.2	180	- 120	- 30
r	25.7	25.5	24.7	-12.0	-12.3	-13.0	-13.6	-13.8	-14.5	180	- 120	- 30
i	25.0	24.8	24.0	-12.7	-13.0	-13.7	-14.3	-14.5	-15.2	180	- 120	- 30
z	24.3	24.1	23.3	-13.4	-13.7	-14.6	-15.0	-15.2	-15.9	180	- 120	- 30
y	23.1	22.9	22.1	-14.6	-14.9	-15.6	-16.2	-16.4	-17.1	180	- 120	- 30

Table 1: The 30-second 5-sigma depths are taken from Bianco et al., 2022 (in orange). The absolute magnitudes in each filter are given at two reference distances (350 Mpc and 700 Mpc). These depths are scaled to 120s and 180s assuming we are background limited. Relevant exposure times are provided for those absolute magnitudes.

WHY RUBIN

large sky maps, faint targets

Simulated KN light curves in the six Rubin filters for different properties of the ejecta (mass and velocity) at four representative distances (30, 100, 200, and 300 Mpc)

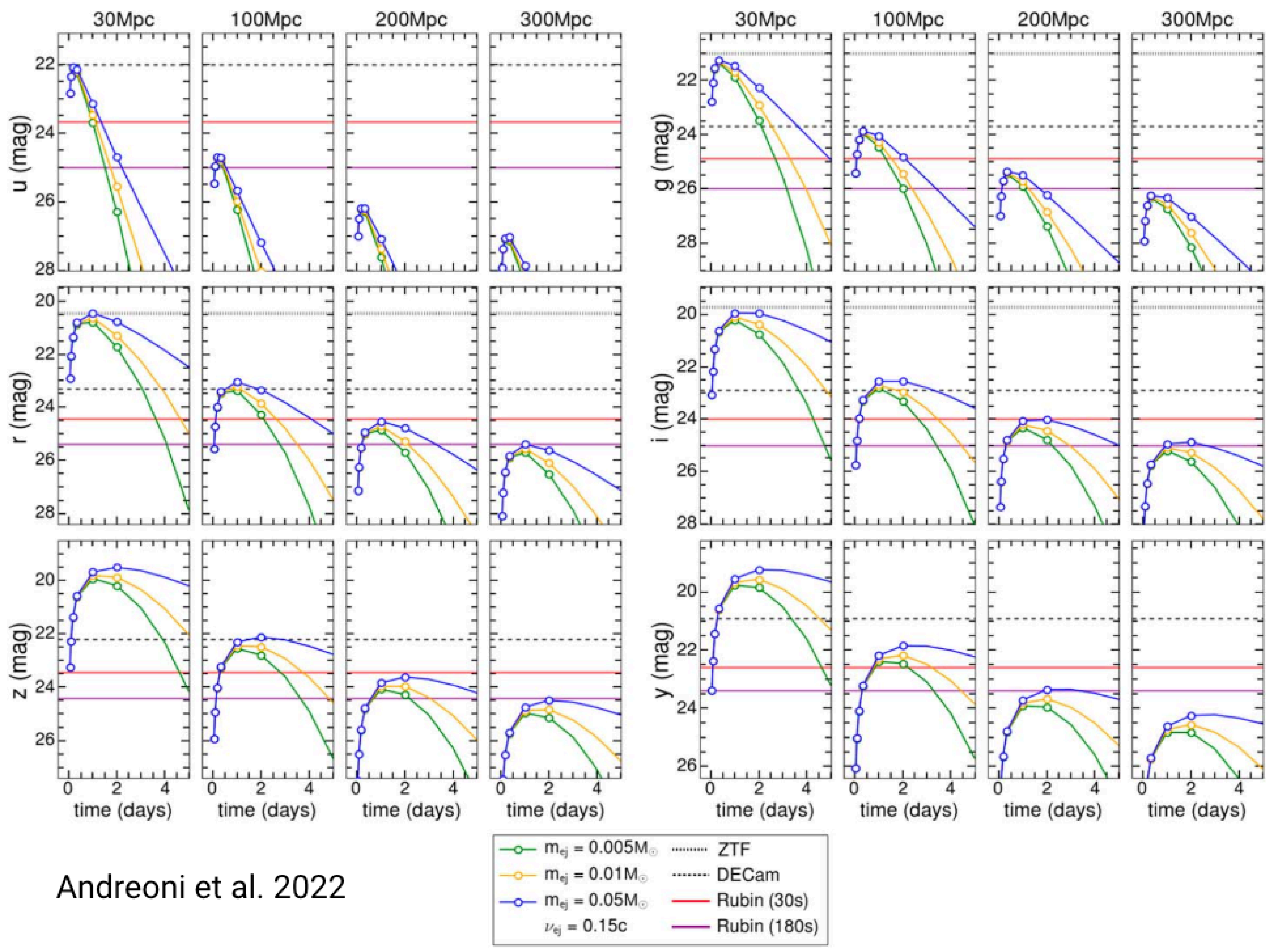


Andreoni et al. 2022

GET ON TARGET PROMPTLY and deep

- “Blue” and luminous kilonovae
- Optimistically, DECam (and potentially Pan-STARRS) could reach the sources
- But this is optimistic ***and*** we will need to go ~1 mag deeper to see a rapid fade and reduce false positives

large sky maps, faint targets



Andreoni et al. 2022

- "Red" and faint kilonovae
- Impossible with any other facility than Rubin
- In reality - quite possible true candidates will be somewhere in between

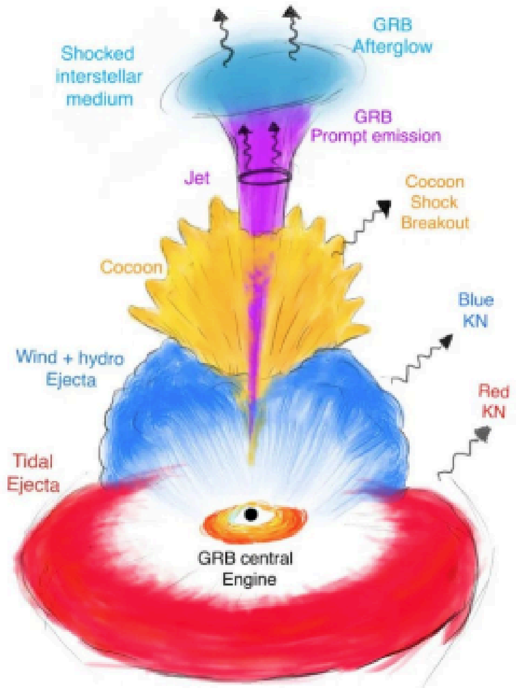
Rubin is gold!
Essential, unique and game changing facility in this area

WHY RUBIN

What is the frontier after GW170817?

EM counterparts of GW sources studies with Rubin LSST

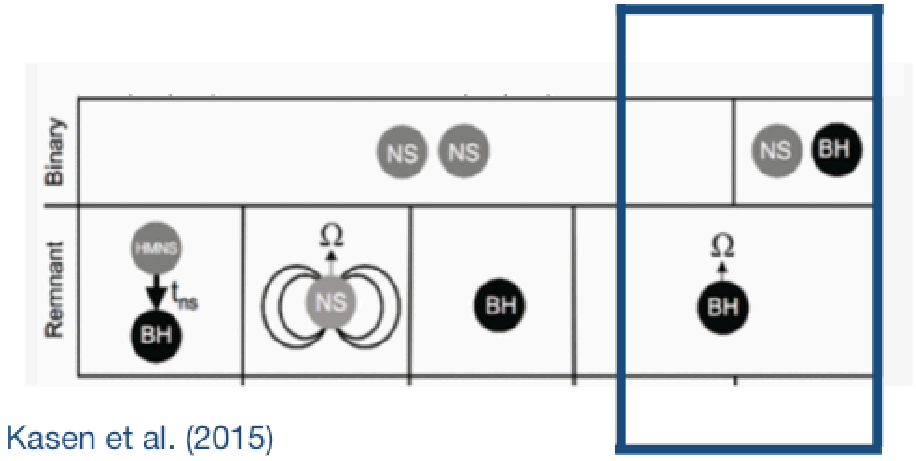
- Kilonovae (KN)
  Blue component
  + discovery of
  new emission
  components



Ascenzi et al. 2021

- Population studies:
  mapping the diversity
  of binary neutron star
  (BNS) merger
  outcome

- Discovery of a EM counterparts of a
  BH-NS merger



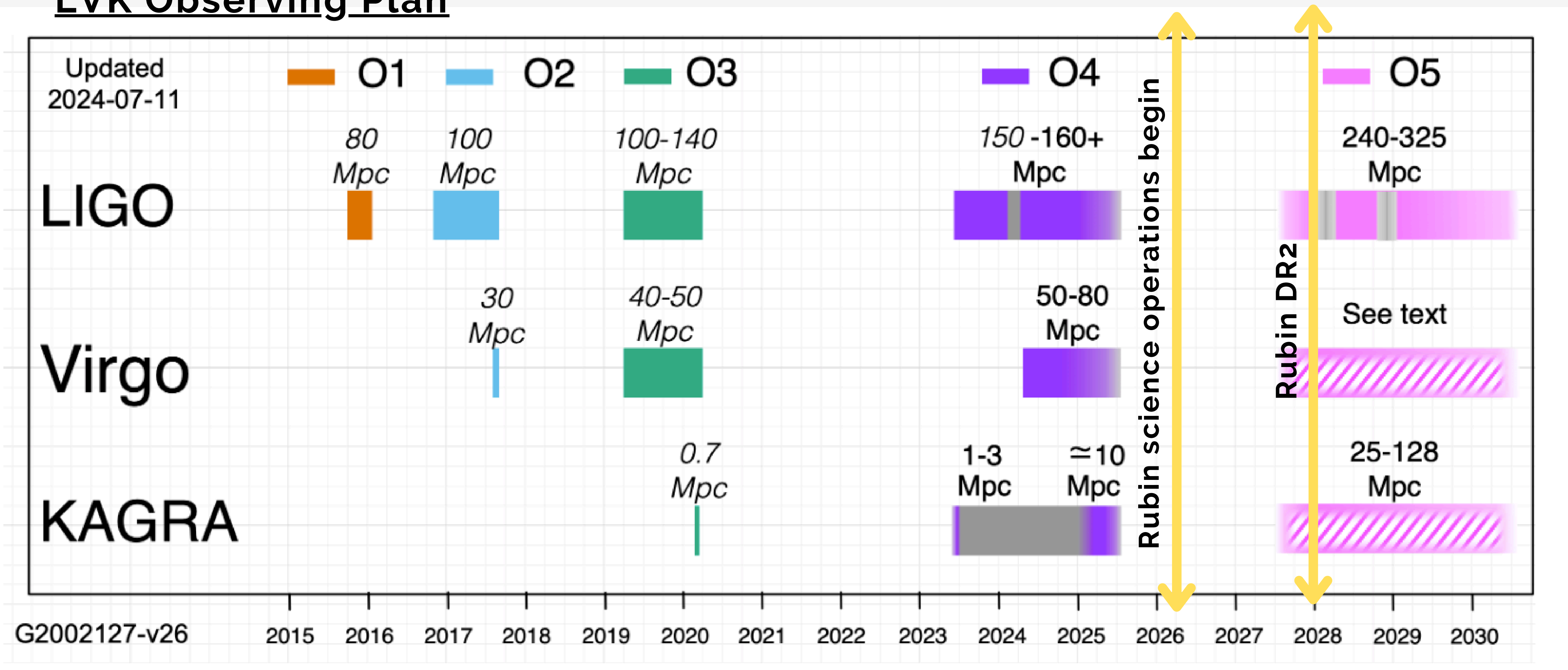
Kasen et al. (2015)

- EM counterparts of BH-BH
  merger or lensed BNS

- get on target promptly!
- go deep (over the entire LVK localization region)!

Immediate goals for Rubin - LVK O5 updated

LVK Observing Plan



Rates of BNS and NSBH detections still very uncertain

$R_{BNS} = 98^{+260}_{-85}$ Gpc^{-3} yr^{-1} (LVK, binned GP model ; N. Sarin)

Naive estimate: $R_{BNS} = 19^{+33}_{-18}$ yr^{-1} (rate of production of BNS by the Universe)

Shah et al. 2024: $R_{BNS} = 17^{+22}_{-10}$ yr^{-1}

Our case will focus specifically on what we can achieve in O5.

We are not (yet) proposing a strategy for 10 years of lifetime of Rubin.

WHY RUBIN

How many BNS and NSBH might we expect to occur in O5?

all sky

Sky area Ω (sq deg)	Median number of BNS	90% confidence range of BNS with maps < Ω/year	90% confidence range of NS-BH with maps < Ω/year
50	14	6-31	0 - 3
100	18	8-41	1 - 4
150	20	9-45	1 - 5
250	25	11-56	1 - 7
500	32	14-70	2 - 9
1000	37	17-83	2 - 11

Table 2: Projected ranges of the number of BNS and NS-BH mergers in O5 (90% confidence) with the expected sky map size. The ranges highlight the current uncertainty in rates and projected detector performance in O5. In the rest of this document, we base our time ToO recommendation on the median number from the calculation described in the text.

with Rubin

roughly ⅓ of the events in Table 2 are available **for immediate Rubin observing**.

Event rate (triggers/year): calculated by Shreya Anand at the meeting, with SNR > 12

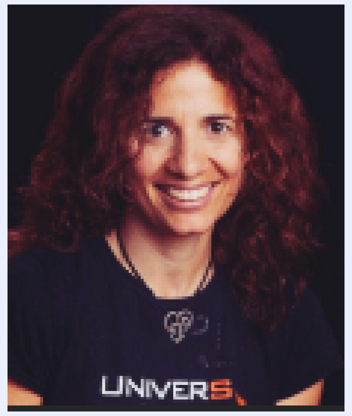
Calculated using information from the official LVK observing scenarios study (Kiendrebeogo et al., 2023)

Note this was before the recent update on Virgo, and assumed distance range DBNS for Virgo was ~150 - 240 Mpc

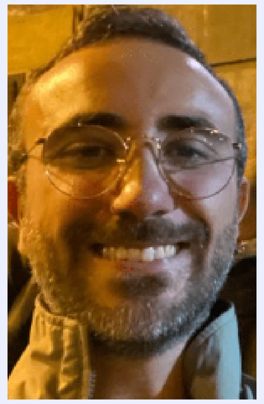
OUR INAF TEAM & EXTERNAL COLLABORATORS

Italian National Institute of Astrophysics

SILVIA PIRANOMONTE



ANDREA MELANDRI

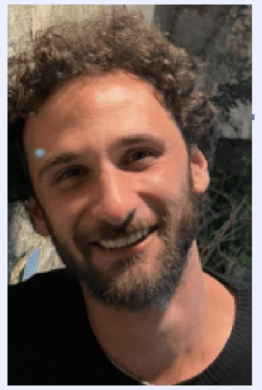


FABIO RAGOSTA

FRANCESCA ONORI

with

IGOR ANDREONI (USA)



AND
MARICA BRANCHESI,
ELEONORA LOFFREDO,NANDINI HAZRA (GSSI)

WHY RUBIN

Multimessenger studies with Rubin

Prospects for kilonovae detections with the next-generation multi-messenger observatories - **Loffredo et al 2024**

Kilonova Parameter Estimation with LSST at Vera C. Rubin Observatory - **Ragosta et al. 2024**

Discovering gravitationally lensed gravitational waves: predicted rates, candidate selection, and localization with the Vera Rubin Observatory - **Graham P. S. et al. 2022**

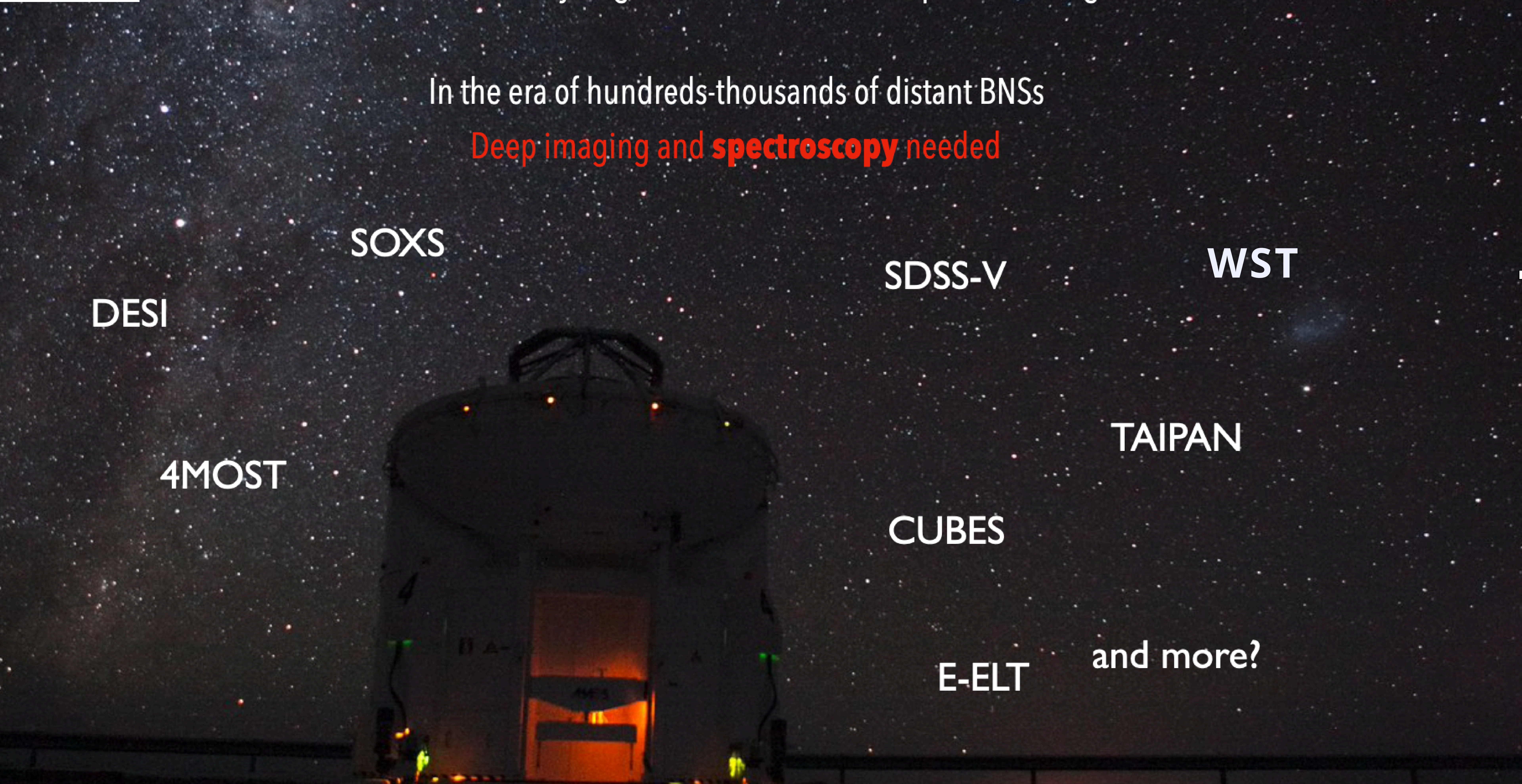
Target of Opportunity Observations of Gravitational Wave Events with Vera C. Rubin Observatory - **Andreoni, I. et al. 2022**

Optimizing Cadences with Realistic Light Curve Filtering for Serendipitous Kilonova Discovery with Vera Rubin Observatory - **Andreoni, I et al. 2021**

For tens of nearby bright events, small telescopes are enough.

In the era of hundreds-thousands of distant BNSs

Deep imaging and **spectroscopy** needed



SOXS

SDSS-V

WST

DESI

TAIPAN

4MOST

CUBES

E-ELT

and more?

THANKS!

silvia.piranomonte@inaf.it

https://rubinobservatory.org/for-scientists

https://www.youtube.com/watch?v=clMsIDxUlmA

Data policy

Alerts on variable objects **publicly available 60 secs after image acquisition** through 7 selected full-stream **Alert Brokers** (software systems that ingest and process the data and publish alerts) and 2 downstream Alert Brokers. Expected about **10 million alerts per night!** (Graham et al. 2020, DMTN-102)

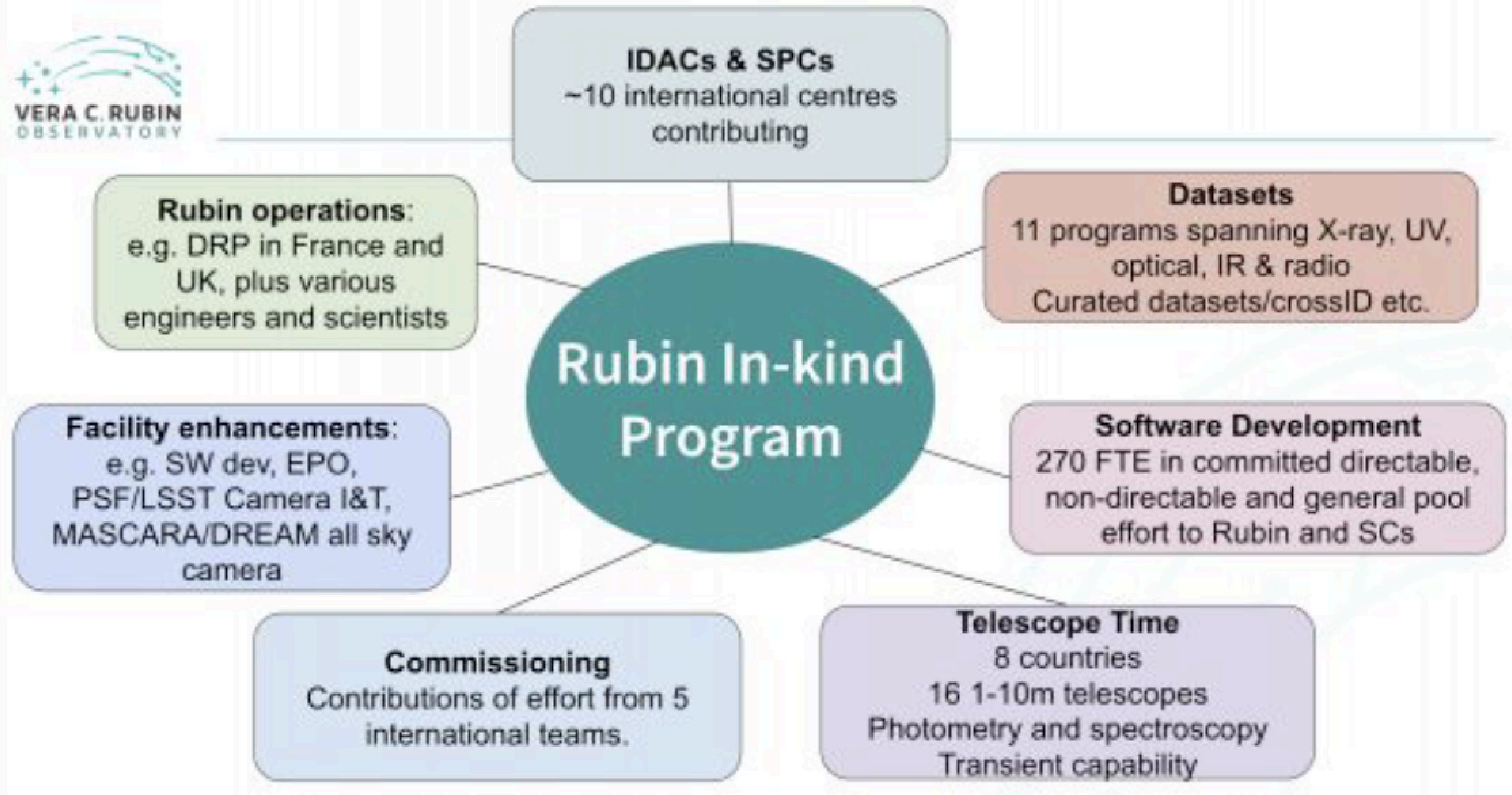
11 Data Releases
Data will become public **after 2 years** from the release for which they are associated.

BUT

Prompt access to full Rubin-LSST data possible through the **Rubin Science Platform (RSP)** for data right holders.

Data rights are guaranteed to scientists in US and Chile, while international partners must provide **in-kind contributions**.

153 in-kind contributions from 43 teams in 30 countries.



courtesy of C. Raitieri

Total BNS+NS-BH summary recommendation for the whole of O5

Type	Skymap size	Number of triggers	Time per trigger	Total
Gold (3-filter+deep)	100	16	9 hrs	144 hrs
Silver	500	6	16 hrs	96 hrs
Grand total				**240 hrs**

Table 3: Total Summary recommendation for BNS and NS-BH during the LVK O5 run

Note on the 3% ToO Rubin Time budget :
Assume these triggers happen between start of Rubin and end of 2029 (4 years of Rubin operations)
3% of Rubin open shutter, science time, has been estimated at 50-60 hrs per year.
Hence our request is consistent with the 3% budget that the Rubin Observatory may allocate to ToOs

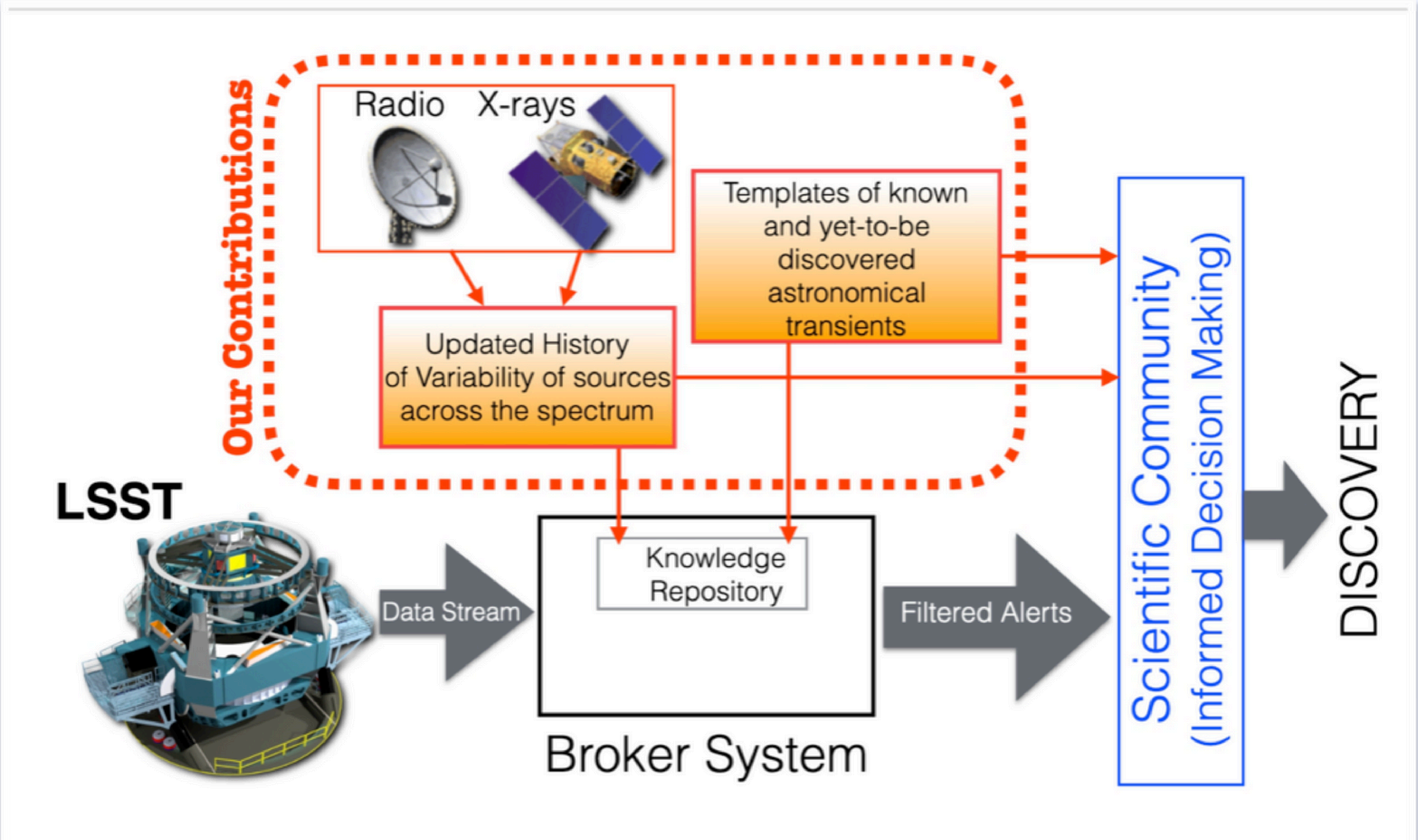
WHY RUBIN

What would be our trigger criteria for Rubin ?

Trigger Criteria

- *Only trigger on an Initial map, do not trigger on Preliminary*[6]
- *The probability of being BNS or NS-BH should be greater than 90%:* ***BNS+NS-BH >= 0.9***
- *False alarm rate less than 1 per 1 year:* ***FAR < 1.6e-08 Hz***
- *90% sky area less than 500 square degrees (then we consider one of the two scenarios below):* □ ***< 500***
- *For NS-BH events, require that there is a good probability that mass has been ejected (these numbers will be changed based on O4 results and O5 projections):* ***HasNS >= 0.5 and HasRemnant >= 0.5,*** *which correspond to the probability that at least one of the two merging objects is a neutron star and the probability that the system ejected a non-zero amount of neutron star matter*[7]*, respectively.*

Rubin-LSST = DISCOVERY machine



From Margutti et al., LSST Science Support Proposal