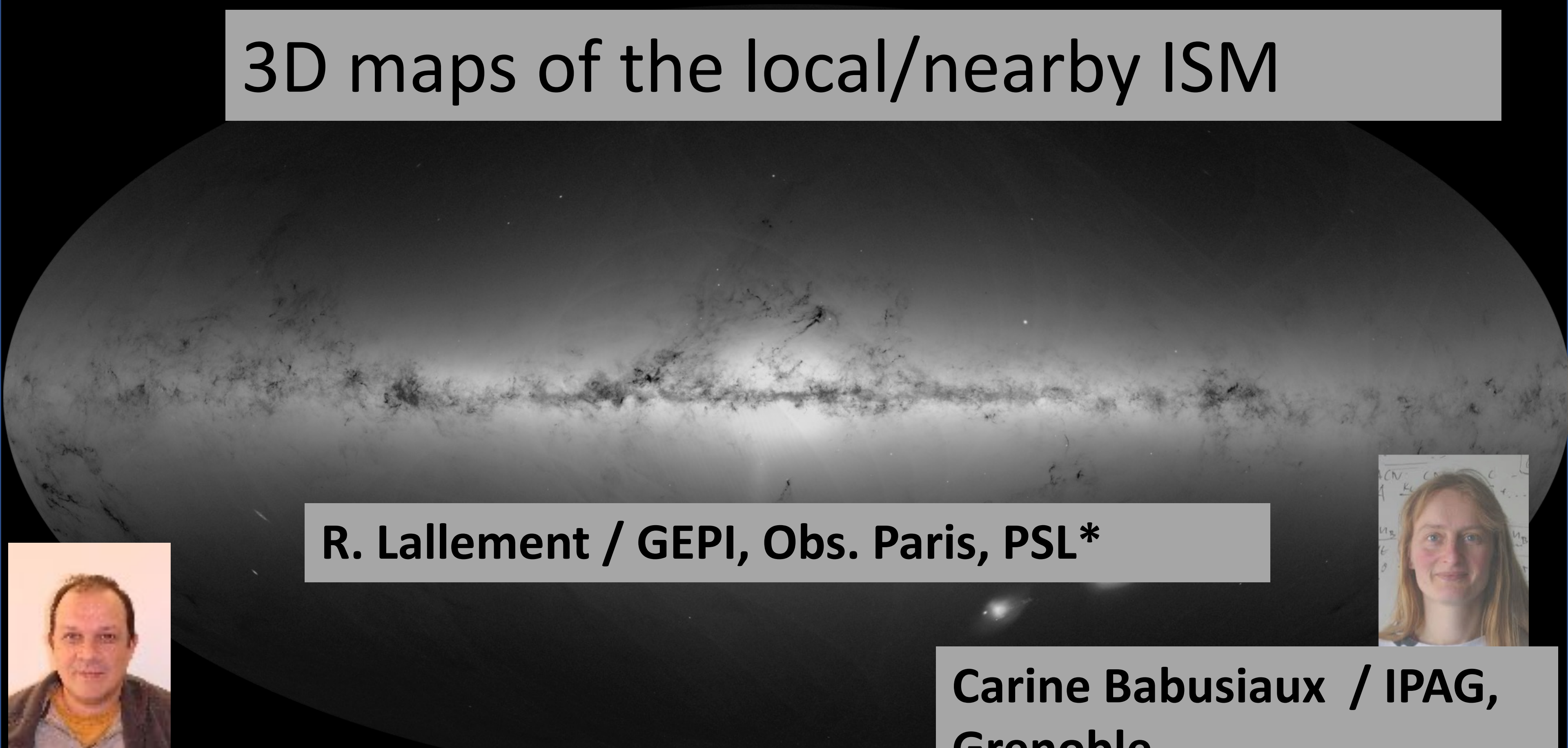
3D maps of the local/nearby ISM

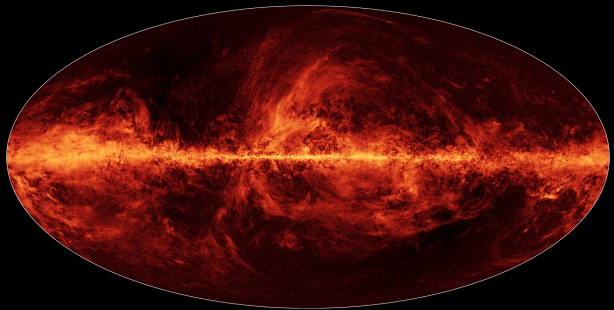


R. Lallement / GEPI, Obs. Paris, PSL*

Jean Luc Vergely / ACRI-ST , Sophia-Antipolis

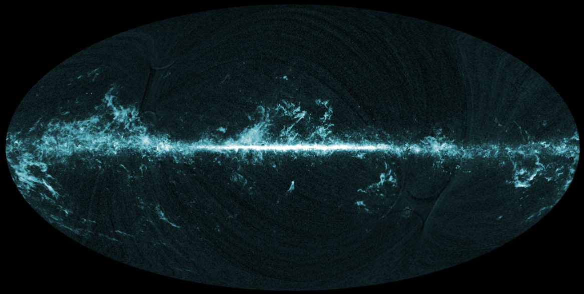
Carine Babusiaux / IPAG, Grenoble

DUST



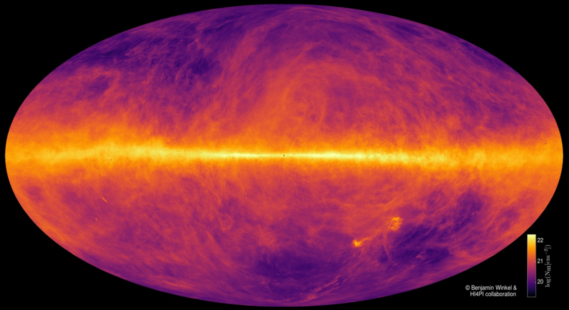
353 GHz (Planck)

Dense, molecular GAS



CO (Planck)

ATOMIC GAS



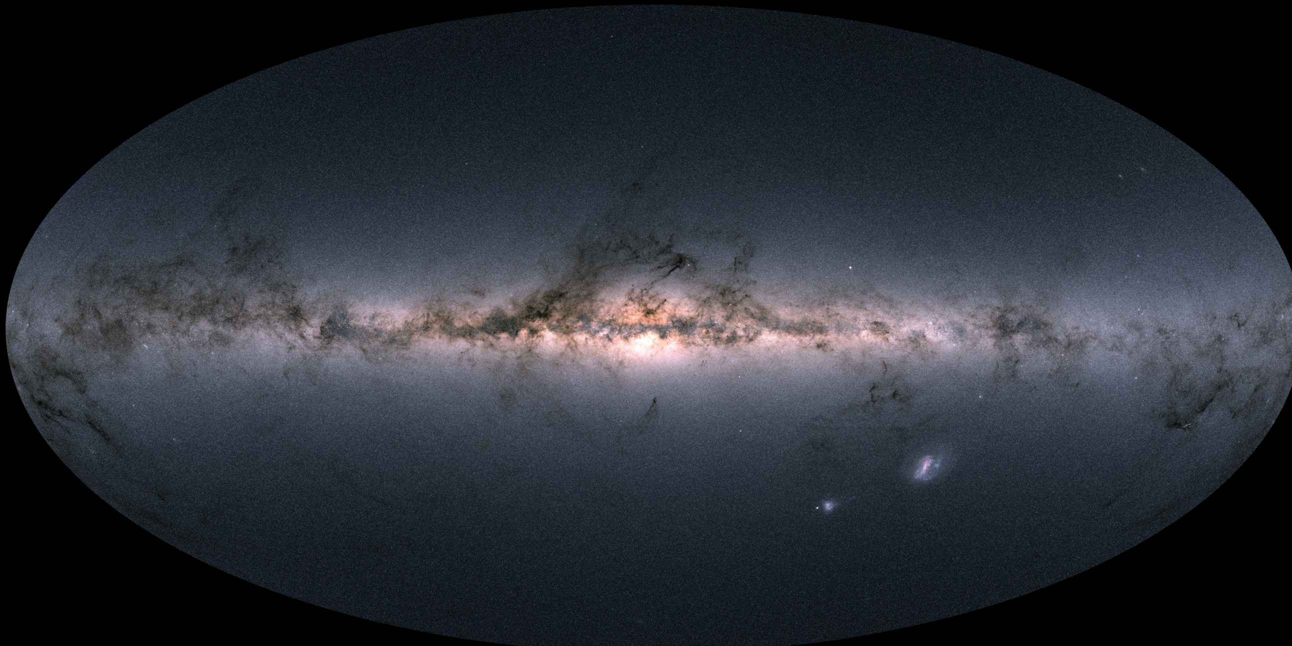
HI 21cm (ground)

Increasingly detailed **2D** images of interstellar (IS) dust and gas come from integrated EMISSION!

no information on distance!

3D maps need quantities measured for <u>individual sources distributed in space at known distances ! => stars</u>

Parallactic distances



GAIA

We need **more than the apparent color** of the stars (due to intrinsic color + dust reddening):

We need the **change in spectrum produced** by the intervening **dust** (or extinction, which is roughly proportional to reddening)

Individual stellar extinction/reddening

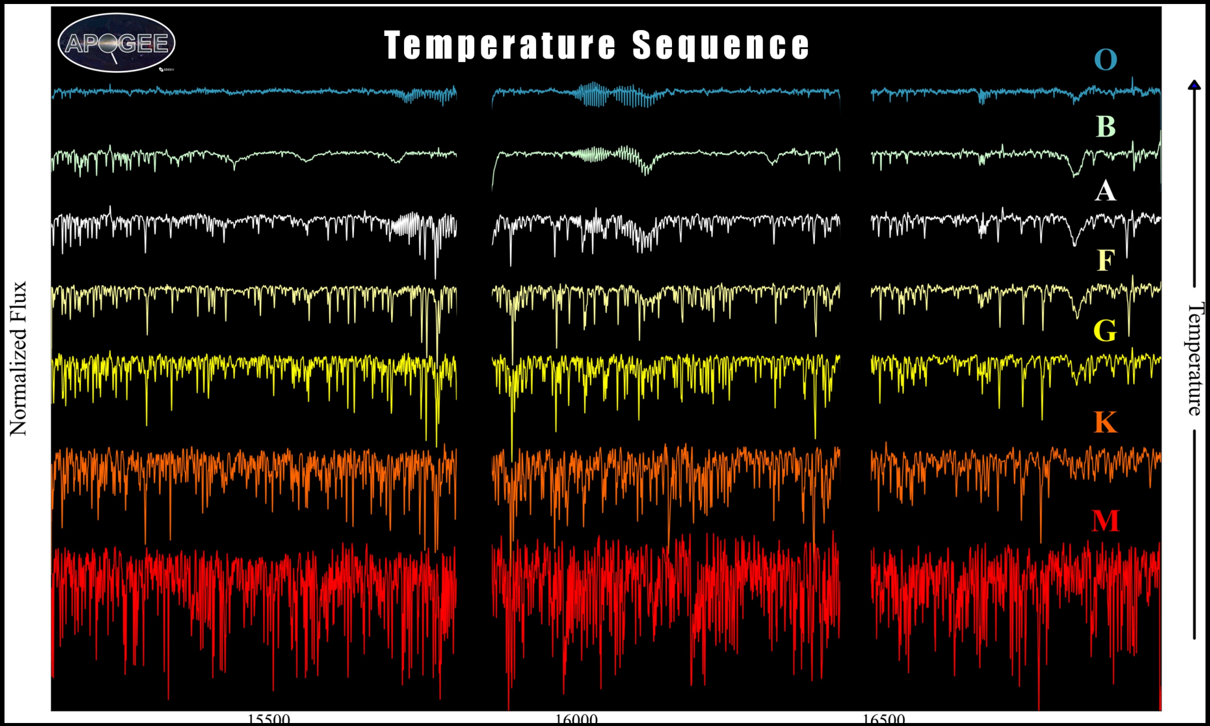
1) deduced from models and photometric measurements in different spectral bands)

GAIA Accu photometry in the GB e), G(visible), GR (red) bands

Temperature- degeneracy

Massive Ground-ba Photometric Stellar Surveys

Individual stellar extinction/reddening
2) deduced from spectra and photometric measurements (colors)



+ input from massive spectroscopic surveys from ground => star characteristics => more accurate determination of the extinction of their targets

Carine Babusiaux

Gaia (catalog eDR3, G, BP, RP bands), 2MASS (J, H, K) et empirical laws linking star colors=> 35 Millions individual extinctions of stars

+ **precise Gaia astrometric distance (parallax)

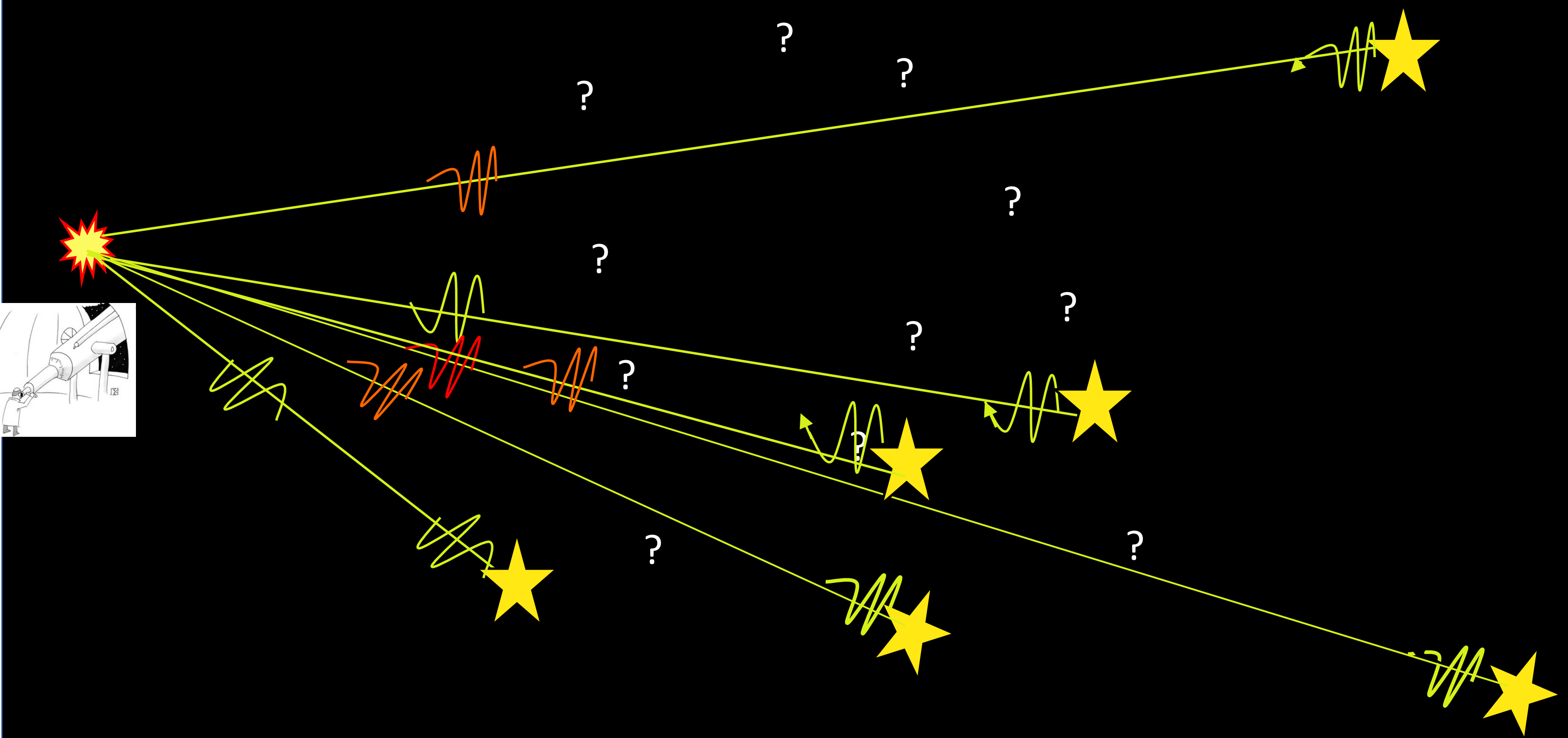
+ 6 millions extinctions from spectroscopic surveys and Gaia + 2MASS photometry (*Sanders et al, 2018, Queiroz et al, 2020*),
surveys GALAH, LAMOST, APOGEE, RAVE, GES, SEGUE

** distances from astrometry and/or -spectrophotometry

Jean-Luc Vergely

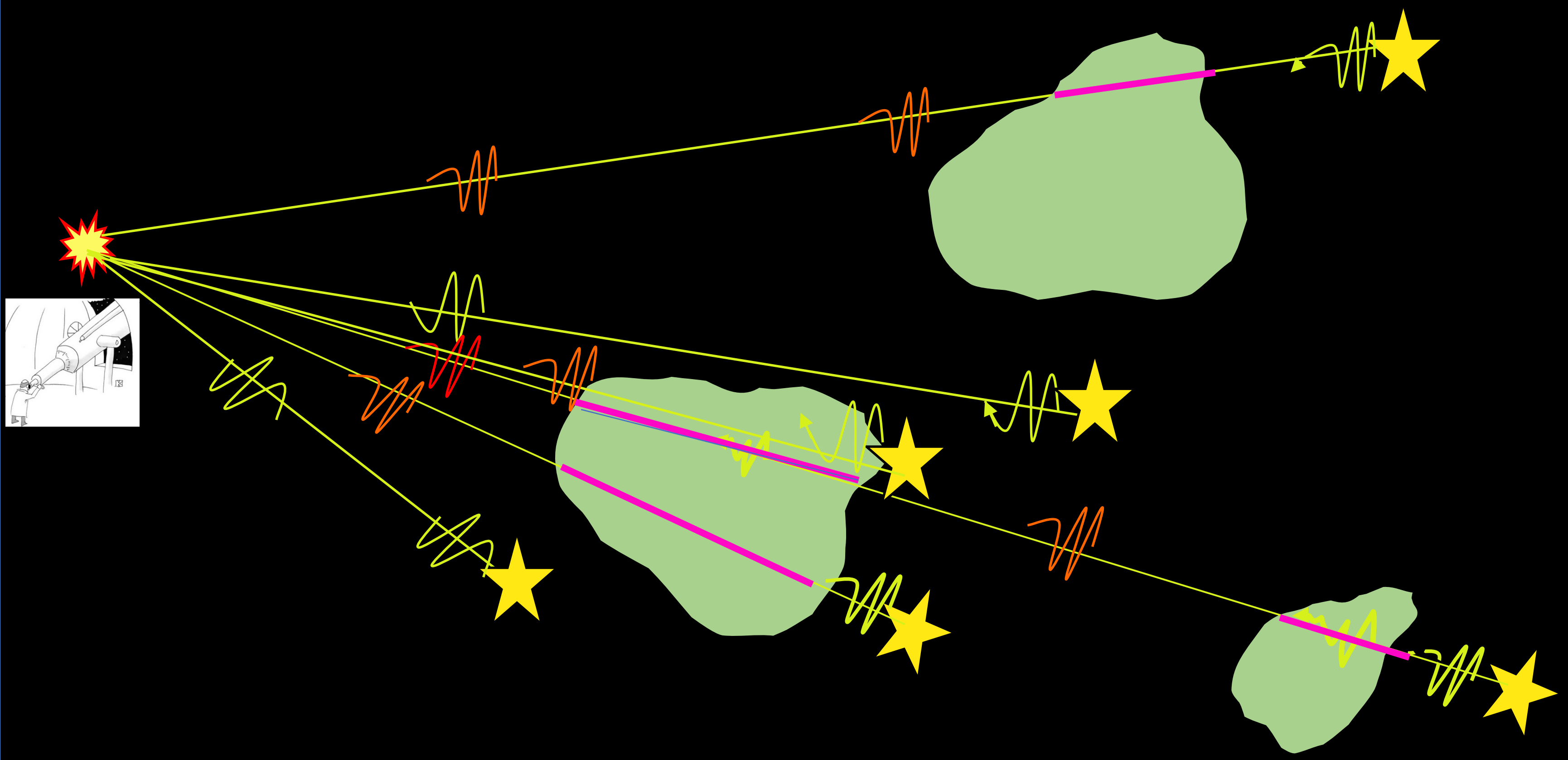
+ intercalibration of spectroscopic surveys, then of surveys and Gaia/2MASS

+ hierarchical inversion => regularized extinction tomography

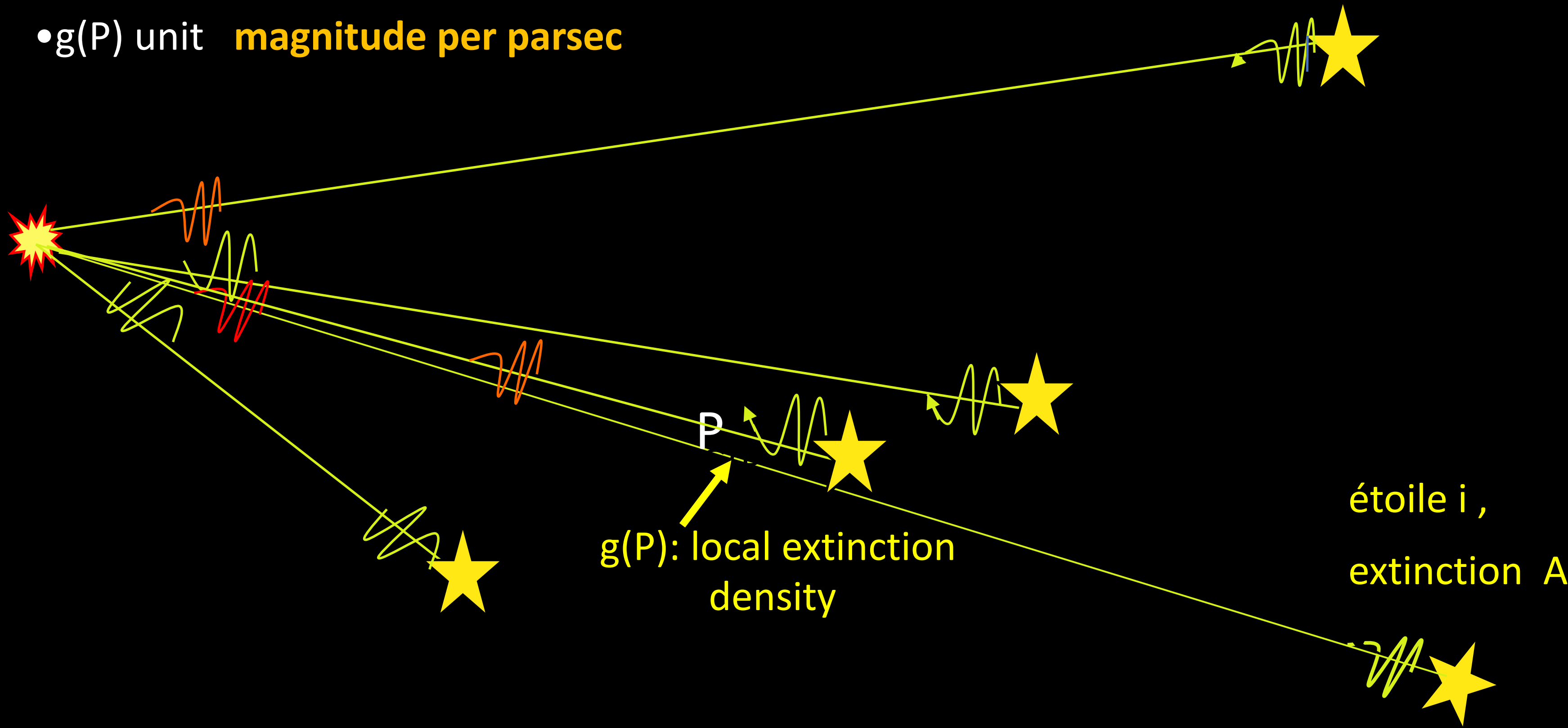


Latest map: REDDENING/extinction of the light of a 41 millions stars: inversion to produce 3D maps of the intervening dust

REDDENING/extinction of the light of a large catalog of stars: inversion to produce 3D maps of the intervening dust



- Goal: estimate for **each point P in 3D space** the local extinction density g(P)
- g(P) is the **extinction per distance** a light ray suffers when crossing the point P region
- g(P) unit **magnitude per parsec**

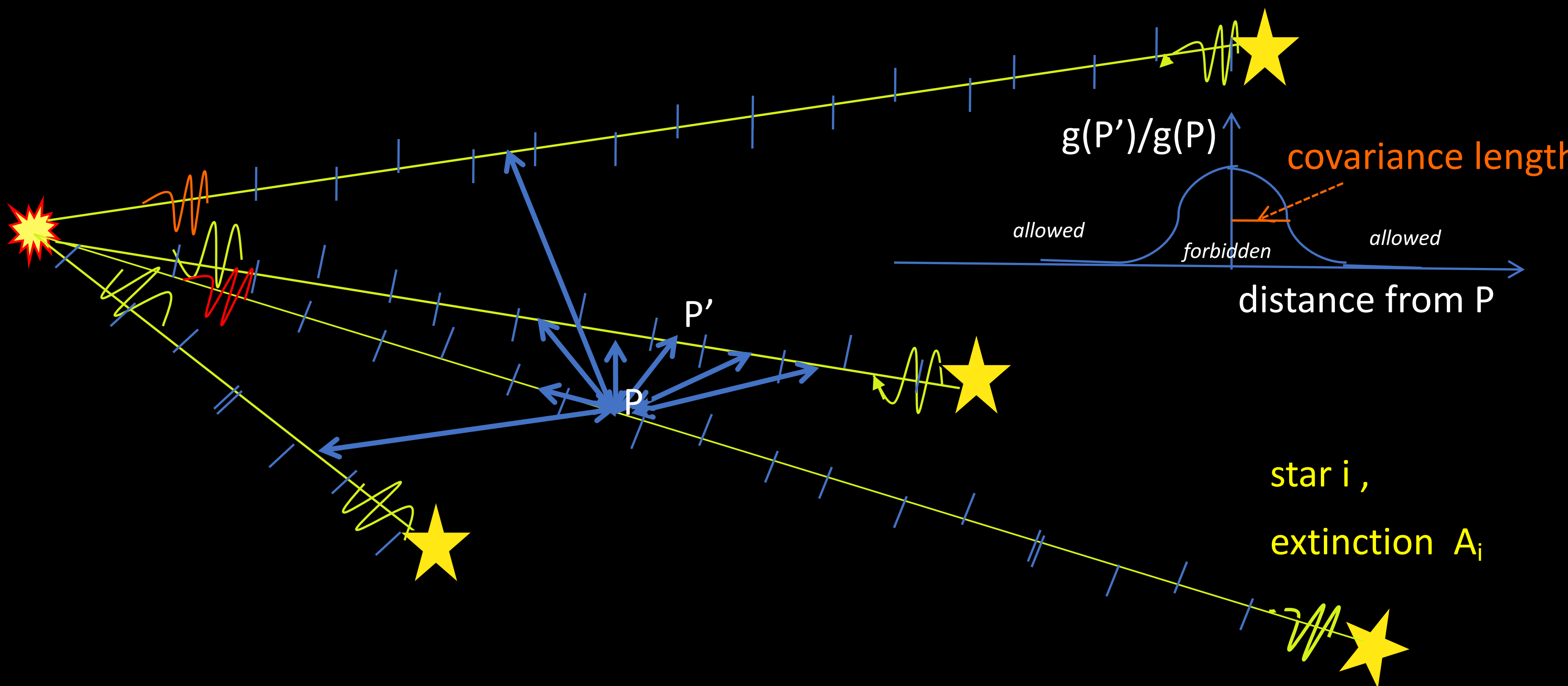


- Data: individual extinctions $A_i = \int g(P)\, dP$ i= 1, N (all N stars)

A **highly undetermined problem:➔ requires regularization**

Choice of Bayesian methods with well adapted prior solutions

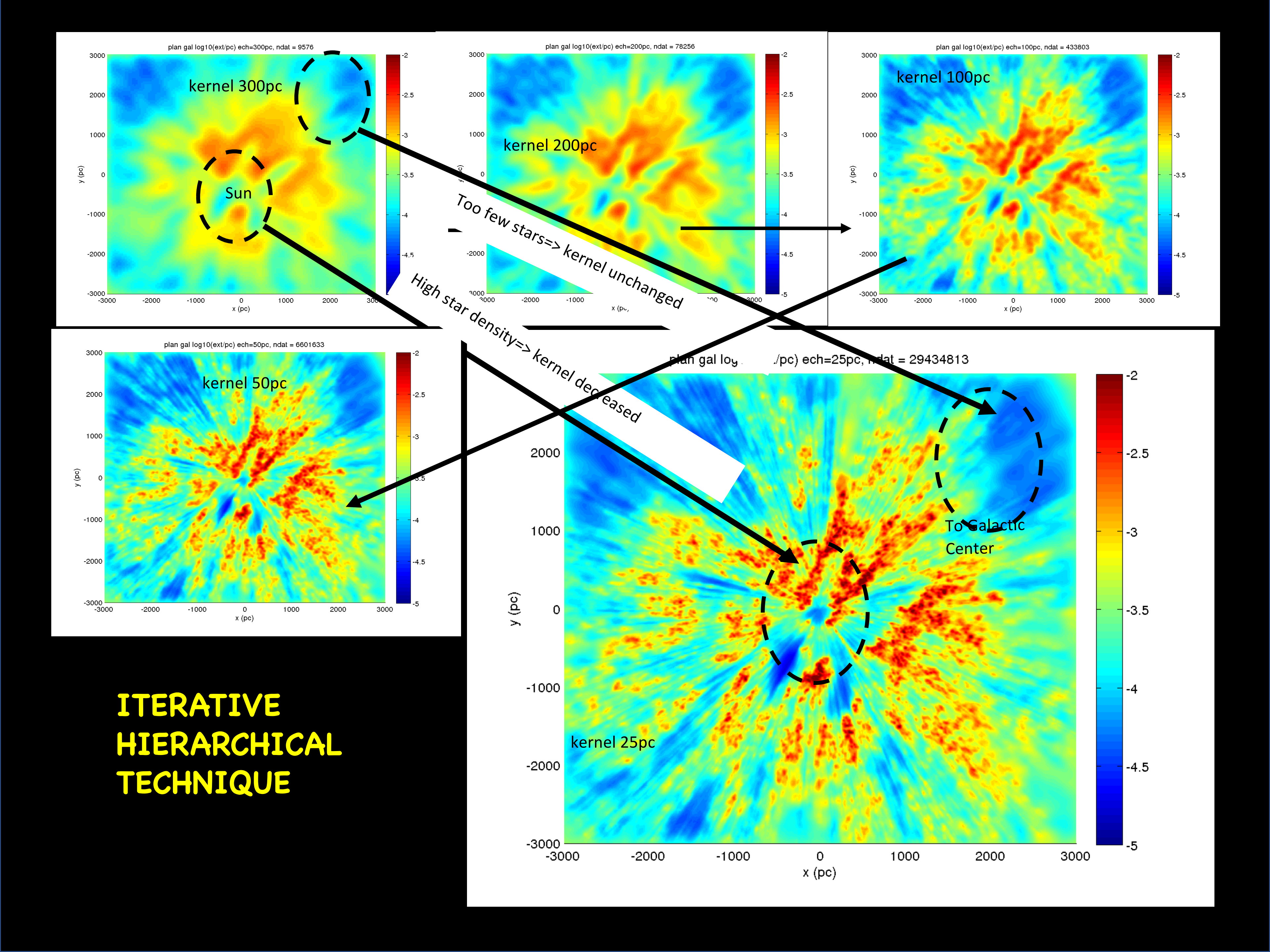
Full 3D tomography: omni-directional regularization



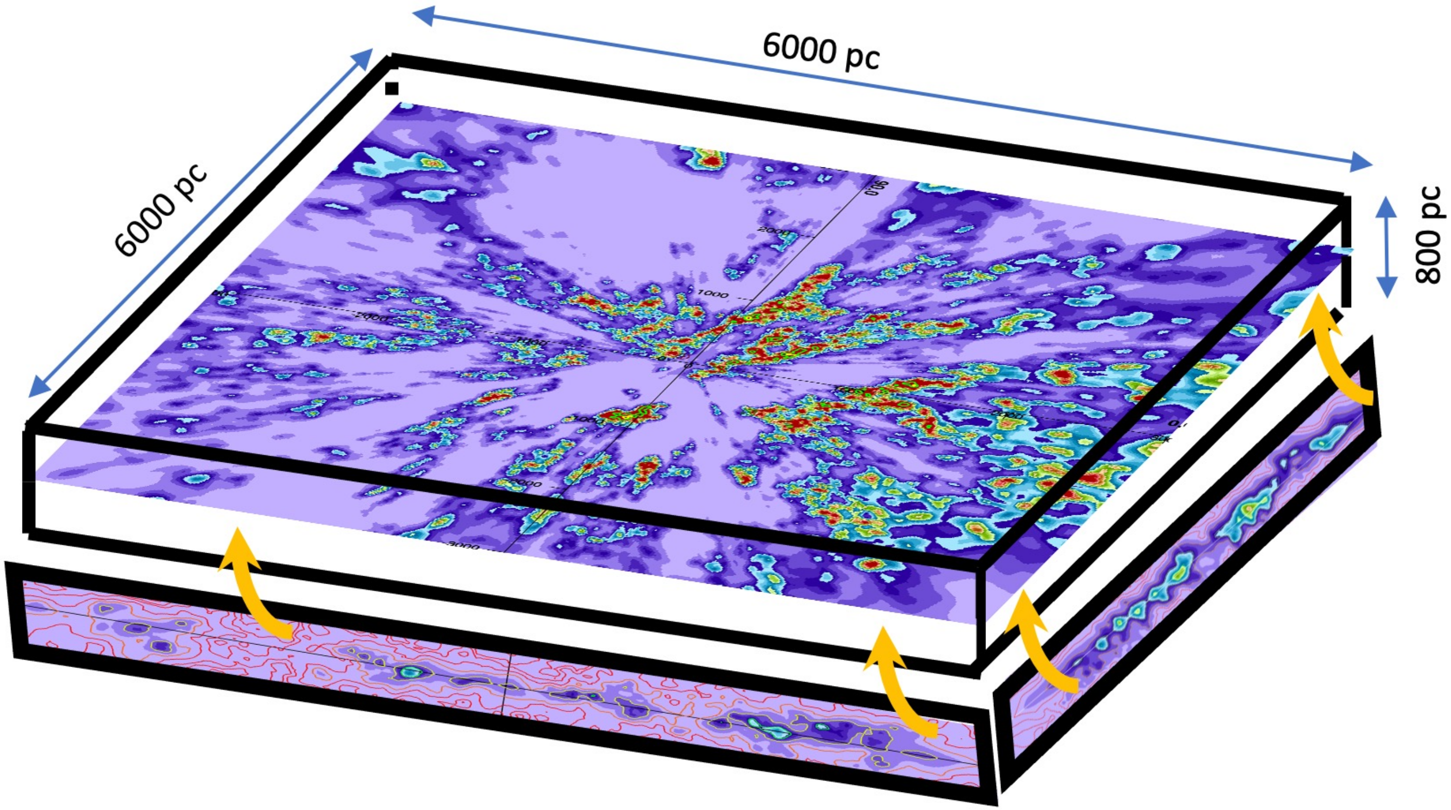
- 3D covariance kernel(s) => minimum size of structures (regularization)=> g(P')/g(P) limited

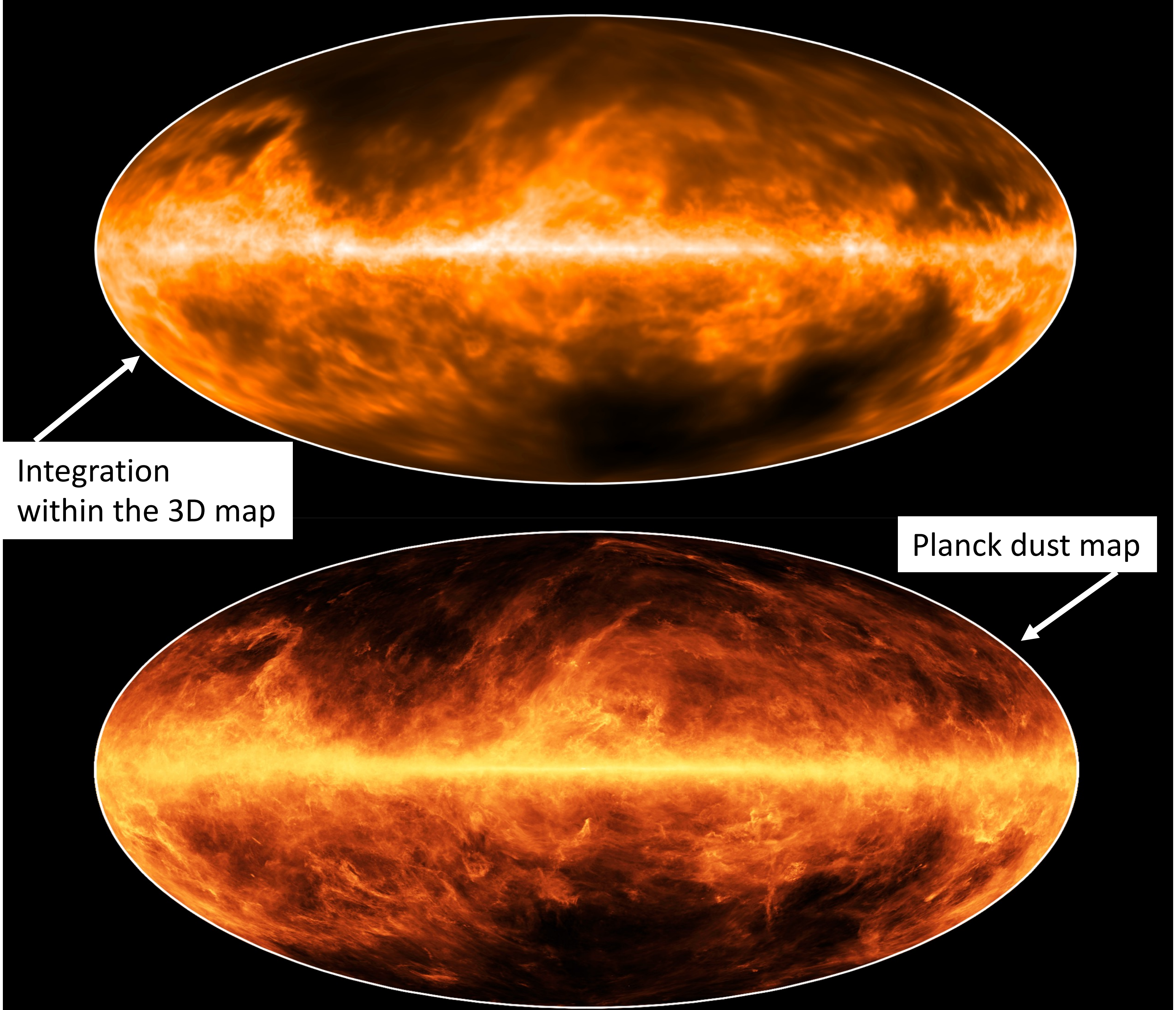
See Tarantola & Valette, 1982, Vergely et al, 2000, 2010, Lallement et al, 2014, 2018 , Capitanio et al, 2017 for applications of the above method

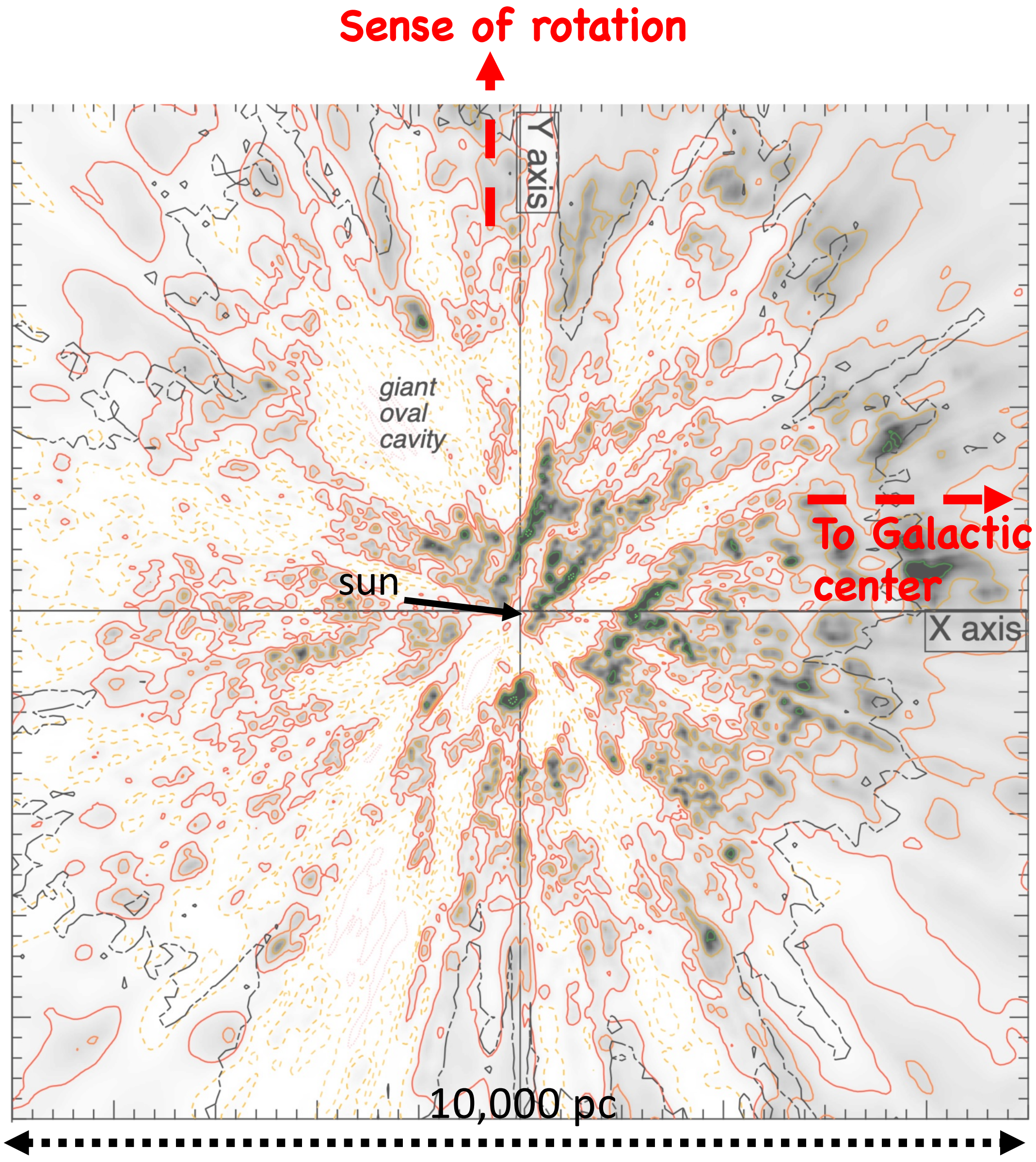
+ prior conditions on the 3D distribution (Bayesian aspect)


plan gal log10(ext/pc) ech=300pc, ndat = 9576
kernel 300pc
Sun
plan gal log10(ext/pc) ech=200pc, ndat = 78256
kernel 200pc
plan gal log10(ext/pc) ech=100pc, ndat = 433803
kernel 100pc
Too few stars=> kernel unchanged
High star density=> kernel decreased
plan gal log10(ext/pc) ech=50pc, ndat = 6601633
kernel 50pc
./pc) ech=25pc, ndat = 29434813
To Galactic Center
kernel 25pc
x (pc)
y (pc)
ITERATIVE
HIERARCHICAL
TECHNIQUE

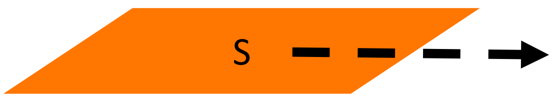
Extinction density 3D distribution (at 5500 A) around the Sun (here 6 kpc x 6 kpc x 0.8 kpc)




Integration
within the 3D map
Planck dust map

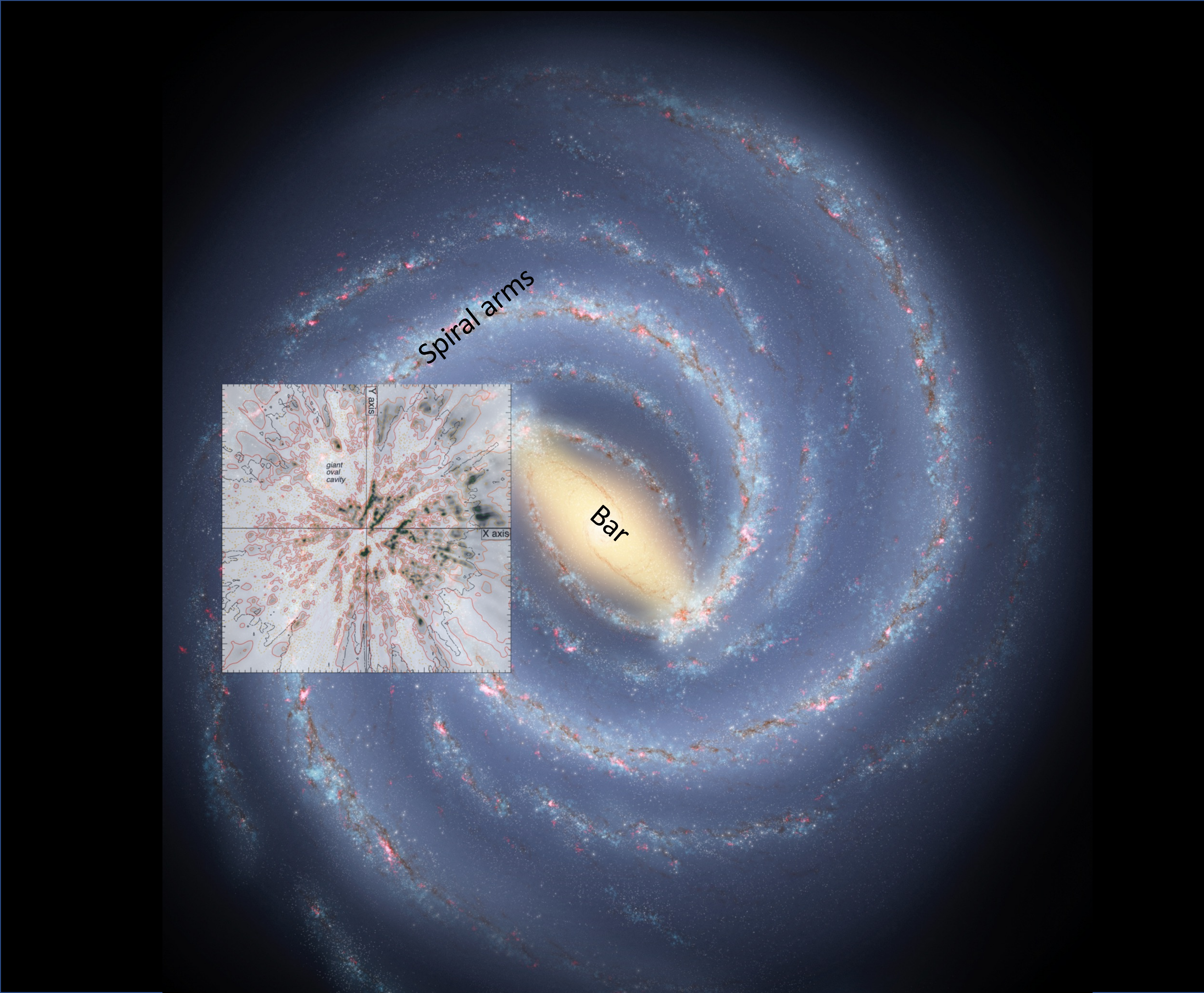


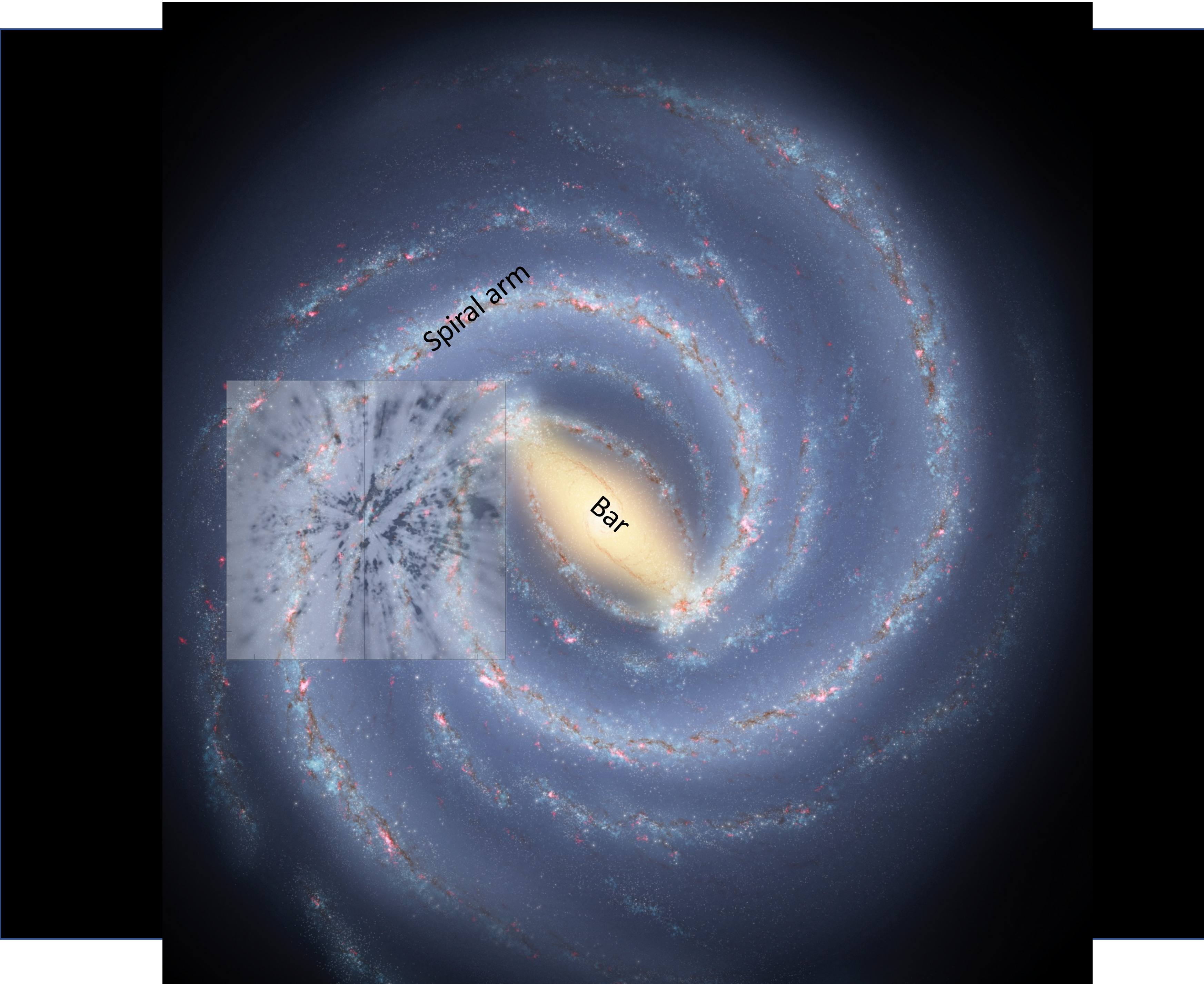
Galactic Plane = Plane of the image

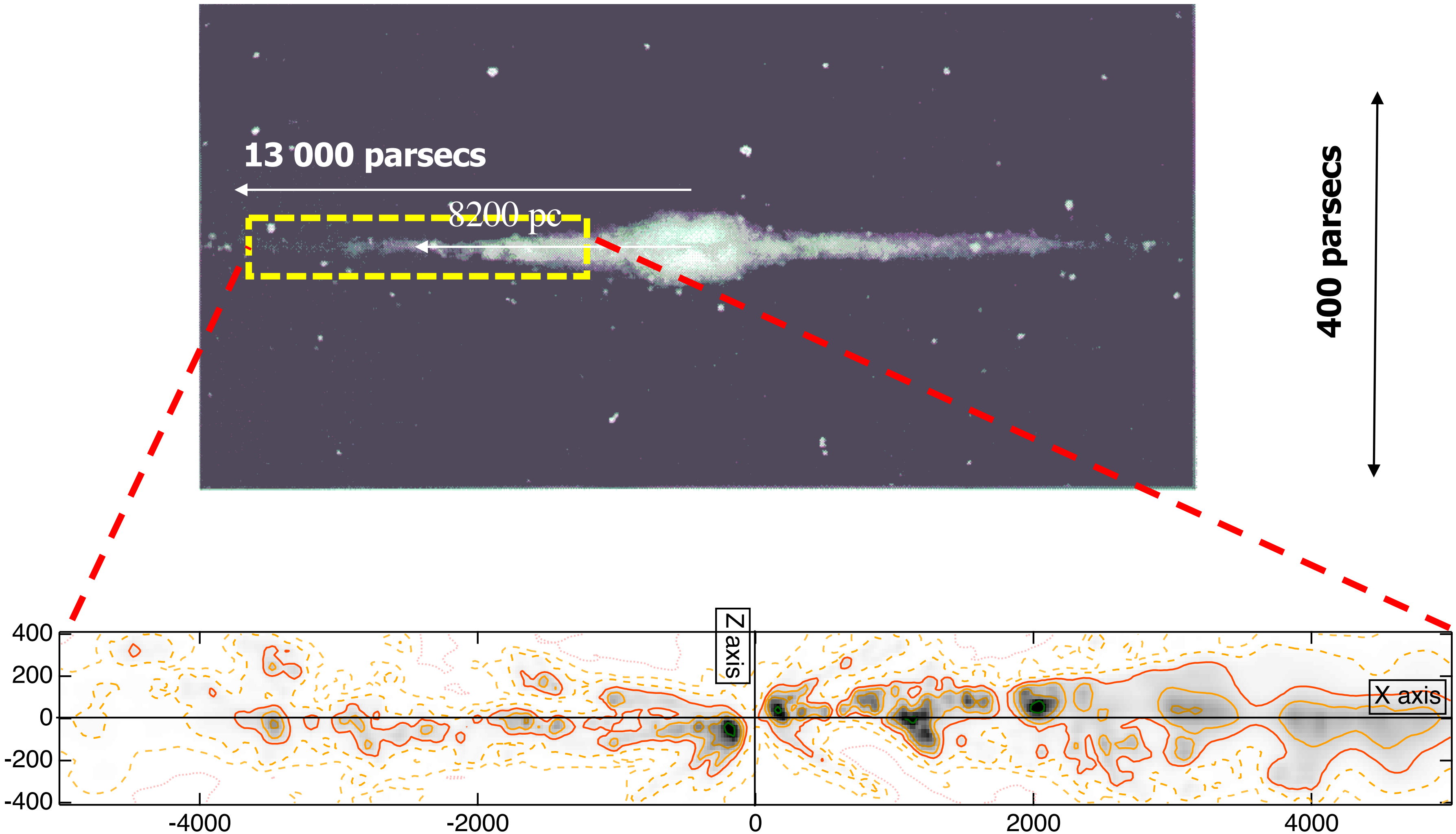


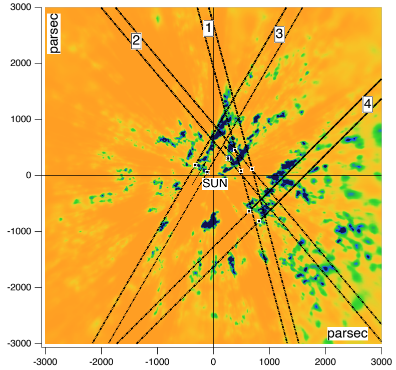
Black: dense dust clouds

Represented quantity:
extinction per parsec (in mag)

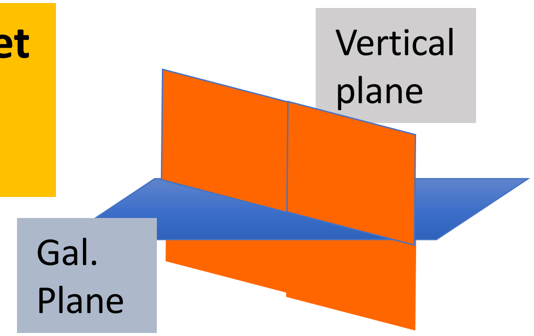

Spiral arms
Bar
giant
oval
cavity
Y axis
X axis

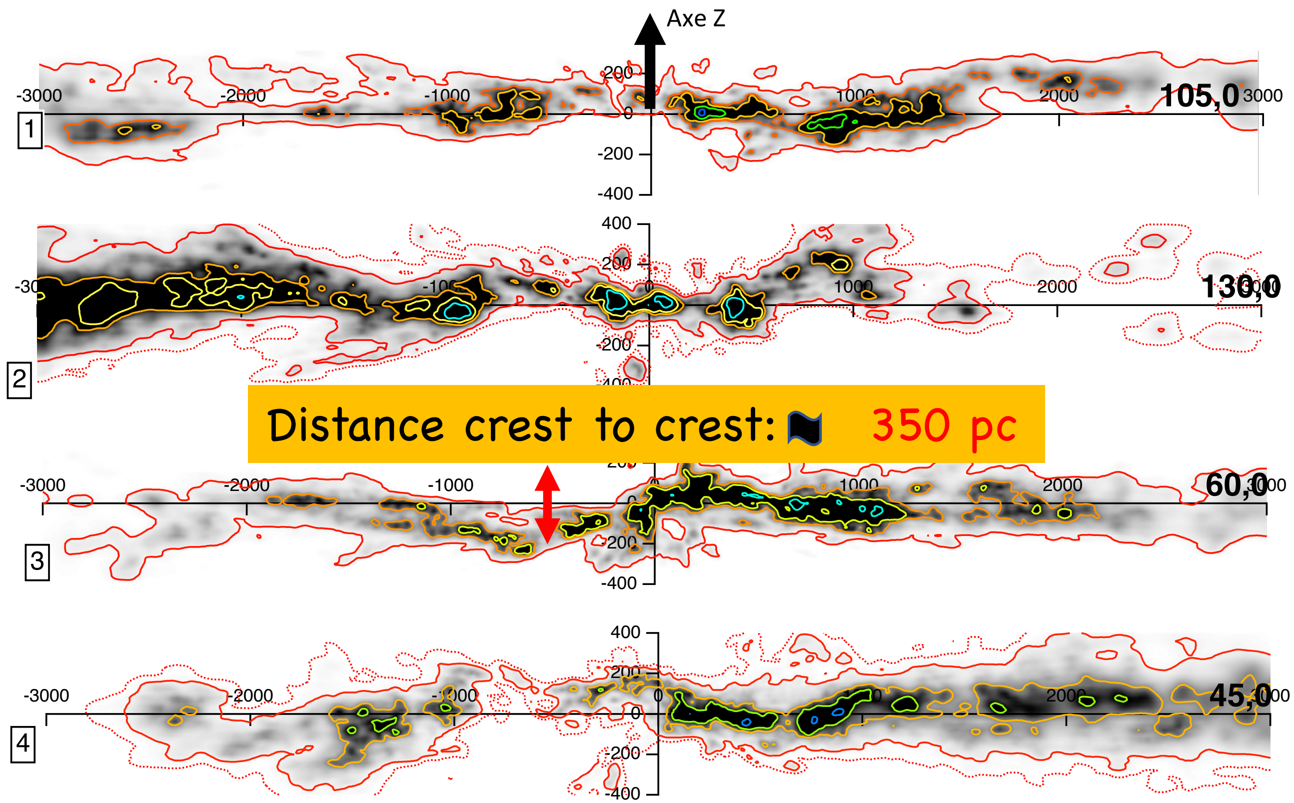

Spiral arm
Bar


13 000 parsecs
8200 pc
400 parsecs
Z axis
X axis
400
200
0
-200
-400
-4000
-2000
0
2000
4000

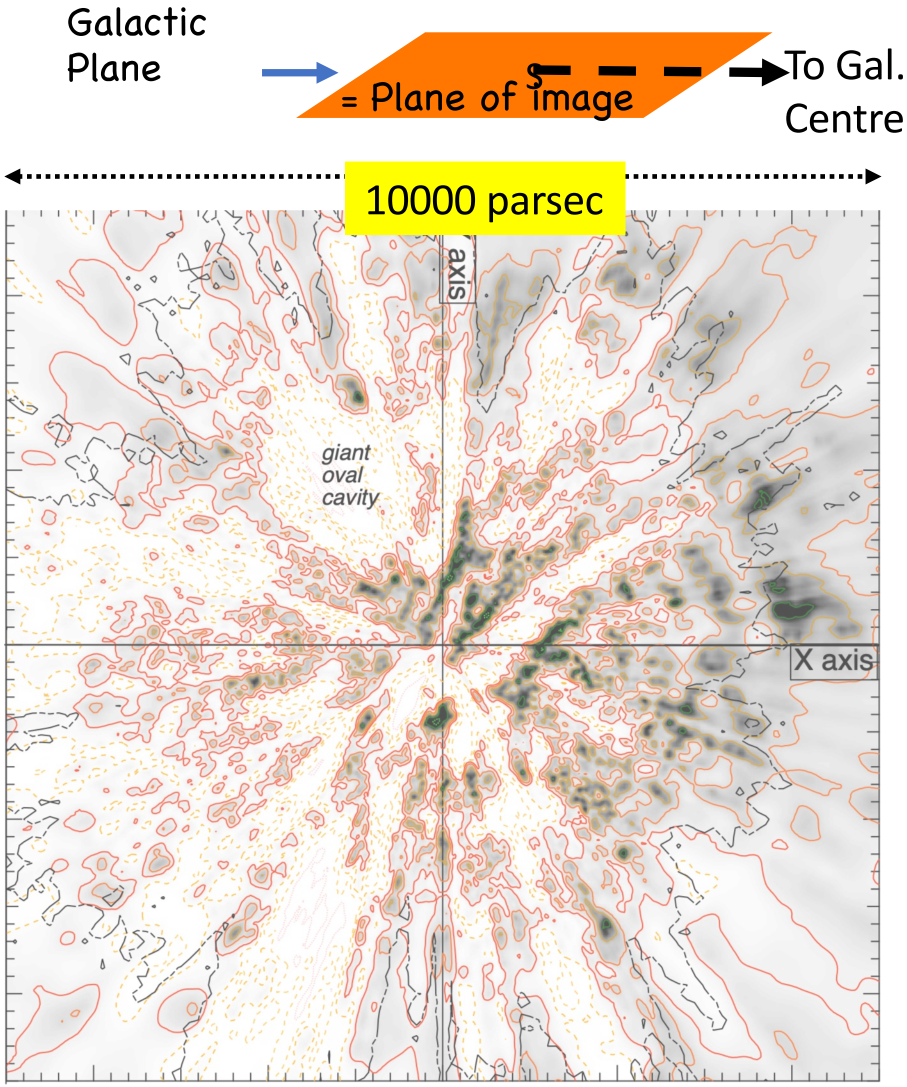


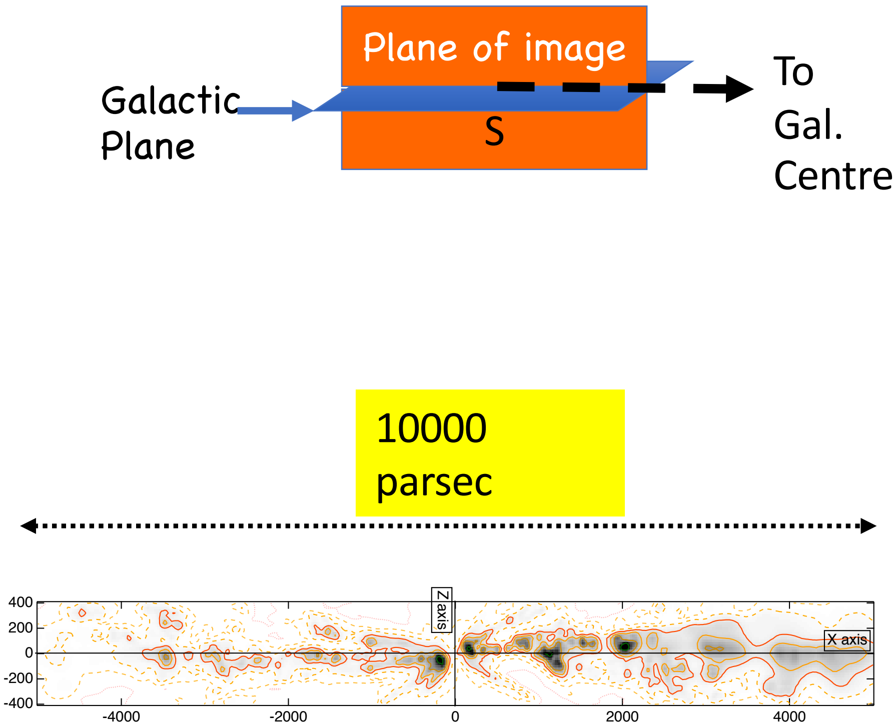
Ondulations of the dust sheet around the Galactic plane: vertical planes

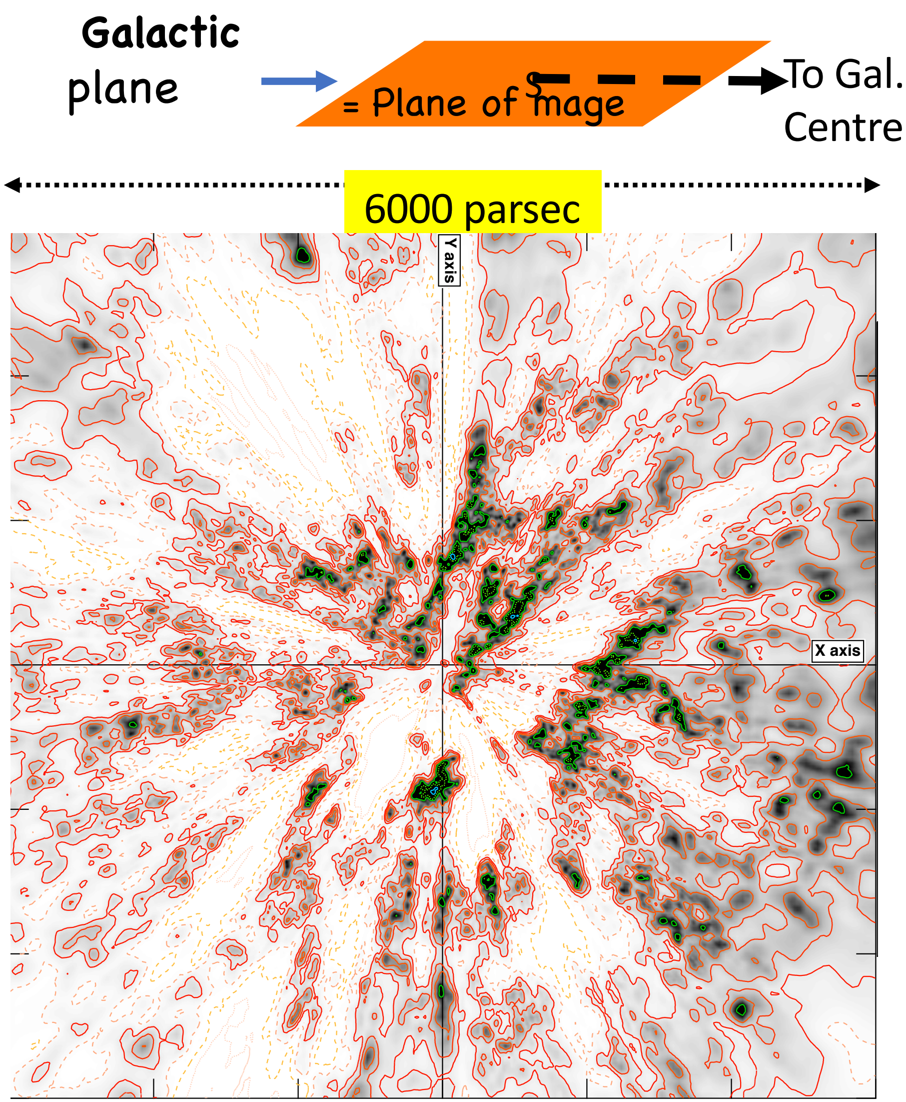


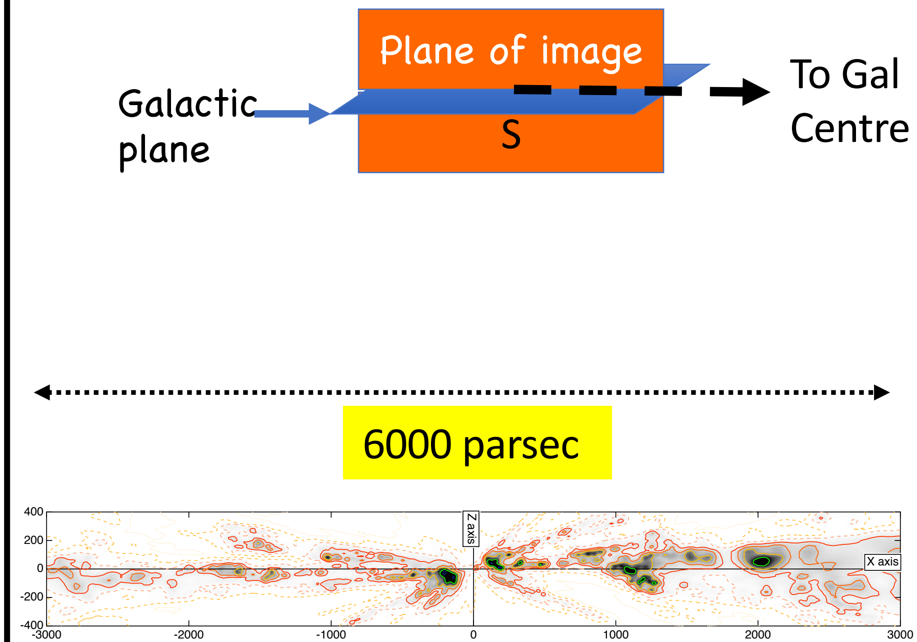


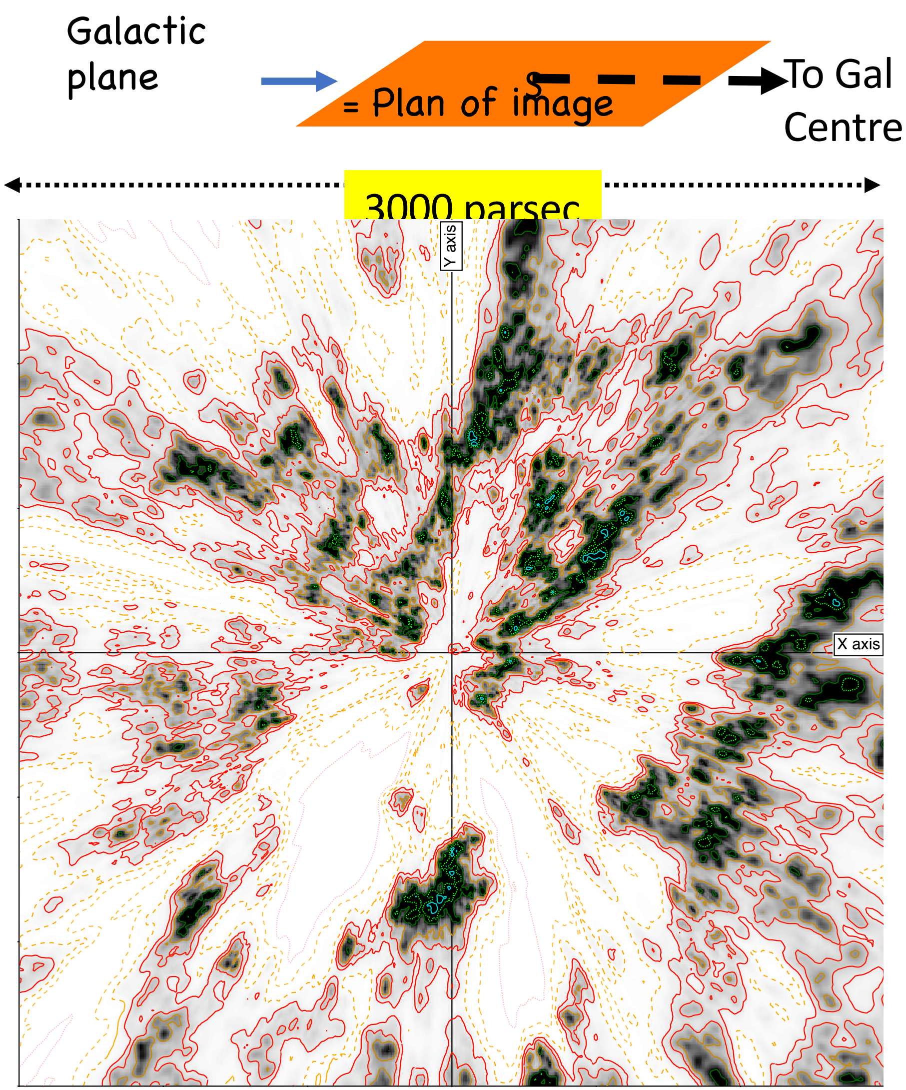
Distance crest to crest: 350 pc


Galactic Plane
= Plane of image
S
To Gal. Centre
10000 parsec
axis
giant oval cavity
X axis

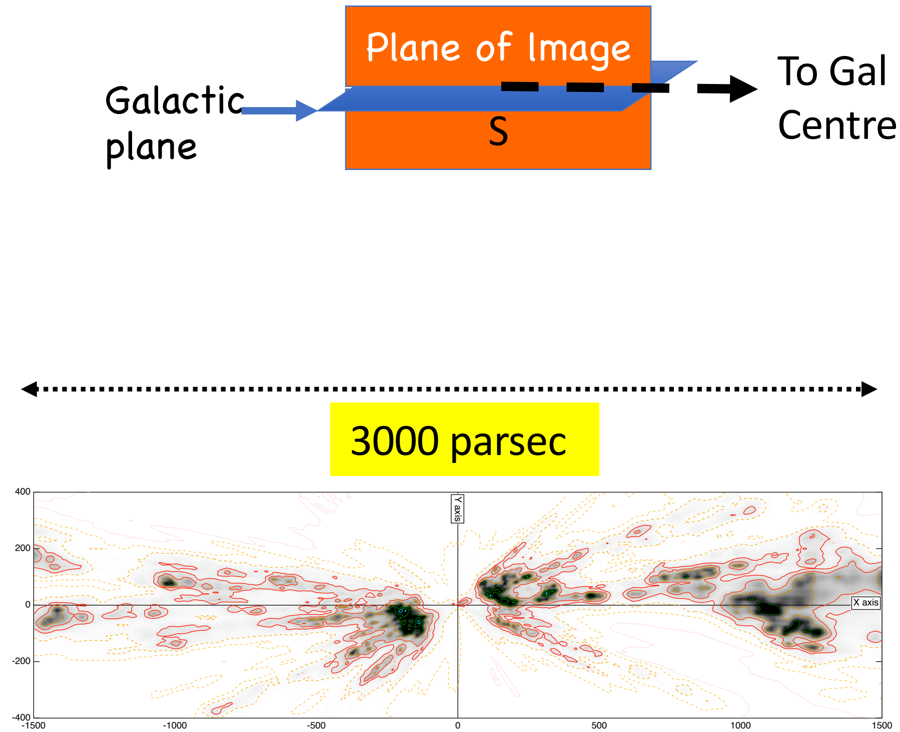

Plane of image
Galactic Plane
S
To Gal. Centre
10000 parsec
Z axis
X axis
400
200
0
-200
-400
-4000
-2000
0
2000
4000


Galactic plane
= Plane of image
S
To Gal. Centre
6000 parsec
Y axis
X axis

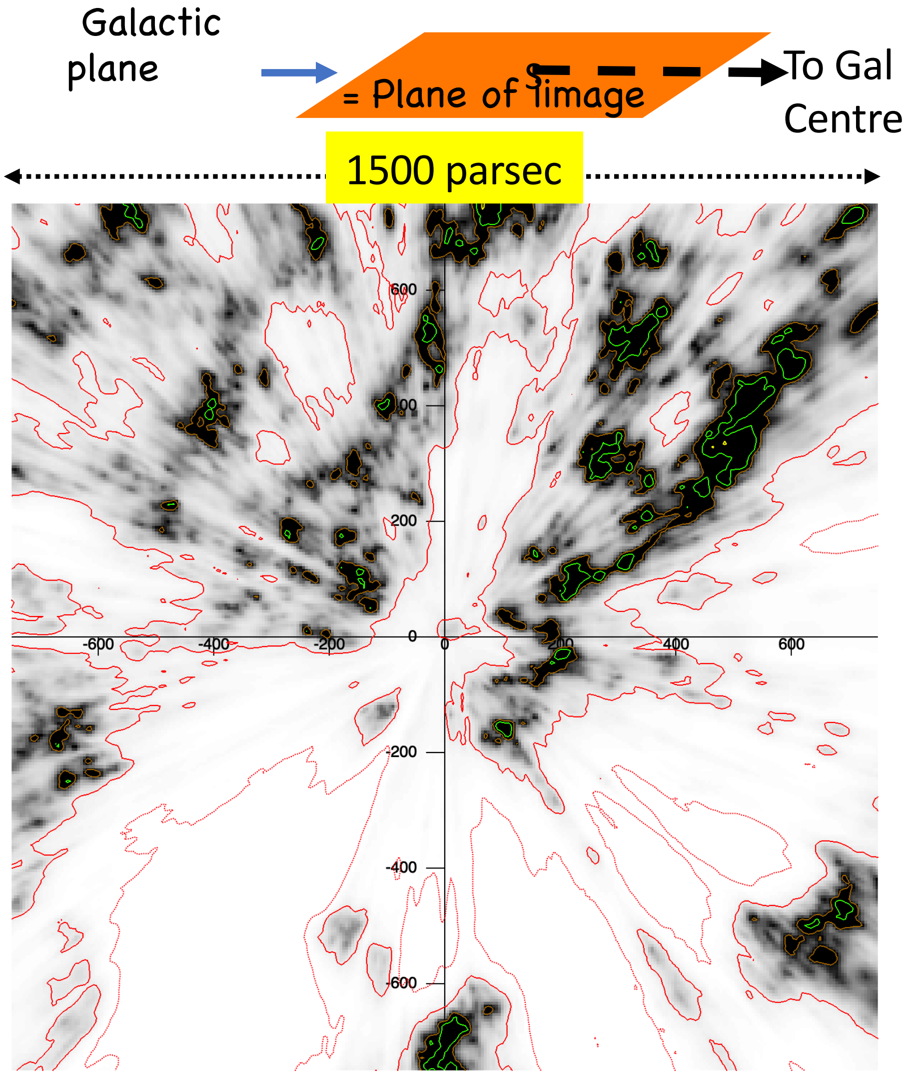

Plane of image
Galactic plane
S
To Gal Centre
6000 parsec
Z axis
X axis
400
200
0
-200
-400
-3000
-2000
-1000
0
1000
2000
3000

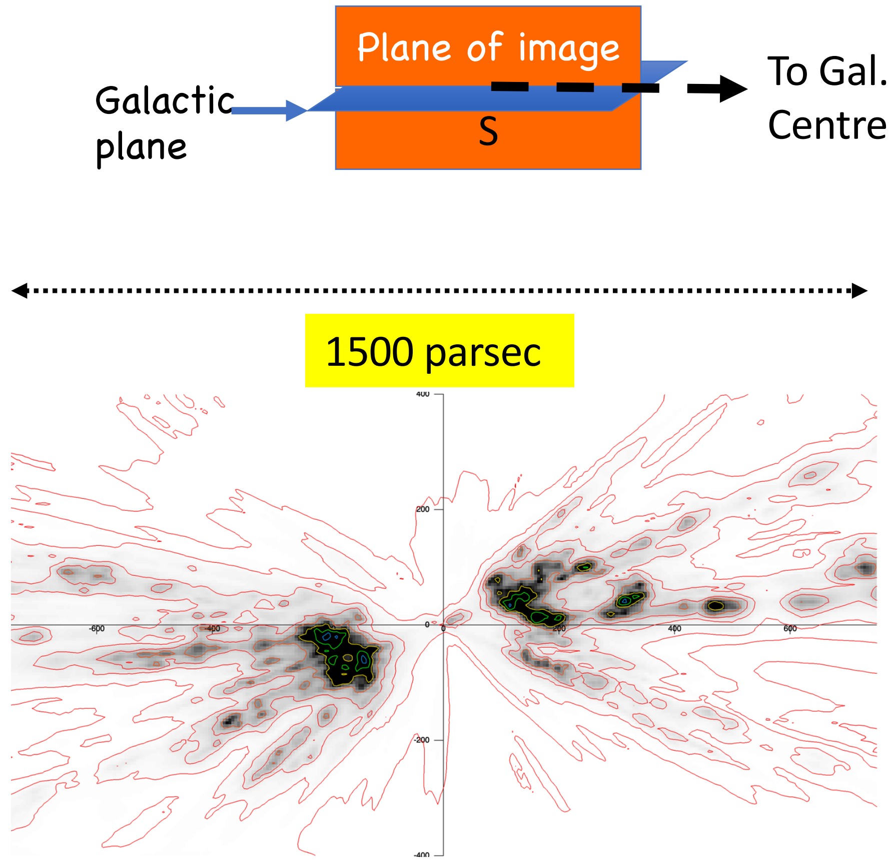


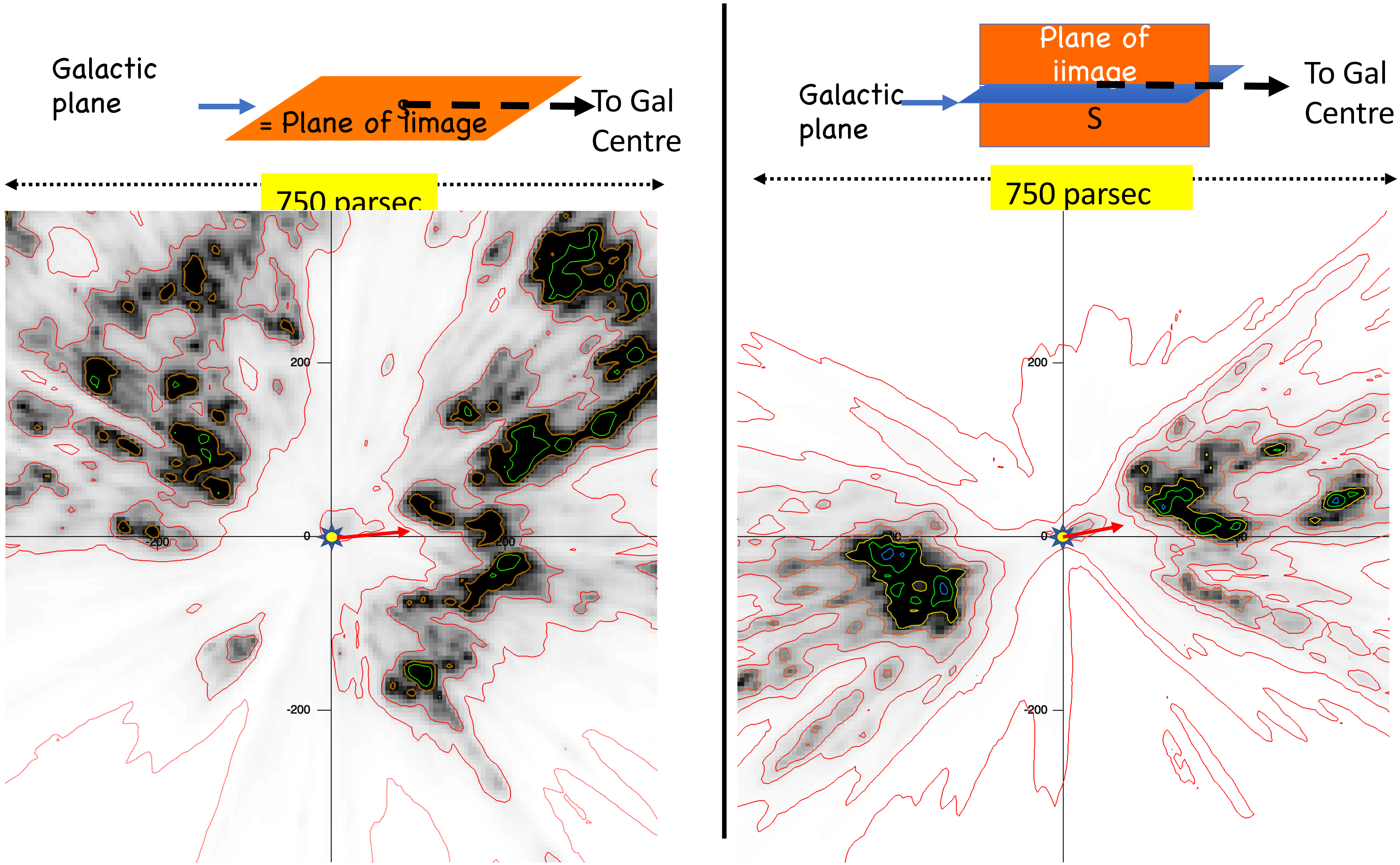
Galactic plane
= Plan of image
S
To Gal Centre
3000 parsec
Y axis
X axis

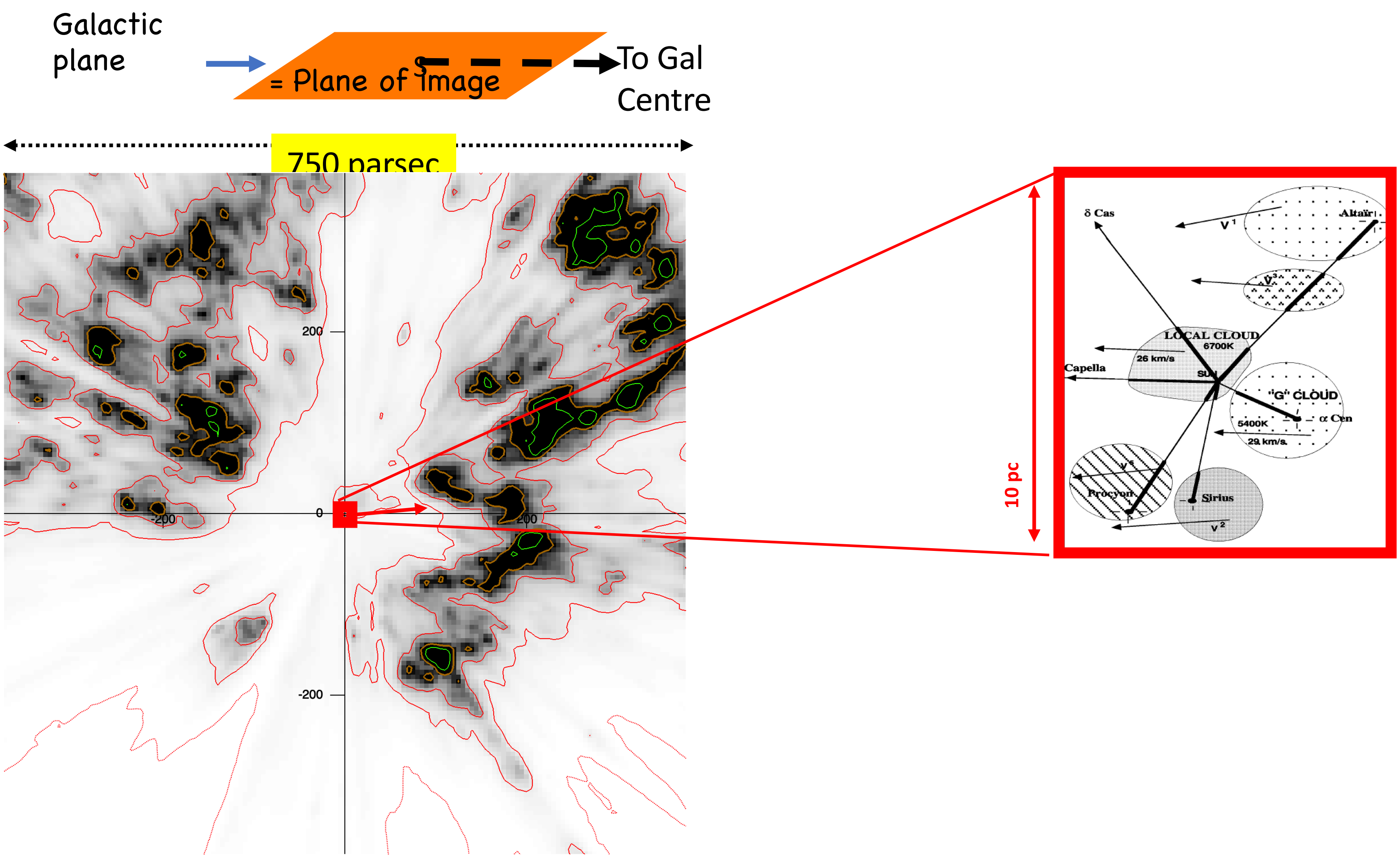


Plane of Image
Galactic plane
S
To Gal Centre
3000 parsec
Y axis
X axis
400
200
0
-200
-400
-1500
-1000
-500
0
500
1000
1500


Galactic plane
= Plane of image
S
To Gal Centre
1500 parsec
600
400
200
0
-200
-400
-600
-600
-400
-200
0
200
400
600


Plane of image
Galactic plane
S
To Gal. Centre
1500 parsec


Galactic plane
= Plane of iimage
S
To Gal Centre
750 parsec
200
0
-200
200
-200
Plane of iimage
Galactic plane
S
To Gal Centre
750 parsec
200
0
-200

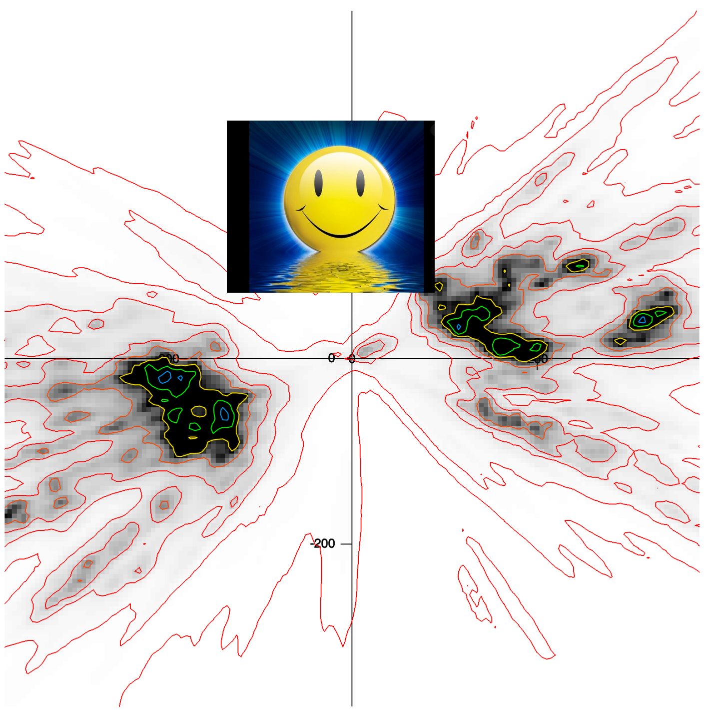

Galactic plane
= Plane of image
To Gal Centre
750 parsec
200
0
-200
200
-200
10 pc
δ Cas
Altair
Capella
LOCAL CLOUD
6700K
26 km/s
"G" CLOUD
5400K
α Cen
29 km/s
Procyon
Sirius

Our location in the Galaxy

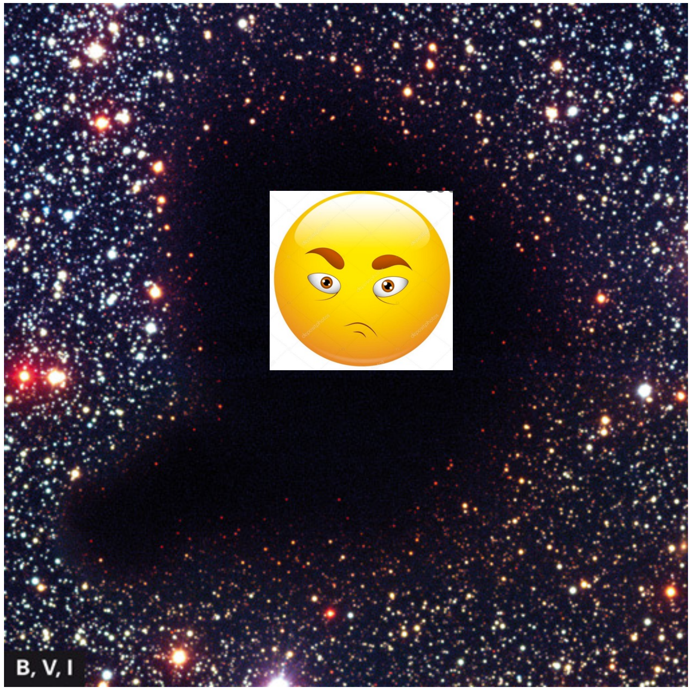
-We have starry nights!

« **C'est une bien faible** lumière qui nous vient du ciel **étoilé**. Que serait pourtant la pensée humaine si nous ne pouvions pas percevoir ces **étoiles** ?

« It is a very weak light that comes to us from the starry sky. But what would human thought be if we could not perceive these stars? » Jean Perrin

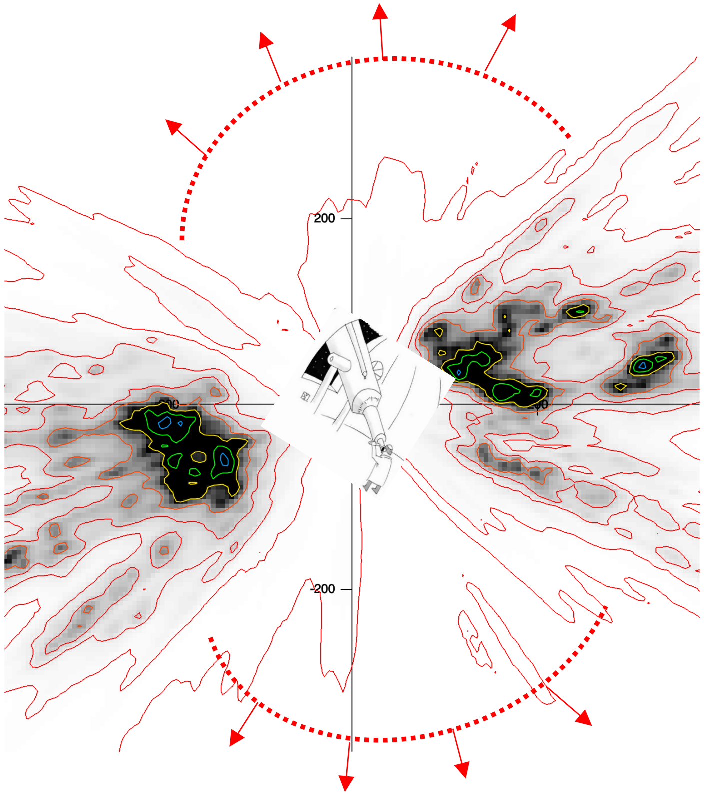


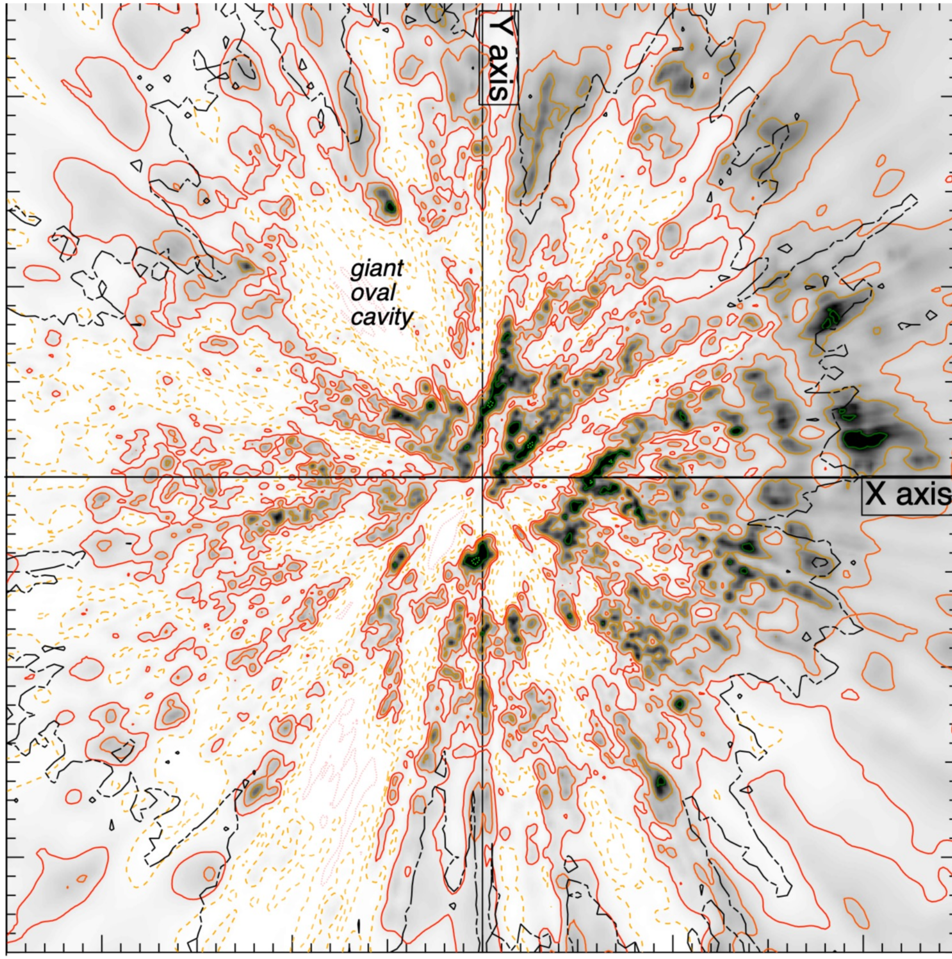
Barnard 68 30 mag extinction at center

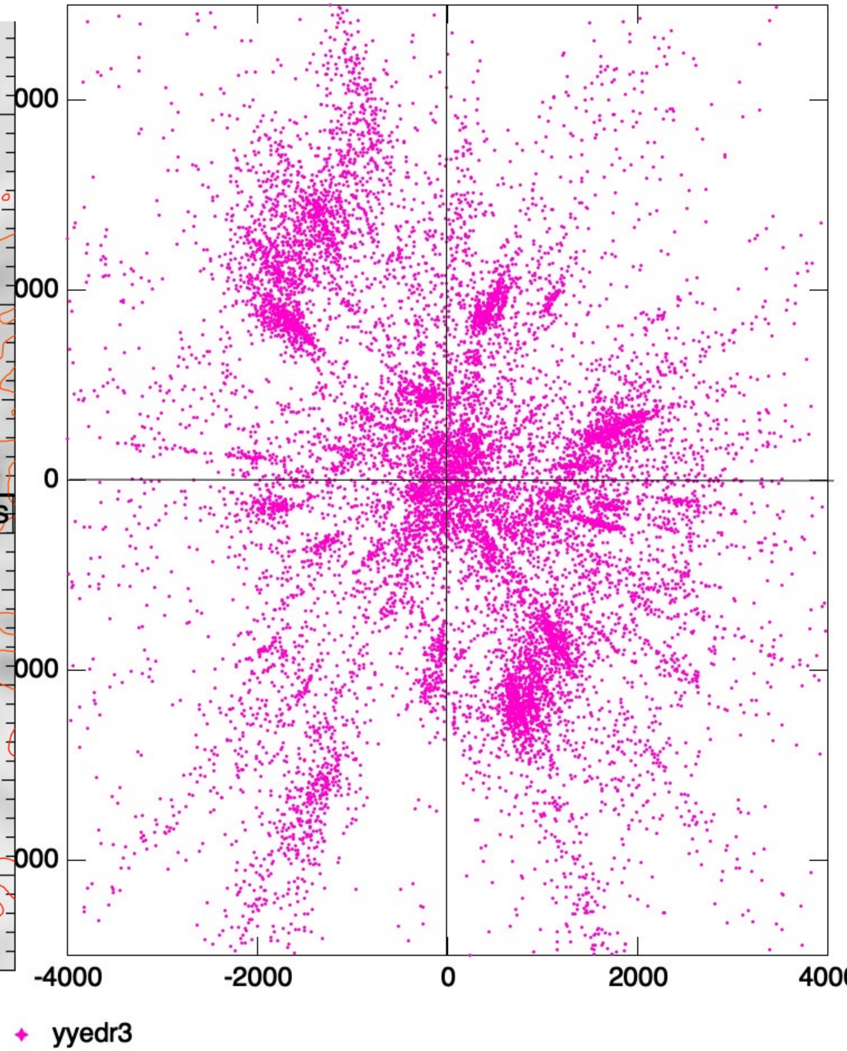


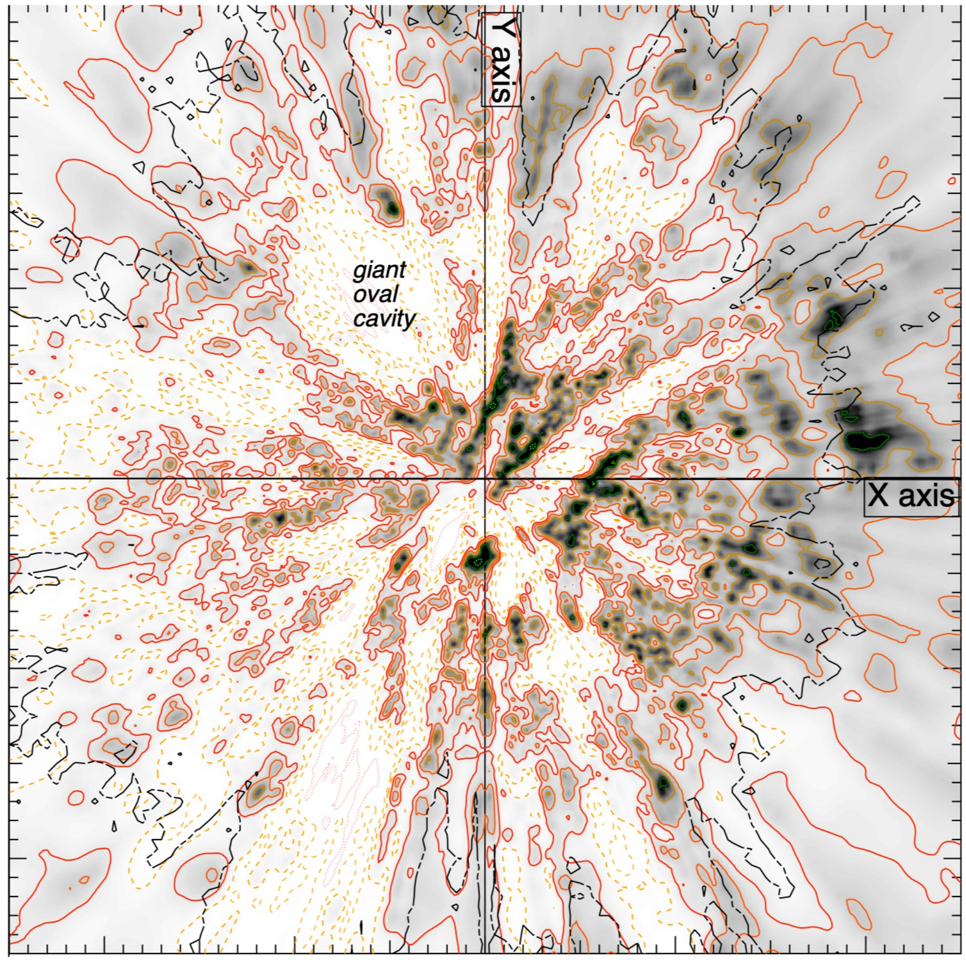
-Unobscure view toward Northern and Southern halos

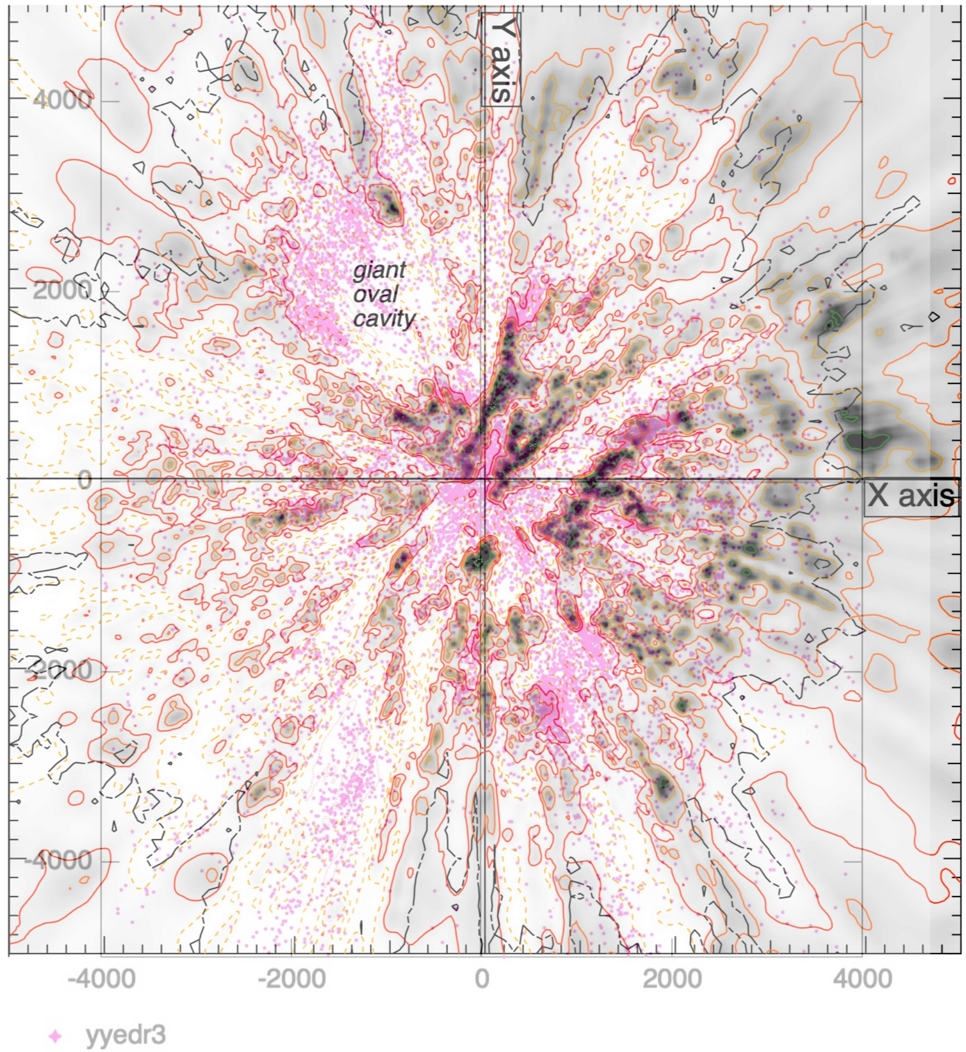
=> Extragalactic, CMB, etc..



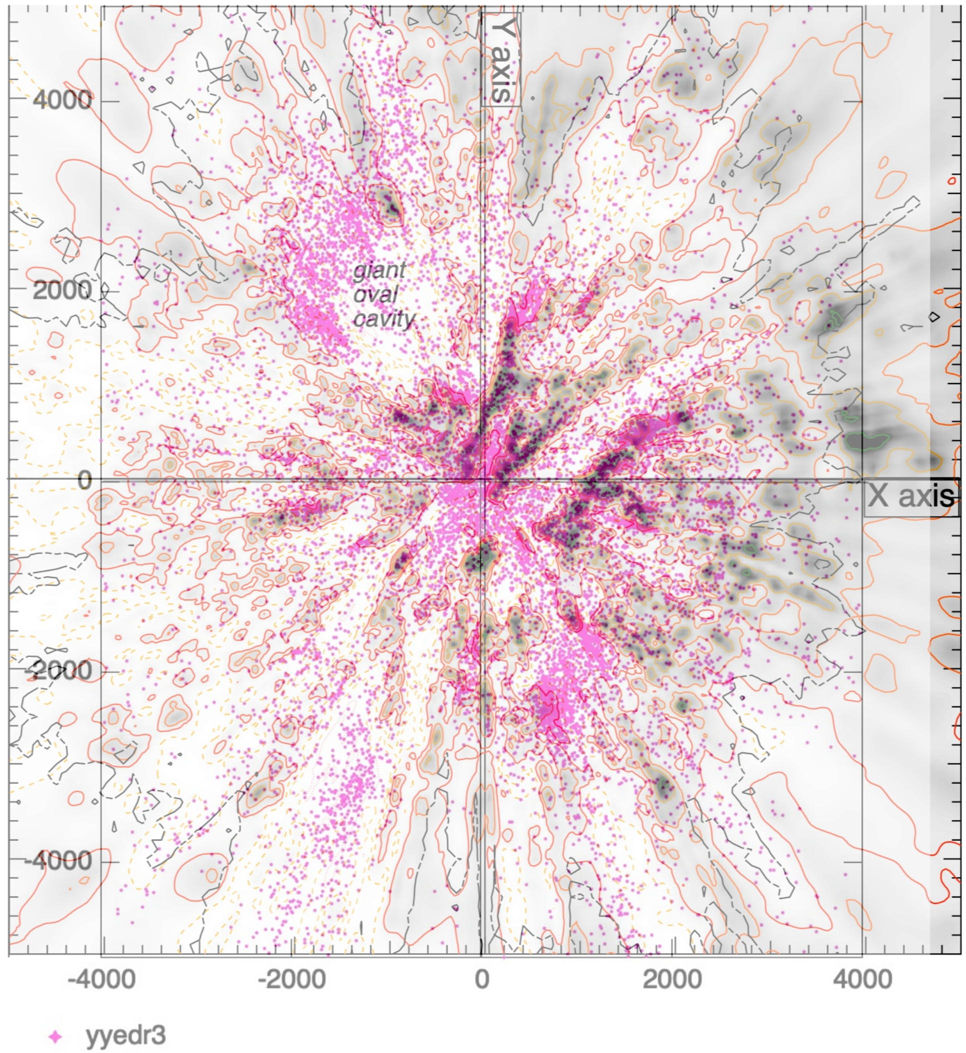

Y axis
giant
oval
cavity
X axis


000
000
0
000
000
-4000
-2000
0
2000
4000
yyedr3

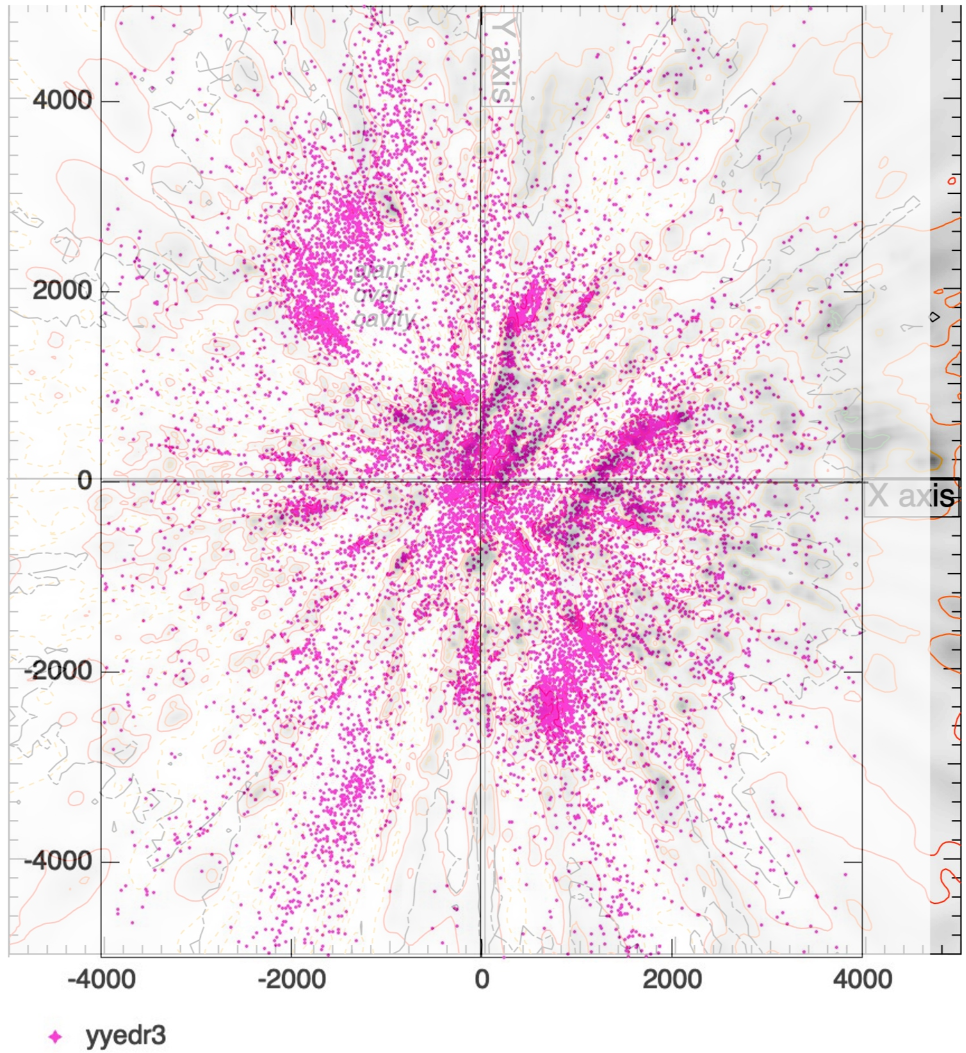

Y axis
giant
oval
cavity
X axis

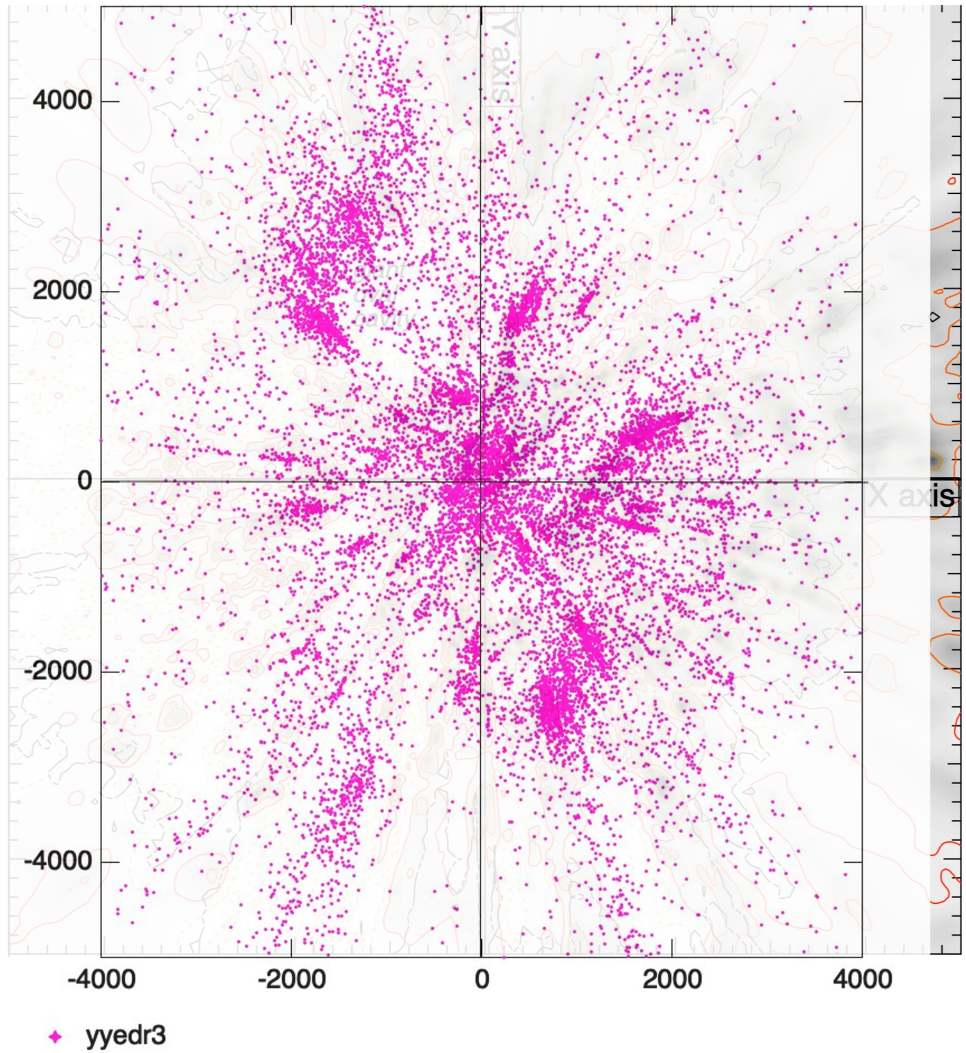


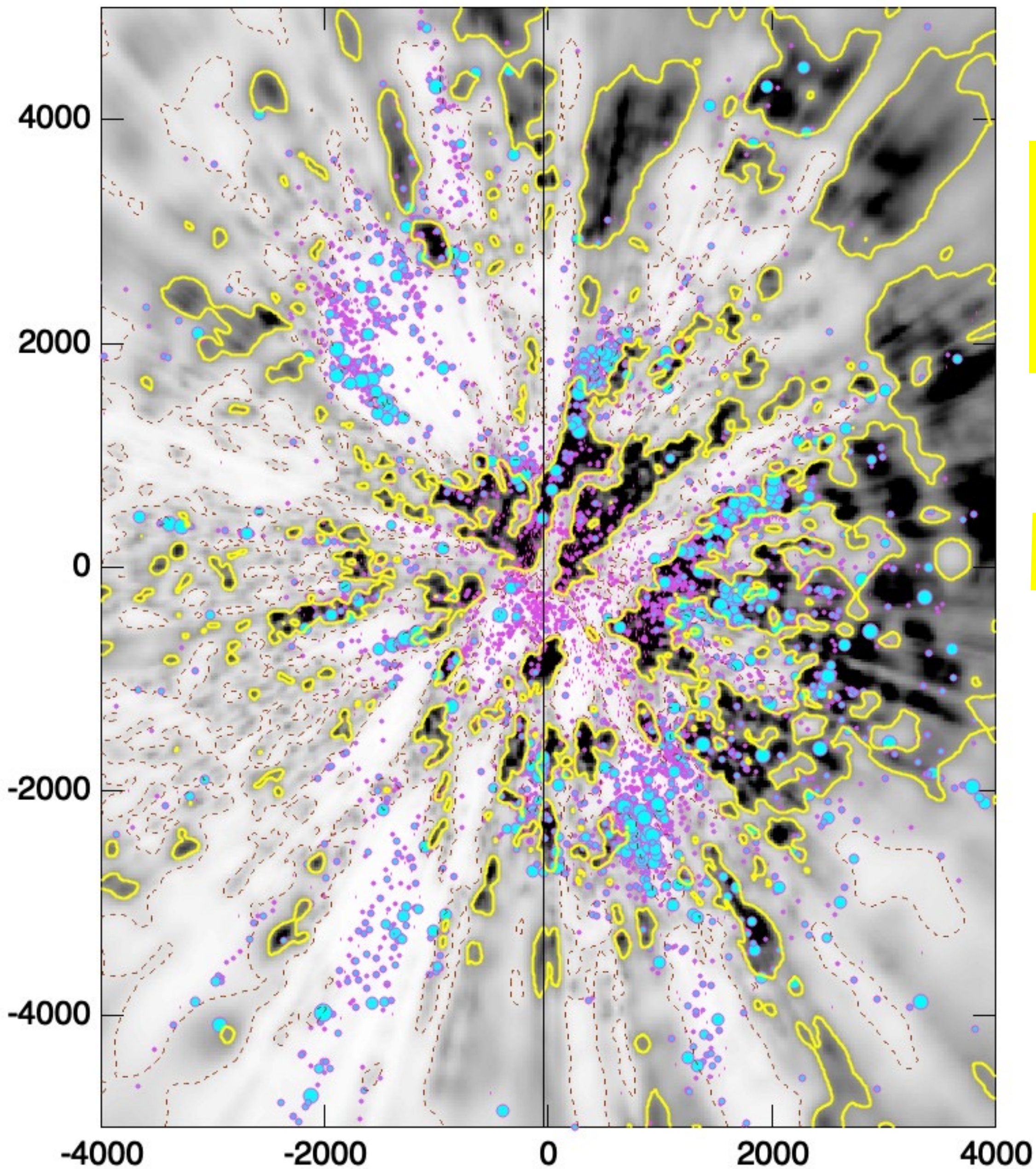
Y axis
X axis
giant
oval
cavity
4000
2000
0
-2000
-4000
-4000
-2000
0
2000
4000
yyedr3



4000
2000
0
-2000
-4000
-4000
-2000
0
2000
4000
Y axis
X axis
giant
oval
cavity
yyedr3


4000
2000
0
-2000
-4000
-4000
-2000
0
2000
4000
Y axis
X axis
yyedr3


4000
2000
0
-2000
-4000
-4000
-2000
0
2000
4000
Y axis
X axis
yyedr3

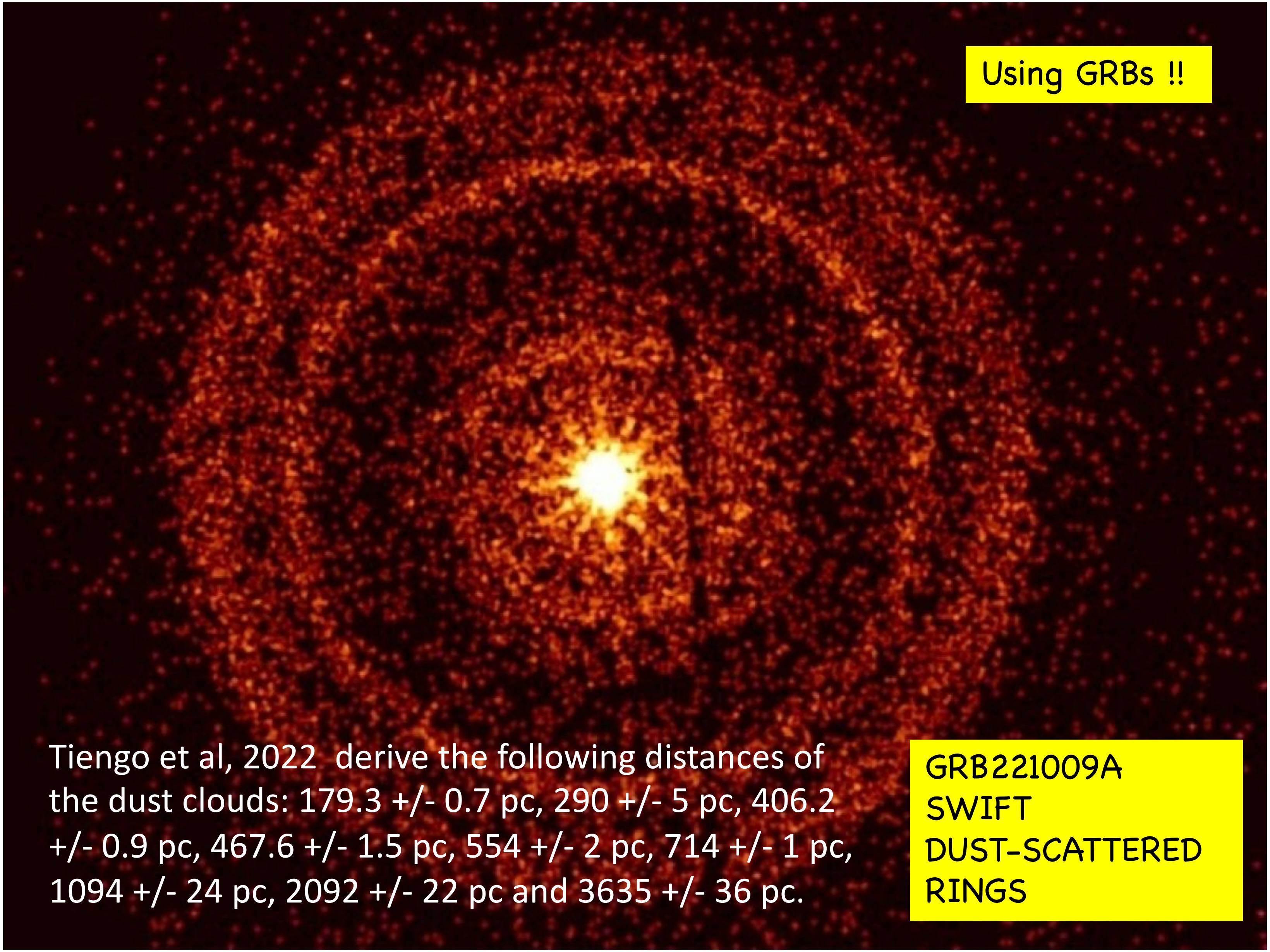


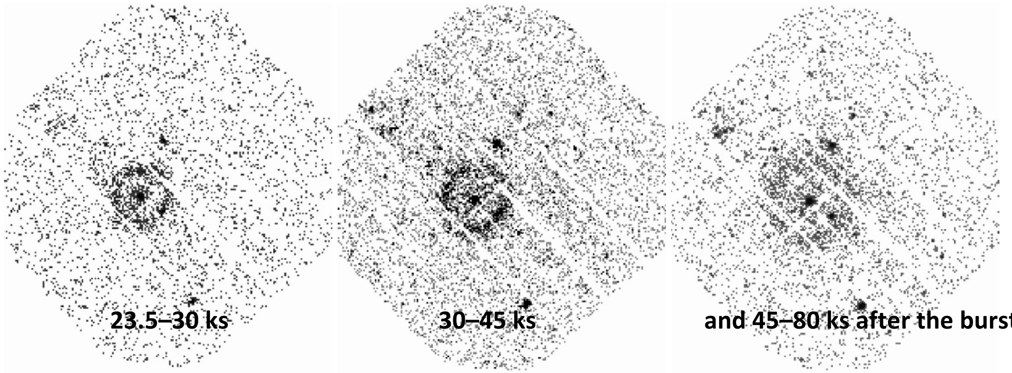
yyedr3Mallz

Massive O, B stars
From blue to pink
O3 to B9

To Galactic Center

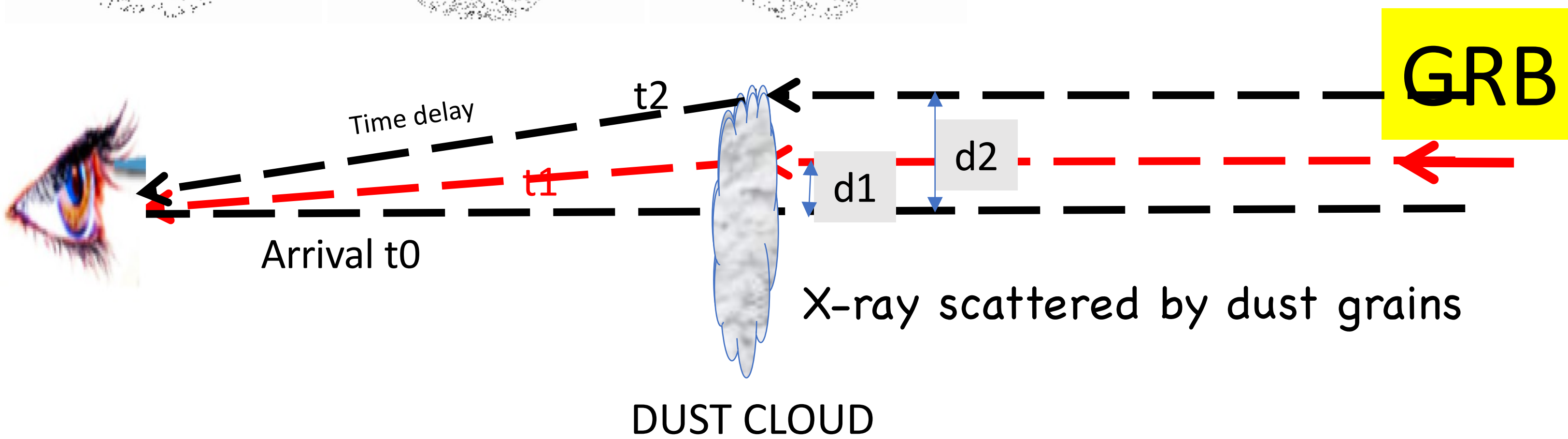
Validation of the reconstructed 3D maps of dust



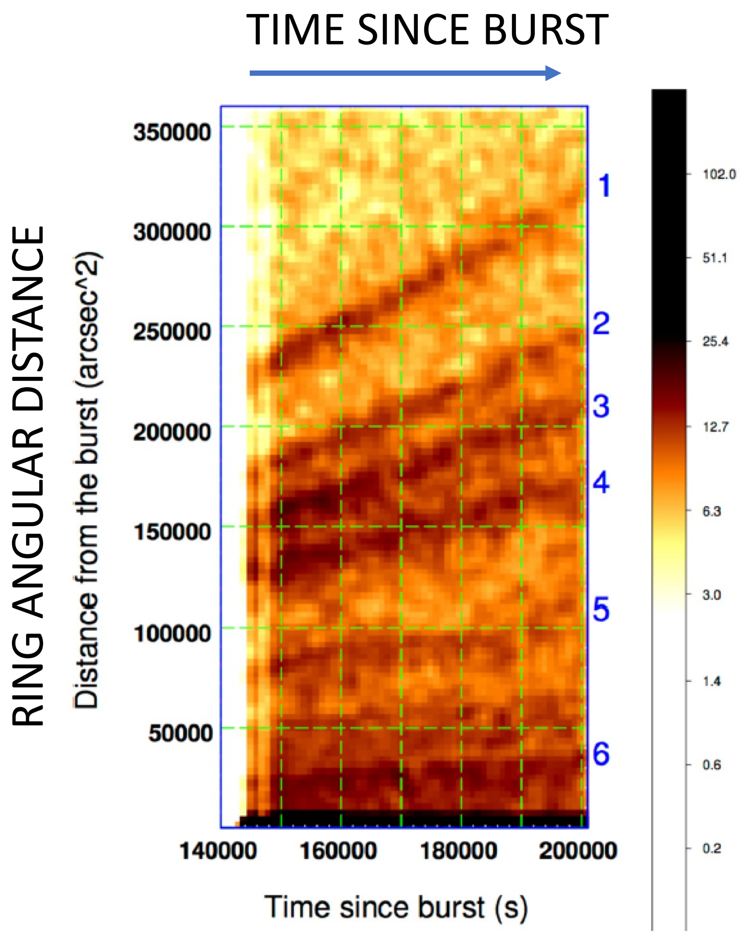


Tiengo et al, 2006,
GRB031203

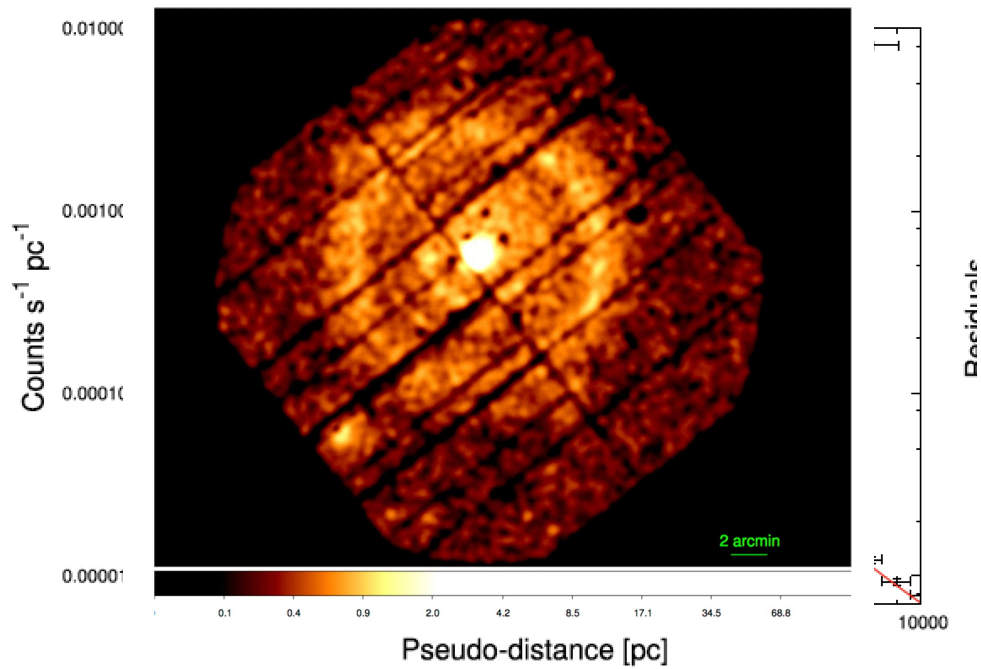
XMM-Newton EPIC-PN

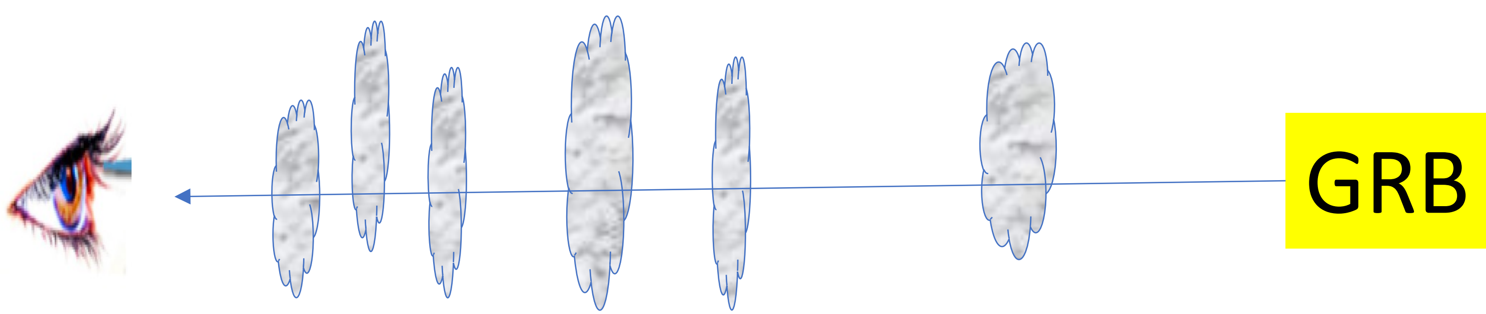


Rings associated with a dust screen increase in size



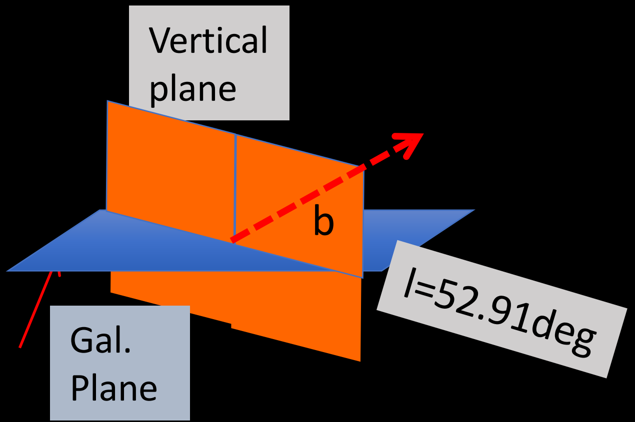
Pintore et al, 2017 GRB 160623A

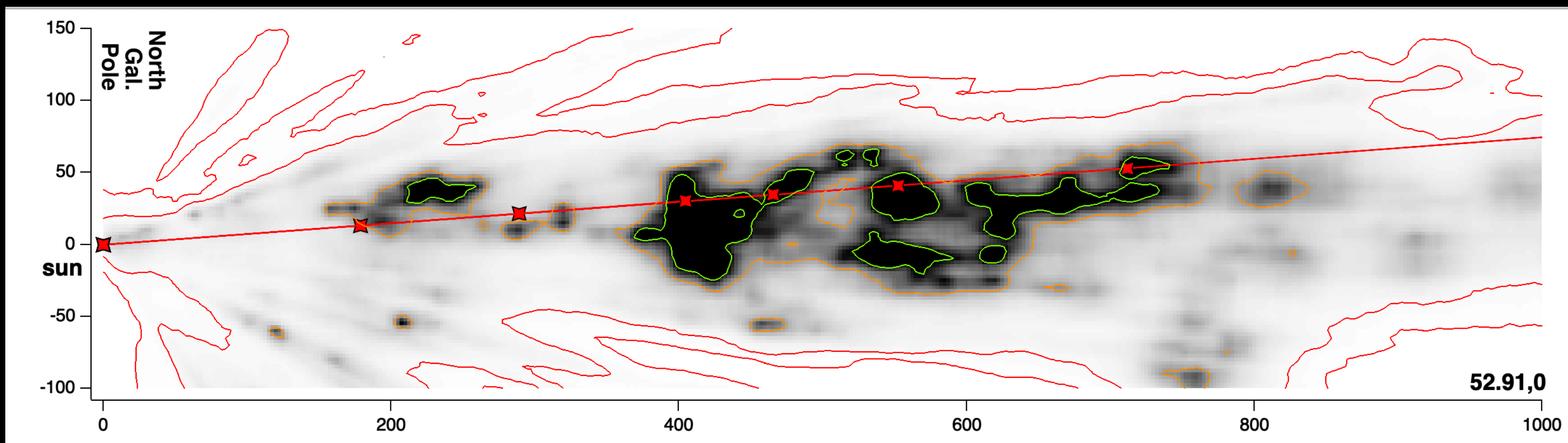


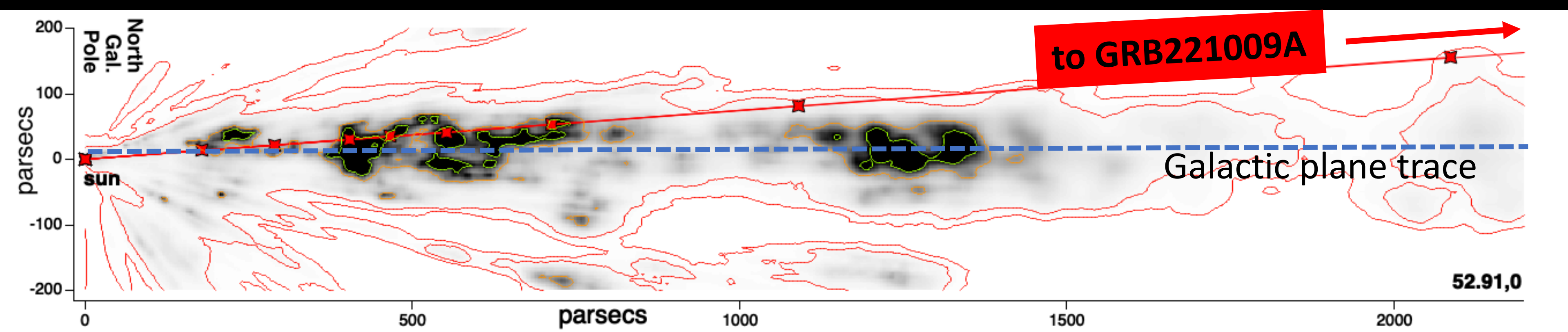


GRB 221009A (l,b)= (42.91°, +4.25°)

Tiengo et al, 2022 derive the following distances of the dust clouds: 179.3 , 290 pc, 406.2 pc, 467.6 pc, 554 , 714 , 1094 +/- 24 pc, 2092 +/- 22 pc and 3635 +/- 36 pc.







3D dust density distributions and tools are available at the EXPLORE project platform

https://explore-platform.eu/sdas

3 types of download

-1) **full 3D distribution** (.h5 files) to be used locally

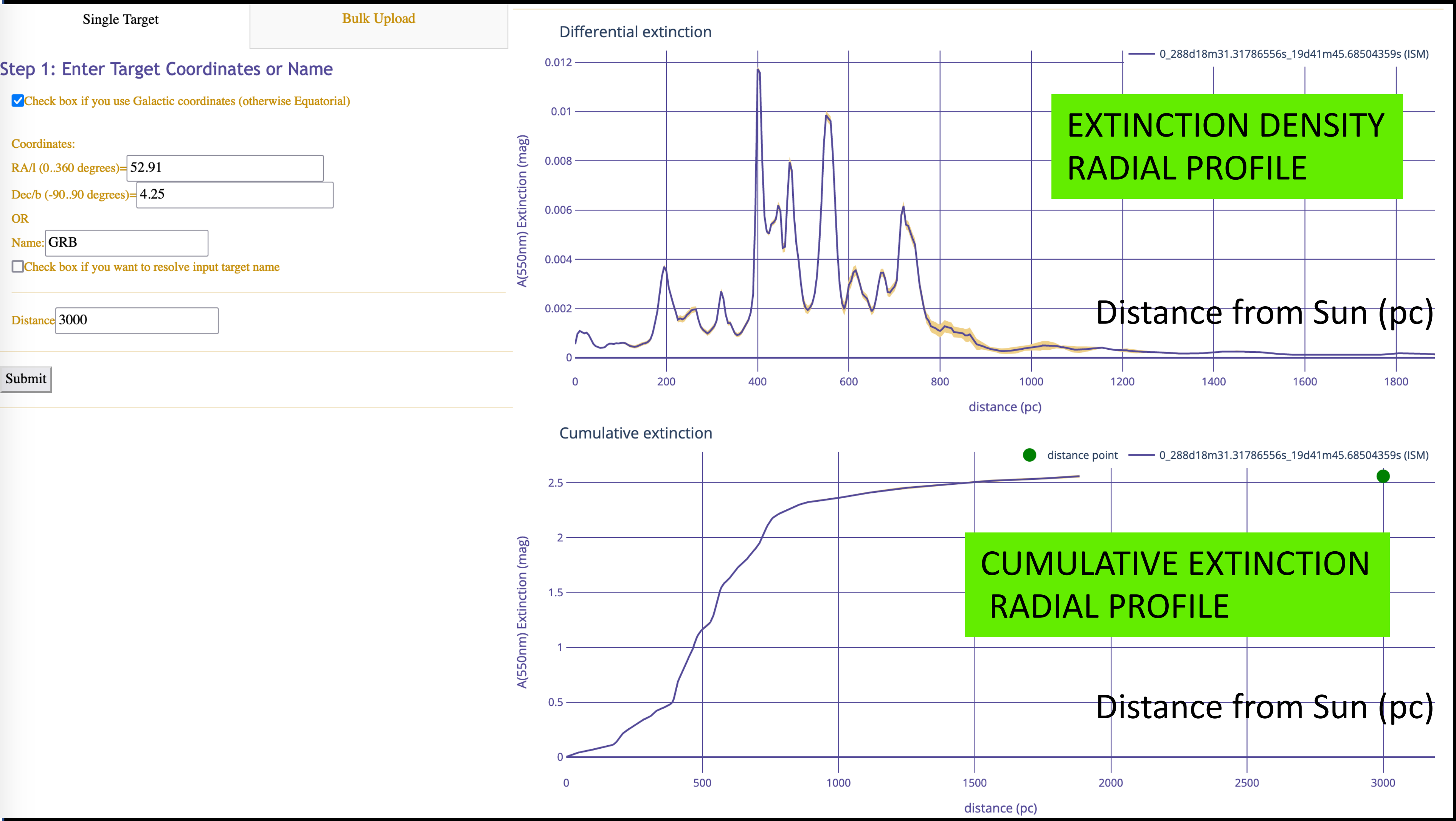
-2a) integrated (**cumulative) extinction for any direction**

-2b) **local extinction density** (prop. to dust density) **for any direction**

-3) **images of the extinction density** (prop. to dust density) **in any plane** containing the Sun or not

EXPLORE PLATFORM G-TOMO

https://explore-platform.eu/



EXPLORE PLATFORM G-TOMO

https://explore-platform.eu/

DUST IN A VERTICAL PLANE containing the Sun and oriented along l= 52.9° -232.9°

Frame: Galactic

Spherical coordinates of the map origin

Longitude of origin: 0

Latitude of origin: 0

Distance of origin: 0

Submit — Please note that it may take a little while to compute the new planar slice. Please be patient.

Download csv

Polar coordinates of the direction defining the normal to the plane of the image

Longitude of normal: 141.91

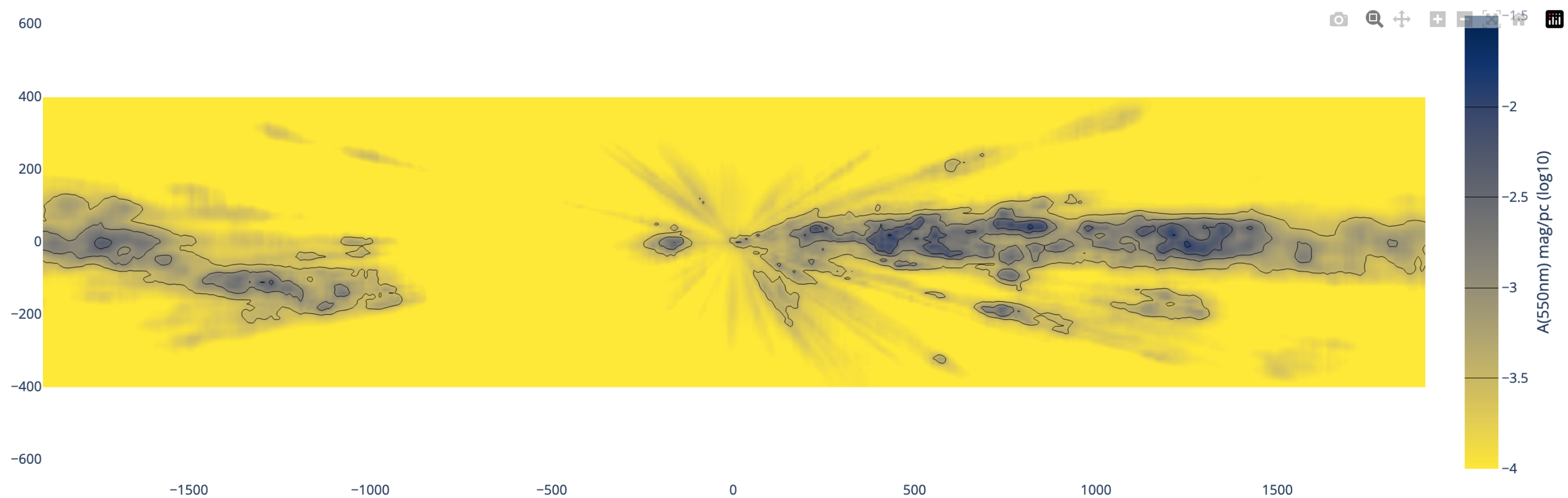
Latitude of normal: 0

Cube v2: Resolution 10pc (sampling: 5pc - size: 3 x 3 x 0.8 kpc)

'Origin (l=0.0°,b=0.0°), distance=0.0pc --- Normal to the plane (l=141.9°,b=0.0°)'

'Left to right towards ⇒ (l=51.9°,b=0.0°)'

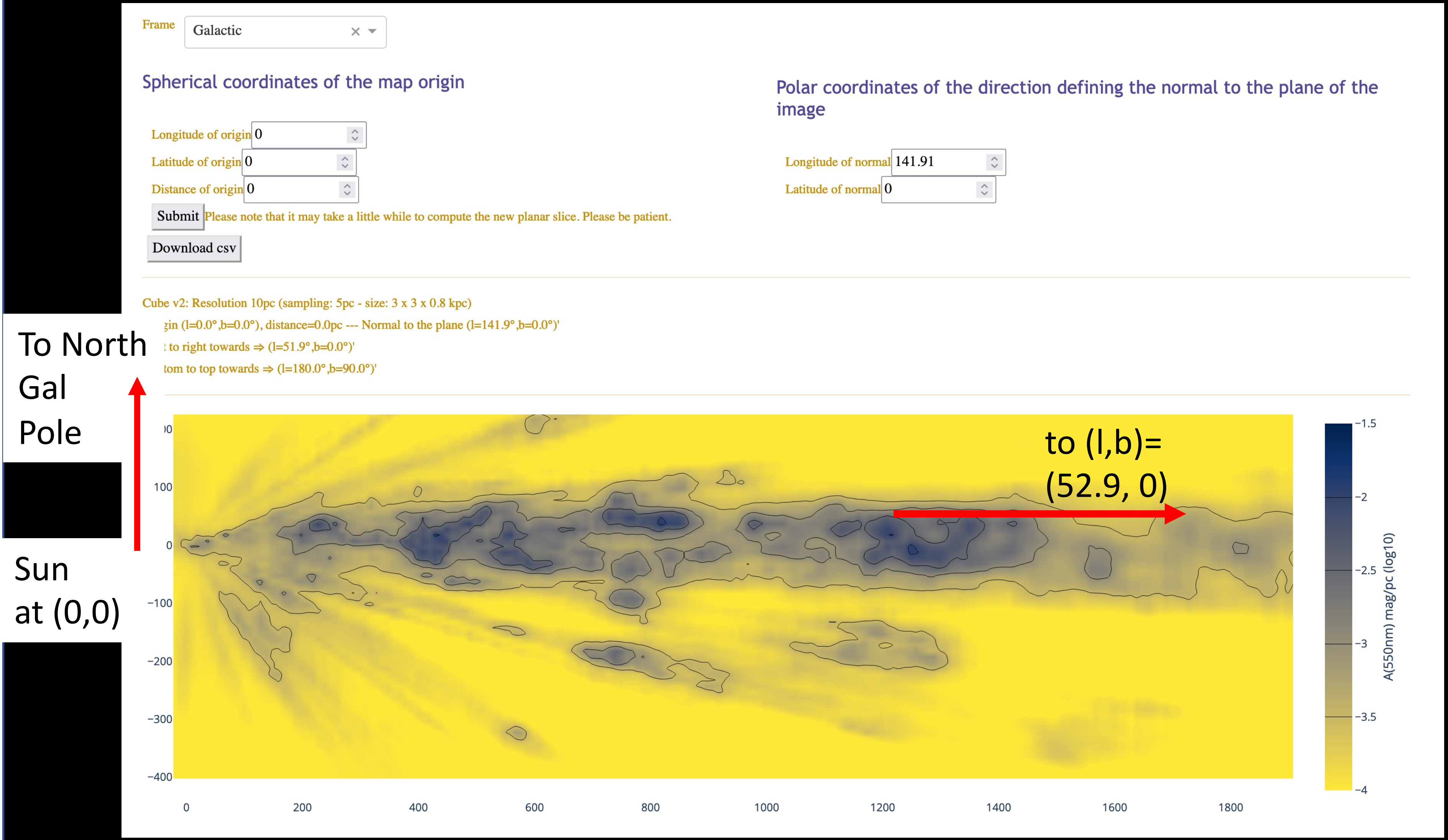
'Bottom to top towards ⇒ (l=180.0°,b=90.0°)'



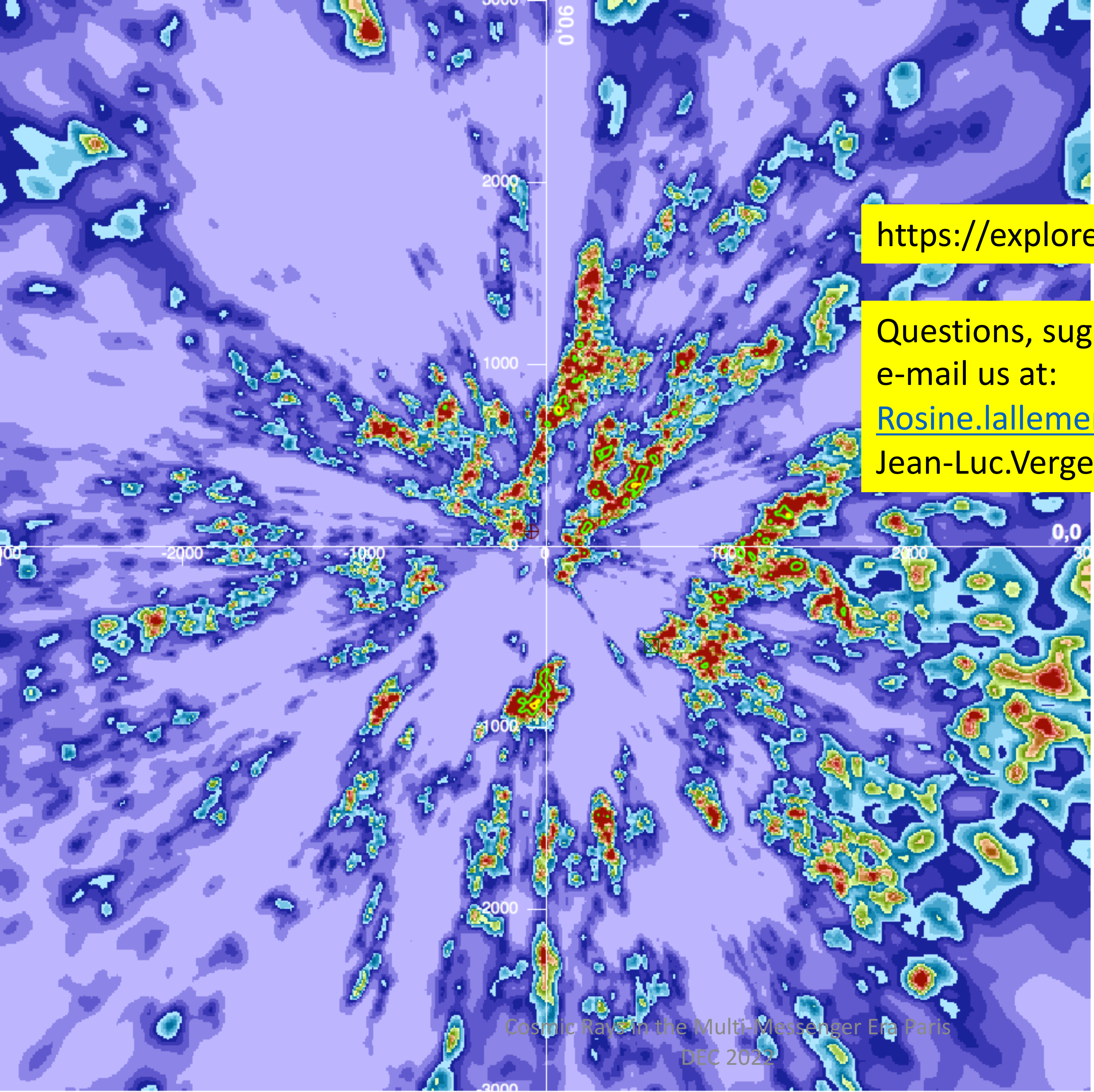
his project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004214.

EXPLORE PLATFORM G-TOMO

DUST IN A VERTICAL PLANE containing the Sun and oriented along l= 52.9°



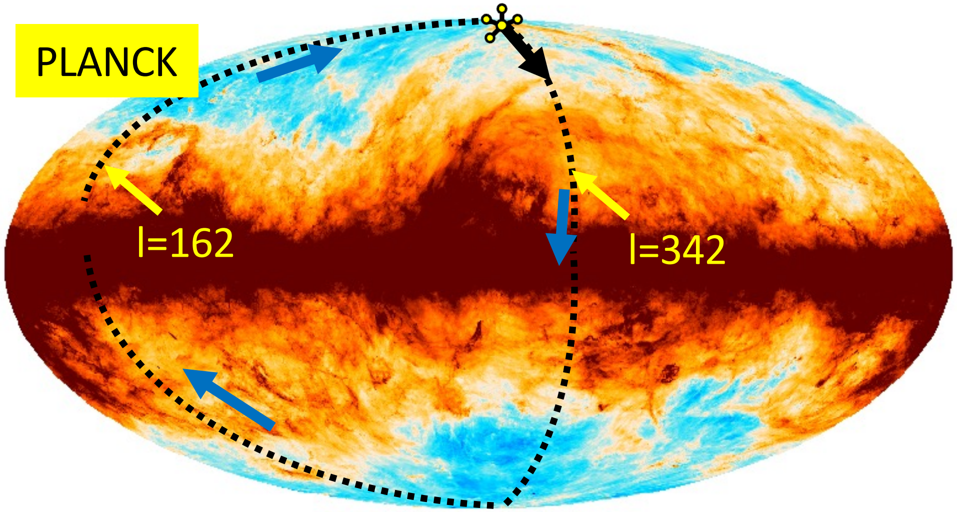
https://explore-platform.eu/

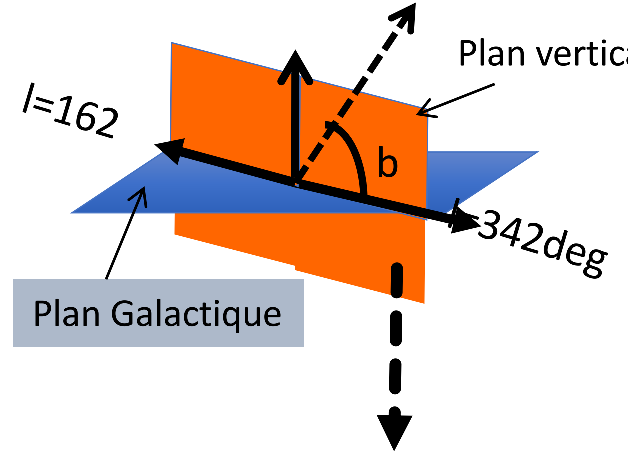


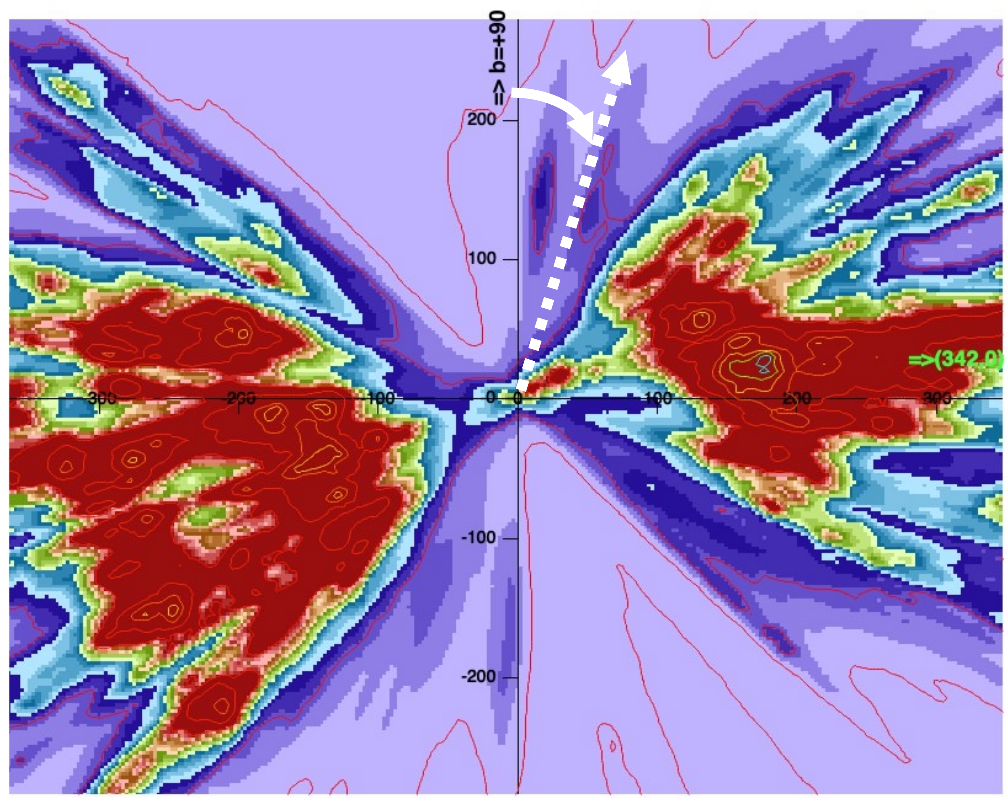
Thank you!

https://explore-platform.eu/sdas

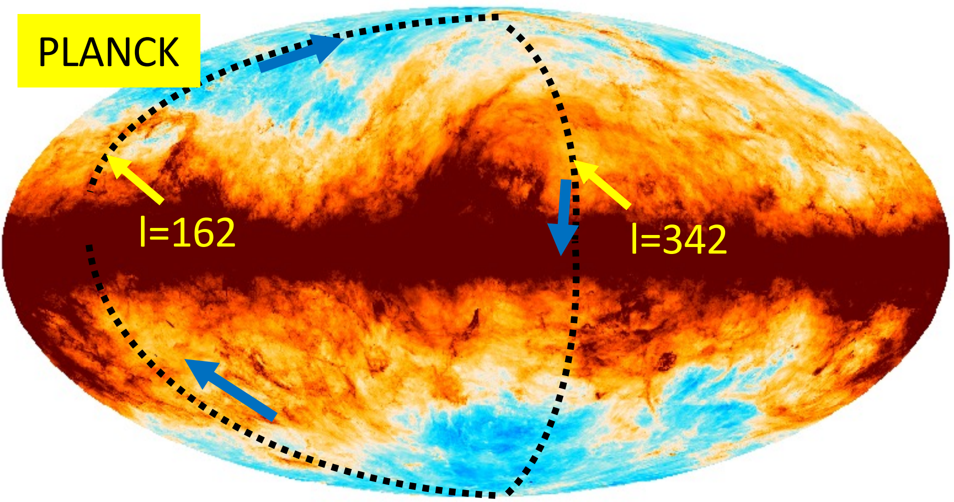
Questions, suggestions please e-mail us at:
Rosine.lallement@obspm.fr
Jean-Luc.Vergely@latmos.ipsl.fr

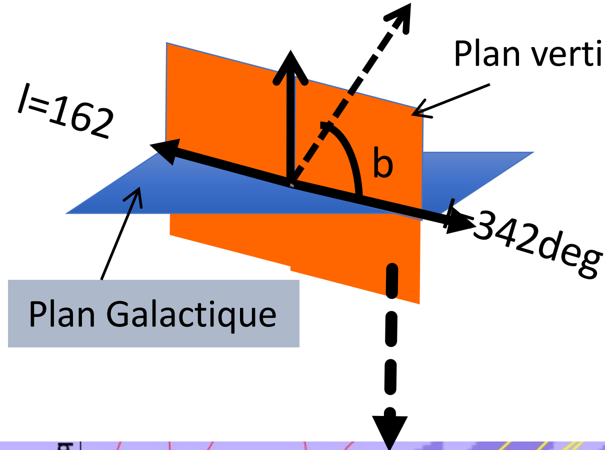


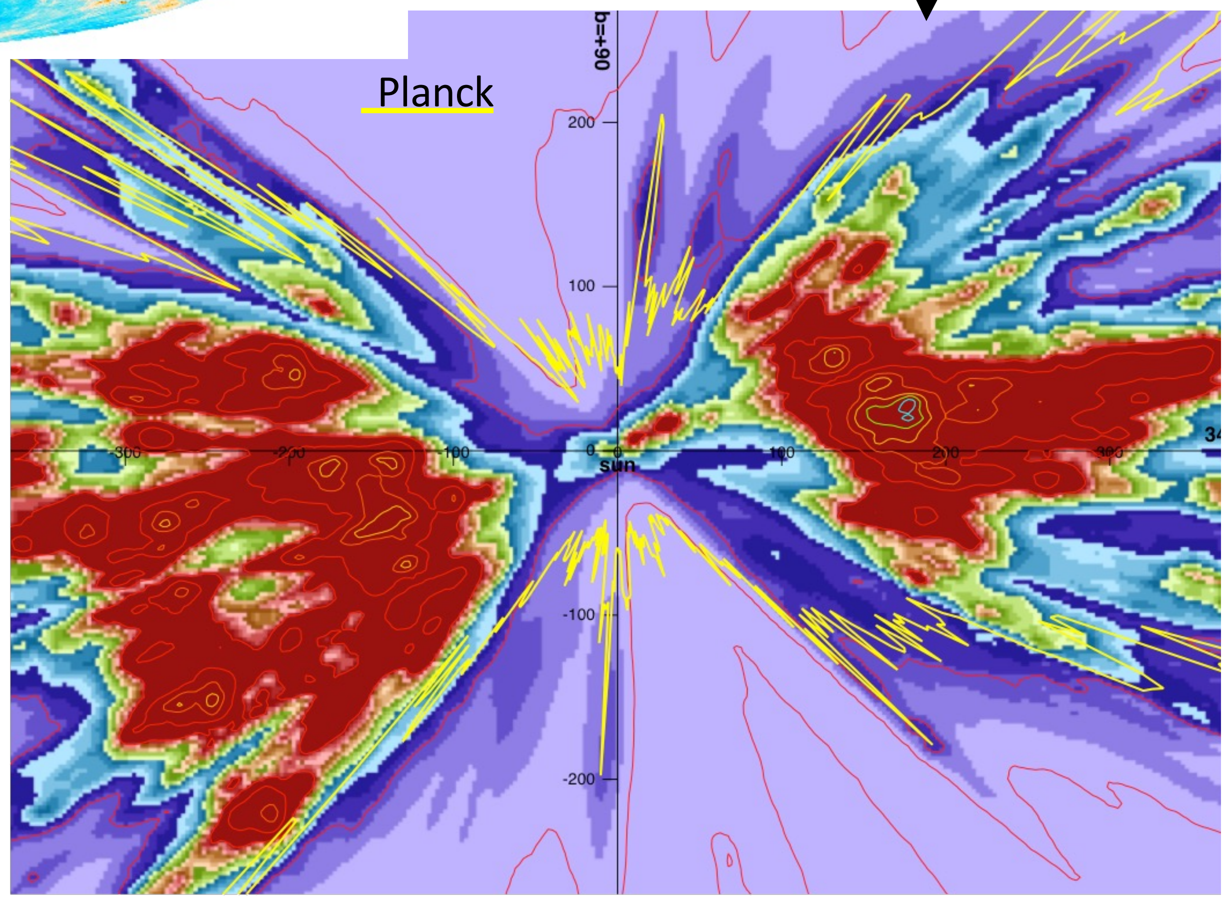




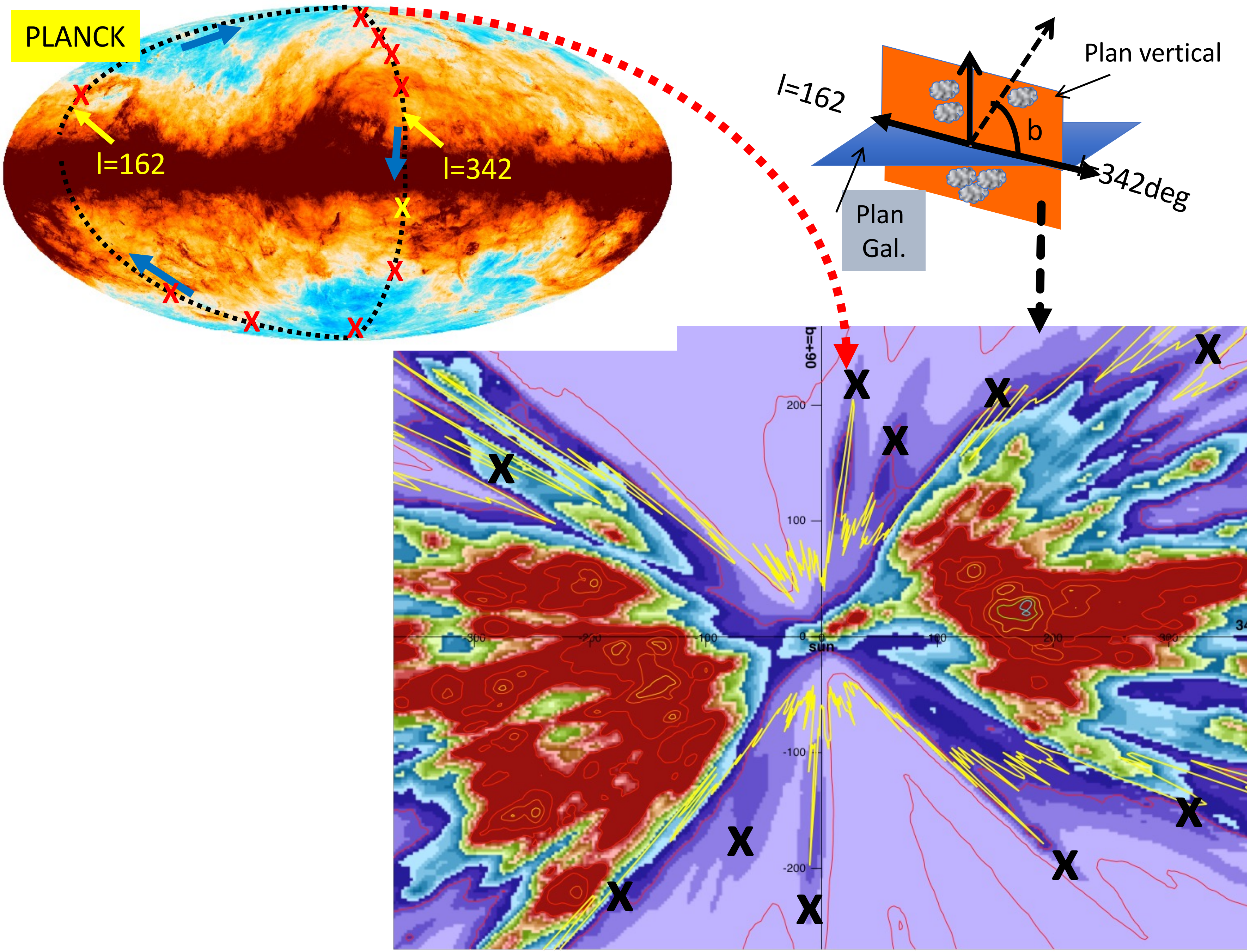
Interstellaire avec Gaia



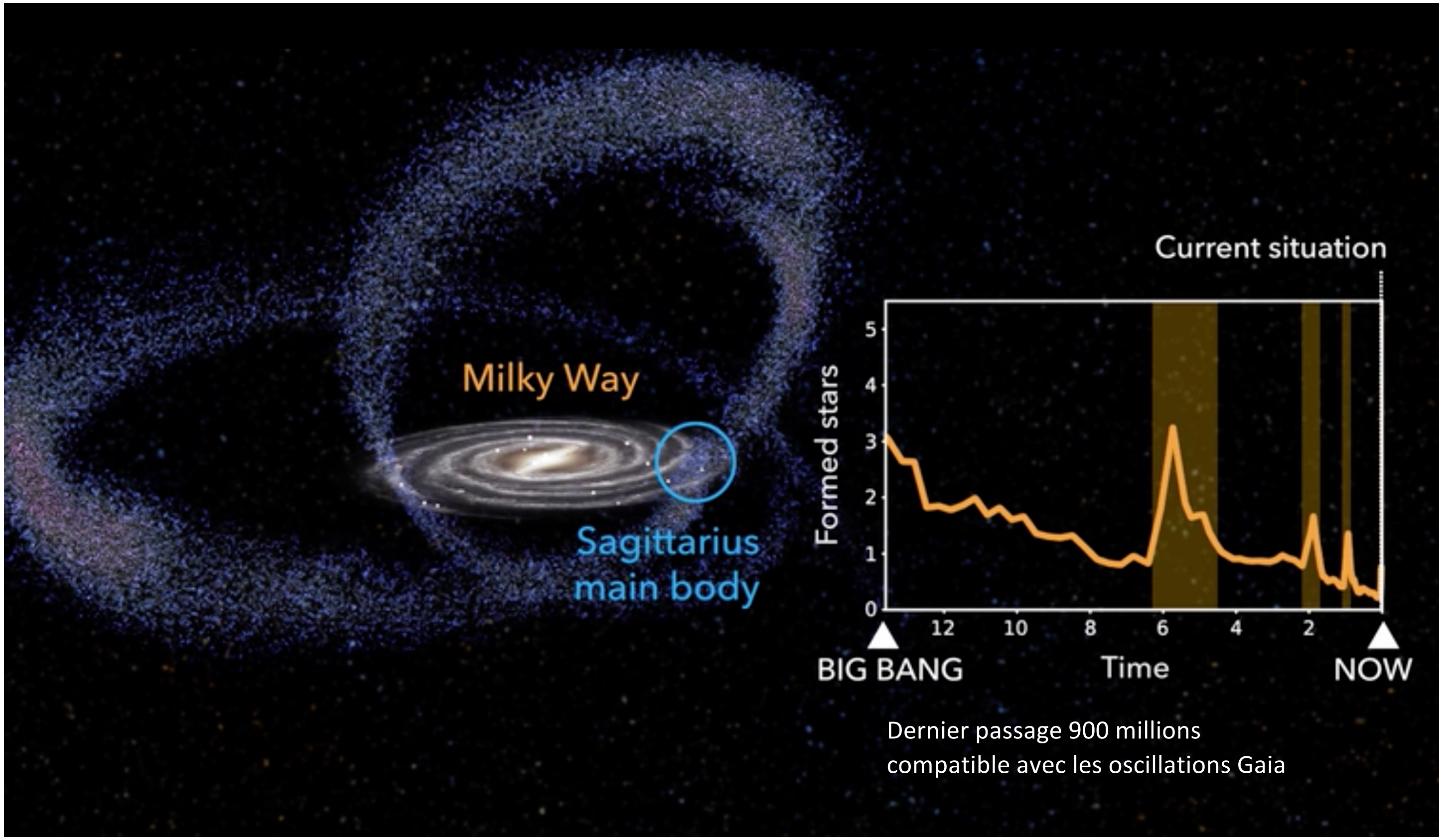




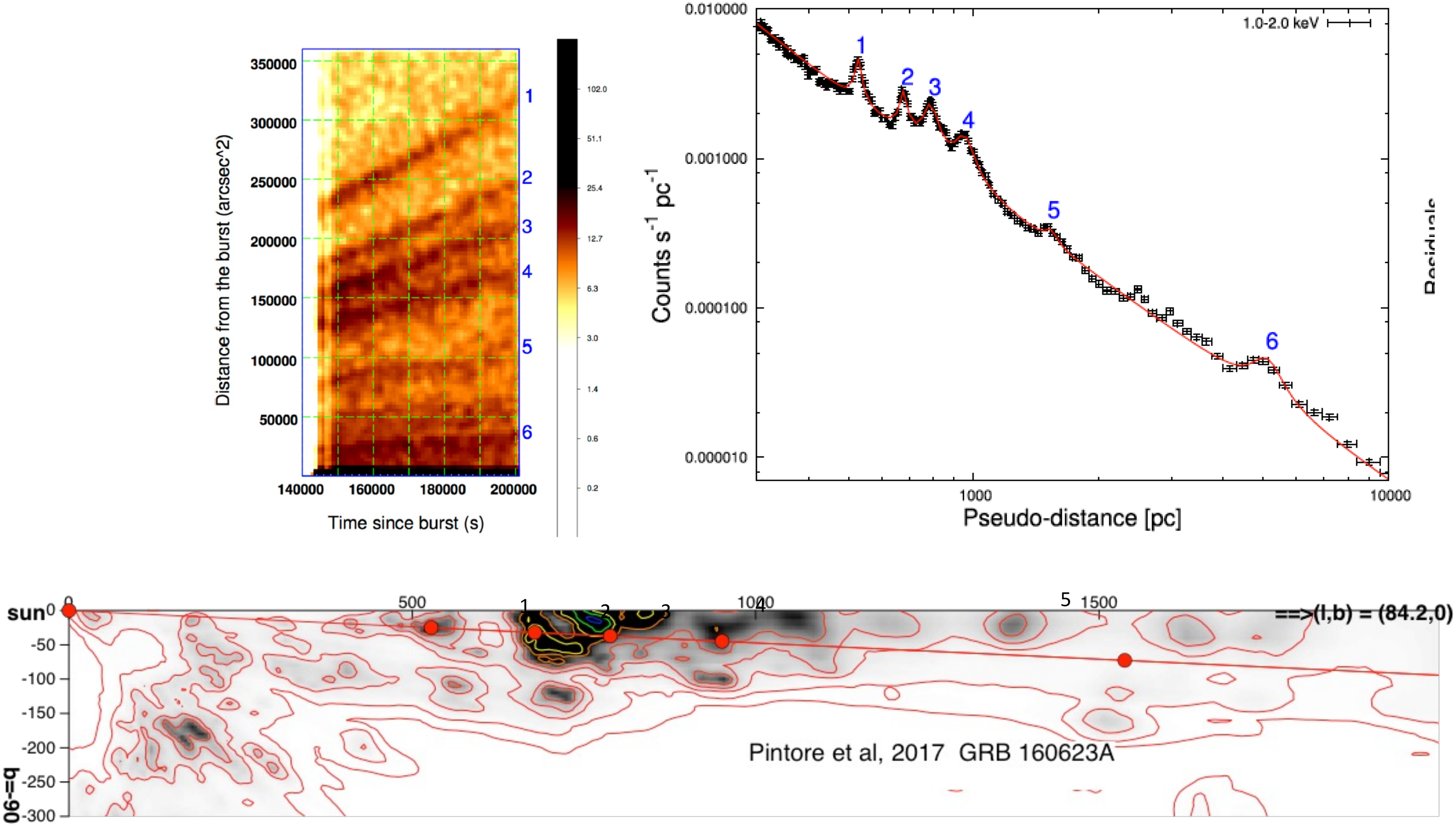
Planck:
épaisseur optique
des grains à 353 GHz
= contours jaunes
coordonnées polaires

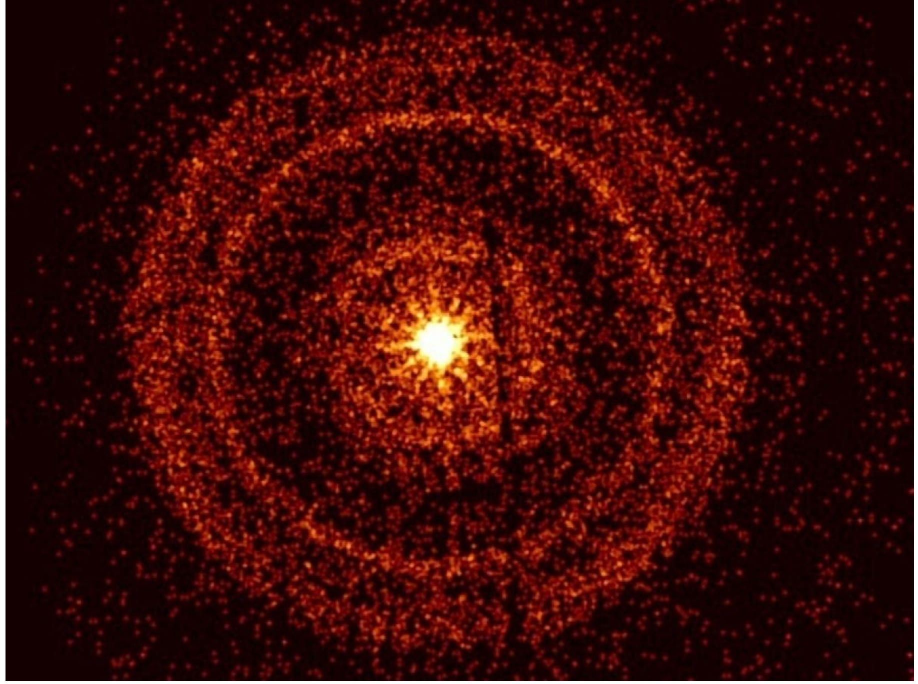


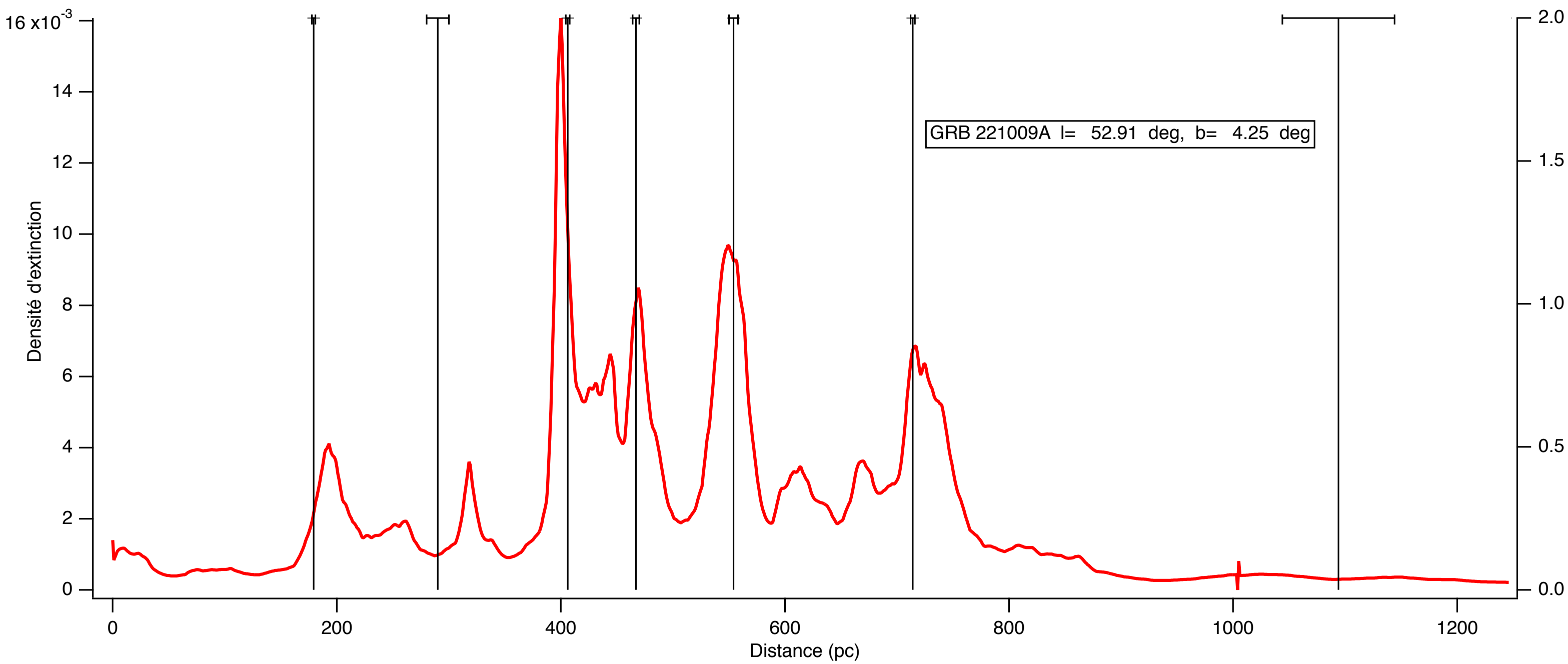
PLANCK
l=162
l=342
Plan vertical
l=162
b
342deg
Plan
Gal.
b=+90
200
100
-300
-200
-100
0
sun
100
200
300
-100
-200



-Les perturbations du gaz (et des grains) peuvent intégrer des simulations complètes (N corps + hydrodynamiques) et les observations des grains apporter des contraintes supplémentaires

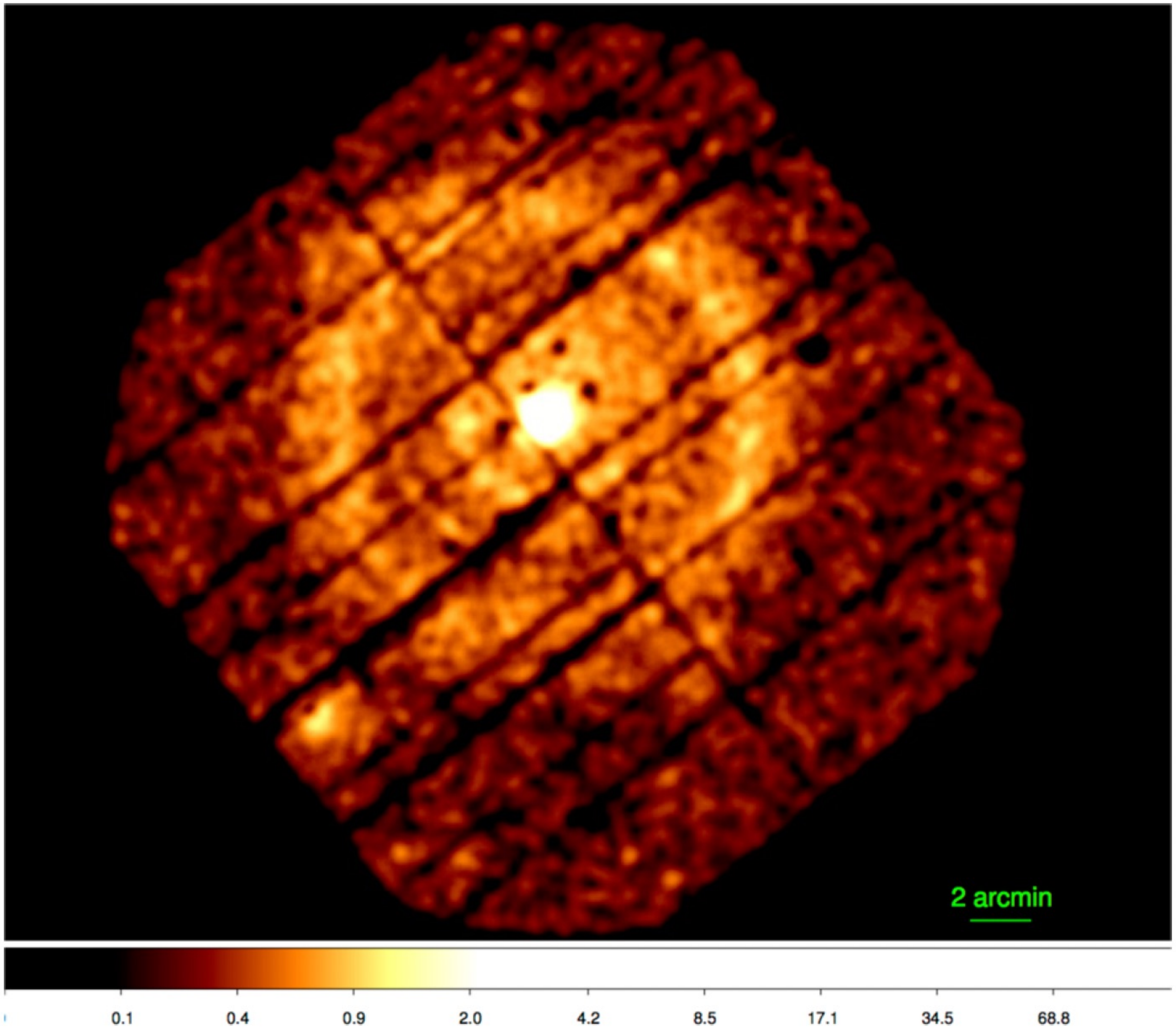

350000
300000
250000
200000
150000
100000
50000
Distance from the burst (arcsec^2)
140000
160000
180000
200000
Time since burst (s)
1
2
3
4
5
6
102.0
51.1
25.4
12.7
6.3
3.0
1.4
0.6
0.2
0.010000
0.001000
0.000100
0.000010
Counts s-1 pc-1
1.0-2.0 keV
1000
10000
Pseudo-distance [pc]
Residuals
sun
0
-50
-100
-150
-200
-250
-300
b=-90
500
1000
1500
==>(l,b) = (84.2,0)
Pintore et al, 2017 GRB 160623A





GRB 221009A l= 52.91 deg, b= 4.25 deg
Densité d'extinction
16 x10^-3
14
12
10
8
6
4
2
0
2.0
1.5
1.0
0.5
0.0
0
200
400
600
800
1000
1200
Distance (pc)

Comment valider la position reconstruite des nuages de poussières?



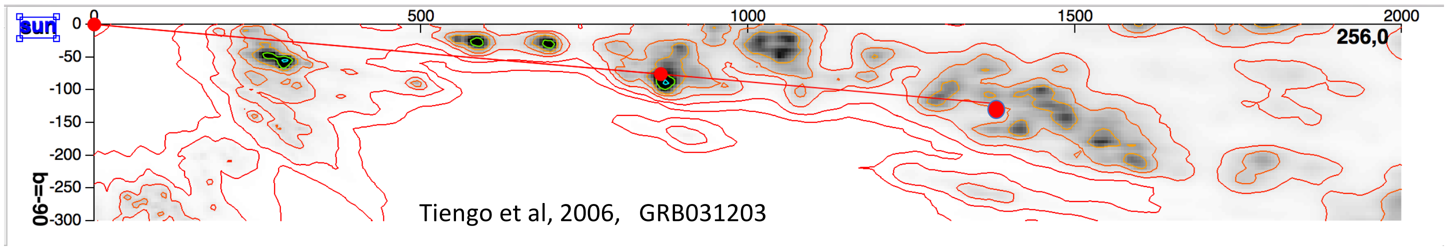
Réponse: en utilisant , les sursauts gamma !!!!!

Evénements extragalactiques, les + énergétiques

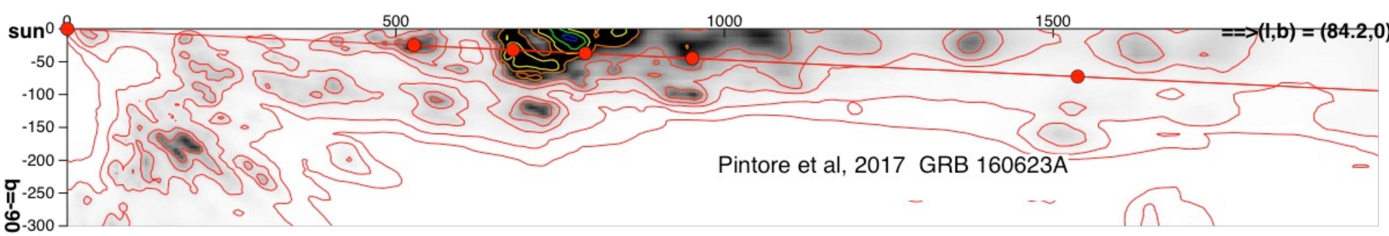
Anneaux visibles en rayons X dans la direction du sursaut gamma GRB 160623A 2 jours après le début du sursaut

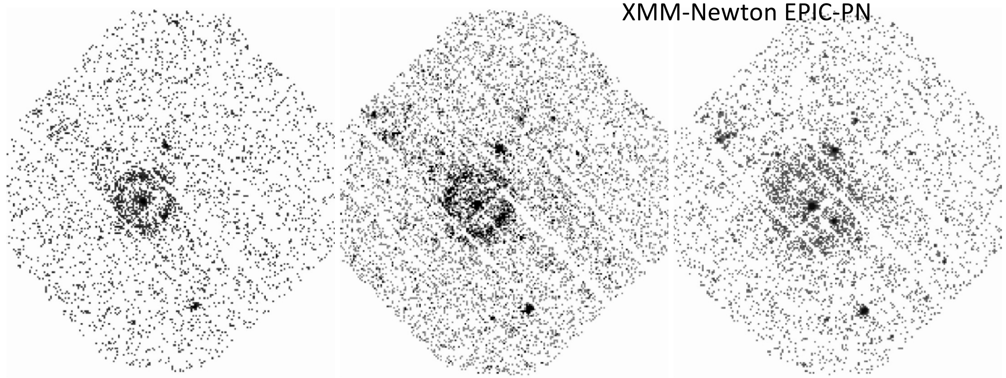
Pintore et al, 2017

Comparisons with other cloud distance determinations:
X-ray rings associated with gamma-ray bursts



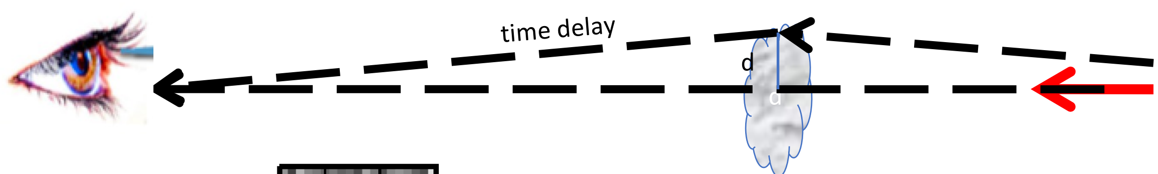
locations of the “dust screens” producing the X-ray rings deduced from time delays and ring diameters

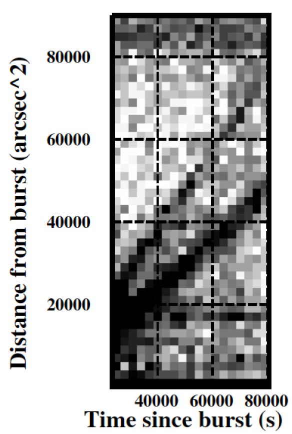


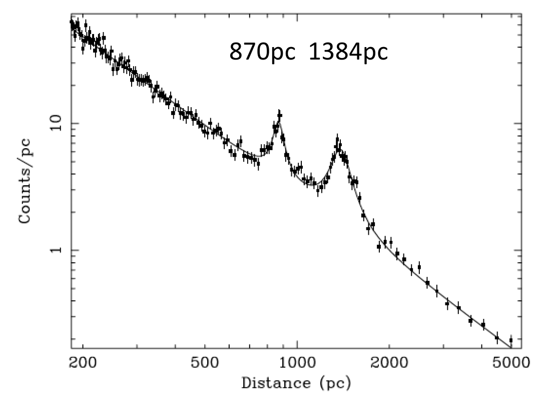


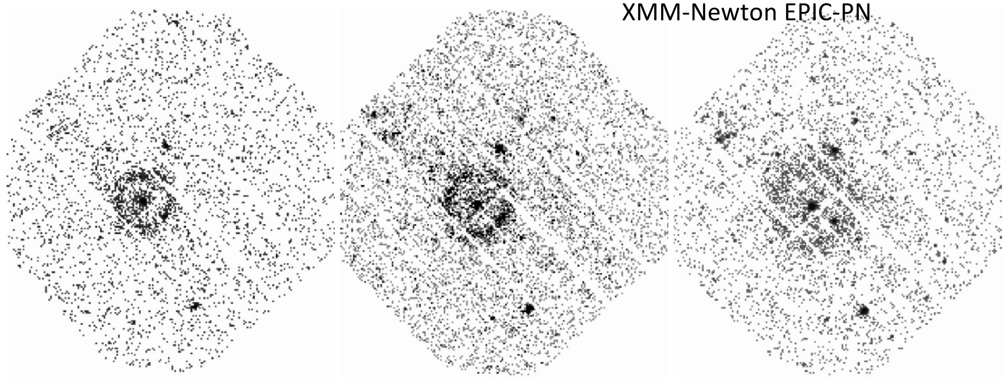
Tiengo et al, 2006,
GRB031203

23.5–30 ks **30–45 ks** **and 45–80 ks after burst**



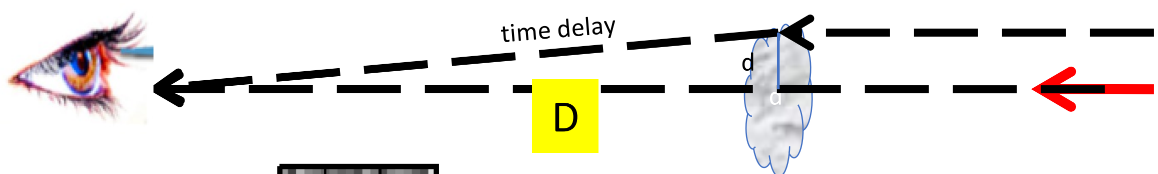


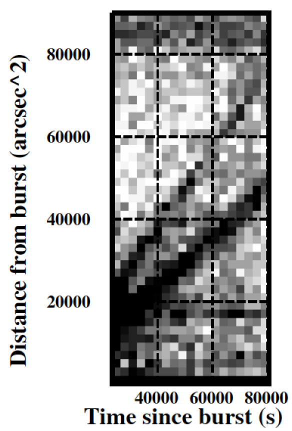


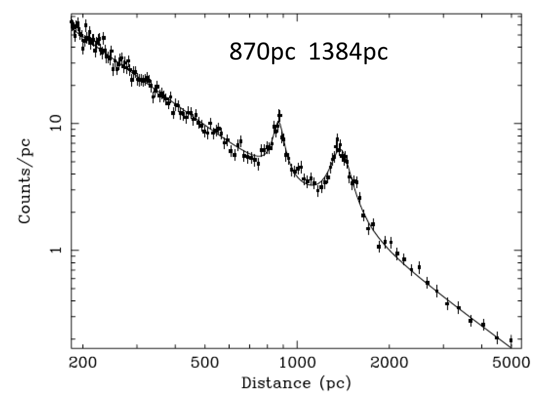


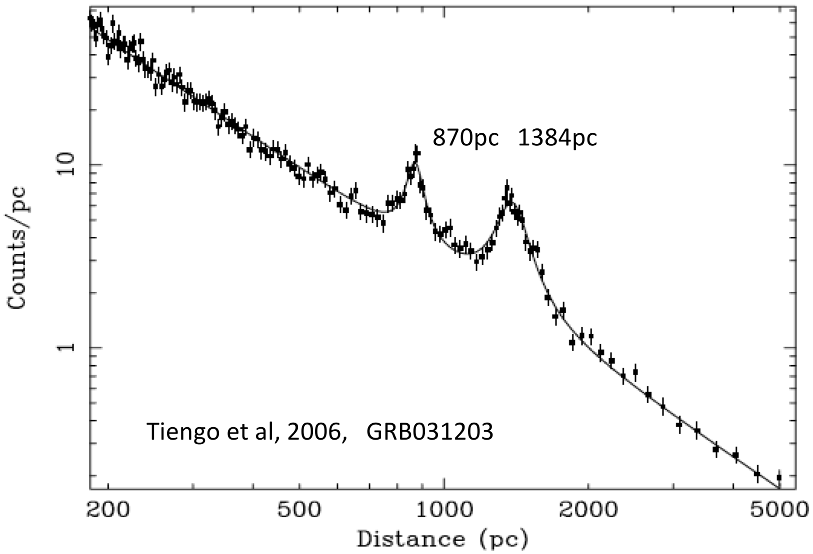
Tiengo et al, 2006, GRB031203

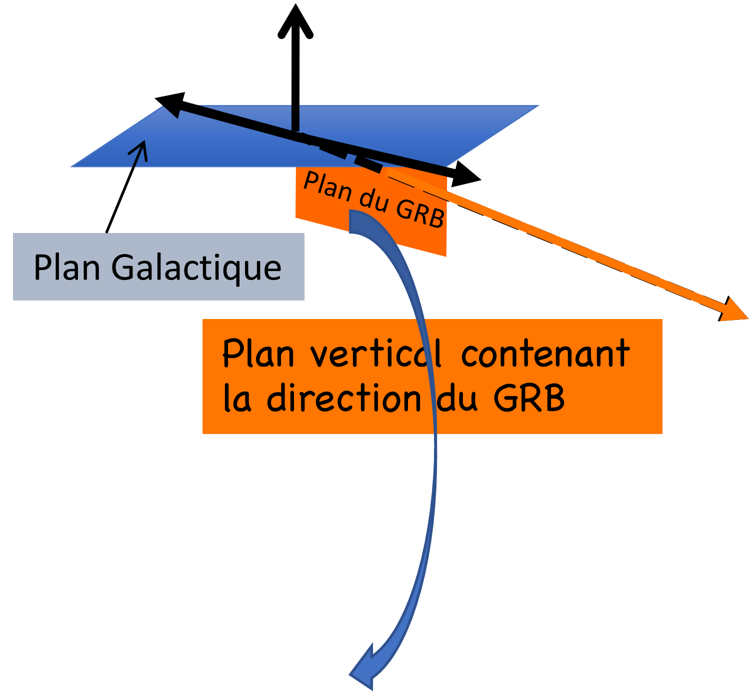
23.5–30 ks **30–45 ks** **and 45–80 ks after burst**

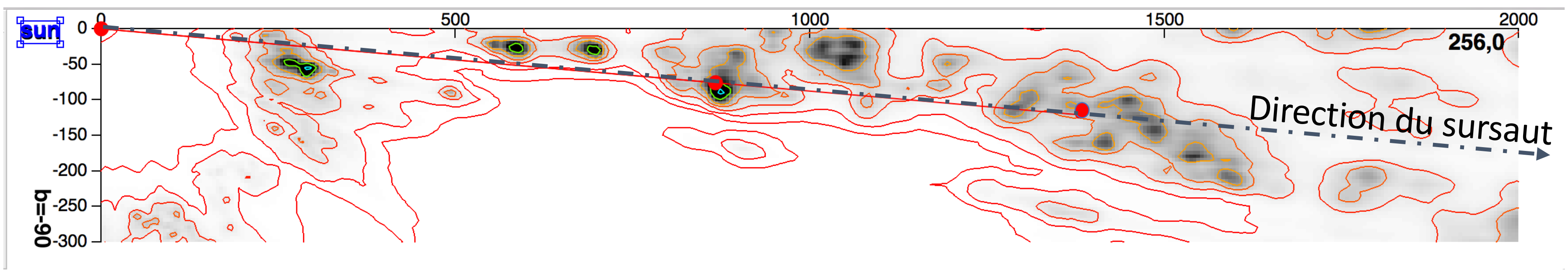






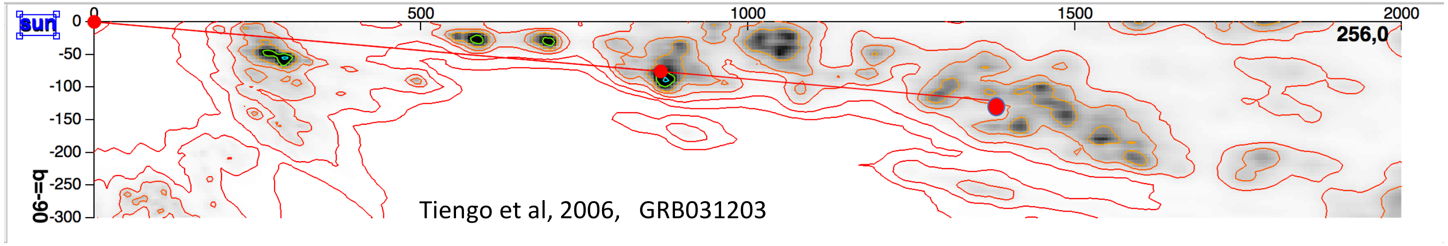




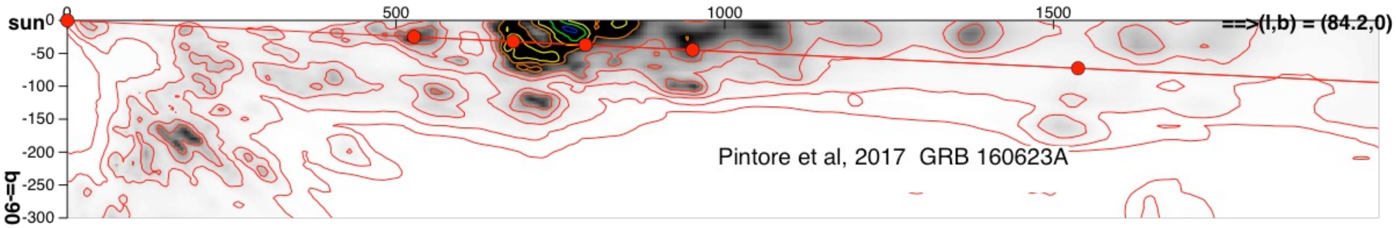


Comparaisons entre les distances aux écrans de poussière déduits des anneaux X et les cartes 3D

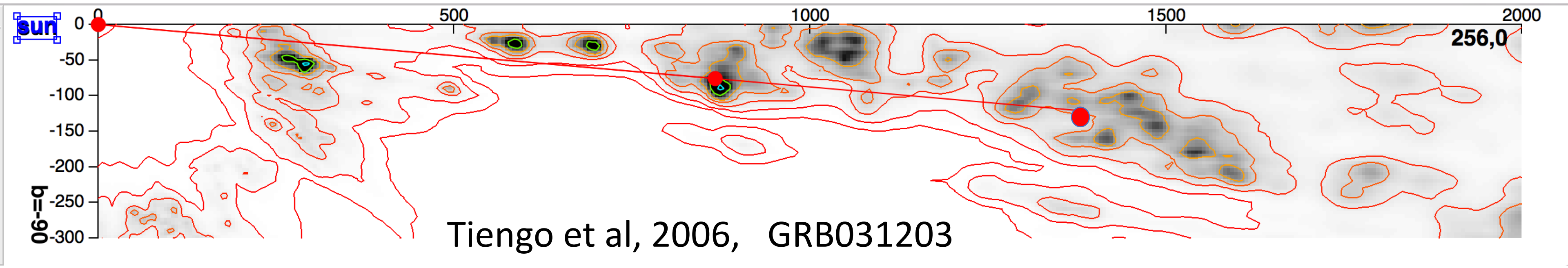
Comparisons with other cloud distance determinations:
X-ray rings associated with gamma-ray bursts



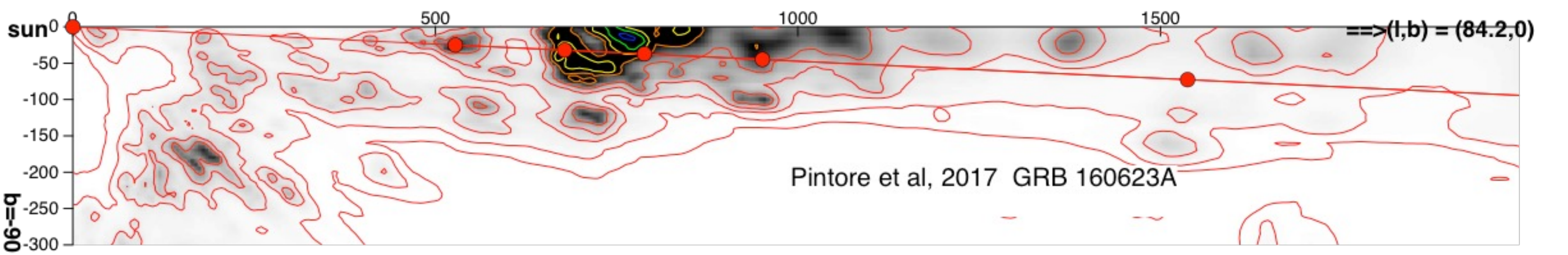
locations of the “dust screens” producing the X-ray rings deduced from time delays and ring diameters



Comparisons with other cloud distance determinations:
X-ray rings associated with gamma-ray bursts

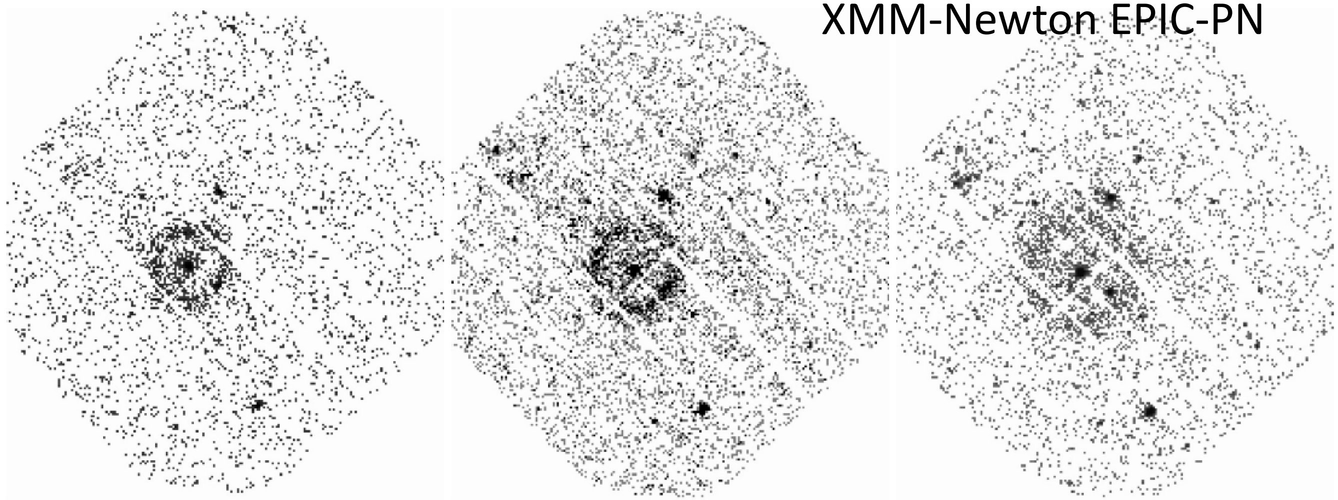


locations of the “dust screens” producing the X-ray rings deduced from time delays and ring diameters

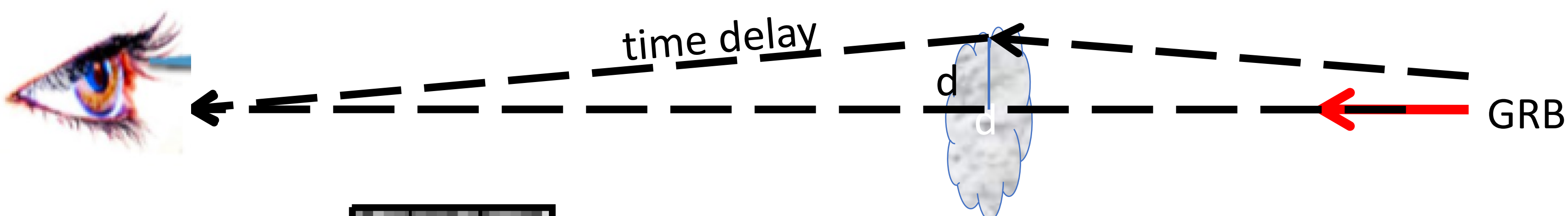


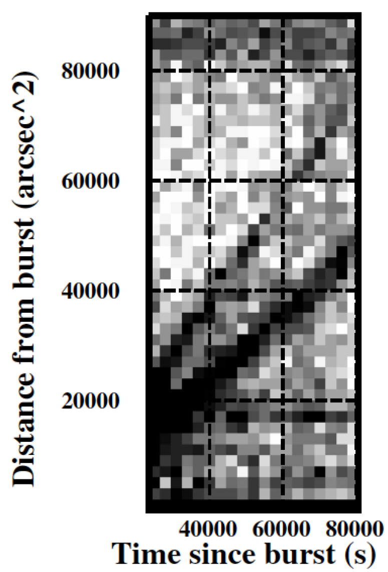
XMM-Newton EPIC-PN

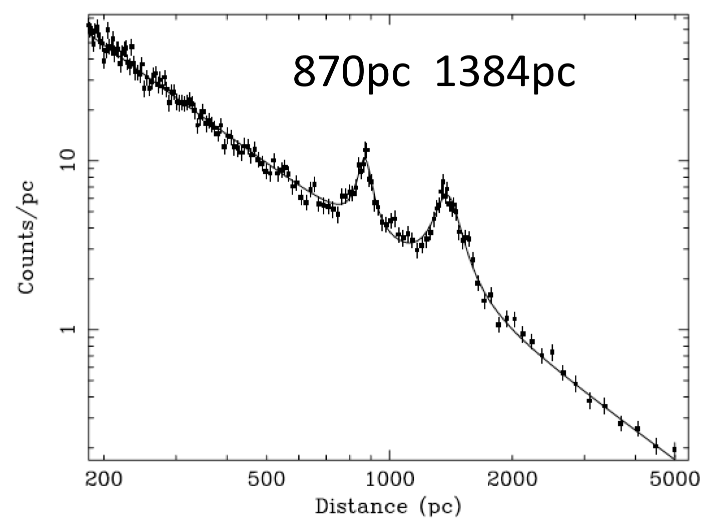
Tiengo et al, 2006, GRB031203



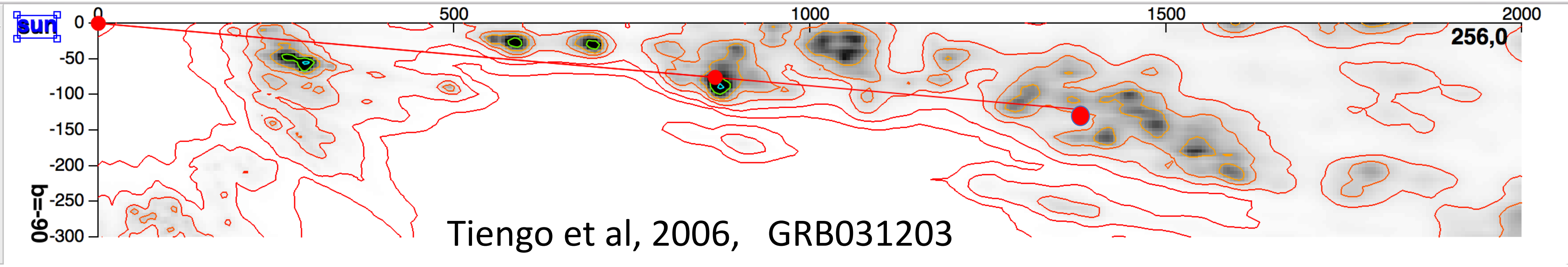
23.5–30 ks **30–45 ks** **and 45–80 ks after burst**



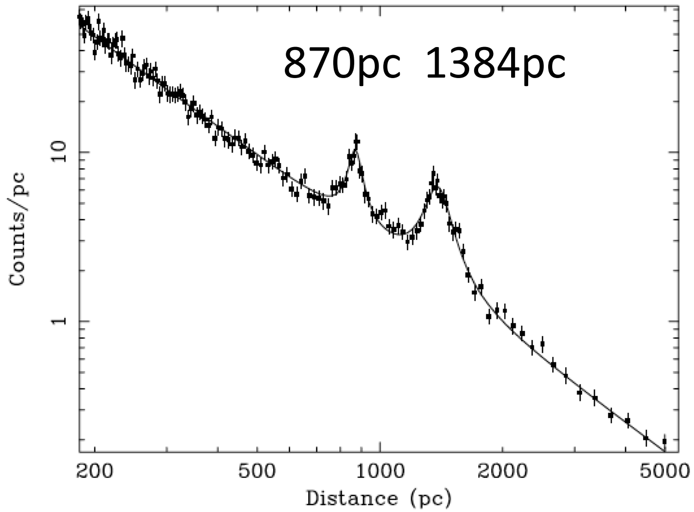


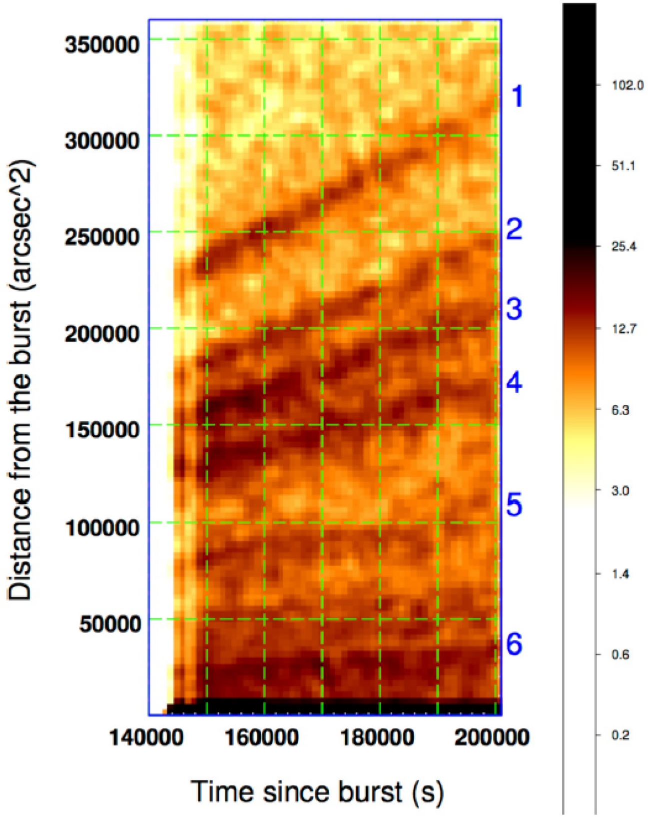


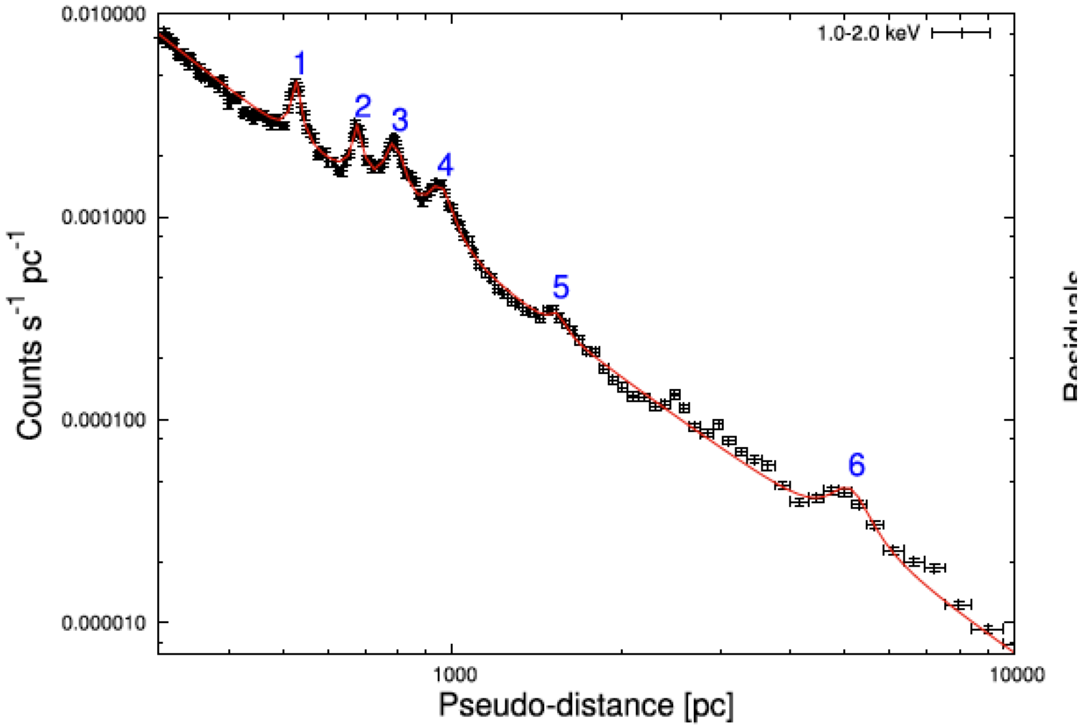
Comparisons with other cloud distance determinations: X-ray rings associated with gamma-ray bursts

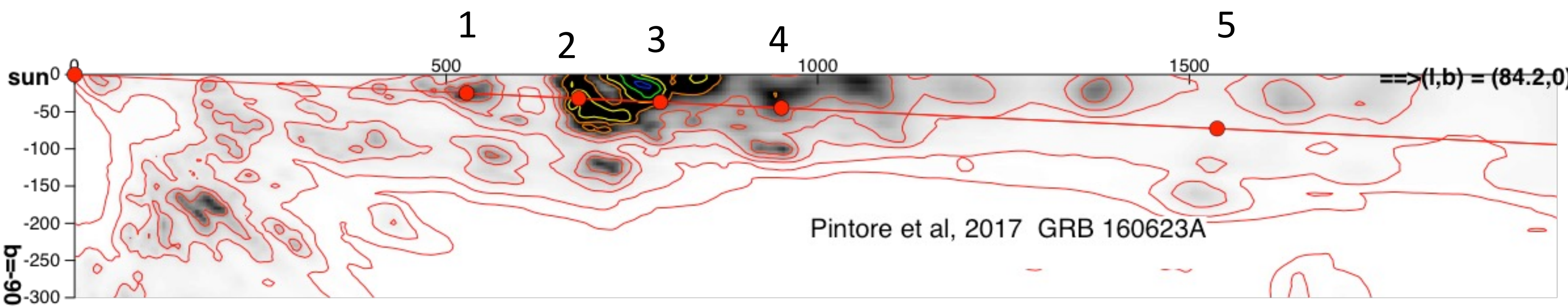


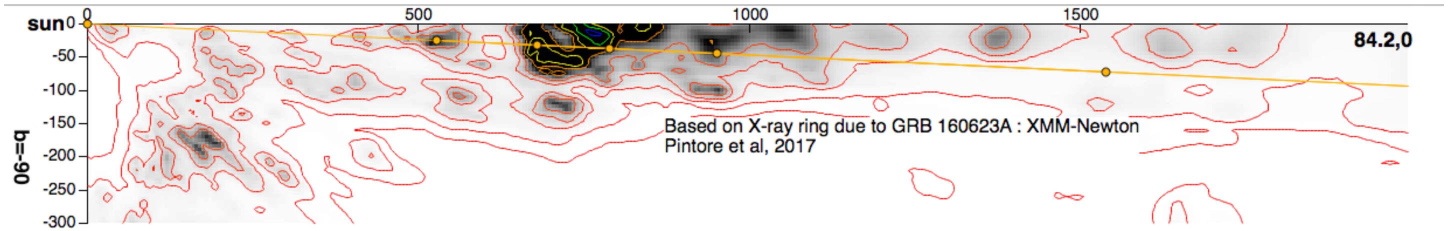
Tiengo et al, 2006, GRB031203

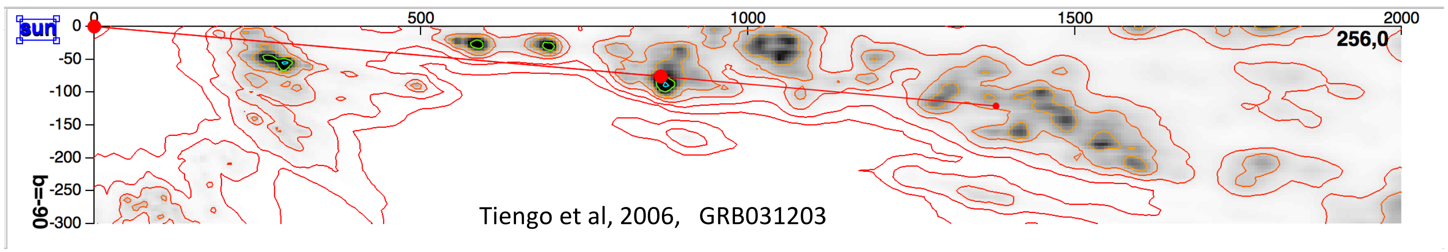


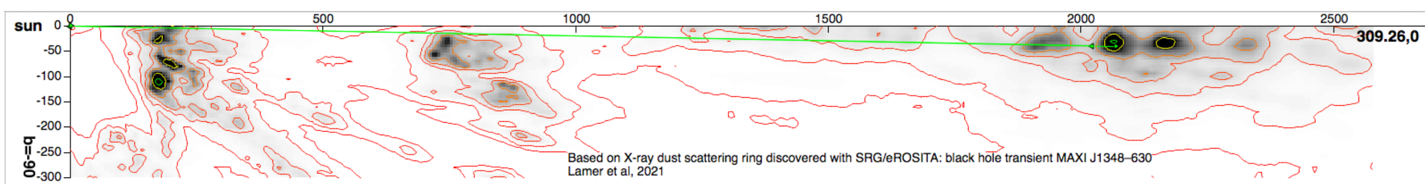

Distance from the burst (arcsec^2)
350000
300000
250000
200000
150000
100000
50000
140000
160000
180000
200000
Time since burst (s)
1
2
3
4
5
6
102.0
51.1
25.4
12.7
6.3
3.0
1.4
0.6
0.2

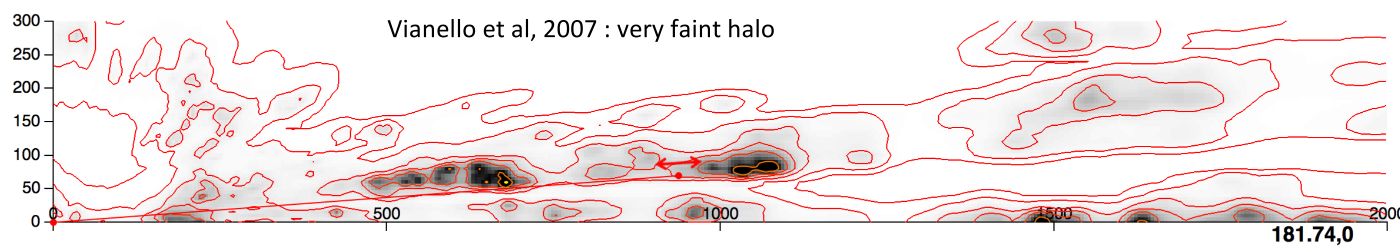

Counts s^{-1} pc^{-1}
0.010000
0.001000
0.000100
0.000010
1000
10000
Pseudo-distance [pc]
1.0-2.0 keV
1
2
3
4
5
6

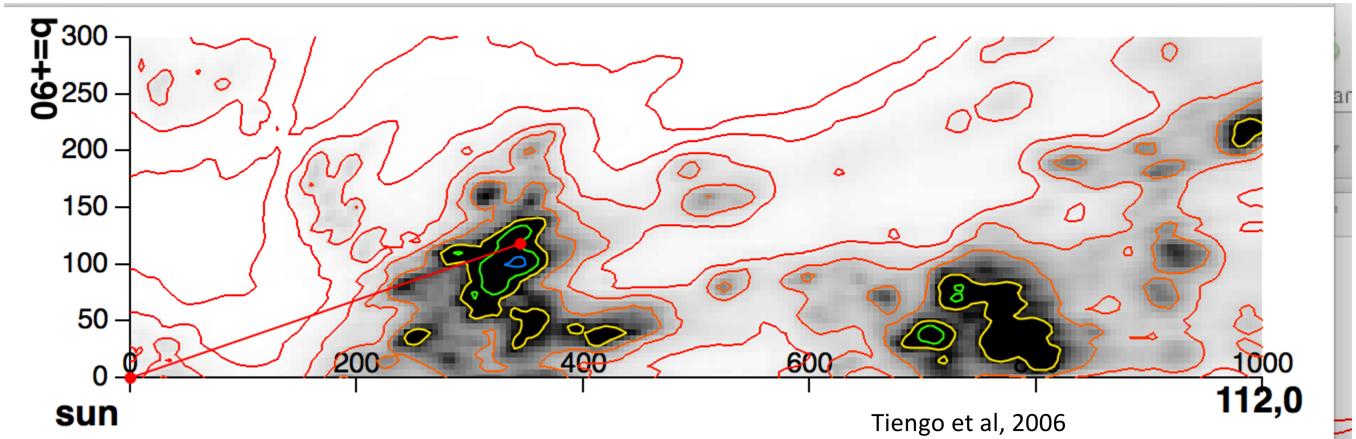

1
2
3
4
5
sun
0
500
1000
1500
==>(l,b) = (84.2,0)
-50
-100
-150
-200
-250
-300
b=-90
Pintore et al, 2017 GRB 160623A


sun
84.2,0
Based on X-ray ring due to GRB 160623A : XMM-Newton
Pintore et al, 2017
b=-90

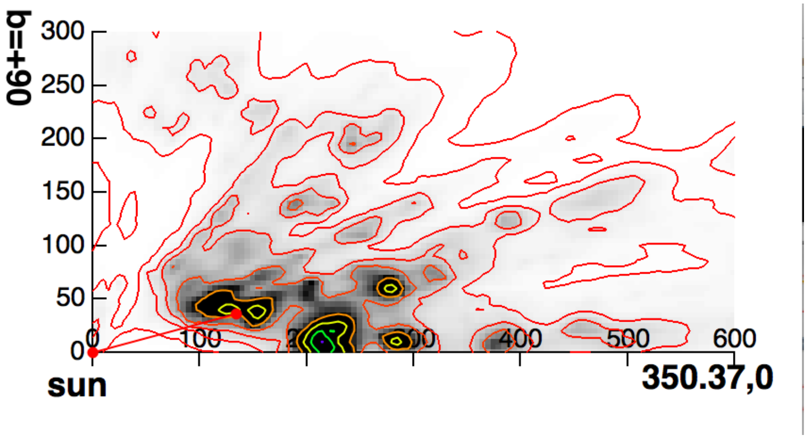

sun
256,0
Tiengo et al, 2006, GRB031203
b=-90


sun
309.26,0
Based on X-ray dust scattering ring discovered with SRG/eROSITA: black hole transient MAXI J1348–630
Lamer et al, 2021
b=-90


Vianello et al, 2007 : very faint halo
181.74,0



Tiengo et al, 2006



Tous les « heureux hasards » de notre position dans la Galaxie

-Nos nuits sont étoilées !

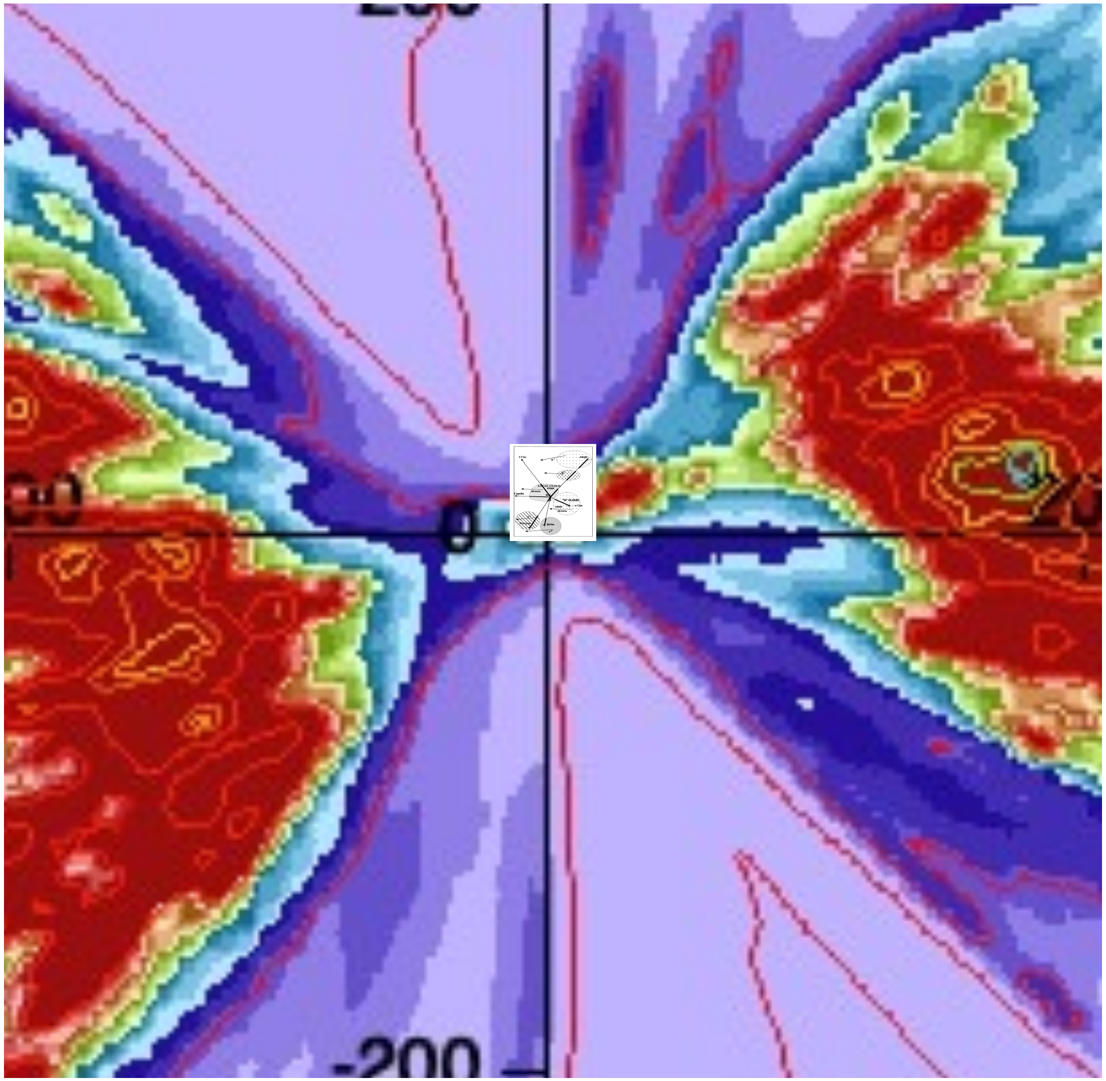
« **C'est une bien faible** lumière qui nous vient du ciel **étoilé**. Que serait pourtant la pensée humaine si nous ne pouvions pas percevoir ces **étoiles** ? »
Jean Perrin

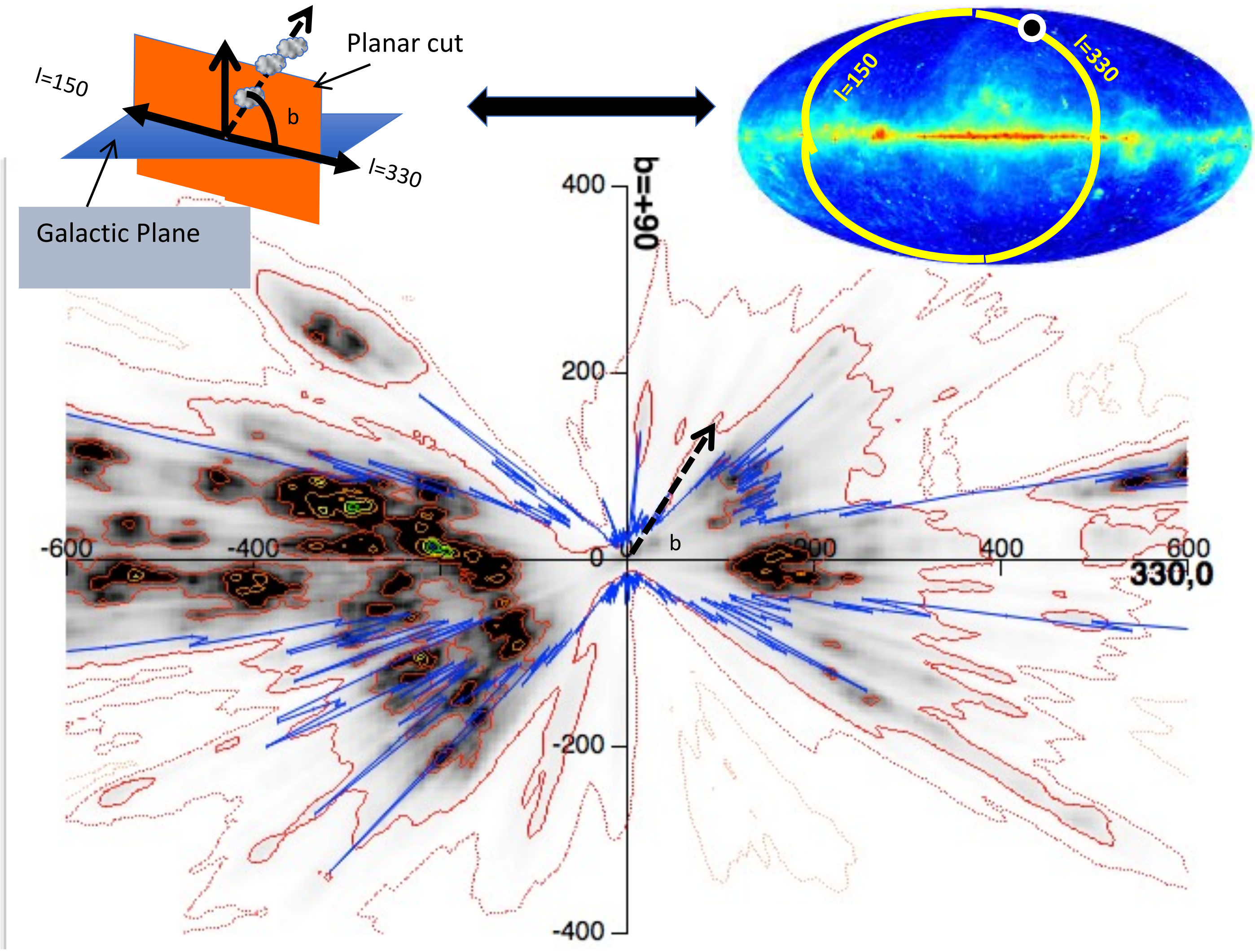
-Nous avons une vue dégagée sur les halos Nord et Sud

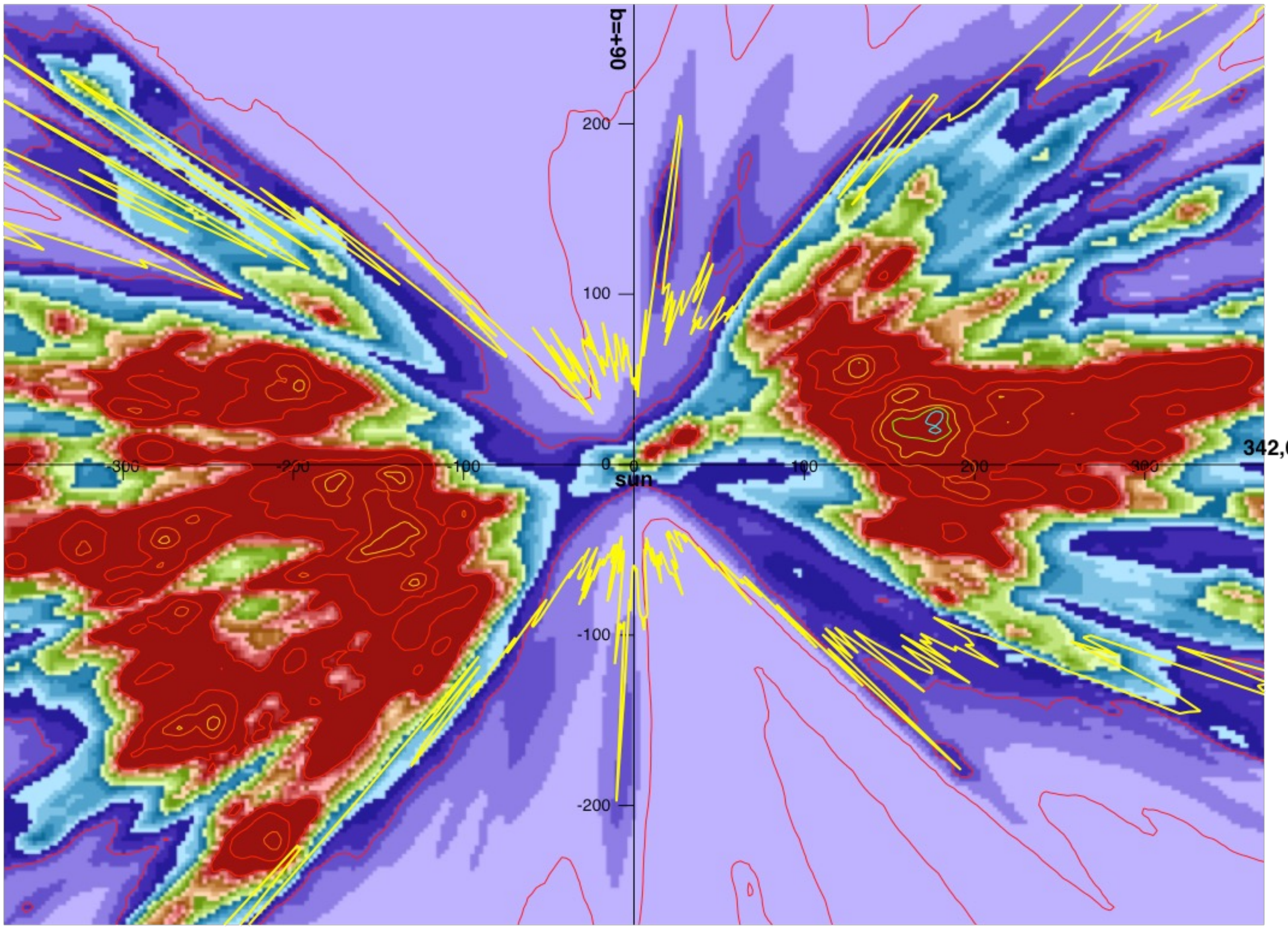
=> Autres galaxies, fond diffus , etc..

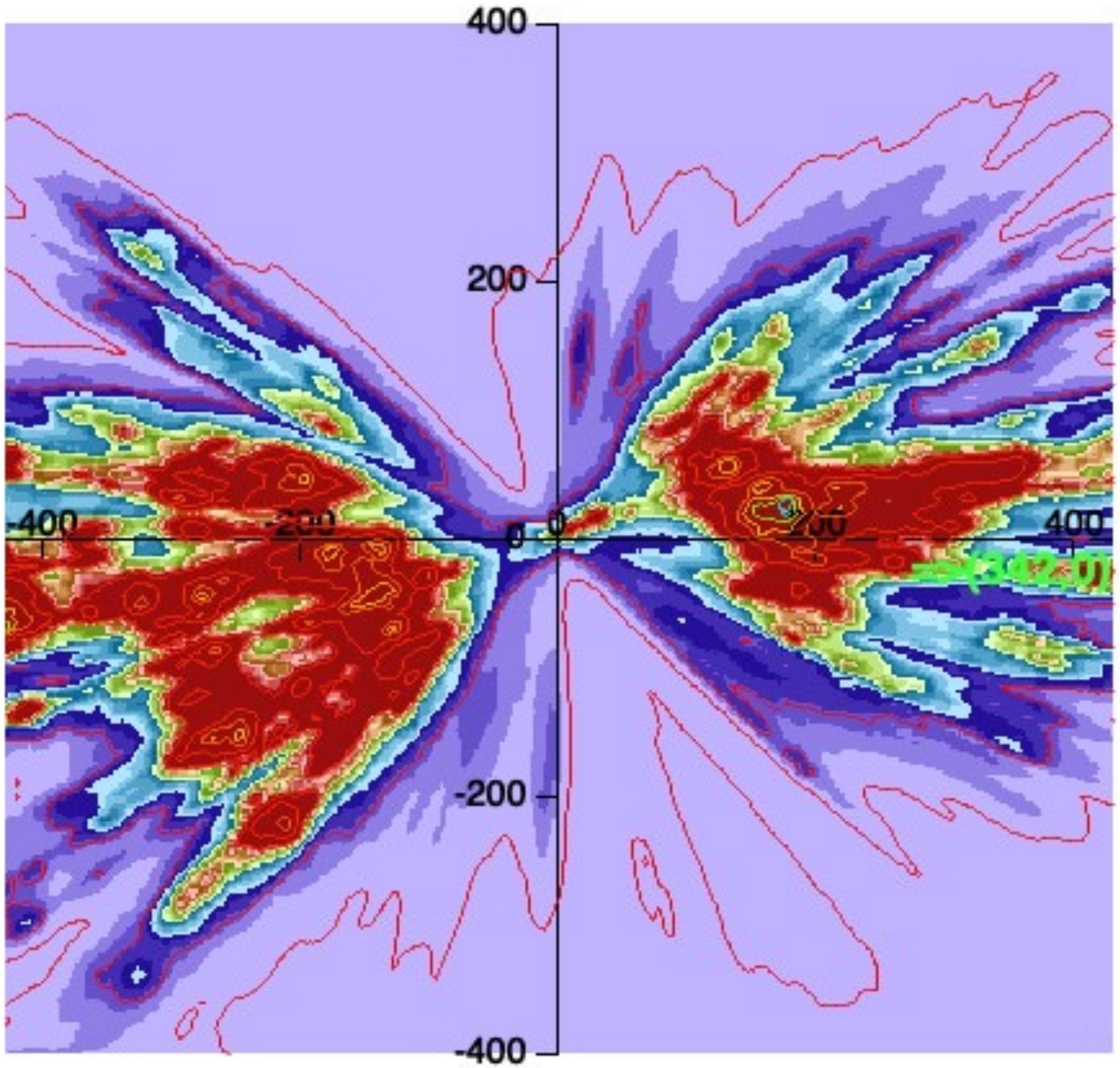
-Le vent solaire peut nous protéger

⇒ La pression exercée par le milieu interstellaire traversé est assez faible pour que vent solaire dépasse l'orbite terrestre

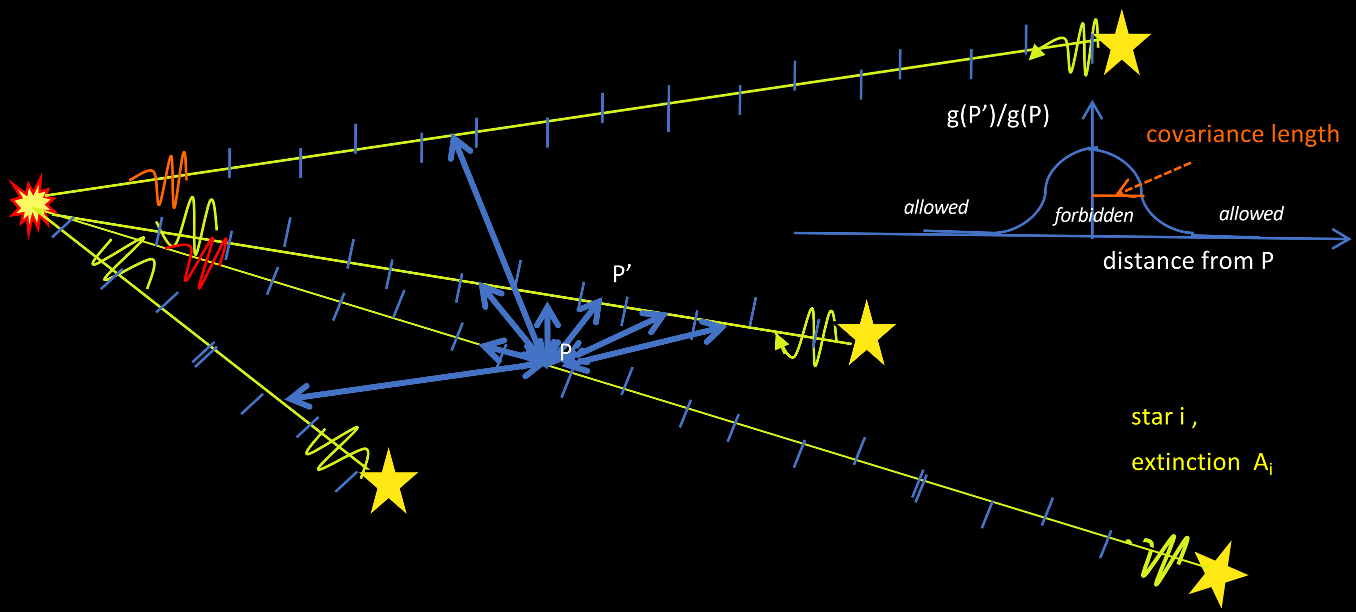

0
-200


Planar cut
l=150
b
l=330
Galactic Plane
l=150
l=330
b=+90
400
200
0
-200
-400
-600
-400
200
400
600
330,0
b


b=+90
200
100
0
sun
-100
-200
-300
-200
-100
100
200
300
342,0


400
200
0
-200
-400
-400
-200
0
200
400

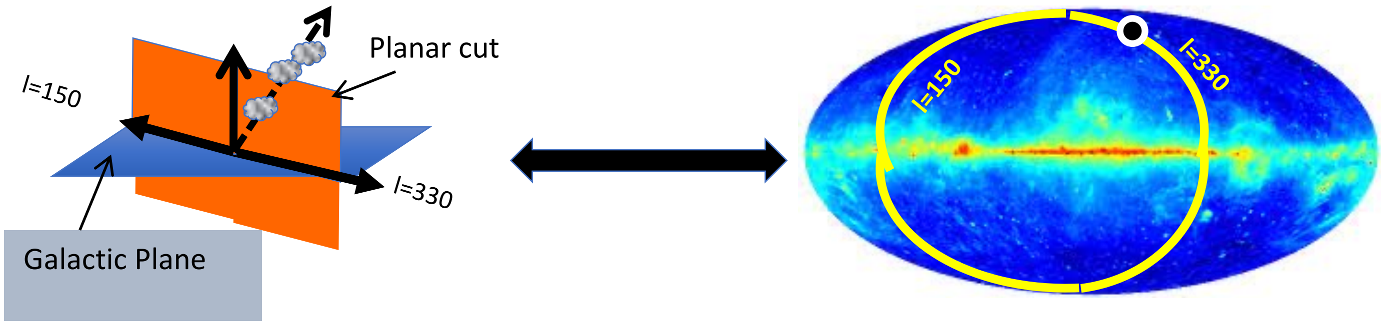
Full 3D tomography: omni-directional regularization

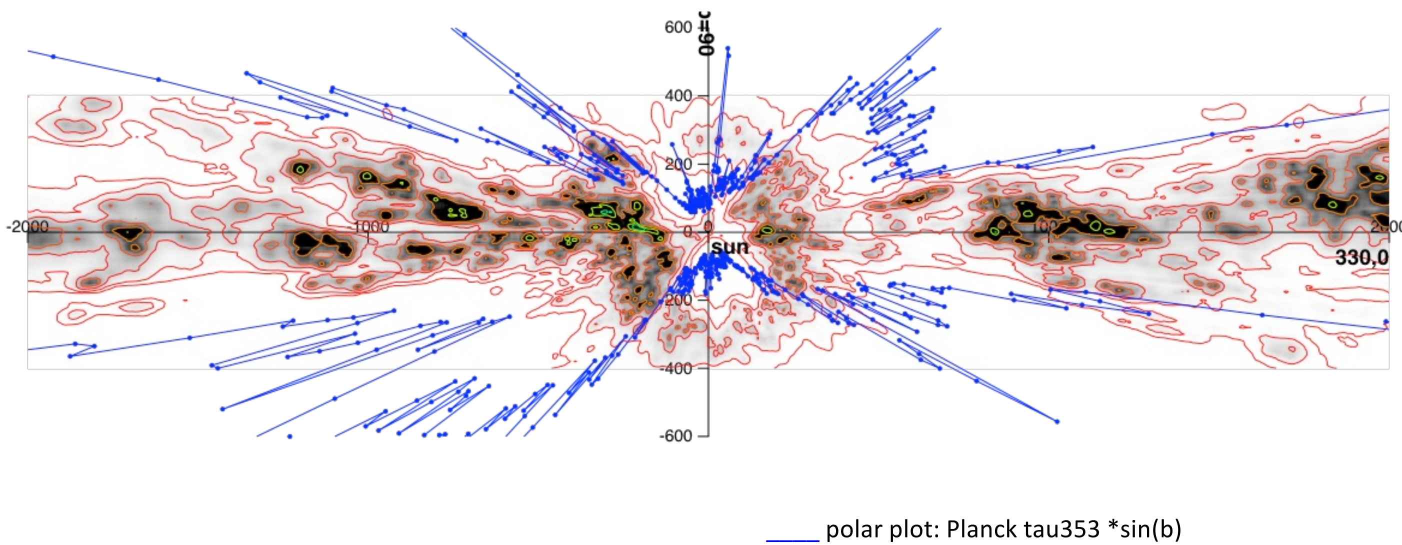


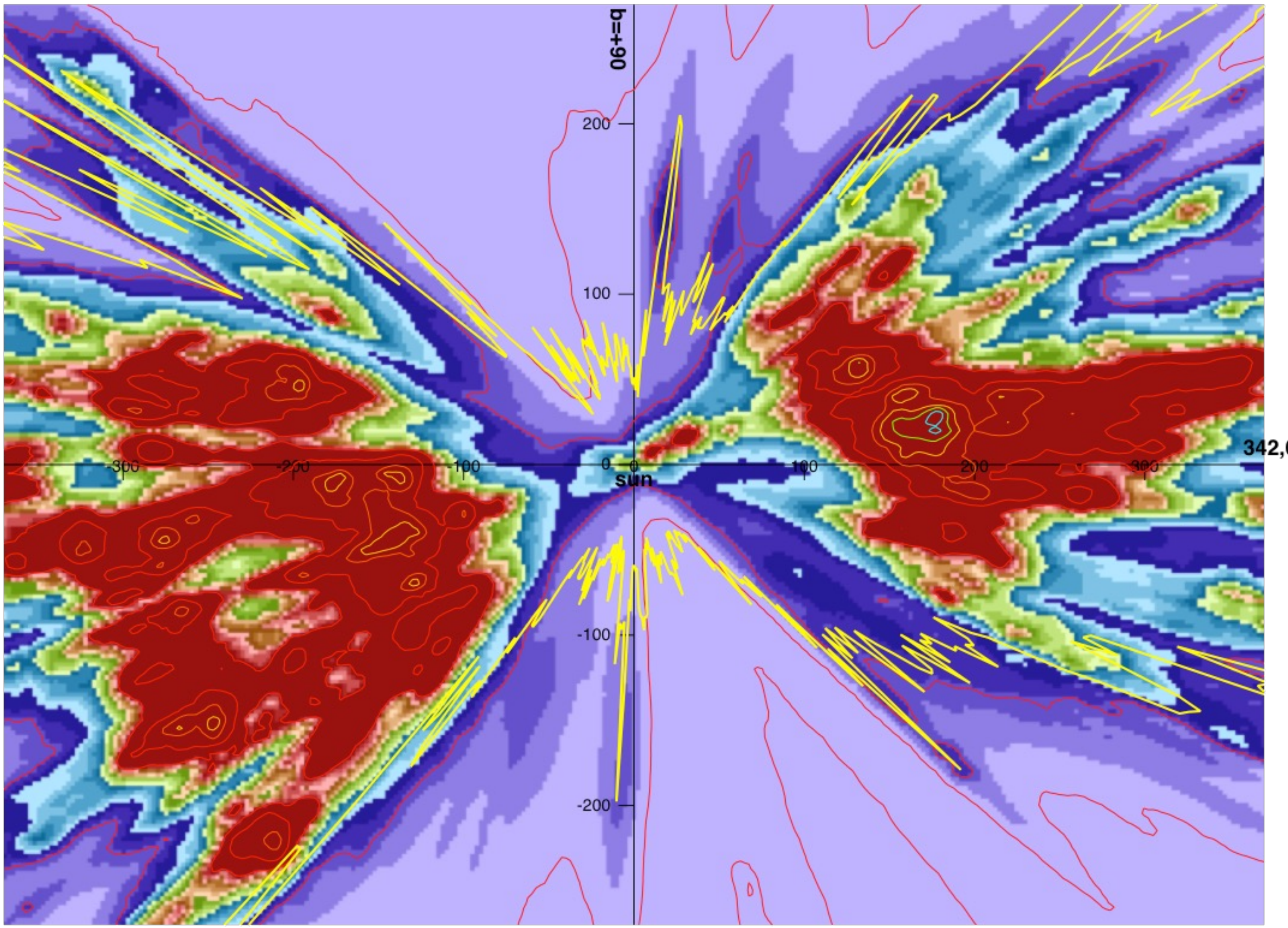
- 3D covariance kernel(s) => minimum size of structures (regularization)=> g(P')/g(P) limited

See Tarantola & Valette, 1982, Vergely et al, 2000, 2010, Lallement et al, 2014, 2018 , Capitanio et al, 2017 for applications of the above method

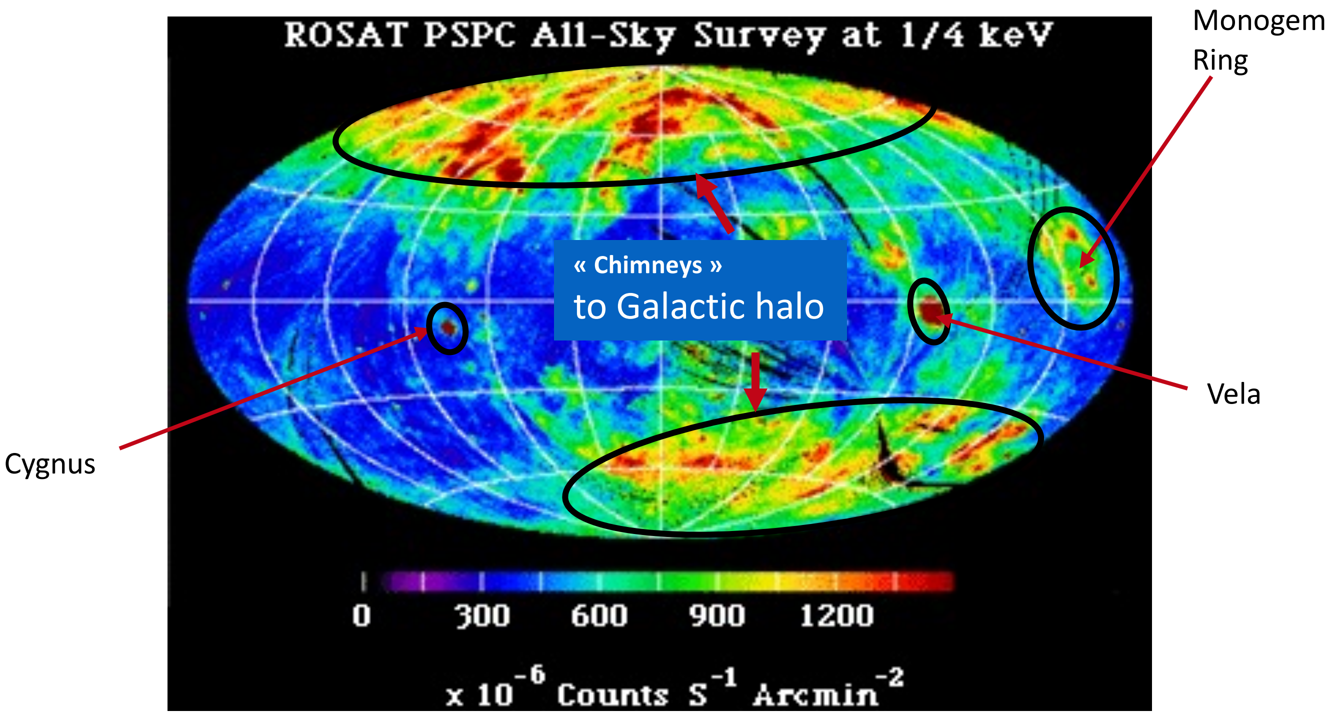
+ prior conditions on the 3D distribution (Bayesian aspect)


Planar cut
l=150
l=330
Galactic Plane
l=150
l=330

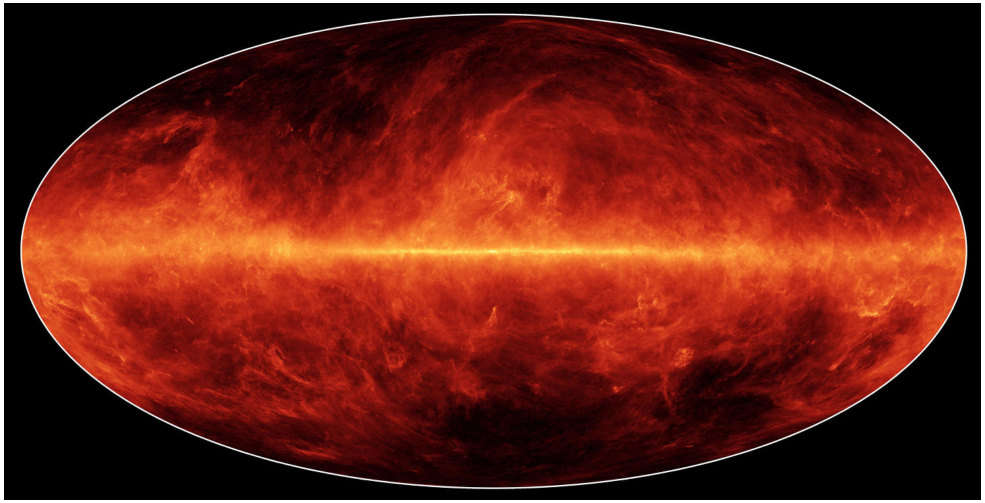

600
400
200
0
-200
-400
-600
-2000
1000
2000
sun
330,0
polar plot: Planck tau353 *sin(b)


b=+90
200
100
-300
-200
-100
0
sun
100
200
300
342,0
-100
-200

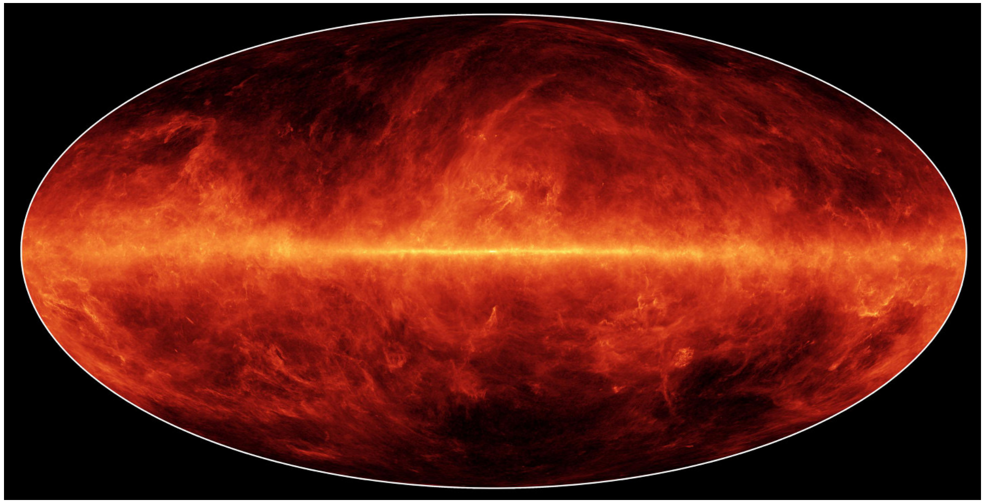
ULTRA-SOFT X-rays ROSAT 0.25keV (Snowden et al 1998).



X-ray halo emission: stronger from the Northern hemisphere



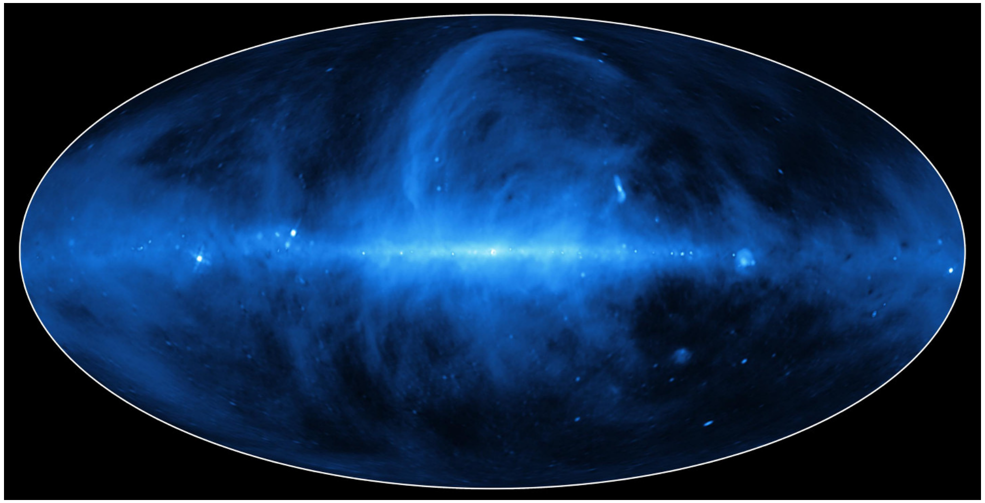
Dust and HI
local and seem to be
associated
with local bubble “caps”



Dust and HI
local and seem to be
associated
with local bubble “caps”

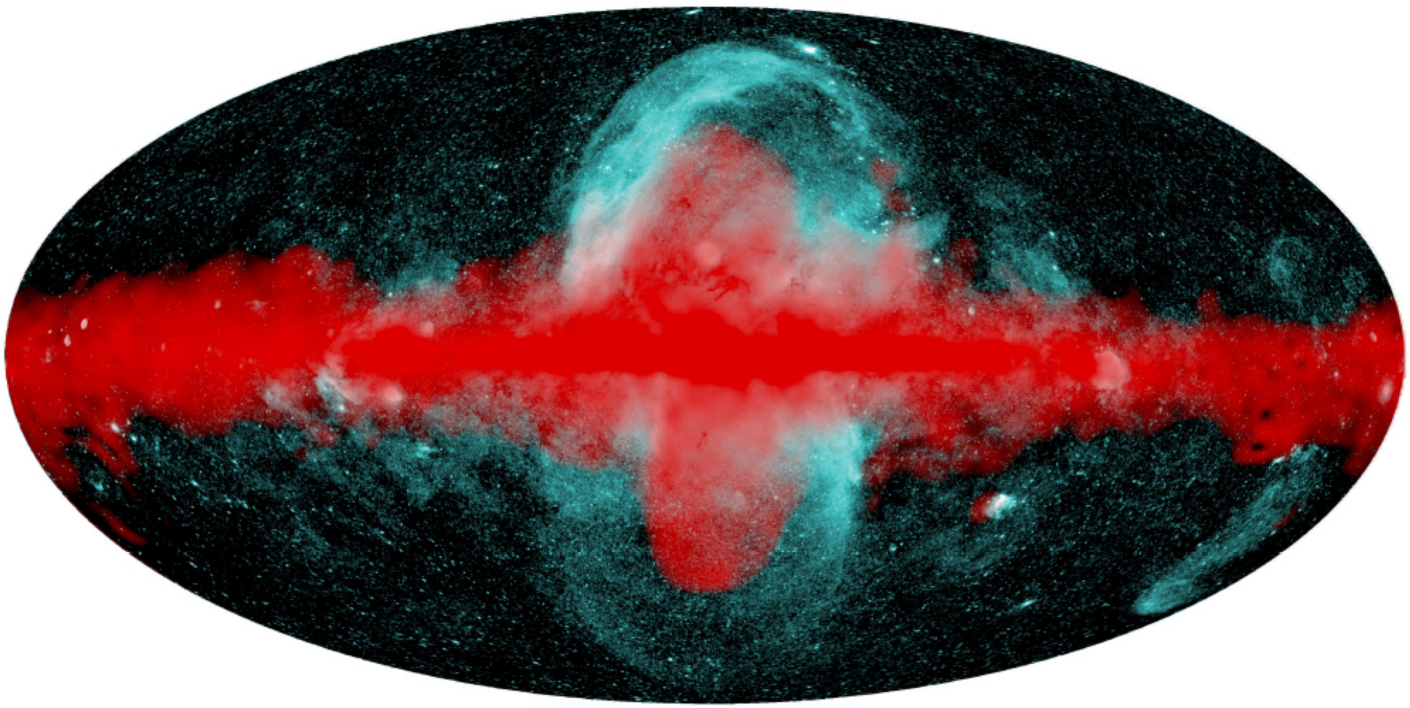
Synchrotron ➔

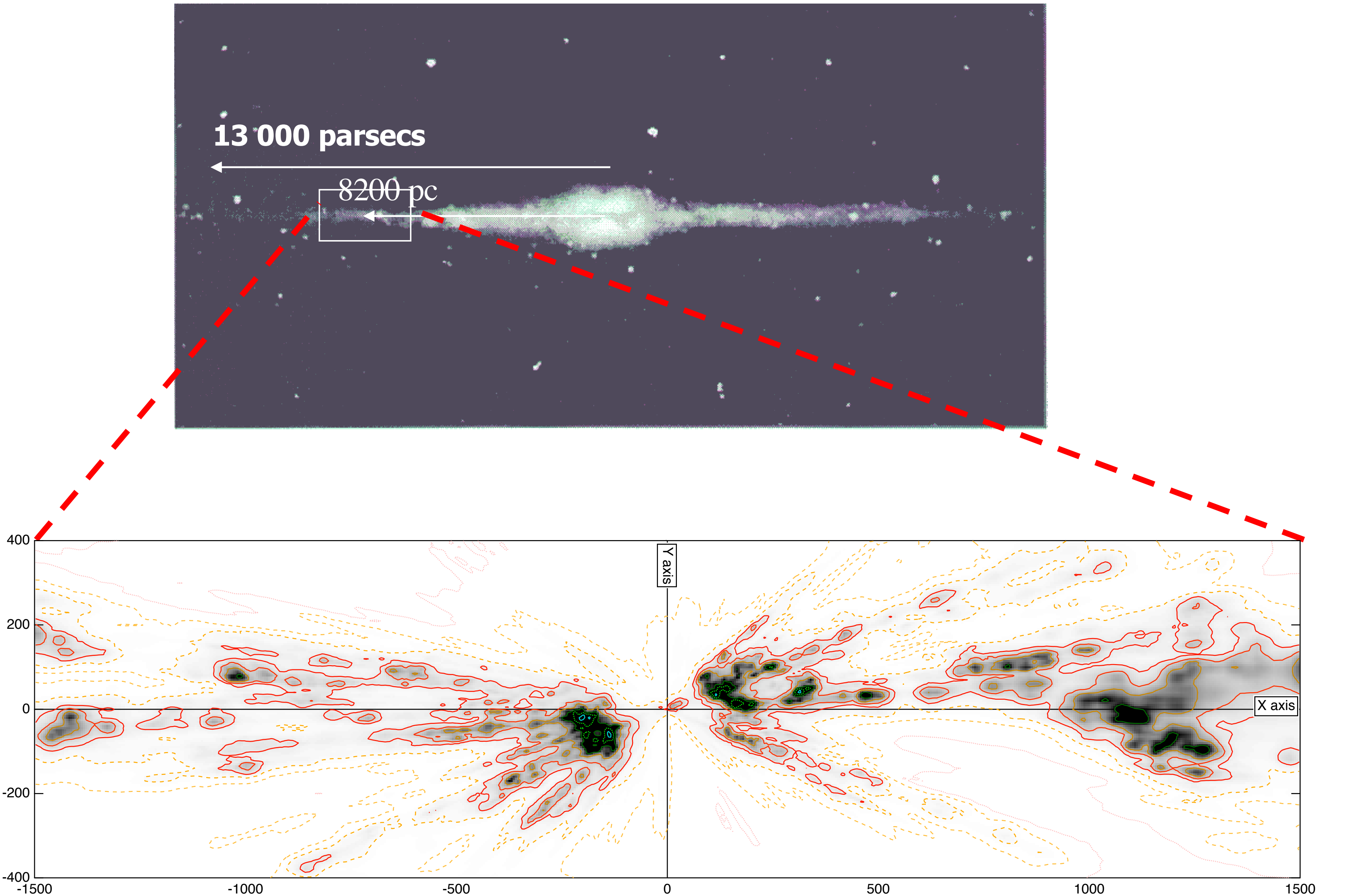
+ X-rays, gamma
of different origin



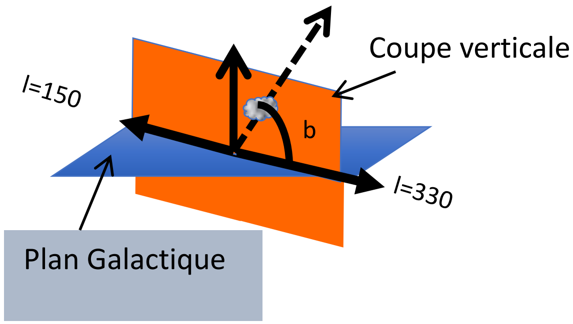
FERMI + SRG/E-ROSITA (0.6-1keV)

Predehl et al, 2020

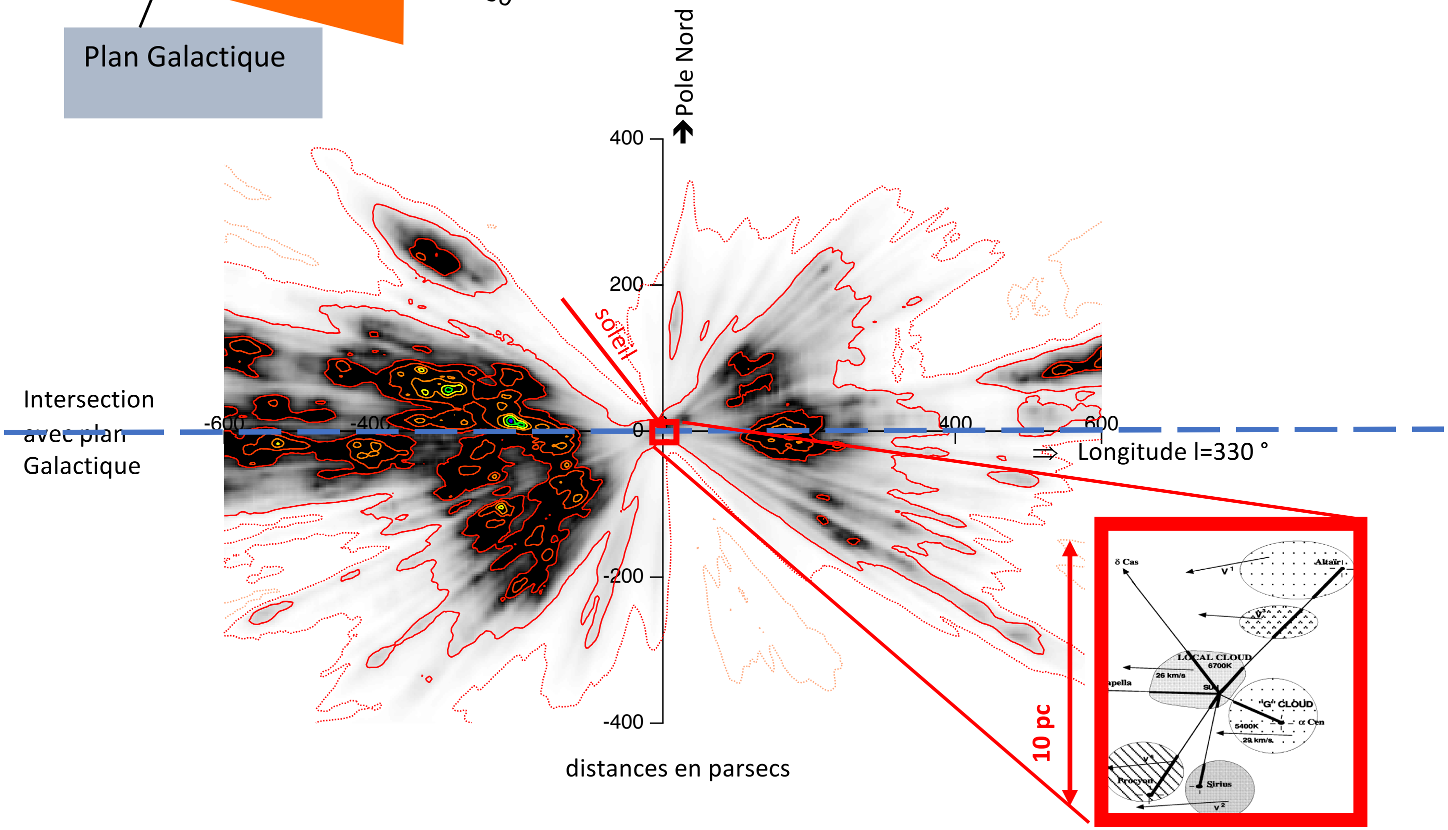


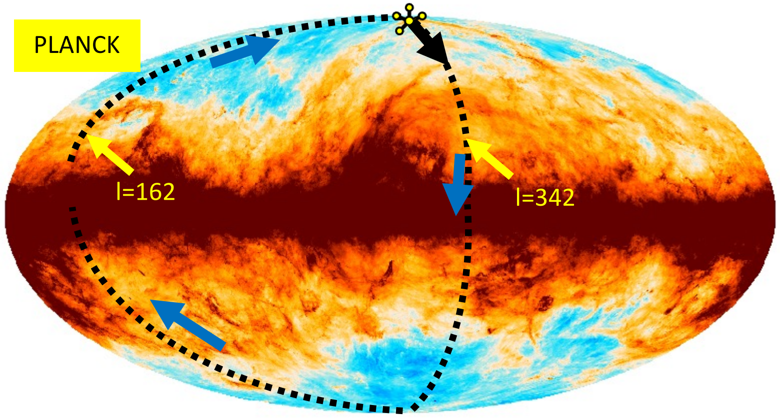


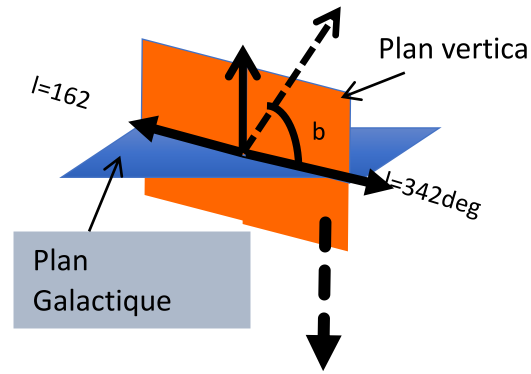
IAP Avril 2022 R. Lallement Le Milieu Interstellaire avec Gaia

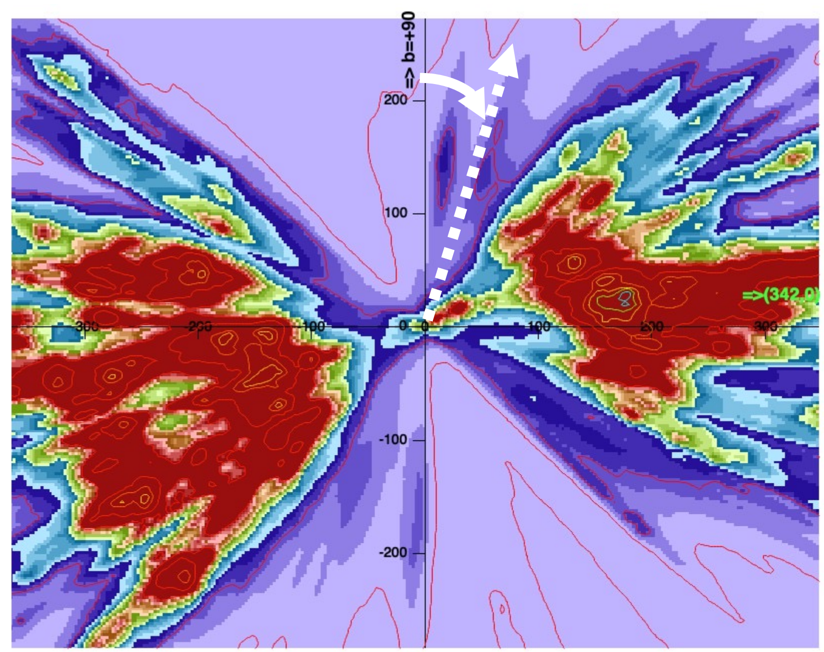


Cartes <u>locales à noyau 5pc</u> obtenues en incluant les extinctions déduites de <u>6 relevés spectroscopiques sol</u> = = +6 millions de mesures précises




PLANCK
l=162
l=342


Plan vertical
l=162
b
l=342deg
Plan
Galactique


=> b=+90
200
100
-100
-200
300
200
100
0
=>(342,0)

Spectro-photometric instrument

End of mission products

Blue: 330–680 nm, 3-27 nm/pixel

Red: 640–1050 nm, 7-15 nm/pixel

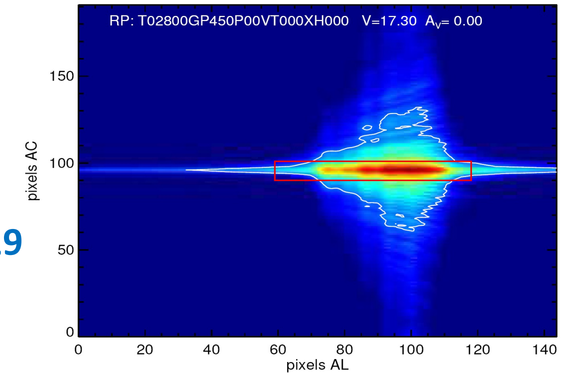
Well-defined and huge sample:

- limiting magnitude as a function of stellar density

Stellar parameters

- Teff to a few 10 K **V ≤ 15**
  to < 200 K **V ≤ 19**
- Gravity to 0.1 – 0.2 dex **V ≤ 19**
- Metallicity to 0.1 – 0.35 dex **V ≤ 19**
- Extinction to 0.05-0.2 mag **V ≤ 15**
  to < 1 mag **V ≤ 19**

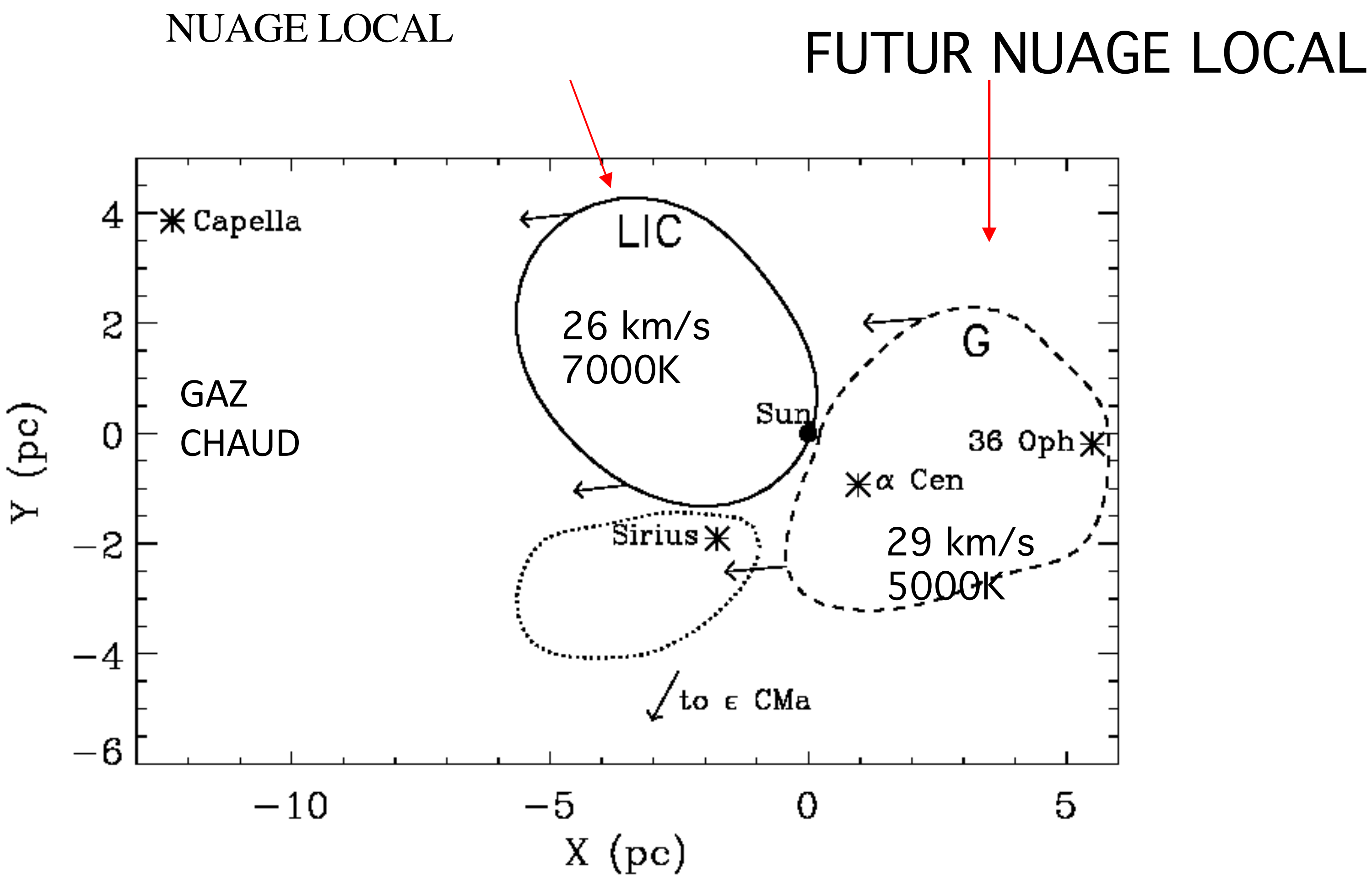
RP spectrum of M dwarf V=17.3



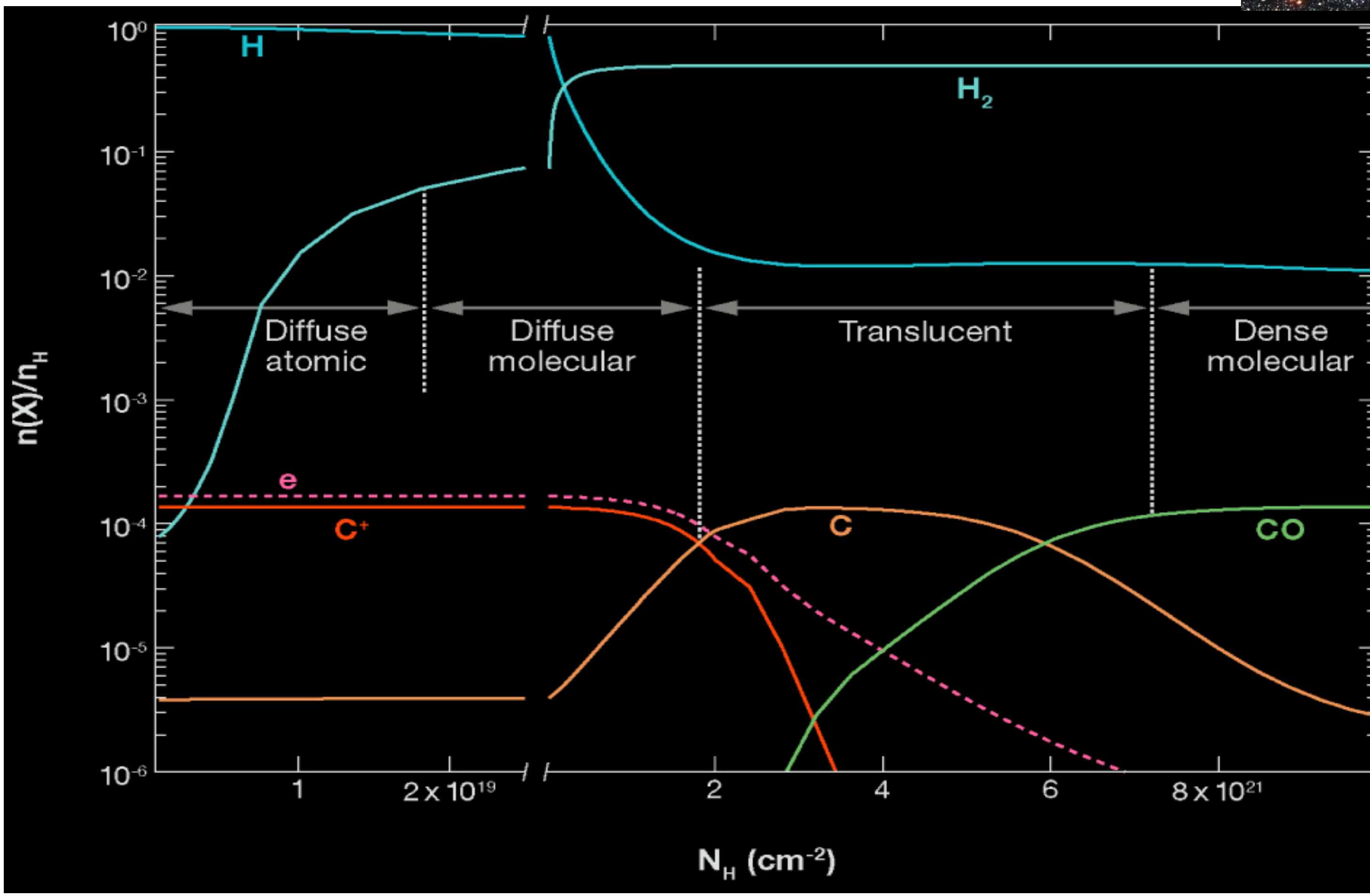
End-of-mission photometric errors: < 10 mmag for BP/RP and V ≤ 18
1-3 mmag for G up to G = 20

New Data/ GAIA

LE SOLEIL TRAVERSE UN GROUPE DE NUAGES INTERSTELLAIRES DIFFUS



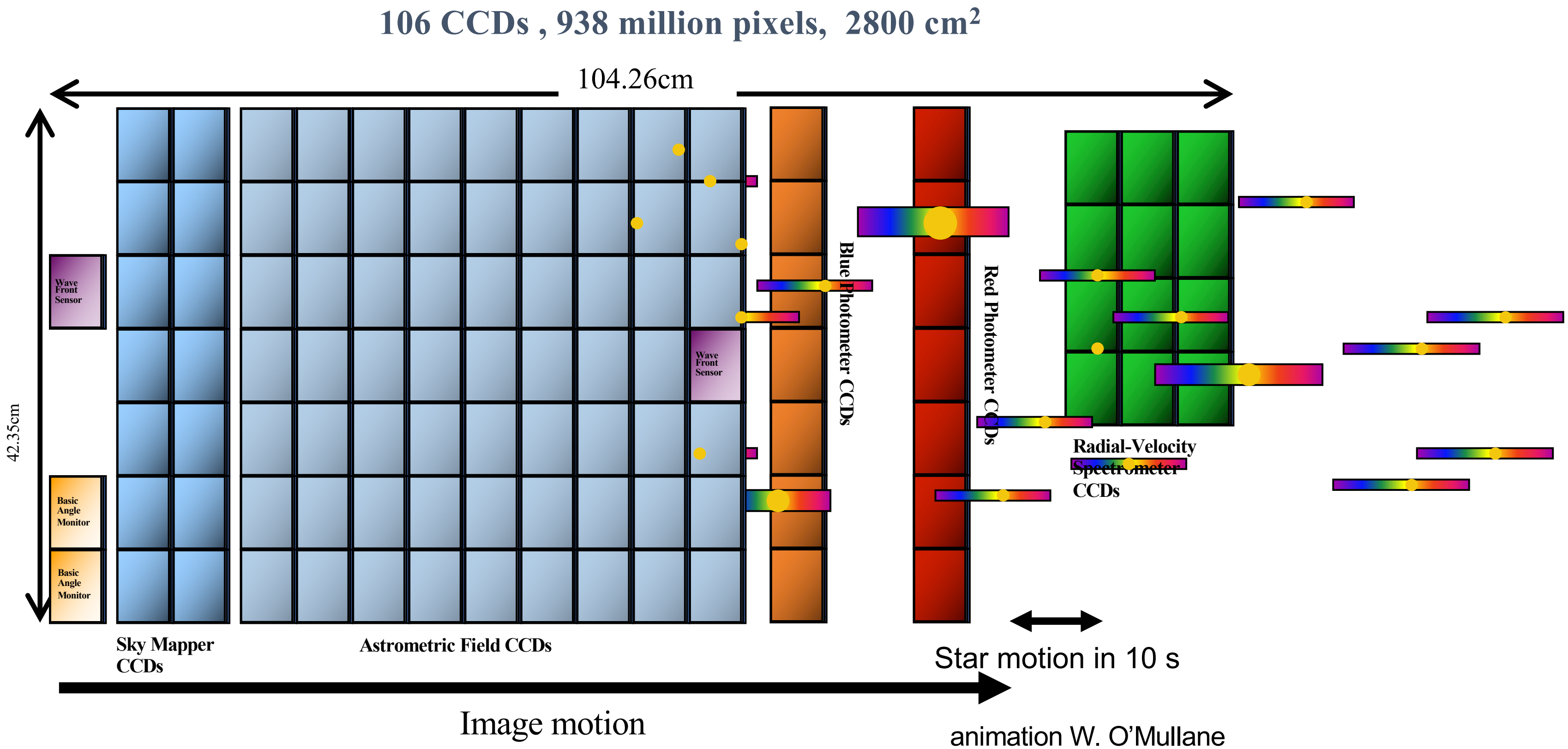
Stellar motion perturbed by a giant planet



DIFFUSE $A_V < 1$ mag T ~ 100 K, n_H ~ 100-500 cm^{-3}

DENSE $A_V > 5$ mag (up to 60) T < 20K $n_H >= 1000$ cm^{-3}

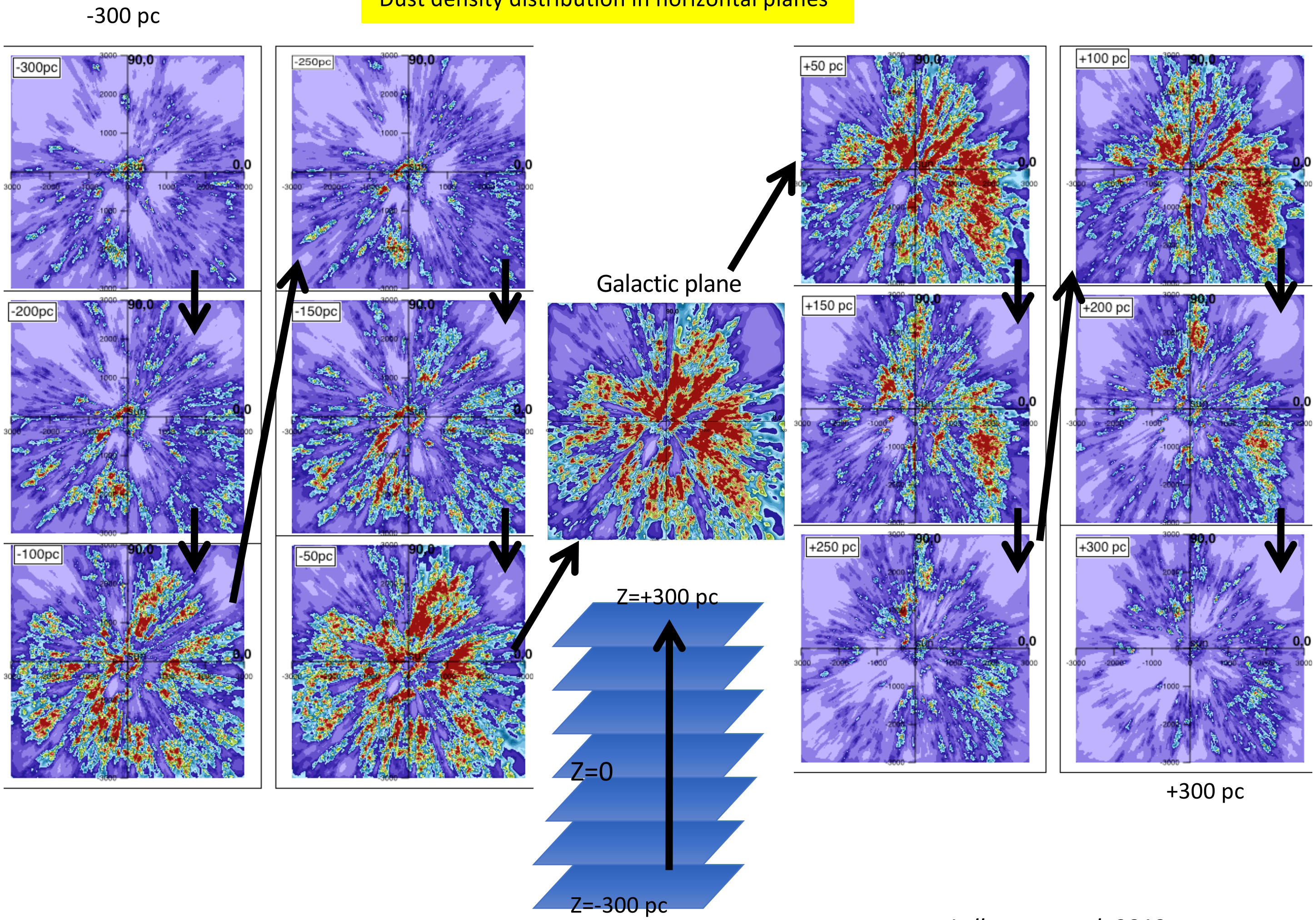
Quasi-simultaneous astrometric, photometric and spectroscopic observations



animation W. O'Mullane

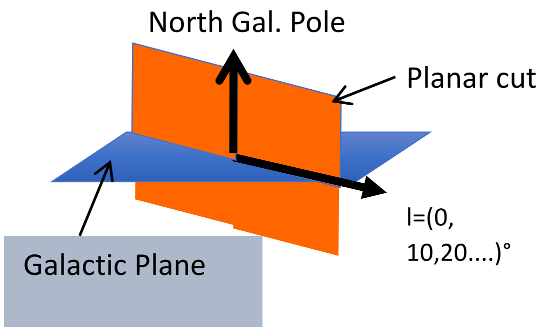
New Data/ GAIA

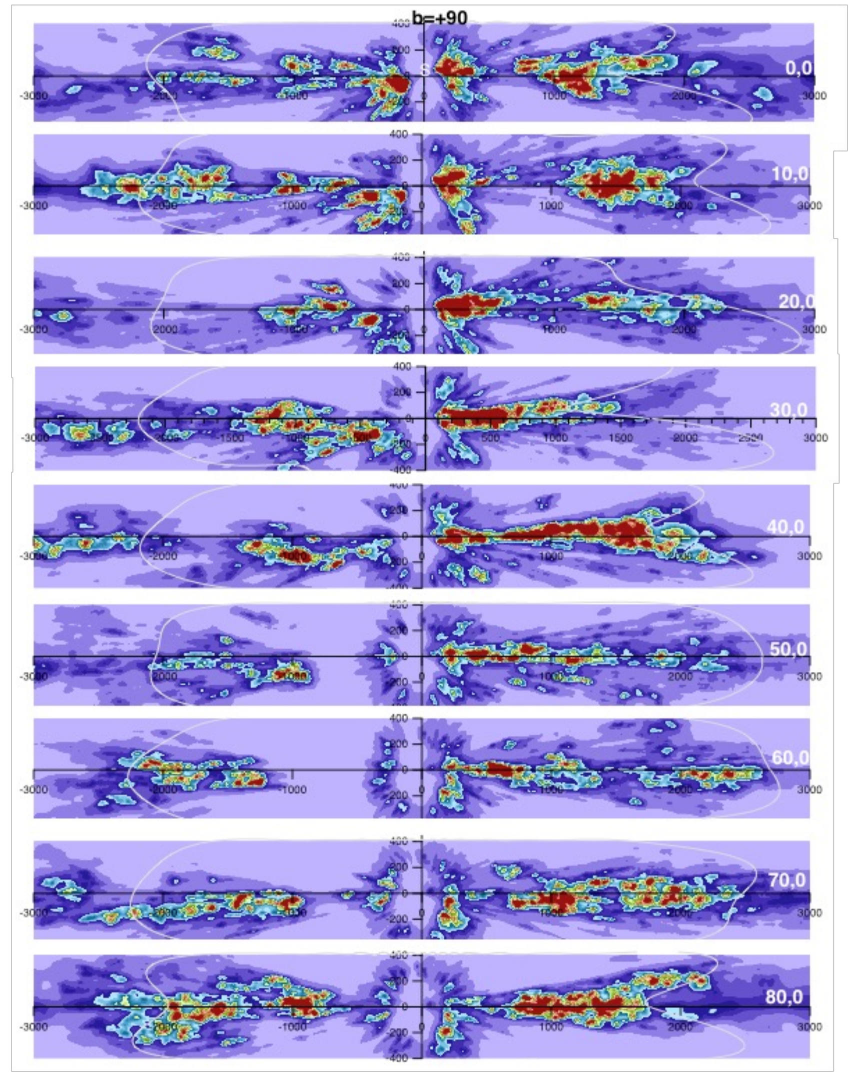
Dust density distribution in horizontal planes



Lallement et al, 2019

Dust density distribution in vertical planes





SEVERAL WAYS OF ESTIMATING REDDENING/EXTINCTION

INDIVIDUAL METHODS

The “CLASSICAL WAY”

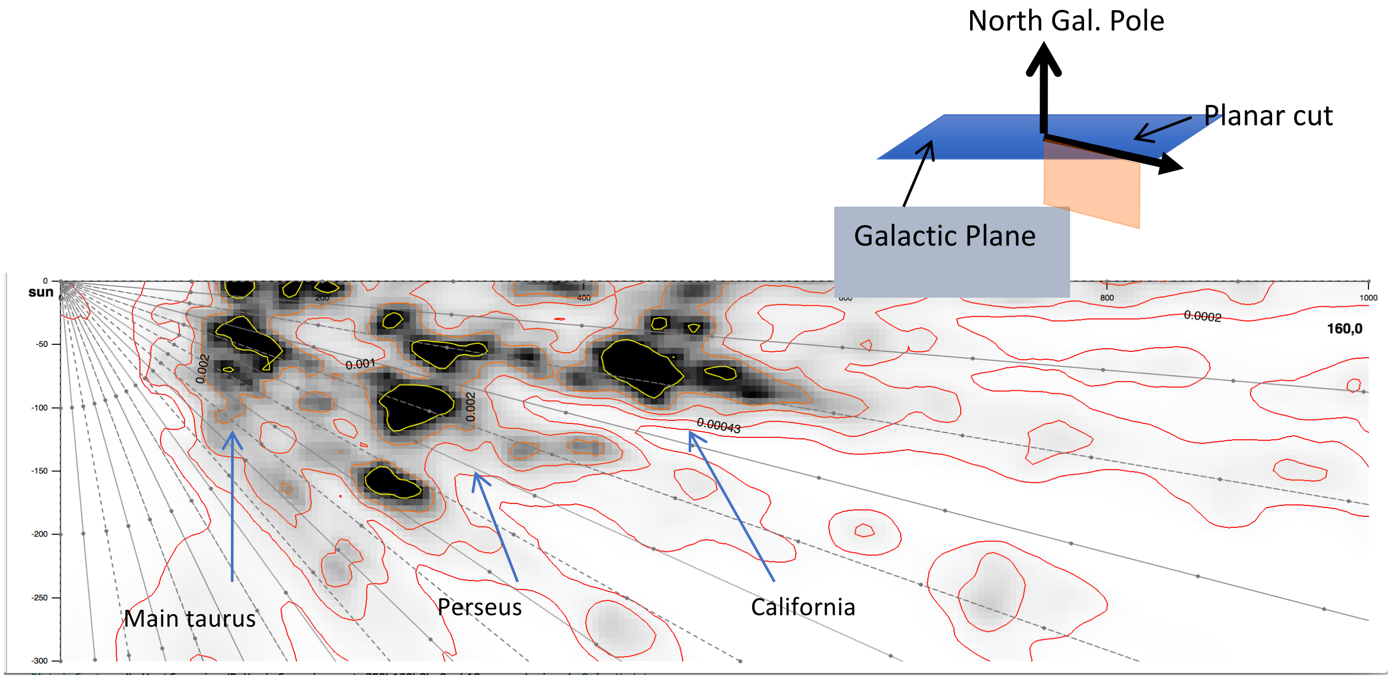
Individual (star by star) estimates of extinctions using visible+infrared bands and comparison with stellar photometric models + **independent parallactic distances**

For fainter (and more numerous) targets:

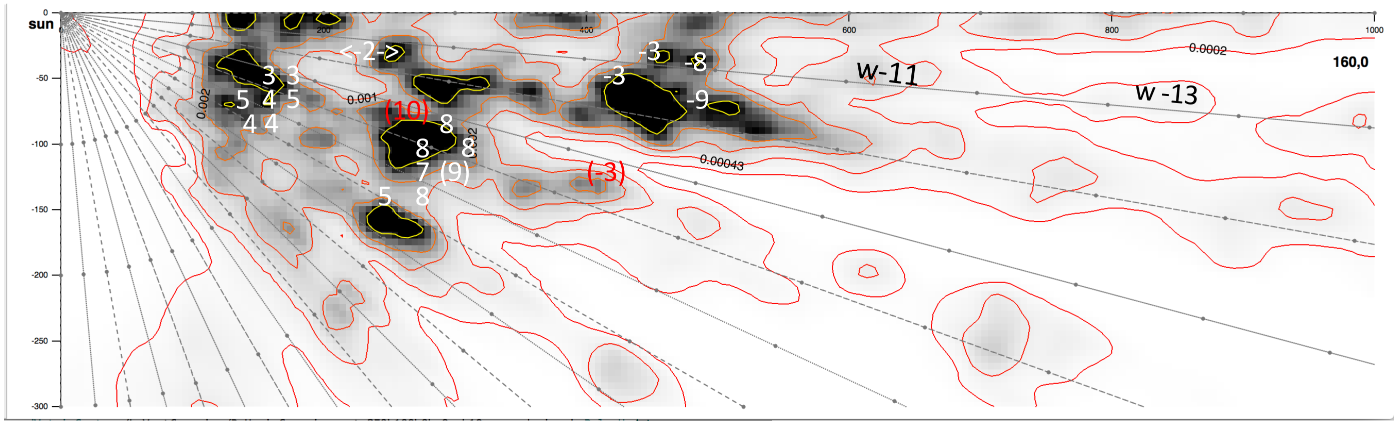
Individual estimates of coupled extinctions and distances using visible+infrared bands and comparison with stellar photometric models (using distance and luminosities to disentangle between dwarf and giants stars) **Parallactic distances used as “prior” when available**

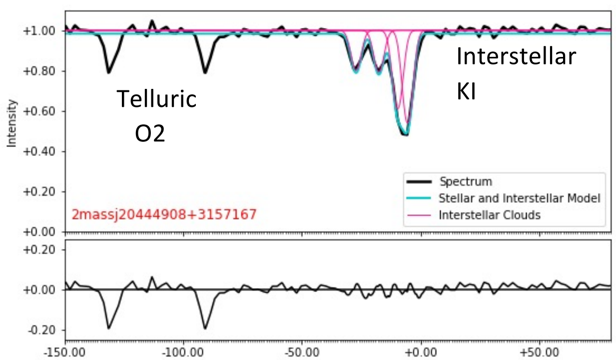
ADAPTED TO “ACCURATE” DATASETS

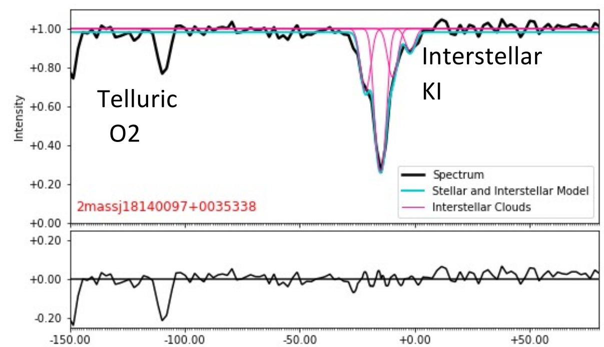
Extraction


North Gal. Pole
Planar cut
Galactic Plane
sun
160,0
0.0002
0.001
0.002
0.00043
Main taurus
Perseus
California

Assigning radial velocities to the Taurus clouds







TBL/NARVAL spectra of stars within (or very close to) the vertical plane

7699 A KI line, multi-cloud fit => allows to disentangle clouds by means of radial velocities