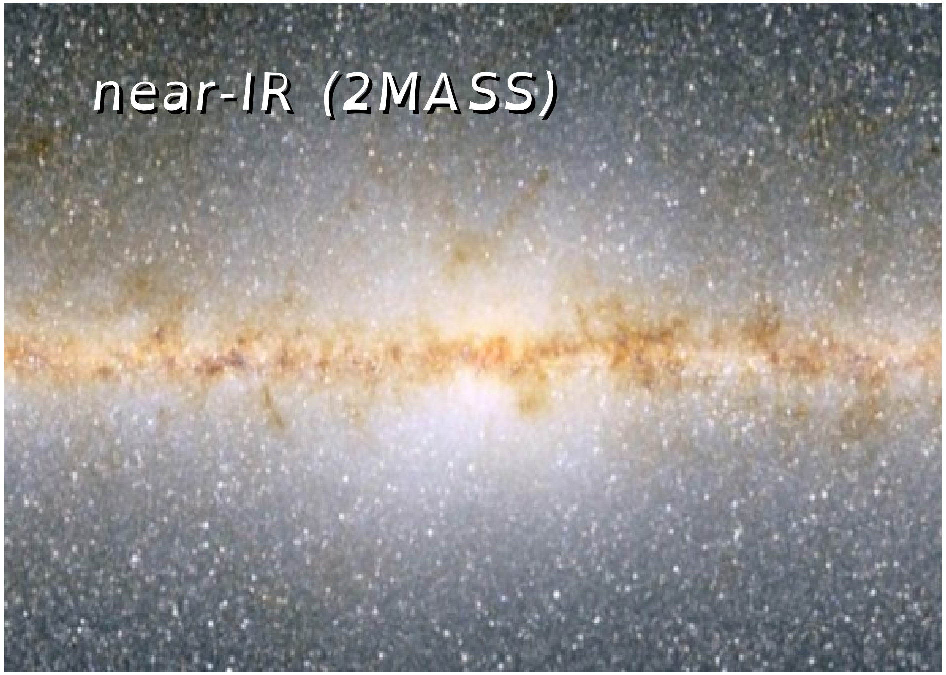
# 2.5 Global Structural Properties

# OVERVIEW

- Nucleus
- Nuclear Bulge
- Bulge
- Disk
- Halo

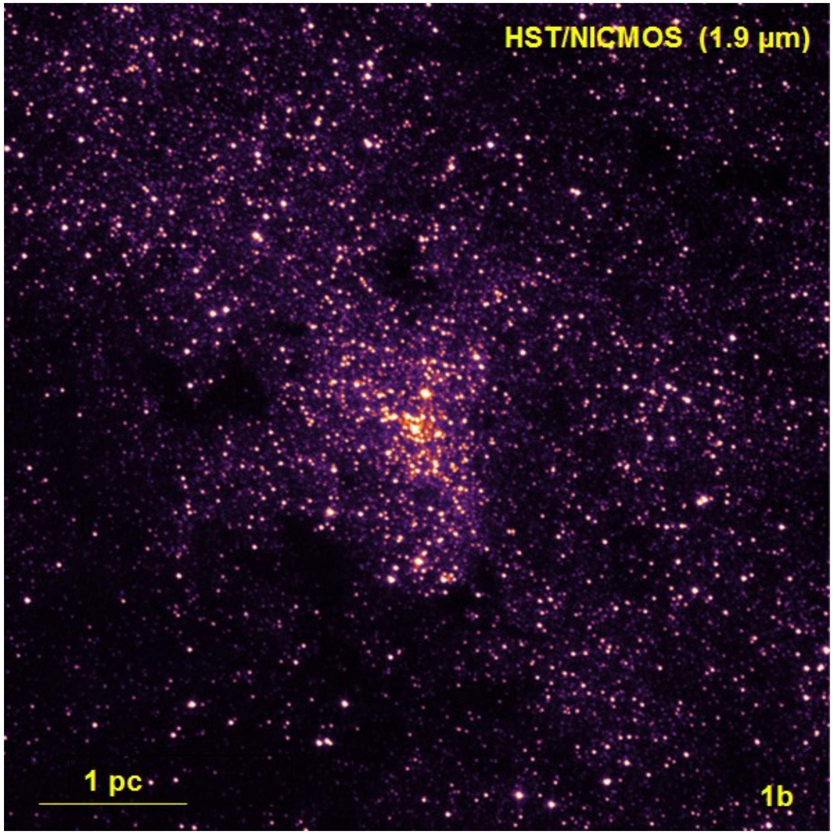
# 1 – THE NUCLEUS

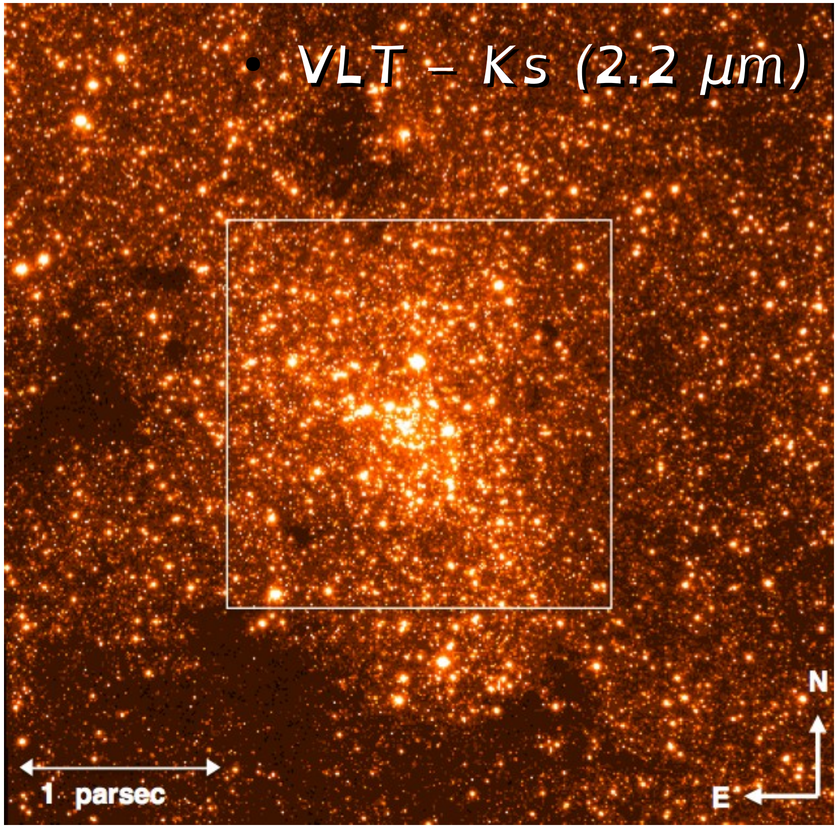
- We know that looking through the Galaxy in optical is hopeless!
- However even in the IR dust absorption could be significant

# THE NUCLEUS - IR

- Galaxy center (in IR) shows a cluster of bright (young) stars
- Extremely high density → possible central compact object



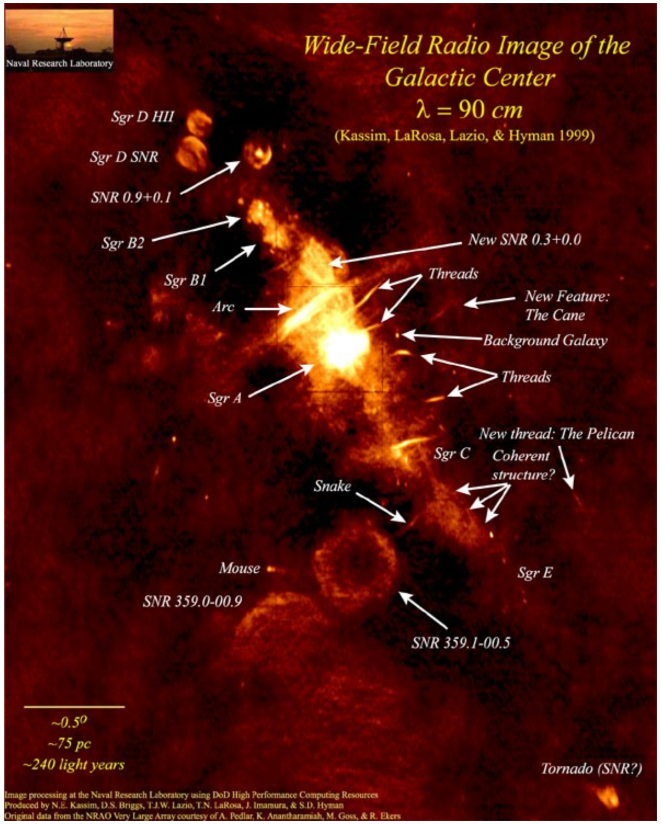




[Gallego-Cano (2017)]

# THE NUCLEUS - RADIO

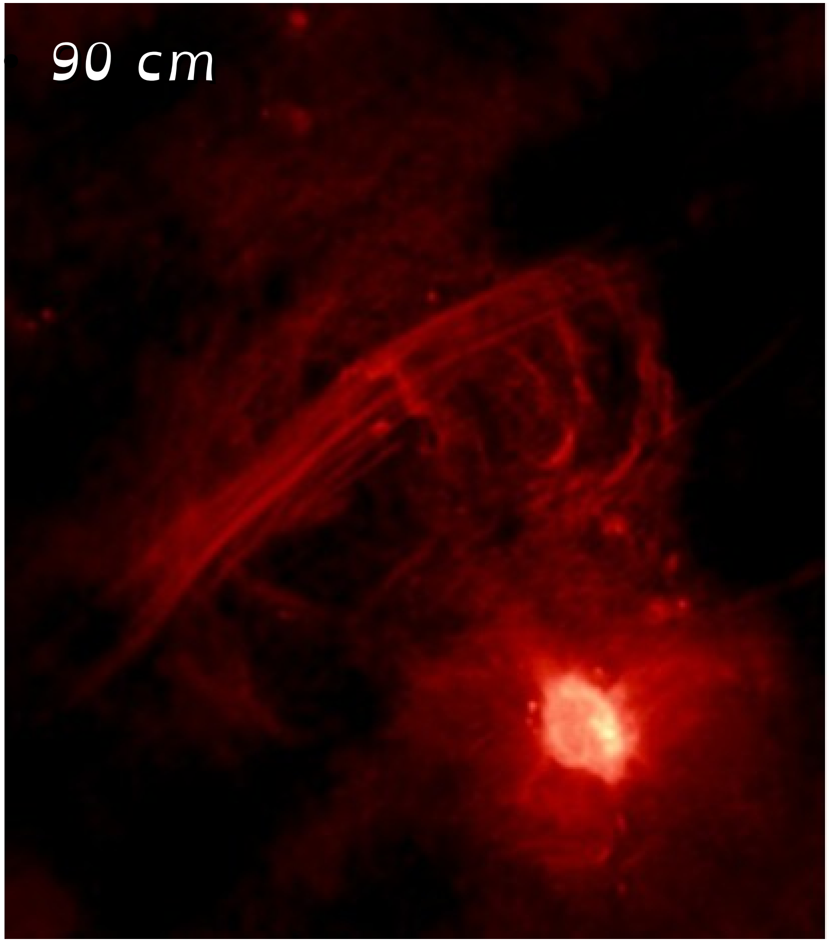
- At radio frequencies the galaxy is more “transparent”

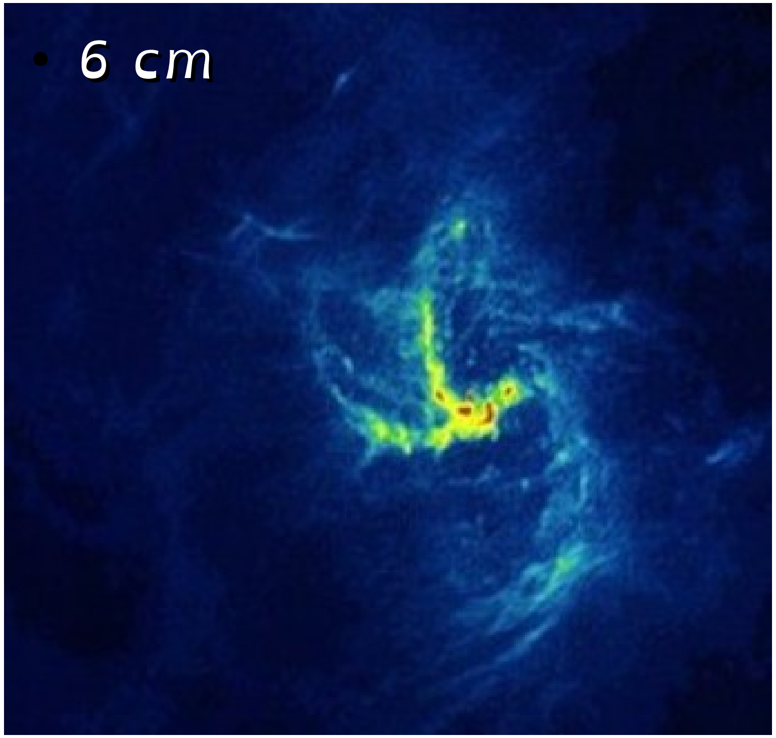
- Emission is dominated by synchrotron:
  - diffuse
  - SNR
  - stripe (?)
  - nucleus (SgrA)



# THE NUCLEUS - RADIO

- A zoom on the nucleus reveals a mini-spiral structure (face-on)

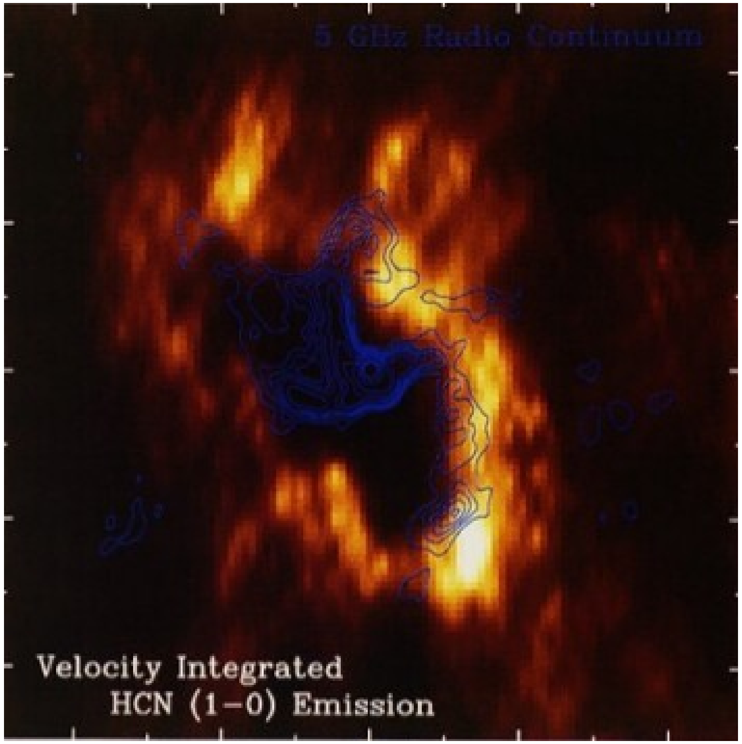


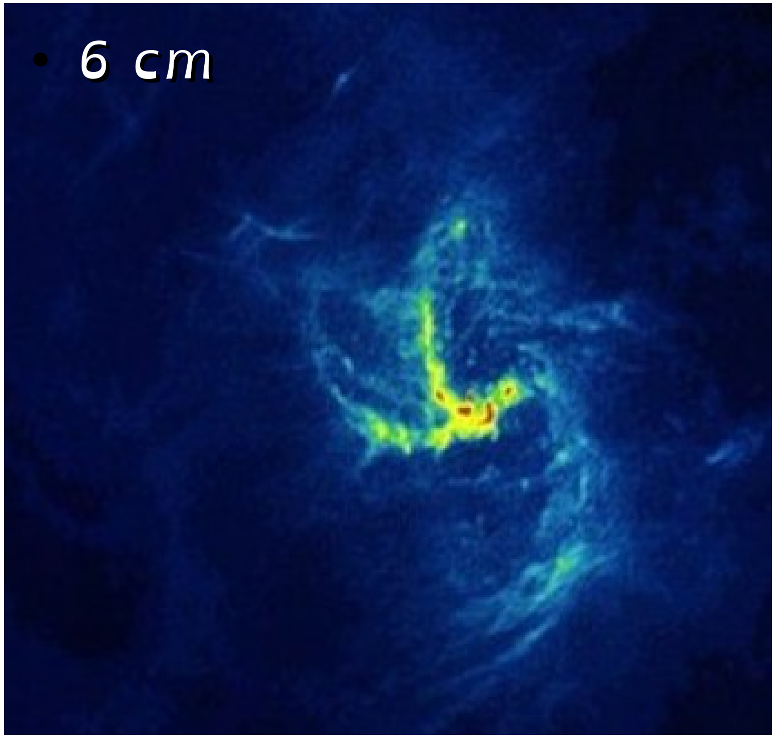



# THE NUCLEUS - RADIO

- From the emission of HCN → molecular ring around spiral

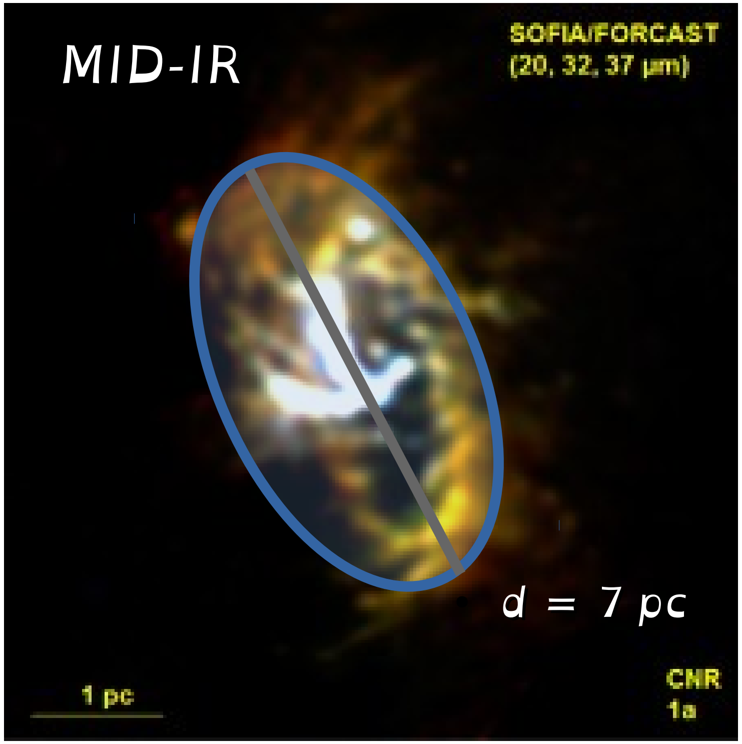
  The origin of these 2 structures is unknown

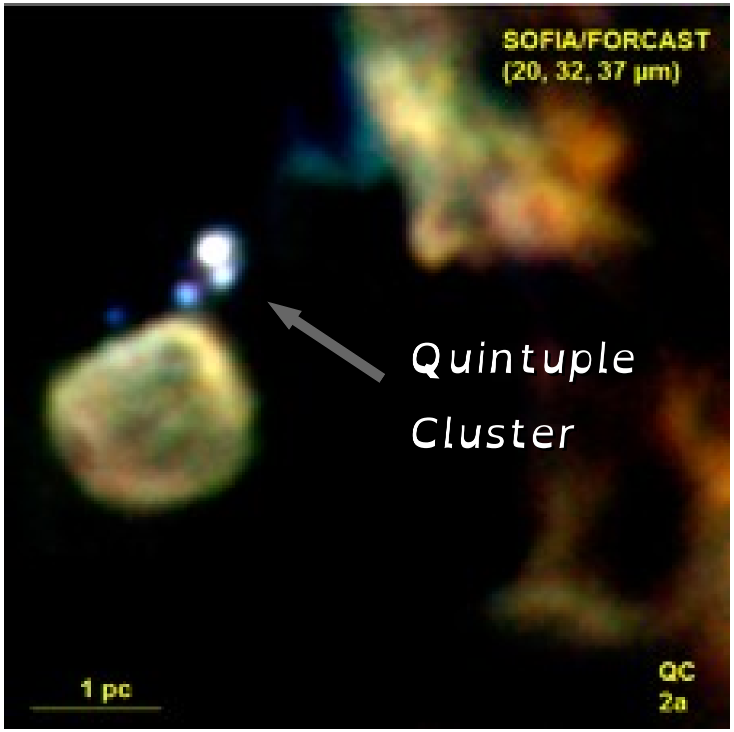


# THE NUCLEUS – DUST RING

- The ring is also visible at MID-IR
- MID-IR also reveals extremely bright stars around the ring
  → indication of on-going circum-nuclear star formation

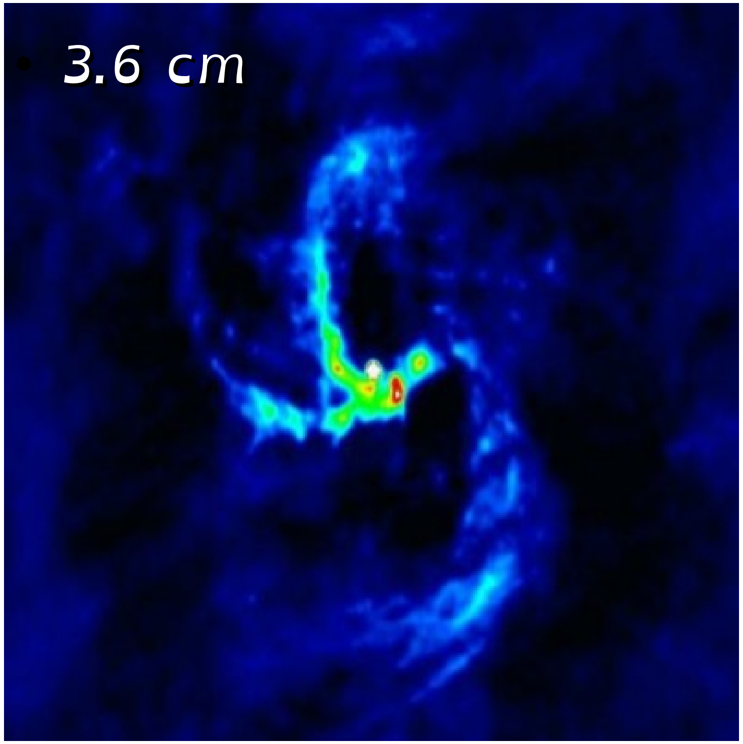


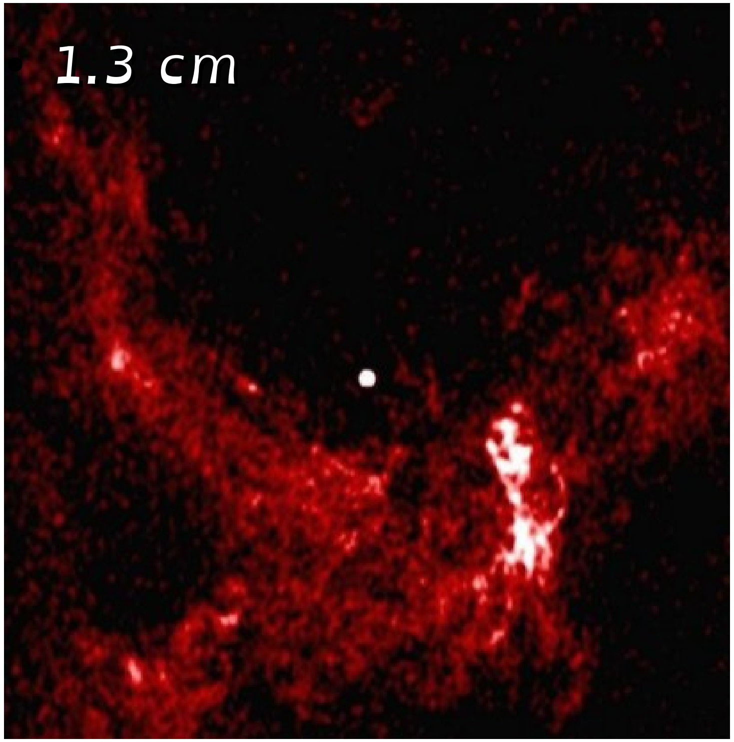



# THE NUCLEUS - SgrA*

- Moving at lower λ we can obtain higher resolution
- We identify a point source → SgrA* (accretion disk or jet?)

  Variable source: period ~hundreds days *[Beaklini & Abraham 2013]*

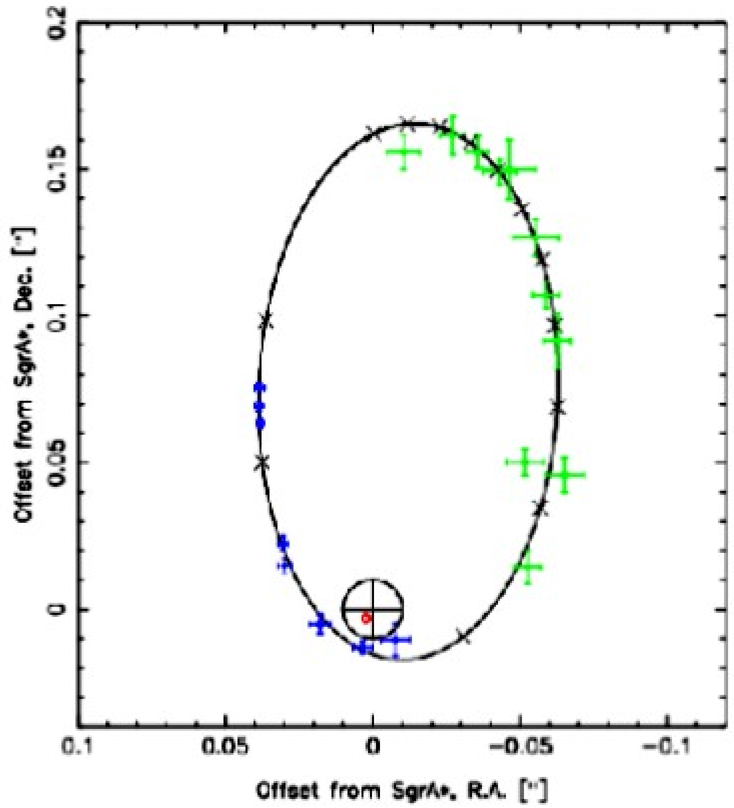


# THE MASS OF SgrA*

- The mass of SgrA* can be deduced from stellar motion
- S2: star with best measured orbit (best constrain) → $10^6$ $M_{SUN}$

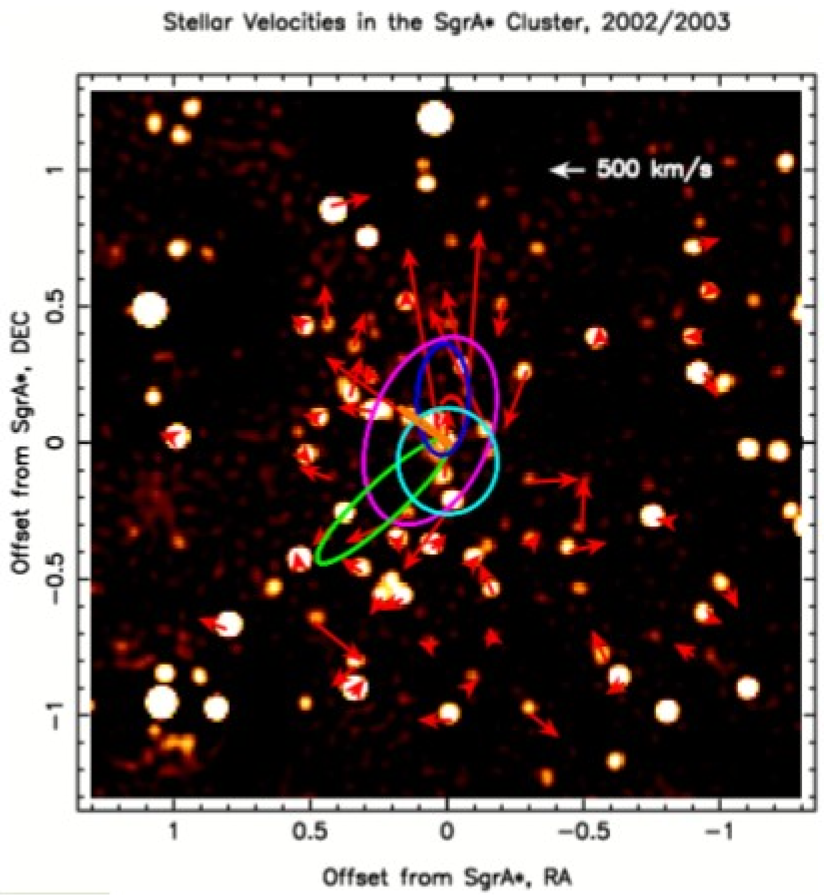
*NOTE: mass alone does not prove is a BH*




- To distinguish between BH or an other source (e.g. dense cluster) → need to estimate the *density*

# THE MASS OF SgrA*

- Let's consider the population of stars around SgrA*




- If SgrA* is a "diffuse" object:

$$M_{SgrA*} \text{ (inner orbits)} \;!=\; M_{SgrA*} \text{ (outer orbits)}$$

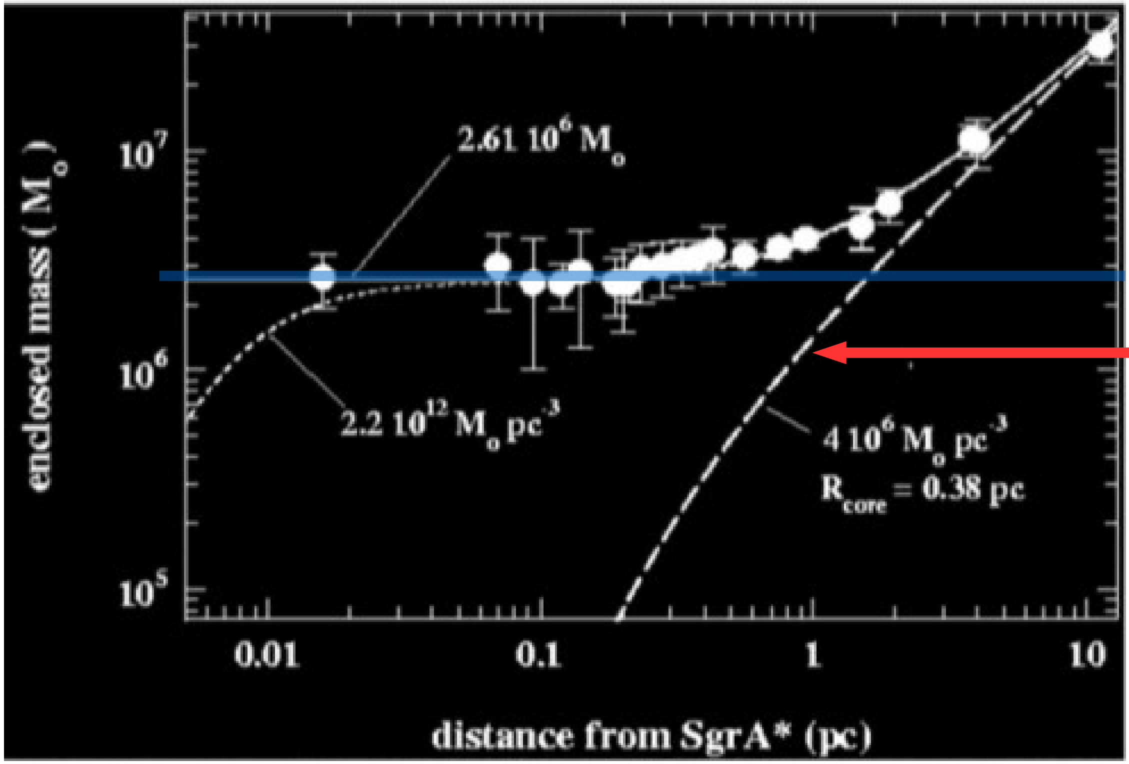
- If SgrA* is a BH:

$$M_{SgrA*} \text{ (inner orbits)} = M_{SgrA*} \text{ (outer orbits)}$$

# SgrA* IS A BH!

- $M_{SgrA*}$ as derived from different orbital distances:

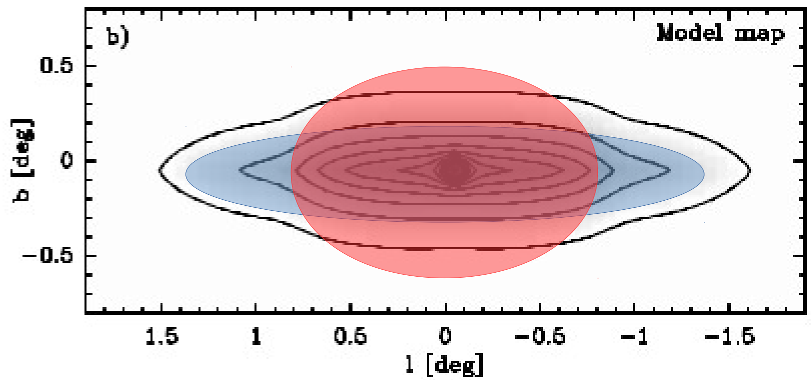
compact source (BH)




stars/DM around BH

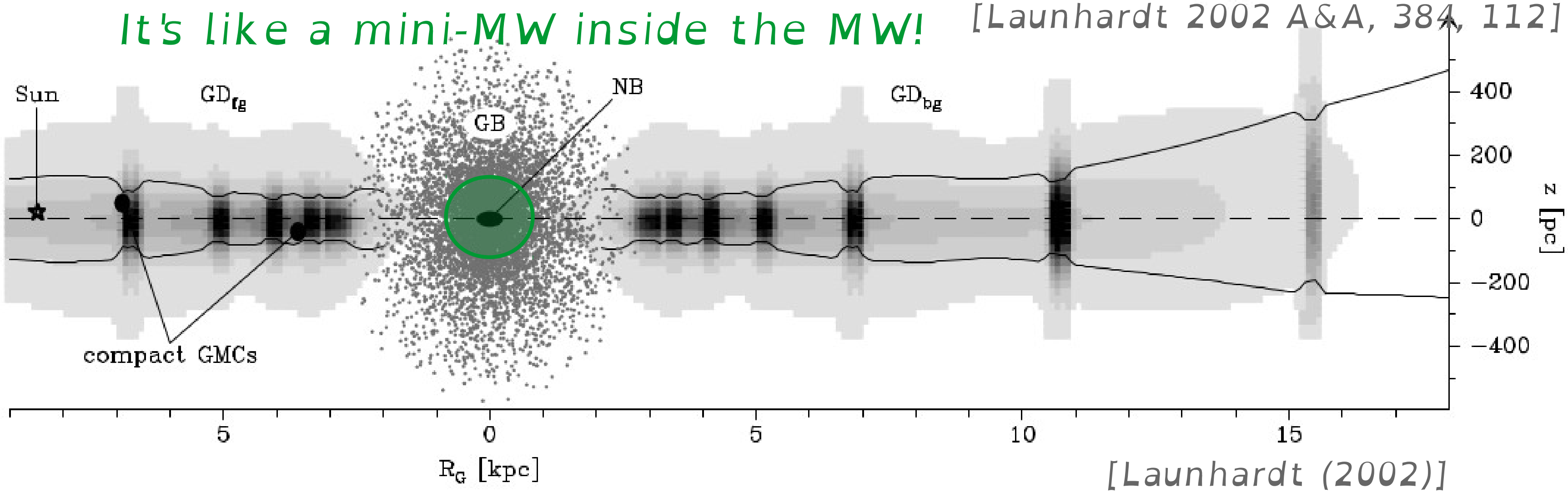
# 2 – THE NUCLEAR BULGE

- Let's start zooming out from SgrA, from center of Milky Way
- We encounter Nuclear Bulge (NB)
- 5% of $L_{TOT}$, composed by:
  - Nuclear Stellar Cluster (NSC)
  - Nuclear Stellar Disk (NSD)




[Launhardt 2002 A&A, 384, 112]

*It's like a mini-MW inside the MW!*

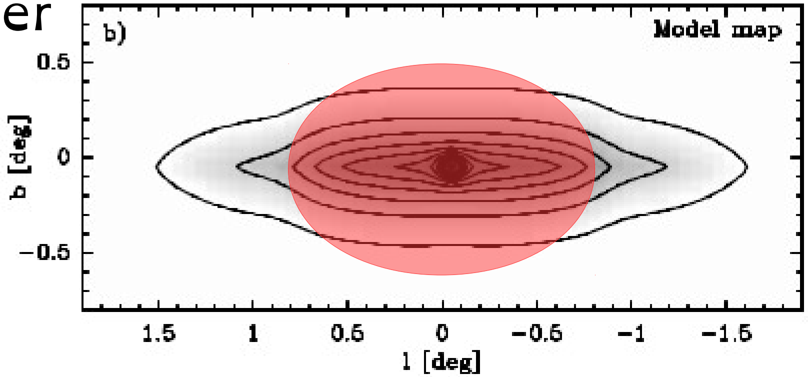



[Launhardt (2002)]

# THE NUCLEAR STELLAR CLUSTER (NSC) - MORPHOLOGY

- NSCs are common in both Elliptical and Spiral galaxies

  Look like GCs/bulges, but much denser




*[Launhardt 2002 A&A, 384, 112]*

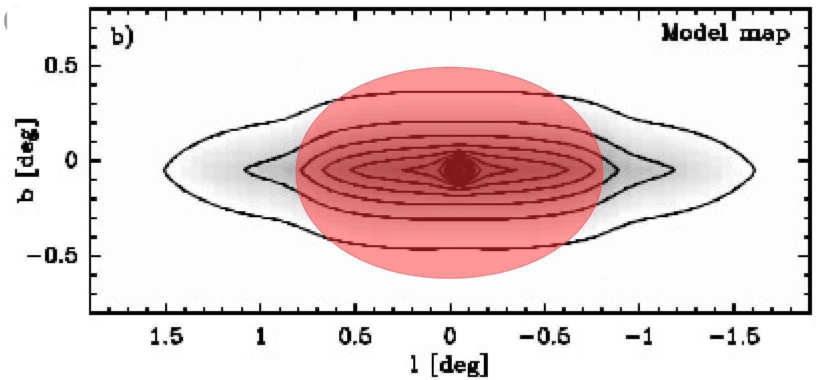
- Morphology of the MW NSC:
  - centered on SgrA* (±0.2 pc)
  - slightly flattened (b/a ~ 0.7)
  - radial profile → Sersic n = 2
  - Re ~ 4 pc
  - L ~ 4 x $10^7$ $L_{SUN}$ → M ~ 3 x $10^7$ $M_{SUN}$

*Schödel et al. 2014, A&A, 566, 47 ; Schödel 2015, arXiv:1502.03397*

# THE NUCLEAR STELLAR CLUSTER (NSC) - KINEMATICS

- NSCs are common in both Elliptical and Spiral galaxies

  Look like Gcs/bulges, but much dens




*[Launhardt 2002 A&A, 384, 112]*

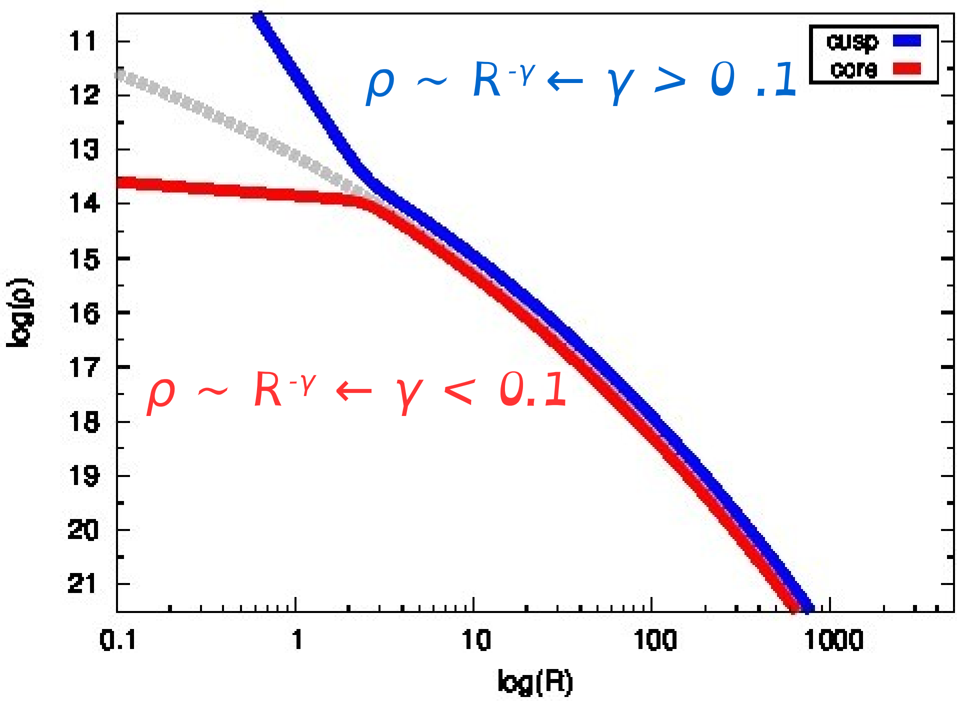
- Kinematics of the MW NSC:
  - rotation parallel to MW disk

    *(MAX 30-40 km/sec)*
  - kinematic mass ~ photometric mass (previous slide)
  - small tilt (9°) w/r to MW plane
  - flattening consisting with isotropic rotator

  *Feldmeier et al. 2014, A&A, 570, 2 ; Chatzopoulos et al. 2015, MNRAS, 447, 948 ; Schödel 2015, arXiv:1502.03397*

# NSC – CUSP OR CORE?

- It is expected that stellar density near a MBH grows like a power law (= *cusp*)

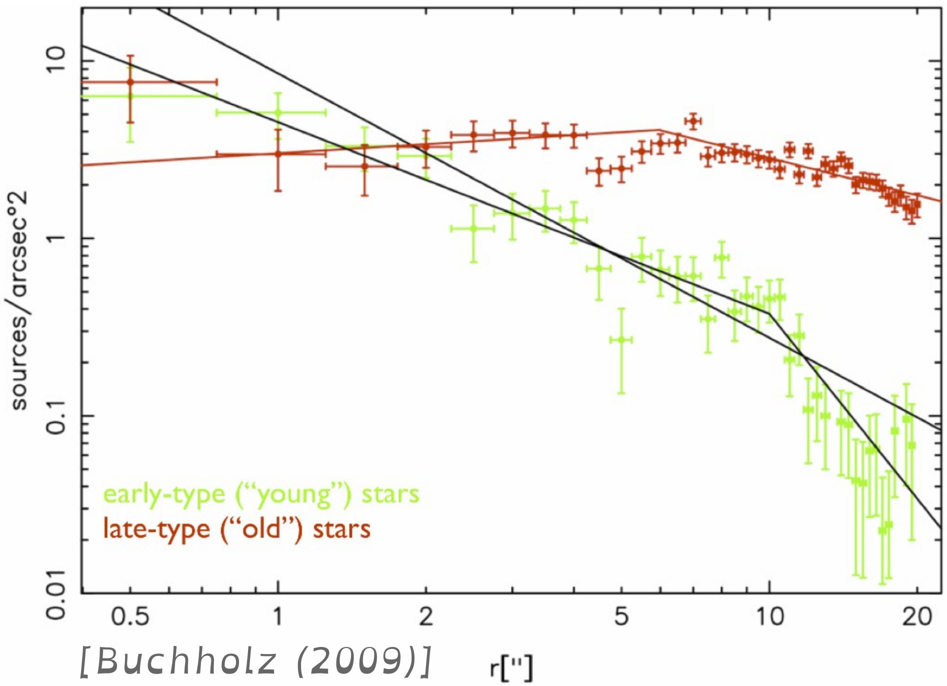


# NSC – CUSP OR CORE?

- Within the sphere of influence of the BH:

  (= containing as much mass as $M_{BH}$)

  $\rho \sim R^{-0.8} \rightarrow$ cusp!
- However, in the inner 0.5 → core (see old stars)




[Buchholz (2009)]

- Could be a *real* core:
  - excavated by SMBH
  - stellar black holes moved inward and stars moved outwards
- Could be a *fake* core:
  - stars lost their envelopes and are not visible

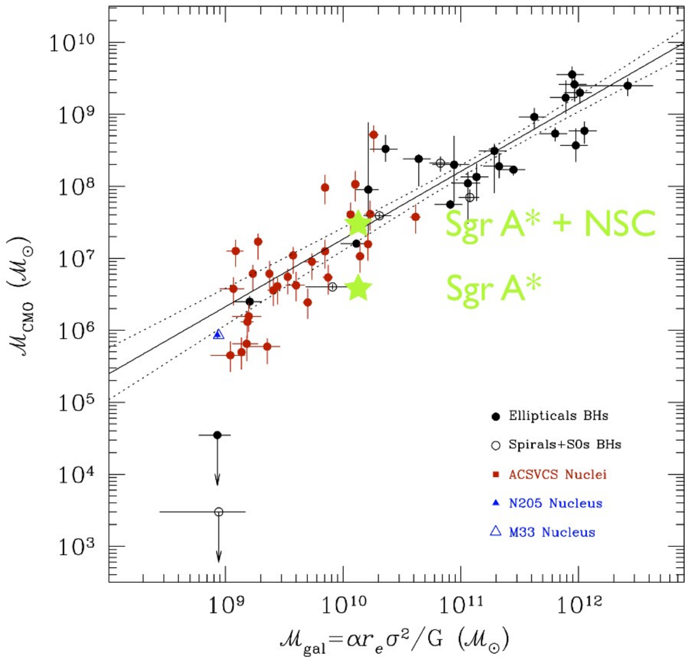
# NSC – EVIDENCE IN FAVOR OF CORE

- If core created by SMBH, is expected: $M_{NSC}^{EJECTED} \sim M_{BH}$ (= $M_{sgrA*}$)

  In other words:

$$M_{NSC}^{REAL} = M_{NSC}^{MEASURED} + M_{NSC}^{EJECTED}$$

$$M_{NSC}^{REAL} \sim M_{NSC}^{MEASURED} + M_{SgrA*}$$




[Schoeadel arXiv:1001.4238 (2011)]

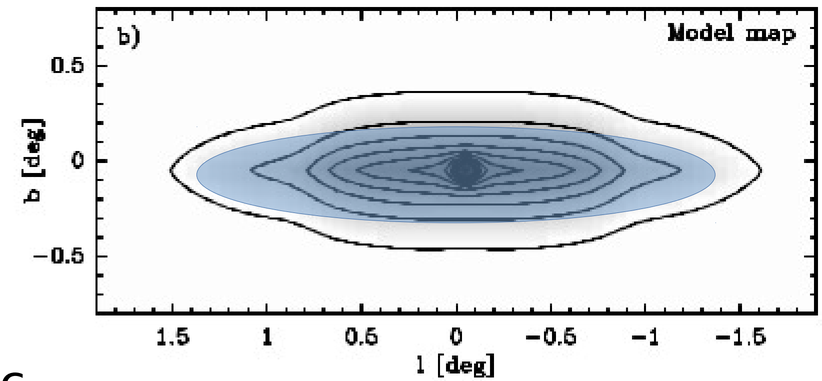
← Scaling relation $M_{NSC}$ – vel. Dispersion (σ)

We insert the MW $M_{NSC}$ we observe that we need to add $M_{sgrA*}$ to match the scaling relation

→ core excavated by SMBH !

# THE NUCLEAR STELLAR DISK (NSD) - MORPHOLOGY

- The NSD is accompanied by a similar disk of molecular gas, with on-going star-formation



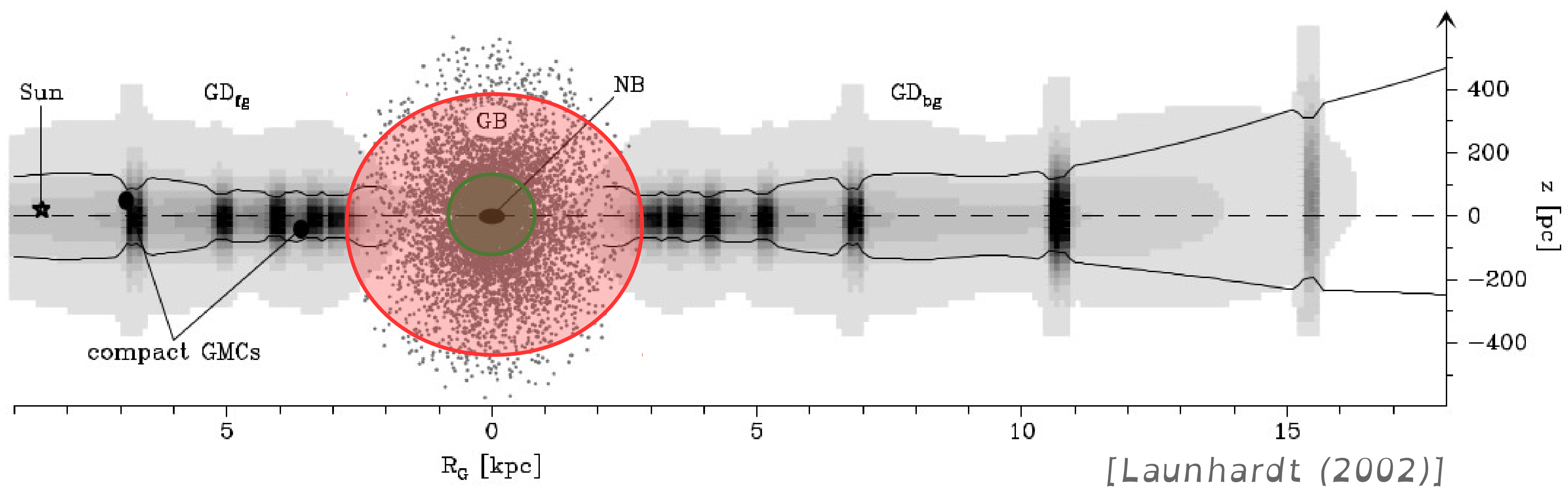

*[Launhardt 2002 A&A, 384, 112]*

- Morphology of the MW NSD:
  - R ~ 230 pc
  - possible density drop at R ~ 120 pc
  - h ~ 45 pc
  - L ~ 7 x $10^8$ $L_{SUN}$ → M ~ 1 x $10^9$ $M_{SUN}$

  *Launhardt 2002 A&A, 384, 112*

# 3 - BULGE

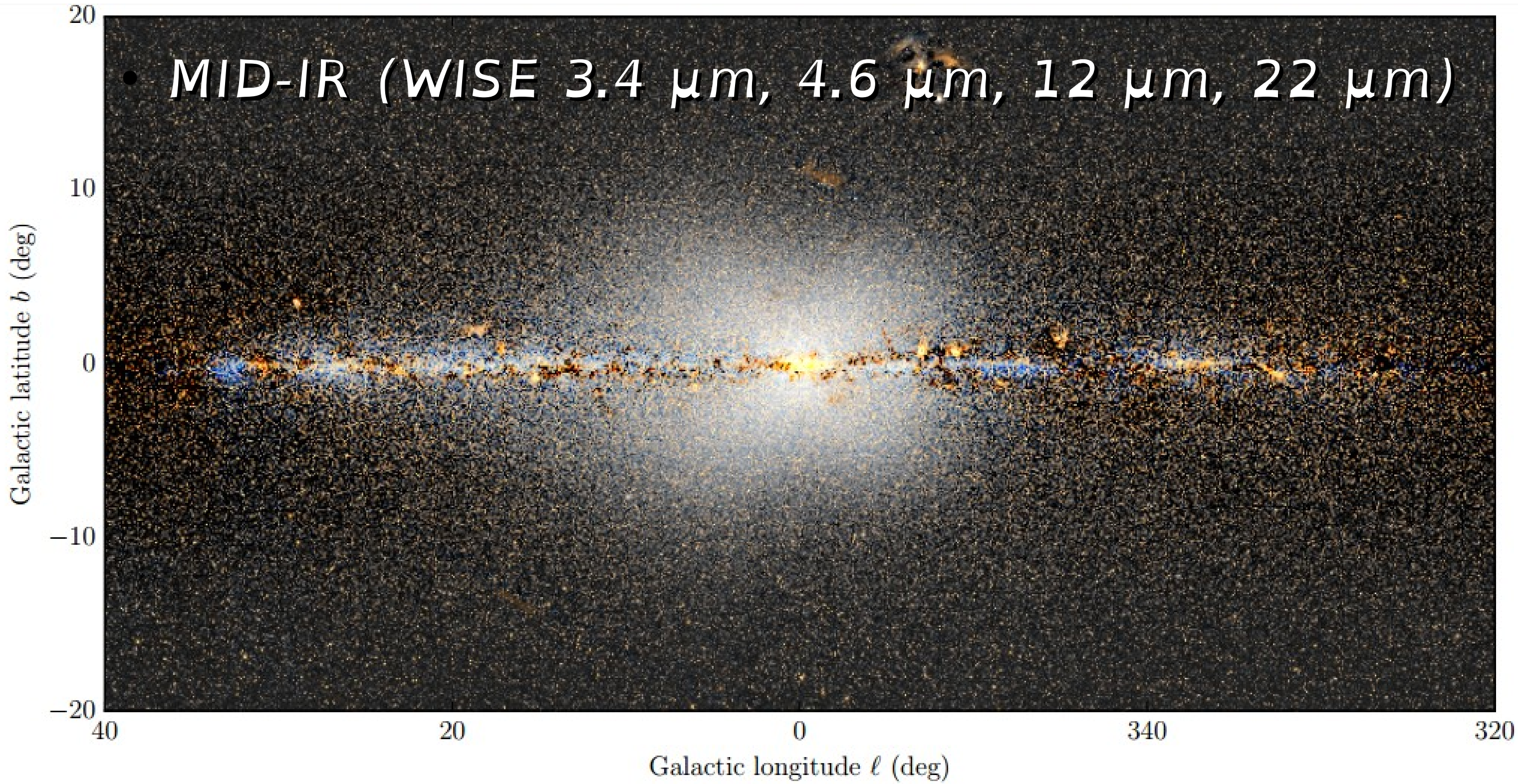
- It's common, in galaxy centers, to have nested structures
  → nested bulges, bars, NSC, etc.
- In the MW, the NB is nested inside the Galactic bulge (GB)
  NOTE: they are dynamically separated features!




[Launhardt (2002)]

# GALACTIC BULGE IN MID-IR

- Seen from within the MW, the bulge appears as a "peanut" ("*peanut/X-shaped bulge*")

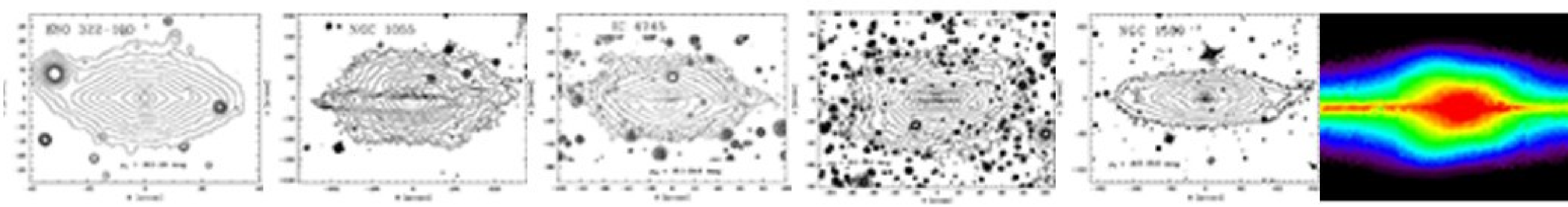



*[Ness & Lang 2016, AJ, 152, 14]*

# PEANUT BULGES

- Peanut bulges are found in several spiral galaxies

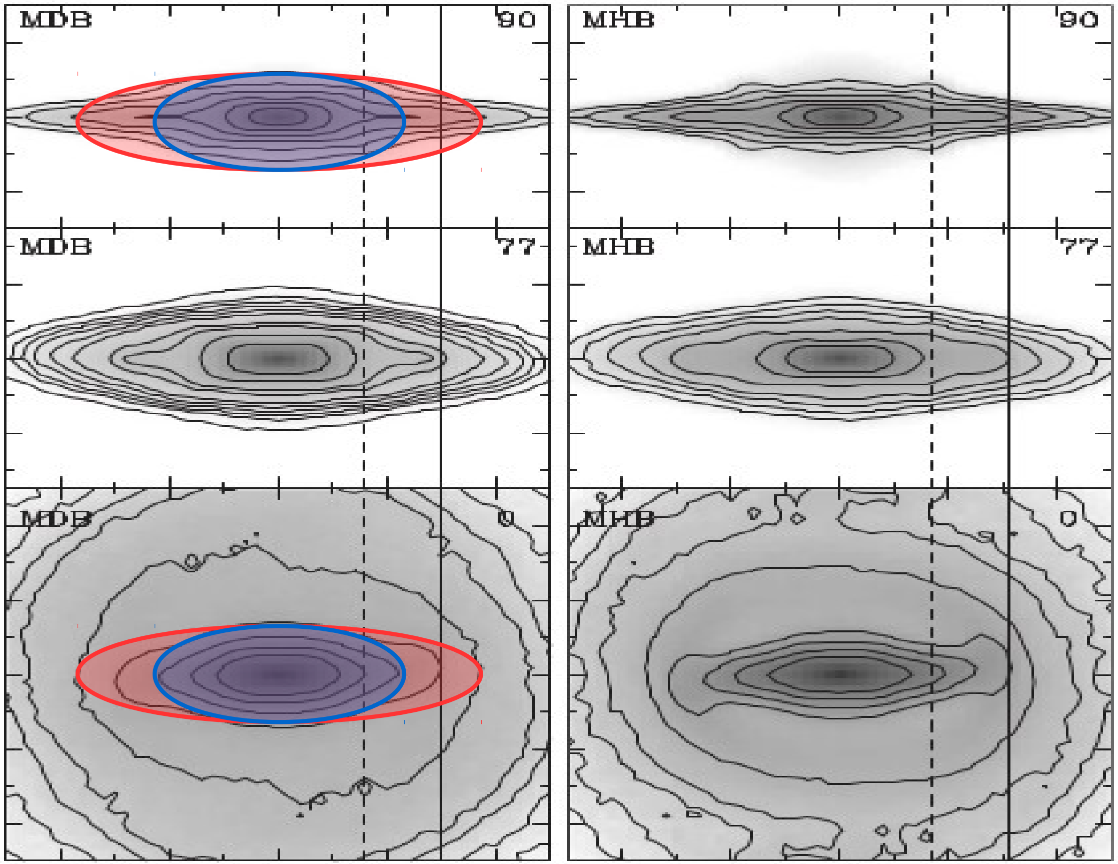

NGC 4710 | NGC 3628 | ESO 597-G036 | NGC 7020 | IC 4767 | NGC 128



ESO 322-100 | NGC 1055 | IC 4745 | IC 4757 | NGC 1589 | Milky Way

# PEANUT BULGES AND BARS

- Simulations → peanut bulges are part of bars seen edge-on
  → the MW peanut bulge IS just a sub-structure of the bar !



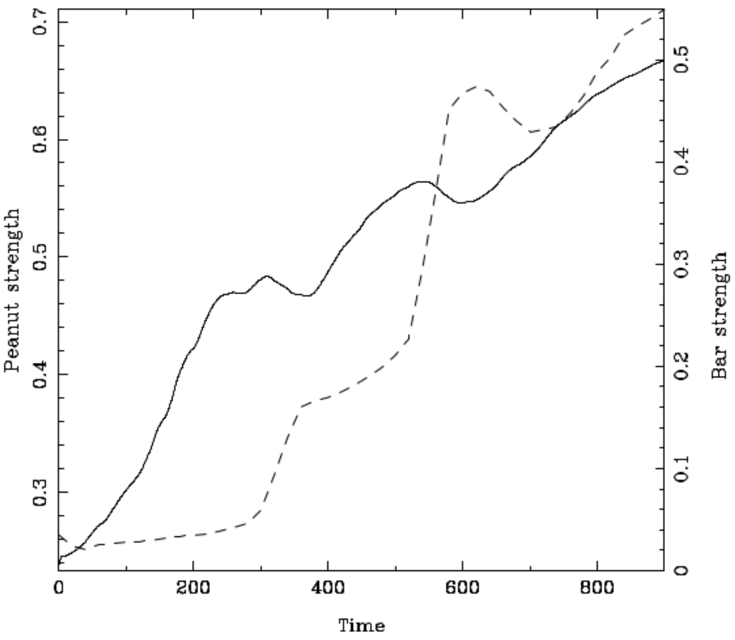

*[Wada K & Combes F – Mapping the Galaxy and Nearby Galaxies]*

# PEANUT BULGES - ORBITS

- The “X-shape” is due to orbits of the x1 family:
  - periodic orbits elongated along the bar
  - closing after 1 revolution around the center and 2 radial oscillations

  *Contopoulos 1980 A&A, 92, 33 ; Athanassoula 1983 A&A, 127, 349*

- When the bar forms, is thin as the disk, but then grows fast (together with the “peanut”)




*[Wada K & Combes F – Mapping the Galaxy and Nearby Galaxies]*

# BULGE MAP

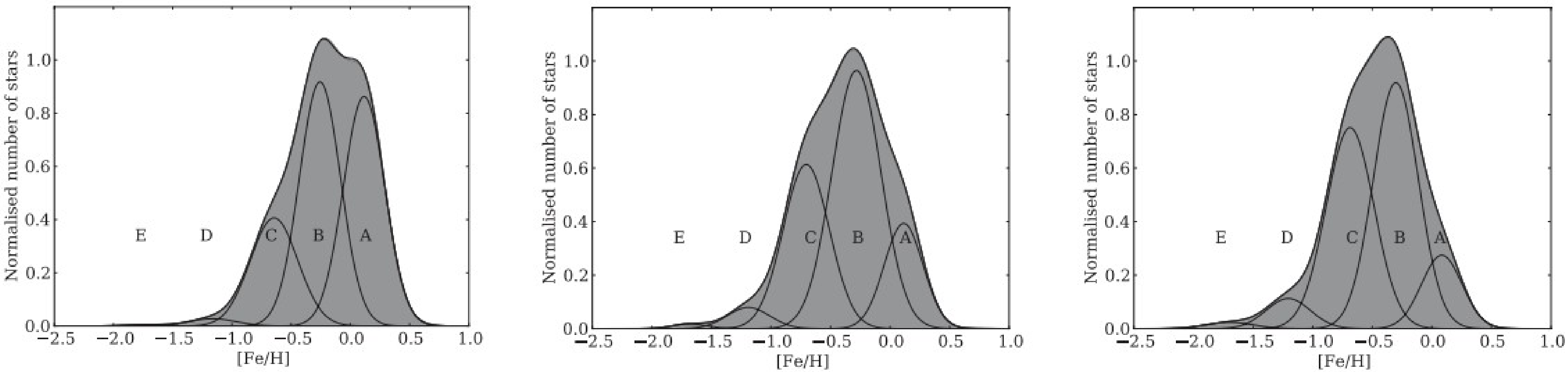
- Detailed map constructed using red clump stars (CONST L)


https://www.eso.org/public/news/eso1339/

# BULGE STELLAR POPULATIONS

- ARGOS spectroscopic survey → bulge hosts 5 populations:

  *https://ned.ipac.caltech.edu/level5/Sept16/Ness/Ness2.html*




(a) $l \pm 15°, b = -5°$ (b) $l \pm 15°, b = -7.5°$ (c) $l \pm 15°, b = -10°$

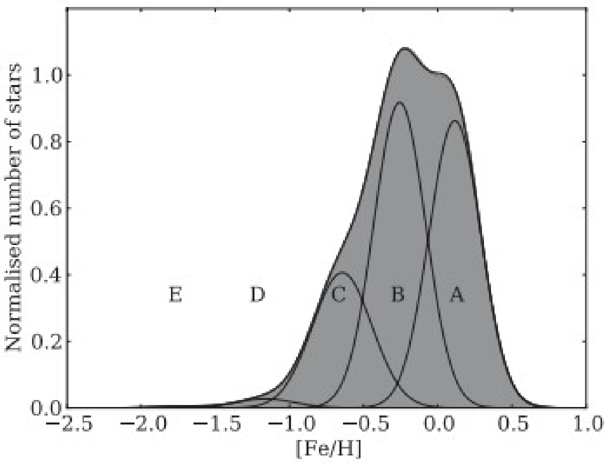
*[Ness 2013 MNRAS, 430, 836]*

- However only A, B belong to bulge (metal richer than disk)
- C, D, E metallicity consistent with contamination by:

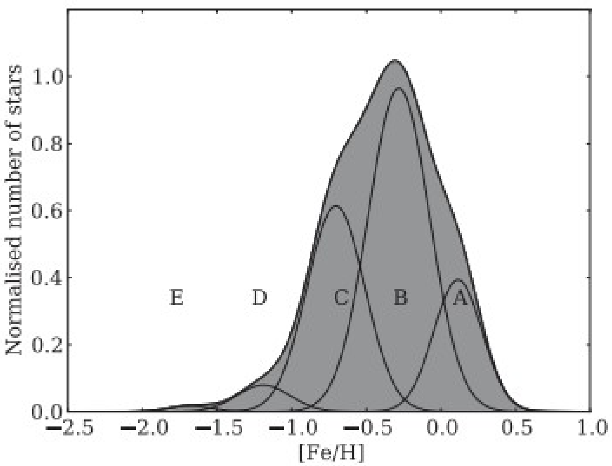
  thick disk (C), metal weak thick disk (D), stellar halo (E)

# BULGE STELLAR POPULATIONS - PEANUT AND THIN PART OF BAR

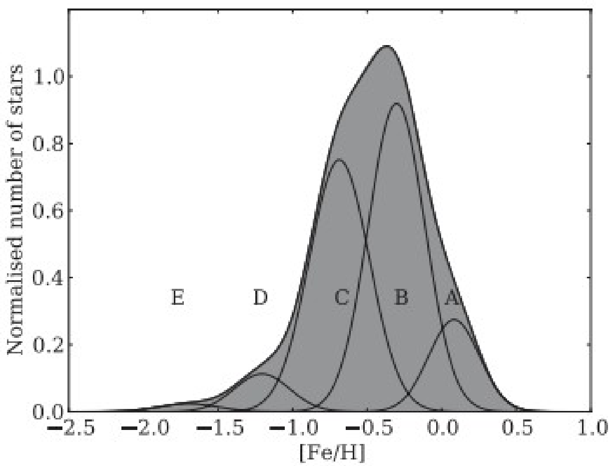
- Number of A, B population change with latitude *b*!
  *(A more abundant at low latitudes and vice versa)*




(a) $l \pm 15°, b = -5°$




(b) $l \pm 15°, b = -7.5°$



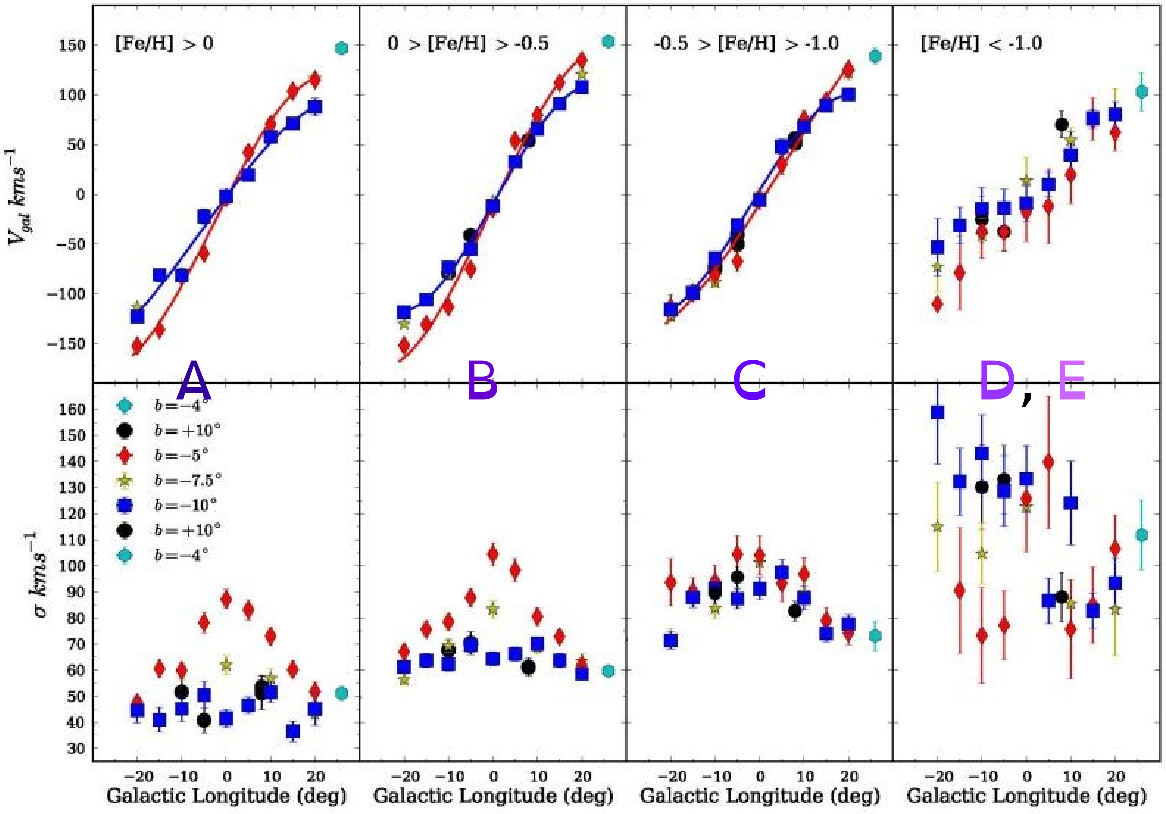

(c) $l \pm 15°, b = -10°$

*[Ness 2013 MNRAS, 430, 836]*

- A → thin part of the bar
- B → thick part of the bar (peanut)

# BULGE STELLAR POPULATIONS - KINEMATICS

- All components are rotating rapidly and cylindrically (almost independently of $b$) → typical of boxy bulges (except for E)




[Ness 2013 MNRAS, 430, 836]

# BULGE STELLAR POPULATIONS - POSSIBLE ORIGINS

- Where did these populations came from?

  They formed in place (in situ), or moved there (secular evolution)?

  *https://ned.ipac.caltech.edu/level5/Sept16/Ness/Ness2.html*

- ~100% secular evolution ← *Ness 2013 MNRAS, 430, 836*
  - A ← young stars from thin disk
  - B ← old stars from thin disk
  - C ← thick disk
  - D ← metal-poor thick disk
  - E ← stellar halo

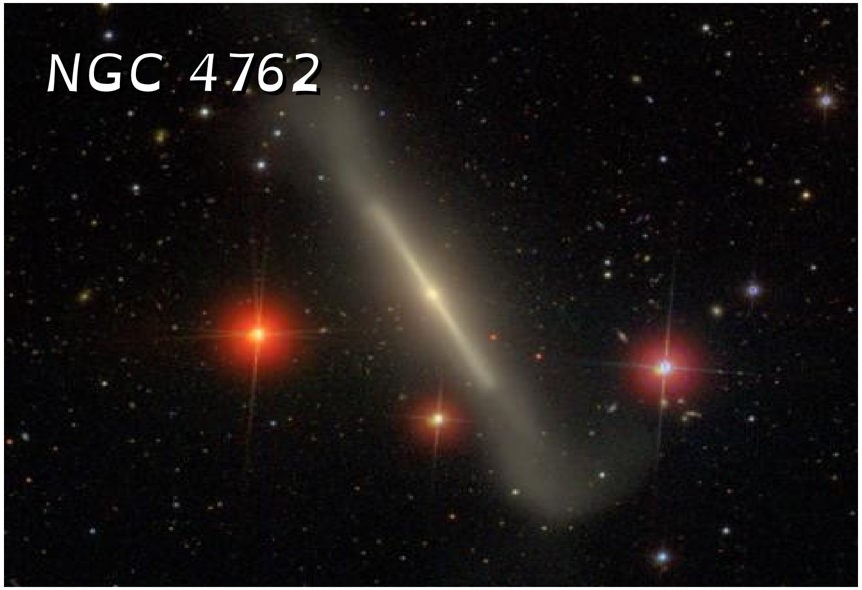
  *(compatibly with metallicities and kinematics seen before)*

- 50%/50% secular/in situ ← *Hill 2011 A&A, 534, A80*
  - Population 1 ← young stars from disk
  - Population 2 ← stars formed in an old bulge

# 4 - DISK

- The idea that our galaxy could contain 2 (*thin* + **thick**) disks was suggested by observation of edge-on spirals

*NOTE: Many (NGC 4762) but not all (NGC 4244) spirals have 2 disks*




# THIN/THICK DISK

- Morphology: exponential both in vertical and horizontal direction

$$\Sigma(x) = \Sigma_0 \exp\left(-\frac{x}{h}\right)$$

Vertical scales:

- *thin* disk: h ~ 250 pc (95% of stars)
- **thick** disk: h ~ 1000 pc

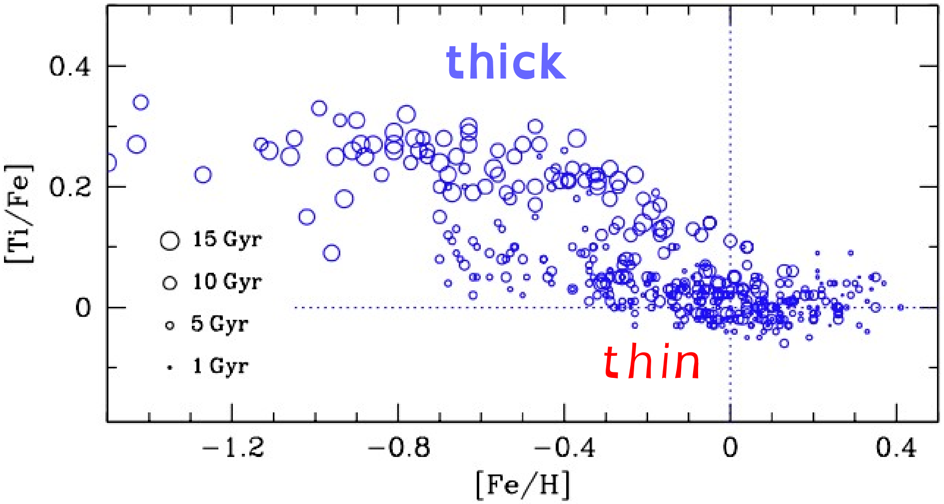
Horizontal scales:

- *thin* disk: h ~ 3.5 – 4.5 kpc (uncertain)
- **thick** disk: h ~ 4.5 kpc

# THIN/THICK DISK – α ELEMENTS

- α-elements (Mg, Si, Ca, Ti) trace "speed" of metal enrichment:
  - high [α/Fe] , low [Fe/H] → metals created in massive SNII explosions
  - low [α/Fe] , high [Fe/H] → metals created in white dwarf SNIa

  therefore:
  - high [α/Fe] , low [Fe/H] → quick enrichment by death of young stars
  - low [α/Fe] , high [Fe/H] → progressive enrich. by evolution of old stars




*[Bensby 2014 A&A, 562, A71]*

**thick** (<[α/Fe]> ~ 0.3):

- quick enrichment, low [Fe/H]

→ was created fast

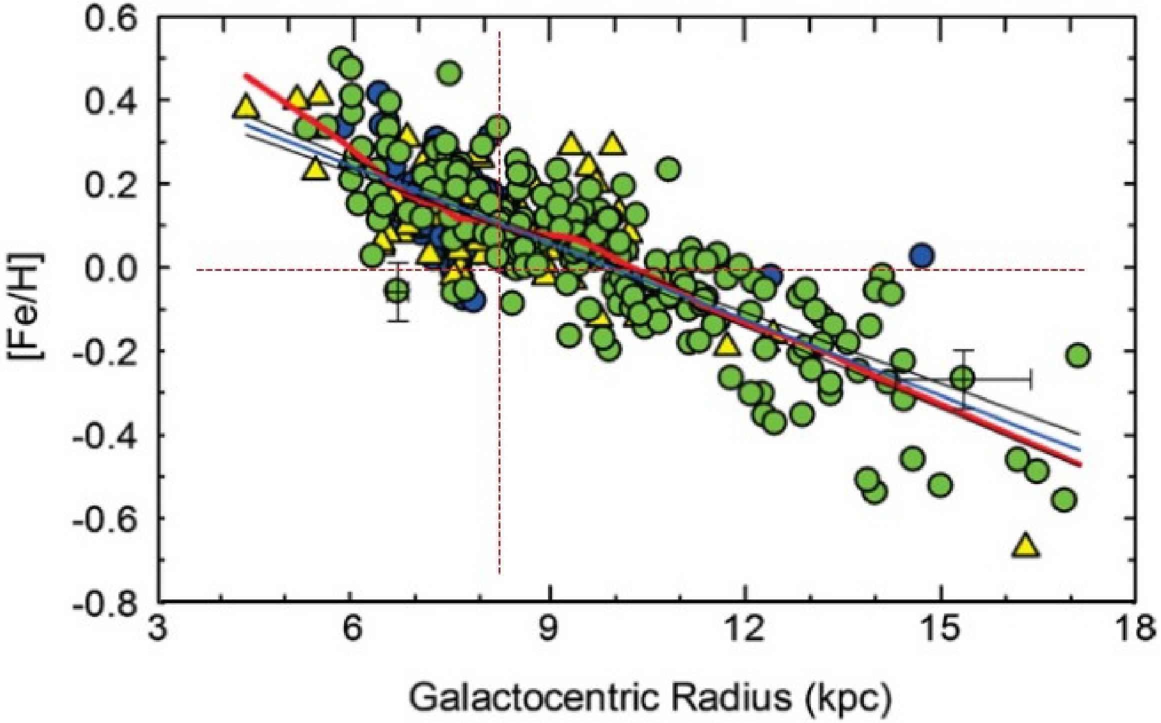
*thin* (<[α/Fe]> ~ 0.1)

- slow enrichment

→ continuous stellar formation

# DISK – METALLICITY GRADIENT

- Metallicity shows a global radial gradient (using Chepheids)

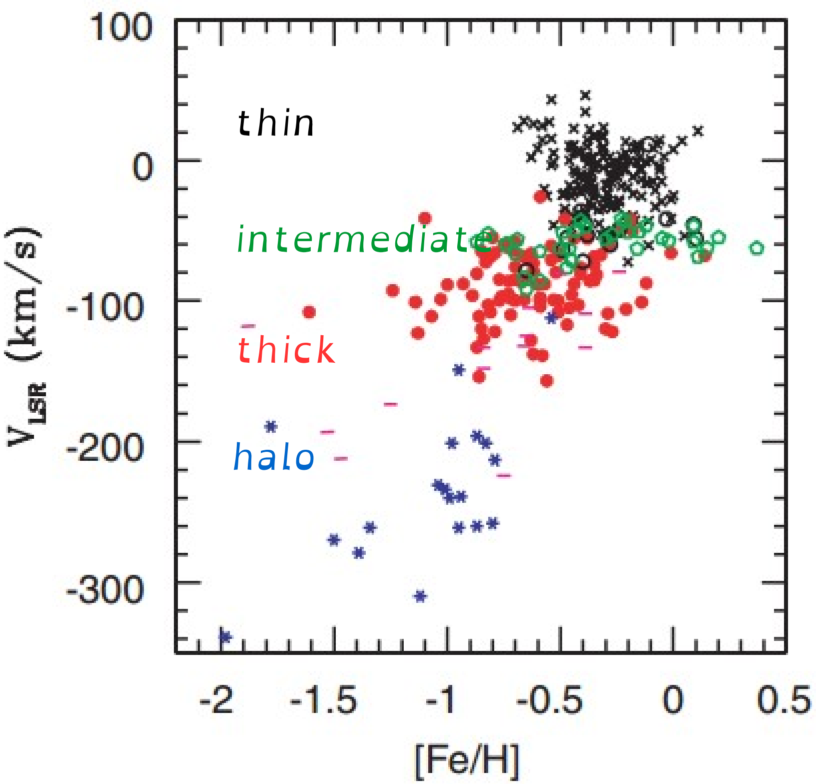



*[Luck & Lambert 2011 AJ, 142, 136]*

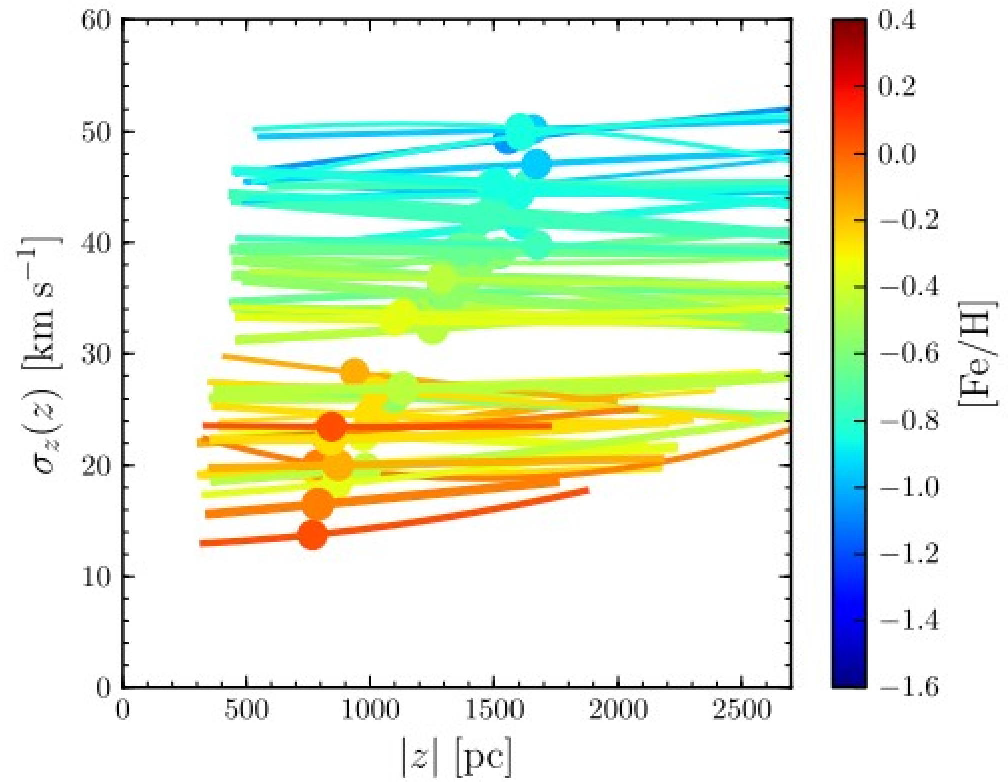
- *thin* disk <[Fe/H]> ~ -0.3 ← similar to bulge <[Fe/H]>
- **thick** disk <[Fe/H]> ~ -0.6

# DISK - KINEMATICS

- Kinematics (again, from local stars)




[Reddy 2006 MNRAS, 367, 1329]

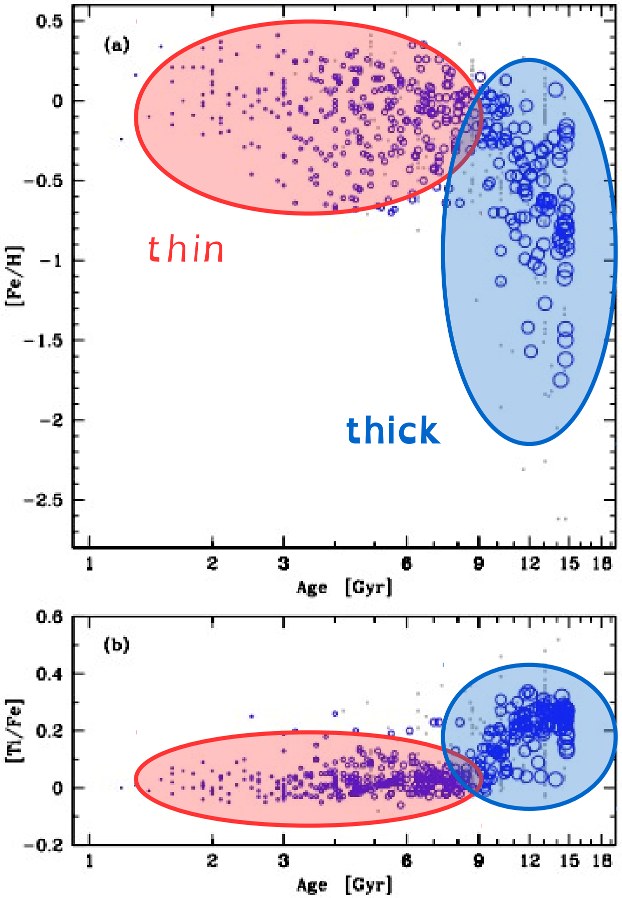



[Bovy 2012 ApJ, 755, 115]

- *thick* disk lags behind the LSR
- *metal poorer* stars ↔ higher $\sigma_Z$

# DISK – AGE-METALLICITY RELATION

- thin/**thick** disks occupy very distinct areas in the relation:




*[Bensby 2014 A&A, 562, A71]*

NOTE: thin/**thick** disks can be distinguished by metallicity

thin disk → continuous, slow formation

**thick** disk → coeval, fast formation

# DISK - SUMMARY

- Summary of disk characteristics:

*thin* disk:

- hosts younger stars
- same h as the gas
- narrower, denser
- horizontal h ~ 3.5 - 4.5 kpc
- metal richer
- lower σ
- continuous, slow star-formation

**thick** disk:

- hosts older stars
- larger h as the gas
- thicker, less dense
- horizontal h ~ 4.5 kpc
- metal poorer
- higher σ
- coeval, fast star-formation

# DISK – POSSIBLE ORIGIN

- Possible origins of *thin* disk:

  - star formation in gas disk

- Possible origins of **thick** disk:

  - heating of thin disk by merger and re-creation of thin disk
  - progressive disturbance of the orbits of stars from thin disk
  - dissolution of giant gas clouds

    *[Elemgreen 2005, ApJ, 634, 101]*

- Disks might form inside-out (in radial direction)

  From dissolution of gas clouds

  *(Elemgreen 2005, ApJ, 634, 101)*

# DISK – POSSIBLE ORIGIN

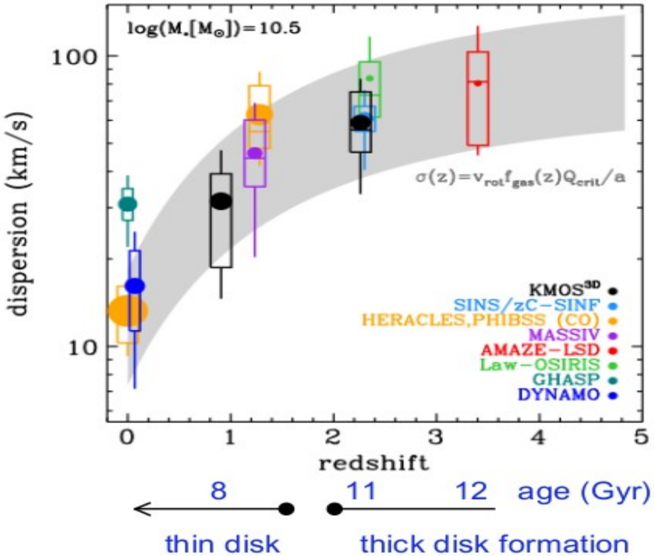
- Disks might form upside-down (in vertical direction)

  *(Bird 2013, ApJ, 773, 43)*

Gas becomes less turbulent in time

→ old, high-σ, metal-poor stellar populations: formed at high z

→ young, low-σ, metal-rich stellar populations: formed at low z



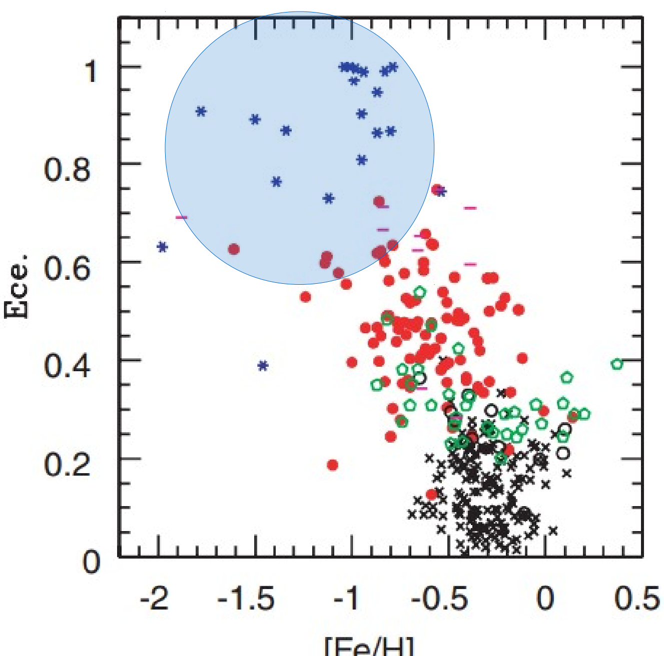

← in fact, spiral at high z have higher σ !

*(more turbulent)*

*[Wisnioski 2015 ApJ, 799, 209]*

# 5 – HALO

- The halo surrounding the MW is composed by:
  - stellar halo (GCs + field stars; ~1% of total stellar mass)
  - **dark matter halo**
- Identify halo stars near Sun → high $v_{LSR}$ and elongated orbits

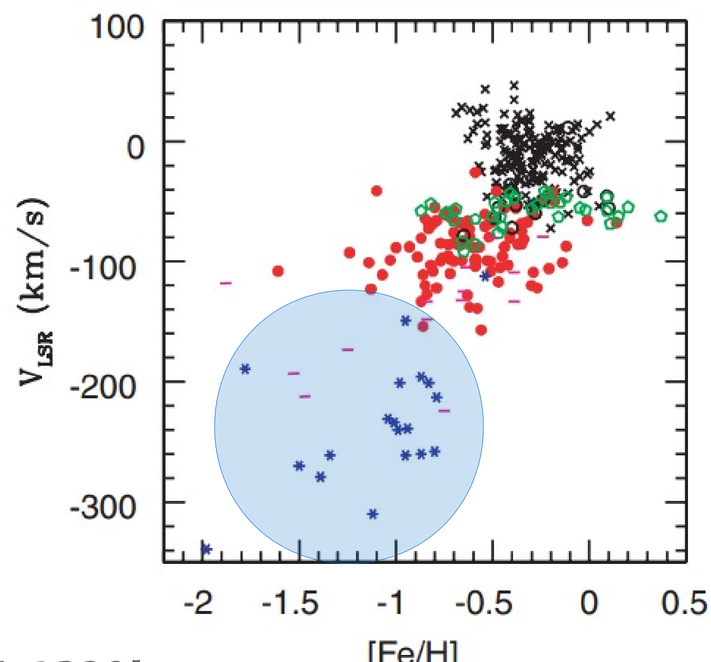



*thin*

*intermediate*

*thick*

*halo*




*[Reddy 2006 MNRAS, 367, 1329]*

# GALACTIC STELLAR HALO – FIELD STARS

- Stellar halo is traced up to ~100 kpc with giant stars (RR Lyrae)

- Composed of 2 populations, both metal-poor:

  *(Carollo 2007 Nature, 450, 1020)*

Inner halo:

- R < 10-15 kpc
- flatter density distribution
- metal “richer” $\langle[Fe/H]\rangle \sim -1.6$
- small prograde rotation (0 ÷ 50 km/s)

⬆ early merger of sub-Galactic fragments with high eccentricity

Outer halo:

- R > 15-20 kpc
- rounder density distribution
- metal “poorer” $\langle[Fe/H]\rangle \sim -2.2$
- small counter-rotation (-40 ÷ -70 km/s)

⬆ later accretion of small satellites (next class)

# GALACTIC STELLAR HALO – GCs

- Galaxy contains ~150 GCs up to ~150 kpc

  *(Harris 1996 AJ, 112, 1487)*

- Generally metal-poor, but can divided in:

  - (~80%) metal poorer <[Fe/H]> ~ -1.6

    → spatially associated with **halo**

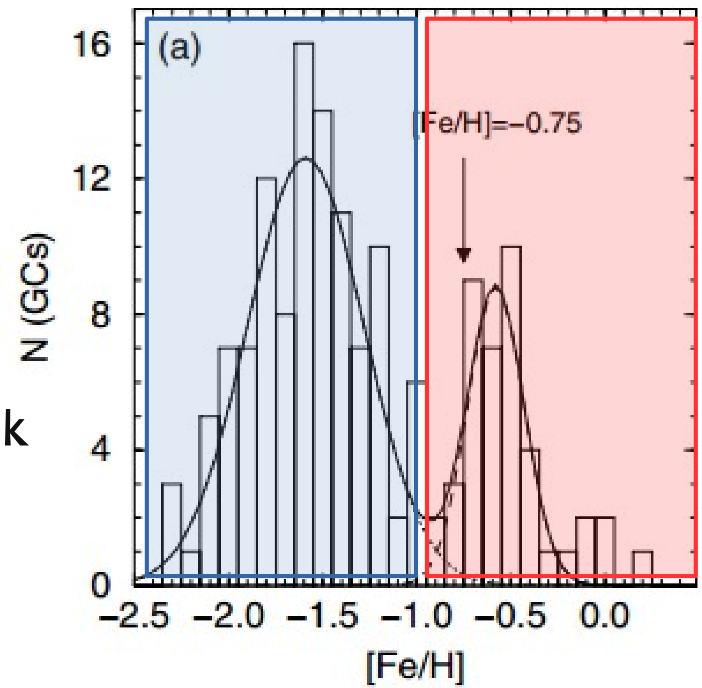
  - (~20%) metal richer <[Fe/H]> ~ -0.6

    → initially spatially associated with thick disk

    → now associated with bulge

    (found mostly towards galactic center)

  *(see Bica 2006, and references therein)*



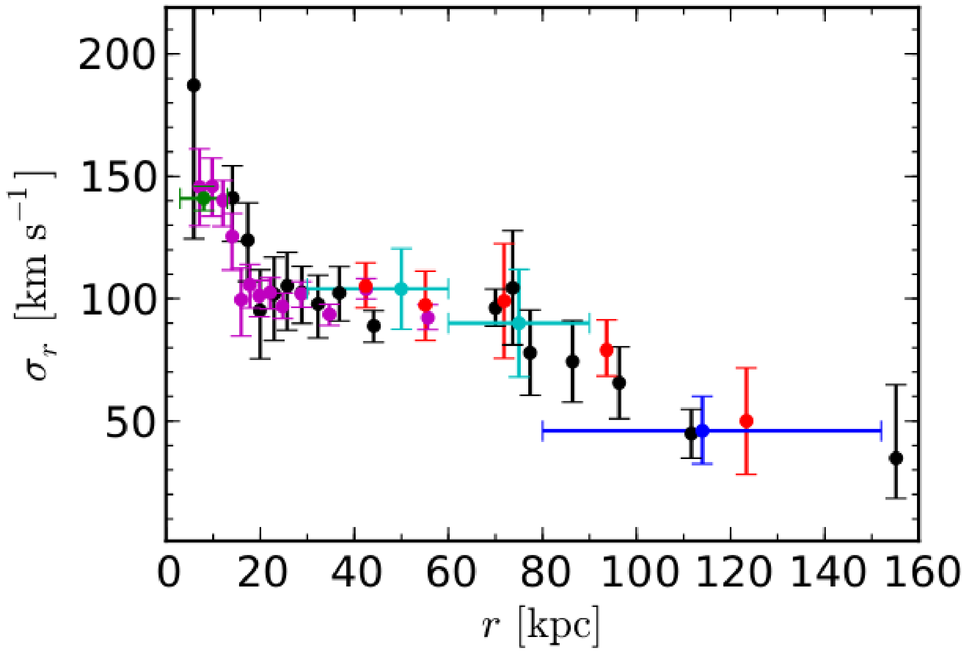

*[Bica 2006 A&A, 450, 105]*

NOTE: Some GCs might have been nuclei of disrupted satellites

NOTE: GCs can "evaporate" and release some stars in the halo

# STELLAR HALO – KINEMATICS

- The σ of the halo can be constructed using different tracers (giant stars, Gcs, etc)
  - Inner halo → dispersion supported until R~20 kpc (same as HI disk)
  - Outer halo → rotation supported (completely dominated by DM)




[Bland-Hawthorn 2016, ARA&A, 54, 529]

# DARK MATTER HALO

- DM mass is estimated using tracers in the halo:
  - stars
  - Gcs
  - satellites

- We can also use the "timing" argument: $M_{M31}$ and $M_{MW}$ must overcome universal expansion and have the present kinematics *(Khan 1959, ApJ, 130, 705)*

# DARK MATTER HALO - MASS

- We usually refer to the DM virial mass

  *(Bland-Hawthorn 2016, ARA&A, 54, 529)*

- Profile of DM theoretically extends to infinite

  → setting integration limit of ρ at some multiple of $\rho_{CRIT}$:

$$\rho_{\rm vir} = \Delta_{\rm vir}\Omega_{\rm M}\rho_{\rm crit}$$

- It follows that:

$$r_{\rm vir} = 258\left(\frac{\Delta_{\rm vir}\Omega_{\rm M}}{102}\right)^{-1/3}\left(\frac{M_{\rm vir}}{10^{12}\,M_{\odot}}\right)^{1/3}\ \ {\rm kpc}$$

- By choosing the "standard" $\Delta_{vir}$ = 200:

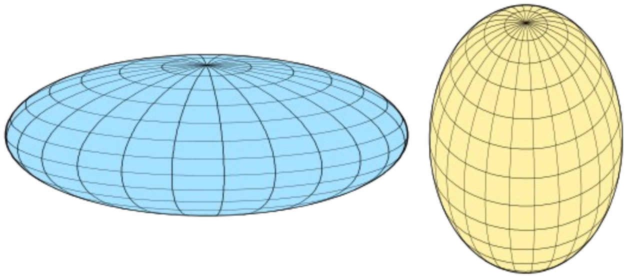
$M_{\Delta vir=200} \sim 10^{12}\ M_\odot$ ← *way more than other components!*

$R_{\Delta vir=200} \sim 200$ kpc

# DARK MATTER HALO - SHAPE

- There is still debate on whether the DM halo is oblate or prolate (shape changes according to the tracer)

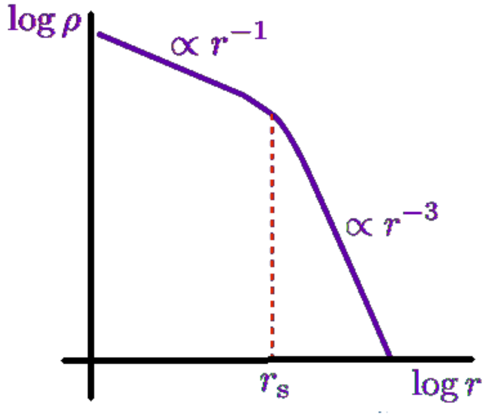
oblate



prolate

- By assuming a Frank-Navarro-White DM radial profile: $r_S \sim 25$ kpc *(van der Marel 2012 ApJ, 753, 8)*

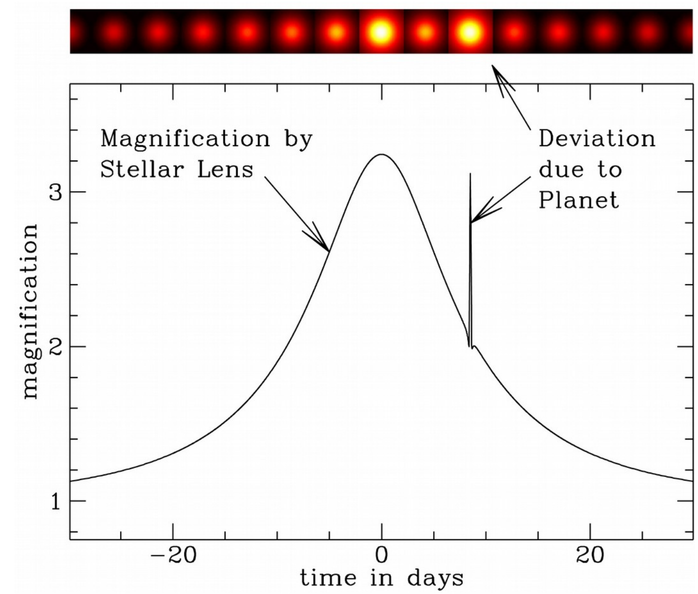
$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$



# HALO - MICROLENSING

- Micro-lensing: an object magnified by a low-mass object (star or planet)
- Lens is too small to produce measurable distortions but produces signal variation

  *NOTE: Brightness variation is produced by several phenomena → must use surveys*




- Lens magnification is best when half-way from the source → halo objects are ideal lenses to study other halo objects

  e.g. Massive astrophysical compact halo objects (MACHOs)

  *(Gates 1996, PhRvD, 53, 4138)*

  MACHO = group of faint objects (e.g. BH, brown & white dwarfs)