Galactic Archaeology

in the era of large surveys

DIS Galactic Archaeology

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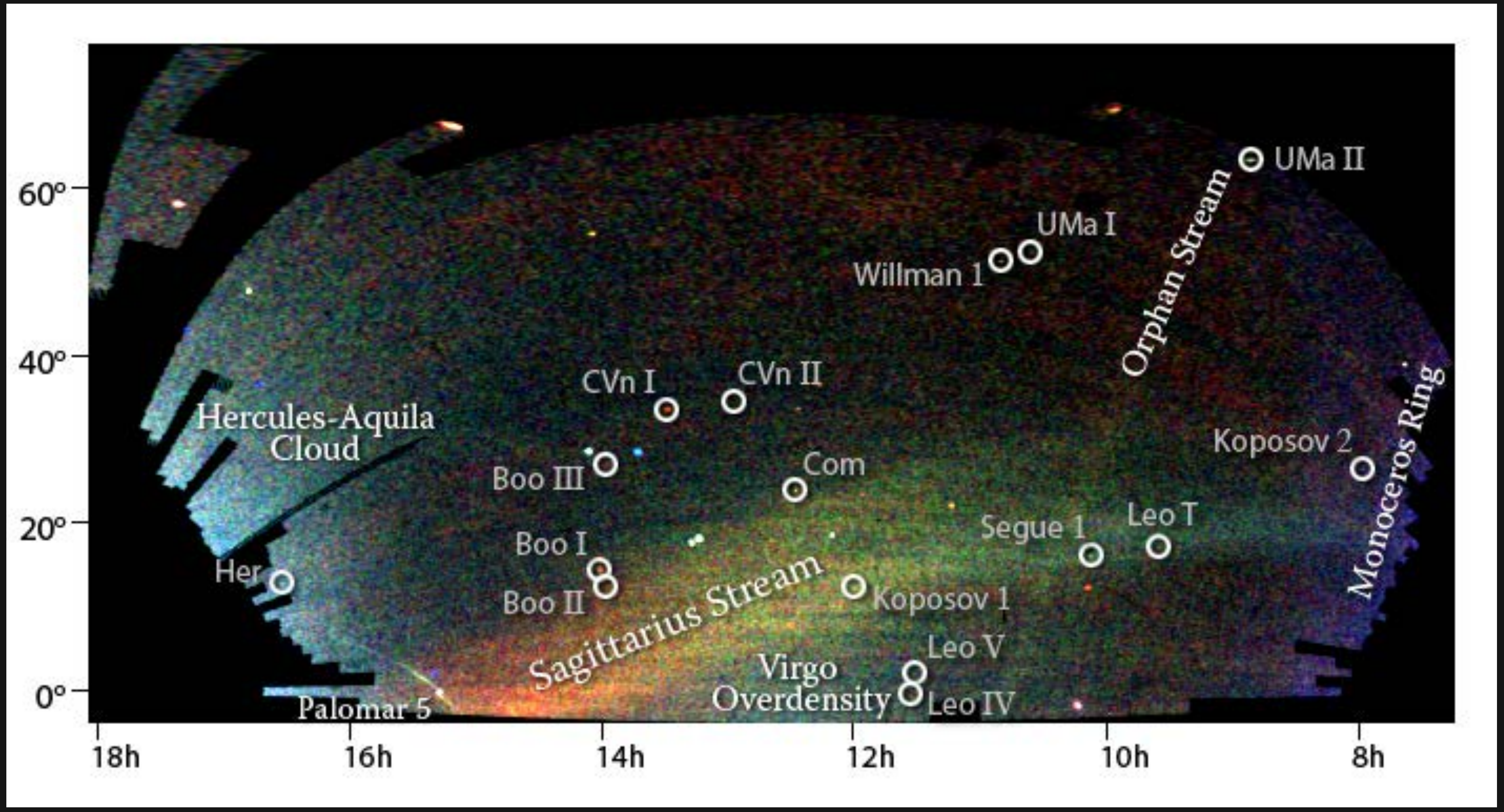
Previously…

- **What we want to know**
  - Testing our physical understanding in Galactic scale
  - Milky Way is an excellent test site!
- **(Dynamical) Overview of our Milky Way**
  - Stellar Disc(s) & Spiral arms
    - Thin (younger) & Thick (older) Discs: Rotationally supported
    - Spiral arms: Very young & hot stars, HII gas; Density wave…?
  - Bar & Bulge
    - Bar: Rotates with Pattern Speed; Funnels gas to the inner Galaxy
    - Boxy/Peanut Bulge: Dynamical origin from Bar
  - Stellar Halo & Streams
    - Made of (very) old stars; Very low density; Velocity dispersion supported
    - Full of Streams resulted from tidal disruption of various satellite bodies in the halo
  - (Dark Halo & Rotation curve) — we will cover it today

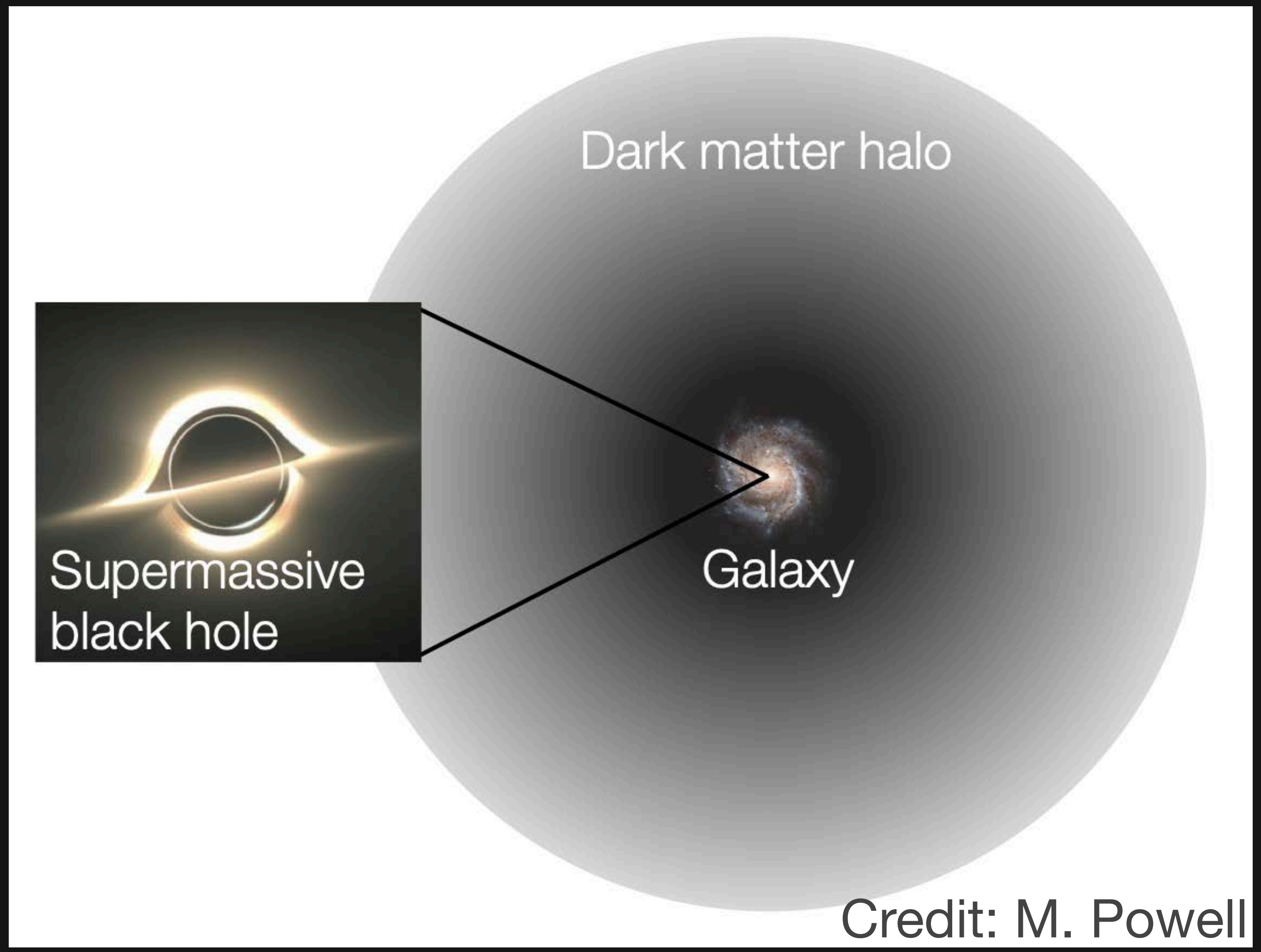


Lecture 8

- **(Dynamical) Overview of our Milky Way**
  - Dark Halo & Rotation curve
- **Various dynamical features**
  - Virial Theorem
  - Kinematics & Dynamics
  - Stellar Orbit
  - Integrals-of-motion (Actions)

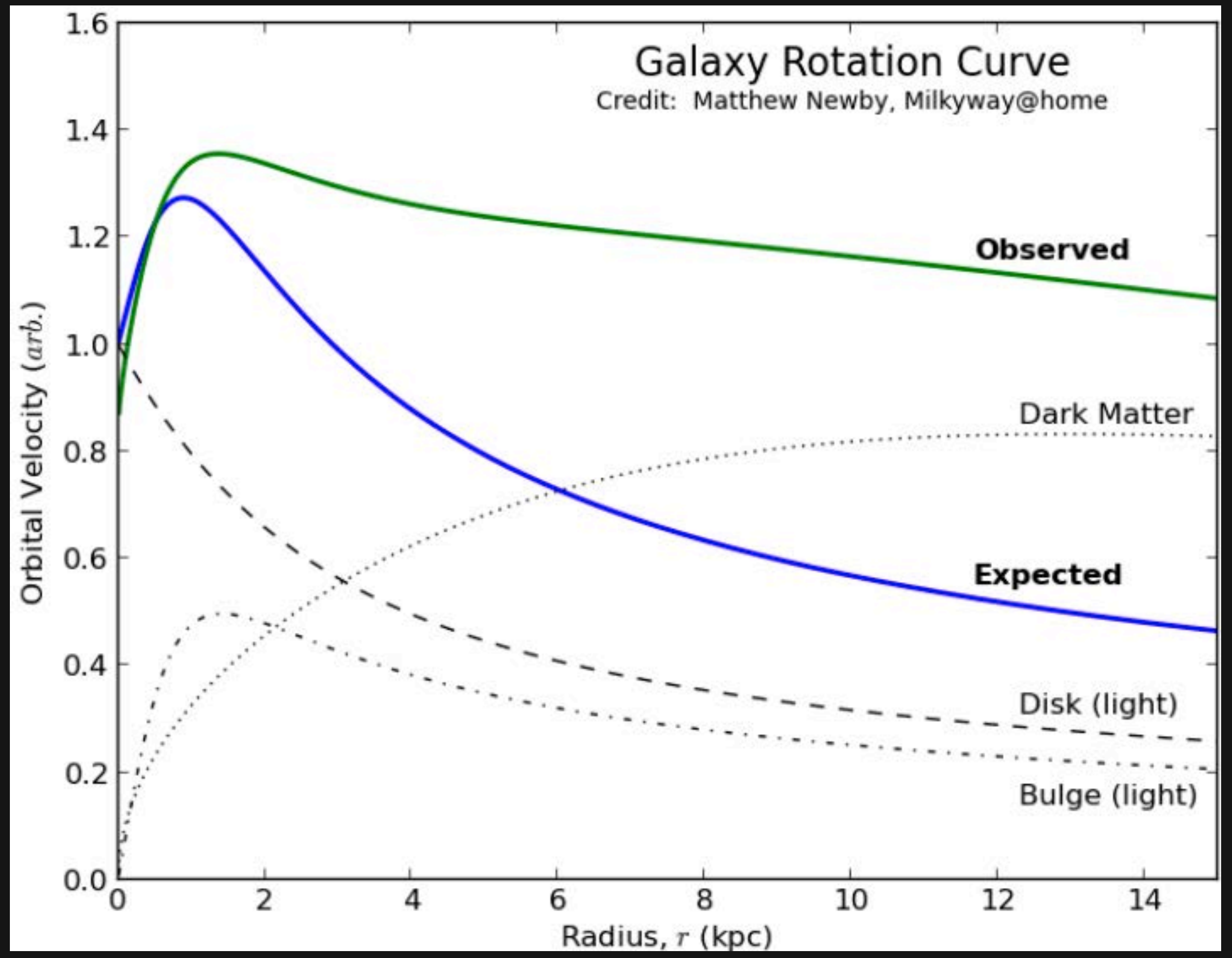
Dark Halo

- **Dark Halo**
  - The first “pocket” for galaxy building
  - The most dominating component of the Galaxy ($\sim 10^{12}\,\mathrm{M}_{\odot}$)
  - Usually described by power-law density profile
  - Evidences (of Dark halo or dark matter in general):
    - Galactic Rotation curve: not Keplerian
    - Stellar stream: sensitive to the mass distribution (and also the potential dark sub halo!)
    - Gravitational lensing: implies the existence of invisible mass
    - X-ray gas in galaxy clusters: too hot to be explained by the gravity of the visible matter alone
    - Cosmic Microwave Background fluctuations: also require a substantial non-baryonic dark matter
    - Large-scale structure formation and evolution needs a substantial amount of mass



Galactic Rotation curve

- **Rotation curve**
  - For a simplistic case, assume a spherical (symmetric) mass distribution, $\mathrm{M(r)} = \int 4\,\pi\,\mathrm{r}^2\,\rho(\mathrm{r})\,\mathrm{dr}$
  - For an object to stay in a circular orbit (e.g., $\mathrm{v_R}$ and $\mathrm{v_z} \ll \mathrm{v}_\phi$), the centripetal and gravitational forces need to be balanced



$$\Rightarrow \frac{\mathrm{m\,v(r)^2}}{\mathrm{r}} = \frac{\mathrm{G\,M(r)\,m}}{\mathrm{r^2}}$$, M(r) is mass inclosed in radius r

$$\Rightarrow \mathrm{v_{circ}(r)} = \sqrt{\frac{\mathrm{G\,M(r)}}{\mathrm{r}}}$$

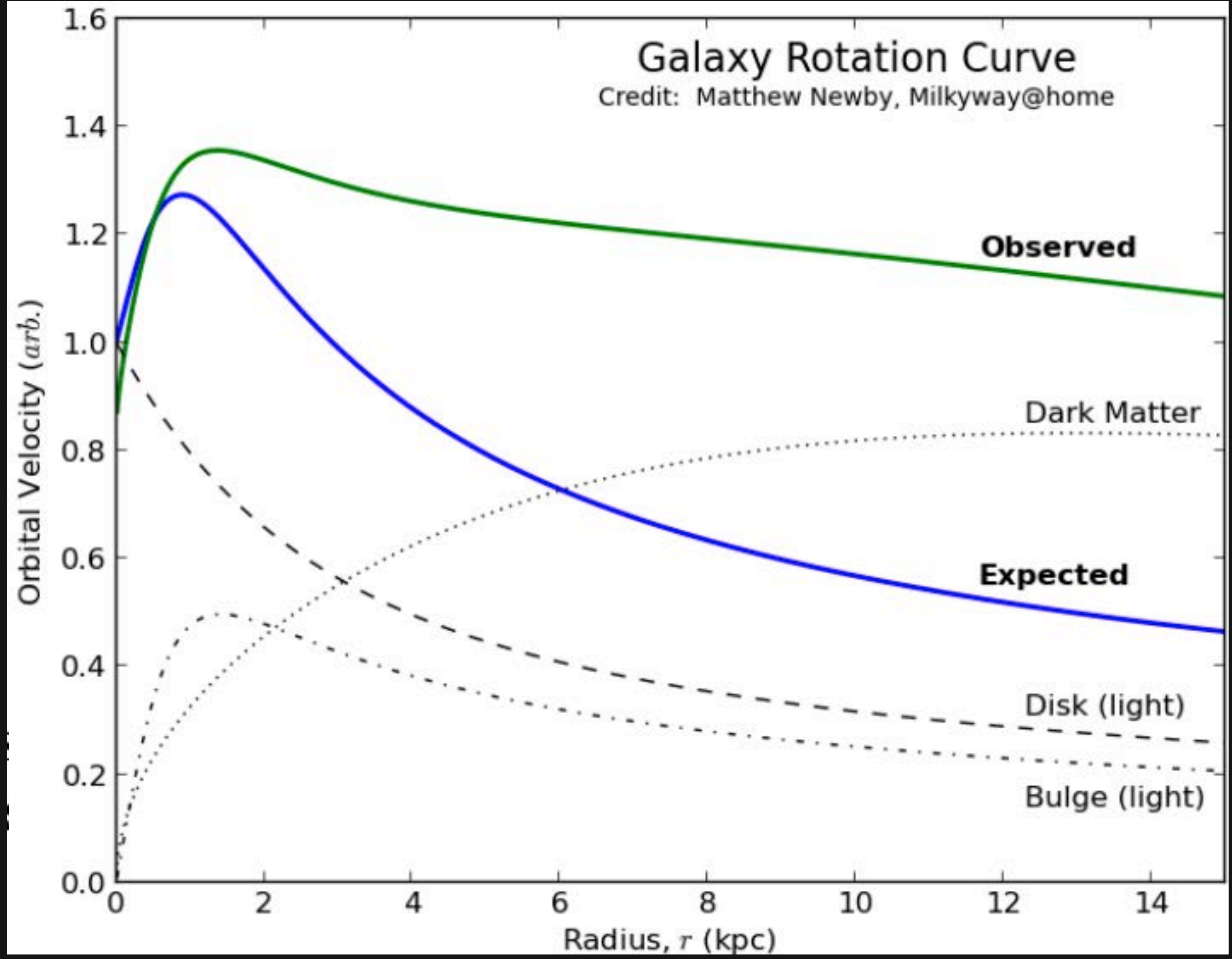
  - Now, close to the Galactic centre, assuming $\rho(\mathrm{r}) \sim \mathrm{const}$. (homogeneous),

$$\Rightarrow \mathrm{M(r)} = \frac{4}{3}\,\pi\,\mathrm{r}^3\,\rho$$, and,

$$\Rightarrow \mathrm{v_{circ}(r)} = \mathrm{r}\sqrt{\frac{4}{3}\,\pi\,\mathrm{G}\,\rho}$$, so $\mathrm{v_{circ}(r)} \propto \mathrm{r}$ (solid body rotation) … roughly right but only for the very inner region of the Galaxy…

  - Imagine that we are on a circular orbit enclosing some mass distribution. Then (in practice), M(r) can be approximated as a point mass M located at the centre (r = 0).
    - And then from Kepler's law, we get, $\Rightarrow \mathrm{v_{circ}(r)} \propto \frac{1}{\sqrt{\mathrm{r}}}$
    - But this is very different from what we observe! The gravity from the visible mass is insufficient for the observed rotational velocity!
  - More mass is required… something "invisible"… because we see a flat galactic rotation curve!

Galactic Rotation curve



- **Rotation curve**
  - To get the observed "flat" rotation curve, $v_{circ}(r) = \sqrt{\frac{G\,M(r)}{r}}$, we expect, $v_{circ}(r) = \text{const}.$
    - This requires $M(r) \propto r$
    - Consider a power-law density profile, $\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\alpha}$

    $\Rightarrow v_{circ}(r) = r^{1-\alpha/2}\sqrt{\frac{4\,\pi\,G\,\rho_0\,r_0^{\alpha}}{3-\alpha}}$, with $\alpha < 3$. (note that denominator is $3-\alpha$, since $M(r) = \int_0^r 4\,\pi\,r^2\,\rho(r)\,dr$)

    $\Rightarrow v_{circ}(r) = \text{const}.$ when $\rho(r) \propto r^{-2}$ (i.e., $\alpha = 2$, called *isothermal sphere*)

    …and indeed, $M(r) \propto r$
  - There are variety of density profiles describing the dark matter halo (e.g., Hernquist, NFW)
  - And indeed, the dark matter dominates at large radii!
  - It also indicates us that dark matter wouldn't be found concentrated in the disc — it would make the velocity dispersion very high! (making "visible" structure, i.e., disc dynamically "hot")
  - Dark matter: non-collisional, not interacting by Electromagnetic nor Strong force, but by Gravity
    - Feels no pressure, no friction, won't dissipate energy! → will reach equilibrium under Virial Theorem! → won't collapse very dense

The Virial Theorem

- **Virtual Theorem**
  - For a star bound to a galaxy, we know its total energy is: $\langle T \rangle + \langle U \rangle < 0$, $\langle T \rangle$and $\langle U \rangle$ are time averaged kinetic and potential energy
  - Consider the moment of inertia of this system, $I \equiv \sum_i^N m_i \mathbf{x_i} \cdot \mathbf{x_i} = \sum_i^N m_i x_i^2$

$$\Rightarrow \dot{I} = \sum_i^N m_i (\dot{\mathbf{x}}_\mathbf{i} \cdot \mathbf{x_i} + \mathbf{x_i} \cdot \dot{\mathbf{x}}_\mathbf{i}) = 2 \sum_i^N m_i \dot{\mathbf{x}}_\mathbf{i} \cdot \mathbf{x_i}$$

$$\Rightarrow \ddot{I} = 2 \sum_i^N m_i (\ddot{\mathbf{x}}_\mathbf{i} \cdot \mathbf{x_i} + \dot{\mathbf{x}}_\mathbf{i} \cdot \dot{\mathbf{x}}_\mathbf{i}) = 2 \sum_i^N m_i \ddot{\mathbf{x}}_\mathbf{i} \cdot \mathbf{x_i} + 2 \sum_i^N m_i \dot{x}_i^2$$

  - Now, we know the kinetic energy of the *i*th particle is $\frac{1}{2} m_i \dot{x}_i^2$. Also, $\sum_i^N m_i \ddot{\mathbf{x}}_\mathbf{i} \cdot \mathbf{x_i}$ is related to the gravitational potential energy

$$\Rightarrow \ddot{I} = 2U + 4T$$

  - And for the time averaged case

$$\Rightarrow \langle \ddot{I} \rangle = 2 \langle U \rangle + 4 \langle T \rangle$$

  - Now, a system at dynamical equilibrium: the time-averaged moment of inertia, *I*, is constant, i.e., the second derivative is zero!

$$\Rightarrow 2 \langle T \rangle + \langle U \rangle = 0$$

  - If we know the kinetic energy of the system (from the measured r.m.s. velocity dispersion) then we can estimate the system's total mass!

The Virial Theorem

- **Virial Theorem — A simple case**
  - Let's imagine the circular orbit case:
  - For an object to stay in a circular orbit, the centripetal and gravitational forces need to be balanced

$$\Rightarrow \frac{m\,v^2}{r} = \frac{G\,M\,m}{r^2}$$

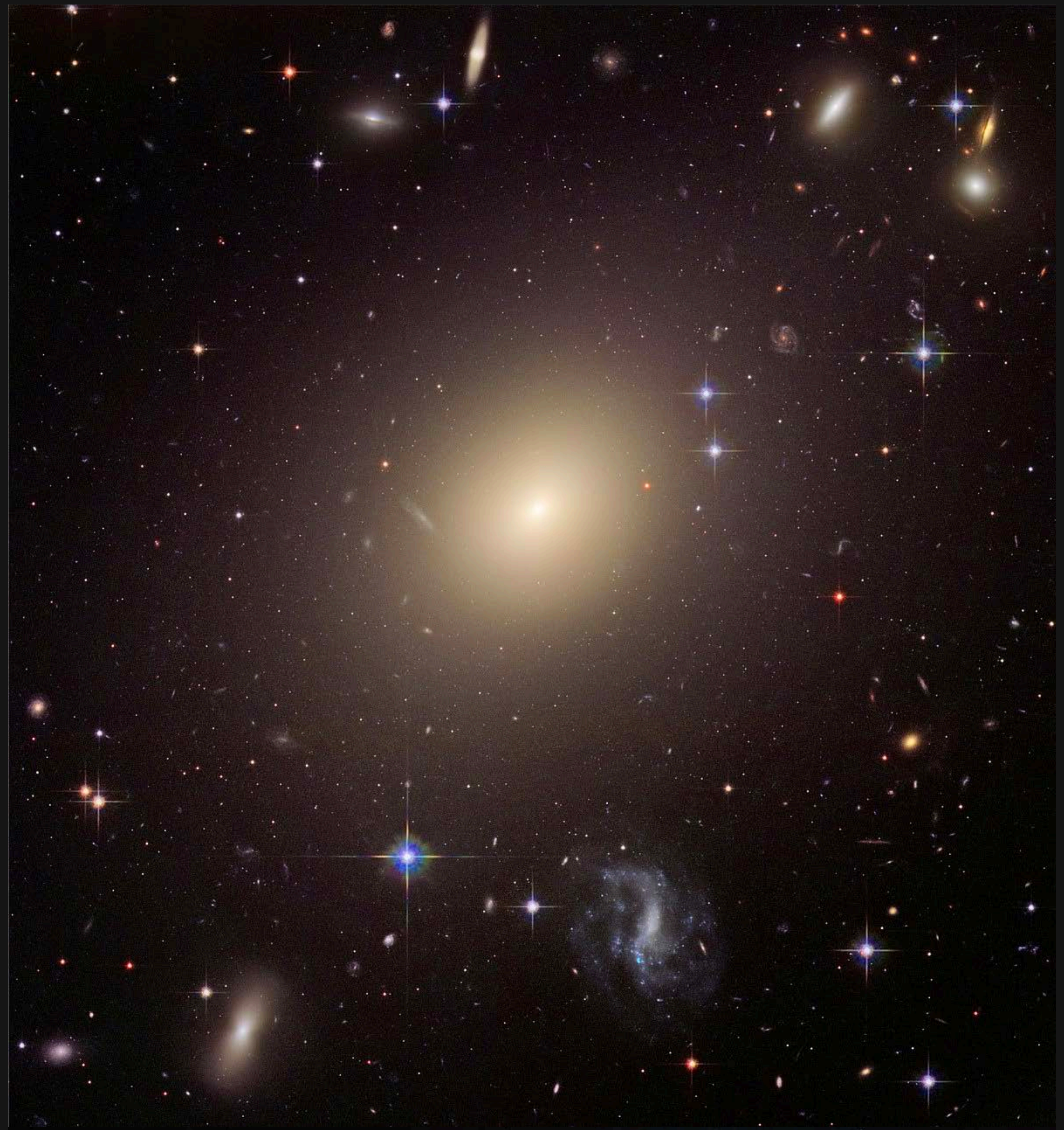
$$\Rightarrow m\,v^2 = \frac{G\,M\,m}{r}$$

- We know the kinetic energy is $\frac{1}{2} m\,v^2$ and potential energy is $-\frac{G\,M\,m}{r}$

$$\Rightarrow 2\,T + U = 0$$

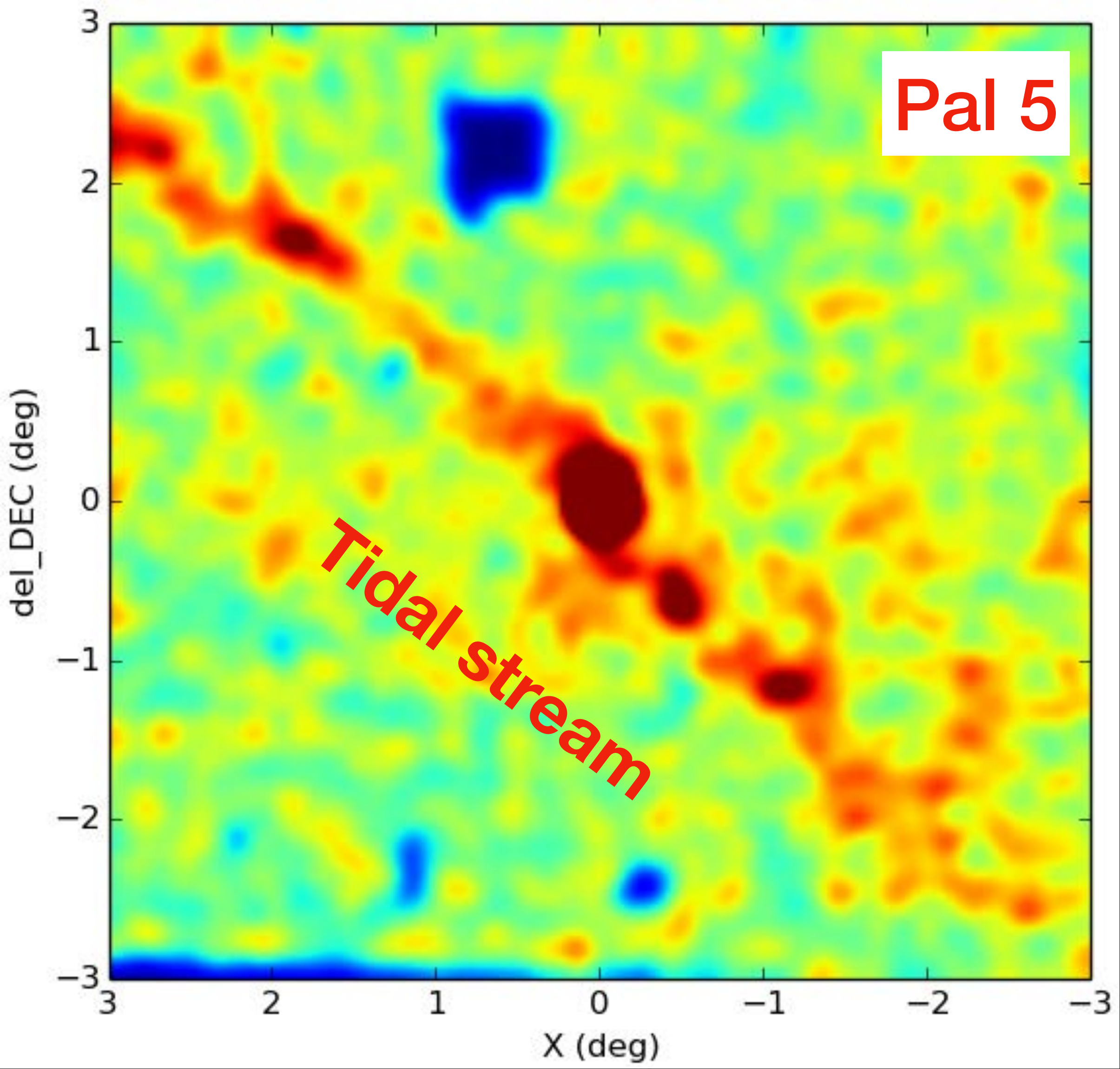
The Virial Theorem

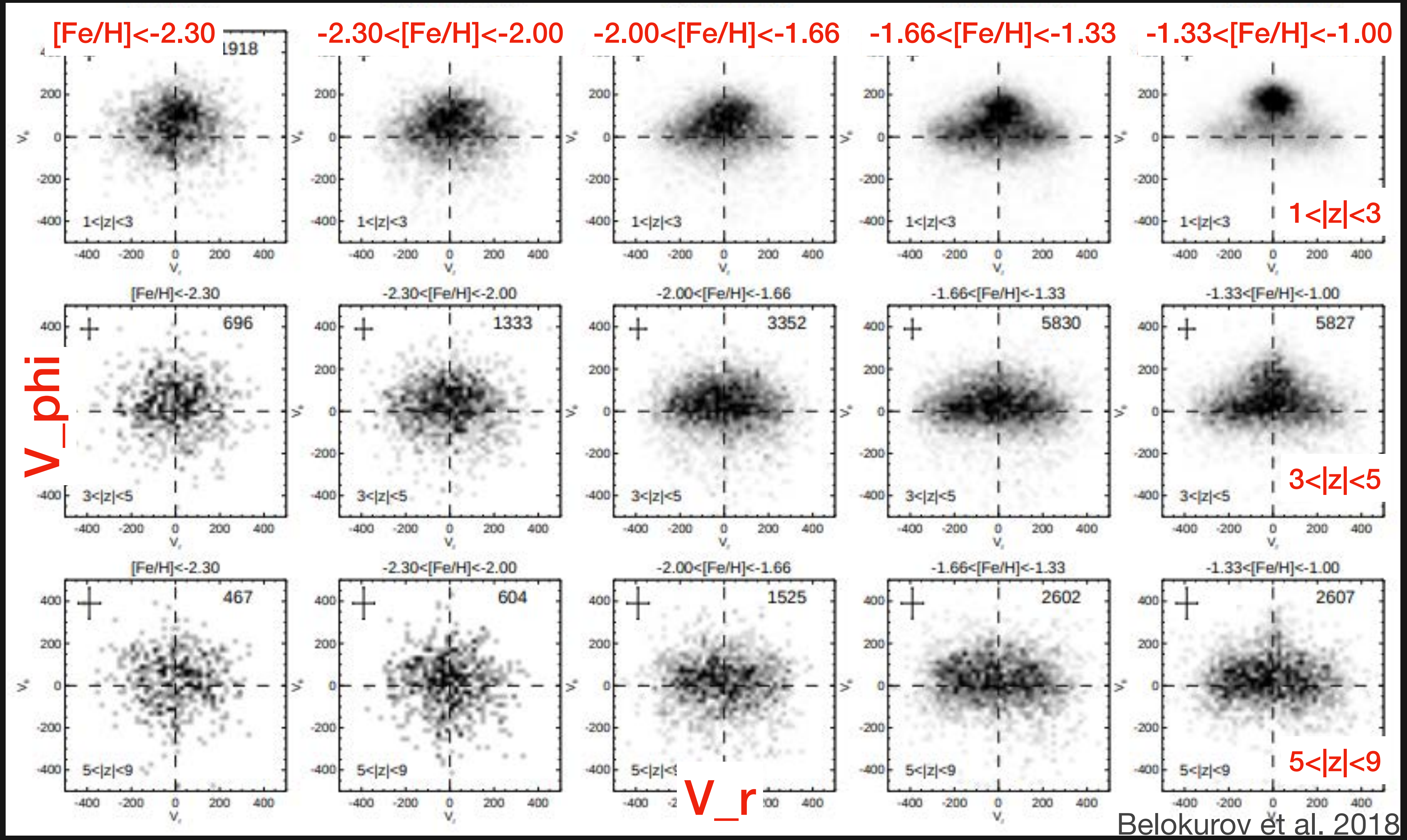
- **Virial Theorem can be used:**
  - Systems of stars at a steady equilibrium state — macroscopic properties do not change over time
    - Elliptical galaxies
    - Evolved globular clusters, e.g. globular clusters
    - Evolved galaxies clusters
- **Virial Theorem cannot be used:**
  - Systems of stars NOT at a steady equilibrium state
    - Merging galaxies
    - Newly formed star clusters
    - Clusters of galaxies that are still forming/still have infalling galaxies
- **Virial theorem provides easy (…but rough) estimates on various key properties of the system (including the total mass)**



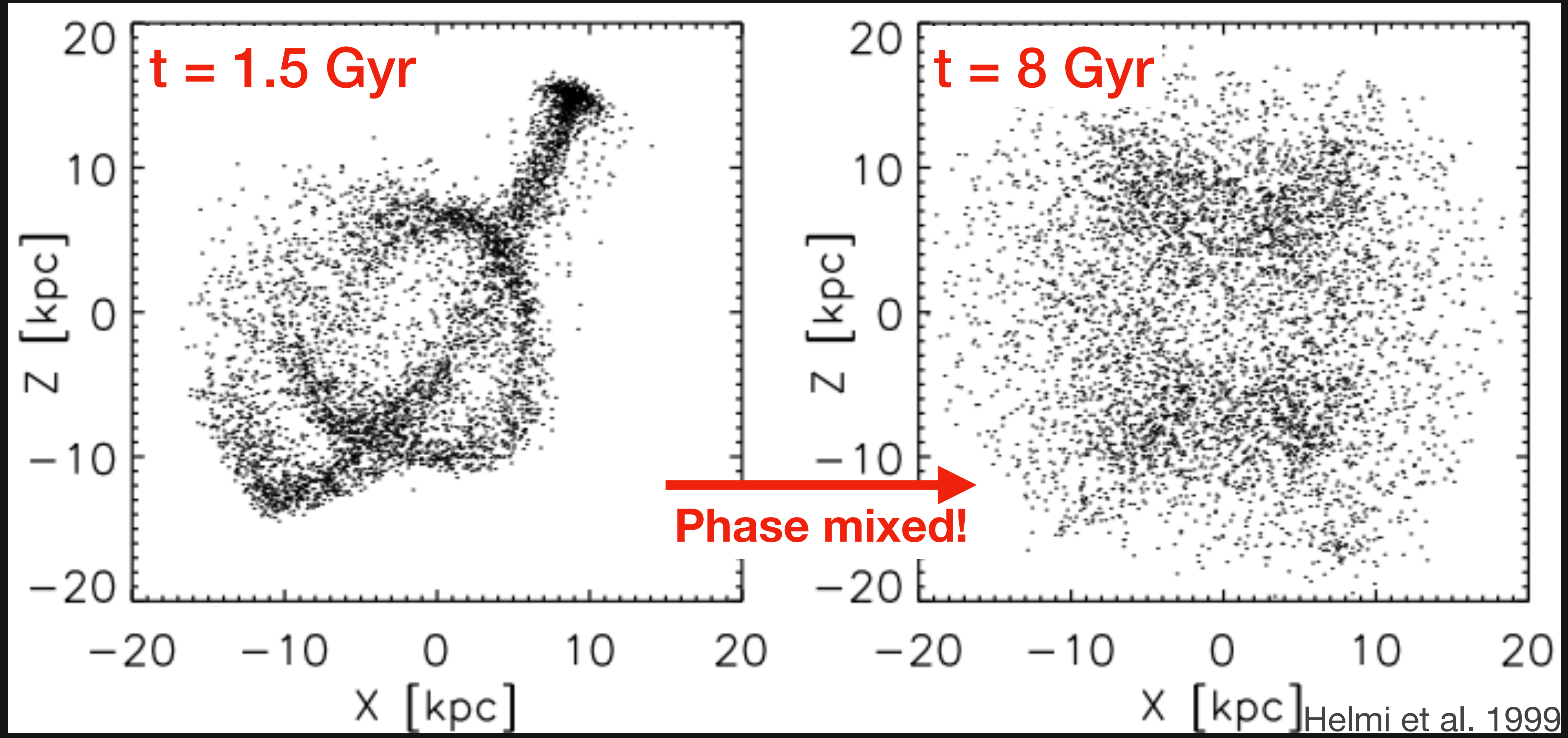
Structural view

- Various perspectives…
  - Spatial distribution in configuration space (or even, on the sky)
    - substructure as a spatial correlation
    - not-so-smooth footprint, and complex selection function
  - Current kinematics: velocity components
    - distribution, mean, and dispersion
    - directly looking for currently “co-moving” groups (e.g., clustering in velocity space)





Belokurov et al. 2018



Helmi et al. 1999

Structural view

- More "dynamic" perspective
  - Orbital parameters (e.g., energy, eccentricity, inclination from orbital integration)
  - **Action-angle variables**
    - a set of canonical coordinates on phase space
      - for a closed (& periodic) orbit, action, J, is constant (i.e., integrals-of-motion)
      - for an axisymmetric potential:
        - action variables can characterise the orbit of an object (e.g., star) in radial (J_R), azimuthal ($J_\phi = L_z$), and vertical (J_z) components
          → what the orbit is
        - angles are conjugate variables and constantly increase from 0 to 2π
          → where on the orbit
    - **adiabatic invariant**
      → stays approximately constant over the slow change of system (e.g., slow growth of the MW)
    - "phase mix" is not necessarily a problem!