Gaia and the Local Dark Matter Density

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arXiv:1507.08581

Why do we care about local DM density?

WIMP, sterile neutrino & axion direct detection via nuclear/electron recoils (e.g. XENON1T, LUX)

$$\frac{\mathrm{d}R}{\mathrm{d}E} = \frac{\rho_\odot}{m_{\mathrm{DM}} m_{\mathcal{N}}} \int_{v>v_{\mathrm{min}}} \mathrm{d}^3 v \, \frac{\mathrm{d}\sigma}{\mathrm{d}E}(E, v) \, v \, f(\vec{v}(t))$$

Indirect Detection through Solar Capture and annihilation to neutrinos (e.g. IceCube, Antares, KM3NeT, Super-

$$C^\odot \approx 1.3 \times 10^{21} s^{-1} \left(\frac{\rho_{local}}{0.3\mathrm{GeV\ cm}^{-3}}\right) \left(\frac{270\mathrm{km\ s}^{-1}}{v_{local}}\right) \times \left(\frac{100\mathrm{GeV}}{m_\chi}\right) \sum_i \left(\frac{A_i(\sigma_{\chi i,SD} + \sigma_{\chi i,SI}) S(m_\chi/m_i)}{10^{-6}\mathrm{pb}}\right)$$

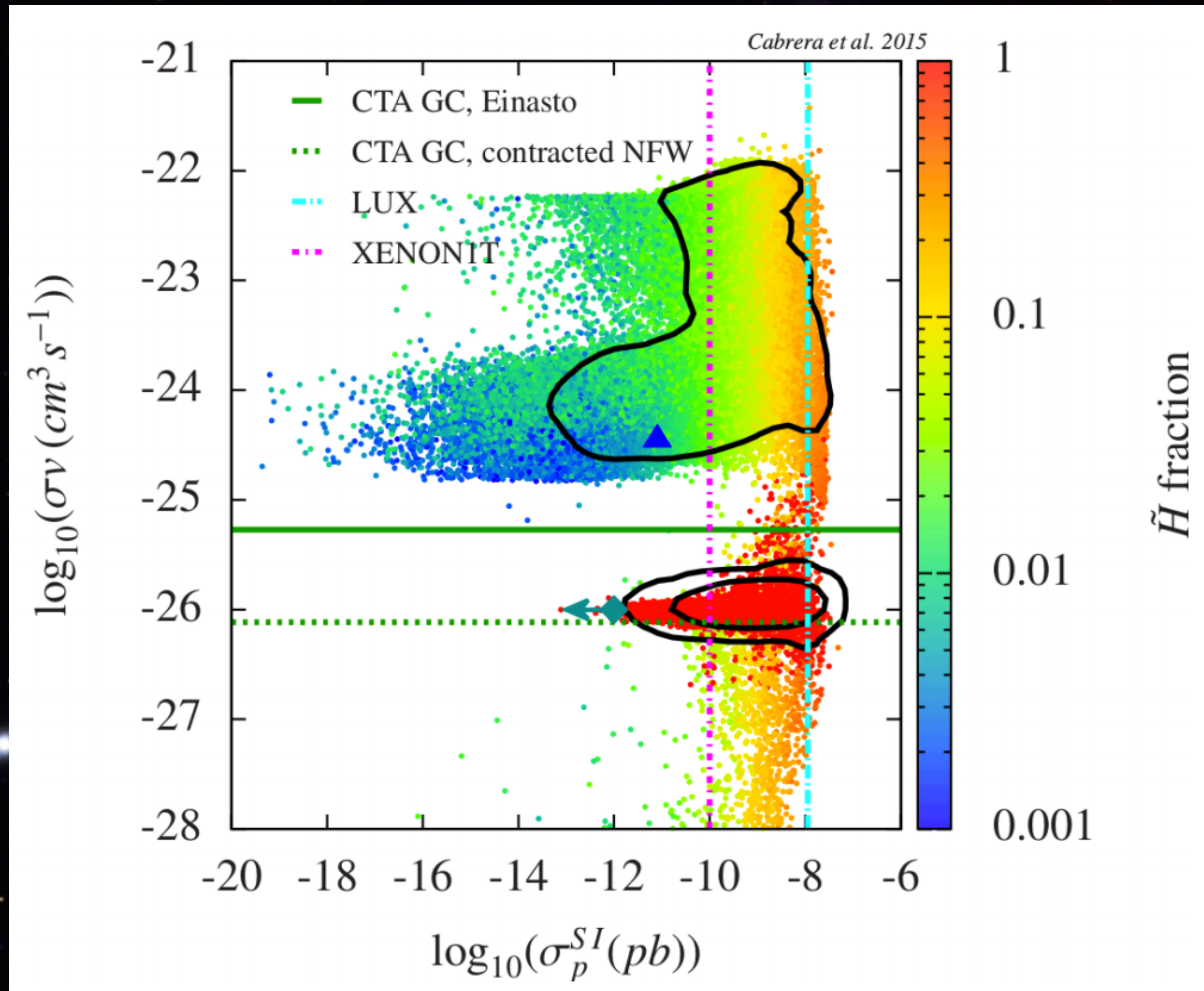
Relic Axion Searches via conversion to photons (e.g. ADMX)

$$P = \frac{2\pi\hbar^2 g_{a\gamma\gamma}^2 \rho_{\mathrm{DM}}}{m_a^2 c} \cdot f_\gamma \cdot \frac{1}{\mu_0} B^2 V_{nlm} \cdot Q$$

→ Scans of theoretical parameter space, eg Supersymmetry

Why do we care about local DM density?

Scans of theoretical parameter space, eg Supersymmetry



MSSM9 scans, Cabrera+ 2015, 1503.00599v2

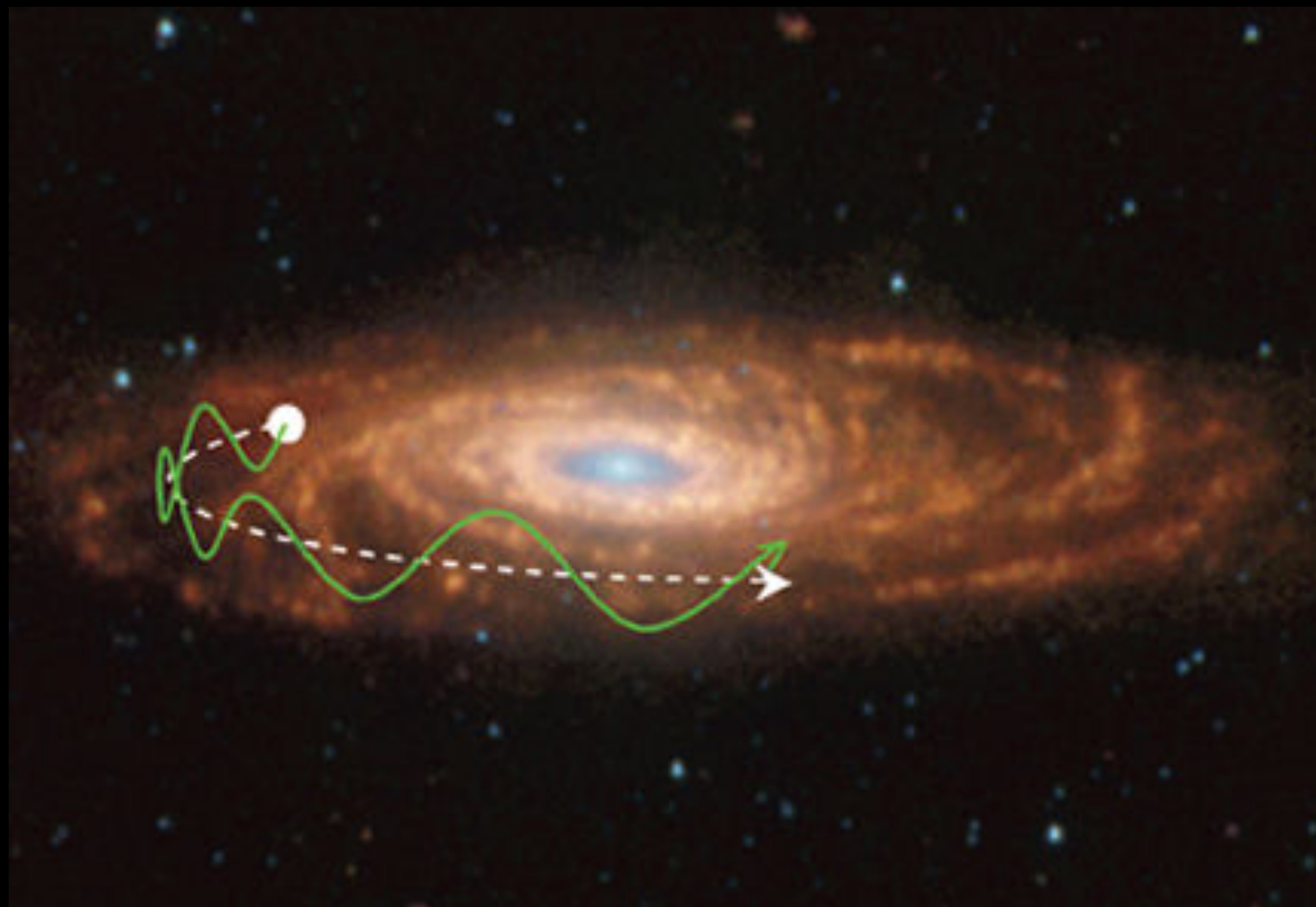
How do we measure the local DM density?

- Fit global model to global measurements, extrapolate local value: powerful, but we have to assume global properties of the halo. E.g. rotation curves, distribution function modelling
  e.g. Dehnen & Binney 1998; Weber & de Boer 2010; Catena & Ullio 2010; Salucci et al. 2010; McMillan 2011; Nesti & Salucci 2013; Piffl et al. 2014; Pato & Iocco 2015; Pato et al. 2015; Binney & Piffl 2015,

- Local model and local measurements: larger uncertainties but fewer assumptions
  e.g. Jeans 1922; Oort 1932; Bahcall 1984; Kuijken & Gilmore 1989b, 1991; Creze et al. 1998; Garbari et al. 2012; Bovy & Tremaine 2012; Smith et al. 2012; Zhang et al. 2013; Bienaymé et al. 2014, Xia et al. 2016

Local DM from Vertical Oscillations

- Gives a measure of the total mass in the plane pulling the star down again

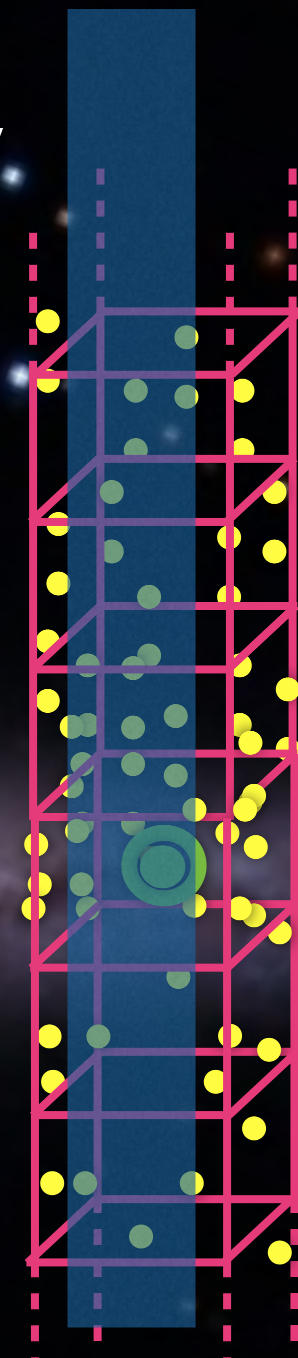


e.g. Jeans 1922; Oort 1932; Bahcall 1984; Kuijken & Gilmore 1989b, 1991; Creze et al. 1998; Garbari et al. 2012; Bovy & Tremaine 2012; Smith et al. 2012; Zhang et al. 2013; Bienaymé et al. 2014, Xia et al. 2016

Local Jeans Modelling - One Dimensional

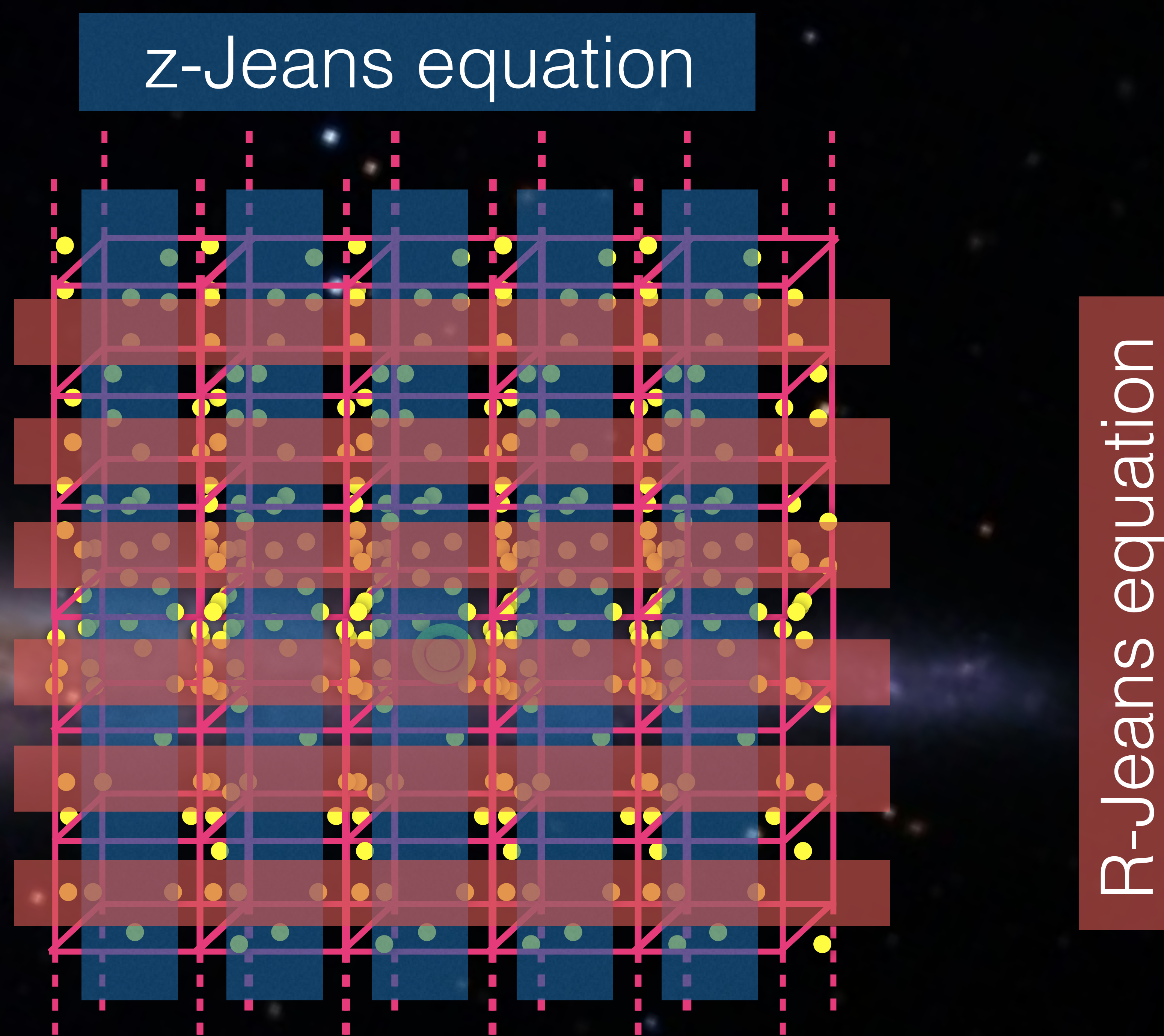
z-Jeans equation

Dark Matter density	Baryon density	Tracer density	Velocity averages	
⋮	⋮	⋮	⋮	⋮
ρ_{DM3}	ρ_{B3}	ν_3	$\overline{v_R v_z}, 3$	$\overline{v_z^2}, 3$
ρ_{DM2}	ρ_{B2}	ν_2	$\overline{v_R v_z}, 2$	$\overline{v_z^2}, 2$
ρ_{DM1}	ρ_{B1}	ν_1	$\overline{v_R v_z}, 1$	$\overline{v_z^2}, 1$
ρ_{DM0}	ρ_{B0}	ν_0	$\overline{v_R v_z}, 0$	$\overline{v_z^2}, 0$
ρ_{DM-1}	ρ_{B-1}	ν_{-1}	$\overline{v_R v_z}, -1$	$\overline{v_z^2}, -1$
ρ_{DM-2}	ρ_{B-2}	ν_{-2}	$\overline{v_R v_z}, -2$	$\overline{v_z^2}, -2$
⋮	⋮	⋮	⋮	⋮



Local Jeans Modelling - Two Dimensional

- Possible with Gaia DR2
- Solve both R & Z-Jeans eqns.



Jeans Equation

- Start with the R- and z-direction Jeans Equations, derived from the Collisionless Boltzmann Equation.

R: $$0 = \frac{\partial(\nu \overline{v_R})}{\partial t} + \frac{\partial(\nu \overline{v_R^2})}{\partial R} + \frac{1}{R}\frac{\partial(\nu \overline{v_R v_\phi})}{\partial \phi} + \frac{\partial(\nu \overline{v_R v_z})}{\partial z} + \frac{\nu}{R}\left(\overline{v_R^2} - \overline{v_\phi^2}\right) + \nu \frac{\partial \Phi}{\partial R}$$

Z: $$0 = \frac{\partial(\nu \overline{v_z})}{\partial t} + \frac{\partial(\nu \overline{v_R v_z})}{\partial R} + \frac{1}{R}\frac{\partial(\nu \overline{v_\phi v_z})}{\partial \phi} + \frac{\partial(\nu \overline{v_z^2})}{\partial z} + \frac{\nu}{R}\overline{v_R v_z} + \nu \frac{\partial \Phi}{\partial z}$$

0 from dynamical equilibrium

0 from axisymmetry

Integrated Jeans Equation

- Integrate z-Jeans equation to avoid additional noise from differentiating binned data:

Average Squared Velocities

Tracer Density

Vertical Force (Baryons + Dark Matter)

Tilt Terms

$$\overline{v_z^2}(R,z) = \frac{1}{\nu}\int_0^z \left[\nu K_z - \frac{1}{R}\frac{\partial\left(R\nu\,\overline{v_R v_z}\right)}{\partial R}\right] dz' + \frac{C_z}{\nu}$$

$$\overline{v_R^2}(R,z) = \frac{1}{R\nu}\int_{R_0}^{R_1} \left[R'\nu K_R - R'\frac{\partial(\nu\overline{v_R v_z})}{\partial z} + \nu\overline{v_\phi^2}\right] dR' + \frac{C_R}{\nu}$$

Radial Force (Baryons + Dark Matter)

Rotation term

MODELS	BAYESIAN FIT	DATA
Tracer Density		Tracer Density
ϕ-velocity mean		ϕ-velocity mean
Rz-velocity mean		Rz-velocity mean
Baryon distribution		Baryon distribution
Dark Matter distribution		Dark Matter distribution
R-velocity mean		R-velocity mean
z-velocity mean		z-velocity mean

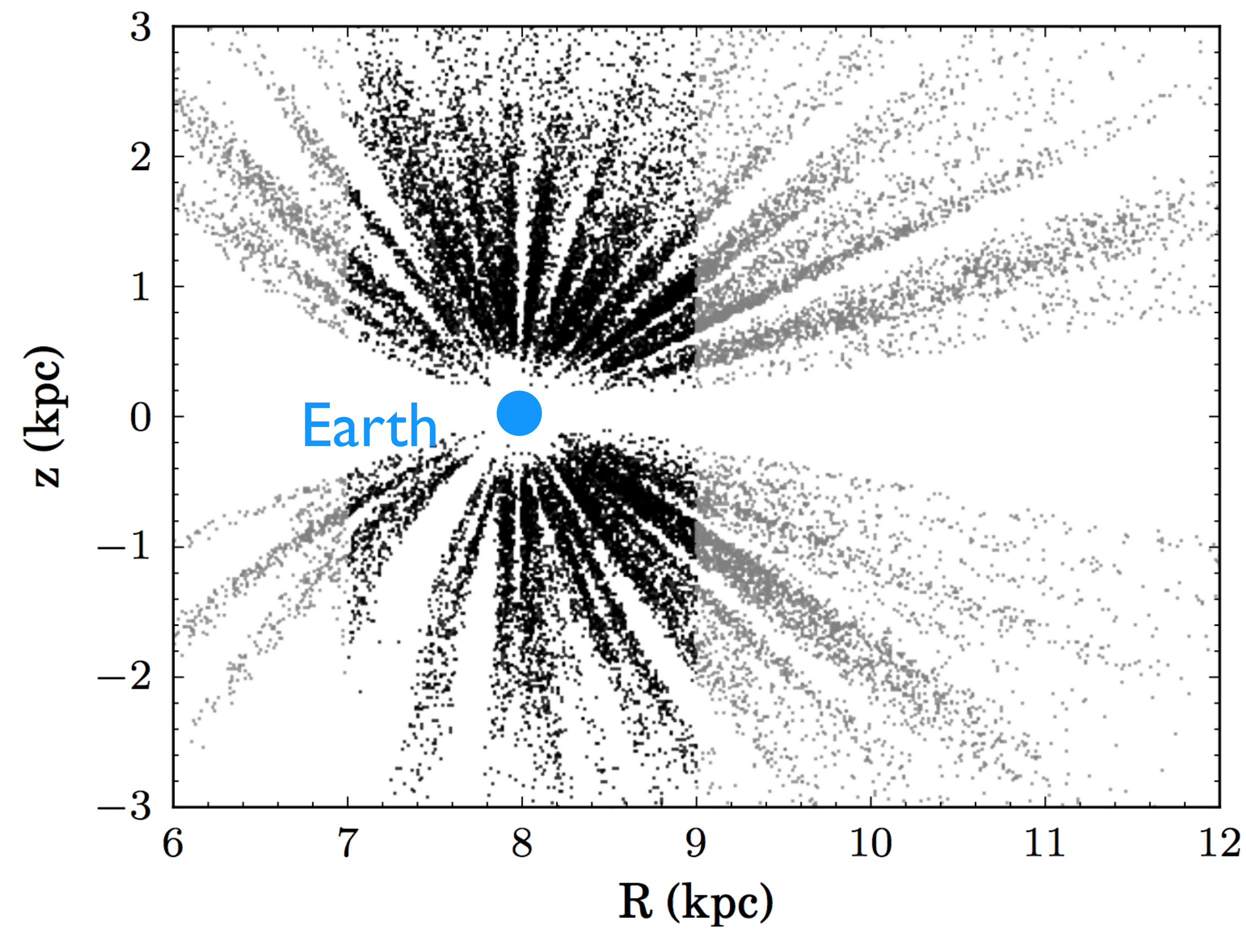
SDSS G-dwarf Analysis

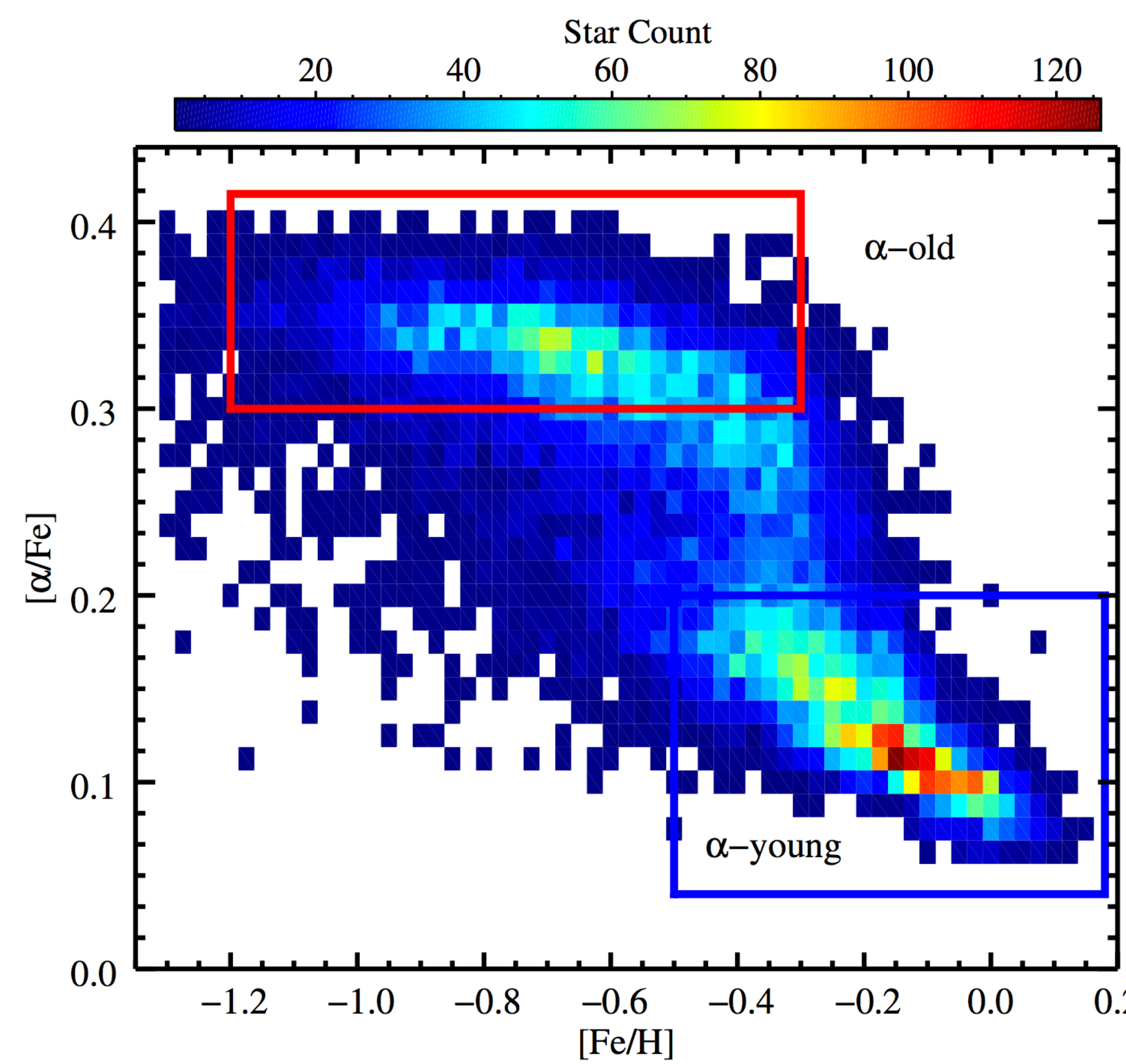
Sivertsson et al. 1708.07836

Stellar kinematics data of 16,000 SDSS/SEGUE G-dwarfs from Budenbender+ arXiv: 1407.4808.

Two populations:

- α-young (high metallicity, *thin disk*)
- α-old (low metallicity, *thick disk*)





SDSS G-dwarf Results

- α-young (thin disc) not as sensitive to tilt term as the α-old (thick disc)
- mismatch between α-young and α-old results…

		α-young		α-old		Combined analysis
		Tilt	No Tilt	Tilt	No Tilt	Tilt
95% CR upper	GeV cm^{-3}	**0.59**	0.57	0.85	0.51	0.48
	$M_\odot$ pc^{-3}	**0.016**	0.015	0.022	0.013	0.013
68% CR upper	GeV cm^{-3}	**0.53**	0.53	0.79	0.48	0.43
	$M_\odot$ pc^{-3}	**0.013**	0.014	0.021	0.013	0.012
Median	GeV cm^{-3}	**0.46**	0.48	0.73	0.46	0.40
	$M_\odot$ pc^{-3}	**0.012**	0.013	0.019	0.012	0.011
68% CR lower	GeV cm^{-3}	**0.37**	0.42	0.68	0.44	0.37
	$M_\odot$ pc^{-3}	**0.0098**	0.011	0.017	0.012	0.0097
95% CR lower	GeV cm^{-3}	**0.30**	0.35	0.60	0.42	0.34
	$M_\odot$ pc^{-3}	**0.0078**	0.0092	0.016	0.011	0.0091

Problems with the α-old population: Disequilibria

$$0 = \frac{\partial(\nu\,\overline{v_R})}{\partial t} + \frac{\partial(\nu\,\overline{v_R^2})}{\partial R} + \frac{1}{R}\frac{\partial(\nu\,\overline{v_R v_\phi})}{\partial \phi} + \frac{\partial(\nu\,\overline{v_R v_z})}{\partial z} + \frac{\nu}{R}\left(\overline{v_R^2} - \overline{v_\phi^2}\right) + \nu\frac{\partial \Phi}{\partial R}$$

$$0 = \frac{\partial(\nu\,\overline{v_z})}{\partial t} + \frac{\partial(\nu\,\overline{v_R v_z})}{\partial R} + \frac{1}{R}\frac{\partial(\nu\,\overline{v_\phi v_z})}{\partial \phi} + \frac{\partial(\nu\,\overline{v_z^2})}{\partial z} + \frac{\nu}{R}\overline{v_R v_z} + \nu\frac{\partial \Phi}{\partial z}$$

- **MW is not in equilibrium (see talks from TA and PR)**
- Banik+ 2016: disequilibria generate systematic errors of 25% or more c.f. SDSS stat error ~±20%
- … and can produce different *ρ* for different populations.
- Near term: use disequilibrium mocks to test impact on our method.
- In future we need to start modelling the disequilibria term and marginalising over it.

Disequilibria Modelling

Model disequilibria and non-axisymmetries and marginalise over like the tilt term.

$$\overline{v_z^2}(R,z) = \frac{1}{\nu}\int_0^z \left[\nu K_z - \frac{1}{R}\frac{\partial\left(R\nu\,\overline{v_R v_z}\right)}{\partial R}\right] dz' + \frac{C_z}{\nu}$$

$$\overline{v_z^2}(R,z) = \frac{1}{\nu}\int_0^z \left[\nu K_z - \frac{1}{R}\frac{\partial\left(R\nu\,\overline{v_R v_z}\right)}{\partial R} - \frac{\partial}{\partial t}\left(\nu\,\overline{v_z}\right) - \frac{1}{R}\frac{\partial}{\partial\phi}\left(\nu\,\overline{v_\phi v_z}\right)\right] dz' + \frac{C_z}{\nu}$$

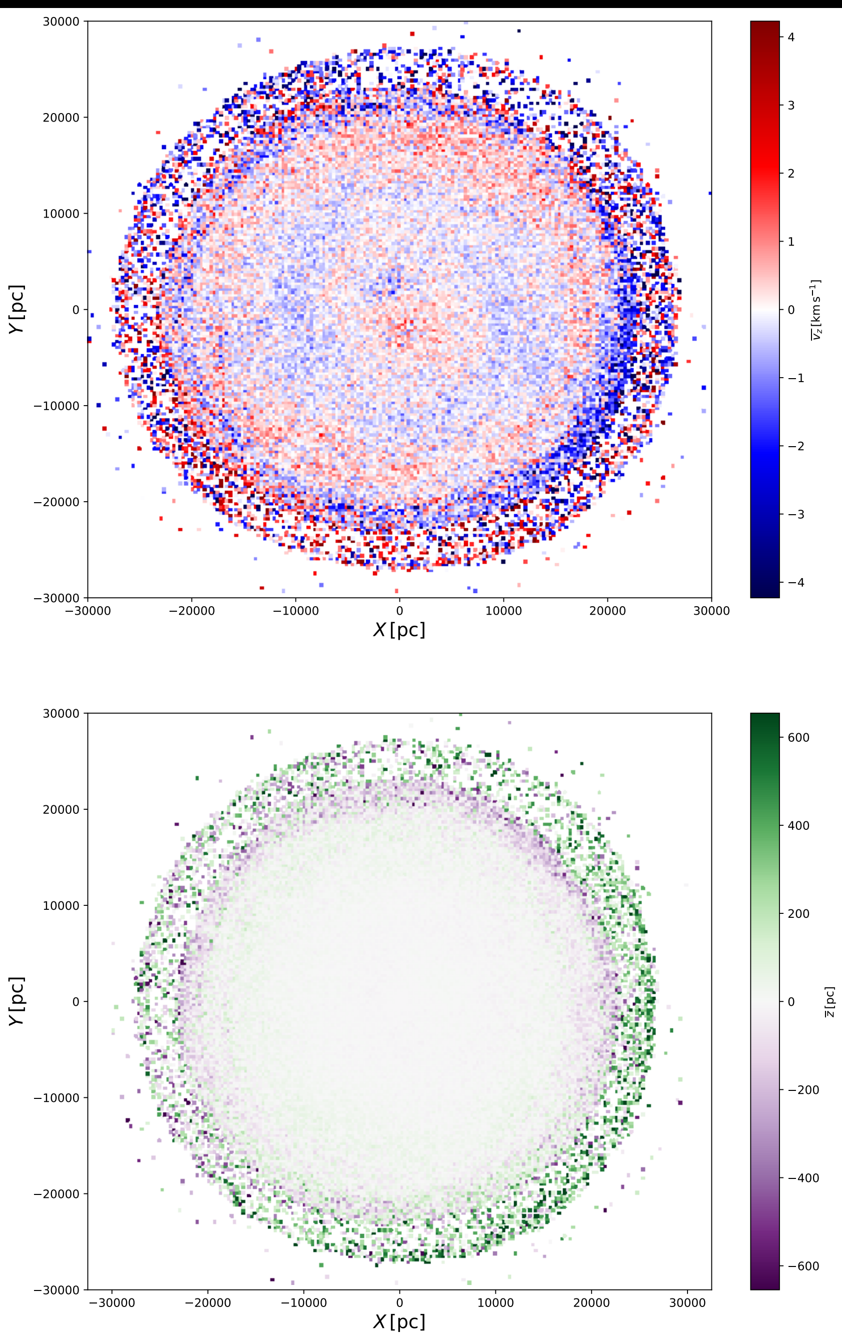
Time Term

Axial Term

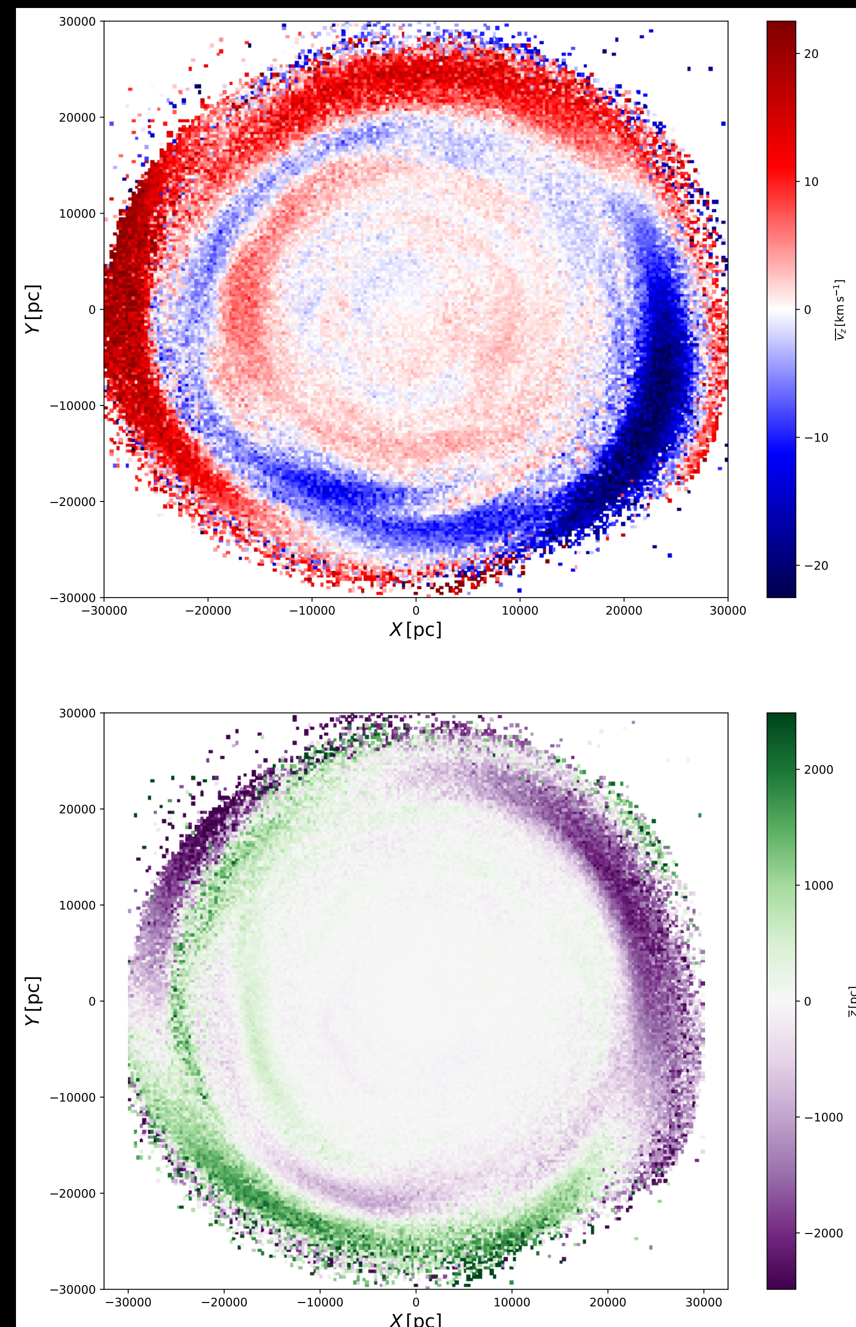
Disequilibria Features in Simulations

- Simulations from 2011 by Silvia Garbari & Justin Read.
- Large satellite merger (~20% of halo mass), at high and low inclinations.
- Control simulation with no merger.

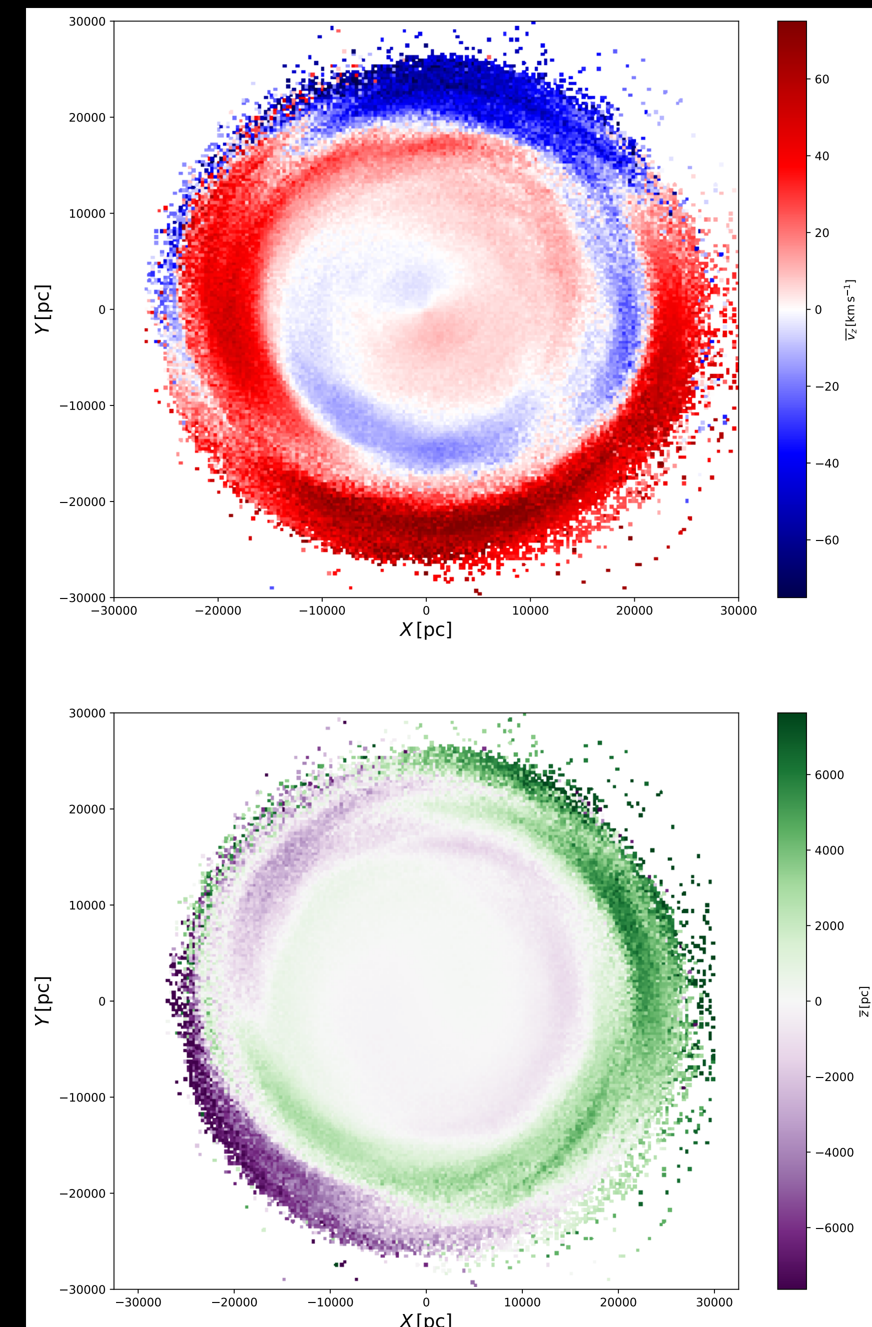
Disequilibria Features in Simulations



No merger

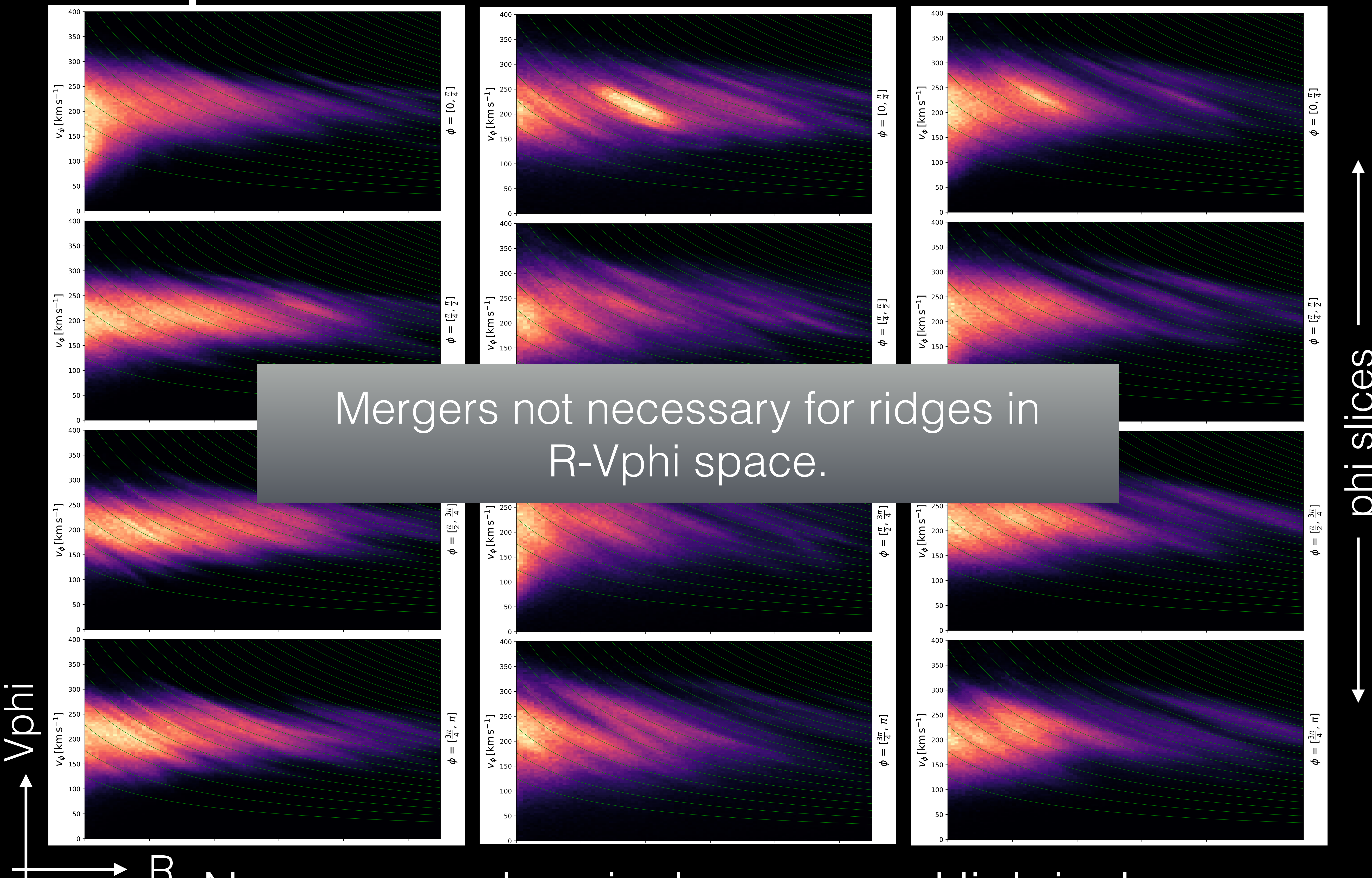


Low inclination merger



High inclination merger

Disequilibria Features in Simulations

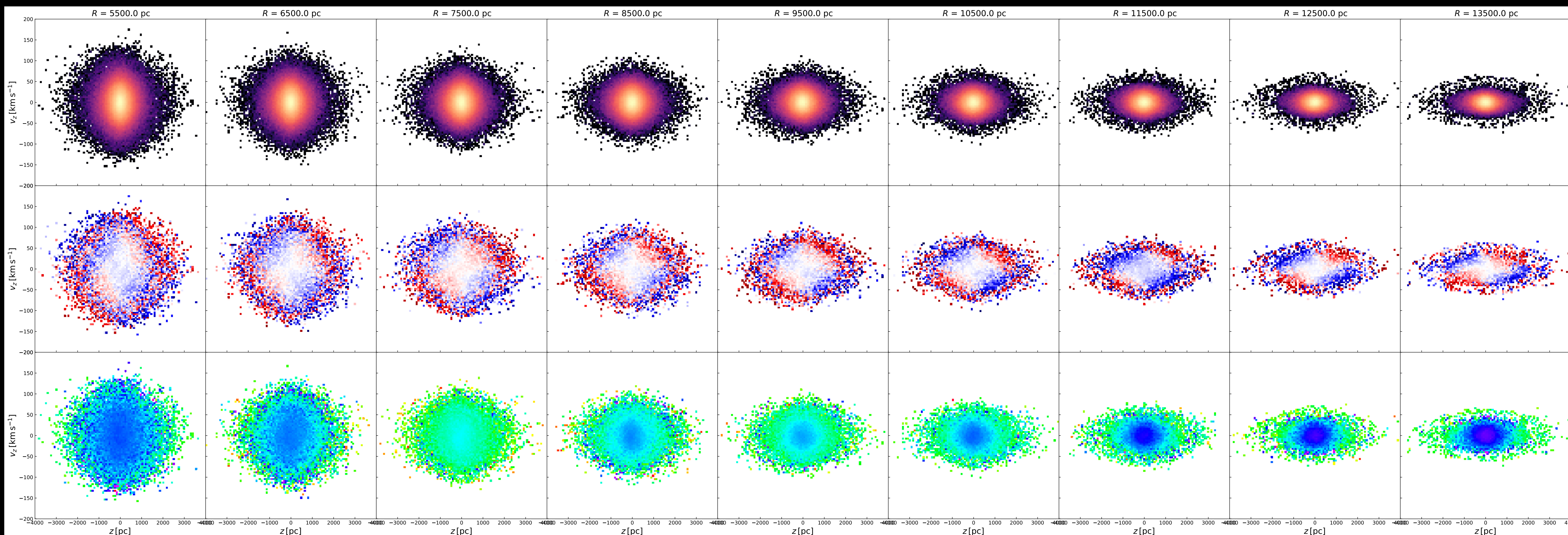


Mergers not necessary for ridges in R-Vphi space.

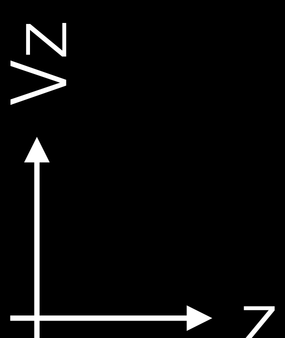
No merger | Low incl. merger | High incl. merger

Disequilibria Features in Simulations

One pi/4 phi slice



R=5.5kpc R=6.5kpc R=7.5kpc R=8.5kpc R=9.5kpc R=10.5kpc R=11.5kpc R=12.5kpc R=13.5kpc



-Density Histogram-

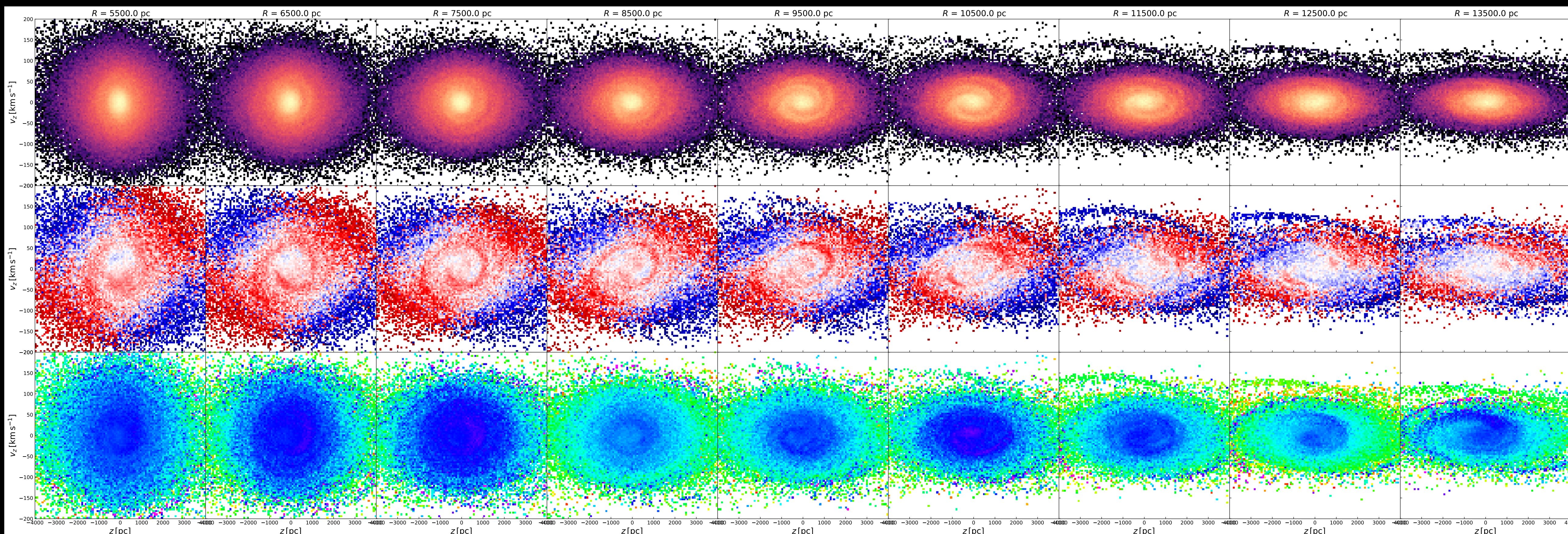
-VR Heat Map-

-Vphi heat map-

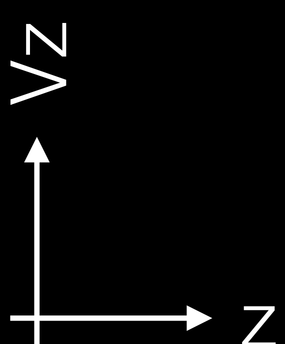
No merger

Disequilibria Features in Simulations

One pi/4 phi slice



R=5.5kpc R=6.5kpc R=7.5kpc R=8.5kpc R=9.5kpc R=10.5kpc R=11.5kpc R=12.5kpc R=13.5kpc



-Density Histogram-

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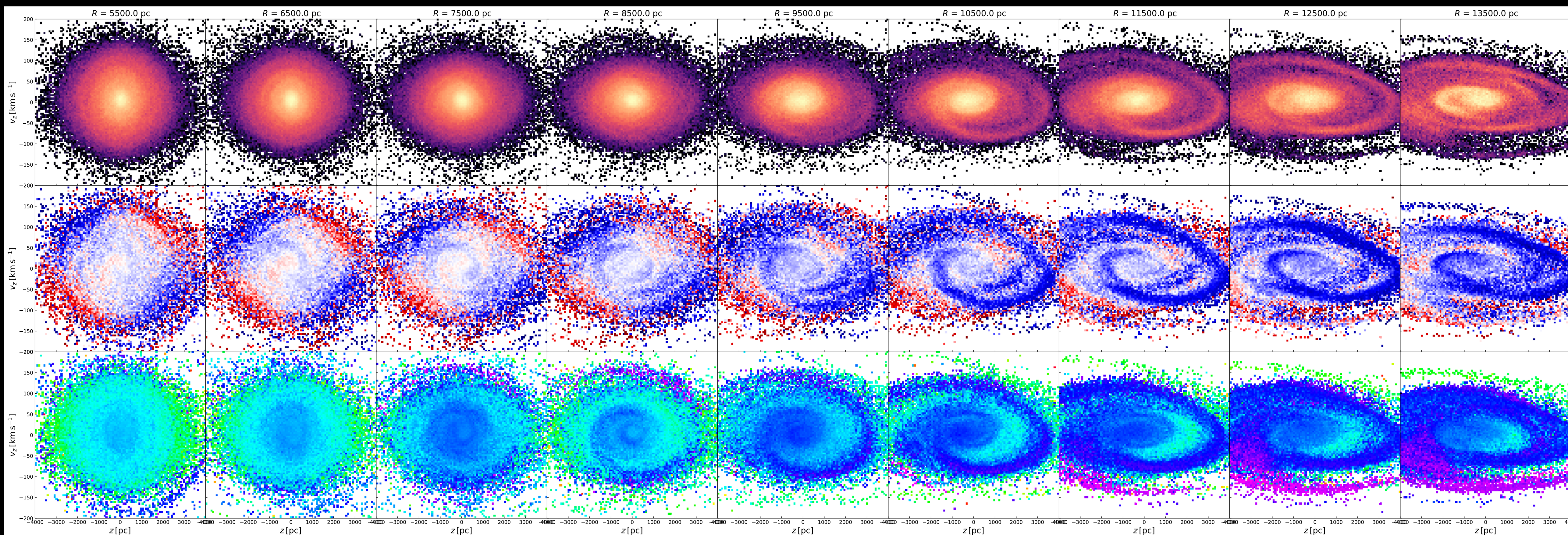
-Vphi heat map-

Low incl. merger

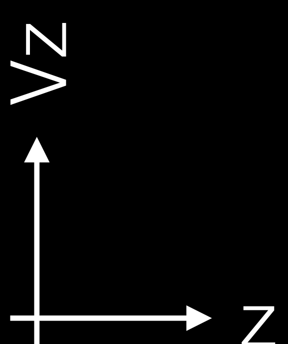
Disequilibria Features in Simulations

Spirals only form in merger simulations

One pi/4 phi slice



R=5.5kpc R=6.5kpc R=7.5kpc R=8.5kpc R=9.5kpc R=10.5kpc R=11.5kpc R=12.5kpc R=13.5kpc



-Density Histogram-

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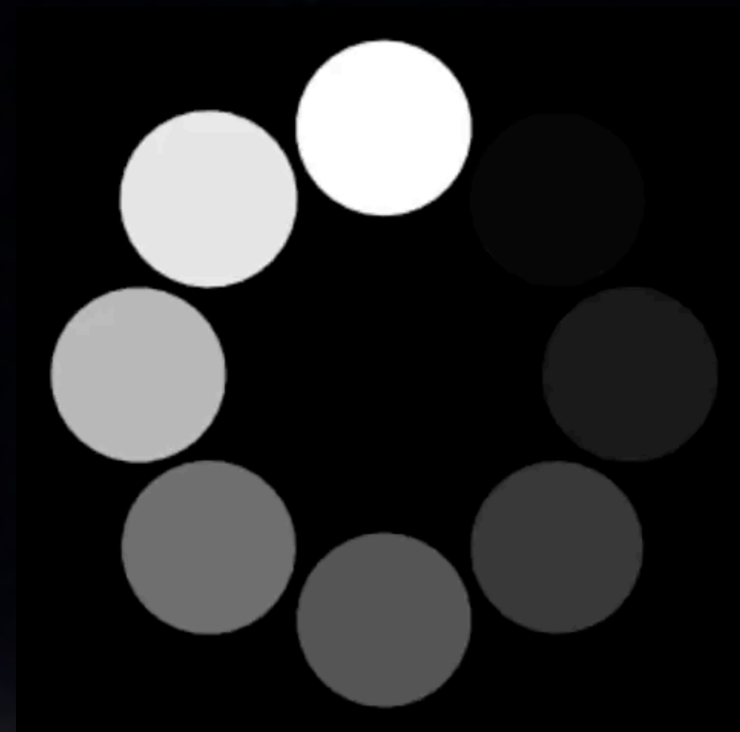
High incl. merger

2D Mock Data Tests



Gaia and the Local Dark Matter Density

DR2 will allow us to fix the radial behaviour of the tilt term and look inwards/outwards from the solar position.

Disequilibria and Axial Term:

- 16000 stars → 20% stat error
- Disequilibria → ~25% syst error.
- We need to model and marginalise over disequilibria and non-axisymmetries.