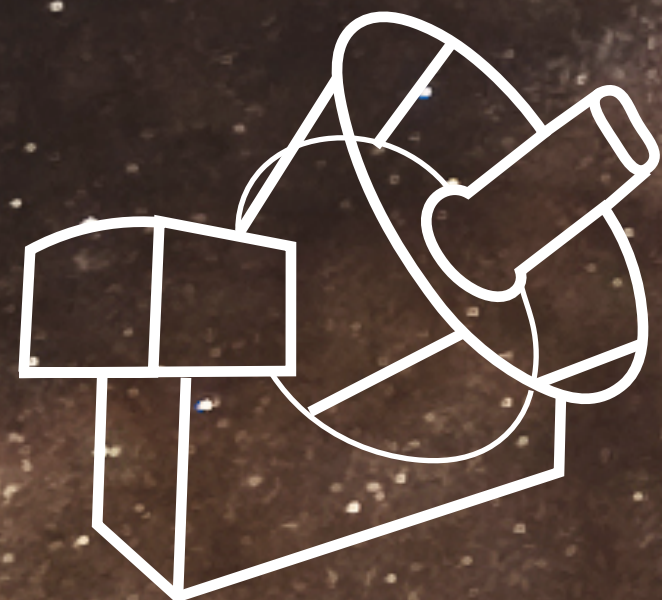


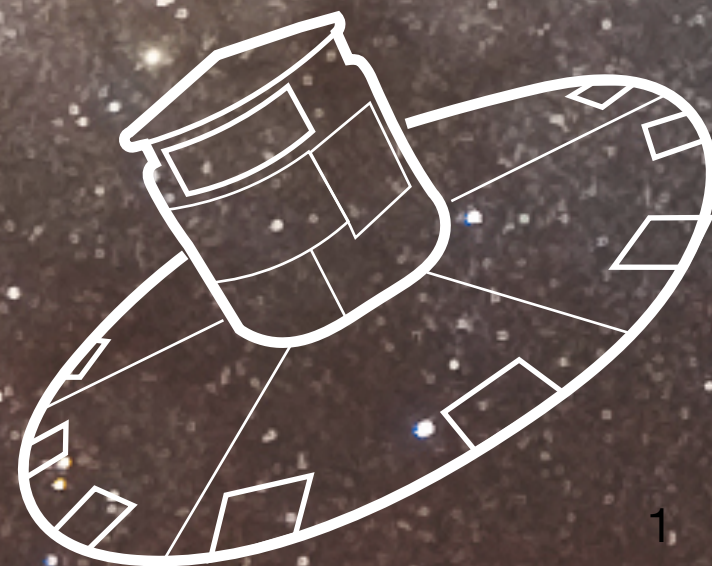
The epoch of bar formation in the Milky Way

Jason Sanders, UCL — Galactic Bars, Granada — July 2023

With Daisuke Kawata, Noriyuki Matsunaga, Leigh Smith, Hanyuan Zhang, Mattia Sormani, Philip Lucas, Dante Minniti, Ortwin Gerhard

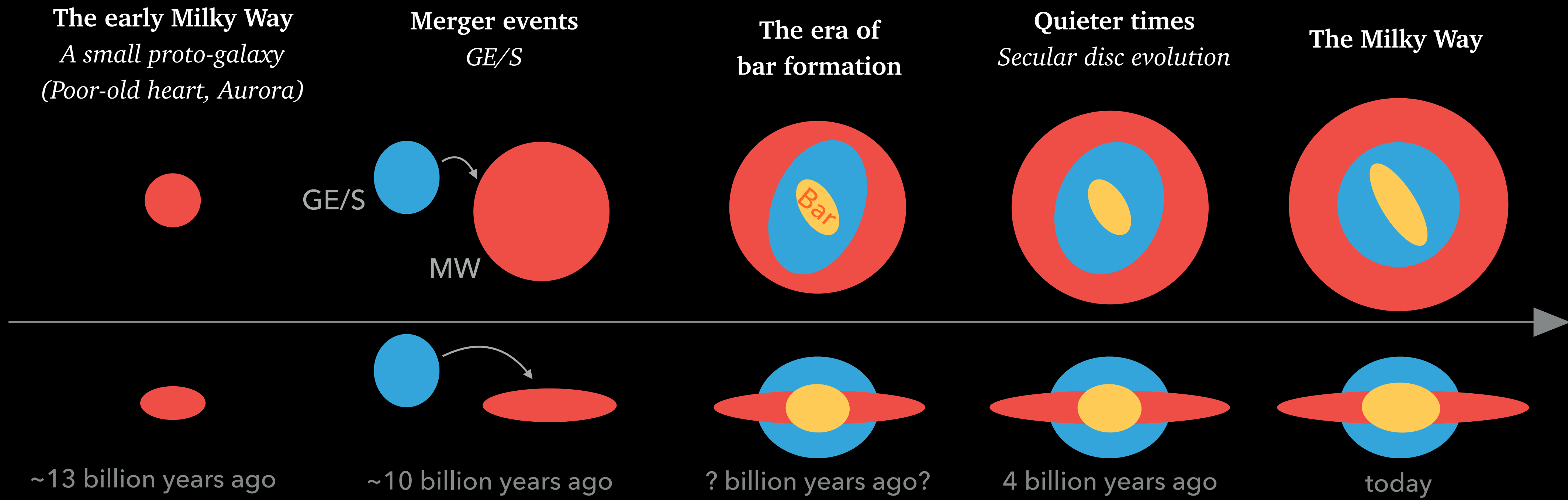
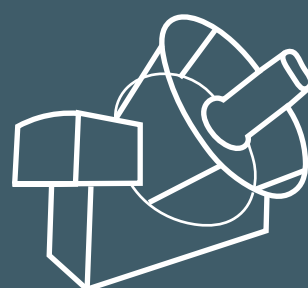


VVV

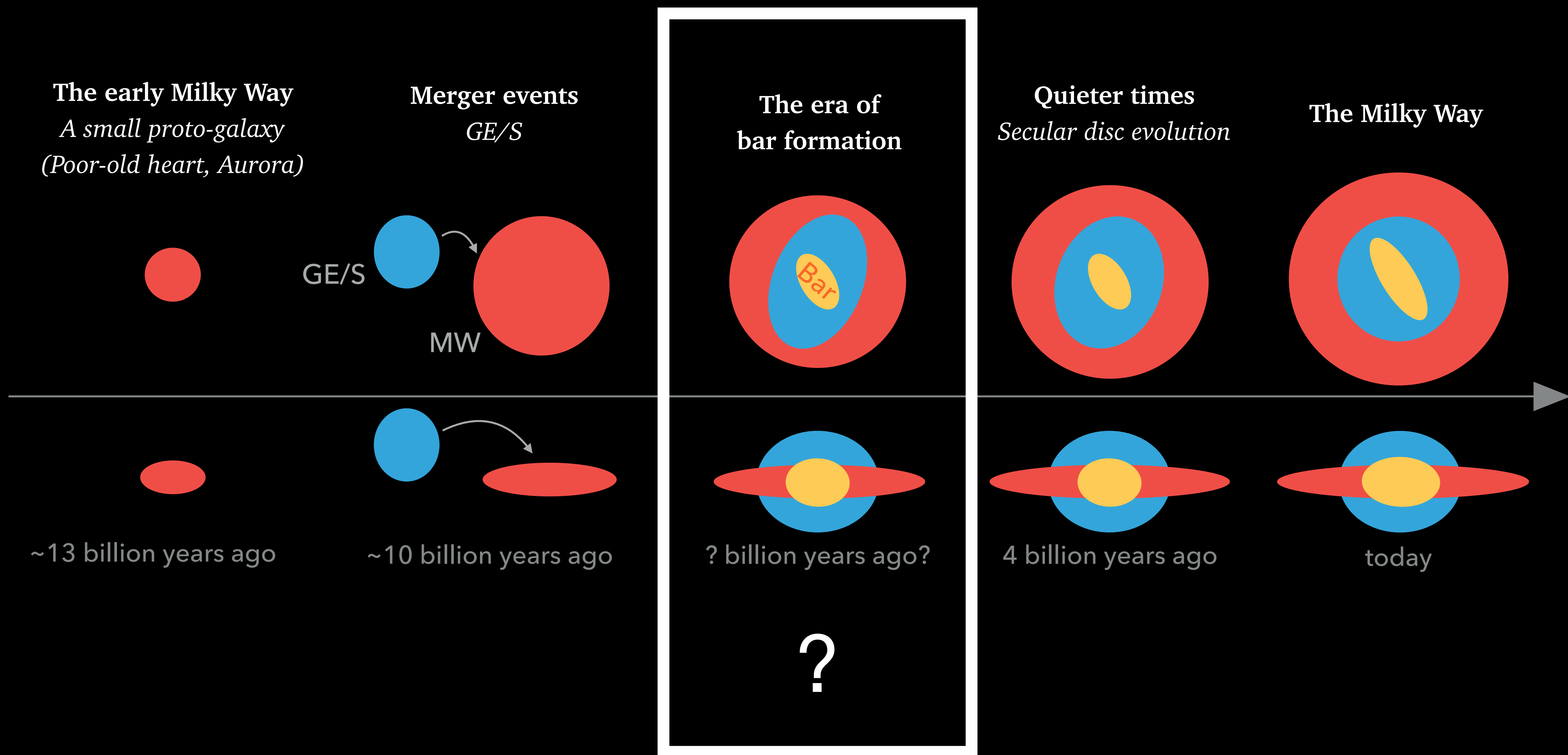
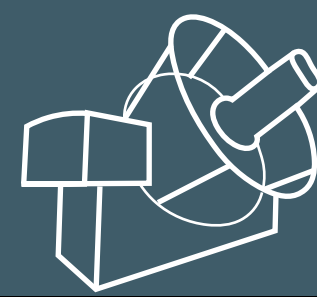


gaia

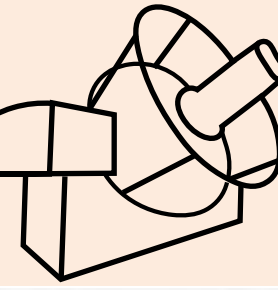
The Galactic timeline



The Galactic timeline



Why is the age of the bar an important property?



1

Disc restructuring

(Resonances, radial migration)

2

**Slowing due to DM
interaction**

(Dynamical friction)

3

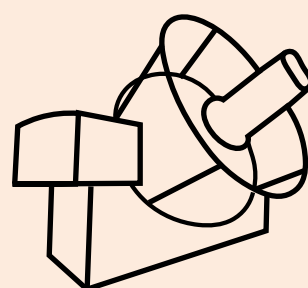
**Conditions of MW at time
of formation**

e.g. baryon vs. DM dominance

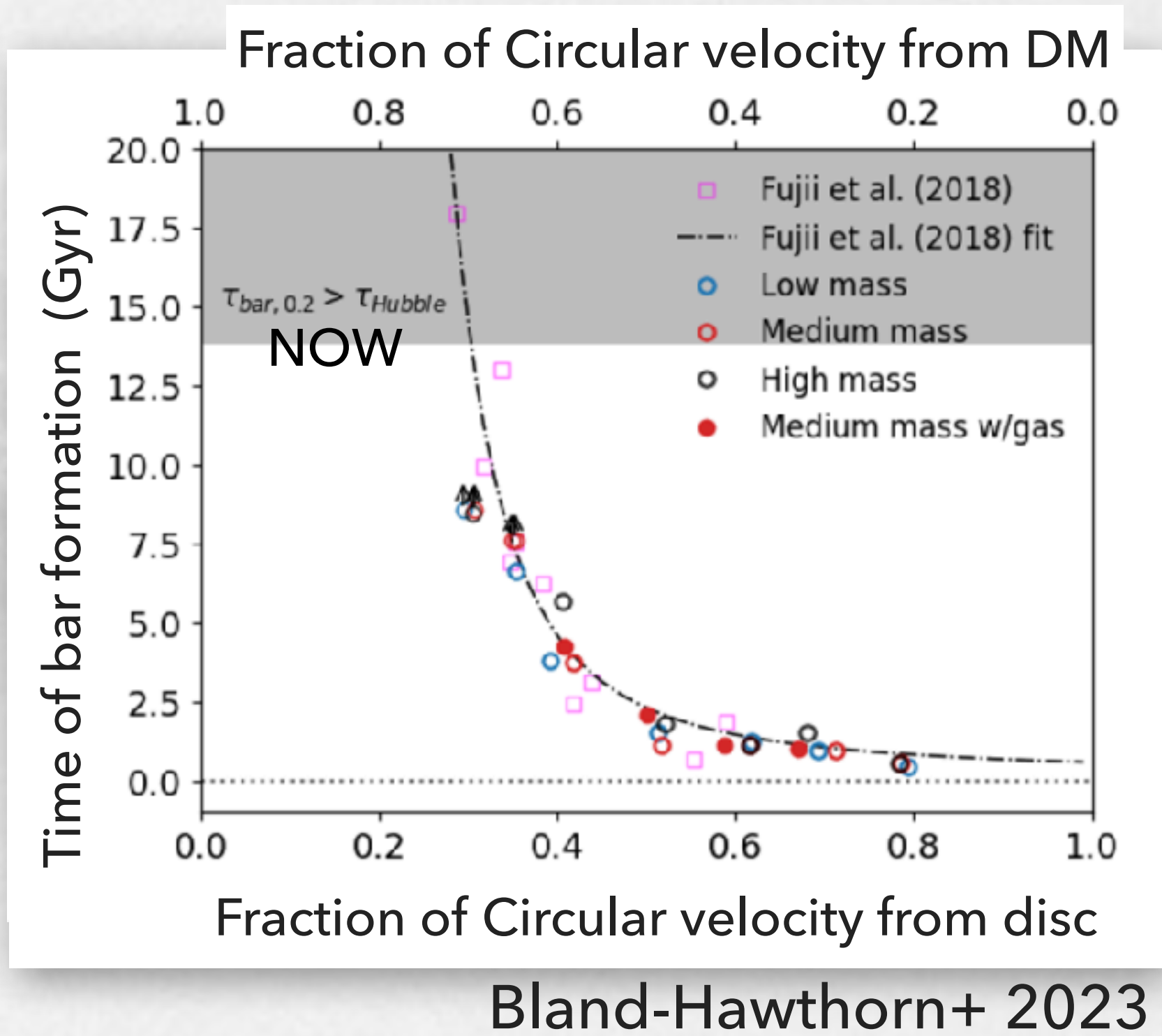
4

Bars funnel gas

When do bars form in simulations?

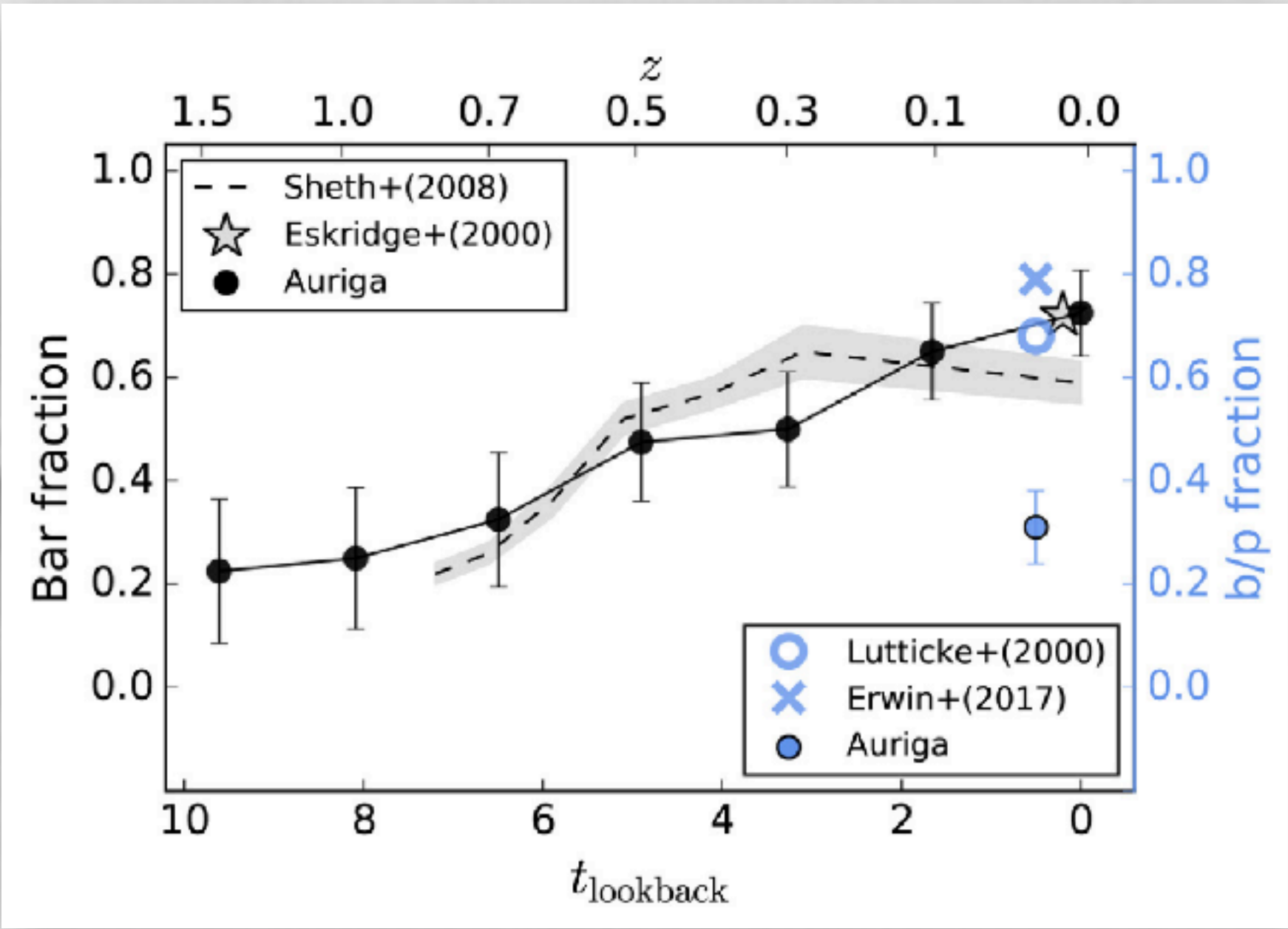


Controlled simulations

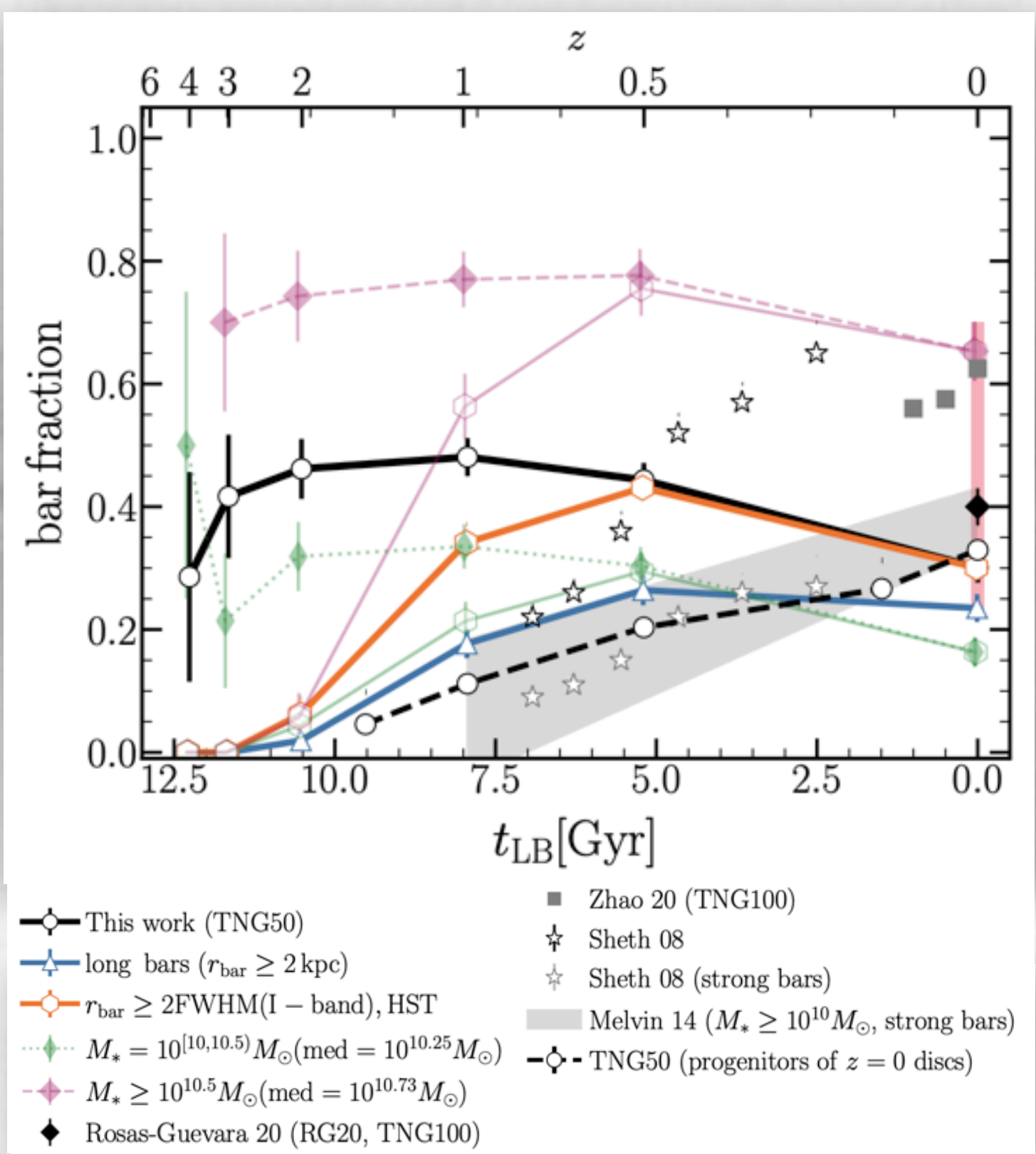


Cosmological simulations

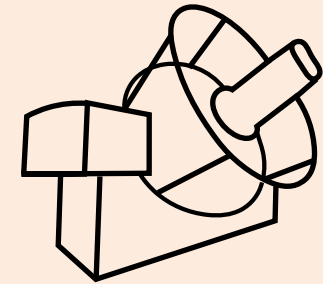
Auriga



IllustrisTNG

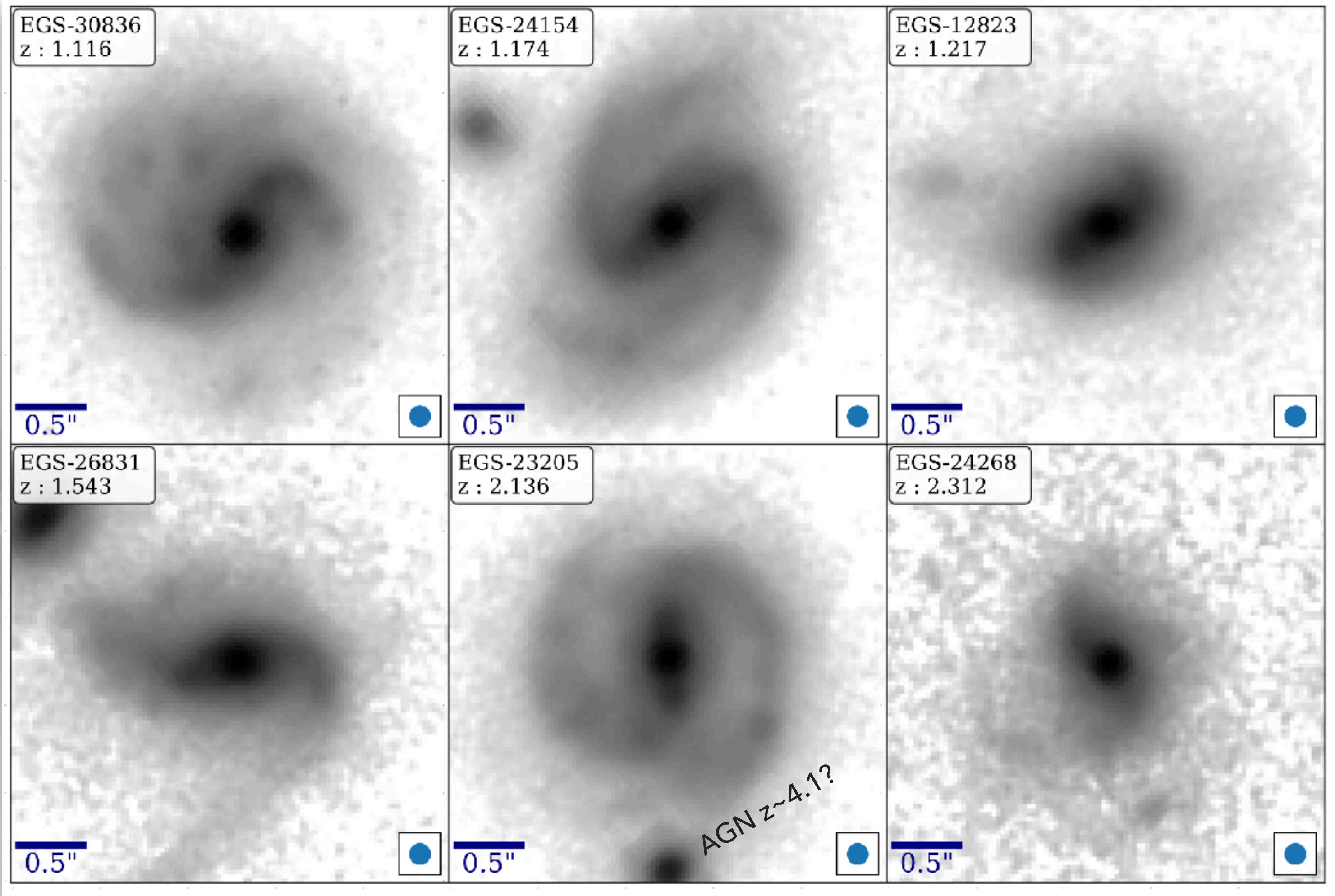


Bars at high redshift with JWST



F444W ~ Rest-frame NIR

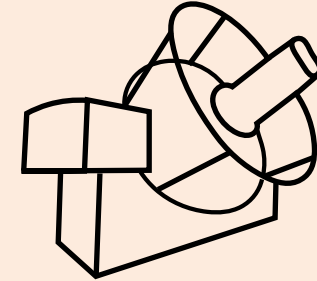
Guo+ 2023: JWST Early CEERS



Six barred galaxies $z > 1$, formed ~8–11 Gyr ago

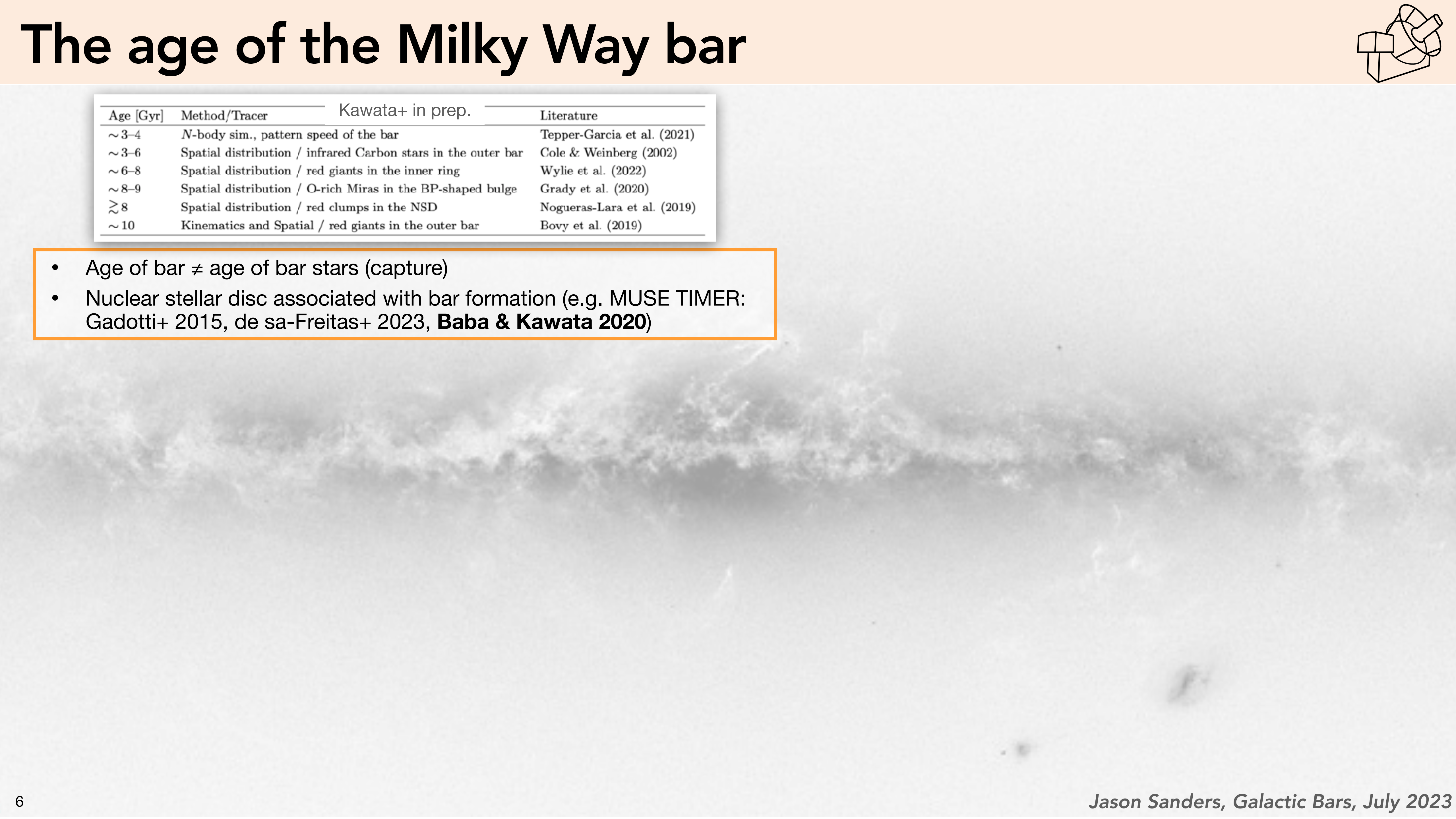
See also Jacobs+ 2022, Chen+ 2022, Ferreira+ 2022

The age of the Milky Way bar

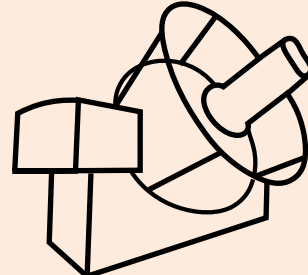


Age [Gyr]	Method/Tracer	Kawata+ in prep.	Literature
~ 3–4	<i>N</i> -body sim., pattern speed of the bar		Tepper-Garcia et al. (2021)
~ 3–6	Spatial distribution / infrared Carbon stars in the outer bar		Cole & Weinberg (2002)
~ 6–8	Spatial distribution / red giants in the inner ring		Wylie et al. (2022)
~ 8–9	Spatial distribution / O-rich Miras in the BP-shaped bulge		Grady et al. (2020)
≥ 8	Spatial distribution / red clumps in the NSD		Nogueras-Lara et al. (2019)
~ 10	Kinematics and Spatial / red giants in the outer bar		Bovy et al. (2019)

- Age of bar ≠ age of bar stars (capture)
- Nuclear stellar disc associated with bar formation (e.g. MUSE TIMER: Gadotti+ 2015, de sa-Freitas+ 2023, **Baba & Kawata 2020**)



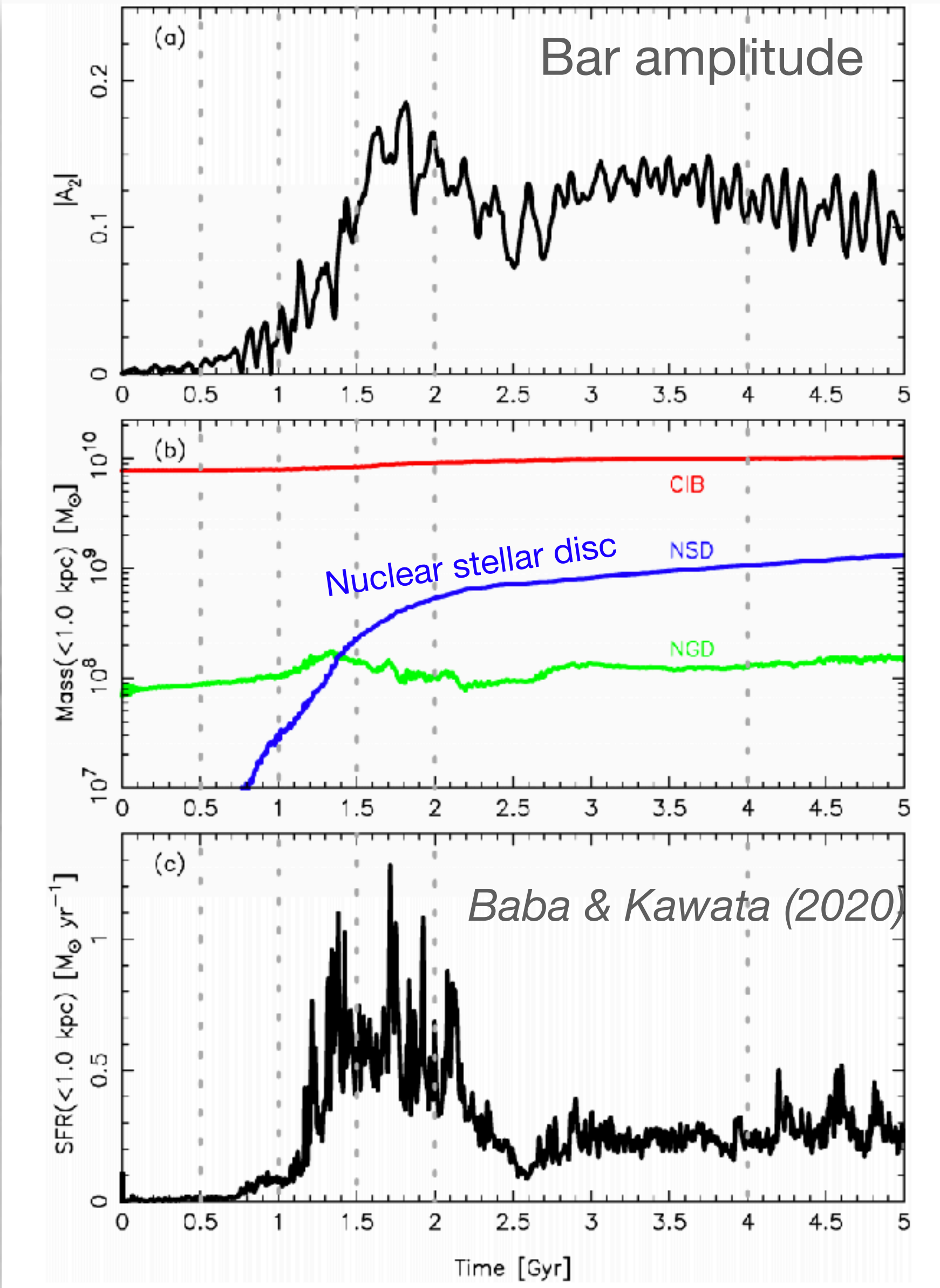
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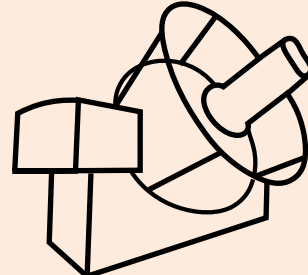
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Controlled simulation

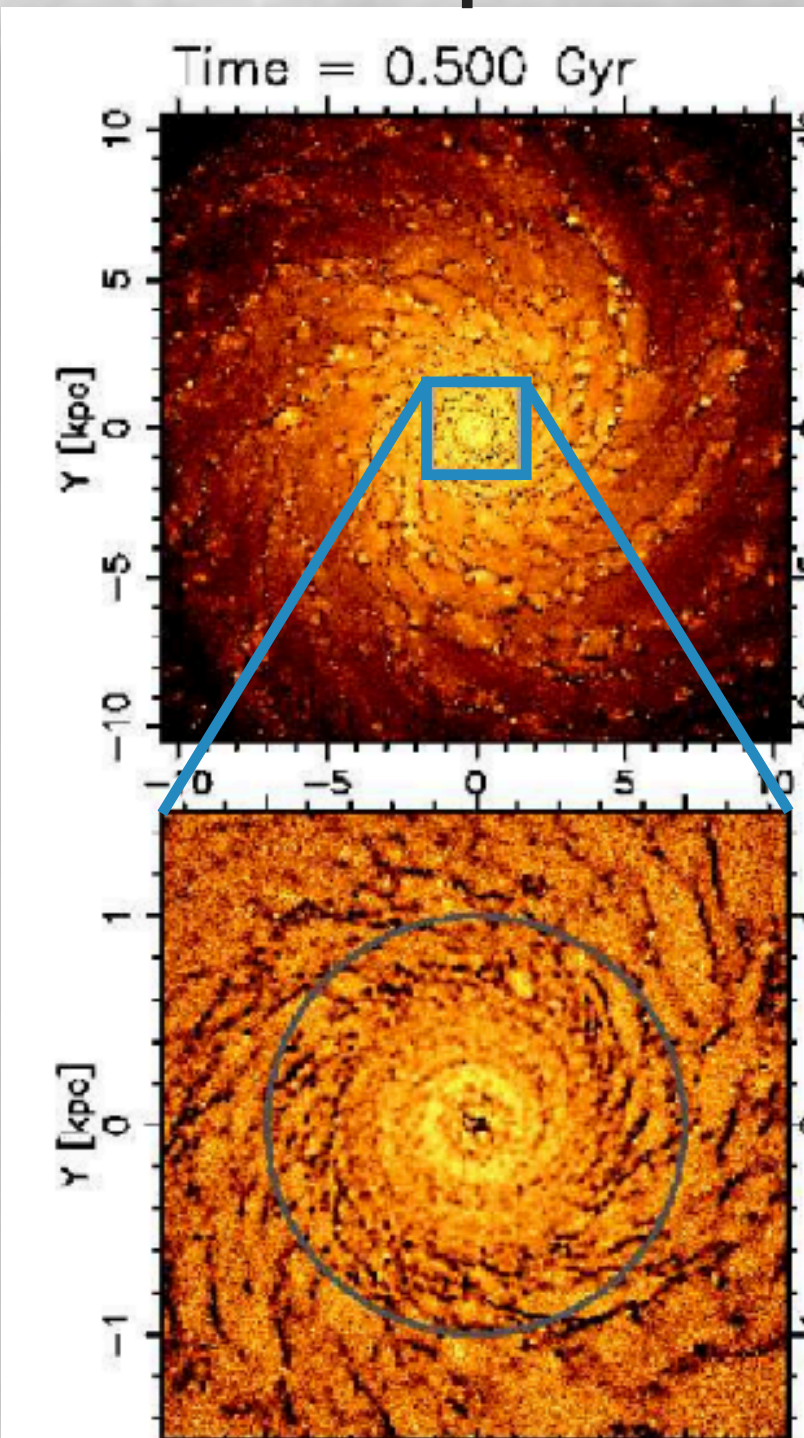


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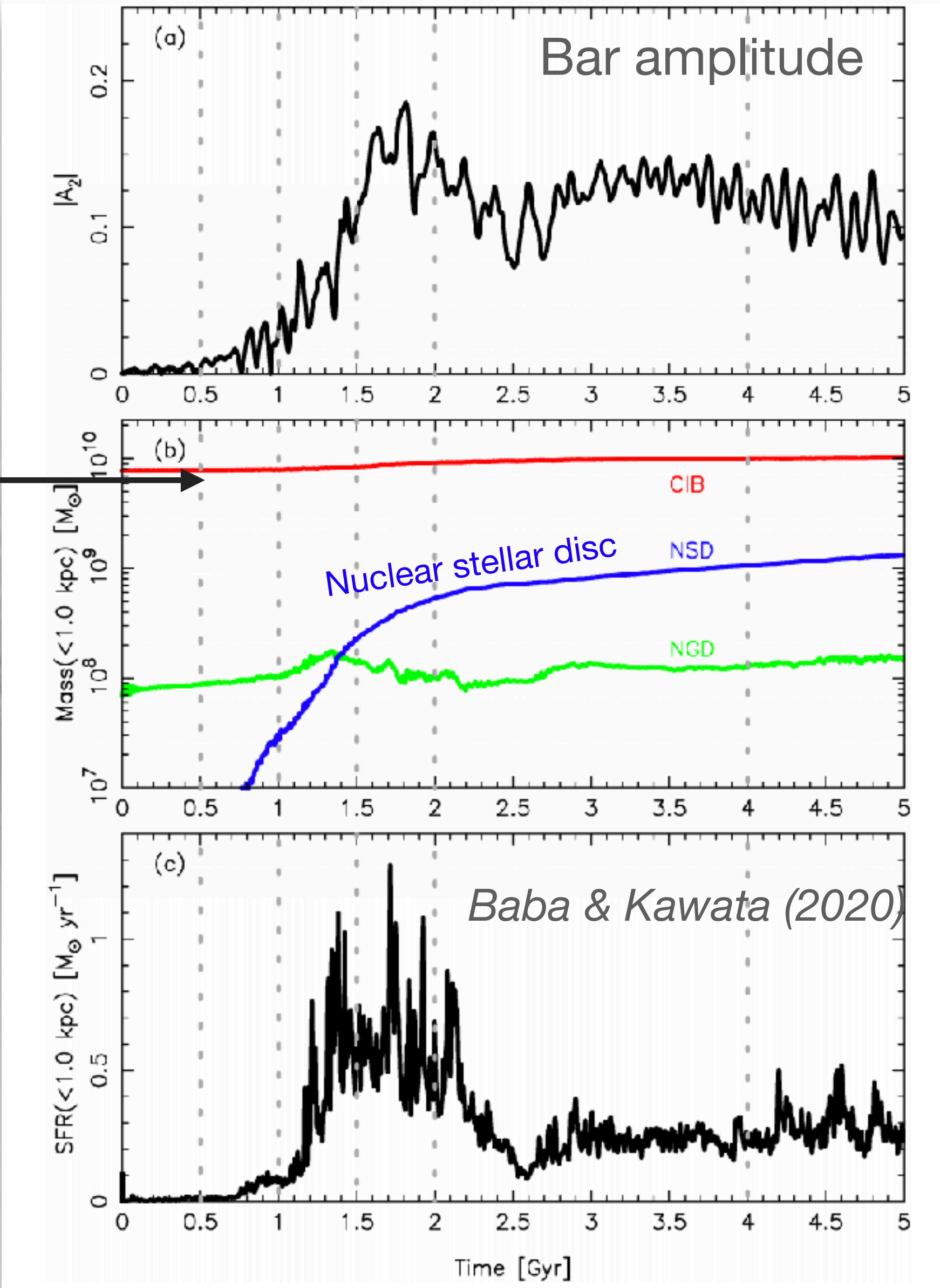


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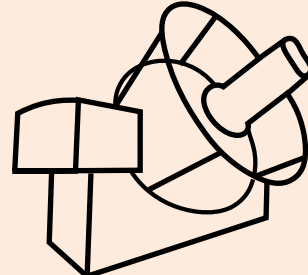
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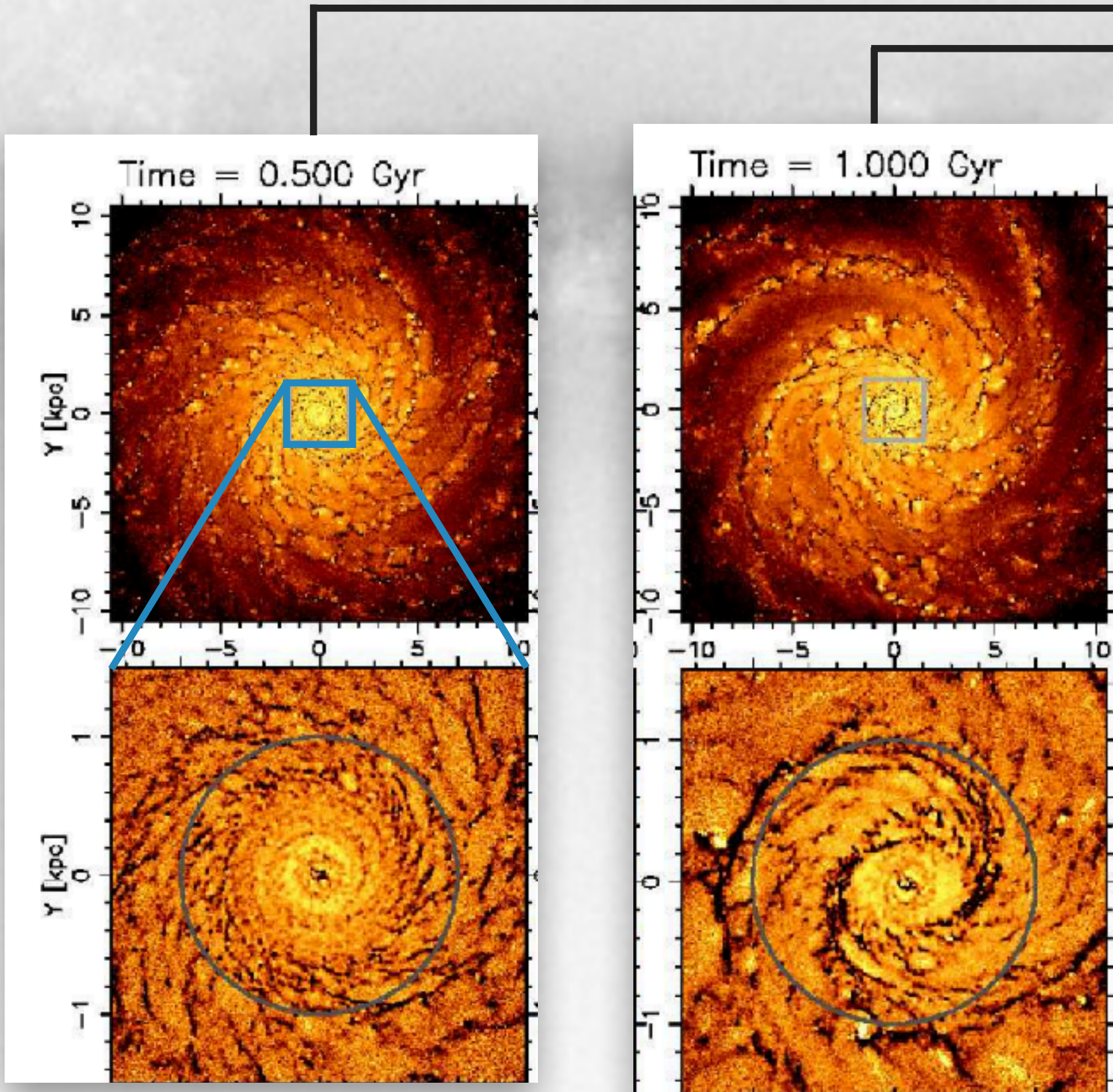


The age of the Milky Way bar

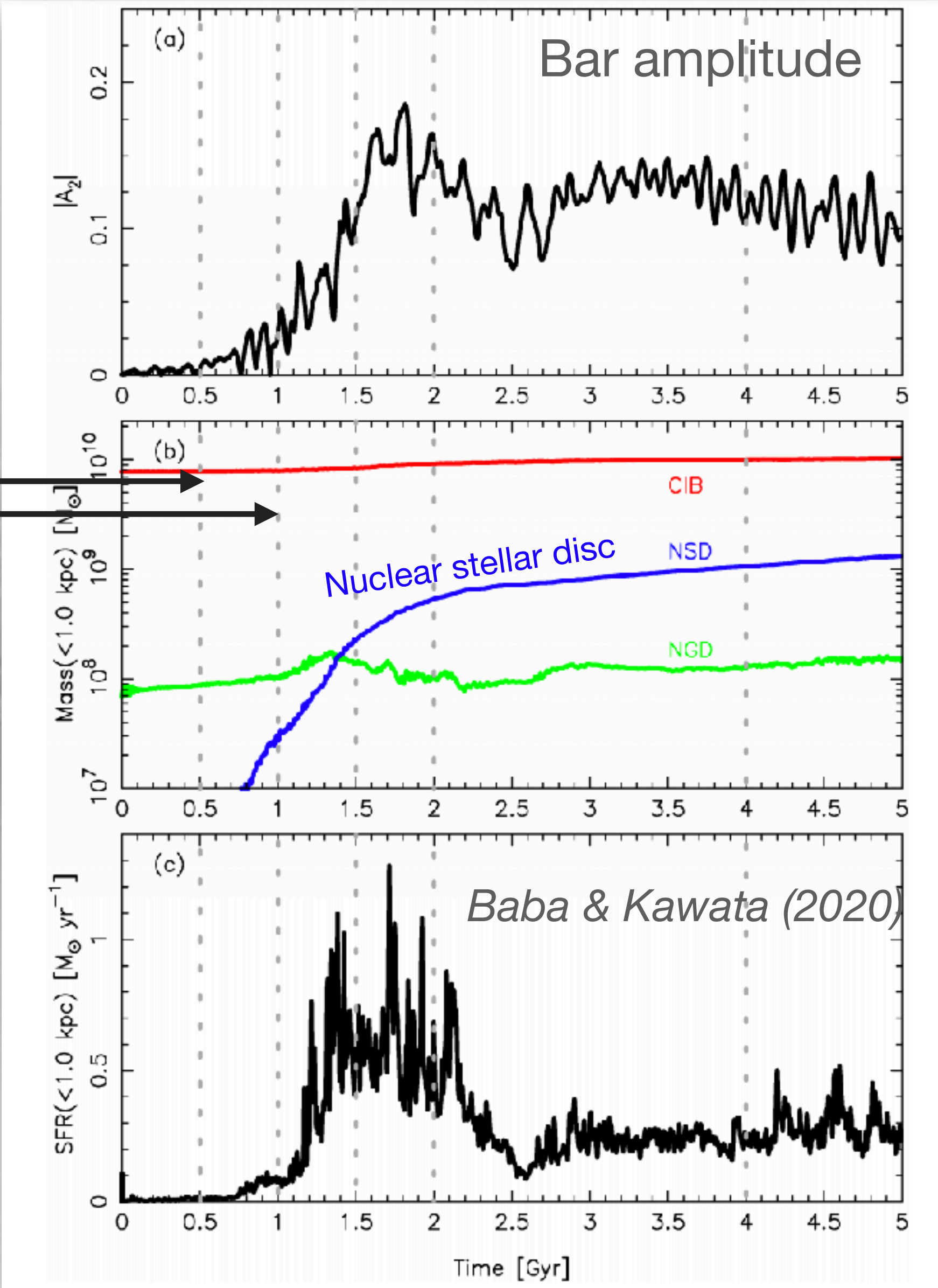


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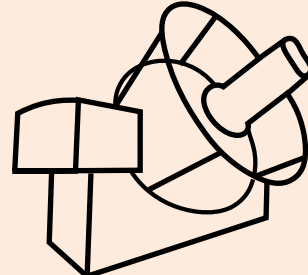
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Controlled simulation

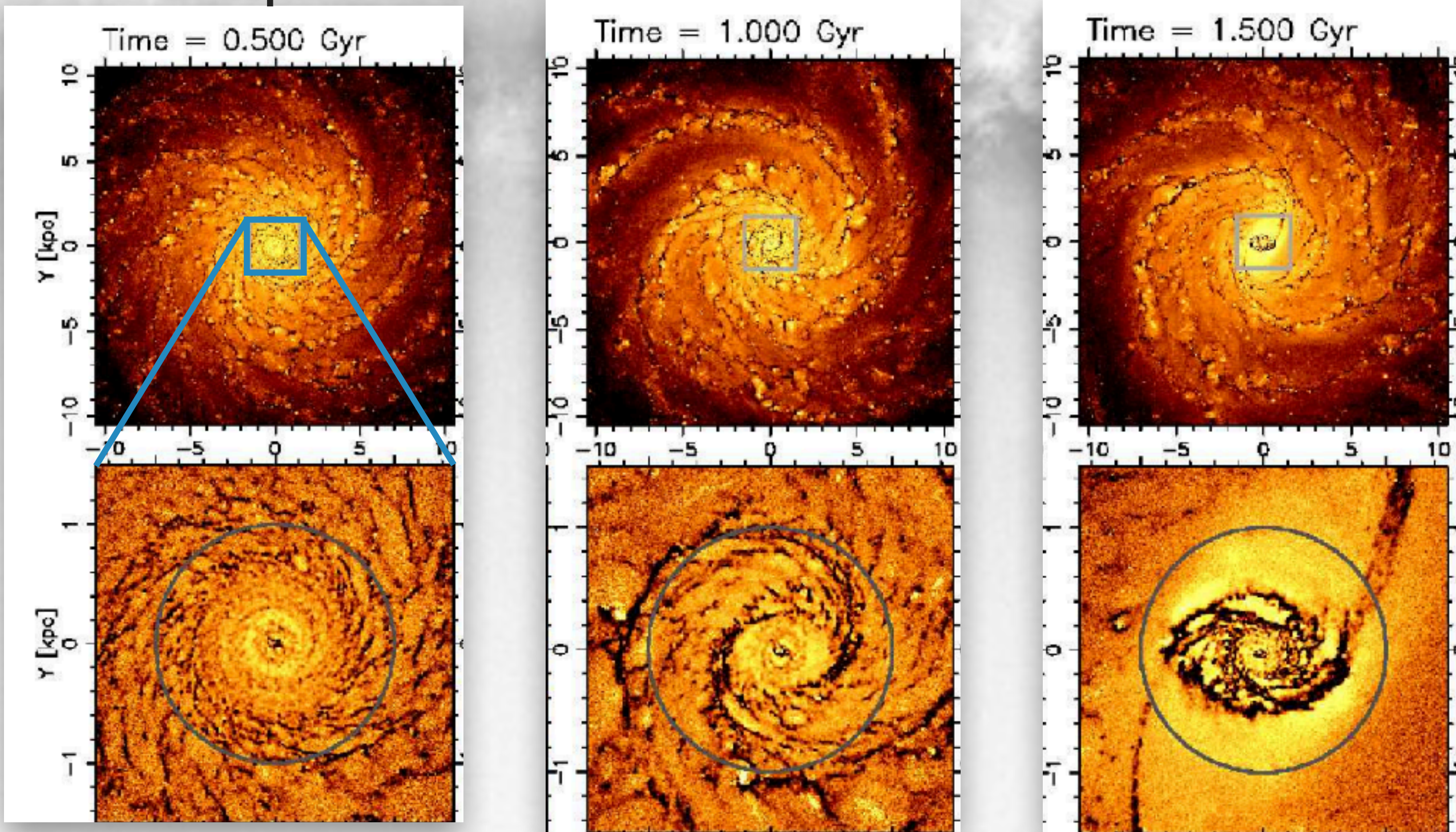


The age of the Milky Way bar

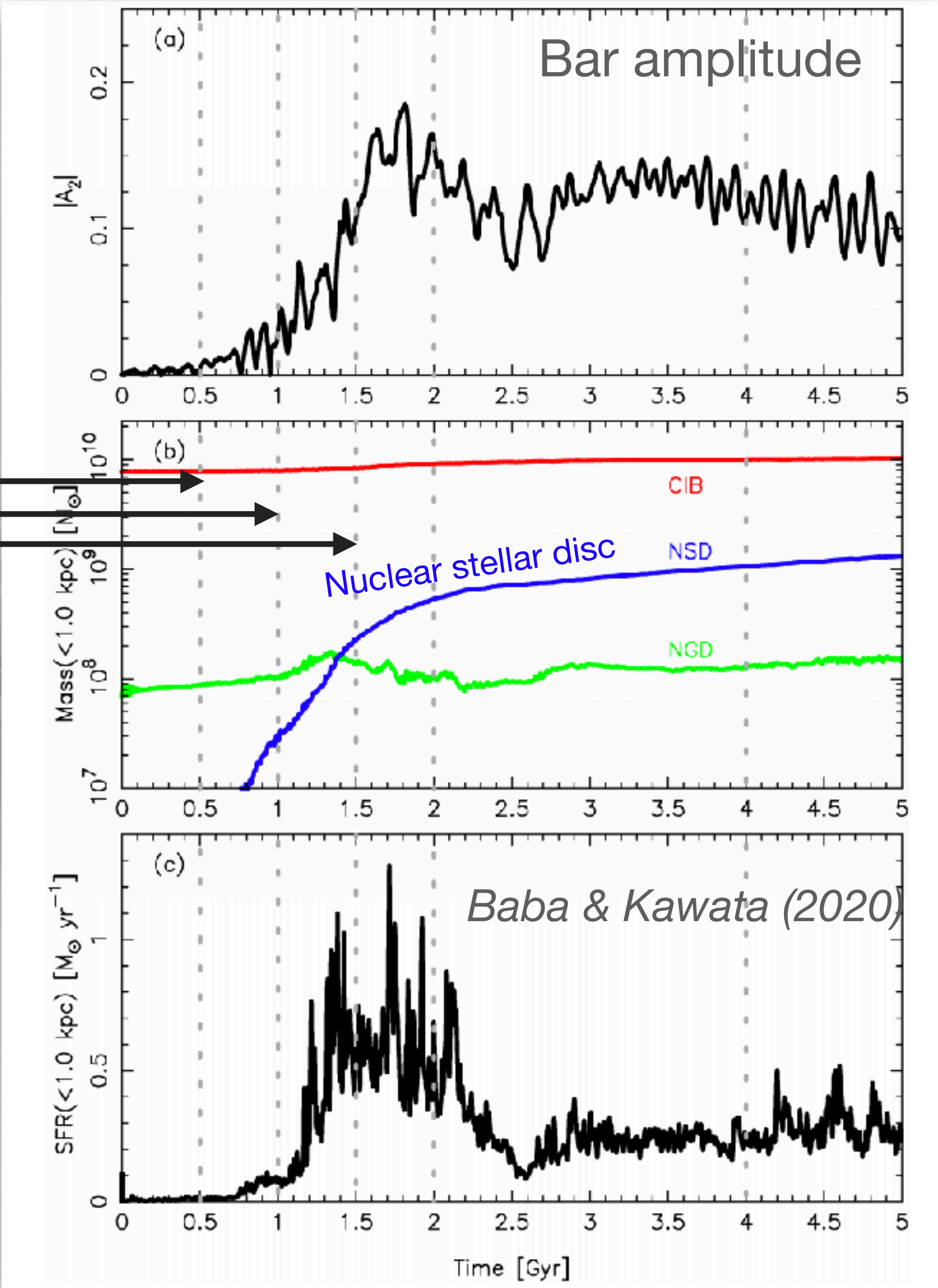


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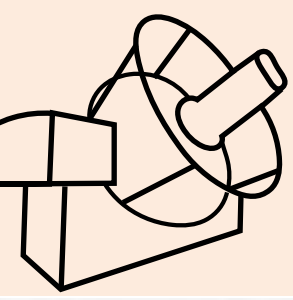
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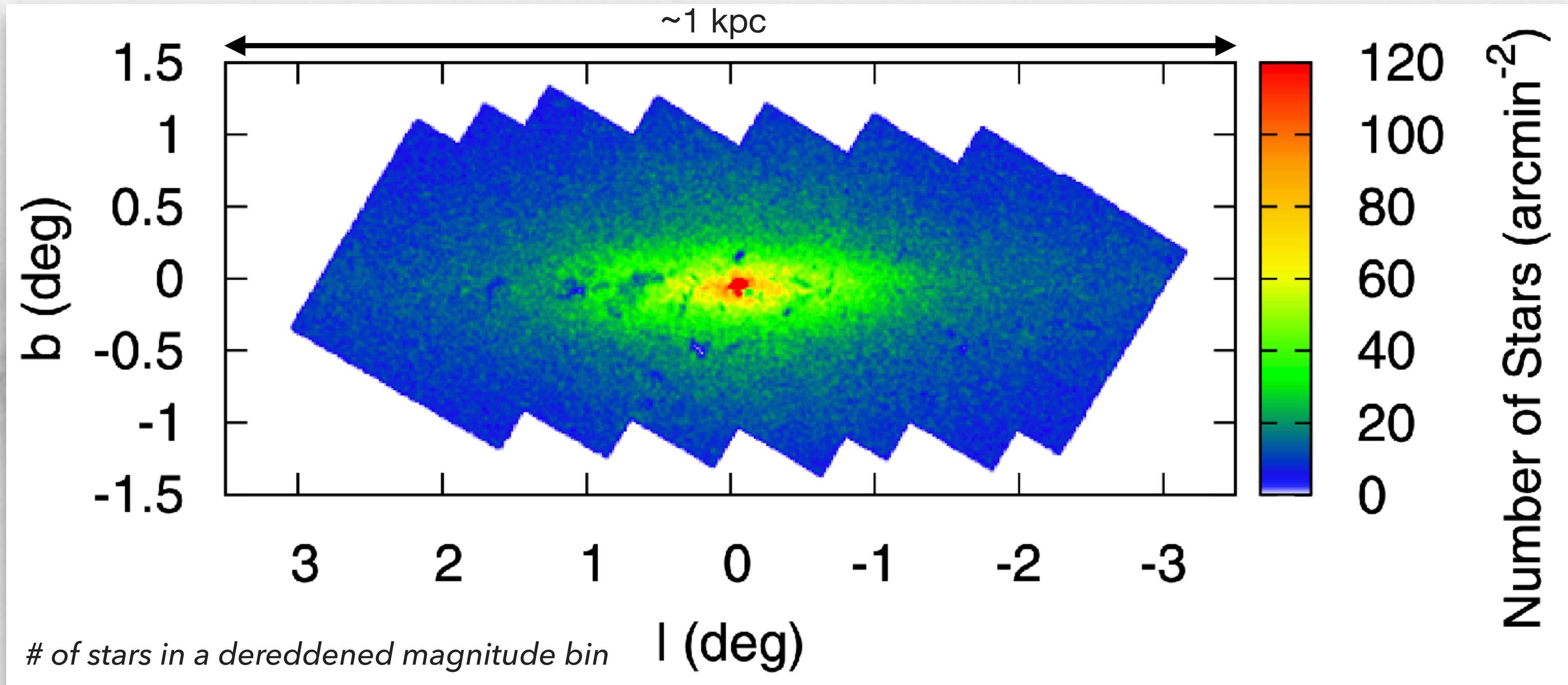
Controlled simulation



Structure of the Milky Way Nuclear Stellar Disc

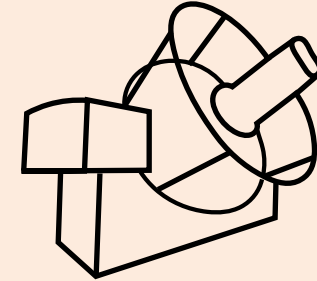


Nishiyama+ 2013

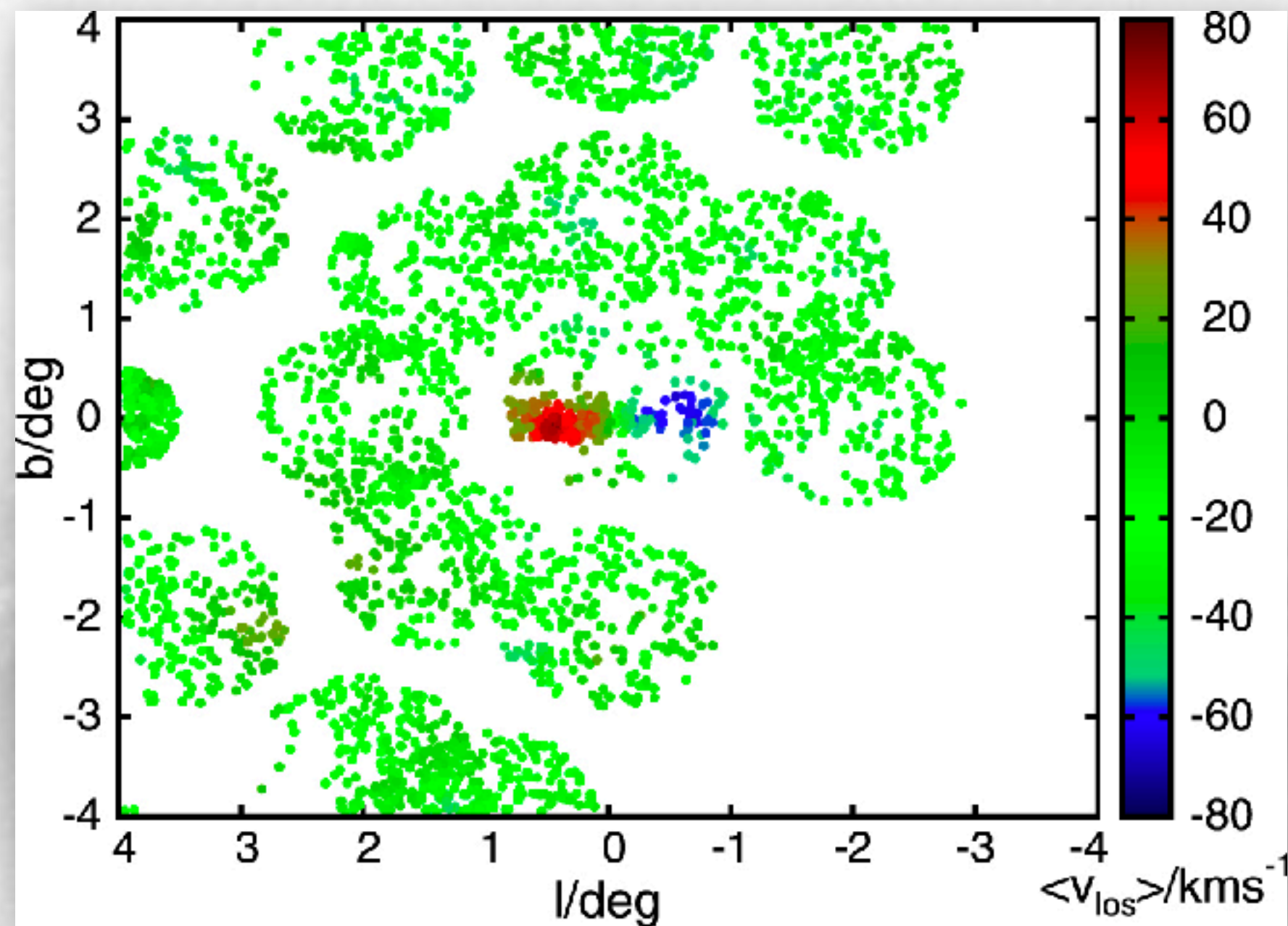


Morphology (disc or bar?): Alard+ (2001); Launhardt+ 2002, Gonzalez+ 2012, Gerhard+ 2012

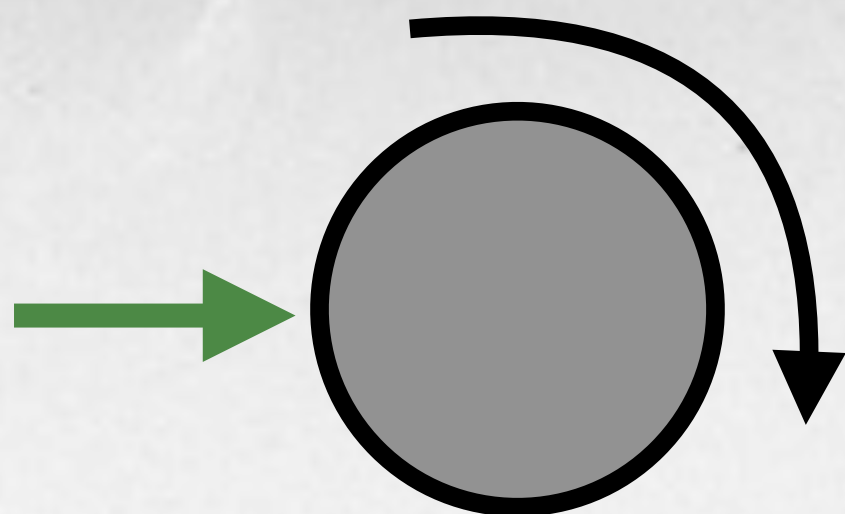
Kinematics of the Milky Way Nuclear Stellar Disc



Line-of-sight velocity Schoenrich+ 2015

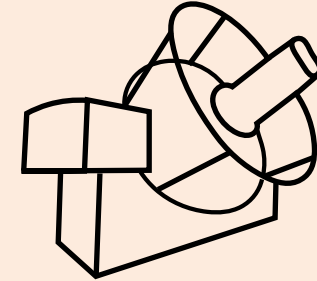


$\langle v \rangle \sim 80 \text{ km/s}$

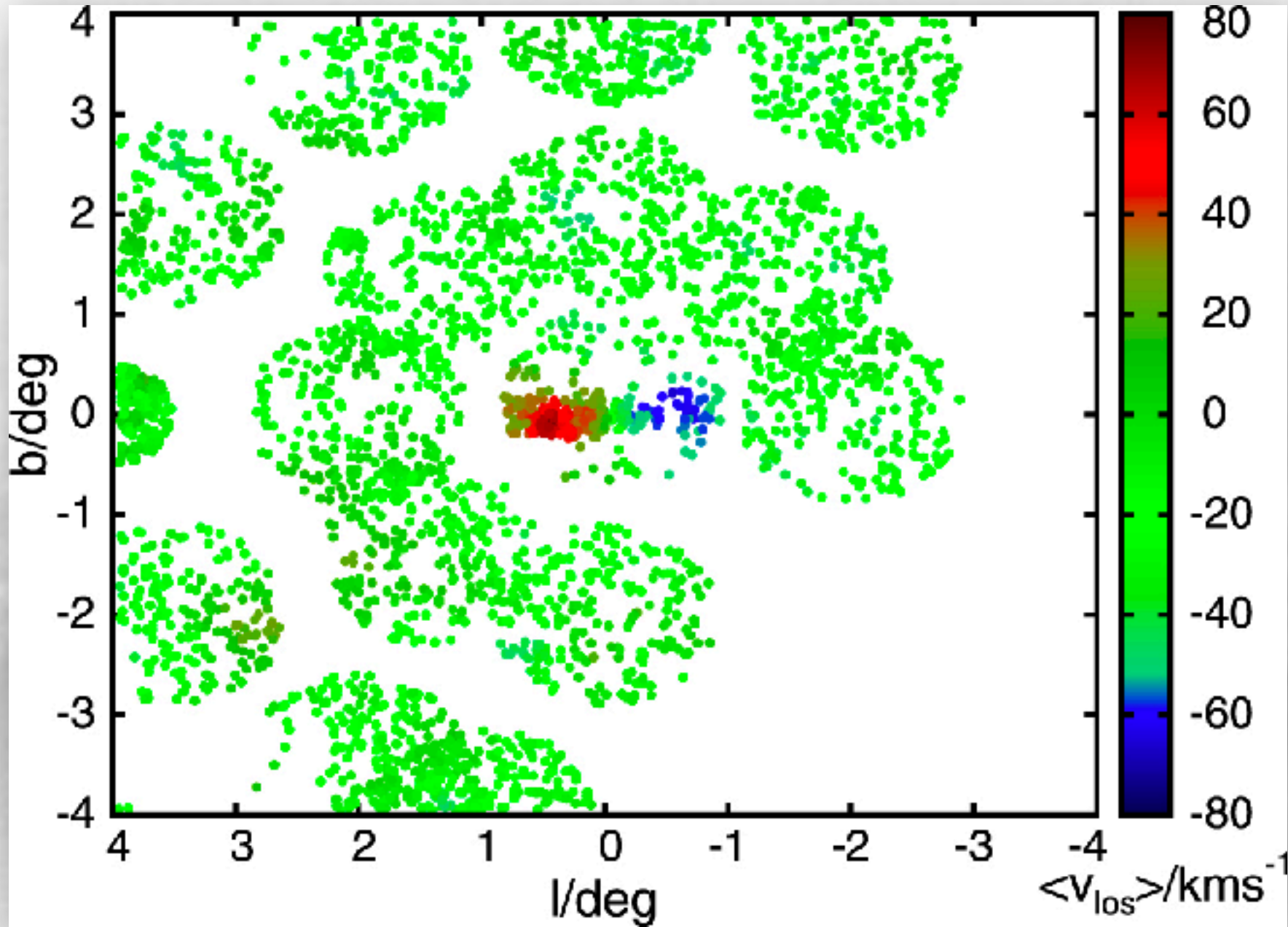


Kinematics: Lindqvist+ (1992), Habing+ (2006), Schoenrich+ (2015), Shahzamanian+ 2022, Schultheis+ 2022

Kinematics of the Milky Way Nuclear Stellar Disc

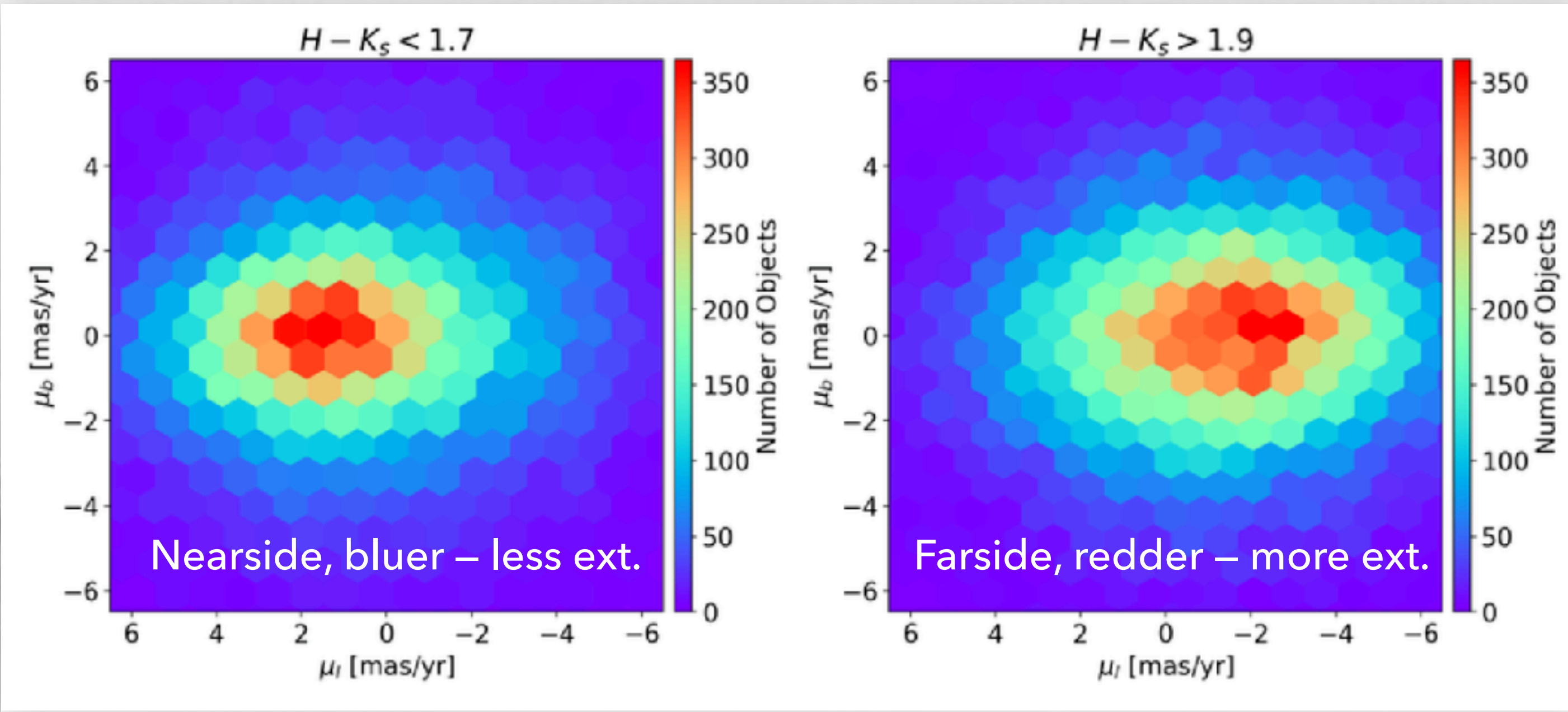


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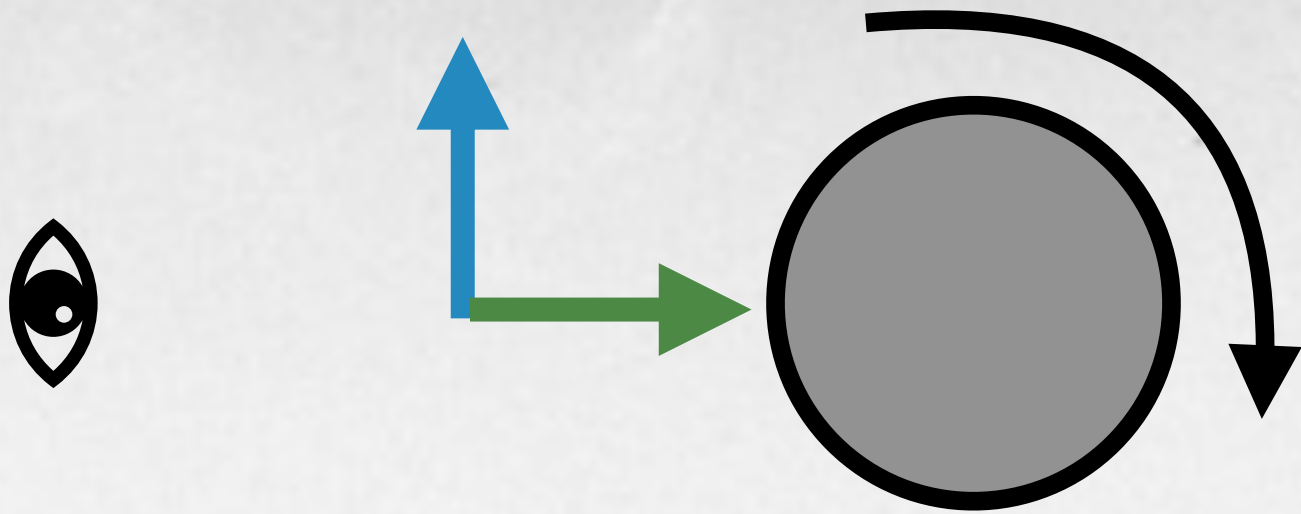


Proper motions

Shahzamanian+ 2022

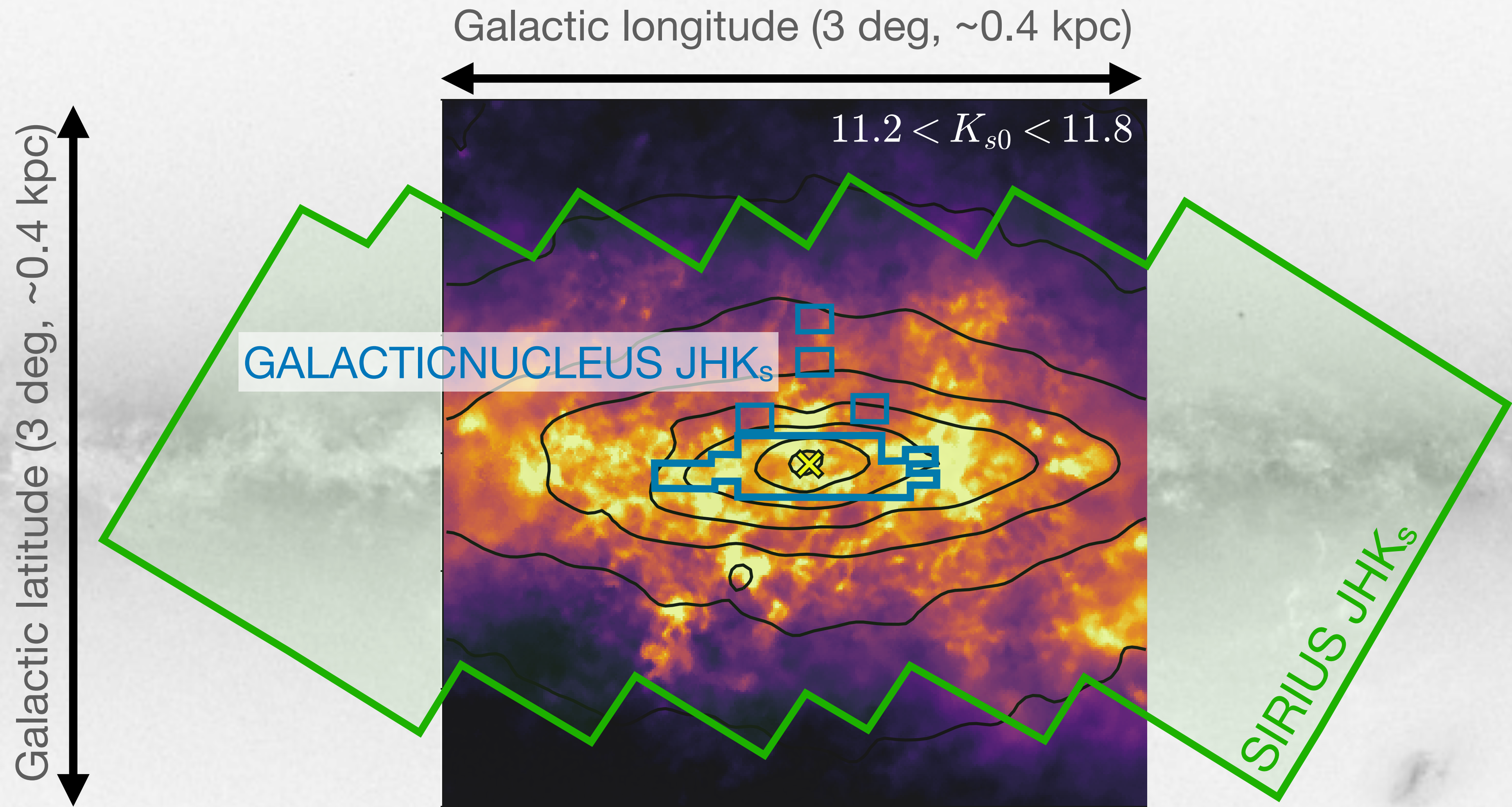
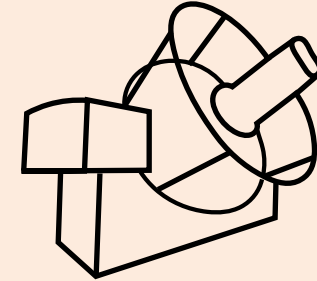


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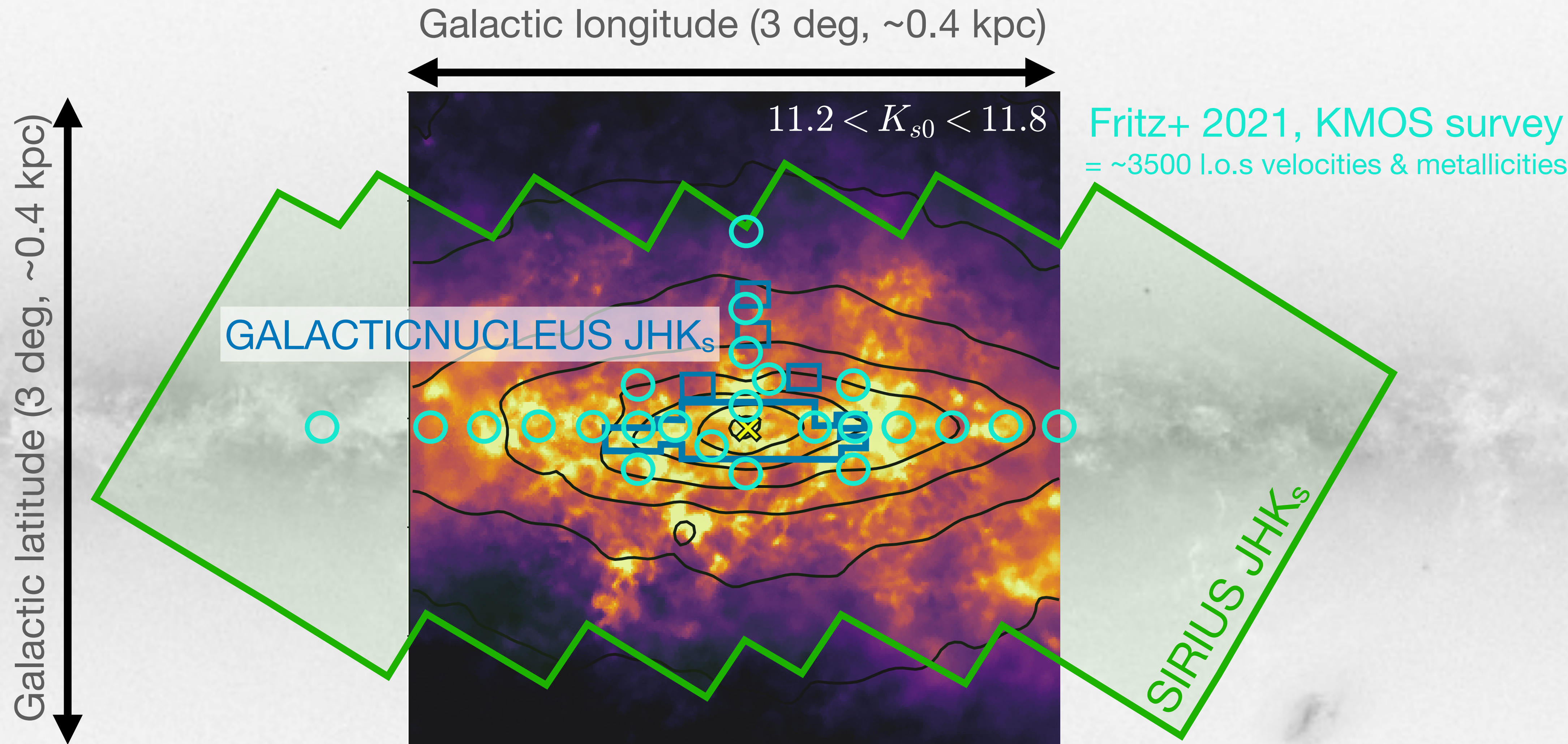
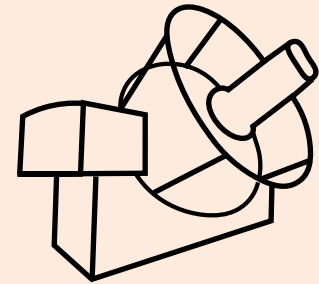


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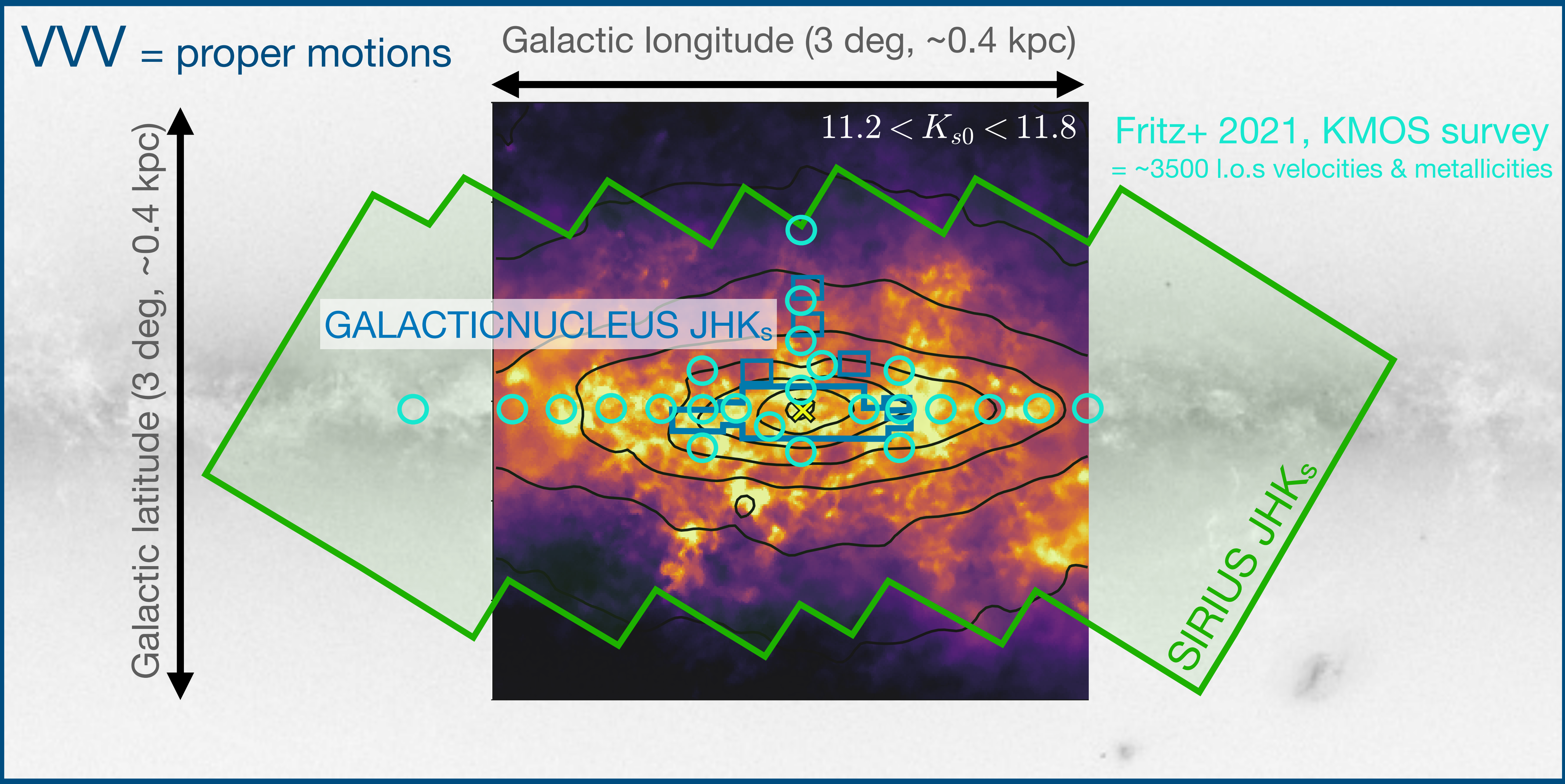
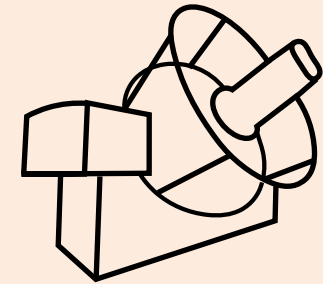
Current generation of surveys: Nuclear Stellar Disc

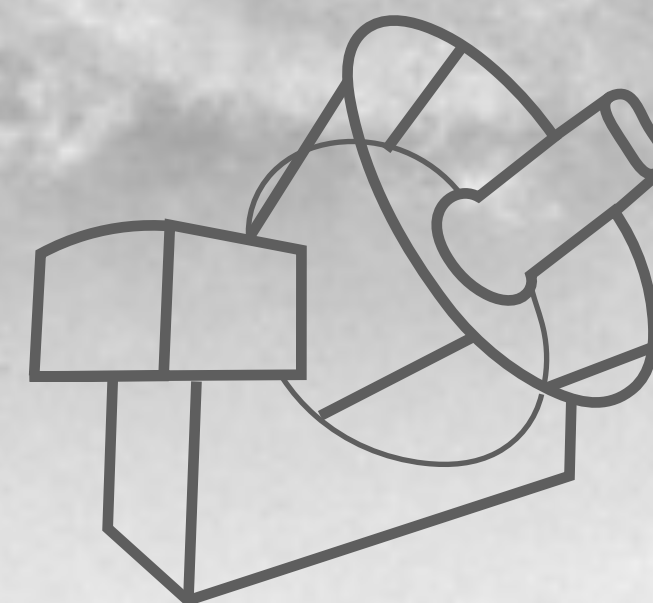
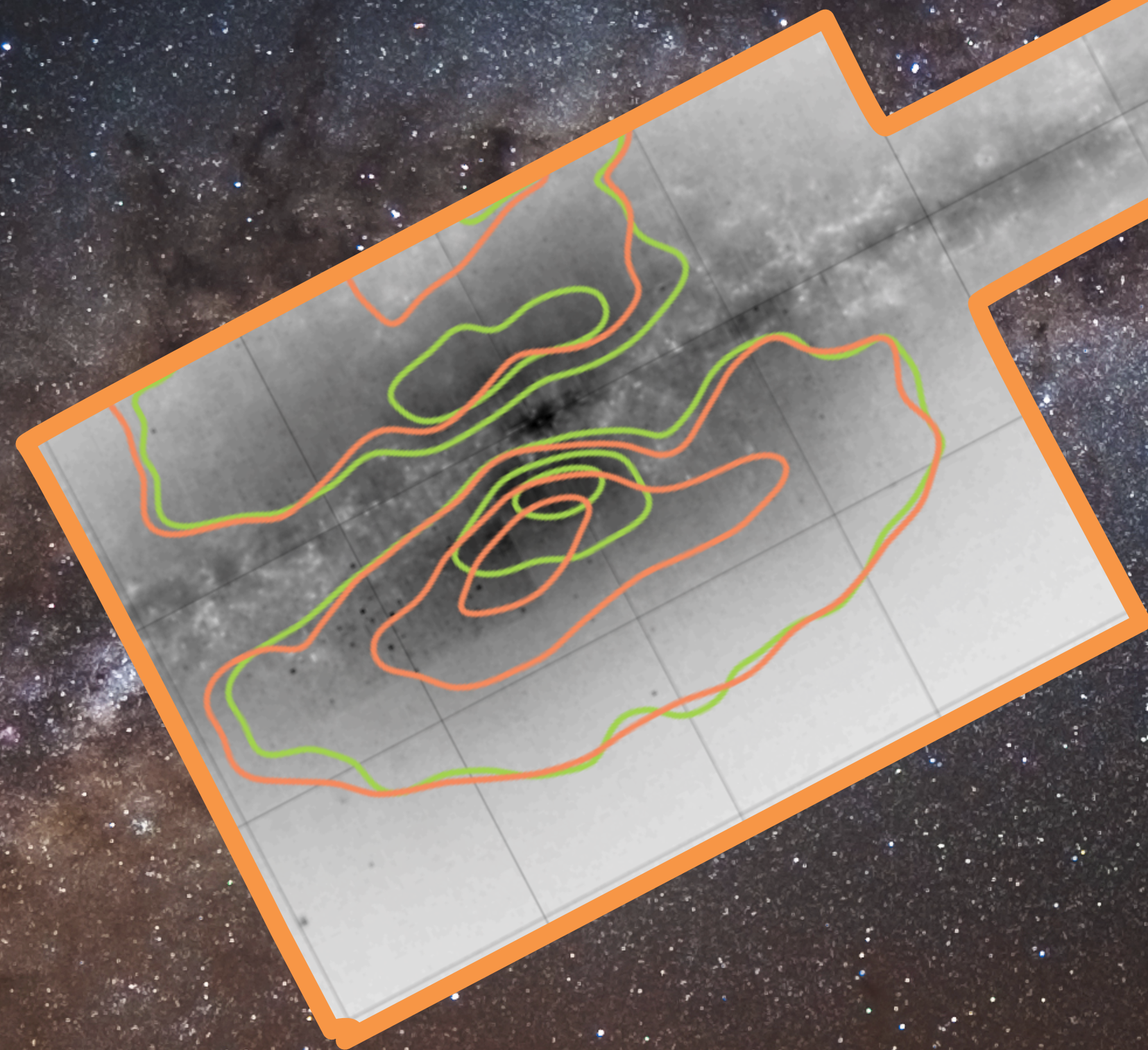


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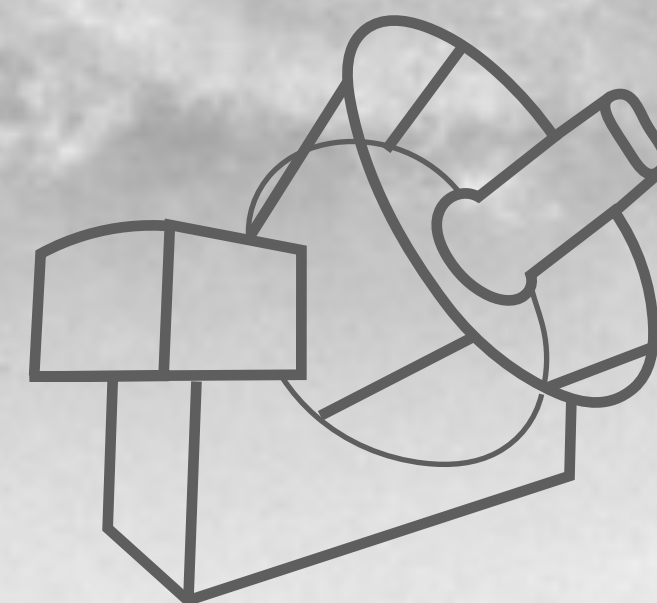
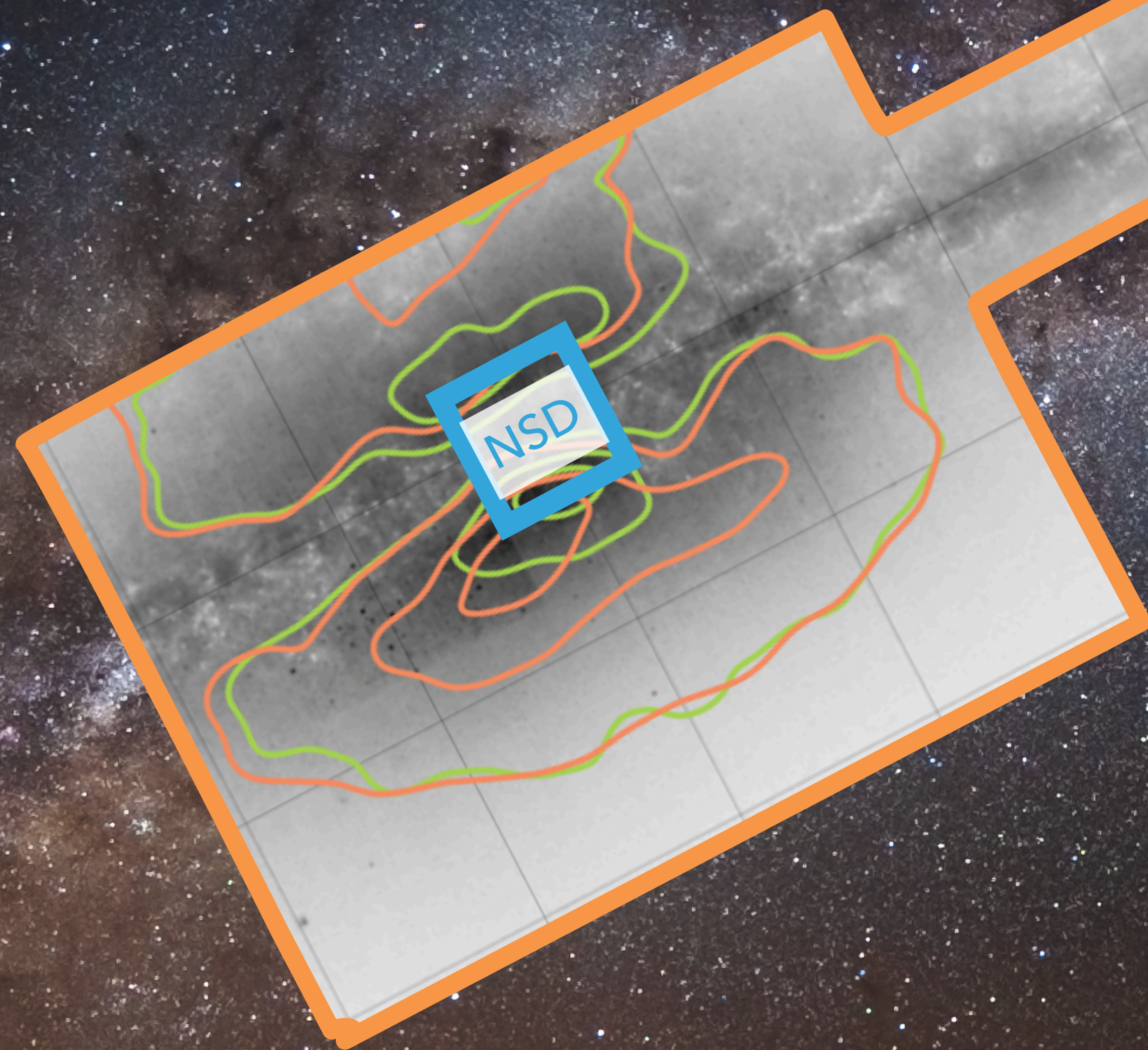




VVV Survey

VISTA Variables in Via Lactea
~500 million light curves
Observations over ~10 years, ~200 Ks epochs
ZYJHKs (sees through dust)

Jason Sanders, Galactic Bars, July 2023

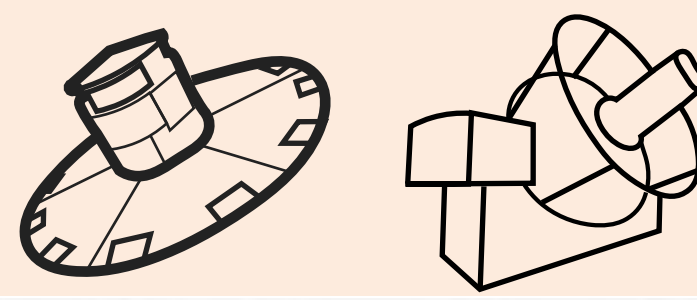


VVV Survey

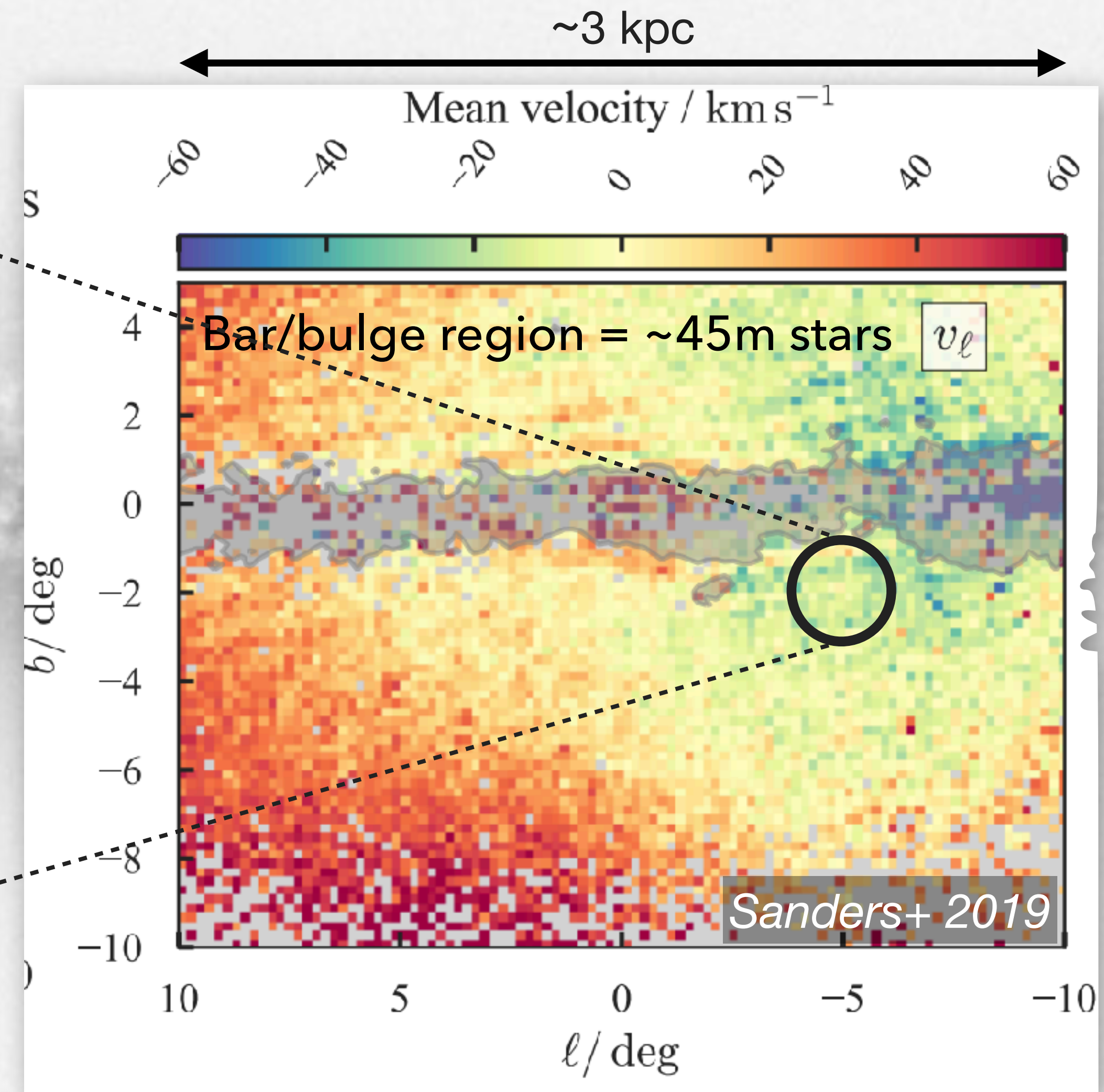
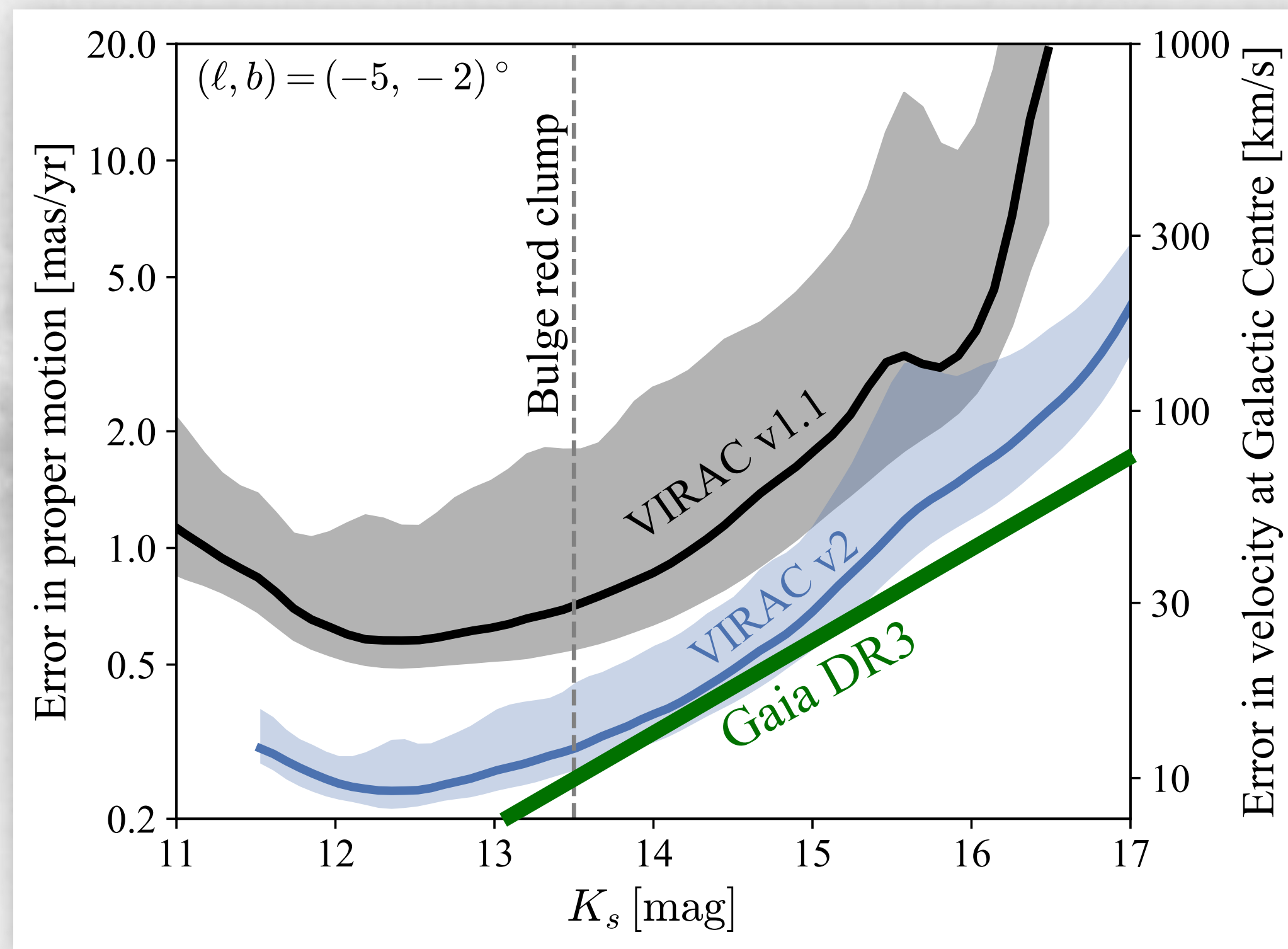
VISTA Variables in Via Lactea
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VV (VIRAC) proper motions

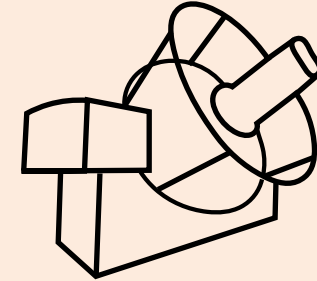


- Absolute proper motions for first time **anchored to Gaia DR3** (Smith+ 2018, Sanders+ 2019, Clarke+ 2019, Smith+ in prep.)
- Previously relative (e.g. Rattenbury+ 2007, Vieira+ 2007, Koslowski+ 2006)

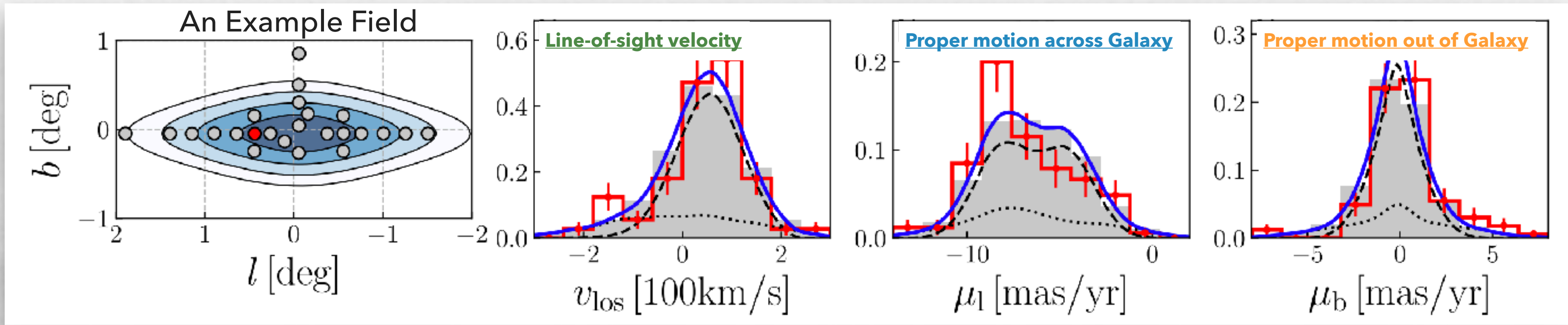


- Used by Sanders+2019, Clarke+19,21 to measure pattern speed via Tremaine-Weinberg method & M2M

Dynamical modelling of NSD



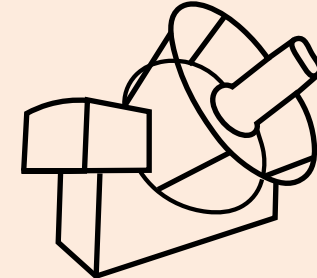
Self-consistent axisymmetric modelling using action-based models of *VVV proper motions* + *Fritz+ 2021 spectroscopy*
Mass: $\sim 1e9$ Msun, Scalelength ~ 90 pc, Scaleheight ~ 30 pc



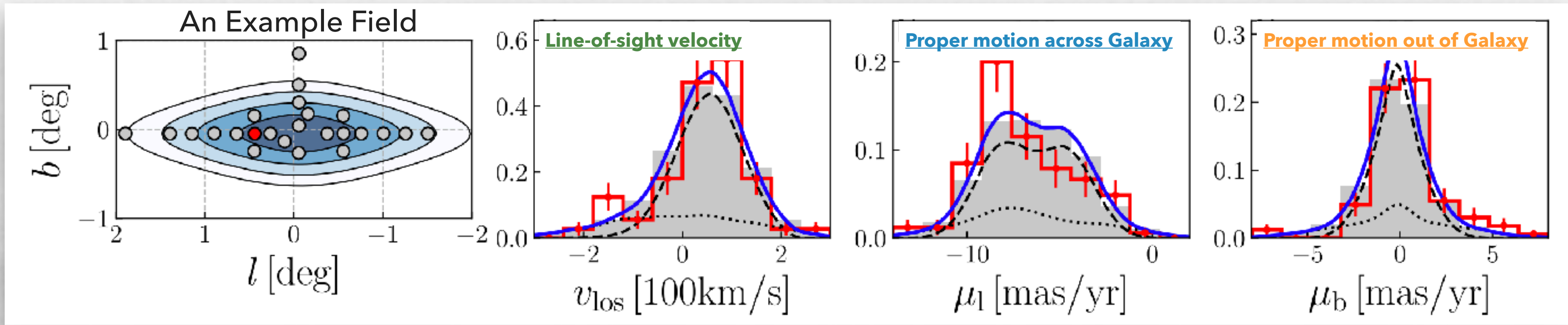
$$\rho_{\text{NSD}}(\boldsymbol{x}) = \int d^3\boldsymbol{v} f(\boldsymbol{J}[\boldsymbol{x}, \boldsymbol{v}|\Phi])$$
$$\nabla^2\Phi = 4\pi G(\rho_{\text{NSD}} + \rho_{\text{other}})$$

**spatial distribution not used in analysis*
Jason Sanders, Galactic Bars, July 2023

Dynamical modelling of NSD

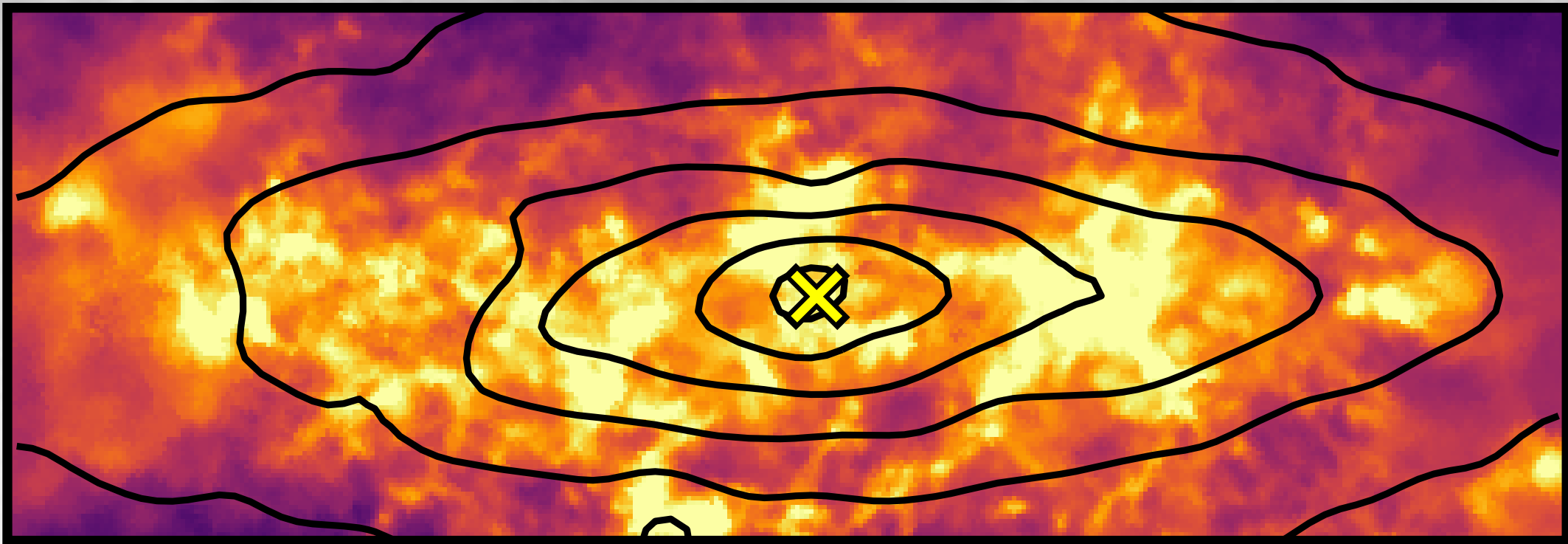


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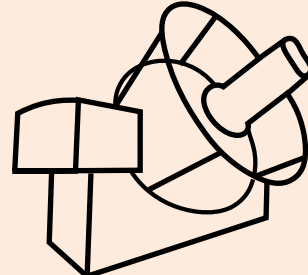
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Density of AGB bump stars

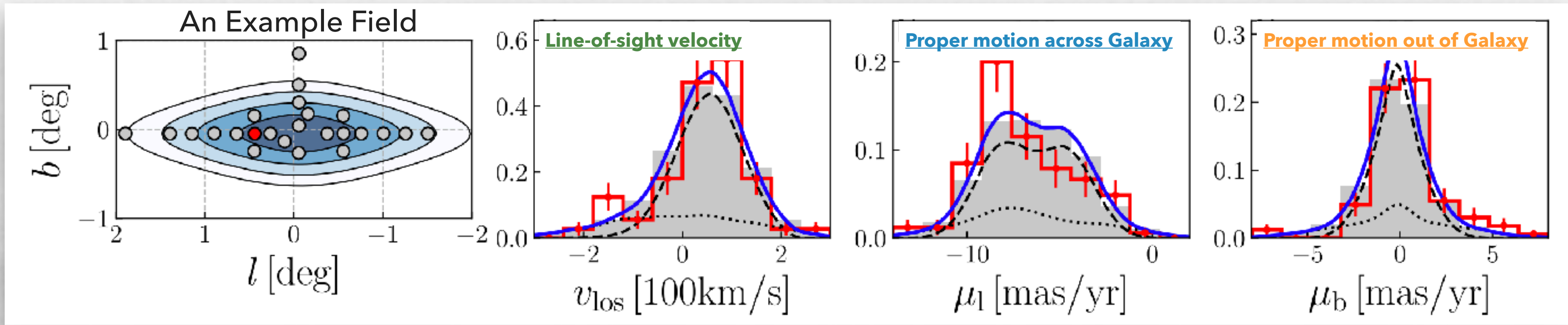


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Jason Sanders, Galactic Bars, July 2023

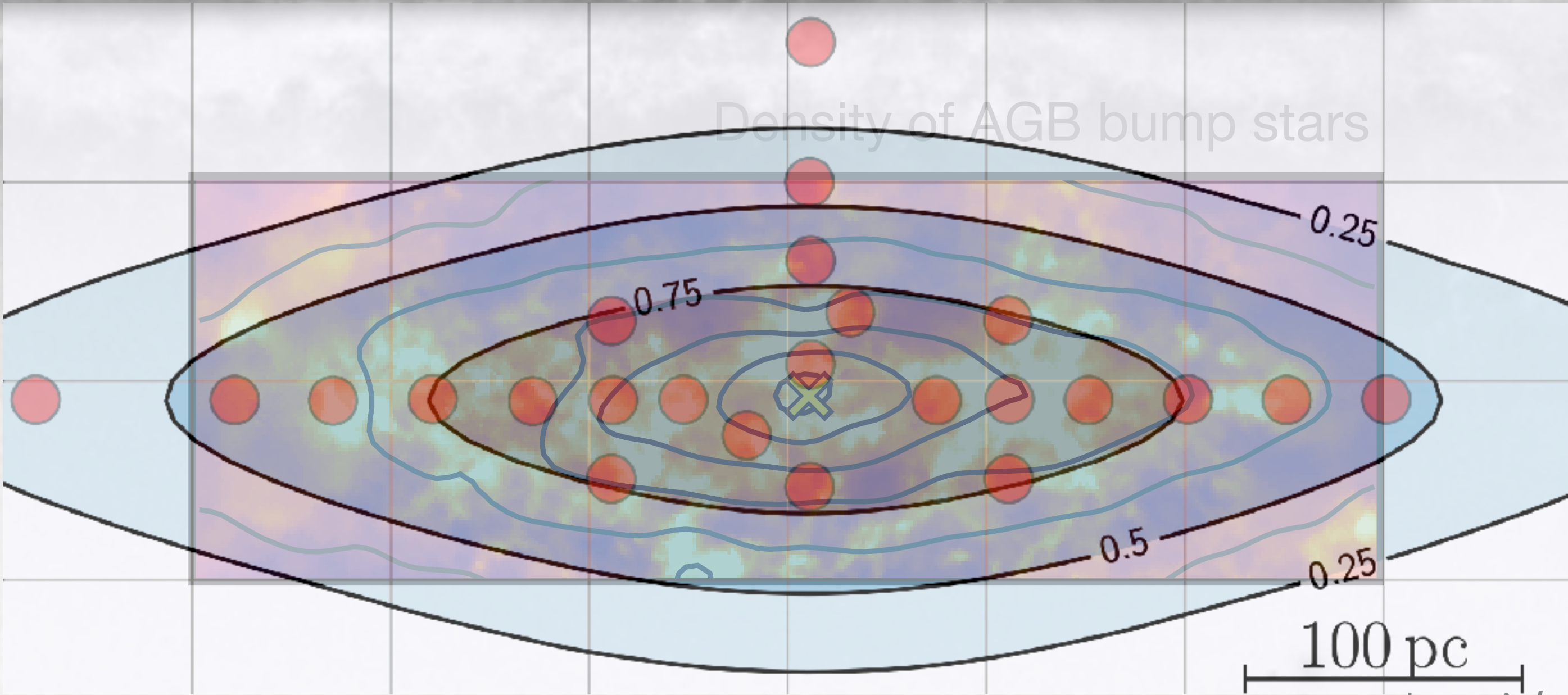
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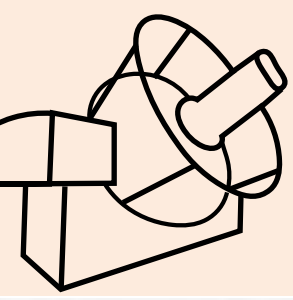
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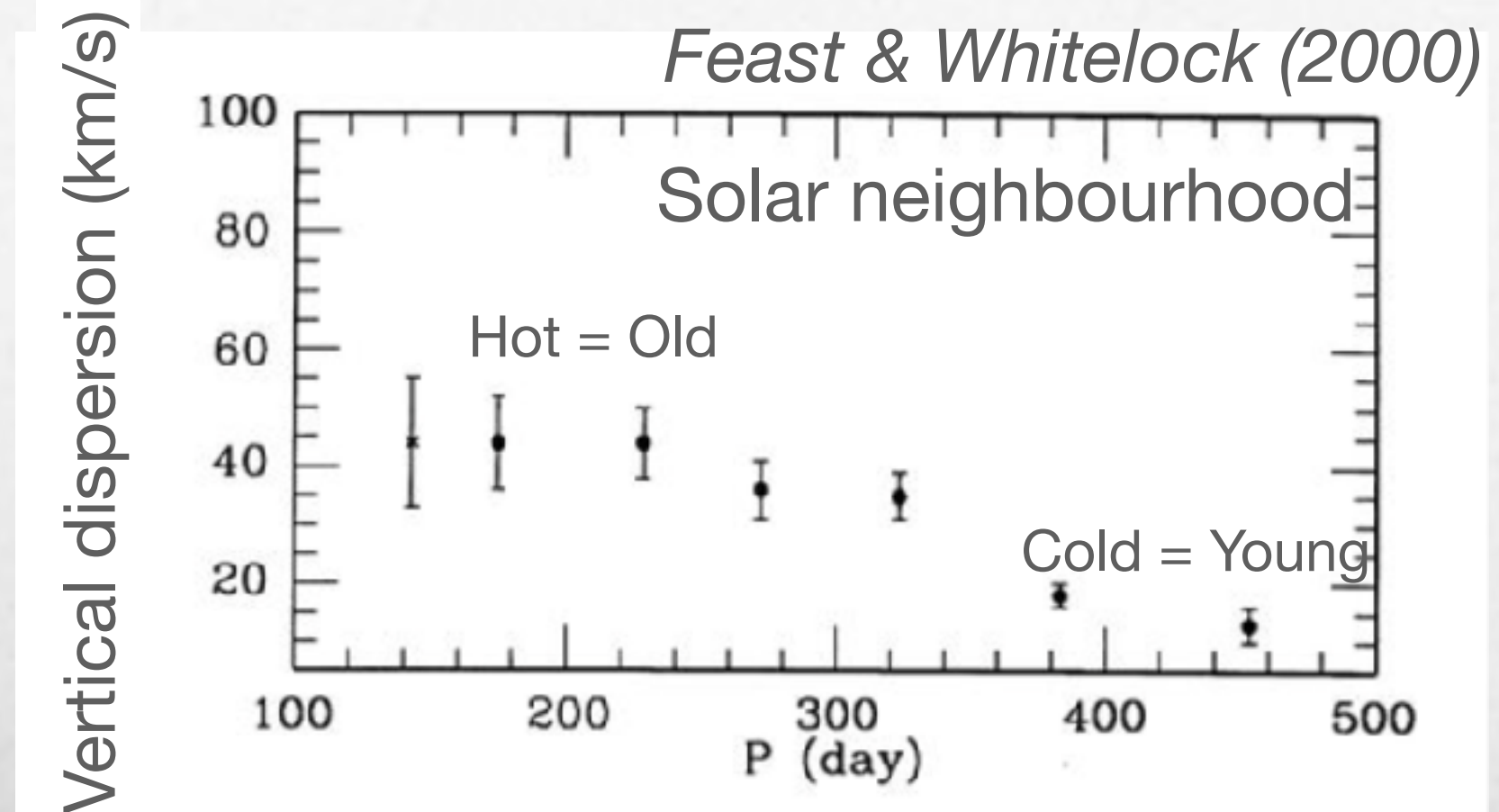
*spatial distribution not used in analysis

Jason Sanders, Galactic Bars, July 2023

Returning to the question: how old is the NSD?



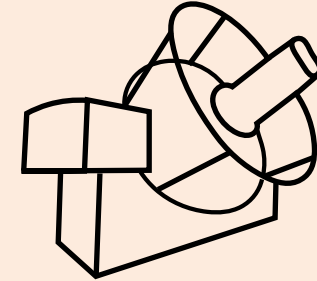
- **High amplitude** ($\Delta K_s \gtrsim 0.3$) thermally pulsing asymptotic giant branch stars (periods 80-1000 days)
- **Bright:** $M_{K_s} \sim -7$ (for period=200 days) & **low contamination**
- Used for disc (Grady+19,21) and bar/bulge studies (Catchpole+15, Semczuk+22)
- ~1800 Mira variables in VVV with proper motions (Sanders+22)



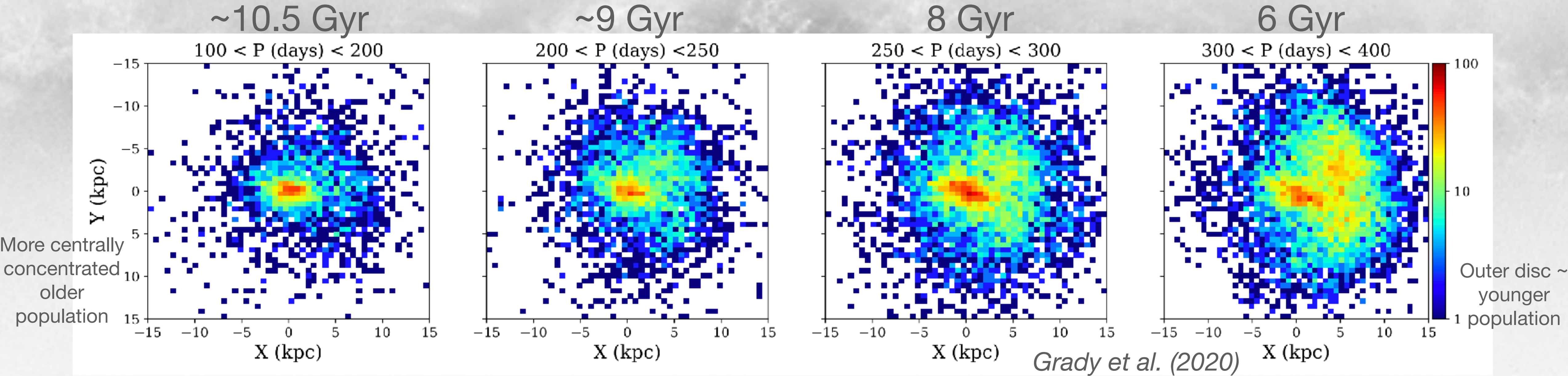
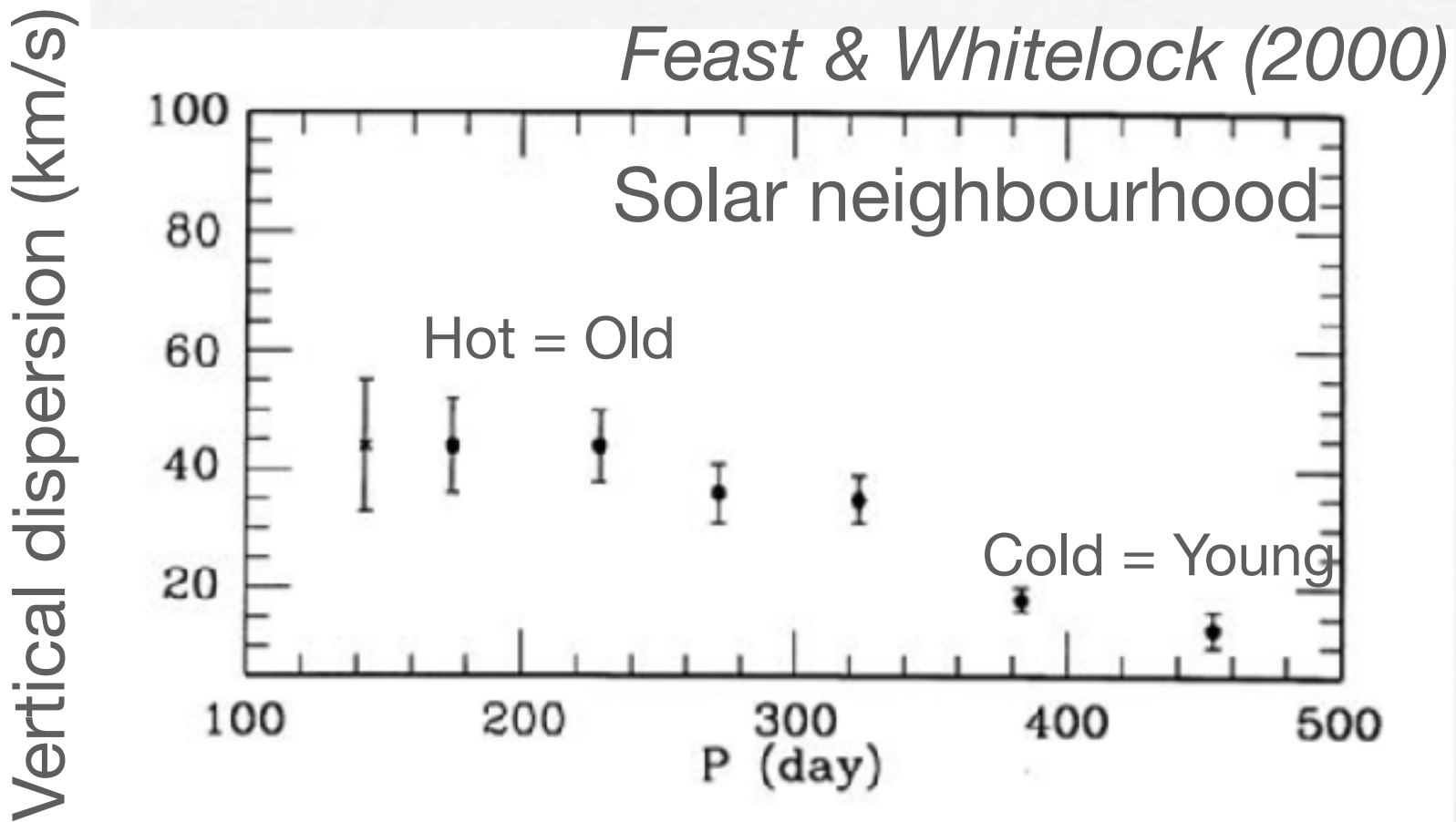
See also Marcin Semczuk poster

Jason Sanders, Galactic Bars, July 2023

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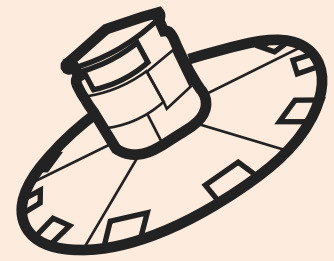


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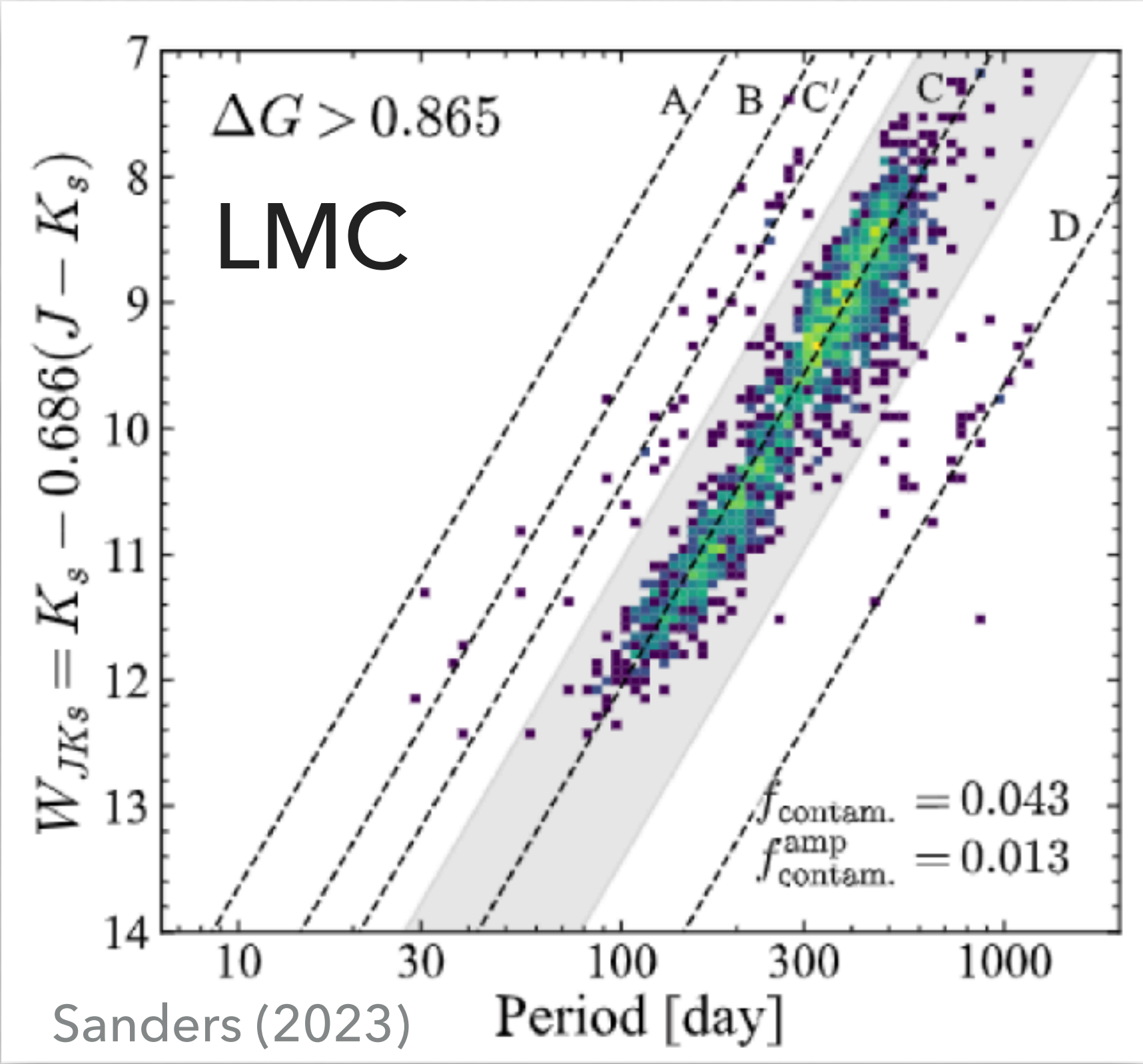
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Jason Sanders, Galactic Bars, July 2023

Mira variable period-age relation calibration with Gaia DR3



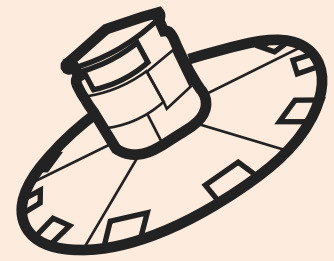
Gaia DR3 Mira variables

- Lebzelter+ 2022 (Gaia DR3 LPV catalogue): periods and amplitudes
- Fit action-based dynamical models
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Useful for Hubble tension too...

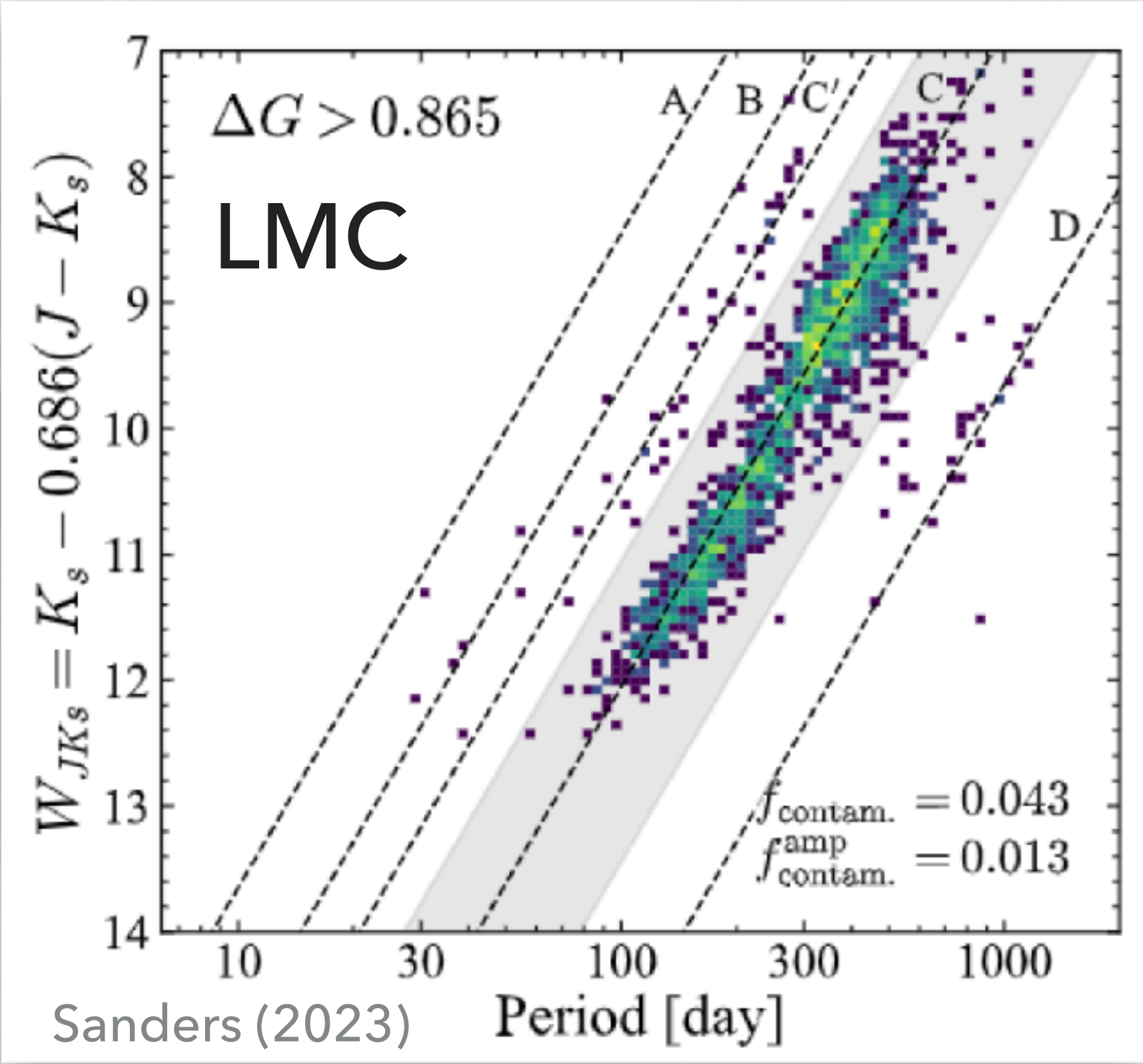
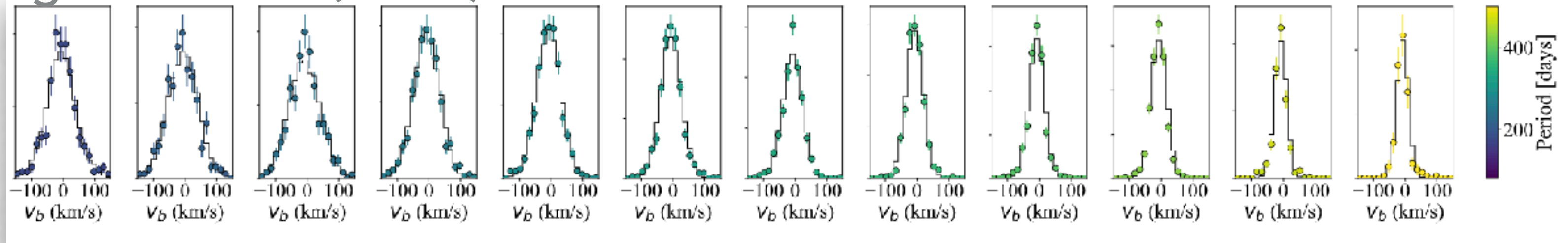
Mira variable period-age relation calibration with Gaia DR3



Gaia DR3 Mira variables

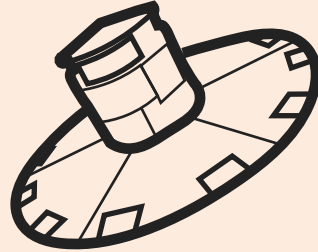
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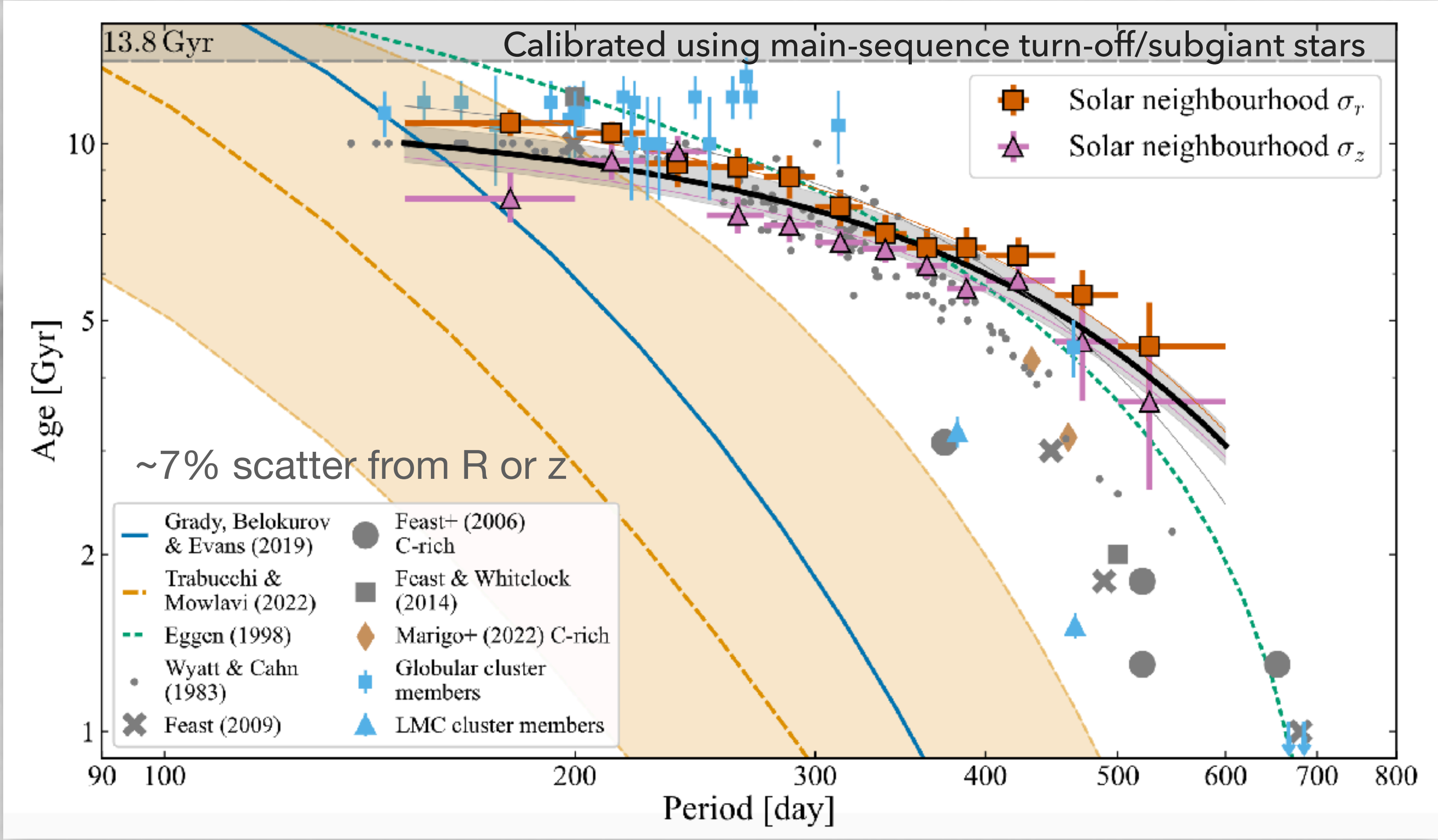
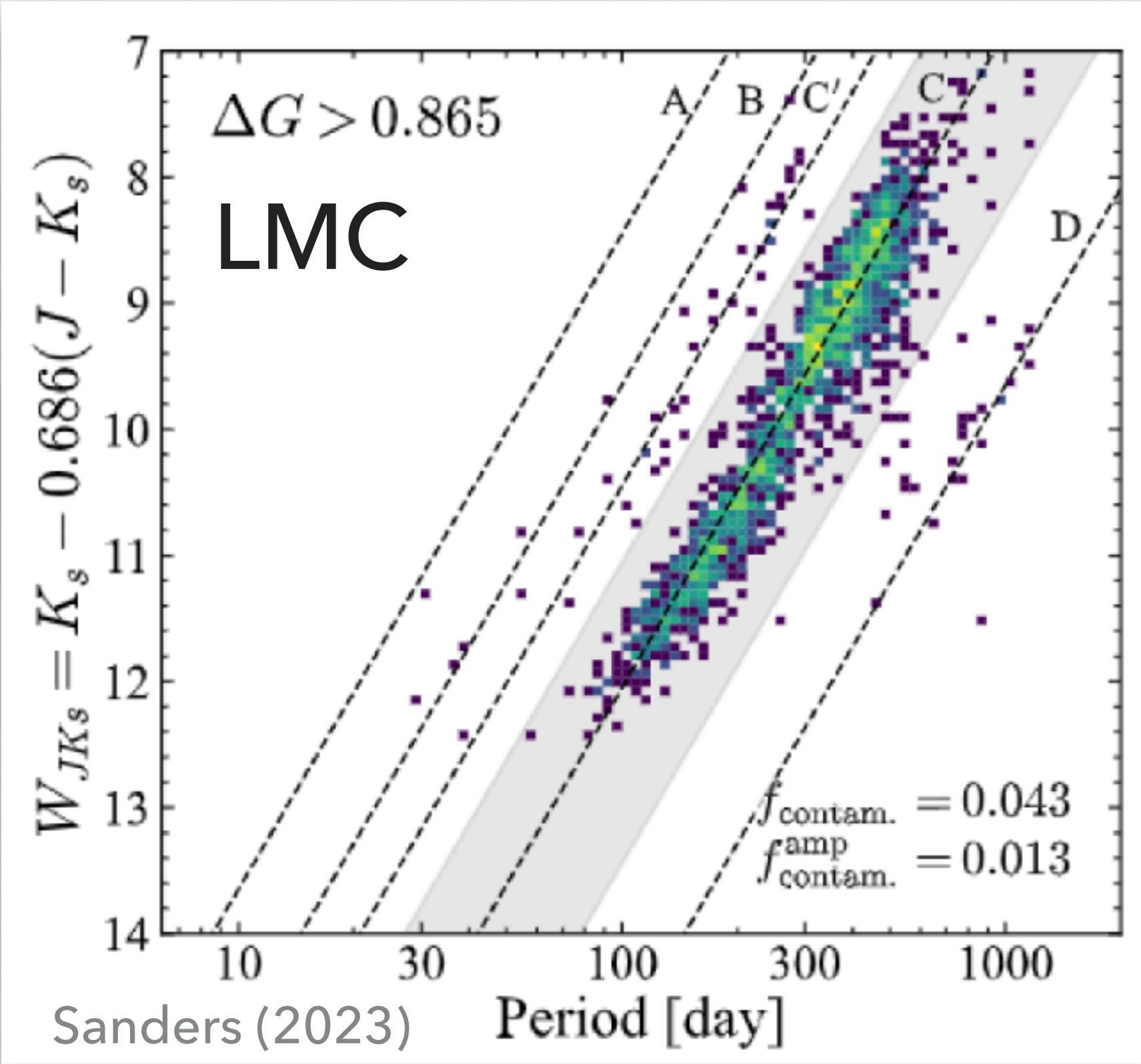
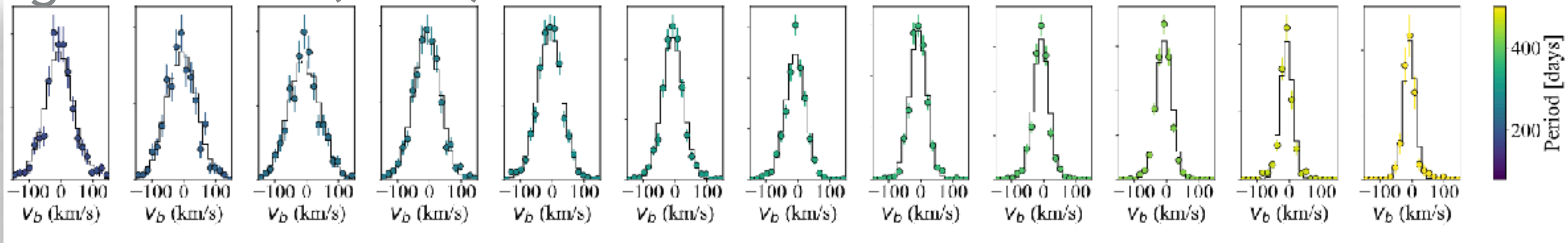
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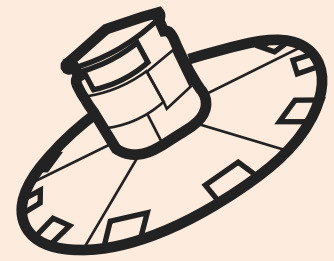
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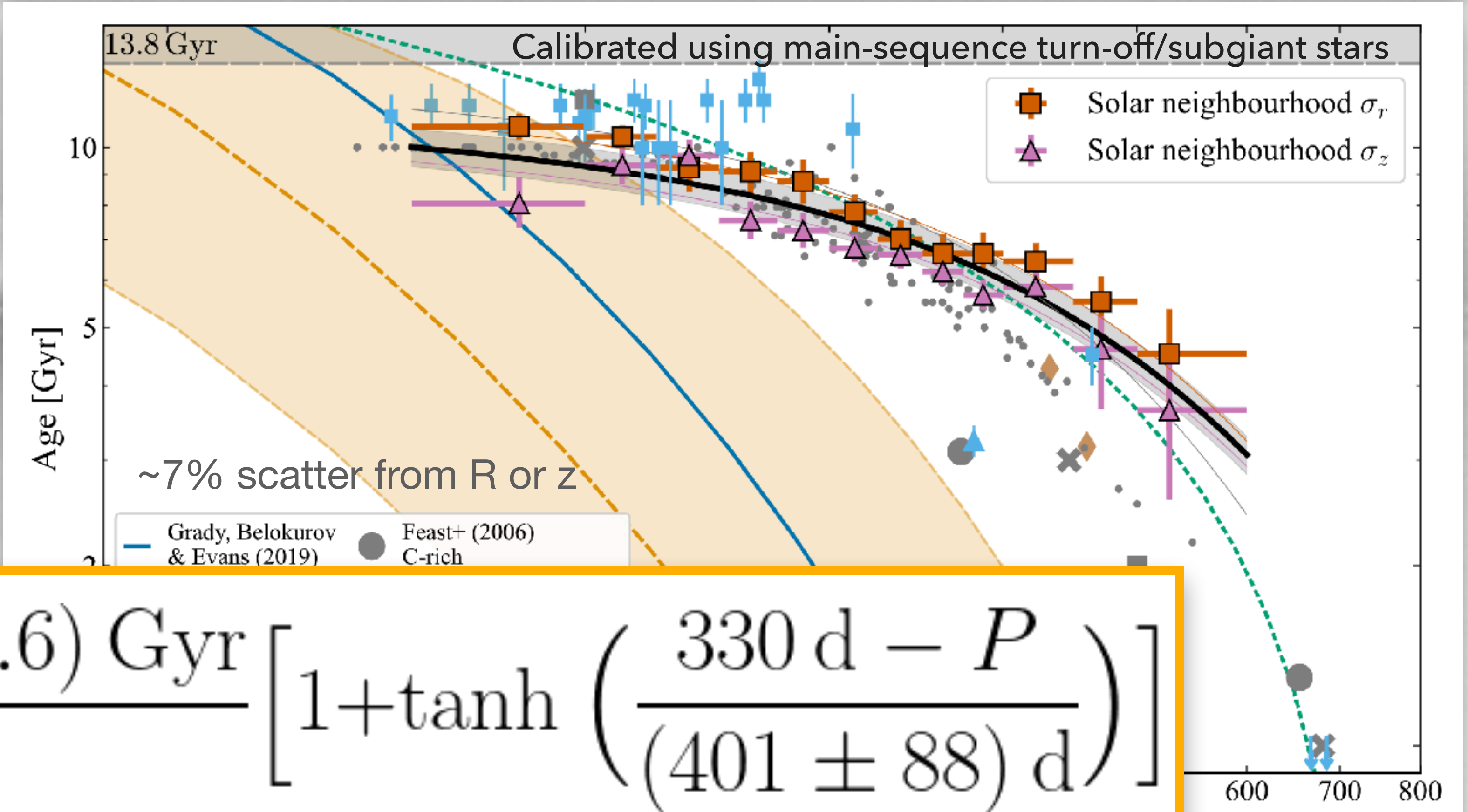
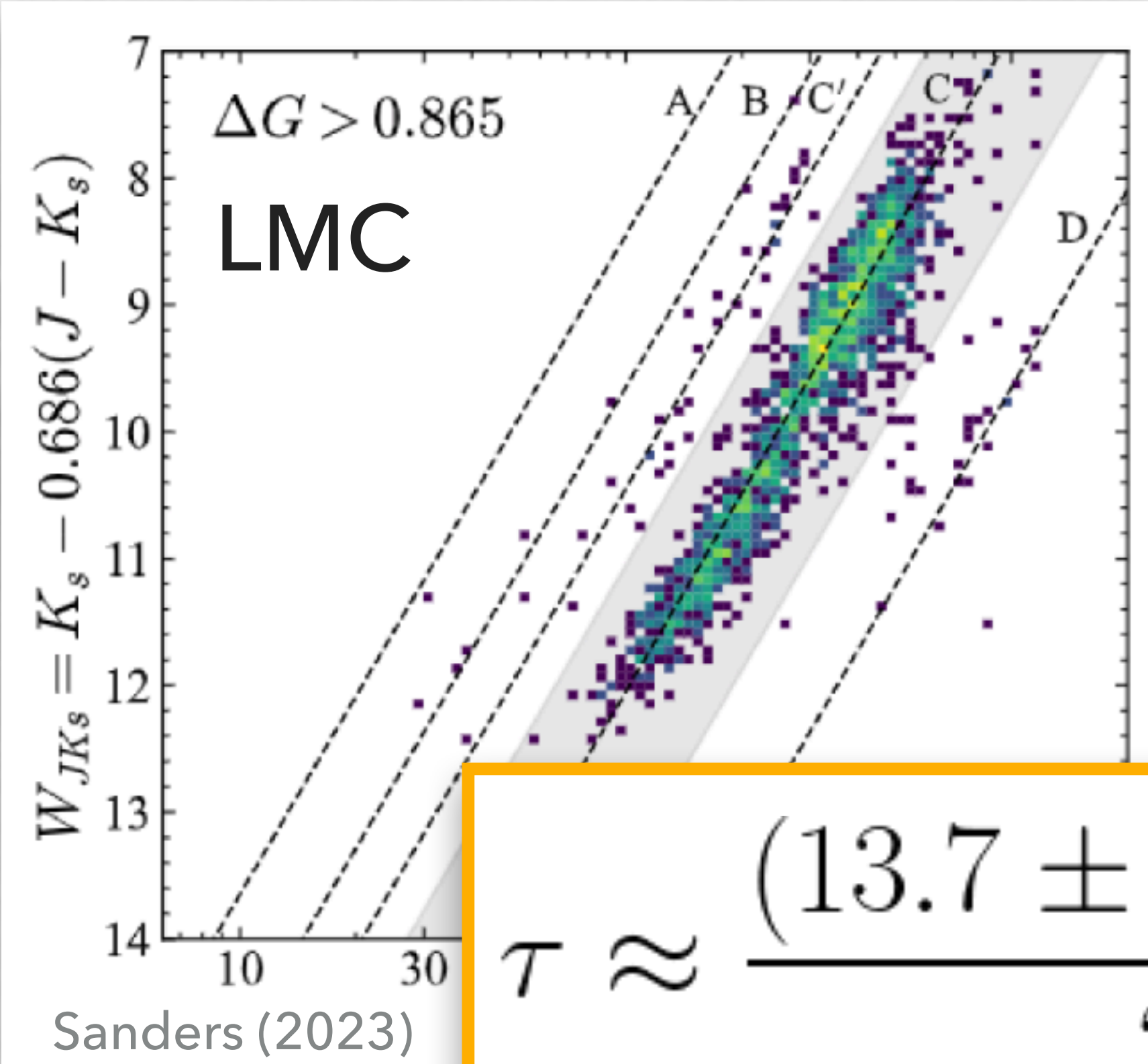
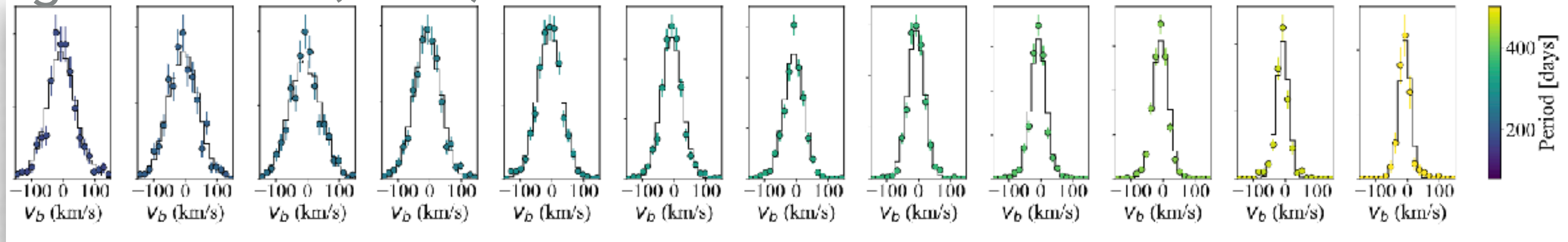
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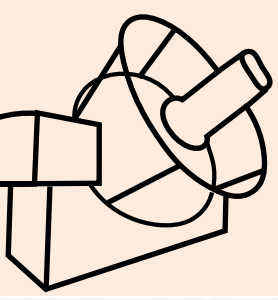
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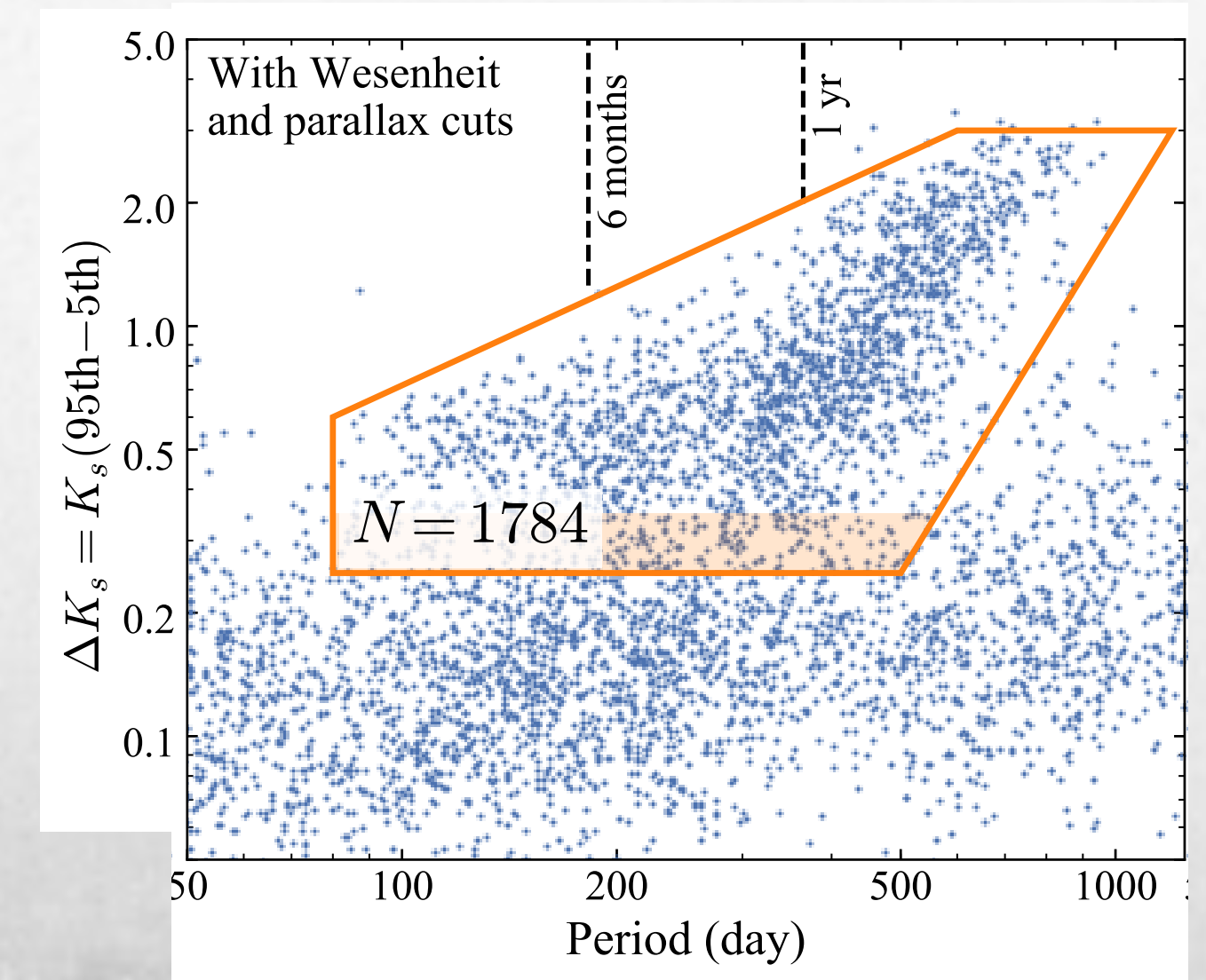
$$\tau \approx \frac{(13.7 \pm 0.6) \text{ Gyr}}{2} \left[1 + \tanh \left(\frac{330 \text{ d} - P}{(401 \pm 88) \text{ d}} \right) \right]$$

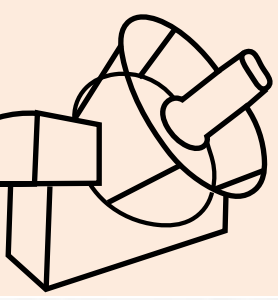
Useful for Hubble tension too...

Mira variables in the NSD



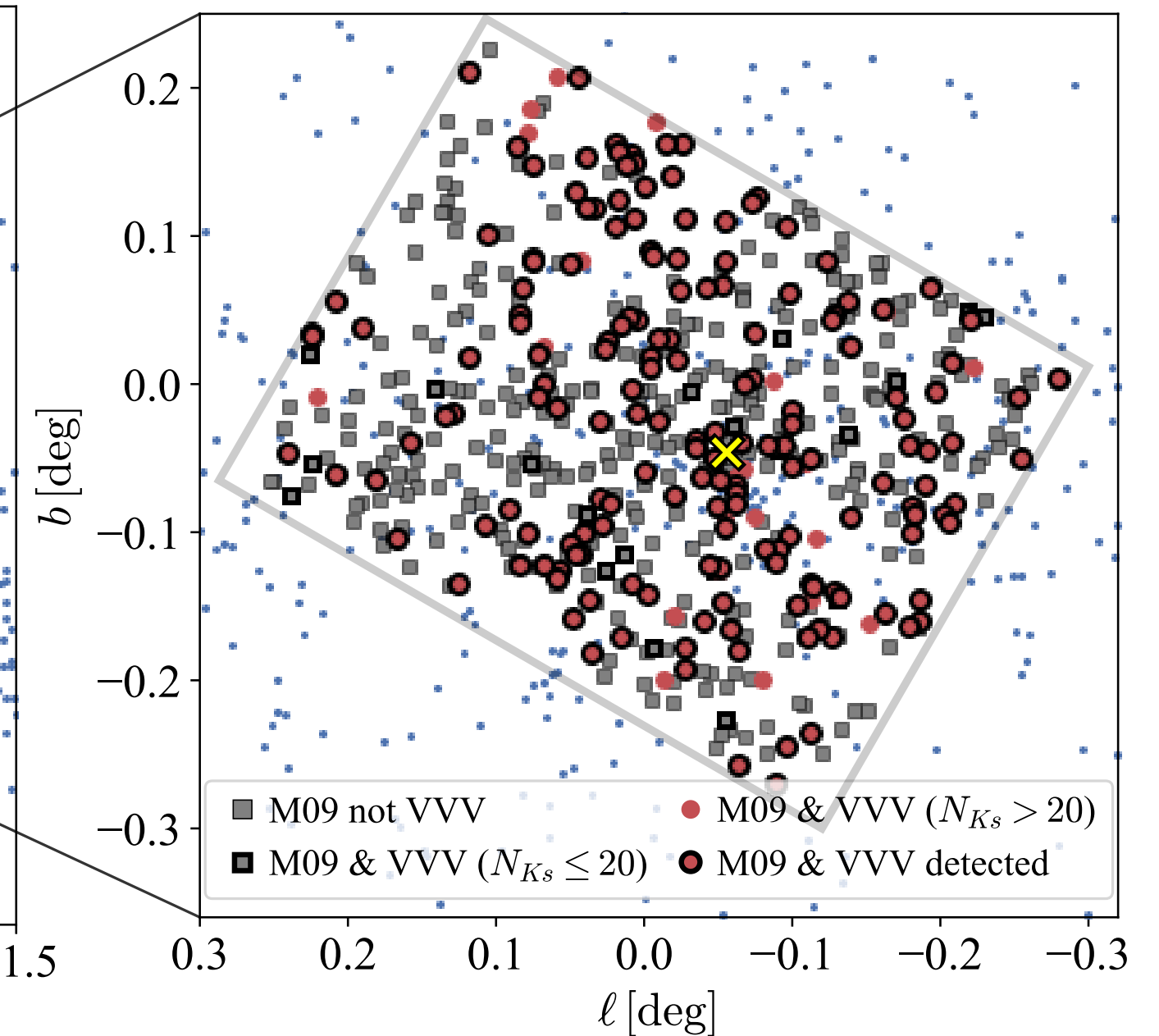
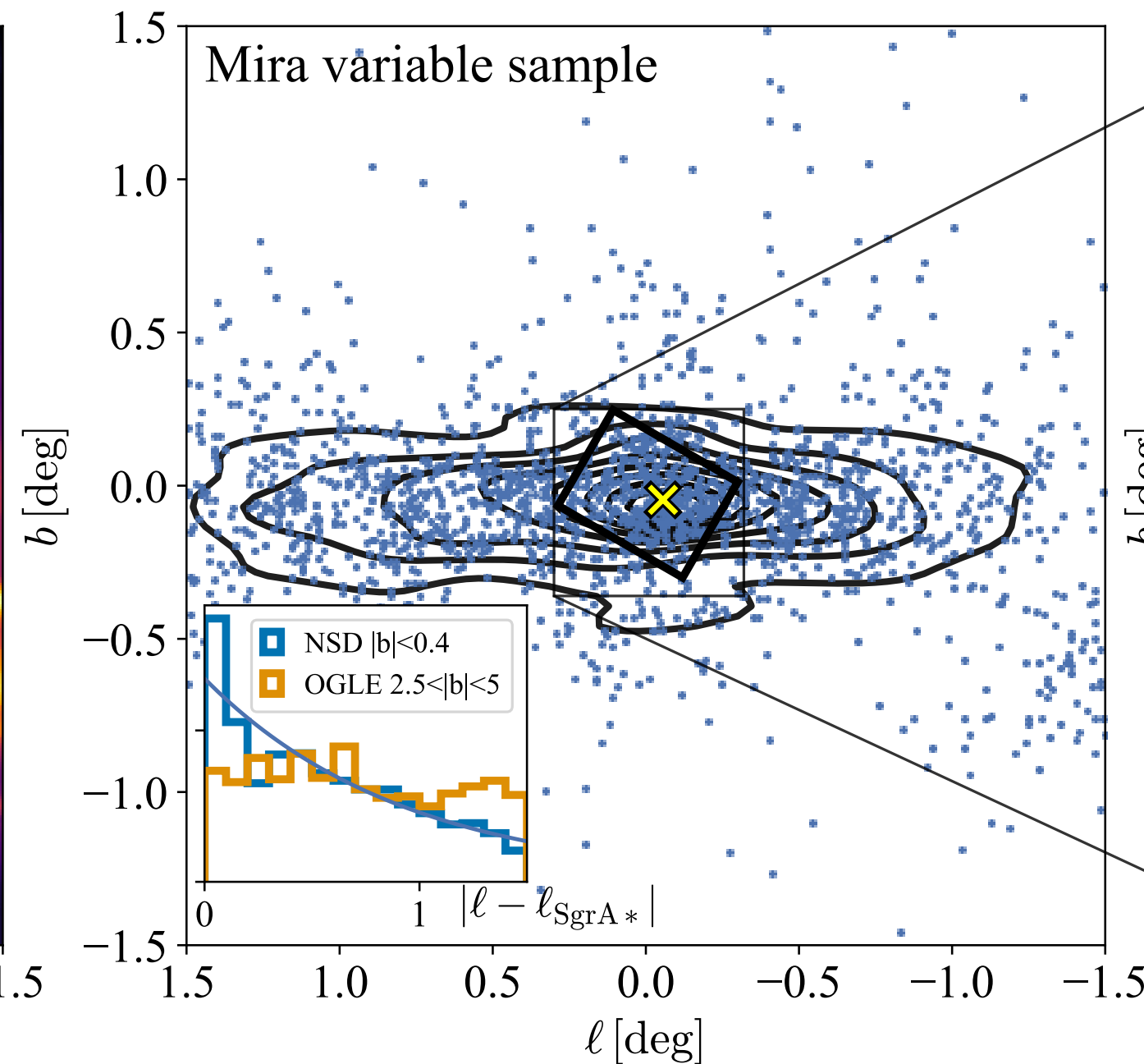
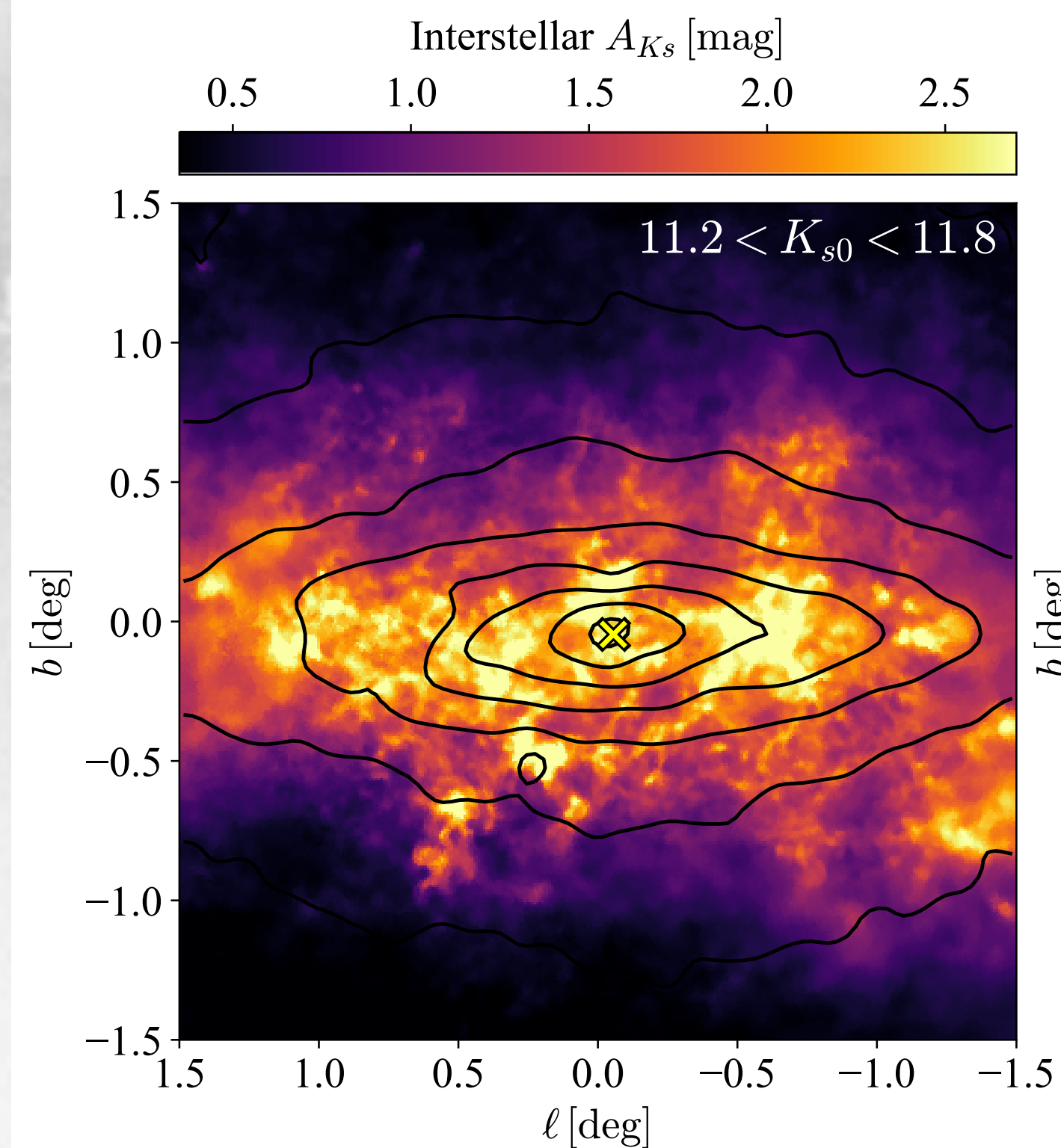
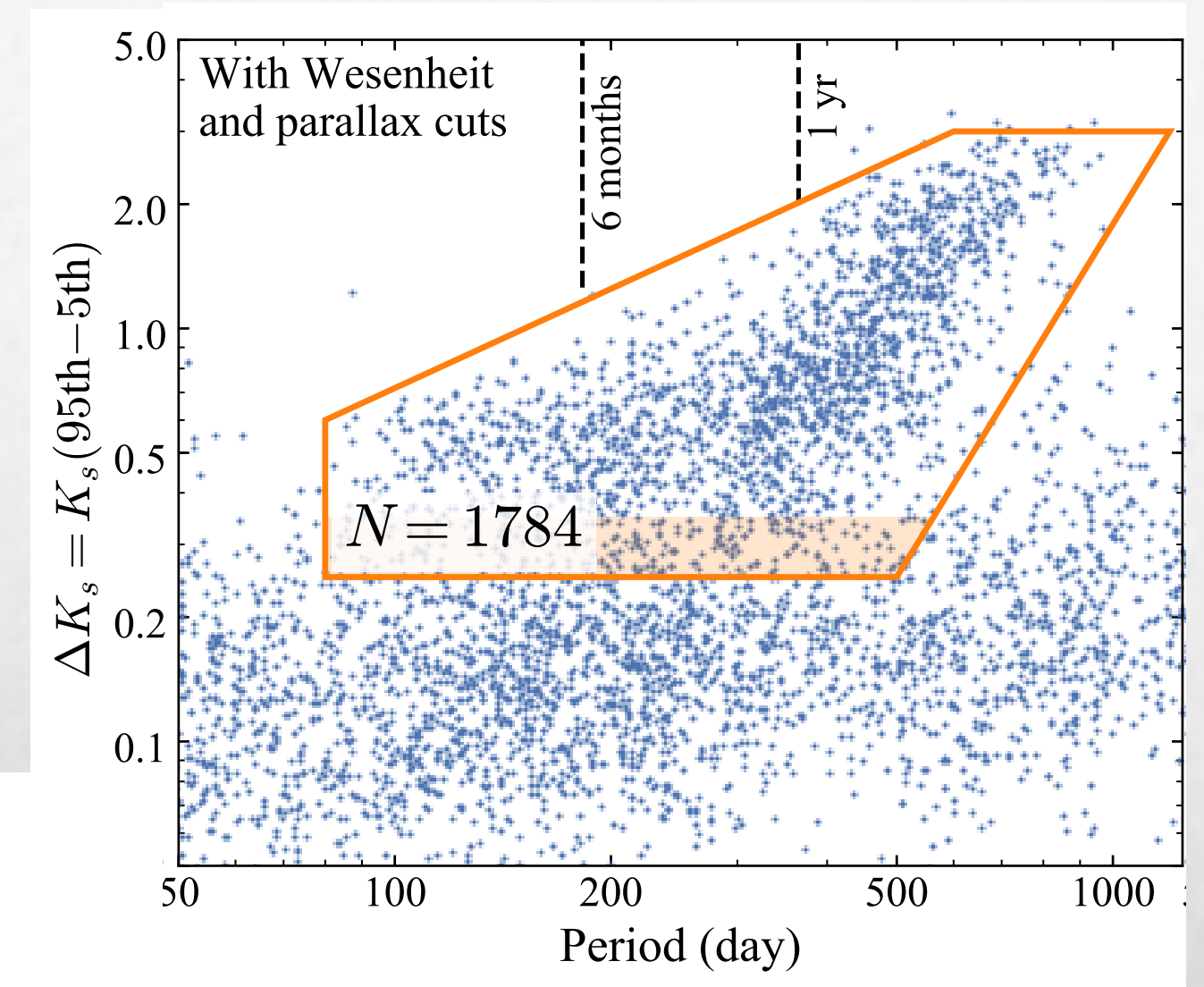
- **High amplitude** ($\Delta K_s \gtrsim 0.3$) thermally pulsing asymptotic giant branch stars (periods 80-1000 days)
- **Bright:** $M_{K_s} \sim -7$ (for period=200 days) & **low contamination**
- Used for disc (Grady+19,21) and bar/bulge studies (Catchpole+15, Semczuk+22)
- ~1800 Mira variables in VVV with proper motions (Sanders+22)



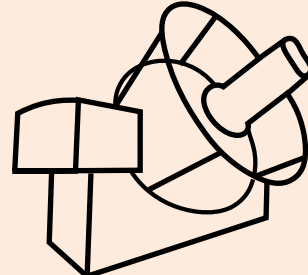


Mira variables in the NSD

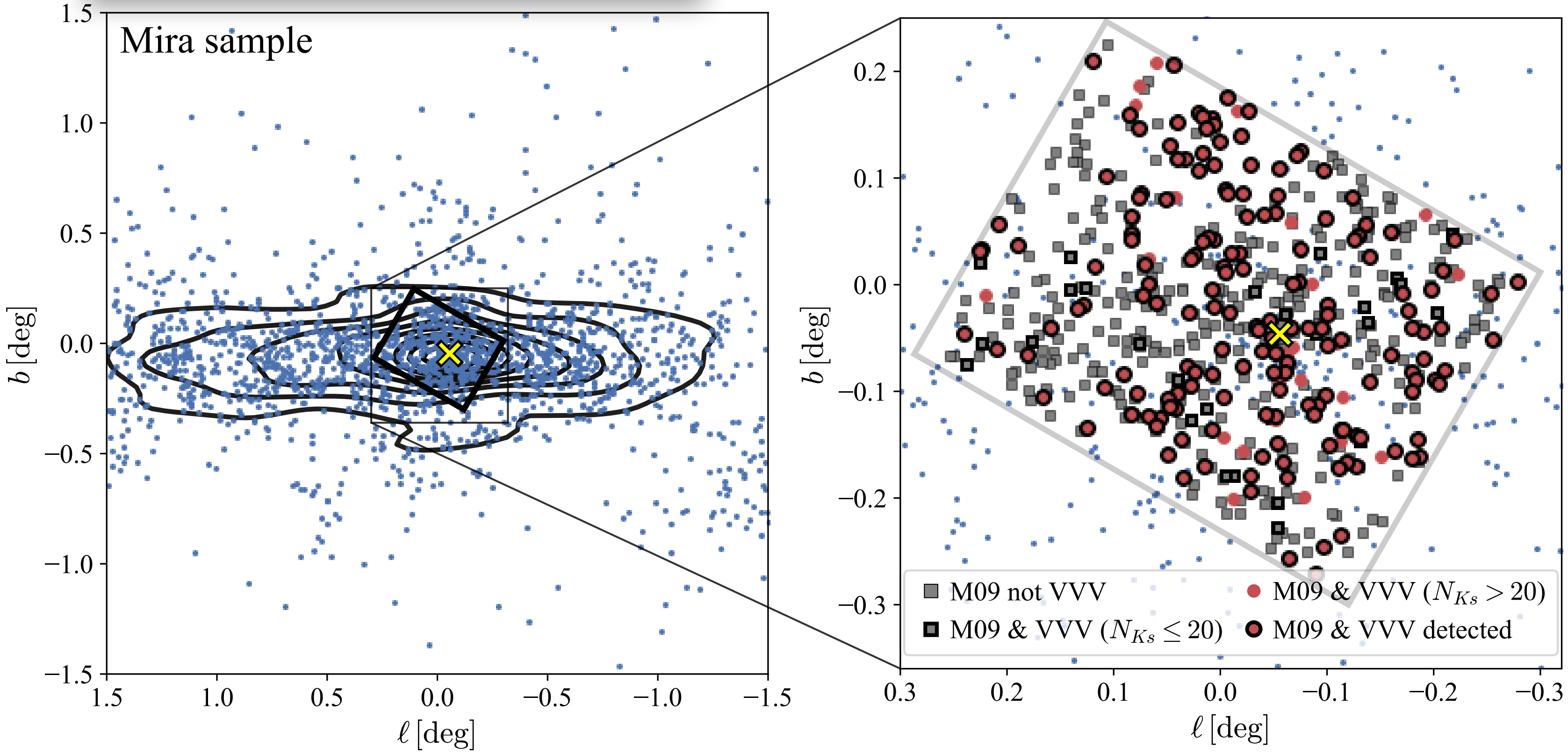
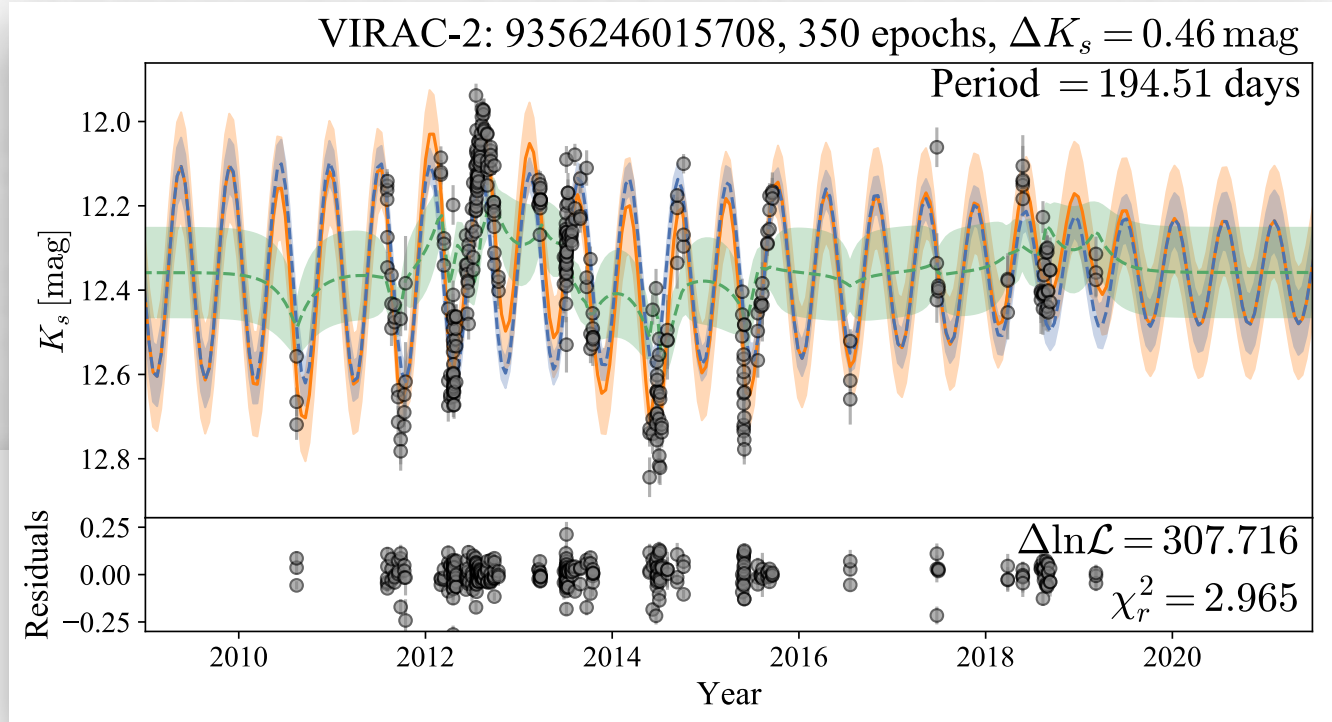
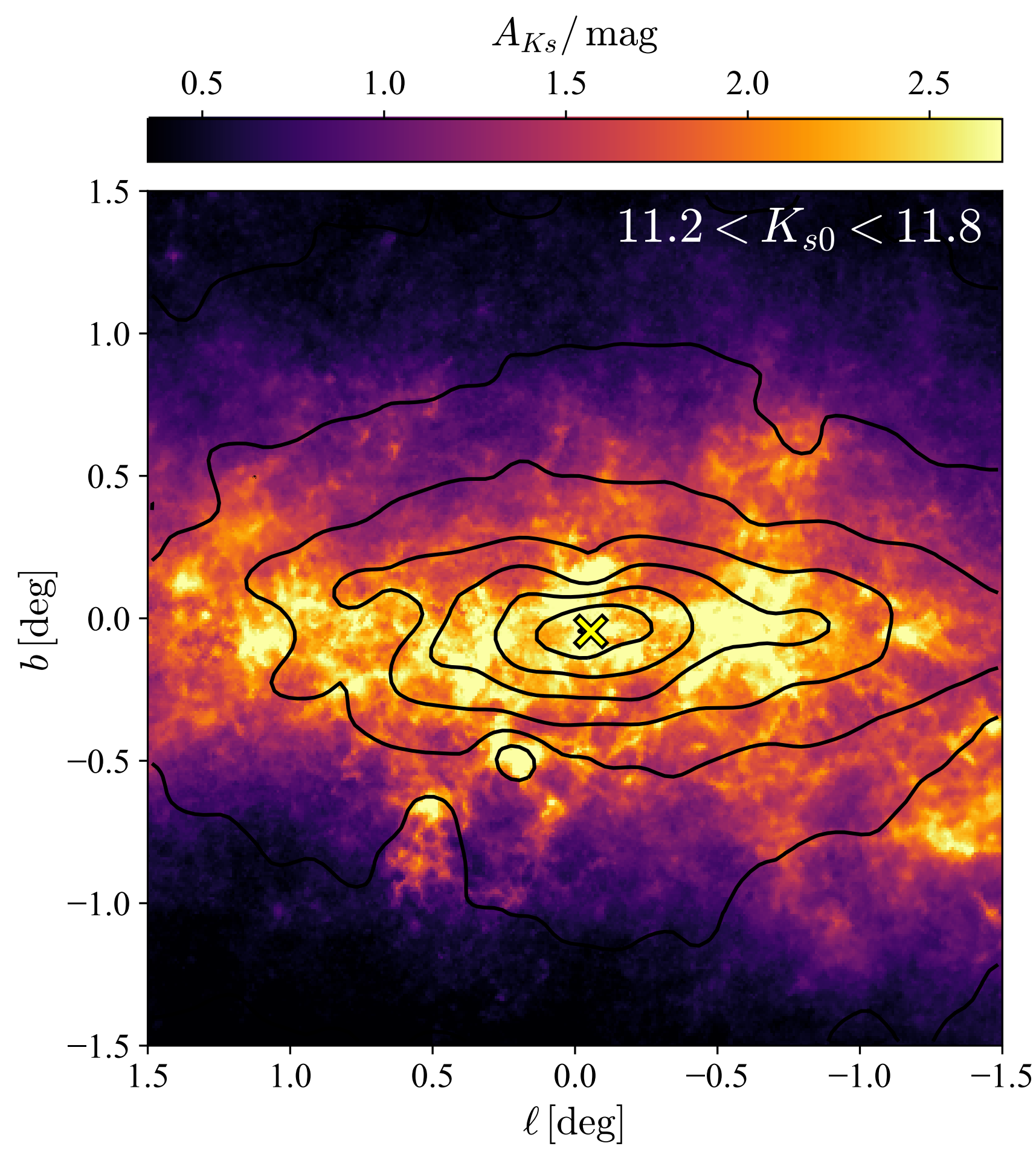
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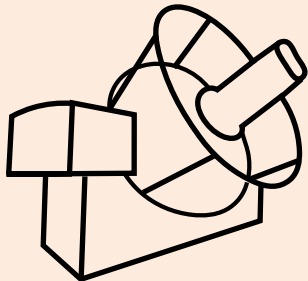
Properties of NSD Mira variables — Completeness



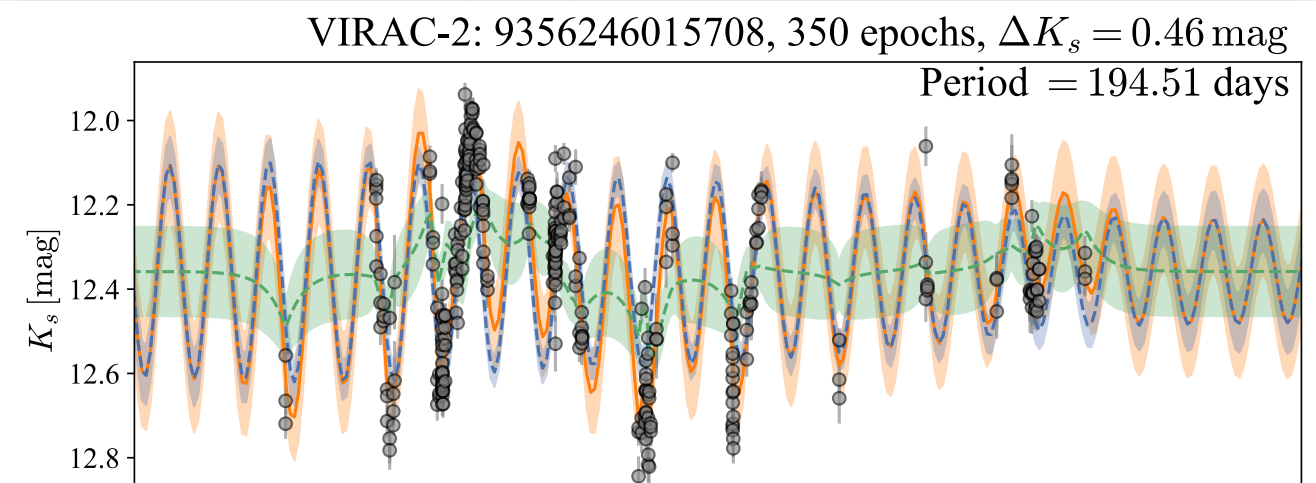
1785 Mira variables



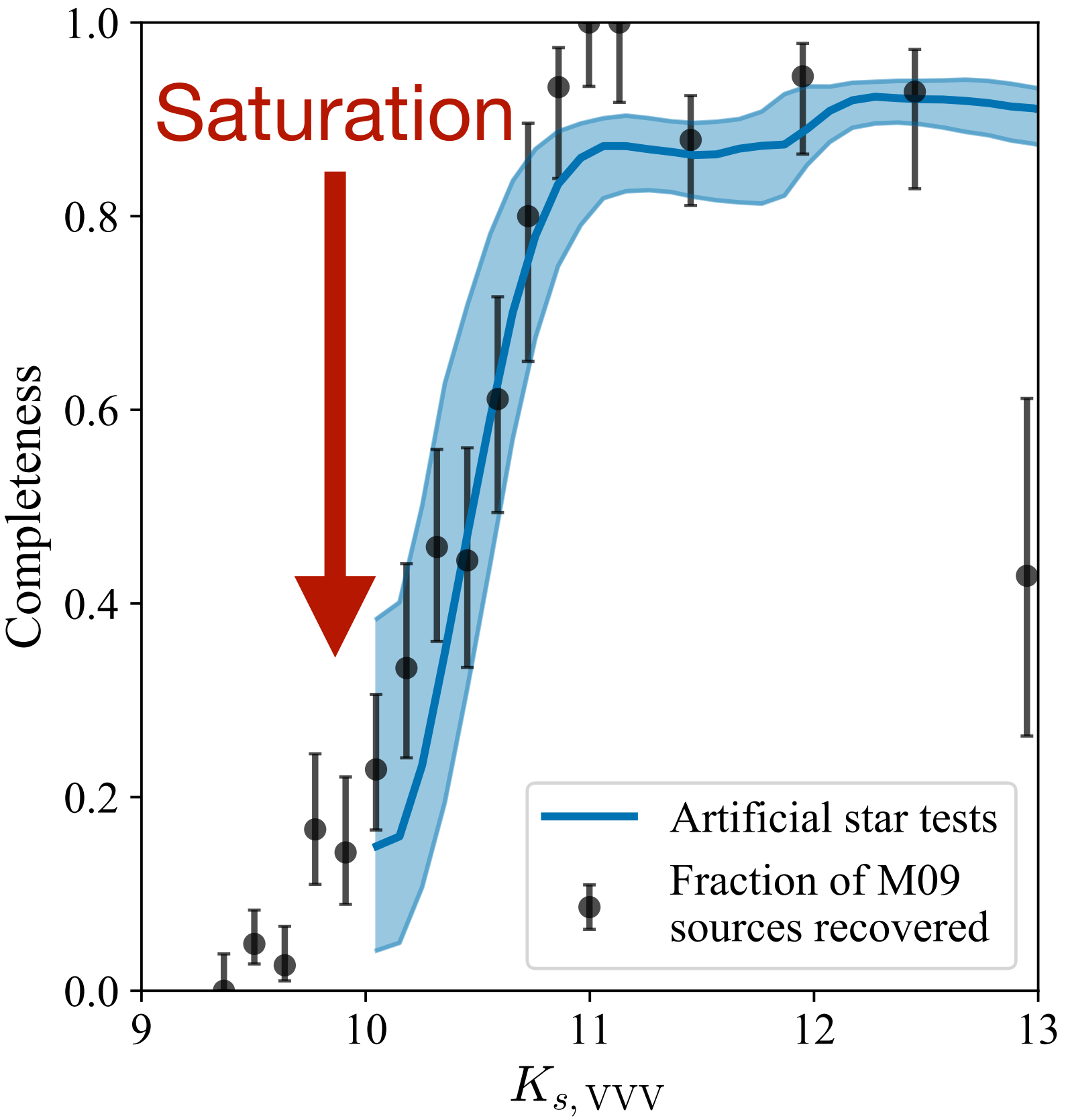
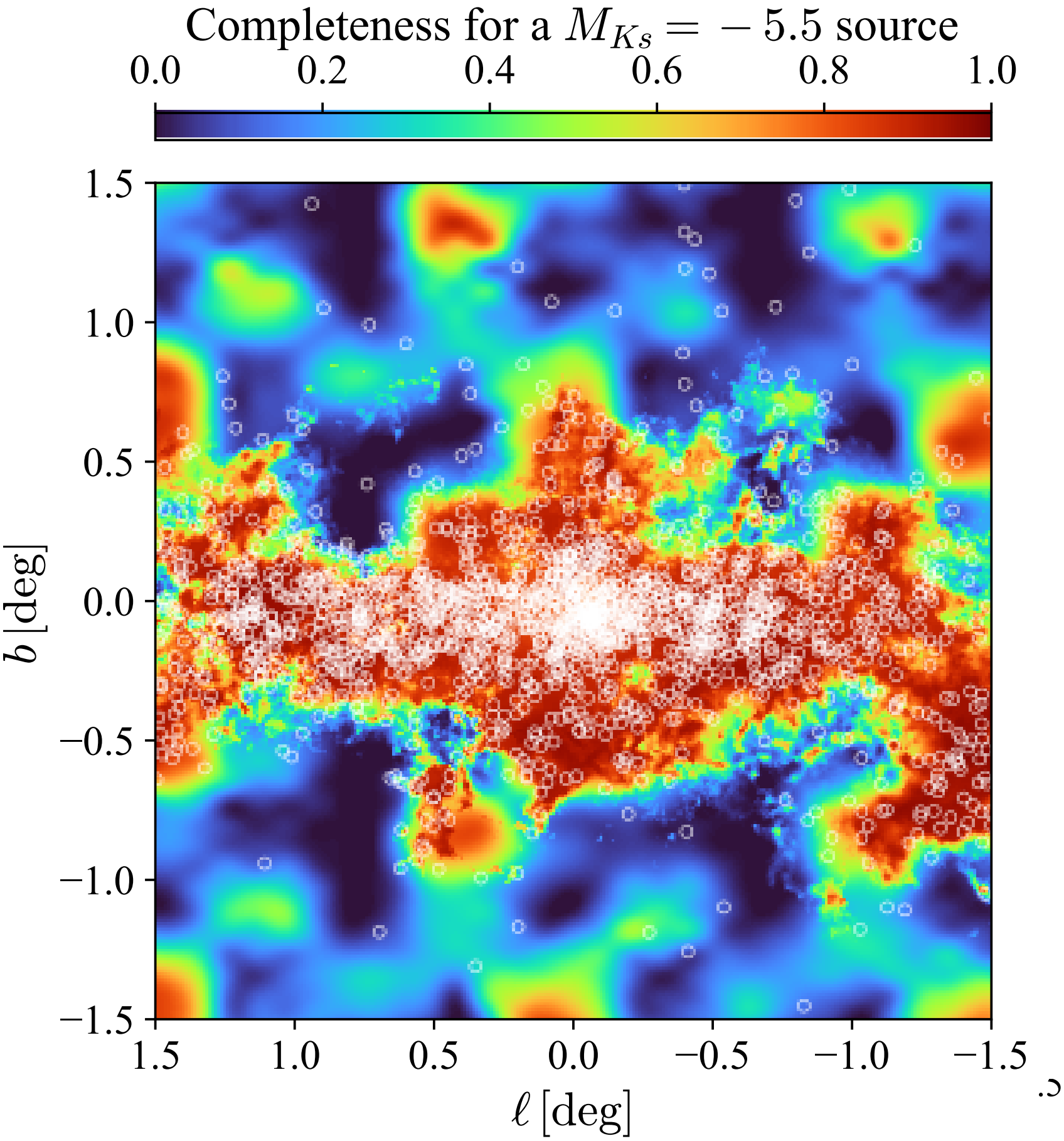
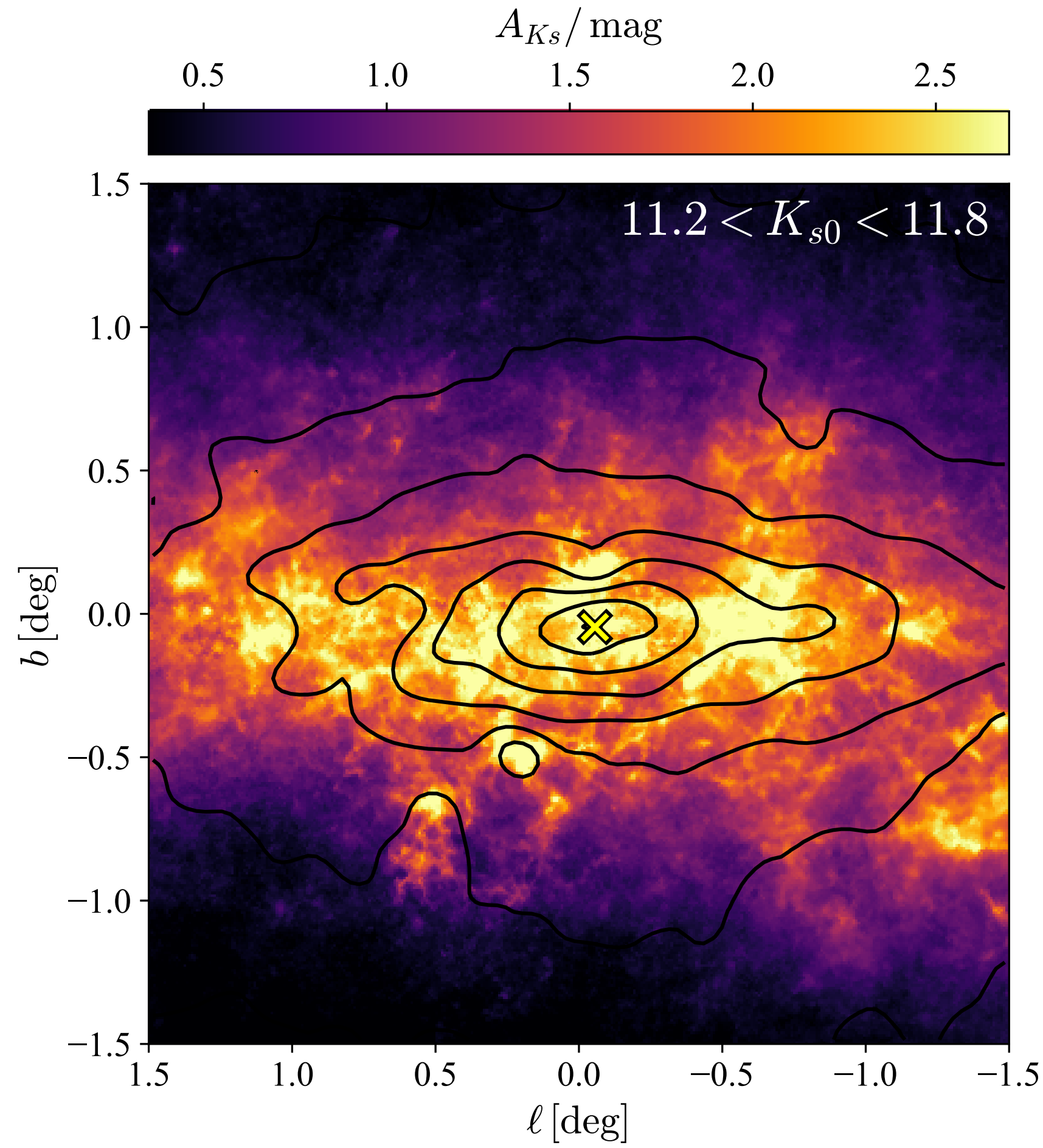
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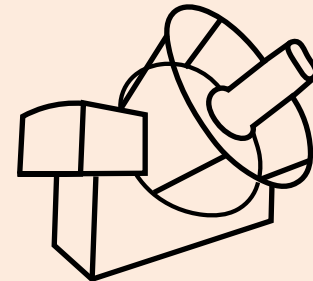
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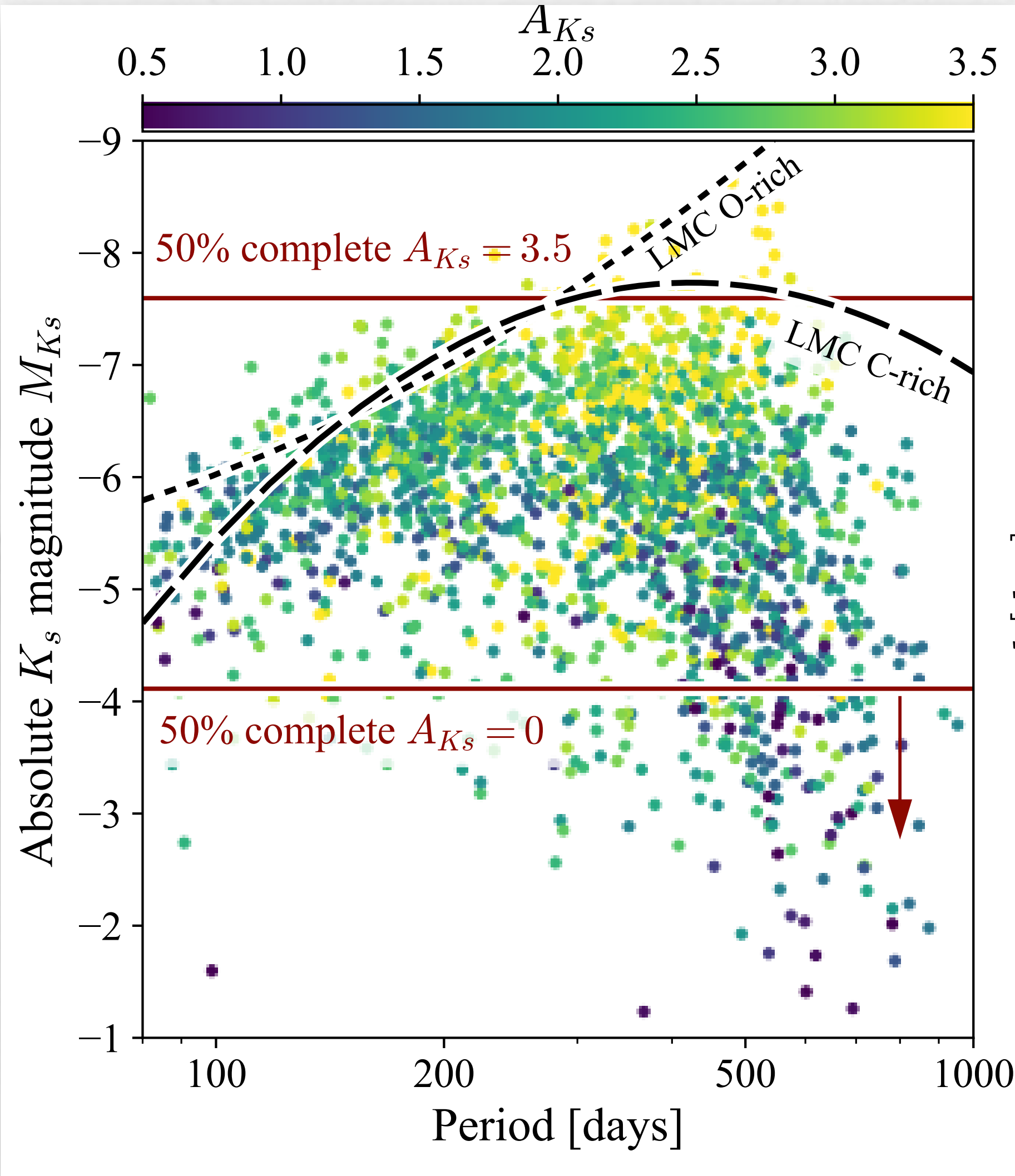
VVV saturates below $K_s \sim 11.5$. An unextincted 200 day Mira variable is $K_s \sim 8$. **Rely on extinction to observe.** Completeness linked with extinction



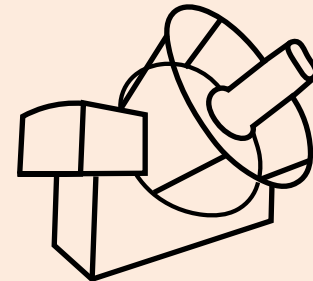
Properties of NSD Mira variables — Distances



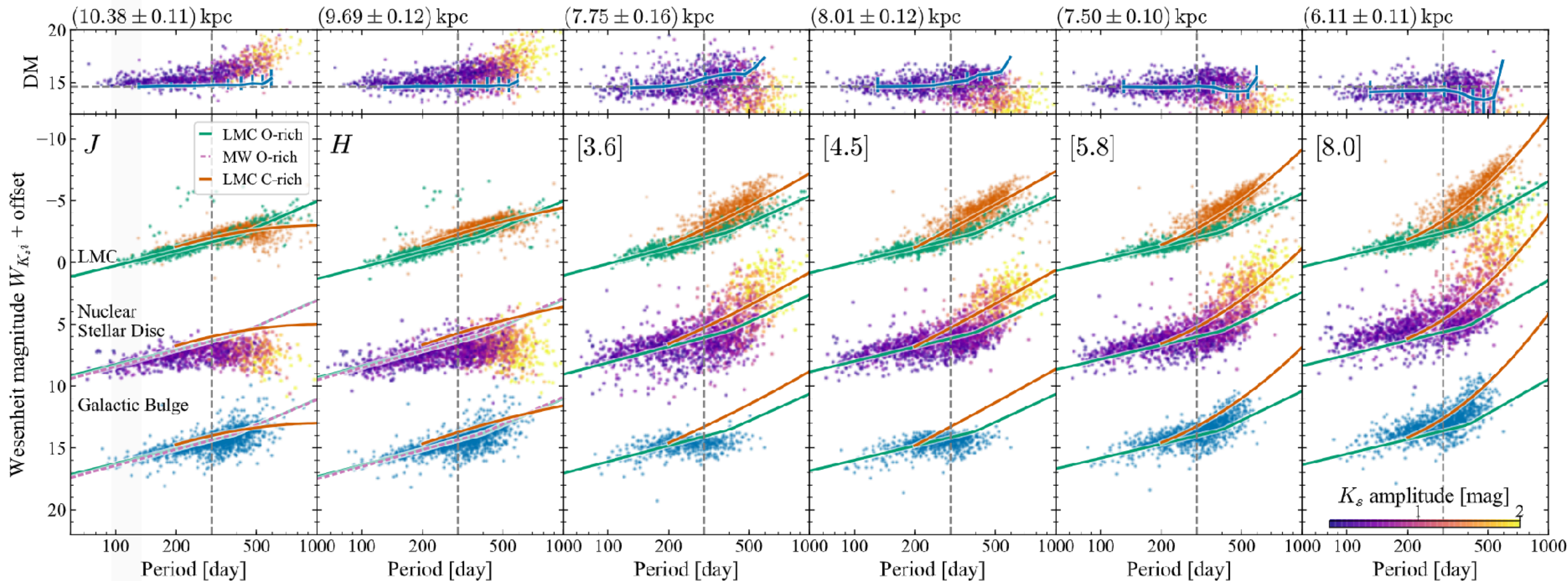
Short-period ($< \sim 300$ d) **consistent with NSD distance**, longer period = very dusty (unclear)



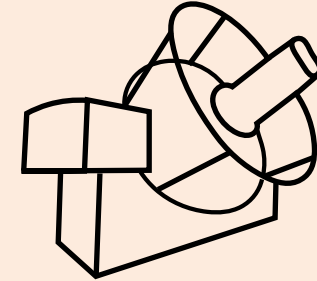
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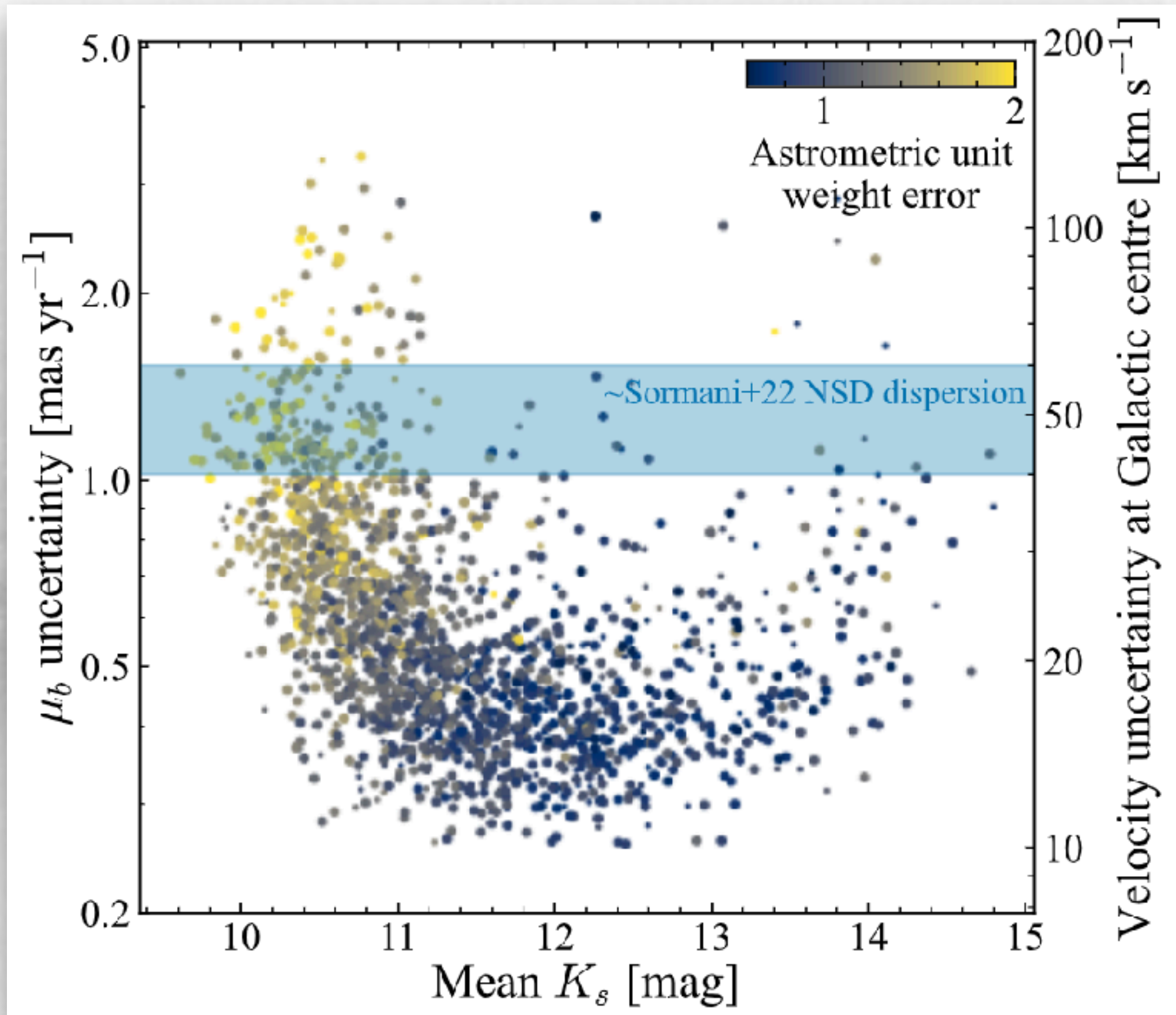
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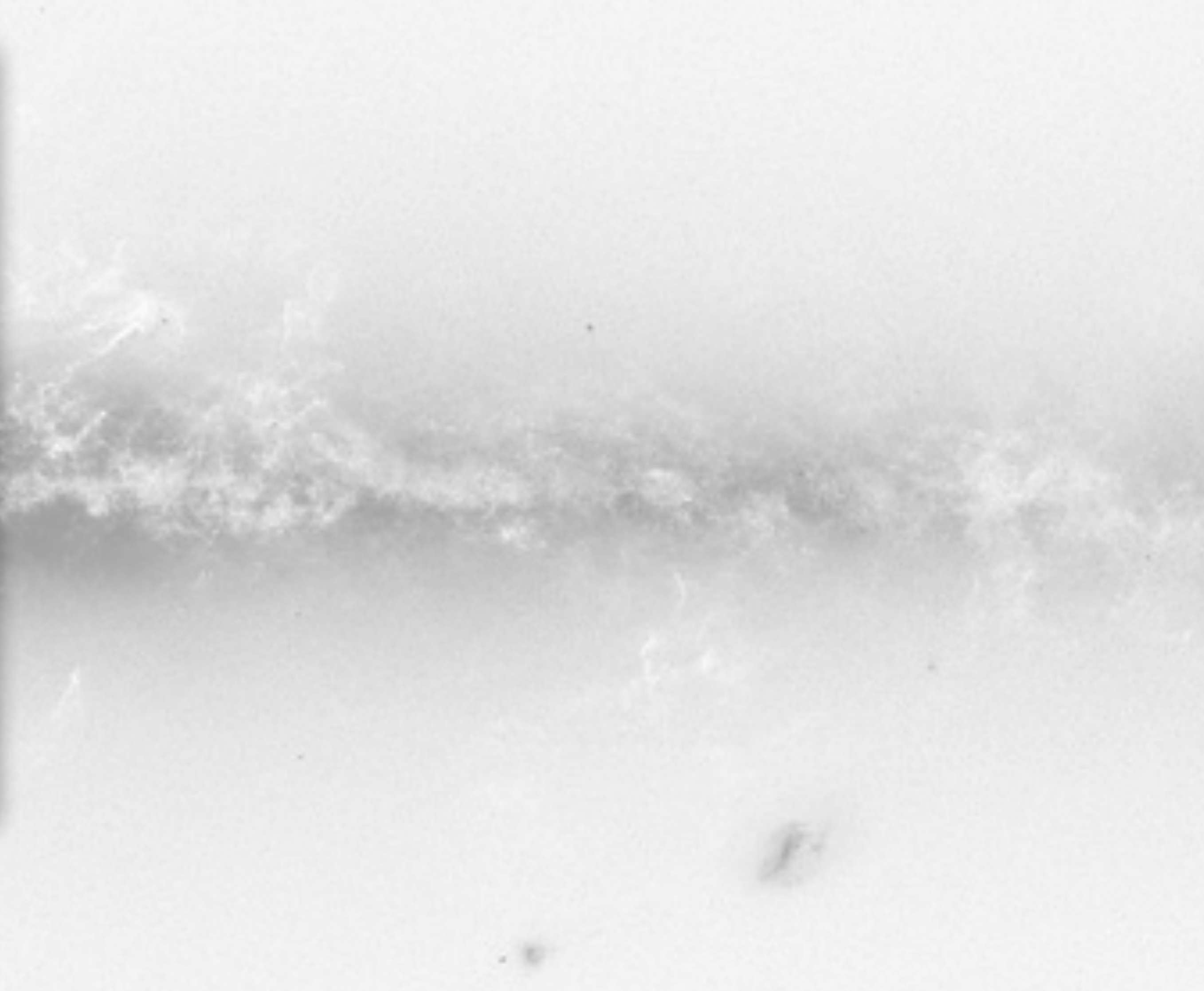
Properties of NSD Mira variables — Kinematics



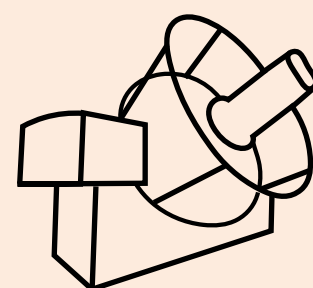
Sanders+ (in prep.)



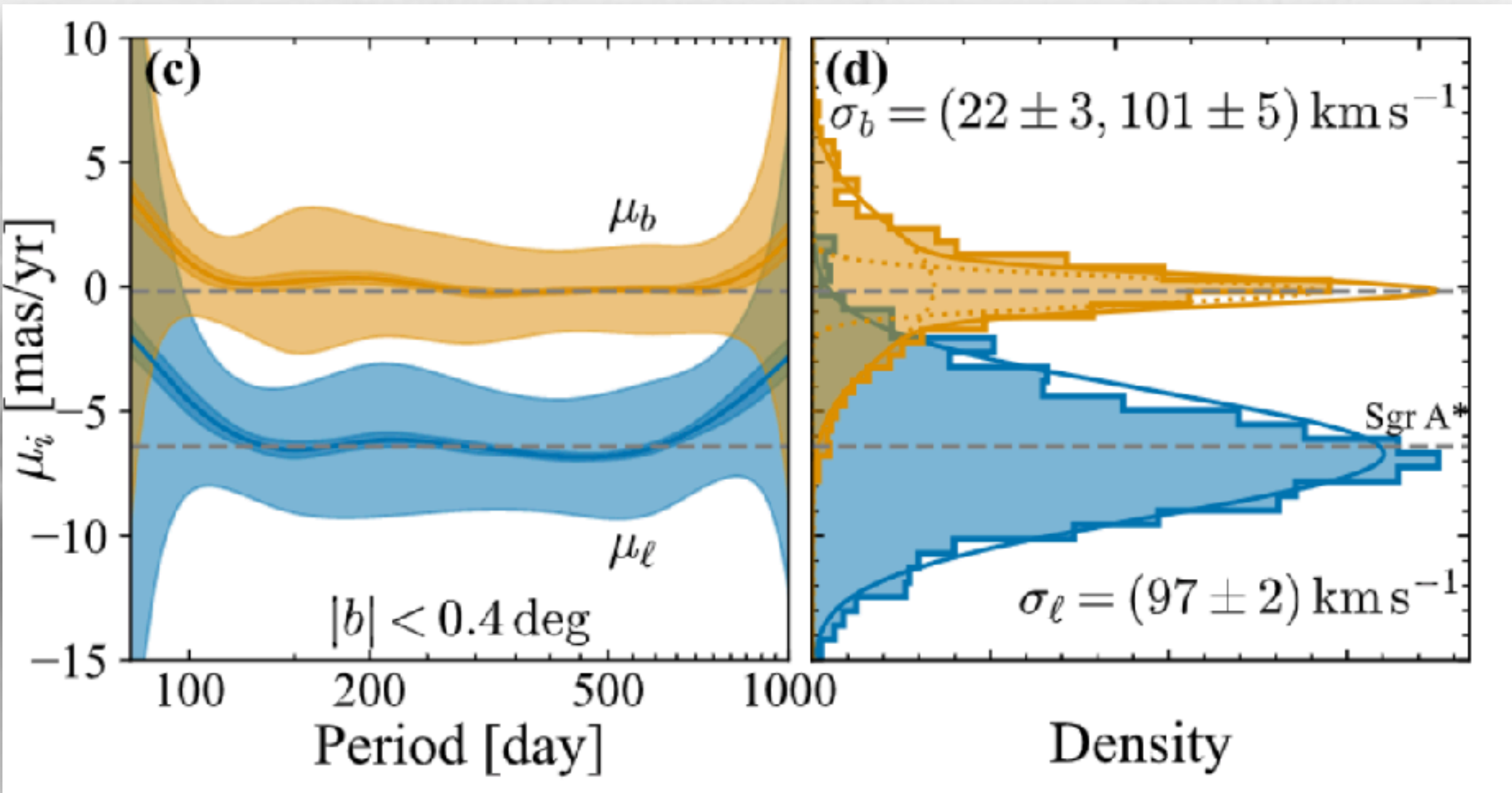
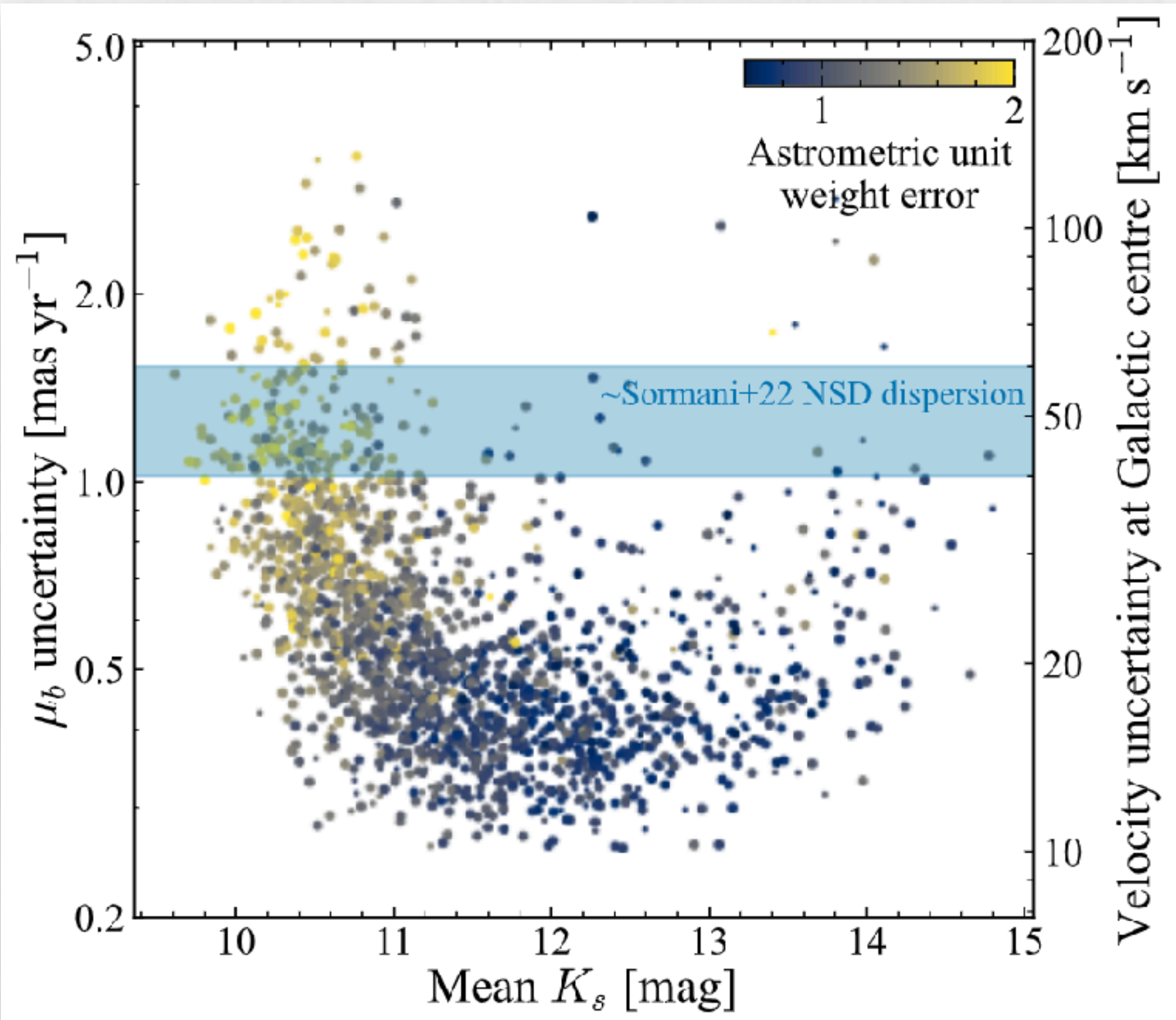
Proper motion uncertainties **~20km/s at GC** \approx
NSD disc dispersion



Properties of NSD Mira variables — Kinematics



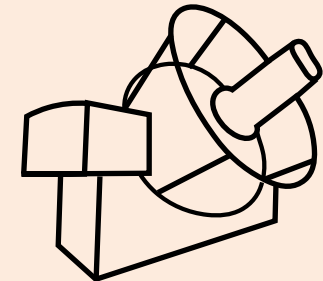
Sanders+ (in prep.)



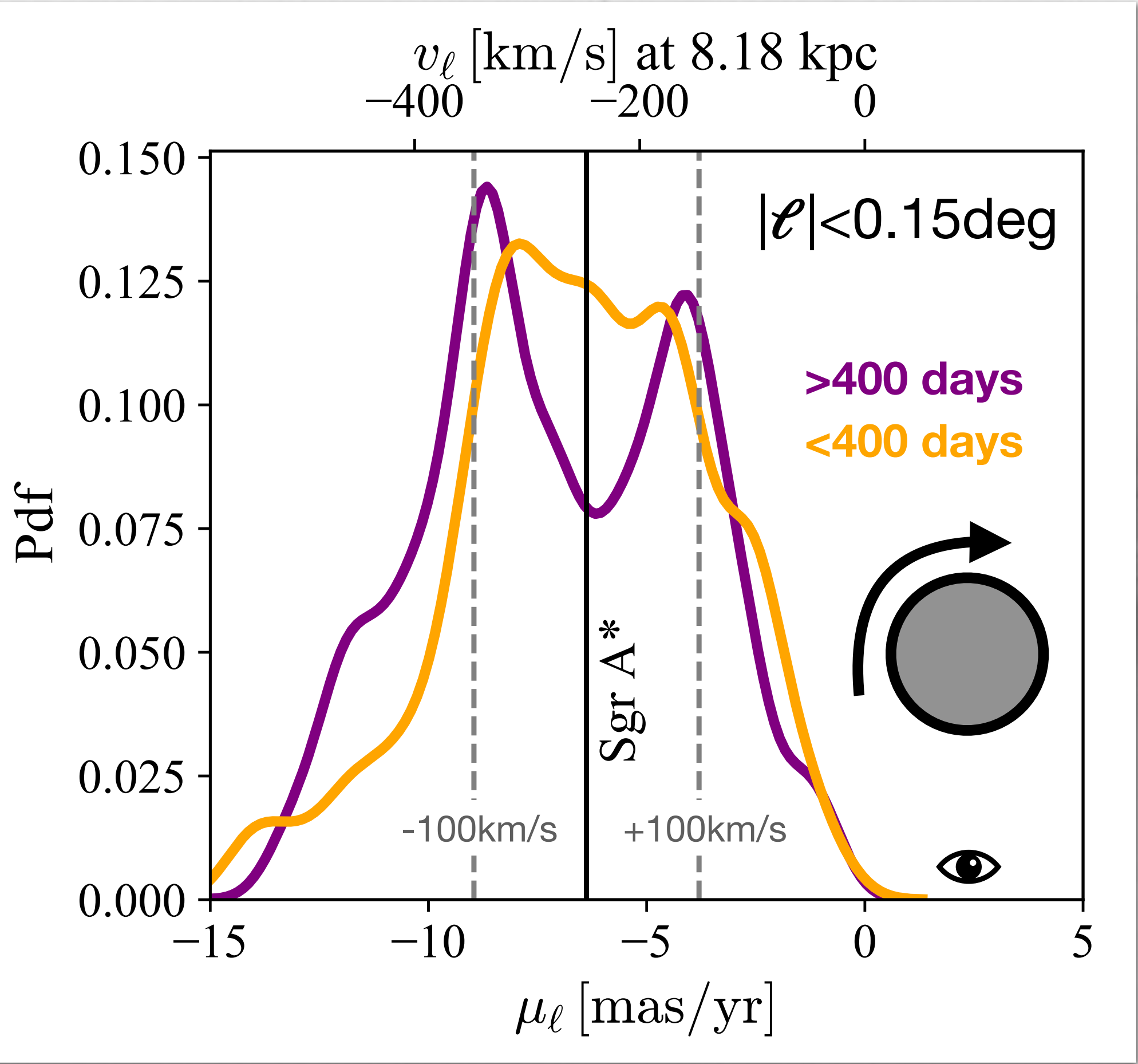
Proper motion uncertainties **~20km/s at GC** \approx **NSD disc dispersion**

Mean velocities consistent with GC
Vertical dispersion = two components

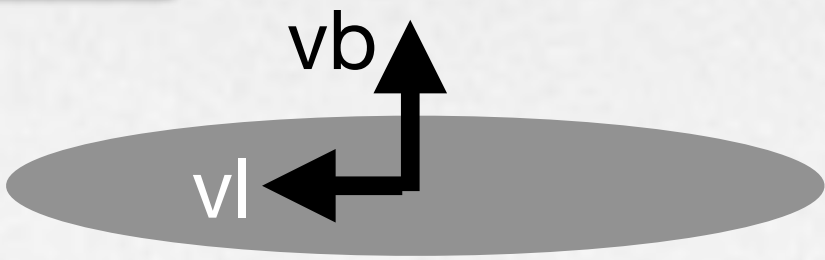
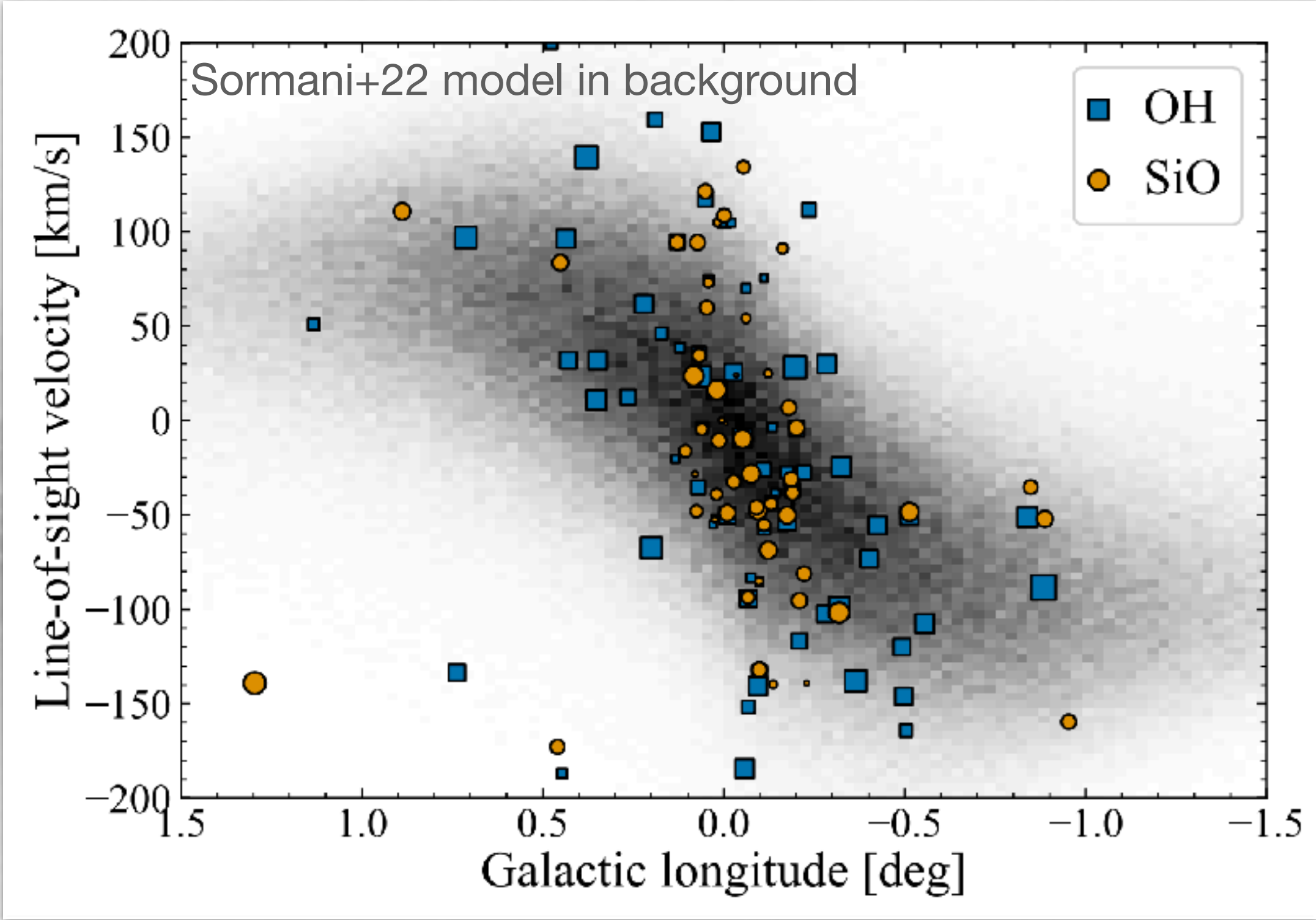
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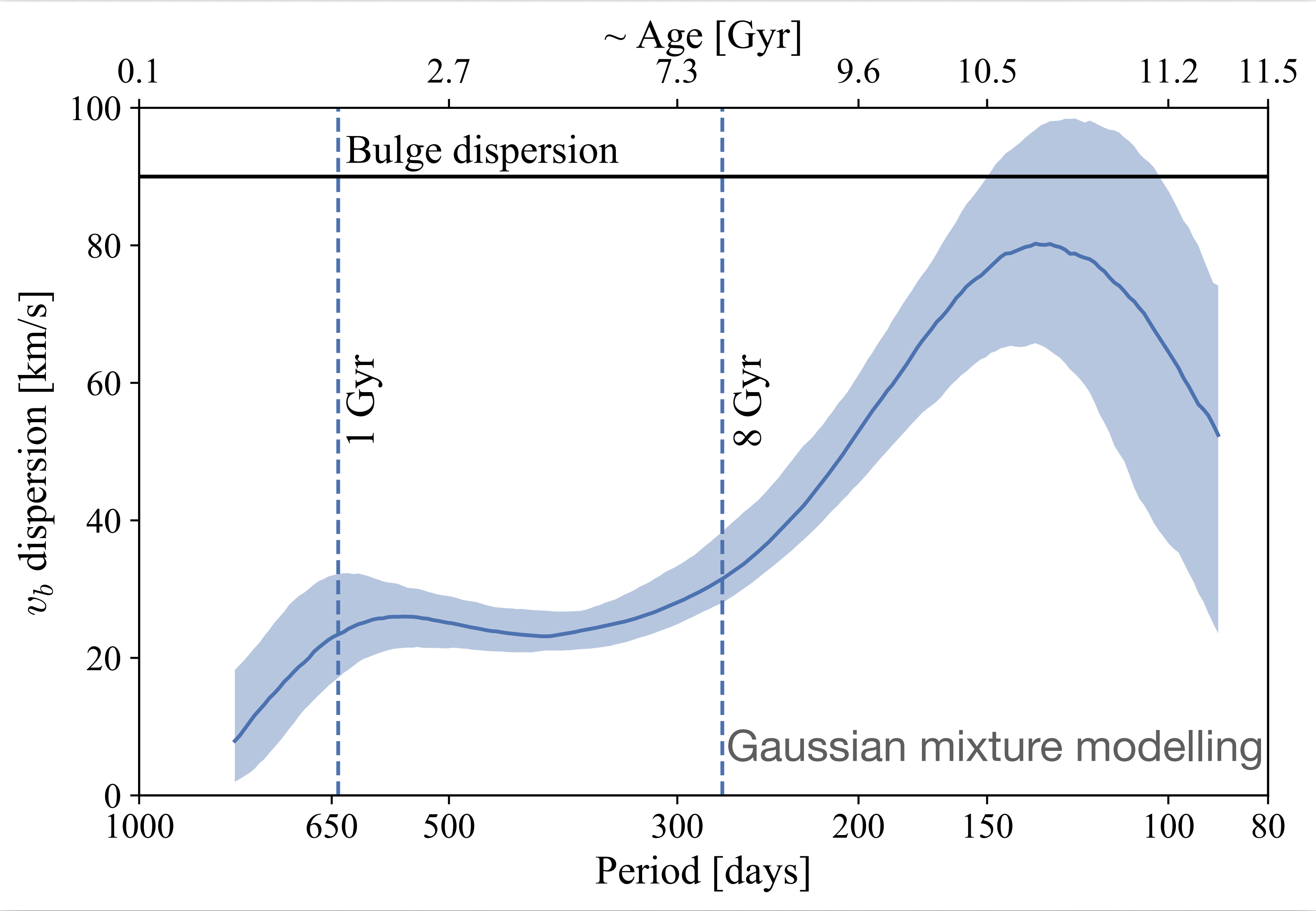
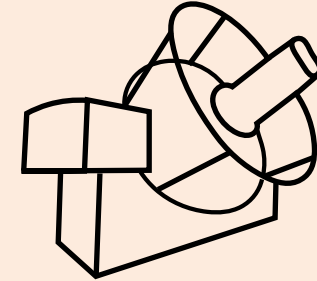
Sanders+ (in prep.)



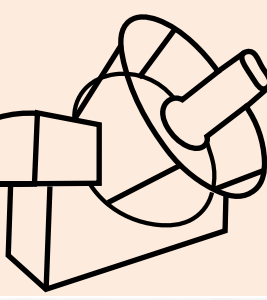
Sanders+ 2022



Properties of NSD Mira variables — Kinematics



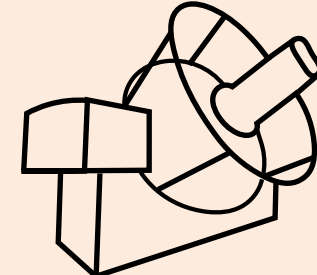
Dynamical modelling of NSD Mira variables



$$p(\overset{\text{PM}}{\downarrow} \tilde{\boldsymbol{\mu}}, \overset{\text{Distance}}{\downarrow} s | \overset{\text{On-sky}}{\swarrow} \ell, \overset{\text{Period}}{\swarrow} b, P) = \frac{p_{\text{NSD}}(\ell, b, s, \tilde{\boldsymbol{\mu}} | P) + w(P)p_{\text{bar}}(\ell, b, s, \tilde{\boldsymbol{\mu}})}{p_{\text{NSD}}(\ell, b | P) + w(P)p_{\text{bar}}(\ell, b)}.$$

Mixture model for kinematics given on-sky
position and period (marginalised over distance)

Dynamical modelling of NSD Mira variables

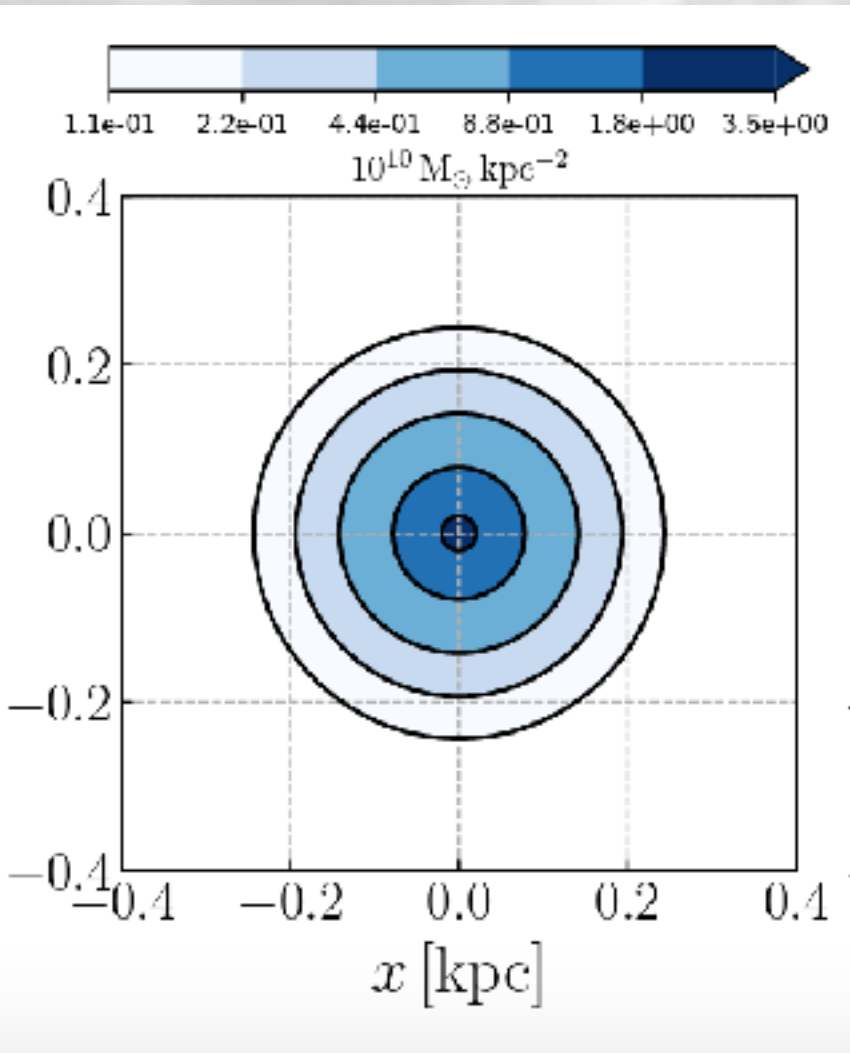
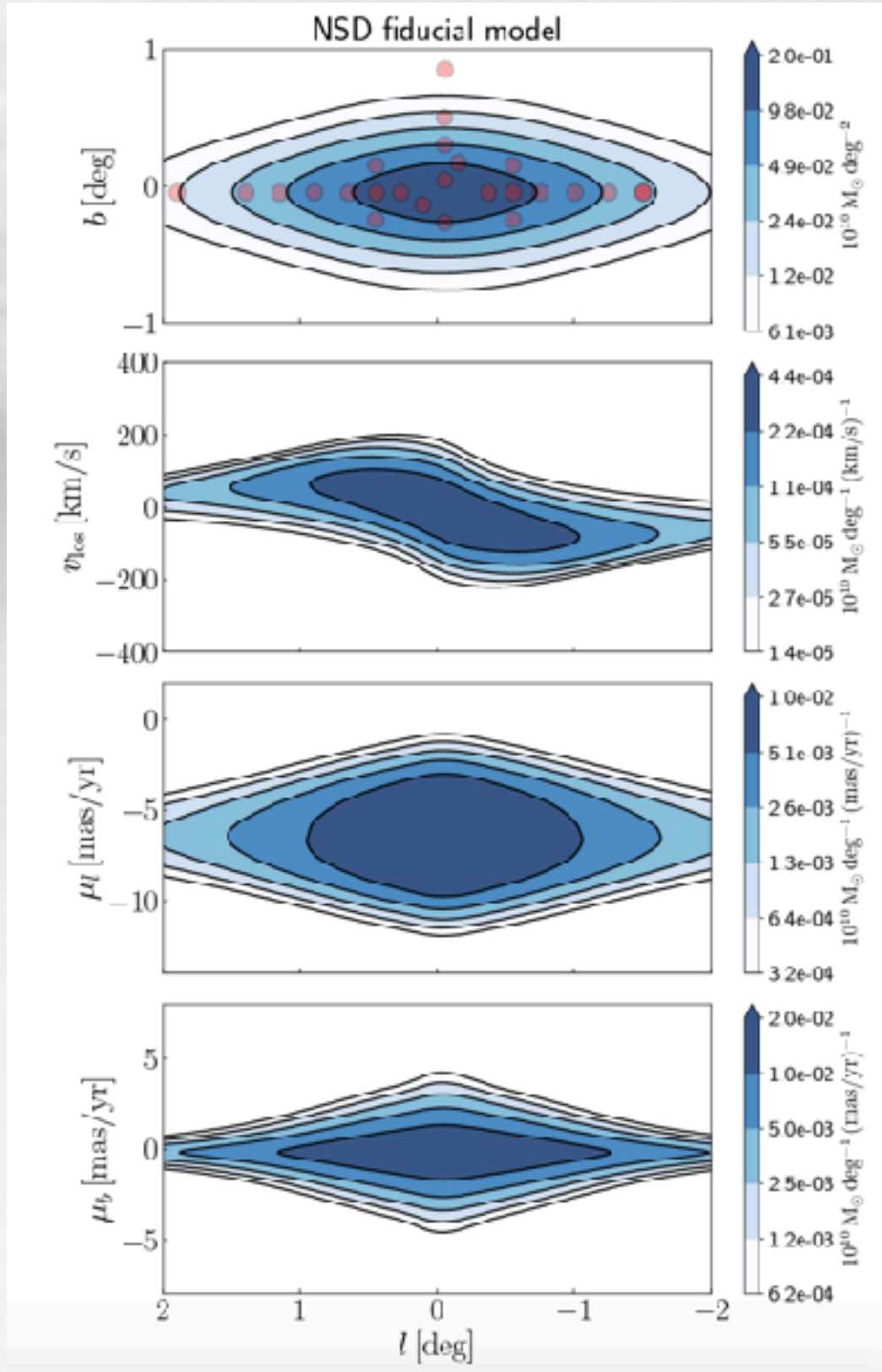


PM Distance On-sky Period

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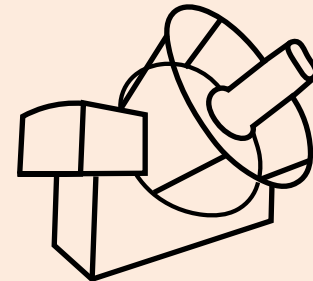
Sormani, Sanders+ 2022 NSD model
Action-based, axisymmetric

Mixture model for kinematics given on-sky position and period (marginalised over distance)



Fitted to proper motions
and spectroscopy

Dynamical modelling of NSD Mira variables



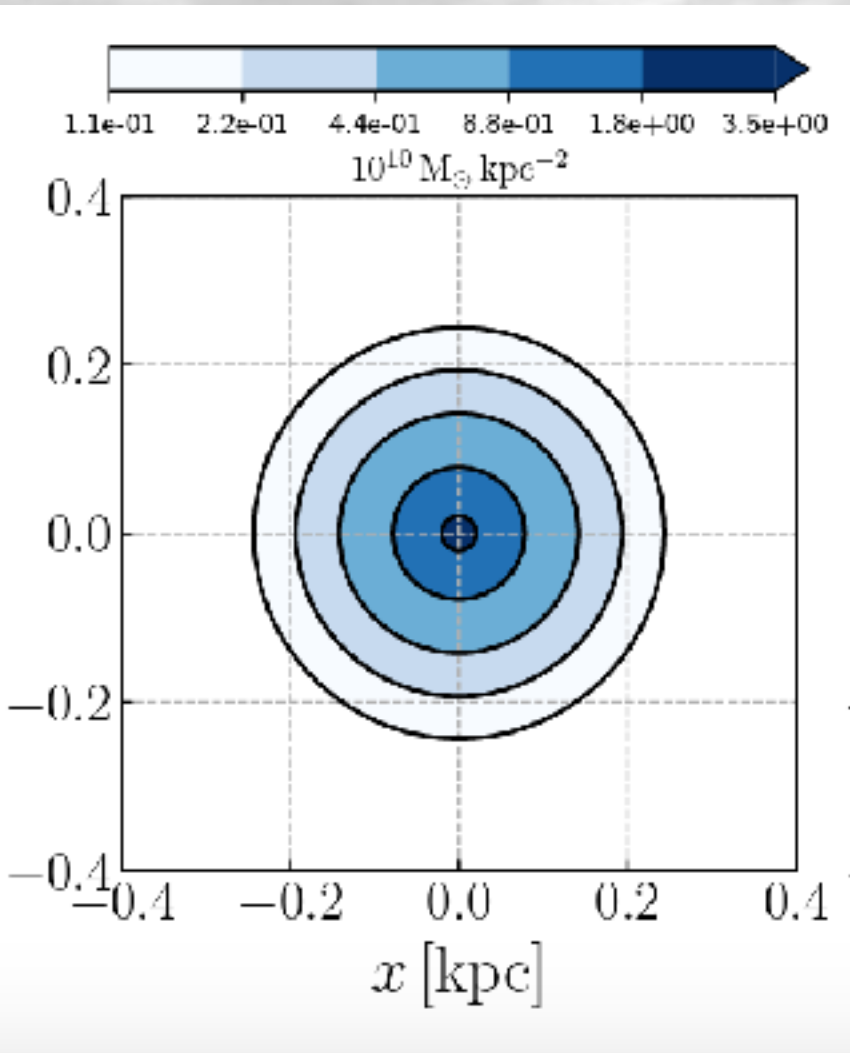
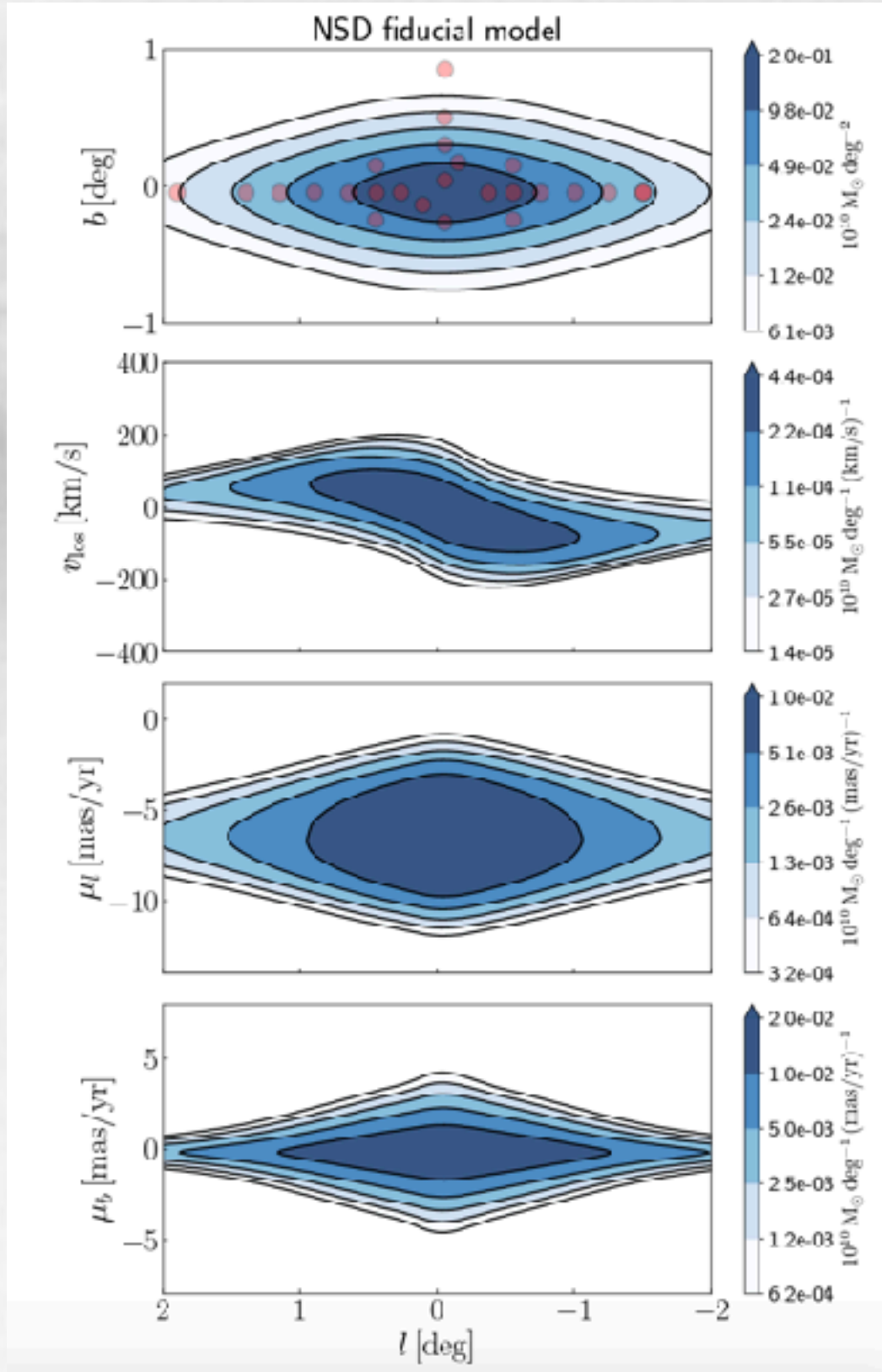
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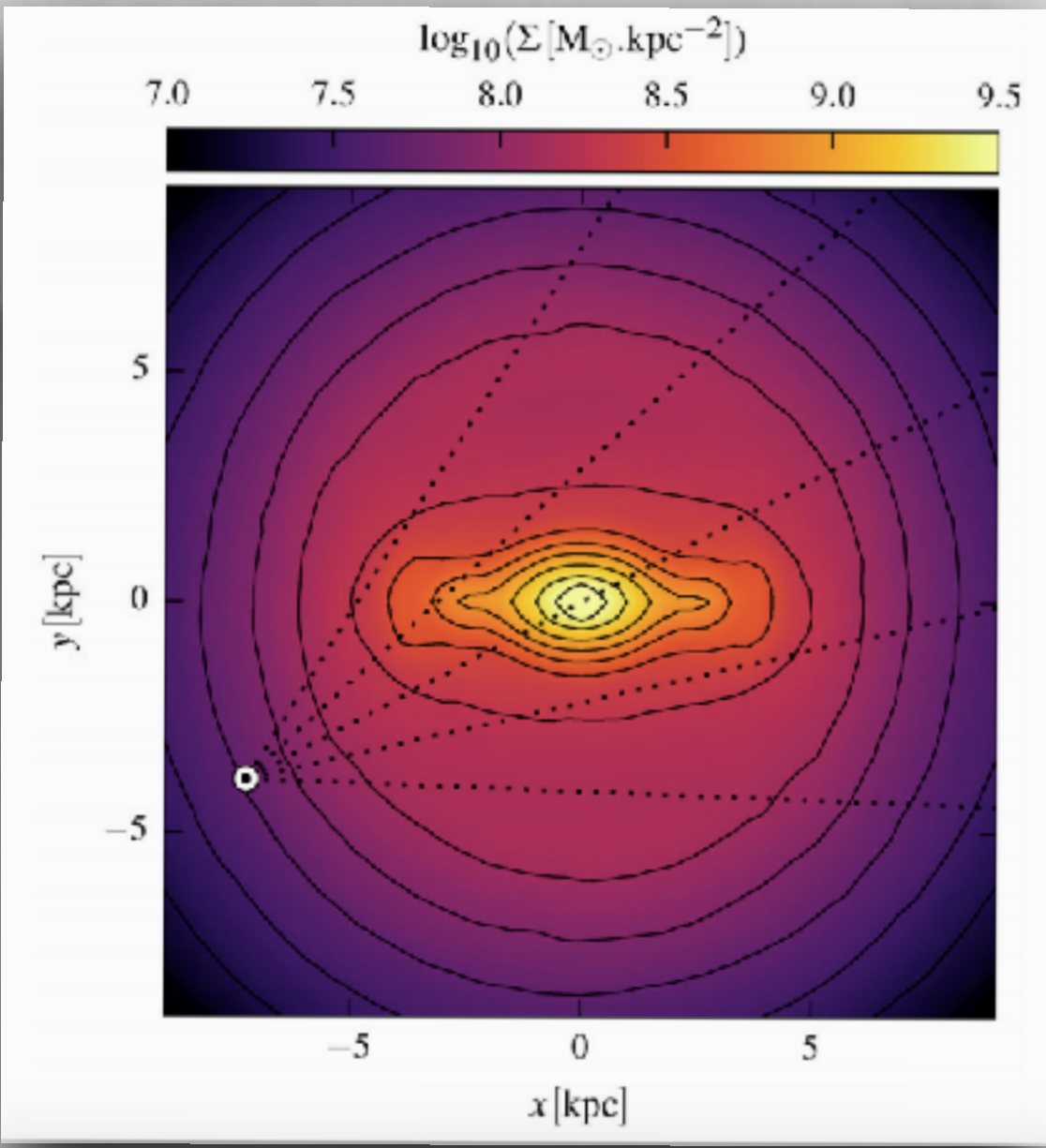
Sormani, Sanders+ 2022 NSD model
Action-based, axisymmetric

Mixture model for kinematics given on-sky position and period (marginalised over distance)

Portail et al. (2017) bar/disc model
(central component removed)

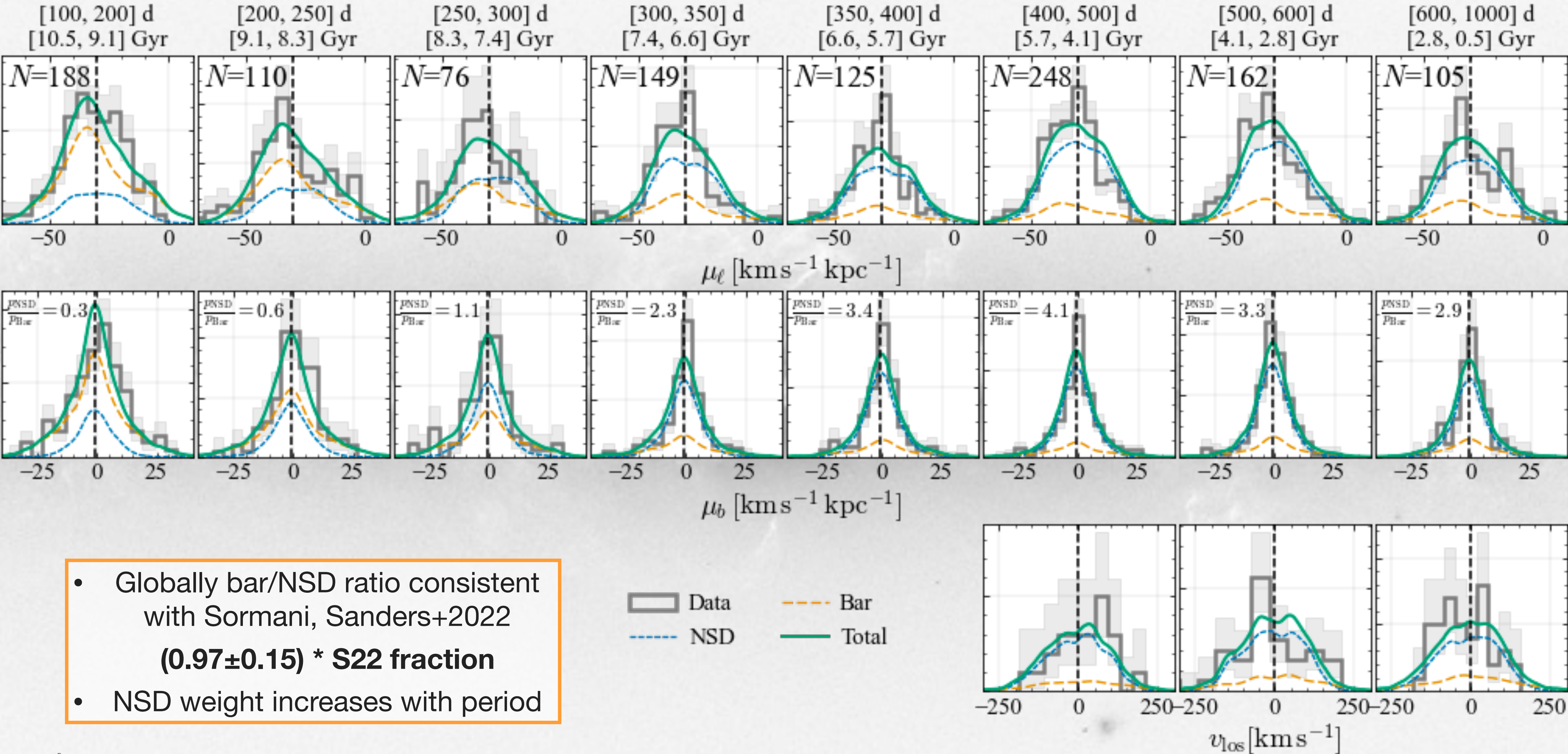
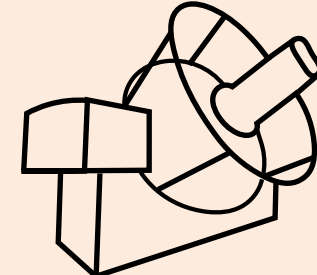


Fitted to proper motions and spectroscopy

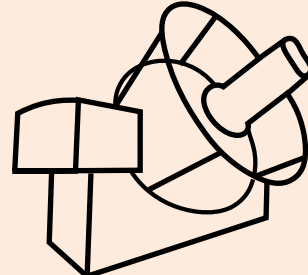


Made-to-measure modelling
Matched to star counts, spectroscopic data

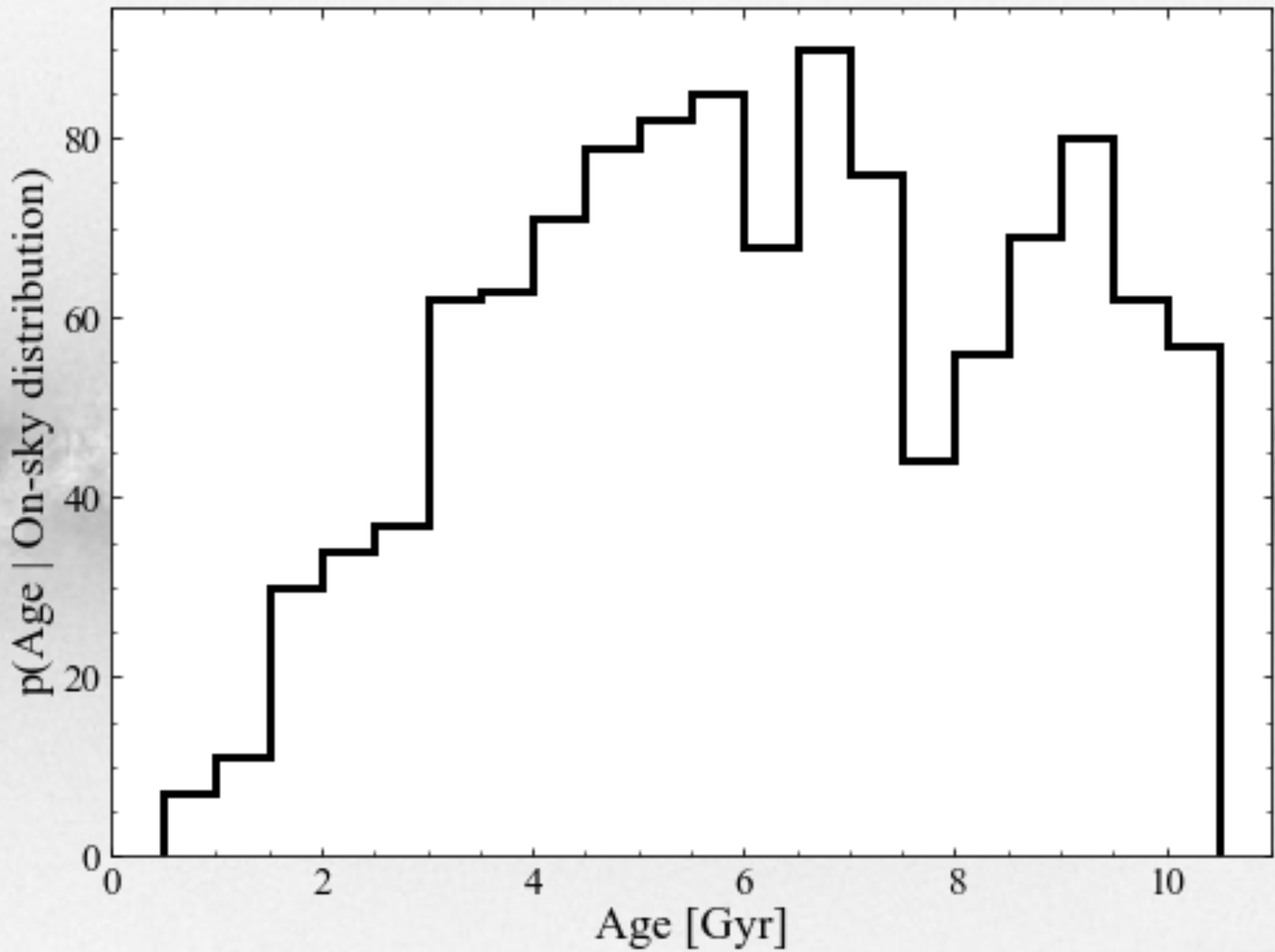
Dynamical modelling of NSD Mira variables



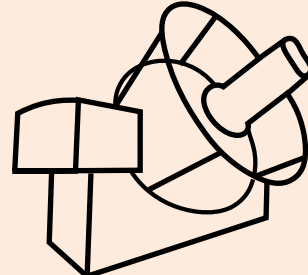
Dynamical modelling of NSD Mira variables



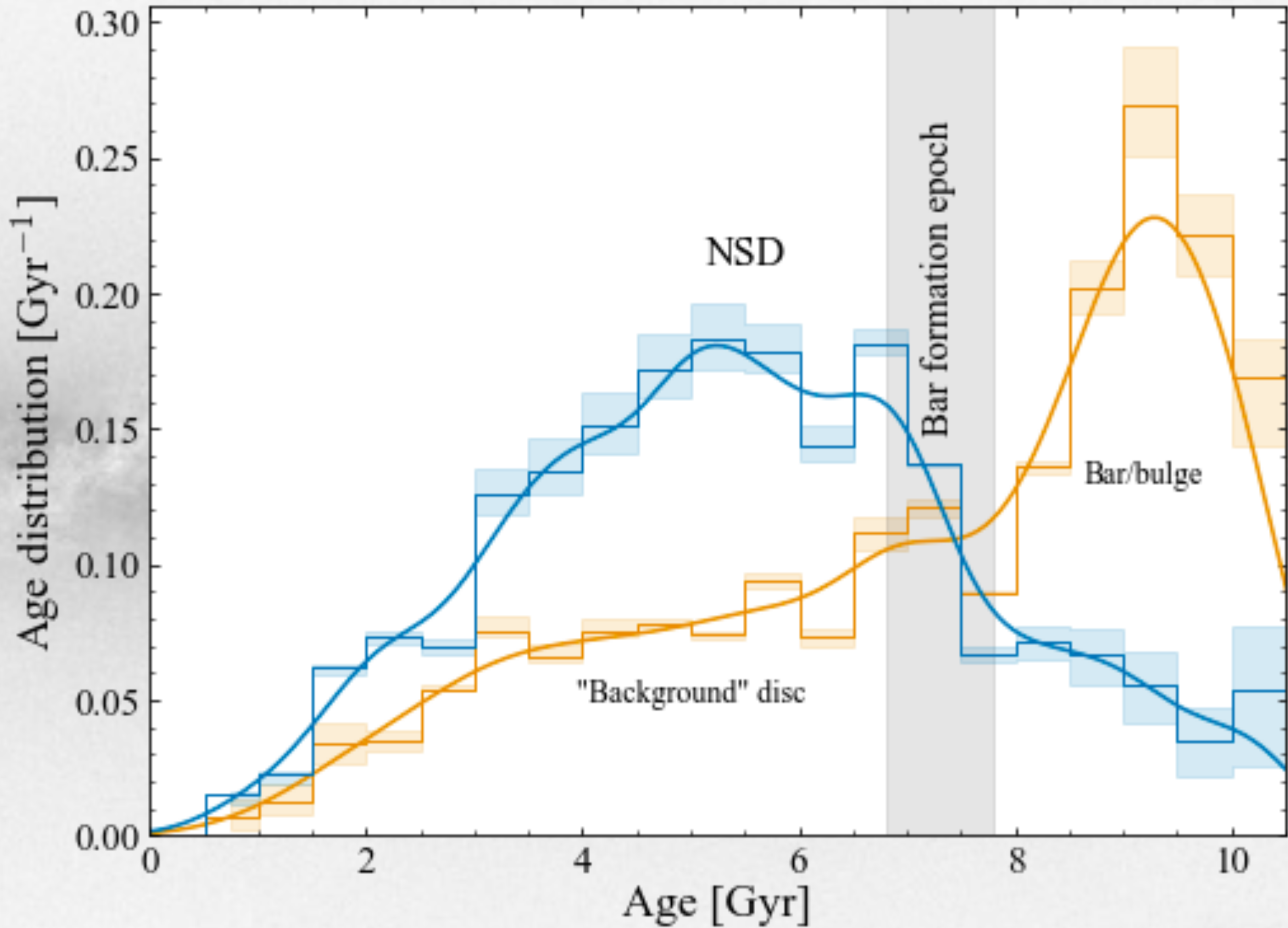
Reweight period/age distribution by membership probability at each on-sky location



Dynamical modelling of NSD Mira variables

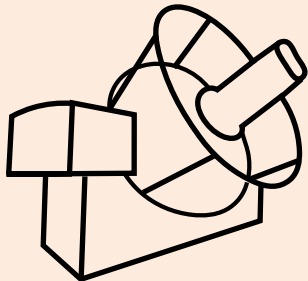


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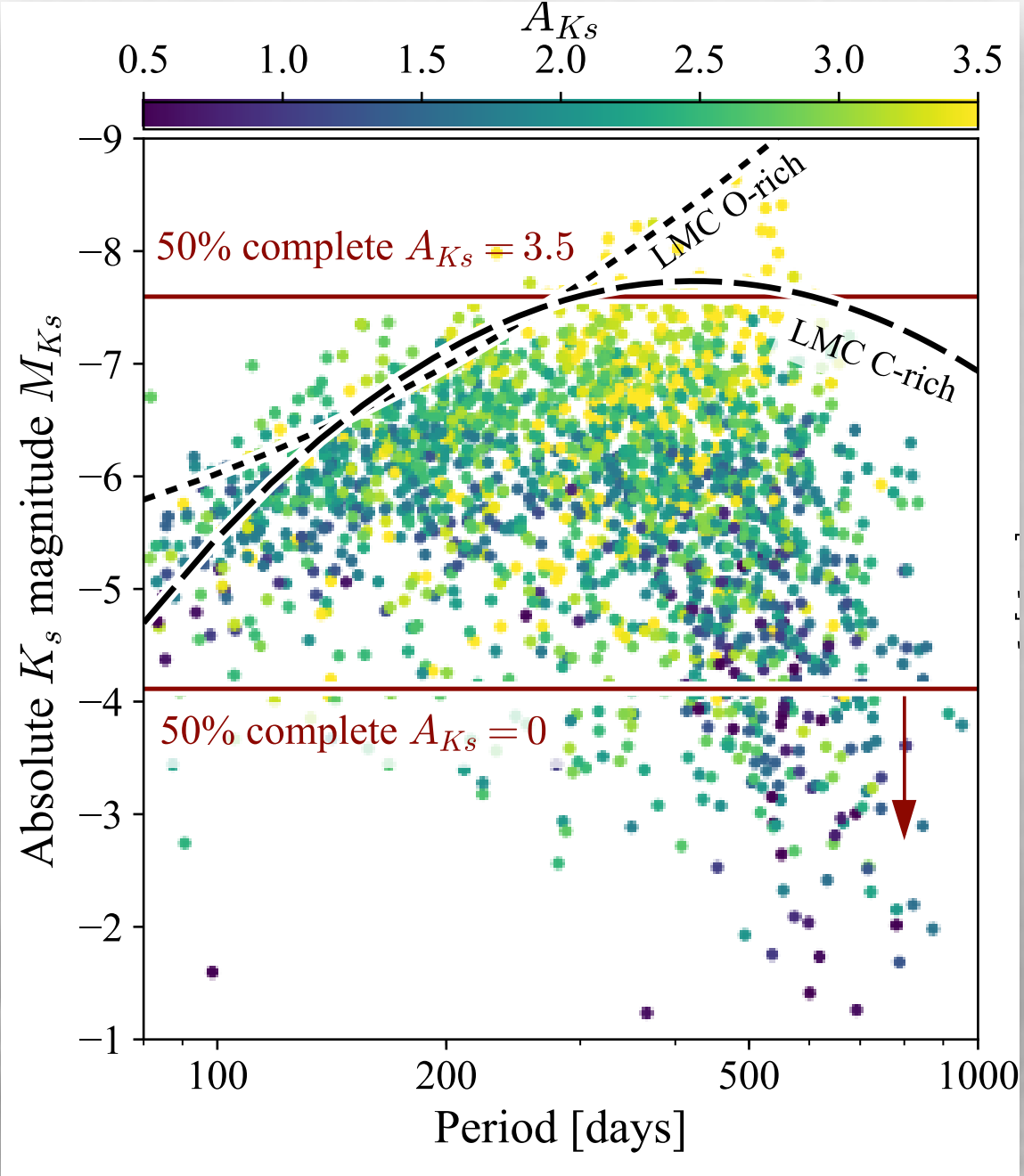
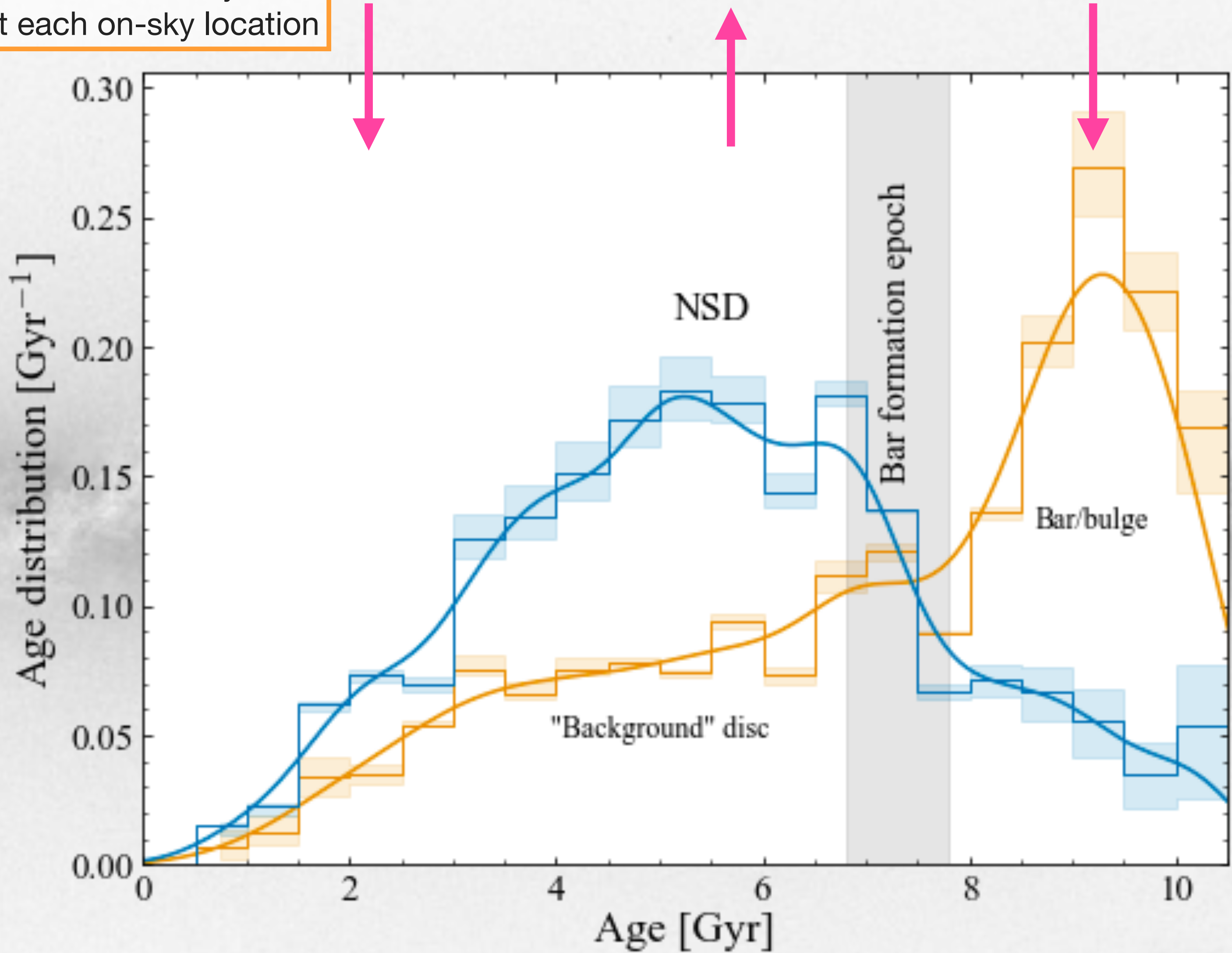


Caveat: selection function $S(\text{on-sky, period, distance})$ not accounted for as period-luminosity relation is not well known for v dusty sources

Dynamical modelling of NSD Mira variables

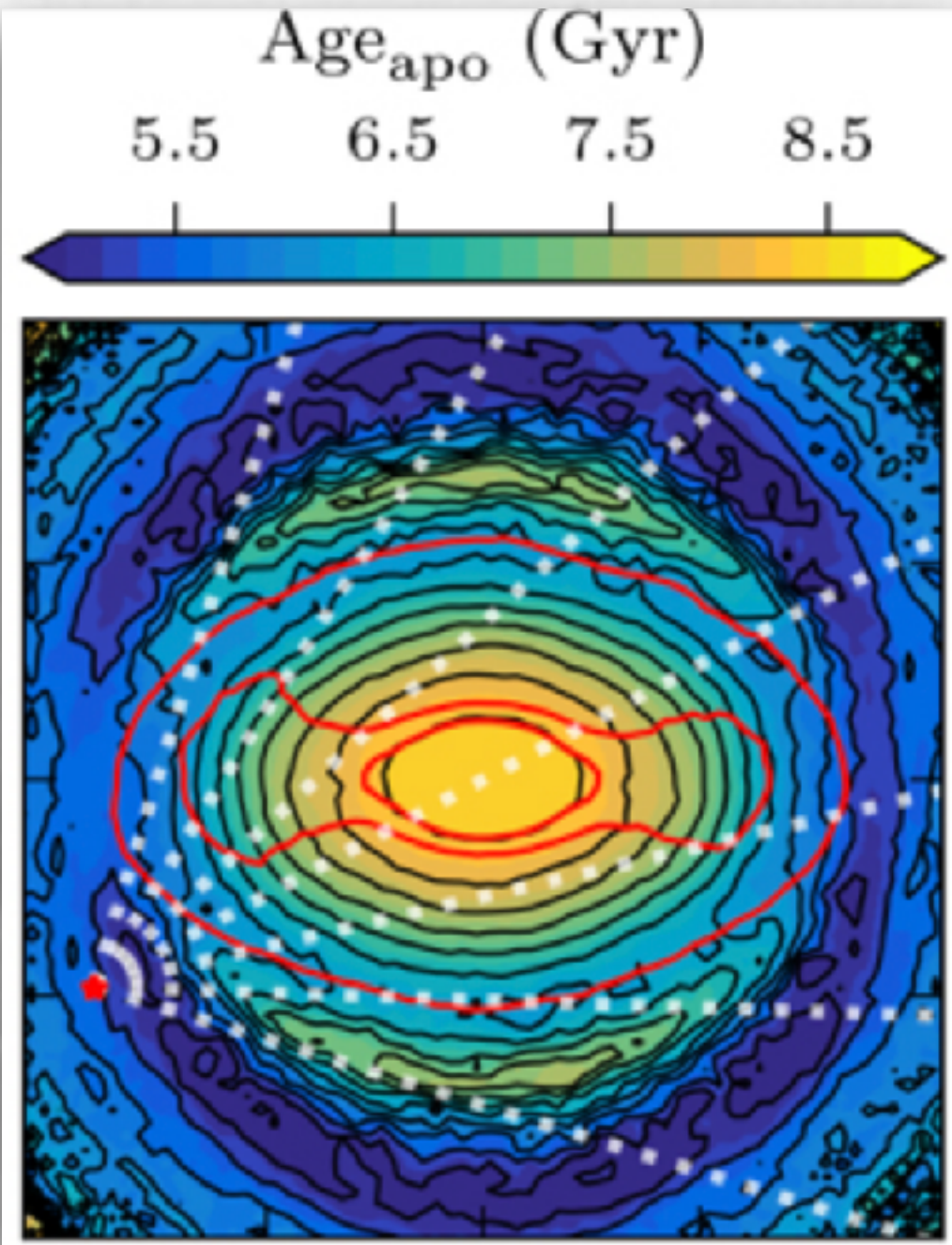
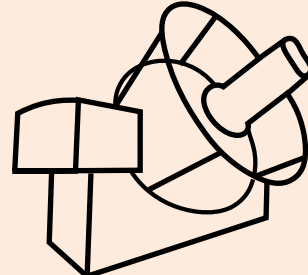


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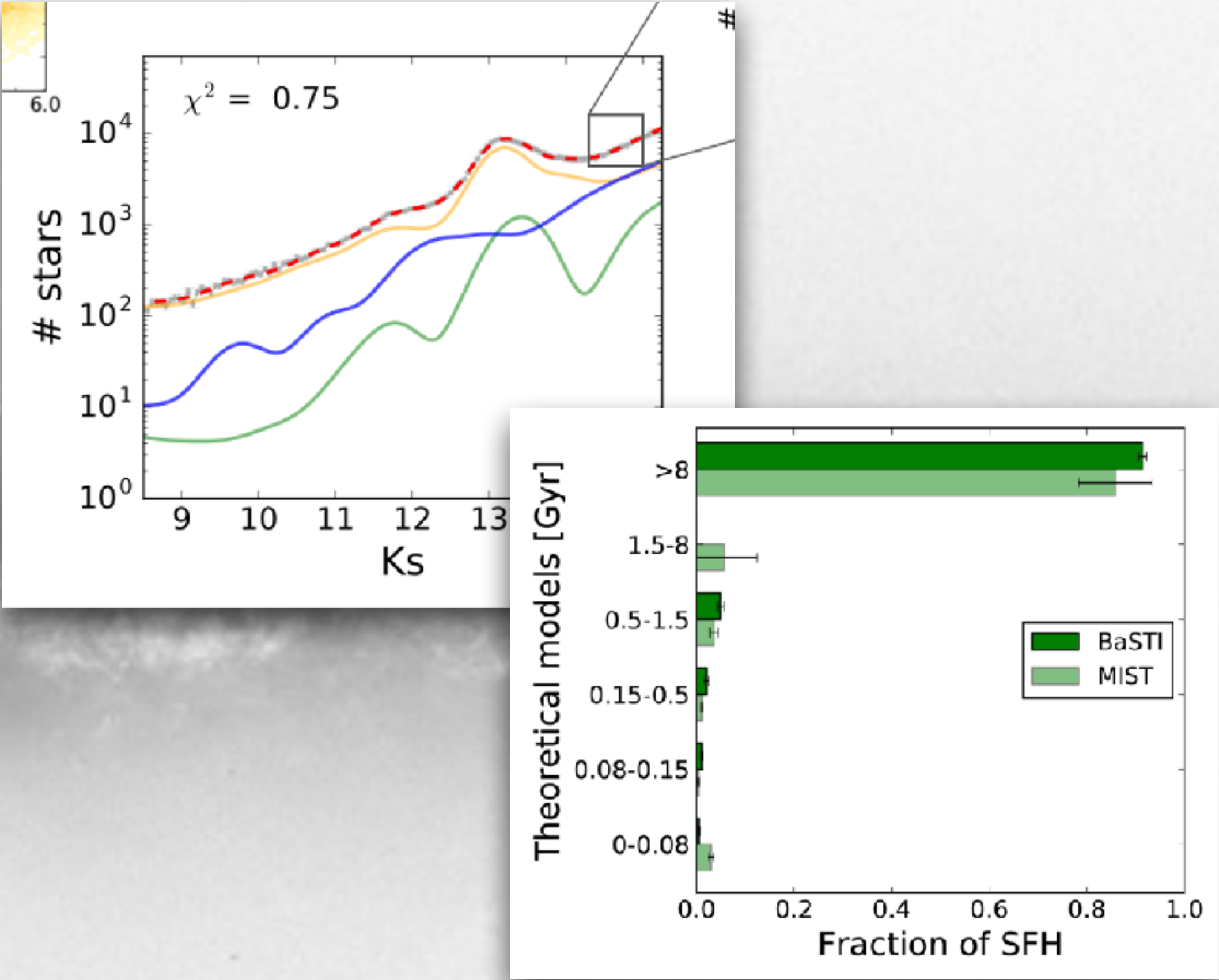


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A consistent picture

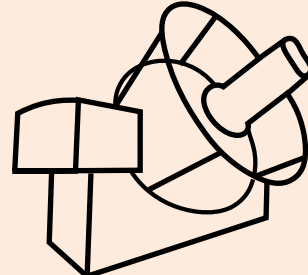


Wylie+ 2021 — APOGEE C/N
ages of stars in inner ring
>~7Gyr

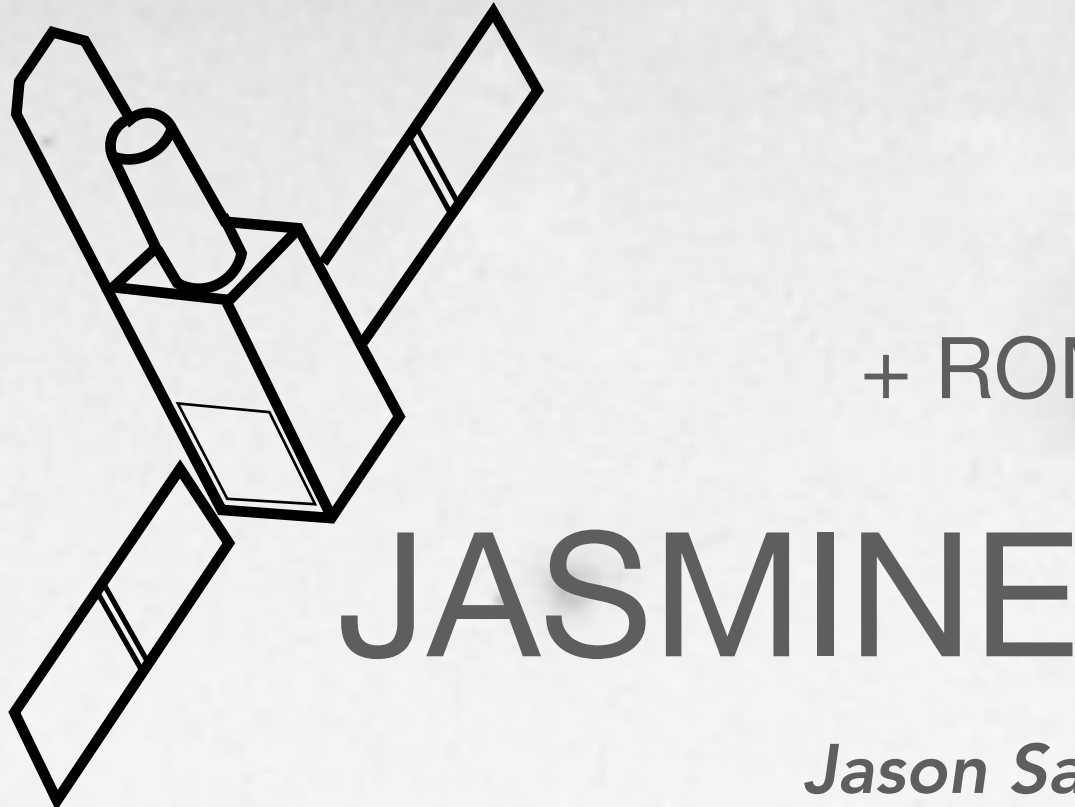
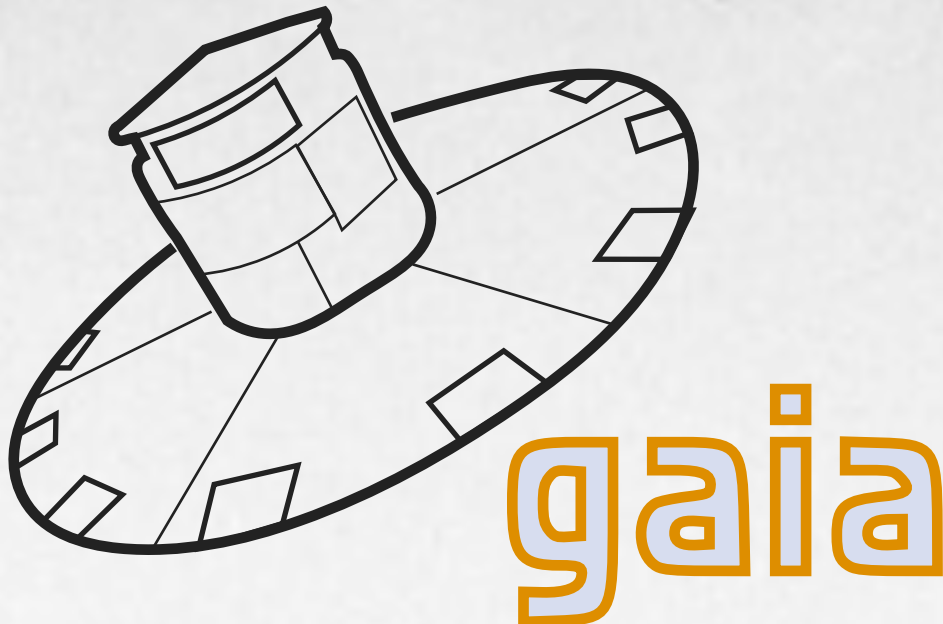
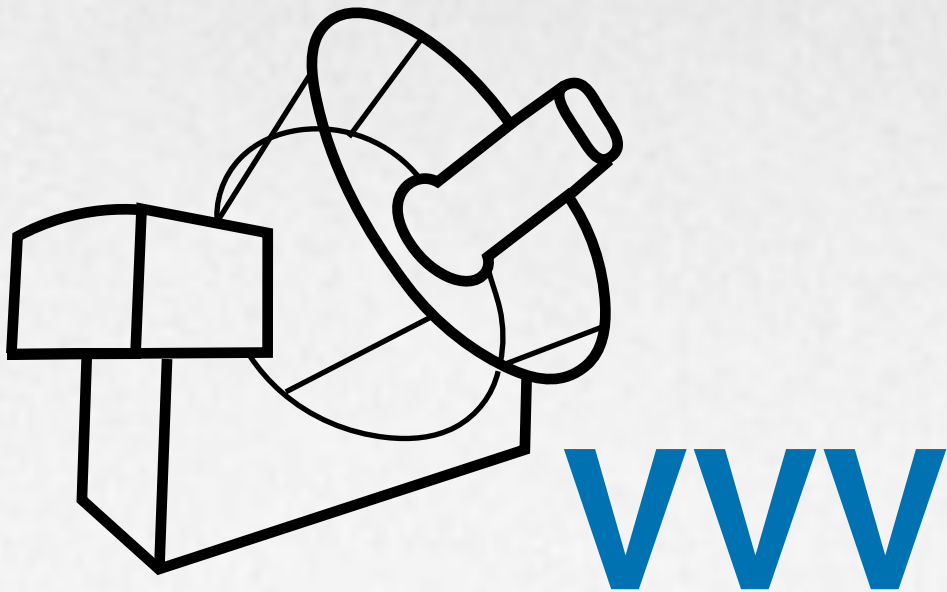
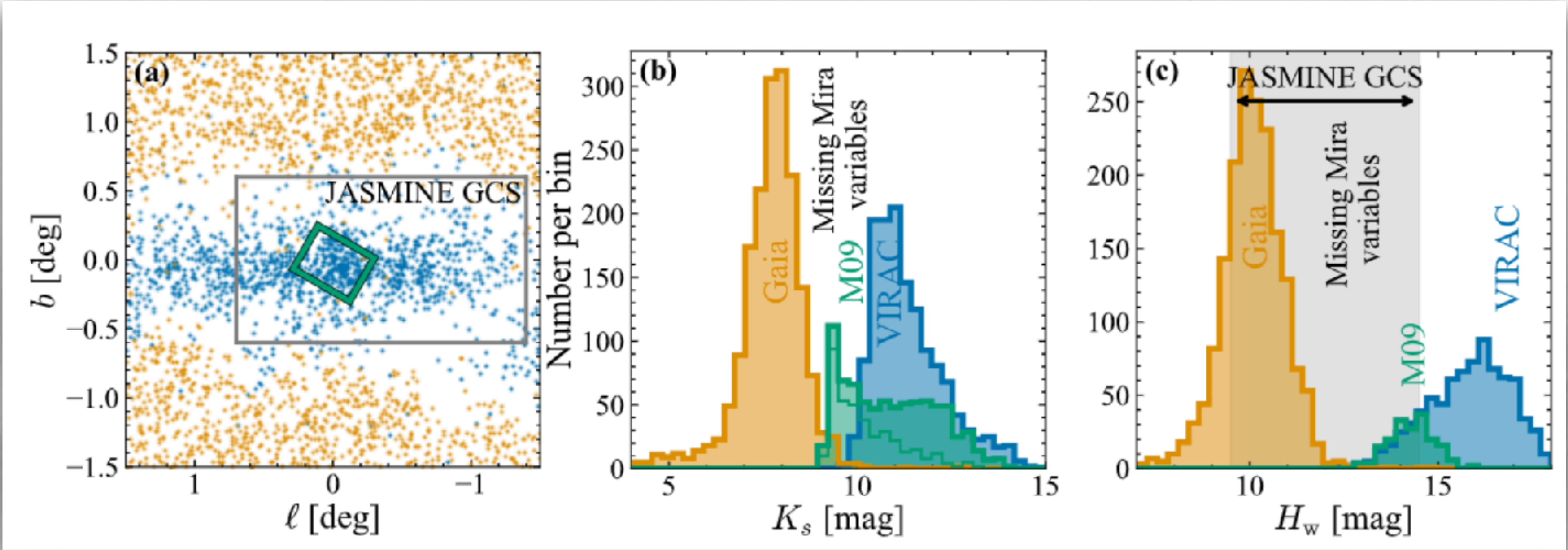


Nogueras-Lara+ 2019 (also NL+23, Schoedel+23)
Giant branch modelling of GALACTICNUCLEUS
e.g. red clump/red giant branch bump ratio
>8Gyr

Future prospects

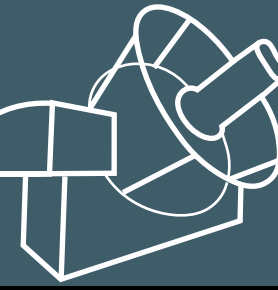


Missing Mira variables **with astrometry** between Gaia and VVV — low-extinction/outer NSD → **JASMINE** will fill in



+ ROMAN... (MSTO; Terry+23)

Summary, Interpretation & Speculation



Dynamical modelling of proper motions of Mira variables in the NSD suggest the MW bar is *7-8Gyr old*

Fitting in the Galactic timeline

- *Belokurov+22, Rix+22, Semenov+23a,b* — MW disc in place early compared to MW analogues
- GE/S — Splash *Belokurov+2020, Bonaca+2021* ~ 10Gyr
- Thin (low α)-thick (high- α) transition — ~8Gyr
- Sgr dSph first pericentric passage ~6Gyr (Das+23)
- Bar buckling (B/P symmetry): Khoperskov+19 — Gaia snail unlikely bar related
- Relation to bar slowdown measurements (Chiba+21) — $d\Omega/dt \sim 4.5 \text{ km/s/kpc/Gyr} \rightarrow \Omega \sim 68 \text{ km/s/kpc}$ at formation? But only 24% change required for Hercules

