Interpreting the EROS observations towards the Galactic spiral arms

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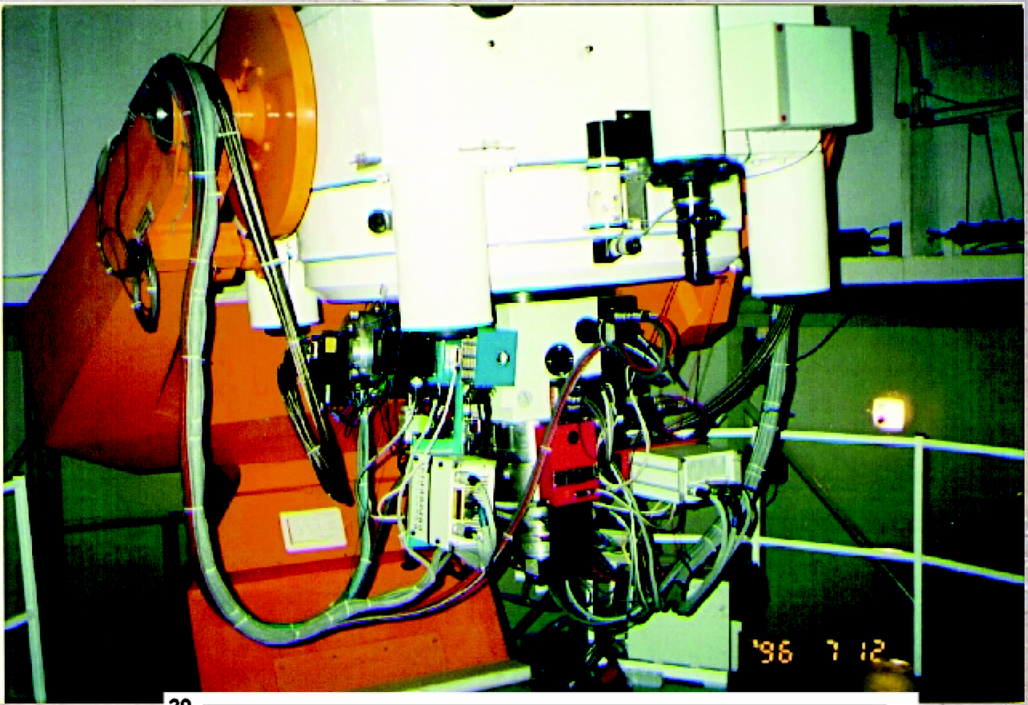
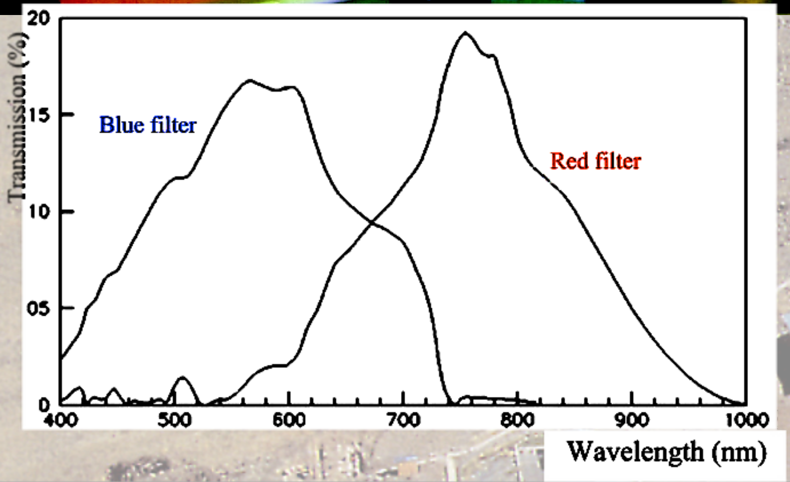
ArXiv/1701.07006

Expérience de Recherche d'Objets Sombres



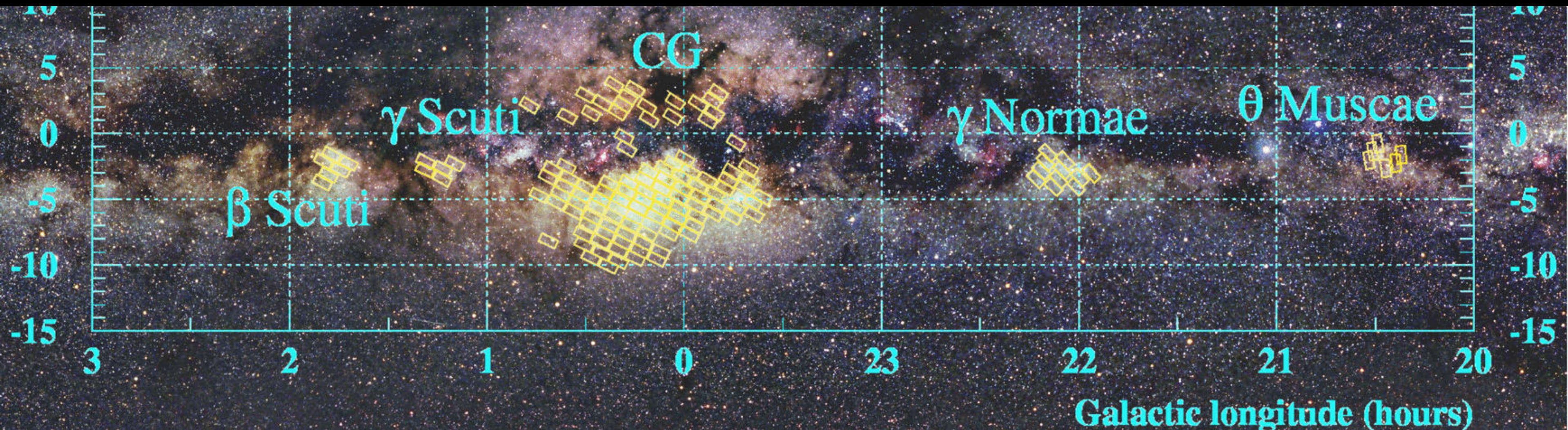


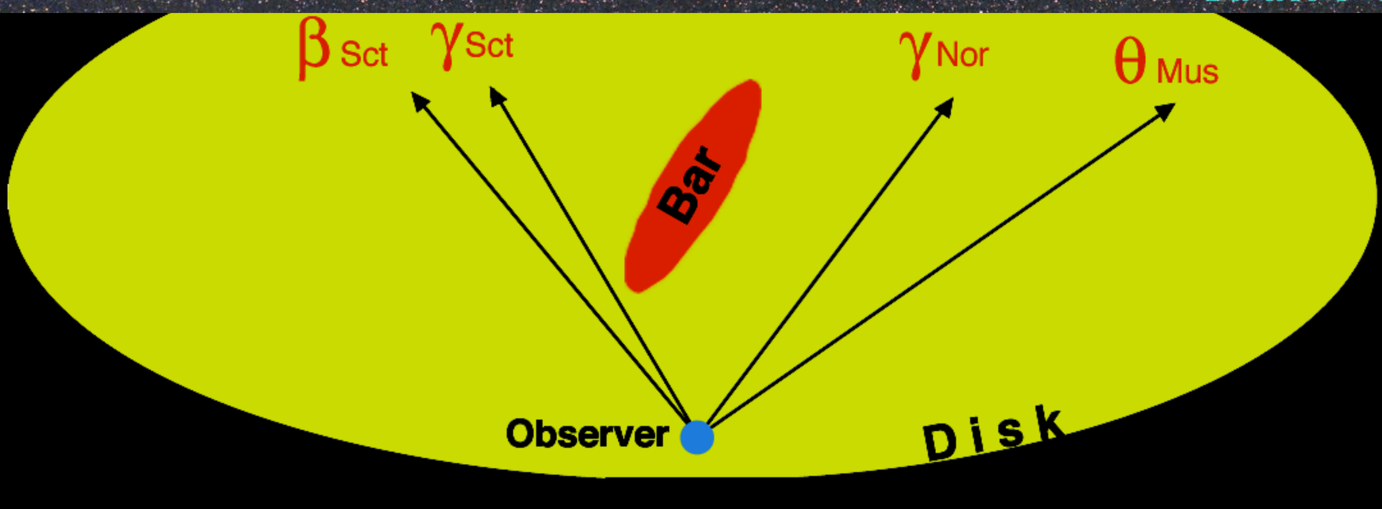
- 1m telescope in Chile
- Wide-field cameras R & B -> 32Mpix each
- 7 years operation
- ***50 Terabytes of data***
- 850,000 images processed
- ~77 10^6 stars measured 300 to 500 times
- **EROS1 (1990-1994)**
- **EROS2 (1996-2003)**

Spiral arms fields

29 fields in 4 zones away from Galactic center : 13×10^6 stars

Stars (10^6)	3.0	2.4	5.2	2.3
Field $(°)^2$	4.5	3.8	8.8	4.0
Image #	2x268	2x277	2x454	2x375





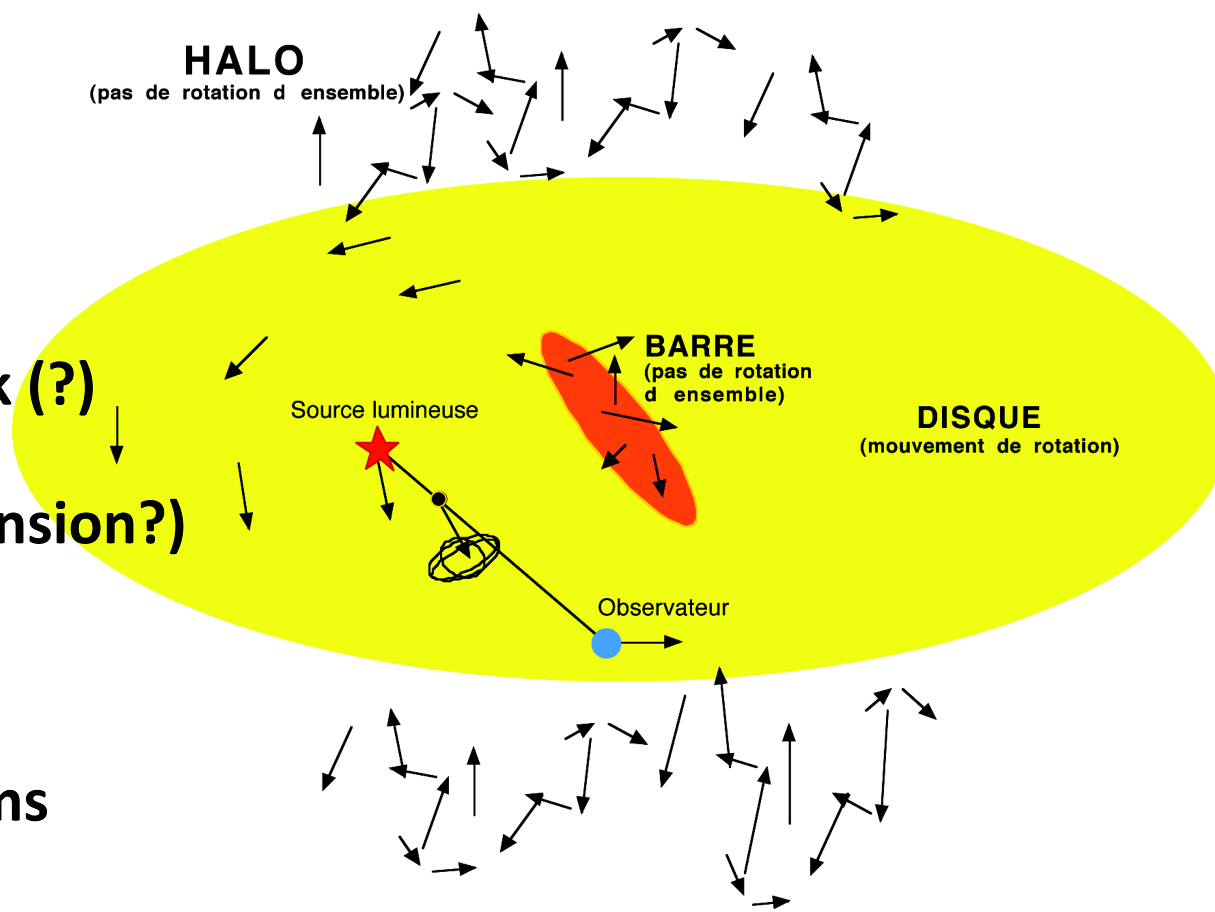
Specific difficulties compared with LMC/SMC/GC searches

1: Lenses belong to several structures

- Density, local (lens) IMF, kinematics

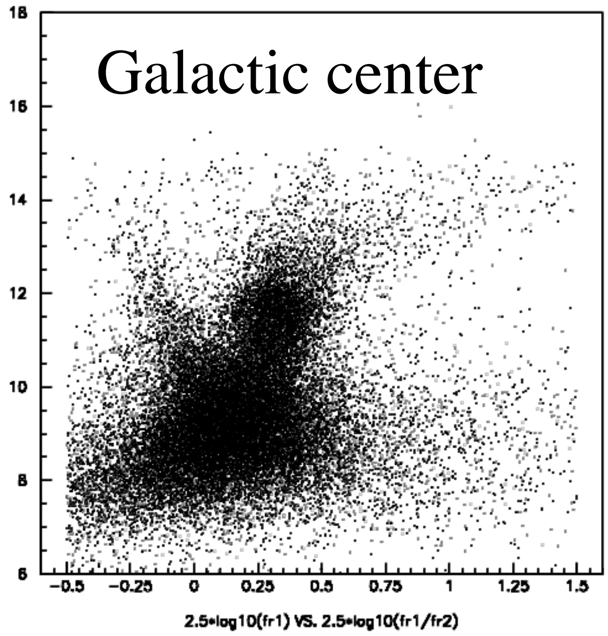
Different Distances/Masses/Velocities

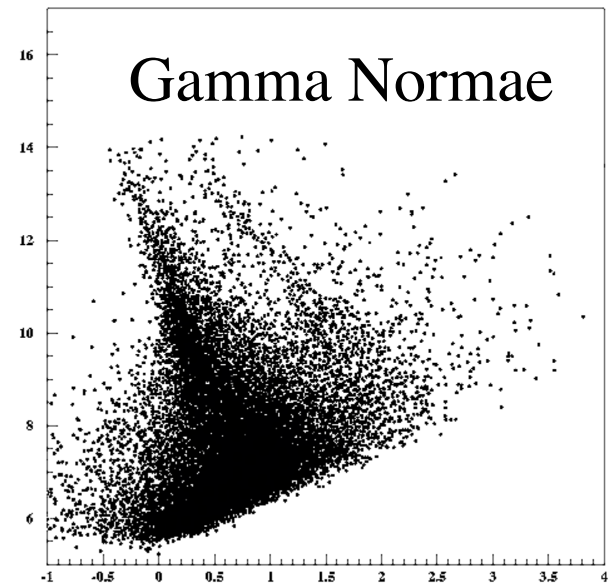
- Bulge
- Thin disk
- Thick disk (?)
- Bar (extension?)
- Halo
- Spiral arms



2: Source distances widely distributed !

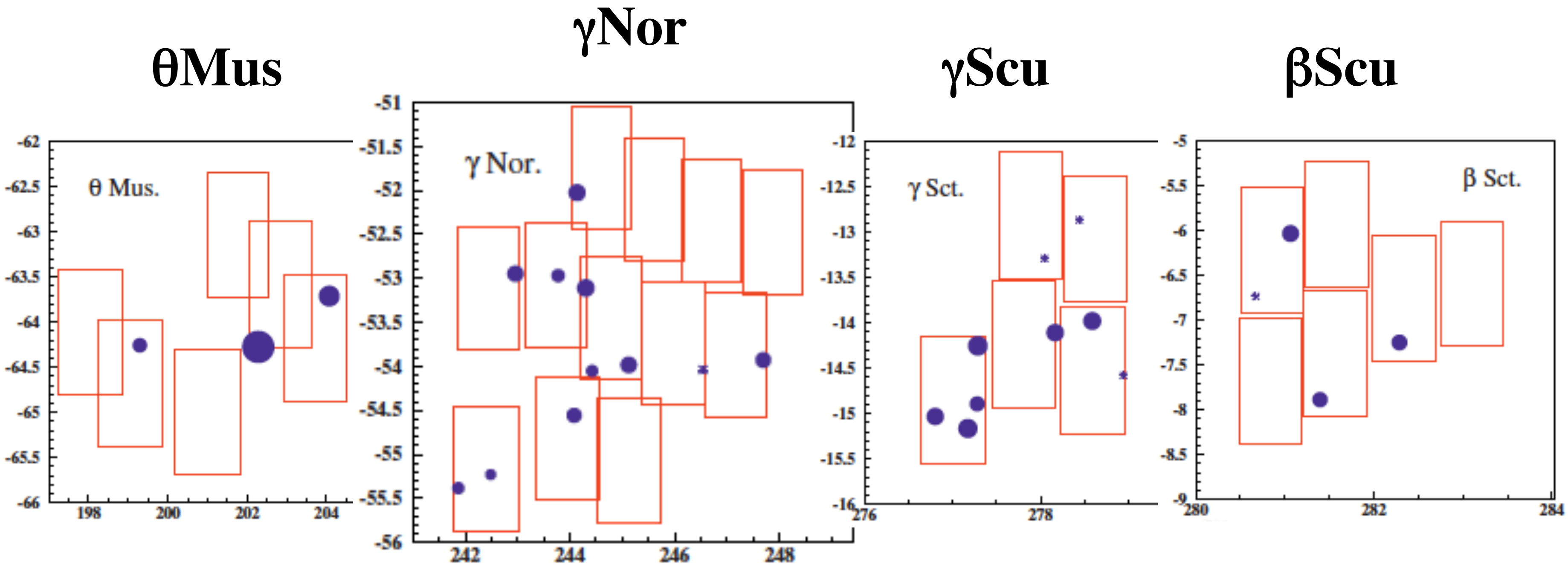
- Also strong and very variable interstellar absorption. For example: **red giant clump** not well defined in magnitude-color diagrams of spiral arms





-> Use concept of τ(catalog), instead of τ(distance)

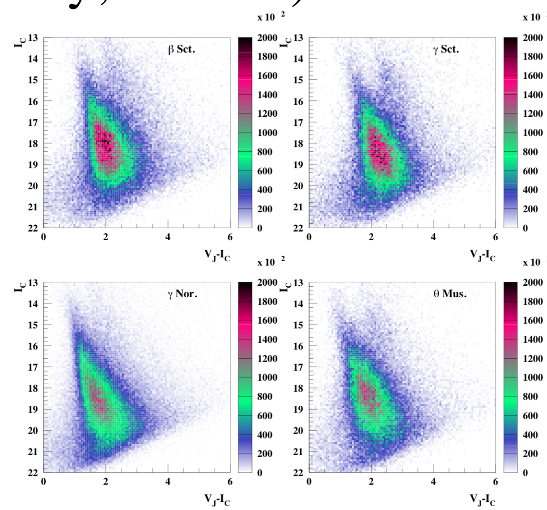
Spatial distribution of the 27 events found in 7 years



See **Rahal et al. (EROS coll.) A&A500, 1027 (2009)**

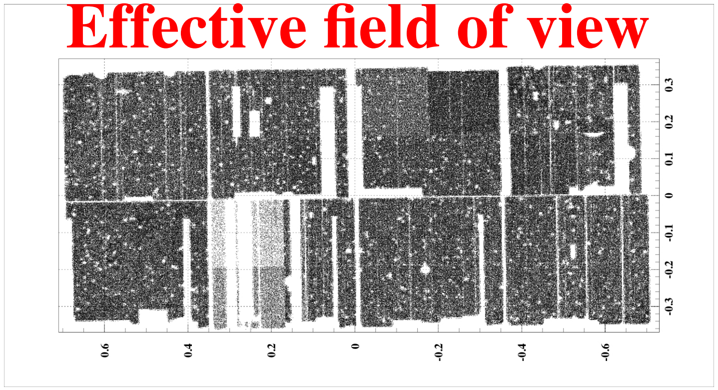
Ingredients for a full interpretation

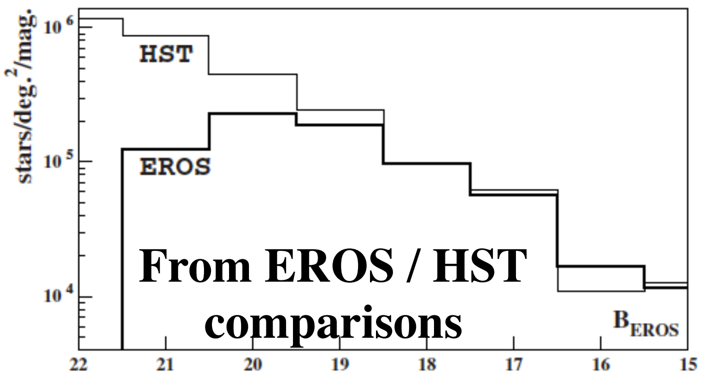
- **The EROS observations**: CMDs, τ, t_E distribution
  - CMD described with (mean stellar surface density, <color>)
  - τ, and t_E distribution described with (τ, $<t_E>$)
- **Knowledge of the selection effects**
  - Effective field
  - Stellar detection efficiency
  - Photometric uncertainties
  - Microlensing efficiency

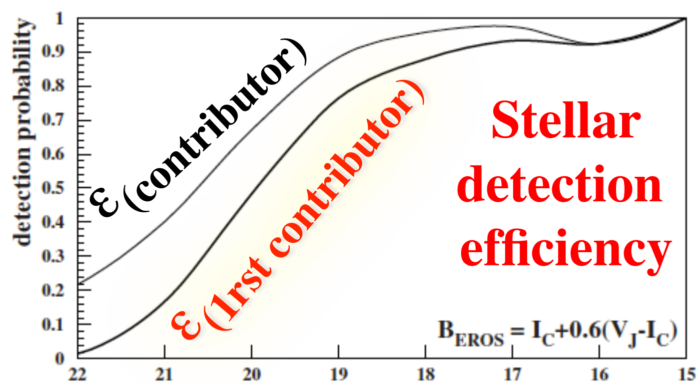


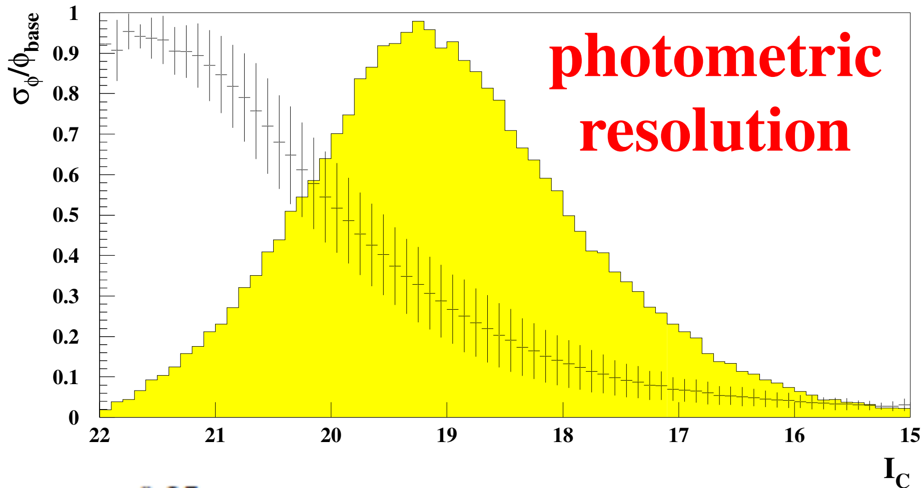
- **Galactic density models** (shape and mass of each structure), built to fit all known observations
- **Stellar luminosity distribution** -> for source population
- **Stellar mass distribution (IMF)** -> for lens population
- **3D absorption map** -> ESSENTIAL

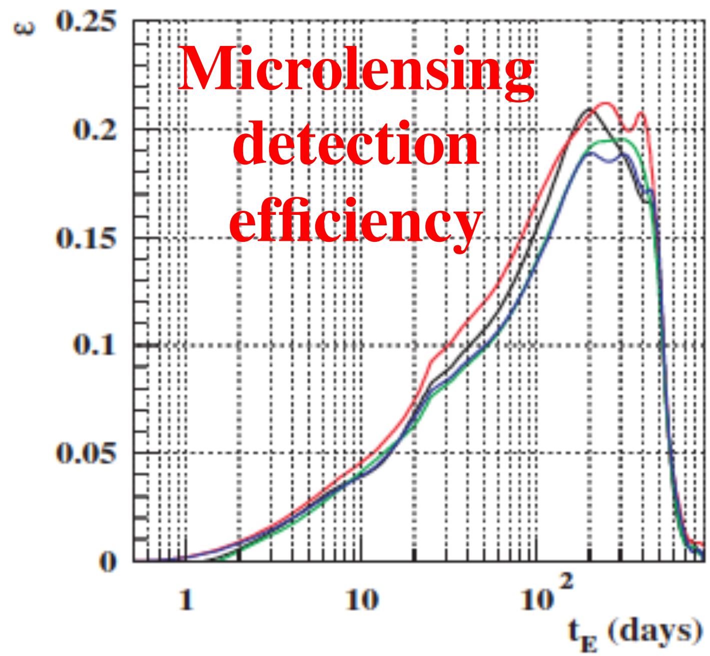
Deep understanding of the detector





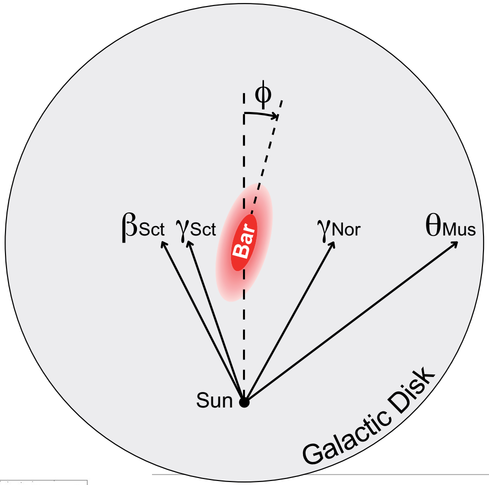




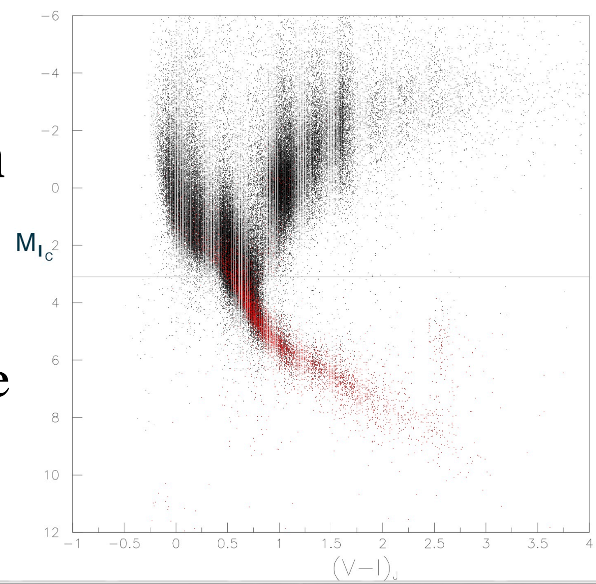


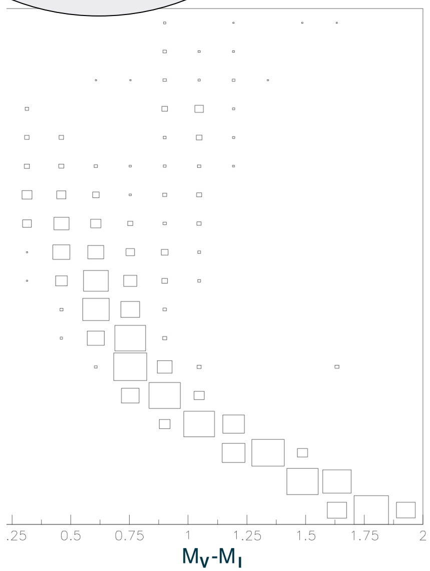
Simulation: Sources

- **Density models**: Besançon / simple home-made
  - Disk(s)
  - Bar ($\phi = 13°$)



- **Local CMD built from debiased Hipparcos**
  - Use only objects within their completion distance (such that V<7.5)
  - Assume same CMD within the disk





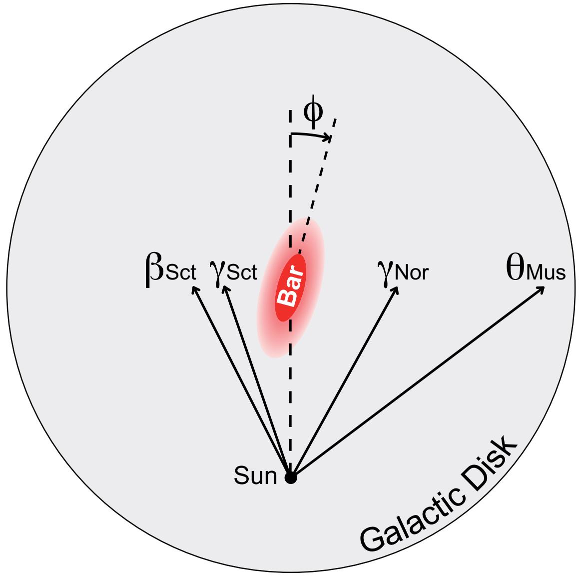
- **3D extinction map**
  - Marshall et al. 2006

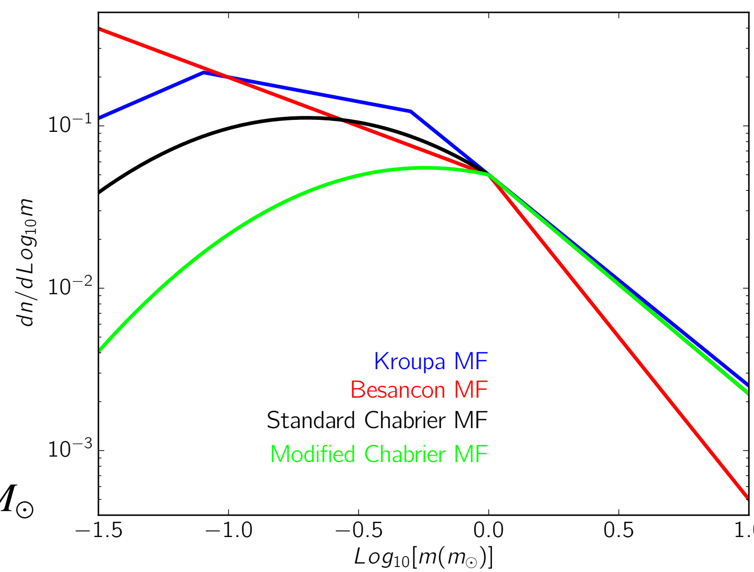
Fast spatial variations

Simulation: Lenses

- **Density models**: Besançon / simple home-made
  - Disk(s)
  - Bar (ϕ = 13°)
- **Kinematics** from the galactic models -> V_T
  - disk orbital velocity
  - Maxwellian V in bar
  - Peculiar velocities have negligible impact
- **IMF** -> R_E
  - Modified Chabrier (m_0 # 0.2)

$$\xi(\log m/M_\odot) = 0.093 \times exp\left[\frac{-(\log m/m_0)^2}{2\times(0.55)^2}\right],\ for\, m \leq M_\odot$$





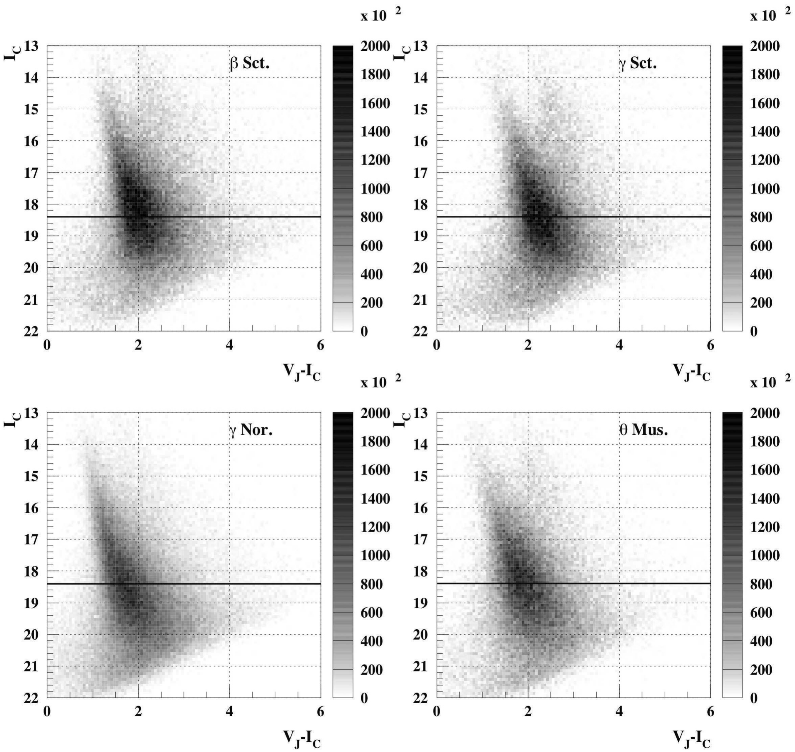
Fit to the observations

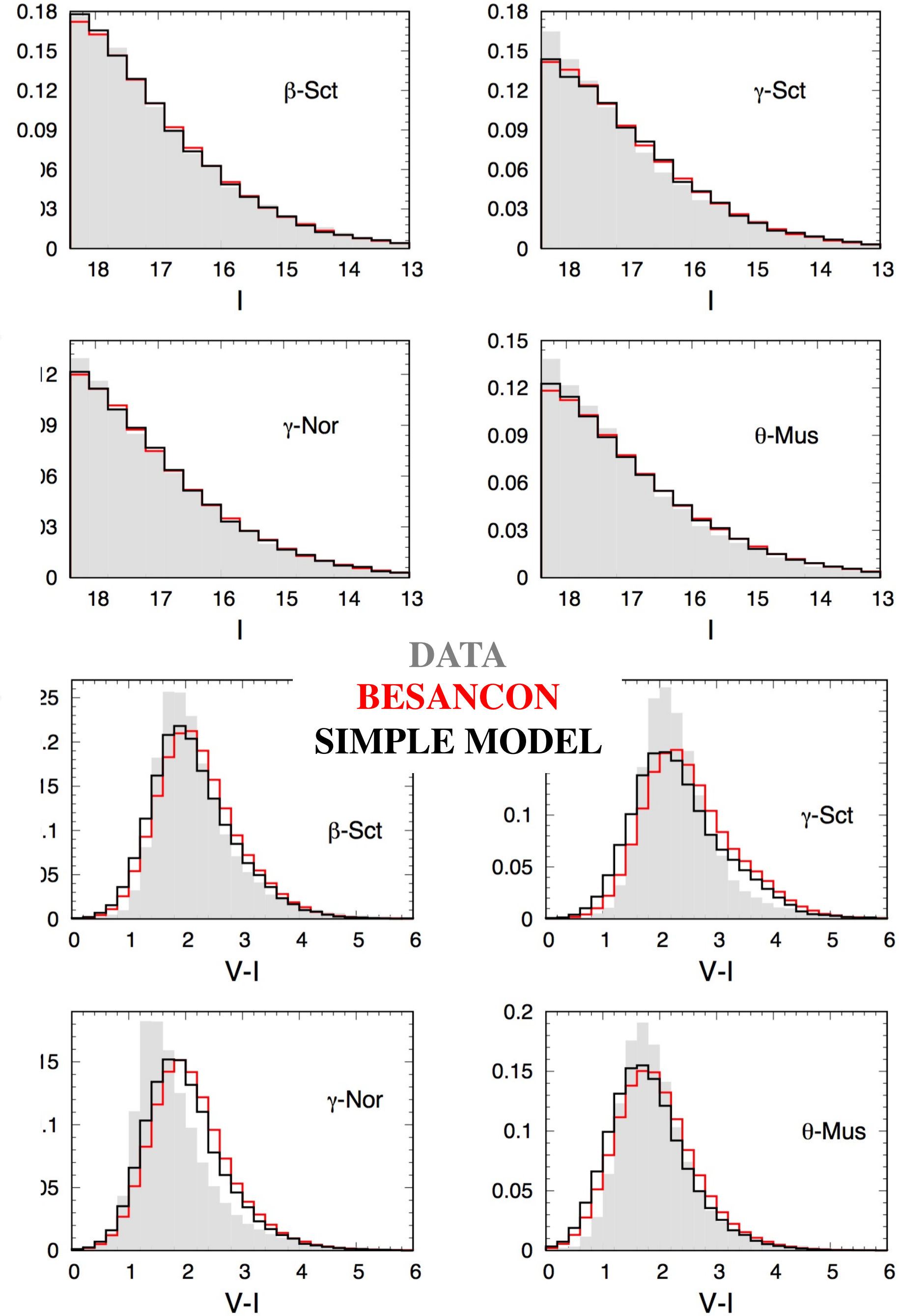
- Consider only stars with I < 18.4 to have the best control on detection efficiency
- Use simulation to connect 3-4 physical parameters ($\boldsymbol{\phi_{bar}}$, $\mathbf{M_{thick\ disk}}$, **IMF**, kinematic deviations…) with 16 observables: 4 x (**ρ*, <V-I>, τ, <t_E>**)
- Minimize differences (simulation%observed) from linearised χ^2 with ***∂(observable)/∂(parameter)***

-> Necessary to adjust mapped extinctions by assuming 4 syst. & 1 stat. uncertainties (5 parameters)

Results: CMD

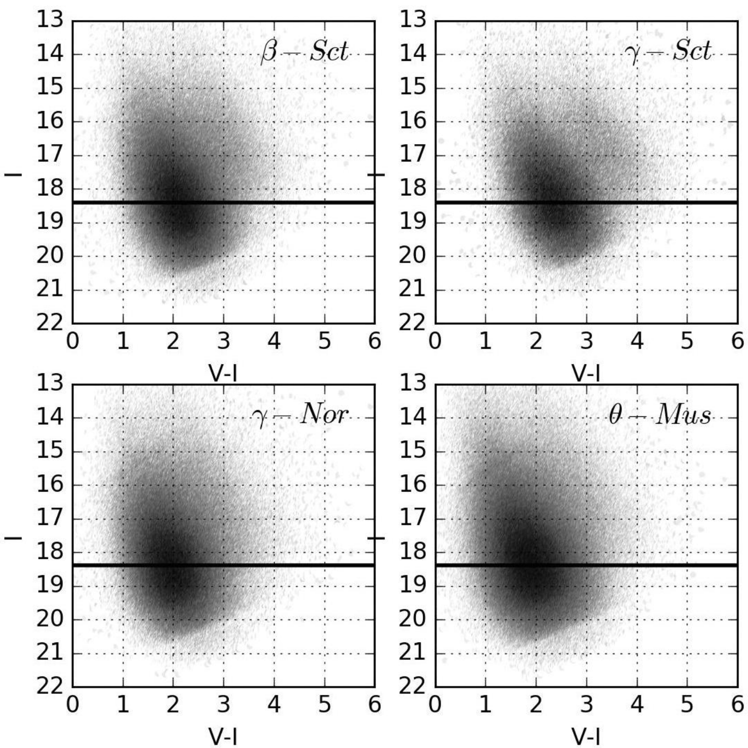
Data

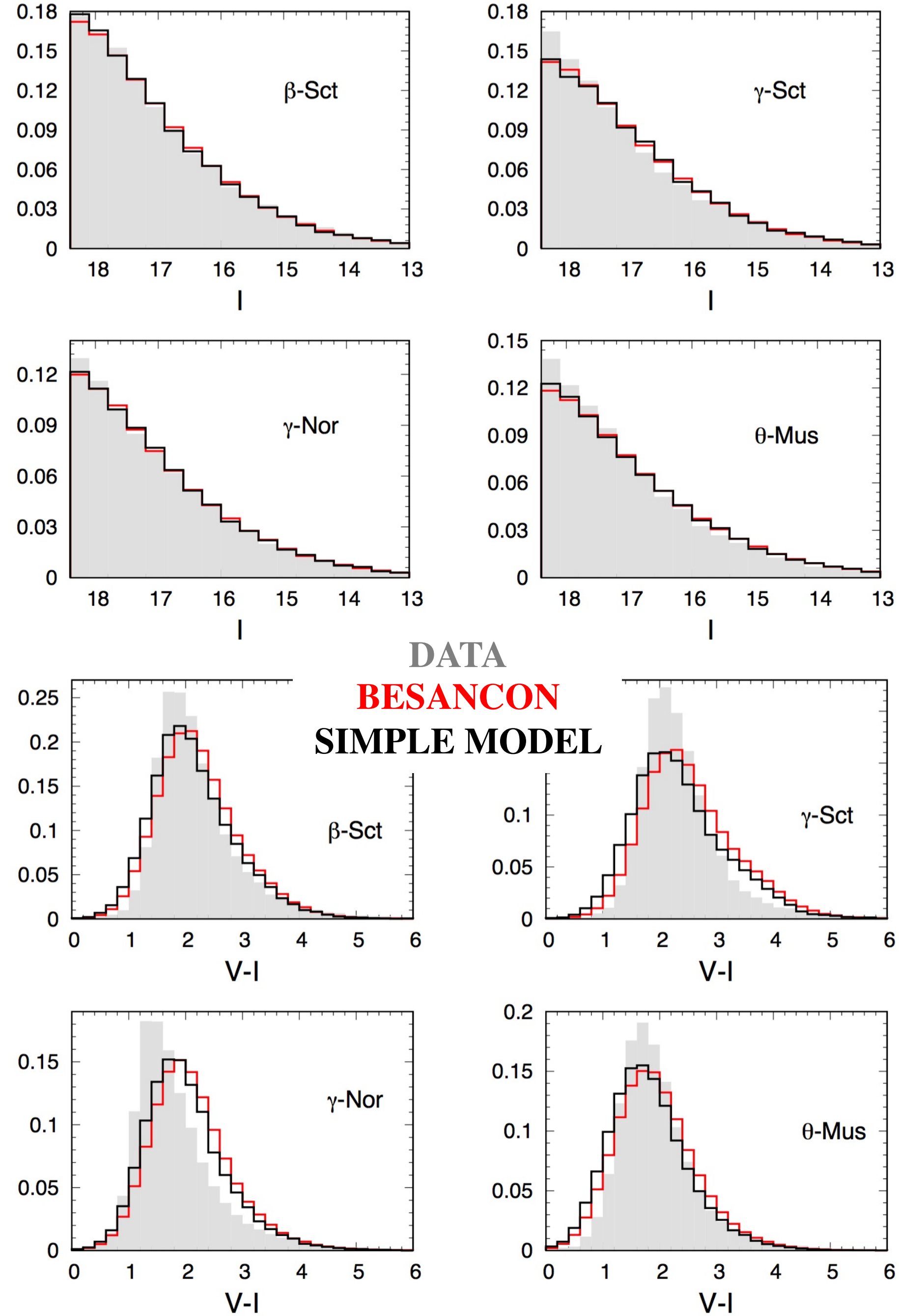




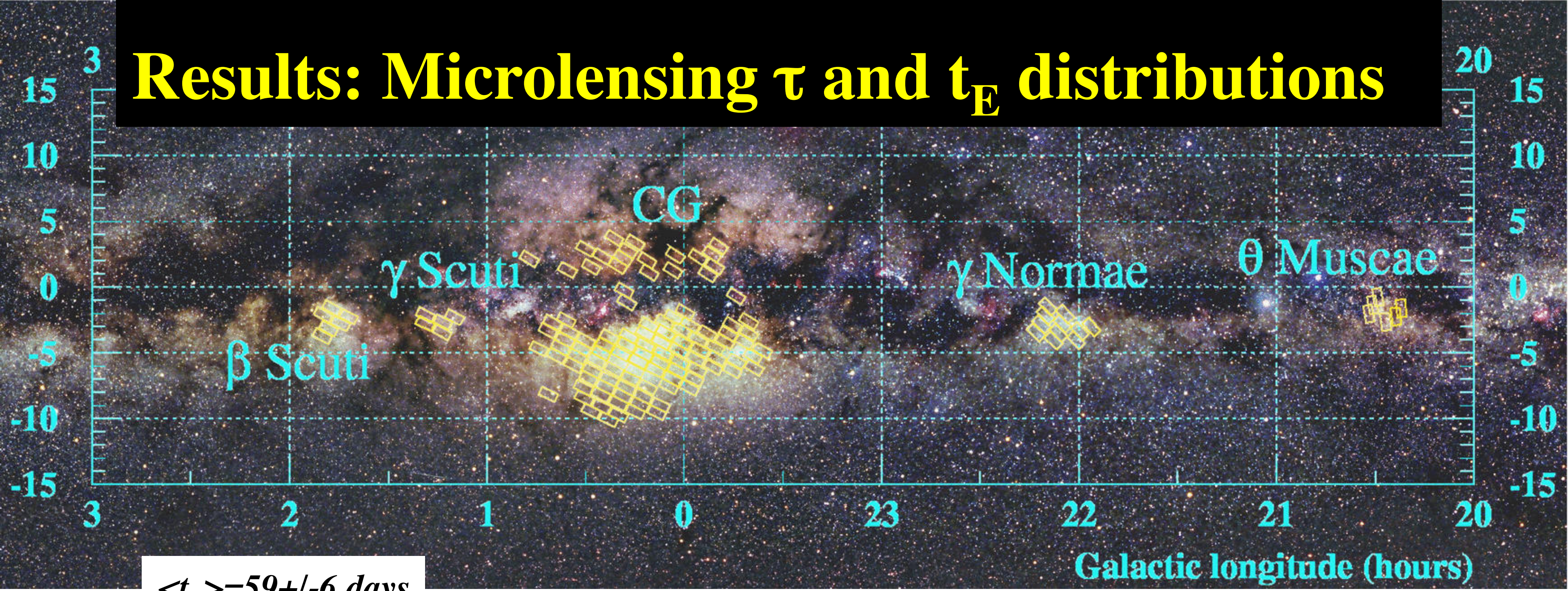
Results: CMD

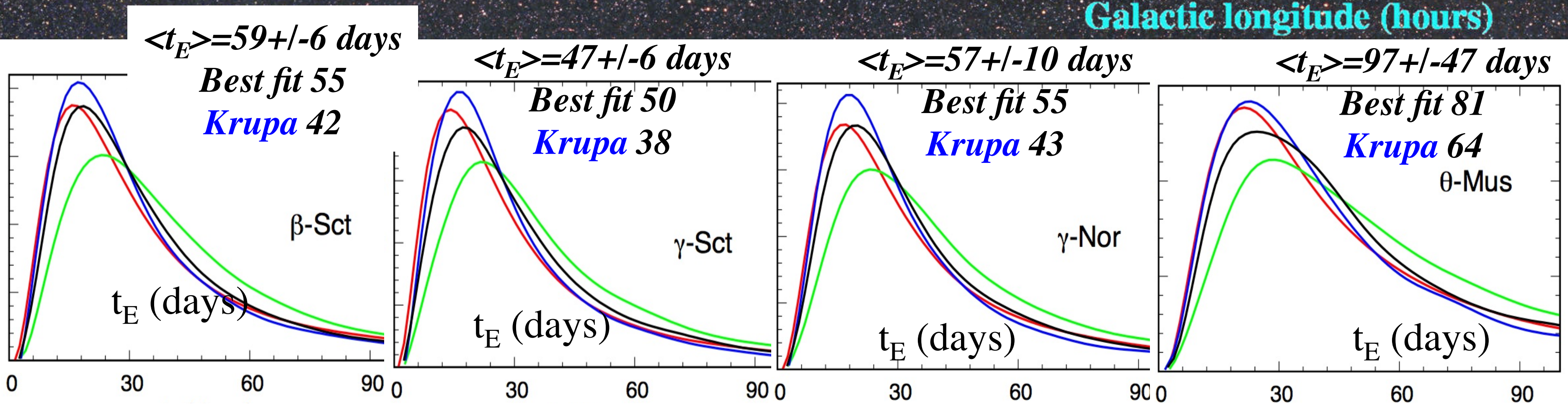
Simulation





Results: Microlensing τ and t_E distributions



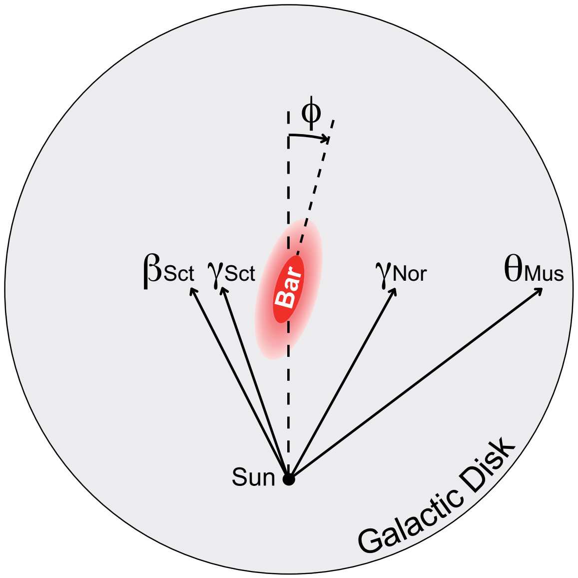


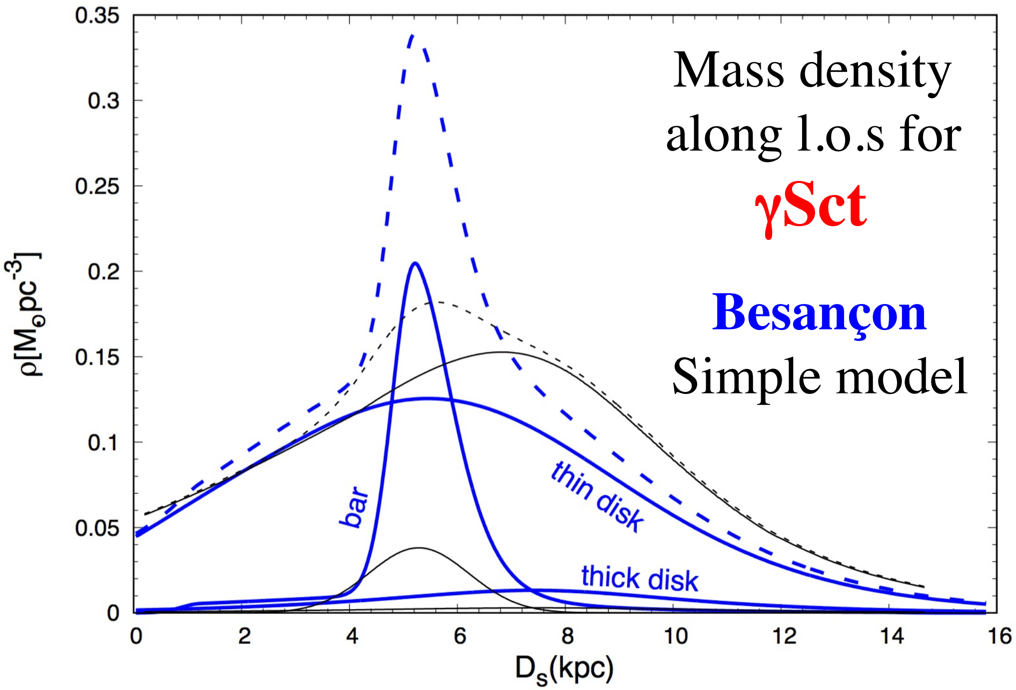
τ_{obs} =	$0.30^{+.23}_{-.20}$	$0.72^{+.41}_{-.28}$	$0.49^{+.21}_{-.18}$	$0.67^{+.63}_{-.52}$
$\tau_{simple\ mod.}$ =	0.45	0.43	0.38	0.23
$\tau_{Besançon}$ =	0.40	0.44	0.34	0.22

No need for massive spiral structure or thick disk of hidden compact objects

γSct and the bar

- **γSct** l.o.s intercepts the bar
- Significant contribution expected from bar stars for **τ**
  - Clearly visible
  - Weak constraint on orientation, but large angle (~ 45°) ruled out
- -> Promising way to further contrain the bar (through more stat.)





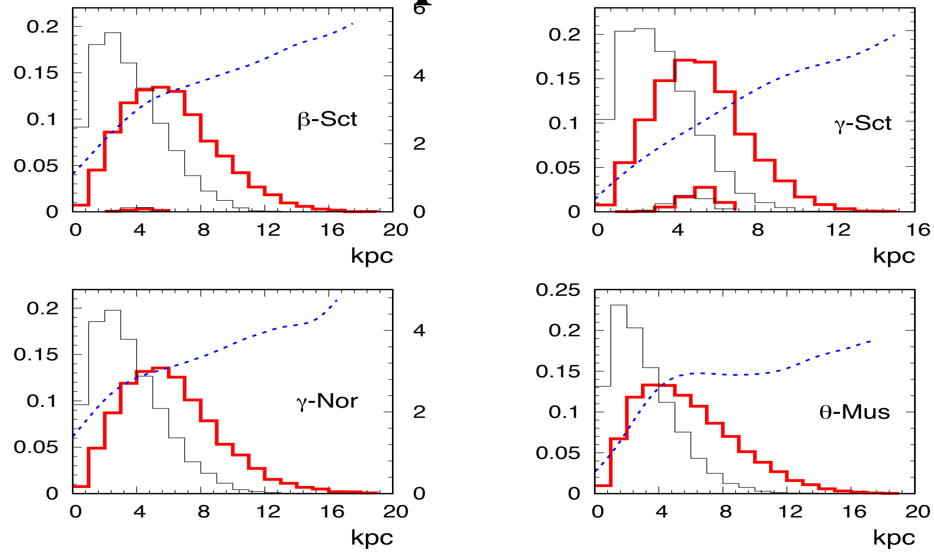
Distances of sources/lenses

____ Lensed sources

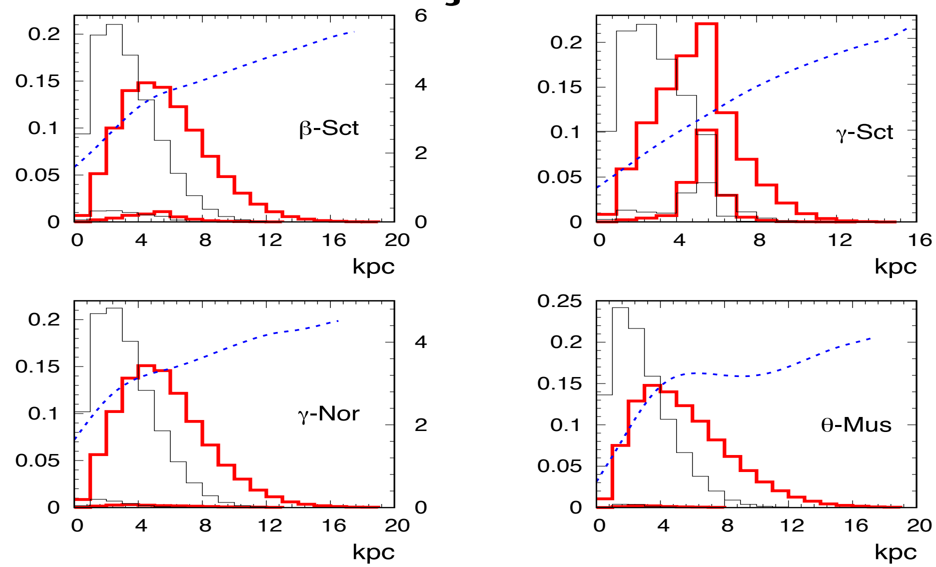
___ Lenses

--- extinction of the lensed sources (avg)

Simple model



Besançon model



Results in numbers

	Target	θ Mus	γ Nor	γ Sct	β Sct
$\rho_*^{I<18.4} \times 10^6$ (stars / sq. deg.)	measured	$0.25 \pm .037$	$0.23 \pm .035$	$0.28 \pm .042$	$0.34 \pm .051$
		$\pm 7.3\%$ common systematics			
	simple model	0.22	0.26	0.28	0.32
	Besançon	0.23	0.26	0.30	0.33
$\overline{V-I}$ (mag.)	measured	$1.95 \pm .15$	$1.86 \pm .15$	$2.36 \pm .15$	$2.20 \pm .15$
		± 0.16 common systematics			
	simple model	1.83	2.02	2.35	2.13
	Besançon	1.94	2.11	2.52	2.22
σ_{V-I} (mag.)	measured	0.71	0.78	0.71	0.75
	simple model	0.72	0.73	0.83	0.74
	Besançon	0.73	0.74	0.81	0.73
$N_{event}(u_0 < .7)$	observed	3	10	6	3
$\overline{N}_{event}(u_0 < .7)$	simple model	4.0	8.6	3.6	2.2
	Besançon	4.0	9.9	3.5	2.4
$\tau \times 10^6$	measured	$.67^{+.63}_{-.52}$	$.49^{+.21}_{-.18}$	$.72^{+.41}_{-.28}$	$.30^{+.23}_{-.20}$
	simple model	0.23	0.38	0.43	0.45
	Besançon	0.22	0.34	0.44	0.40
$\overline{t_E}$ (days)	measured	97 ± 47	57 ± 10	47 ± 6	59 ± 6
	Besançon	68.5	51.9	43.0	49.3
	simple model	80.5	55.3	50.4	54.6
	with Kroupa IMF	64	43	38	42

Conclusions

The Besançon model and a simple model fit CMDs and microlensing observations towards the 4 spiral arms targets

⇒ Only need to assume absorption systematics (by < 0.1mag)

⇒ No need for hidden compact objets in the Milky Way plane: **$M_{thick\ disk} < 5\text{-}7 \times 10^{10}\ M_{sol}$**

⇒ **Bar** : Inclination confirmed

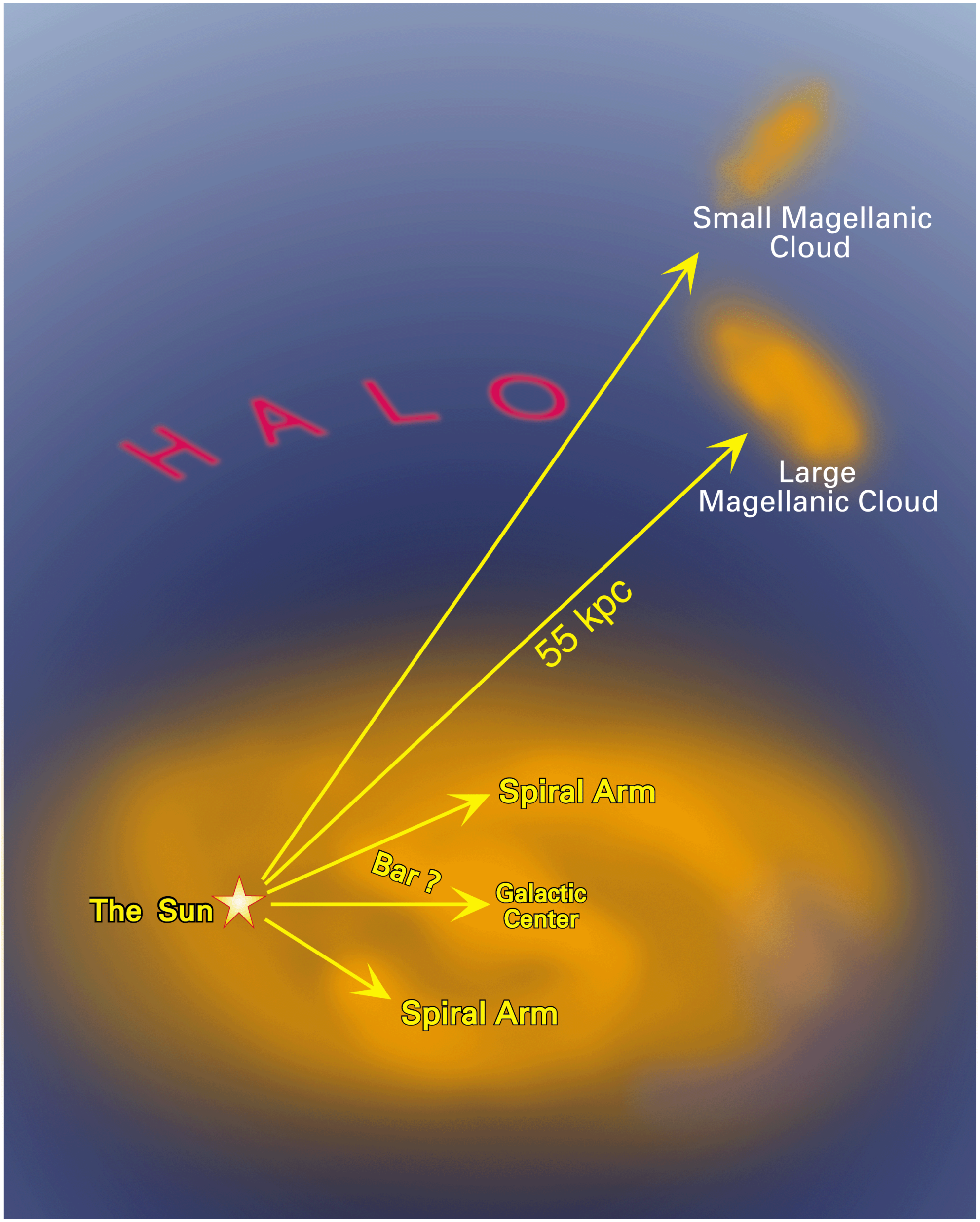
⇒ **Lens IMF** : Krupa disfavoured, modified Chabrier favoured

⇒ **Galactic dynamics**: marginal sensitivity to proper motion parameters with available statistics.

- **(Long term) perspectives**:
  - Improve absorption map
  - Increase statistics + extend mapping (through dust) with IR survey
    - VVV at VISTA: K-survey within the galactic bulge and disk
    - OGLE IV, GAIA, WFIRST, LSST, Euclid

Details in ArXiv/1701.07006

Supplements

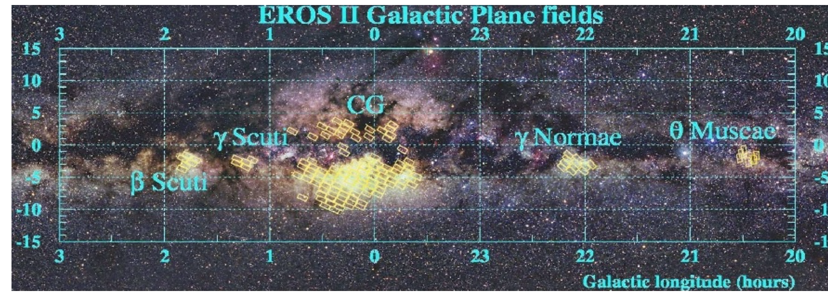


The targets

- **Magellanic Clouds** => probe hidden matter in **halo** **($\tau \sim 5.10^{-7}$)**
- **Galactic center** => probe ordinary stars as lenses in **disk/bulge ($\tau \sim 2.10^{-6}$)**
- **Spiral arms** => probe ordinary stars in **disk, bar** + hidden matter in **thick disc ($\tau \sim 5.10^{-7}$)**
- Non-microlensing (**SN**, **proper motion**)

Events found after 7 years of data taking

- ✓ **Galactic Center: hundreds of microlensing events found**
  - 20 million stars monitored
  - 5.6 million **Red Giant** stars
  - **120 microlensing** events on **RG**
- ✓ **Spiral arms**
  - 13.3 million stars monitored
  - **27 microlensing** events
- ✓ **LMC**
  - 29.2 million stars monitored
  - 5.5 million « bright » stars
  - **0 microlensing** event on bright stars
- ✓ **SMC**
  - 4.2 million stars monitored
  - 0.84 million « bright » stars
  - **1 microlensing** event on bright stars

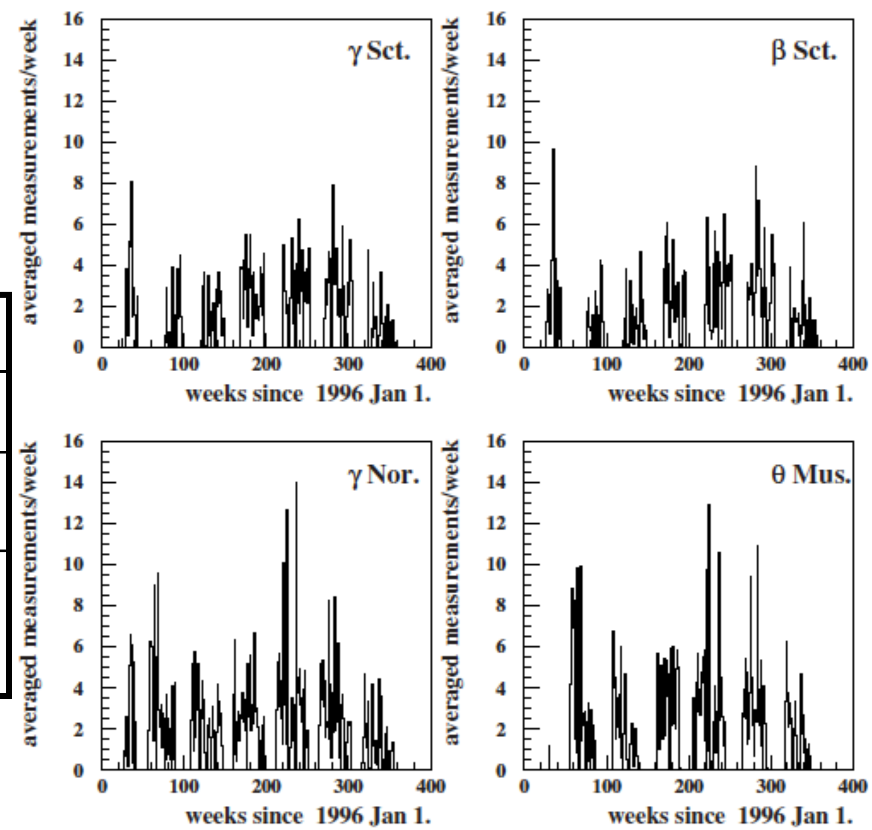


7 years of data: Spiral arms

Spiral arms

- 13 million stars
- 7 seasons -all data-

<Measurements> per object per week



Direction	βScu	γScu	γNor	θMus
Stars ($x10^6$)	3.0	2.38	5.24	2.28
Effective field$(°)^2$	4.5	3.75	8.8	4.0
Measurements (per colour)	268	277	454	375

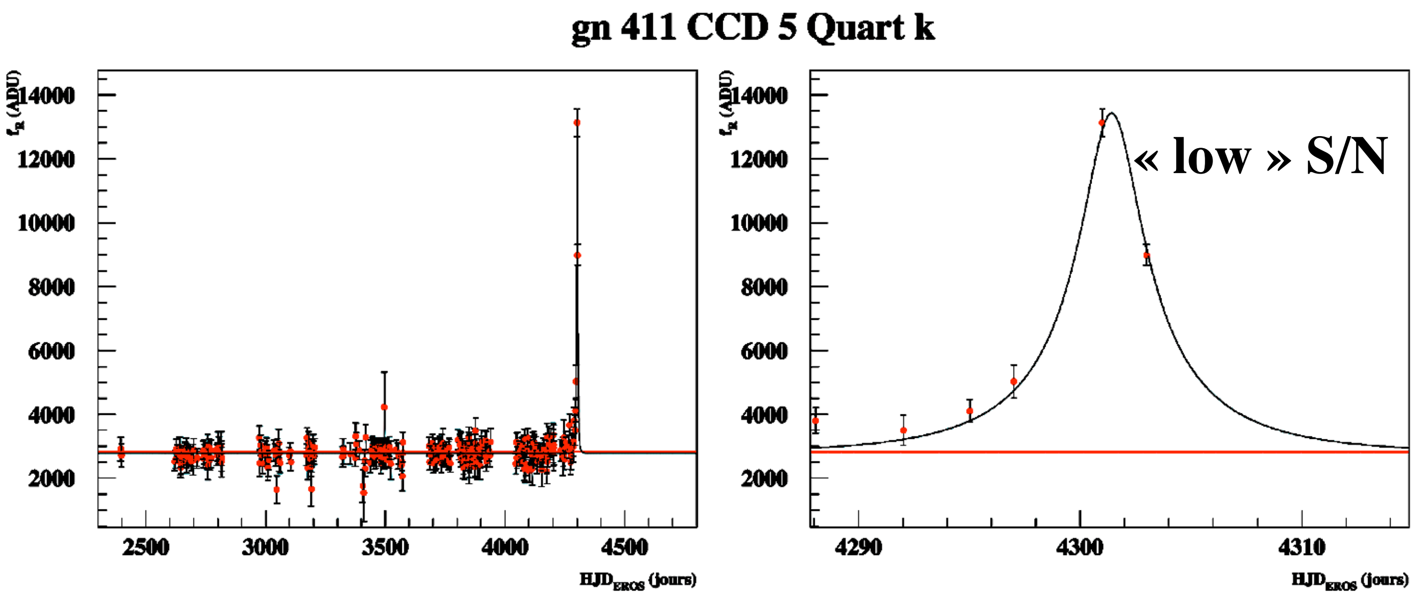
Event selection

- After "standard" pre-filtering
  - 2nd fluctuation probability : $\log_{10}(P_2)/\log_{10}(P_1)_{B,R} < 0.5$
  - B and R fitted peak overlap : $> 40\%$
  - Sampling : $\Delta T_{peak} = \Delta T_{u<2} < \Delta t_{obs}$ - 600 days
    $|t_{max} - t_{closest\ meas.}| < 0.4 \times \Delta T_{peak}$
  - Goodness of (simple) ML fit: $(\chi^2_{monochromatic\ ML}/N_{dof})_{B,R} < 1.8$
  - Stability out of the peak : $\chi^2_{Base}/N_{dof} < 8$
  - Improvement vs constant fit : $\Delta\chi^2_B + \Delta\chi^2_R > 60$
  - Fitted impact parameter : $u_0 < 1$

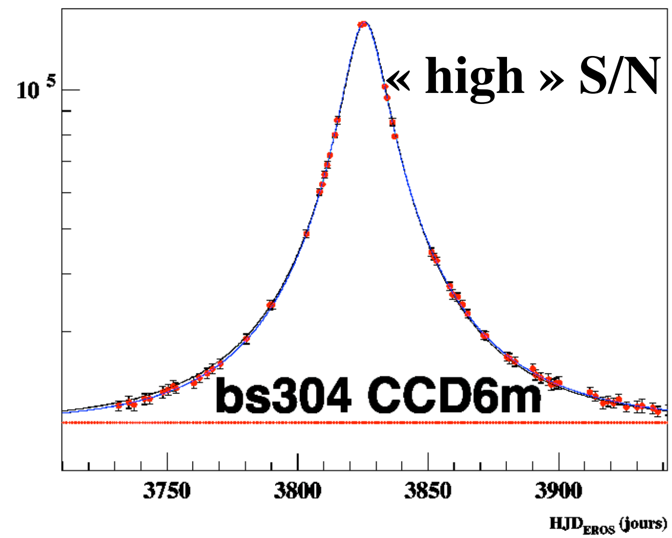
  ⇒ 27 **candidates** (incl. 1 uncertain -very long duration), **22 with** $u_0 < 0.7$

Small contamination (no SNs through dust)

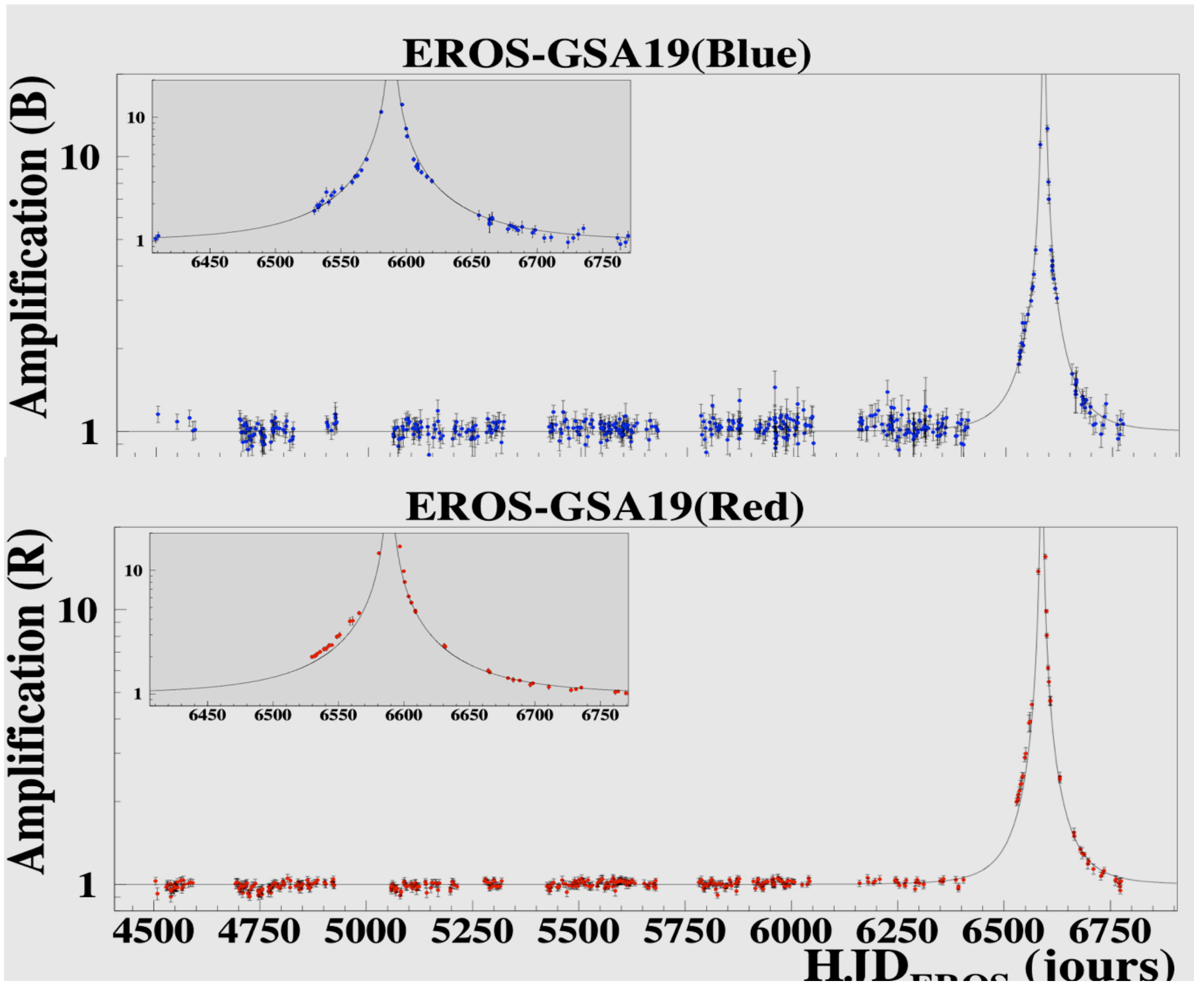
27 candidates / 22 with u_0<0.7



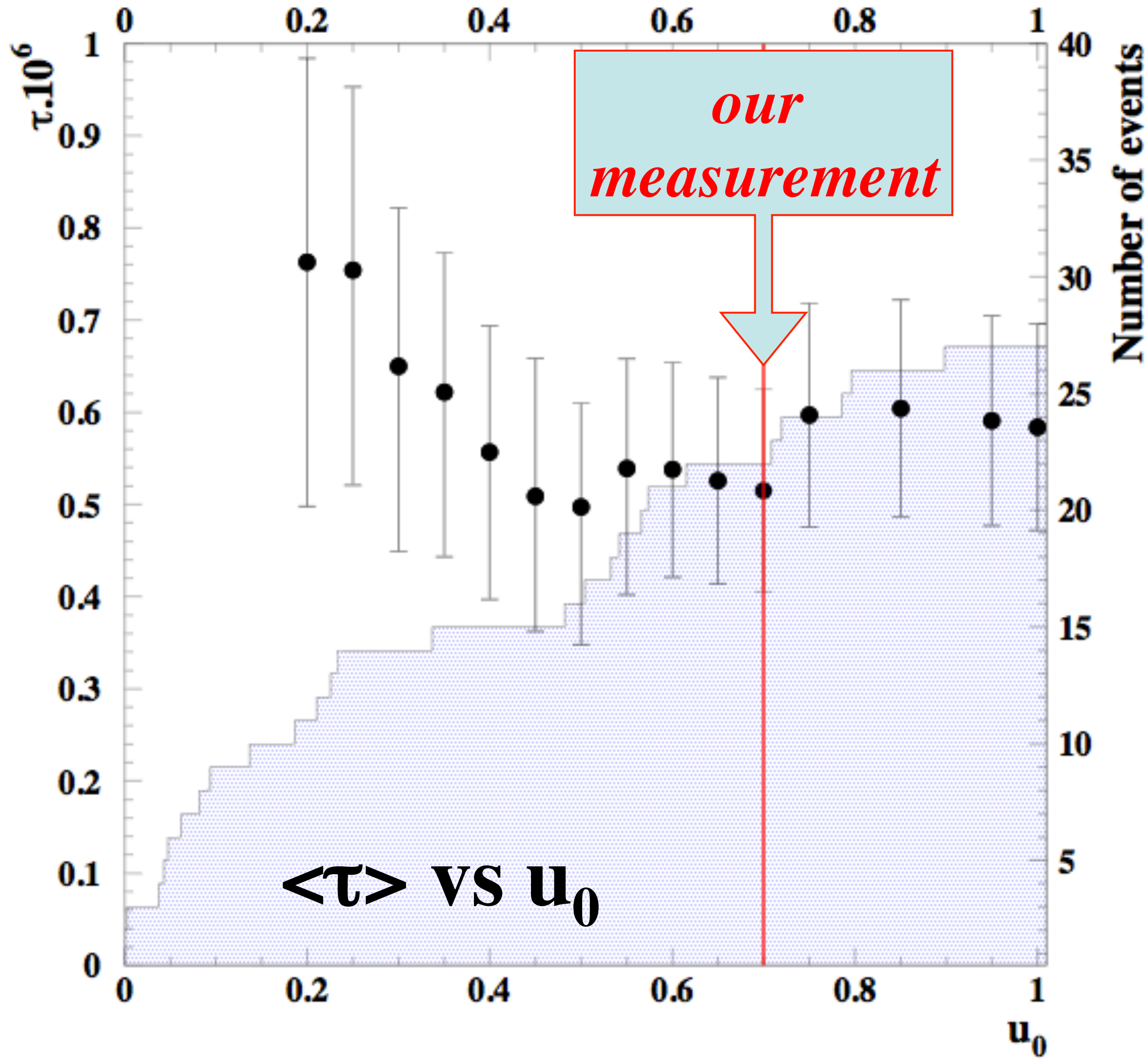
- 2 candidates with parallax
- 4 with blending
- 2 Xallarap (**A&A 351, 87-96, 1999**)



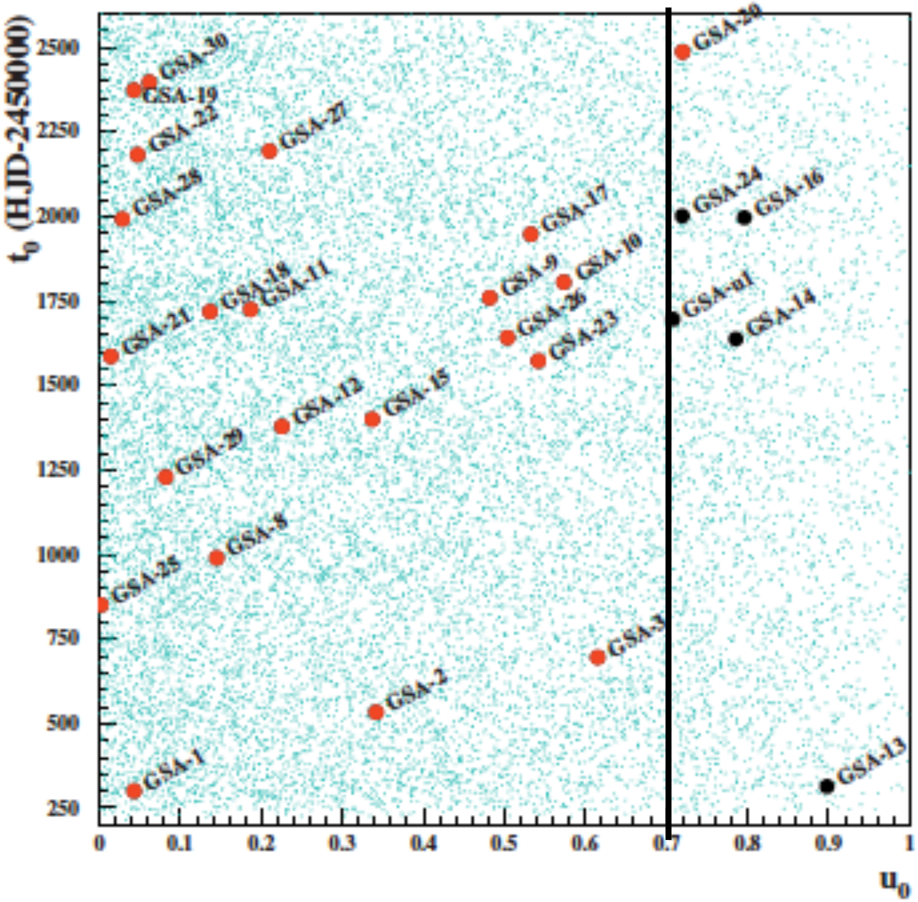
Xallarap event
with extremely red source

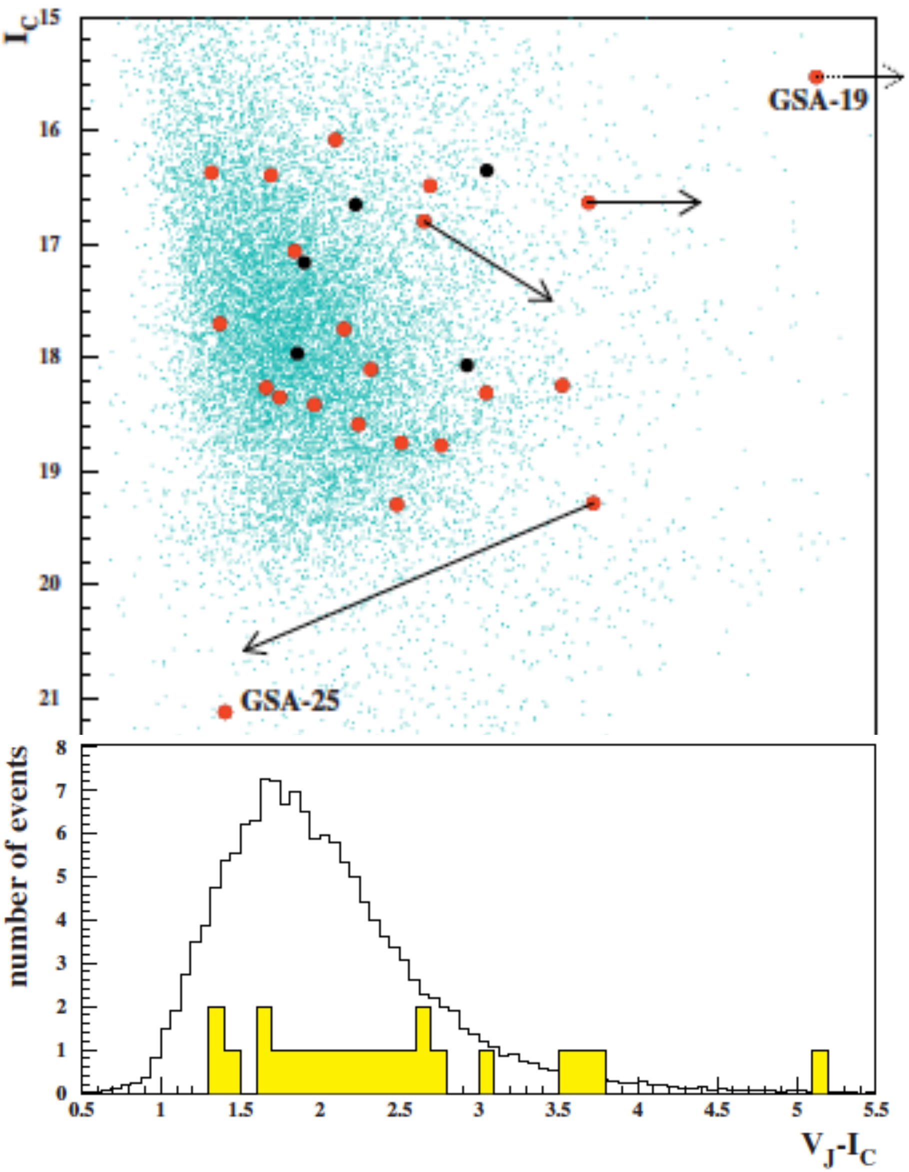


Stability of $<\tau>_{directions}$ measurement



Statistical representativity of the events



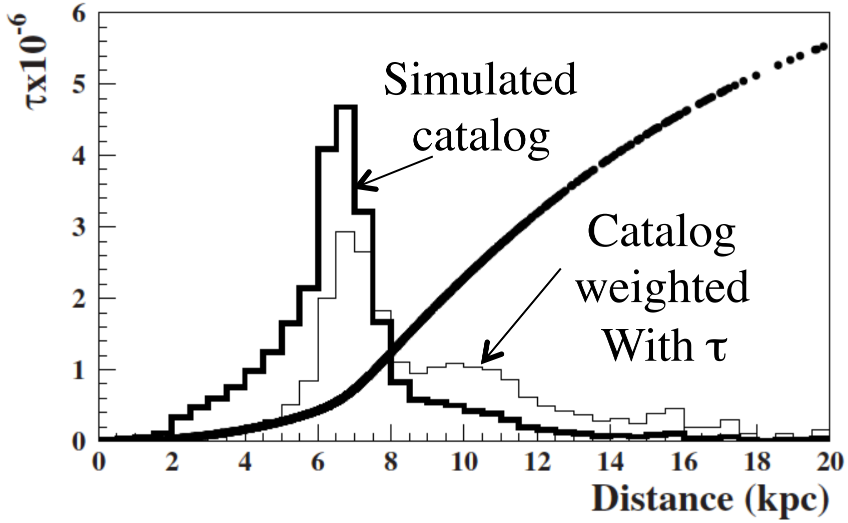


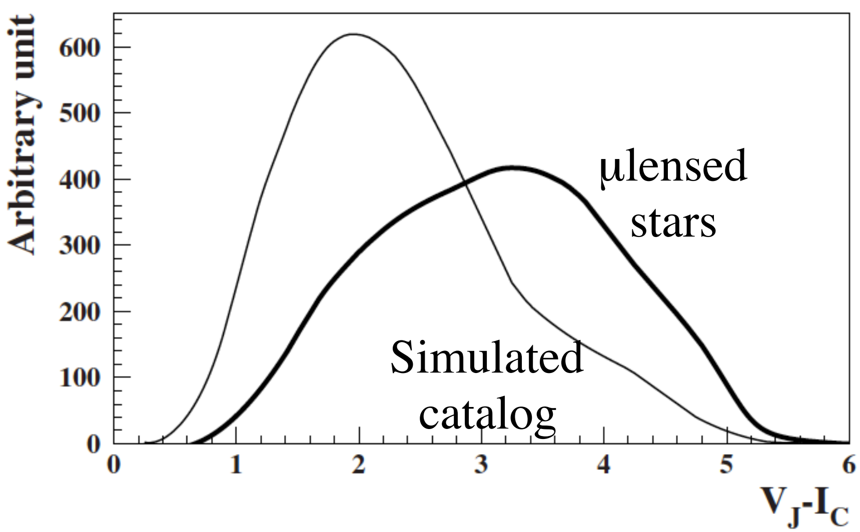
Microlensed stars are redder

An effect of the non-uniformity of source distance

✓ τ increases with distance
✓ I increases with distance
BUT faint stars do not enter the catalog => <I> is ~ stable
✓ Absorption increases with distance => (V-I) increases

Microlensed stars are redder





Check hypothesis with a synthetised « EROS-like » catalog:

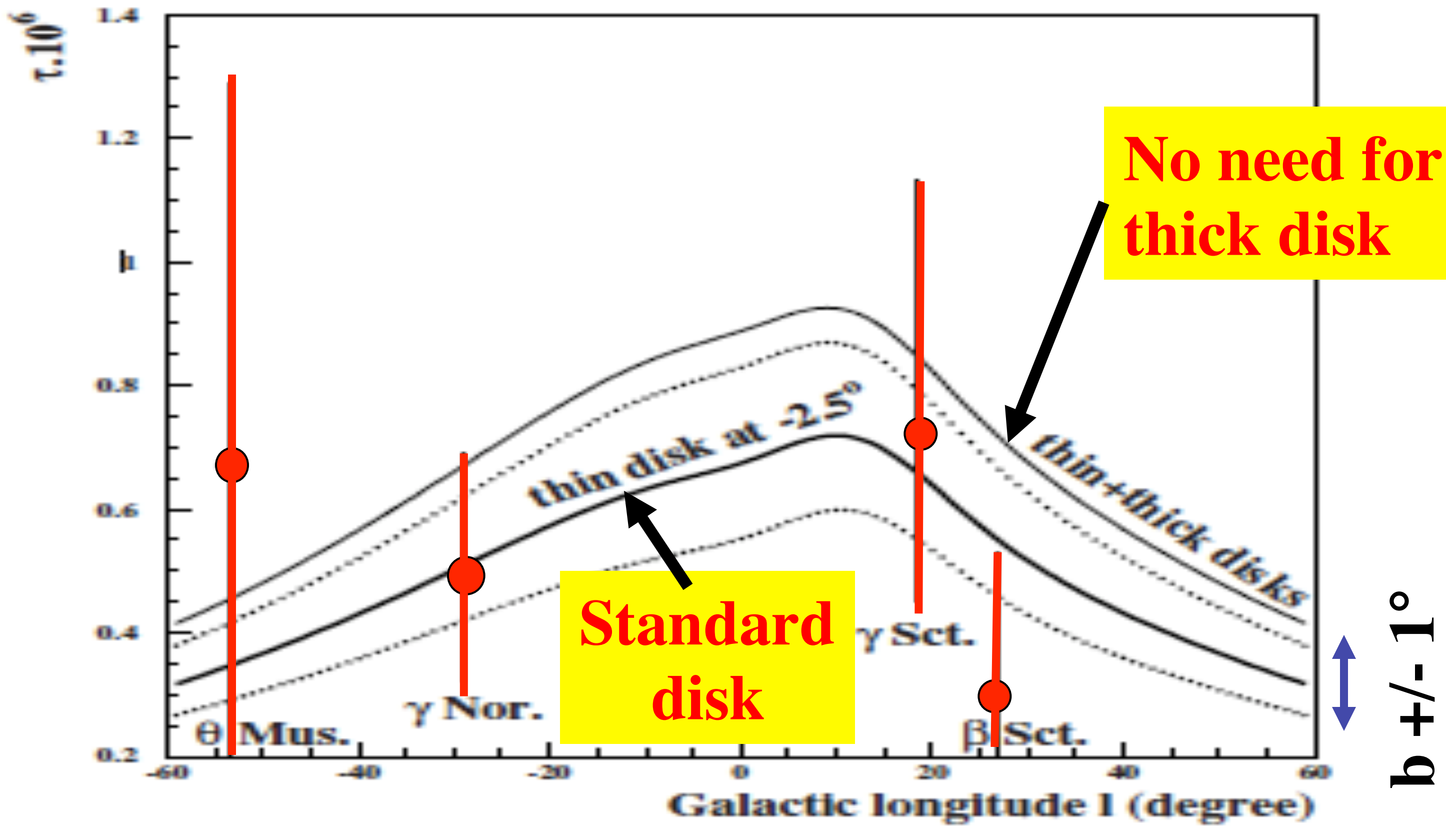
- Hipparcos debiased local HR diagram

- density + absorption model

- EROS acceptance

Interpretation of the optical depths

[A&A 500, 1027 (2009)]



τ vs galactic longitude @7kpc and b=-2.5°