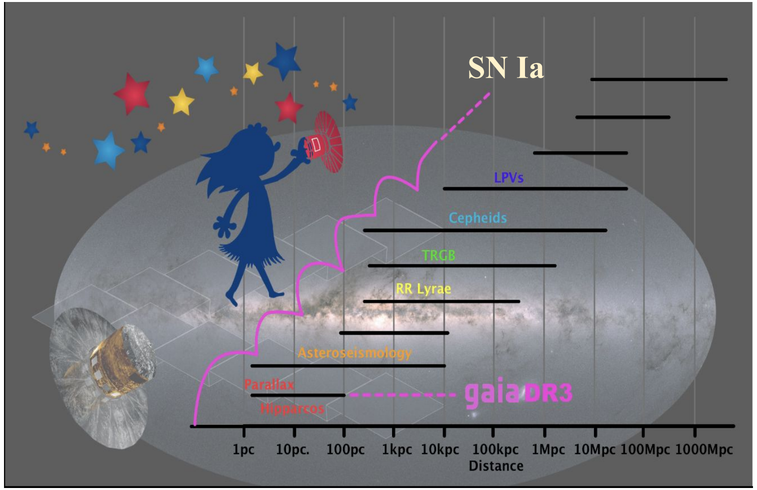
VARIABILI, TRANSIENTI E SCALA DELLE DISTANZE

Con il contributo di M. T. Botticella, G. Clementini, M. Della Valle, G. De Somma, N. Elias De La Rosa, D. Farias, A. Garofalo, I. Giudice, L. Izzo, S. Leccia, E. Luongo, M. Marconi, R. Molinaro, L. Monti, T. Muraveva, V. Petrecca, V. Ripepi, I. Salmaso, E. Trentin, M. wang

Pulsating stars as distance indicators and population tracers

Cepheids & RR Lyrae



Cepheids and RR Lyrae stars are the most important **stellar standard candles** and form the basis of the astronomical distance ladder. They are also excellent **tracers** of the **structure** of the MW and **its formation** through accretion and merger events.

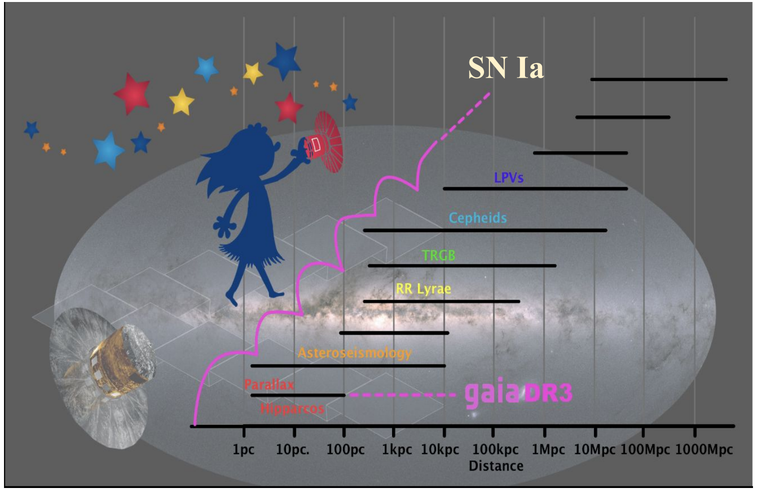
Classical Cepheids

P = 0.2 - 100 days, $A_V \lesssim 1.5$ mag, Sp Type: F6 – K2, mass: 3-13 $M_\odot$, M_V = -2 to -7 mag,
pulsation modes: F, 1O, 2O, multiple modes
Pop I → **young (50-500 My) and metal rich,** Evo. Phase: Blue Loop (He-core burning)
PL relation, **Leavitt law** (Leavitt 1912)

RR Lyrae stars

P = 0.2 – 1 day, $A_V \lesssim 1.2$ mag, Sp Type: A3– F8, mass: 0.6 - 0.8 $M_\odot$, $M_V \approx 0.6 \pm 0.2$ mag,
pulsation modes: F (RRab), 1O (RRc), double mode (RRd)
Pop II → **old (10 - 13 Gyr) and metal poor,** Evo. Phase: Horizontal Branch (He-core burning)
M_V - [Fe/H] and PL_{IR} relations

Cepheids & RR Lyrae



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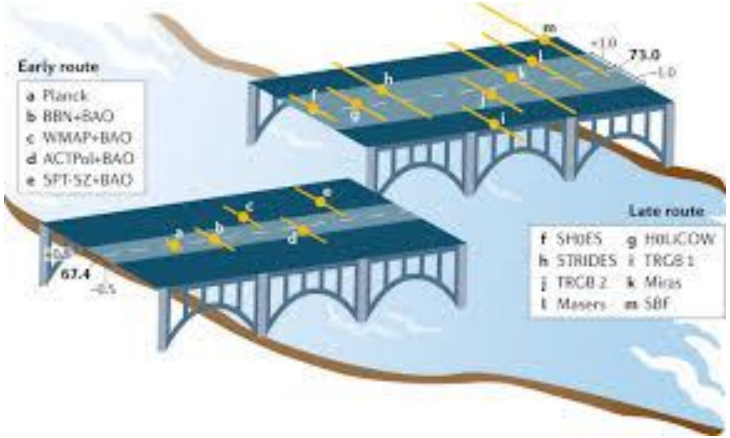
Hubble Tension



…ars

$M_V \approx 0.6 \pm 0.2$ mag,

…ranch (He-core burning)

Cepheids & RR Lyrae: Gaia impact

- **Gaia's parallaxes**

With parallax accuracy of 10 μas for V < 12-13 mag ⇒ trigonometric distances and absolute calibration via parallax of the **PL(Z)**, **PW(Z)** relations for **Cepheids,** and the **M_V-[Fe/H], PL_{IR}(Z)**, **PW(Z)** relations for **RR Lyrae stars** ⇒ **DISTANCE SCALE** ⇒ **H_0**

- **Gaia's positions + proper motions + RVS radial velocities**

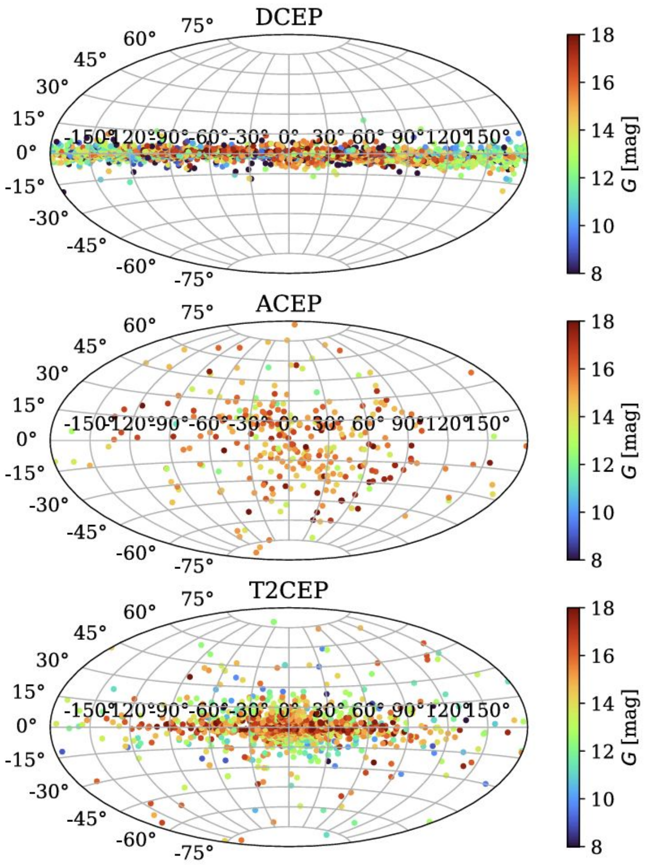
Spatial distribution of young and old populations, identification of structures, galactic bars, streams, new satellites …. ⇒ **MW structure, formation and assembling process**

- **Gaia's parallaxes + photometry + RVS spectroscopy and radial velocities**

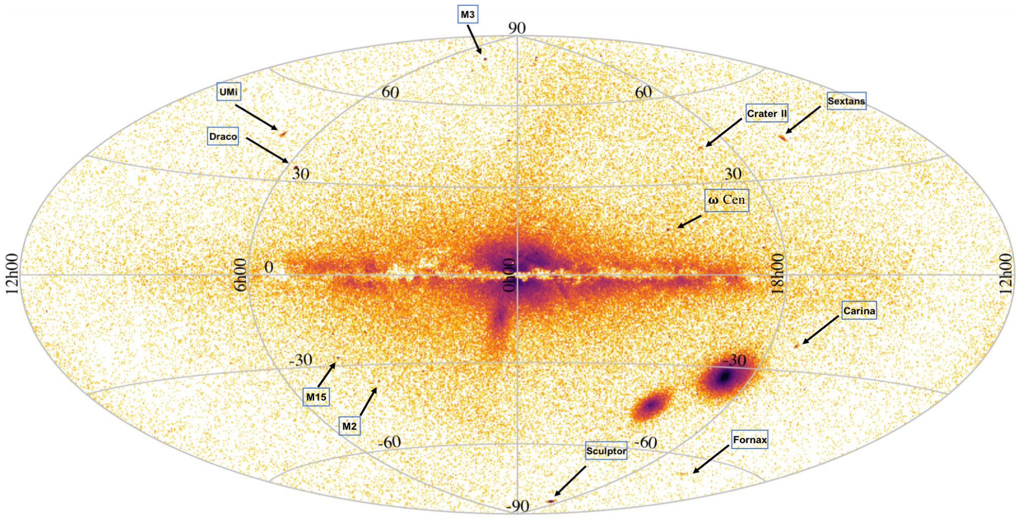
Improved pulsation properties (periods, amplitudes, Fourier parameters) ⇒ **metallicities, absorption values, physics of stars, constraints on evolutionary and pulsation models**

Spatial Distribution of Cepheids and RR Lyrae in Gaia DR3

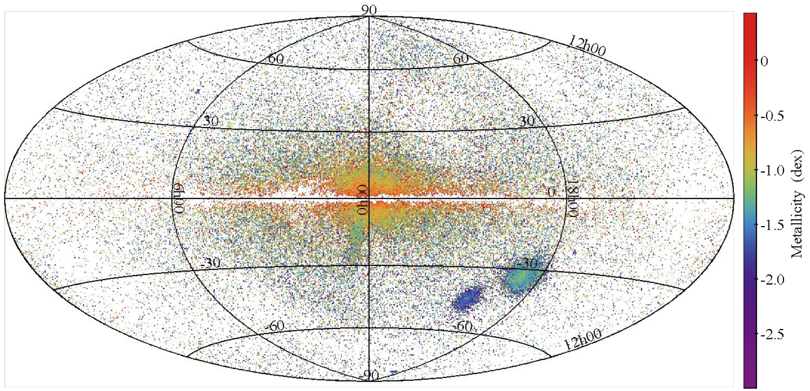
More than 15000 Cepheids of all types (Ripepi+2022)



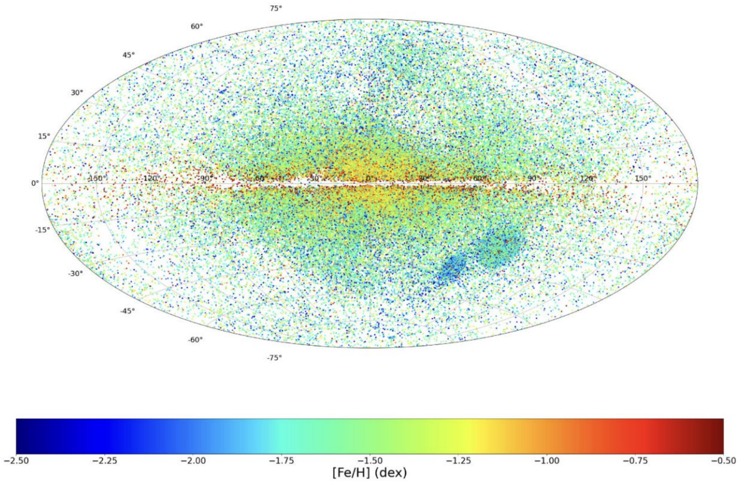
More than 270,000 RR Lyrae in DR3 in MW and 35,000 in the Magellanic Clouds



RR Lyrae Metallicities from the G-band light curves

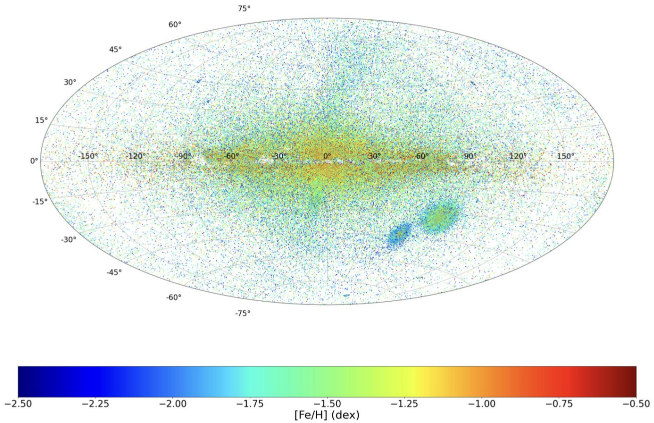


Clementini et al. 2023

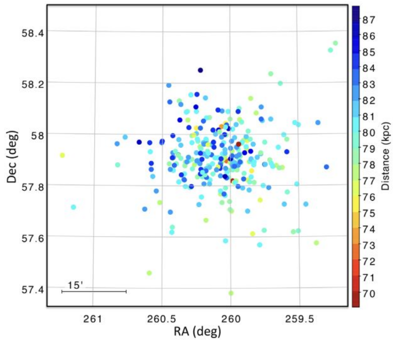


Muraveva et al. 2025a, ML methods, deriver metallicity from the Fourier parameters of the G-band light curves

Monti et al. 2025, DL methods., derive metallicity directly from the G-band light curves

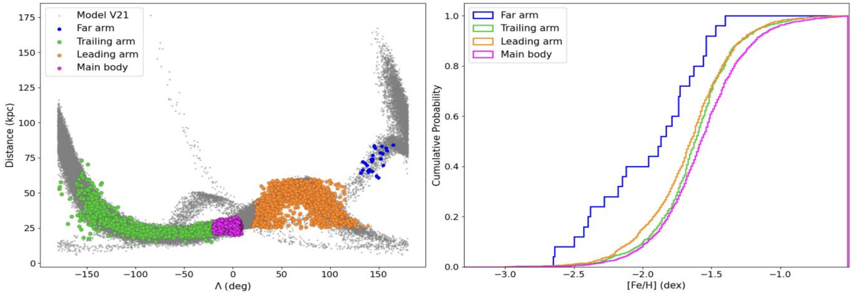


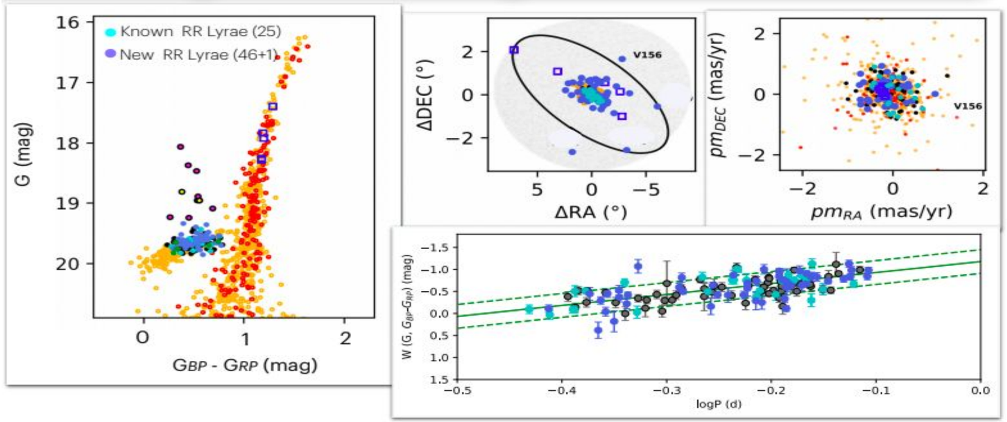
RR Lyrae stars as structure tracers



The Draco dSph (Muraveva et al. 2020):
Sample: 285 RRLs
Results: Draco μ = 19.53 ±0.07 mag, evidence that RRLs in the western/south-western region of Draco appear closer to us (possible MW interaction).

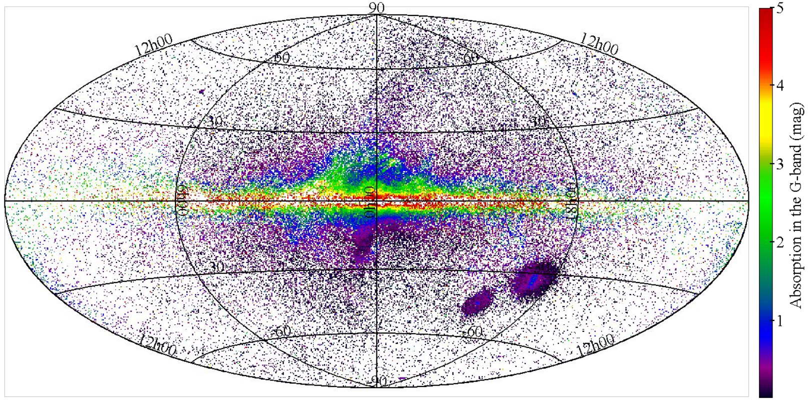
The Sagittarius stream (Muraveva et al. 2025b):
Results: Sgr [Fe/H]=-1.62 dex, metallicity gradient of 0.05 dex/Gyr, indicating that metal-poor RRLs were stripped earlier during the accretion process, study of the far arm.





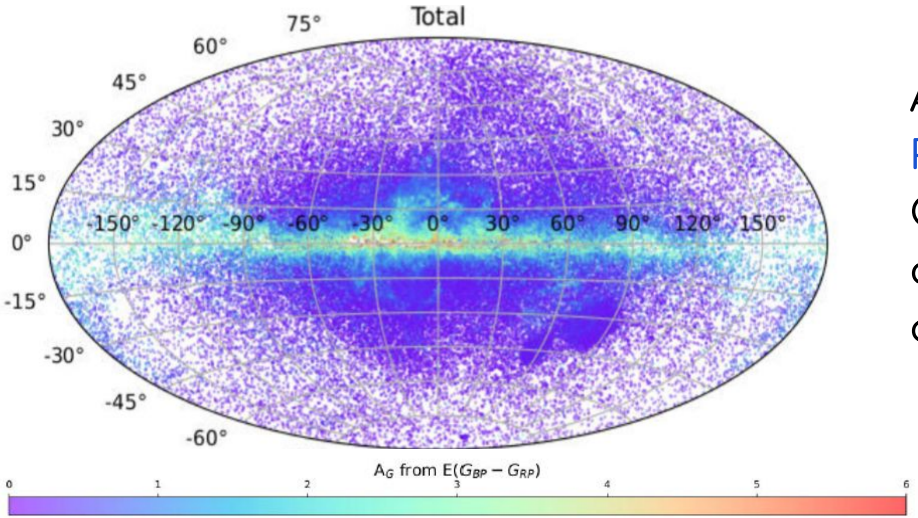
The Ursa Minor DSph (Garofalo et al. 2025)
Results: updated the census of UMi's variable stars (+36%).
We reclassified/ revised properties for some sources. New RR Lyrae stars identified from Gaia DR3 are new members of UMi.
RR Lyrae stars suggest that the older population of UMi is more spherical and extended than previously found.

Absorption in the G-band for DR3 RRab stars



A_G values for 142,660 DR3 RRab stars, based on Piersimoni et al. (2002) relations in V, V-I transformed to G, G - G_{RP}

Clementini et al. 2023



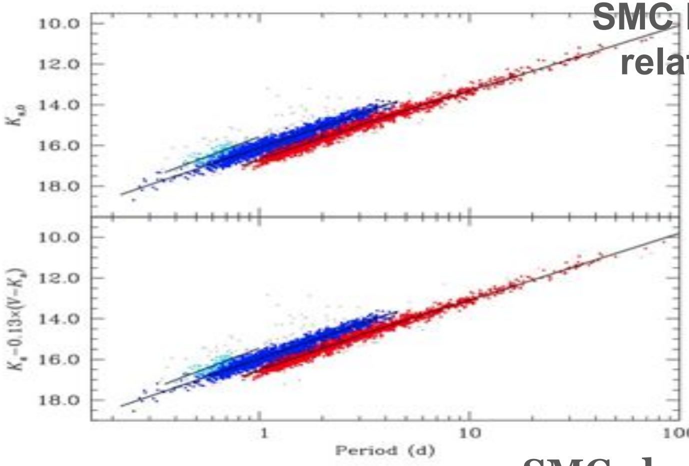
A_G values for 188.733 DR3 RR Lyrae stars, RRab+RRc types from the new calibration of Garofalo et al. (2025) which is directly based on the Gaia DR3 G, G_{BP} - G_{RP} magnitudes and colours

Garofalo et al in prep.

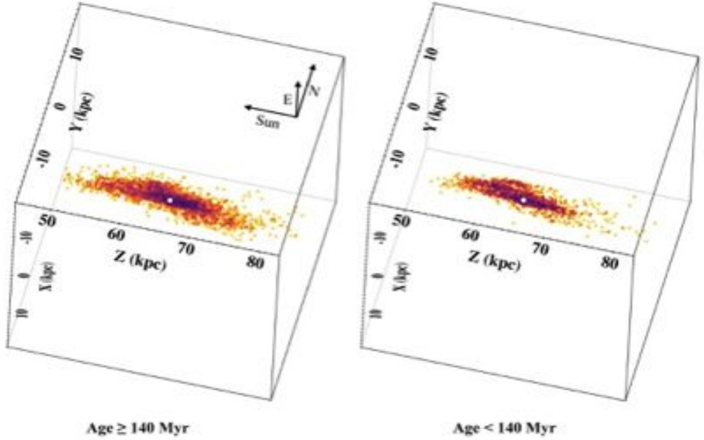
Cepheids as tracers of the young stellar population in Galaxies

- Classical Cepheids Leavitt Law provide **accurate relative distances** for these pulsators → **3D geometry** of the young stellar population (50-300 Myrs).
- Vista Magellanic Cloud (VMC) survey → time-series near infrared photometry (Y,J,Ks) for ~10,000 Cepheids in the Magellanic Clouds.
- 3D distribution of the Cepheids in the SMC not planar but heavily elongated for more than 25-30 kpc in the E/NE towards SW direction → result of repeated interaction between the Clouds.
- The LMC shows a non-planar distribution, with complex structuring. The disc appears 'flared' and thick, with a disc scale height of h ~ 0.97 kpc → strong tidal interactions with the MW and/or the SMC or past merging events with now disrupted LMC satellites.

SMC PL/PW relations



SMC elongation



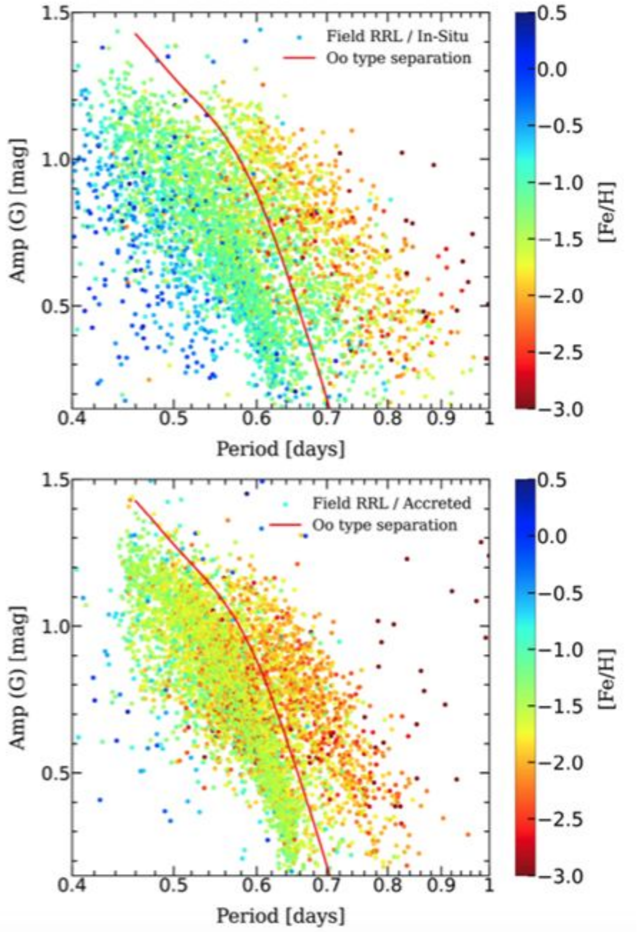
Ripepi et al. 2017, 2022

RR Lyrae variables as probes of the Galactic assembly

- The "**Oosterhoff dichotomy**"— a gap in the pulsational periods of RR Lyrae stars in Galactic Globular Clusters and field — has been a puzzle for almost 80 years.

- Thanks to Gaia and other surveys data → orbit calculation (integrals of motion) for > 10,000 RR Lyrae variables → **separation between "in situ" (native to the Galaxy) or "accreted" (from merged satellite galaxies).**

- **The Oosterhoff dichotomy is only present in the "accreted" population,** while the "in situ" stars show a continuous distribution, proving that **this dichotomy was brought into the Milky Way by the merging events that shaped the Galaxy.**



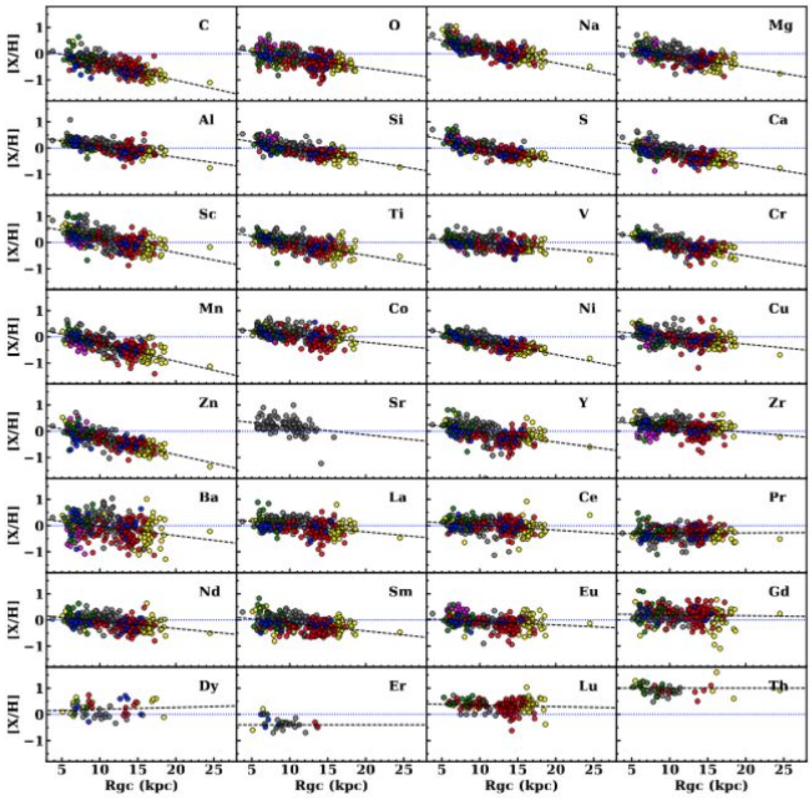
Luongo et al. 2024

Cepheids as tracers of Galactic disc radial abundance trends

- **Classical Cepheids as tracers to map the Galactocentric radial gradients of chemical elements** and analyze the young stellar population's spatial distribution in the Milky Way disc.

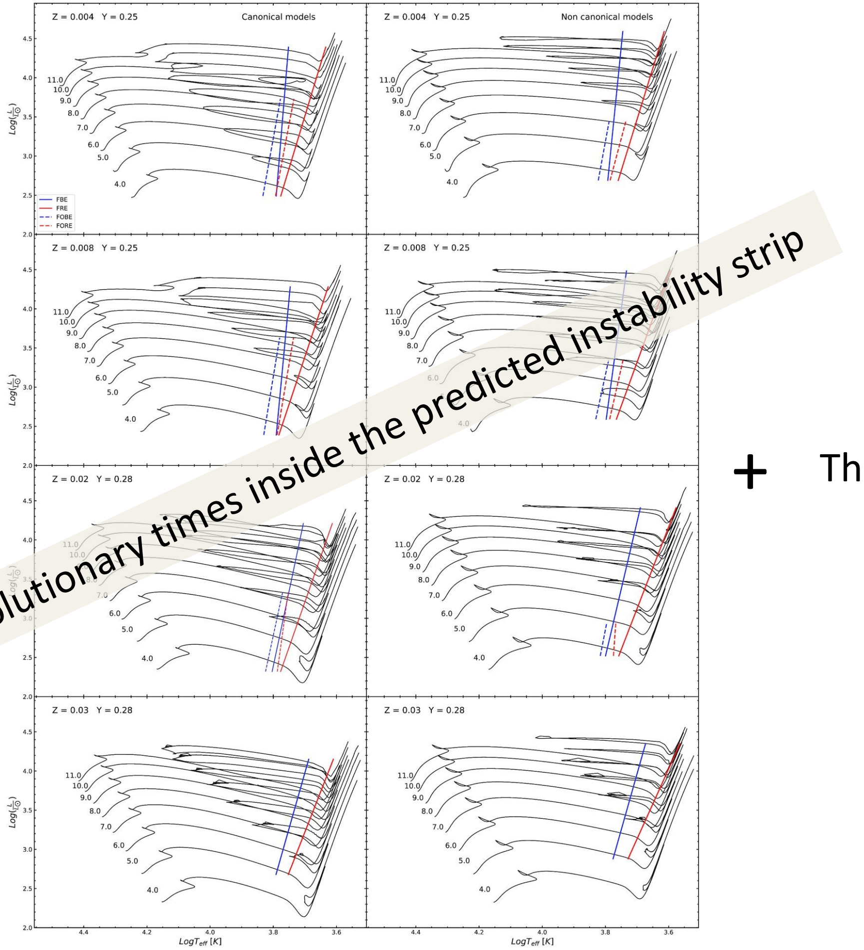
- Homogeneous high-resolution spectroscopy for 340 Classical Cepheids → **radial trends for 32 chemical species, including the rare elements Dysprosium, Erbium, Lutetium, and Thorium**

- **A Fe radial gradient of -0.064±0.002 dex/kpc is found,** confirming a clear negative trend for most chemical species across the Galactic disc,



Trentin et al. 2026

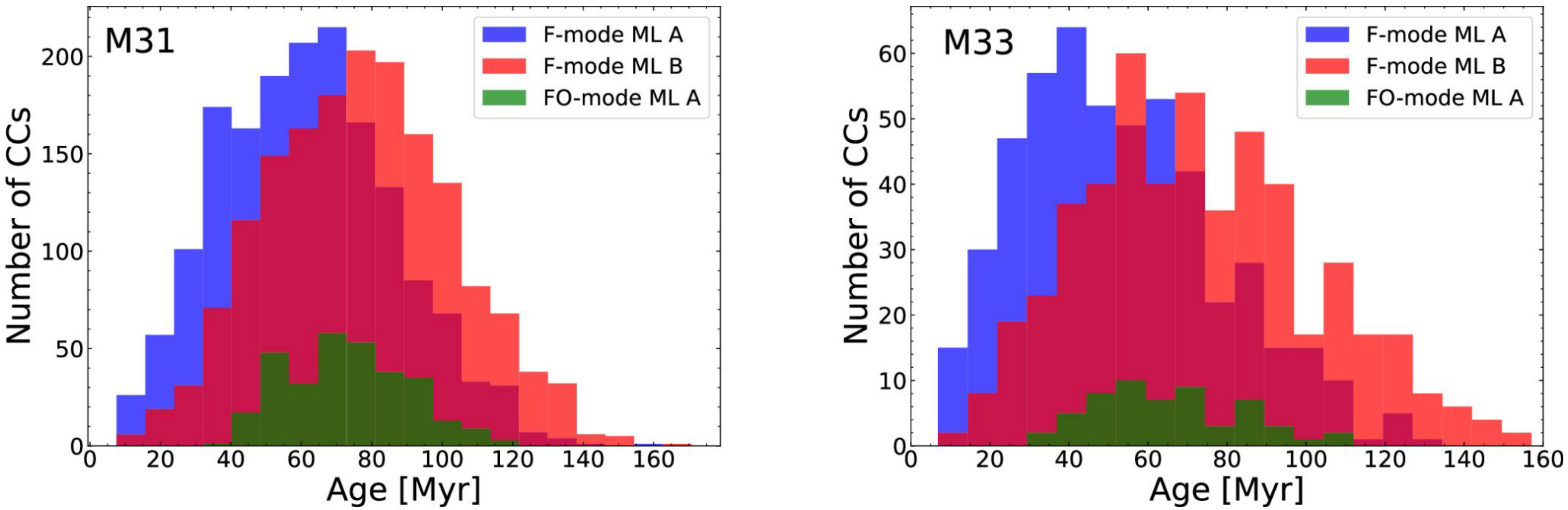
Period-Age(-[Fe/H]) and Period-Age-Color(-[Fe/H]) relations



+ Theoretical PLMT relation → PA, PAC
PAZ, PACZ

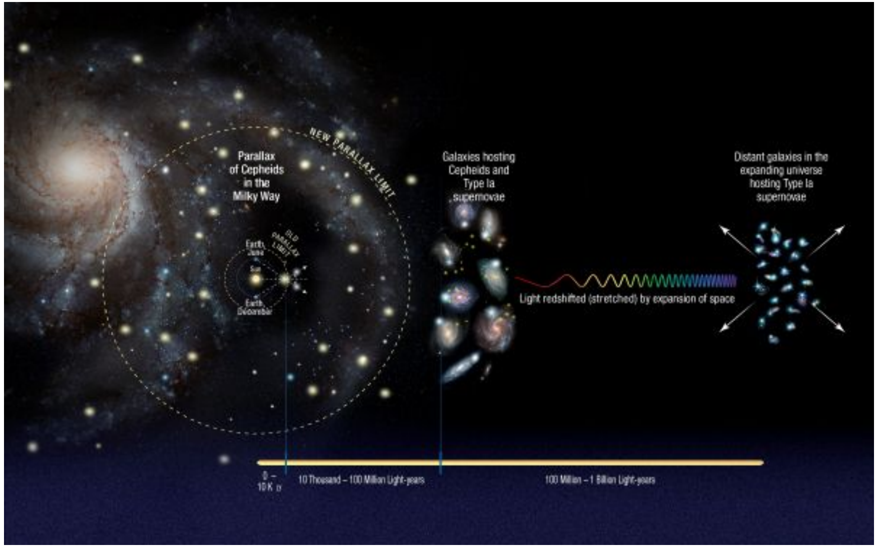
De Somma et al. 2020, 2021 MNRAS

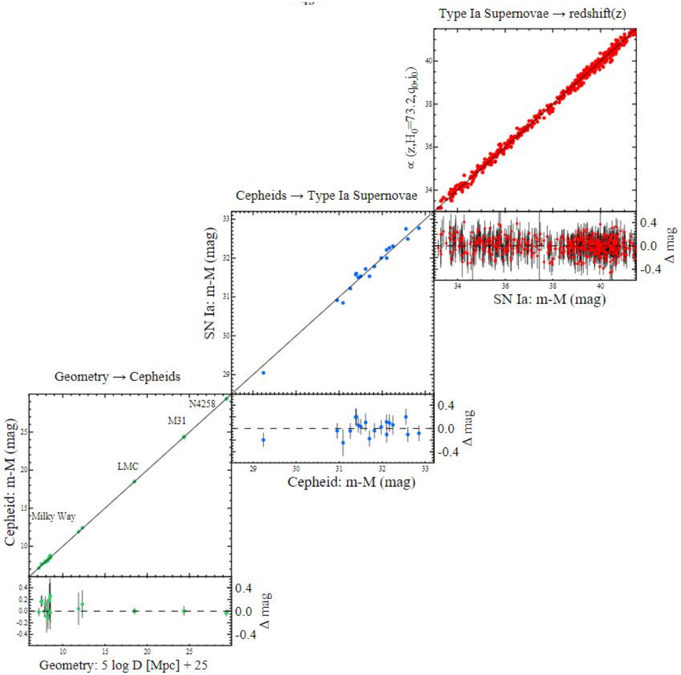
The cases of M31 and M33



De Somma et al. 2025 ApJ

Cosmic distance Scale





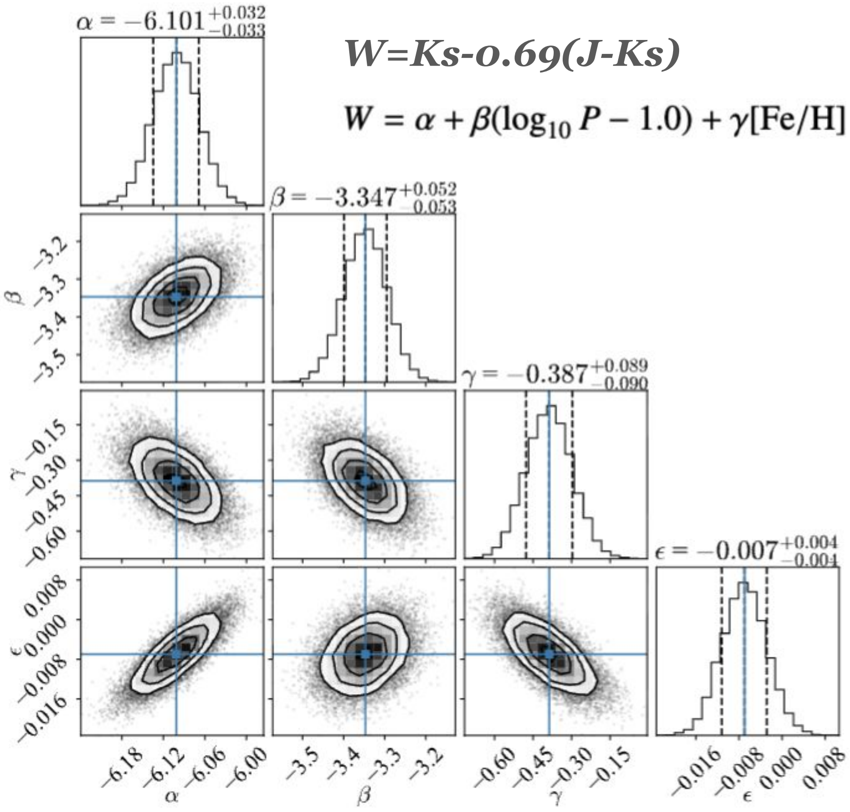
Identification and resolution of possible systematic errors in the first rung through:

- Properties and reliability as standard candles using theoretical pulsational models (calibration of known relationships and identification of new relationships, dependence on metallicity)
- Empirical and theoretical tests based both on models and on the use of photometric and spectroscopic surveys
- Use of parallaxes from Gaia DR3 → DR4

Significant impact expected in the near future with the **Rubin-LSST survey**, which will allow going 5 magnitudes deeper than Gaia and extend the results obtained and being obtained with Gaia in the Milky Way to the Local Group, along with those from **JWST and ELT**"

Cosmic distance scale: metallicity dependence of Cepheid's Leavitt-Law

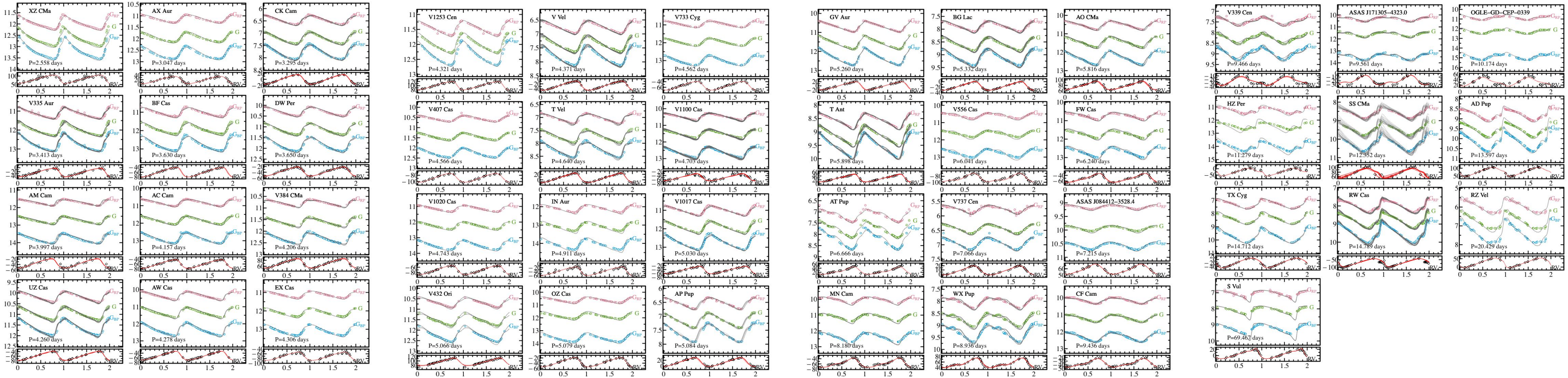
- Reduce uncertainties in the cosmic distance ladder by precisely calibrating the effect of metal content (metallicity) on the period-luminosity relationship of Classical Cepheids (C-MetaLL project).
- Using the largest and most homogeneous spectroscopic sample to date (290 stars), we applied a robust Bayesian photometric parallax technique to simultaneously fit period, metallicity, and ***Gaia*** parallax zero-point correction.
- The study finds a stronger metallicity dependence (ɣ~ -0.5 mag/dex in optical and -0.4 mag/dex in near-infrared) than previously reported.
- If confirmed, the value of H0 would be reduced by 1-2%, slightly reducing the amount of the Hubble tension.



Ripepi et al. 2025

Light and radial velocity curve model fitting for Galactic Cepheids in the Gaia database

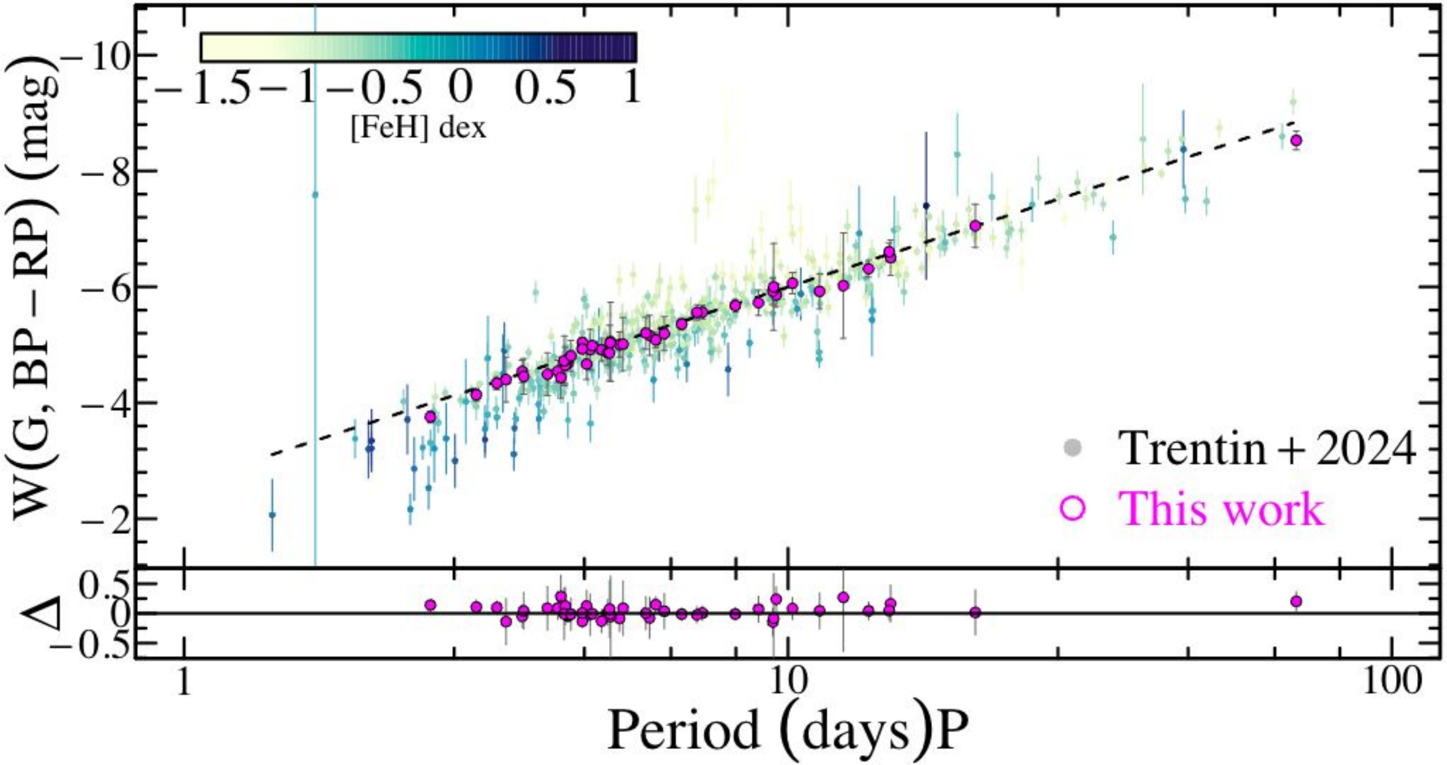
Molinaro et al. 2025 A&A



→ Masses, luminosities, effective temperatures, mean magnitudes and colors, distances (!)

The inferred PW relation: theory versus observations.

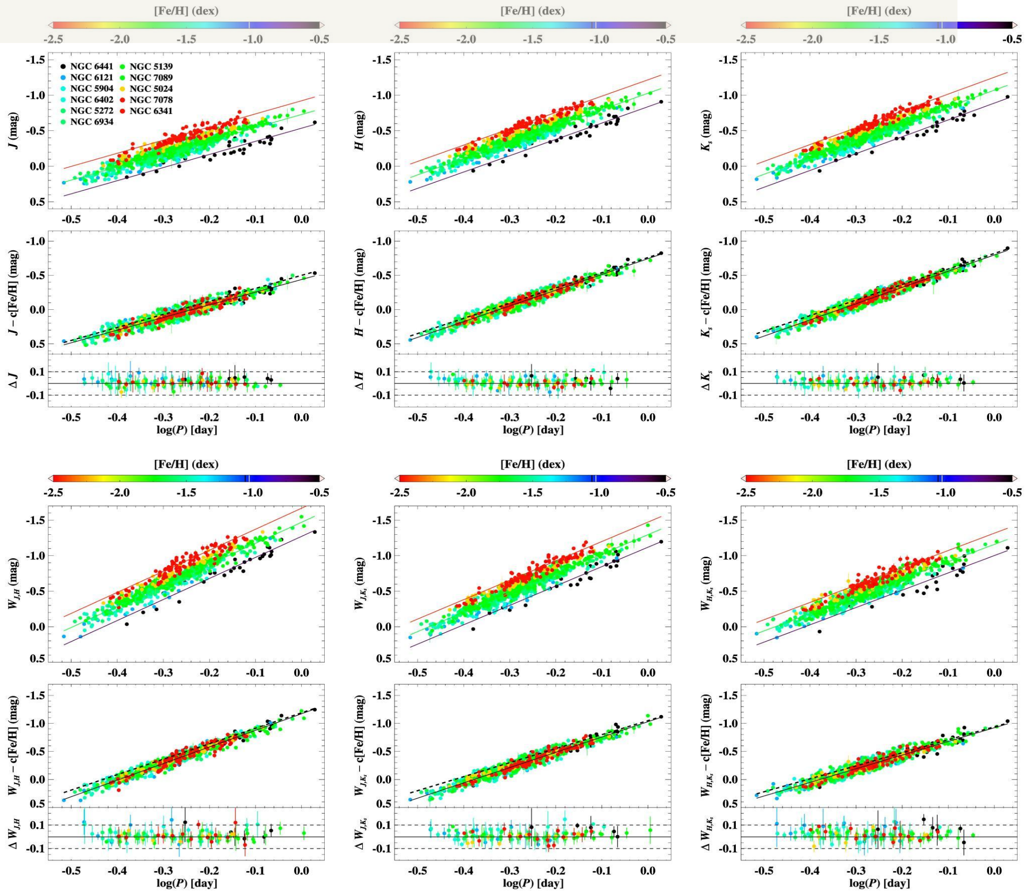
Molinaro et al. 2025 A&A



PLZ and PWZ relations for RRL: theory versus observations

Bhardwaj+ 2023 MNRAS

The lines are the theoretical relations by Marconi et al. 2015 ApJS



TRANSIENTS: LINKING ALL MAJOR FIELDS OF MODERN ASTROPHYSICS

EXPLOSIVE PHENOMENA & COMPACT OBJECTS

- Explosive & transient events (**SNe, GRBs, FRBs, Novae, Kilonovae**)
- Physics of compact objects (**BHs, NSs, WDs** & their merging)

GALACTIC EVOLUTION & FEEDBACK

- Metal Enrichment (**Galaxies Nucleosynthesis**)
- Energy Injection (**Feedback on ISM & CGM**)
- Tracers of Star Formation Rates (SFRs)
- **Evolution of stellar Populations and Galaxies**

COSMOLOGY & FUNDAMENTAL PHYSICS

- Distance Indicators & Tracers of Cosmological Models
- Cosmology, **Dark Energy**, **Dark Matter**

MULTIMESSENGER & HIGH-ENERGY PROBES

- Multimessenger Sources (**neutrinos and GWs**)
- Bright Background Sources (**CBM/IGM studies**)
- Cosmic Rays (**SN Remnants**)

TRANSIENTS: ELDS
OF MODERN A

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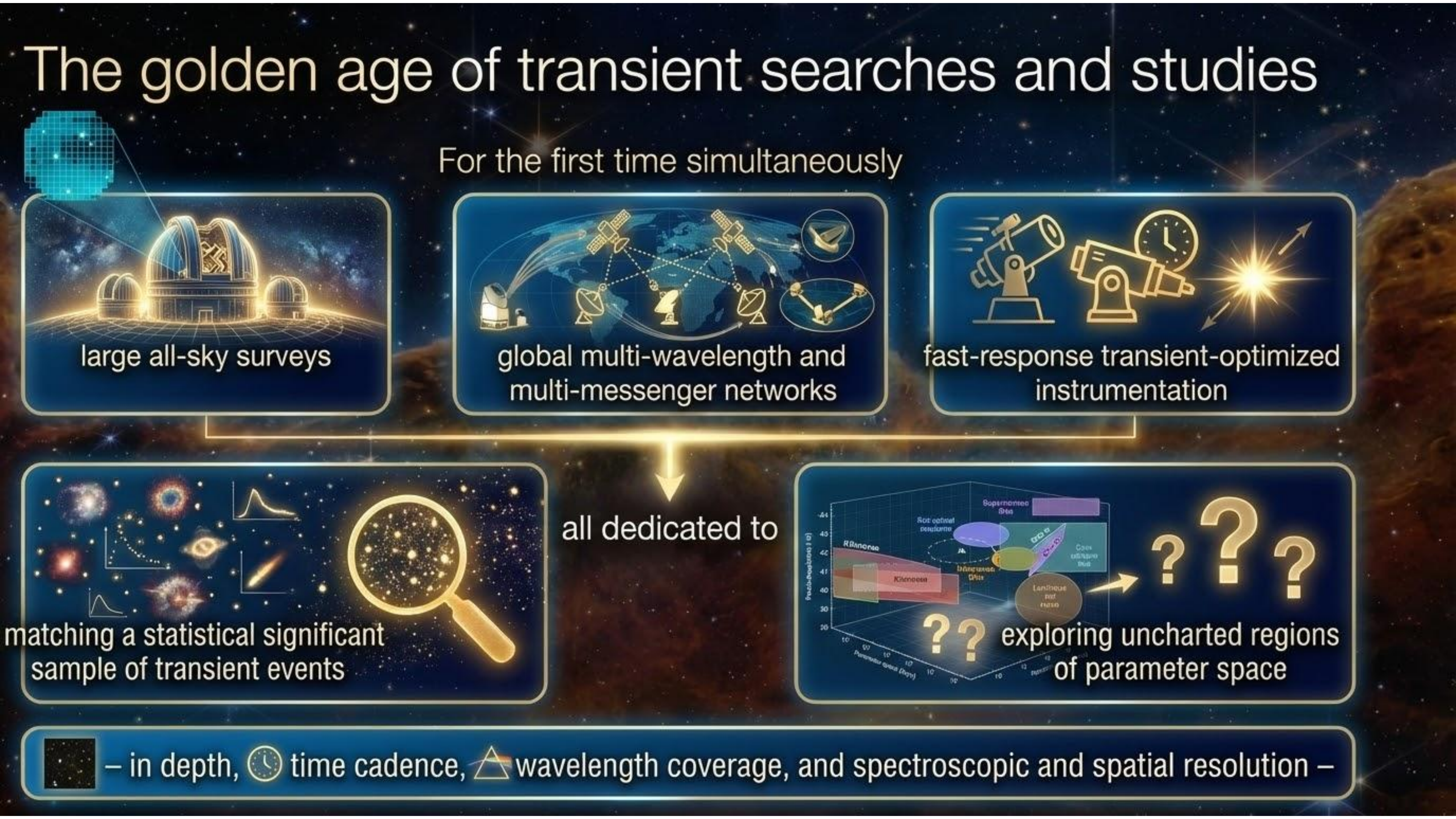
cross-cutting RSN2 RSN4


The golden age of transient searches and studies
For the first time simultaneously
large all-sky surveys
global multi-wavelength and multi-messenger networks
fast-response transient-optimized instrumentation
all dedicated to
matching a statistical significant sample of transient events
exploring uncharted regions of parameter space
– in depth, time cadence, wavelength coverage, and spectroscopic and spatial resolution –

SN progenitors and their variability

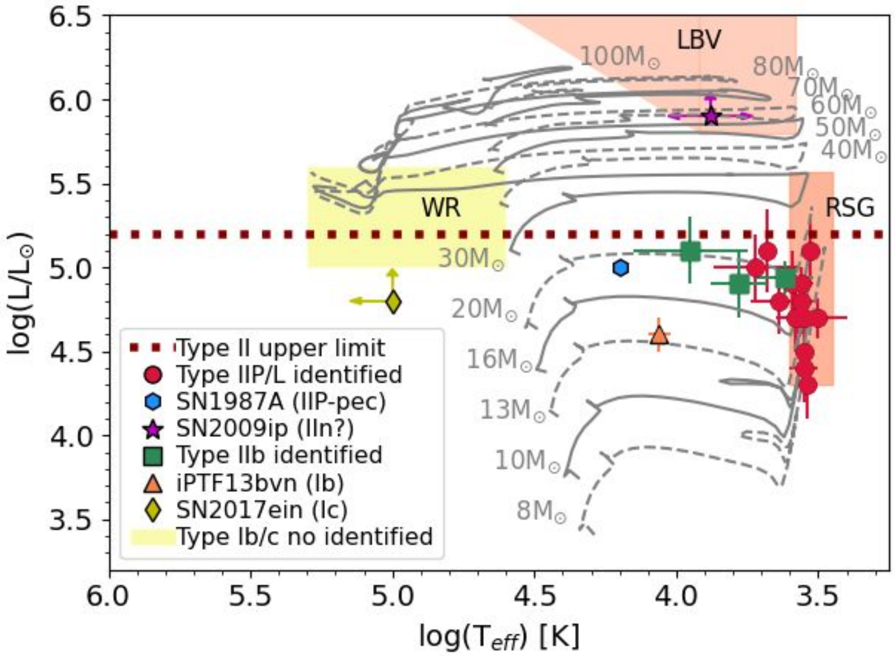
various transient events

connect

star properties and evolution

discovery + understanding = progress

observations



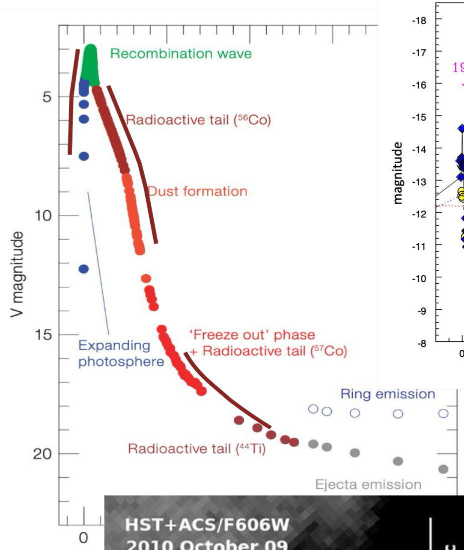
Proceeding Lorent Center, Elias-Rosa 2018 = Serenelli et al. 2020
https://sngroup.oapd.inaf.it/progenitors.html

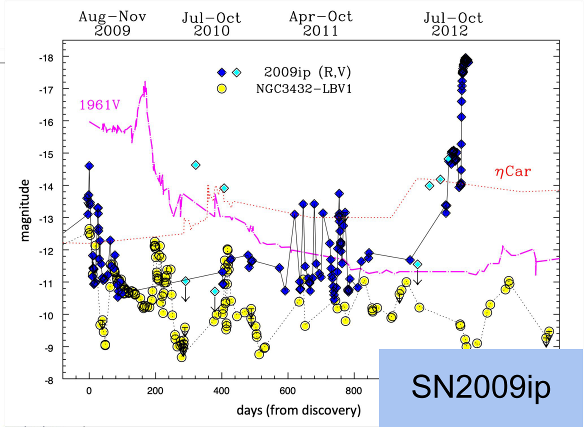
SN progenitors and their variability

How?

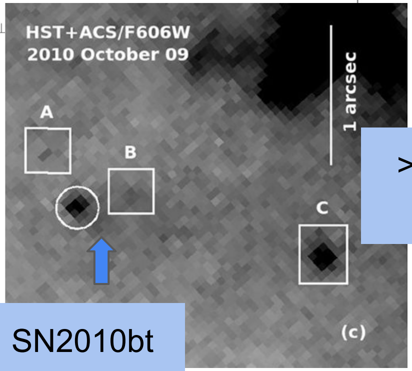
➡ Indirect evidences from:
- light curves and spectral evolution
- over-time history
- local SN environments
- multi-wavelength observations

➡ Search science archives for optical and IR pre-explosion images





SN2009ip



> 50 M☉ star in outburst

SN2010bt

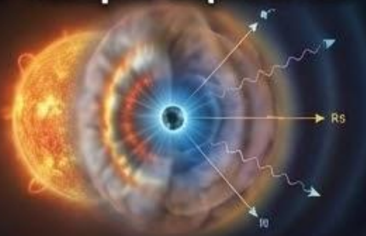
Leibundgut & Suntzeff 1991; Pastorello+ 2013; Elias-Rosa+ 2018
https://sngroup.oapd.inaf.it/progenitors.html

Main Science Cases

Thermonuclear Supernovae

- Distinguish between single-degenerate and double-degenerate channels.
- Identify the role of sub-Chandrasekhar vs Chandrasekhar-mass explosions.
- Test explosion models.
- Search for neutrinos and gravitational waves from WD mergers.

Core-Collapse Supernovae



- Early optical emission probes shock breakout, progenitor radius, envelope structure, and explosion energetics, temporally overlapping with neutrino bursts and potential GW emission from core-collapse and accretion onto newborn NS and BH.

Pair Instability Supernovae

- Constrain the initial mass function (IMF) of Population III stars
- Explain the upper mass gap in black hole masses
- Study radiative + mechanical feedback in first galaxies
- Impact on subsequent star formation and reionization.

Kilonovae and Compact-Object Mergers

- The earliest optical rise traces cocoon emission, ejecta geometry, and r-process nucleosynthesis at the moment of merger,
- providing the electromagnetic anchor for GW and neutrino signals, including sub-threshold events.

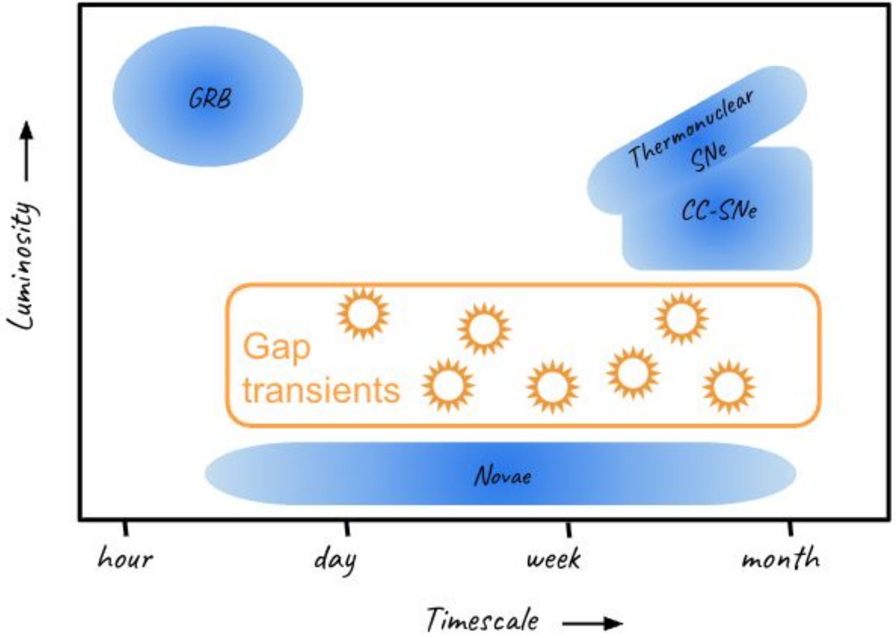
Gamma-Ray Bursts, Fast radio bursts and Relativistic Engines

- jet launching, cocoon expansion, and the connection between accretion history and relativistic outflows, before later afterglow phases dominate.

Fast and Failed Transients

- Rapidly evolving novae, fast blue optical transients, and "failed supernovae" (direct collapse to black holes).

Gap transients



-10 mag < M_v < -15 mag

Include:

- Major LBV eruptions (Eta-Car, SN2000ch, 2009ip-like in 2009-2012)
- Isolated major stellar outbursts
- Long-lasting stellar eruptions (S Dor variability)
- Stellar mergers (Luminous Red Novae)
- Candidate Electron Capture SNe (Intermediate Luminosity Red Transients)

https://graspa.oapd.inaf.it/gap.html

MAIN GOALS

SURVEY SYNERGY & DATA COLLECTION

- Enhance synergies across multiple surveys.
- Collect large samples of transients spanning a wide range of redshifts and multiple wavelengths.
- Cross-match transients detected in the same sky fields by different surveys.

ANALYSIS & DISCOVERY

- Enable the discovery of rare transients.
- Constrain the nature of transient progenitors.
- Investigate the physical properties of previously unknown classes of transients.

BROADER SCIENCE & TOOLS

- Support cosmological studies.
- Utilize transients as probes of the cosmic SFH.
- Develop advanced tools for photometric and spectroscopic classification.
- Build a robust training dataset for machine-learning–based classification methods.

MULTI-MESSENGER COUNTERPARTS

- Search for electromagnetic counterparts associated with neutrino and/or GW signals.

GROUND BASED AND SPACE INSTRUMENTATION

EUCLID

to detect transients at high redshift or intrinsically very faint

LSST (VERA RUBIN OBSERVATORY)

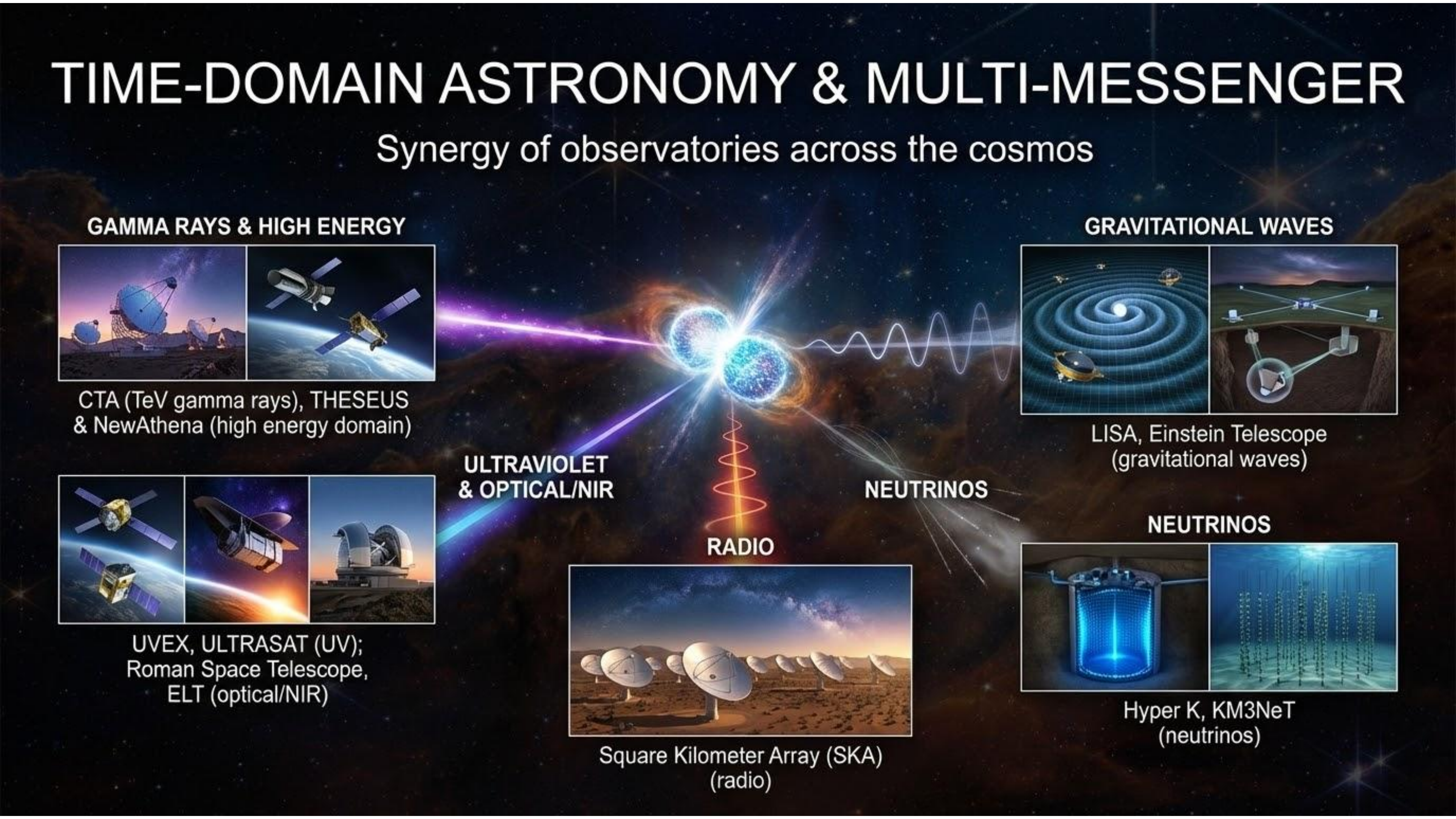
to collect a large number of events and discover rare transients

VST

to support the other surveys and obtain well sampled light curves

SOXS & LBT

to classify transients and collect a training set for photometric classification


TIME-DOMAIN ASTRONOMY & MULTI-MESSENGER
Synergy of observatories across the cosmos
GAMMA RAYS & HIGH ENERGY
CTA (TeV gamma rays), THESEUS & NewAthena (high energy domain)
ULTRAVIOLET & OPTICAL/NIR
UVEX, ULTRASAT (UV); Roman Space Telescope, ELT (optical/NIR)
RADIO
Square Kilometer Array (SKA) (radio)
NEUTRINOS
GRAVITATIONAL WAVES
LISA, Einstein Telescope (gravitational waves)
NEUTRINOS
Hyper K, KM3NeT (neutrinos)