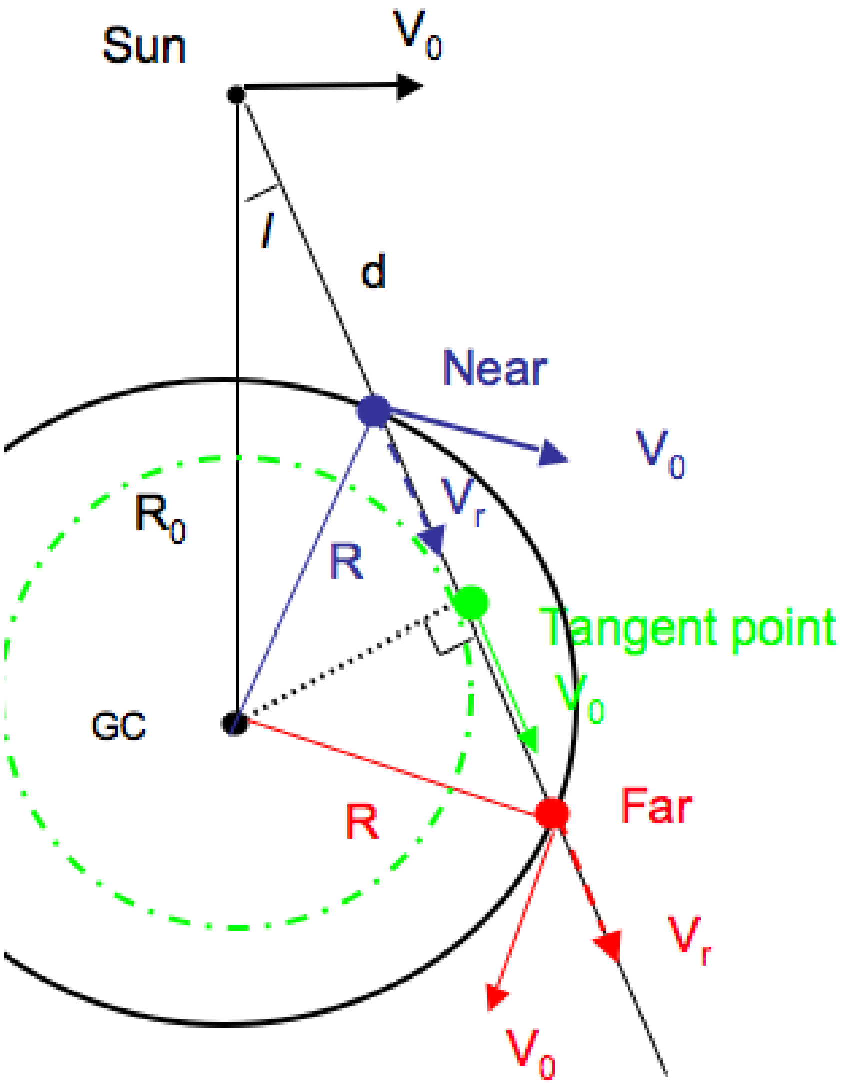
Tangent Point Method to Estimate Galactic Rotational Velocity



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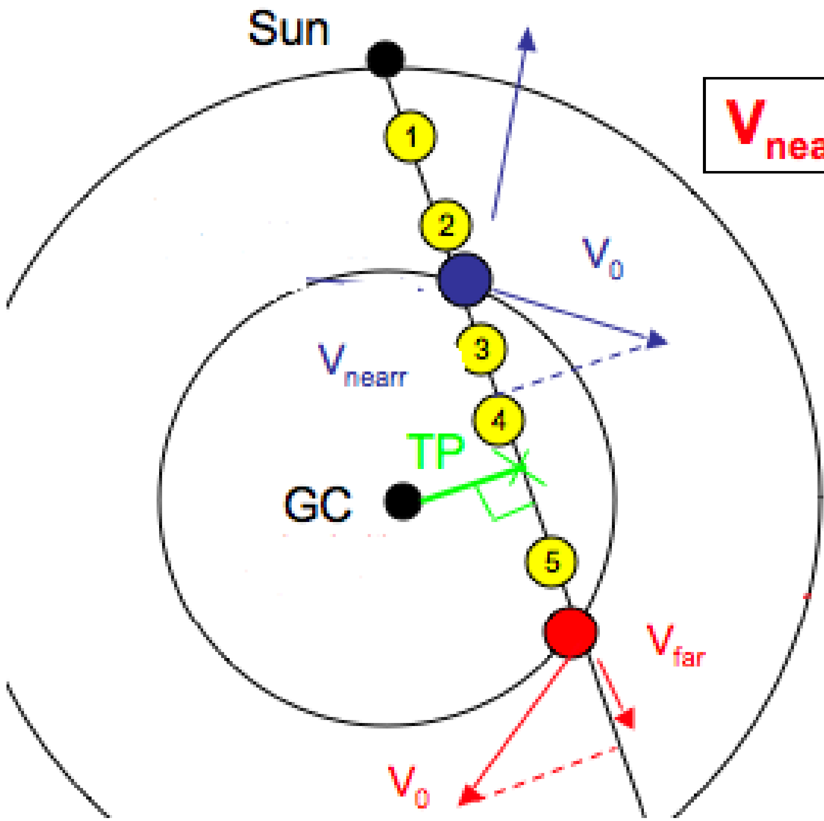
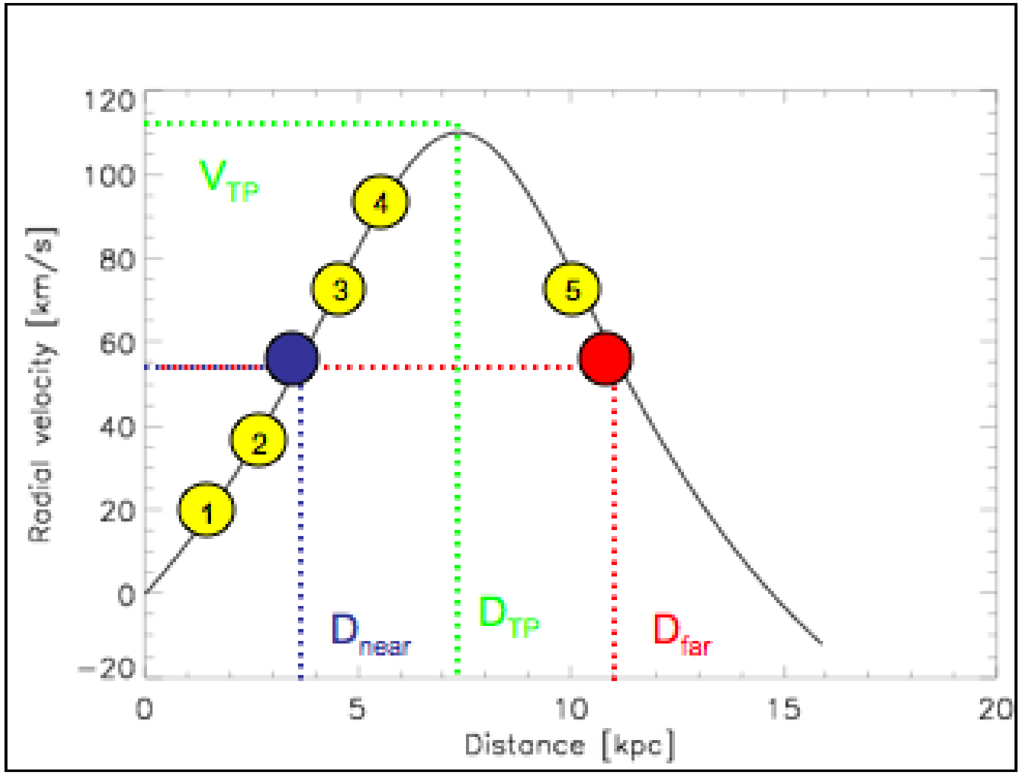
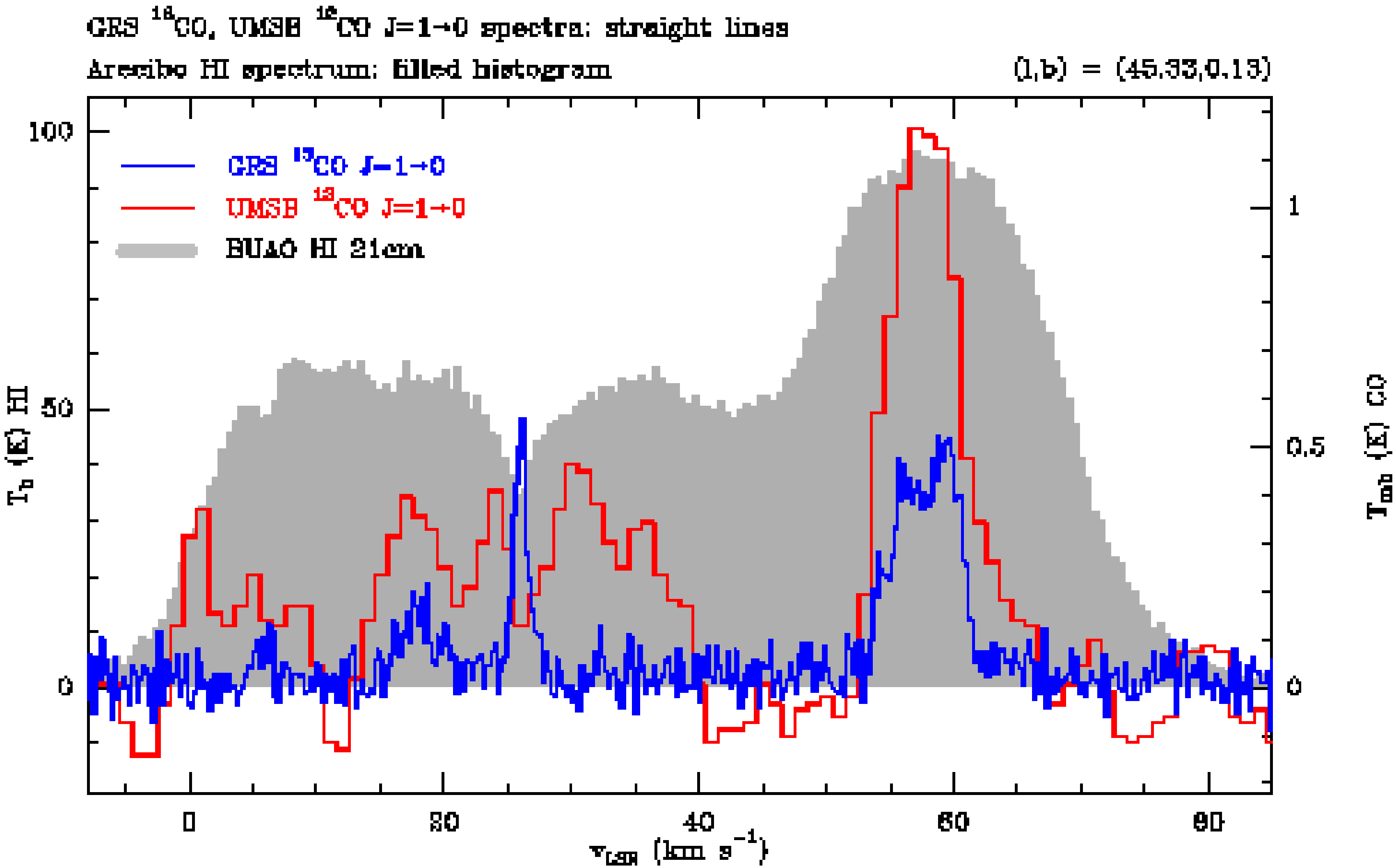


$V_{near} = V_{far}$

Maximum velocity is for the material at tangent point

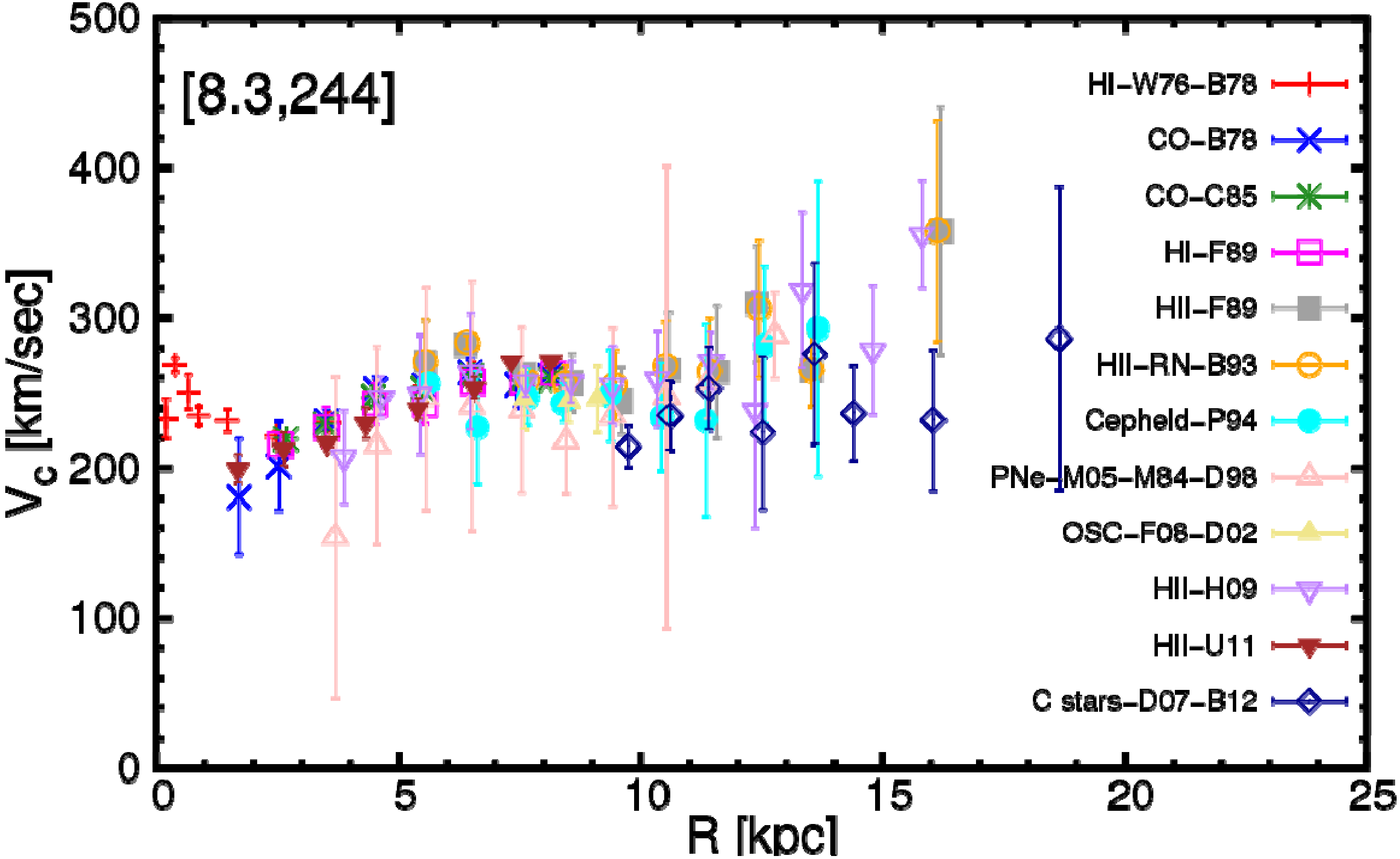




The BU-FCRAO Milky Way Galactic Ring Survey; Simon et al.

Milky Way Rotation Curve

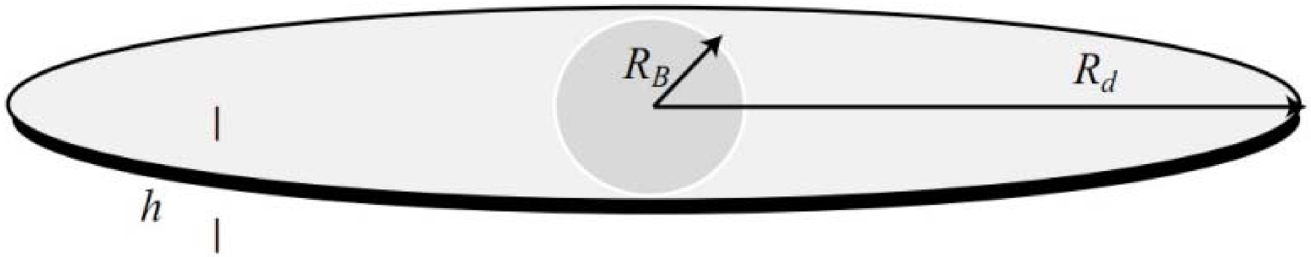
Bhattacharjee et al. (2014, ApJ) (see next slide for source of data)



Different tracers of rotation curve in the disk of the Galaxy, used by Bhattacharjee et al. (2014, ApJ) "Rotation Curve of the Milky Way out to 200 kpc" (a compilation of results from other work)

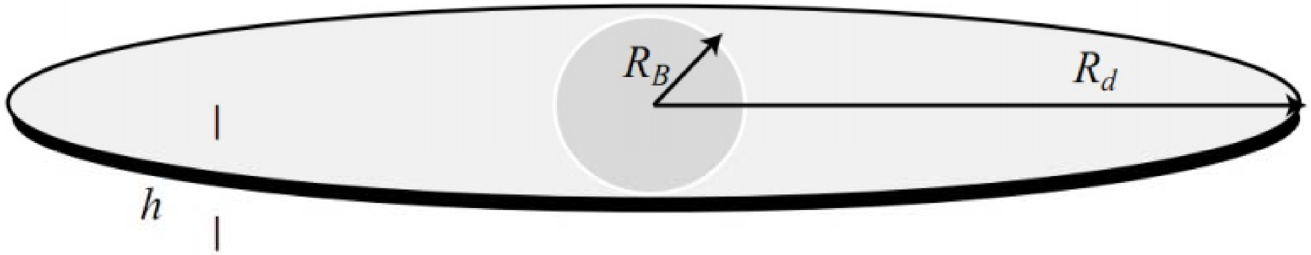
Tracer Type	Data Source	(l, b) Ranges
HI regions[a] (HI-W76-B78)	Westerhout (1976); Burton & Gordon (1978)	$1° < l < 90°$
CO clouds[a] (CO-B78)	Burton & Gordon (1978)	$9° < l < 82°$
CO clouds[a] (CO-C85)	Clemens (1985)	$13° < l < 86°$
HI regions[a] (HI-F89)	Fich et al. (1989)	$15° < l < 89°$ and $271° < l < 345°$
HII regions (HII-F89)	Fich et al. (1989)	$10° < l < 170°$ and $190° < l < 350°$
HII regions & reflection nebulae (HII-RN-B93)	Brand & Blitz (1993)	$10° < l < 170°$ and $190° < l < 350°$
Cepheids (Cepheid-P94)	Pont et al. (1994)	$10° < l < 170°$ and $190° < l < 350°$; $\|b\| < 10°$
Planetary nebulae (PNe-M05-M84-D98)	Maciel & Lago (2005); Maciel (1984); Durand et al. (1998)	$15° < l < 345°$; $\|b\| < 10°$
Open star clusters (OSC-F08-D02)	Frinchaboy & Majewski (2008); Dias et al. (2002)	$10° < l < 170°$ and $190° < l < 350°$; $\|b\| < 9°$
HII regions (HII-H09)	Hou et al. (2009)	$10° < l < 170°$ and $190° < l < 350°$
HII regions[a] (HII-U11)	Urquhart et al. (2011)	$10° < l < 65°$ and $280° < l < 350°$
C stars (C stars-D07-B12)	Demers & Battinelli (2007); Battinelli et al. (2012)	$54° < l < 150°$; $3° < \|b\| < 9°$

Rotation Curve of Milky Way



Spiral galaxies : central spherical bulge + circular disk. Stellar and gas distribution is different in the bulge and the disk

Rotation Curve of Milky Way



The bulge **has a roughly constant density of stars**

Mass enclosed within a radius *r*

$$M(r) = \frac{4}{3}\pi r^3 \rho_b \qquad (r < R_b)$$

Rotational velocity in the bulge

$$v^2(r) = \frac{GM(r)}{r} = \frac{4}{3}\pi \rho_b G r^2 \qquad (r < R_b)$$

In the disk**, the stellar density declines exponentially**

$$v^2(r) = \frac{GM(r)}{r} \qquad (R_b < r \leq R_d)$$

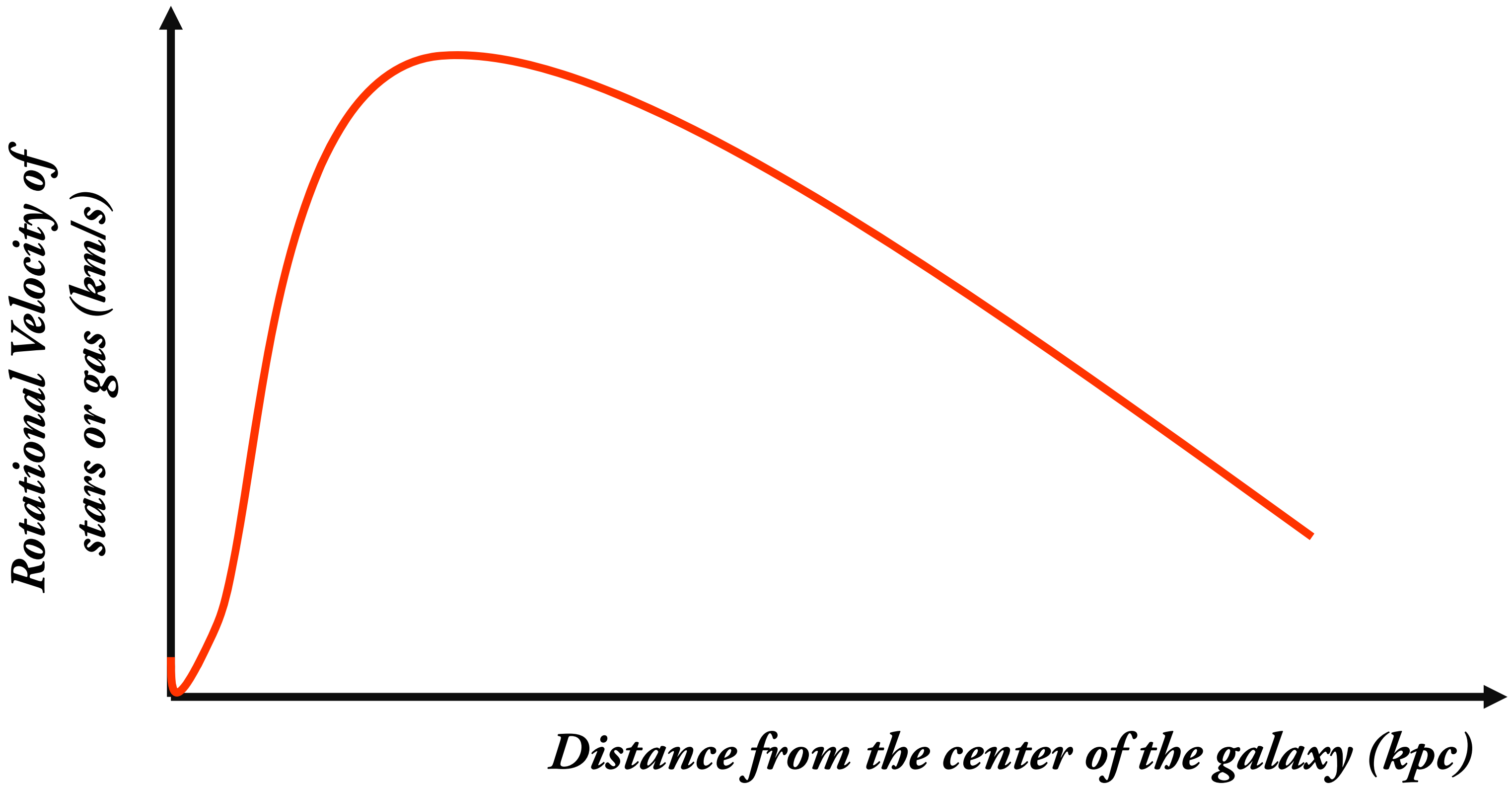
r ↑ $M(r)$ ↑

ρ ↓ $M(r)$ ↓

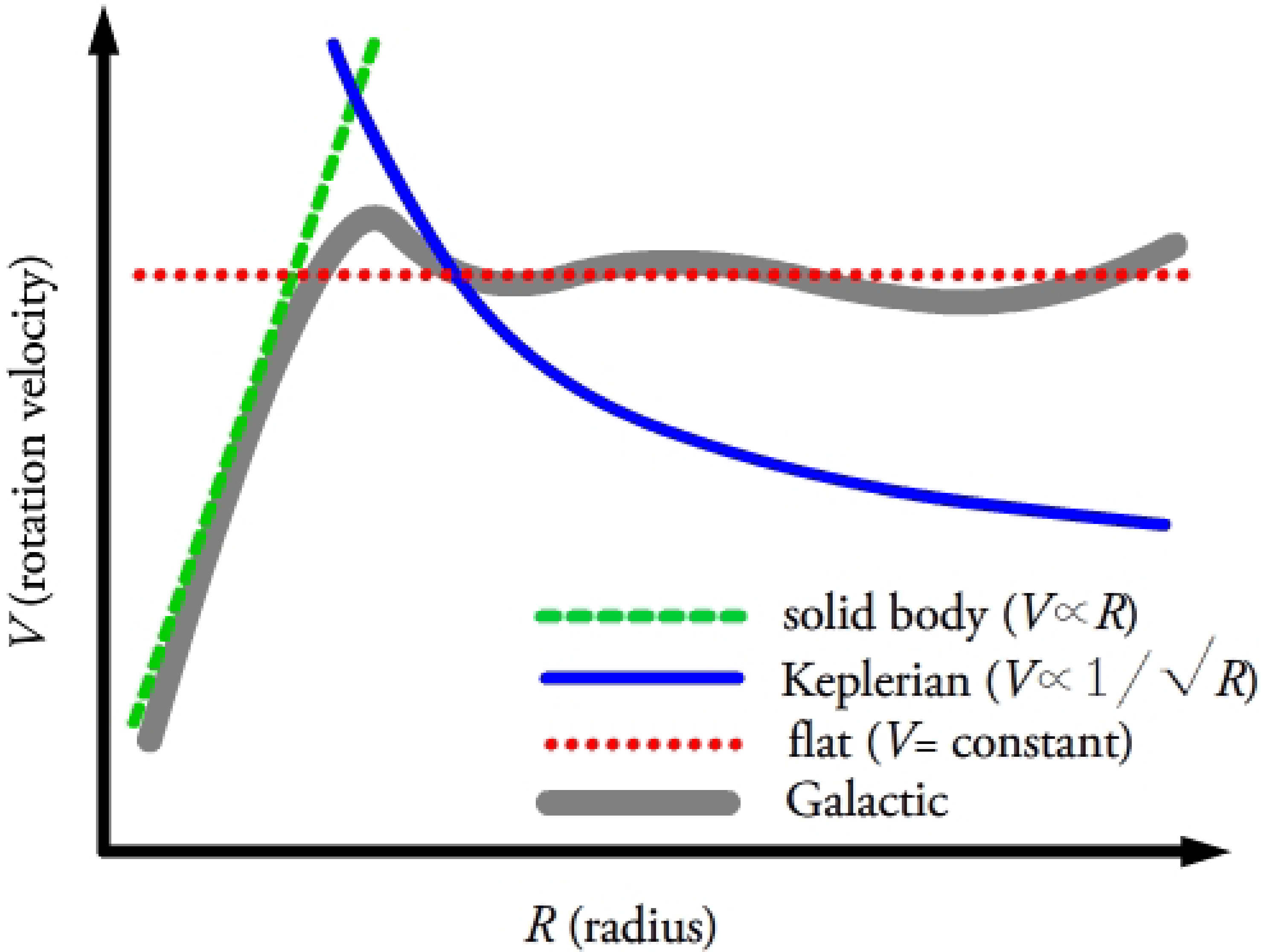
Rotation Curve of Milky Way

- **Bulge :** $v(r) \propto r$
- **Disk :** $v(r) \propto \sqrt{\frac{1}{r}}$

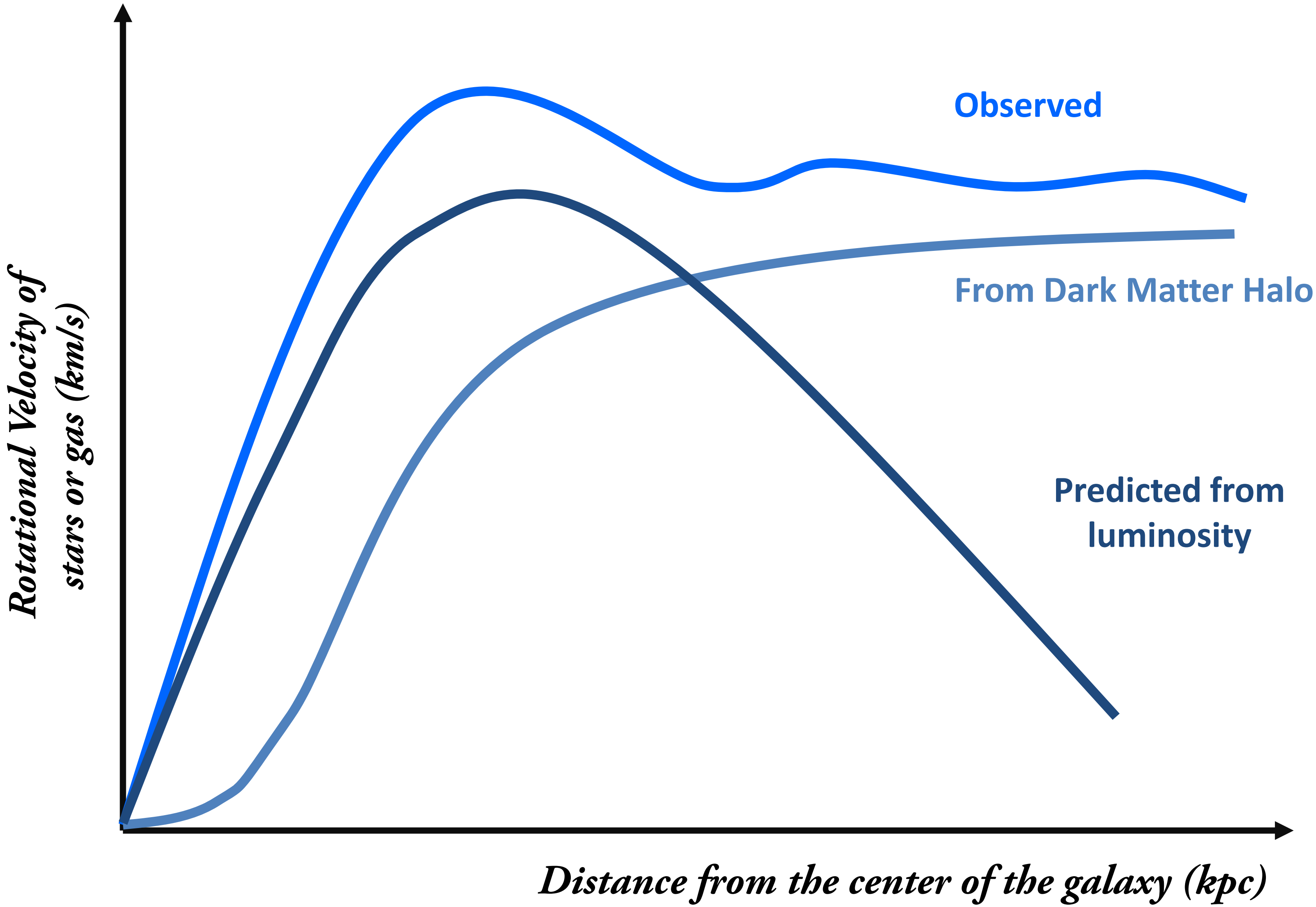
Rotation Curve of Spiral Galaxies Expected from the Observed Distribution of Luminous Matter



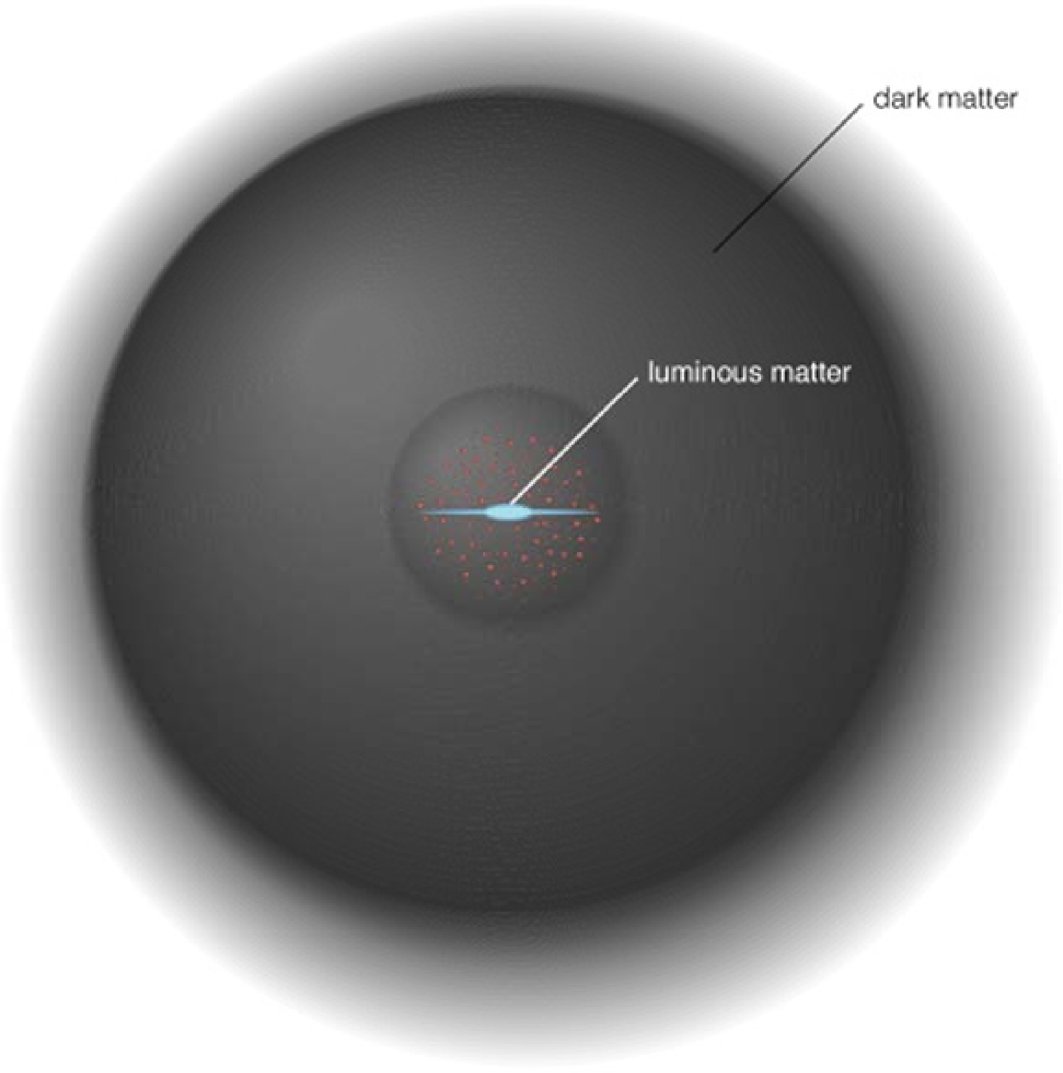
Rotation Curve



Rotation Curve of Milky Way



Rotation Curves of Spiral Galaxies : *Evidence for Dark Matter*



Rotation Curves of Spiral Galaxies : *Evidence for Dark Matter*

- Missing mass ~ 10 times the luminous mass

- Dark matter in the halo. Large dark matter in the disk can disturb the long-term stability of the disk against tidal forces.

- Some fraction of dark matter in the disk can be *baryonic* - dim stars (brown dwarfs, black dwarfs), and compact stellar remnants (neutron stars, black holes)

- The dark halo emits no light and thus has a completely unknown spatial distribution. Density profile of dark matter in the halo

$$\rho \propto r^{-2}$$

Mass(es) of the Milky Way

- **Stellar mass ~ 10^{10} $M_\odot$** *(all sky surveys, point source counting)*
- **ISM mass ~ 10^9 - $10^{10} M_\odot$** *(H I 21 cm surveys)*
- **Luminous mass (Stellar + ISM) ~ 10^{10} $M_\odot$**
- **Dynamical mass ~ 10^{12} $M_\odot$**
  dominated by dark matter (from rotation curve)