Astrometric Cosmology

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Presentation Outline

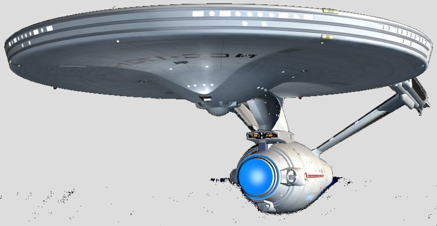
- **Chapter I: The new astrometry**
- **Chapter II: Astrophysical astrometry**
- **Chapter III: Relativistic astrometry → The Gaia era**
- **Chapter IV: Astrometry is “local” anyway!**
- **Chapter V: Is there a cosmology at the local scale?**
- **Chapter VI: Technology: really reach/approach the μas and deal with systematic errors →Beyond Gaia**
- **Chapter VII: Conclusions**

• Chapter I: The new astrometry

Realization/materialization of the reference frame that, depending on the accuracy needed (i.e., on the physics utilized) would be called inertial/absolute/non-rotating or, simply, local (reference) frame: Astronomical catalogs (catalog astronomy)

Deep space navigation cannot do without astronomical catalogs.

Pointing and operation of the largest ground-based and space-borne observatories like the HST



Key words are:

- **Access to all directions (All-sky)**
- **Access to faint magnitudes (Densification, Completeness)**

The GSC2.3 all-sky catalog

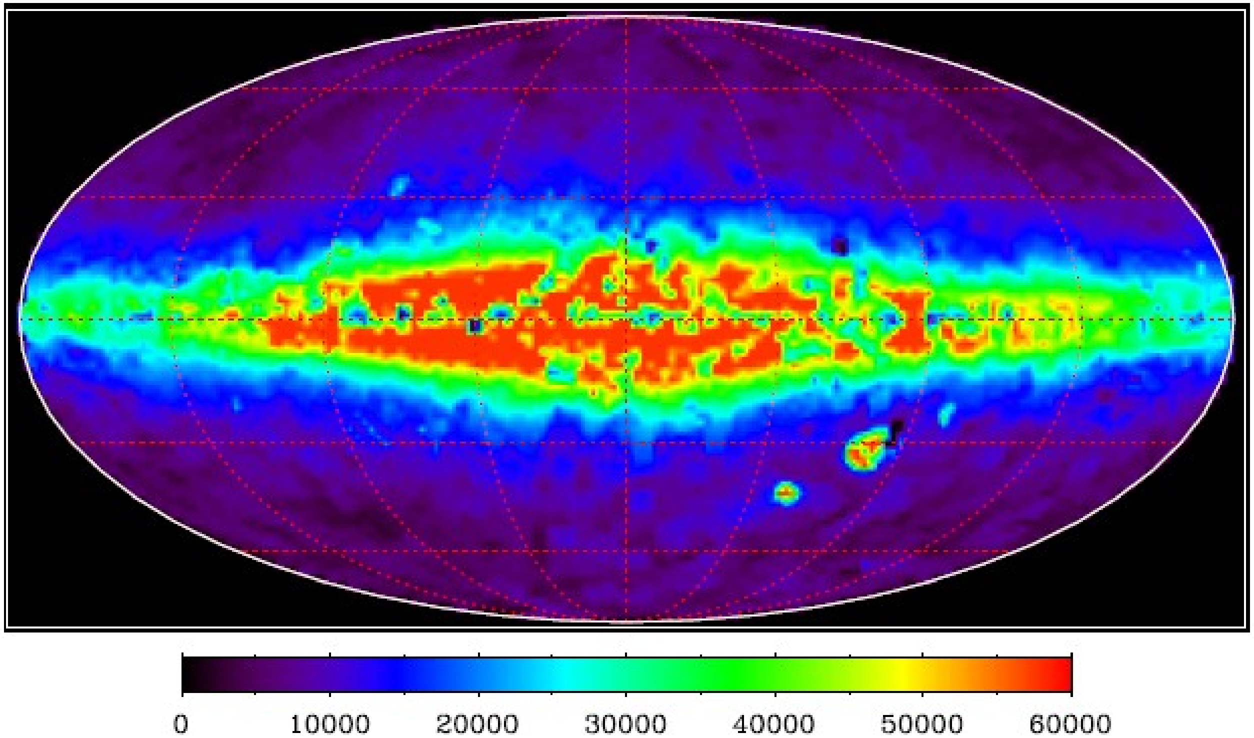


Fig. 13.— GSC 2.3 all-sky map. Cumulative counts in galactic coordinates, including both stellar and extended objects. The color scale indicates the GSC 2.3 density ranging from 0 to 60 thousand objects per square degree. The image resolution is a smooth version of the densities obtained from the HTM counts.

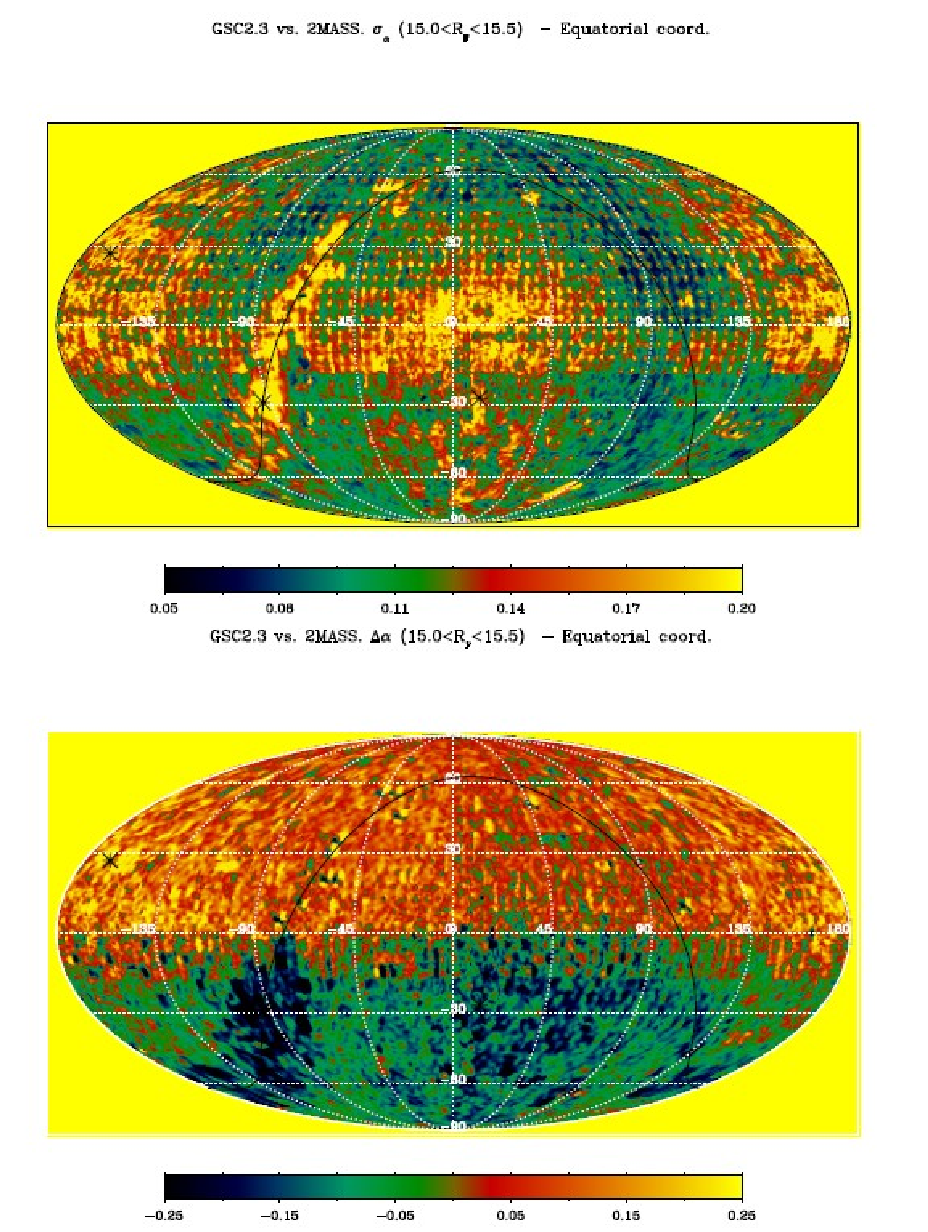
Released to the community in 2006 and published in the Summer of 2008 is made of

1 billion objects complete to the red magnitude R=20.

(Lasker, MGL et al. 2008)

The most detailed view of the Milky Way at optical wavelengths, to date!

Also USNOB!



…. And the faintest materialization of the ICRF reference frame in the visible domain

Errors in the materialization of the reference frame. Random Part (precision)

Errors in the materialization of the reference frame. Systematic Part (accuracy)

Da Lasker, Lattanzi et al, 2008

Astrometry is also the science of measuring distances to celestial objects. Its fundamental potential for astrophysics comes from its ability to contribute to the direct, i.e. model independent, calibration of radiant and gravitational energy, the two forms of energy that dominate in the universe.

However, stars are far away and their angular motions are small as they decrease with the inverse of distance itself.

Earth's atmosphere is then a serious limitation for accurate distances and if astrometry is to move away from the immediate solar neighborhood, it is essential to go into space, posing tremendous technological challenges.

The Hipparcos mission

Hipparcos-like astrometric solution: formulation

$$\begin{pmatrix}\text{Observed}\\ \text{location of image}\\ \text{in pixel stream}\end{pmatrix} = \begin{pmatrix}\text{Star position}\\ \text{on sky}\end{pmatrix} + \begin{pmatrix}\text{instrument}\\ \text{Attitude}\end{pmatrix} + \begin{pmatrix}\text{CCD / pixel}\\ \text{offset}\end{pmatrix} + \text{noise}$$

Star position on sky: 5 astrometric parameters $(\alpha_0\ \delta_0\ \pi_0\ \mu_\alpha\ \mu_\delta)$ (radial velocity assumed known)

Instrument Attitude: quaternion $q(t)$ represented by cubic spline coefficients

CCD / pixel offset: geometric calibration

Noise: white gaussian, known σ

Symbolically: $O = f(S, A, C) + n$

Self-calibrating Instrument

Results from the HIPPARCOS mission

No. of objects measured:	**118 218**
Limiting magnitude:	**V< 12.4 (complete to 9)**
Median precision on position :	**0.77 / 0.64 mas**
Median precision on parallax:	**0.97 mas**
Median precision on proper motion:	**0.88 / 0.74 mas**

With the success of the Hipparcos mission the New Astrometry establishes itself as indispensable in modern astronomy because of:

increasing emphasis on the fundamental contribution that it can bring to the solution of the open problems in modern astrophysics (stellar and galactic).

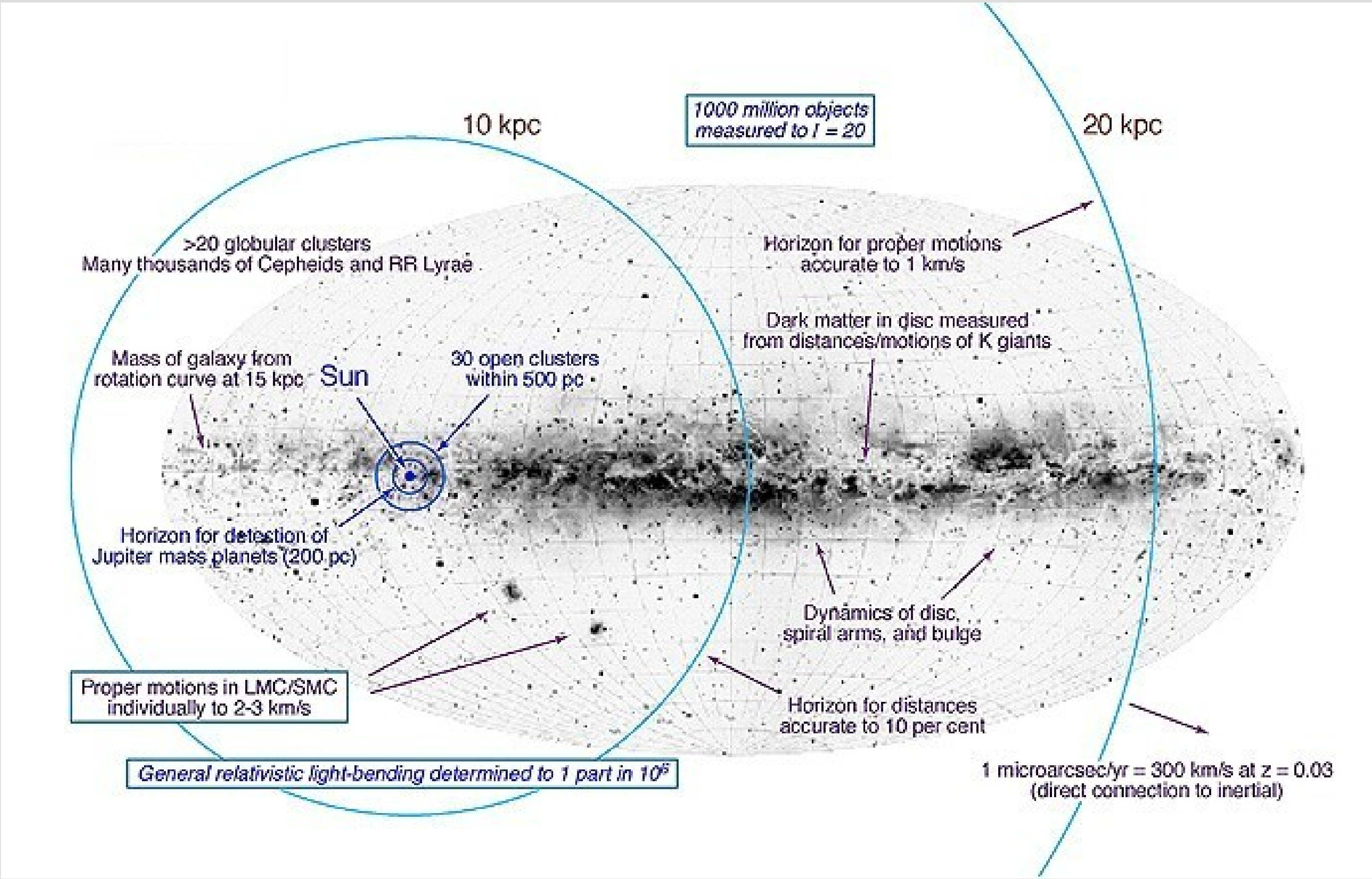
A new tradition is established

that hinges on one more key word:

ACCURACY !

•**Chapter II: Astrophysical astrometry**

What is modern astrometry to do?……….



Measure fundamental quantities independently from models:

- **Distance → energetics, initial/boundary condition for Milky Way dynamics**
- **Position (angular): accurate alignment of emissions at different wavelengths → testing structural and energy models of active extragalactic objects**
- **Mass (to 3%) → stellar models, characterization of extrasolar planets**
- **Photospheric dimensions → stellar models**
- **Velocity → dynamical models, initial/boundary conditions for the dynamics of the Milky Way**

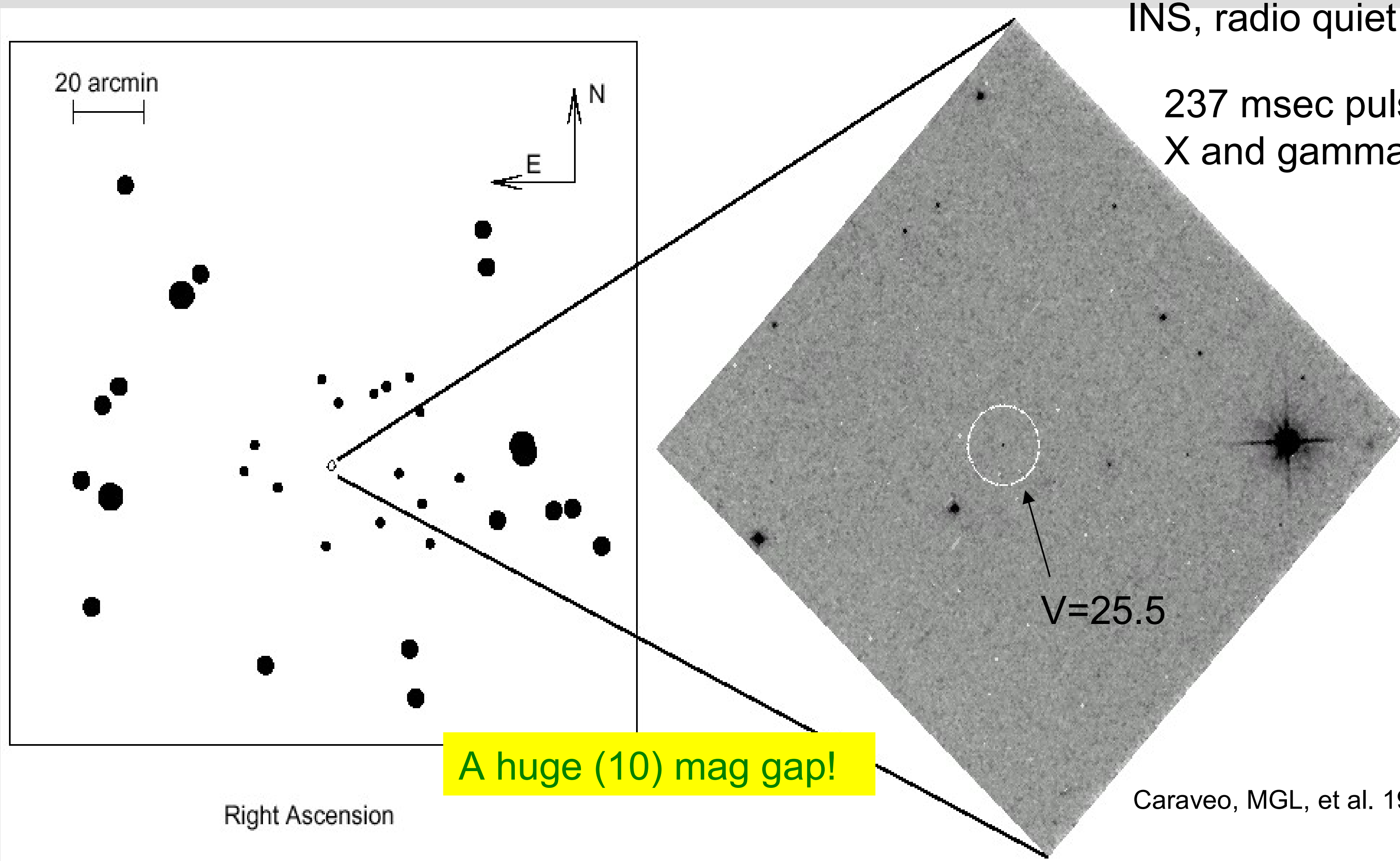
Examples of
“astrophysical astrometry”:
Galactic and extragalactic!

Model independent characterization of galactic and extra-galactic phenomena, which are often faint at optical wavelengths.

Absolute registration of HST images

…….Importance of densification

Neutron star nature: the braking number of Geminga



Caraveo, MGL, et al. 1998)

INS, radio quiet

237 msec pulse in X and gamma rays

Quantity: $P/\dot{P}$ has dimensions of time and is obviously related to the `age' of the pulsar.

$\Omega = 2\pi / P$

$$\frac{d\Omega}{dt} = -k\Omega^n$$

k is a positive constant, n is a constant called the **braking index** that describes how the pulsar spins down. Simplest model for pulsar radiation predicts that the braking index n = 3.

$$\tau = \frac{1}{1-n}\frac{\Omega}{\dot{\Omega}} \longrightarrow \tau = \frac{1}{n-1}\frac{P}{\dot{P}}$$

$$n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2}$$

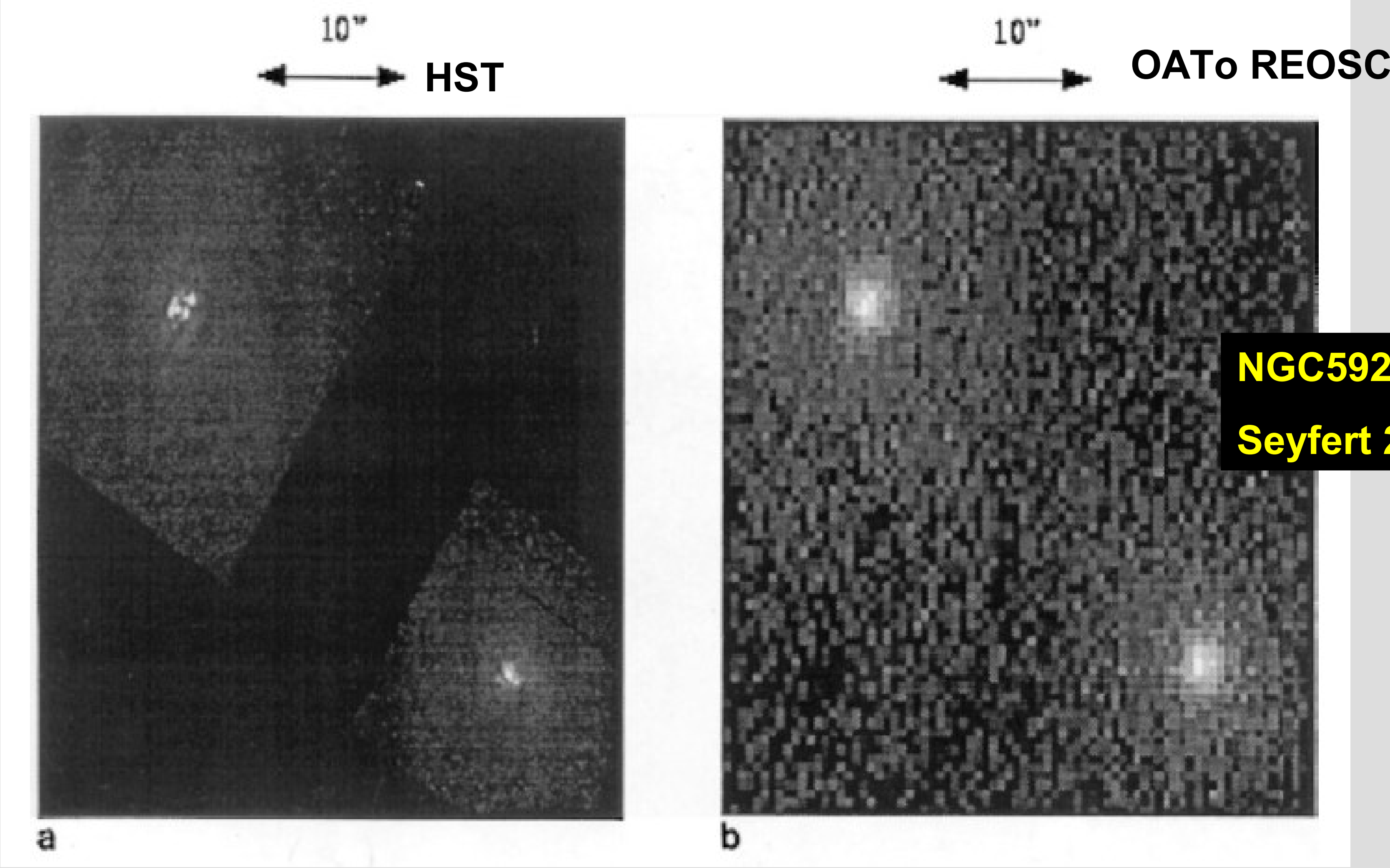
Model independent determination of *n*

Neutron star nature: the braking number of Geminga – Cont.

step [N. images]	telescope/detector	field of view [epoch]	primary grid	secondary grid	ϵ_r	ϵ_{tr}	*mag*
step 1 2	OATo 38cm refractor plate, 30”/mm	70’ x 70’ [1984.19]	19 Tycho/PPM	17	0”.102	0”.044	14
step 2 2	OATo 105cm reflector plate, 20”.7/mm	30’ x 30’ [1984.19]	16	28	0.061	0.020	17
step 3 2	OATo 105cm reflector CCD, 0”.48/px	9’ x 10’ [1996.13]	26	21	0.026	0.011	19.5
step 4 1	ESO NTT 3.5m, SUSI CCD 0”.13/px	2.5’ x 2.5’ [1992.86]	16	10	0.015	0.008	26
step 5 1	HST 2.4m, PC2 CCD, 0”.046/px	35” x 35” [1995.21]	10	Geminga	[0.005]	[0.003]	26

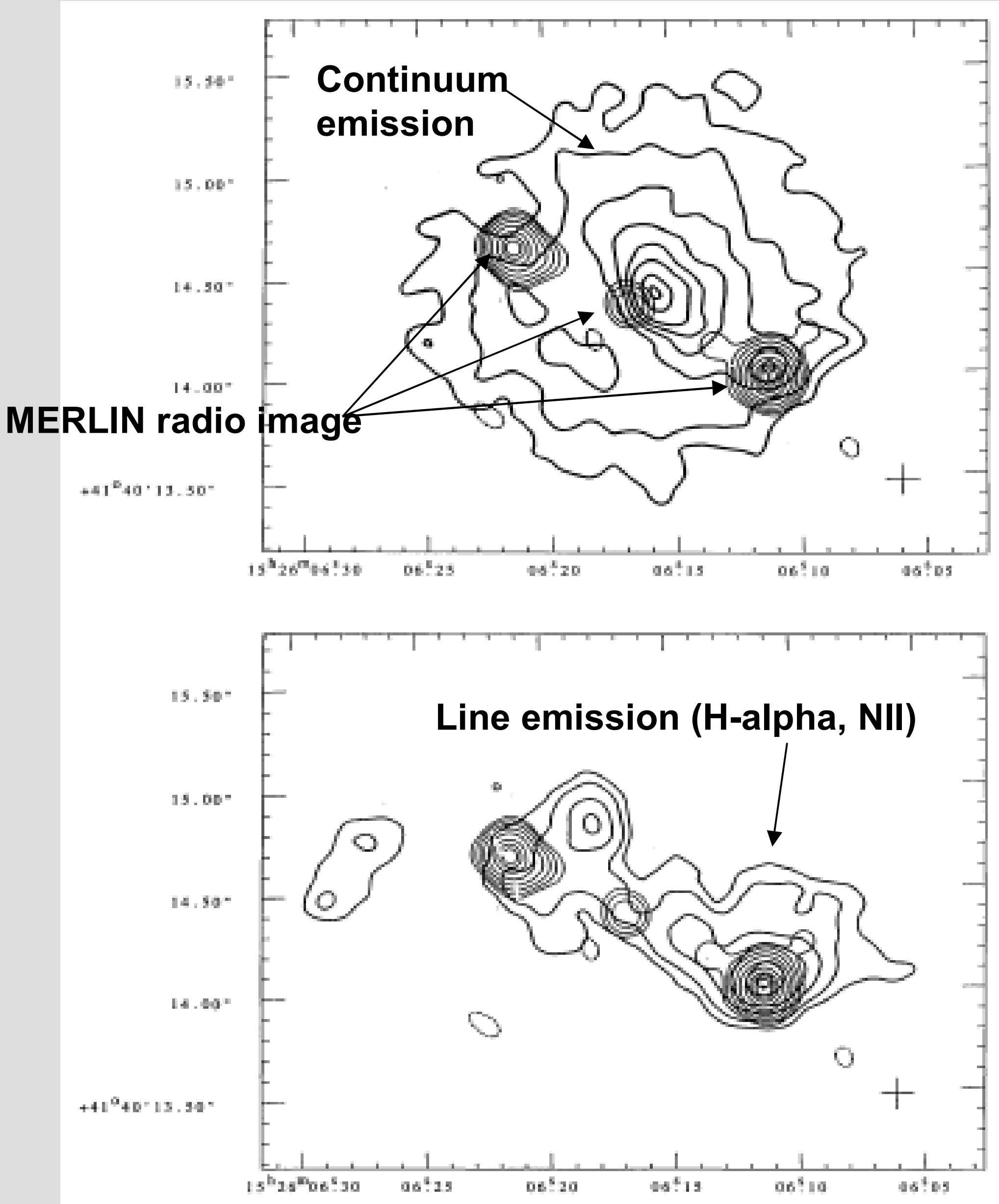
A 5-step 5mas registration

Absolute registration of HST images - Seyfert 2 galaxies



NGC5929

Seyfert 2

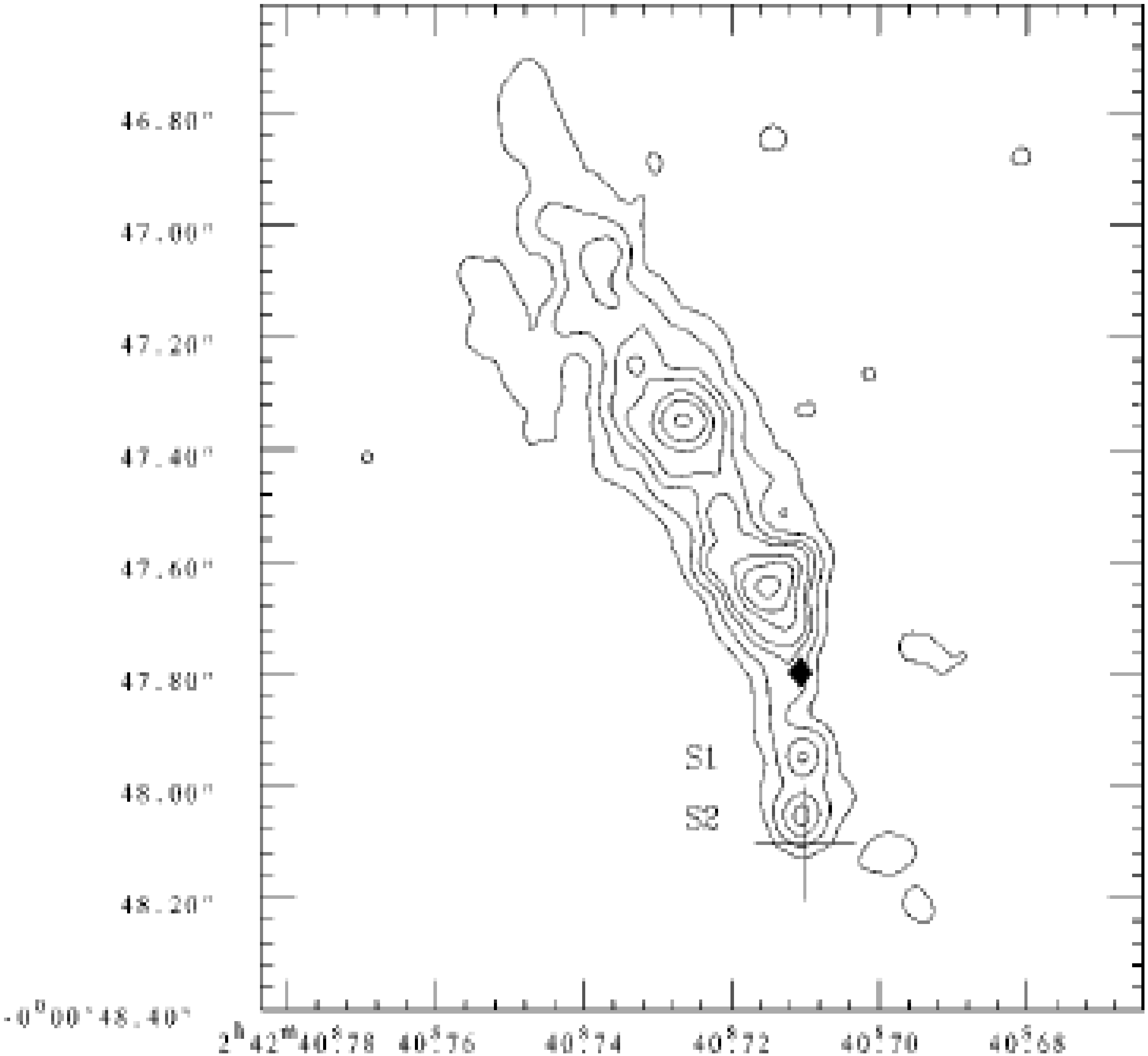


Seyfert 2 Galaxy, NGC5929

To obtain accurate absolute astrometry of Hubble Space Telescope images (visible). Ground based images are used to link HST images to standard astrometric stars defining the optical frame of reference. The method was used to register optical images of the Seyfert 2 galaxy NGC 5929 to the corresponding radio maps, allowing the exploration of the relationship between radio and optical emission within the galaxy.

Registration to 100 mas

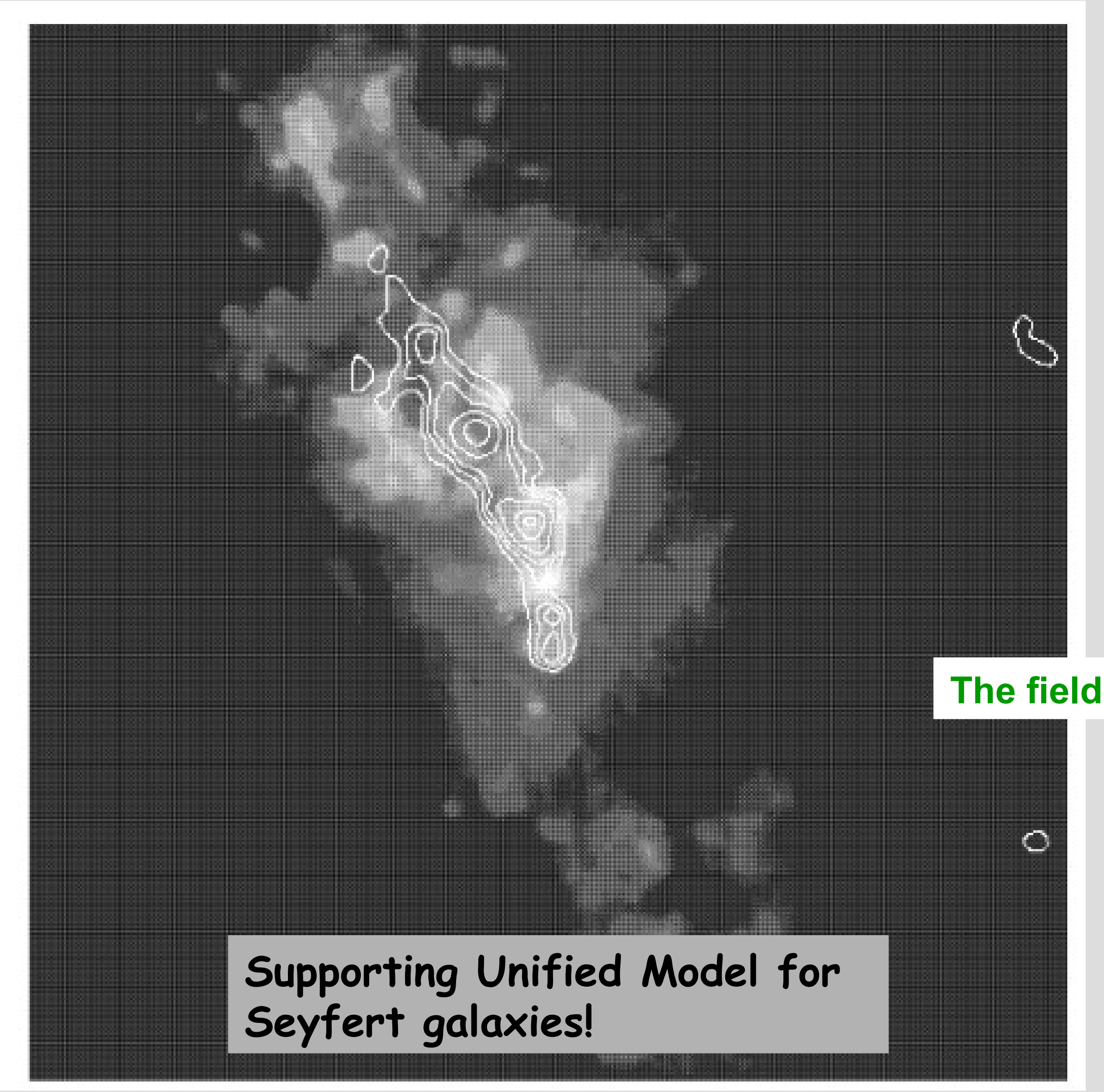
(MGL, Capetti, Macchetto, 1997)



NGC1068

Class prototype Seyfert 2 Galaxy

(Capetti, Macchetto, MGL, Apj, 1997)



NGC1068

6cm MERLIN overlaid to [OIII]-line **HST image**

The field of view is 4” x 4”!!

….And, this is what we wish for the Milky Way:

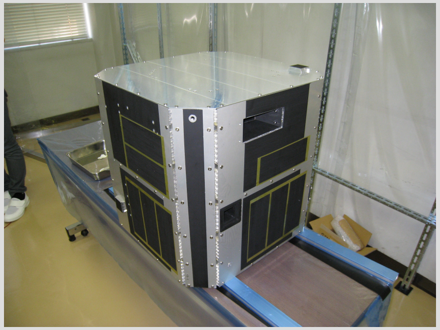
a full 6-dimensional snapshot!

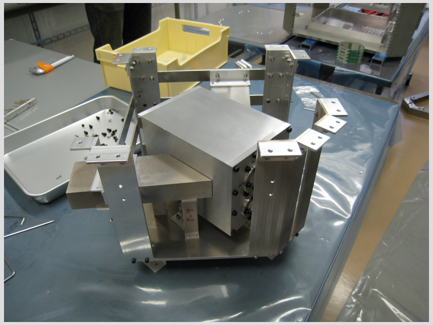
With the success of the Hipparcos mission, space astrometry demonstrated its technological maturity.

On the brink of the new century, space had become the new frontier for precision astrometry; the oldest branch of astronomy was finding itself at the forefront of 21st science and technology.

Three space astrometry missions are scheduled to be launched over the next two to three years, with the ESA mission Gaia aiming at the highest precision of approximately 7 micro-arcsec, more than 100 times better than Hipparcos!

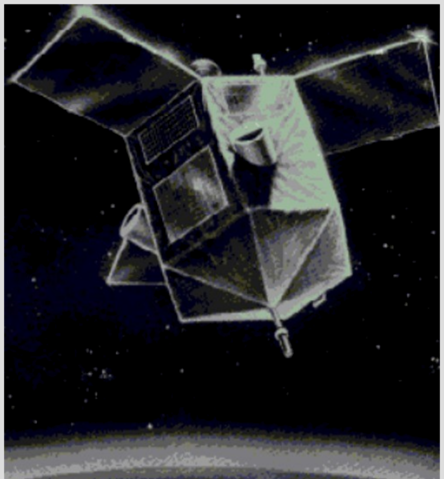
- Nano-JASMINE, 2012, Japan - Hipparcos-class
- JMAP, 2012 (?), USA DoD – Hipparcos class
- Gaia, 2013, ESA – 100x-Hipparcos mission!

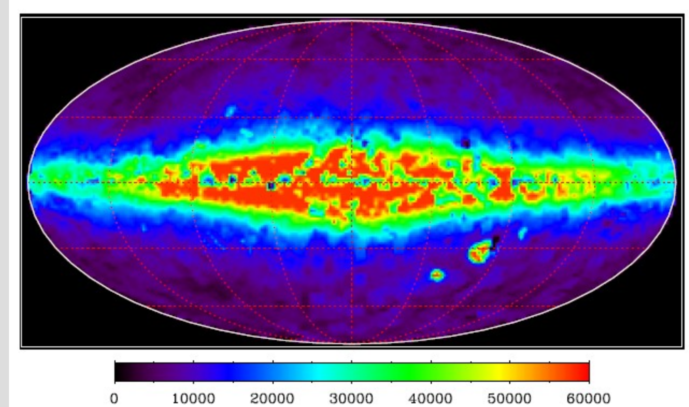




Gaia: 21st century space astrometry.

Bringing together "all sky access (+completeness)", "faint limit", and "accuracy".





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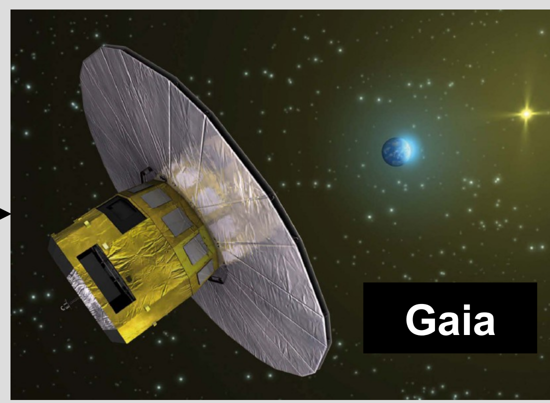


Gaia’s

End-of-life astrometric performance

µas	B1V Req.	B1V Perf.	G2V Req.	G2V Perf.	M6V Req.	M6V Perf.
V < 10 mag	< 7	8.4	< 7	8.6	< 7	10.6
V = 15 mag	< 25	26.3	< 24	24.4	< 12	9.4
V = 20 mag	< 300	328.7	< 300	292.8	< 100	97.7

2011 astrometric error budget table

(JdB, 2011)

•Chapter III: Relativistic astrometry

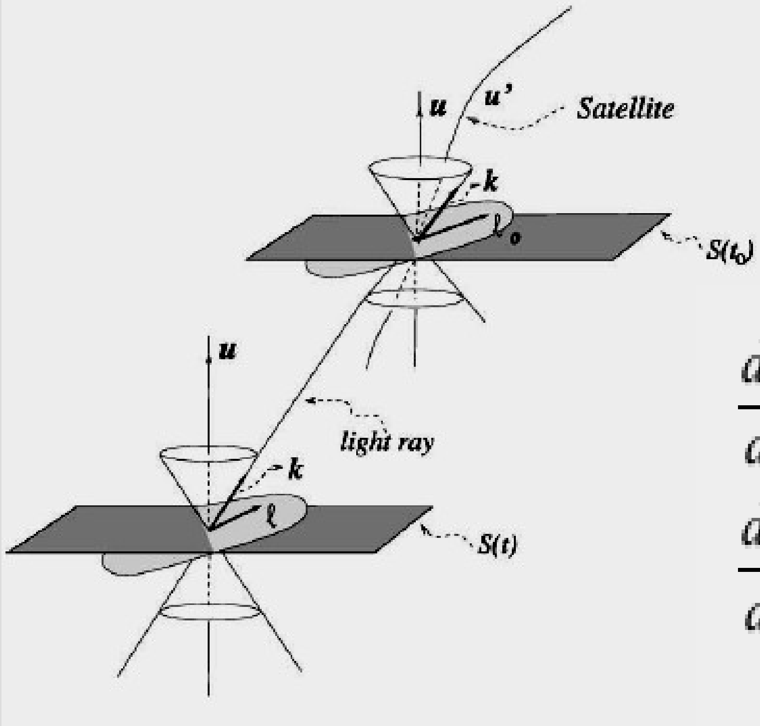
At these accuracies light does not propagate in straight lines and time does not beat the same everywhere:

photons follow geodesics and physical time is only that of the observer.

Welcome to the land of General Relativity where

Prof. Einstein rules!!

Astrometry becomes fully relativistic



$$\frac{d\bar{l}^0}{d\sigma} - \bar{l}^i\bar{l}^j\partial_i h_{0j} - \frac{\partial_0 h_{00}}{2} = 0,$$

$$\frac{d\bar{l}^k}{d\sigma} - \bar{l}^k\bar{l}^i\bar{l}^j\frac{\partial_0 h_{ij}}{2} + \bar{l}^i\bar{l}^j\left(\partial_i h_{kj} - \frac{\partial_k h_{ij}}{2}\right) + \bar{l}^k\bar{l}^i\frac{\partial_i h_{00}}{2}$$
$$+\bar{l}^i(\partial_i h_{k0} + \partial_0 h_{ki} - \partial_k h_{0i}) - \frac{\partial_k h_{00}}{2} = 0.$$

$$h_{00}^{(a)} = \left(\frac{2G\mathcal{M}^{(a)}}{c^2 r^{(a)}}\right)(1 + \tilde{v}^{(a)}\cdot\hat{n}^{(a)}) + O(1/c^4),$$
$$h_{jk}^{(a)} = \left(\frac{2G\mathcal{M}^{(a)}}{c^2 r^{(a)}}\right)(1 + \tilde{v}^{(a)}\cdot\hat{n}^{(a)})\delta_{jk} + O(1/c^4),$$
$$h_{0j}^{(a)} = w_j^{(a)} + O(1/c^4),$$

RAMOD model

(Crosta's talk)

Basic equation of relativistic astrometry

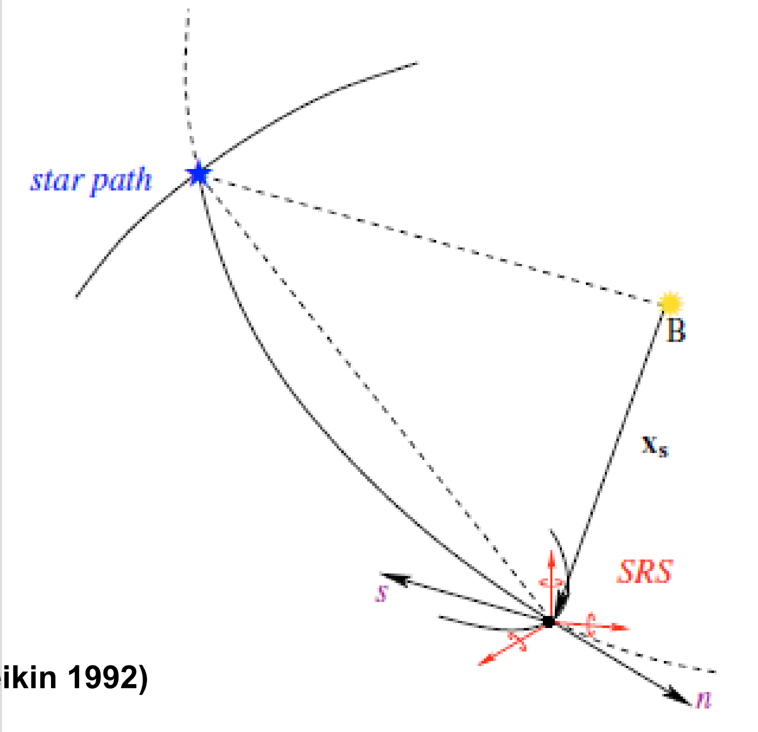
$$\bar{l}^i = n^i\left(1 - \frac{h_{00}}{2}\right) + O\left(\frac{v^4}{c^4}\right)$$

$h_{00} = 2\omega/c^2$

The spatial light direction $\bar{l}^i$ is expressed in terms of its Euclidean counterpart, $\boldsymbol{n^i}$, at the satellite location in the gravitational field of the solar system.
(Crosta & Vecchiato, 2010)

Fundamental result of the REMAT Unit (Klioner coordinator, part of the DPAC CU3)

Generalization to the full problem in Crosta (2011, submitted)



(Klioner, Kopeikin 1992)

•Chapter IV: Astrometry is “local” anyway!

Such a striking improvement in space-borne astrometry allows astronomers to reach the scale of the Milky Way,

yet this is not enough to directly probe the mega-parsecs of the extragalactic distance scale, which would require angular accuracies in the nano-arcsec regime, beyond today's and near future technology.

Space astrometry continues to share this limitation to the local universe with its ground-based traditions!

On the other hand, improvements in **cosmological models** have recently **produced quantitative predictions** on the **present day consequences of the evolution of the Universe**, something that is often referred to as **Local Cosmology**.

These “cosmological consequences” could manifest themselves as characteristic signatures in the main components of the Milky Way (halo, disk) or as **small perturbations** in the gravity in action in our own Solar System. As we will see, some of these perturbations are well **within the reach of Gaia’s astrometry**. Therefore **astrometry can, once again, contribute direct and model independent tests** not just of astrophysics, but ,this time, **of cosmology**!

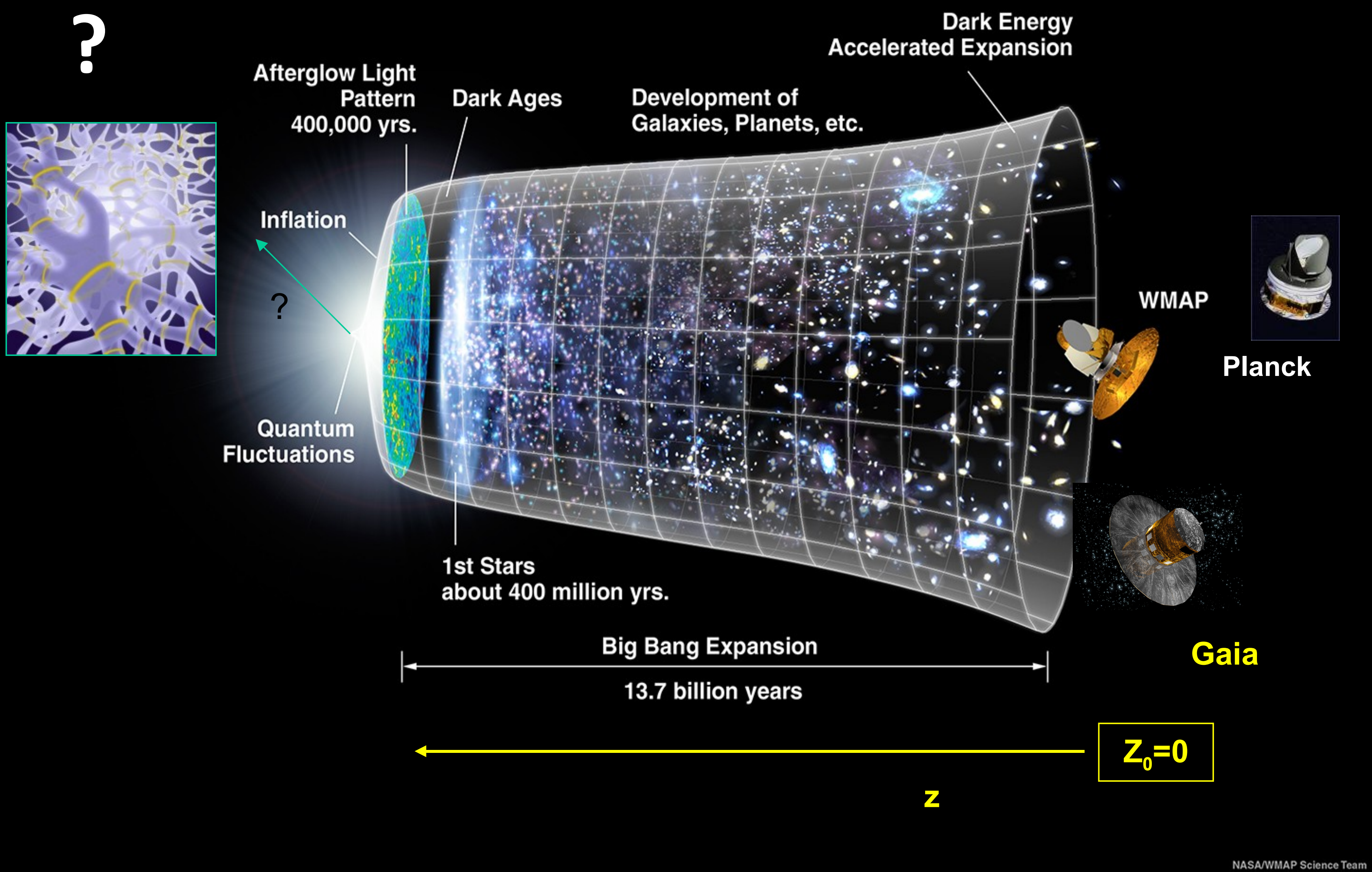
- **Chapter V: Is there Cosmology at the local scale?**

“Local” Cosmology?

How is it possible to investigate with “local measurements” on the nature of the Universe ......

Does Local Cosmology really exists?

Gaia and Local Cosmology



DE and DM from the Observations

- Universe evolution is characterized by different phases of expansion

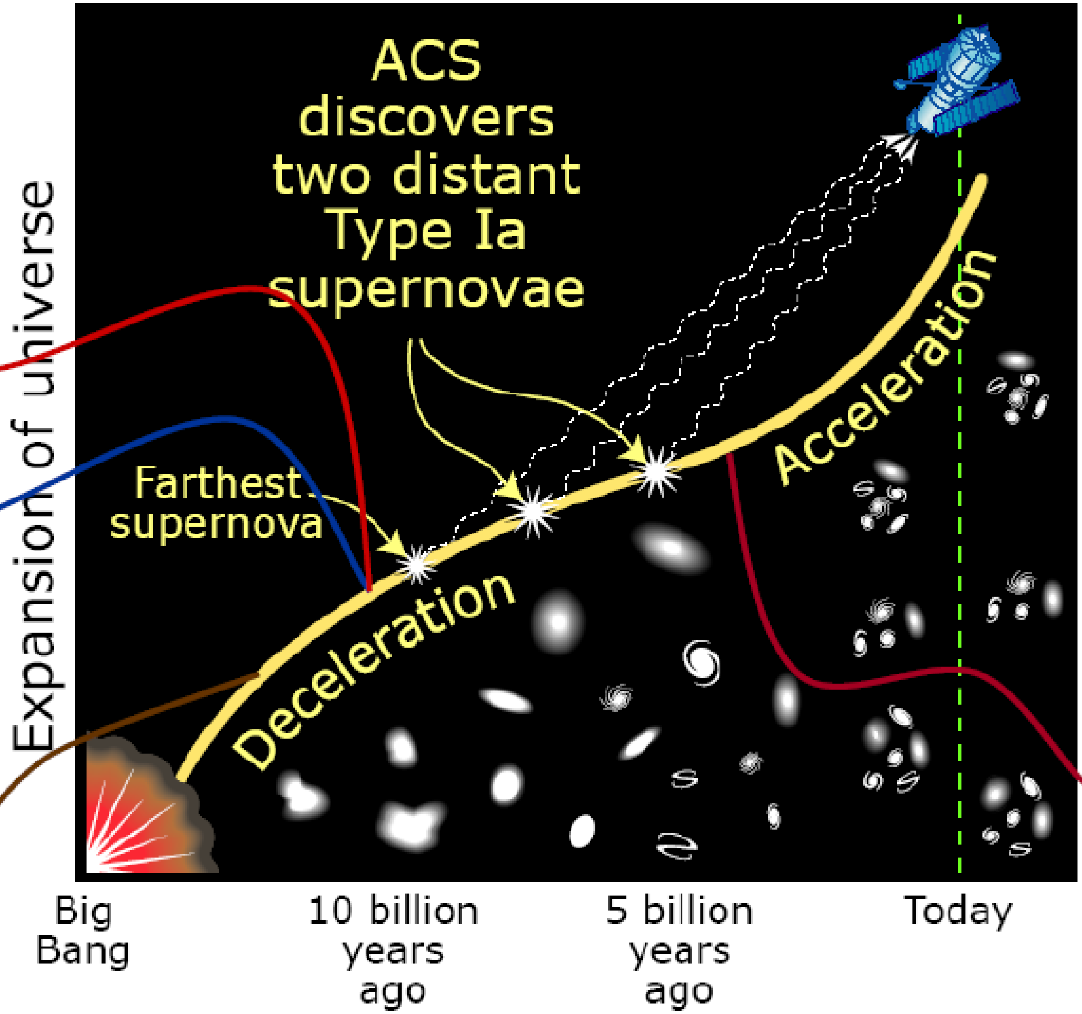
Dark Matter

25%

Ordinary Matter

5%

Radiation

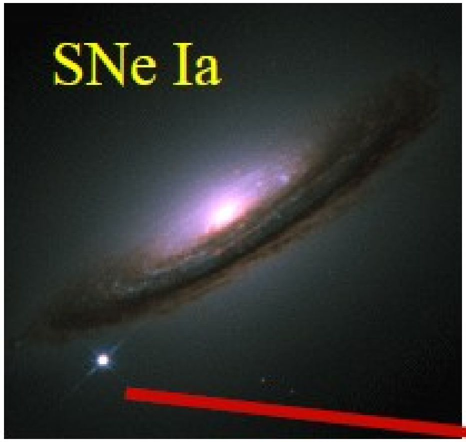


Dark Energy

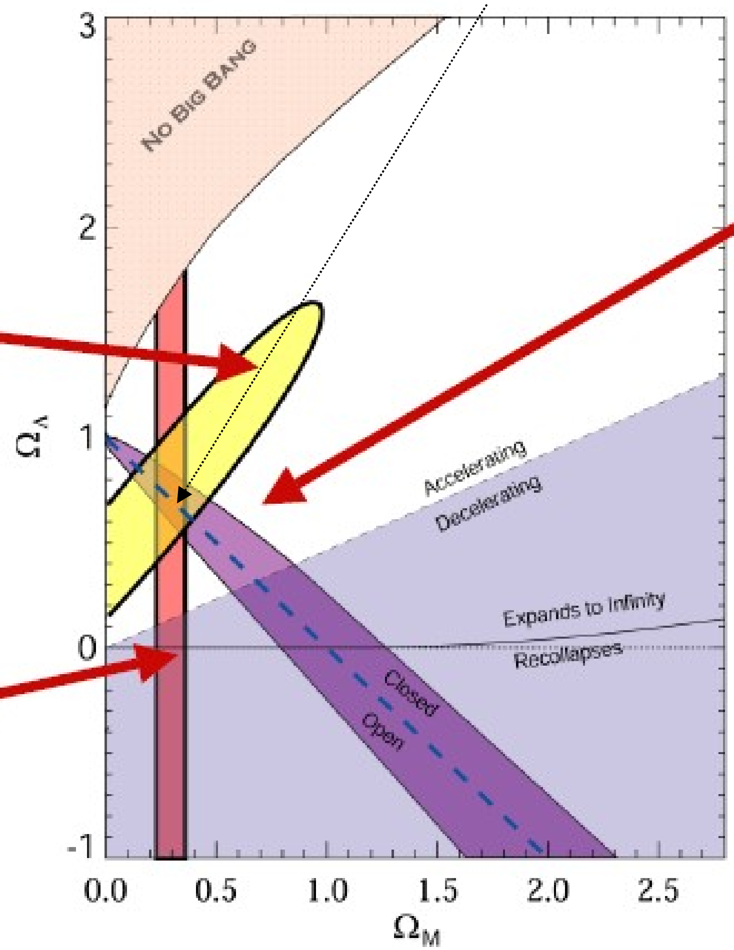
70%

Main observational evidences for Dark Energy

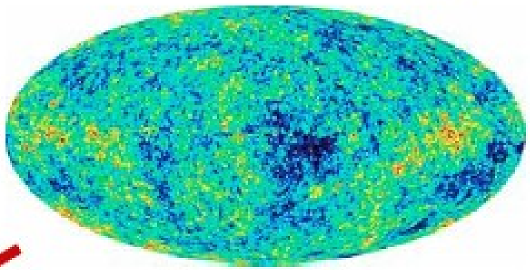
After 1998, more and more data have been obtained confirming this result.



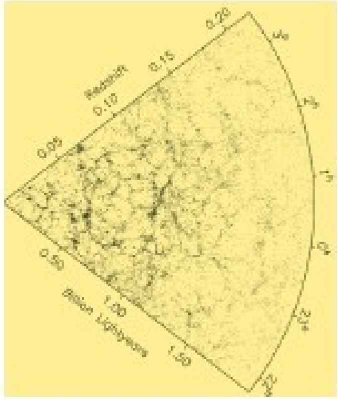
Coincidence issue: observer existing right when $\Omega_M \sim \Omega_\Lambda$



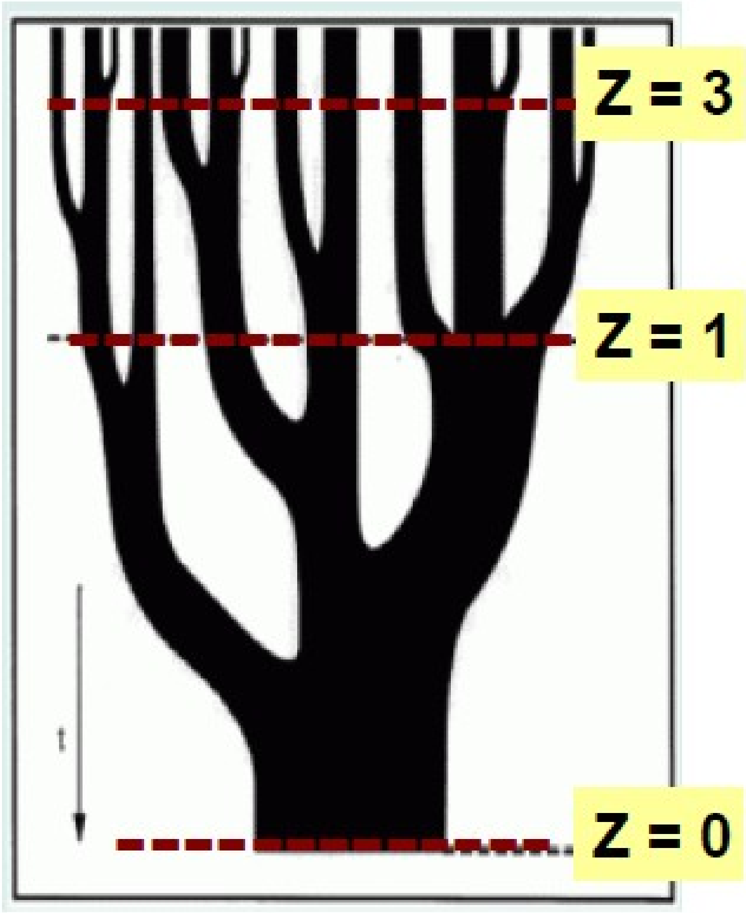
CMB(WMAP)

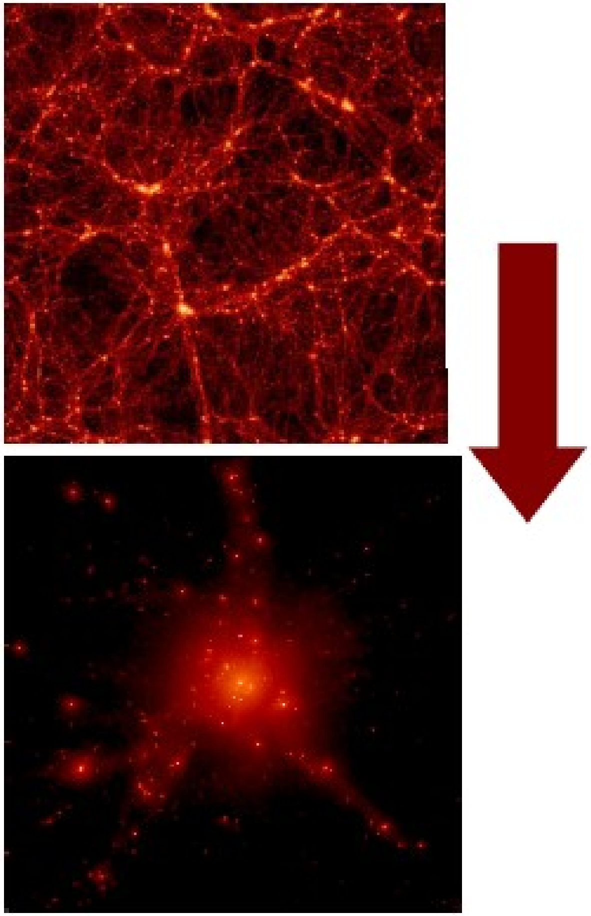


LSS



ΛCDM

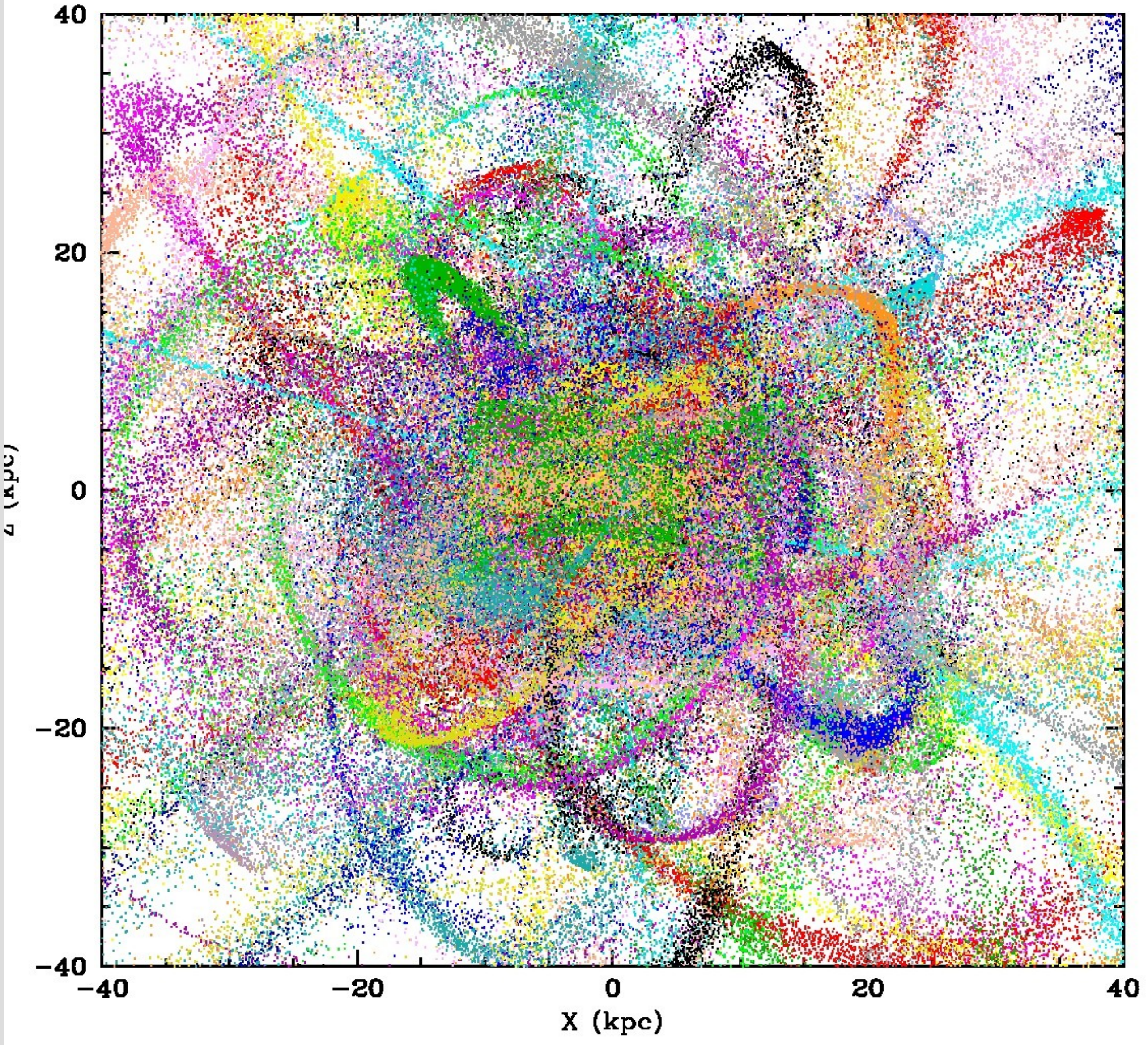




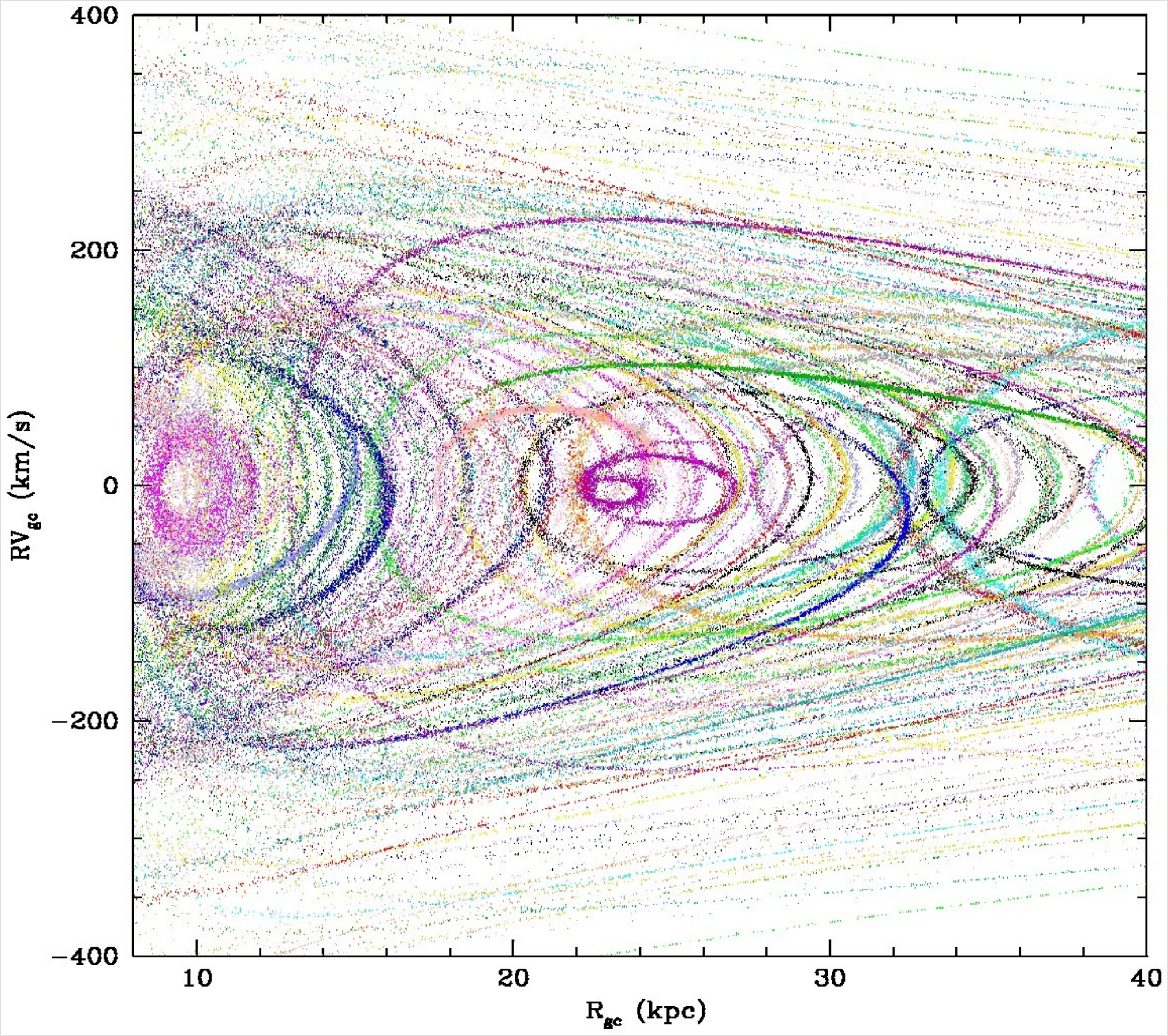
Lacey & Cole (1993) merger tree.
Figure by McCarthy & Mitchell (2009)

But sometimes big DM haloes at higher z!

Is there cosmology at zero redshift? - I



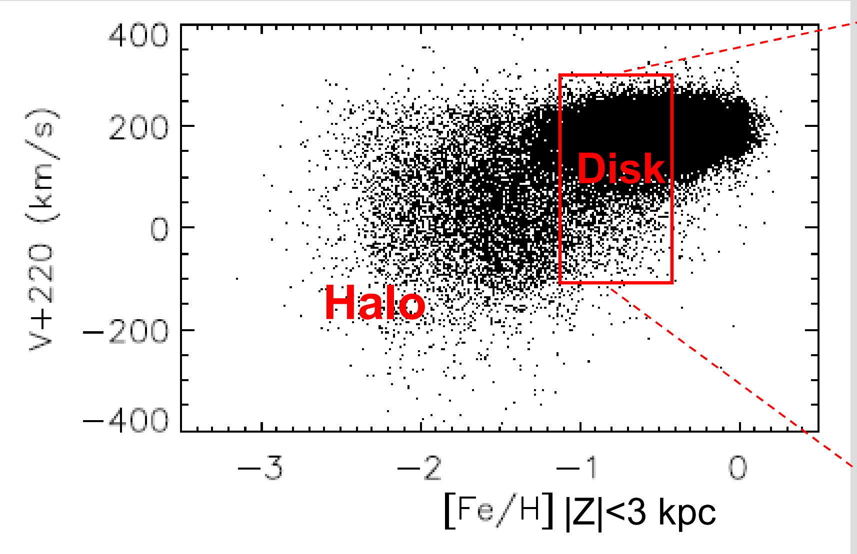
Is there cosmology at zero redshift? -II

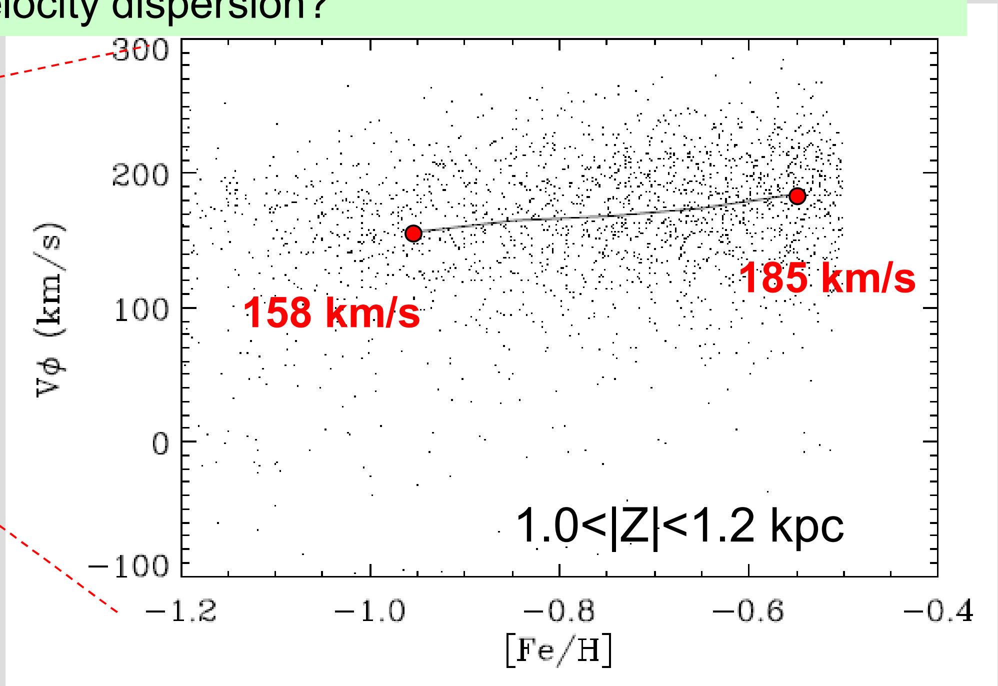


Fossils, "streams", in phase space as a result of a simulation, developed in the context of a CDM model, of the merging of 100 dwarf galaxies with the halo of the Milky Way. Different colors mark different merging events. R_{gc} is the distance from the galactic center (in kpc) and RV_{gc} is the radial velocity.

ARCHEOLOGY OF THE DISK:
ROTATION-METALLICITY CORRELATION IN THE TICK DISK OF THE MILKY WAY

Origin of the thick disk
Heating of a pre-existing thin disk from a**ccretion** of a dwarf galaxy? Or, **secular evolution** (migration from radial diffusion and churning (from a bar) + heating (going to higher z from galactic plane) – velocity dispersion?





27,000 dwarf FGK (from a SDSS-GSC-II kinematical survey)

(Vϕ) vs. [Fe/H] : **50 ± 5 km/s /dex**

(*Spagna, MGL et al*, 2010)

The MW disk: Evidence of a rotation-metallicity correlation

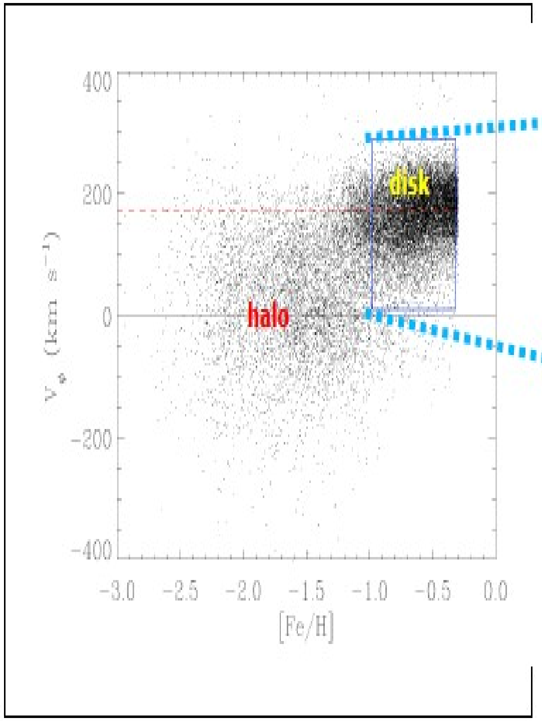


Figure 1. *The disk and halo populations are apparent in the velocity-metallicity distribution of 20 251 stars with |z| = 1.0–3.0 kpc and [Fe/H] < −0.3.*
The dashed line indicates the thick disk rotation, Vφ = 173 km s−1 at |z| = 1.24 kpc.The box defines the region, shown in Fig. 2, in which the thick disk population dominates.

We analyzed a *new kinematic survey* that includes accurate proper motions derived from SDSS DR7 positions, combined with multiepoch measurements from the GSC-II database (*Lasker et al.* 2008).

By means of the SDSS spectro-photometric data (*T*eff, log *g*, [Fe/H], and radial velocities), we estimate photometric parallaxes for a sample of 27 000 FGK (sub)dwarfs with [Fe/H] < −0.5, which we adopted as tracers of the 7D space distribution (***X***, ***V***, *[Fe/H]*) of the thick disk and inner halo within a few kiloparsecs of the Sun.

We find evidence of a *kinematics-metallicity correlation*, $\partial V\varphi/\partial$[Fe/H] ≈ 40 ÷ 50 km s^{-1} dex^{-1}, amongst thick disk stars located between 1 kpc and 3 kpc from the plane and with abundance −1 < [Fe/H] < −0.5. No significant correlation is present for [Fe/H] > −0.5

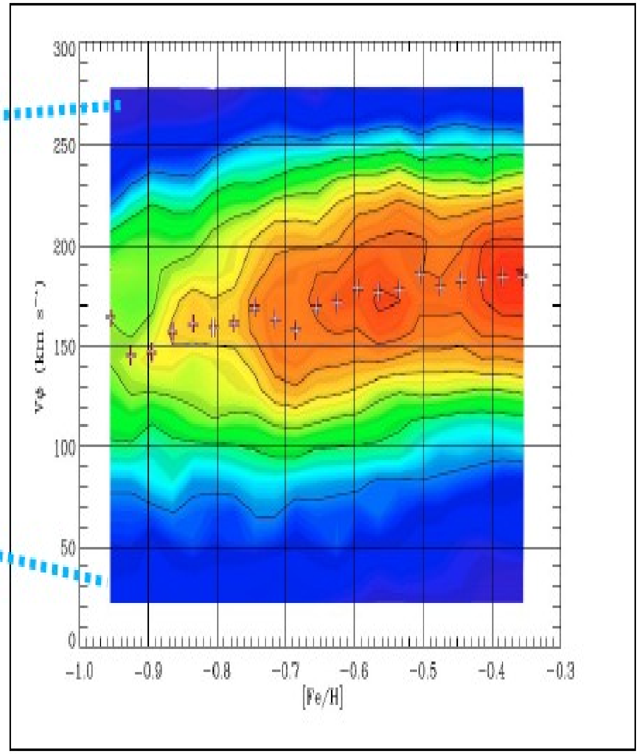
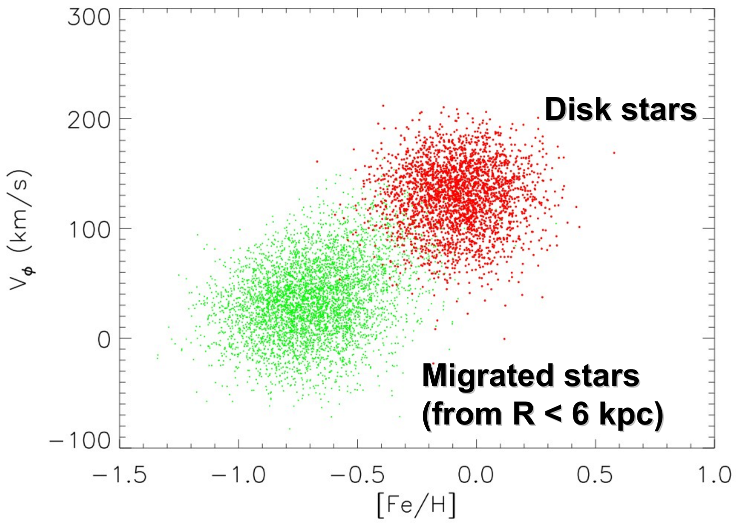


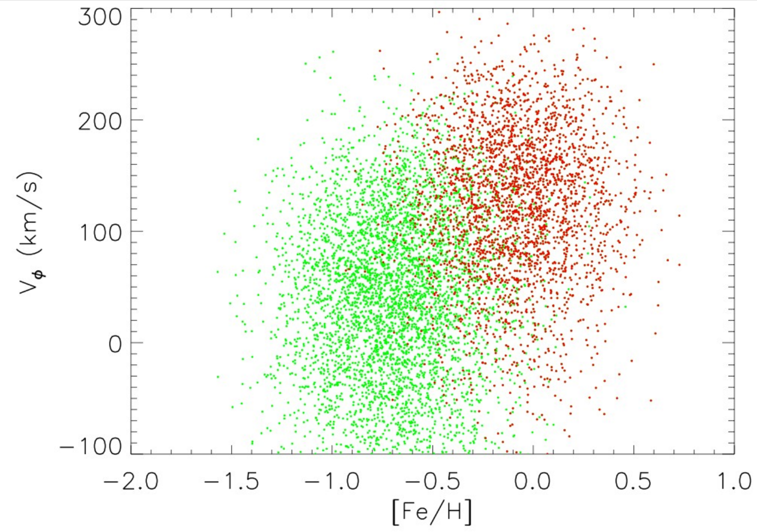
Figure 2. *Iso-density contours of 13 108 metal-poor stars from the SDSS-GSC-II catalo: −1.0 < [Fe/H] < −0.3 and |z| = 1.0–3.0 kpc. White crosses mark the ridge line of the maximum likelihood Vφ vs. [Fe/H].*
Notice the bimodal distribution with a secondary maximum at [Fe/H]≈−0.55, close to the value of the mean metallicity of the thick disk, and the peak at [Fe/H]−0.38 due to thin disk stars.
As in Bond et al. (2010), no correlation appears in the transition region between the thin and thick disks ([Fe/H] > −0.5). Instead, a shallow but clear slope appears for [Fe/H] < −0.5, which indicates that the metal-rich stars tend to rotate faster than the metal-poor ones.

Spagna, MGL, et al 2010

HIGH RES. N-BODY SIMULATIONS: STAR MIGRATION IN THE GALACTIC DISK

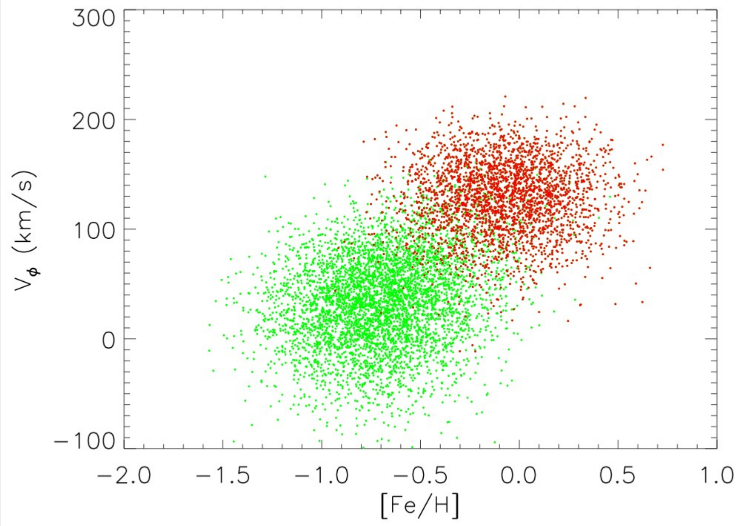


|z| > 1.5 kpc, 8 kpc < R <10 kpc, T = 5 Gyr



Injecting GSCII-SDSS errors

Full dynamical simulation



Gaia's view

Curir, Spagna, Lattanzi, et al (2011, in prep.)

One simple calculation in…."astrometric cosmology"

We wish to identify structures, tracing them by the individual measurement of a sufficiently large number of stars up to 10 Kpc from the Sun. Let's assume to position each star with a 10% accuracy. Then,

With distance d in pc and parallax ▯ in arcsec

$$\sigma_d \,/\, d = \sigma_{\square} \,/\, \square = 0.1$$

$$\sigma_{\square} = 10^{-5}\,\text{arcsec} = 10\ \mu\text{arcsec!}$$

One more simple calculation in…."astrometric cosmology"

$H_0 r = v_{rec}$

$V_{rot} = 4{,}74\ \mu\ r$

$V_{rec} = V_{rot}$

$\mu = H_0 / (5 * 10^6)$

$\mu = 2\ 10^{-5}$ arcsec/year, H_0=100 km/sec/Mpc

$\mu = 1.5\ 10^{-5}$ arcsec/year, H_0=75 km/sec/Mpc

Cosmological rotation of Quasars…?

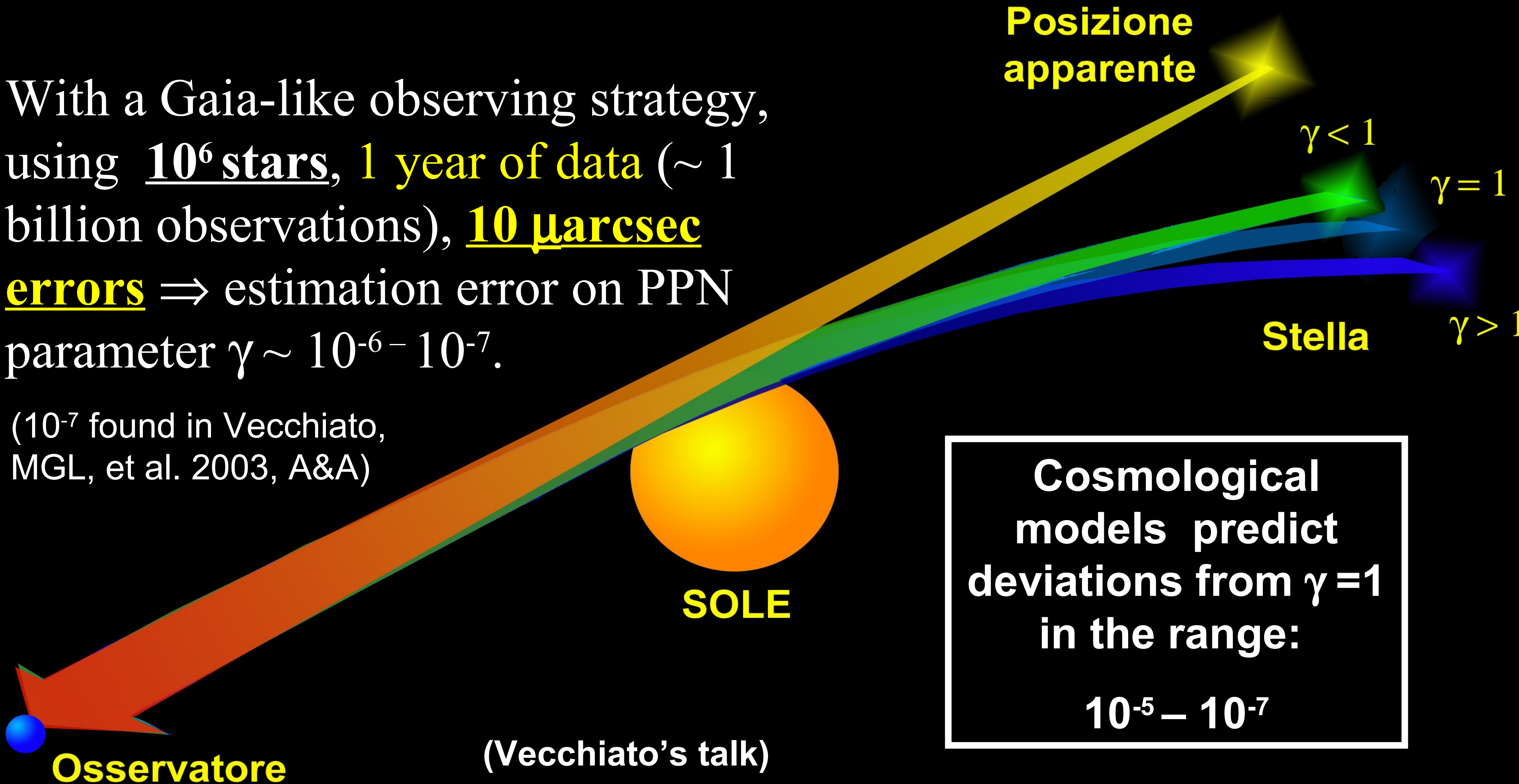
The scalar field which dominated inflation

The small variations in the CMB temperature were *the* seeds that led to the formation of structures and eventually to galaxies. Those ripples are thought to be the result of fluctuations in a scalar field that drove inflation.
There is the possibility that this inflation field, which couples with Gravity, fades with time. Today (z=0), the residue of that field would manifest itself through very small deviations from Einstein's General Relativity. Manifestations of this fossil field would constitute a powerful proof of our understanding of the cosmological past and its role in a possible new theory of Gravity.
Astrometric observations are a very powerful tool to trace back the presence of this scalar field, through accurate measurements of the deflection of the light at the Solar System coming from bright stellar sources.

Cosmological tests of GR in the low gravity of the SS

With a Gaia-like observing strategy, using **<u>10^6 stars</u>**, 1 year of data (~ 1 billion observations), **<u>10 μarcsec errors</u>** ⇒ estimation error on PPN parameter $\gamma \sim 10^{-6} - 10^{-7}$.

(10^{-7} found in Vecchiato, MGL, et al. 2003, A&A)



Cosmological models predict deviations from $\gamma = 1$ in the range:

$10^{-5} – 10^{-7}$

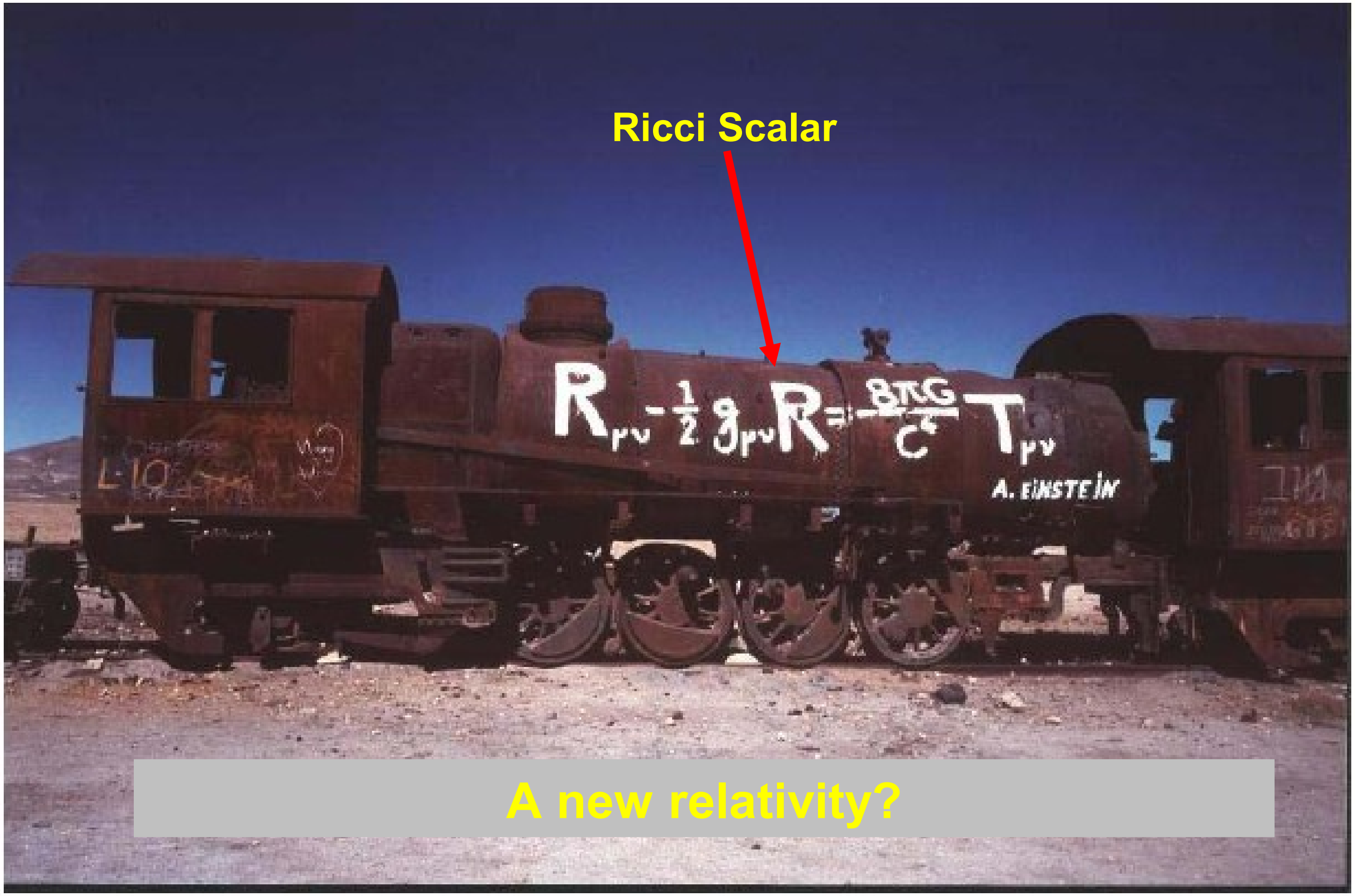
(Vecchiato's talk)

E.g.: measuring $|1 - \gamma| = 3\times10^{-7}$ ⇒ 3σ deviation from General Relativity detected!

Dark Matter (DM) and Dark Energy (DE)

The burden is on the Stadard Model of Particle Physics to break the degeneracy and find the exotic particles in the lab!

Are extragalactic observations and cosmology probing the breakdown of General Relativity at large (IR) scales?



f(R) – Gravity

[SC, Nojiri, Odintsov, Troisi PLB 2006]

Ideal fluid description

Scalar tensor Gravity

Realistic cosmology can be realized via modified gravity

R: Ricci scalar

[Capozziello & Francaviglia Gen. Relativ Gravit 40, 2008 and references therein]

Cosmological implications

- Dark Matter and Dark Energy were introduced to explain experimental data, therefore: *f(R)* - modified gravity theories for:
  - Fit to observations at cosmological scales
  - *f (R)* gravitation within Solar System

Rationale:

replacement in Einsten's field equations of source terms [**new particles**] on one side with geometry terms [**curvature**] on the other side

Higher Order Theories of Gravity

- ✓ Generalization of the Hilbert-Einstein action to a generic (unknown) f(R) theory of gravity

$$\boxed{\mathcal{A} = \int d^4x \sqrt{-g}\left[f(R) + \mathcal{L}_{(matter)}\right]}$$

$$\boxed{f'(R)R_{\alpha\beta} - \frac{1}{2}f(R)g_{\alpha\beta} = f'(R)^{;\mu\nu}(g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\beta}g_{\mu\nu}) + \tilde{T}^{(matter)}_{\alpha\beta}}$$

If f(R) = R

Einstein's equations are immediately recovered

SC's talk

f(R) gravitation within Solar System

Parametrized Post-Newtonian limit of fourth order gravity inspired by scalar-tensor gravity

- Exploiting the fourth order gravity – scalar tensor gravity analogy, the previous PPN formalism can be generalized to *f(R)* Lagrangians

- The PPN parameters are recovered through *R* dependent quantities *via* the relations

$$\boxed{\gamma_R^{\mathrm{PPN}} - 1 = -\frac{f''(R)^2}{f'(R) + 2f''(R)^2}}$$

$$\boxed{\beta_R^{\mathrm{PPN}} - 1 = \frac{1}{4}\,\frac{f'(R)\cdot f''(R)}{2f'(R) + 3f''(R)^2}\,\frac{d\gamma_R^{\mathrm{PPN}}}{d\varphi}}$$

[Capozziello & Troisi 2005]

Local measurements ⇒ cosmological constraints !

Astrometric Cosmology~~?~~

Thus … Local Cosmology really requires the micro-arcsecond of arc accuracy level!

Perhaps <u>**exceeding Gaia capabilities**</u> in certain circumstances.

But, what is a "micro-arc-second"?
Is it actually accessible?................

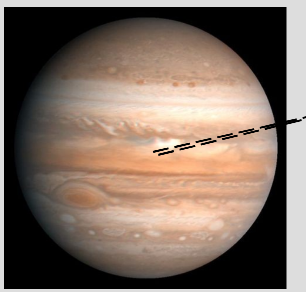
Hey, It's the technology baby!

It is improved technology that has allowed space astrometry to access these levels of accuracy, unthinkable just a few years back!

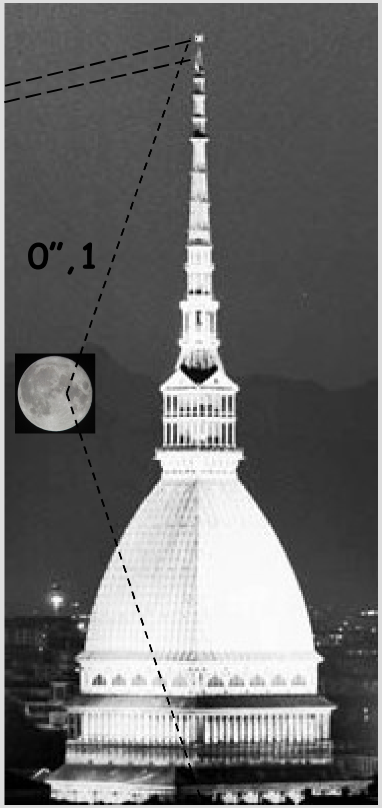
Chapter VI: Technology: really reach the µas and deal with systematic errors

what is one 1 μarcsec?

1 μ-arcsec = 4.8 10^{-12} radians



0'',000001 = micro(μ) arc sec

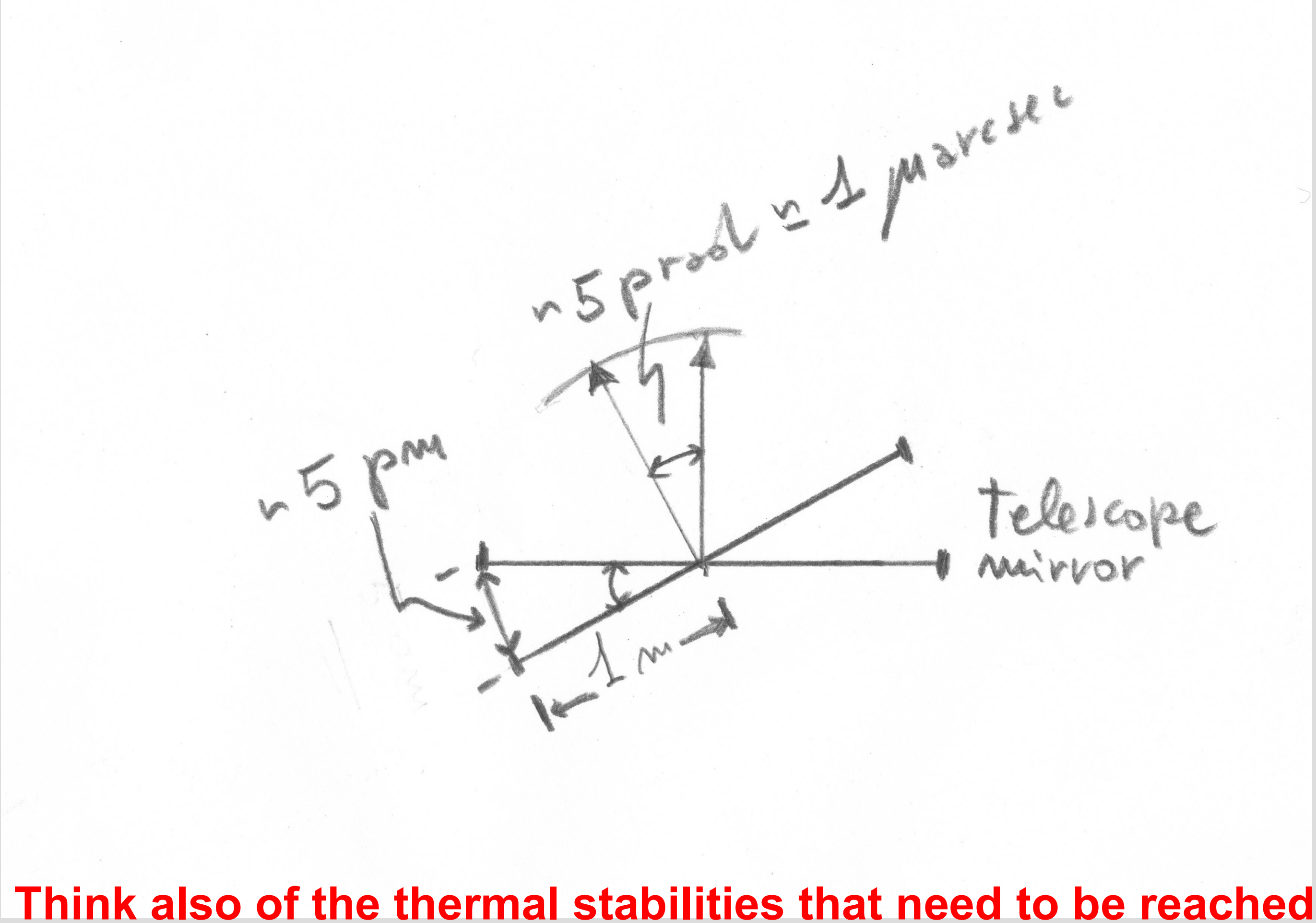


From Jupiter!!

800.000.000 km ~ 5.5 au

Torino

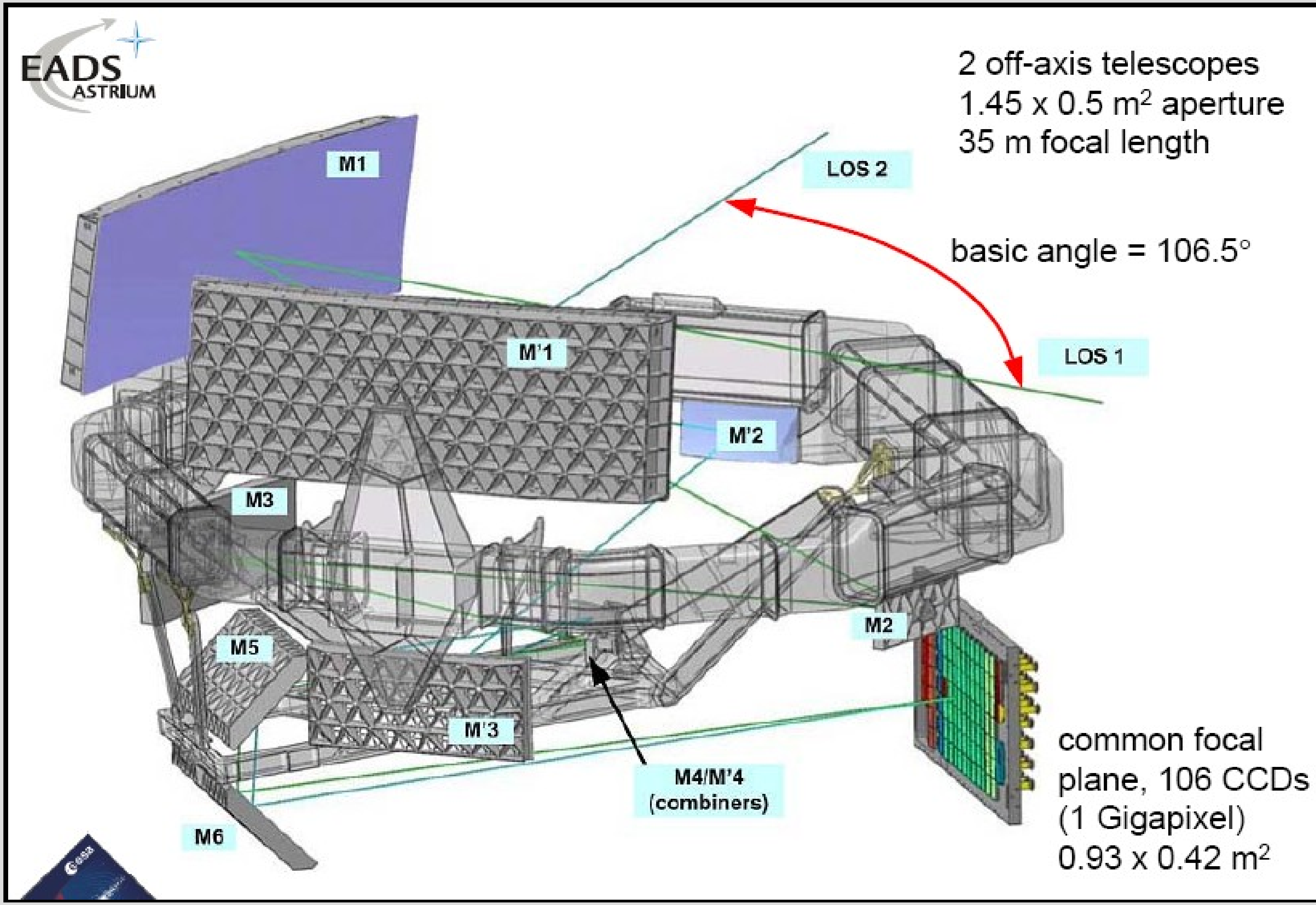
Micro-arcsec, pico radians, picometers……

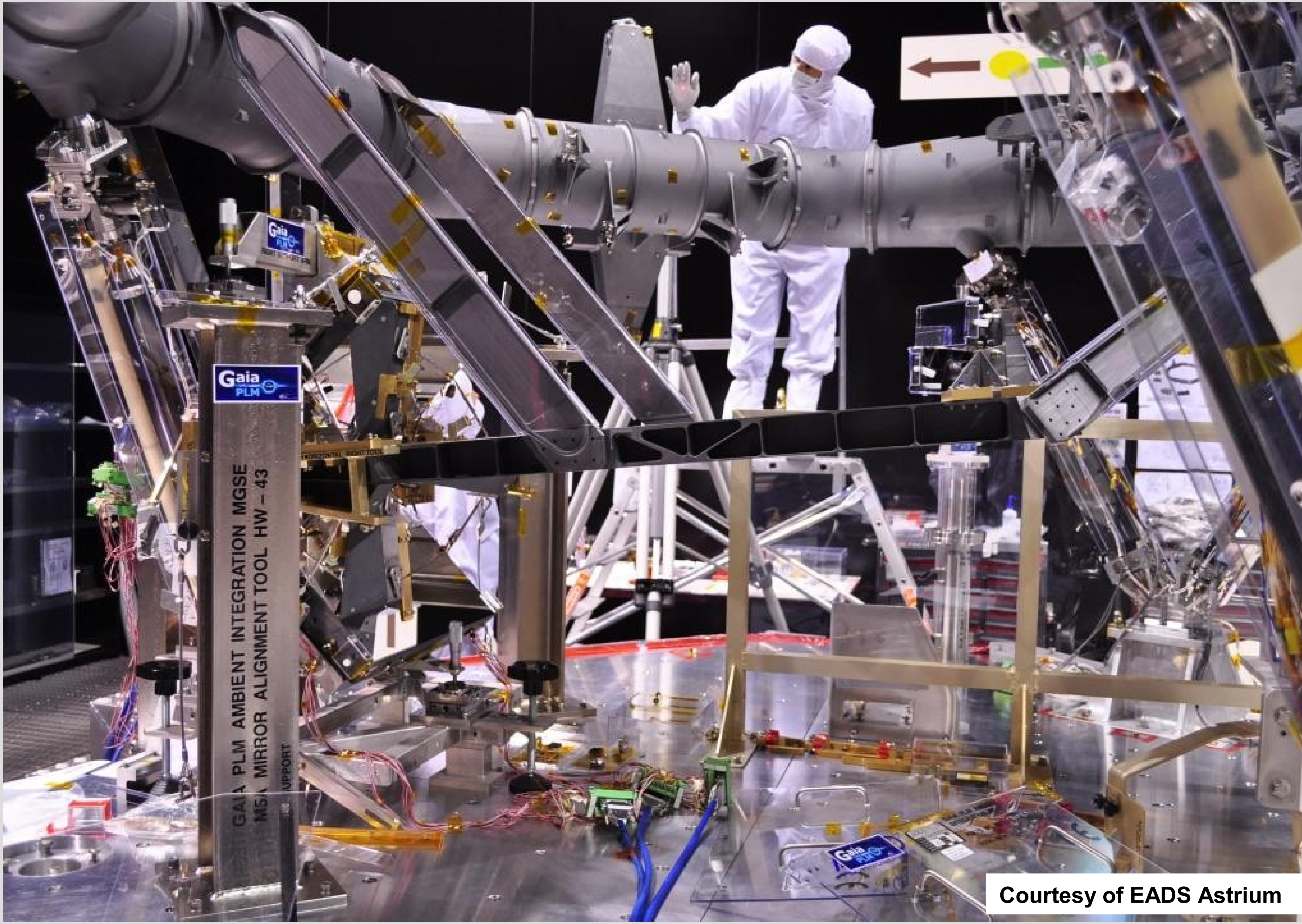


Recall that atomic dimensions are of the order af 1 Angstrom = 10^{-10} m

Think also of the thermal stabilities that need to be reached over volumes of tens of cubic meters! [Like in the case of the Gaia payload.]

Gaia's astrometric payload!!




Gaia PLM
GAIA PLM AMBIENT INTEGRATION MGSE
M5A MIRROR ALIGNMENT TOOL HW – 43
Courtesy of EADS Astrium

….. Stabilizing macrostructures to the picometer level is possible!

(Bertinetto & Canuto 2001, Optical Engineering, 40(1), 76-80)

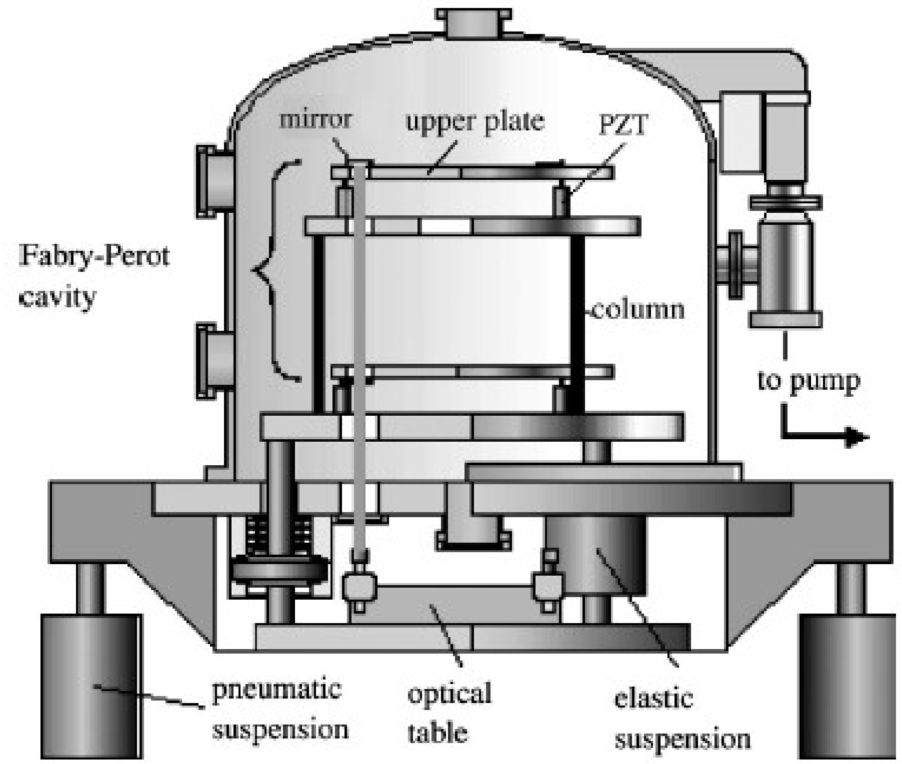


Fig. 1 Schematic illustration of the COSI test bed.

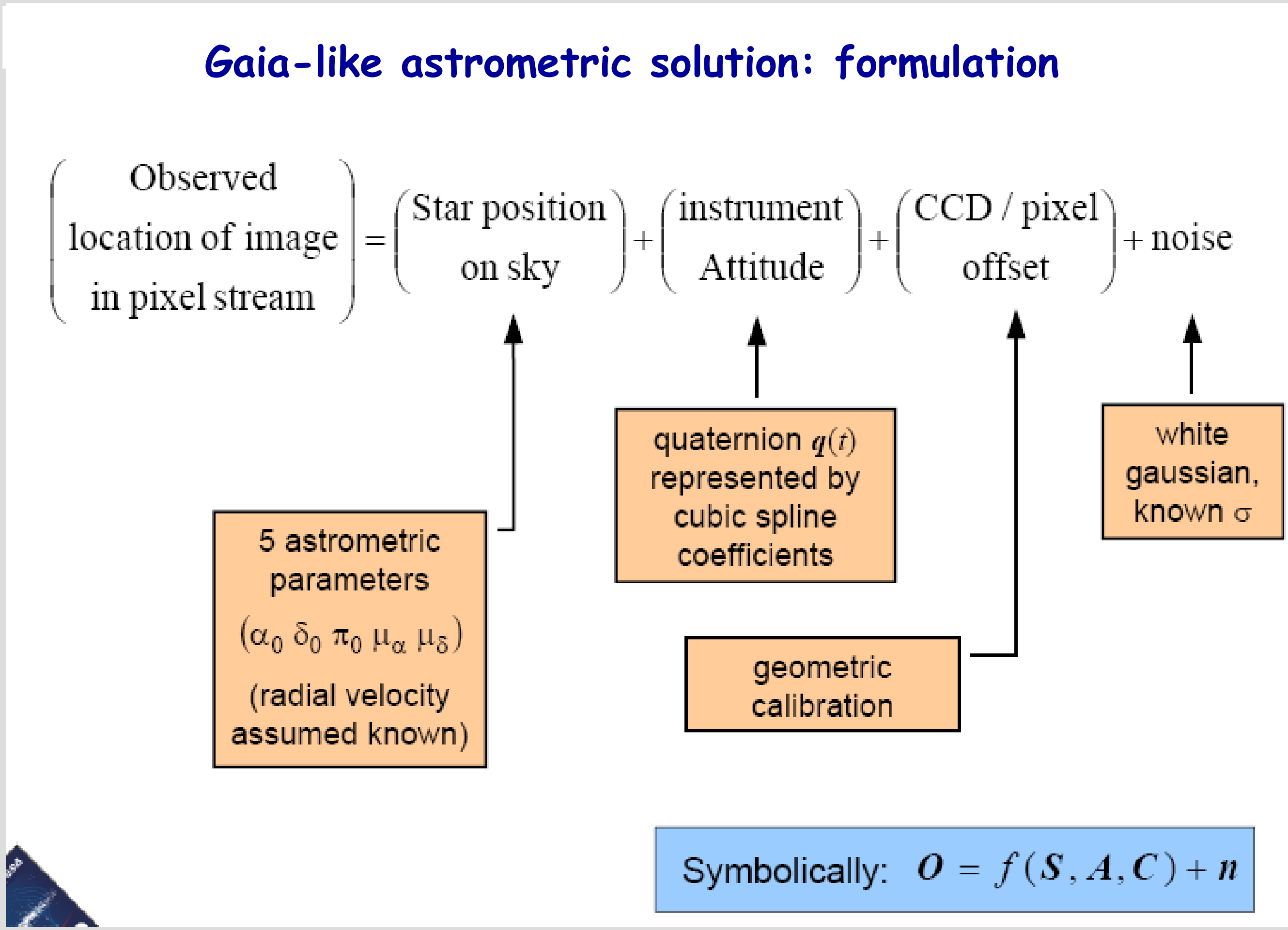
~12 pm error (1 σ) over 3 hours

achieved

Also, JPL efforts toward SIM

(M. Shao et al..) which evolved, in part, into NEAT (F. Malbet et al 2011)

Beyond Gaia


Gaia-like astrometric solution: formulation
$$\begin{pmatrix}\text{Observed}\\ \text{location of image}\\ \text{in pixel stream}\end{pmatrix} = \begin{pmatrix}\text{Star position}\\ \text{on sky}\end{pmatrix} + \begin{pmatrix}\text{instrument}\\ \text{Attitude}\end{pmatrix} + \begin{pmatrix}\text{CCD / pixel}\\ \text{offset}\end{pmatrix} + \text{noise}$$
5 astrometric parameters
$(\alpha_0\ \delta_0\ \pi_0\ \mu_\alpha\ \mu_\delta)$
(radial velocity assumed known)
quaternion $q(t)$ represented by cubic spline coefficients
geometric calibration
white gaussian, known σ
Symbolically: $O = f(S, A, C) + n$

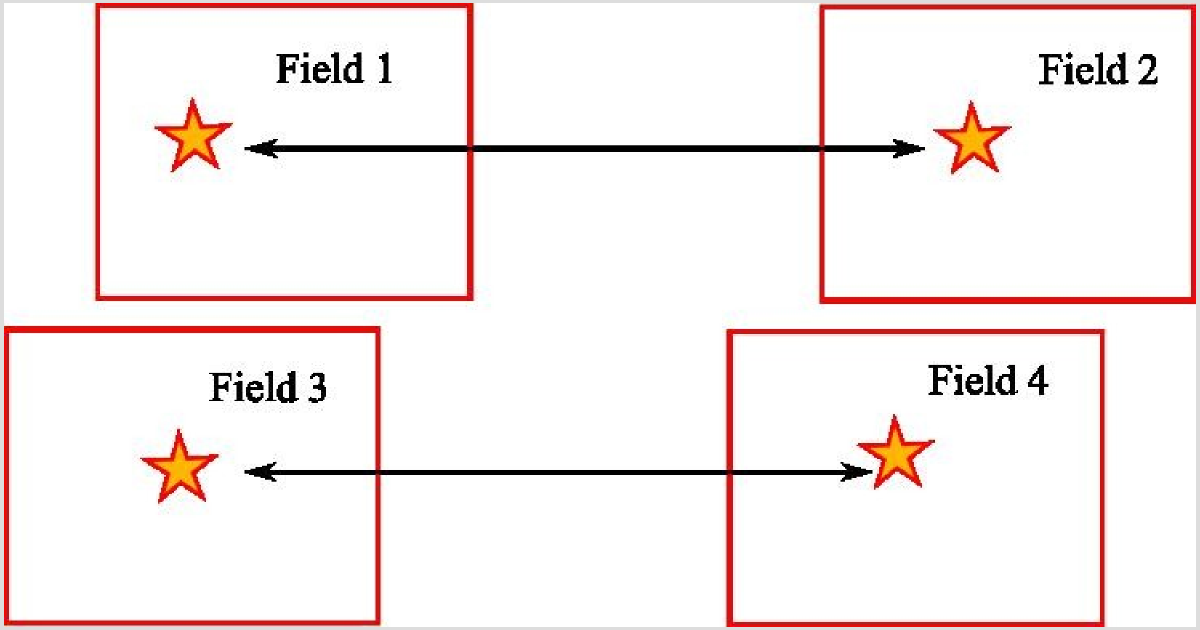
The GAME mission main features:

Gai et al 2011

- Multiple epoch observation sequence
- **Differential measurements** on superposed fields
- Systematic error control
- Precision on image location / separation
- The Fizeau interferometer / coronagraph
- Elementary astrometric performance
- **Photon limited mission performance**

→ PPN parameter γ to ~ $10^{-6} - 10^{-8}$. → **Gai's talk**

Multiple epoch observation sequence



Deflection $\delta\psi$ measurement

Calibration fields, $\delta\psi \cong 0$

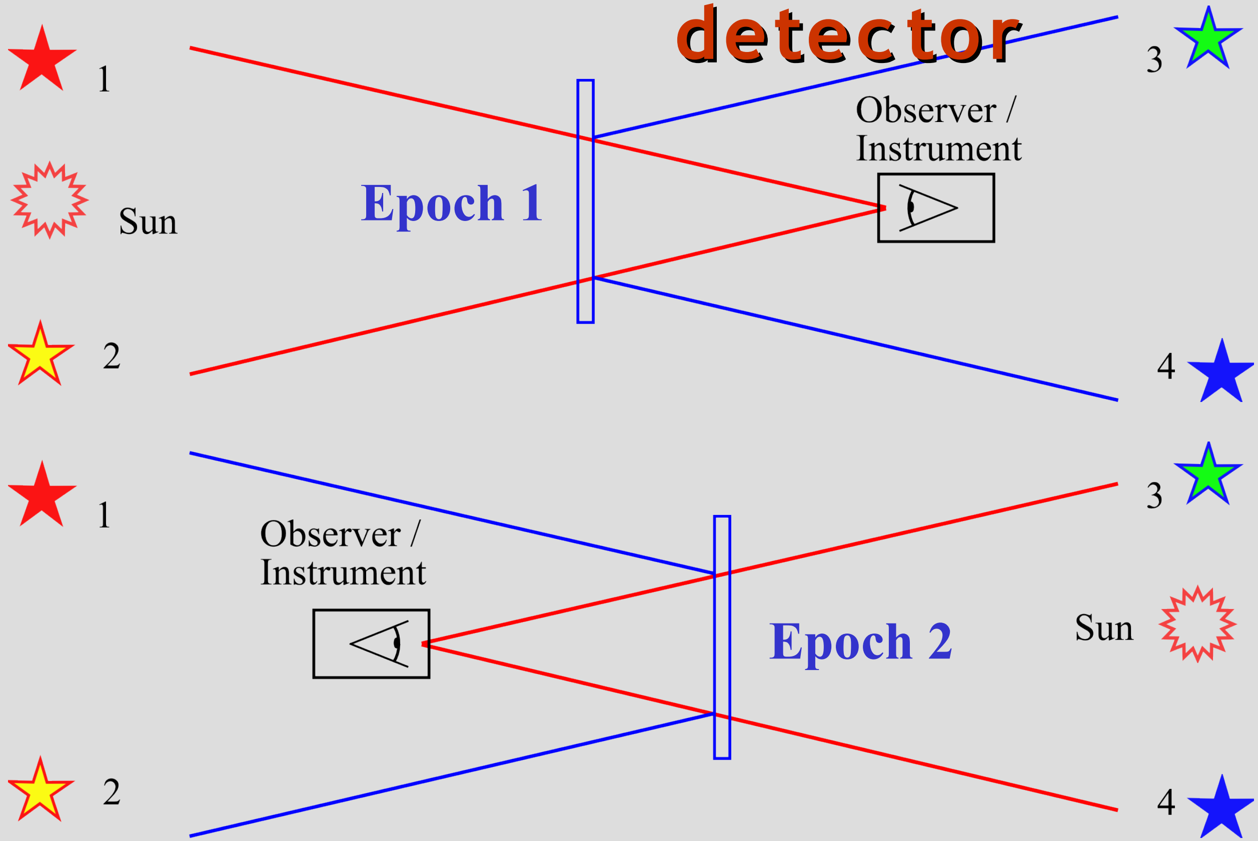
Fields F1, F2 measured close to and away from the Sun:

2+ measurements epochs to <u>modulate</u> deflection
(Sun "switched" on/off)

Calibration fields: low deflection in all epochs

Gai's talk

Multiple field multiplex on telescope + detector



Epoch 1↔2:

deflection modulation switched between field pairs

Star separation variation: deflection ψ + instrument [base angle]

Additional epochs (calibration): low deflection on all fields

Gai's talk

•**Chapter VII: Conclusions**

Conclusions (1/4)

- Role of astrometry revamped thanks to technology (access to space). Thanks also to the Gaia mission the next decade or two we will know more of the real story of DM and DE and the validity of GR: **astrometric cosmology!**

Conclusions (2/4)

The hope is that the actual geometry of the Universe, which astrometry might help unveiling, will regain ordinary matter, the baryons of which we are made, some of its role that the story told today by the Concordance Model assigns almost entirely to the mystery of dark matter and dark energy!

Conclusions (3/4)

- From the technological stand point, space astrometry appears to provide the most direct "access" to the light bending properties (Toward the repetition of the 1919 Dayson, Eddington,… experiment, but 21° century technology)

- However, precision must improve from Gaia to the one-µas level, and the same holds for accuracy: <u>**differential fully 2-D measurements**</u>

Conclusions (4/4)

- The next astrometric mission will have all-sky access availability as a requirement; the possibility to allocate observing time with magnitude; completeness, on the other hand, is not going to be a driving design parameter.

- Differential measurements call for a relatively cheap, although highly rewarding, payload/satellite design.

- Accuracy highly scalable with size of payload (telescope): tested with a baloon flight at, say, 10^{-4} then pushed to the 10^{-8} for an ESA medium class mission.