Young Stellar Populations in the Milky Way

The Next Frontier with GaiaNIR

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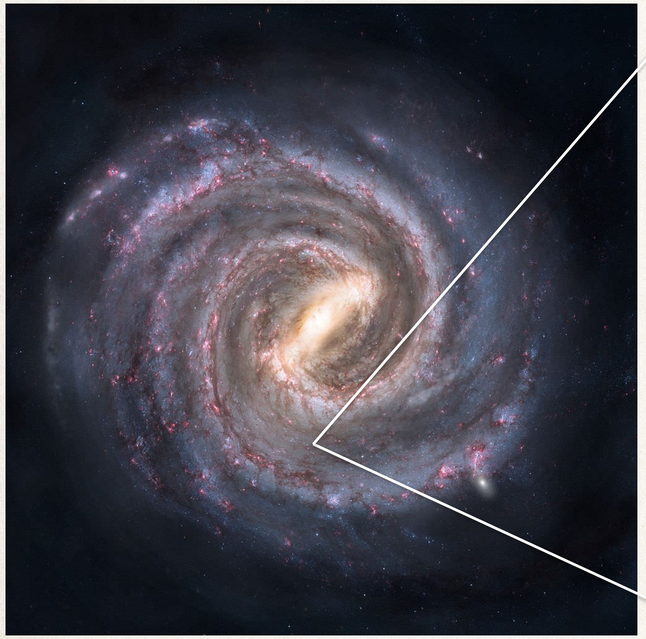


GaiaNIR slide content & simulation figures courtesy of David Hobbs (GaiaNIR PI)

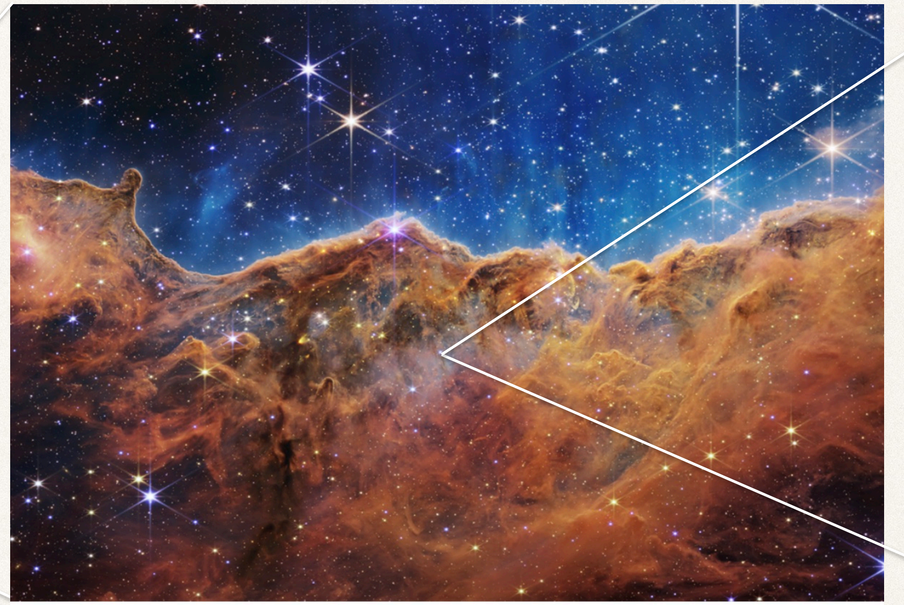
PIAZZI 200: New frontiers in astrometry, small bodies and technologies

October 2, 2026 - Palazzo Steri Palermo

Key questions:
few Myr old populations at three different spatial scales

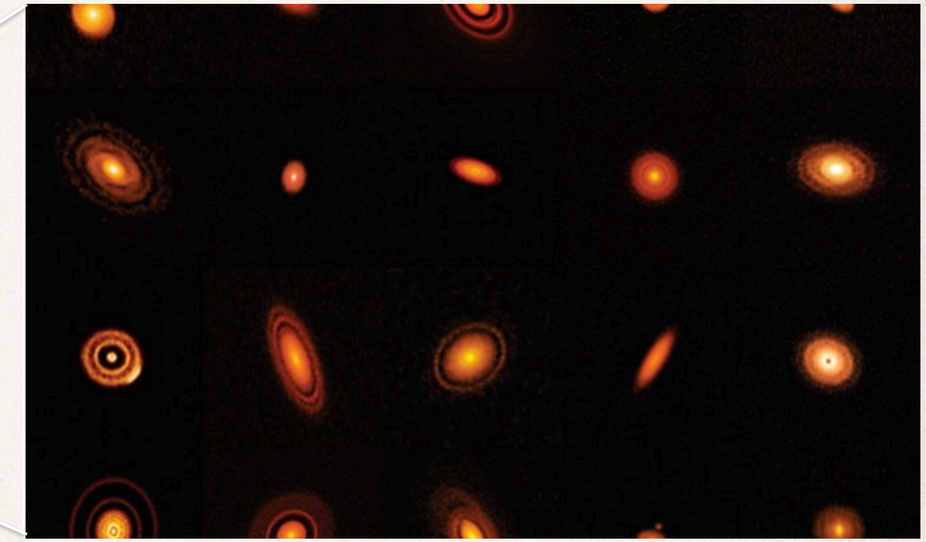


What are the **global properties** and **dynamics** of the youngest e**mbedded** stellar component of the Milky Way?



JWST NIRCam Image

How do physical mechanisms and **dynamics** drive **cluster formation**?

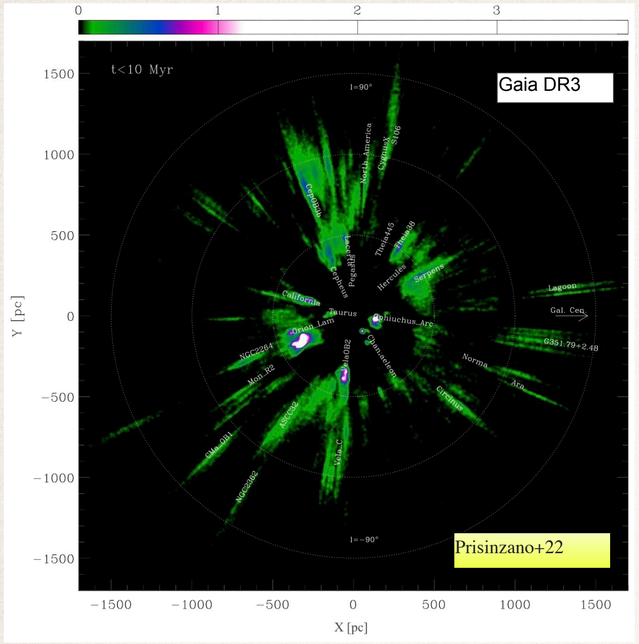


ALMA (ESO/NAOJ/NRAO), NRAO/AUI/NSF

Which physical mechanisms are involved in the formation of **individual stars and planets?**

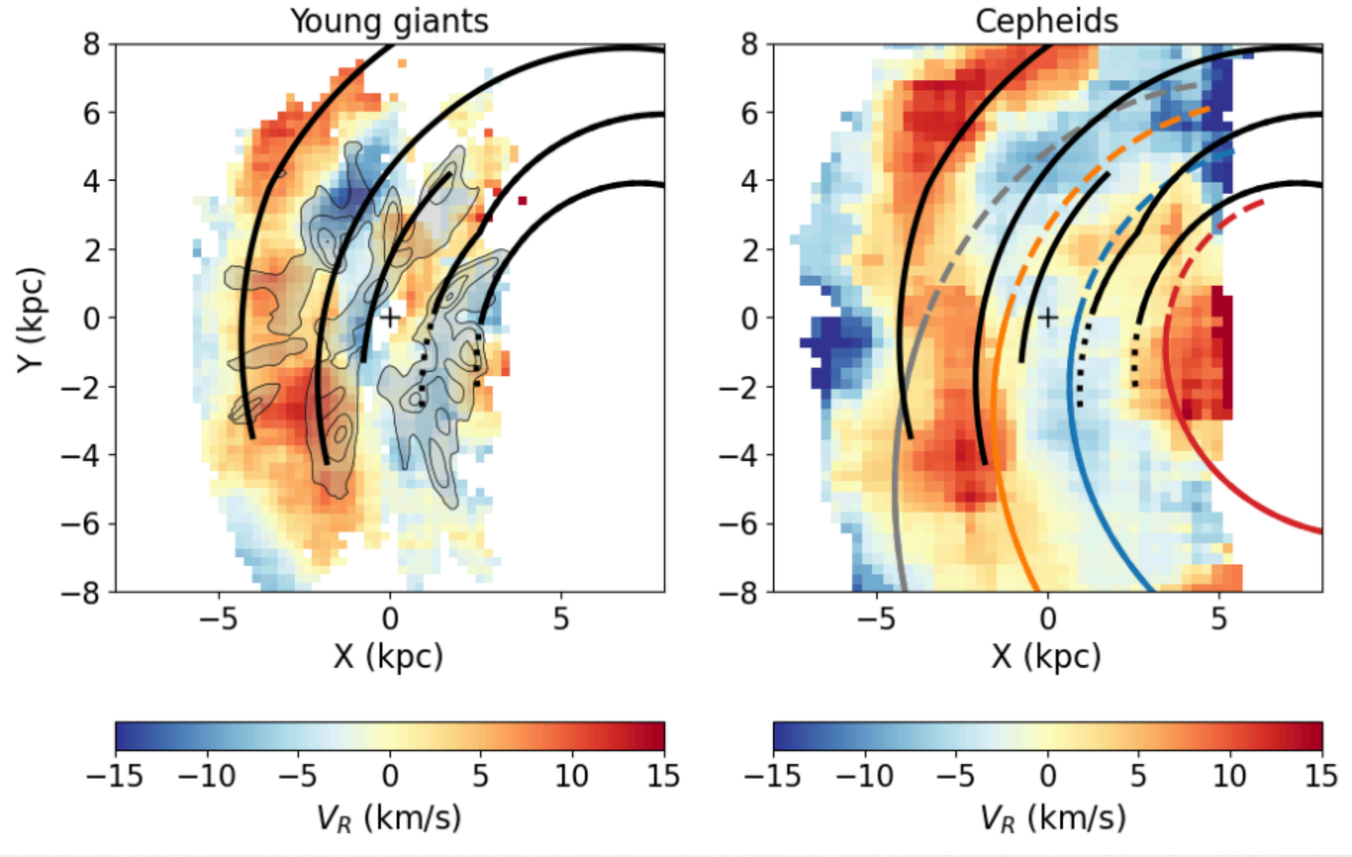
Why Map Embedded Young Stellar Populations?

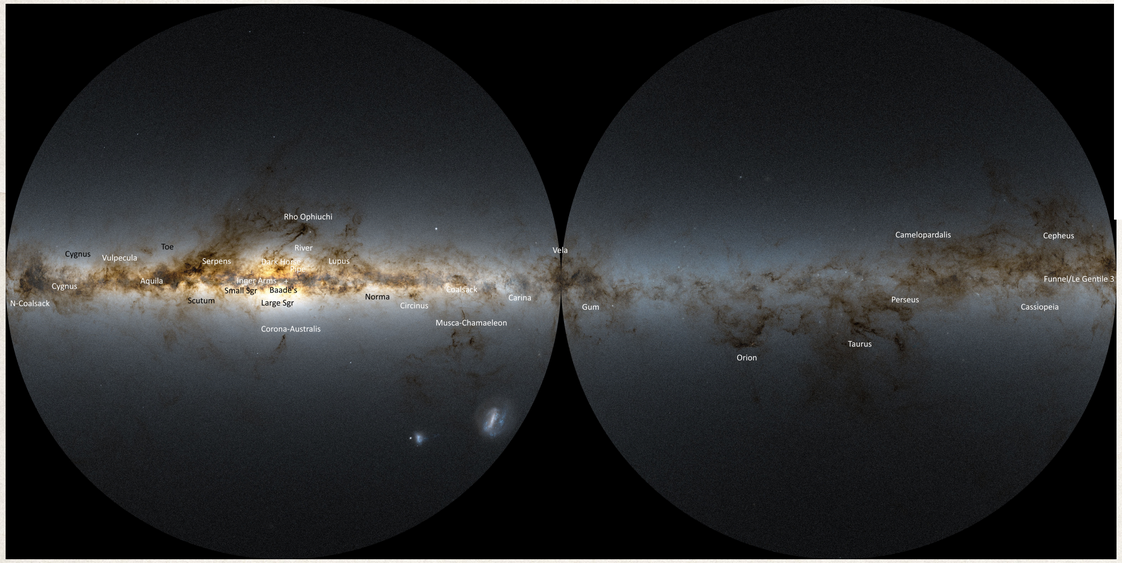
Poggio+25



Gaia heritage:

- local spiral structures and clusters within a few kpcs
- hints of a large-scale vertical corrugation propagating outwards in the MW (**Poggio+25**)





MW as seen by Gaia: **bright** regions show dense **star clouds**
dark features are massive **dust clouds**

- **Build a Dynamical Model of the MW**
- **Uncover Large-Scale Structures**
- **Discover Large-Scale Dynamics**

IR observations are needed!

2000: The IR revolution started with 2MASS



76 new discovered embedded clusters in 2003
(15 yrs of IR observations & $K_{lim} \lesssim 14$, **Lada & Lada 2003**)

- embedded clusters birthrate is ~10 times the open clusters birthrate ➡ **high infant mortality rate of proto-clusters**

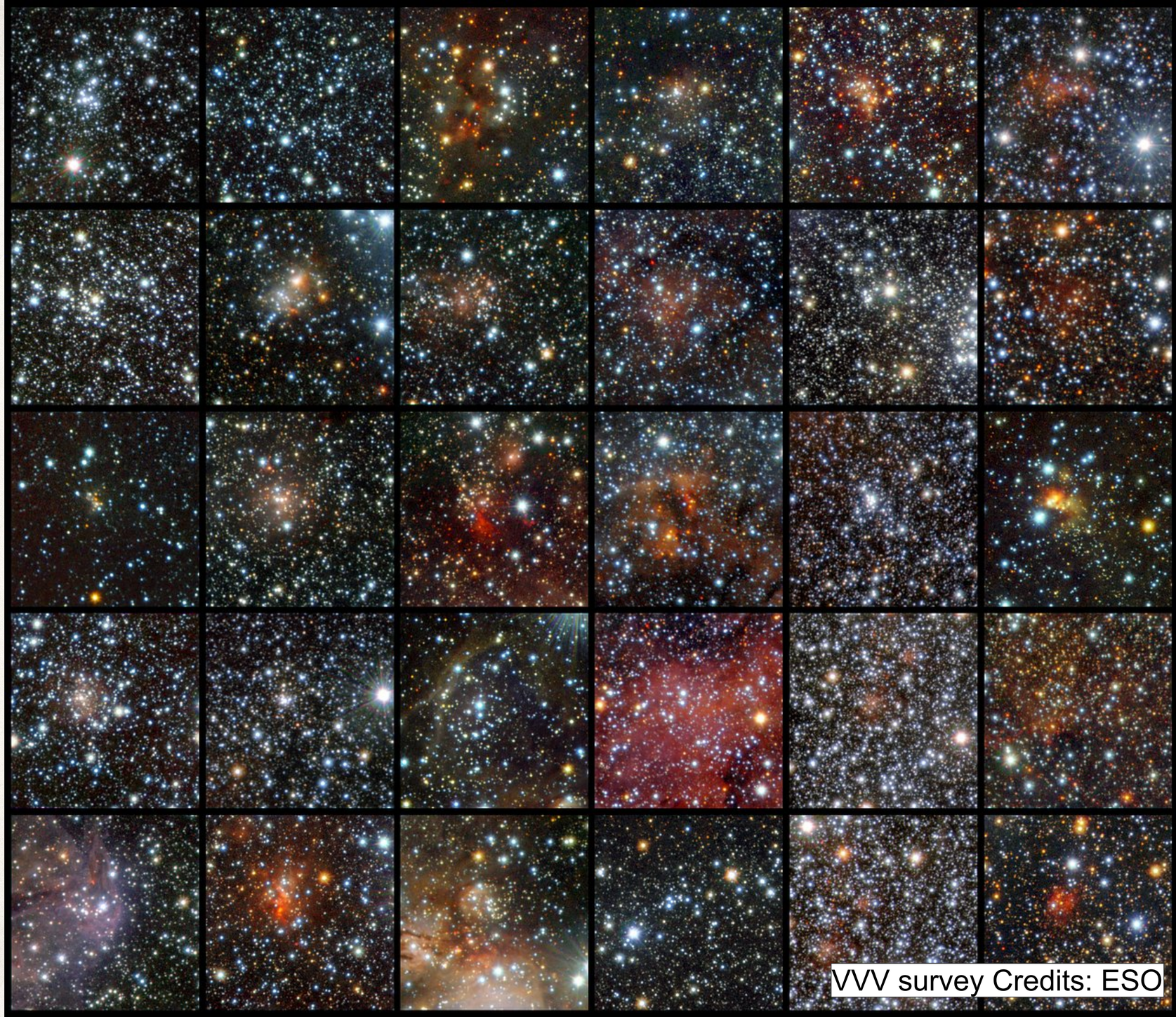
- for more than 20 embedded clusters only 1 evolve in a Pleiades like system

Embedded Clusters: Dynamics at Birth

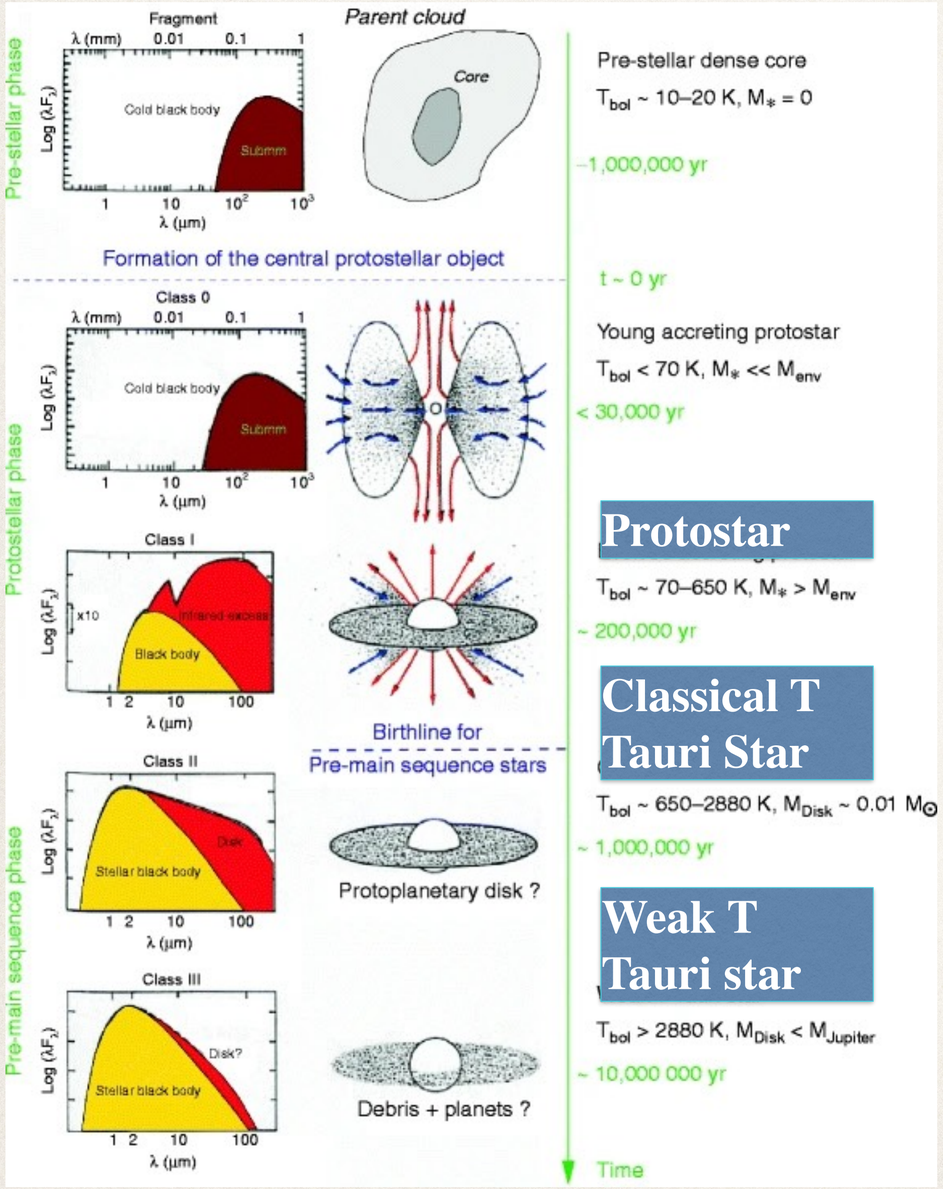
2010s: VVV@VISTA
deep photometry K_{lim}=18
+96 Embedded Star Clusters

2020s: Gaia DR3 high precision astrometry
(e.g. Castro-Ginard+21, Hunt+23, Hunt+26)

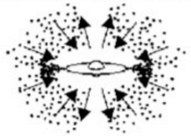
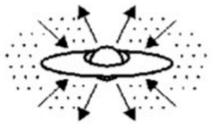
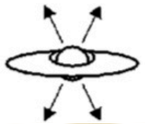
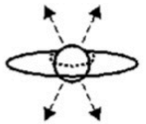
a combination of the two would revolutionise our understanding of cluster formation



A revolution for low mass Young Stellar Objects



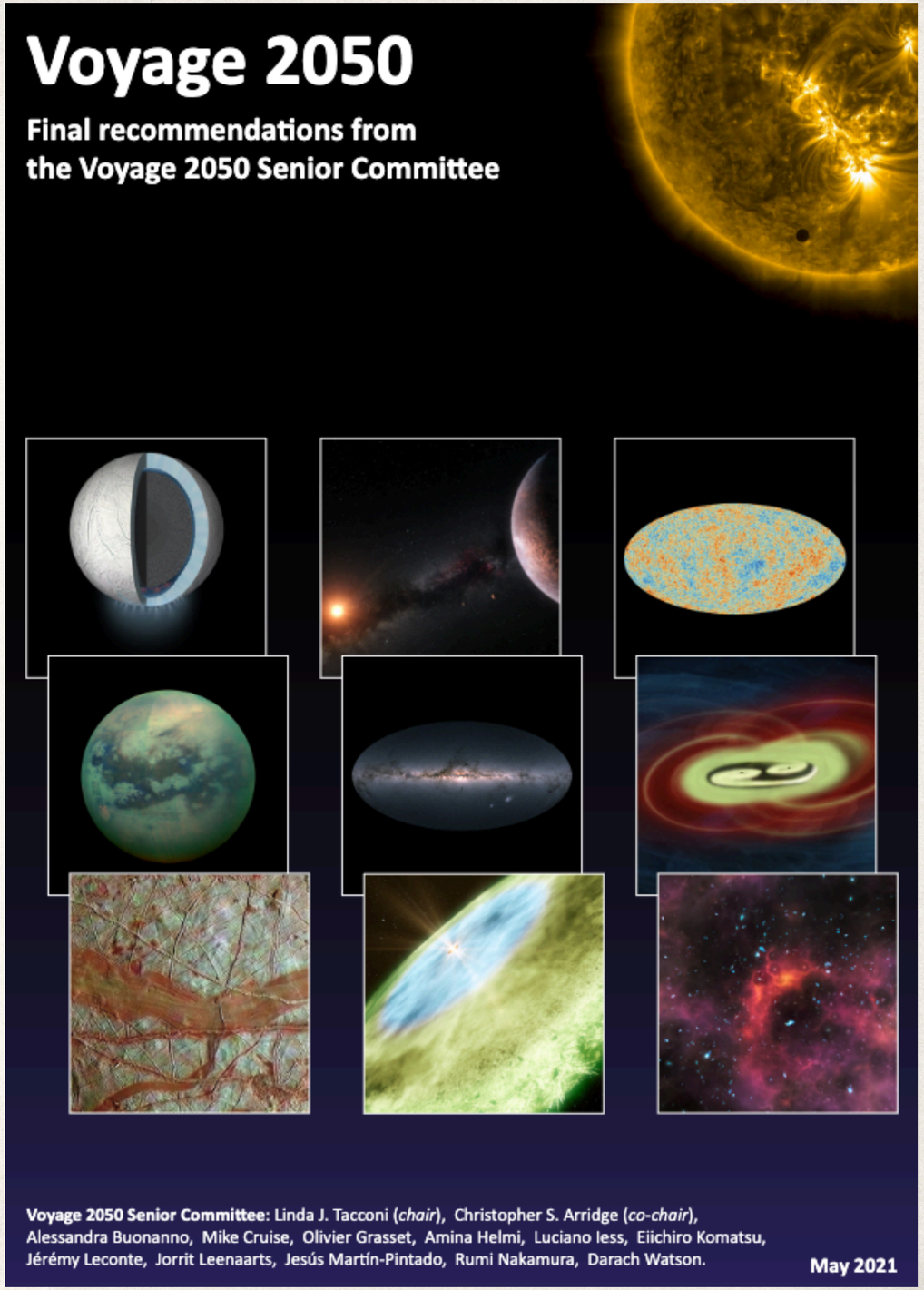
Spectral classification of embedded stars (André 2011)

PROPERTIES	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
SKETCH					
AGE (YEARS)	10^4	10^5	10^6 - 10^7	10^6 - 10^7	> 10^7
mm/INFRARED CLASS	Class 0	Class I	Class II	Class III	(Class III)
DISK	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-RAY	?	Yes	Strong	Strong	Weak
THERMAL RADIO	Yes	Yes	Yes	No	No
NON-THERMAL RADIO	No	Yes	No ?	Yes	Yes

Stages of YSO evolution (Feigelson & Montmerle 1999)

The GaiaNIR project

- 2016: **ESA Call for New Science ideas**
- 2018: ESA Concurrent Design Facility study
- 2019: White paper to ESA's Voyage 2050: *All-Sky Visible and Near Infrared Space Astrometry (Hobbs+19)*
- **2021: Voyage 2050** recommended theme: *"The Galactic Ecosystem with Astrometry in the Near-infrared"* for an **L-Class** ESA mission
- *2025:* ESA Ministerial Council: working on an ESA proposal for an **L-Class mission**



Core Mission Objectives

- **Probe the dynamically hidden region of our Galaxy**: going deeper into dust-obscured regions in the NIR.
- **A 40-Year Temporal Baseline:** Combining Gaia and GaiaNIR anchors >2.5 billion common stars across a 20-year mission gap, unlocking **extraordinary precision** for long-term **Proper Motions (PMs)**.
- **Securing the Reference Frame:** Arresting time-degradation of the Gaia catalogue and expanding the optical reference frame into the NIR using highly obscured quasars.

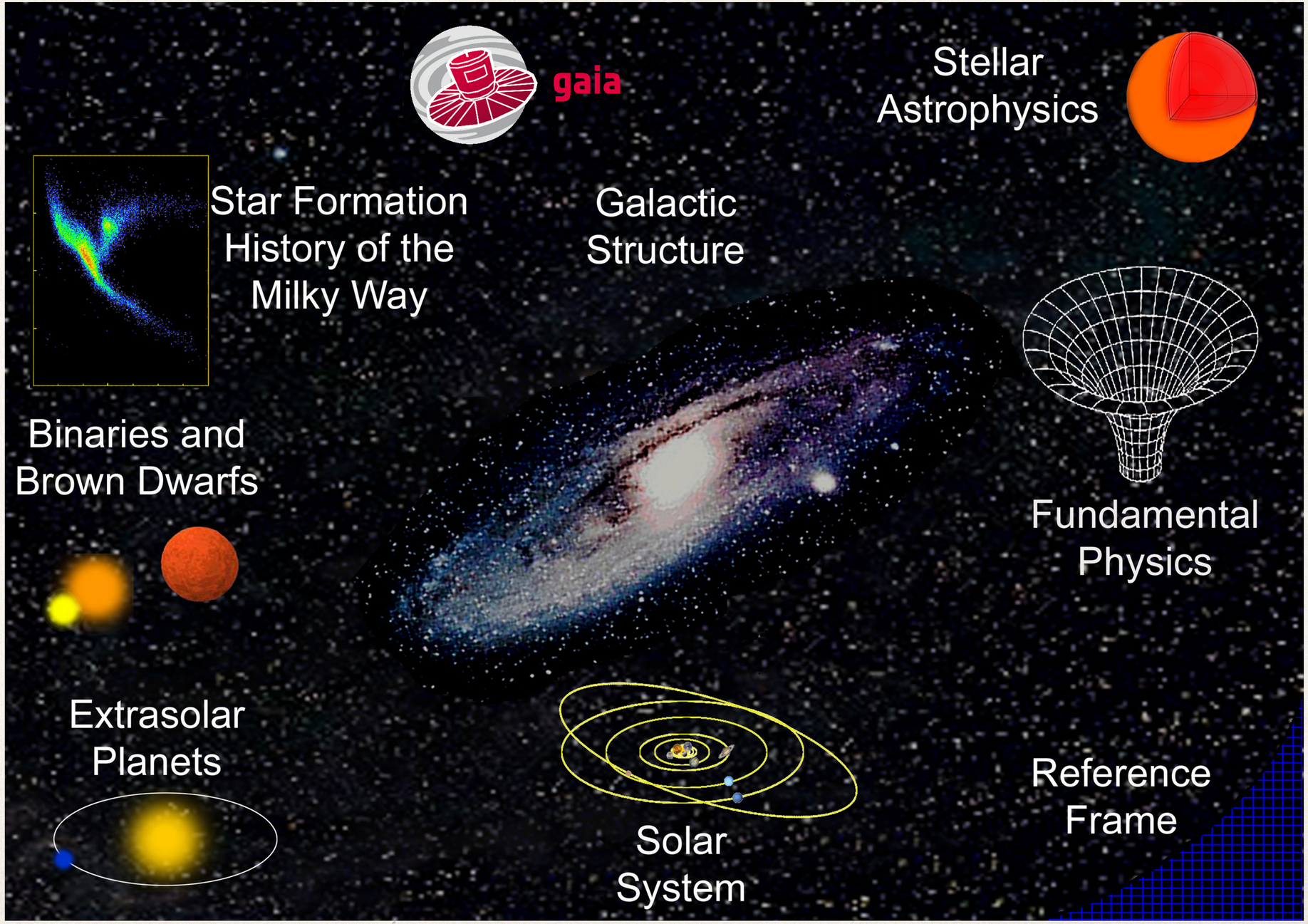




Gaia 10 years

10 years GaiaNir

From Gaia to GaiaNIR: Science Cases



Courtesy of D. Hobbs

GaiaNIR Design

GaiaNIR$_{Large}$

M1

D = 1.7m

D = 1.7m

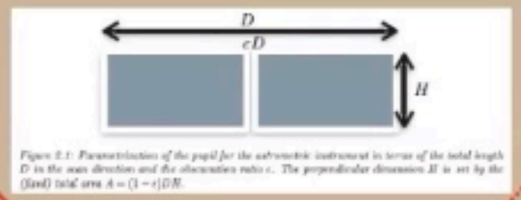


Figure 5.1: Parametrisation of the pupil for the astrometric instrument in terms of the total length D in the scan direction and the obscuration ratio ϵ. The perpendicular dimension H is set by the (fixed) total area $A = (1-\epsilon)DH$.

Mission	Resolution
Gaia (λ_{mid}=700nm)	0.12" with D=1.45m
GaiaNIR$_{Medium}$ (λ_{mid}=1550nm)	0.24" with D=1.7m
GaiaNIR$_{Large}$ (λ_{mid}=1550nm)	0.11" with D=3.5m

BA

Two Improvements:

GaiaNIR$_{Medium}$
double the hight of the primary and BA mirrors

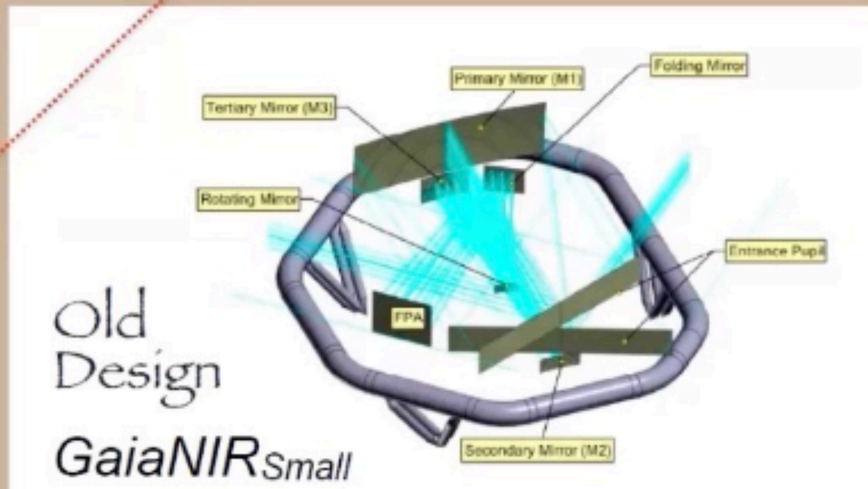
GaiaNIR$_{Large}$
double the width of the primary as a segmented mirror

The resolution and parallax errors are inversely proportional to the length of the primary mirror D_{max}

$$\sigma_{\varpi} \propto \frac{\lambda}{D\sqrt{N}\sin\xi}$$

D_{max} = 3.5m

Aim for launch on Ariane 6



Old Design

GaiaNIR$_{Small}$

Figure 5-34: GaiaNIR optical surfaces and the light path

Detector Challenge: High-Speed Avalanche Photodiodes (LmAPDs)

Problem 1: Time Delay Integration (TDI)

- GAIA: due to the rotation, the detector electronically shifts its accumulated charge at the exact same speed as the star's image moves across the focal plane.
- In GaiaNIR the TDI mode would introduce **excessive read noise**

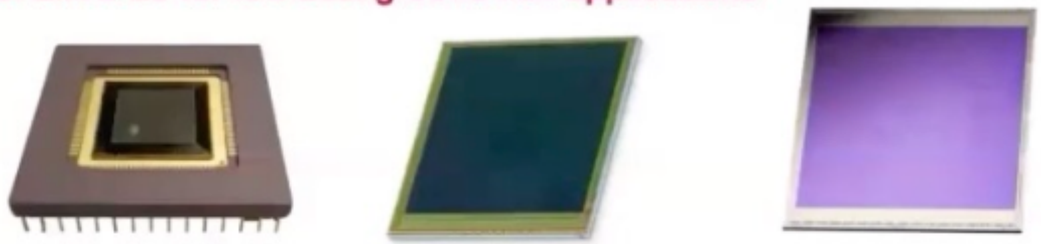
Problem 2: Sensitivity & Thermal Background

Wavelength range: 800–2300 nm cutoff and cryogenic cooling.

Technological Solution: LmAPDs

- Leonardo UK Linear-mode Avalanche Photodiodes: tests currently ongoing in the UK
- Provides internal avalanche **gain >100x.**
- **Saphira-type** detector selected for ultra-fast readout compatibility.

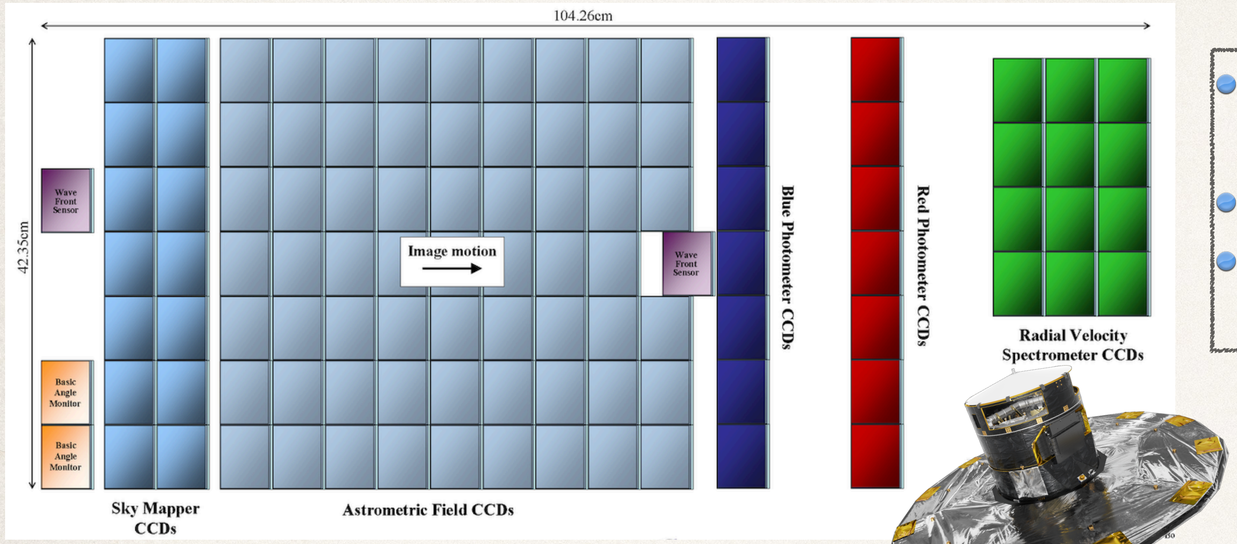
Update of LmAPDs for low background flux applications



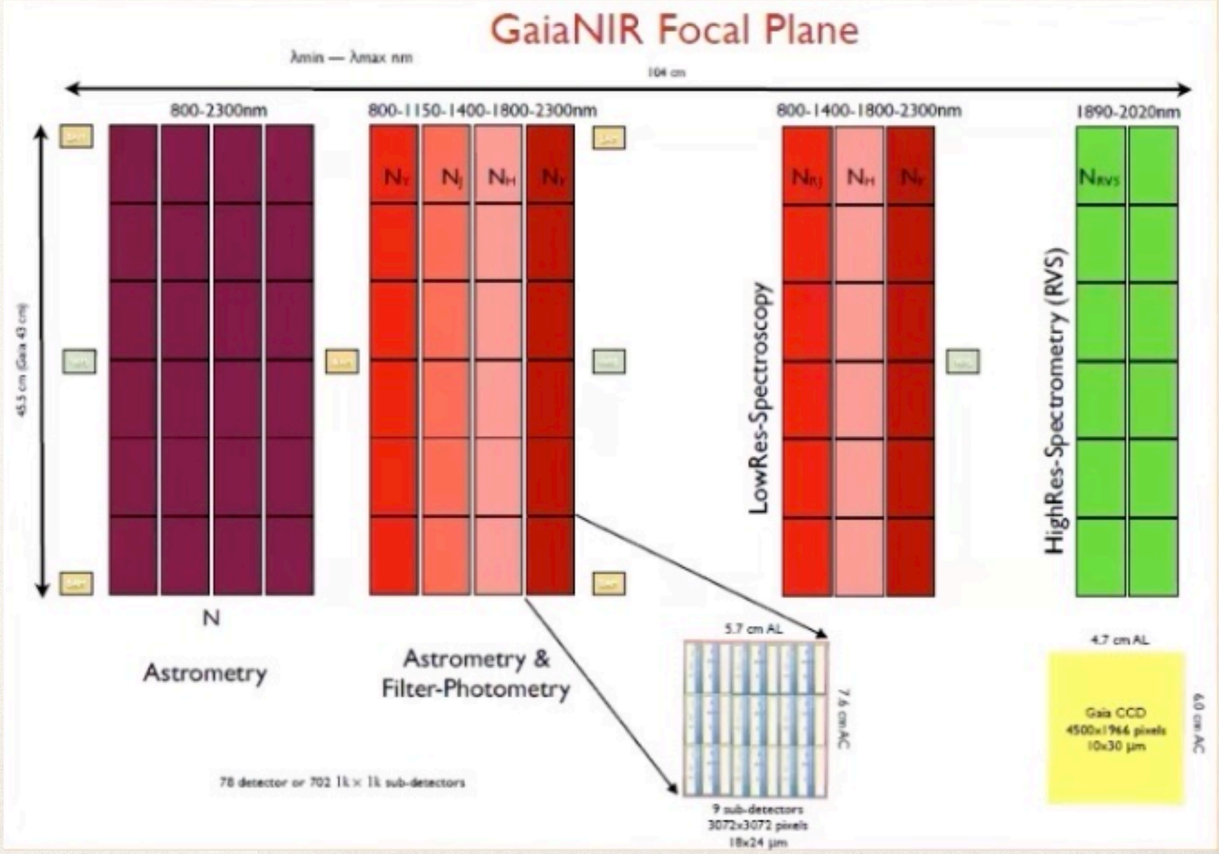
	Large Saphira	Ike-Pono	IBEX
Dimensions	512x512/24µm	1024x1024/15µm	2048x2048/15µm
Status	Detectors provided to consortium partners for evaluation and system development.	First science grade devices under assessment – see **Charles-Antoine** itails.	Prototype arrays manufactured
Collaborator	ESO, Max Planck and NCR	NASA APRA ROSES, University of Hawai'i	ESA
Current Planned Uses	Wavefront sensing for extreme Adaptive Optics (AO) Over 2000 frames per second.	Extreme low dark current applications	Earth Observation

Focal Planes and Filters

Gaia Focal Plane



- **Larger Detectors:** Extended integration time per star to reach fainter targets.
- **Integrated Filters** deposited directly on the astrometric field.
- **Accurate colors** even in highly crowded Galactic plane regions.



Thermal & Field Design

- **Passive Cooling Strategy: at ~90 K to suppress thermal noise.**
- **No Sky Mappers**: Star tracking handled digitally across the focal plane.
- Integrated **Low-Res Spectroscopy & High-Res RVS**.

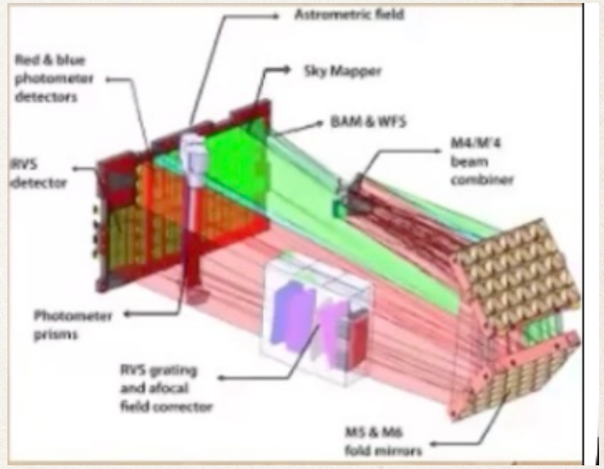
Spectroscopy & RVs: the 6D Galactic Map

The Science Drivers:

- **Chemistry:** Low-resolution spectra to trace the Milky Way's merger history.
- **6D Phase-Space Dynamics:** Radial Velocities (RVs) are critical for Galactic dynamics

How to Increase Survey Depth:

- **Slower Scan Rate:** Optimizing integration time for spectroscopic targets.
- **Wider Detectors:** Larger pixels naturally result in wider detectors, collecting more photons as the spacecraft rotates.
- **Ultra-Low Read Noise:** Modern APD detectors drastically reduce noise, pushing the depth limits.



Expected Yield: 50+ Billion Low-Dispersion Spectra | >1 Billion Radial Velocities

Astrometric accuracy

For Gaia DR5 after ~10 years
(assuming GaiaNIR has the same accuracy)

Gaia DR5 Position errors:

$\sigma_{\alpha*} = 0.8\sigma_\pi = 12.8\,\mu\text{as}$ $\sigma_\delta = 0.7\sigma_\pi = 11.2\,\mu\text{as}$

Gaia DR5 Proper motions errors:

$\sigma_{\mu\alpha*} = 0.29\sigma_\pi = 4.64\,\mu\text{as yr}^{-1}$ $\sigma_{\mu\delta} = 0.25\sigma_\pi = 4.00\,\mu\text{as yr}^{-1}$

The **combined uncertainty** with **ΔT = 20+5+5** is

$$\sigma_{\mu 0} = \frac{(\sigma_{posN}^2 + \sigma_{posG}^2)^{1/2}}{\Delta T}$$

When using a joint solution we get the weighted mean of all three measures.

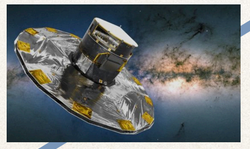
$\sigma_{\mu 0}$ is also independent as positions are independent in their respective catalogues

$$\sigma_\mu = (\sigma_{\mu 0}^{-2} + \sigma_{\mu N}^{-2} + \sigma_{\mu G}^{-2})^{-1/2}$$

$\sigma_{\mu\alpha*}$ = 0.59 μas yr^{-1}

$\sigma_{\mu\delta}$ = 0.52 μas yr^{-1}

2015



First Epoch Gaia 10yr (2020)

2025

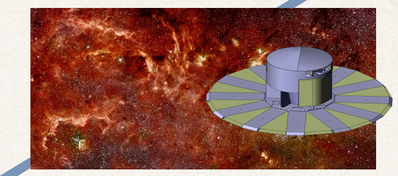
20 Year Gap

2045

Ignoring commissioning time the first crude (**~6 months**) Gaia-GaiaNIR catalogue would use $\sigma_{\mu 0}$ and data up to 2045.5

$\sigma_{\mu\alpha*}$ = 2.09 μas yr^{-1} $\sigma_{\mu\delta}$ = 1.83 μas yr^{-1}

2055



Second Epoch GaiaNIR 10yr (2050)

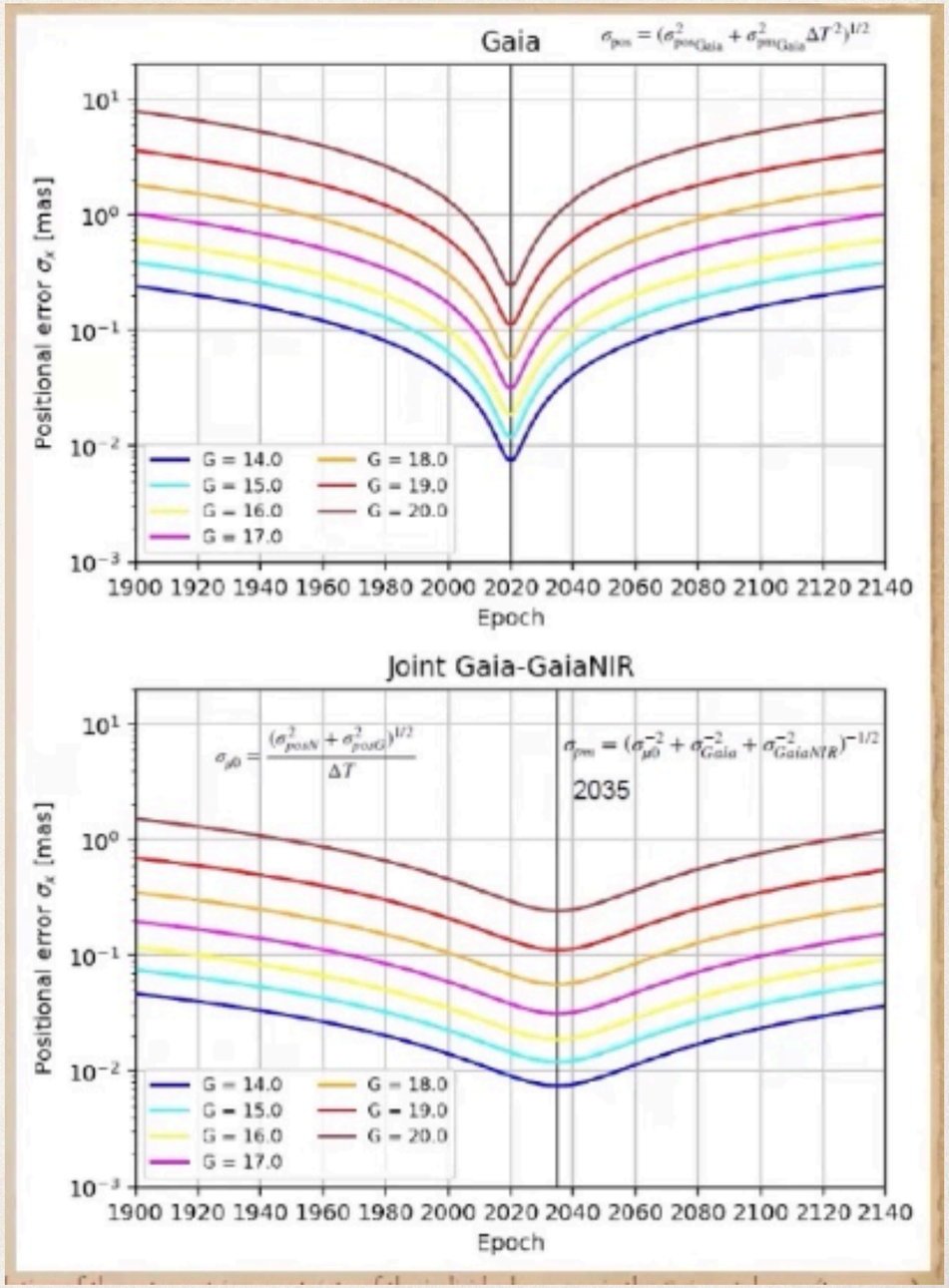
A factor of 21 times better for PM's compared to Gaia DR4 and a factor of 8 times better than Gaia DR5 giving **nano-arcsec** PMs for common stars

Mitigating Catalogue Aging: Gaia vs. Joint GaiaNIR Solution

The Degradation Problem: The Gaia catalogue is centered on reference epoch ~2020. Positional errors grow rapidly over time—degrading by **over 1 order of magnitude within 30 years**.

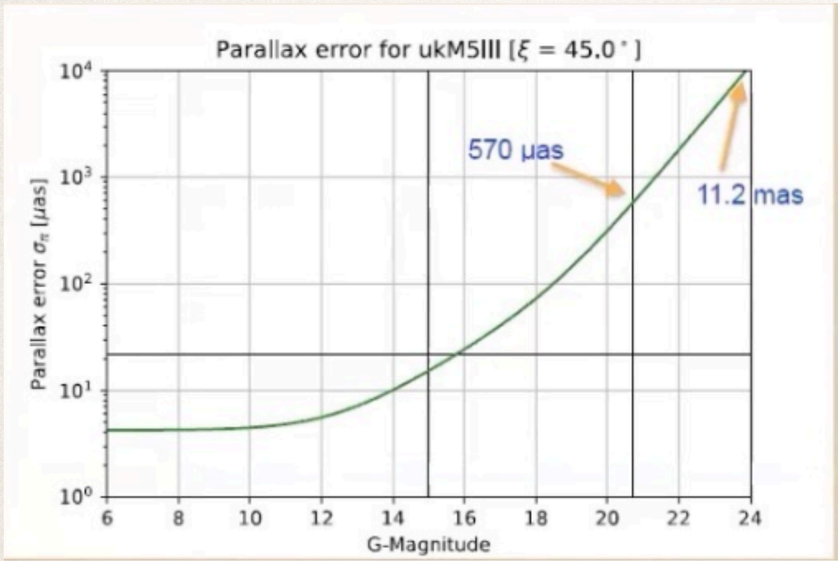
Flattening the Error Curves: Combining Gaia and GaiaNIR into a Joint Solution stabilizes the catalogue over long timescales, limiting degradation to **less than ~0.5 orders of magnitude over 100 years**.

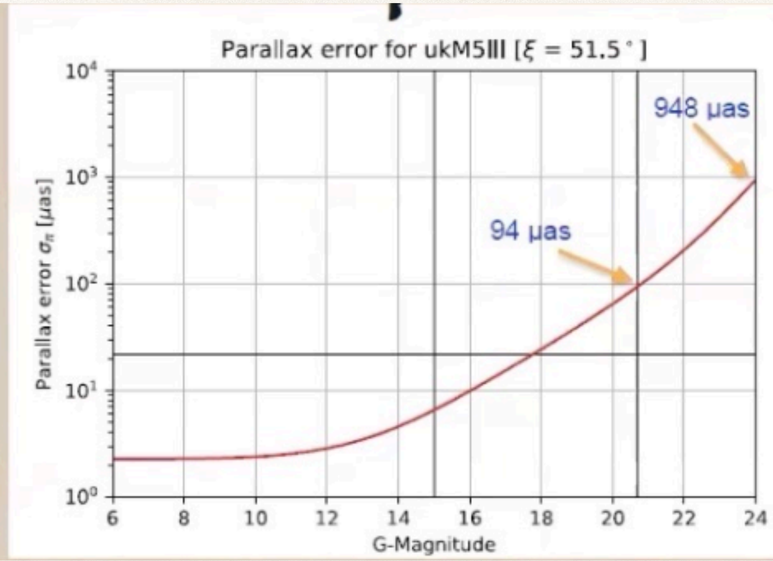
Long-Term Reference Frame: Future data can be continuously added to the joint solution to maintain ultra-precise astrometry and extend the Reference Frame deeper into obscured regions (e.g., unveiling galactic plane quasars).

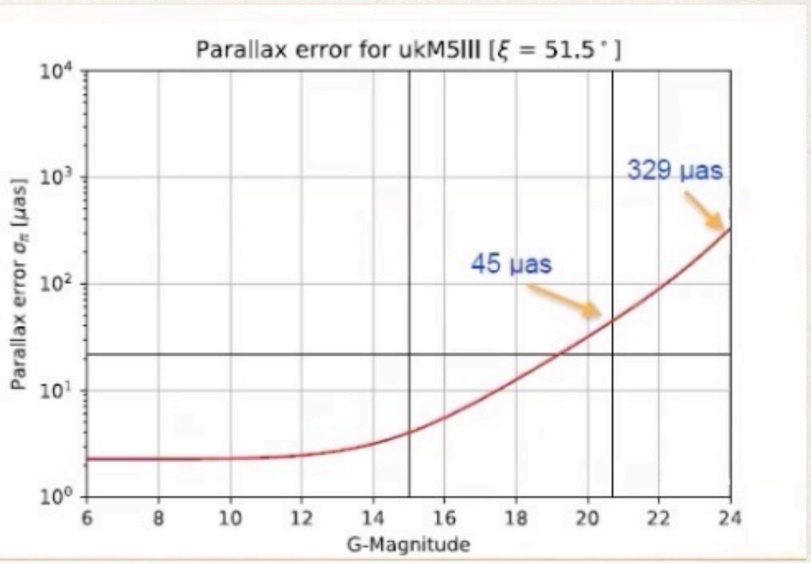


Parallax Precision: Gaia vs. GaiaNIR

10-Year mission simulations using synthetic spectra for M5III Red Giants







Gaia | $GaiaNIR_{Medium}$ | $GaiaNIR_{Large}$

Configuration	G ≈ 20.7 (Limit)	G = 24.0 (Faint End)	Error Growth
Gaia (Optical CCDs)	570 μas	11.2 mas	Exponential
GaiaNIR Medium	94 μas	948 μas	Log-Linear
GaiaNIR Large (Baseline)	**45 μas**	**329 μas**	**Log-Linear (>10x gain)**

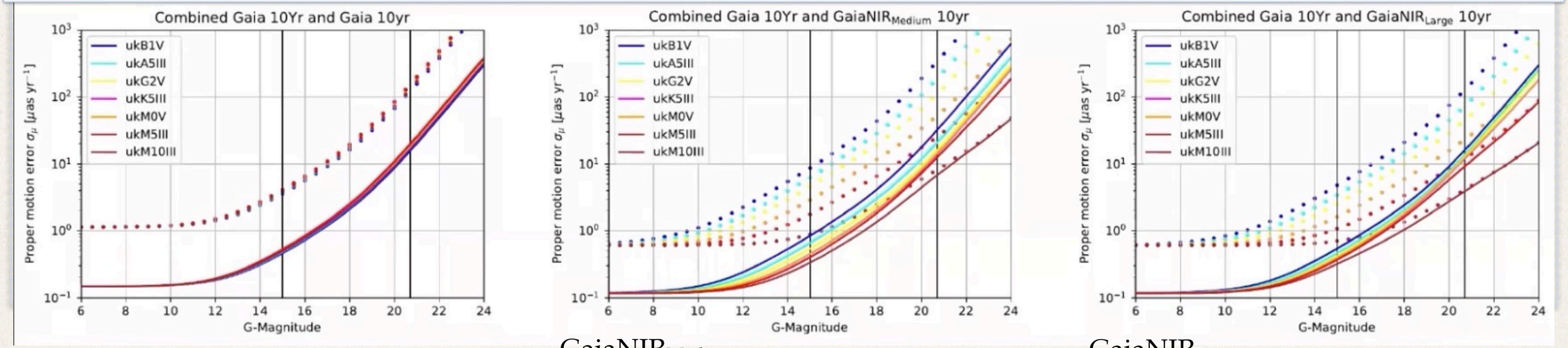
Key Takeaways

- Over >10x accuracy gain at the faint limit (G=20.7): from 570 μas down to 45 μas.
- Unlocks the faint Galactic population down to G=24 with 329 μas precision.
- Linear-mode APDs avoid the exponential noise growth typical of optical CCDs.

Joint Solution PMs: Gaia vs. GaiaNIR

Leveraging a ~30-year temporal baseline ΔT to achieve sub-microarcsecond proper motion precision

Dotted Lines = Single Mission | **Solid Lines = Combined Solution (Gaia + GaiaNIR)**



Gaia GaiaNIR$_{Medium}$ GaiaNIR$_{Large}$

Joint Astrometric Framework

Baseline Offset Precision:

$$\sigma_{\mu_0} = \frac{\left(\sigma^2_{\text{pos},N} + \sigma^2_{\text{pos},G}\right)^{1/2}}{\Delta T}$$

Combined Proper Motion Uncertainty:

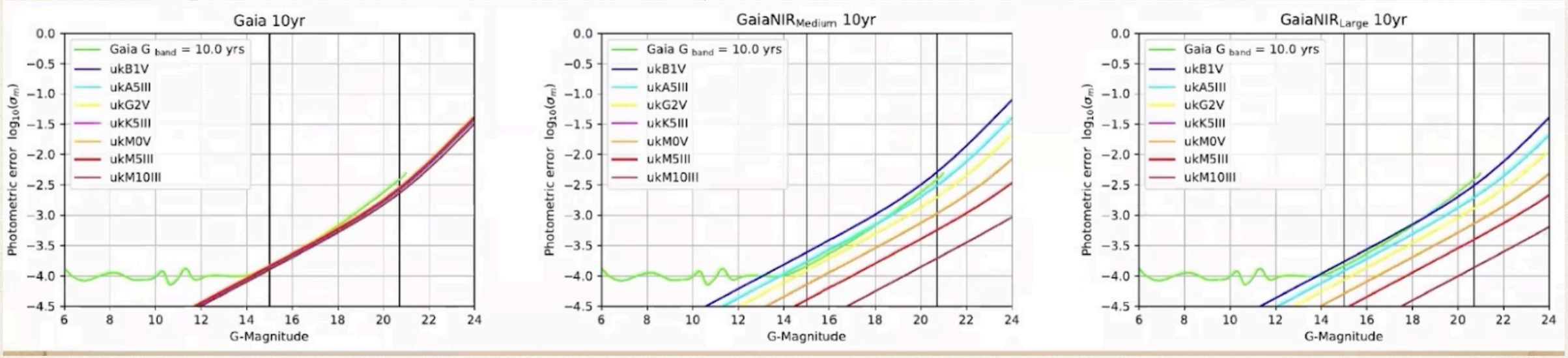
$$\sigma_\mu = \left(\sigma_{\mu_0}^{-2} + \sigma_{\mu,N}^{-2} + \sigma_{\mu,G}^{-2}\right)^{-1/2}$$

Key Scientific Insights

- >10x improvement in PM precision combining Gaia and GaiaNIR data
- Long Temporal Baseline (ΔT ≈ 30 yrs) drastically suppresses baseline offset uncertainty ($\sigma_{\mu 0}$).
- For ultra-cool red stars (e.g., M10III), the joint solution merges with the GaiaNIR Large standalone curve. GaiaNIR delivers high-precision proper motions independently without relying on optical Gaia data.

Photometric Performance: Gaia vs. GaiaNIR

Least-squares photometric error estimates across 10-year mission baselines (**Lund Formalism**)



Photometric Gains & Model Validation

- Model Validation: Gaia 10-year simulations successfully reproduce projected DR3 photometric precision.
- **Up to ~2 Orders of Magnitude Gain: For cool red stars (M-giants / M-dwarfs),** GaiaNIR precision dramatically outperforms optical Gaia.
- Remarkable **Blue Performance:** Despite being an infrared-optimized mission, performance on blue stars remains **nearly as precise as optical Gaia**.

50+ BILLION STARS

High-precision near-infrared photometry extended to over 50 billion Galactic sources, piercing through dust-obscured regions.

Spectroscopic Accuracy: the K-Band

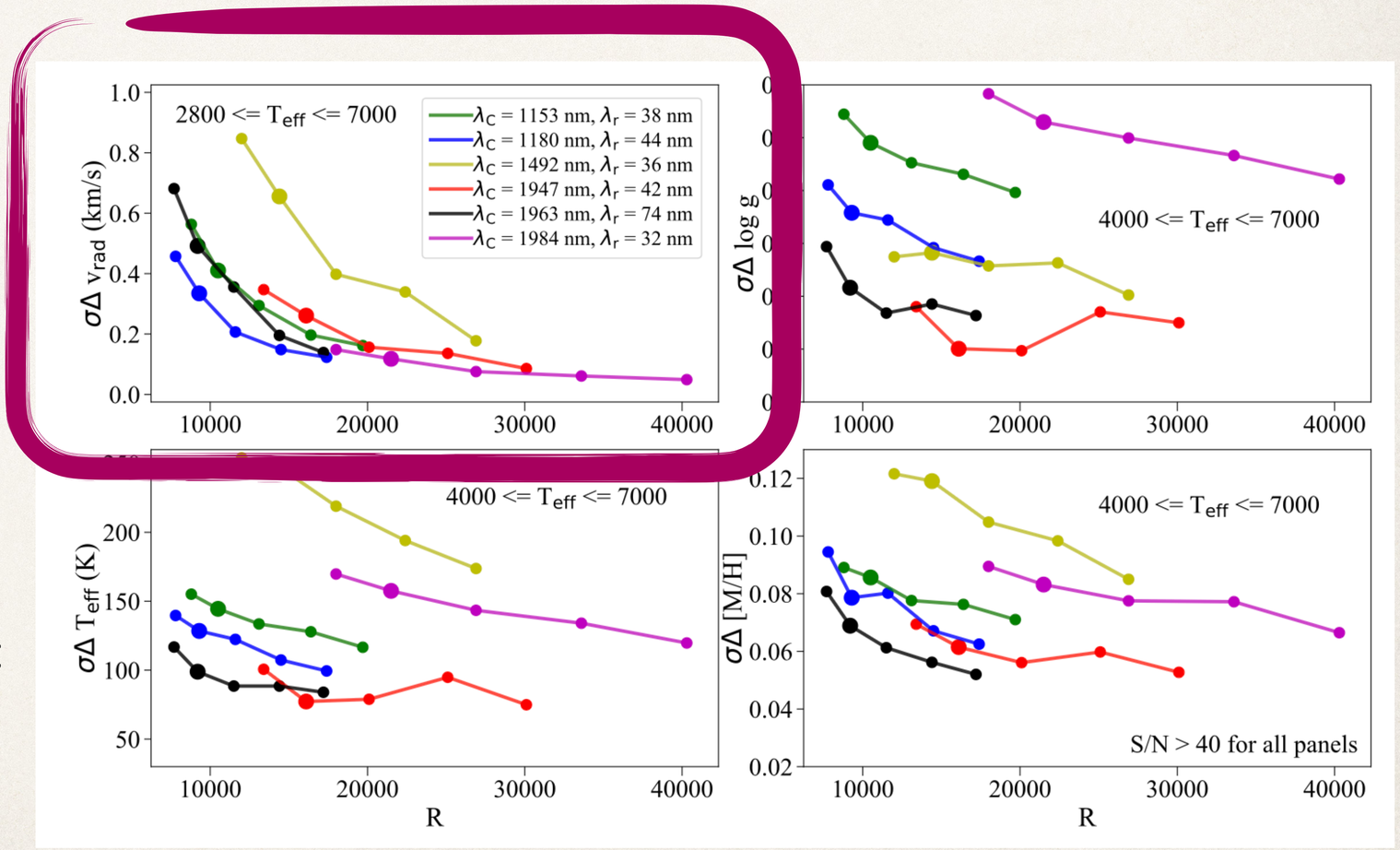
Theoretical performance of the proposed GaiaNIR spectrograph

- **Visualizing Precision:** The plot shows the typical measurement error (vertical axis) dropping as the spectrograph's resolution increases (horizontal axis).

- **The K-Band (1.9 - 2.0 µm)** provides the optimal balance, pushing velocity errors well below 300 m/s for FGKM stars at high resolutions.

- **The GaiaNIR Promise:** RV precision comparable with Gaia's optical RVS, but mapping the obscured Galaxy.

Mészáros et al. 2026



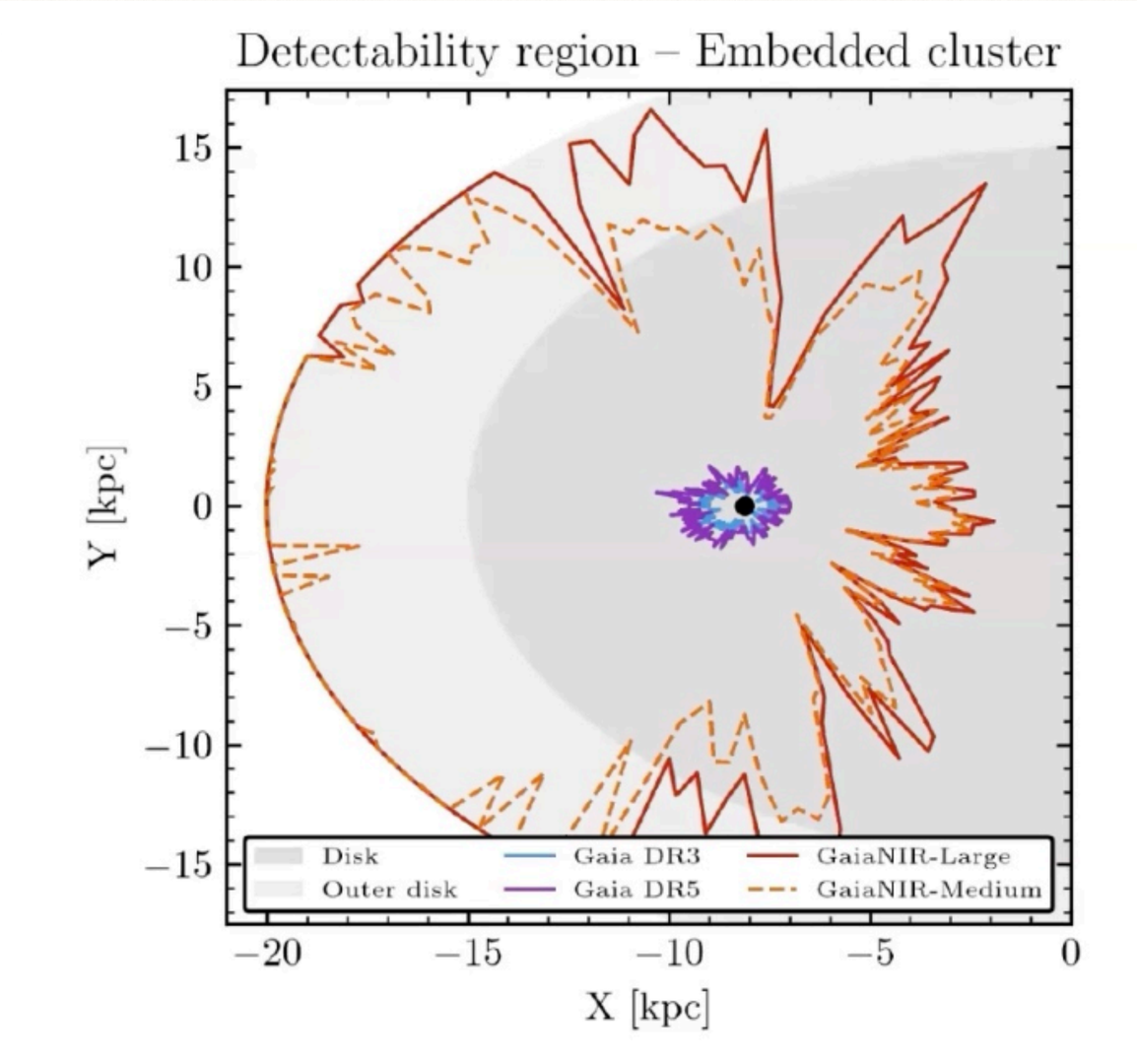
Discovery Potential: Embedded Clusters

Tracing the earliest stages of star formation across the Galactic

- **Optical Limits:** **Gaia** (blue and violet) is **restricted to** the **Solar neighborhood** by heavy dust.

- **NIR Breakthrough:** **GaiaNIR** (red/orange) successfully **penetrates molecular clouds.**

- **Galactic Scale:** **Up to a** ~10x factor gain in distance towards the anti-galactic center, expanding the discovery volume across the entire disc.

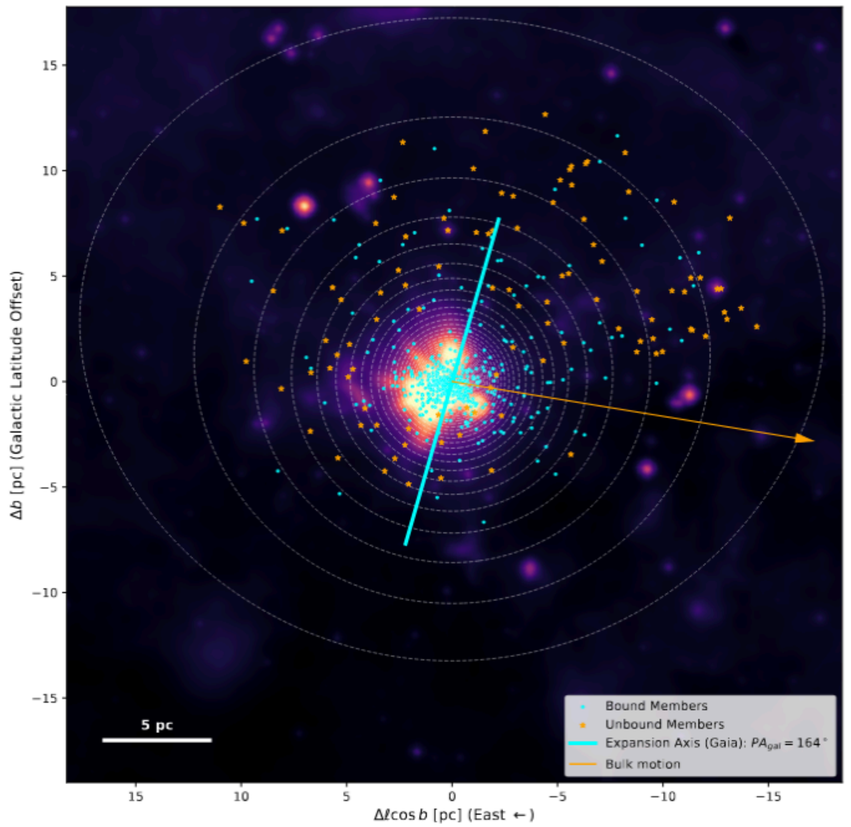


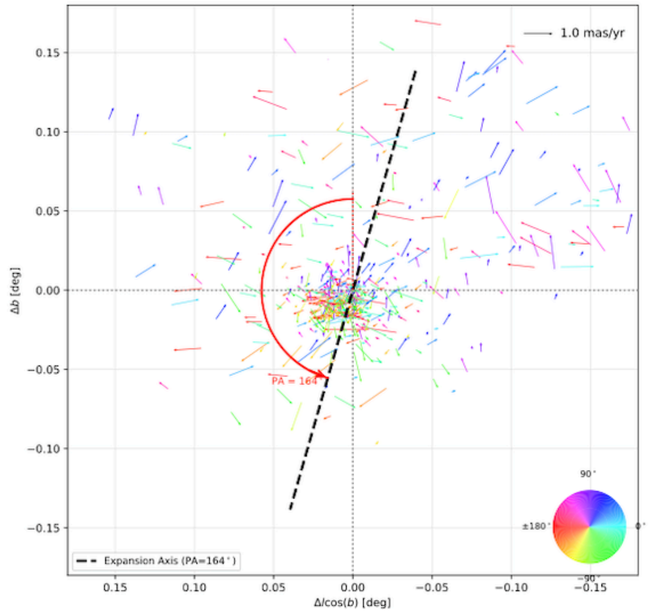
Simulations and figure adapted from ***Hunt et al. 2026, EAS****.*

Cluster Kinematics at 4 kpc: Westerlund 1

Table 2: Results of the 2D kinematic linear fit for different subsamples of Westerlund 1. Physical units are computed assuming $d = 4.21$ kpc.

Sample	N	v_l^0 (km s^{-1})	$\partial v_l/\partial l$ (km s^{-1} pc^{-1})	$\partial v_l/\partial b$ (km s^{-1} pc^{-1})	v_b^0 (km s^{-1})	$\partial v_b/\partial l$ (km s^{-1} pc^{-1})	$\partial v_b/\partial b$ (km s^{-1} pc^{-1})	Div (km s^{-1} pc^{-1})	Vort (km s^{-1} pc^{-1})	PA$_{gal}$ (deg)	$\chi^2_\nu(l,b)$
Bound	421	-85.14 ± 0.28	-0.13 ± 0.11	-0.15 ± 0.13	-13.86 ± 0.26	-0.21 ± 0.10	0.27 ± 0.11	0.14 ± 0.16	-0.06 ± 0.16	$159.2 \pm 8.5°$	11.3, 5.4
DBSCAN All (Bound+Unbound)	524	-85.07 ± 0.38	0.11 ± 0.10	0.19 ± 0.12	-13.74 ± 0.30	-0.41 ± 0.08	0.47 ± 0.10	0.58 ± 0.14	-0.60 ± 0.15	$164.0 \pm 10.1°$	26.2, 15.7





Prisinzano et al. 2026, A&A (under revision 2)

Results:

- 524 members with $\sigma_\mu < 0.5$ mas yr^{-1}
- 103 unbound members
- evidence of expansion and shear
- expansion during the cluster's Galactic disk passage

- **Gaia DR3 astrometry** successfully mapped the **anisotropic expansion and shear** of Wd1 at a distance of ~4.2 kpc.

- **Due to extreme dust extinction** (Av > 10), current optical studies are strictly limited to the most massive stars (M ≥ 7 M_{SUN})

- **The GaiaNIR Revolution:** A ~30-year joint baseline in the NIR will unveil the high-precision kinematics of the **entire stellar population.**

Diffuse SF: the Strings

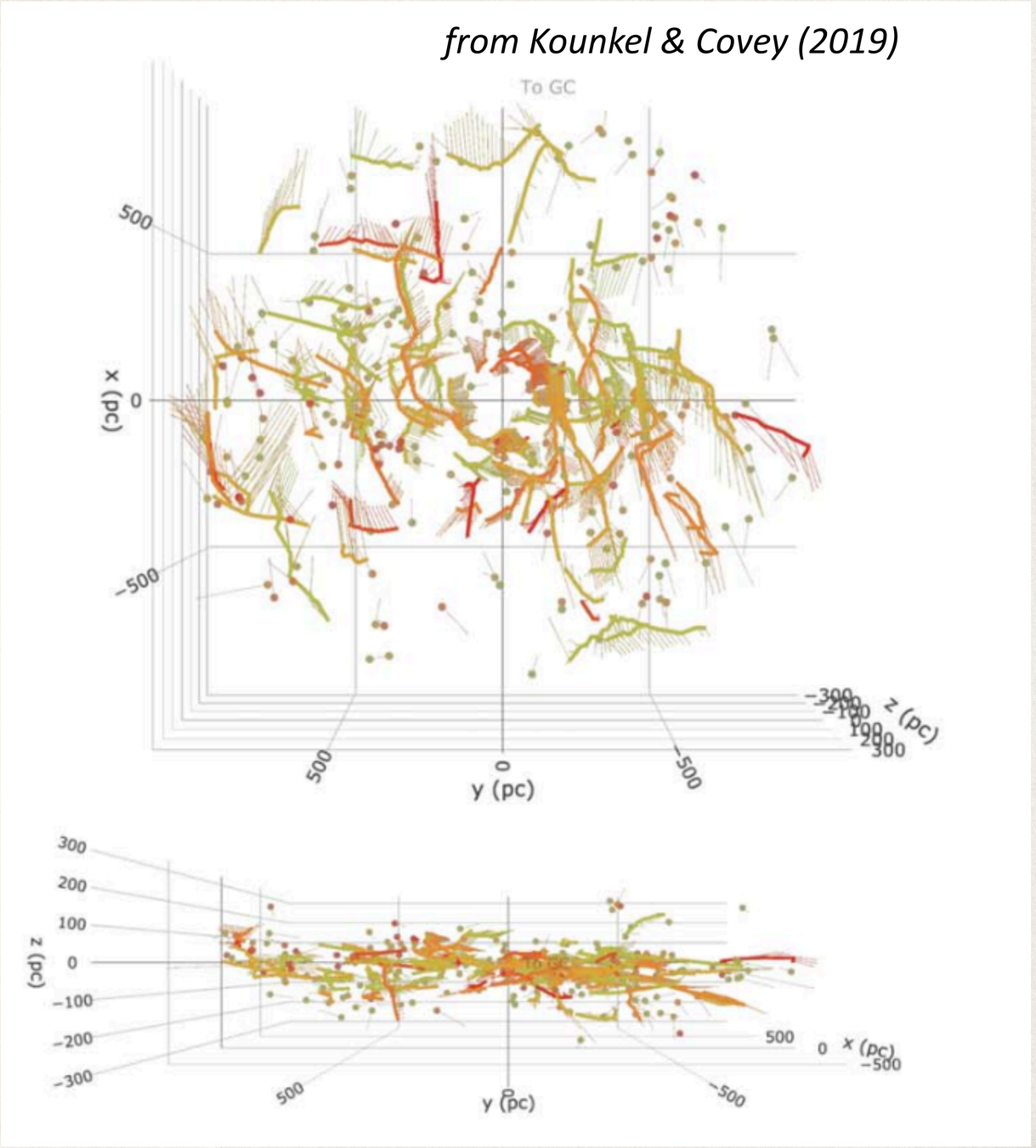
Leveraging GaiaNIR to validate diffuse structures across the GP

- **A New Star Formation Paradigm?**
Kinematically coherent string-like structures spanning hundreds of parsecs (Kounkel & Covey 2019).

- **Are the strings genuine physical structures** tracing extended low-density gas collapse, **or** merely 2D projection **artifacts** of Gaia DR3?

- **The GaiaNIR Solution:** GaiaNIR will map the 6D phase-space of these low-mass stars, definitively validating their 3D physical nature and dynamical coherence.

from Kounkel & Covey (2019)



Summary

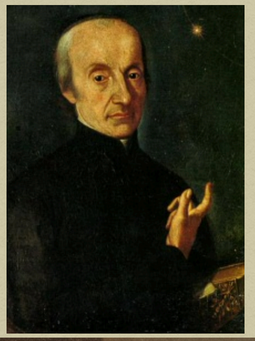
Key Scientific Drivers

- **Unveil Obscured Star Formation**
- **True 6D Phase-Space Dynamics**
- **Probing Galactic Large scale structures**

Technology & Challenges

- **APD Technology**
- **Deep Spectroscopic Survey Yields:** 50+ billion spectra and >1 billion K-band radial velocities.
- **The Telemetry:** Downloading massive data volumes from billions of sources represents a primary operational **challenge** for the mission.

Next Steps: Building the GaiaNIR Consortium towards an L-Class ESA Proposal



Piazzi's blessing on GaiaNIR