Introduction & Theia

Goals of workshop

What scientific breakthroughs with very high precision astrometry?

What telescopes & instruments to achieve these scientific results?

Strategic questions:

- focus on a single telescope OR go for many?
- combine all science OR split exoplanets around nearby stars from rest?
- federate scientists from ≠ continents or work separately?

Where did you come from?

Gary Mamon (*IAP*), *Introduction & Theia*, 11 Sept. 2024

Program

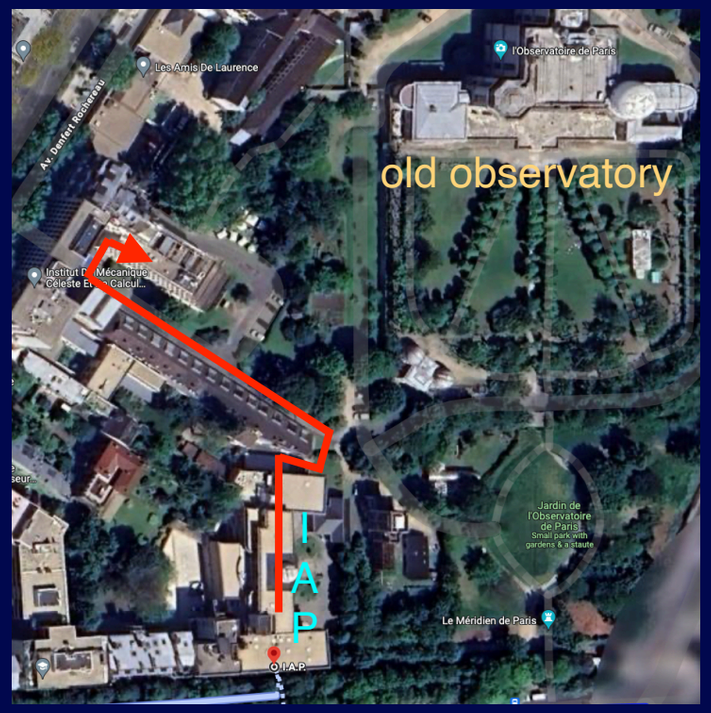
2 last-day cancellations for the Summary

	Wednesday		Thursday		Friday	
9:00					Science: stellar satellites	Sozzetti
9:15			Science: Dark matter II	Boehm		
9:30	Telescopes & missions I	Mamon				Tuthill
9:45				Read		
10:00		Malbet				Carry
10:15				Kim		
10:30		Gouda		Pfalzner	Coffee	
10:45						
11:00	Coffee		Coffee		Instrumentation II	Discussion
11:15						
11:30	Telescopes & missions II	Hobbs	Telescopes & Missions III	Roberge		
11:45						
12:00		Van Belle		Gaudi	Science: Clusters & MW satellites	Watkins
12:15						
12:30		Gandhi		Quanz		Gnedin
12:45						
13:00	Lunch			Vasisht		Demianenko
13:15			Lunch		Lunch	
13:30						
13:45						
14:00						
14:15						
14:30	Science: Dark Matter I	Vitral				
14:45				Hunt		Garcia-Bellido
15:00		Katz	Telescopes & Missions IV		Science: Gravitational waves & Particle physics	
15:15		Chakrabarti		Discussion		Crosta
15:30						
15:45	Coffee					Chen
16:00						Caravano
16:15	Science - BHs, neutron stars & Cosmology	Maccarone	Coffee		Coffee	
16:30						
16:45		Schwartzman	Instrumentation I	Lacour	Science: cosmology & general discussion	Darling
17:00		Nierenberg				
17:15				Busonero		Discussion
17:30		Lu				
17:45				Gai		
18:00						
18:15	Cocktail			Shao	Summary	TBD
18:30						
18:45				Skoffelt	END	
19:00			END			
19:15						
19:30						
19:45						
20:00			Dinner			
20:15						
20:30						
20:45						
21:00						

Food & drinks

Coffee breaks in entrance hall (except Friday: in the 2nd floor Forum)

free **Lunches** at Observatory cafeteria, 3 min walk on campus
outside tables available



all free for all participants (except drinks at dinner)

Cocktail this evening at 6:30PM in entrance hall

Workshop dinner Thursday evening at 7:30PM *Chez Lionel*

WiFi

eduroam

wisecure
login: astrometry2024
password: see blackboard

Other practical issues

Do not try to close or re-open windows!

Remote participants

31 out of 76 participants

We value your input!

Chairpersons: try to take questions from remote audience 1st

Remote participants when not speaking

- Make sure you can see & hear the meeting
- Test your microphone (for questions)
- If anything goes wrong, please raise your Zoom-hand
- Please turn off your microphone except for your talk or question

8 Remote speakers: ditto +

- Check the program for the time of your talk
- Be online > 10 minutes before

IAP Code of Conduct

The Institut d'Astrophysique de Paris (IAP) promotes a respectful, safe, and ethical research environment. As a reminder of the obvious, this includes:

- **Respect** for all people working at IAP (permanent and non-permanent) and intolerance of any discrimination, violence or harrassment;
- The recognition of the need for **open communication** and **civility**;
- The promotion of **diversity and inclusivity**;
- **Scientific integrity**, upholding the highest professional and ethical standards in all conduct.

Discrimination: Everyone at IAP should treat each other with equity and respect, regardless of personal attributes including but not limited to: (alphabetically) age, disability, ethnicity, gender, gender expression, gender identity, lactation, nationality, physical appearance, political affiliation, pregnancy, religion, sexual orientation, and status as a caregiver (including as a parent).

Harassment: By law, the following behaviors are prohibited: verbal, non-verbal or physical harassment of any kind, disparagement, intimidation, exclusion, spreading personal rumors, humiliation.
Behaviors and language acceptable to one person may not be to another. At IAP, everyone must make every effort to ensure that words and actions communicate respect for others. In particular, sexual harassment is not tolerated at the IAP, including but not limited to inappropriate verbal and physical conduct, unwelcome sexual advances, and requests for sexual favors.

Scientific Misconduct: Scientific research has to be performed in a well-documented and ethically sound manner. Falsification of data or results, plagiarism, taking credit for others' work or any other scientific misconduct will not be tolerated.

Who to contact: me or other organisors

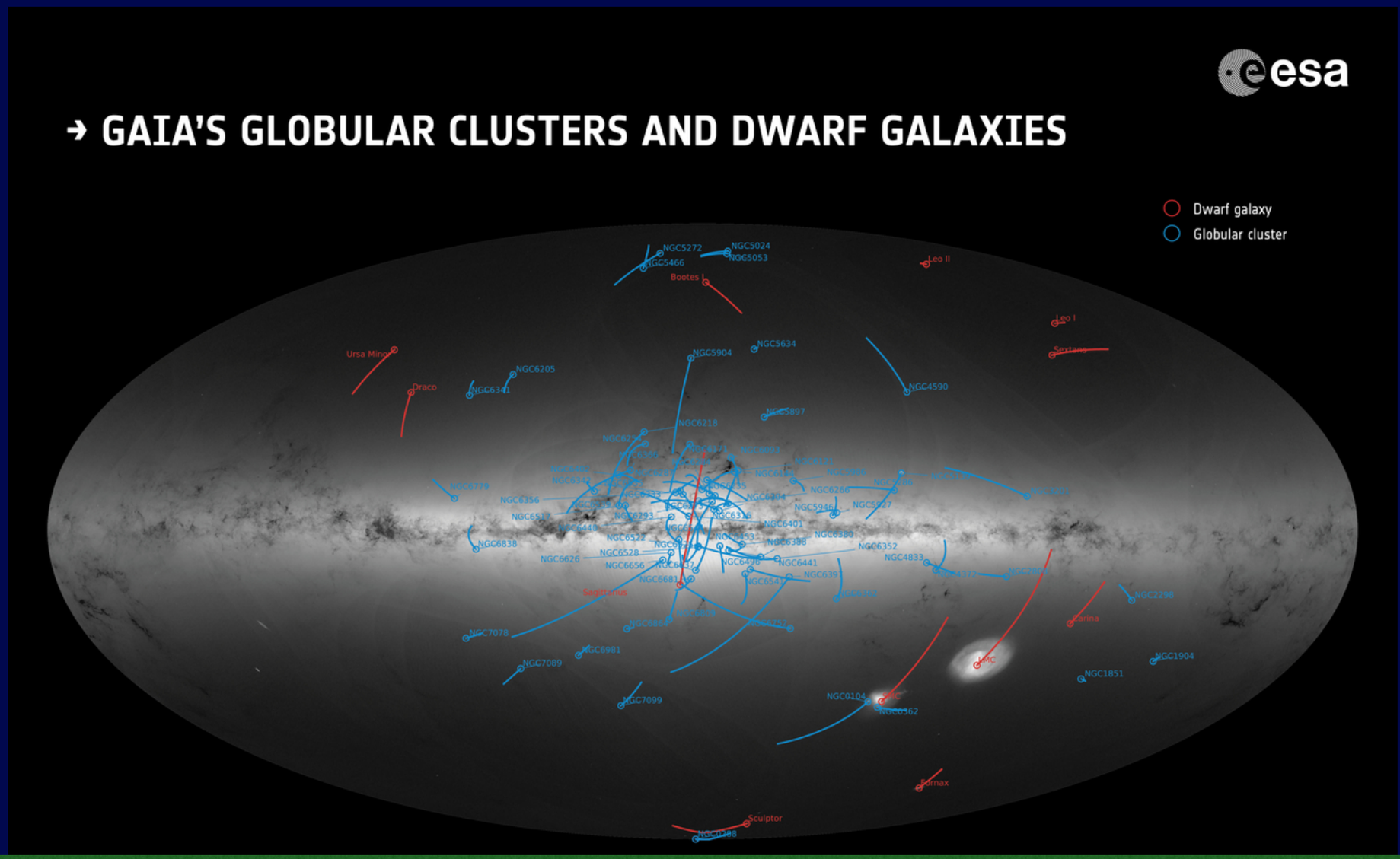
be kind to others, esp. young ones!

Recording of workshop?

- All talks or some talks?
- Questions after talks?
- Discussions?

Theia

Astrometric science with Gaia



The Gaia revolution

- Kinematics of *Milky Way* stars (thin & thick disk, bar, halo…)
- Bulk motions of globular clusters & dwarf spheroidals
- Detection of new members of *Local Group*
- Internal kinematics of globular clusters: what lurks in their cores?
- Black holes in binaries, isolated
- many more!

After Gaia…

… Theia?

very long (1000hr) monitoring on selected targets

Proper motion error

$$\epsilon_{\rm position} \approx \frac{\sqrt{\rm FWHM^2 + jitter^2}}{\rm SNR}$$

$$\rm SNR = \frac{counts_{source}}{\sqrt{counts_{source} + \sigma^2_{sky}}} = \frac{A\, t_{exp} 10^{-0.4\,(m-m_0)}}{\sqrt{A\, t_{exp}\, 10^{-0.4\,(m-m_0)} + \sigma^2_{sky} + \sigma^2_{instrum}}}$$

$$\propto \sqrt{A\, t_{exp}}$$

$$\epsilon_{\rm PM} = \frac{\epsilon_{\rm position}}{\Delta t \sqrt{N_{\rm exp}}}$$

bright sources

$$\epsilon_{\rm PM} = \frac{\rm FWHM\ 10^{0.2\,(m-m_0)}}{\sqrt{A\, t^{\rm total}_{\rm exp}\ \Delta t}}$$

faint sources

$$\epsilon_{\rm PM} = \frac{\rm FWHM\ 10^{0.4\,(m-m_0)}}{\sqrt{A\, t^{\rm total}_{\rm exp}\ \Delta t}}$$

Astrometric mission: 20x 5-yr Gaia's accuracy

	Gaia 10 year	Theia deep	improvement
Telescope Aperture	1.45 × 0.5 = 0.73 m^2	0.8 m → 0.40 m^2	**0.55**
Field of view		0.5 deg	
Coverage	Survey	*Pointed*	
Astrometry	Global	*Differential*	
Exposure time per field	160 × 9 (CCD) × 4.4 sec = 1.76 hr	25 × 40 hr = 1000 hr	**570**

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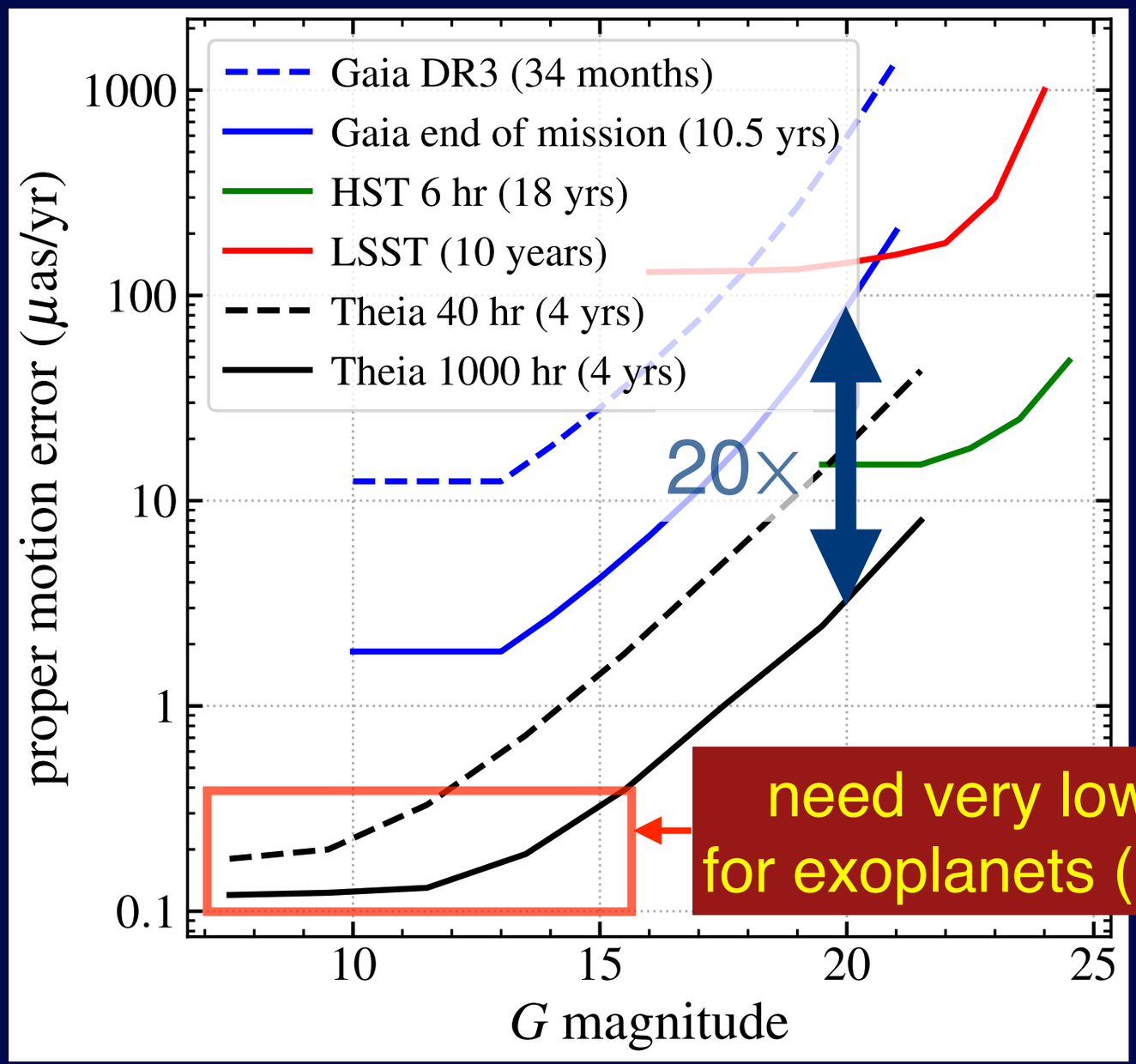
Exposure time per field	160 × 9 (CCD) × 4.4 sec = 1.76 hr	25 × 40 hr = 1000 hr	**570**
Additional factors	2D vs 1D astrometry: 1.4, Gaia Stray light: 1.9		
	naïve global gain = $(0.55 \times 570)^{1/2}$ = 18 ➜ **45** after additional factors		
Proper motion accuracy *G*=10 star	2 μas/yr	0.12 μas/yr	**17**
Proper motion accuracy *G*=15 star	5 μas/yr	0.4 μas/yr	**12**
Proper motion accuracy *G*=20 star	100 μas/yr	5 μas/yr	**20**

Proper motion accuracy

Gaia: based on ESA web site on Gaia performance

HST: based on analysis of Draco dwarf by Vitral+24



need very low systematic errors
for exoplanets (around nearby stars)

What scientific breakthroughs with very high-precision astrometry?

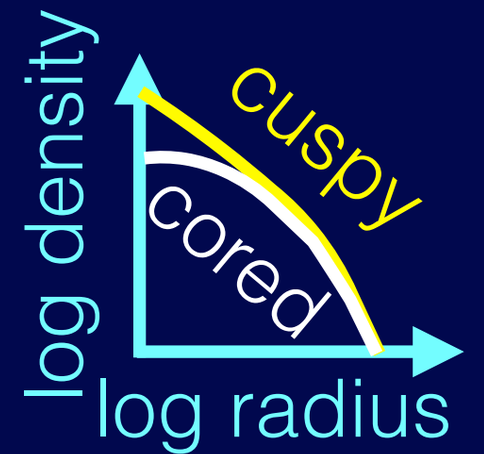
incomplete list: you will enhance it!

Nature of Dark Matter: cold & collisionless?

a. DM halos of dwarf spheroidal galaxies are *cuspy*

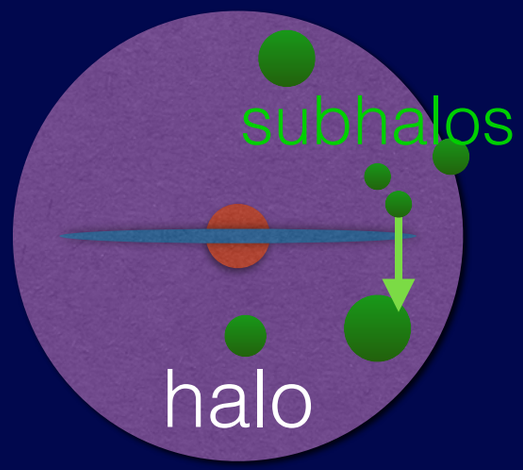
bayesian mass/orbit modeling of 3 dwarf spheroidals using proper motions

see talks by E. Vitral, J. Read, L. Watkins



b. Numerous dark subhalos in Milky Way

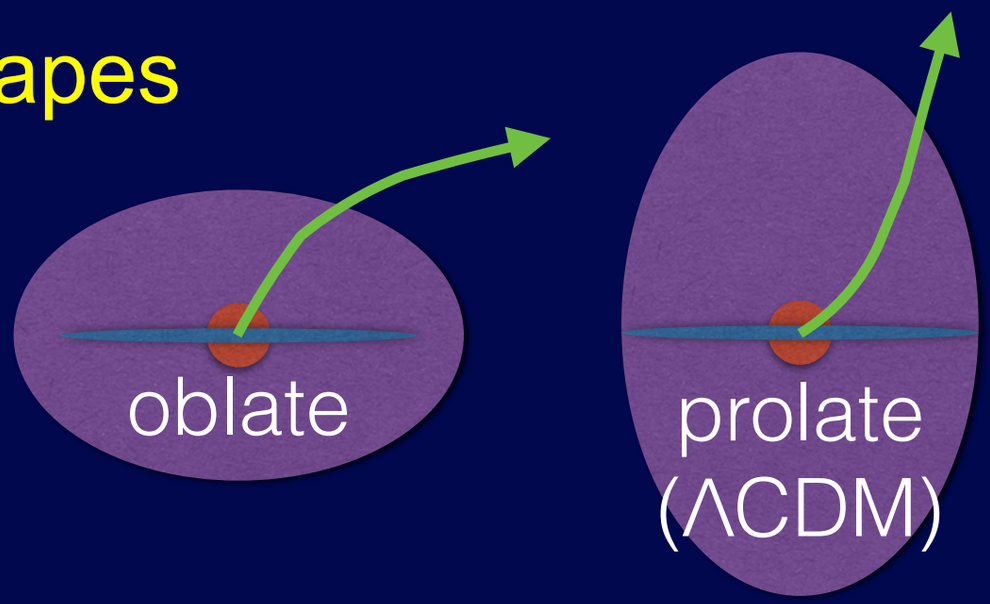
detect by kinematic disturbances to disk stars in 16 lines of sight above/below Galactic Plane



c. Dark Matter halos have *prolate* shapes

measure direction of proper motion in 3 distant *hypervelocity stars*

see talk by O. Gnedin



2) Black holes & Neutron Stars

BH detection by astrometric wobble

see talk by J. Lu

Neutron star physics: see talk by T. Maccarone

- formation
- kick
- equation of state
- misalignment magnetic misalignments

Advances from pointed super-precision astrometric mission

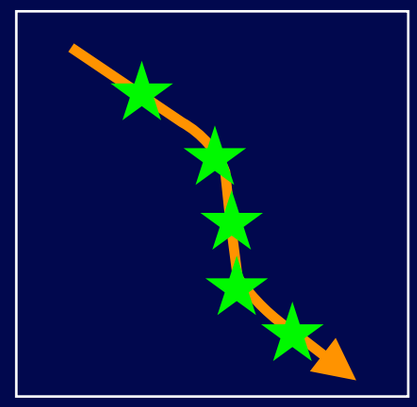
Possible Breakthroughs:

★ Detection of

➡ *Primordial* Black Holes

➡ Ultra-Compact Mini-Halos

astrometric microlensing



see talk by J. Garcia-Bellido

★ Detection of

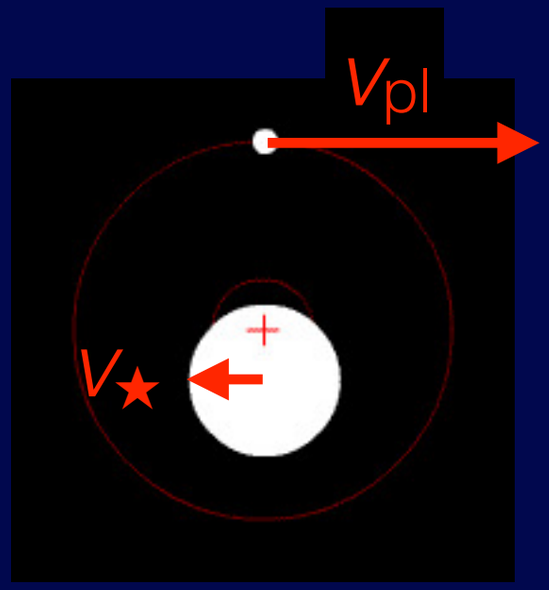
➡ *Primordial* Gravitational Waves

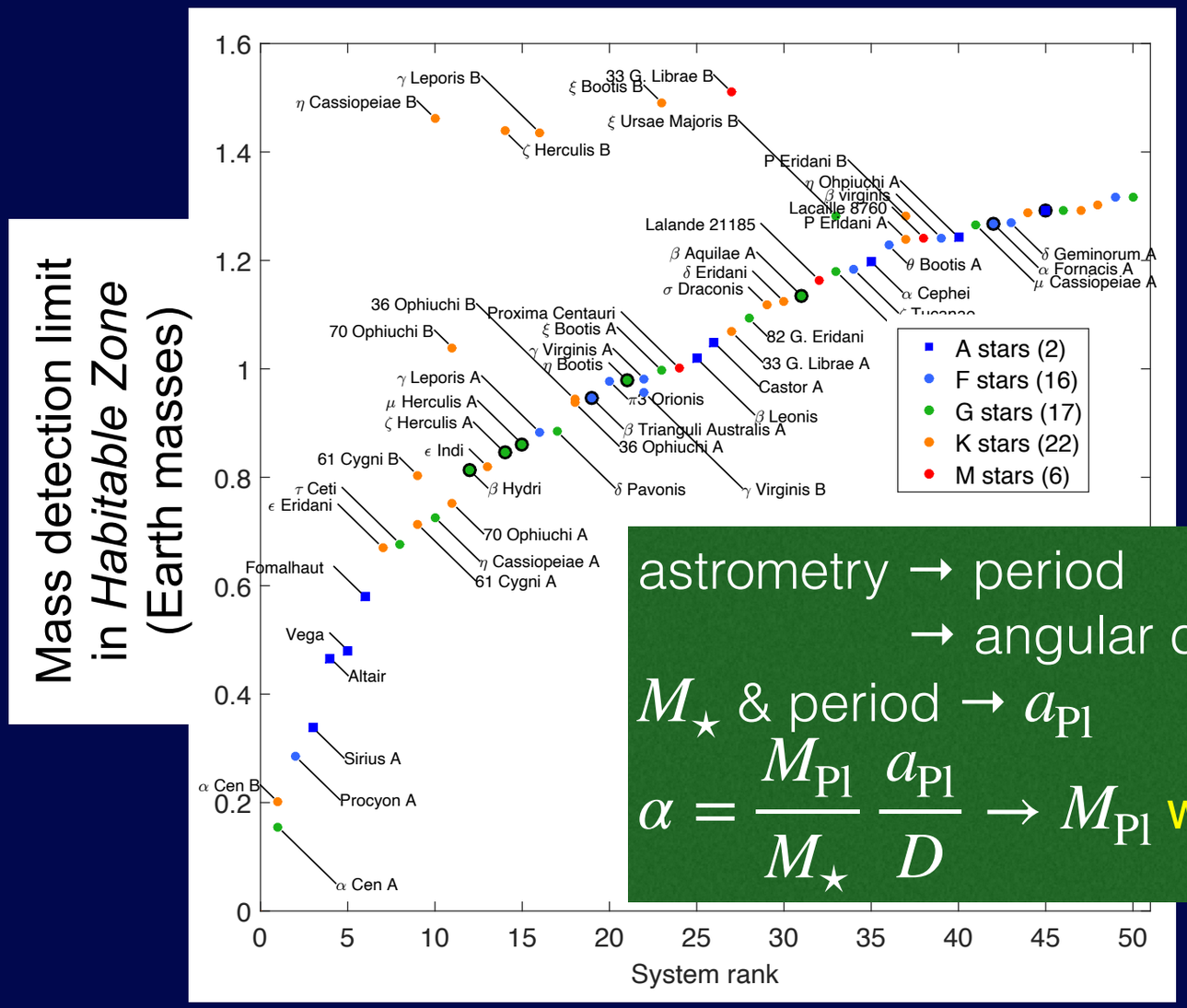
➡ *Gravitational Waves* from merging *Super-Massive* BHs

coherent-time distortions in velocity field

3. Census of Nearby Habitable Exoplanets

see talks by A. Sozzetti & P. Tuthill





astrometry → period

→ angular displacement of star α

$M_\star$ & period → $a_{\rm Pl}$

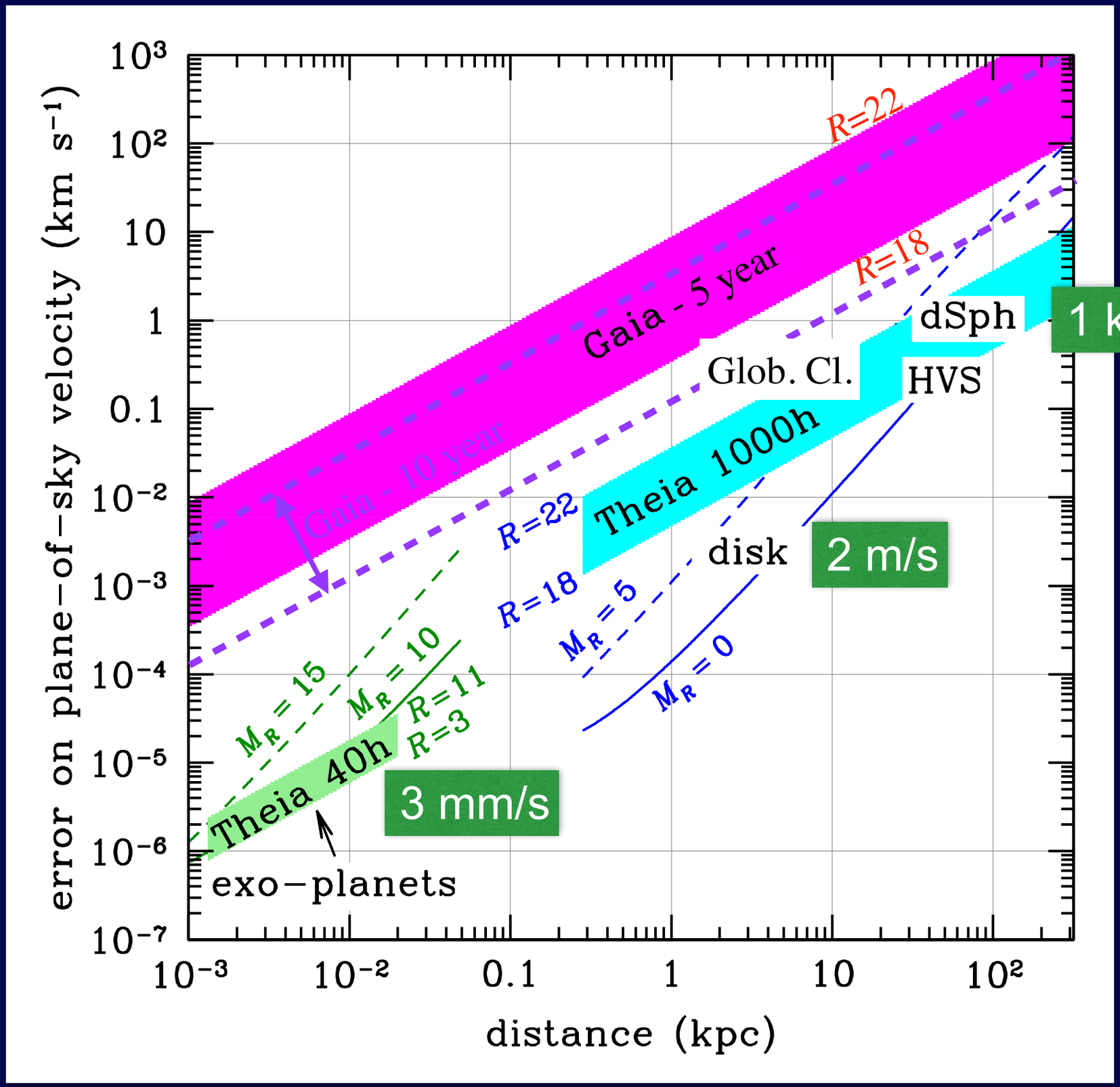
$$\alpha = \frac{M_{\rm Pl}}{M_\star}\frac{a_{\rm Pl}}{D} \rightarrow M_{\rm Pl}$$ with no sin *i* uncertainty!

Census is Complete & Reliable

validated with detailed mocks
Meunier & Lagrange 22

→ allows efficient *followup spectroscopy* → *biospheres*

Plane-of-sky velocity errors



History of Theia proposals to ESA

- M3: NEAT, PI F. Malbet
- S1: MicroNEAT PI. F. Malbet

Main driver:

exoplanets

- M4 Theia PI F. Malbet
- M5 Theia PI C. Boehm

- M6/7 Theia PI A. Sozzetti

dark matter

ESA: lack of Technology Readiness!

Exoplanets: requires very low systematics @ bright end
→ complicates the instrument (metrology)

Before Theia?

Think what Gaia-10 years will bring relative to DR3 (2.3 years)

What other telescpes will do as well if not better?

Proper motion error (repeat)

$$\epsilon_{\rm position} \approx \frac{\sqrt{\rm FWHM^2 + jitter^2}}{\rm SNR}$$

$$\rm SNR = \frac{counts_{source}}{\sqrt{counts_{source} + \sigma^2_{sky}}} \propto \frac{A\, t_{exp} 10^{-0.4\,(m-m_0)}}{\sqrt{A\, t_{exp}\, 10^{-0.4\,(m-m_0)} + \sigma^2_{sky} + \sigma^2_{instrum}}}$$

A = effective area

$$\propto \sqrt{A\, t_{\rm exp}}$$

$$\epsilon_{\rm PM} = \frac{\epsilon_{\rm position}}{\Delta t \sqrt{N_{\rm exp}}}$$

Δt = time baseline

bright sources

$$\epsilon_{\rm PM} \propto \frac{\rm FWHM\, 10^{0.2\,(m-m_0)}}{\sqrt{A\, t^{\rm total}_{\rm exp}\, \Delta t}}$$

faint sources

$$\epsilon_{\rm PM} \propto \frac{\rm FWHM\, 10^{0.4\,(m-m_0)}}{\sqrt{A\, t^{\rm total}_{\rm exp}\, \Delta t}}$$

Time for observing given solid angle at given PM error

$$t^{\rm total}_{\rm exp} \propto \frac{\rm FWHM^2\, 10^{2\alpha\,(m-m_0)}}{A\, \rm FoV^2\, \epsilon^2_{PM}\, (\Delta t)^2}$$

Comparison of telescopes for large fields

Table 1

	diameter	effective area	⟨FoV⟩	pixel size	PM "time" = pixel² / (FoV² area)
unit	m	m²	arcmin	milli-arcsec	mas² (arcmin² m²)
HST/WFC3	2.4	4	2.7	40	54.87
HST/ACS	2.4	4	3.5	50	51.02
Gaia	1.45x0.5	0.7	60	59	1.38
JWST/NIRCAM	6.5	25	2.2	70	40.50
Euclid/VIS	1.2	1.0	45	100	4.94
Rubin/LSST	8.4	35	210	200	**0.03**
Xuntian	2.0	4	63	80	0.40
Roman/WFI	2.4	4.5	32	110	2.63
Theia	**0.8**	**0.5**	**30**	**64**	**9.10**
HWO/UVIS	6.5	100	2.5	17.3	0.48

HWO numbers fixed after talk

LSST is best, then Xuntian & HWO, then Gaia, then Roman

Euclid as an astrometric tool

Successful Euclid launch by SpaceX
→ mission extended to 10-14 years (survey takes 6-7 years)
→ expect large key projects for remaining ~7 years:
→ one could be Theia-like!

	eff. area	⟨FoV⟩	pixel size	PM "time"
unit	**m^2**	**arcmin**	**milli-arcsec**	**mas^2 ($arcmin^2$ m^2)**
HST/WFC3	4	2.7	40	54.87
HST/ACS	4	3.5	50	51.02
Gaia	0.7	60	59	1.38
JWST/NIRCAM	25	2.2	70	40.50
Euclid/VIS	**1.0**	**45**	**100**	**4.94**
Rubin/LSST	35	210	200	0.03
Xuntian	4	63	80	0.40
Roman/WFI	4.5	32	110	2.63
Theia	**0.5**	**30**	**64**	**9.10**
HWO/UVIS	100	2.5	17.3	0.48

Euclid has similar ratios as Theia
(need to check negligible Euclid jitter)

Assume 20% of free time for astrometric science, i.e. ~7000 hours
Aim for 700 hours per target.
Do 10 targets: e.g. 3 dwarfs; 3 hypervelocity stars; 4 globular clusters

Let the worksop begin!