The Distribution of Dark Matter Velocities

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Melbourne, 2017

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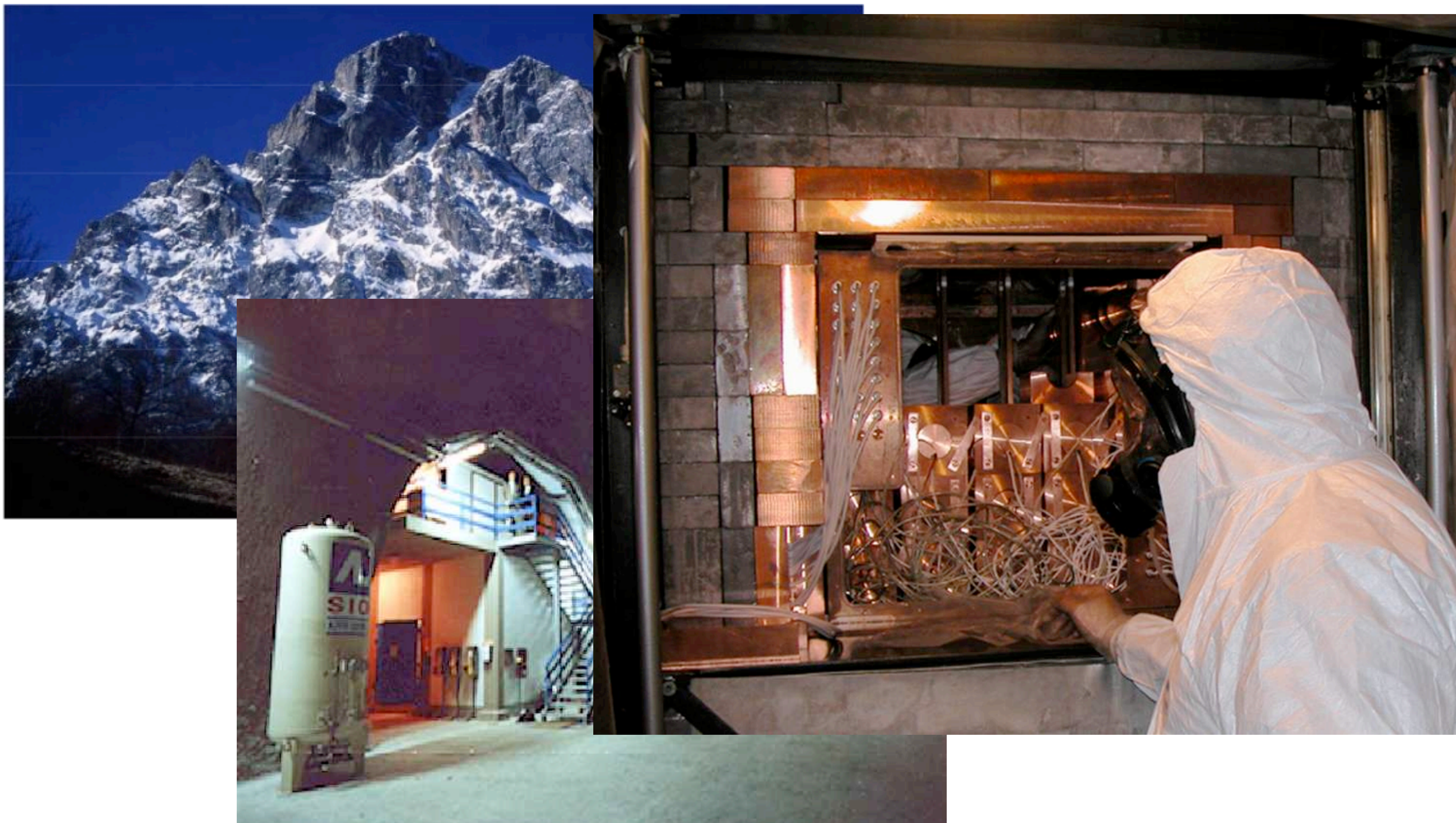
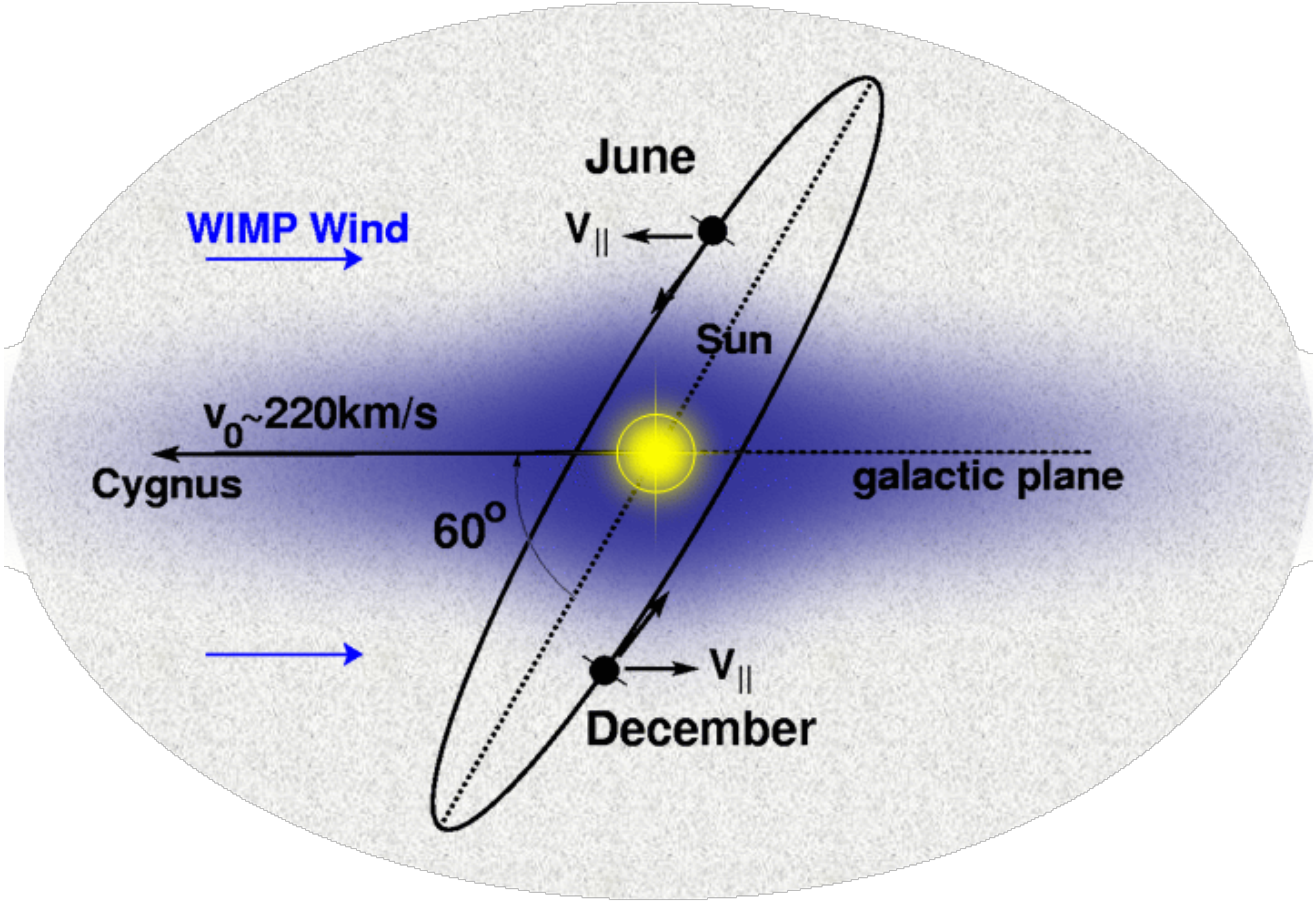
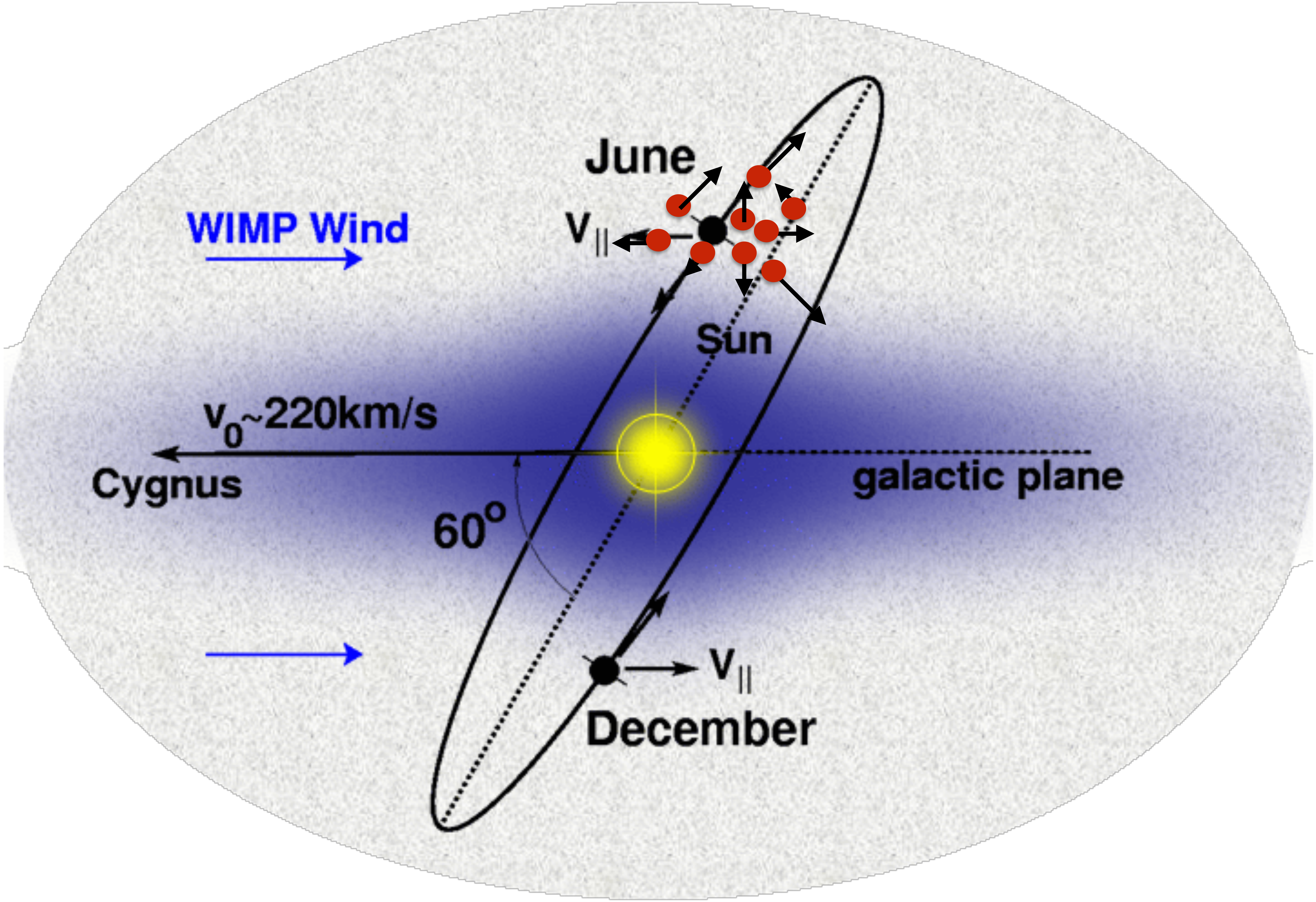
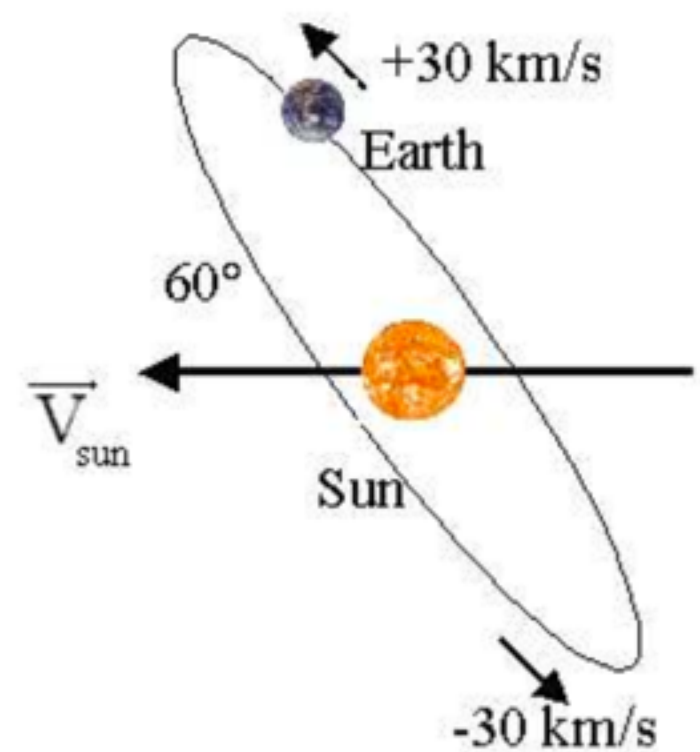
3 steps to measure DM




June
WIMP Wind
$v_{||}$
Sun
v_0~220km/s
Cygnus
galactic plane
60^o
$v_{||}$
December


June
WIMP Wind
$v_{||}$
Sun
v_0~220km/s
Cygnus
galactic plane
60°
$v_{||}$
December

The velocity-spatial distribution of the WIMPs in our galactic halo is not well known. So far the simplest, non-consistent and approximate isothermal sphere model has generally been considered in direct WIMP searches; under this assumption the WIMPs form a dissipationless gas trapped in the gravitational field of our Galaxy in an equilibrium steady state and have a quasi-maxwellian velocity distribution with a cut-off at the escape velocity from the galactic gravitational field. More realistic halo



Bernabei et al, astro-ph/0307403

The dark halo model widely used in the calculations carried out in the WIMP direct detection approaches is the simple isothermal sphere that corresponds to a spherical infinite system with a flat rotational curve. The halo density profile is:

$$\rho_{DM}(r) = \frac{v_0^2}{4\pi G}\frac{1}{r^2} \tag{30}$$

corresponding to the following potential:

$$\Psi_0(r) = -\frac{v_0^2}{2}\log(r^2). \tag{31}$$

In this case, when a maximal halo density is considered, the WIMP velocity distribution is the Maxwell function:

$$f(v) = N\exp\left(-\frac{3v^2}{2v_{rms}^2}\right) \tag{32}$$

Bernabei et al, astro-ph/0307403

Class A: spherical ρ_{DM}, isotropic velocity dispersion			eq.
A0	Isothermal Sphere		(30)
A1	Evans' logarithmic [101]	$R_c = 5$ kpc	(33)
A2	Evans' power-law [102]	$R_c = 16$ kpc, $\beta = 0.7$	(35)
A3	Evans' power-law [102]	$R_c = 2$ kpc, $\beta = -0.1$	(35)
A4	Jaffe [103]	$\alpha = 1$, $\beta = 4$, $\gamma = 2$, $a = 160$ kpc	(37)
A5	NFW [104]	$\alpha = 1$, $\beta = 3$, $\gamma = 1$, $a = 20$ kpc	(37)
A6	Moore et al. [105]	$\alpha = 1.5$, $\beta = 3$, $\gamma = 1.5$, $a = 28$ kpc	(37)
A7	Kravtsov et al. [106]	$\alpha = 2$, $\beta = 3$, $\gamma = 0.4$, $a = 10$ kpc	(37)
Class B: spherical ρ_{DM}, non–isotropic velocity dispersion (Osipkov–Merrit, $\beta_0 = 0.4$)			
B1	Evans' logarithmic	$R_c = 5$ kpc	(33)(39)
B2	Evans' power-law	$R_c = 16$ kpc, $\beta = 0.7$	(35)(39)
B3	Evans' power-law	$R_c = 2$ kpc, $\beta = -0.1$	(35)(39)
B4	Jaffe	$\alpha = 1$, $\beta = 4$, $\gamma = 2$, $a = 160$ kpc	(37)(39)
B5	NFW	$\alpha = 1$, $\beta = 3$, $\gamma = 1$, $a = 20$ kpc	(37)(39)
B6	Moore et al.	$\alpha = 1.5$, $\beta = 3$, $\gamma = 1.5$, $a = 28$ kpc	(37)(39)
B7	Kravtsov et al.	$\alpha = 2$, $\beta = 3$, $\gamma = 0.4$, $a = 10$ kpc	(37)(39)
Class C: Axisymmetric ρ_{DM}			
C1	Evans' logarithmic	$R_c = 0$, $q = 1/\sqrt{2}$	(40)(41)
C2	Evans' logarithmic	$R_c = 5$ kpc, $q = 1/\sqrt{2}$	(40)(41)
C3	Evans' power-law	$R_c = 16$ kpc, $q = 0.95$, $\beta = 0.9$	(42)(43)
C4	Evans' power-law	$R_c = 2$ kpc, $q = 1/\sqrt{2}$, $\beta = -0.1$	(42)(43)
Class D: Triaxial ρ_{DM} [107] (q = 0.8, p = 0.9)			
D1	Earth on maj. axis, rad. anis.	$\delta = -1.78$	(45)(46)
D2	Earth on maj. axis, tang. anis.	$\delta = 16$	(45)(46)
D3	Earth on interm. axis, rad. anis.	$\delta = -1.78$	(45)(46)
D4	Earth on interm. axis, tang. anis.	$\delta = 16$	(45)(46)

Bernabei et al, astro-ph/0307403

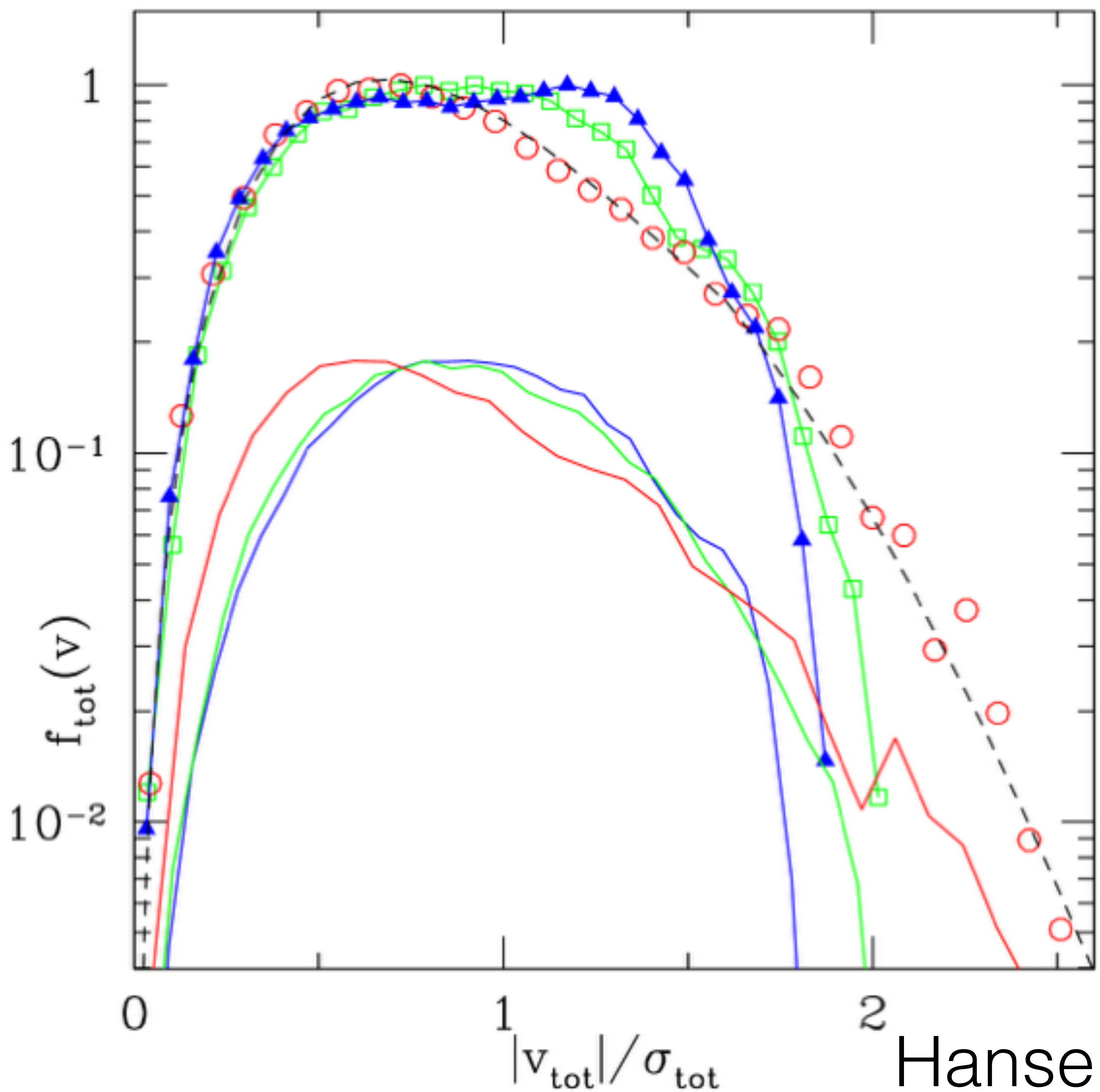
Improved Limits on Scattering of Weakly Interacting Massive Particles from Reanalysis of 2013 LUX data

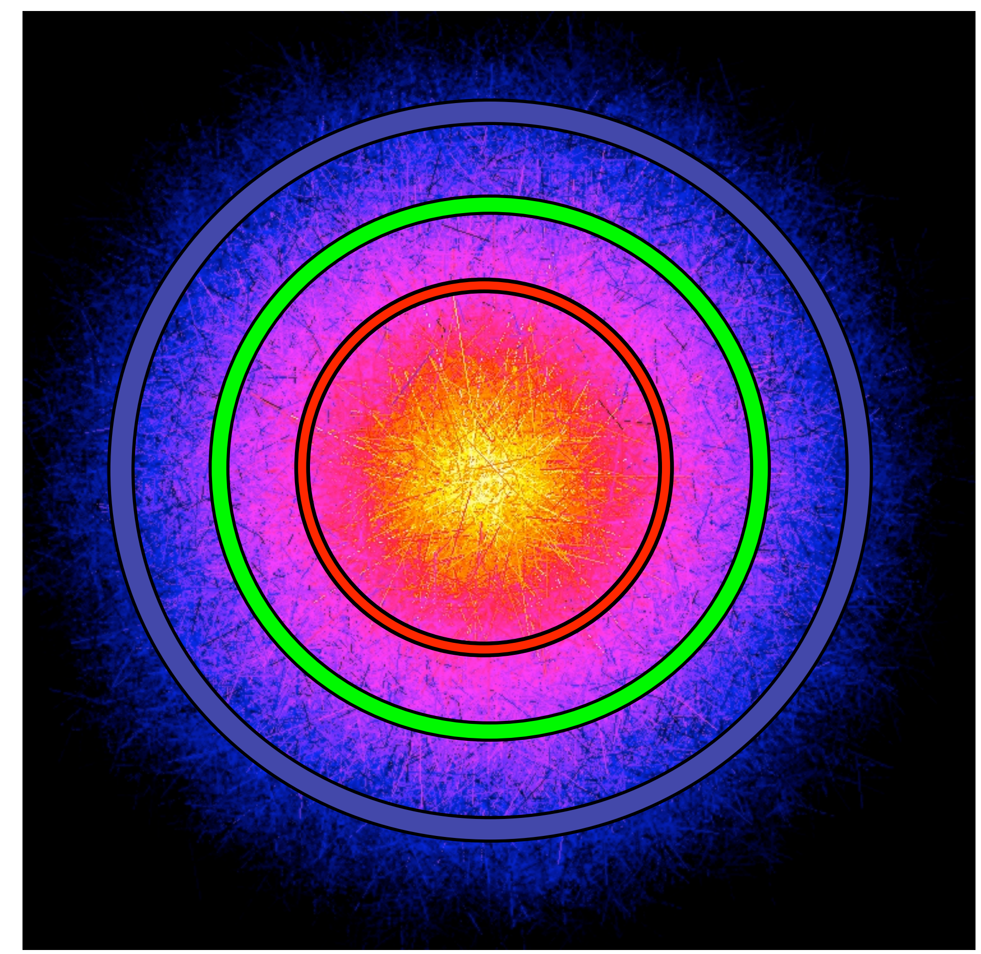
Nuclear-recoil energy spectra for the WIMP signal are derived from a standard Maxwellian velocity distribution with $v_0 = 220$ km/s, $v_{esc} = 544$ km/s, $\rho_0 = 0.3$ GeV/cm^3,

Improved Limits from the Large Underground Xenon Dark Matter Experiment

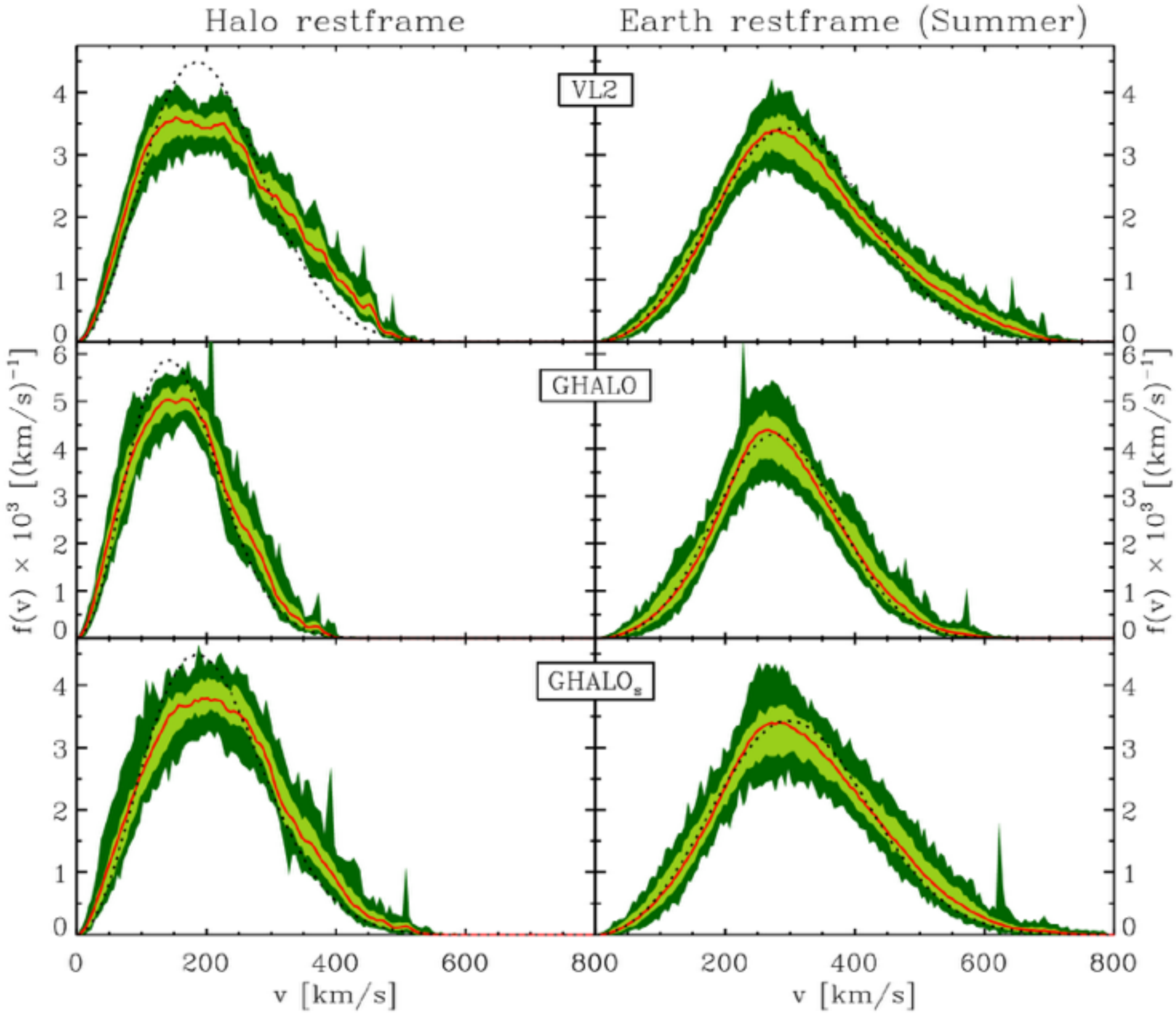
- f(v) depends on halo model: typically Maxwellian truncated at galactic escape velocity (544 km/s) and account for Earth's motion through galaxy (220 km/s + annual modulation)
- Local dark matter density also depends on halo model: $\rho_0 \sim 0.3$ GeV/cm^3

What does the velocity distribution look like?

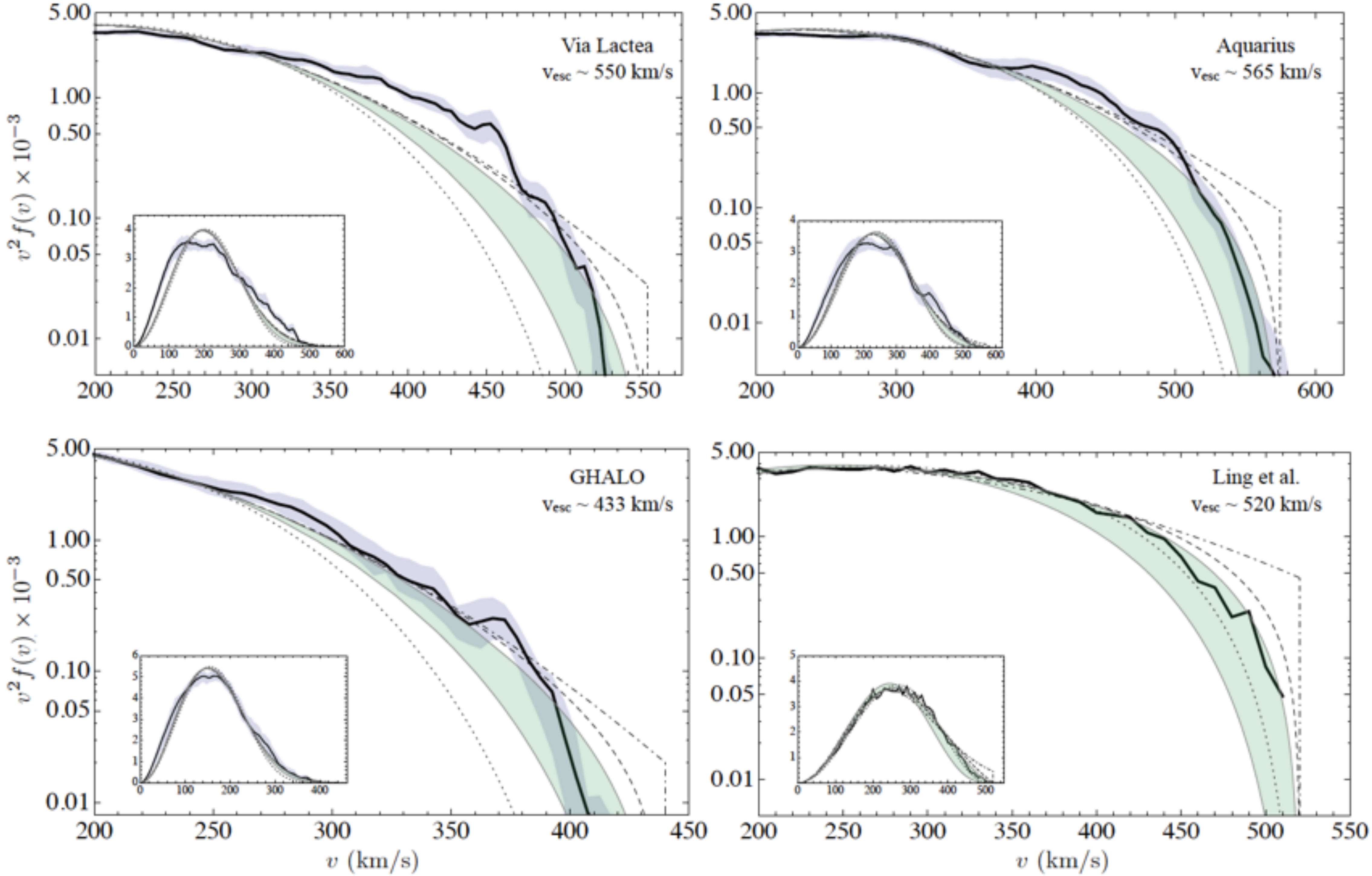




Hansen et al, astro-ph/0505420



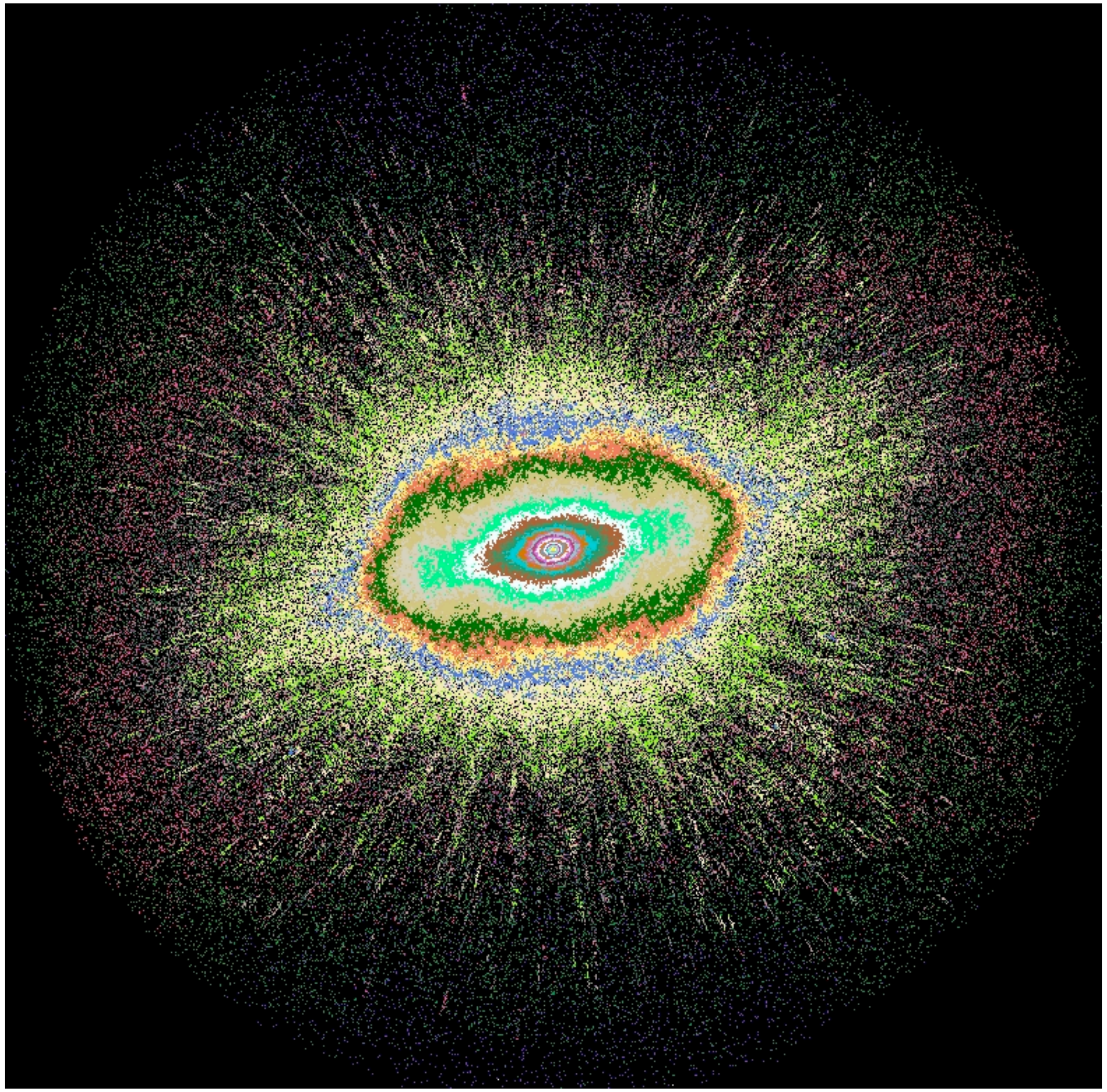
Kuhlen et al, arXiv:0912.2358



Lisanti et al, arXiv:1010.4300

Theoretical velocity anisotropy

The velocity distribution function is exp(-v^2/T) for a normal gas, but what about **collisionless** dark matter?



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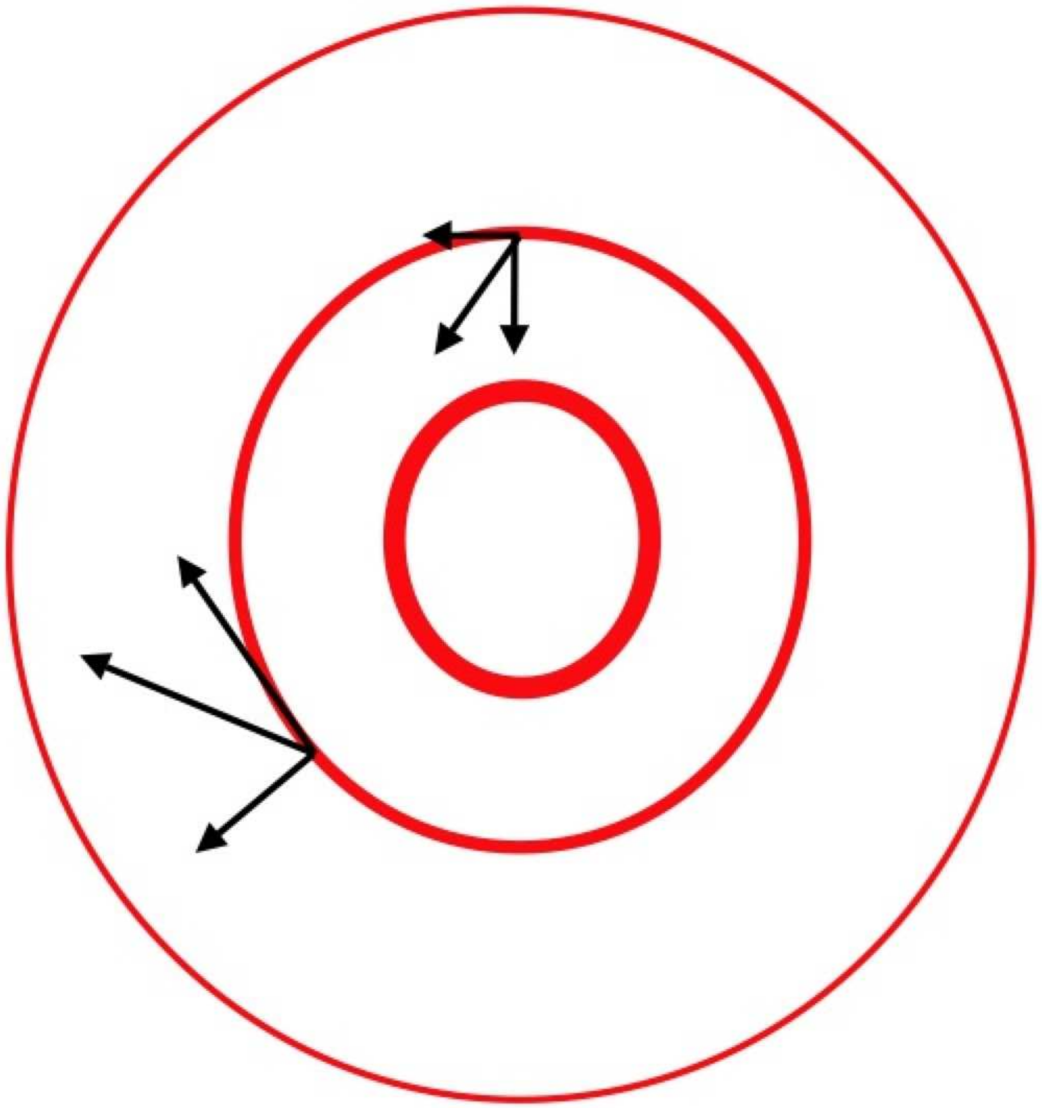
At Earths distance, split in Radial and Tangential



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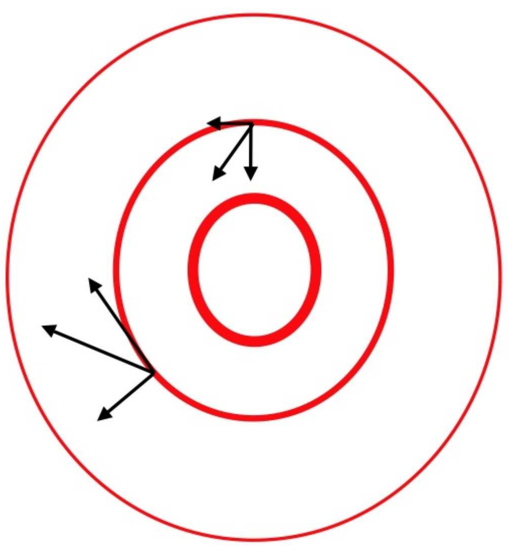
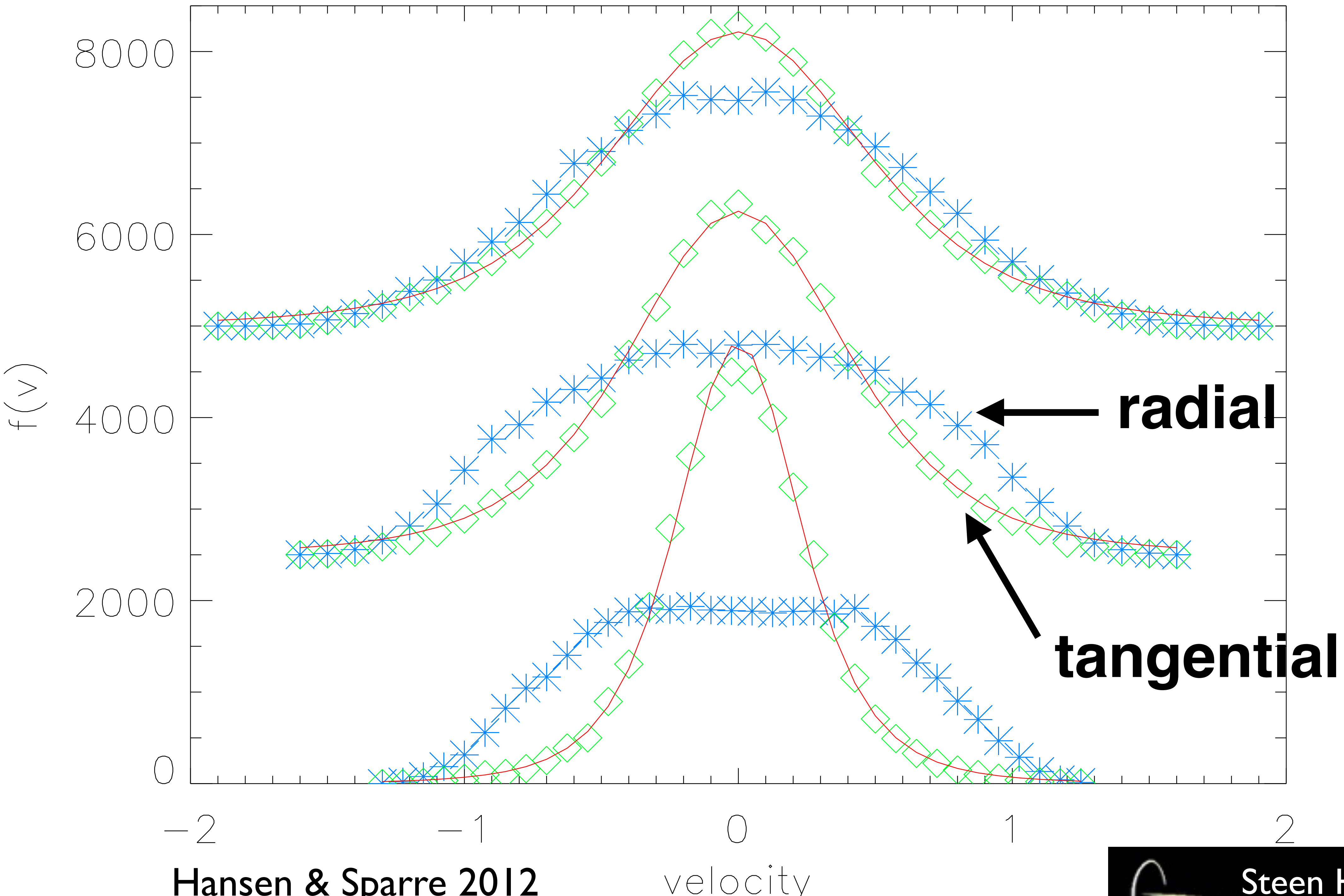
The tangential distribution is quite easy to derive

- If you move along the tangent, then you move in constant density and constant potential
- That we can solve for!



Hansen et al, astro-ph/0407111

We (essentially) understand the tangential distribution function



Hansen & Sparre 2012

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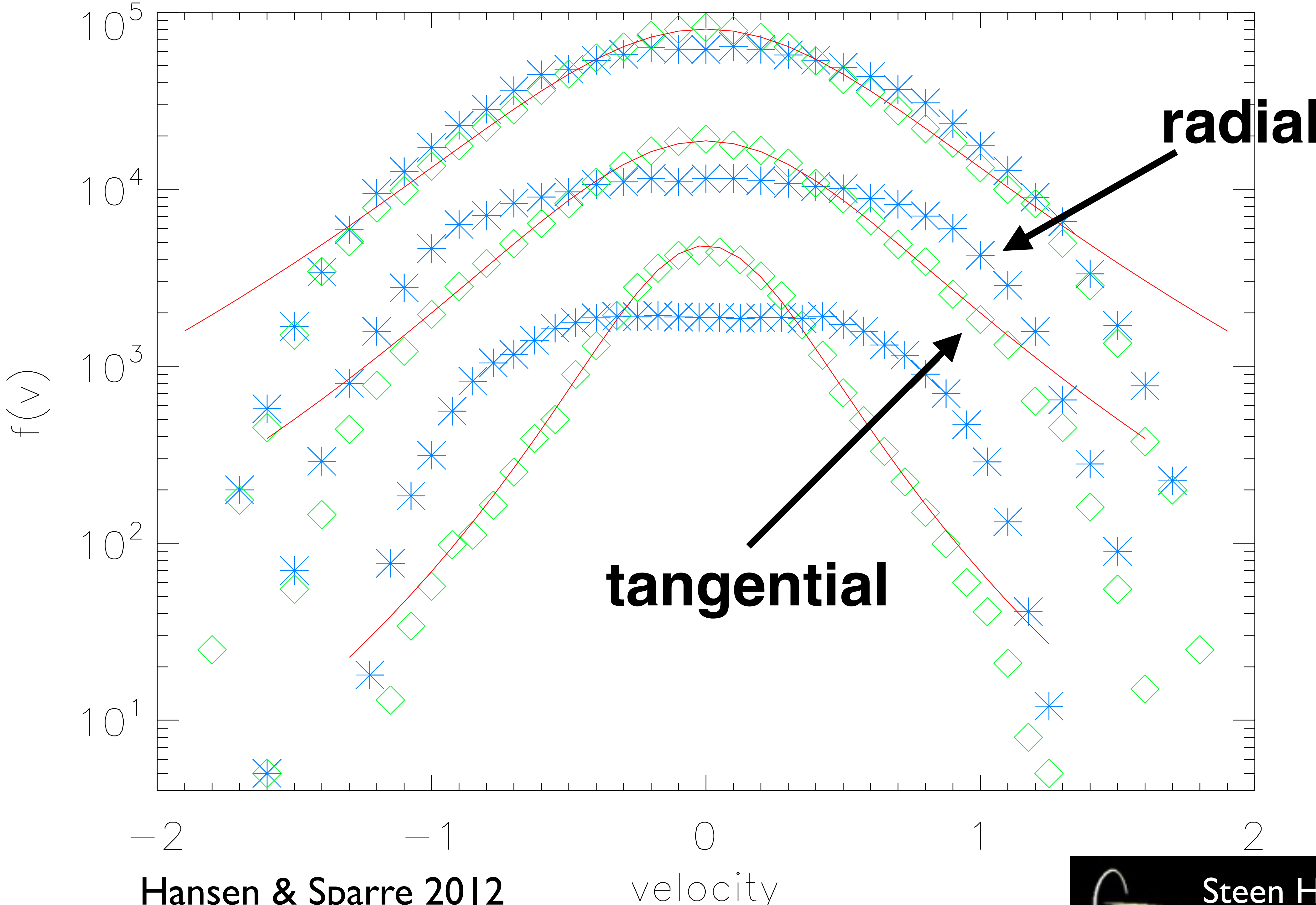
Only the tail of the tangential distribution is wrong...



Hansen & Sparre 2012

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How to derive the radial distribution function?

Jeans equation from integral over the Boltzmann equation

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \vec{v} \cdot \nabla f - \nabla \Phi \cdot \frac{\partial f}{\partial \vec{v}} = 0$$

$$\int v_r \, \frac{df}{dt} \, d^3 v = 0$$

$$\frac{GM(r)}{r} = -\overline{v_r^2} \left(\frac{d\ln(\rho)}{d\ln(r)} + \frac{d\ln(\overline{v_r^2})}{d\ln(r)} + 2\beta \right)$$

How to derive the radial distribution function?

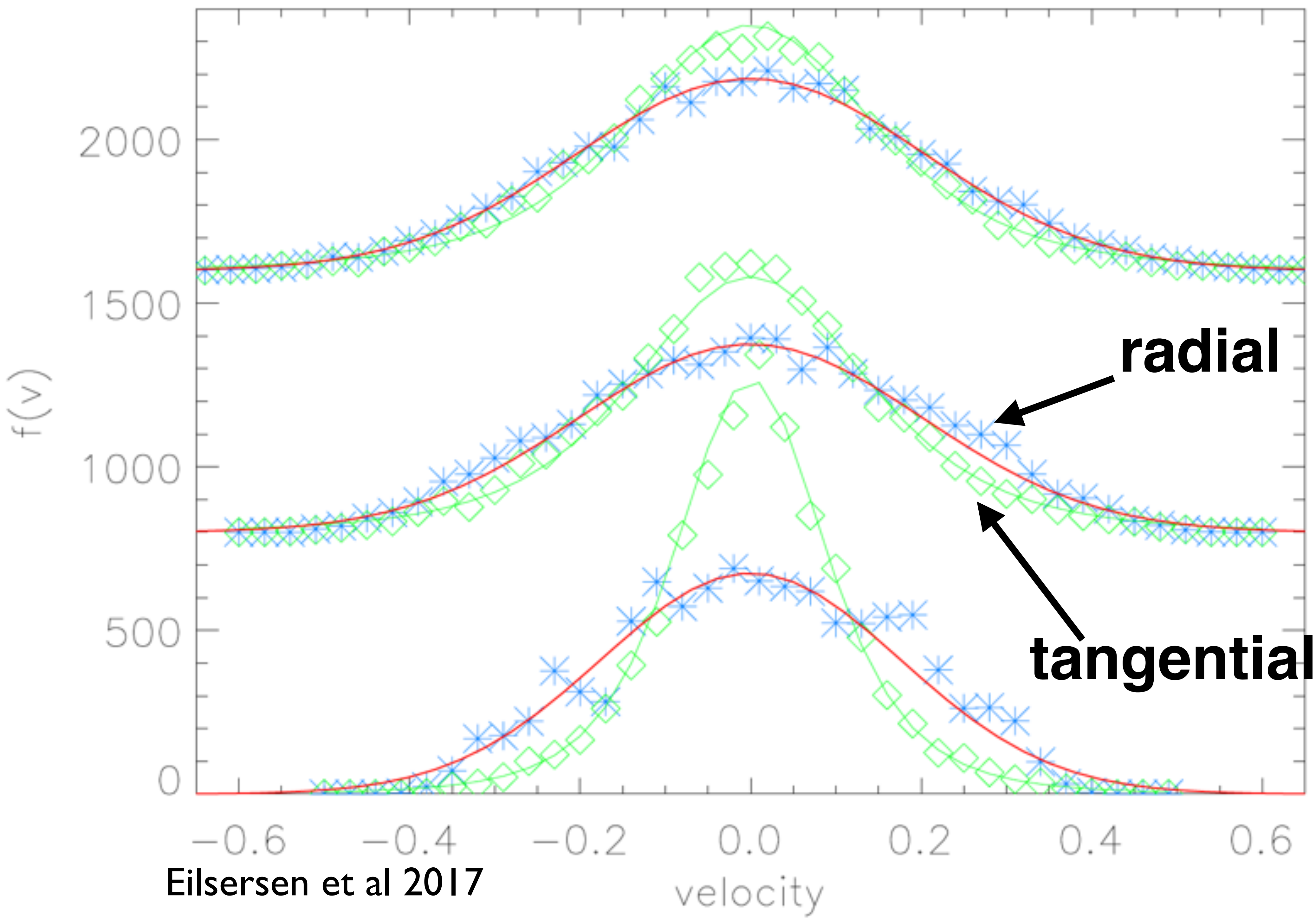
$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \vec{v} \cdot \nabla f - \nabla \Phi \cdot \frac{\partial f}{\partial \vec{v}} = 0$$

$$\int \frac{df}{dt} \, d^2 v_{\theta,\phi} = 0$$

$$v_r \frac{\partial F_R}{\partial r} + \frac{1}{r} \frac{\partial}{\partial v_r} \left(\langle v_\theta^2 \rangle_r + \langle v_\phi^2 \rangle_r \right) - \frac{d\Phi}{dr} \frac{\partial F_R}{\partial v_r} + 2 \frac{v_r \, F_R}{r} = 0$$

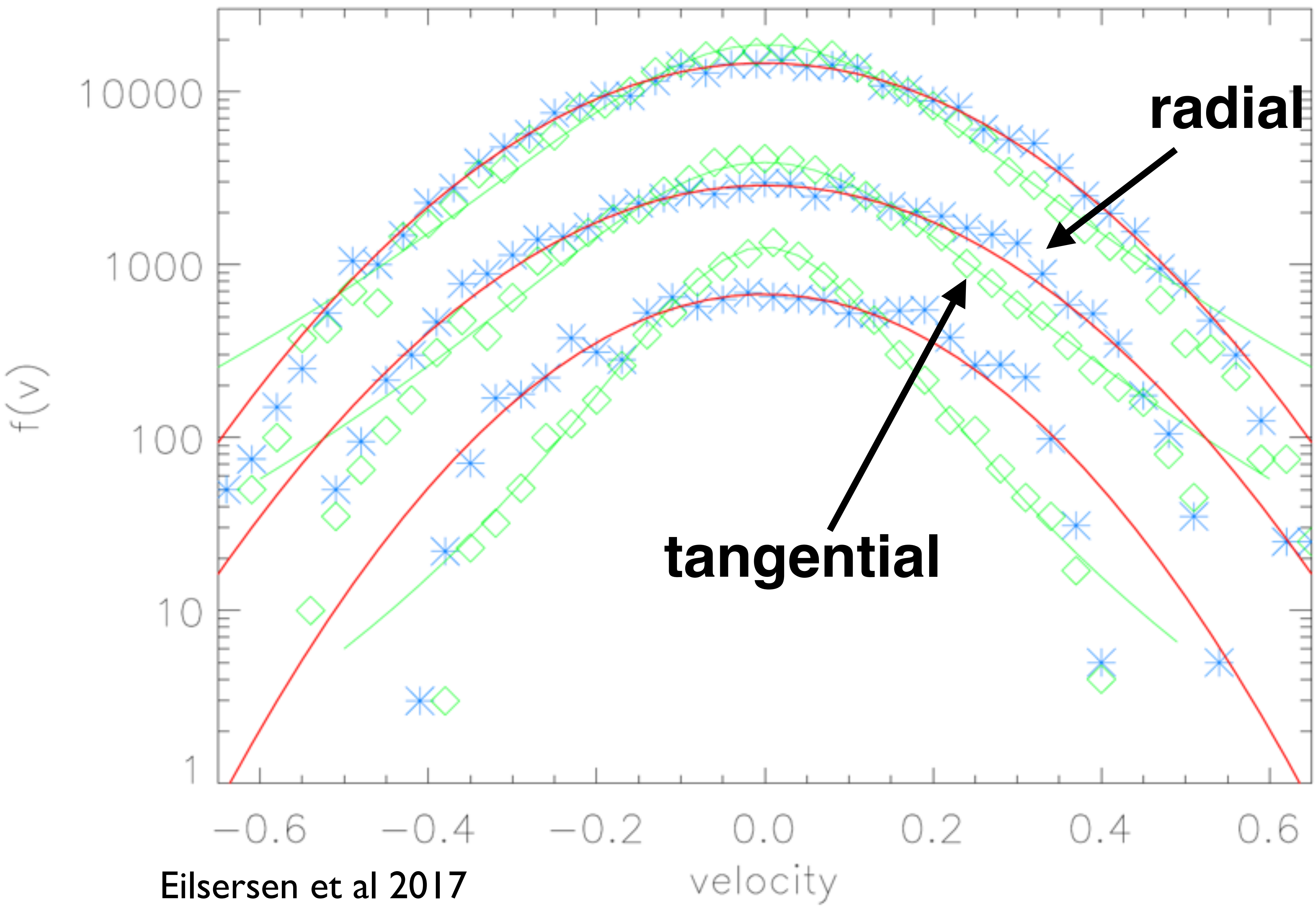
Eilersen et al, arXiv:1701.04908

We (essentially) understand the radial distribution function



Eilsersen et al 2017

Only the tail of the radial distribution is wrong…



Eilsersen et al 2017

Conclusion

- We can analytically calculate the **tangential** velocity distribution (except for the high energy tail)
- We can analytically calculate the **radial** velocity distribution (except for the high energy tail)
- We would like to calculate the tail…