Core-Collapse Supernovae: Future Synergy Between Rubin-LSST and ET

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VERA C. RUBIN OBSERVATORY

CTAO

MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescopes

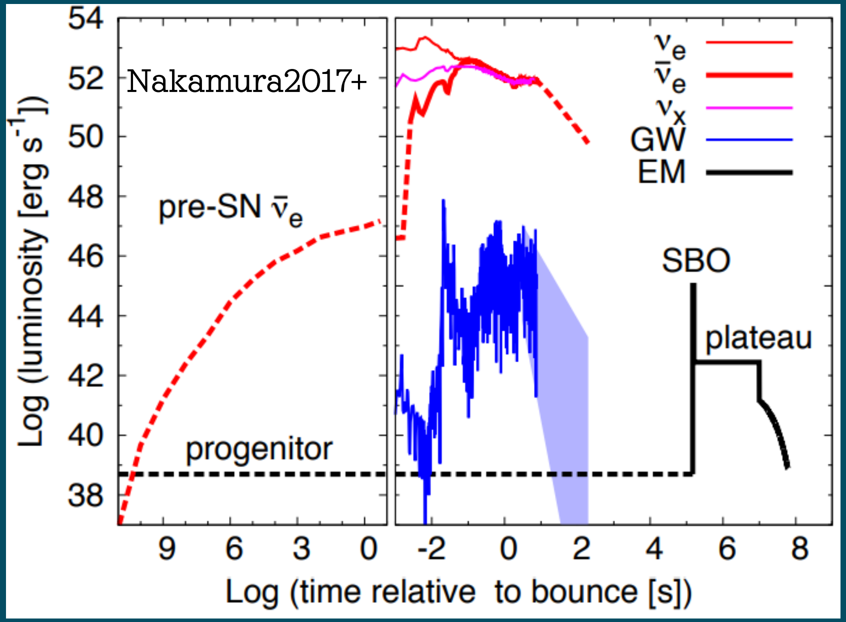
Core collapse SNe

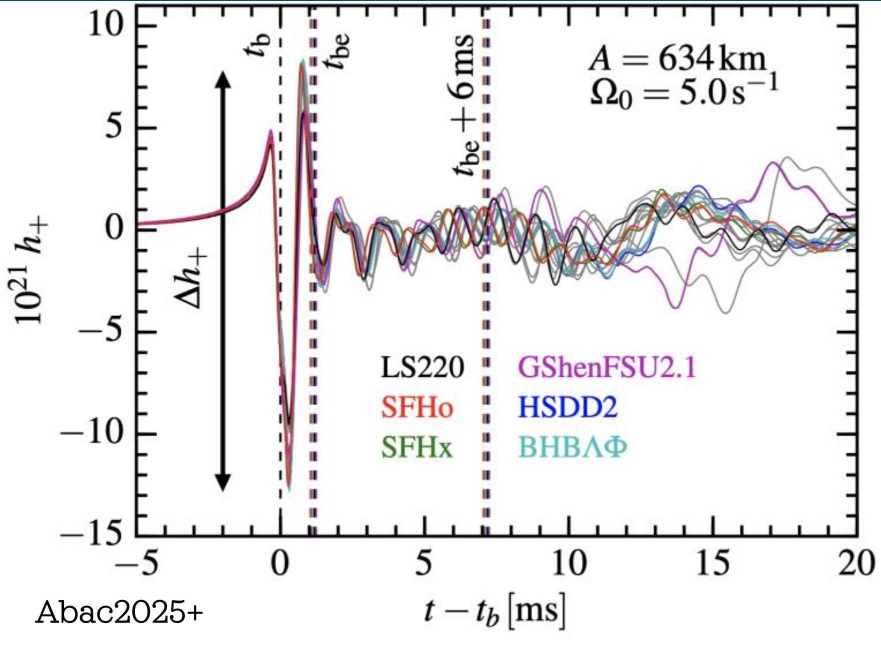
- Massive star $M > 8\,M_{\odot}$.
- Gravitational instability.
- Collapse and core bounce.
- Compact remnants.
- Emission of γ, ν, GWs.
- Multimessenger and multiwavelength sources.
- Among the most energetic phenomena in the Universe.

GWs from CCSNe

- GWs can probe the dynamics of the collapse.
- Anisotropies and fast rotations needed.
- Very weak signal: strain amplitude at 8 kpc between $10^{-21} - 10^{-23}$.
- We need a Galactic Supernova.

(see talk by I. F.Giudice)



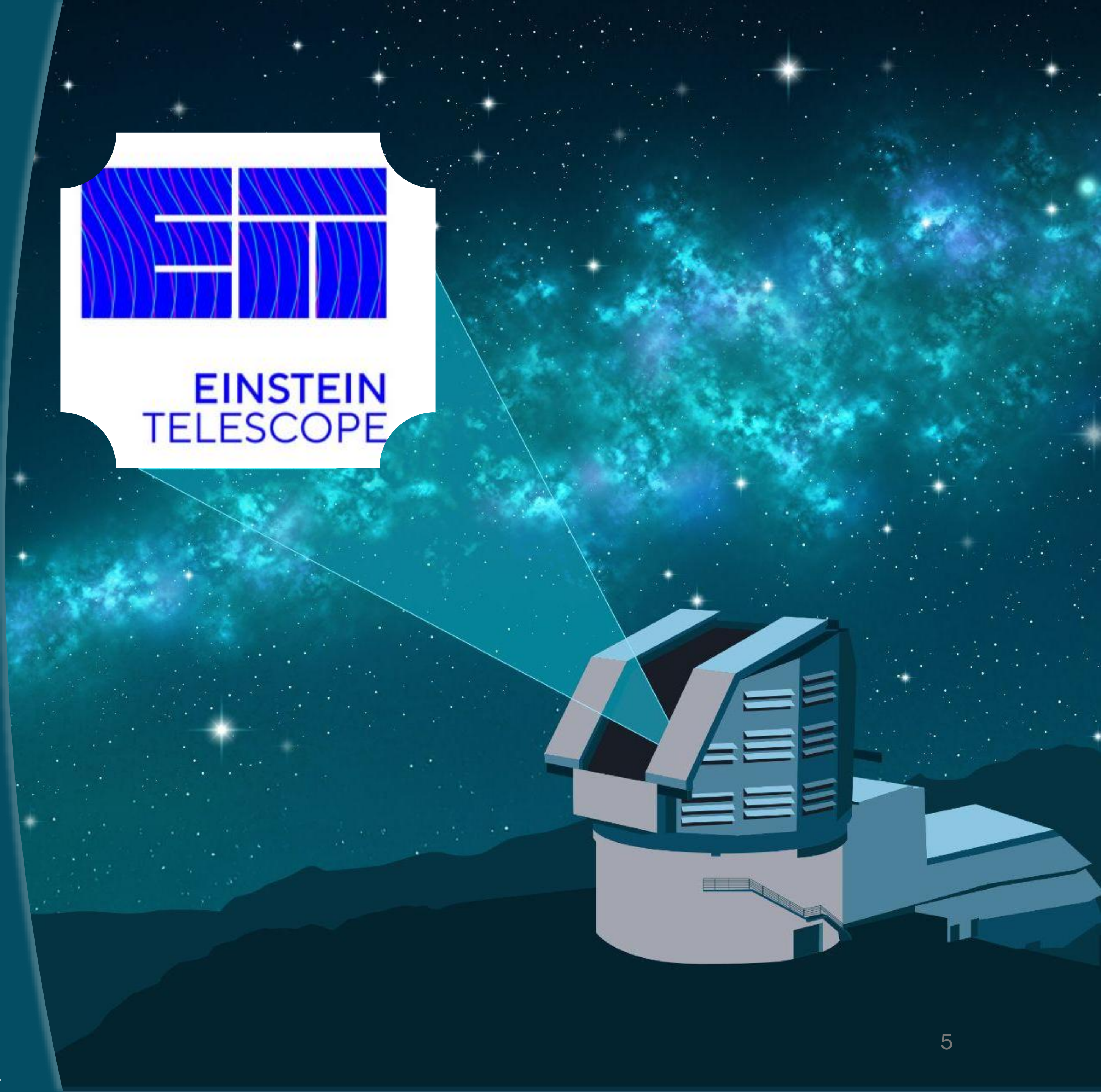


SYNERGY.

LSST + Supernovae*

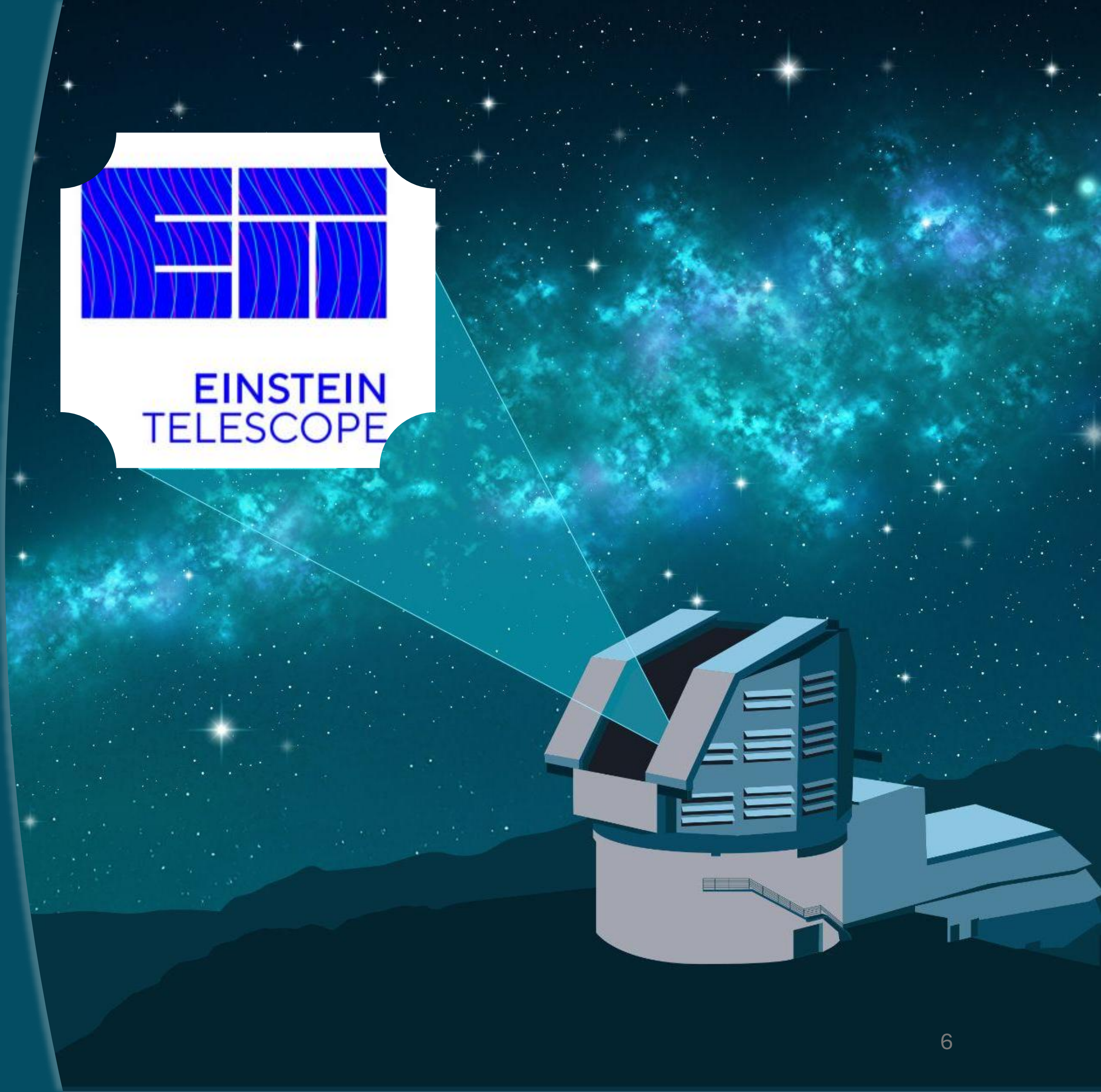
- 10 million SNe detected during 10 years of operation.
- 14 thousands objects in high detail
- Unprecedented opportunity to characterize progenitors of known and peculiar SNe

*Credits: Ivezic et al. 2019

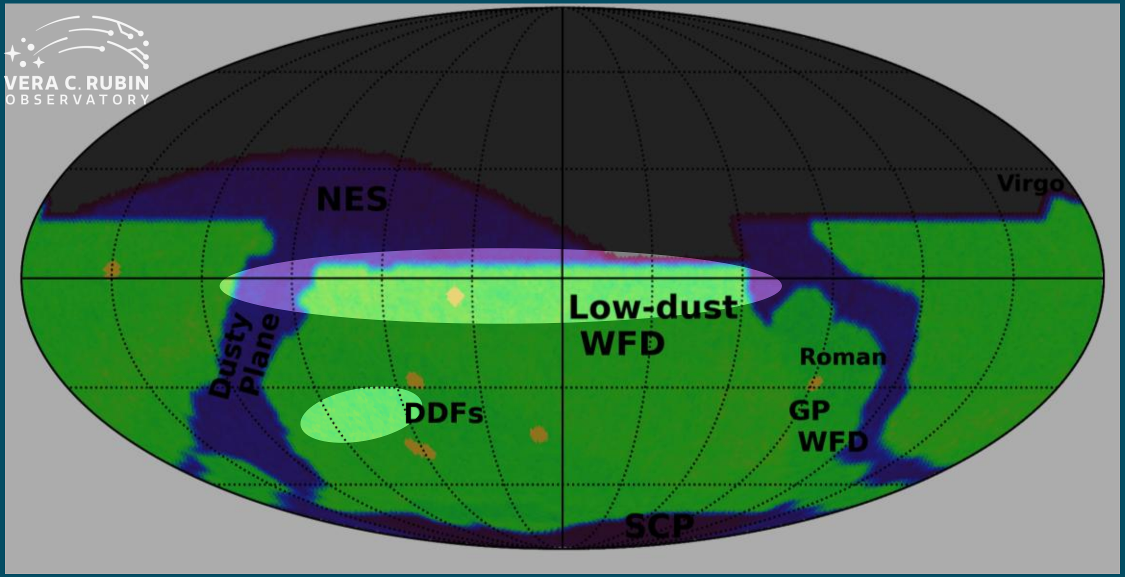


LSST + ET

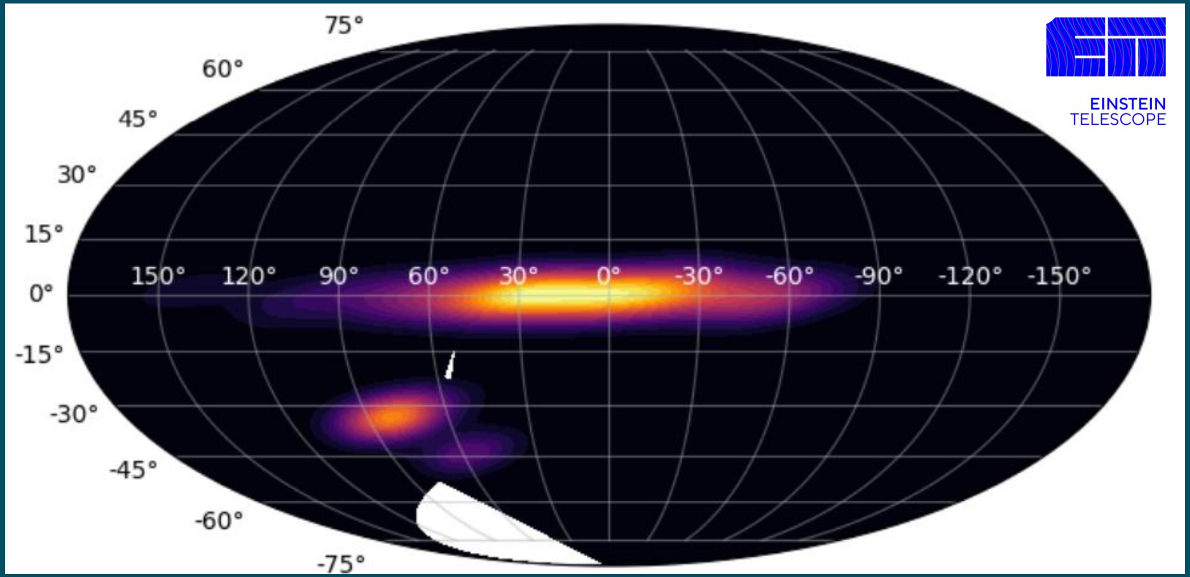
- Boost our knowledge on SN zoo and progenitors' properties.
- Discover new SNe, including peculiar explosions that may emit continuous GWs.
- Catch shock-breakout.
- Characterize stars and explosion environments.
- Prepare the silver plate for ET.
- (maybe) Direct follow-ups after LSST.



Common playground for future



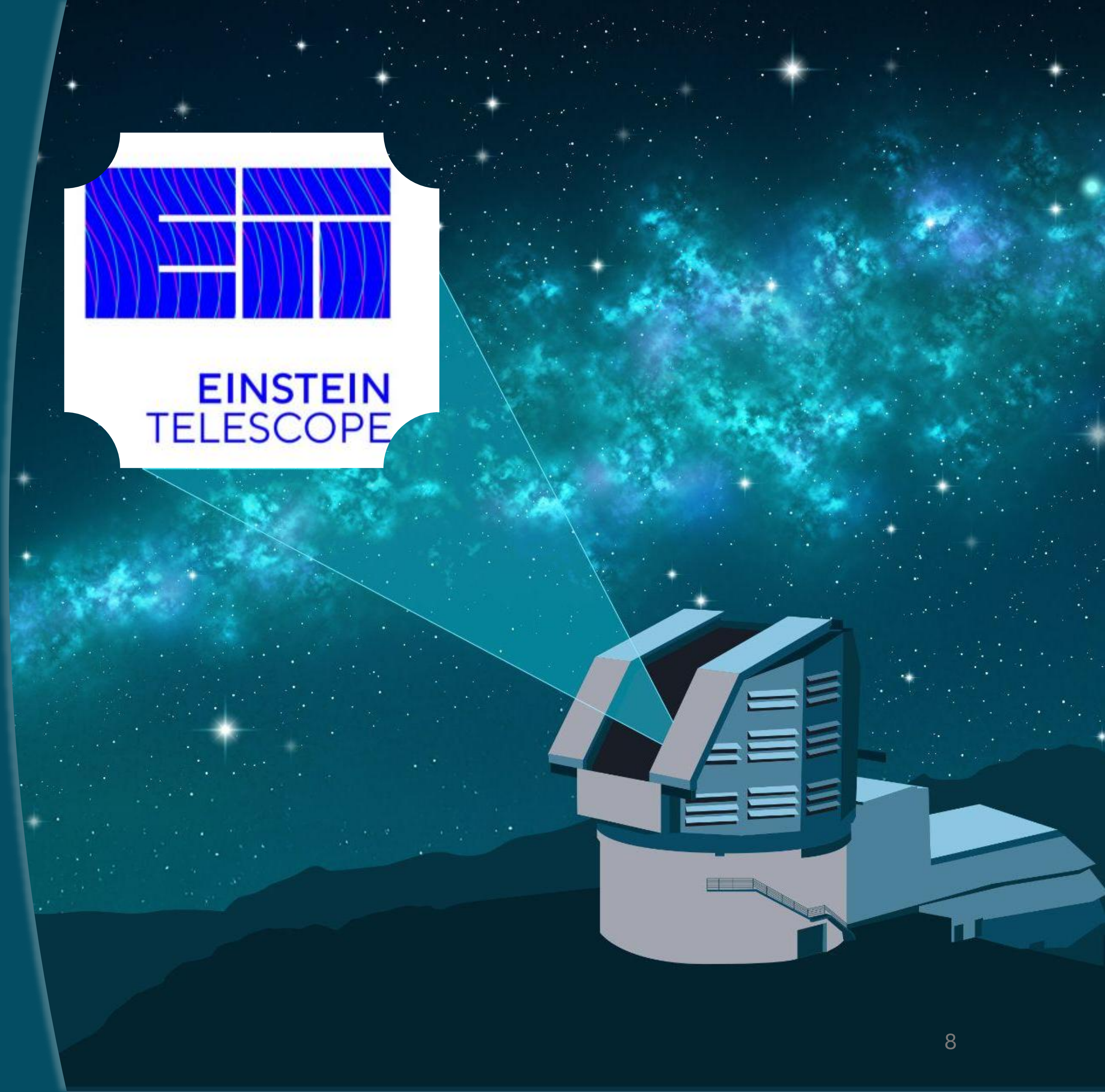
LSST planned visits
(Ivezic2019+)



ET best regions for detection
(Giudice, De Santis et al. in preparation)

Our Work

- Address the possible limits and systematics of CCSNe parameters estimation using only LSST simulated light curves.
- Example of SN characterization on a small sample (things will change quite a bit with 10 million events).
- Analysis of 6730 simulations with the software CASTOR.



OUR WORK.

Data

- Simulations of LSST light curves of SNe*.
- 3D distribution (redshift, reddening, cadence)
- Filters: magnitude limit of the instrument and saturation.
- Interpolation of data (leaving gaps).

*Credits: Moriya et al. 2023

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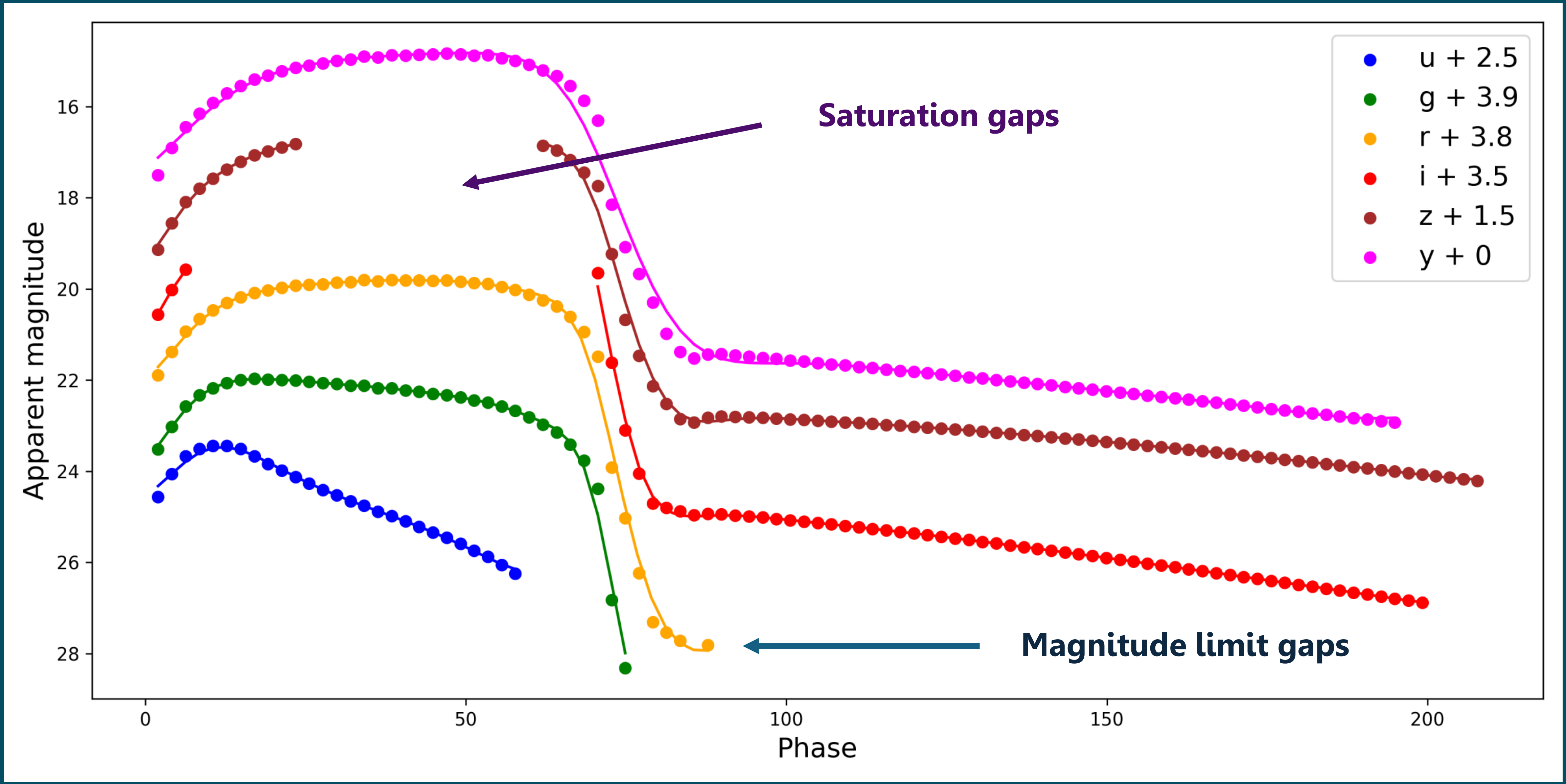
Analysis

- We use CASTOR* to estimate parameters of every event from only the interpolated light curves.
- Three steps:
  1. Comparison
  2. Building synthetic spectra
  3. Parameter estimation

*Credits: Simongini et al. 2024, 2025

How our light curves look like



FIGURES OF MERIT.

KL divergence

The Kullback-Leibler (KL) divergence is a statistical tool that quantifies the difference between two distributions.

$$D_{KL} = \sum_i P_i log_2 \left(\frac{P_i}{Q_i} \right)$$

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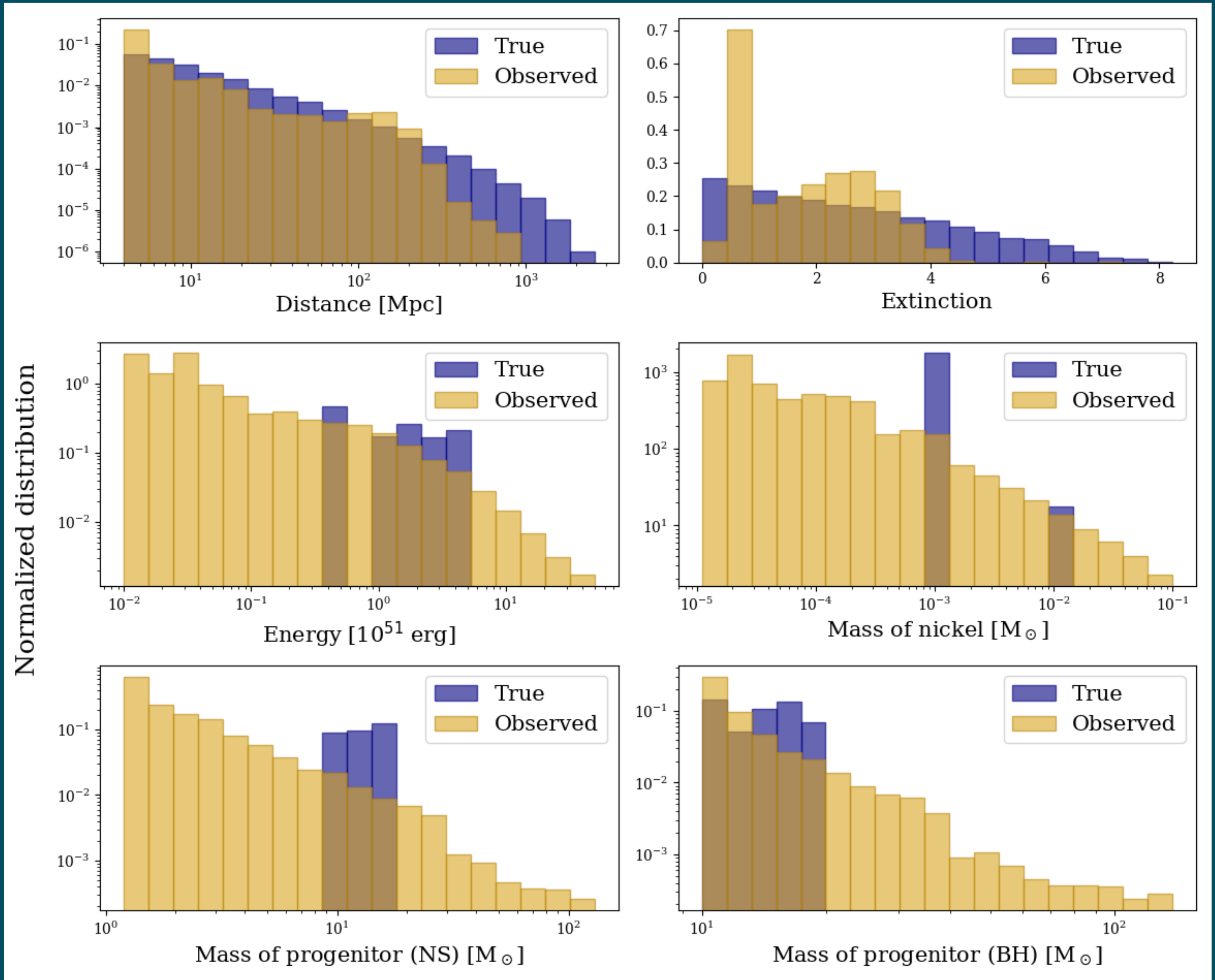
FoM

We define the FoM as the relative deviation of two distributions on a single-event base. It quantifies the relative error of estimation.

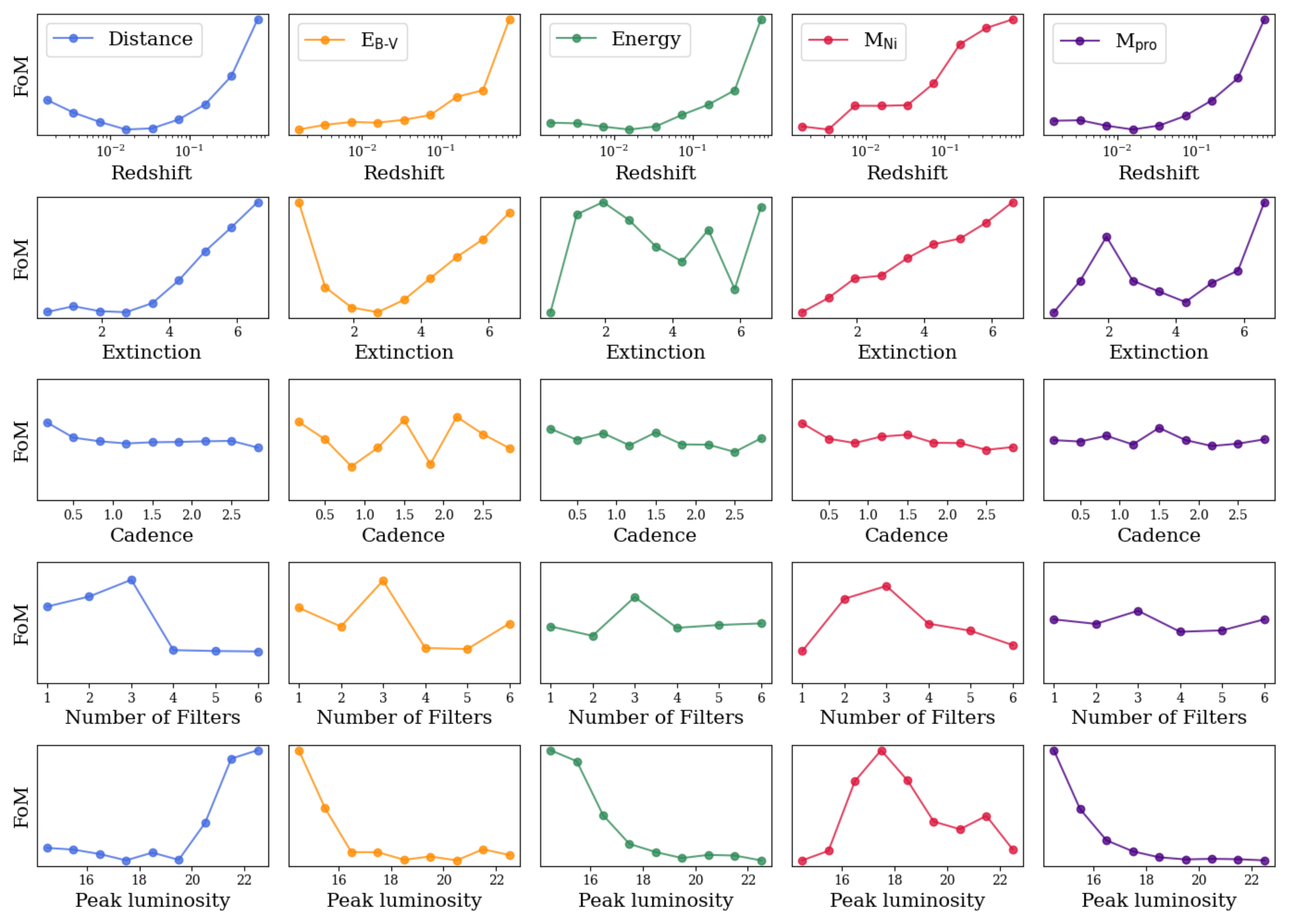
$$\text{FoM} = \frac{1}{n}\sum_i \frac{|S_i - T_i|}{T_i}$$

RESULTS.



Parameter	D_{KL}	FoM
Distance	1.20	2.75
Extinction	0.53	1.69
Energy	1.37	2.61
Mass of nickel	2.15	15.9
Mass of progenitor (NS)	0.74	0.84
Mass of progenitor (BH)	0.18	0.52

Simongini et al. 2025, accepted for publication at A&A



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CONCLUSIONS.

Main results:

- Saturation leads to high errors.
- High redshift requires other techniques.
- Number of filters: if limited, leads to underestimation.
- Technological limit: LSST alone will not suffice for a perfect characterization of every event.
- All these problems can be solved by complementing LSST observations with other telescopes: global Network

Best reconstructed supernova:

- A SN in the range z = 0.01-0.1 with average extinction and peak luminosity, with at least 4 filters and >10 points in the linear decay phase.

Take home message

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- LSST will boost our knowledge of CCSNe, preparing the scientific framework in which ET will operate.
- Need of community: LSST alone will not suffice alone for a complete and accurate characterization of every event.
- LSST will be able to catch Shock Breakout emission and probe explosion geometry and nucleosynthesis (see Ines' talk).
- Future synergy of VRO after LSST: common playground for follow-ups of GW events.

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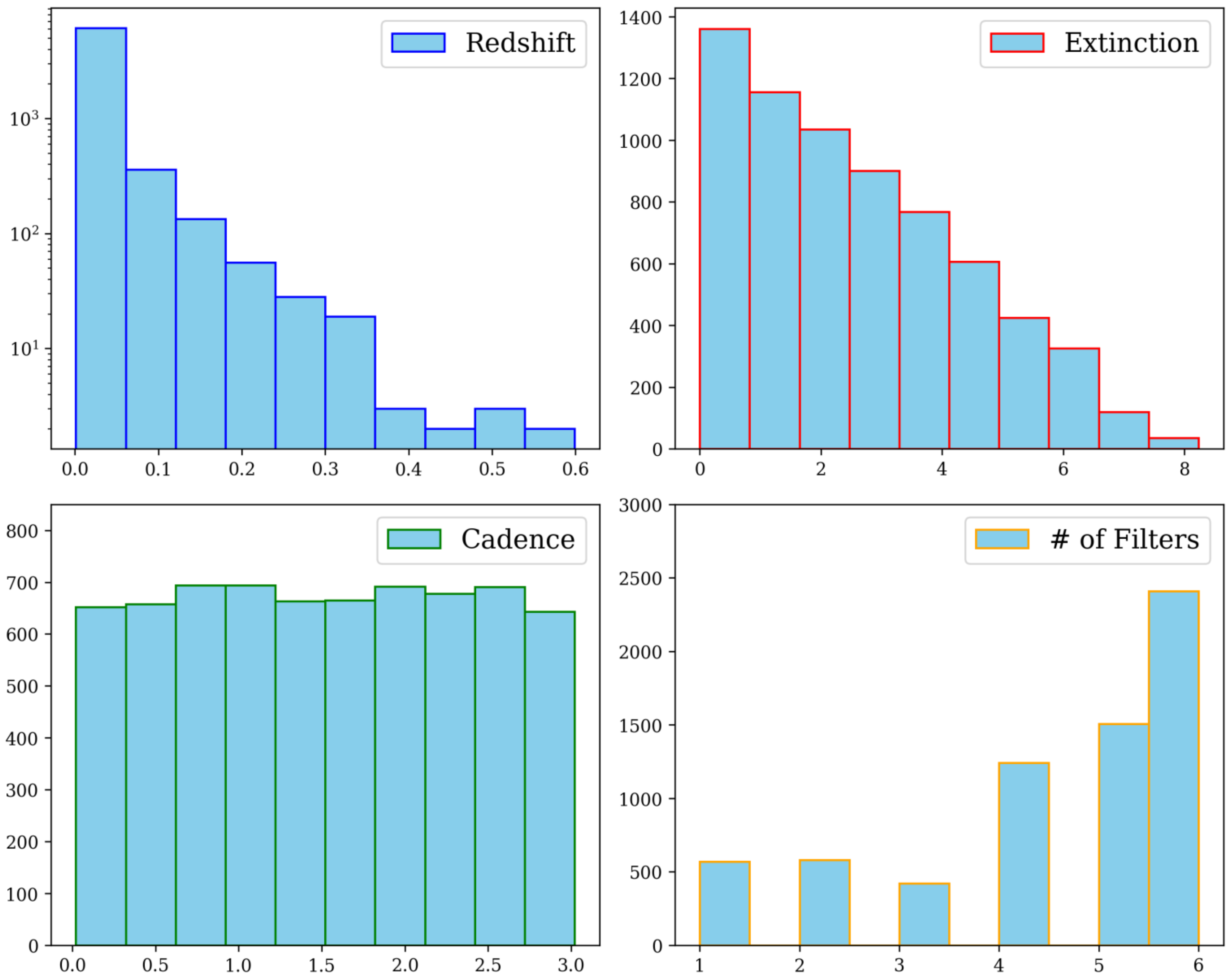
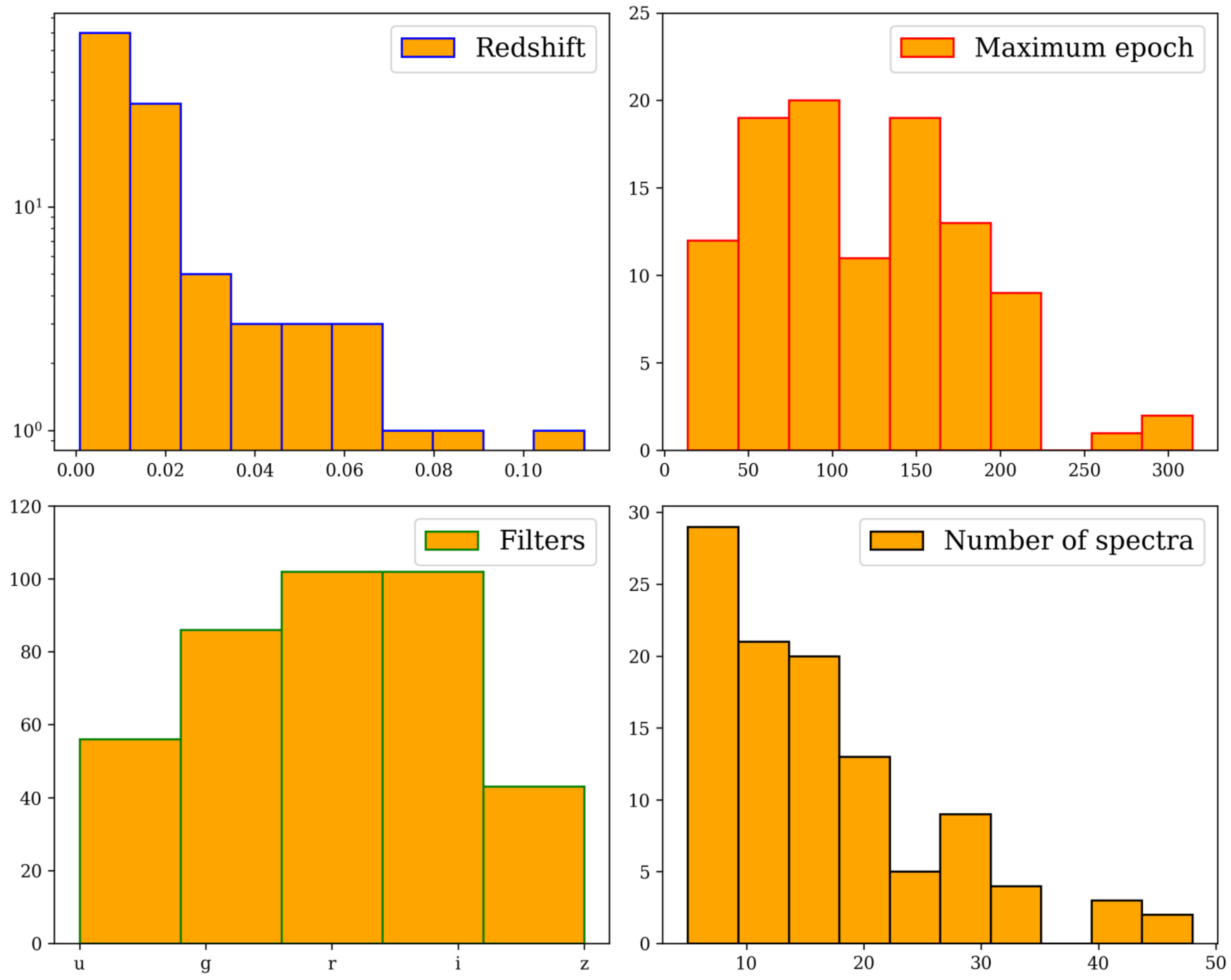
APPENDIX.

A1. Distributions of the simulations



A2. Distributions of the training set



A3. Injected parameters

- Mass of the progenitor
  10, 12, 14, 16, 18 $M_\odot$
- Explosion Energy:
  0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5×10^{51}erg
- Mass of nickel:
  0.001, 0.01 $M_\odot$

A4.
Kernel for GPs

We use a mixture of three Matérn kernel functions setting the lengthstcale parameter as the min, max and mean value of the sampling step.

$$k(x) = A\left(1 + \frac{\sqrt{3x}}{\sigma}\right)\exp\left(-\frac{\sqrt{3x}}{\sigma}\right)$$

A5. Distance

Distance is estimated using the Hubble's law:

$$d = \frac{cz}{H_0}$$

Where the redshift is taken from the relative shift of emission lines in the synthetic spectra using the Doppler's law.

A6. Extinction

Extinction is estimated using the Cardelli's law with the prescriptions from McCall 2004.

The $\boldsymbol{E_{B-V}}$ parameter is taken as the difference between the peak magnitude of a blue and a visible filter.

When the number of filters is < 3 (or there are not the right filters) we simply use the model from Cardelli et al. 1989 averaging over the available filters.

A7.
Energy

We estimate energy using the model from Simongini et al. 2024.

Defining ξ as the neutrino contribution (from SN1987A model) we define the explosion energy as:

$$E = \xi L_{bol} t_{rise}$$

A8. Mass of progenitor

We estimate the mass of progenitor combining the models from Arnett 1982 and Simongini et al. 2024 assuming perfect mass conservation.

The mass of progenitor is defined as:

$$M_{pro} = M_{rem} + M_{ej} = M_{rem} + \frac{10}{3}\frac{E}{v_{ej}^2}$$

A9. Mass of nickel

We estimate the mass of nickel using the model from Lusk & Baron 2017.

The mass of nickel is defined as:

$$M_{Ni} = \frac{L_{Ni}}{s}$$

with:

$$s = 3.90 \times 10^{10} e^{-\gamma_1 t} + 6.78 \times 10^{9} (e^{-\gamma_2 t} - e^{-\gamma_1 t})$$

A10. Additional tests

As additional tests we made two extra runs with (1) fixed extinction and (2) light curves with no saturation.

Parameter	D^1_{KL}	FoM[1]	D^2_{KL}	FoM[2]
Distance	0.78	1.55	1.28	4.26
Extinction	-	-	0.27	1.27
Energy	1.38	2.66	1.56	2.90
Mass of nickel	2.45	15.58	2.69	11.70
Mass of progenitor (NS)	0.64	0.77	0.56	0.69
Mass of progenitor (BH)	0.16	0.49	0.11	0.42

A11.
Mass of nickel

We bin the FoM of the Mass of nickel in terms of the number of points that are observed in the linear decay phase. We notice a huge improvement.