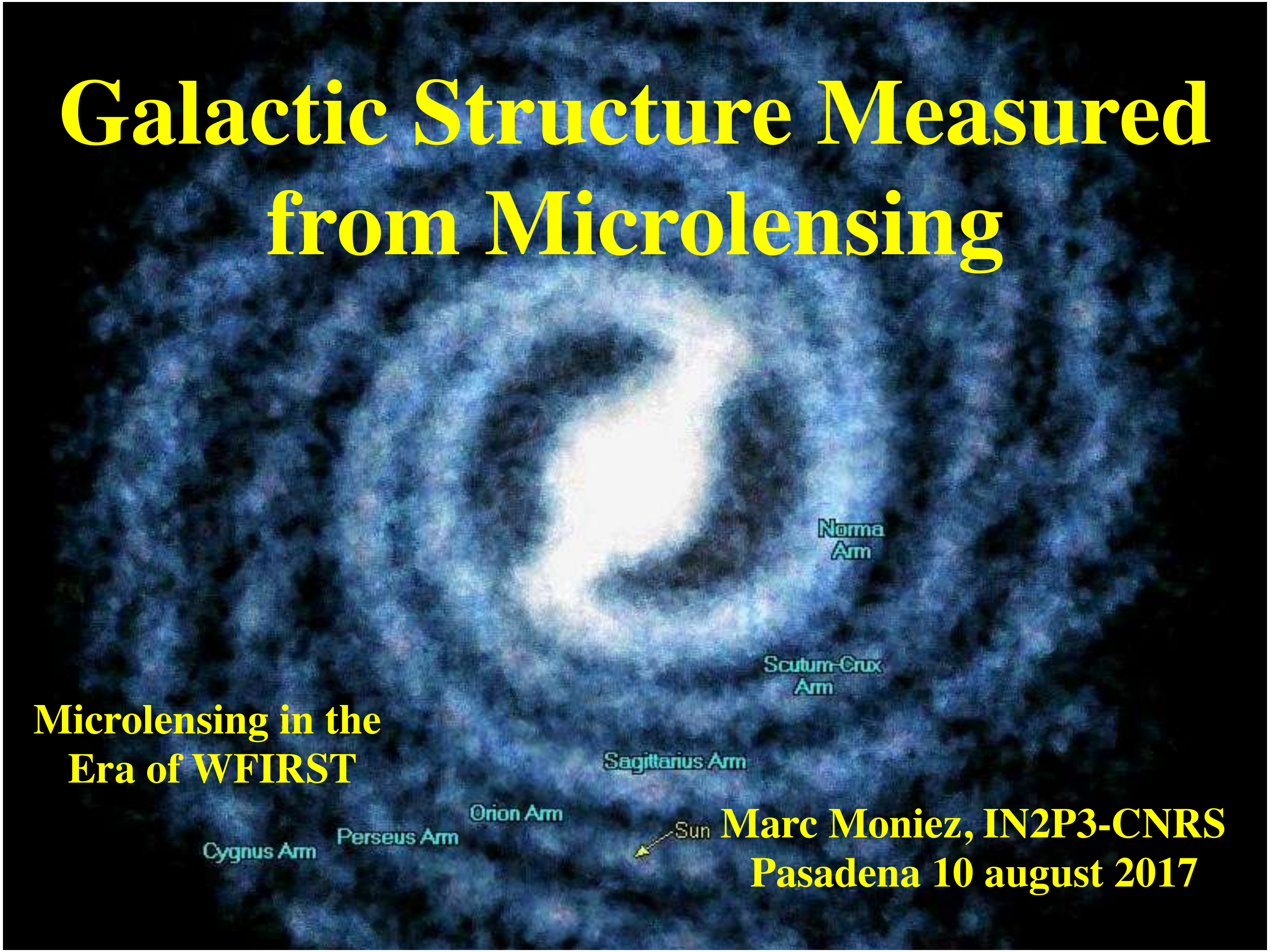
Galactic Structure Measured from Microlensing



Microlensing in the Era of WFIRST

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Pasadena 10 august 2017

Topics

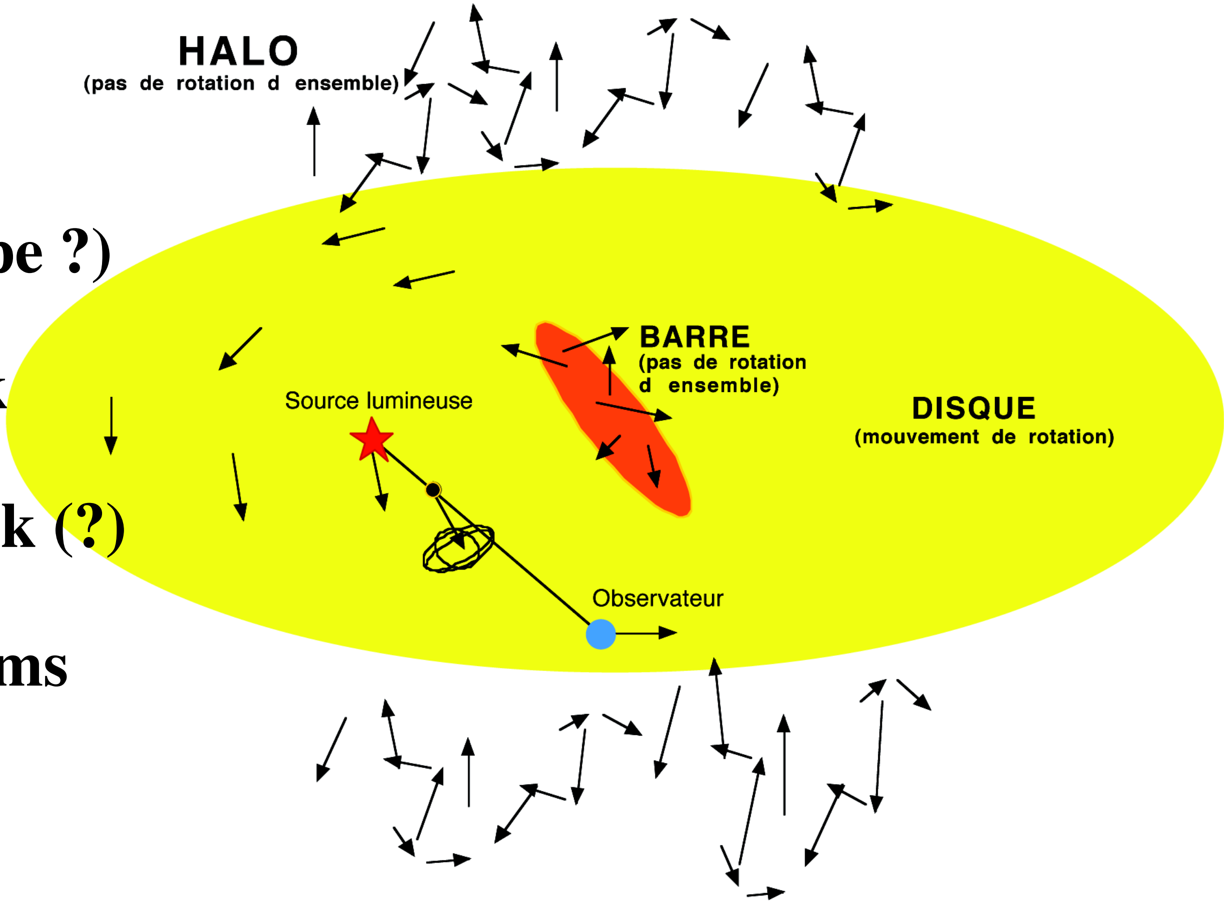
- What microlensing can specifically tell us about the Milky Way structures ?
- The current status for each structure
- What is difficult?
- What could be the next steps?

The microlensing actors belong to several structures

- Density, lens IMF, lens+source kinematics

Different
Distances/Masses/Velocities

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



The microlensing observables

- **Simple events** (point-source, point-lens, constant V_T)
  - Event by event Einstein radius crossing time t_E
  - ***Statistical information from a series of events:***
    - optical depth $\boldsymbol{\tau}$ and t_E distribution
    -> Constraints on total (*visible* + *hidden*) mass
    -> Constraints on lens IMF
    -> Constraints on relative obs/lens/source kinematics
- **Non-standard events**
  - Parallax, Xallarap, extended source, multiple lens/ sources… -> extra-information on distance, mass, velocity
  - Not considered here for statistical studies

Statistical information from a set of events

- Optical depth τ :

probability for a star to be behind an Einstein disk

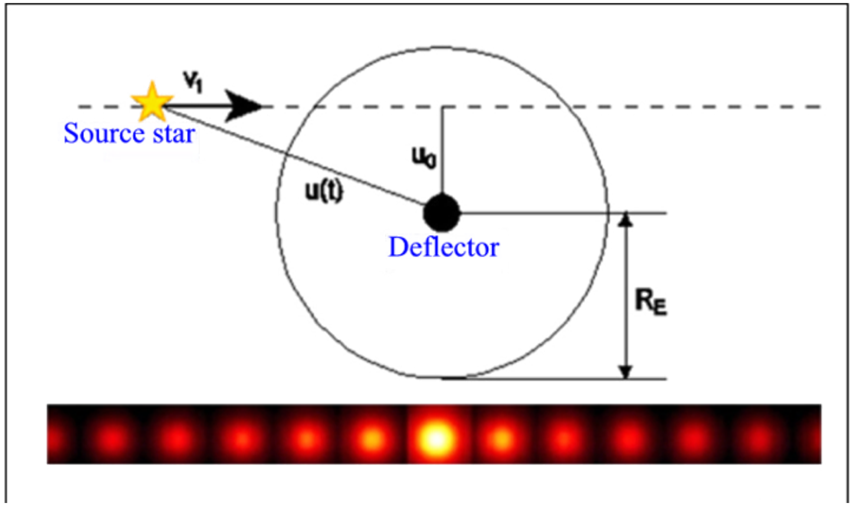
Disk surface α R_E^2 α M_{lens}

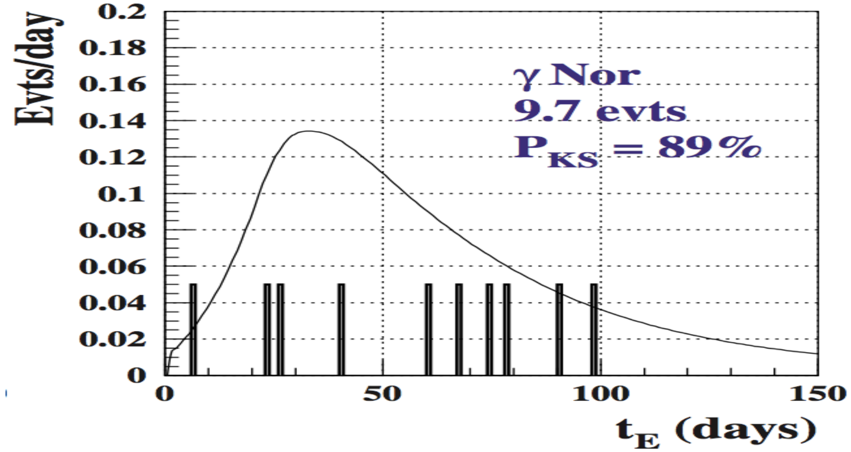
$\Rightarrow \tau \ \alpha \sum M_{lens}$

Does not depend on the mass distribution

- Einstein ring crossing time $t_E = R_E/V_t$ distribution

Use first moments (mean, sigma) or KS-type tests to compare with models





__Note__: u_0 and t_0 do not provide physical information, but should have a flat prior distribution -> use this to __check signal quality__

Basic formulae for optical depth

τ to a *given distance* (LMC or SMC) = fraction of solid angle occupied by Einstein rings up to that distance

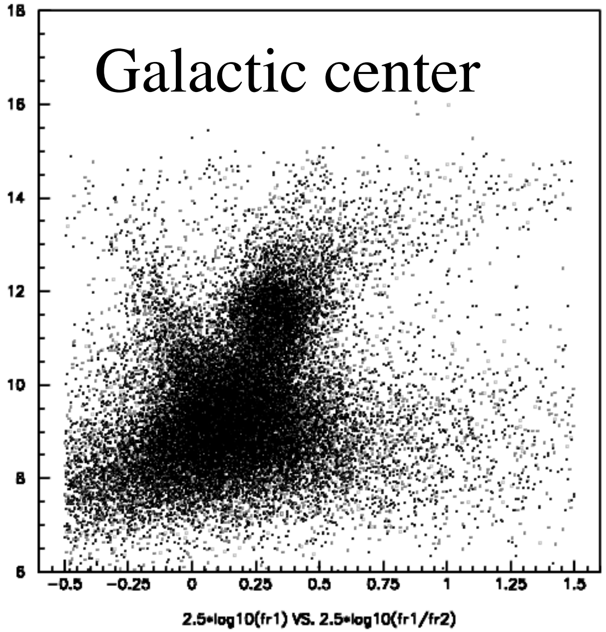
$$\tau(D_S) = \int_0^{D_S} \int_{M=0}^{\infty} \pi\theta_E^2 \times \frac{\rho(D_L)D_L^2}{M} \frac{\mathrm{d}n_L(D_L, M)}{\mathrm{d}M} \mathrm{d}M \mathrm{d}D_L$$

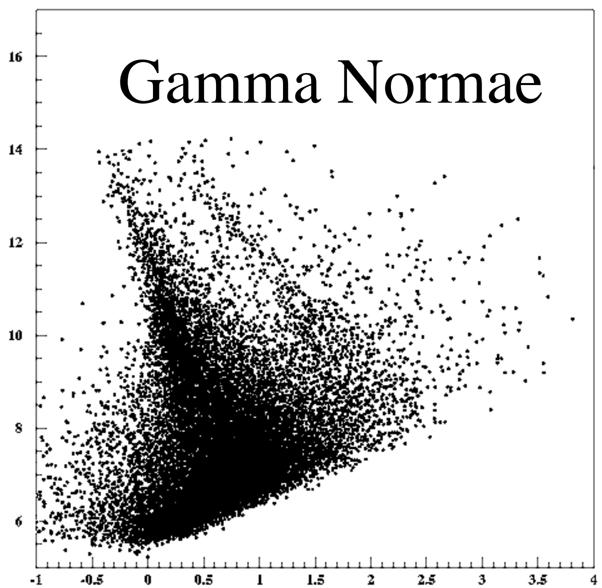
$$\tau(D_S) = \frac{4\pi G D_S^2}{c^2} \int_0^1 x(1-x)\rho(x)\mathrm{d}x$$

Where $x = D_L/D_S$

The source distances can be widely distributed!

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





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τ to a *given source population* $<\tau> = \frac{\int_0^{\infty} \frac{\mathrm{d}n_S(D_S)}{\mathrm{d}D_S} \tau(D_S) D_S^2 \, \mathrm{d}D_S}{\int_0^{\infty} \frac{\mathrm{d}n_S(D_S)}{\mathrm{d}D_S} D_S^2 \, \mathrm{d}D_S}$

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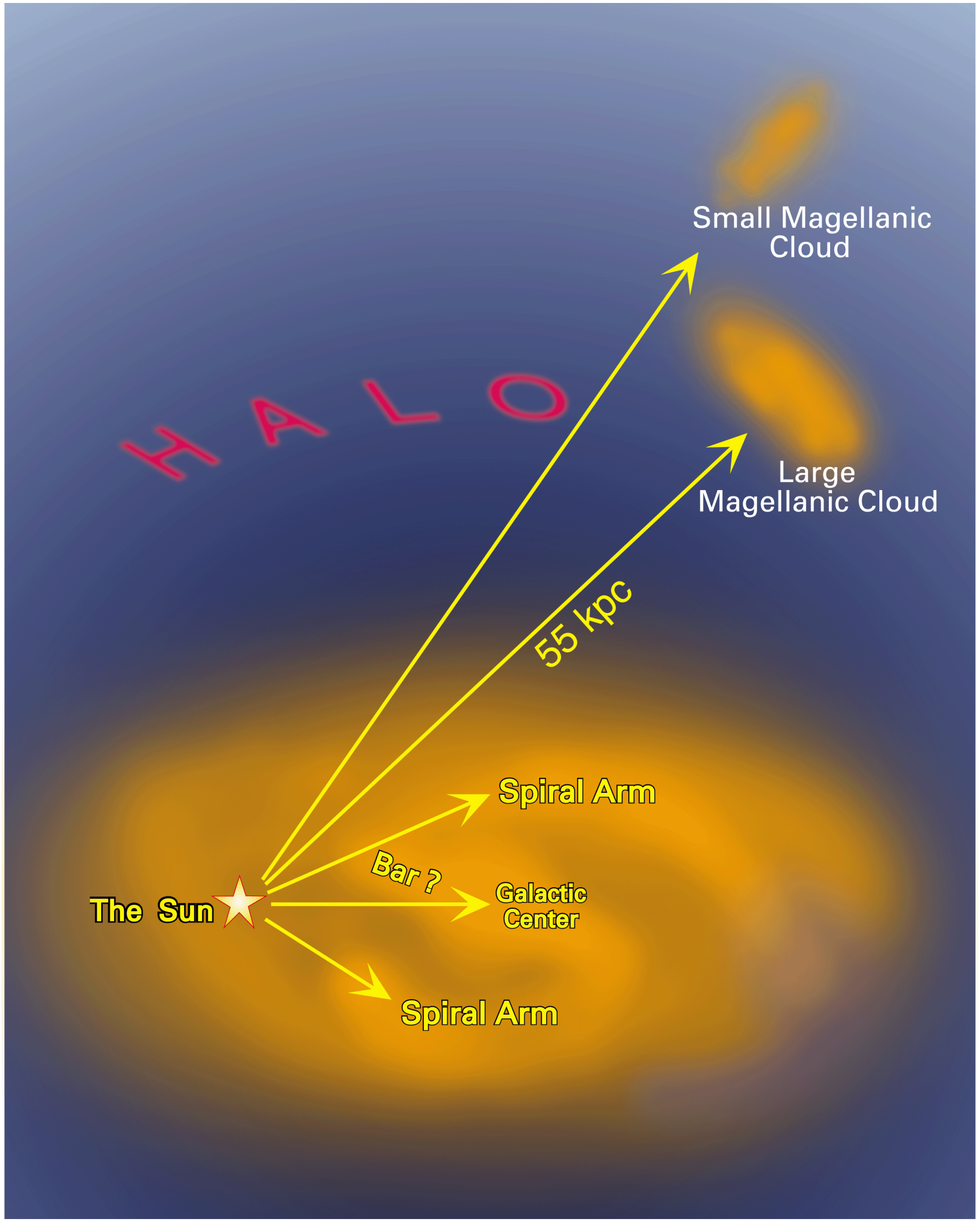
τ estimated from observations = fraction of time with source magnified >1.34 (corresponds to source inside Einstein ring)

$$\tau = \frac{1}{N_{obs}\Delta T_{obs}} \frac{\pi}{2} \sum_{events} \frac{t_E}{\epsilon(t_E)}$$



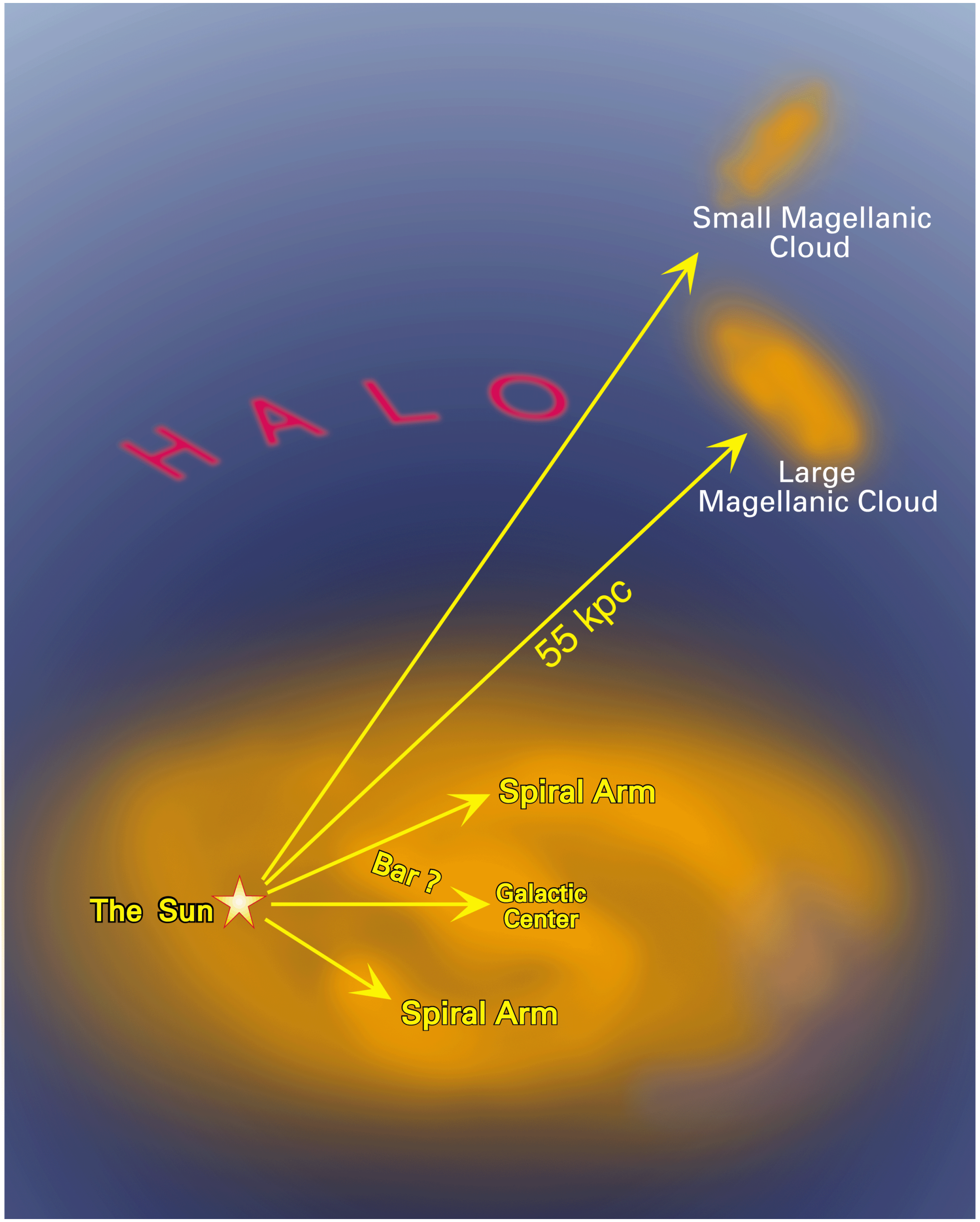
Main targets

- **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 ($\tau \sim 5.10^{-7}$)**
- **M31**

Census of the measured/measurable directions to probe milky-way structure

- **Galactic center**: all surveys -> bright past & future
- **Galactic arms**
  - 4 (low extinction) directions in (V, I): EROS
    - For visible passbands -> LSST is a probable future
  - **Enormous** potential in infra-red (free from extinction): VISTA
    - Future -> WFIRST
- **Galactic halo**
  - LMC/SMC: EROS/MACHO/OGLE/MOA

    -> 27 years of monitoring !
  - M31: AGAPE/MEGA. Difficulty of the pixel-lensing technique; combine Milky-way + M31 lenses
  - Globular clusters (M22)



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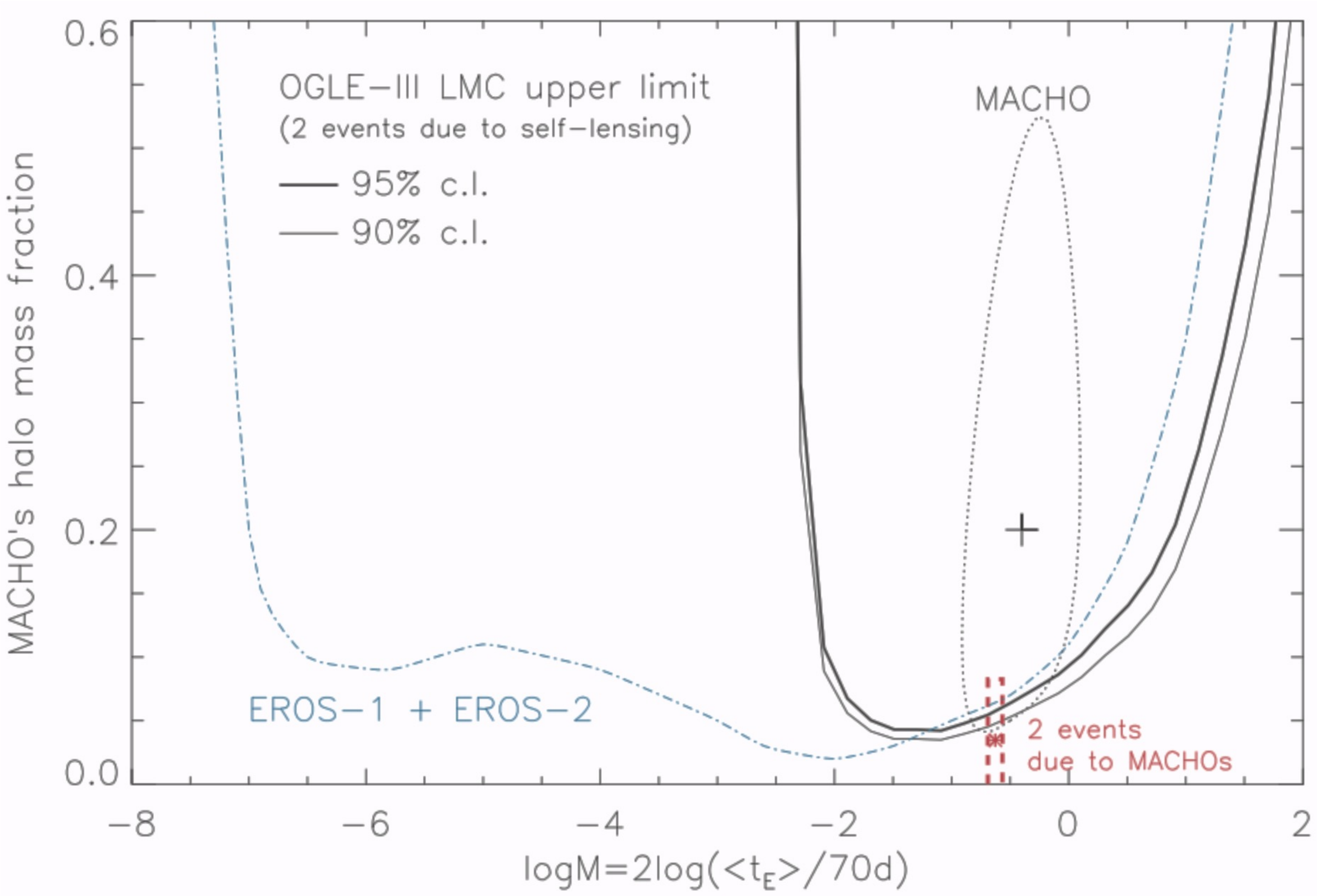
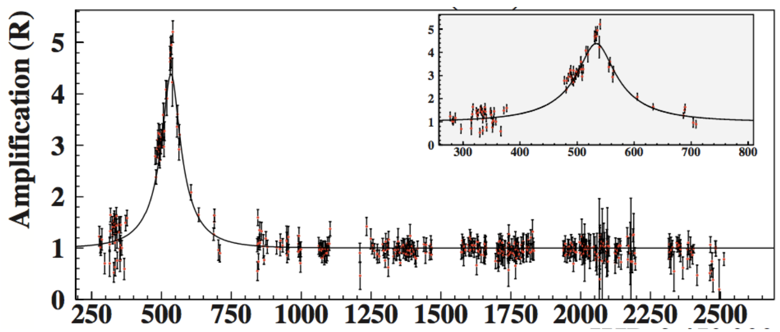
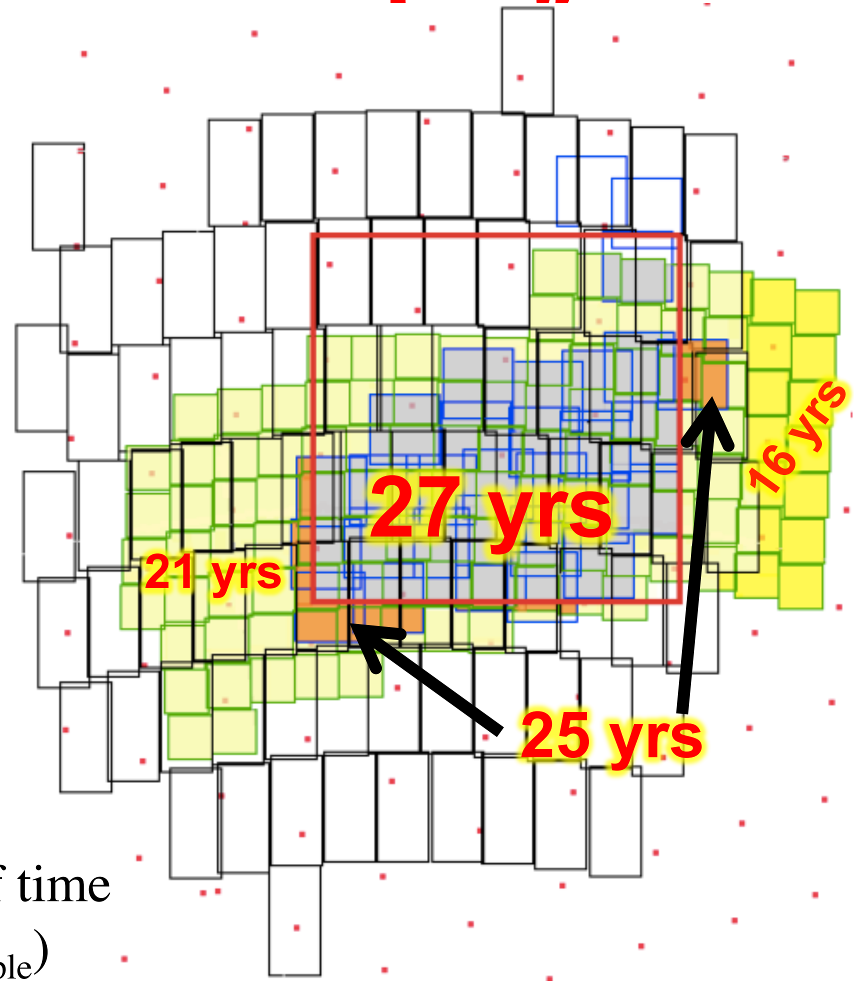
The Milky way halo: LMC surveys



Search for very long events with joined analysis: MEMO project

Moa**E**ros**M**ach**O**gle combined light-curves should provide a much **better efficiency at large t_E**





produced by A. Mirhosseini

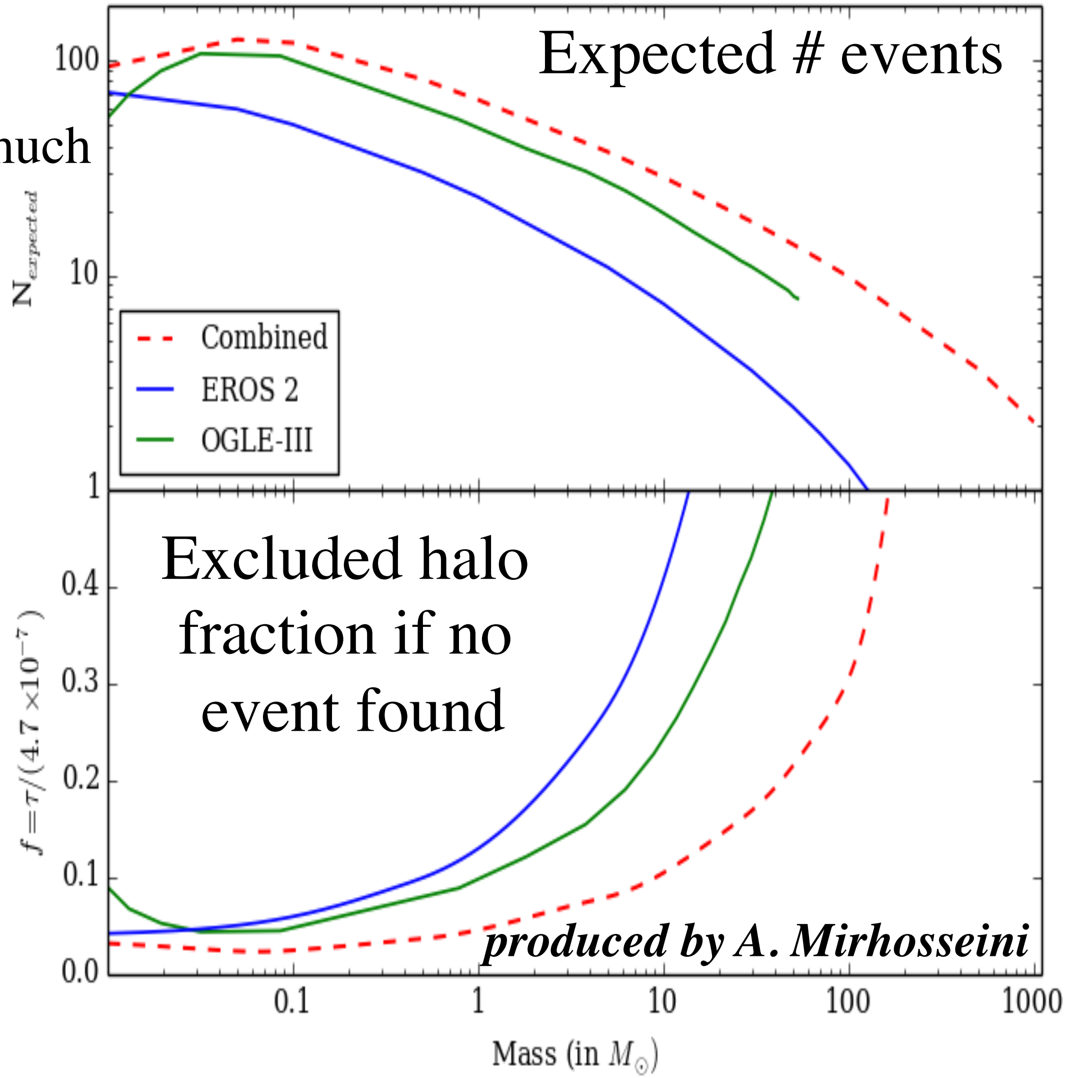
Hypothesis to extrapolate efficiency

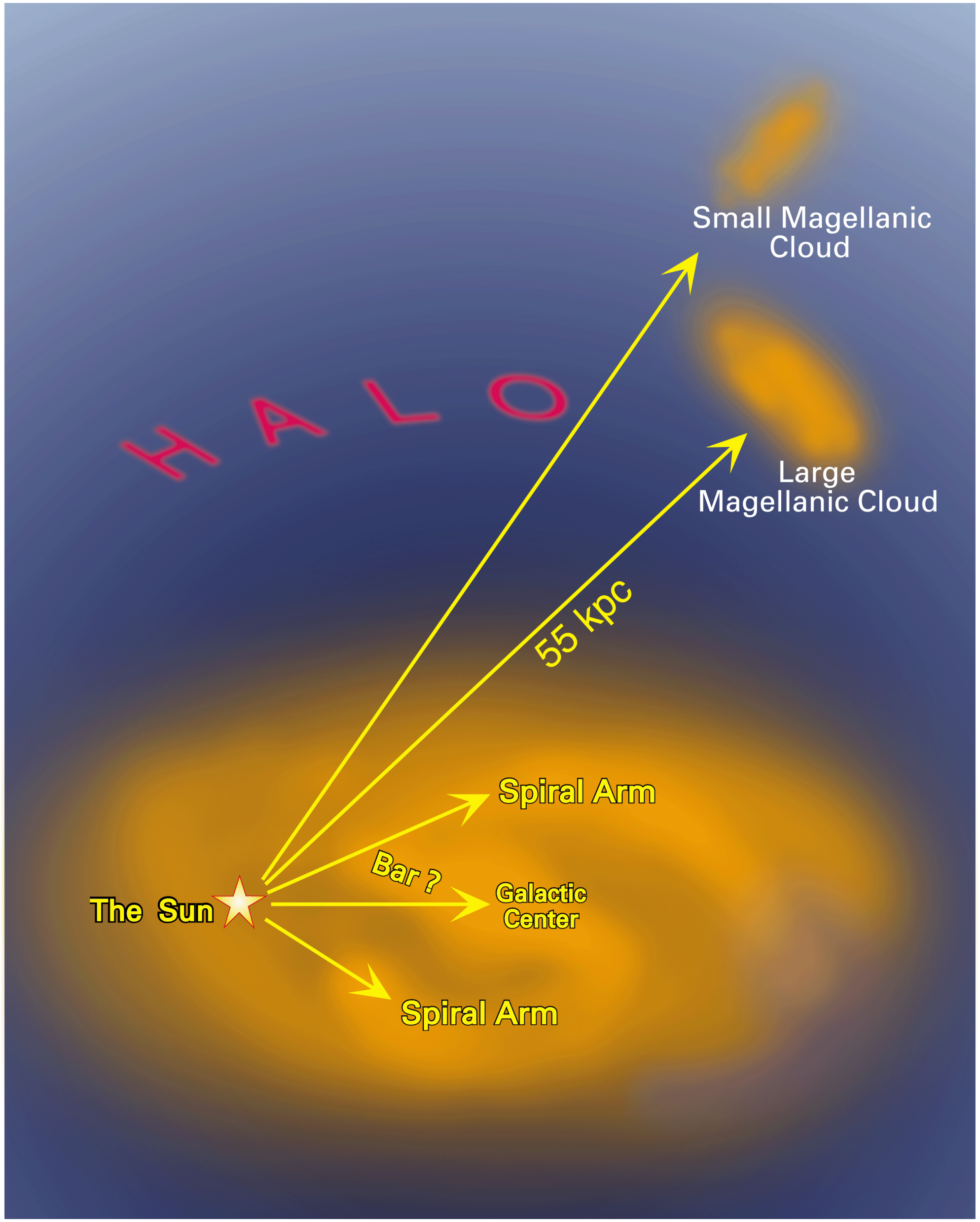
- Efficiency invariant with dilatation of time
  -> $\varepsilon(\alpha t_E, \alpha \Delta t, \alpha t_{sample}) = \varepsilon(t_E, \Delta t, t_{sample})$
- Real sampling is better than αt_{sample}

Expected combined exclusion limit, assuming joined analysis

Moa**E**ros**M**ach**O**gle combined light-curves should provide a much **better efficiency at large t_E**

- **Interesting potential** to merge the existing databases (27 yrs!)
- Motivation: **gravitational wave signal !**





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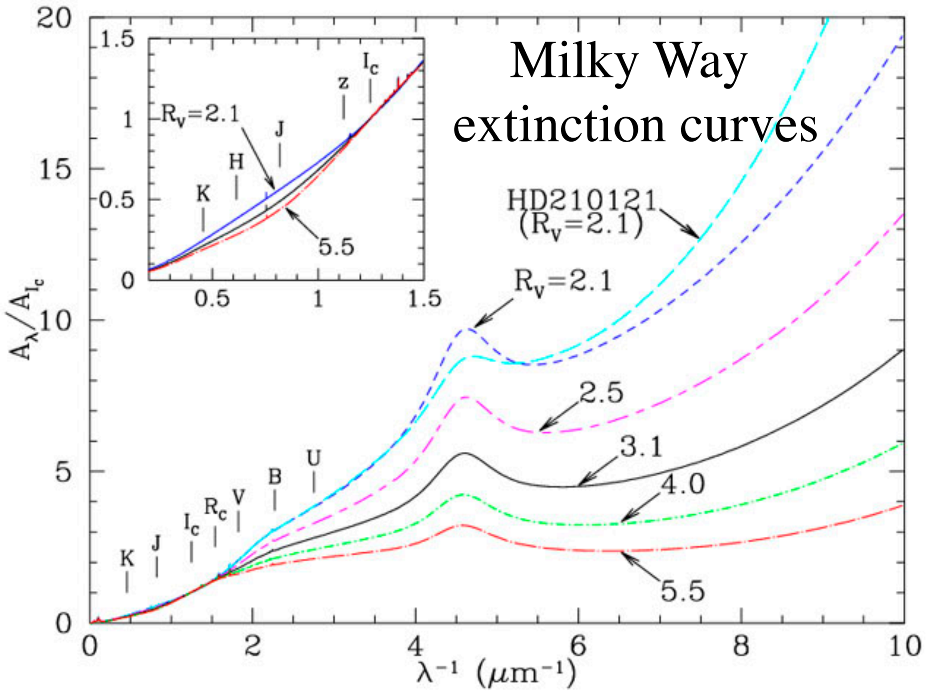
What is critical for the Milky-Way plane study with microlensing?

- **Observational**
  - Extinction map -> impacts D_{os} distribution of catalogued sources
    - Fractal spatial structure…
    - Relation A_X vs A_K depends on kind and size of dust -> fluctuating with position
  - WFIRST potential (less sensitive to extinction)

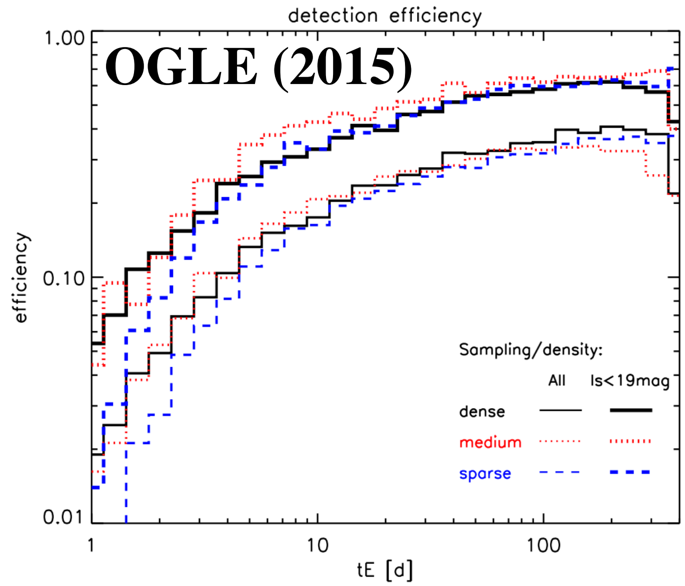


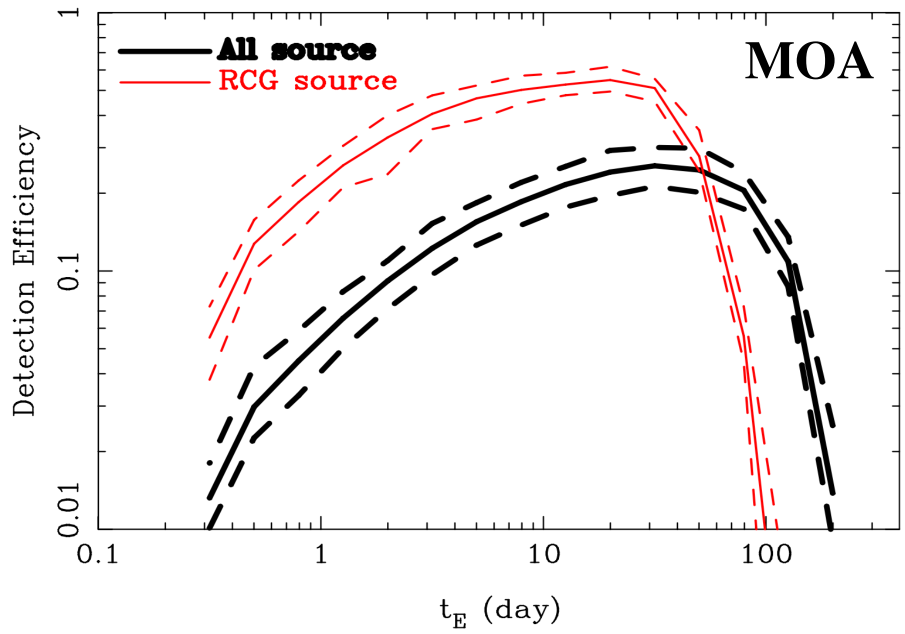
- **Degeneracy (R_E/V_T): Lens Initial Mass Function / kinematics**
- **Analysis**
  - Microlensing **detection efficiency**

Efficiency

- Averaged on a given source population (RG, all)
- Depends on sampling and environment
- Averaged on u_0, t_0

-> to obtain a Function of t_E only





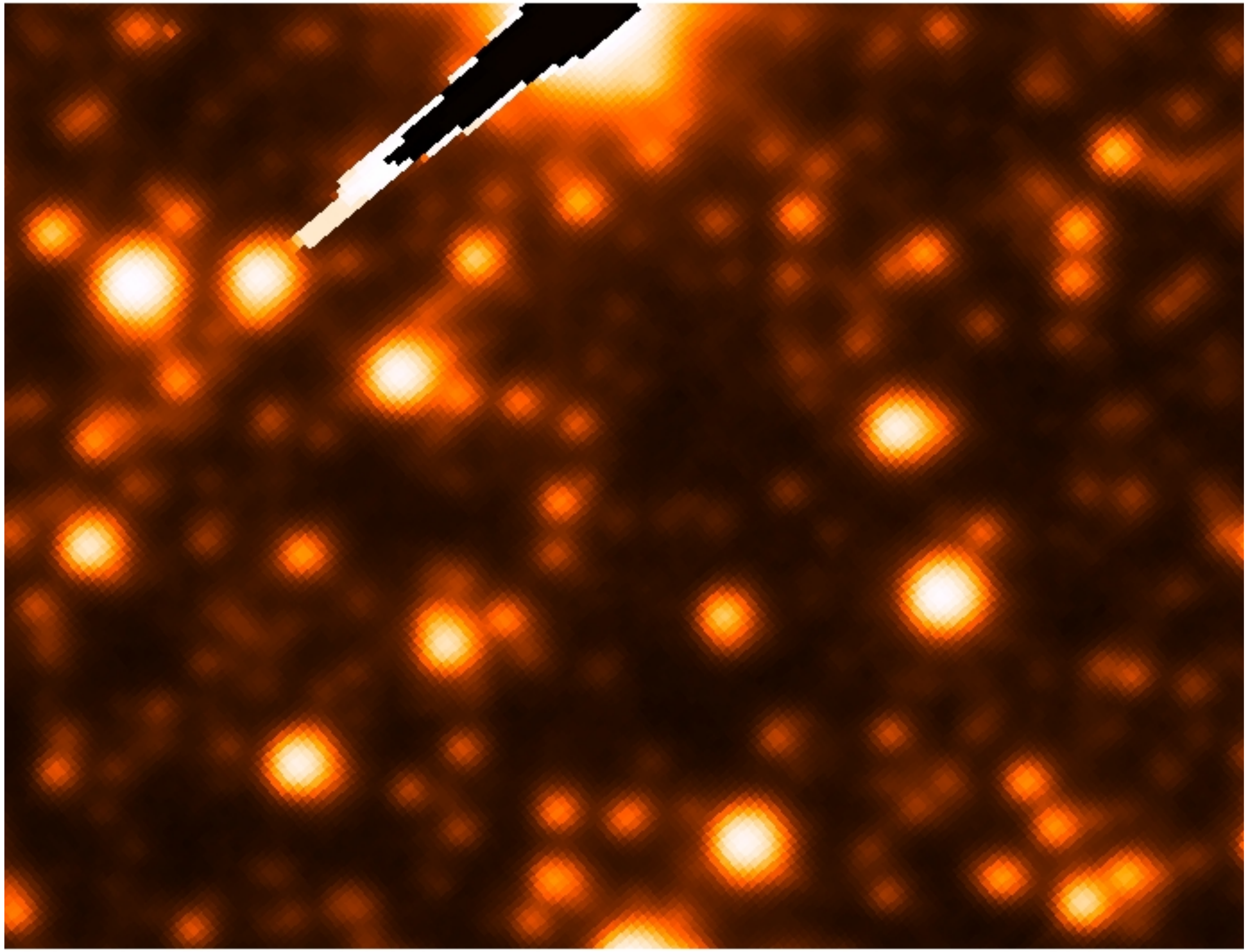
Efficiency estimates

- Mathematically, microlensing detection efficiency is **zero** (infinite range of gravitation)
- It's a matter of definition -> define efficiency as the ratio of detected events to generated events
  - With uniform impact parameter $u_0 < 1$ (typically)
  - With uniform max. mag. time t_0 during the observed period
  - For a given source population (bright, red giants...)
    - Resolved sources or not (Differential Image Analysis)

Efficiency: hard points

- **Blending**
  - Impacts Paczynski curve shape and reconstructed t_E
    - $\varepsilon(t_{E\ rec.})$ differs from $\varepsilon(t_{E\ generated})$
  - Changes the effective # of stars
    - A minor (not catalogued) contributor to an object can emerge with microlensing, apparently increasing ε
    - Images from space telescopes provides true underlying luminosity function and includes spatial correlation between the blend components

EROS vs HST



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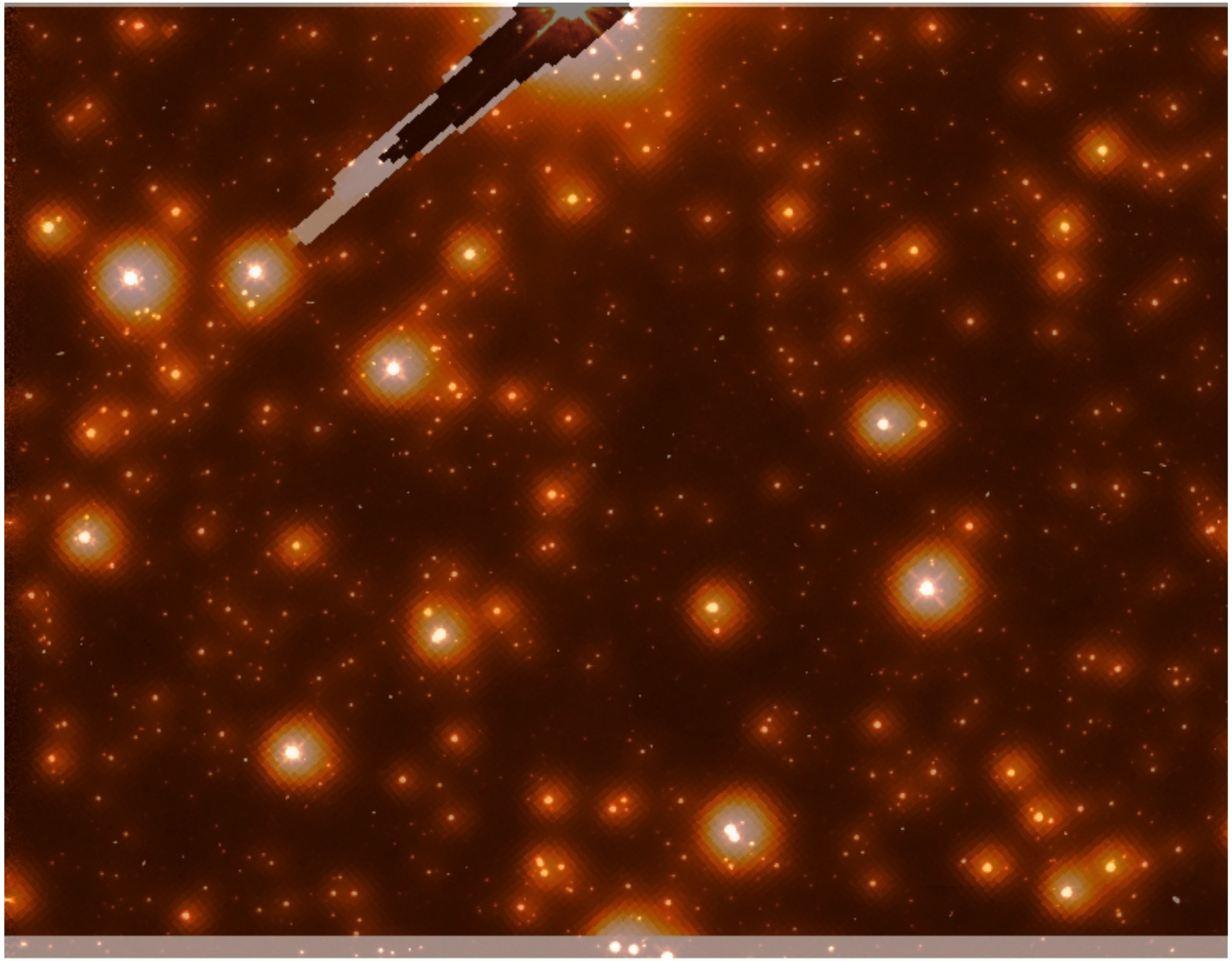

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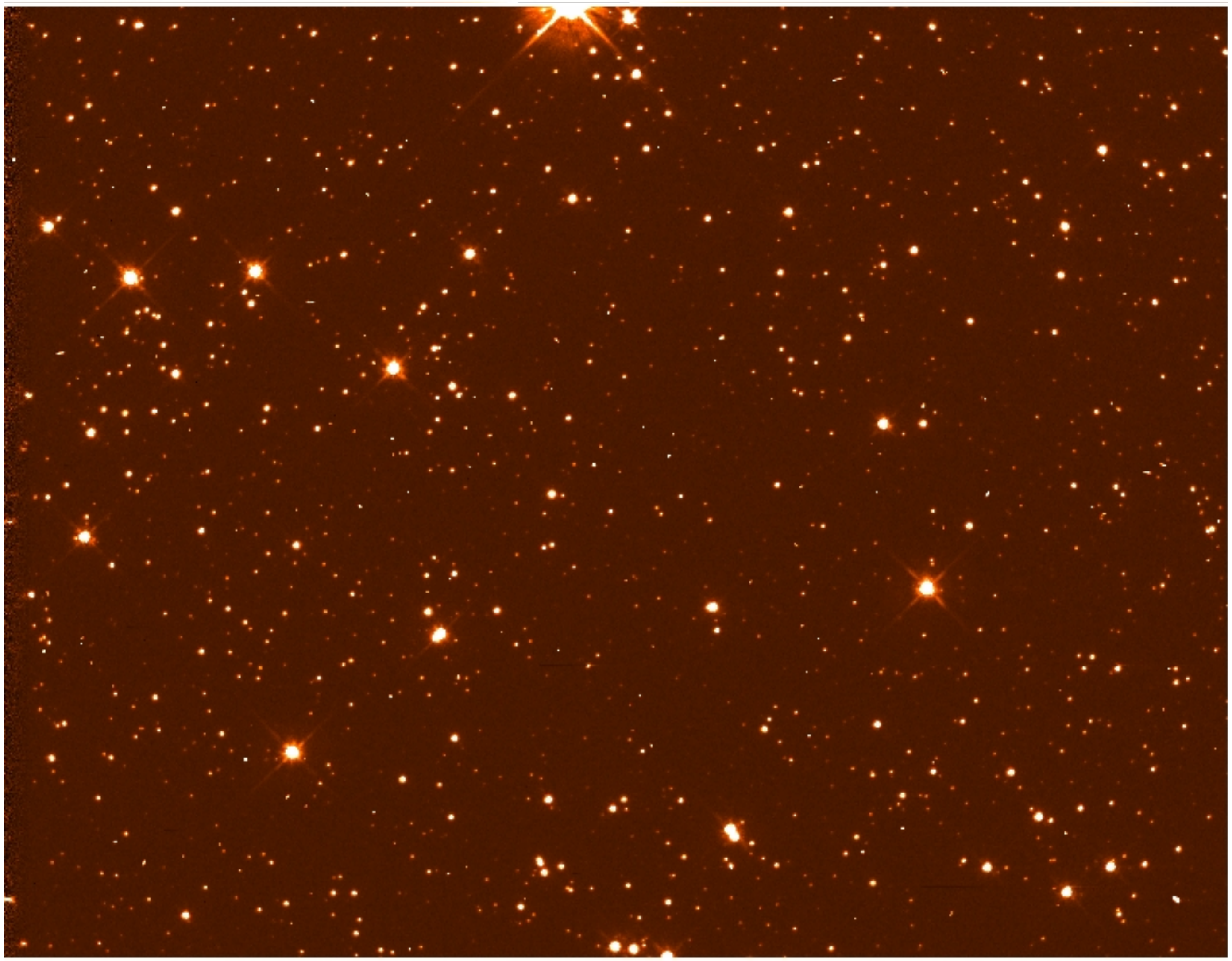

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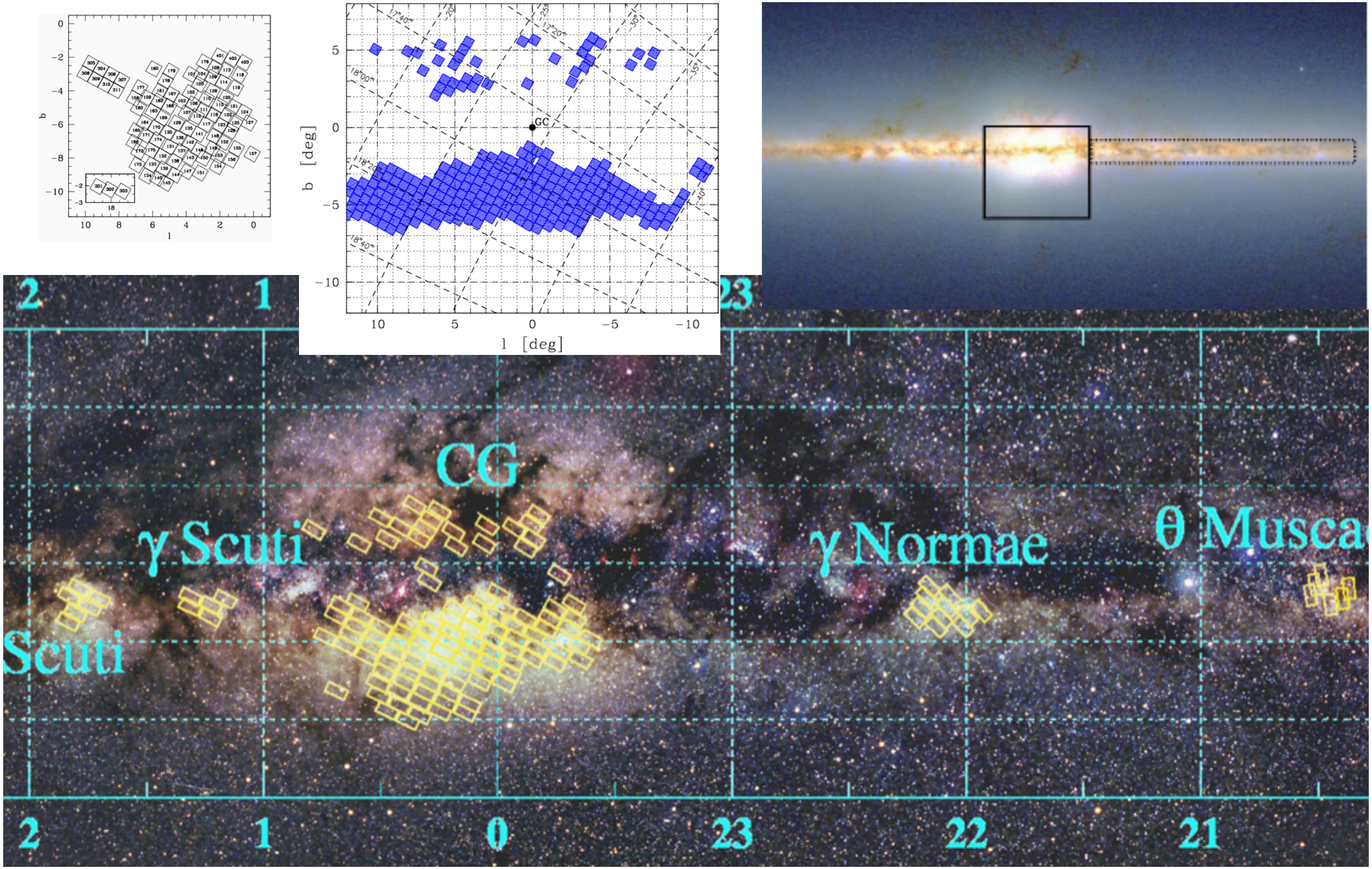
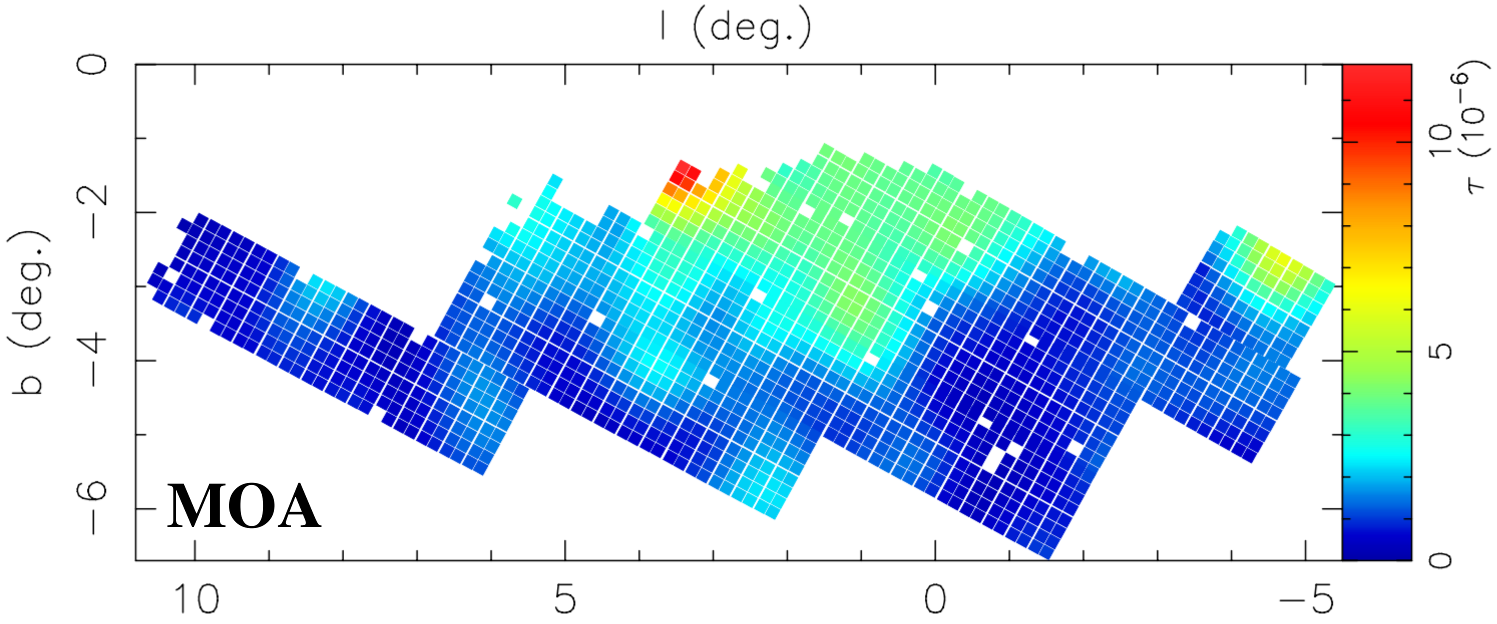
- **Contribution from non-standard events**
  - Generally not generated when estimating efficiency
  - Can be statistically corrected
- **High statistics needed** for reliable use of efficiency (for τ estimates)
  - ε is an *average* with large variations from event to event

$$\tau = \frac{1}{N_{obs}\Delta T_{obs}} \frac{\pi}{2} \sum_{events} \frac{t_E}{\epsilon(t_E)}$$

Monitored fields towards the Galactic plane



Optical depth 2D maps



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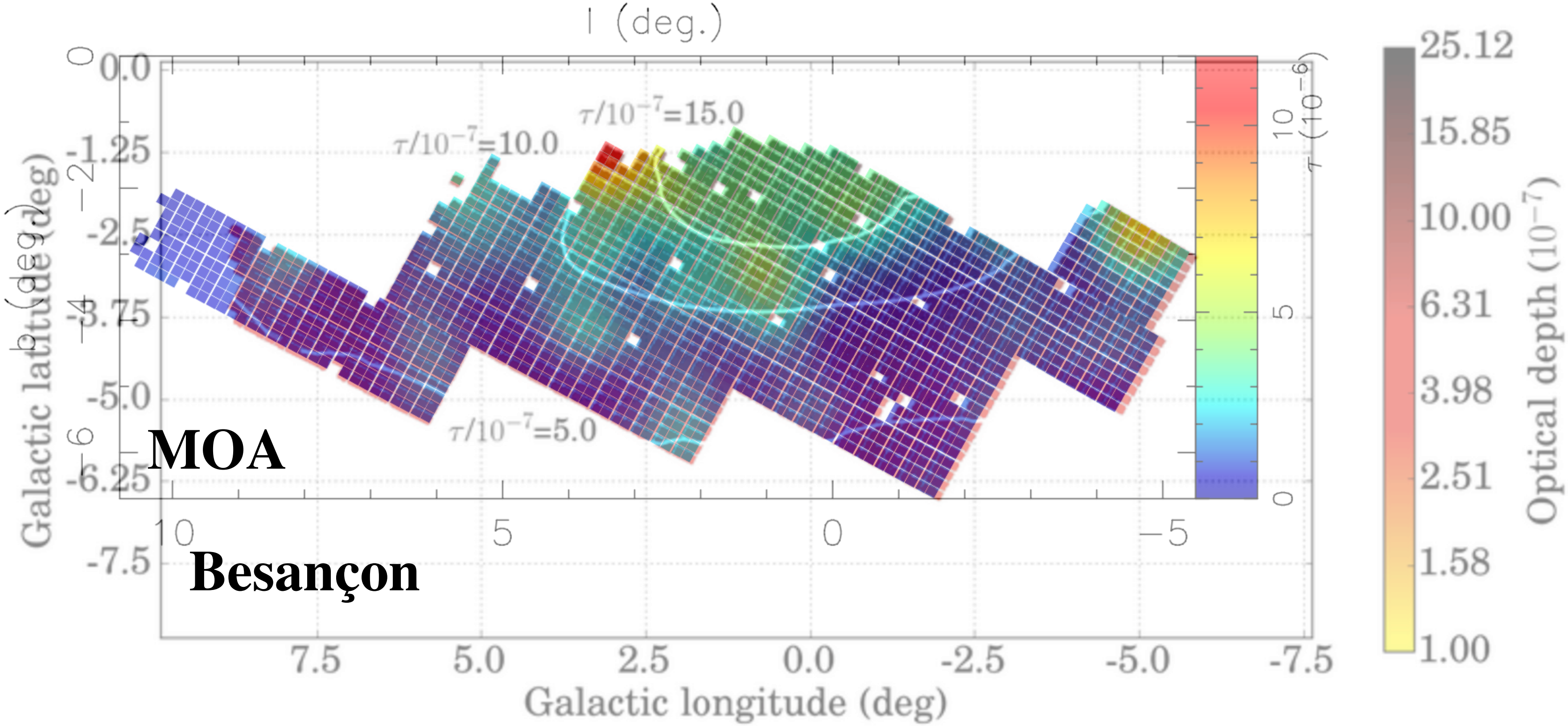

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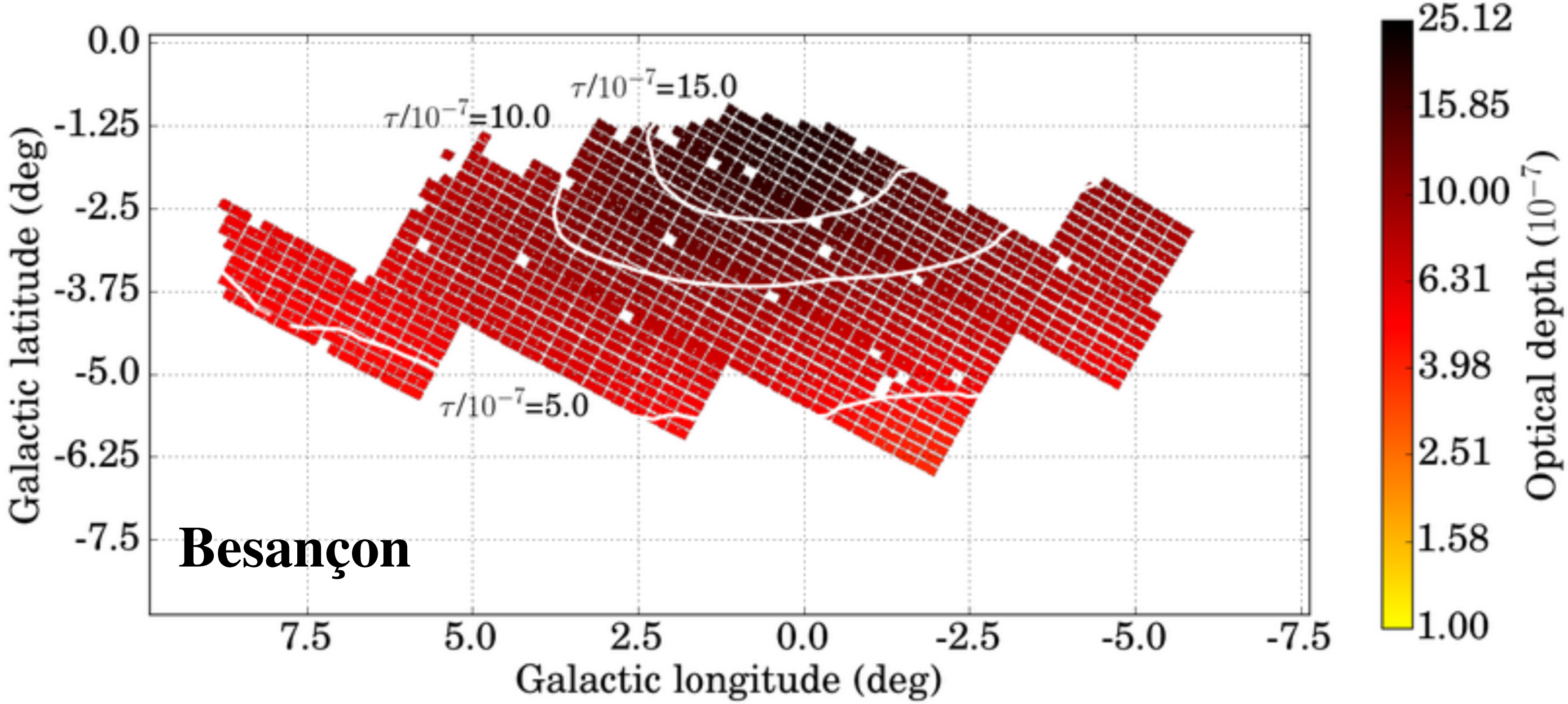
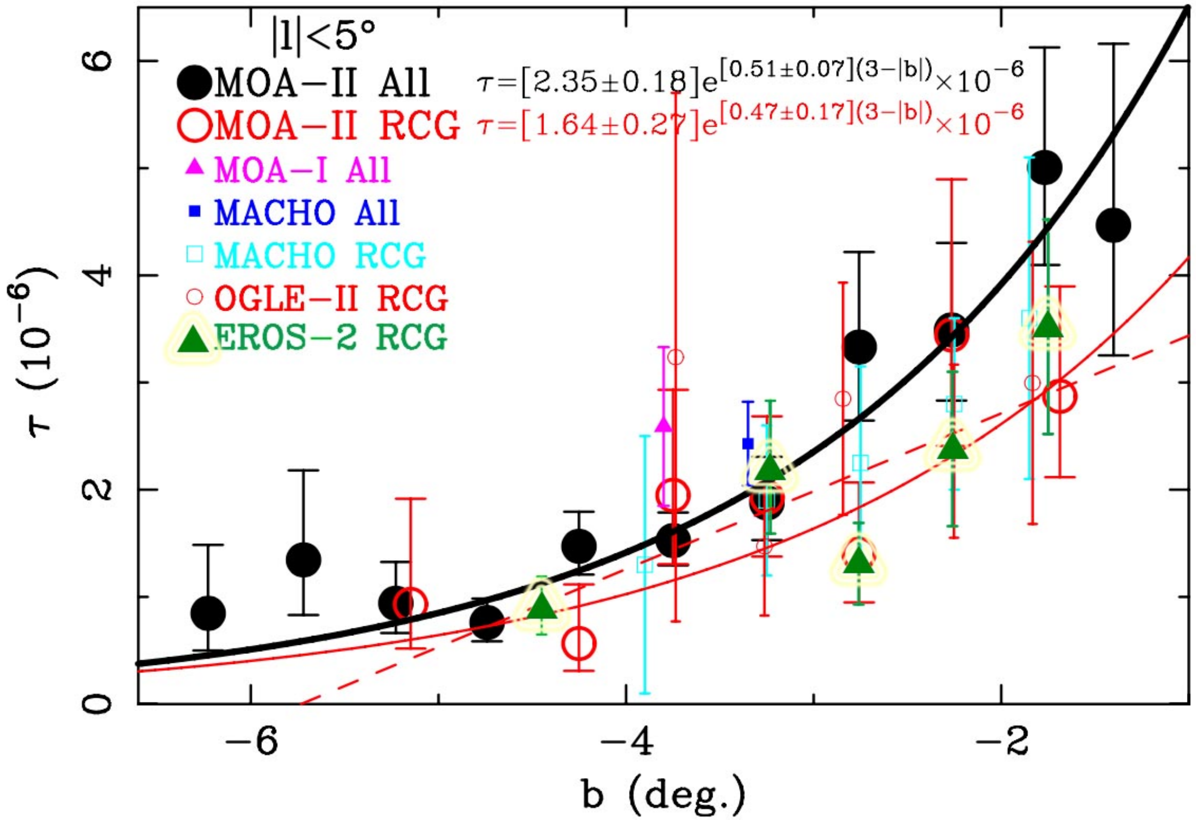
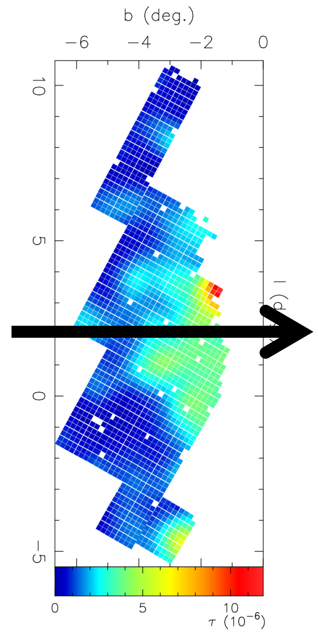


Results toward the Galactic center

[Adapted from Sumi et al. (2013) & Awiphan et al. (2015)]





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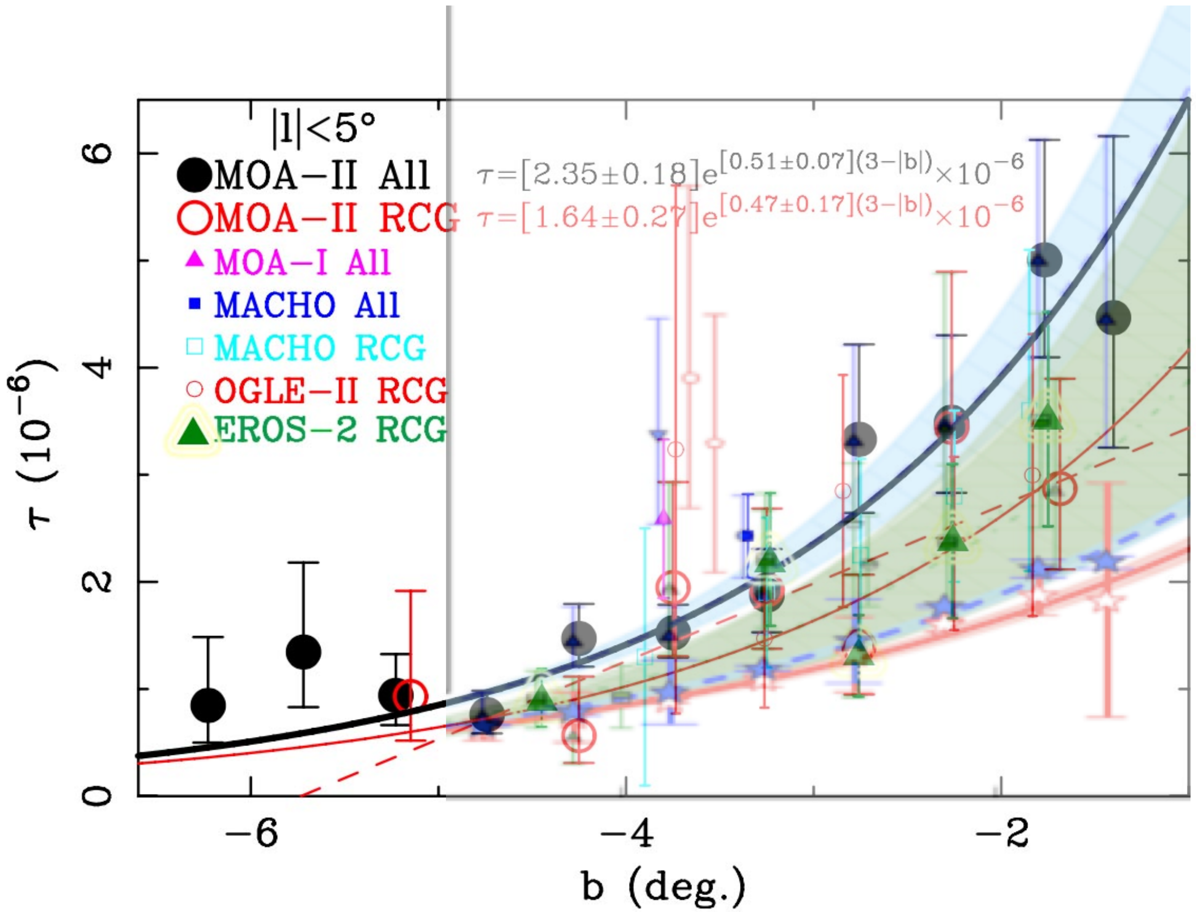

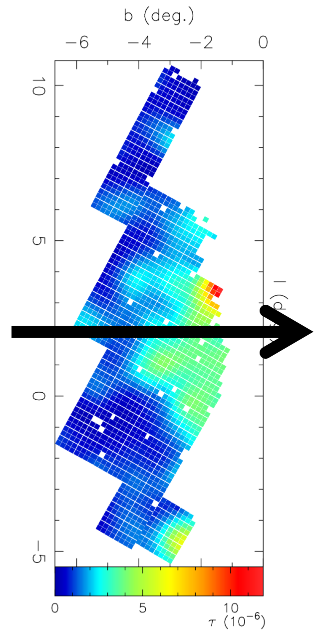

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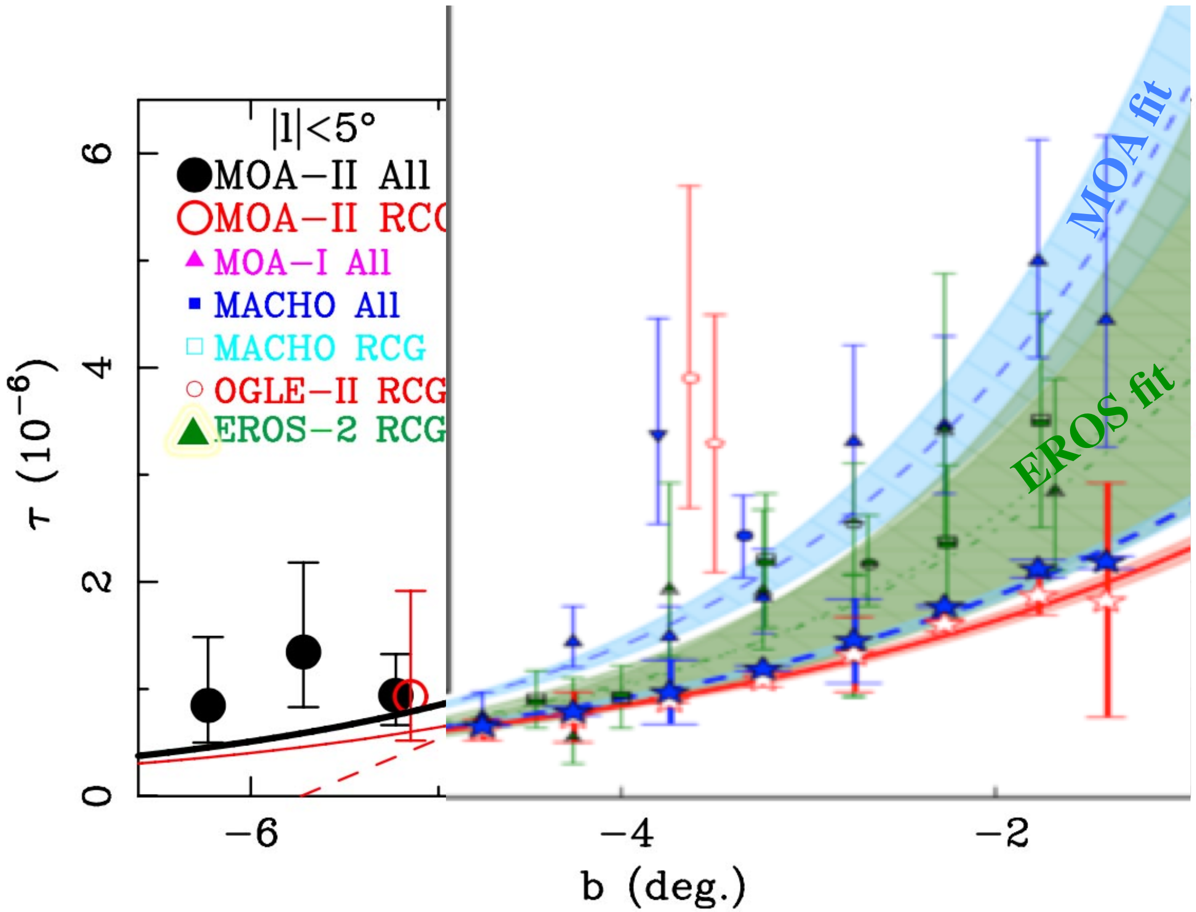


Besançon model

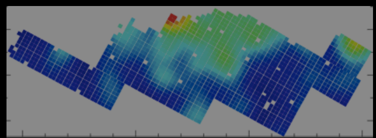
DIA sources

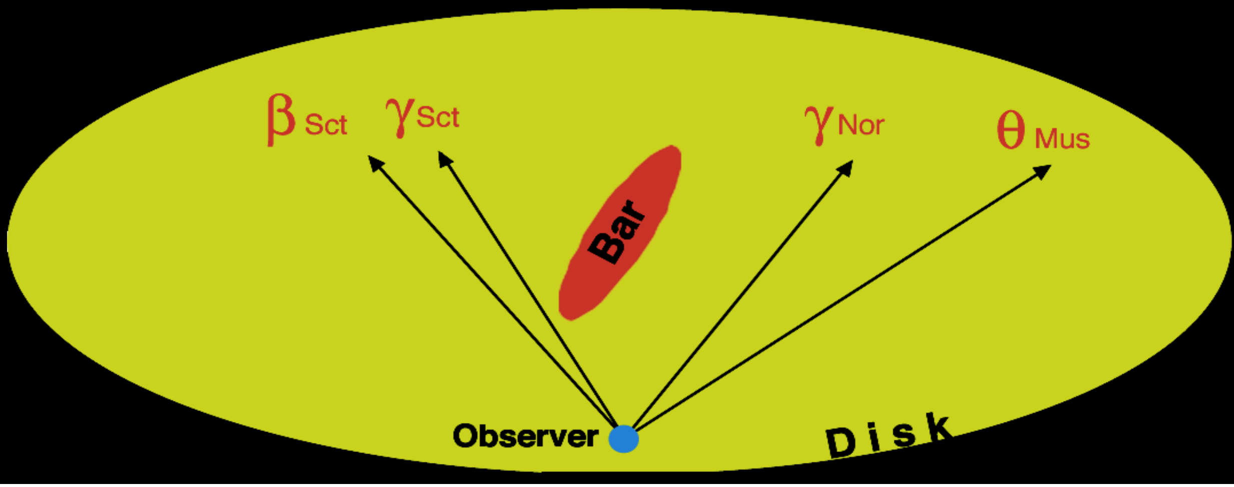
Resolved sources

- ✓ Besançon model ~ OK
- ✓ No need for hidden compact objects

And now with the spiral arms

29 fields in 4 zones away from Galactic center : $13x10^6$ stars





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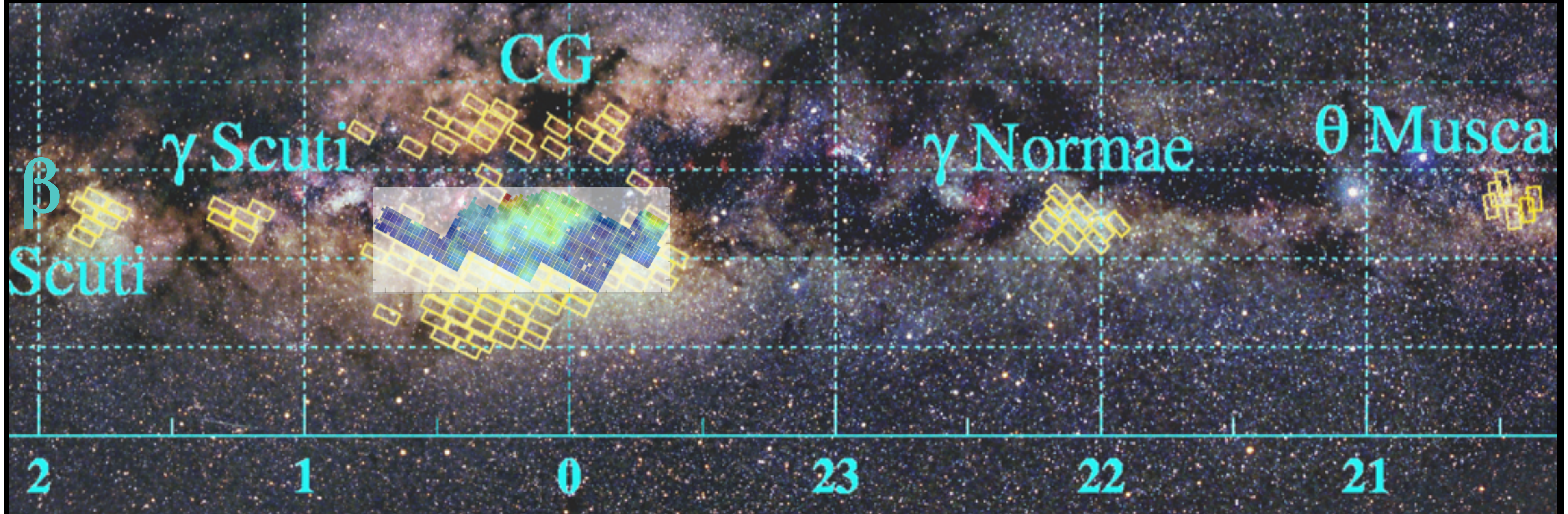
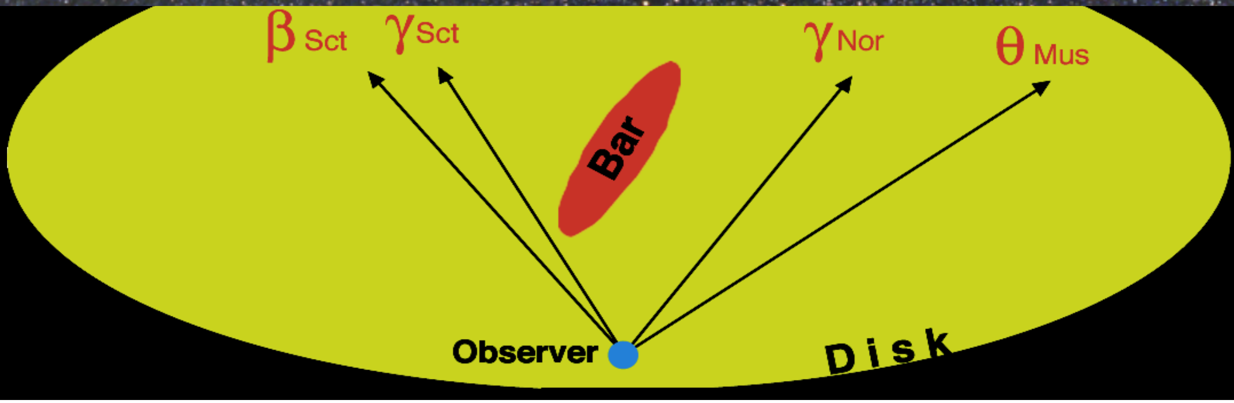
29 fields in 4 zones away from Galactic center : 13x10^6 stars

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





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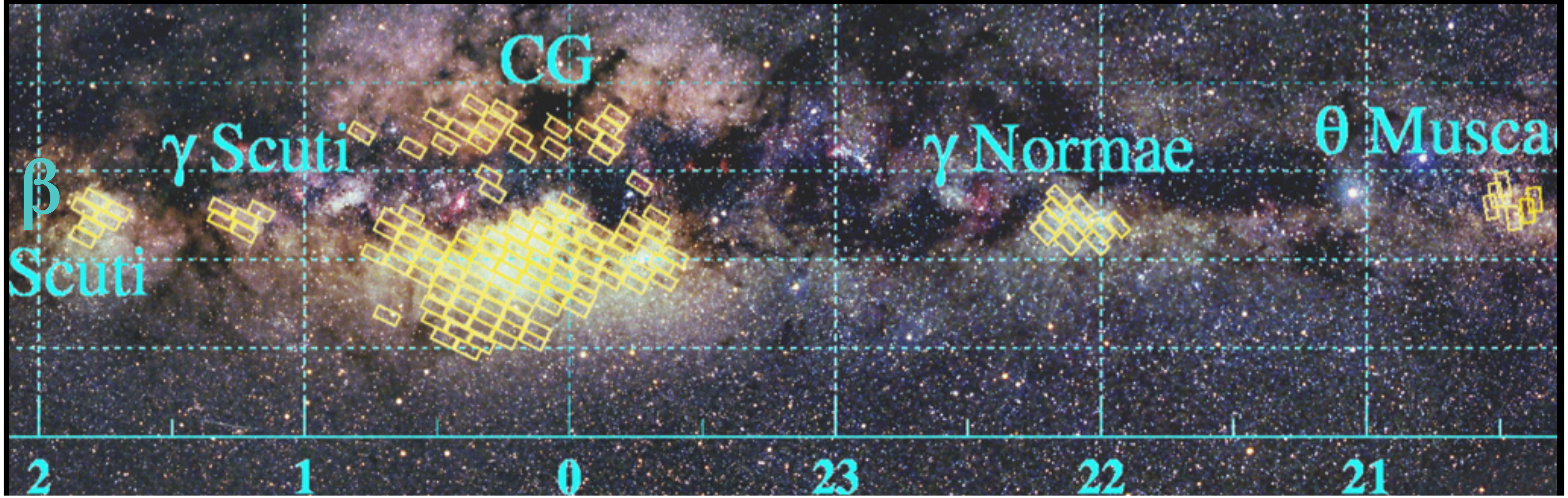
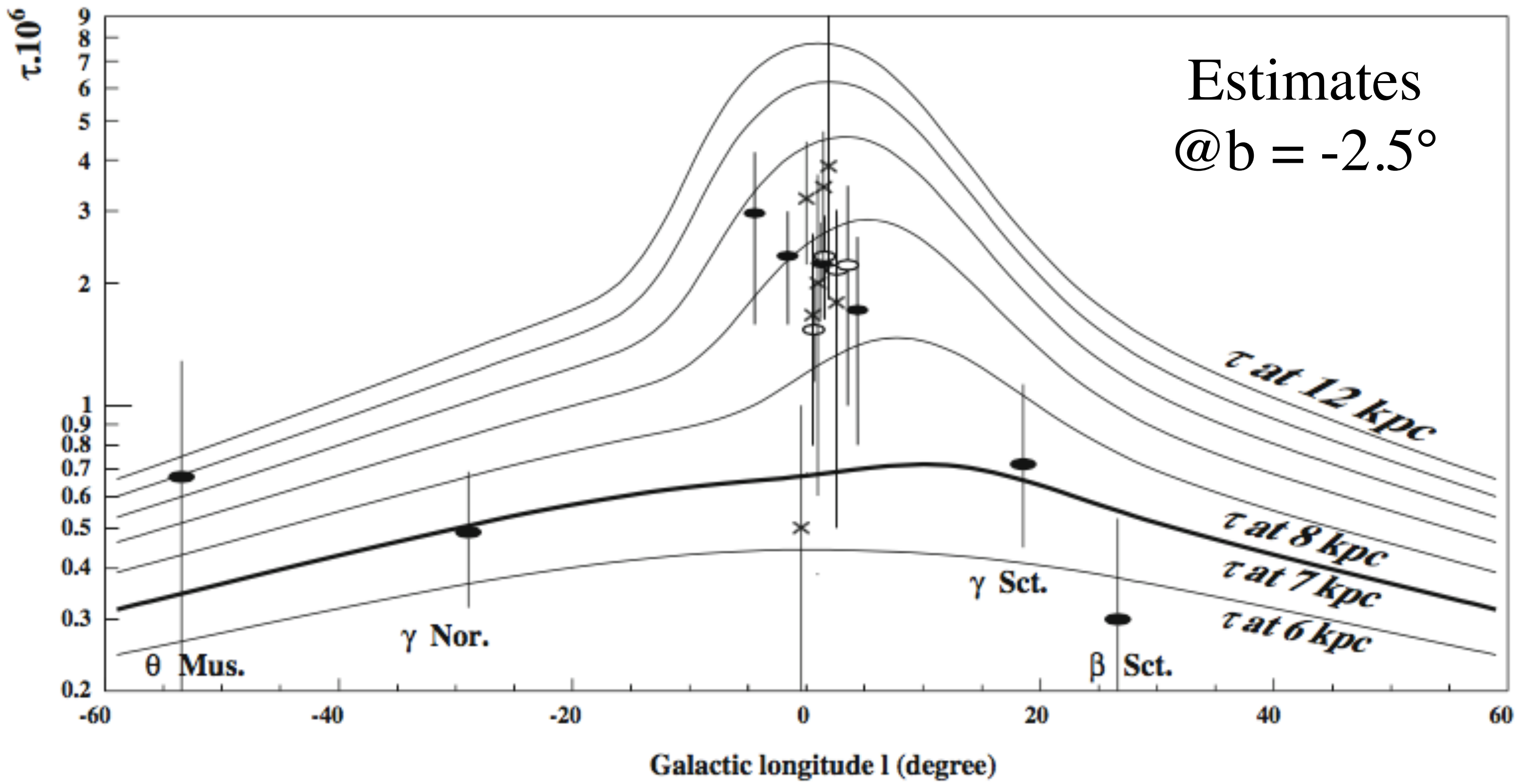


$\tau_{measured}$ =	$0.30^{+.23}_{-.20}$	$0.72^{+.41}_{-.28}$	$0.49^{+.21}_{-.18}$	$0.67^{+.63}_{-.52}$
$\tau_{simple\ mod.}$ =	0.45	0.43	0.38	0.23
$\tau_{Besançon}$ =	0.40	0.44	0.34	0.22

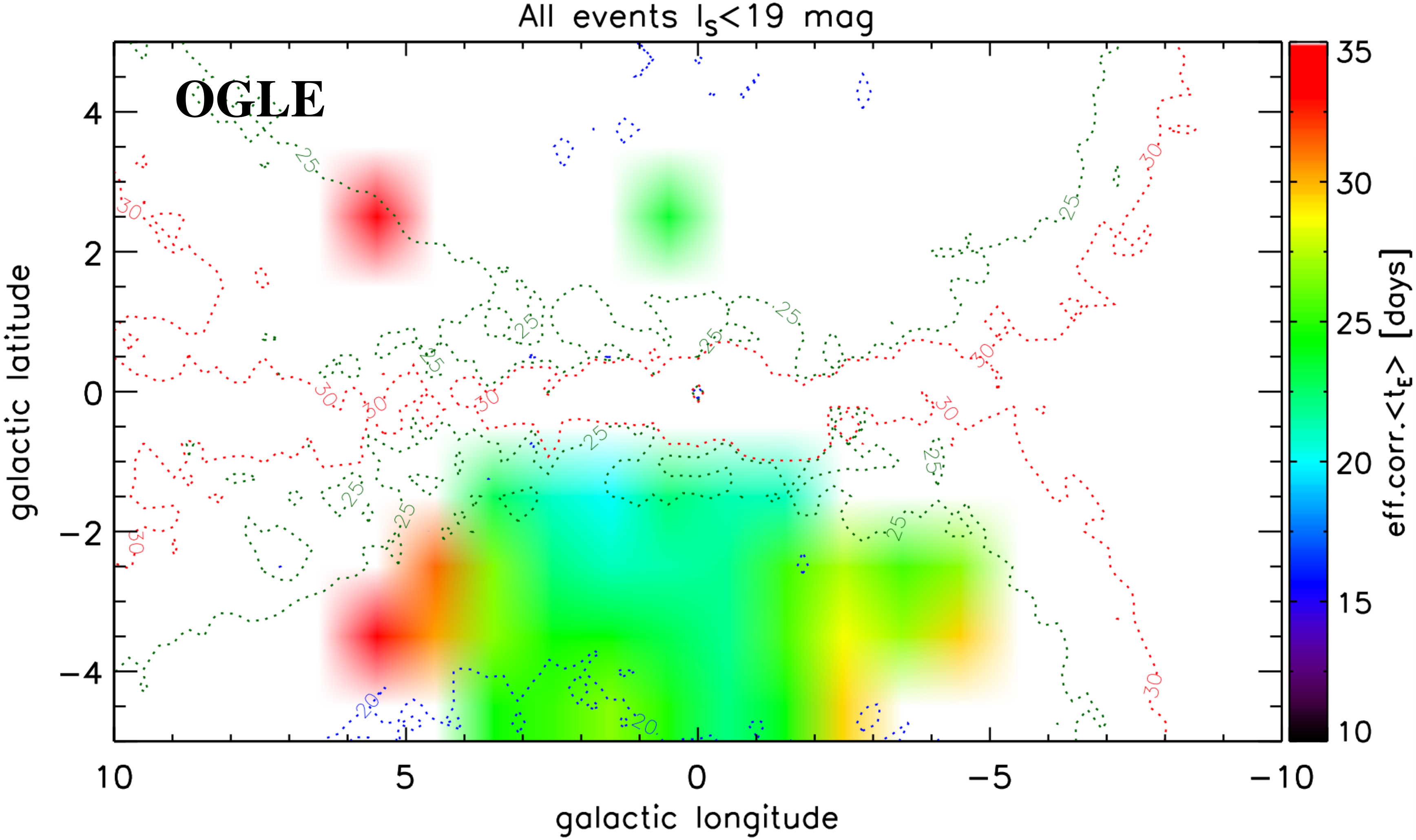
No need for massive spiral structure or thick disk of hidden compact objects

And now with the spiral arms

Mapping of τ in longitude

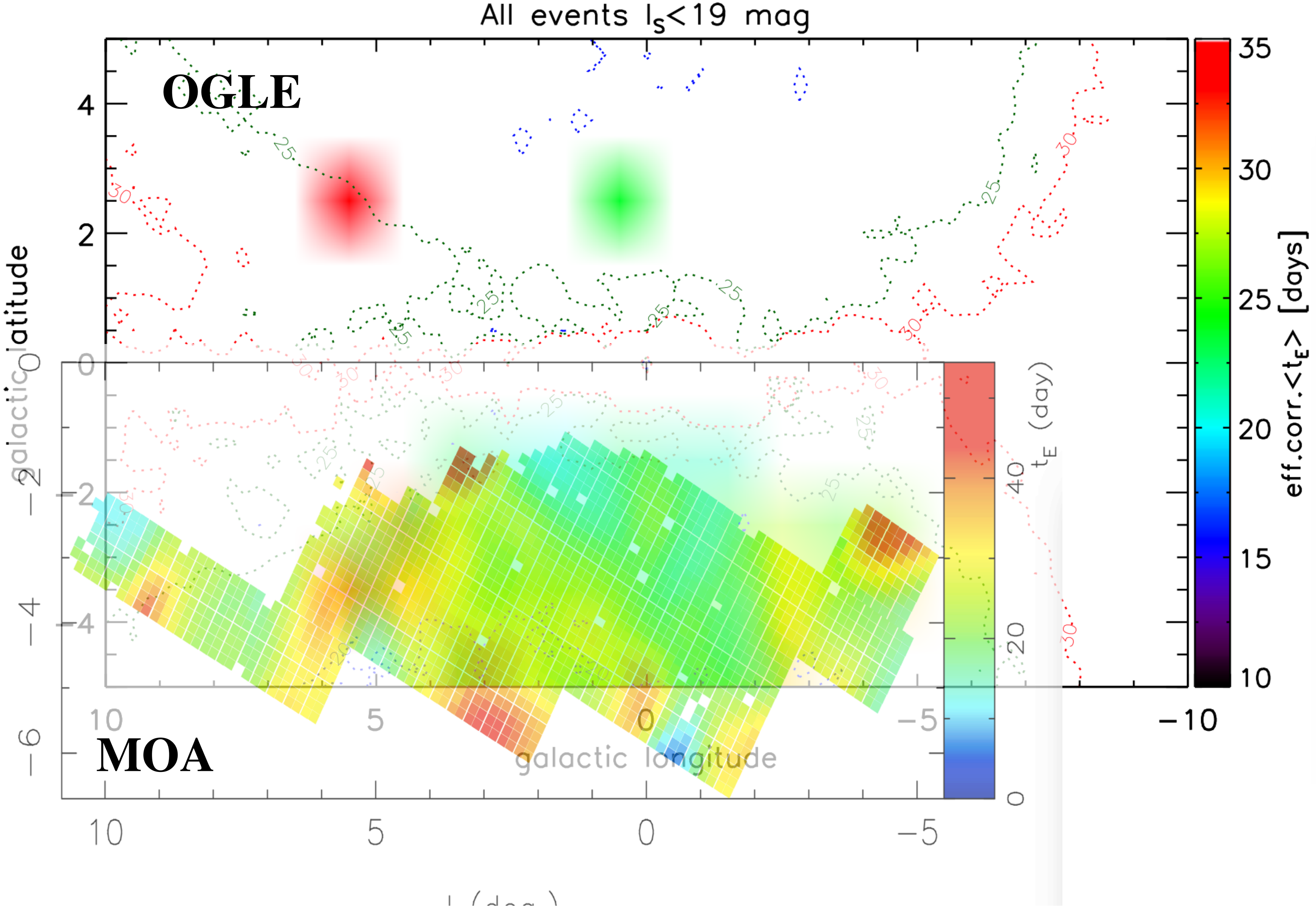


$<t_E>$ maps

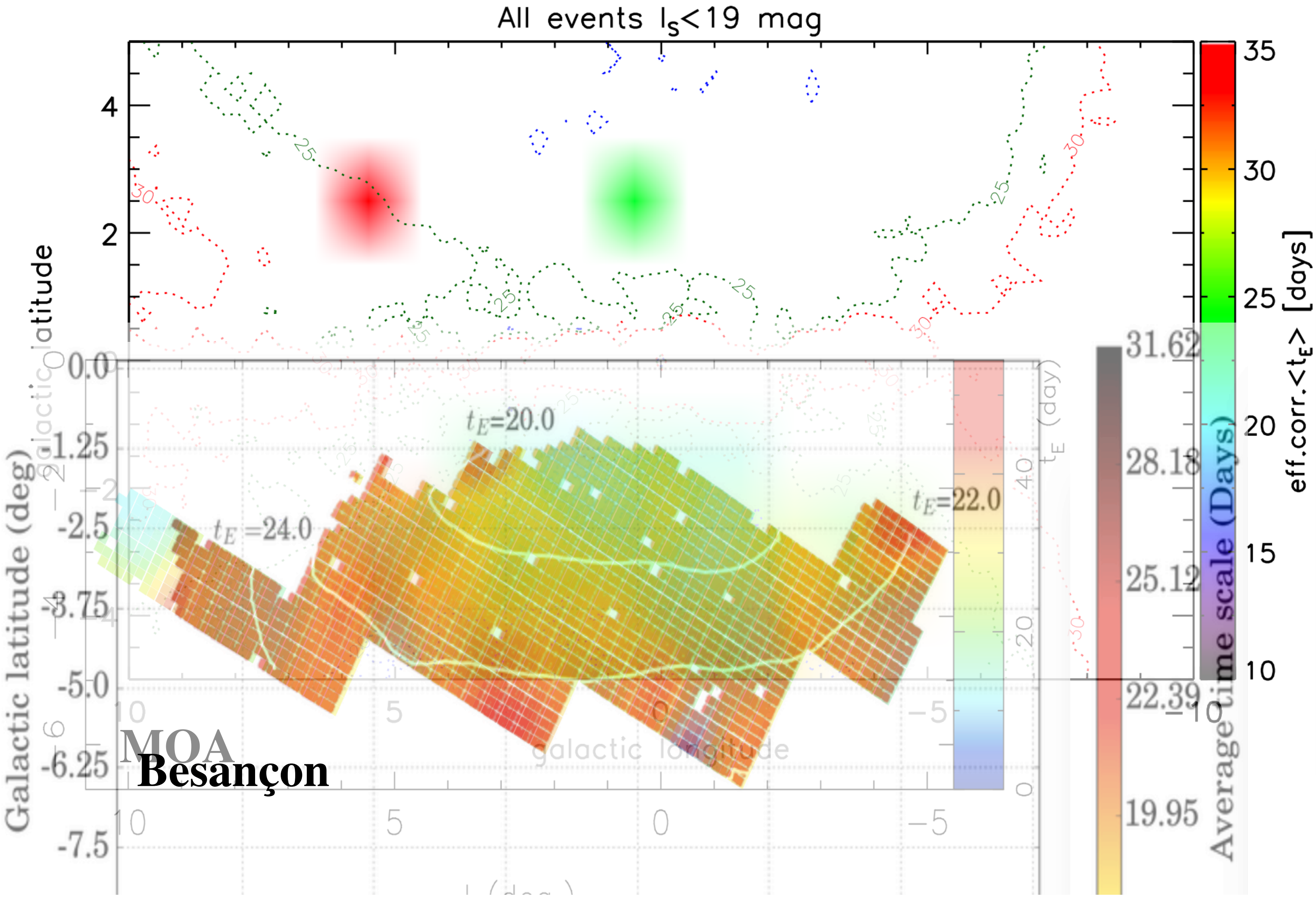


All events I_s<19 mag
OGLE
galactic latitude
galactic longitude
eff.corr.<t_E> [days]

$\langle t_E \rangle$ maps

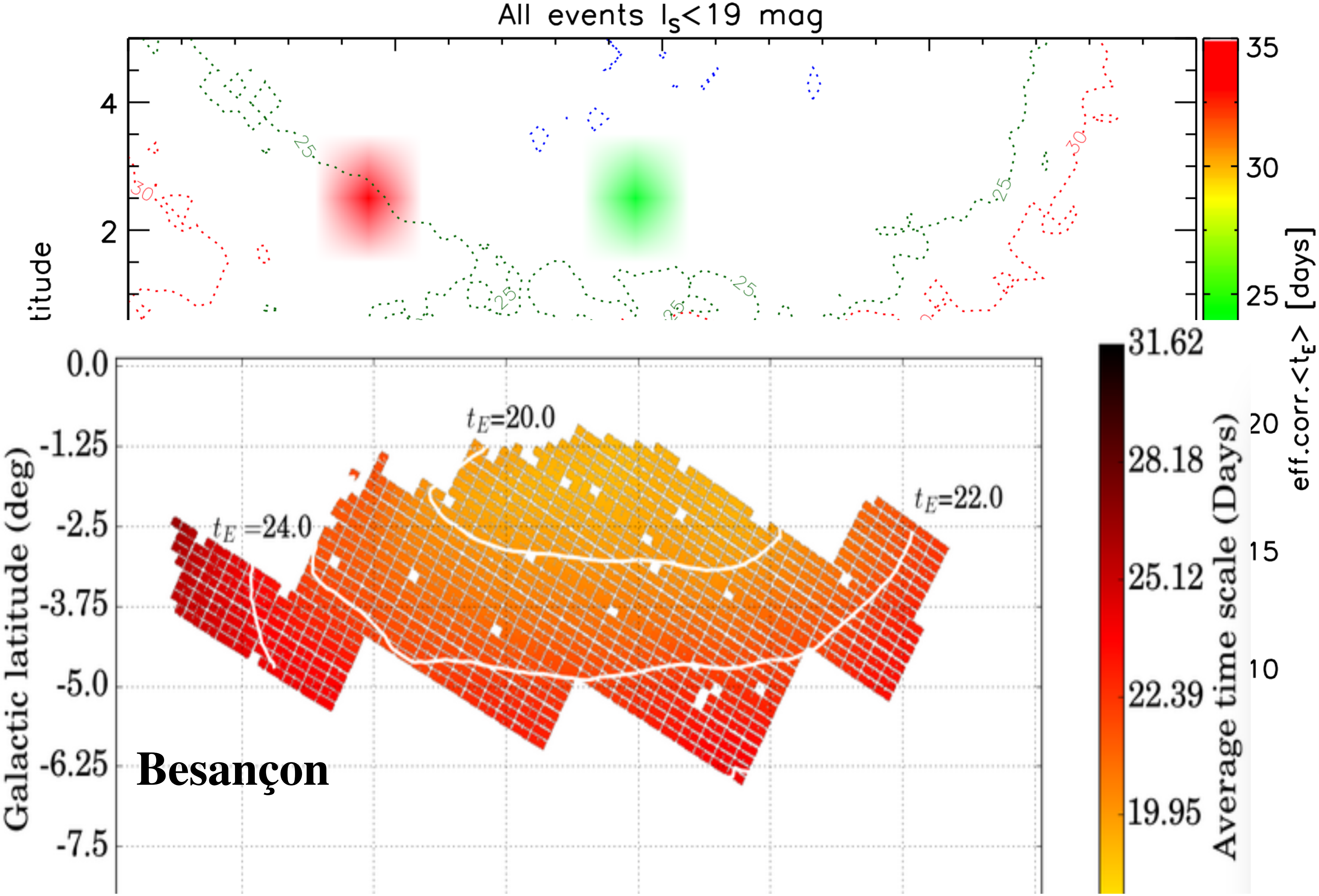


$<t_E>$ maps

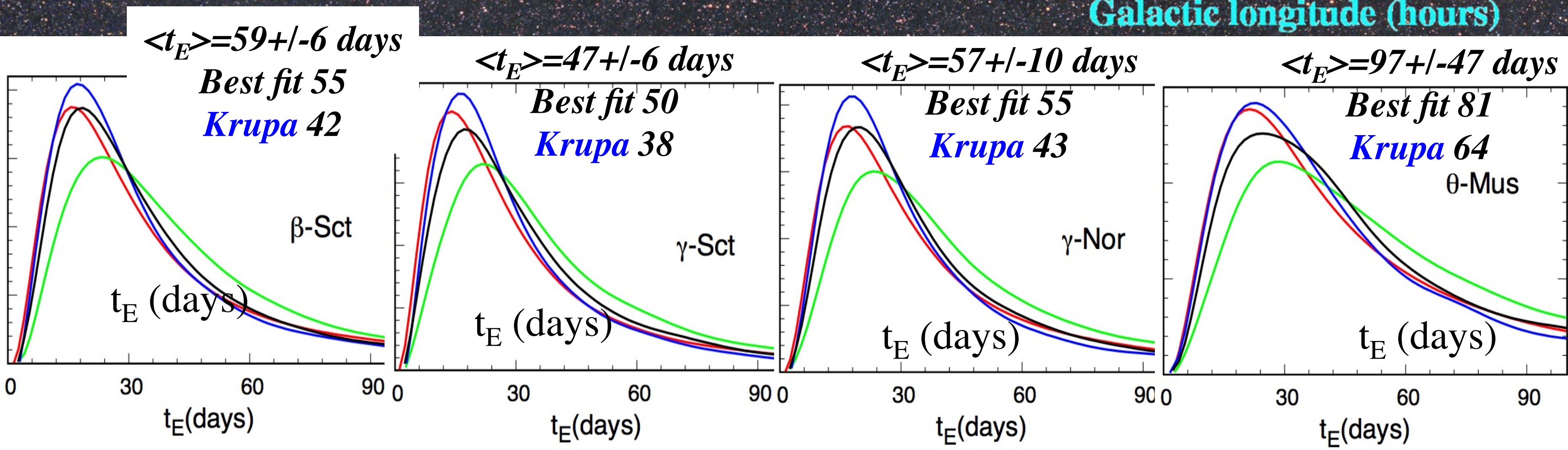


All events I_s<19 mag
MOA
Besançon
t_E=20.0
t_E=24.0
t_E=22.0
Galactic latitude (deg)
galactic longitude
eff.corr.<t_E> [days]
Average time scale (Days)

$\langle t_E \rangle$ maps

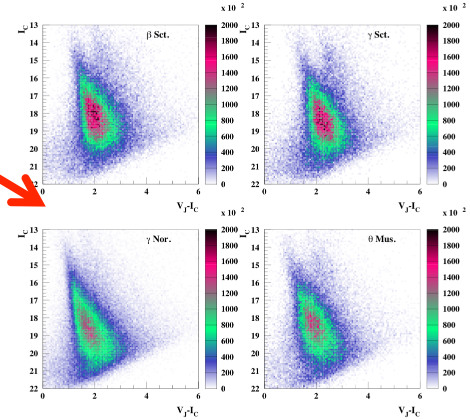


And now with spiral arms

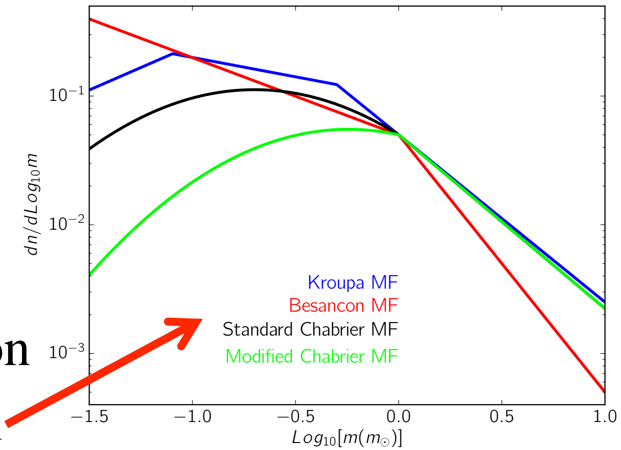


Ingredients for a global interpretation with microlensing

- **Include all the observations**: CMDs, τ, t_E distribution
  - CMD described with mean stellar surface density, <color>
  - τ, and t_E distribution described with (τ, $\langle t_E \rangle$)



- **Knowledge of the selection effects**
  - Effective field
  - Stellar detection efficiency
  - Photometric uncertainties
  - Microlensing efficiency -> ***CRITICAL***
- **Galactic density models** (shape and mass of each structure), built to fit all known observations
- **Stellar luminosity distribution** -> source population
- **Stellar mass distribution (IMF)** -> lens population



- **3D extinction map** -> ***CRITICAL***

Global fit: example of the 4 spiral arms targets

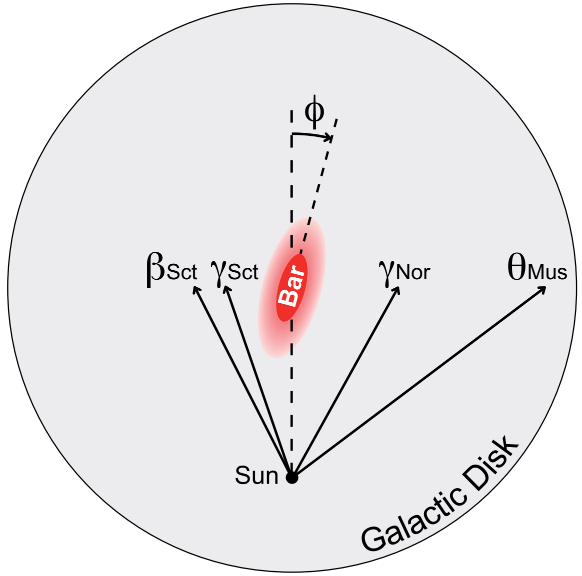
- Consider only stars with I < 18.4 to have the best control on detection efficiency
- Use simulation to connect 3 physical parameters **ϕ_{bar}, $M_{thick\ disk}$, IMF**
  with 16 observables: 4 x (**ρ*, <V-I>, τ, <t_E>**)
- Minimize differences (simulation%observed) from linearised χ^2 with ***∂(observable)/∂(parameter)***

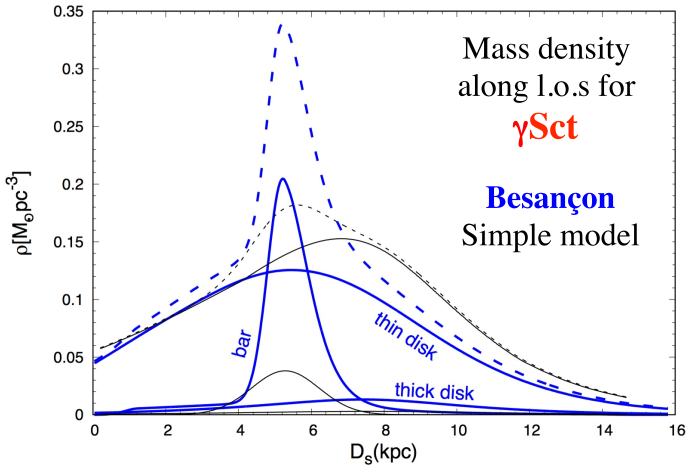
-> Necessary to **adjust mapped extinctions** by assuming 4 syst. & 1 stat. uncertainties (5 parameters)

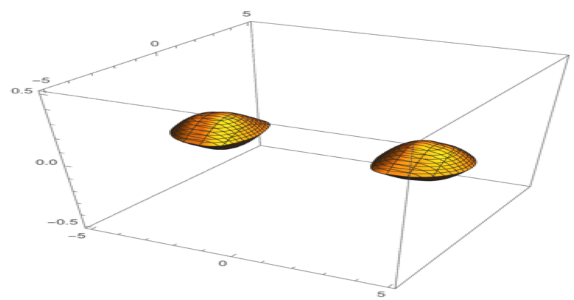
Constraints on the bar from microlensing

From microlensing around γSct

- Significant contribution expected and observed to **τ**
- We can distinguish between ϕ =13° and 45°
  - But not distinguish 14° and 13°
- We can also distinguish between a long and a short bar (1 vs 1.5kpc), massive of light
  - But not go into the details of the bar shape such as double system, boxy shape… (Wegg et al., Zoccali et al.)







Information on the disk(s) from microlensing

About densities

- Distance distributions of sources/ lenses
- No need for an hidden contribution

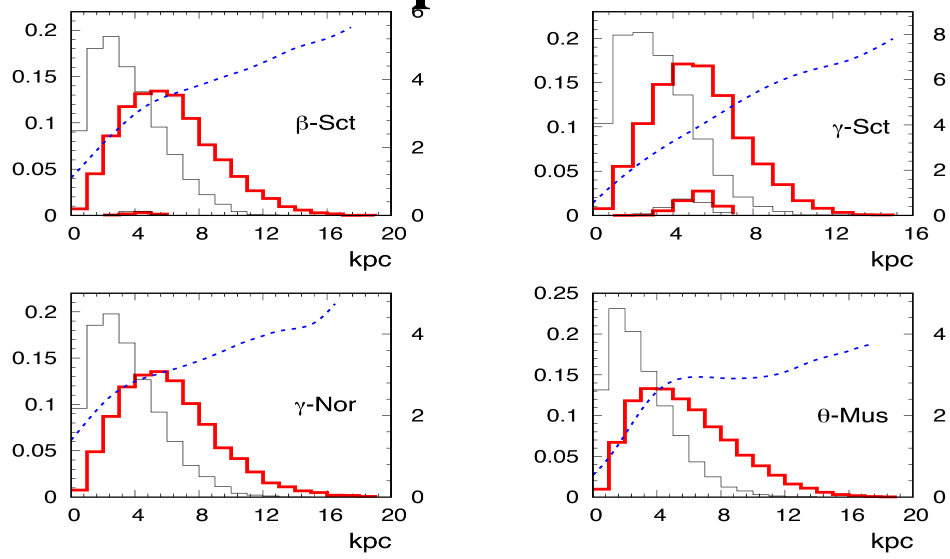
About kinematics

- Orbital velocities dominate proper motions

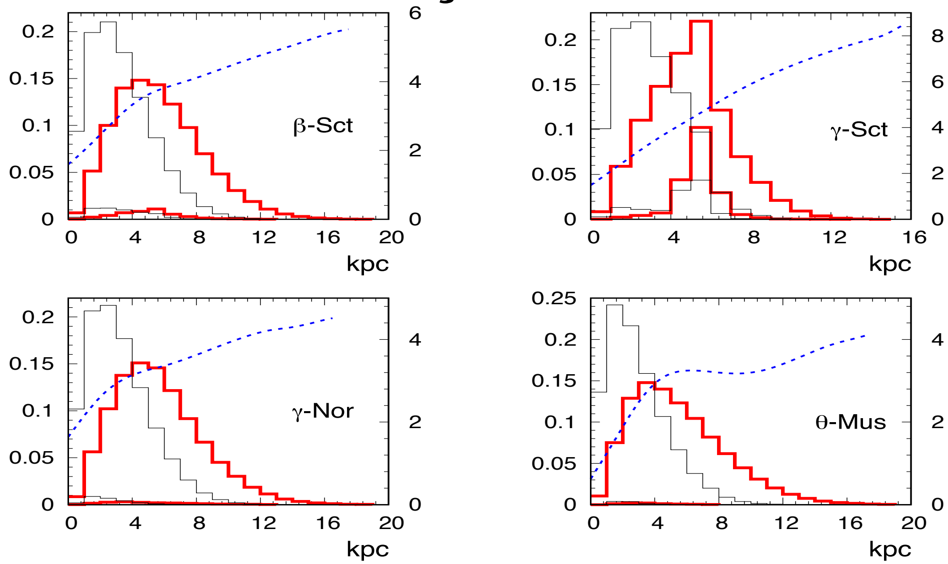
About IMF

- Sensitivity to the lens IMF

Simple model



Besançon model

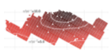


___ Lensed sources

___ Lenses

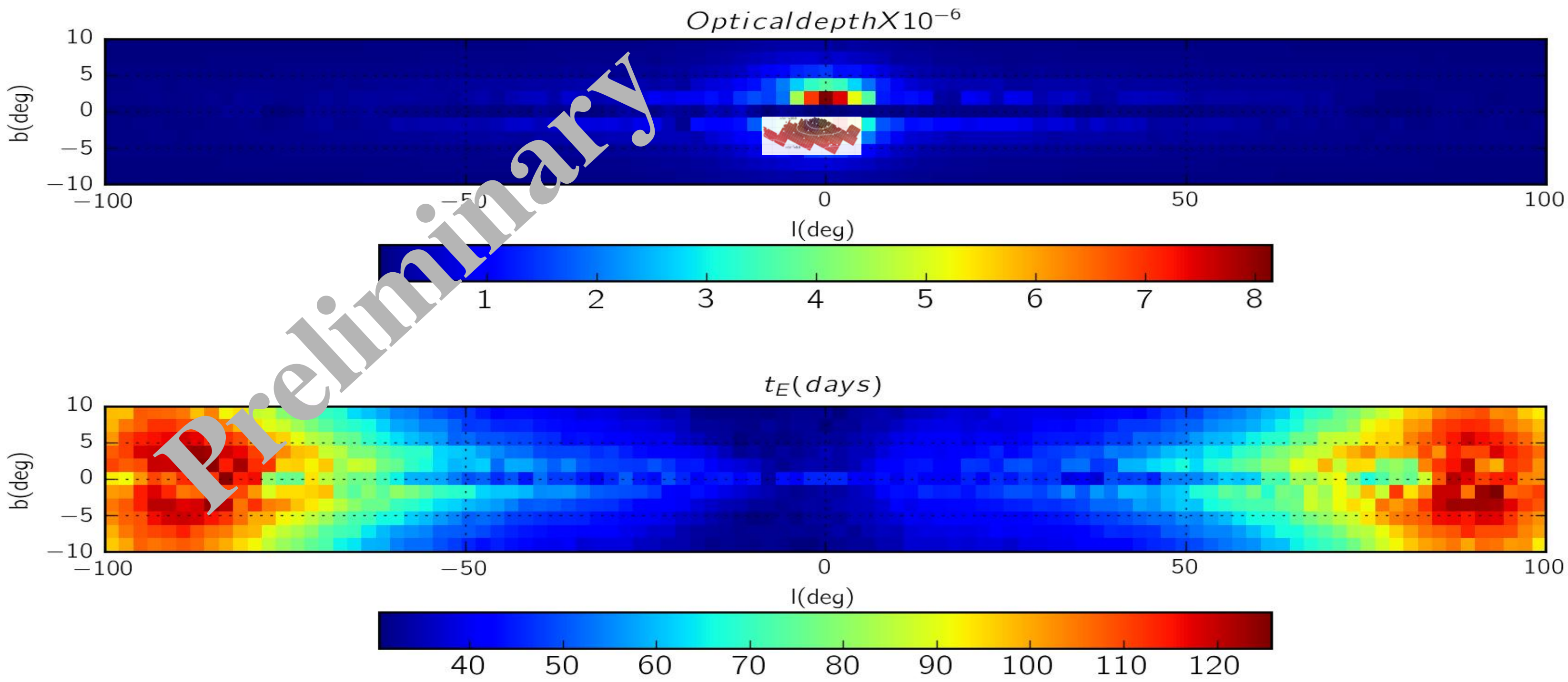
--- extinction in V of the lensed sources (avg)

Extended map
in -100°< longitude < +100°



Extended map in -100°< longitude < +100°

Besançon model,
taking into account the extinction map of Marshall et al. 2006



WFIRST and the Galactic structure

- Should provide exquisite information on each microlensing event
- But only in a small field (2.8 sq. deg. in GC)
- Possibly more fields later (M31, M87)
- **Strong potential** when coupling with wide field surveys on Earth
  - Refine efficiency estimates
    - Calibrate blending corrections
    - Identify complex events…

Conclusions

Microlensing observations and the Milky Way structure

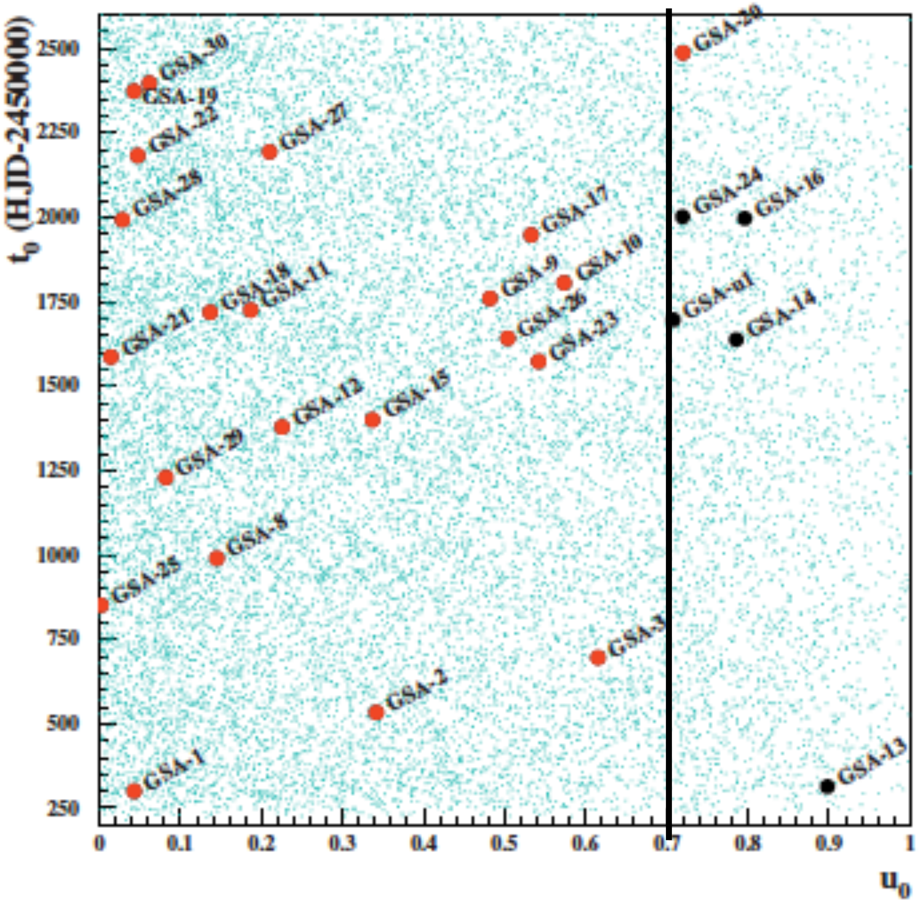
- Best tool to search for black holes [in plane or hidden in halo]
- From Galactic plane microlensing (CG + Spiral arms)
  - ✓ No need for hidden compact objets in the Milky Way plane:
    $\mathbf{M_{thick\ disk} < 5\text{-}7 \times 10^{10}\ M_{sol}}$
  - ✓ **Bar** : Inclination confirmed
  - ✓ **Lens IMF** : Krupa disfavoured, modified Chabrier favoured
  - ✓ **Galactic dynamics**: sensitivity to orbital velocity (not to proper motions). -> can be refined with higher stat.

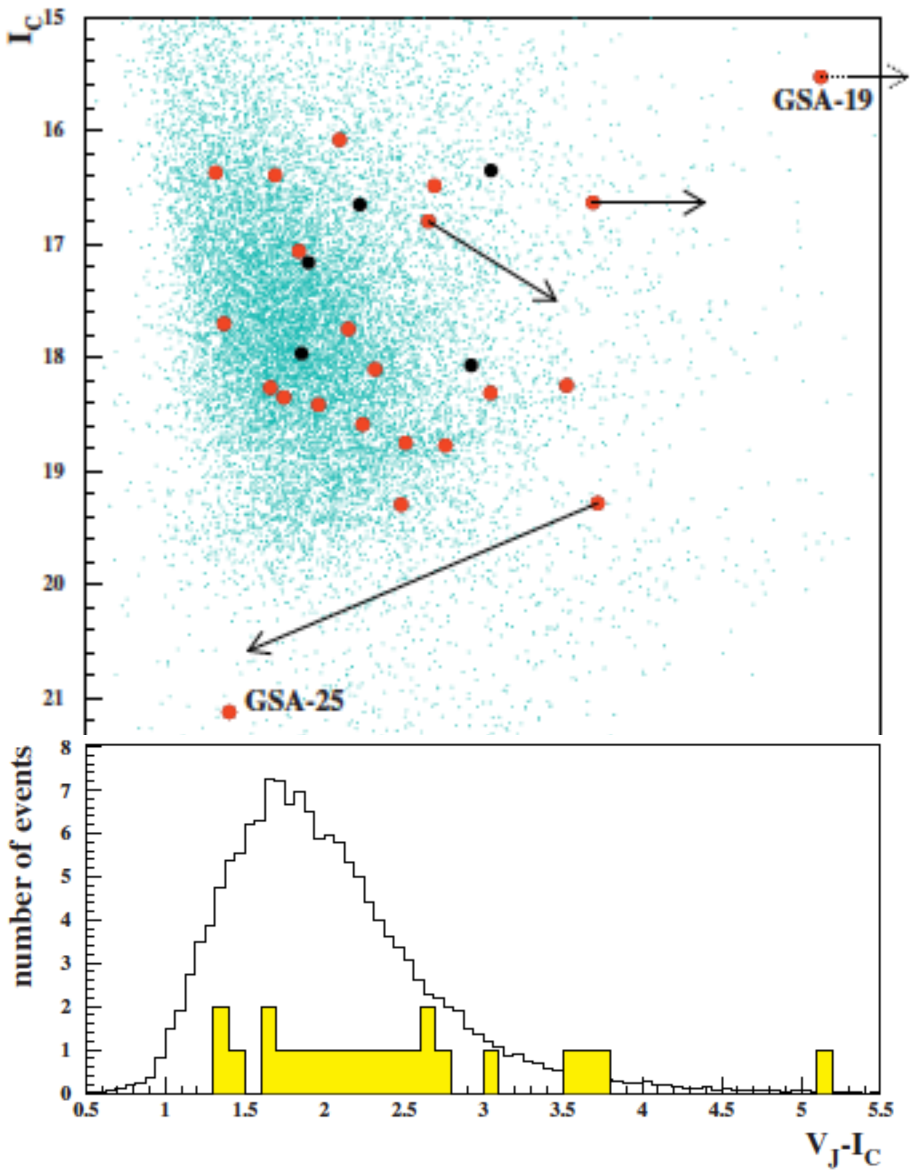
For long term perspectives:

- ✓ Improve absorption map and extinction models
- ✓ Improve efficiency estimates
- ✓ Increase statistics + extend mapping, especially through dust with IR surveys
  - VVV at VISTA: K-survey within the galactic bulge and disk
  - OGLE IV, GAIA, WFIRST, LSST, Euclid

Supplements

Statistical representativity of the events



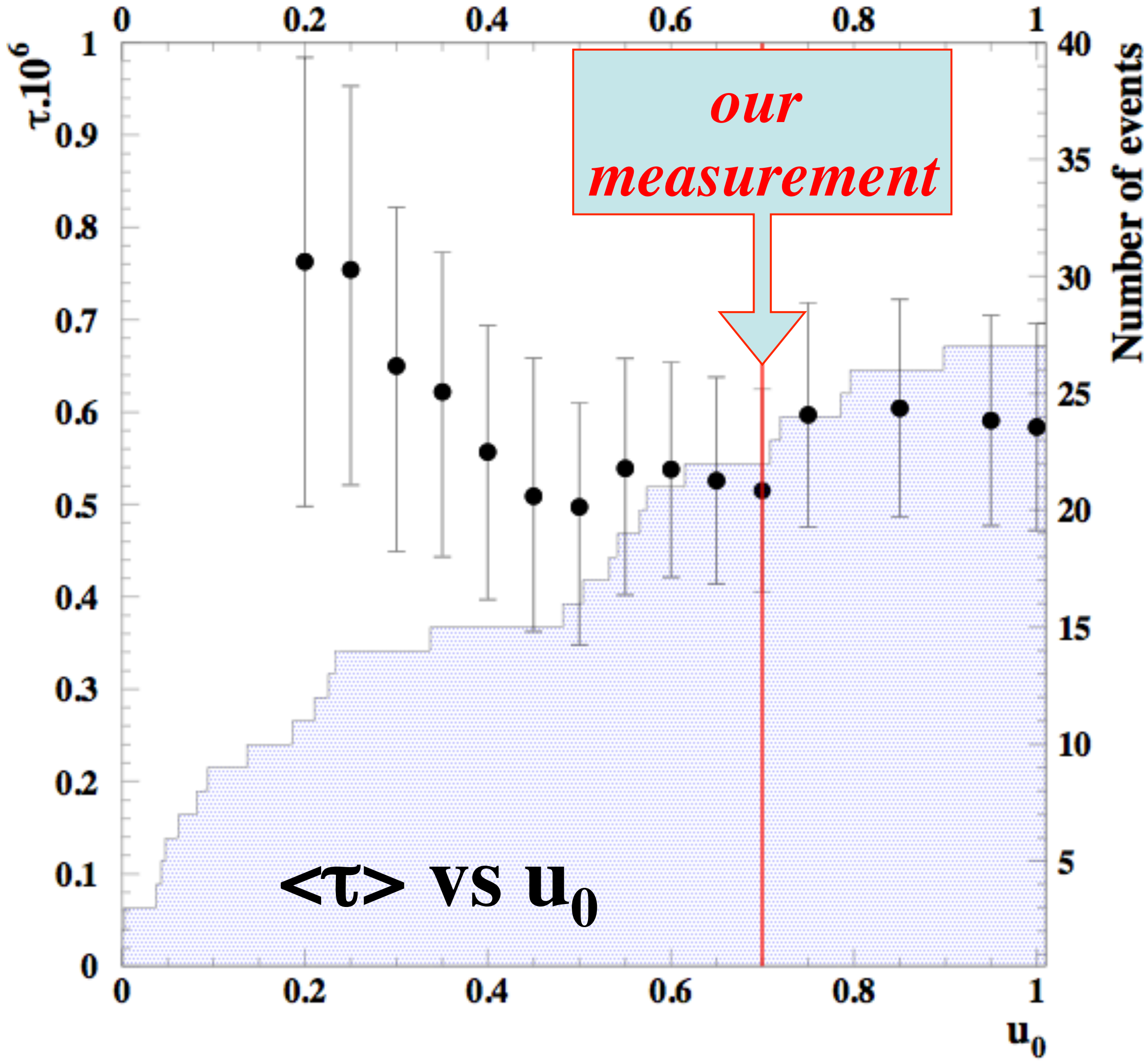


Microlensed stars are redder

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

Stability of <τ>$_{directions}$ measurement



What impacts microlensing distributions?

Mass density spatial distribution model $\rho(r)$ (lenses) -> optical depth

- Galactic plane
  - Disk(s)
  - Bulge / bar
- Galactic halo

Mass distribution of lenses (IMF) -> t_E distribution

Galaxy dynamics (lenses / sources) -> t_E distribution

  - Galactic disk: global rotation + ellipsoid of proper motions
  - Bulge / bar have different dynamics

Spatial distribution of sources

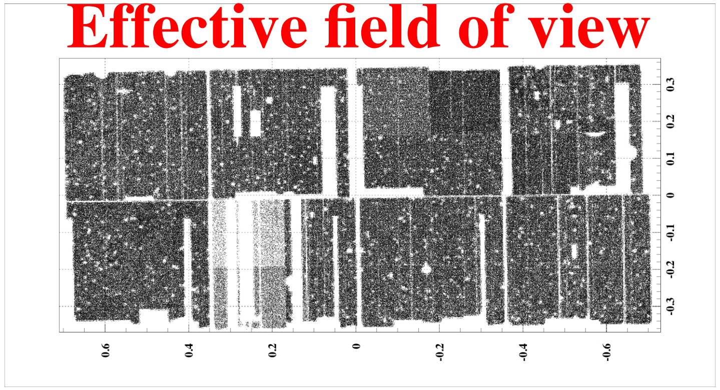
Light transfert

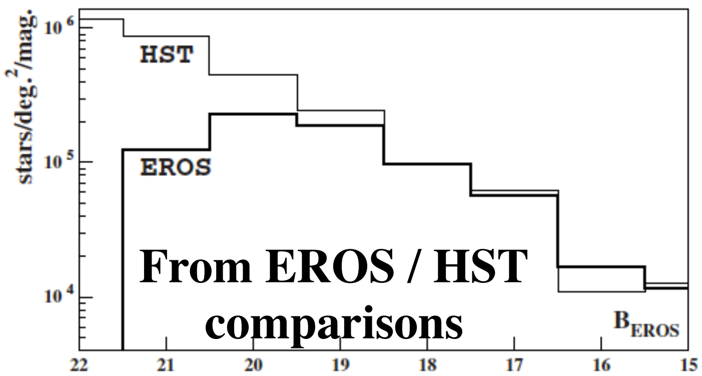
  - Galactic extinction

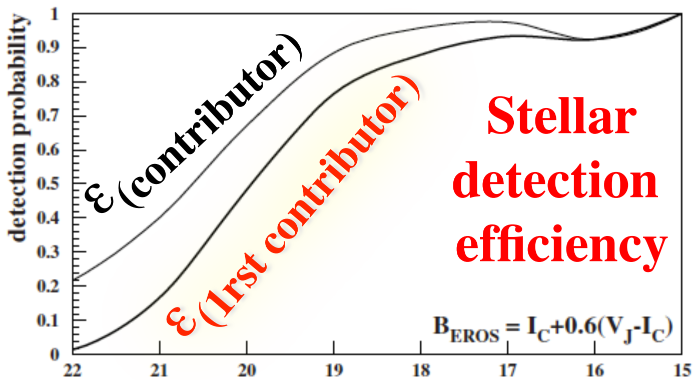
Detector response, analysis

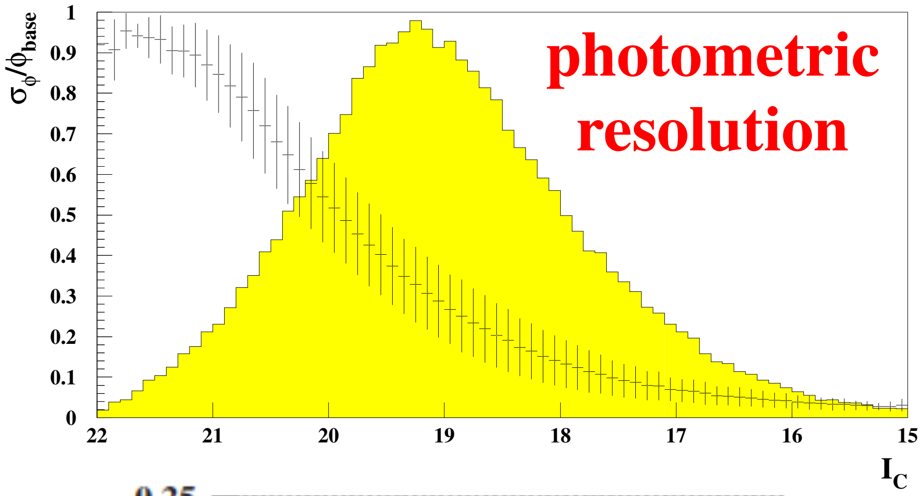
  - Efficiency: photometric quality, time sampling, selection algorithm

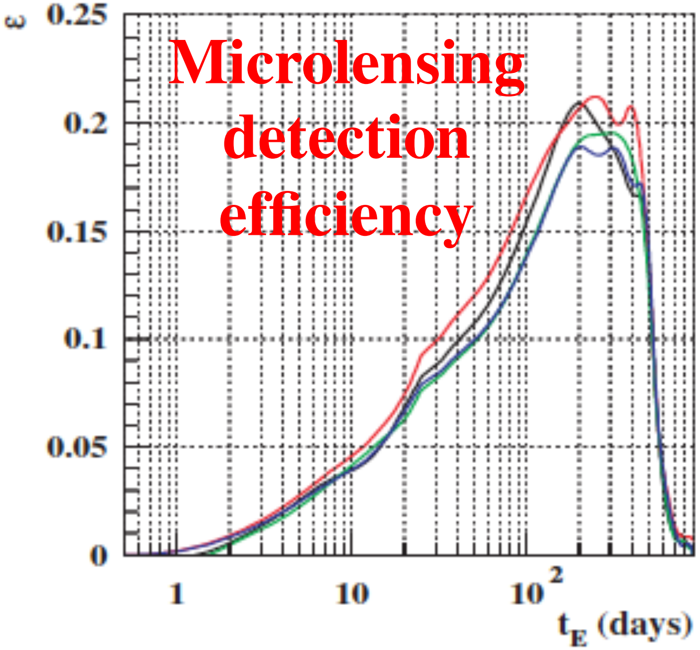
Deep understanding of the detector







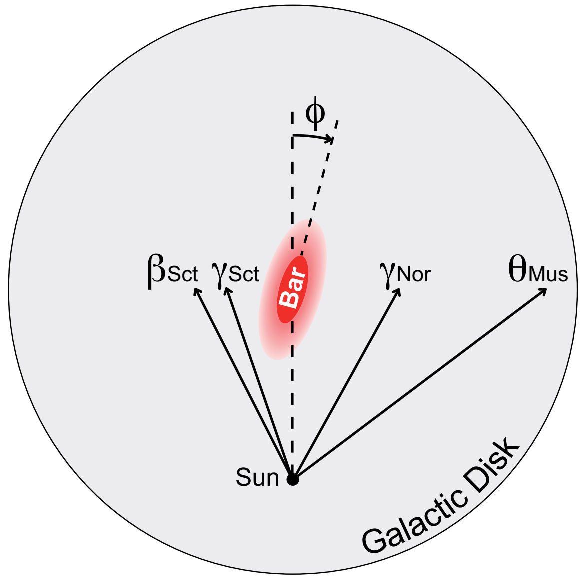


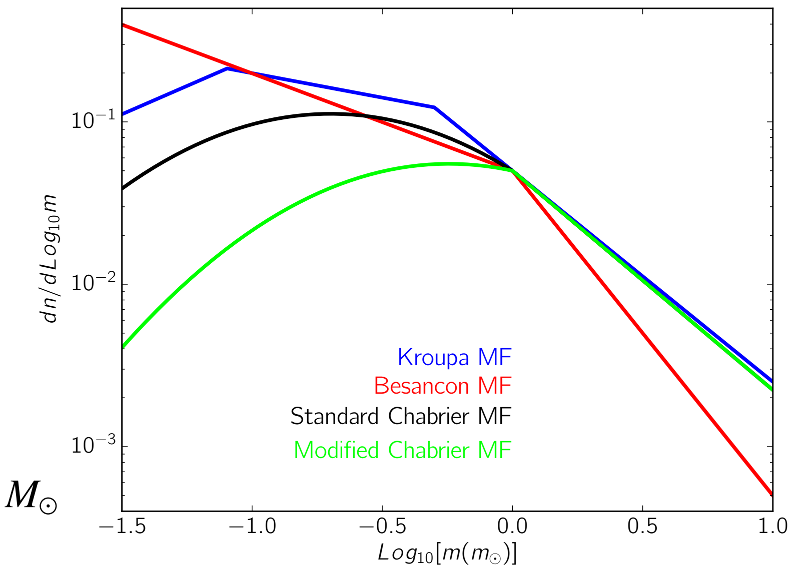


Simulation: Lenses

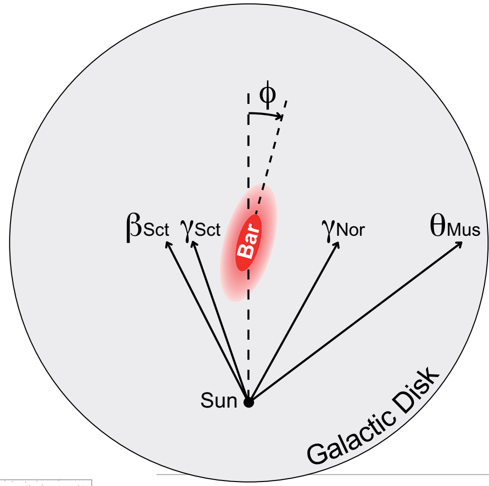
- **Density models**: Besançon / simple home-made
  - Disk(s)
  - Bar ($\phi = 13°$)
- **Kinematics** from the galactic models -> V_T
  - disk orbital velocity
  - Maxwellian V in bar
  - Peculiar velocities have negligible impact
- **Mass Function** -> R_E
  - Modified Chabrier (m_0 # 0.2)

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

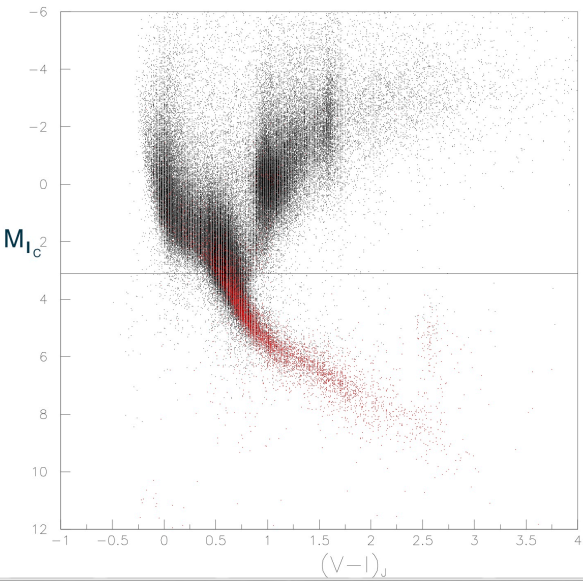


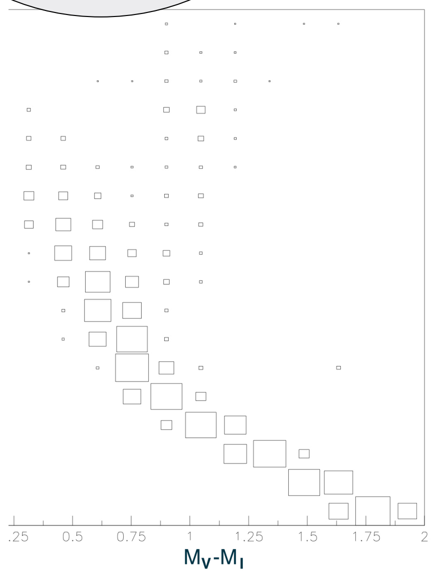


Simulation: Sources



- **Density models**: Besançon / simple home-made
  - Disk(s)
  - Bar (ϕ = 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

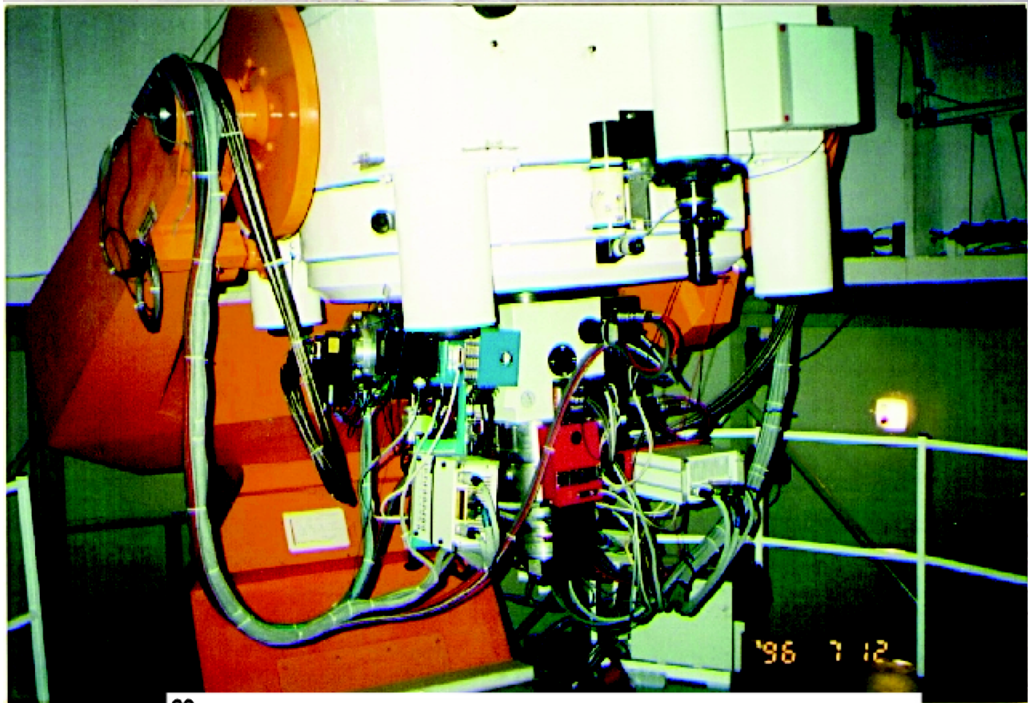


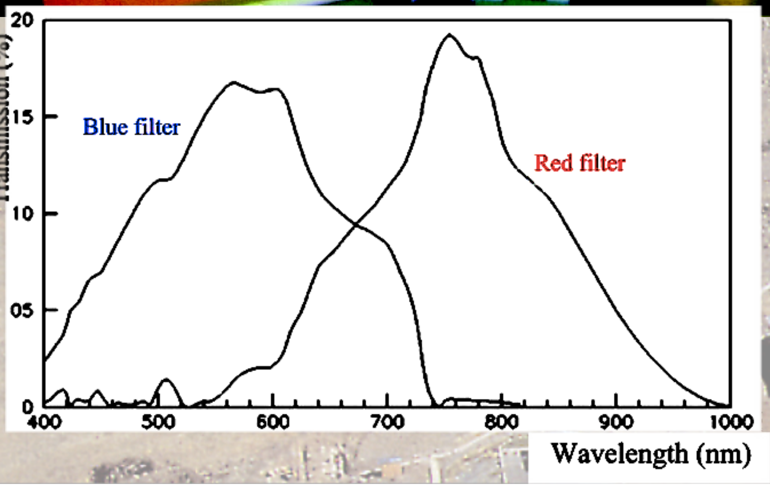


- **3D extinction map**
  - Marshall et al. 2006

  Fast spatial variations

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)**