Measuring anisotropy in the local universe with type Ia supernovae

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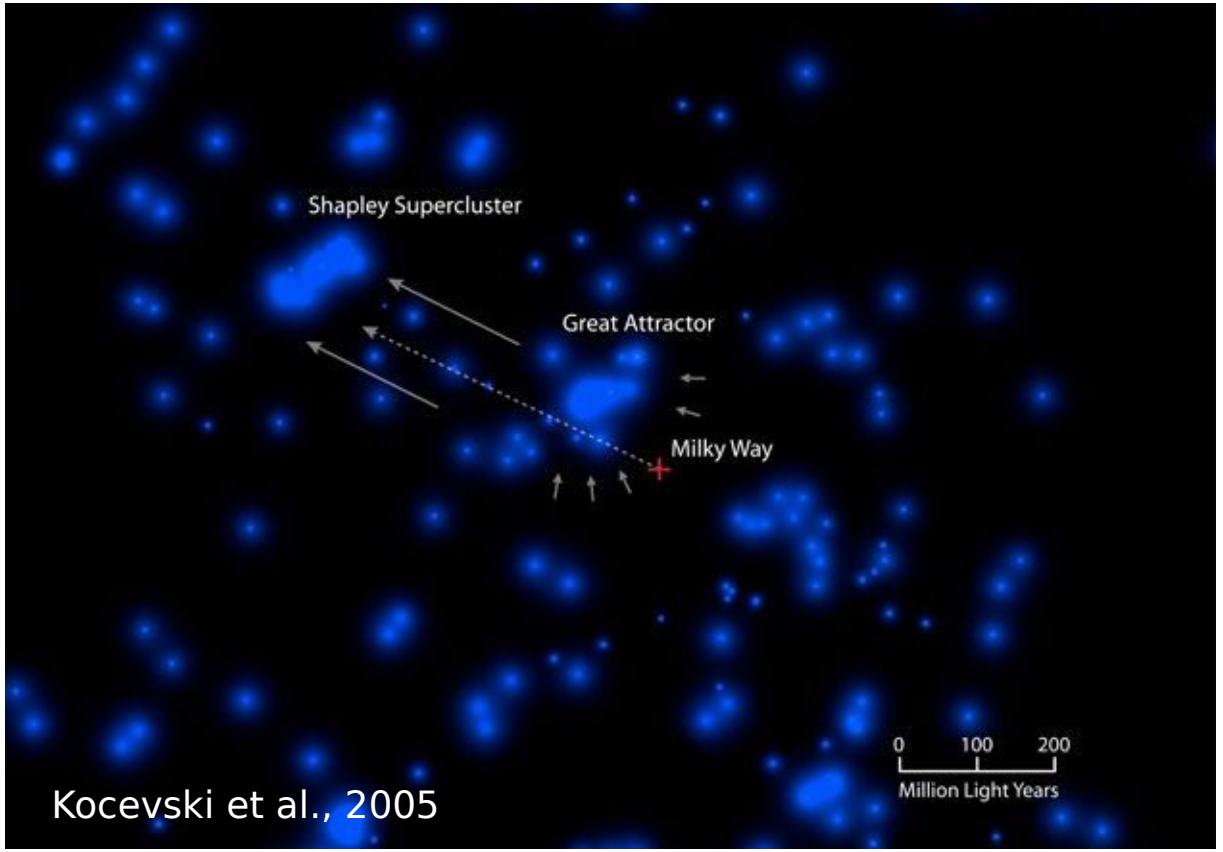
Anisotropies and bulk flow



Kocevski et al., 2005

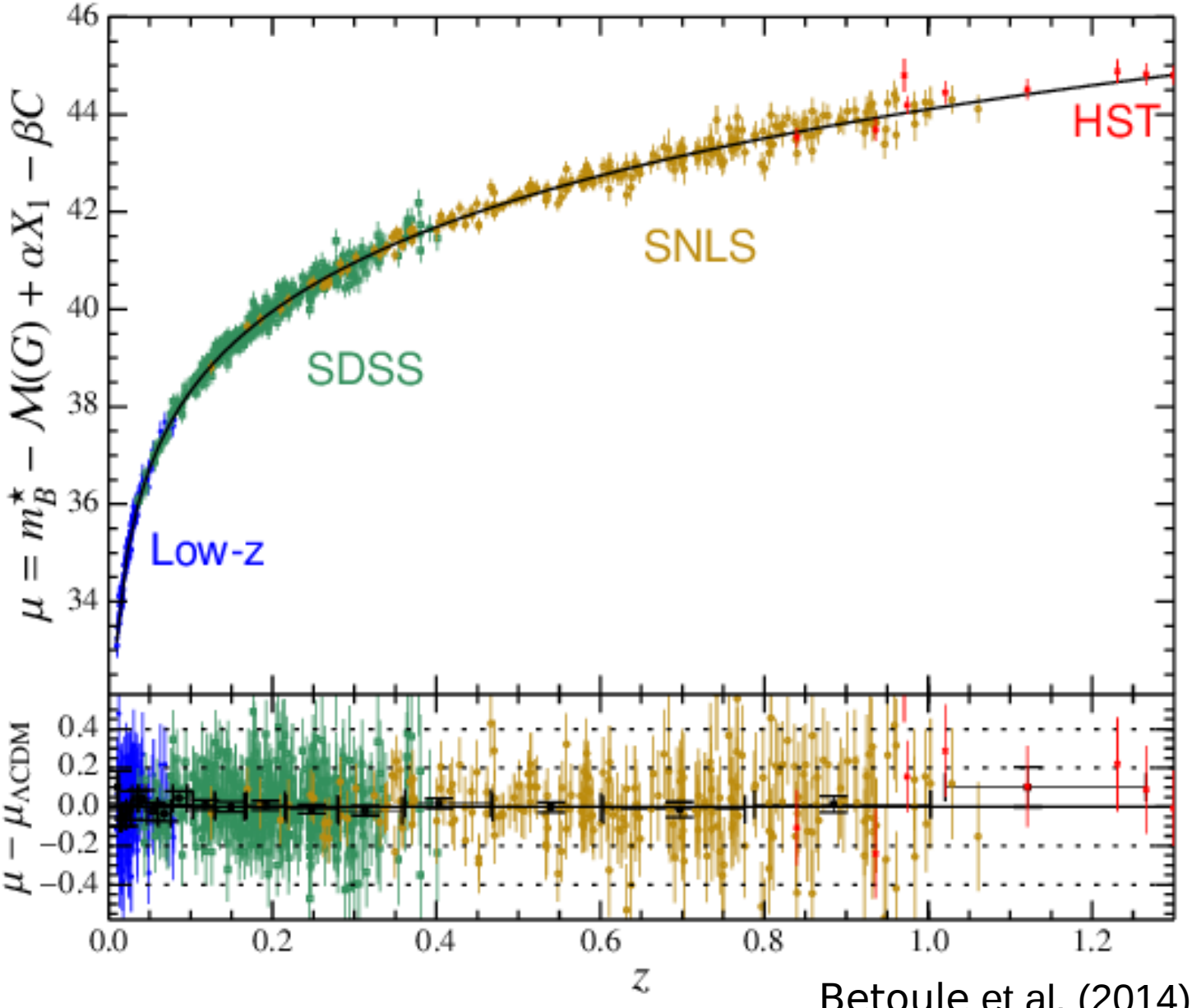
Bulk flow of ~250 km/s within ~100 Mpc ($z < 0.03$):

- What is its source?
- Shapley supercluster?

"Dark flow" of ~1000 km/s found in kSZ data up to $z = 0.25$:

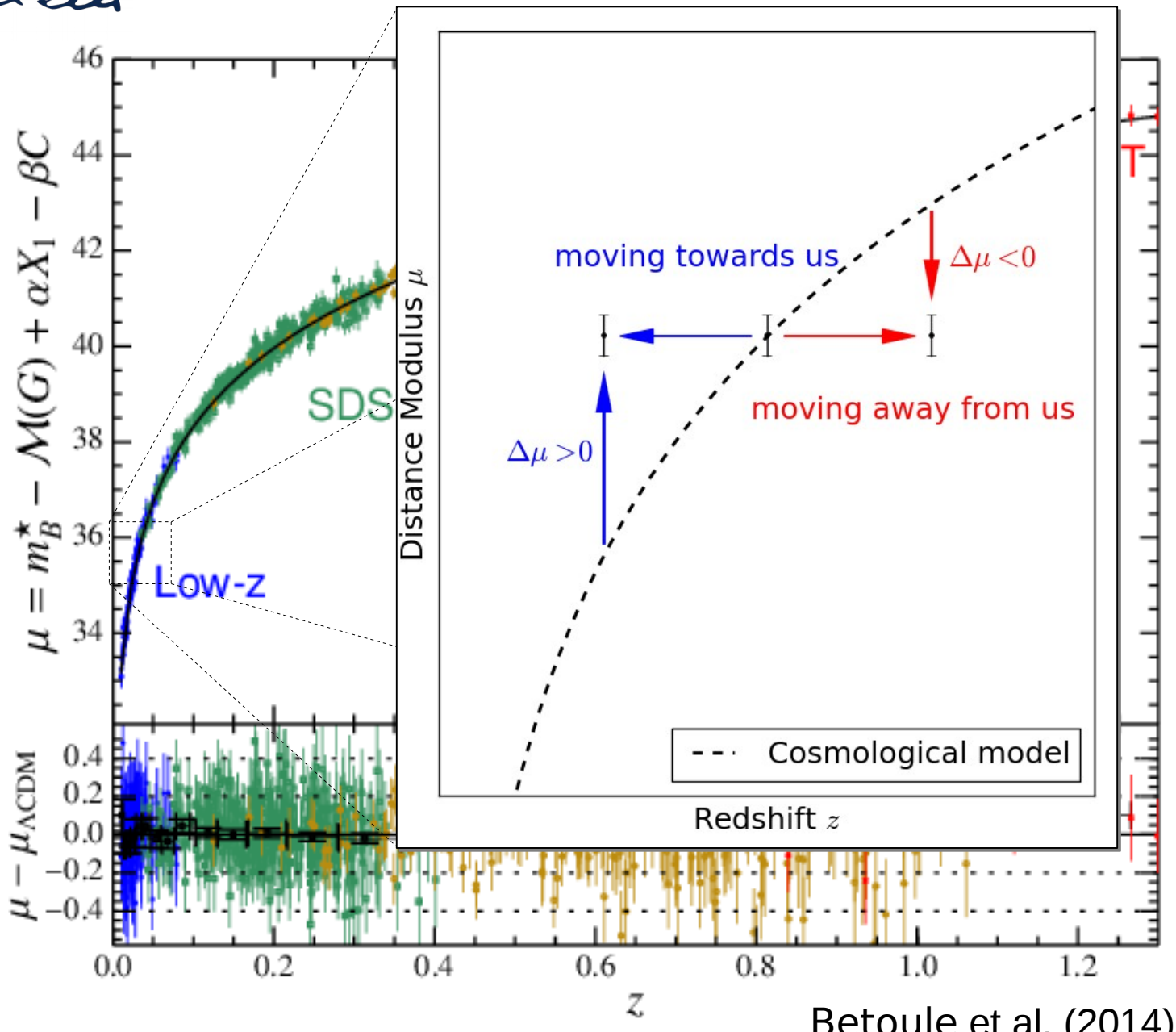
- Cannot be explained by ΛCDM
- Pre-inflationary structure?

SNe Ia and peculiar velocities



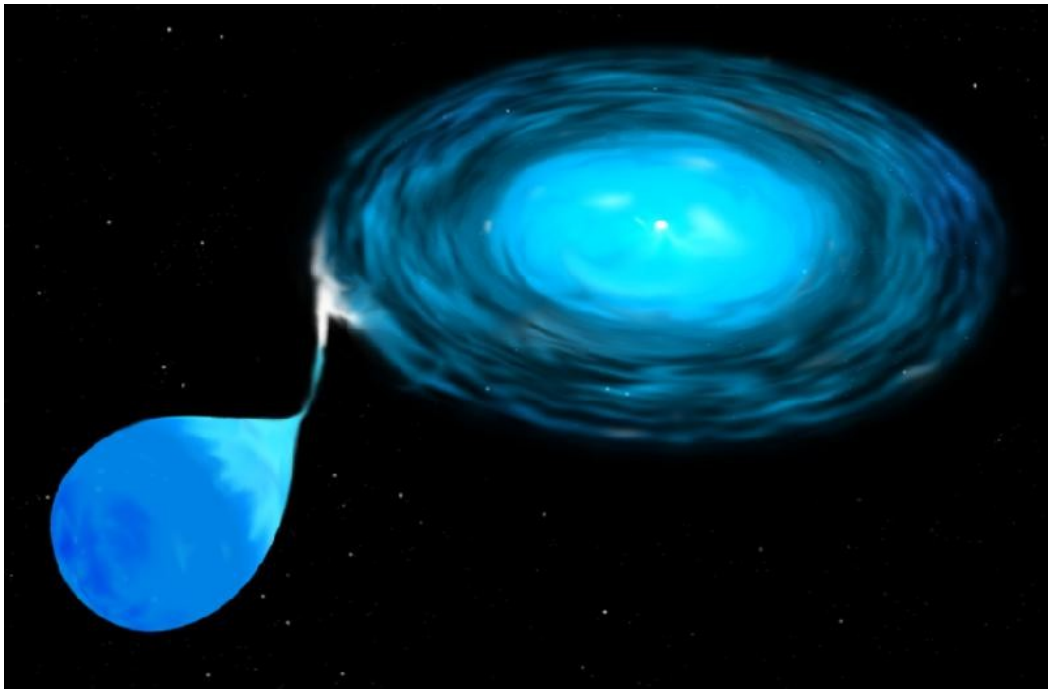
Betoule et al. (2014)

SNe Ia and peculiar velocities



Betoule et al. (2014)

SNe Ia vs. galaxies



	Galaxies	SNe Ia
Precision	~ 15% - 25%	~ 8%
Statistics	~10^4	~10^3 (2020s: >10^4)
Range	$z < 0.05$	$z < 1$

Bulk flow model

- Dipole velocity model (Bonvin et al. 2006):

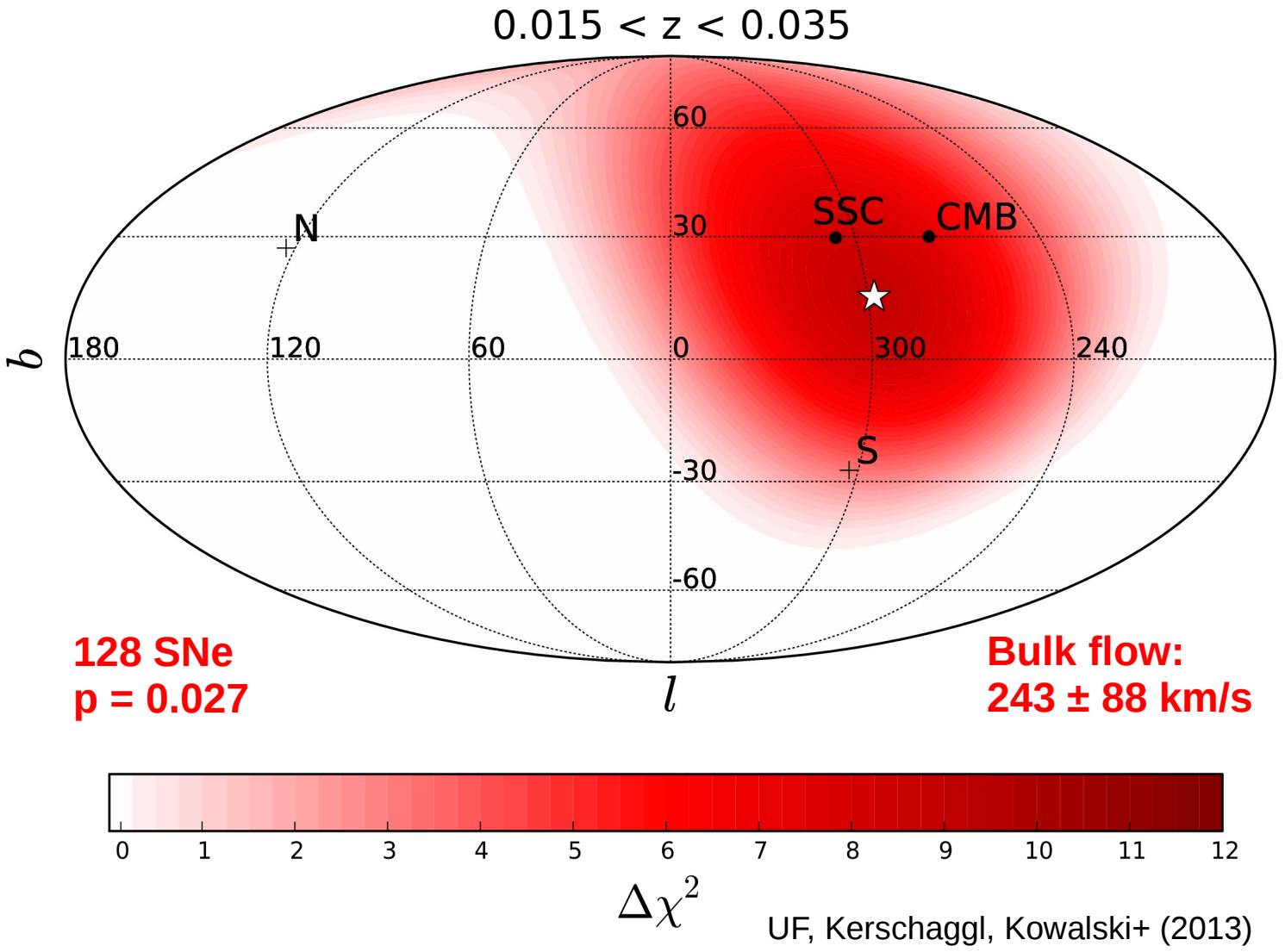
$$\tilde{d}_{\mathrm{L}}(z,\vec{n},\vec{v}_{\mathrm{d}}) = d_{\mathrm{L}}(z) + \frac{(1+z)^2}{H(z)}\vec{n}\cdot\vec{v}_{\mathrm{d}}$$

Isotropic universe Effect of bulk flow

- Minimize χ^2-statistic to find velocity:

$$\chi^2 = \sum_i \frac{\left|\mu_i - 5\log\left(\tilde{d}_{\mathrm{L}}(z_i,\vec{n}_i,\vec{v}_{\mathrm{d}})/10\mathrm{pc}\right)\right|^2}{\sigma_i^2}$$

Bulk flow results



UF, Kerschaggl, Kowalski+ (2013)

- Analysis of 279 SNe ($z < 0.1$) from Union2 and SNfactory
- Nearby bulk flow compatible with direction to Shapley
- No evidence for backside infall seen behind Shapley
- Dark flow at large distance constrained to ~400 km/s
- Results at distance $0.045 < z < 0.1$ driven by SNfactory

Finding attractors

Attractor model:

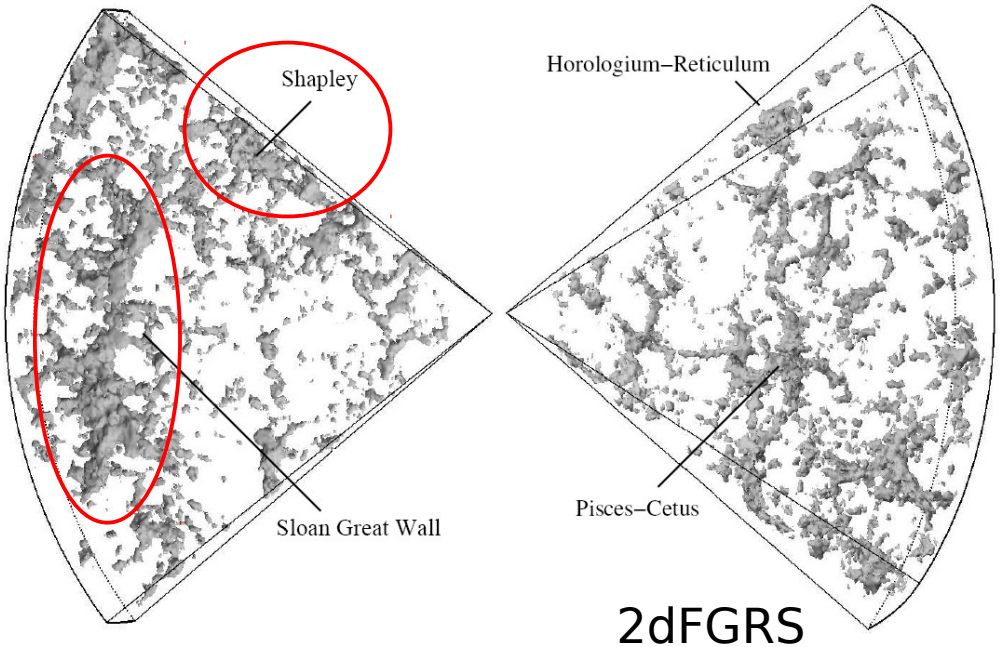
- Use full data set and spherical attractor model

$$v_p(\vec{y}) = \frac{a\Omega_{\mathrm{M}}^{0.55}H}{4\pi}\int \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|^3}\delta(\vec{y})\mathrm{d}^3y \qquad M_{\mathrm{tot}} = \frac{4\pi}{3}R^3\Omega_{\mathrm{M}}\rho_{\mathrm{crit}}(1+\delta)$$

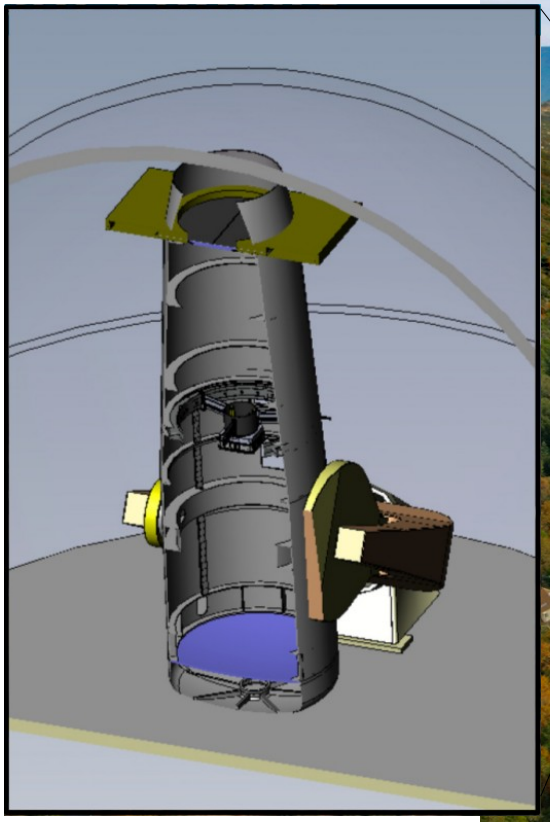
➔ Mass of Shapley supercluster too small to explain the whole observed velocities (but ~30% uncertainty)

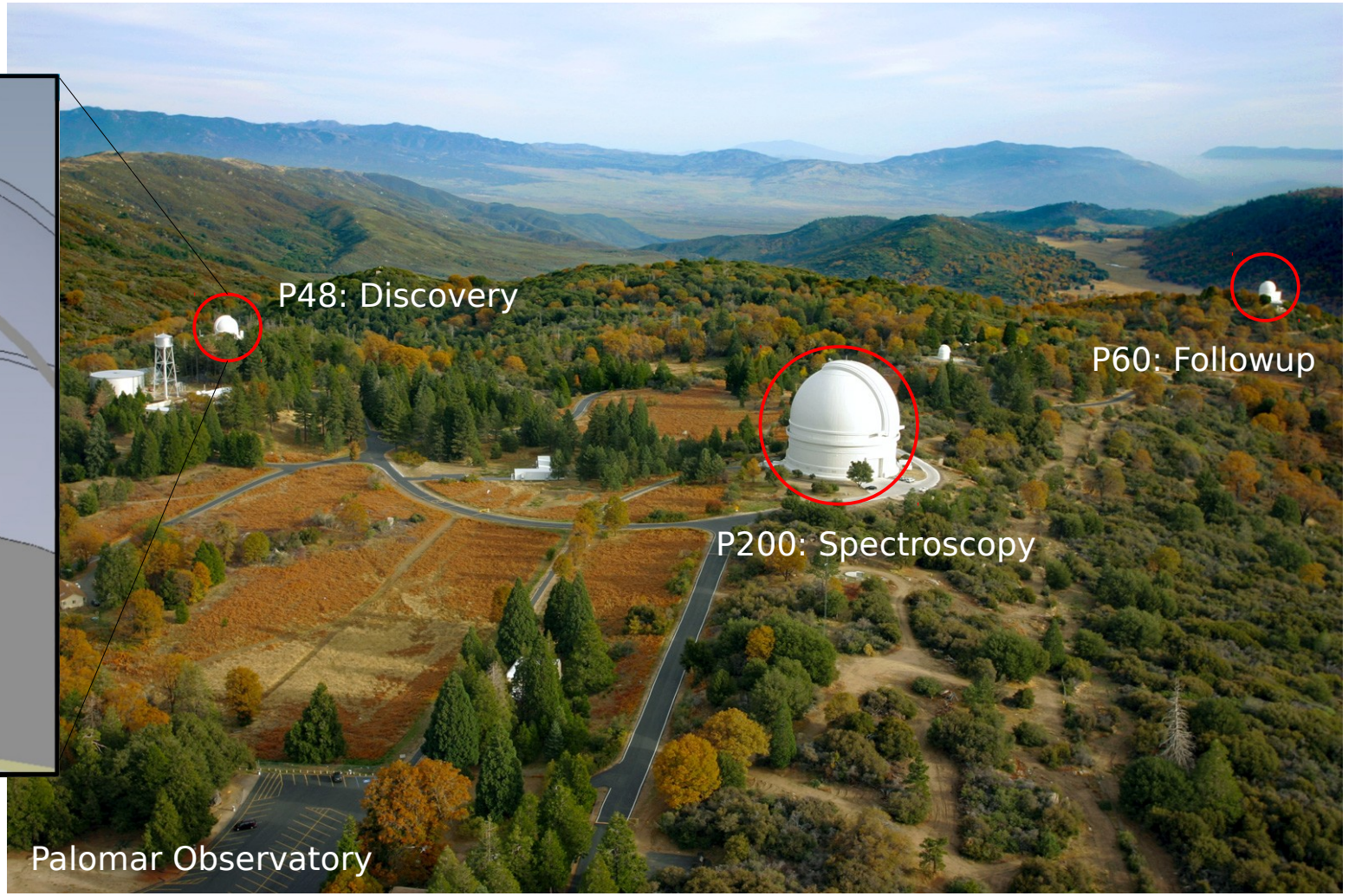
Sloan Great Wall:

- Located at z~0.08 in similar direction as Shapley
- Mass matches missing component

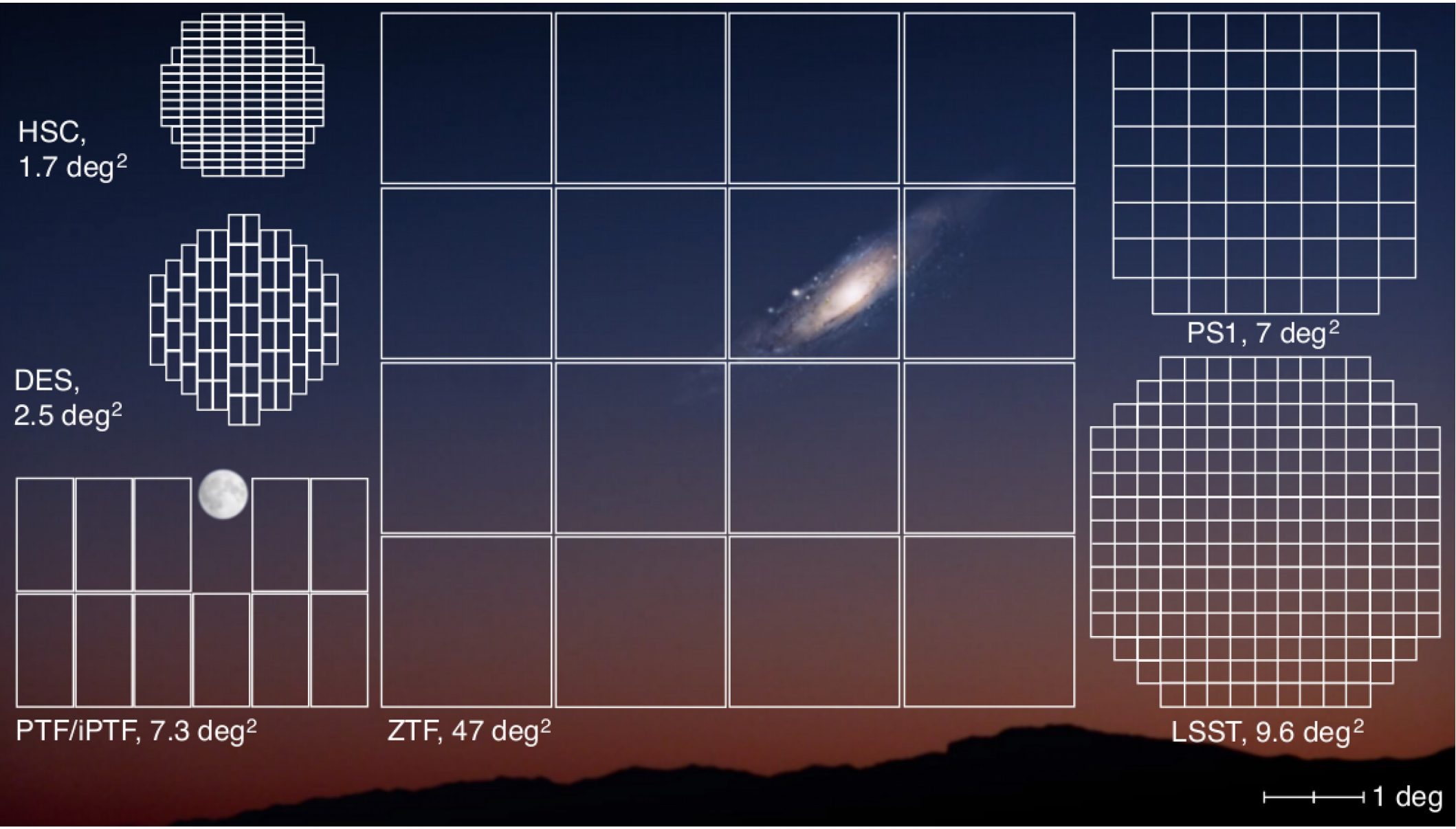


Zwicky Transient Facility (ZTF)

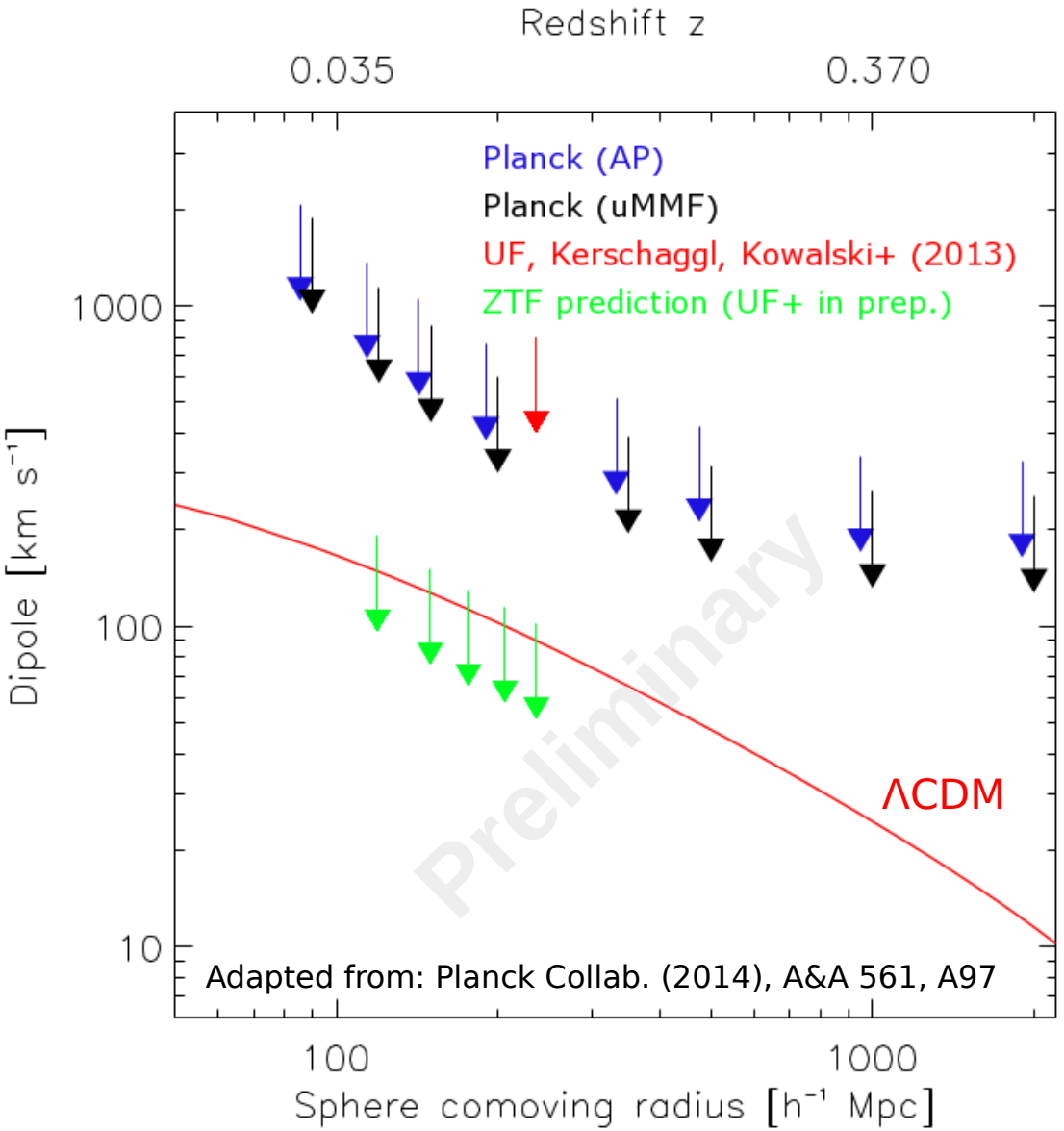




ZTF field of view



ZTF bulk flow prediction



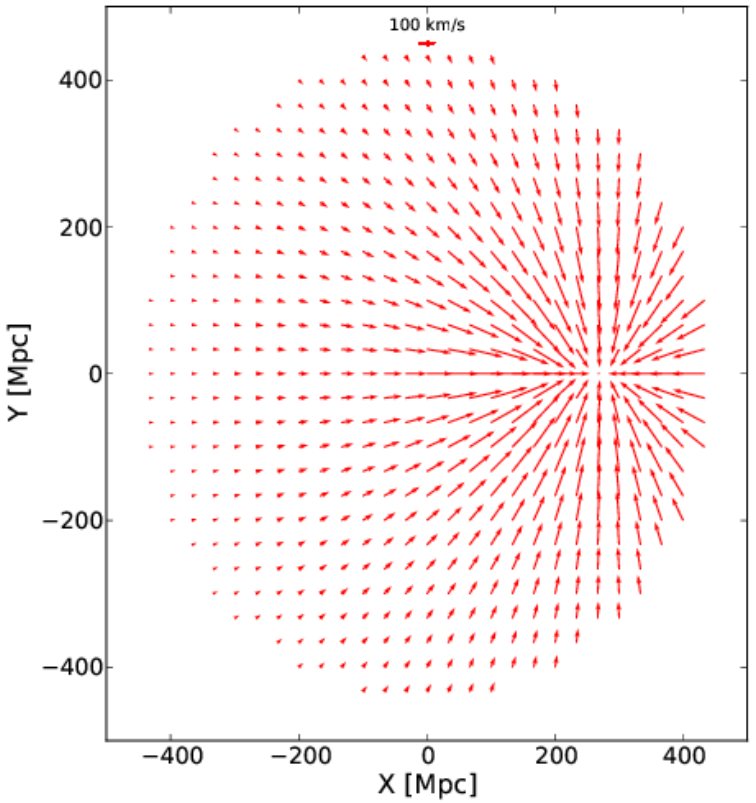
- ZTF will discover thousands of transients
- Expect ~1800 well-sampled SNe Ia lightcurves at $0.03 < z < 0.08$
- Can constrain bulk flow almost within ΛCDM expectation

Shear model

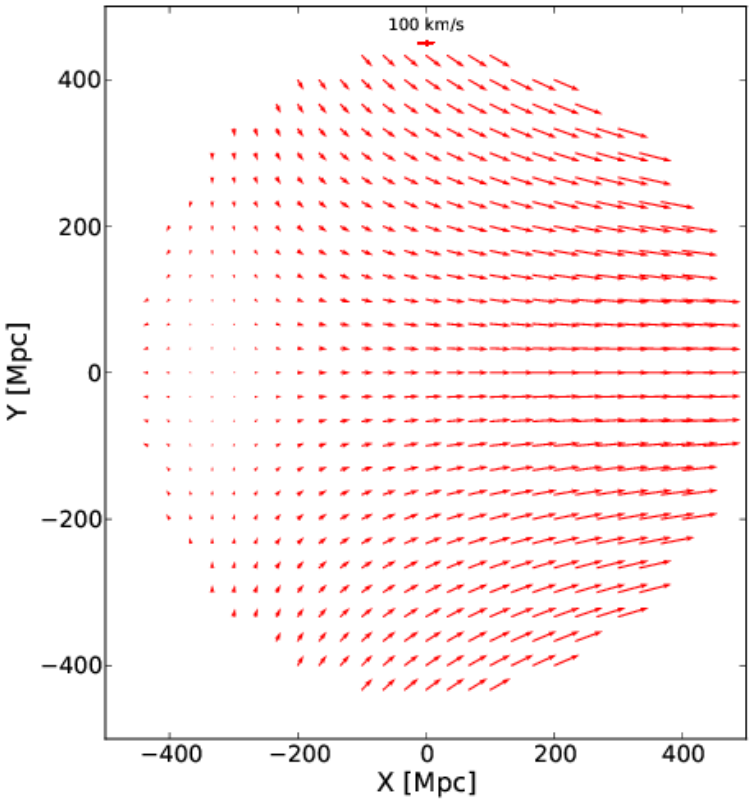
Velocity tidal field:

- Adds 6 new parameters (1 monopole, 5 quadrupole/shear)
- Can estimate distance to attractor as convergence of velocity lines

Spherical attractor



Dipole + Shear



Outlook

- ZTF (starting 2017) at optimal redshift range for velocity studies (z~0.03-0.08), better than DES and LSST

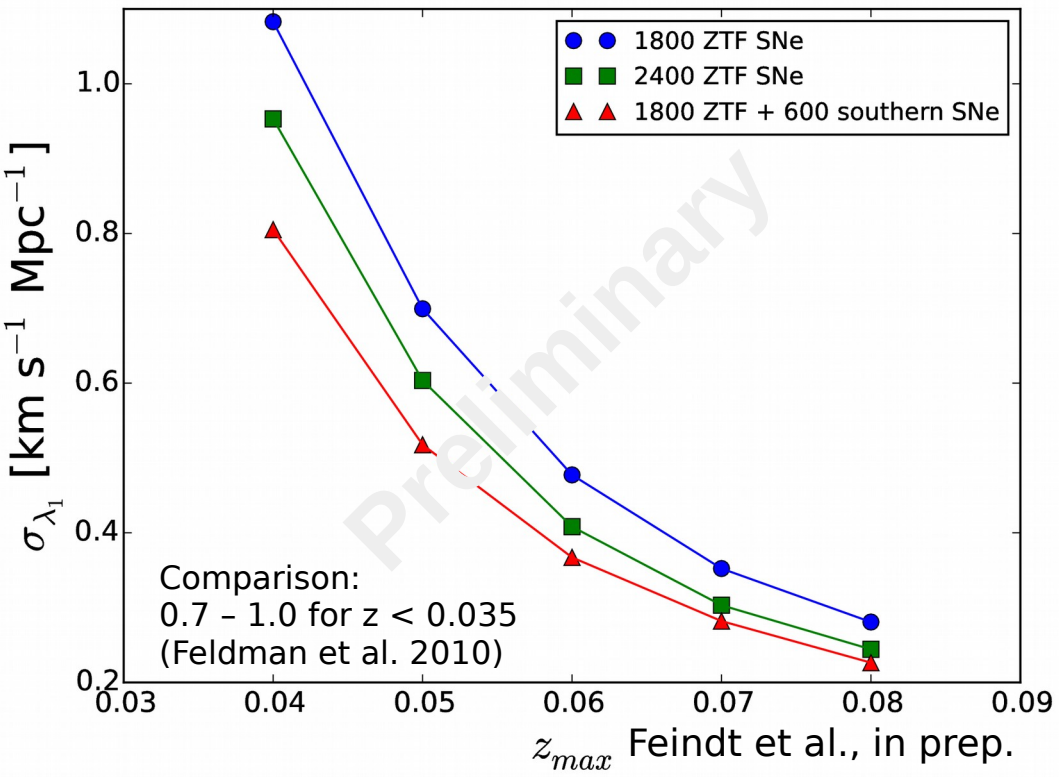
- Number of low-redshift SNe will grow by factor ~10

First simulations:

- Can constrain shear beyond Shapley supercluster

- Require with southern data for best results

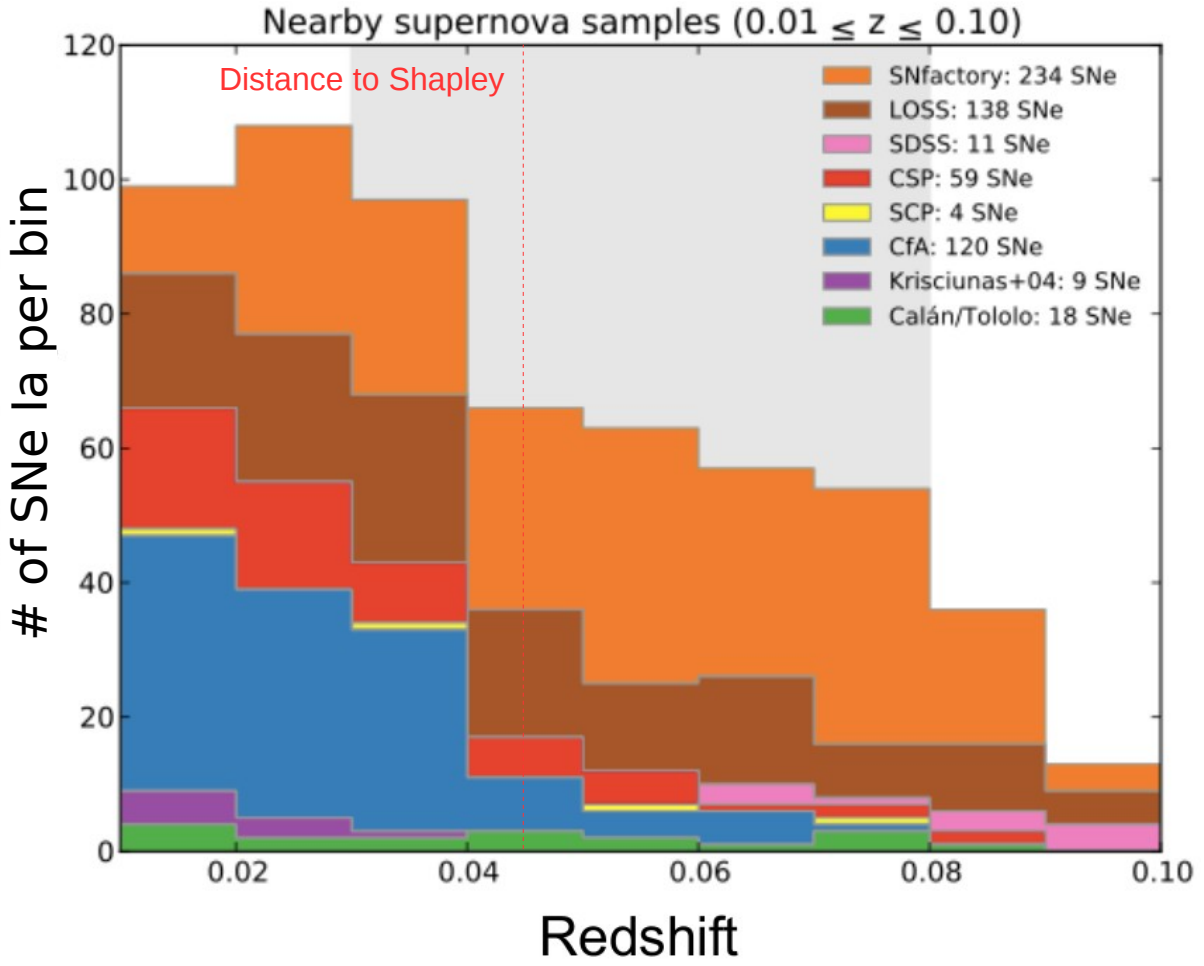
Median uncertainty of first shear eigenvalue from 1000 simulations of ZTF SNe

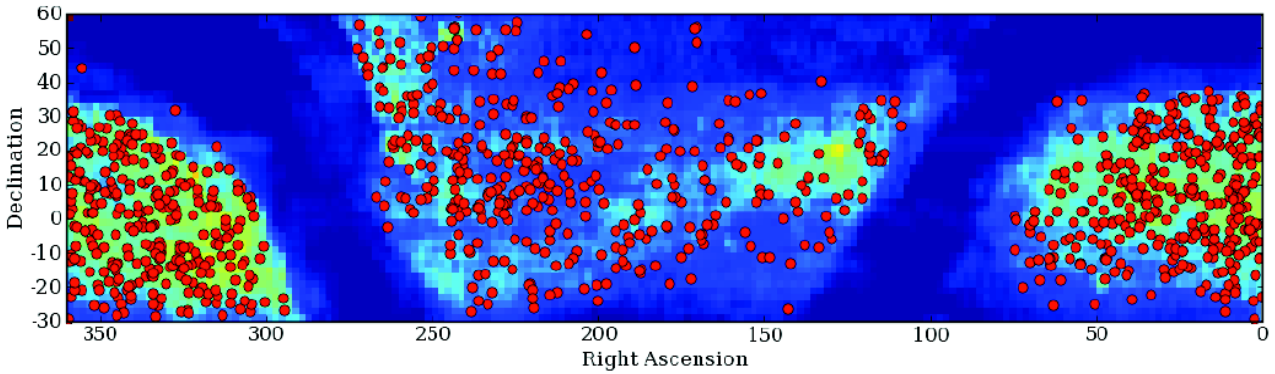


Feindt et al., in prep.

Backup

SNfactory coverage





ZTF camera

	PTF	ZTF
Active Area	7.26 deg^2	47 deg^2
Overhead Time	46 sec	<15 sec
Optimal Exposure Time	60 sec	30 sec
Relative Areal Survey Rate	1x	**14.7x**
Relative Volumetric Survey Rate	1x	**12.3x**

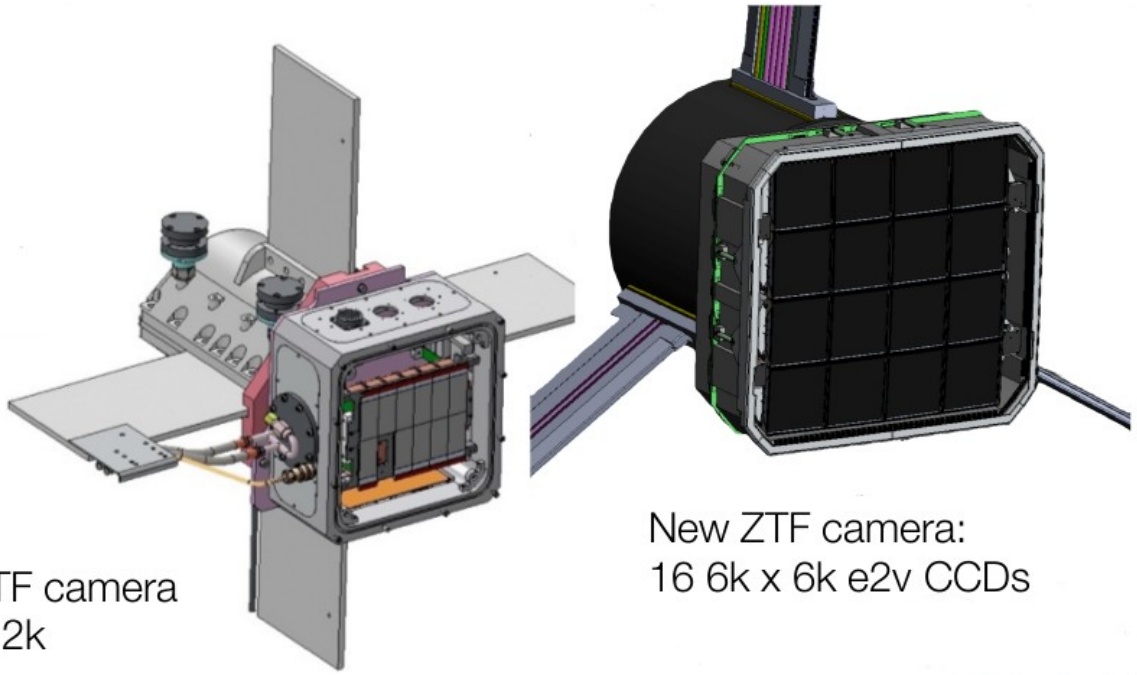
3750 deg^2/hour

➔3π survey in 8 hours

>250 observation/field/year

for uniform survey

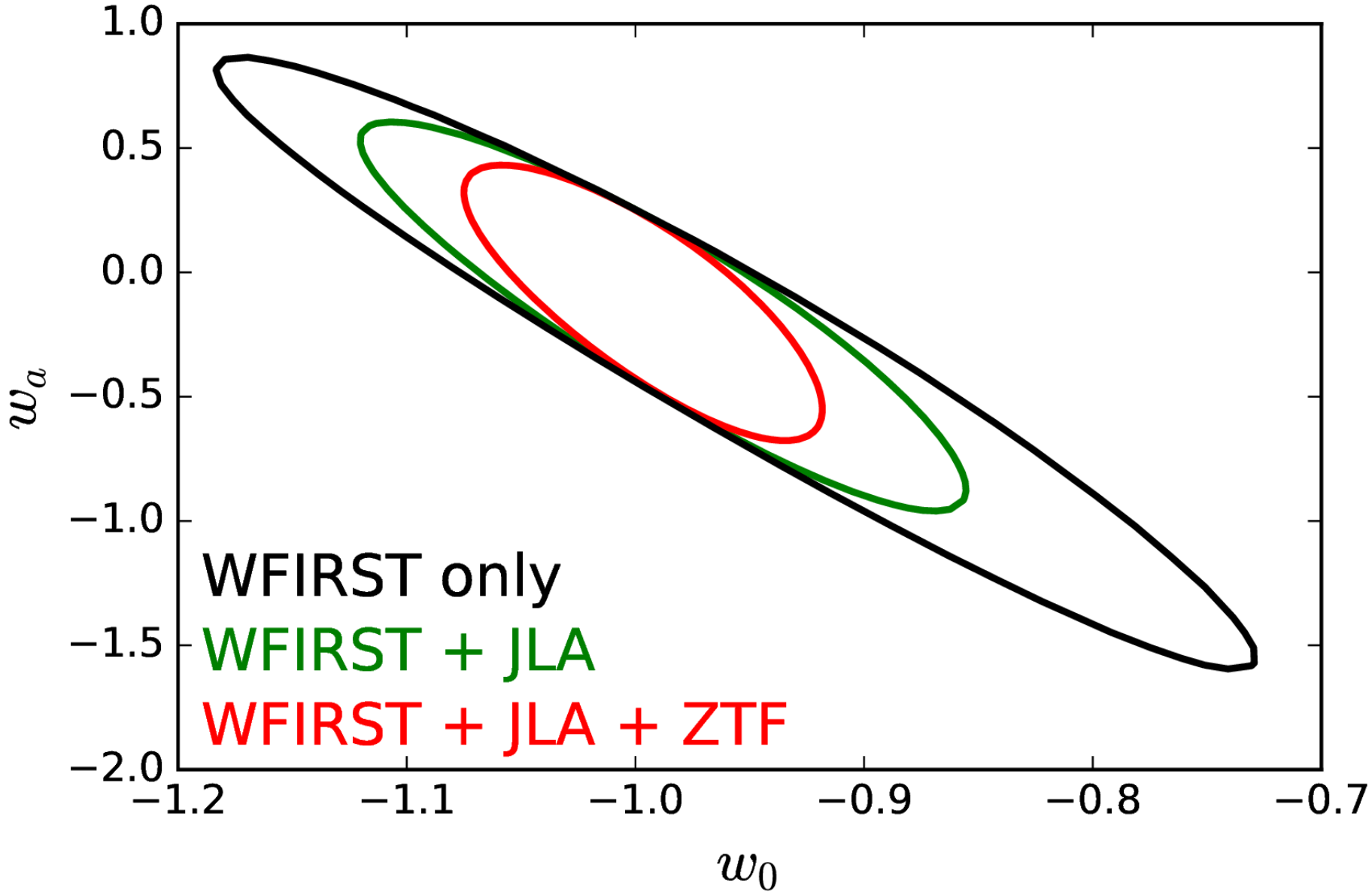
Will observe thousands of SNe



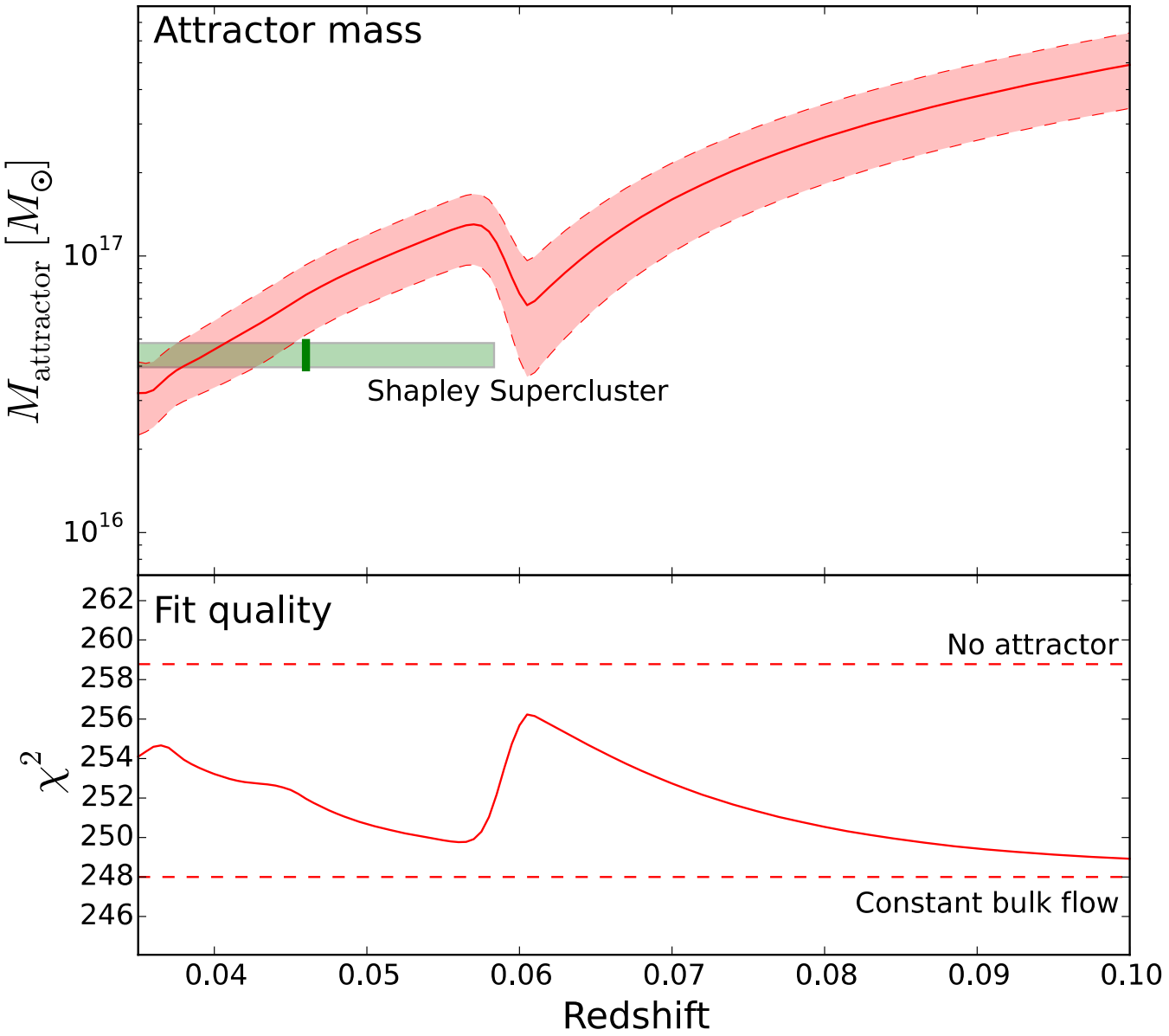
Existing PTF camera
MOSAIC 12k

New ZTF camera:
16 6k x 6k e2v CCDs

Dark energy e.o.s. with ZTF



Attractor result



Modeling the attractor

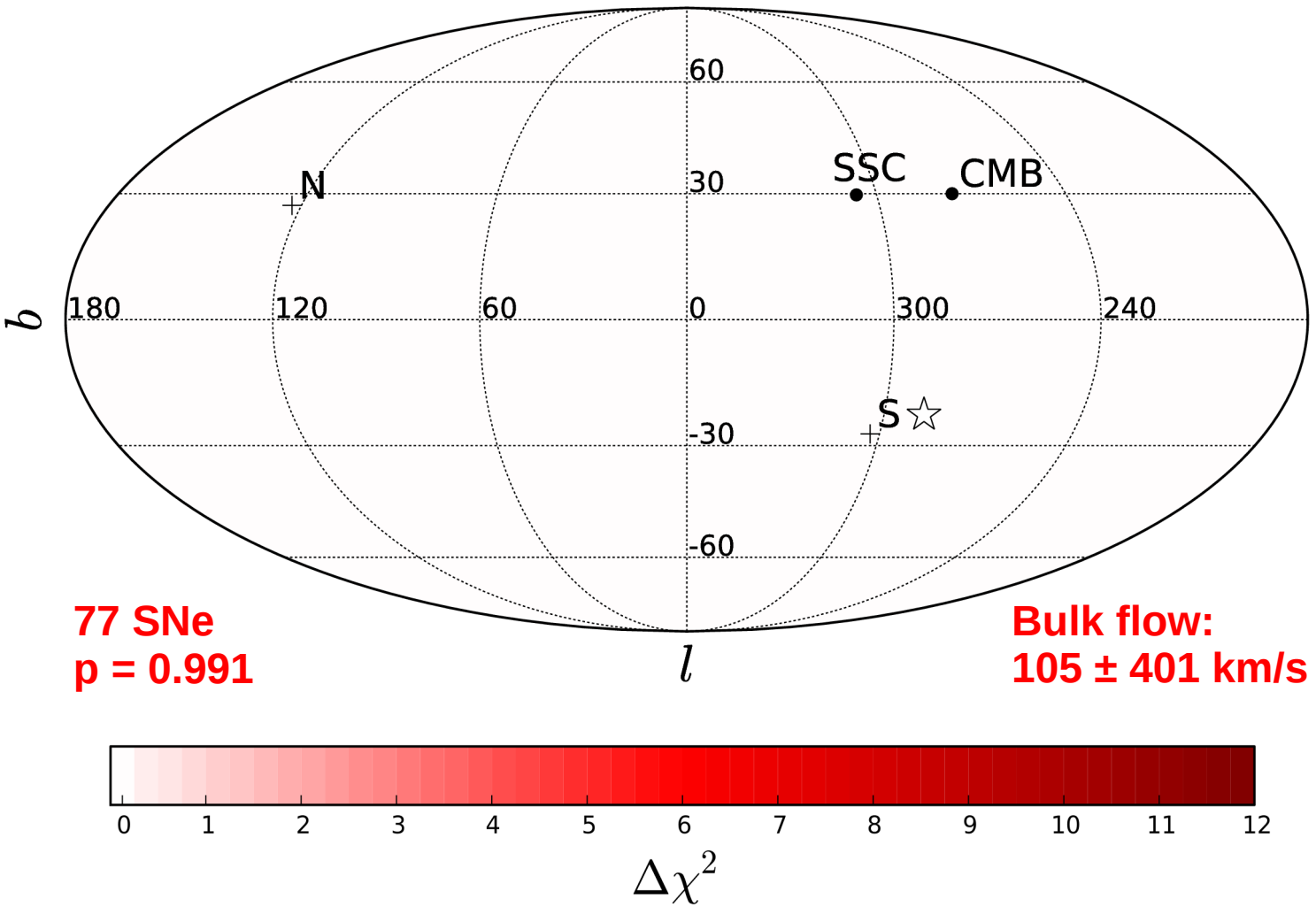
$$M_{\mathrm{tot}} = \frac{4\pi}{3} R^3 \Omega_{\mathrm{M}} \rho_{\mathrm{crit}} (1+\delta)$$

$$v_p(\vec{y}) = \frac{a\Omega_{\mathrm{M}}^{0.55} H}{4\pi} \int \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|^3} \delta(\vec{y}) \mathrm{d}^3 y$$

At location of the Shapley required mass ~50% higher

Shapley disfavored as sole attractor by 2σ compared to constant bulk flow independent of mass

Bulk Flow (0.06 < z < 0.1)



77 SNe
p = 0.991

Bulk flow:
105 ± 401 km/s

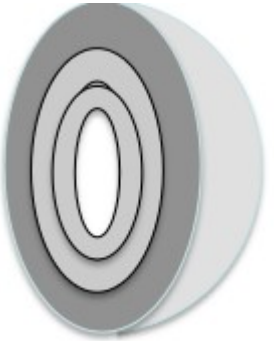
Bulk flow consistent with zero

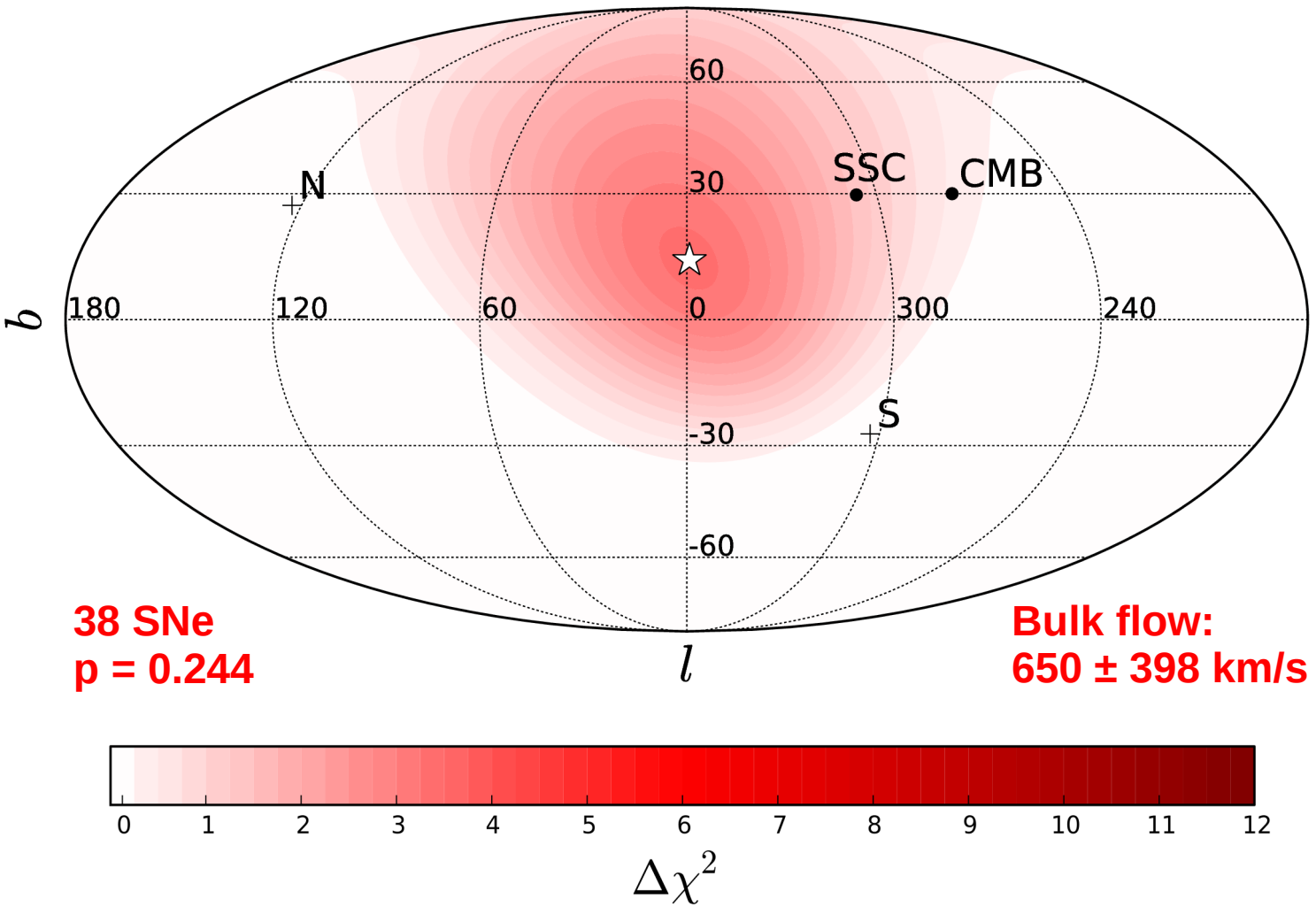
When fitting in Dark flow direction:

34 ± 254 km/s

➔ Rule out a Dark flow of ~1000 km/s

Bulk Flow (0.045 < z < 0.06)

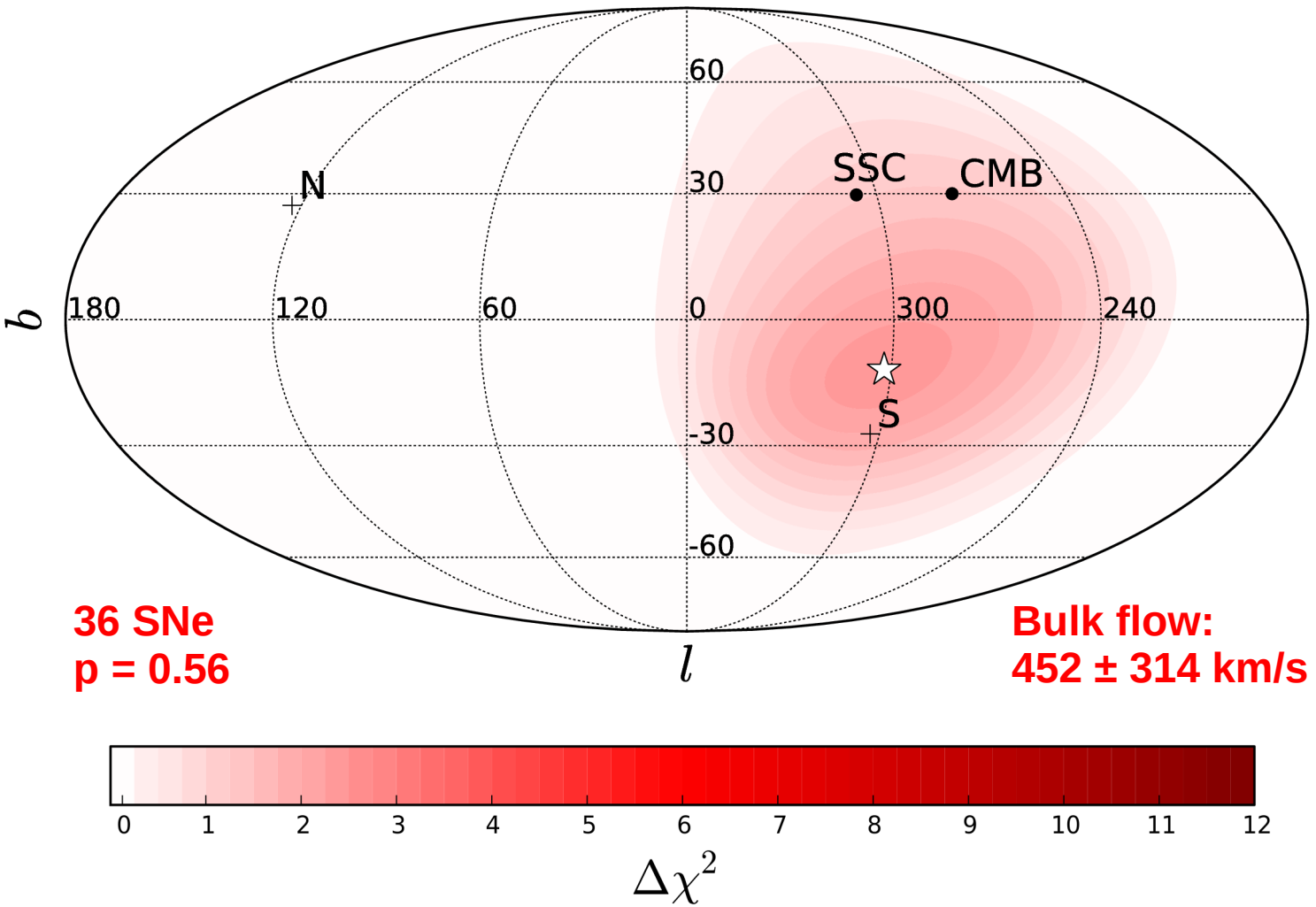




No backside infall behind Shapley

- Contradicts Shapley as the main source of the bulk flow
- Results in this shell are driven by SNfactory data

Bulk Flow (0.035 < z < 0.045)

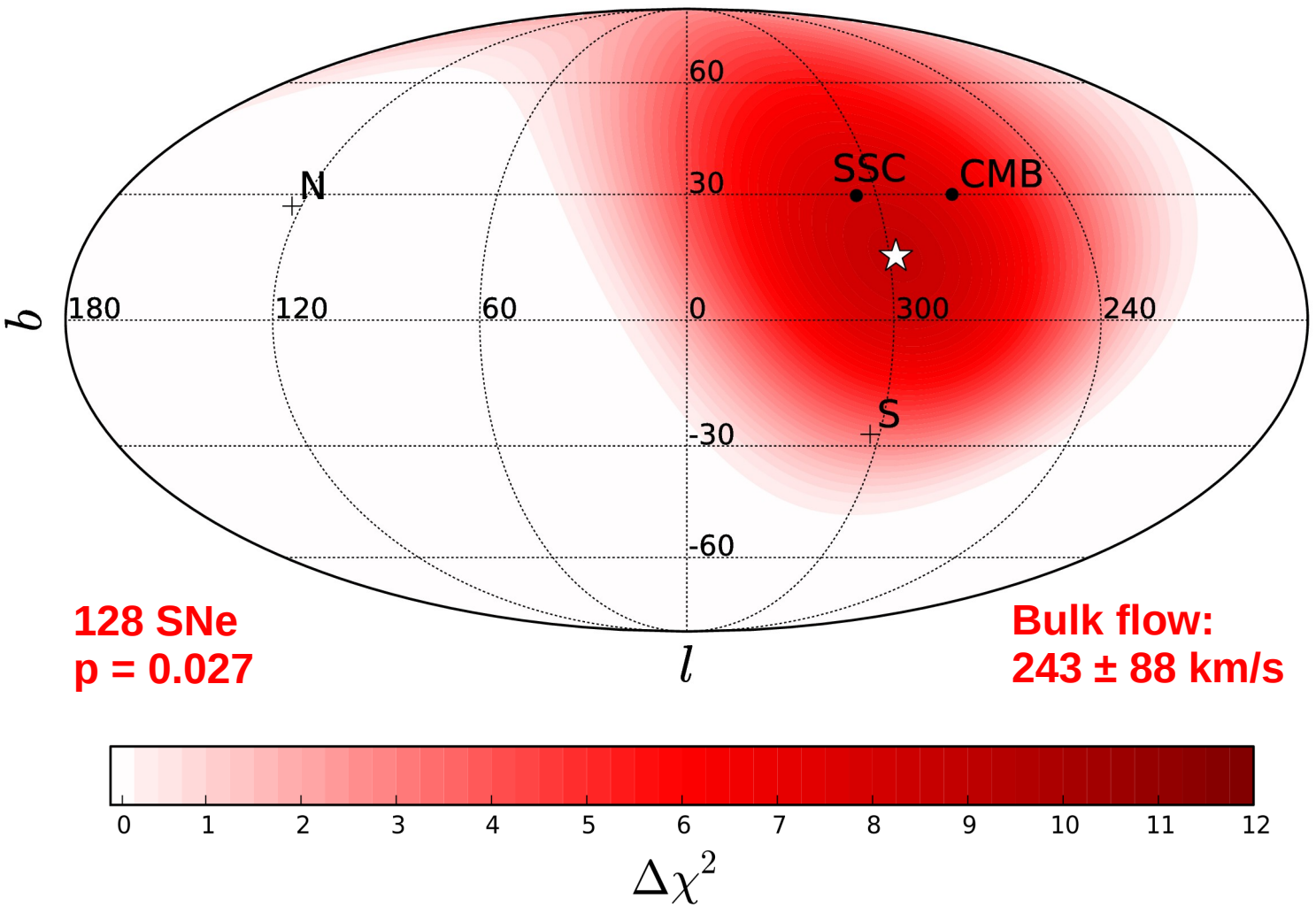


No significant bulk flow detected in intermediate shell

36 SNe
p = 0.56

Bulk flow:
452 ± 314 km/s

Bulk Flow (0.015 < z < 0.035)



Bulk flow modeled as velocity dipole

Best fit direction consistent with direction to Shapley

Result dominated by Union2 data

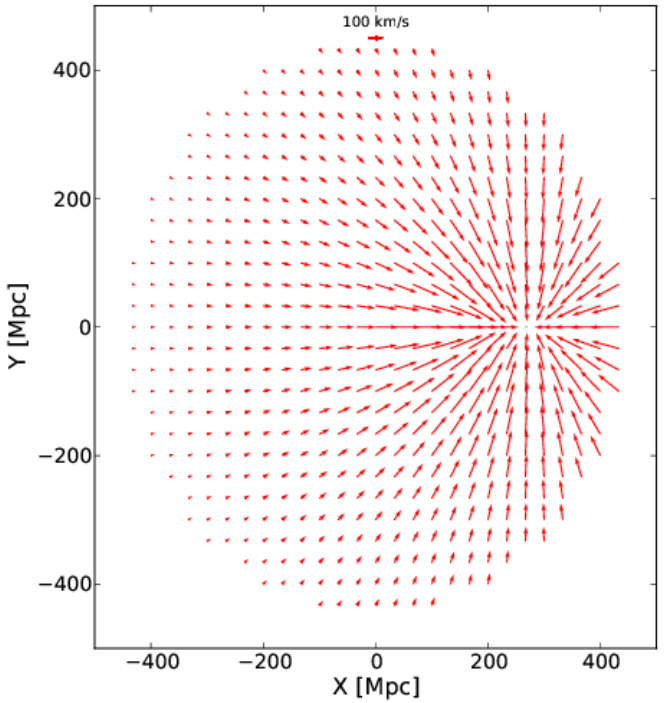
➔ Amplitude matches previous studies

Velocity tidal field

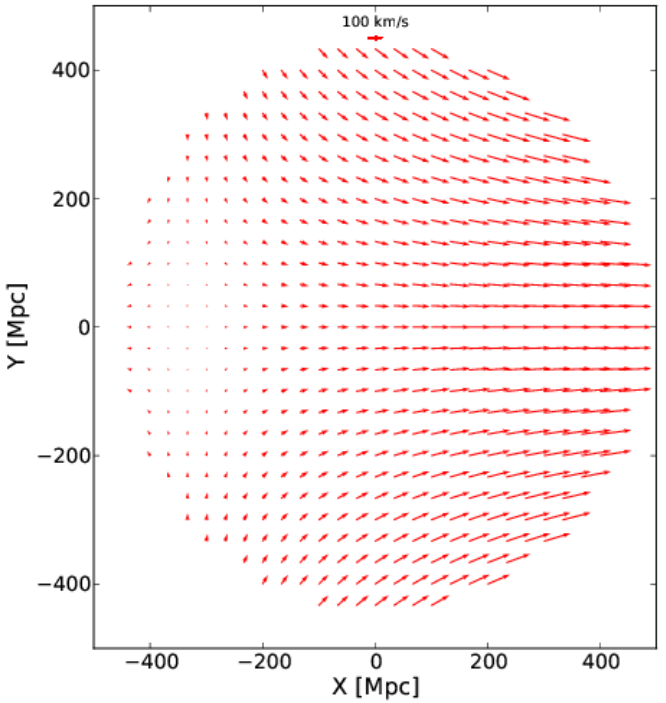
$$\vec{v}(\vec{x}) = \vec{v}_0 + H\vec{x} + \Sigma \cdot \vec{x}$$

Dipole (vector) Monopole (scalar) Quadrupole (symmetric tensor)

Spherical attractor

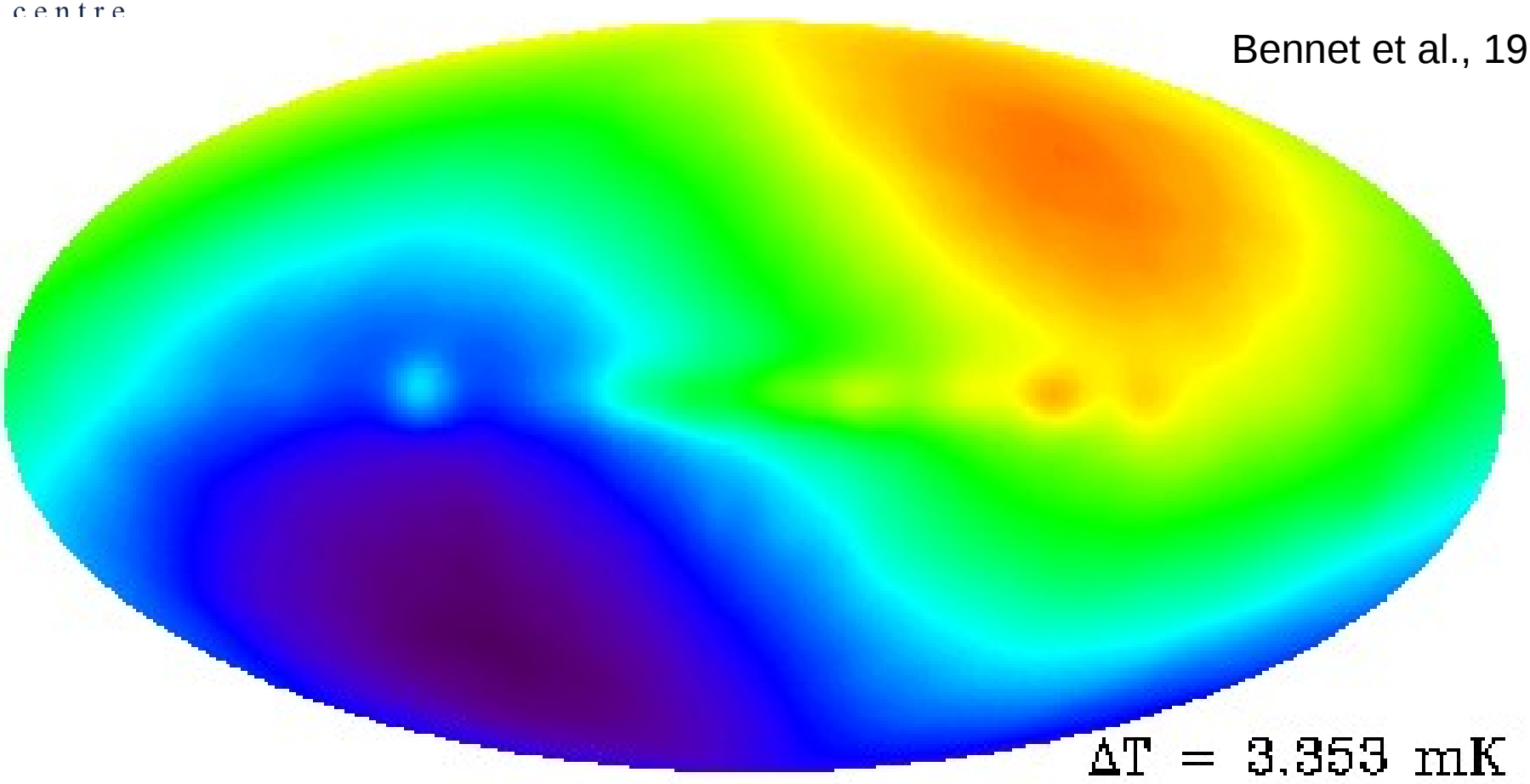


Tidal field



CMB dipole anisotropy

Bennet et al., 1996



Local Group moves at ~ 600 km/s. Why?