Low-mass young stellar populations in the Milky Way

the Next Frontier with GaiaNIR

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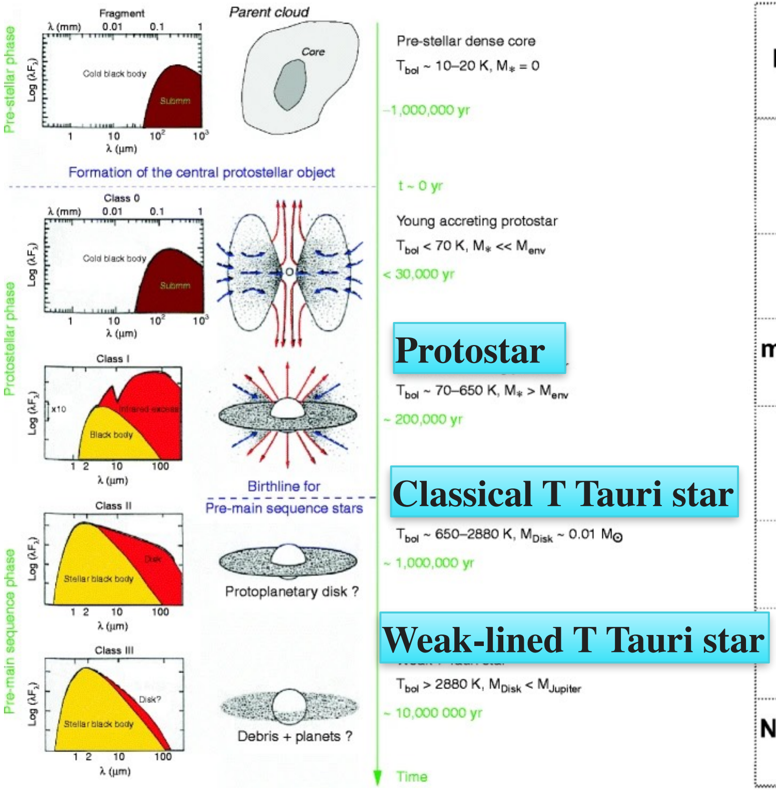
Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

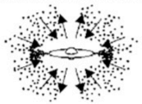
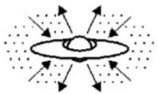
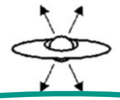
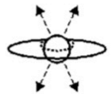
INAF ISTITUTO NAZIONALE DI ASTROFISICA

Gaia-NIR: next generation astrometric mission 17–18 gen 2024 Bologna, OAS

Low mass $M \lesssim 2M_\odot$ Young Stellar Objects(YSO)

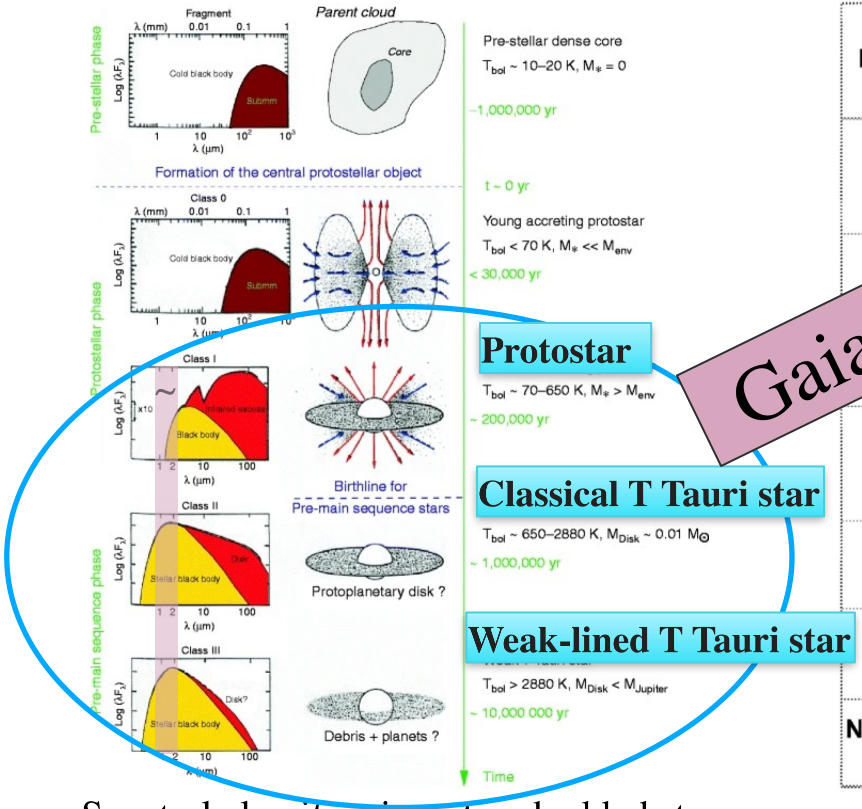


Spectral classification of embedded stars (André 2011)

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)

Low mass M≲2M☉ Young Stellar Objects(YSO)



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GaiaNIR detections

Stages of YSO evolution (Feigelson & Montmerle 1999)

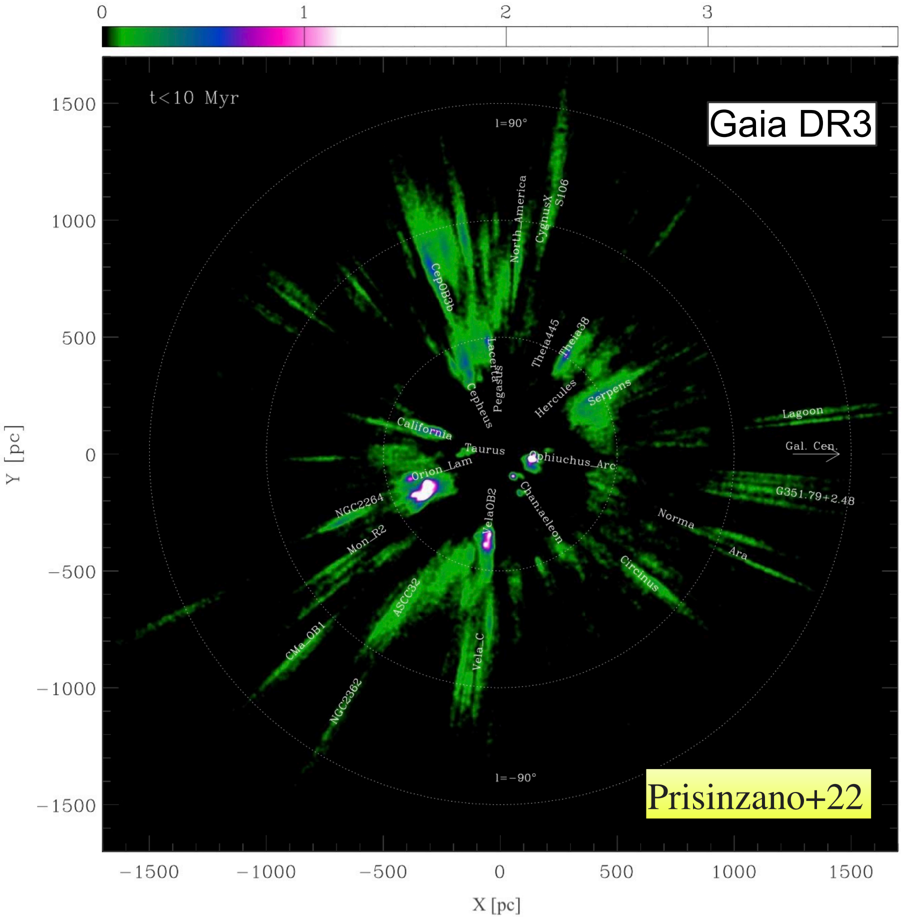
Where are YSOs found?

Star forming regions (SFRs)

- regions with ongoing/recent star formation
- include young, massive stars and clusters of protostars and low mass T Tauri stars

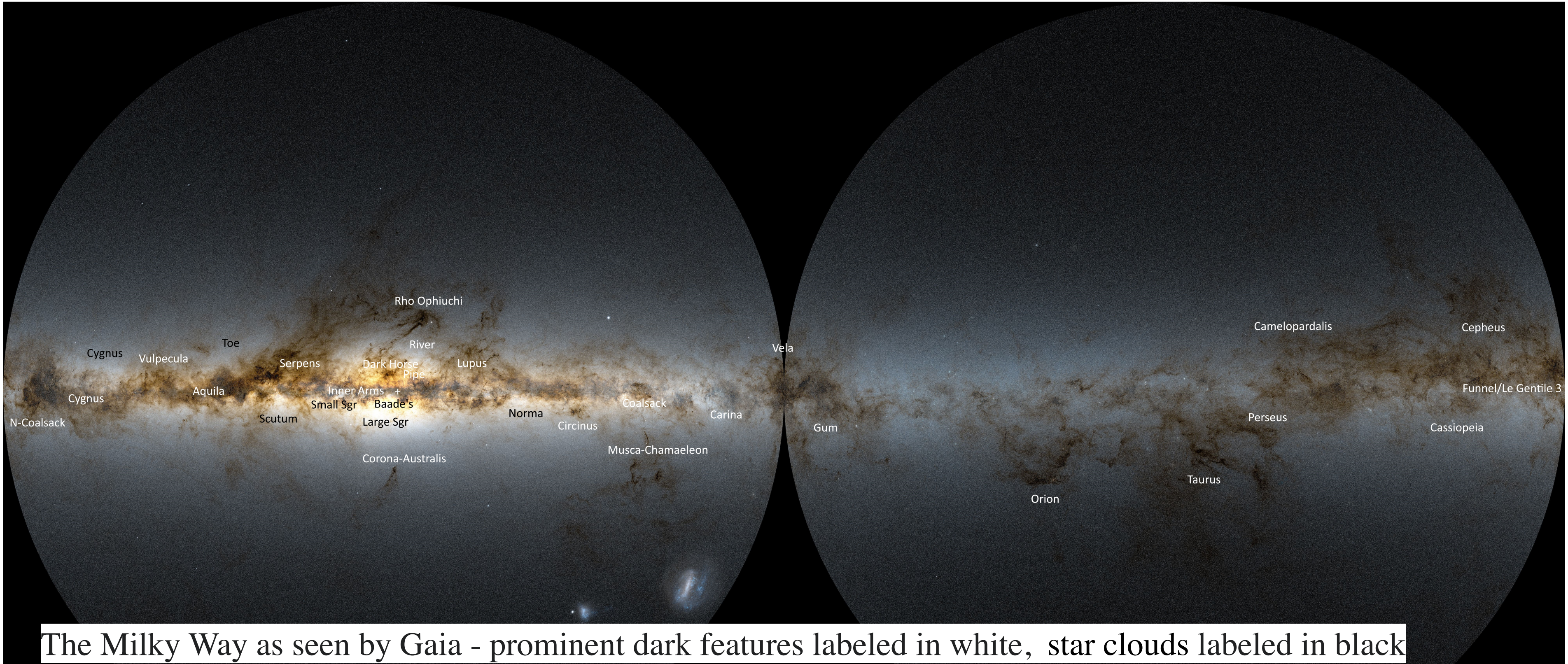
Cosmic Cliffs in the Carina Nebula

JWST NIRCam Image



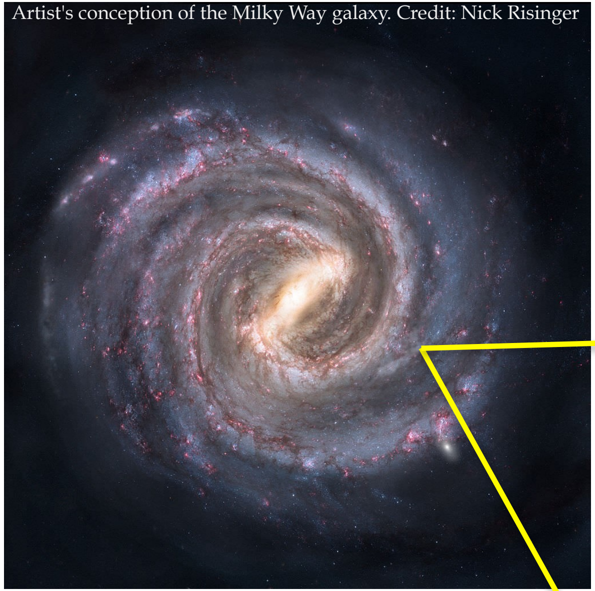
Where are YSOs found?

associated to **Nebulae and H II Regions** - **Dark clouds** - **Giant Molecular Clouds (GMCs)** - **Galactic Spiral Arms**
Galactic Strings (Kounkel & Covey 2019)



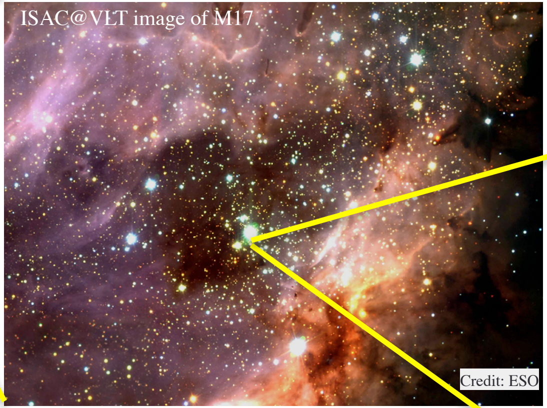
The Milky Way as seen by Gaia - prominent dark features labeled in white, star clouds labeled in black

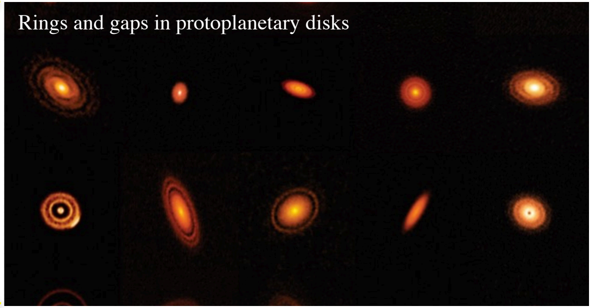
Low mass star formation: key questions


Artist's conception of the Milky Way galaxy. Credit: Nick Risinger

1. What are the **global properties** of the youngest stellar component of the **Milky Way**?

2. What are the dominant physical mechanisms leading to the formation of **stellar clusters**?


ISAC@VLT image of M17.
Credit: ESO

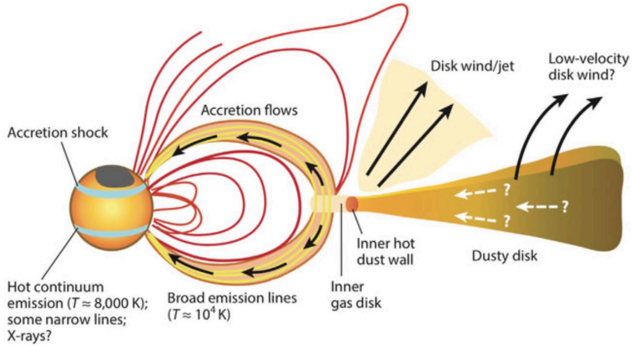

Rings and gaps in protoplanetary disks

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

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

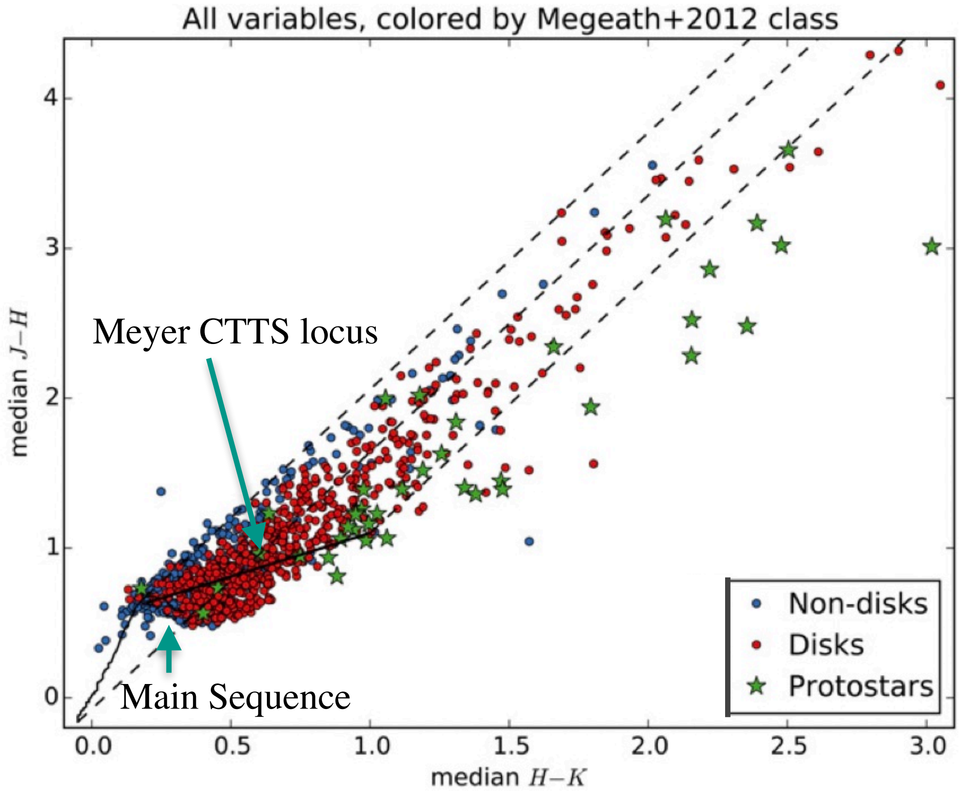
Individual stars

How do the physical mechanisms such as gravitation, angular momentum transport, thermal evolution, magnetic field, involved in the formation of individual stars, **interplay among them?**

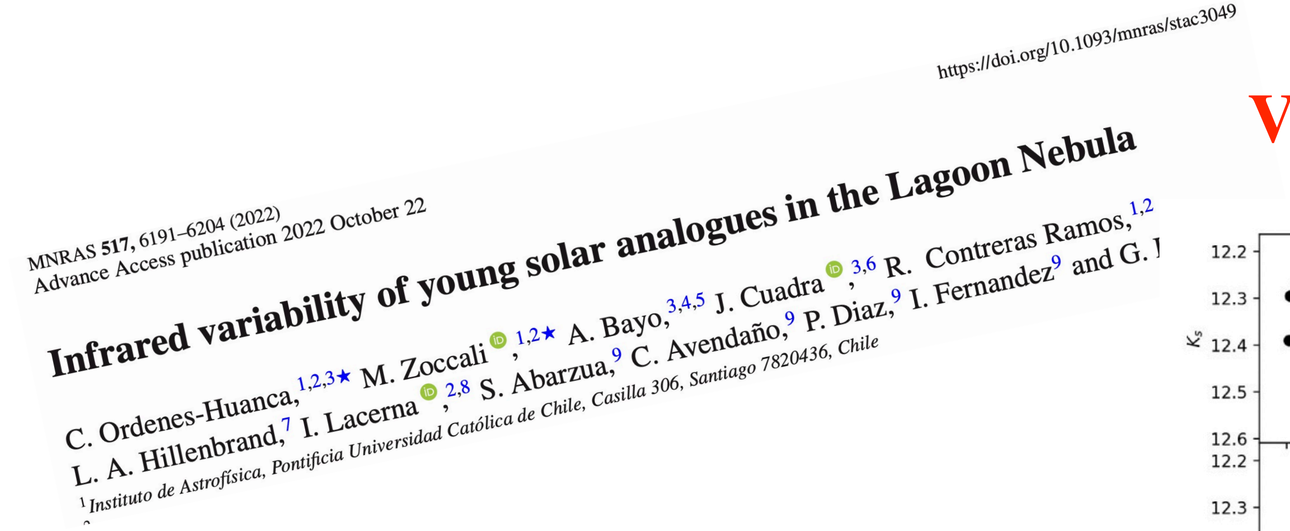


- Dust surrounding YSOs absorbs light and re-emits it in the NIR
- Broad band IR emission by viscous heating

Color analysis



Variable stars in Orion Nebula Cluster (Rice et al. 2015)


https://doi.org/10.1093/mnras/stac3049
MNRAS **517**, 6191–6204 (2022)
Advance Access publication 2022 October 22

Infrared variability of young solar analogues in the Lagoon Nebula

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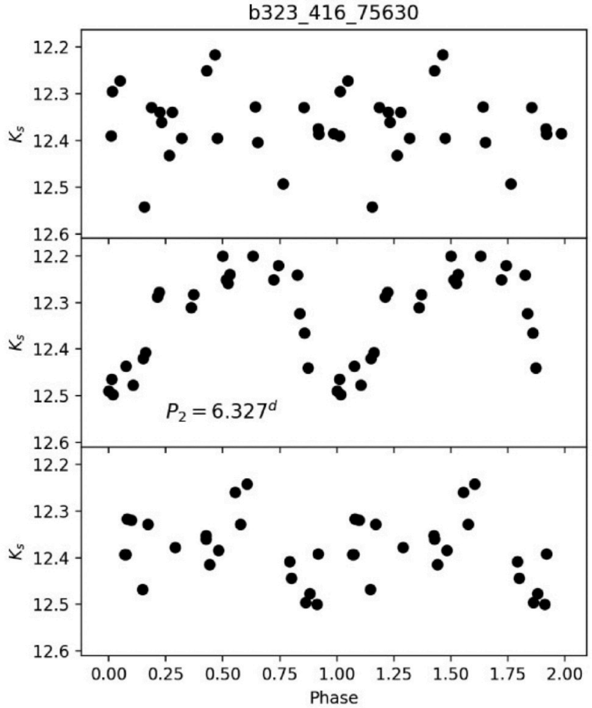
[1] *Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 7820436, Chile*

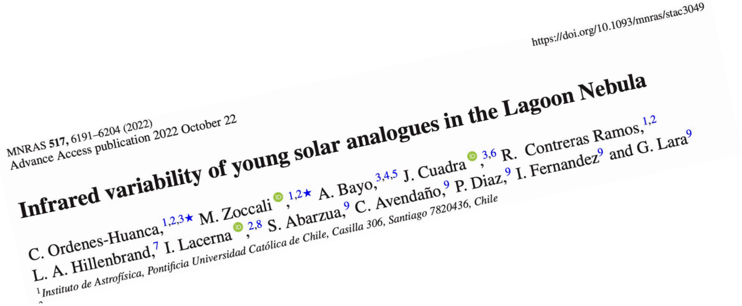
Variability Analysis

Light curves: 379 T Tauri stars in the M8 region
data: VVVX survey data in the Ks-band
temporal coverage: about 8 years
classification criteria: periodicity and asymmetry

GaiaNIR cadence:
crucial to understand the physics and the evolutionary stage of YSOs.



Example of a phased light curve for a Ks periodic star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[1] Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 7820436, Chile

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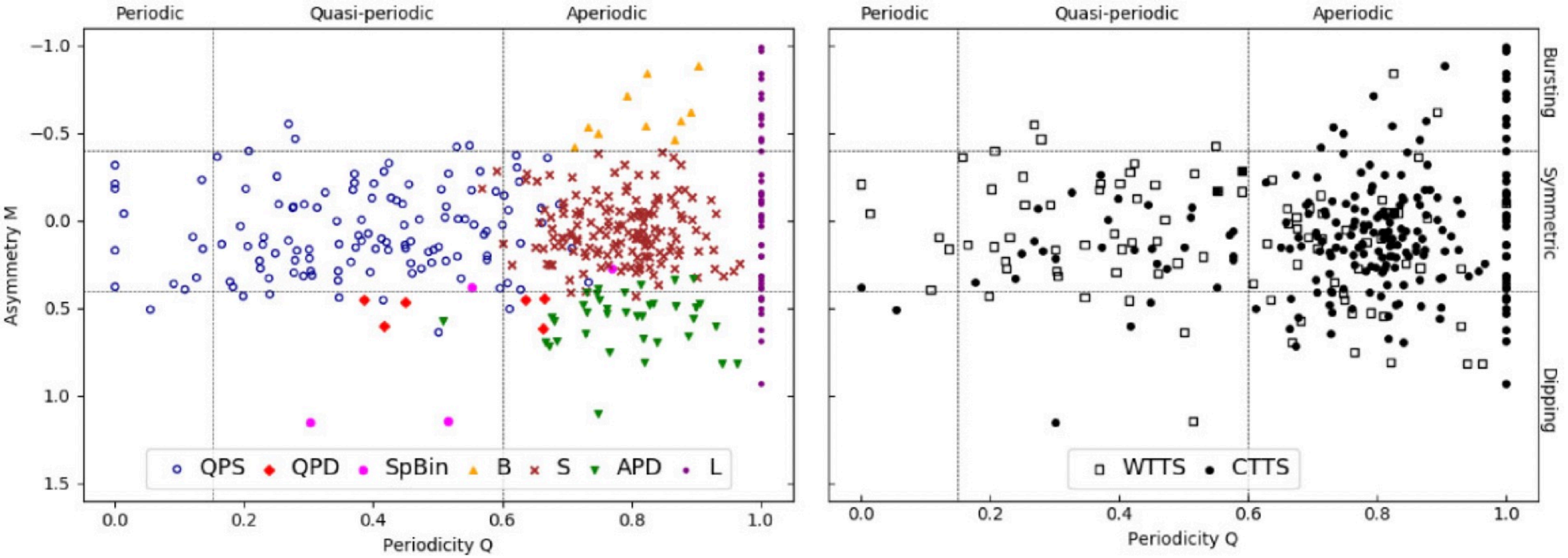


Most of the previously known CTTS are classified as stochastic (S) (see also Rice et al. 2015)

Stellar cluster's science

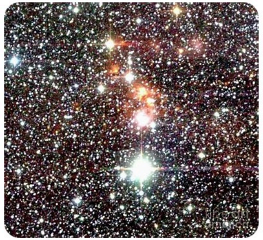
GaiaNIR's strengths:

- unbiased membership
- small reddening effects

Key topics:

- formation of stellar clusters, dynamical evolution and cluster survival (talk by G. Sacco)
- Evolution of circumstellar disks and proto-planet formation in different environments
- unbiased IMF
- Unveiling embedded proto-clusters

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

2011: VVV@VISTA

deep photometry K_{lim}=18

+96 Embedded Star Clusters

2022: Gaia DR3

more than 2600 stellar clusters found with **high precision astrometry**

2045: GaiaNIR

deep IR photometry (K_{lim}=20)

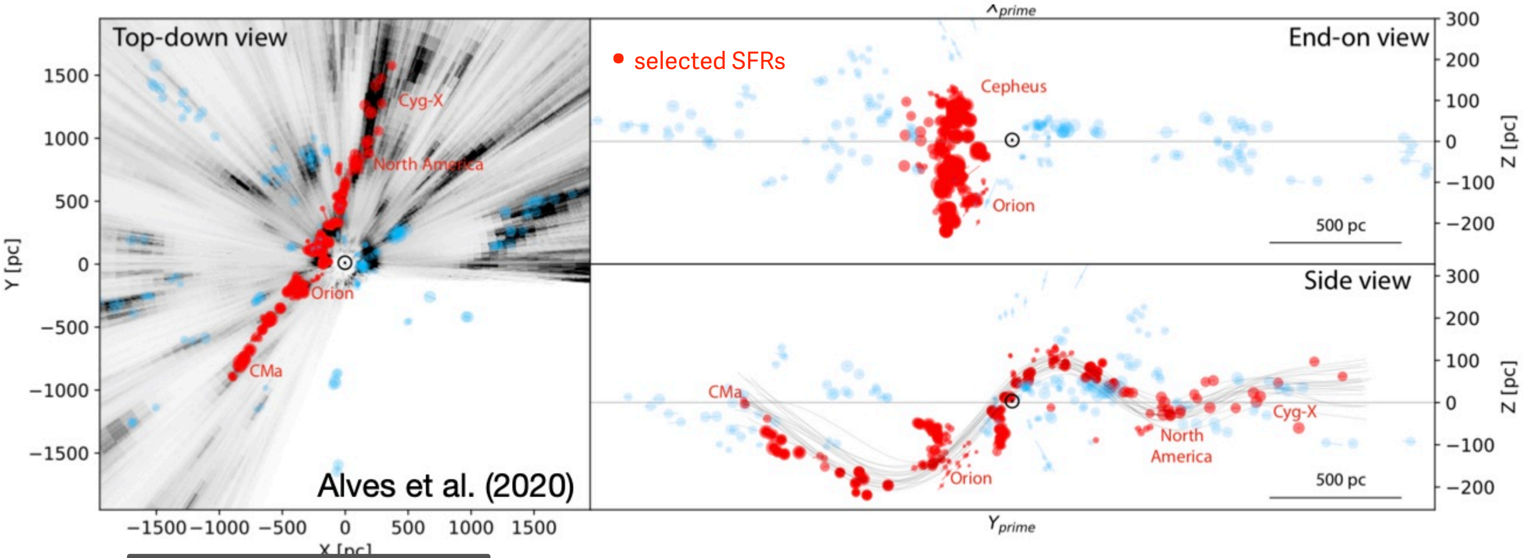
high precision astrometry

GaiaNIR: a double revolution!

YSOs & Galactic structure

Key questions:

- Which are the **global properties** of the youngest stellar component of the **Milky Way**?
- Is the star formation in the Galaxy spontaneous or triggered by perturbations?
- Did the SFRs in the solar neighbourhood originate by a common perturbative mechanism?



integrated dust map in grey

Radcliffe Wave: a spatially and kinematically coherent structure

Based on cloud distances (Zucker et. al 2020)

see also Swiggum et al. (2022)

Kuhn+23

YSOs & Galactic structure

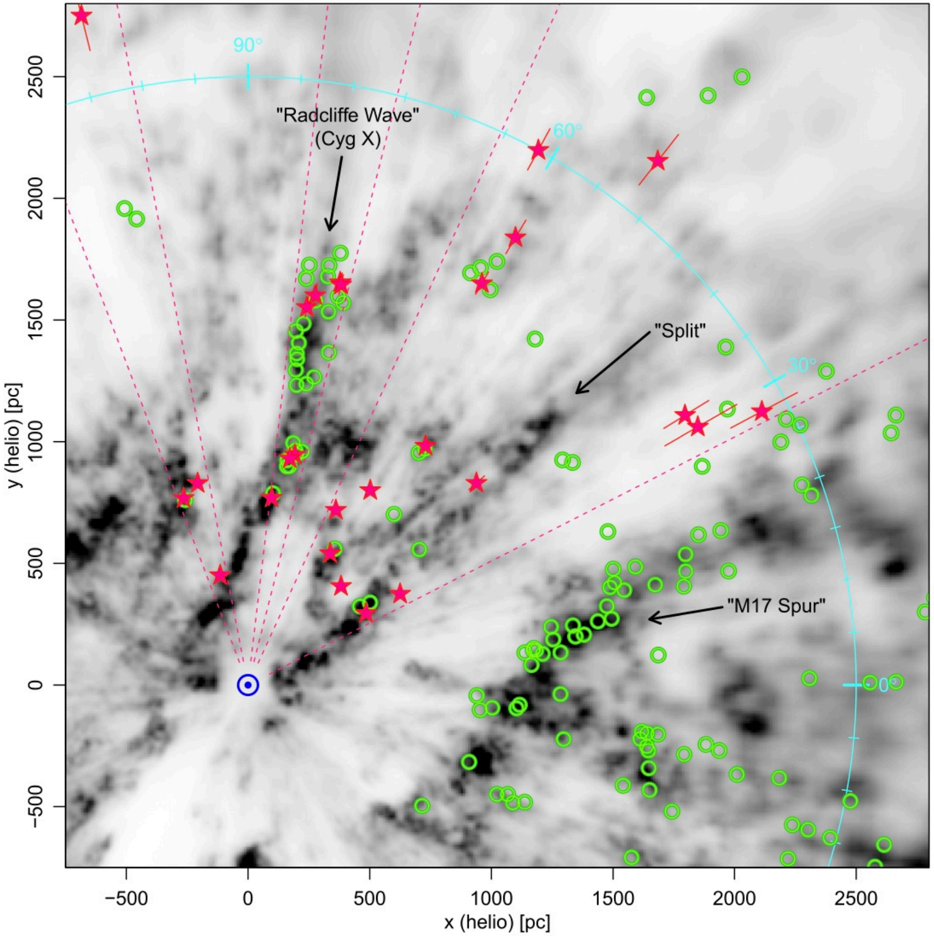
◦ YSO groups

★ isolated YSOs with spectra

Vergely et al. (2022) extinction map (grey scale)

- Young stellar populations preferentially found in high reddened regions and often on the periphery of large star forming complexes

- In the solar neighbourhood, local structures are not the traditional "spiral arms" but substructures (spurs or feathers). Examples are Radcliffe Wave, Split, M17

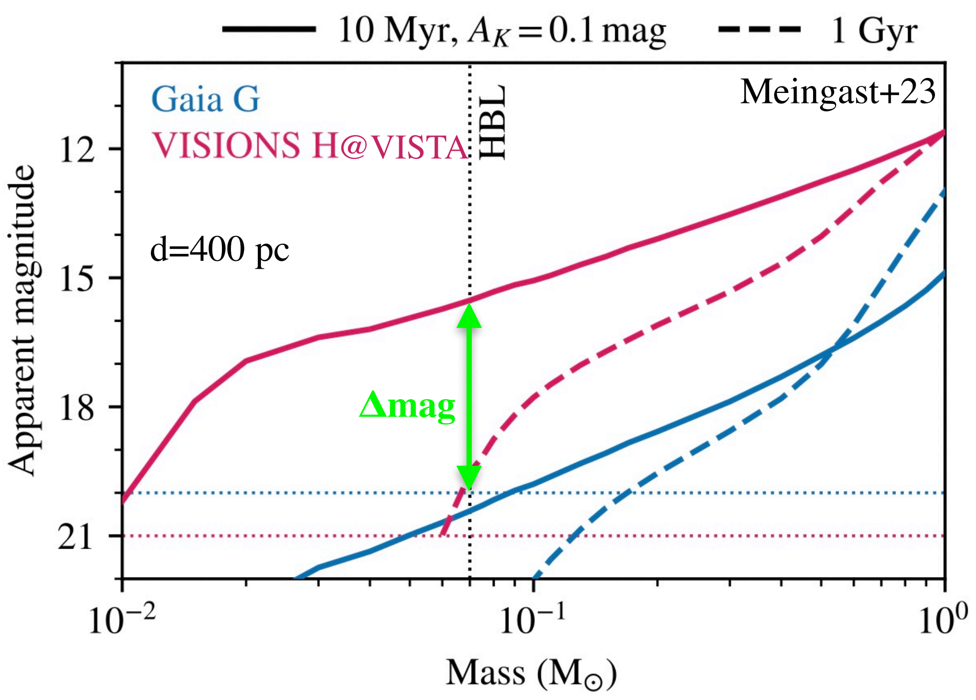


Intrinsic brightness and statistics of YSOs

- YSOs are intrinsically brighter than MS stars

- **Δmag=4** corresponds to a factor 6 in distance
  GaiaNIR would detect a star at the hydrogen burning limit (HBL) at ~2.5 Kpc --> large distances

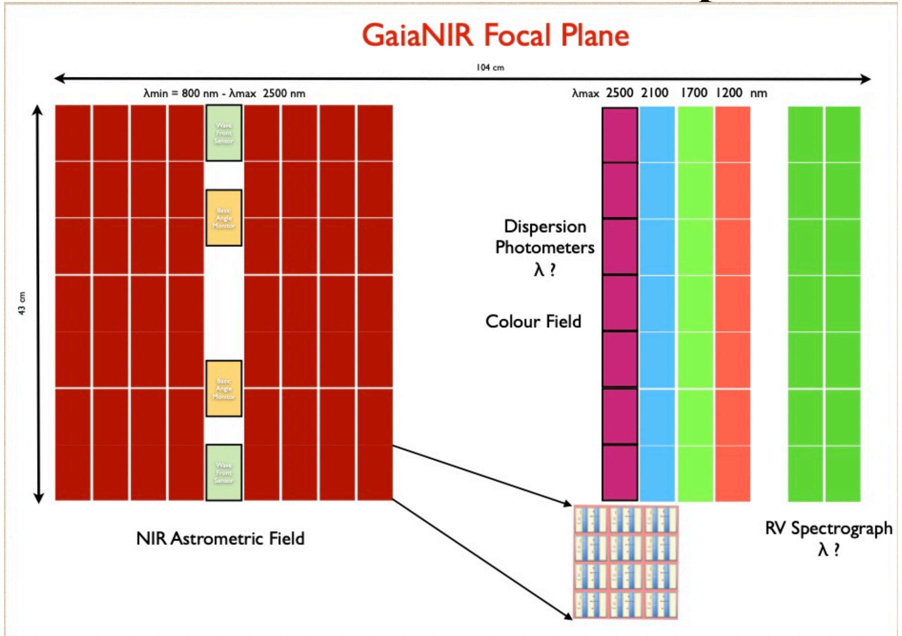
- low mass YSOs (M-type) are the bulk of the stars
  (>80% of the MS stars Lada+06) --> large statistics

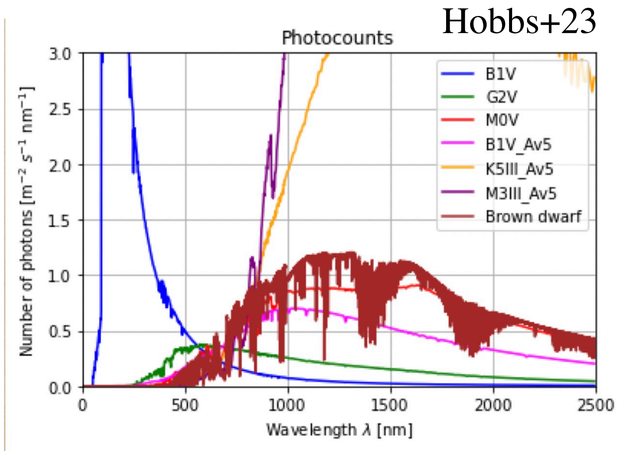


ideal targets for a NIR mission

- high angular resolution (comparable to Gaia)
- K_{lim}=20 (G=21-24 mag) (Hobbs+21)
  (K_{lim}=18 in the VVVX suvery, Minniti+10)
- in the NIR

GaiaNIR photometric requirements





Current design (Hobbs 2023) :

- wavelength range: broad band 0.8–2.5 μm
- YJHK filters

High risks for an **RV Spectrograph** due to the expected star crowding

Recommendations:

max wavelength - **2.5 μm** (K band coverage)

detect YSO disk detection

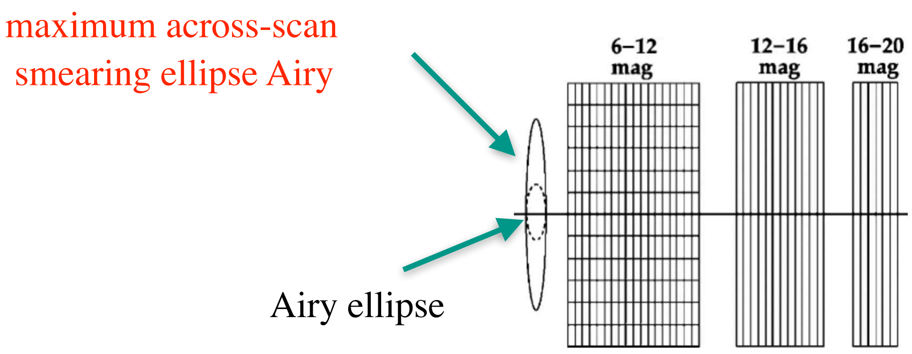
6 times more stars with respect to Gaia at K_{lim}=20 (Hobbs+21)

at leat 3 filters

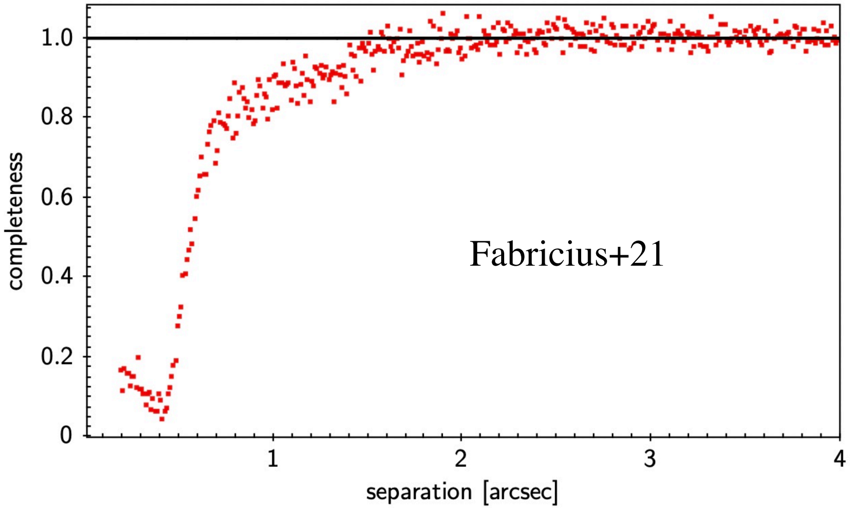
static photometric analysis

YSO characterisation

Gaia angular resolution



credit ESA-Høg



- **spurious solutions** for source pairs with separation 0.18 -0.4 arcsec (Fabricius+21)
- **completeness** in close source pairs decreases rapidly below about 0.7 arcsec

- Gaia **astrometric crowding limit** is **1 050 000 objects deg^{-2}** i.e. 1 object in 12 square arcsec
- in very dense regions, the readout window reaches this limitation (Gaia coll. 2016, 2023)

GaiaNIR Photometric requirements: angular resolution

λ_{Gaia}=0.5 μm and $\lambda_{GaiaNIR}$=2.0 μm ➡ **GaiaNIR minimum angular resolution** expected to be **a factor 4 worse than Gaia**

a new data initial processing from the detector will be implemented to **significantly reduce across-scan smearing (Høg 2023)**

- increased sensitivity
- reduced image overlap
- simpler PSF calibration

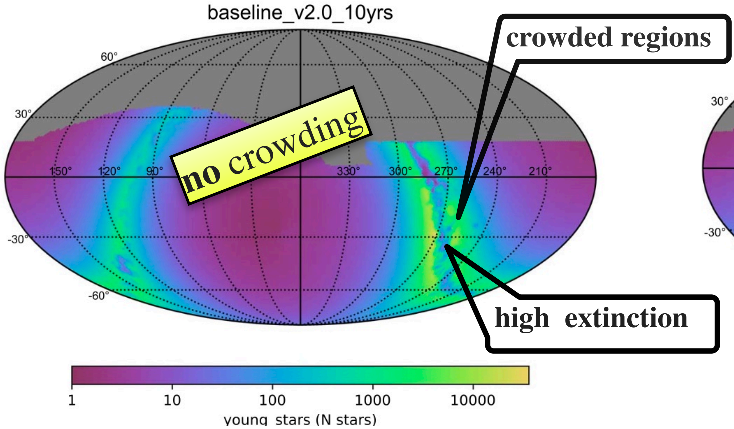
highly recommended to reduce the crowding effects!

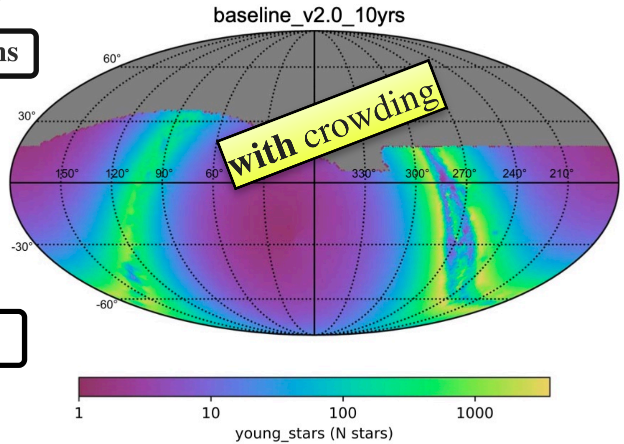
Crowding: predictions for YSOs with Rubin LSST

Nside = 64

Prisinzano+23

Final metrics





crowding metric:
σ_{crowd}=0.25 mag
(Dal Tio+22)

Crowded regions:

detections go down from more than 10,000 to surprisingly low values of 10–100 (sources/HEALPix)

Extincted regions:

detections here remain 100-1000 (sources/HEALPix)

⚠ crowding is worse than reddening!

Keep in mind that Crowding depends on

- instrument spatial resolution
- magnitude limit
- data acquisition and treatment

Summary

GaiaNIR would represent a huge revolution (even more than Gaia) in the field of YSOs

- simultaneous and homogeneous census of YSOs with and without disks
- how stars form
- understanding the primordial phases of cluster formation in embedded star forming regions and in the high reddened Galactic Plane regions
- determine the Initial Mass Function
- discover features (not only spiral arms) of the Milky Way

- We strongly encourage the design for Astrometric Field & Multi-filter photometry
- analysis to evaluate **photometric and astrometric crowding limits** are recommended

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