Growth-rate measurement with type Ia supernovae within the ZTF photometric survey

Bastien Carreres

Image credits: ZTF.Caltech

Outline

- Introduction:
  - The ΛCDM standard model
  - Modified gravity
- Growth rate of structure
  - What is the growth rate of structure?
  - How to measure it?
- Type Ia supernovae
  - What are they?
  - The Zwicky Transient Facility
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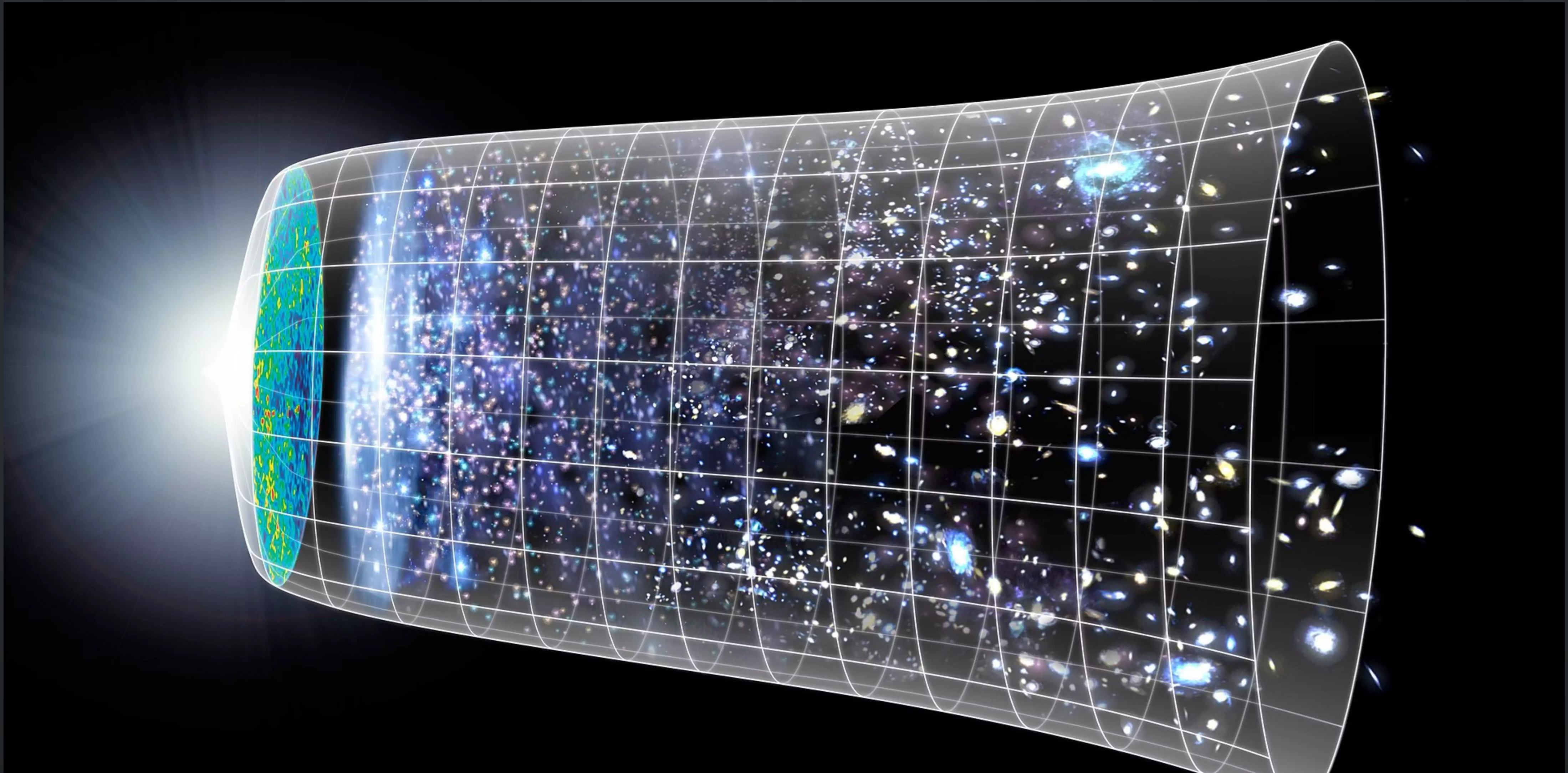
The standard cosmological model: General Relativity + ΛCDM



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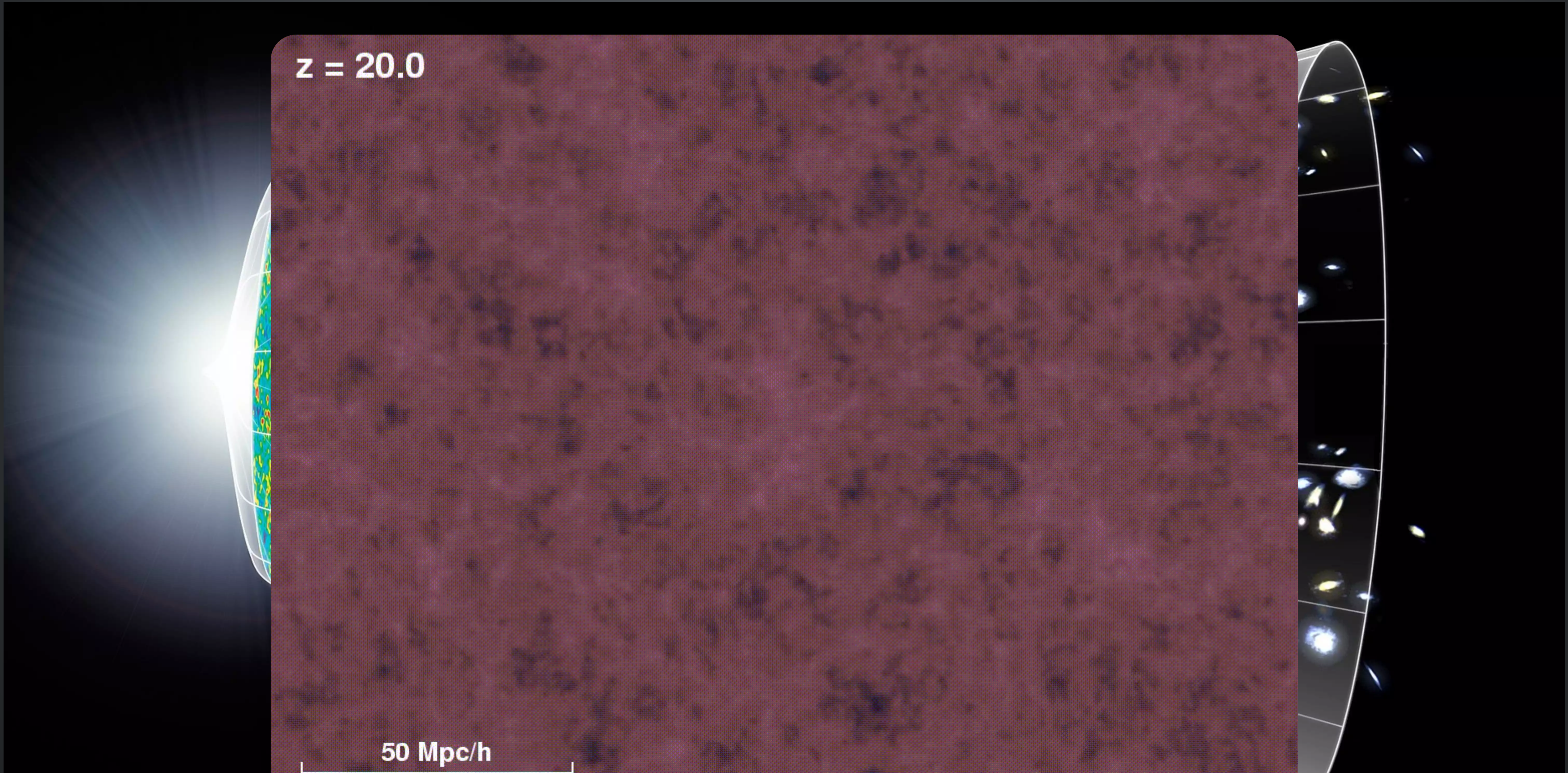

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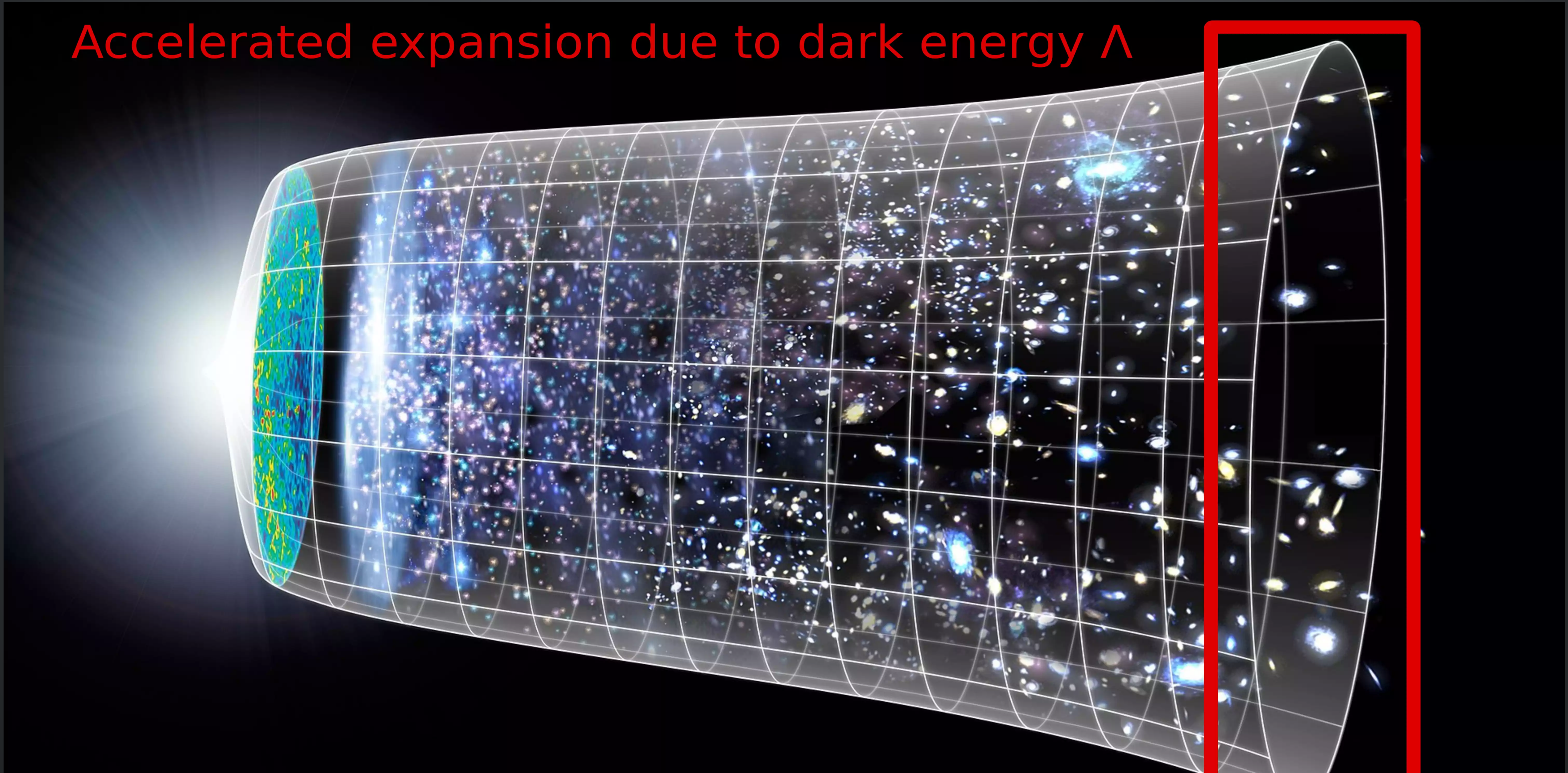

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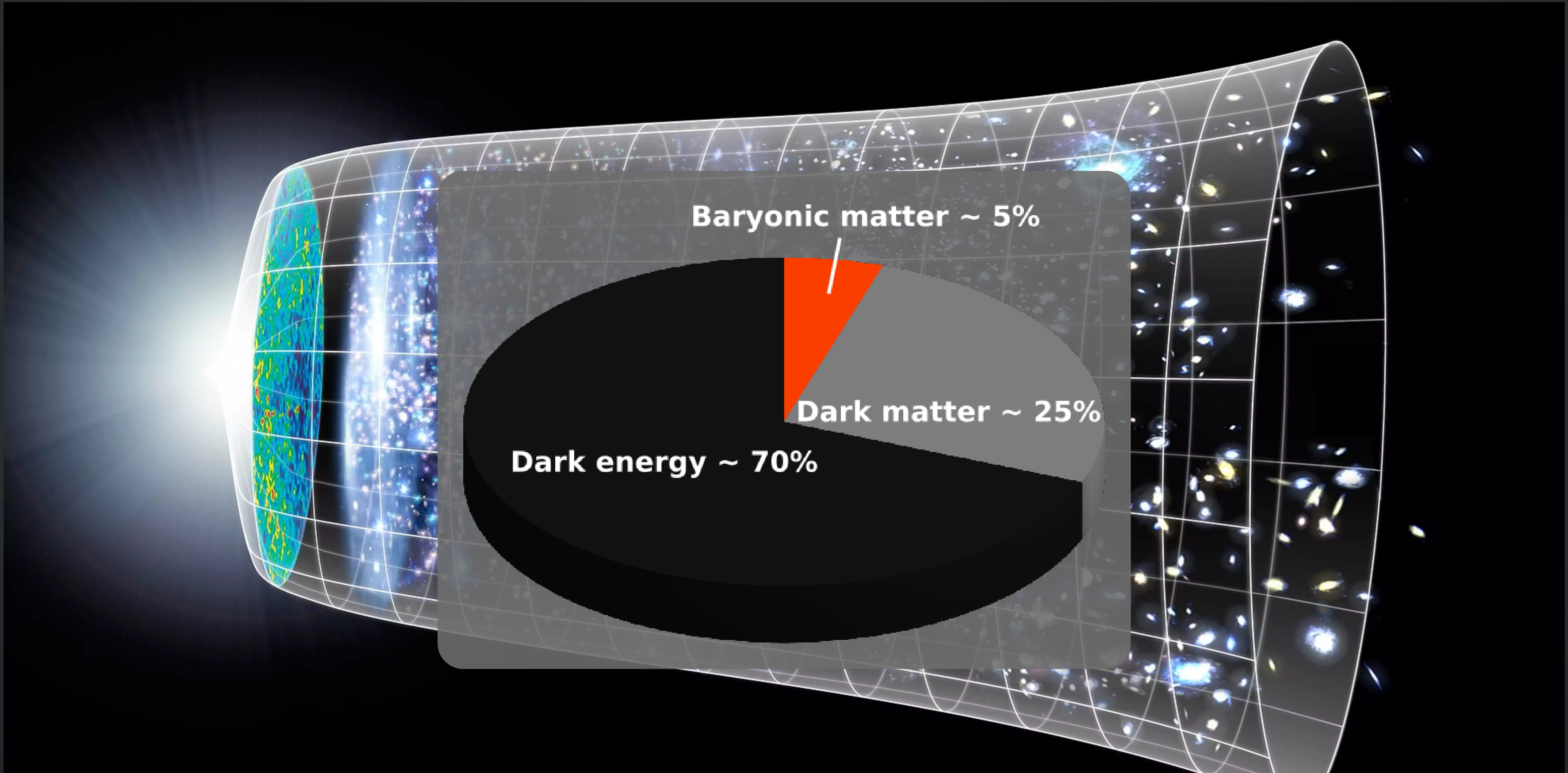

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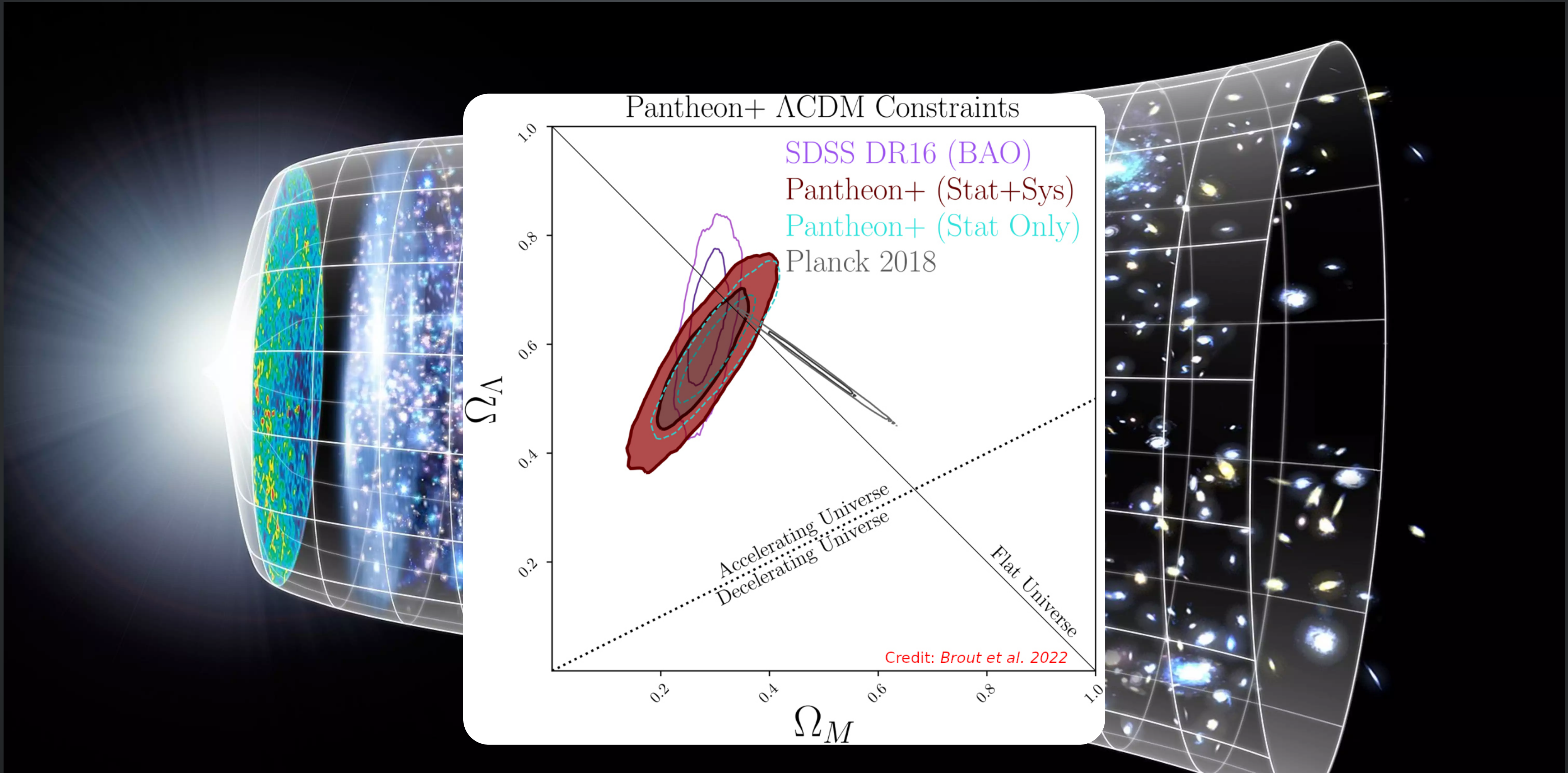

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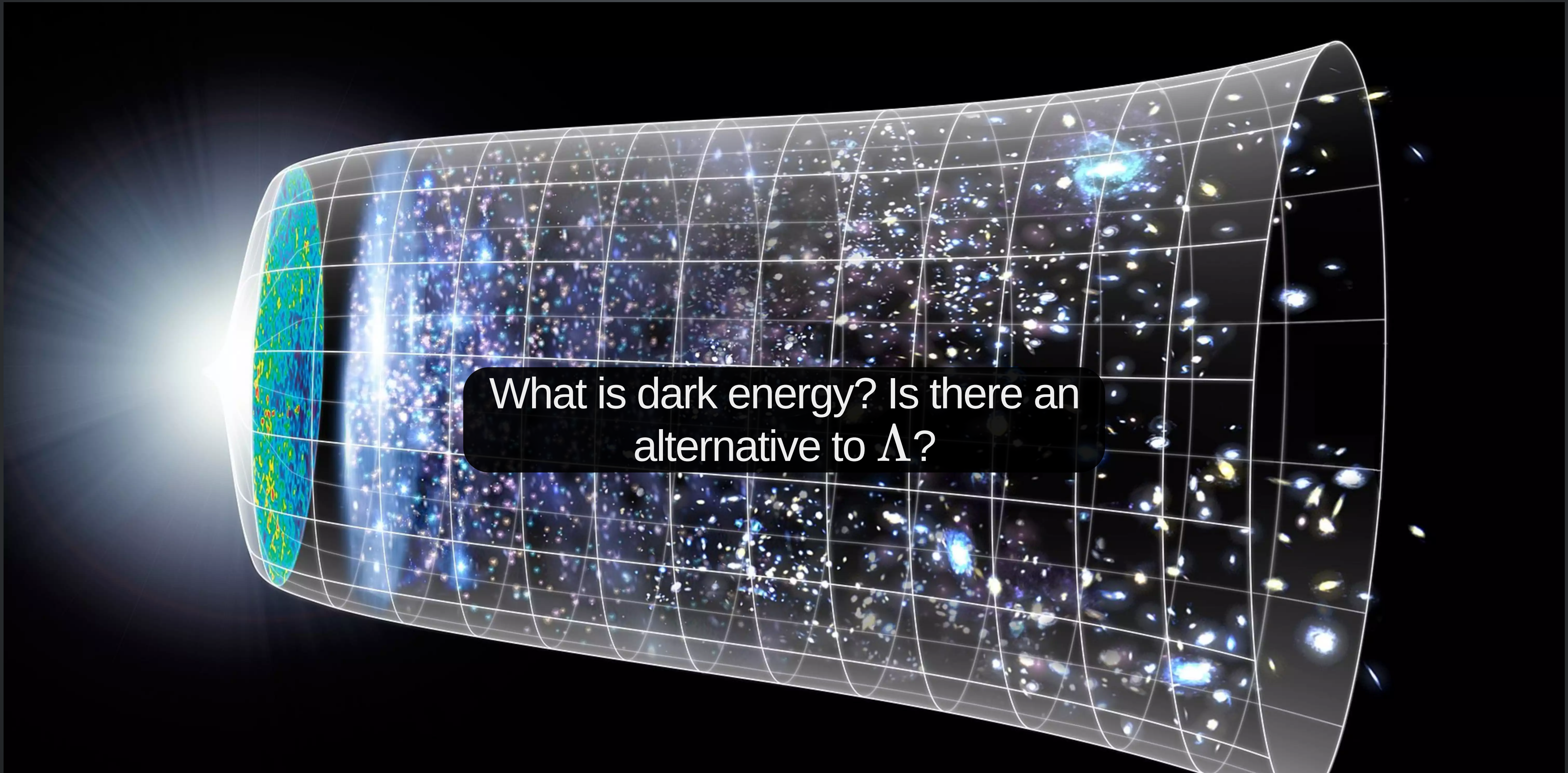

Modified gravity

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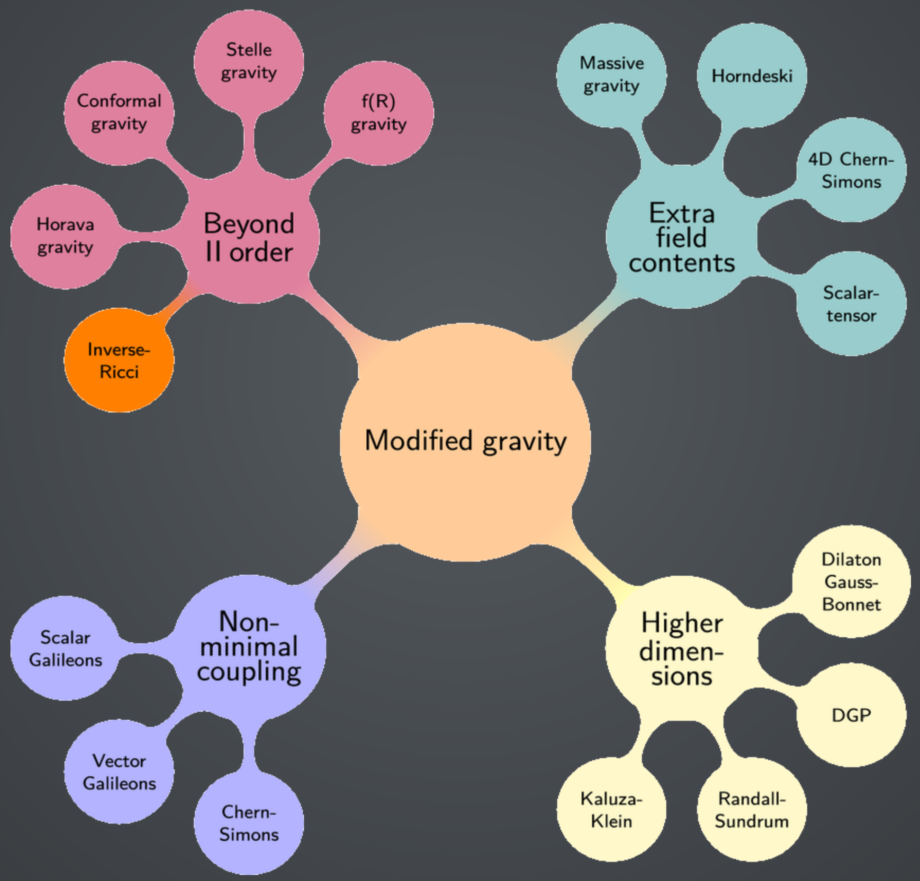

Image credits: arXiv:2204.06533

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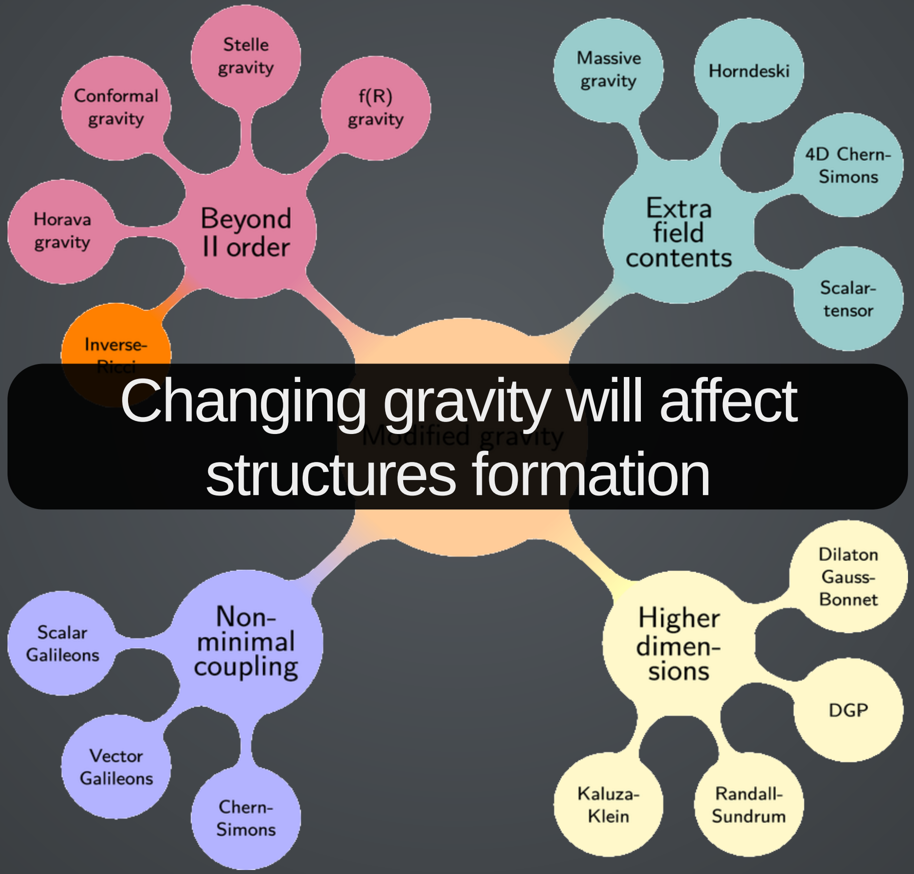

Changing gravity will affect structures formation

Image credits: arXiv:2204.06533

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$f\sigma_8$ as a probe for general relativity

Structure evolution:
Dark energy vs Gravity

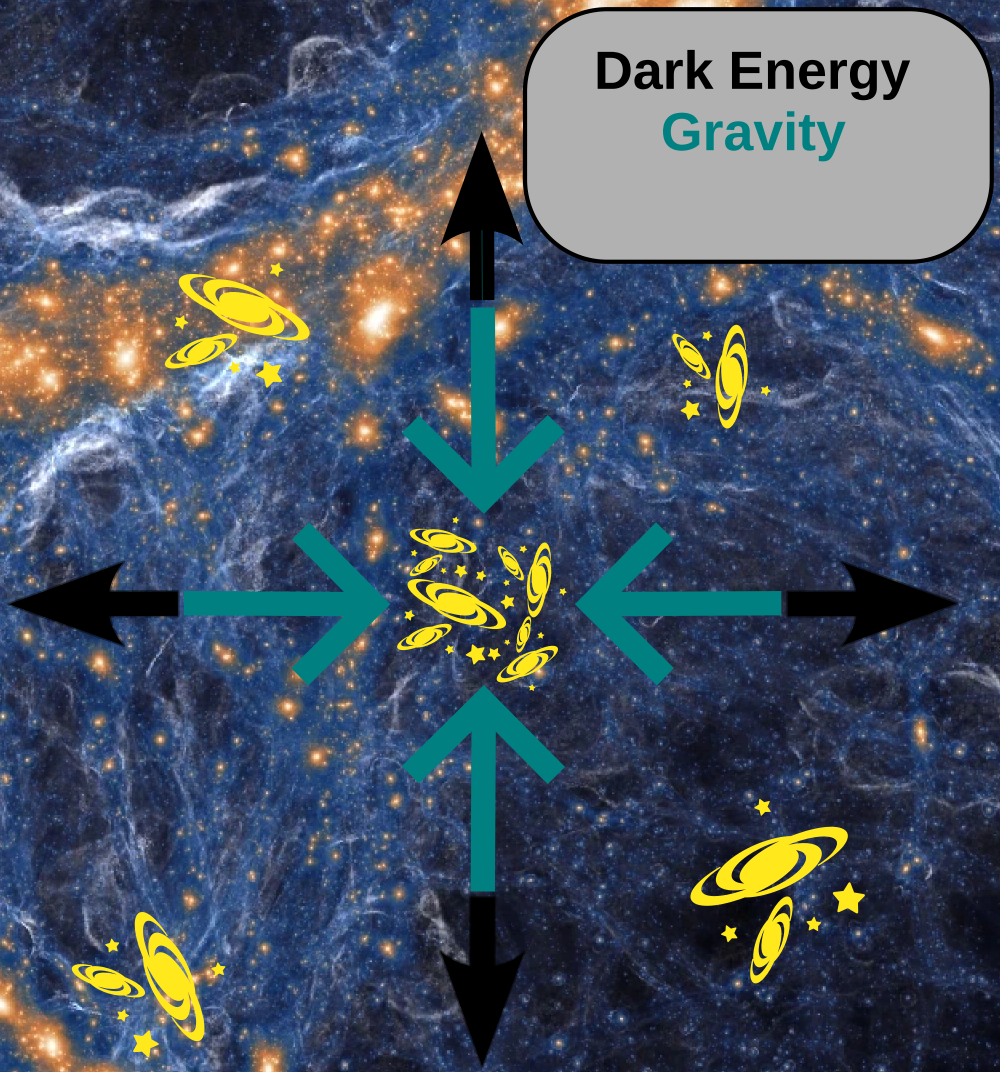

Image credits: Illustris TNG

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Structure evolution:
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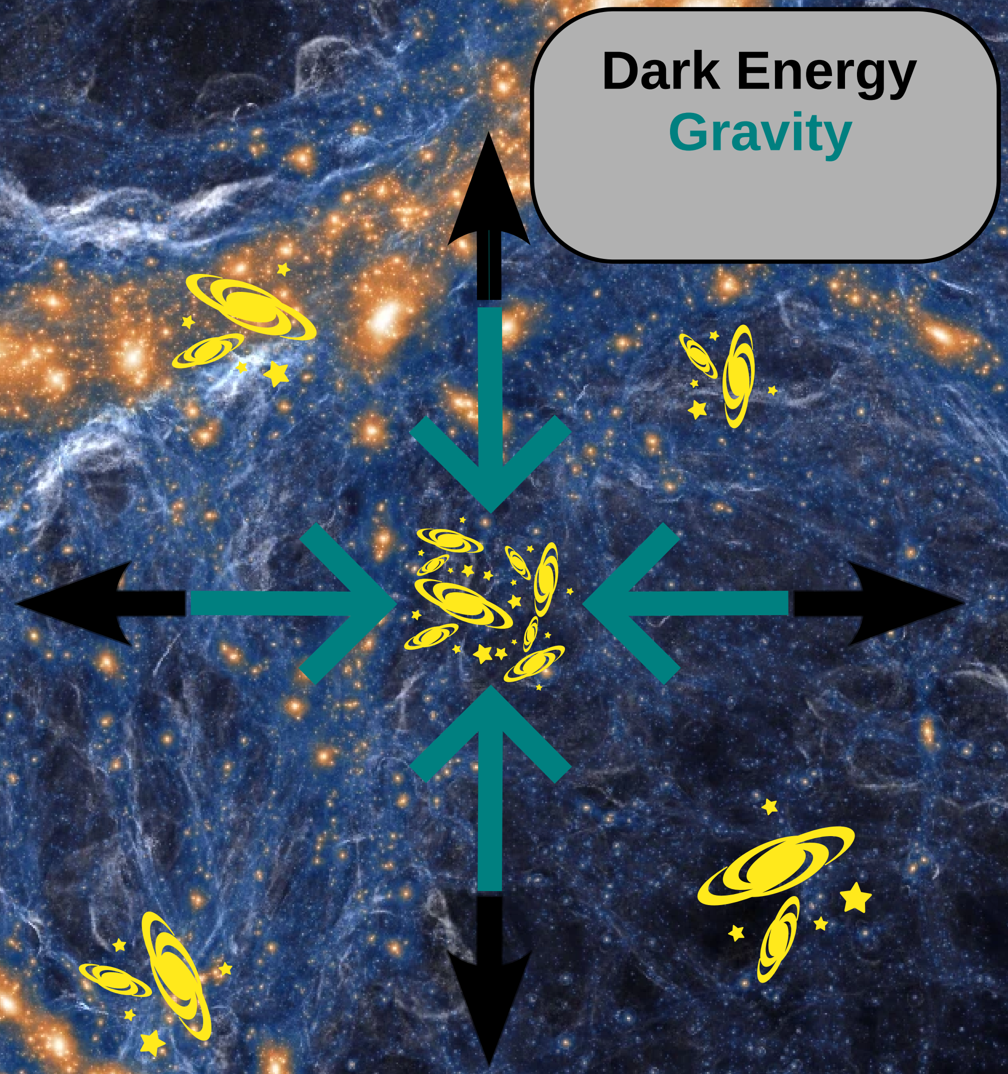
Density contrast: $\delta(\mathbf{x}) = \frac{\rho(\mathbf{x})}{\bar{\rho}} - 1$



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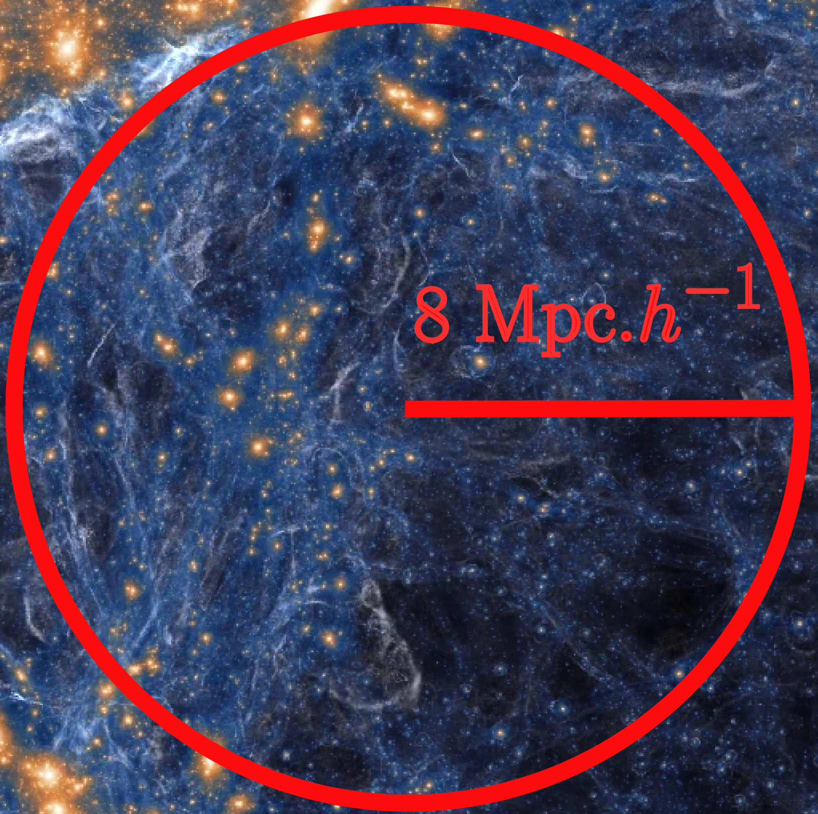
σ_8:
RMS of fluctuation over sphere of
8 Mpc.h^{-1} radius

$$\delta(\mathbf{x}) = \sigma_8 \tilde{\delta}(\mathbf{x})$$



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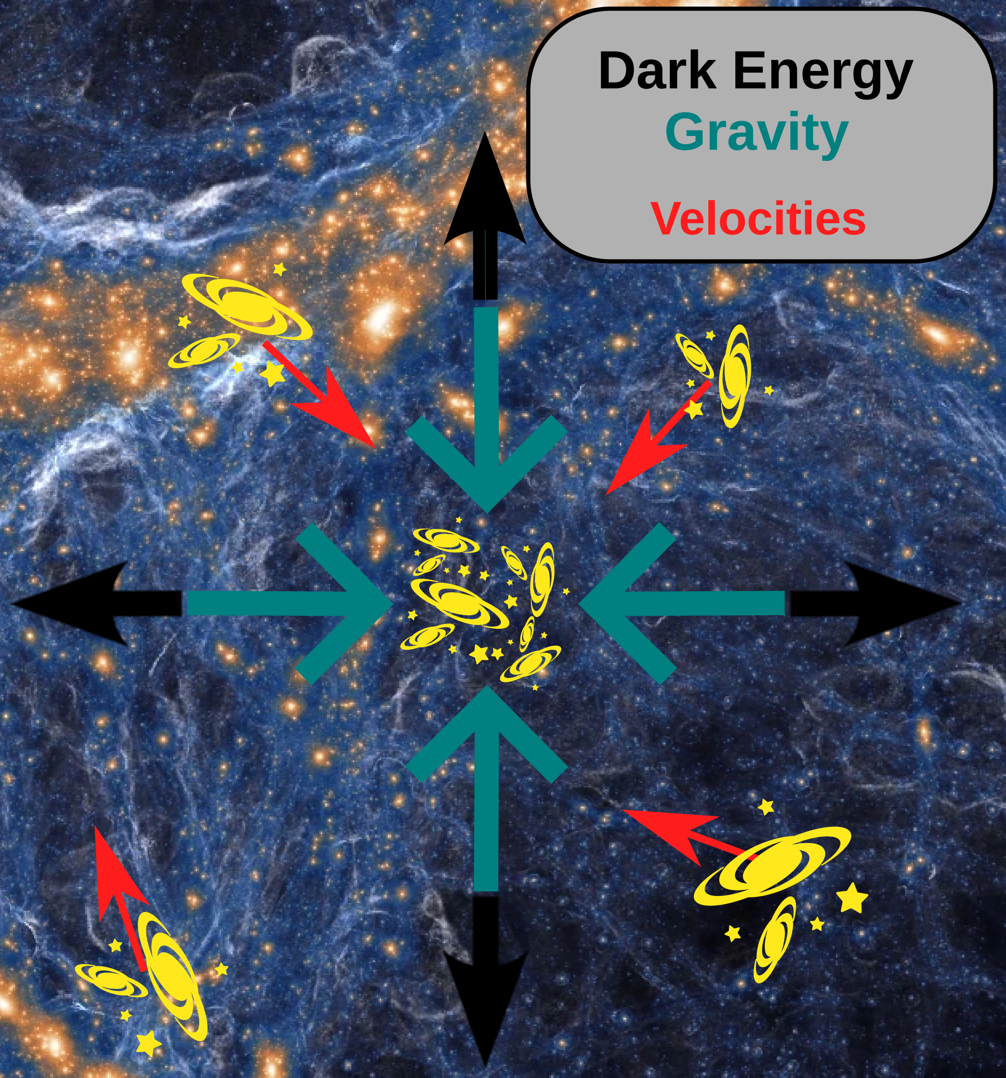
$f\sigma_8$ as a probe for general relativity

Velocities are linked to density through the continuity equation:

$$\nabla . v(\mathbf{x}) \propto f\sigma_8\tilde{\delta}(\mathbf{x})$$

where $f \equiv$ growth rate



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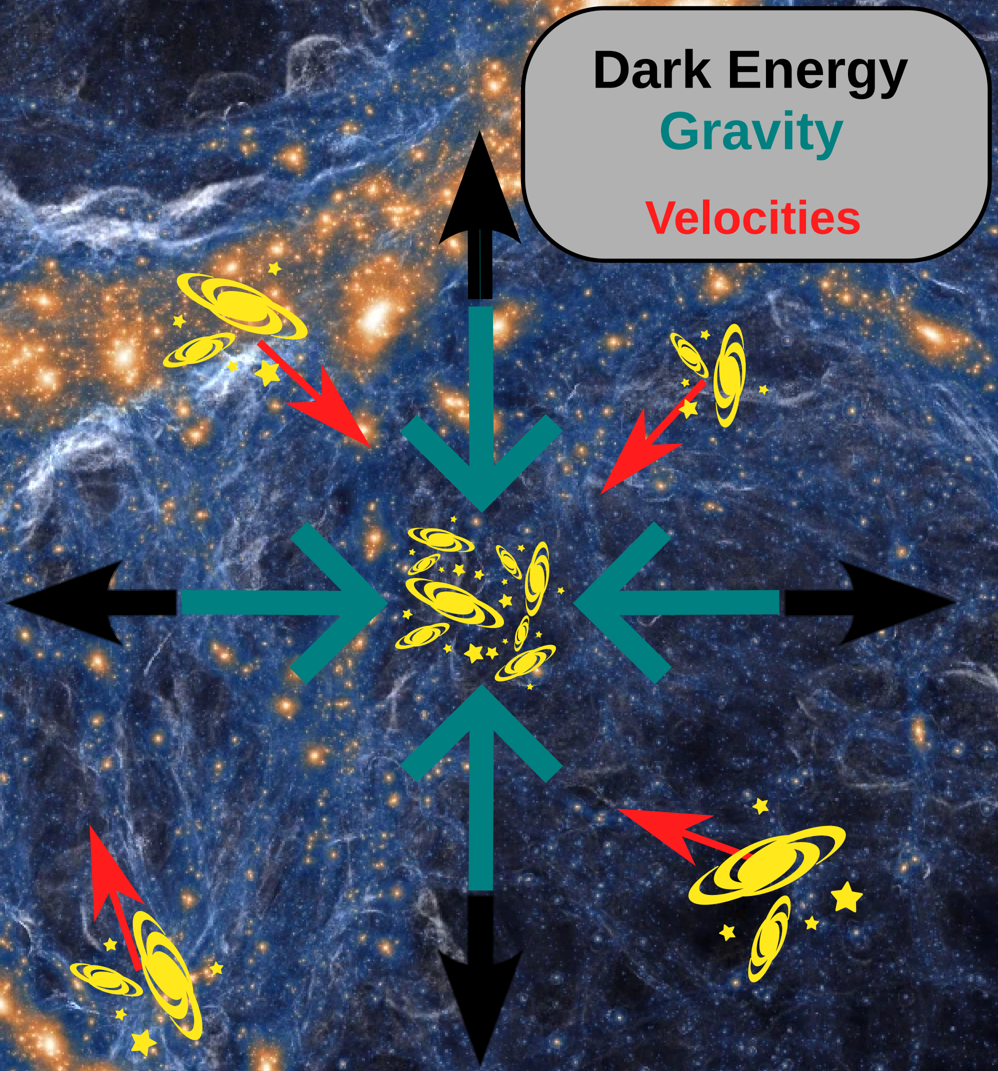
General Relativity + ΛCDM:
$f \simeq \Omega_m^\gamma$ with $\gamma \simeq 0.55$



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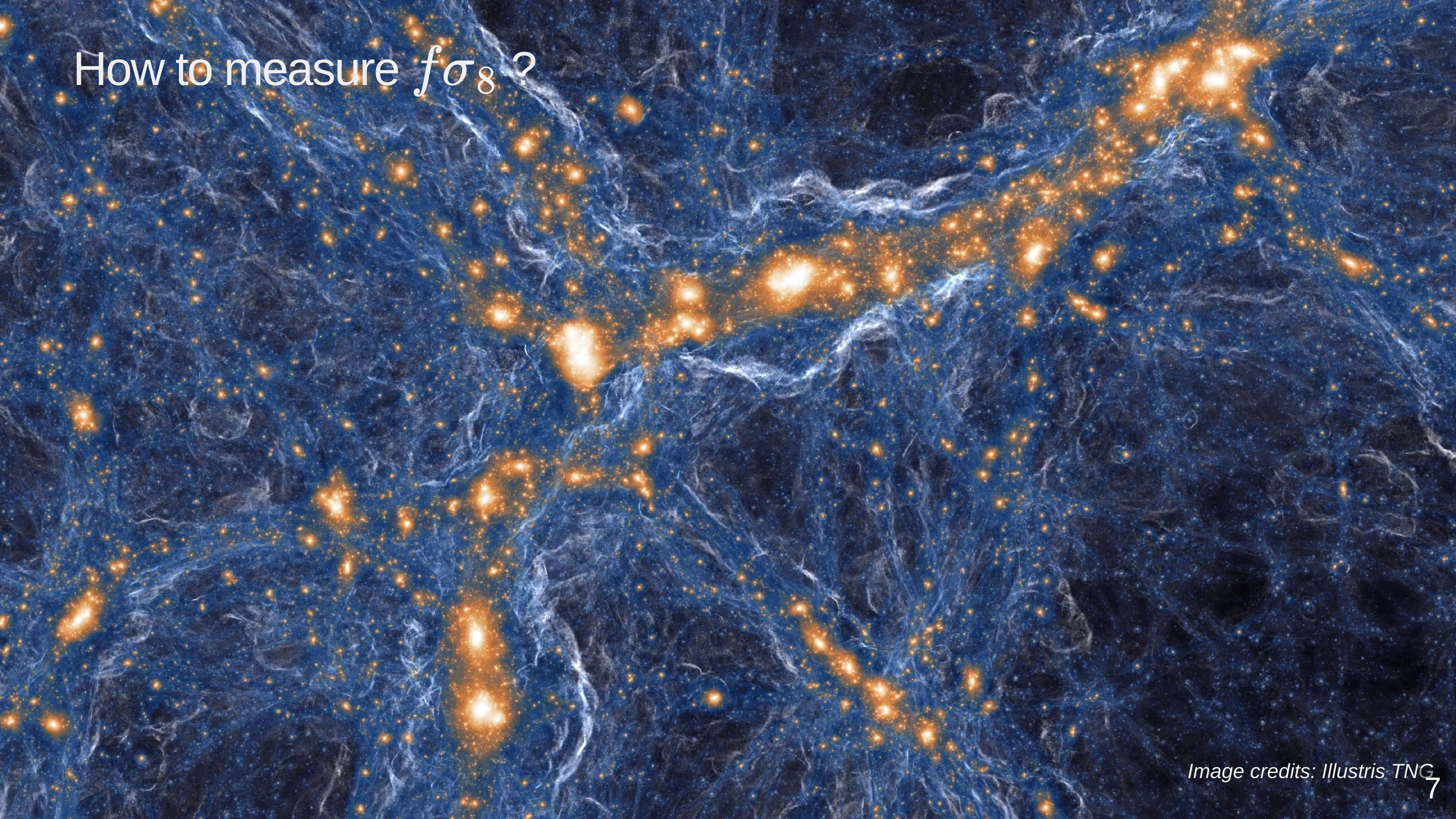
How to measure $f\sigma_8$?



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How to measure $f\sigma_8$?

Velocities as probes of $f\sigma_8$:

$$\nabla . v \propto f\sigma_8$$

Doppler effect on redshift:

$$1 + z_{\mathrm{obs}} = (1 + z_{\mathrm{cos}})\,(1 + z_p)$$

$z_p \simeq \frac{v_p}{c}$, v_p is the line-of-sight velocity

$v_p \sim 300\ \mathrm{km.\,s}^{-1}$ and $z_p \sim 0.001$

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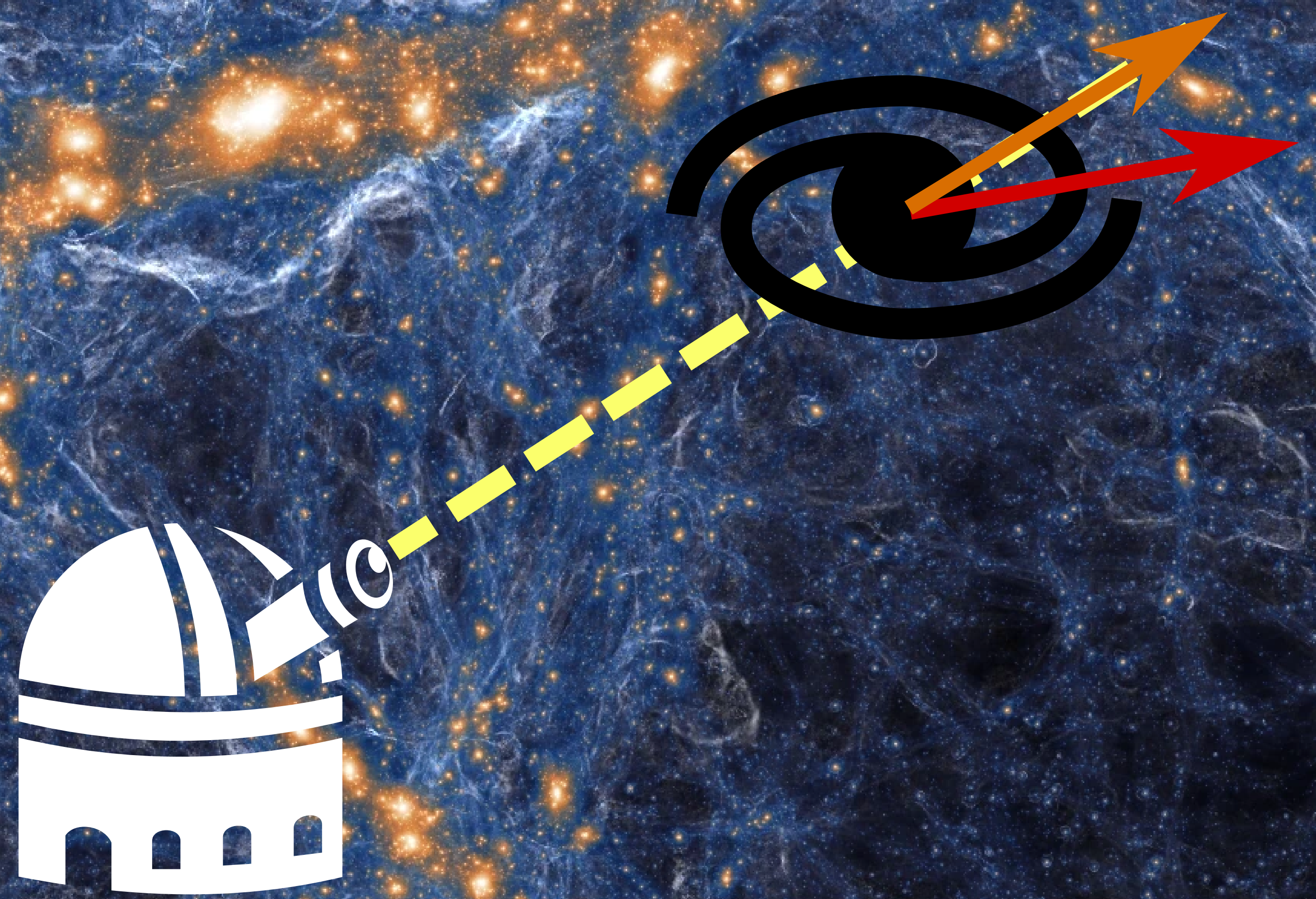

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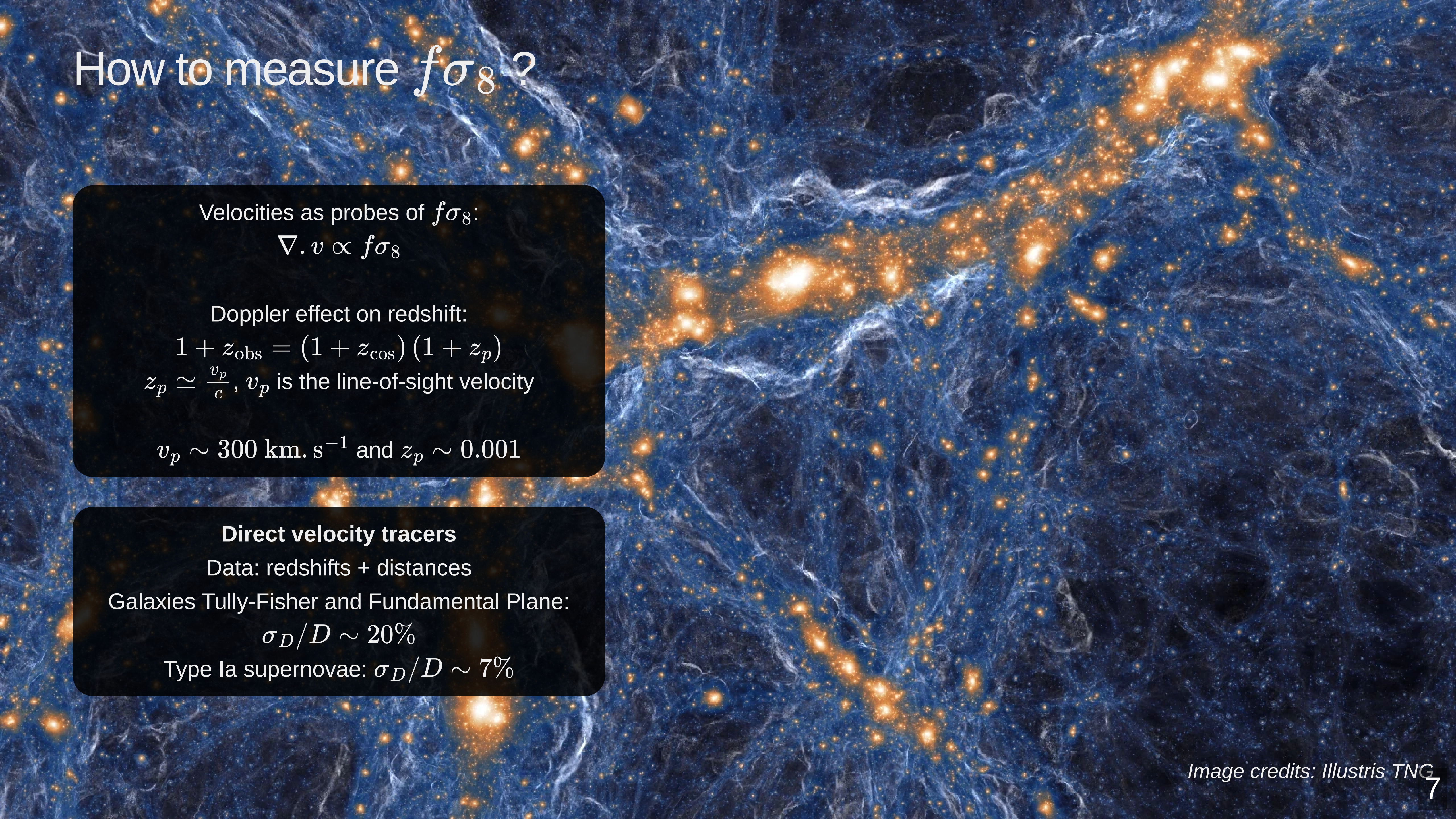

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Direct velocity tracers

Data: redshifts + distances

Galaxies Tully-Fisher and Fundamental Plane:

$$\sigma_D/D \sim 20\%$$

Type Ia supernovae: $\sigma_D/D \sim 7\%$

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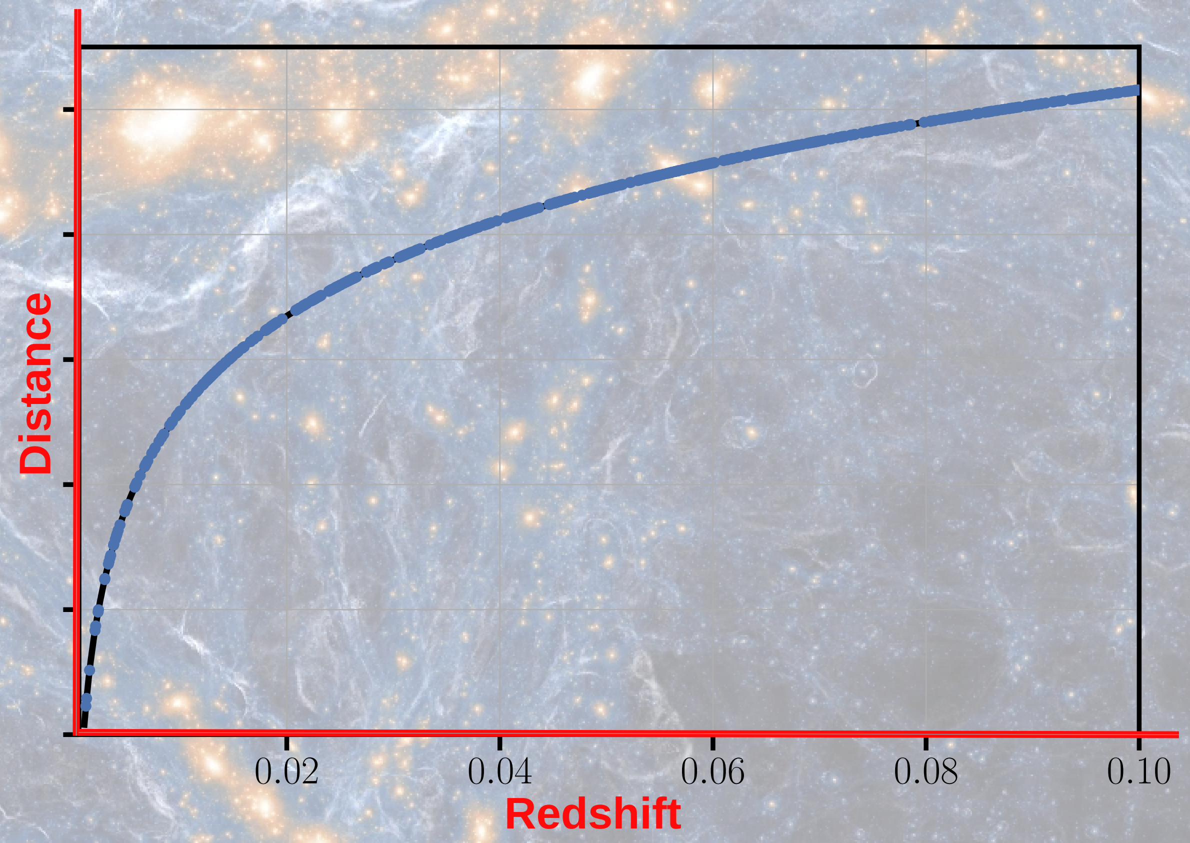

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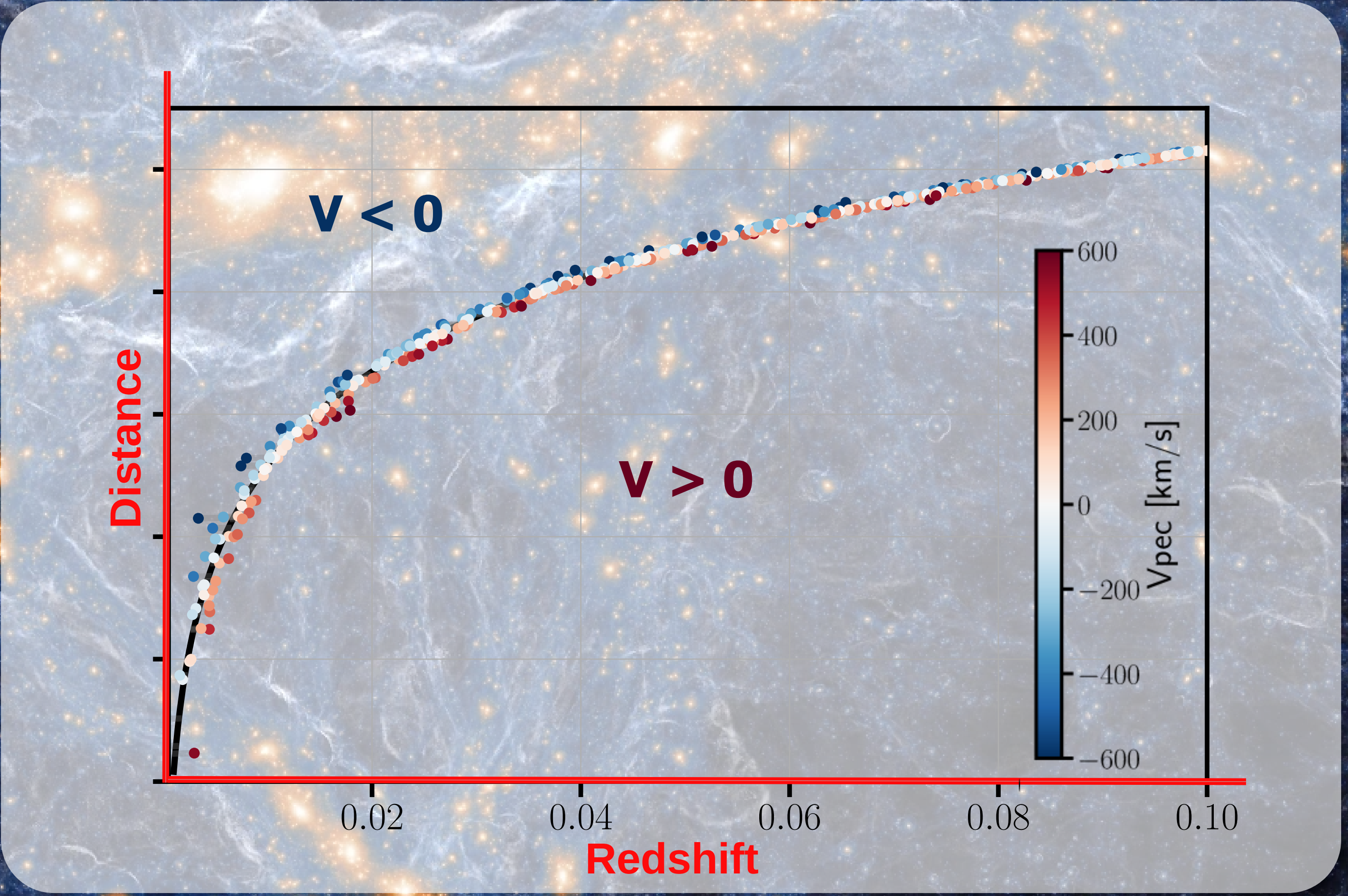

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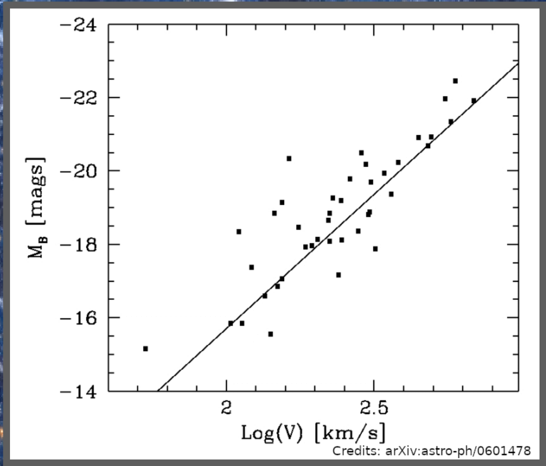
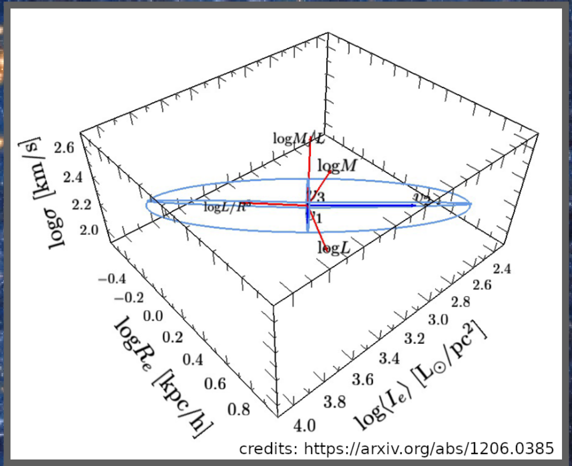
Galaxies: Tully-Fisher & Fundamental plane relation





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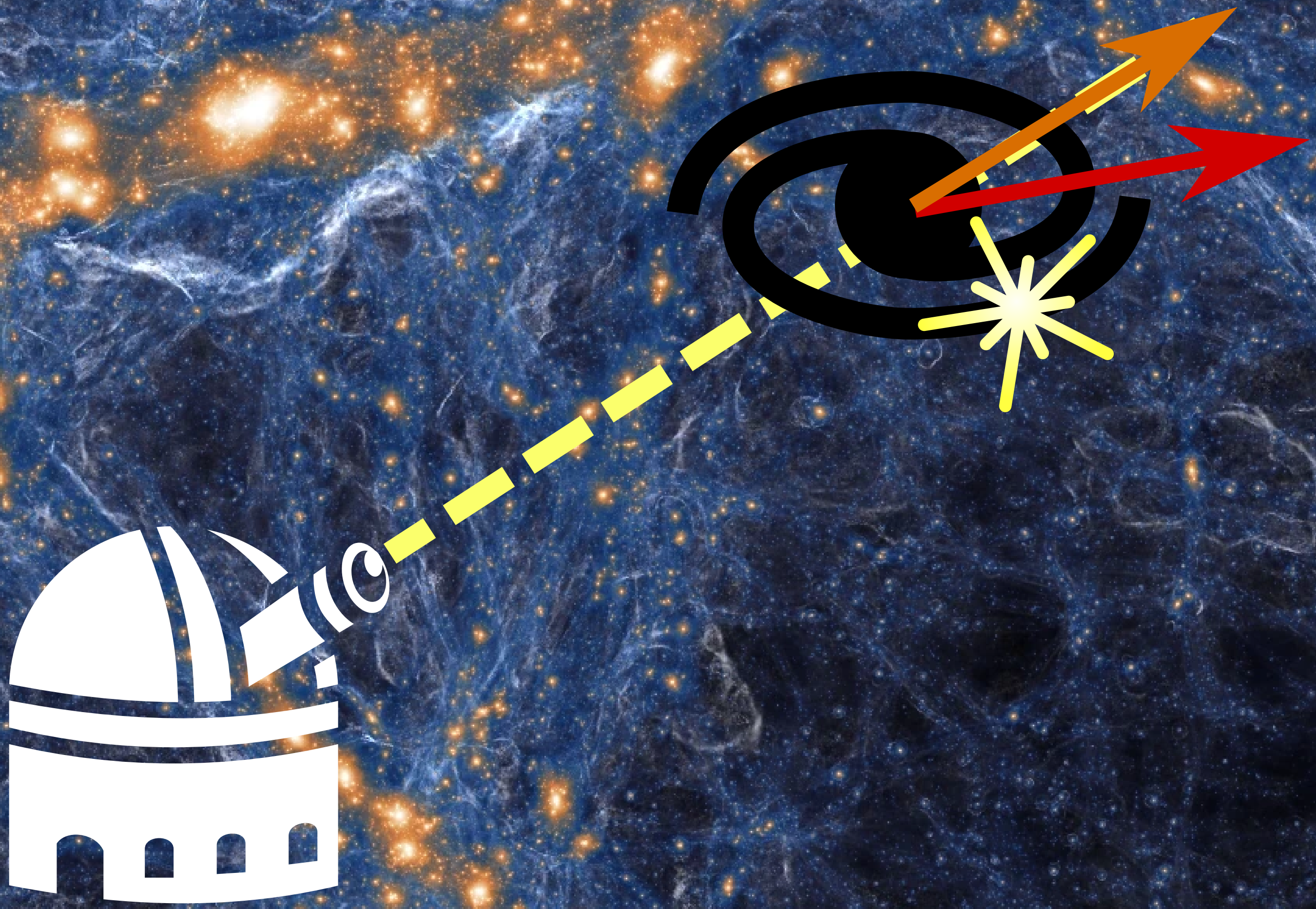

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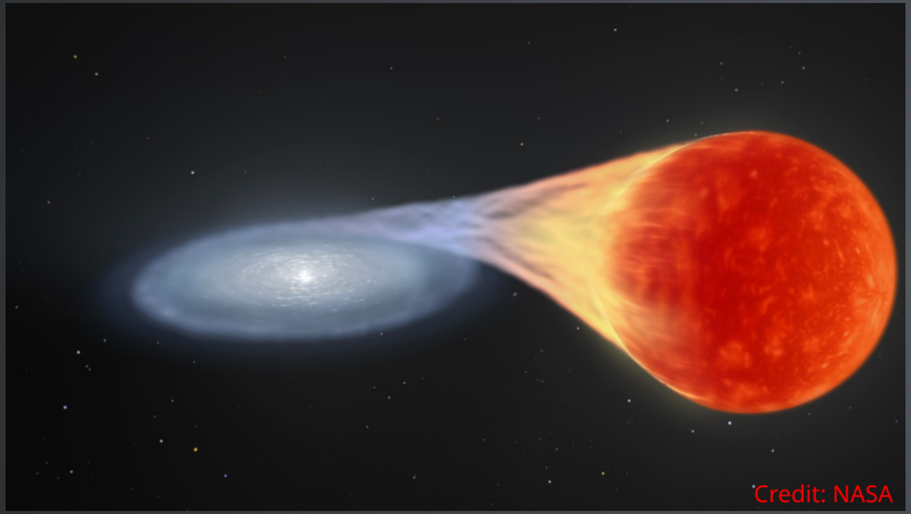

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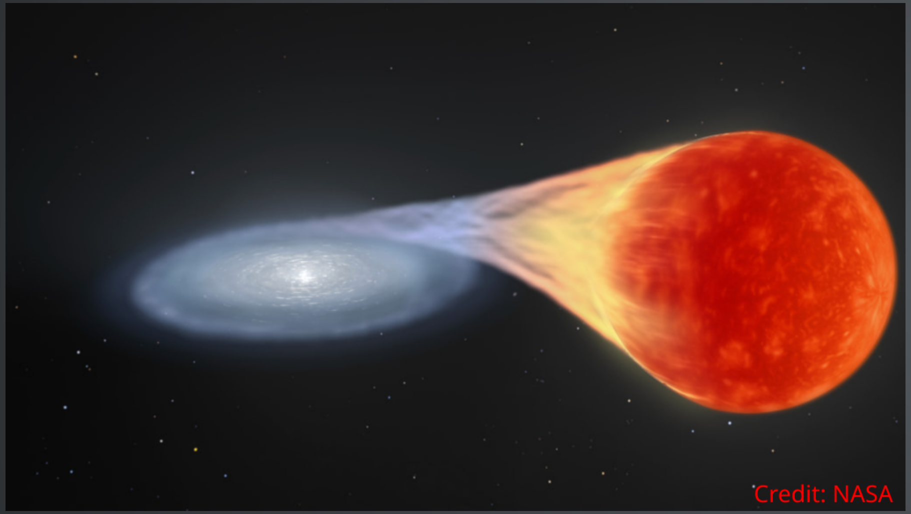
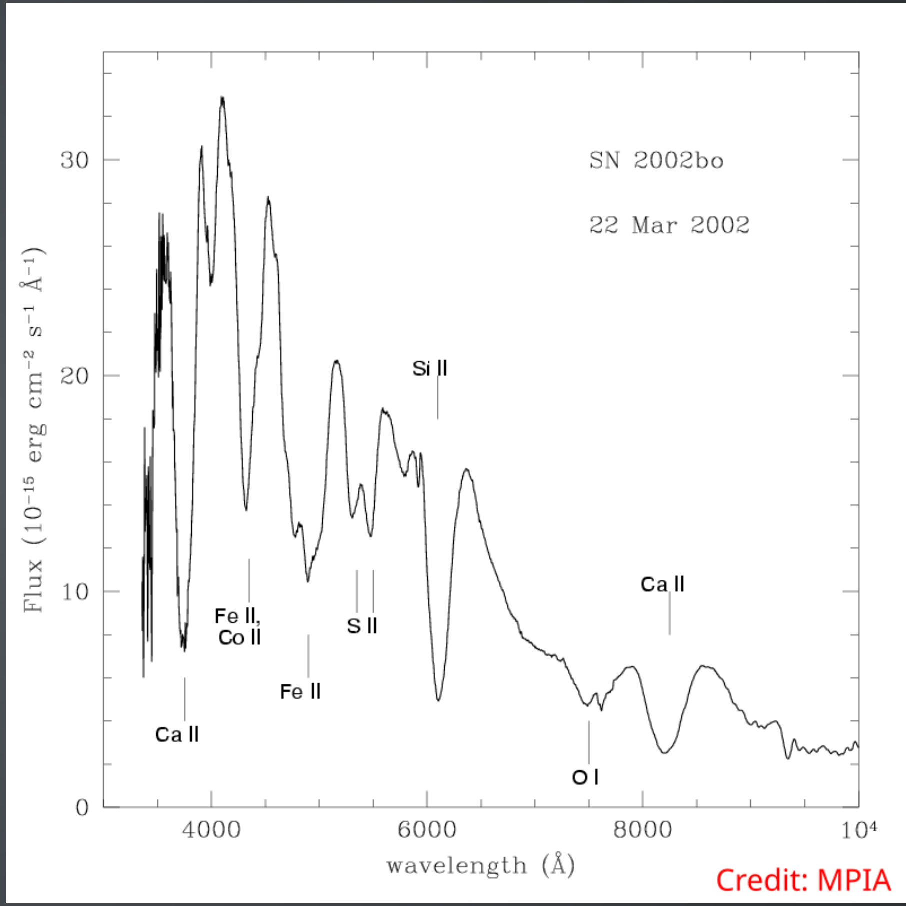
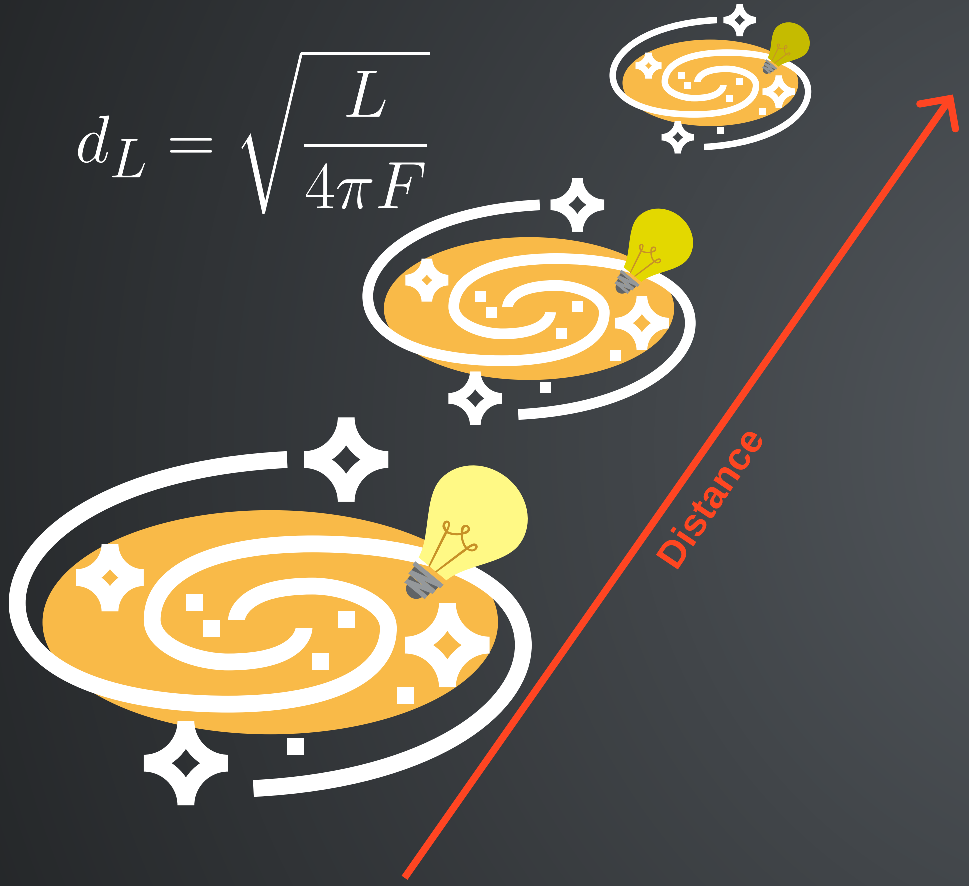




Type Ia supernovae (SNe Ia): powerful probes for cosmology

$$d_L = \sqrt{\frac{L}{4\pi F}}$$



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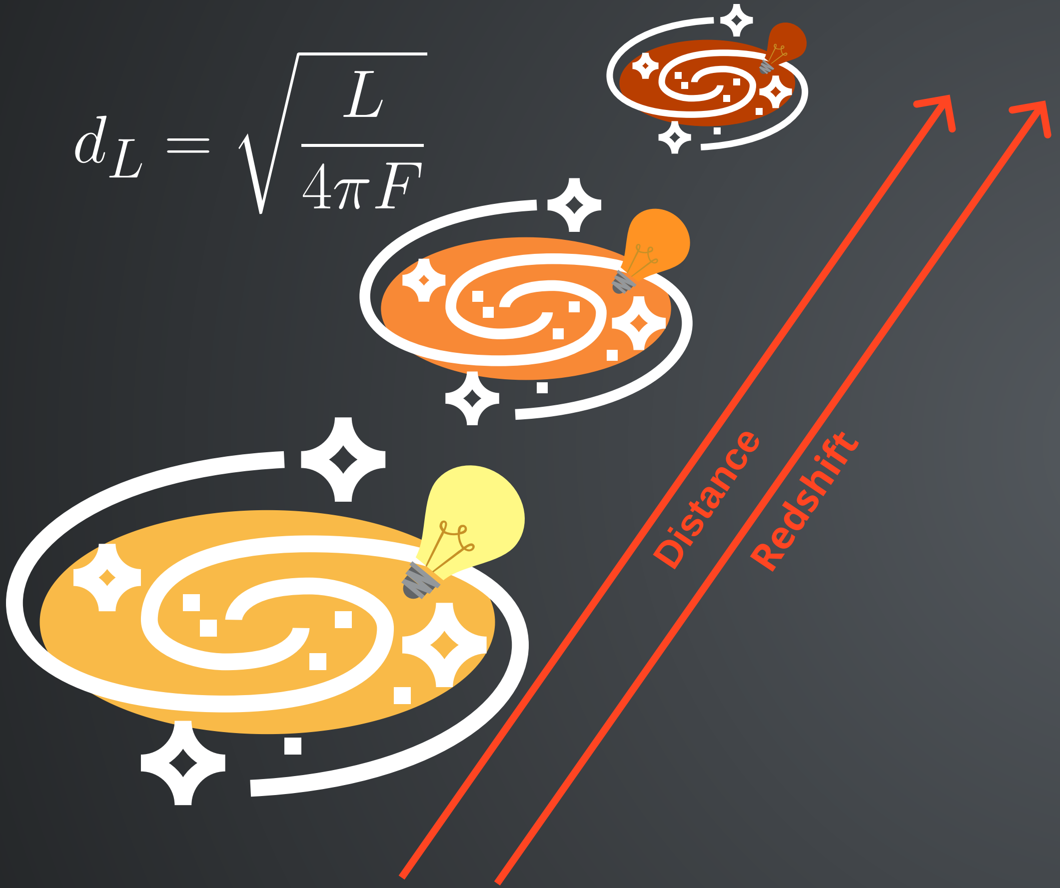

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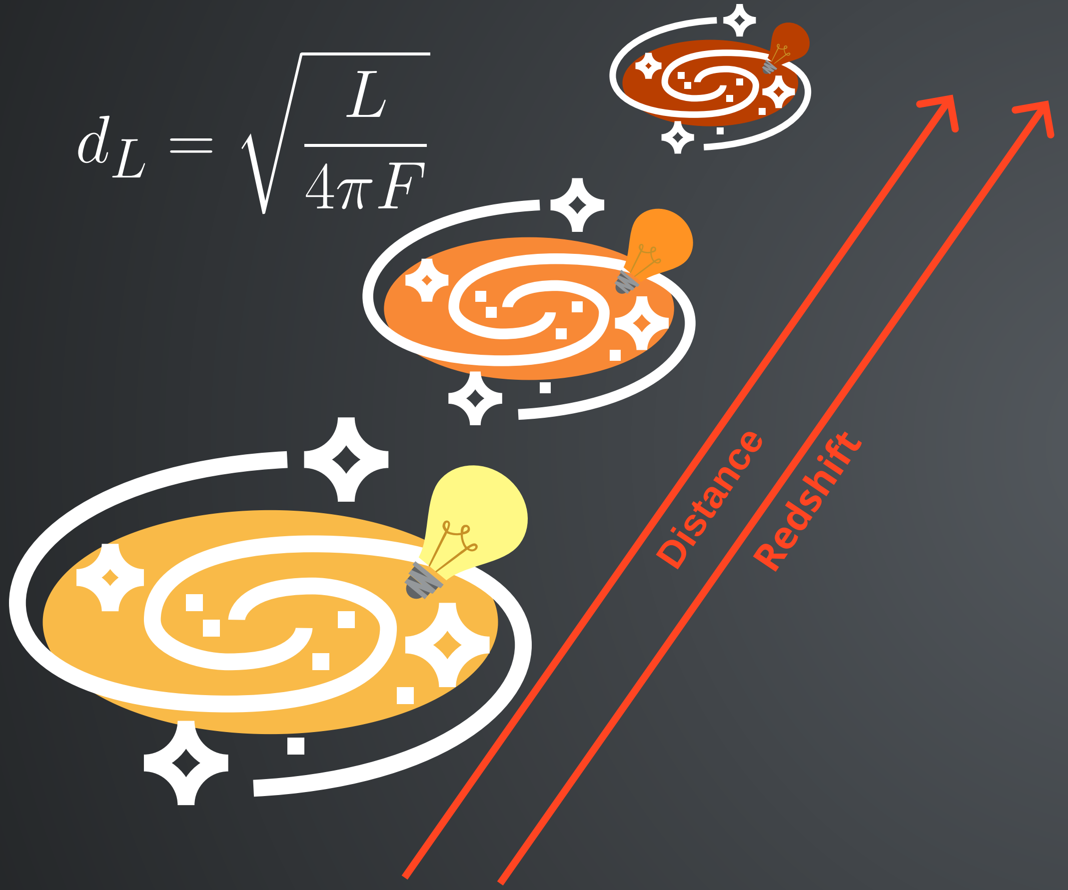

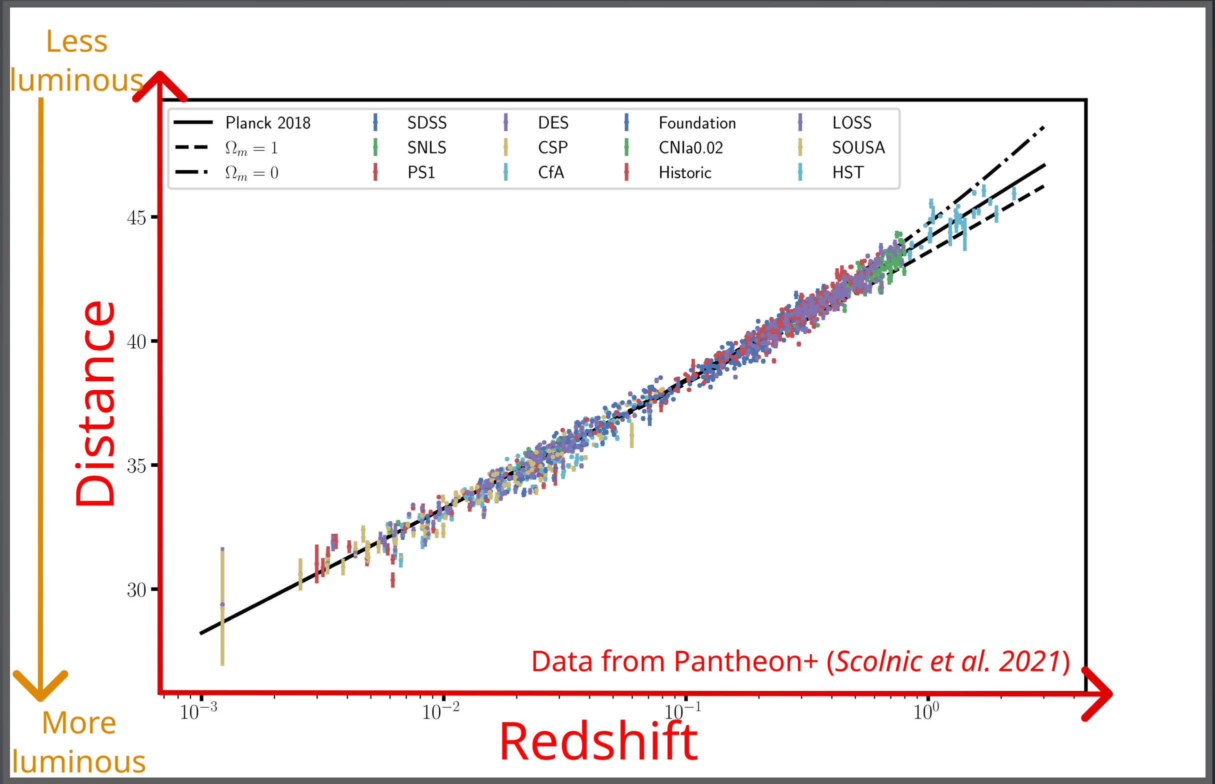

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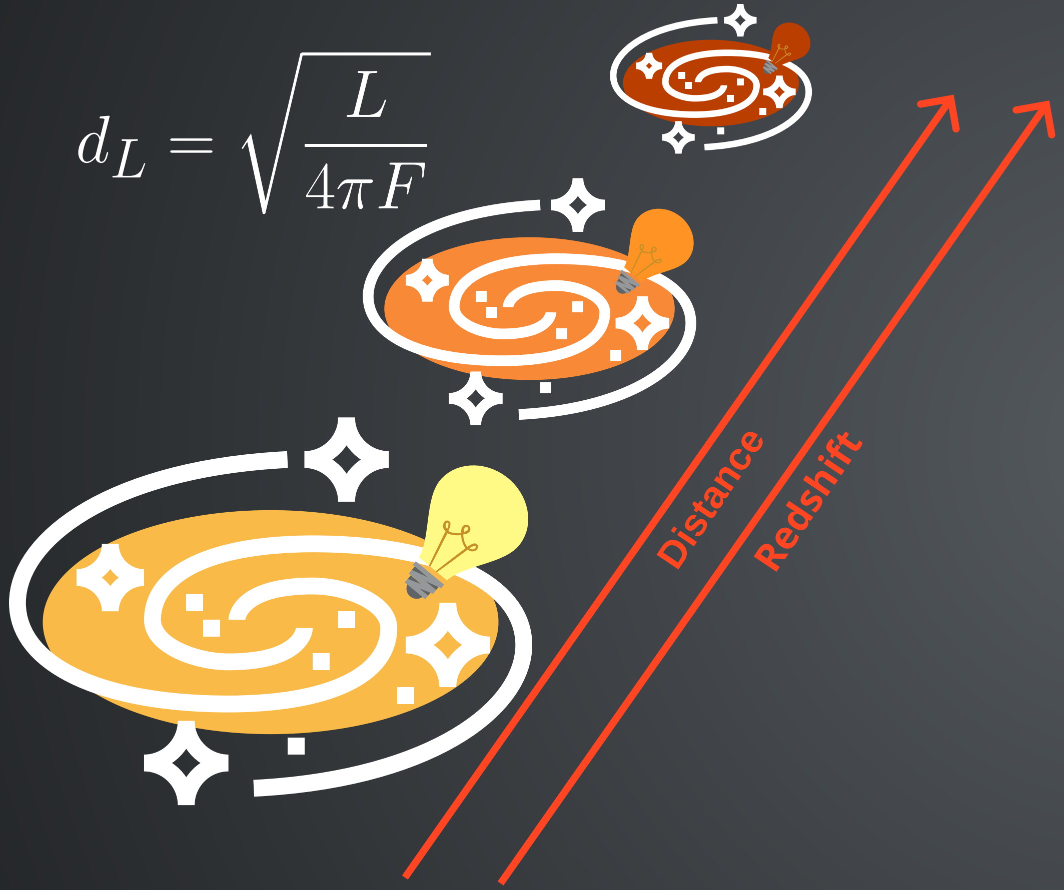

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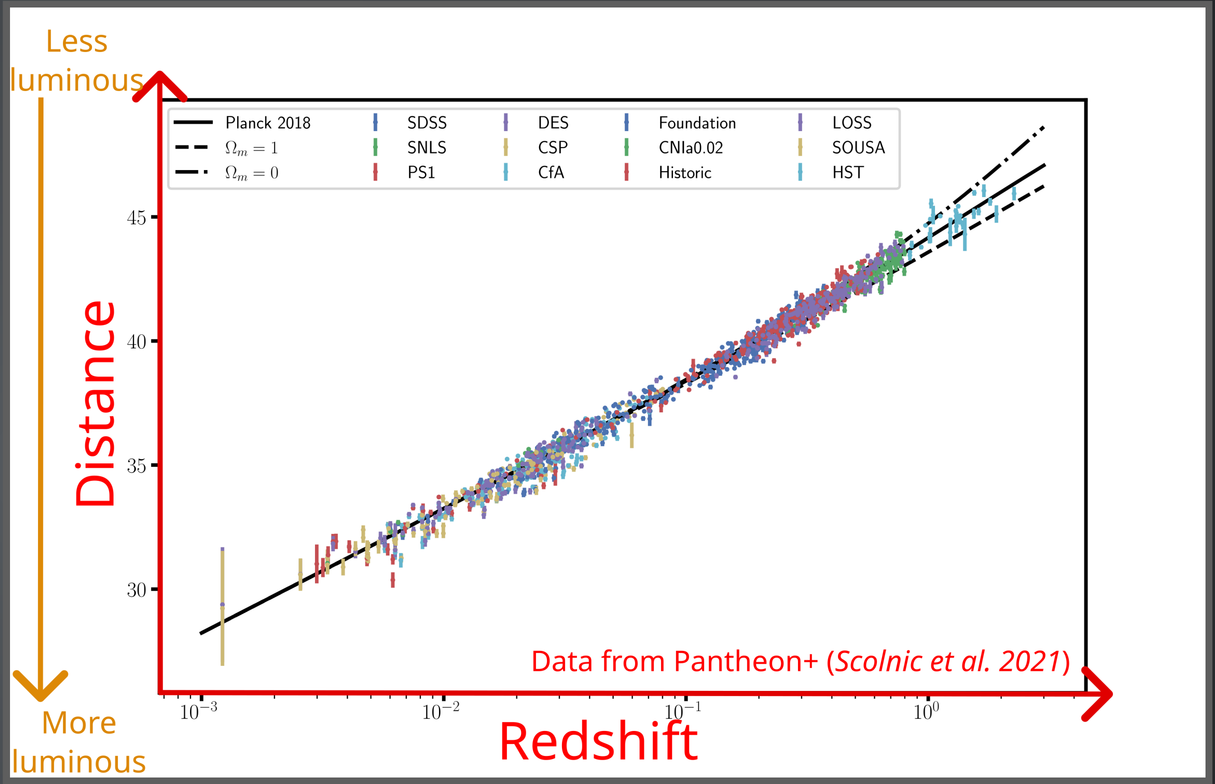

Distance modulus:

$$\mu = m_B - M_B \propto 5\log(d_L)$$

SNe Ia: a few words about standardization

SNe Ia are not perfectly standard !!!

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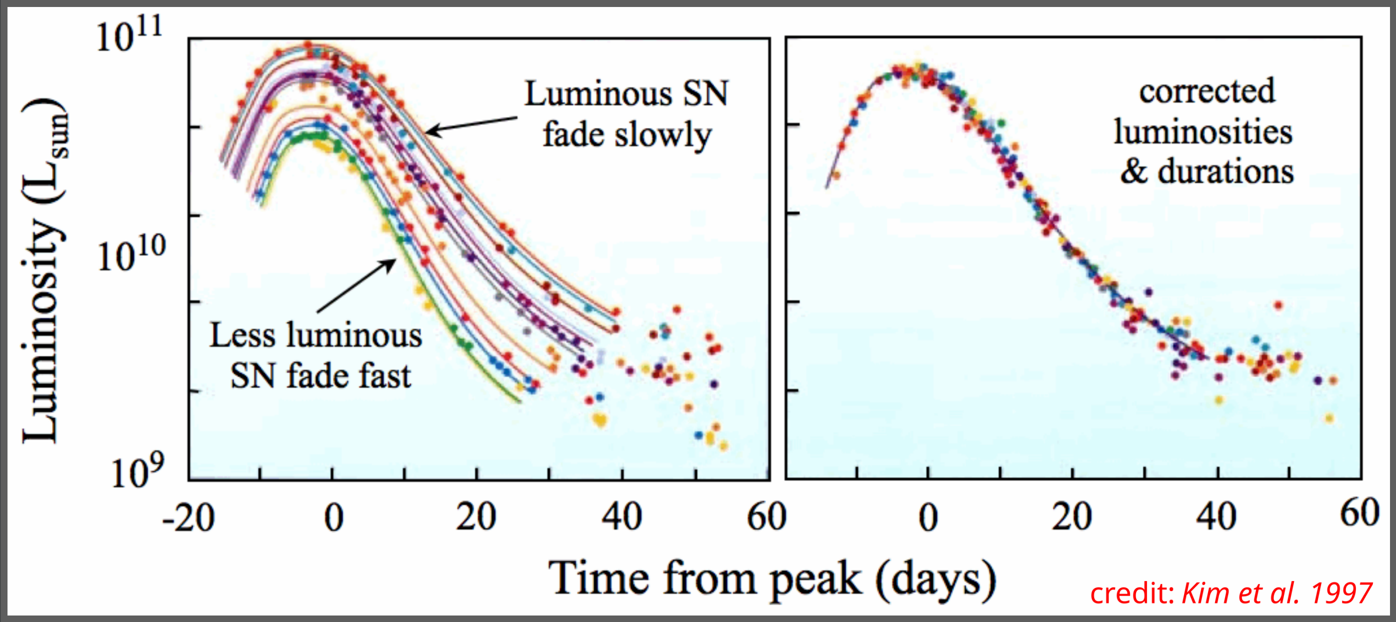
Correlation of peak magnitude with stretch, color and host galaxies exists



credit: *Kim et al. 1997*

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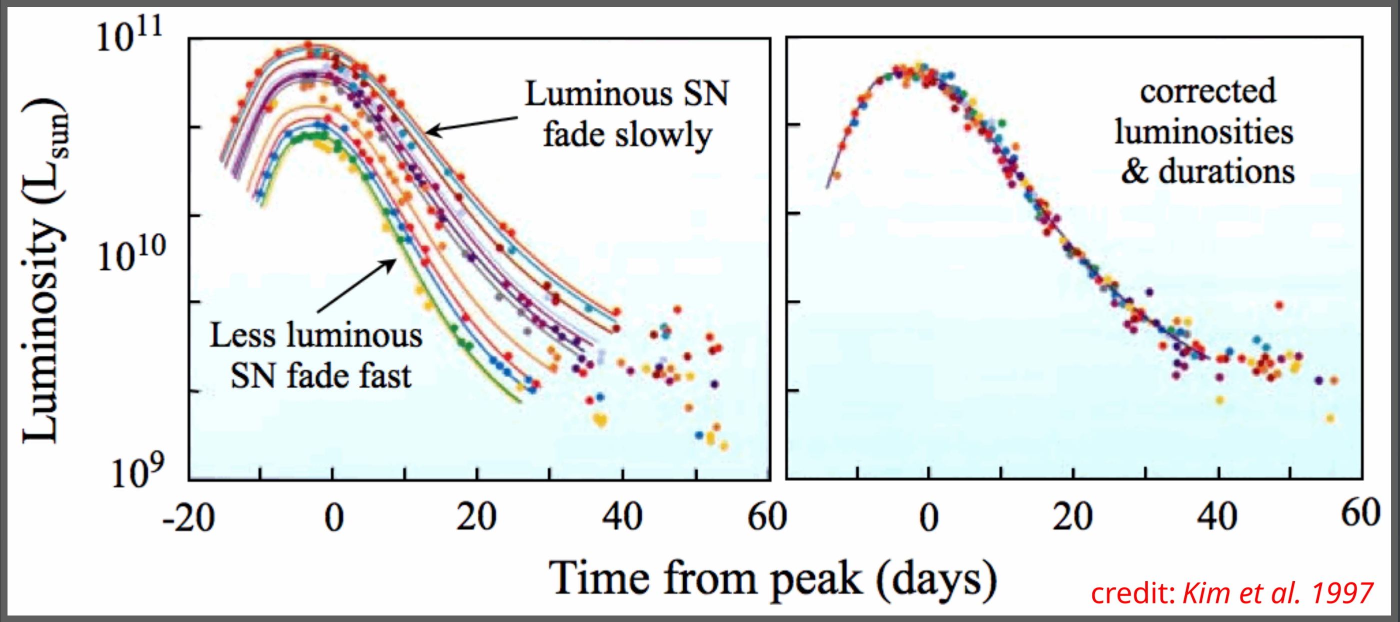

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Tripp relation: $m_B^{\rm std} = m_B + \alpha x_1 - \beta c$

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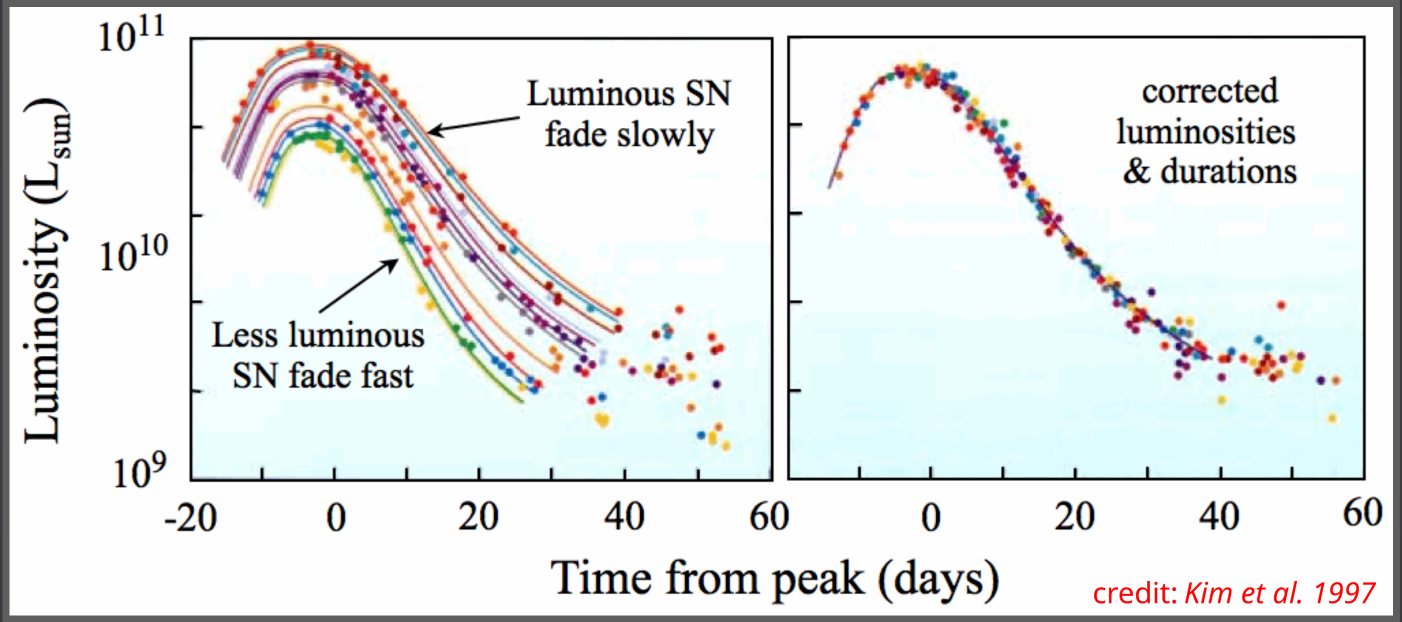


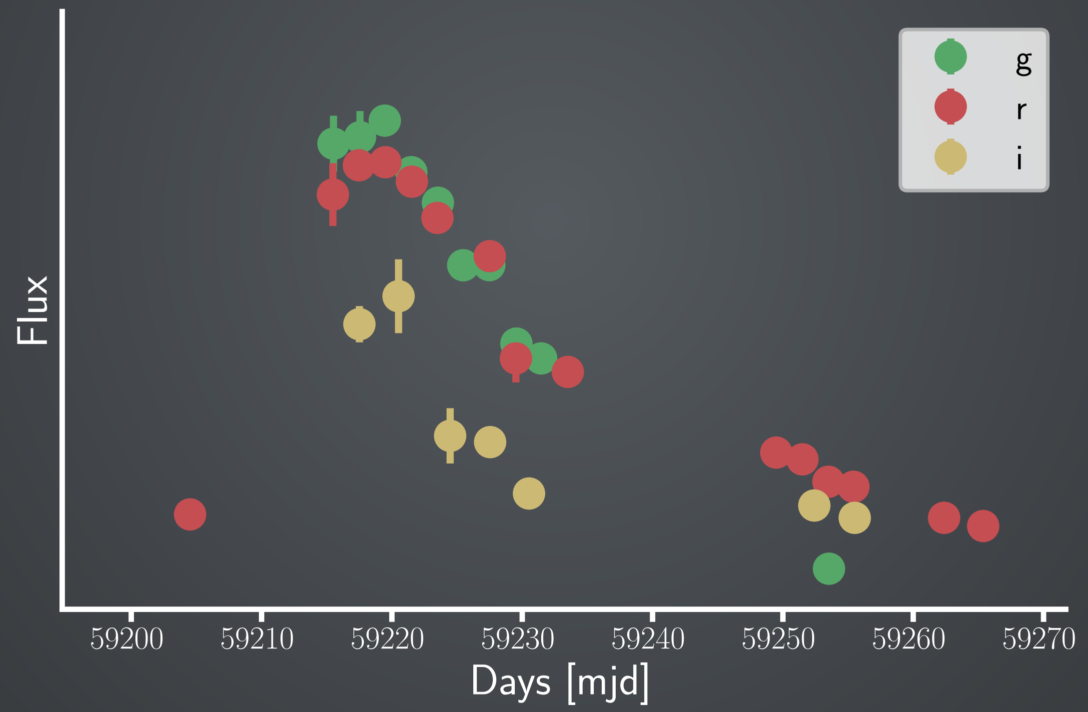
Tripp relation: $m_B^{\mathrm{std}} = m_B + \alpha x_1 - \beta c$

After standardization $\sigma_M \sim 0.12$

SNe Ia: a few words about standardization

How to get m_B, x_1 and c?

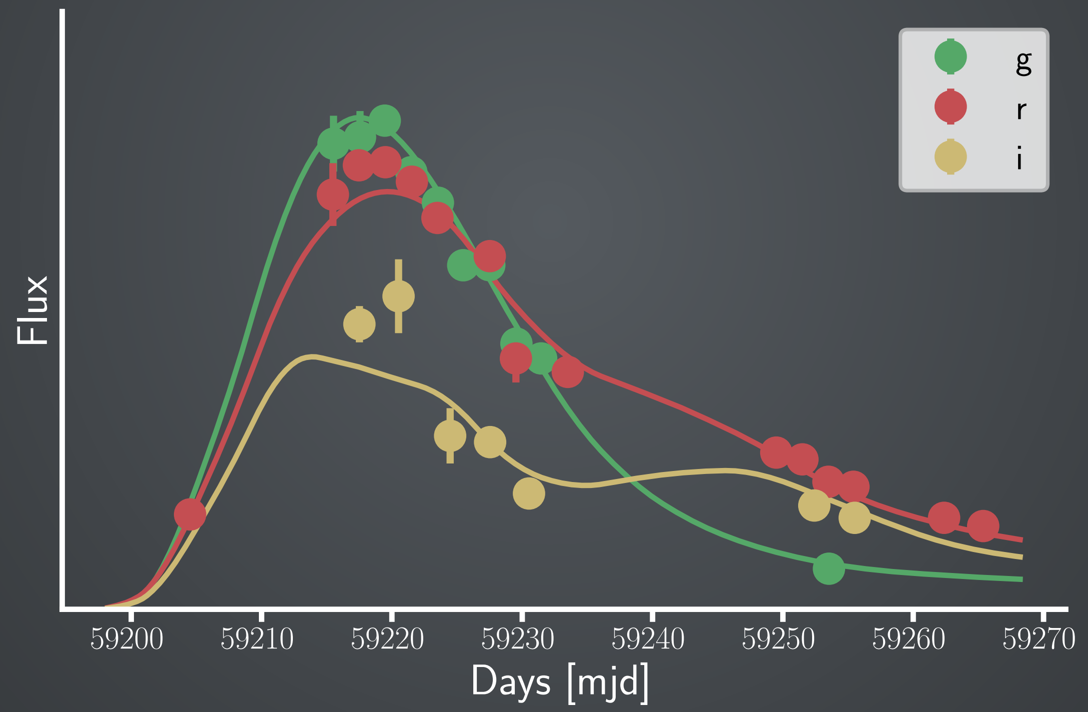
Collect data



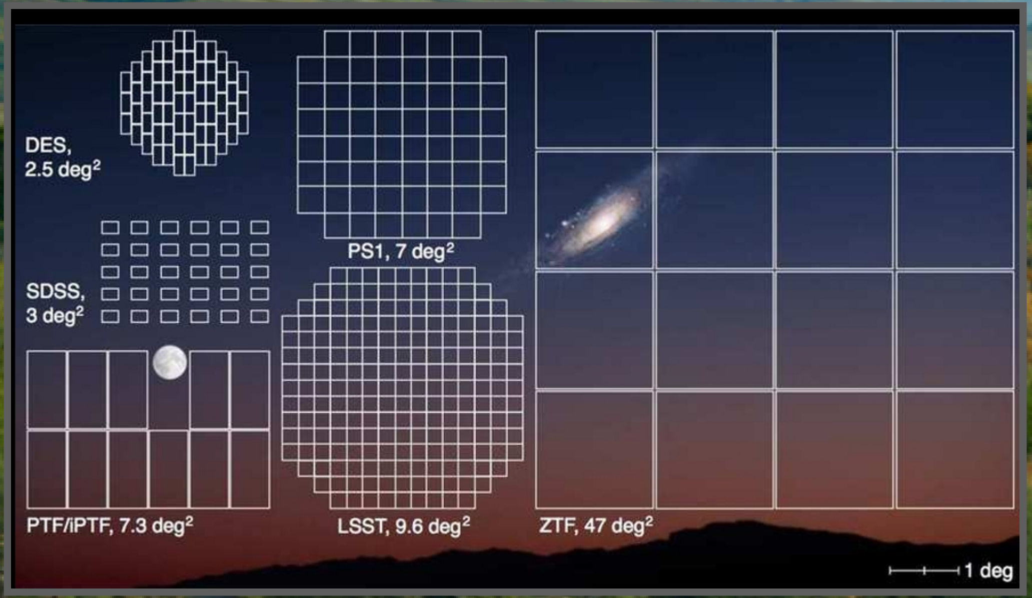
SNe Ia: a few words about standardization

How to get m_B, x_1 and c?

Adjust lightcurve with SALT2 (SED model for SNe Ia)

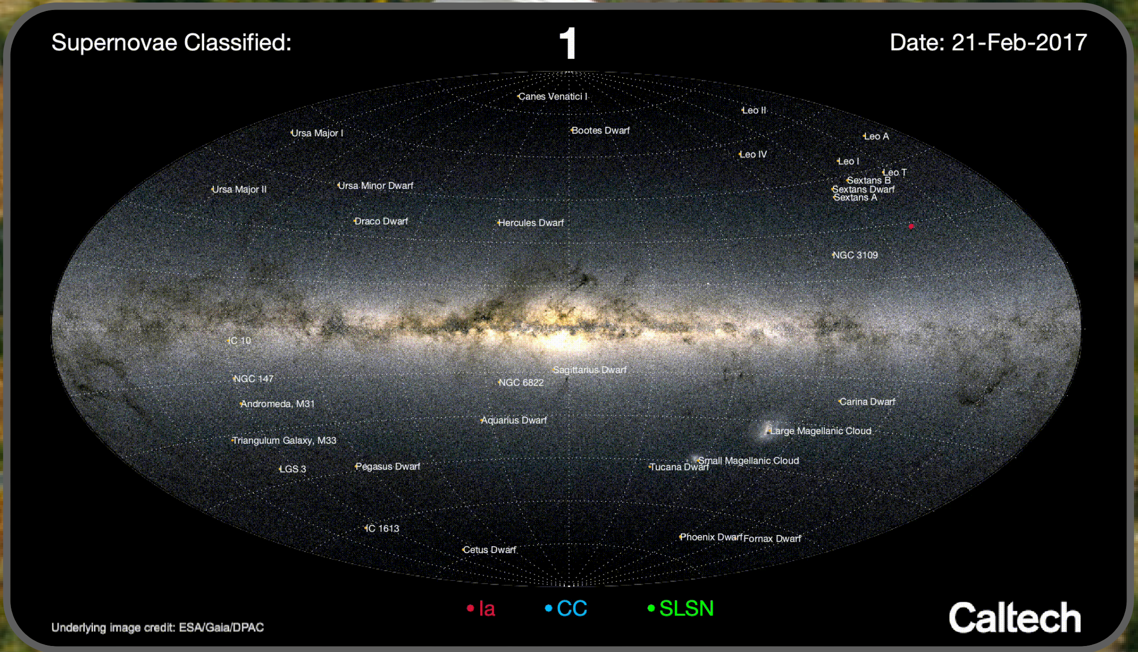


The Zwicky Transient Facility survey



The ZTF survey:

- Photometric telescope observing 3/4 of the sky every $\sim$ 2 nights in 3 bands
- Spectroscopic telescope measuring transient spectra



$\sim$ 8000 classified supernovae

More than 3000 SNe Ia at low redshift

$z < 0.1$

Image credits: ZTF.Caltech

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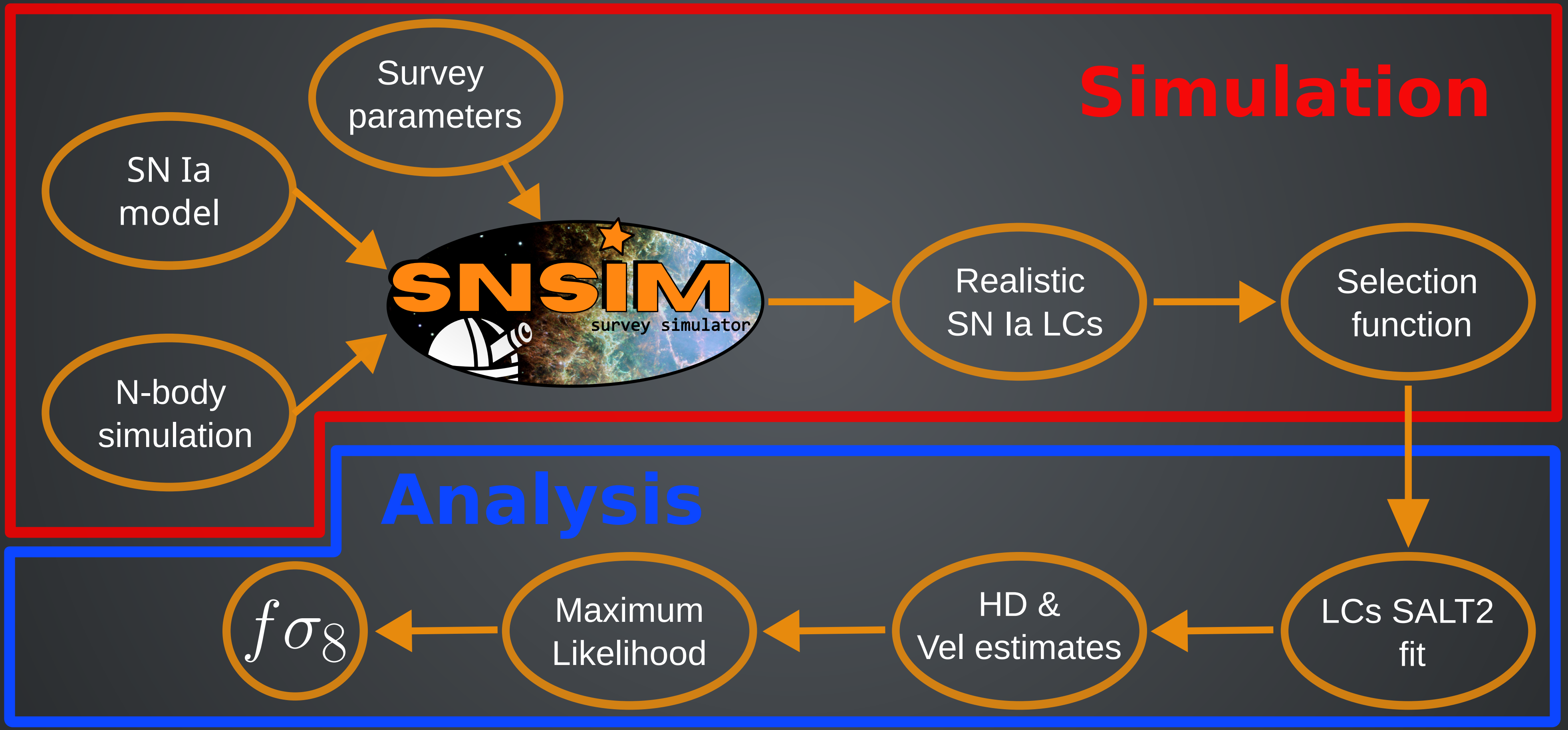

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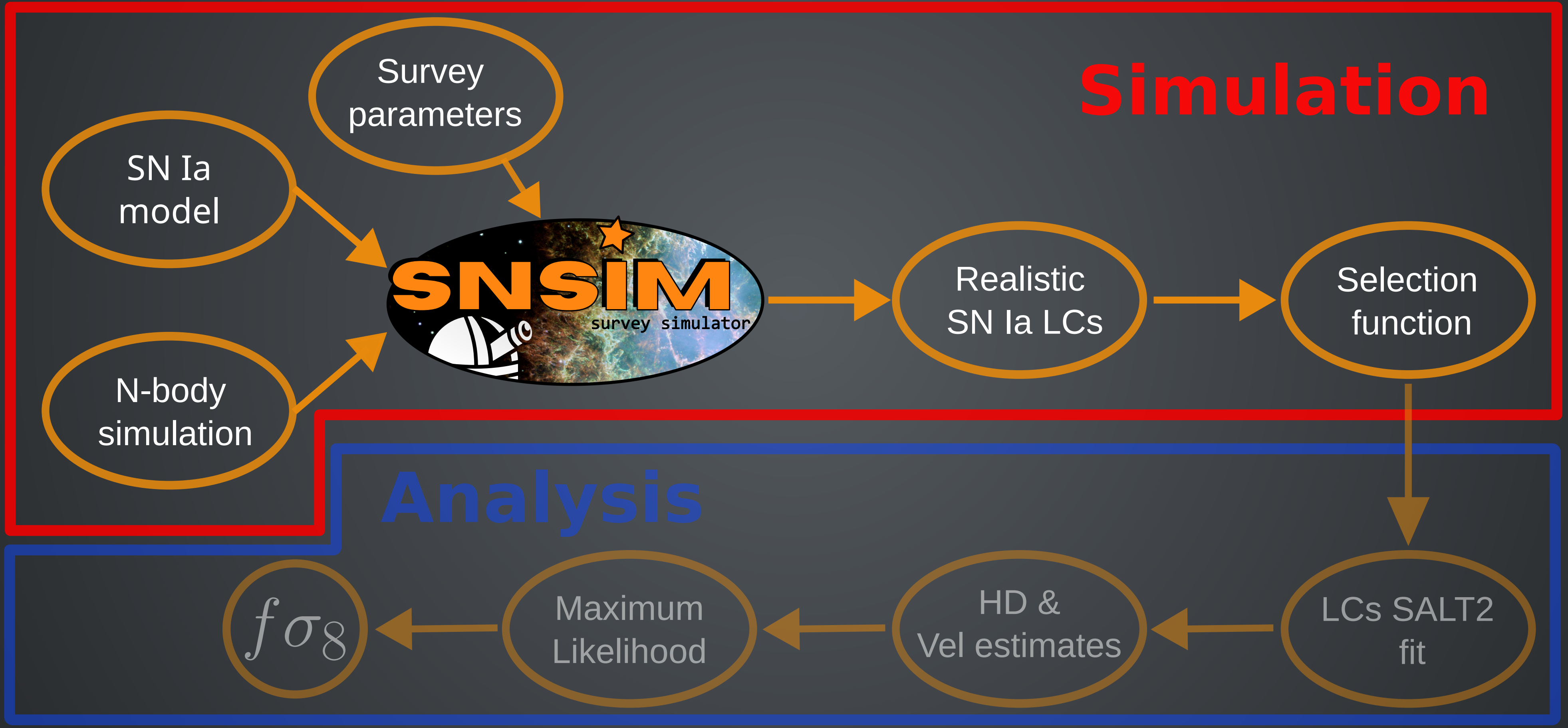

Simulation: the N-Body simulation

OuterRim (*Heitmann et al. 2019*)

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WMAP cosmology, $f\sigma_8 = 0.382$

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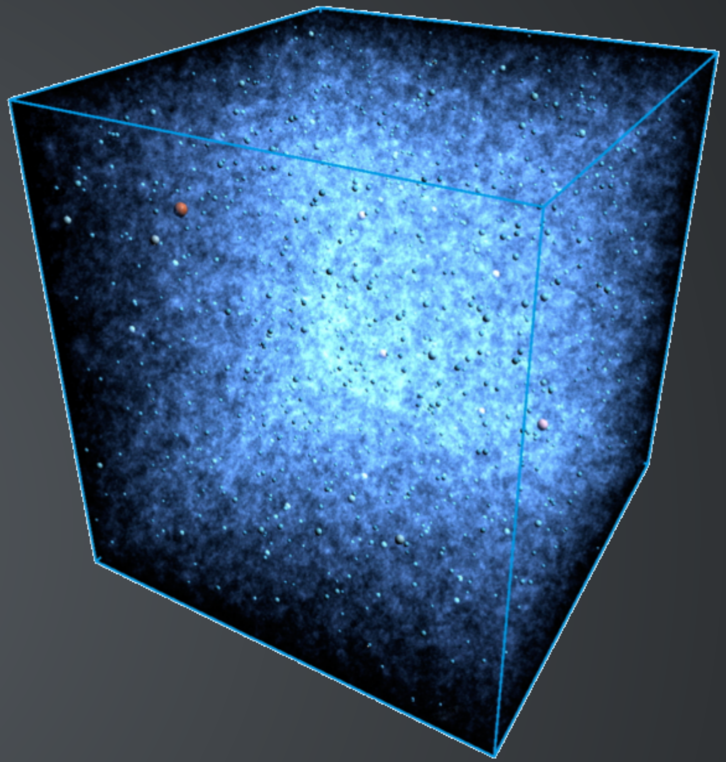
(3 Gpc.h^{-1})^3 box of dark matter halos at $z = 0$
$\Rightarrow$ 27 ZTF realisations up to $z \sim 0.17$



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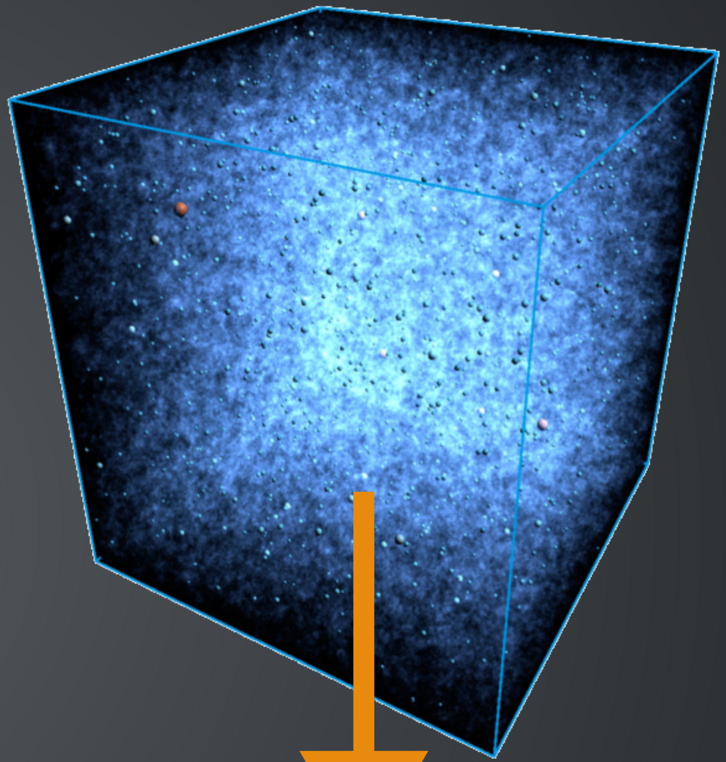
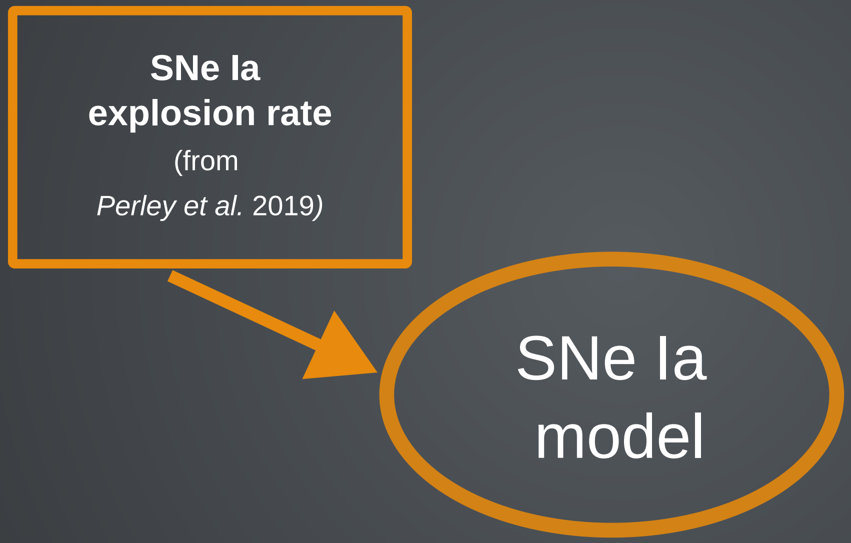


Host catalog
(RA, Dec, z_{cos}, z_p)

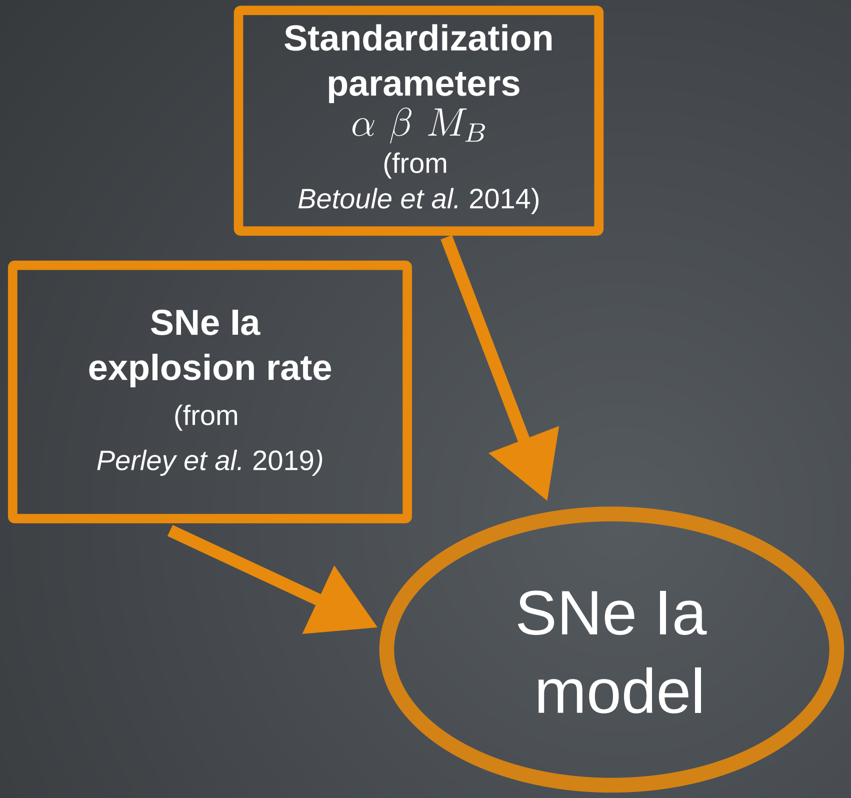
Simulation: SN Ia model

SNe Ia
model

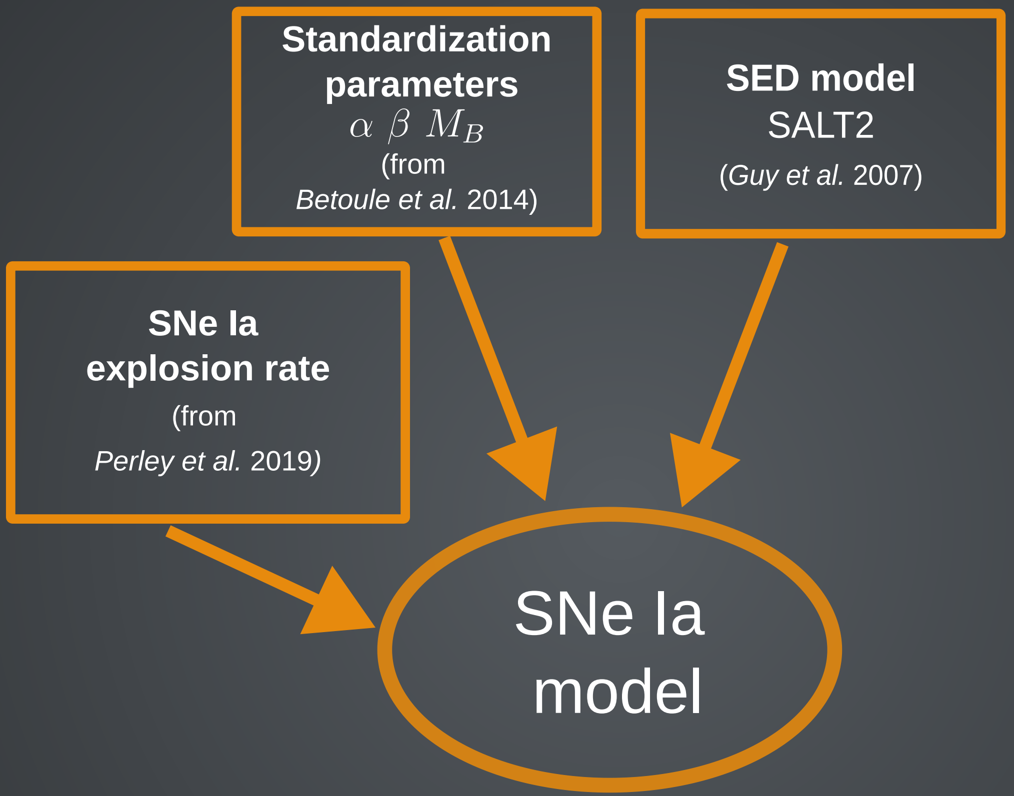
Simulation: SN Ia model



Simulation: SN Ia model



Simulation: SN Ia model



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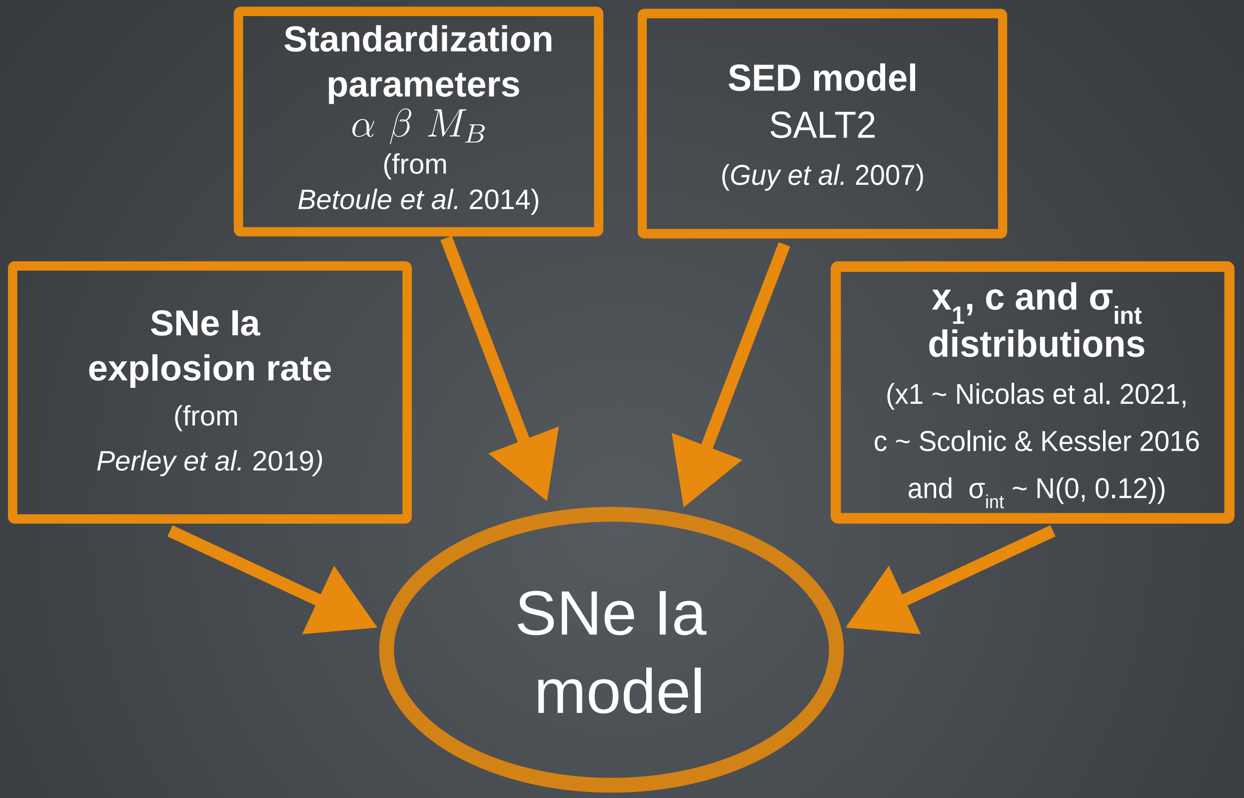


Simulation: SN Ia model

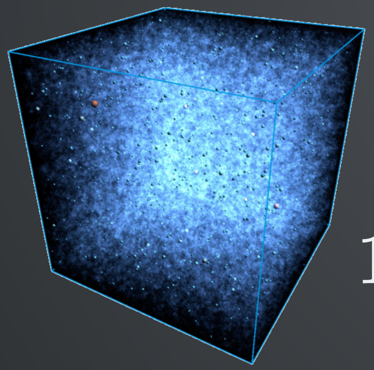
Standardization parameters
$\alpha \ \beta \ M_B$
(from
Betoule et al. 2014)

SED model
SALT2
(*Guy et al.* 2007)

SNe Ia explosion rate
(from
Perley et al. 2019)

x_1, c and σ_{int} distributions
(x1 ~ Nicolas et al. 2021,
c ~ Scolnic & Kessler 2016
and σ_{int} ~ N(0, 0.12))

SNe Ia model



$$1 + z_{\rm obs} = (1 + z_{\rm cos})(1 + z_{\rm p})$$

Simulation: SN Ia model

Standardization parameters
$\alpha \ \beta \ M_B$
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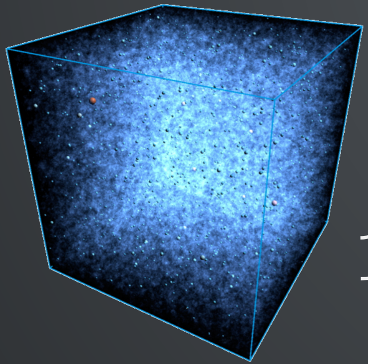


$$1 + z_{\mathrm{obs}} = (1 + z_{\mathrm{cos}})(1 + z_{\mathrm{p}})$$

$$m_{B,i} = M_B - \alpha x_{1,i} + \beta c_i + \sigma_{\mathrm{int},i} + \mu(z_{\mathrm{cos},i}) + 10\log(1 + z_{p,i})$$

Simulation: survey parameters

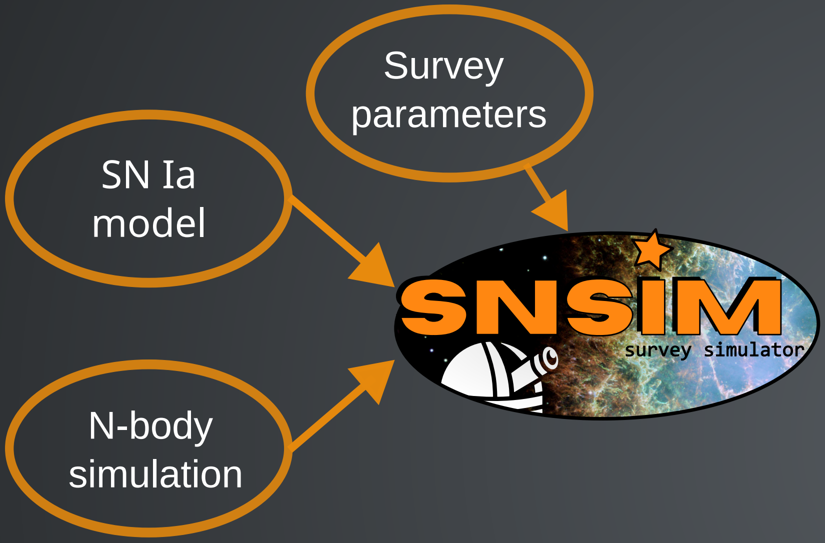
I have worked in ZTF simulation working group to construct ZTF simulation input files

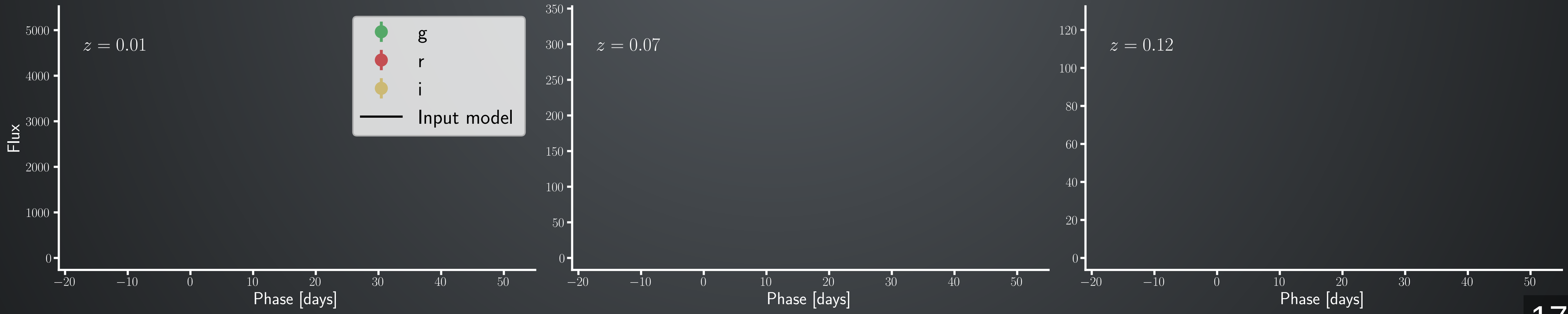
Cadence
(dates, coordinates, filters used)

Instrument & Atmosphere
(CCD gain, zero point, skynoise)

Survey parameters

Simulation: `SNSim` and lightcurves





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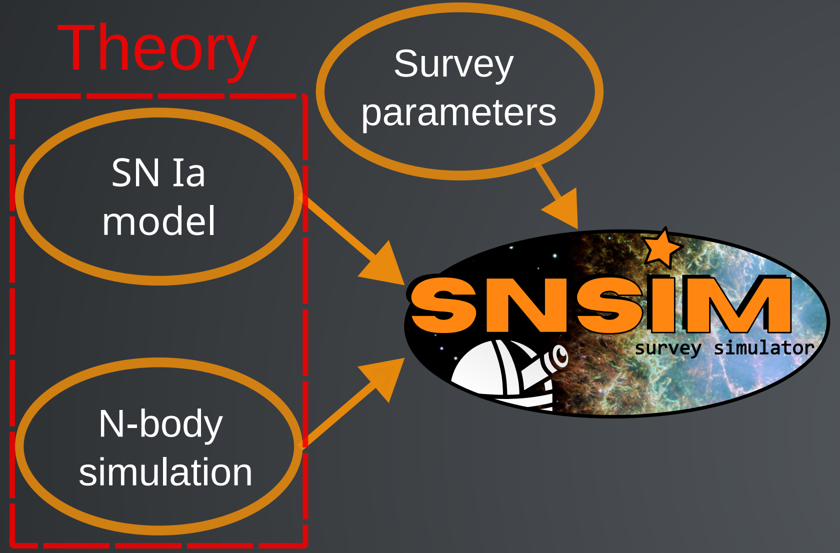

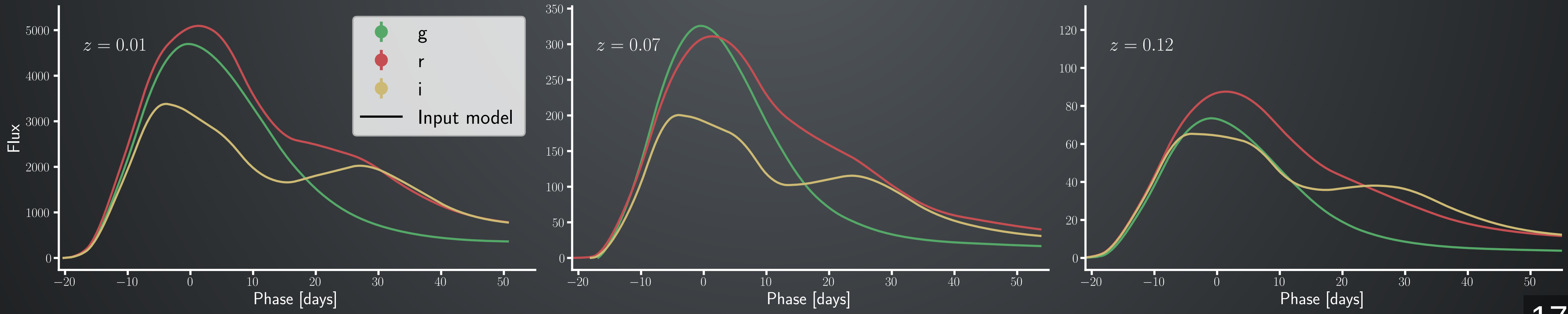

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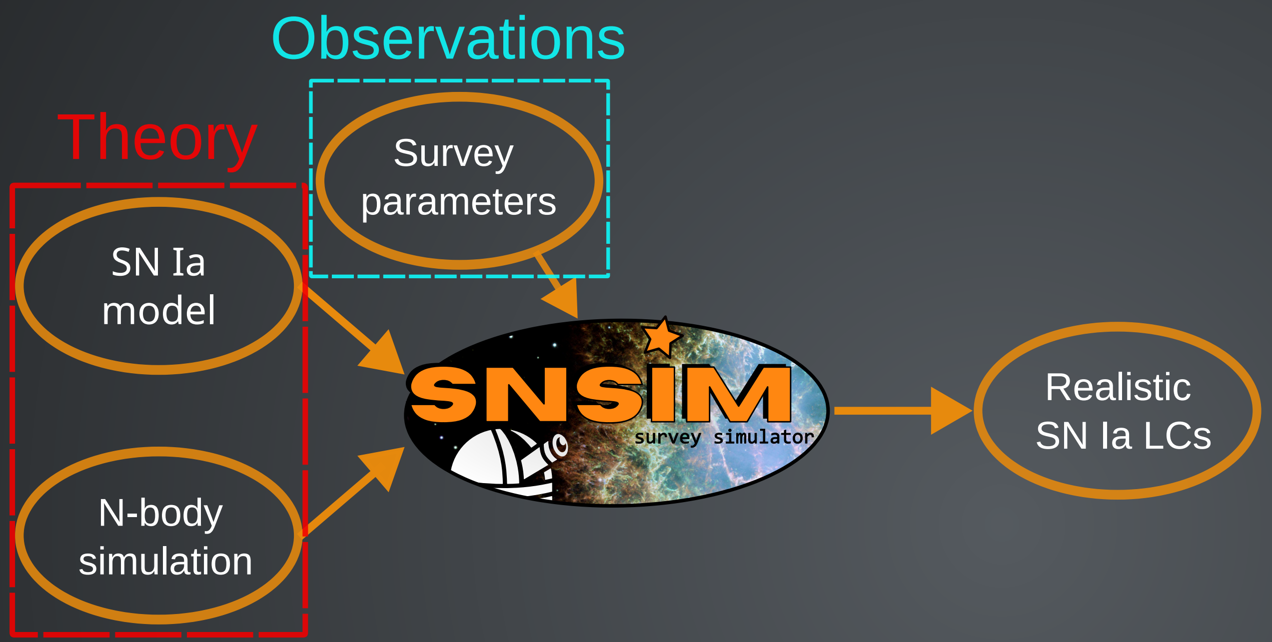
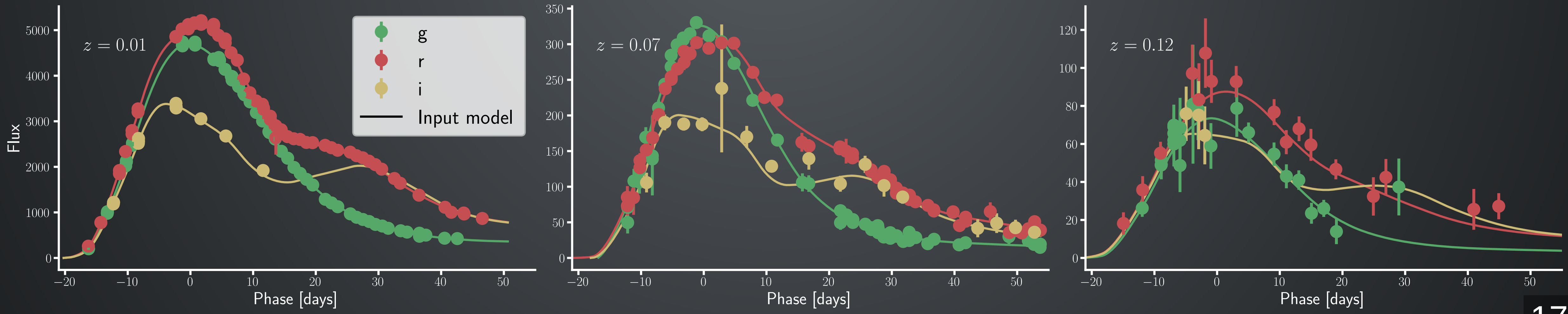
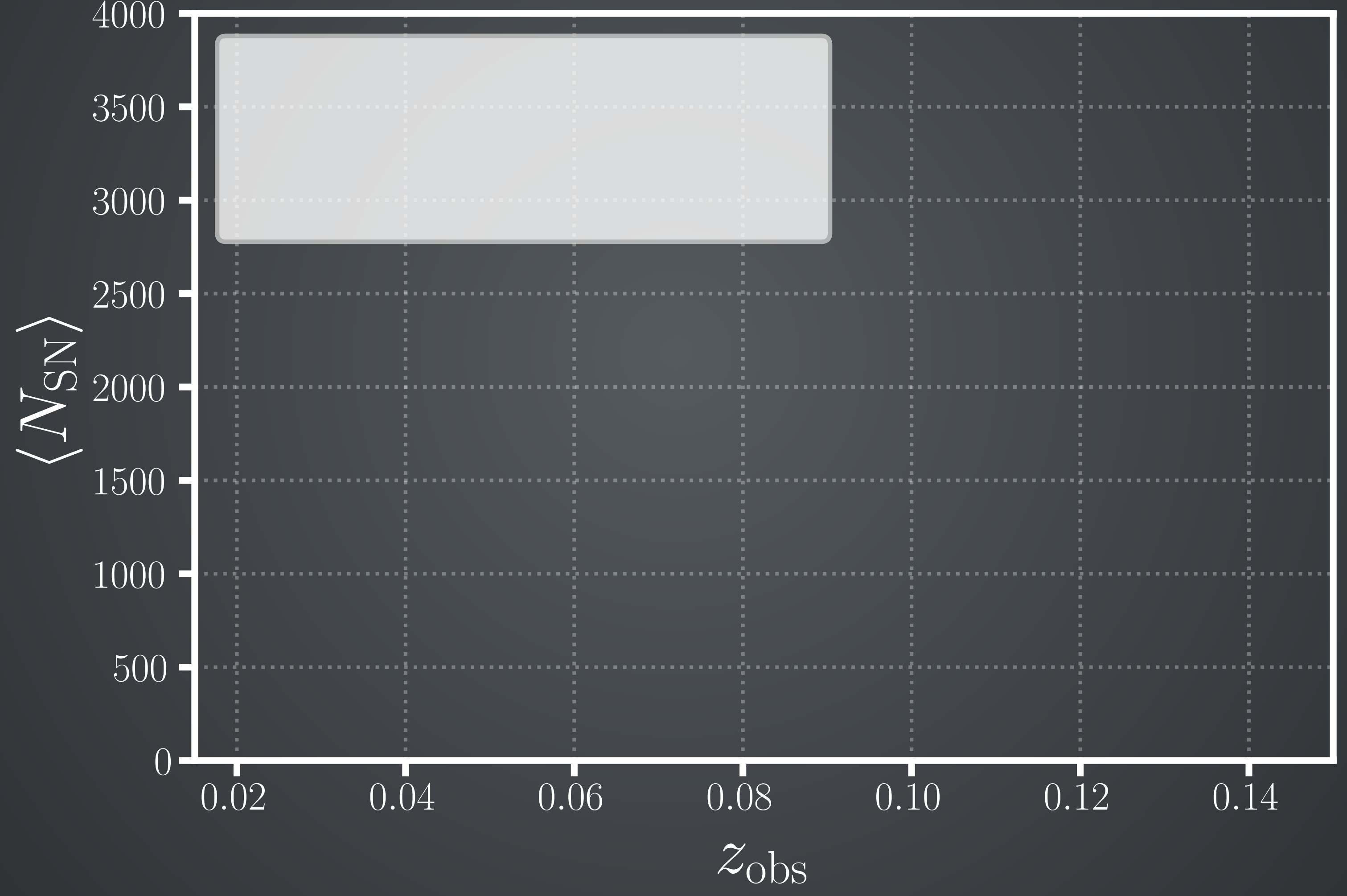


Noise is computed as

$$\sigma_F = \sqrt{F + \sigma_{\rm sky}^2 + \sigma_{\rm ZP}^2}$$



Simulation: applying spectroscopic identification selection function



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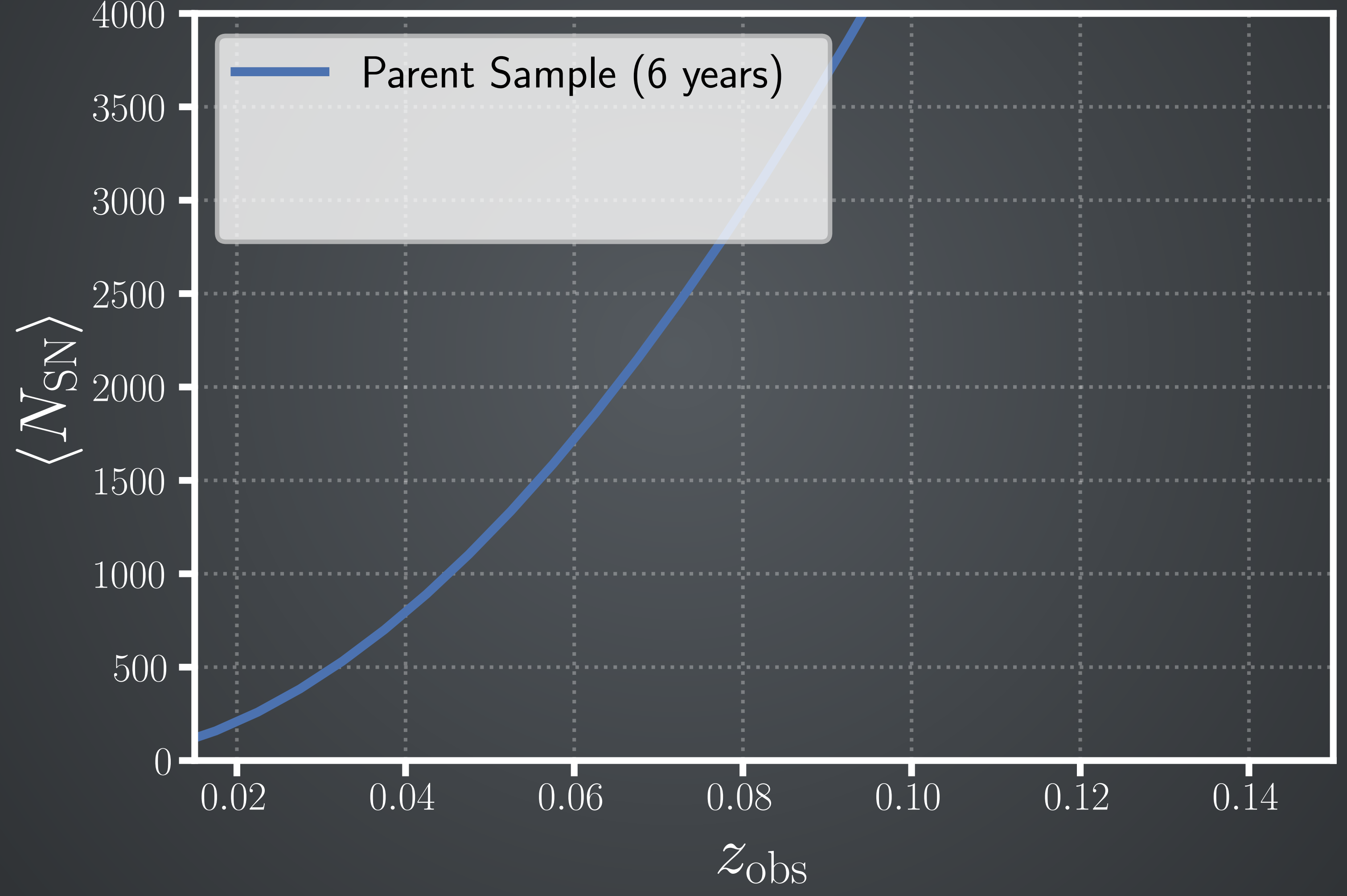
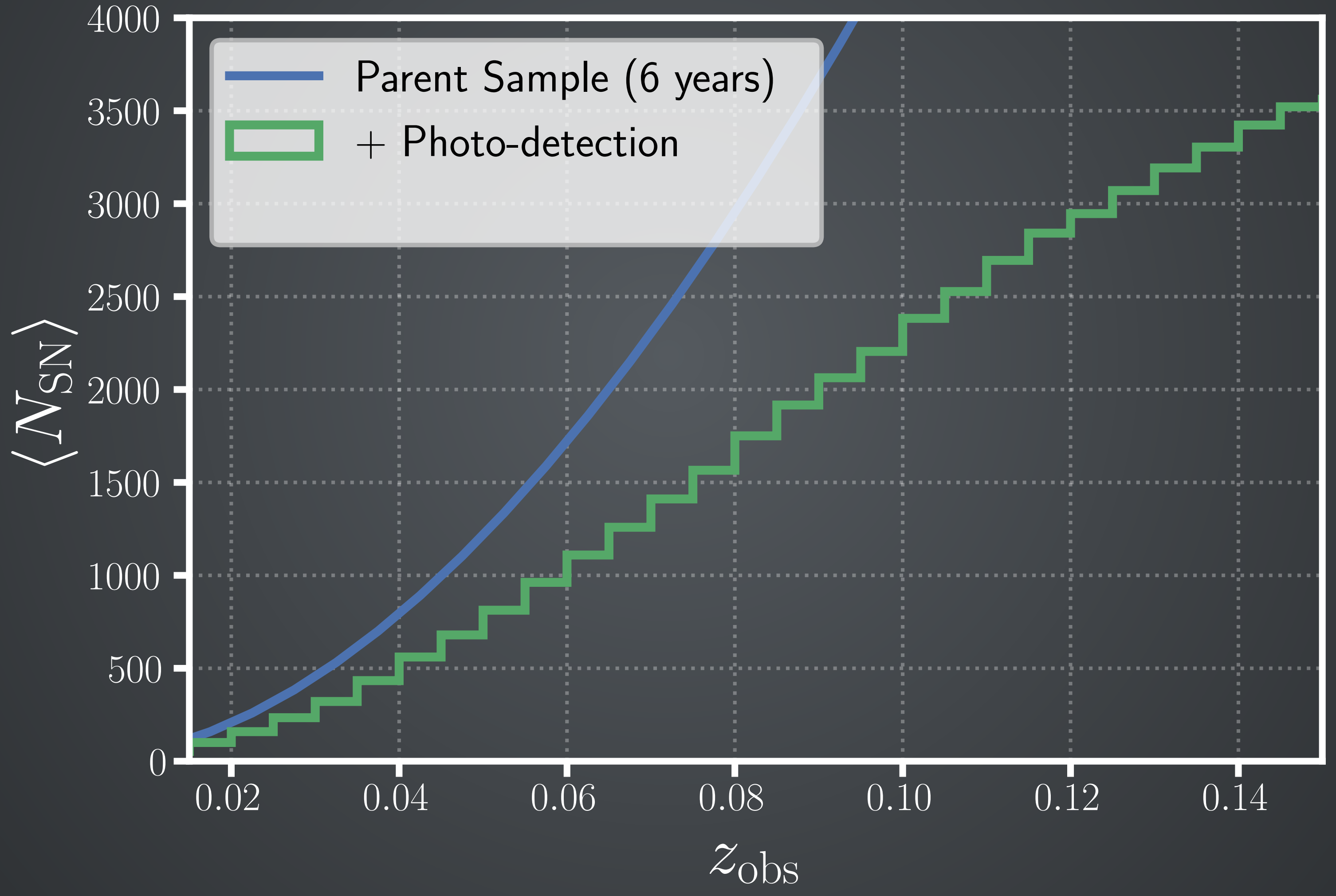


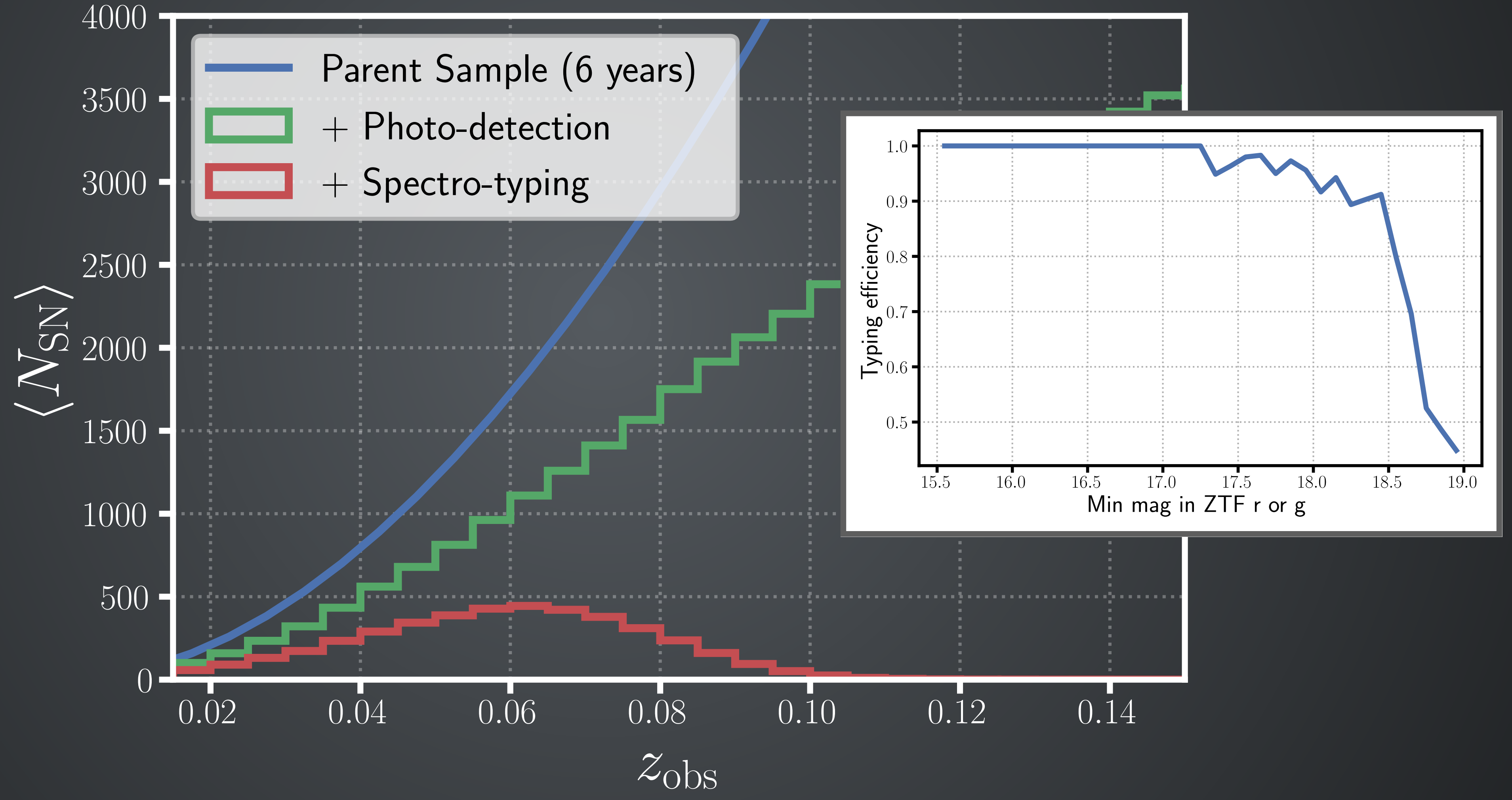
Simulation: applying spectroscopic identification selection function

Detection: 2 points with SNR > 5



Simulation: applying spectroscopic identification selection function

Spectroscopic efficiency from *Perley et al. 2019*



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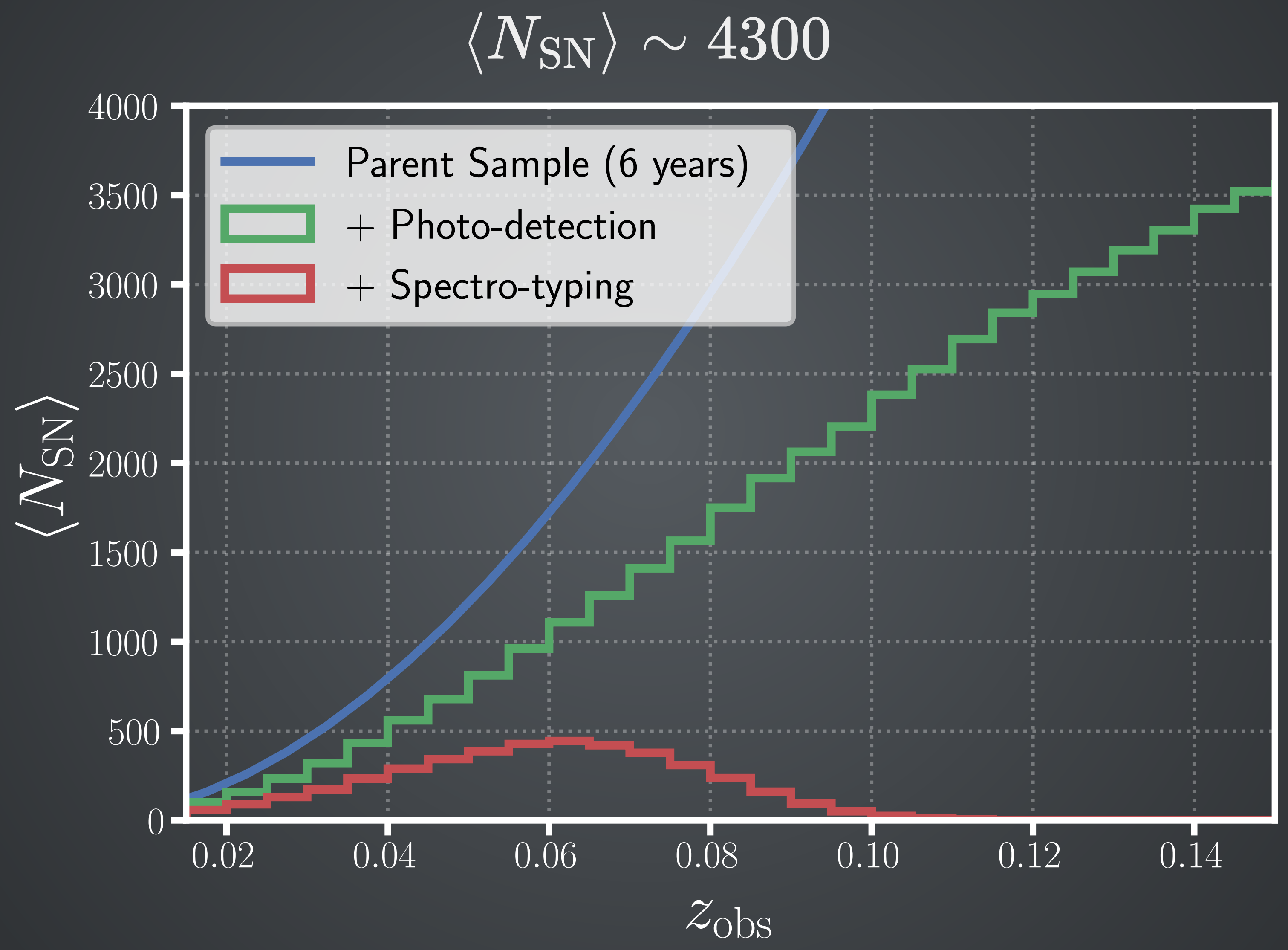
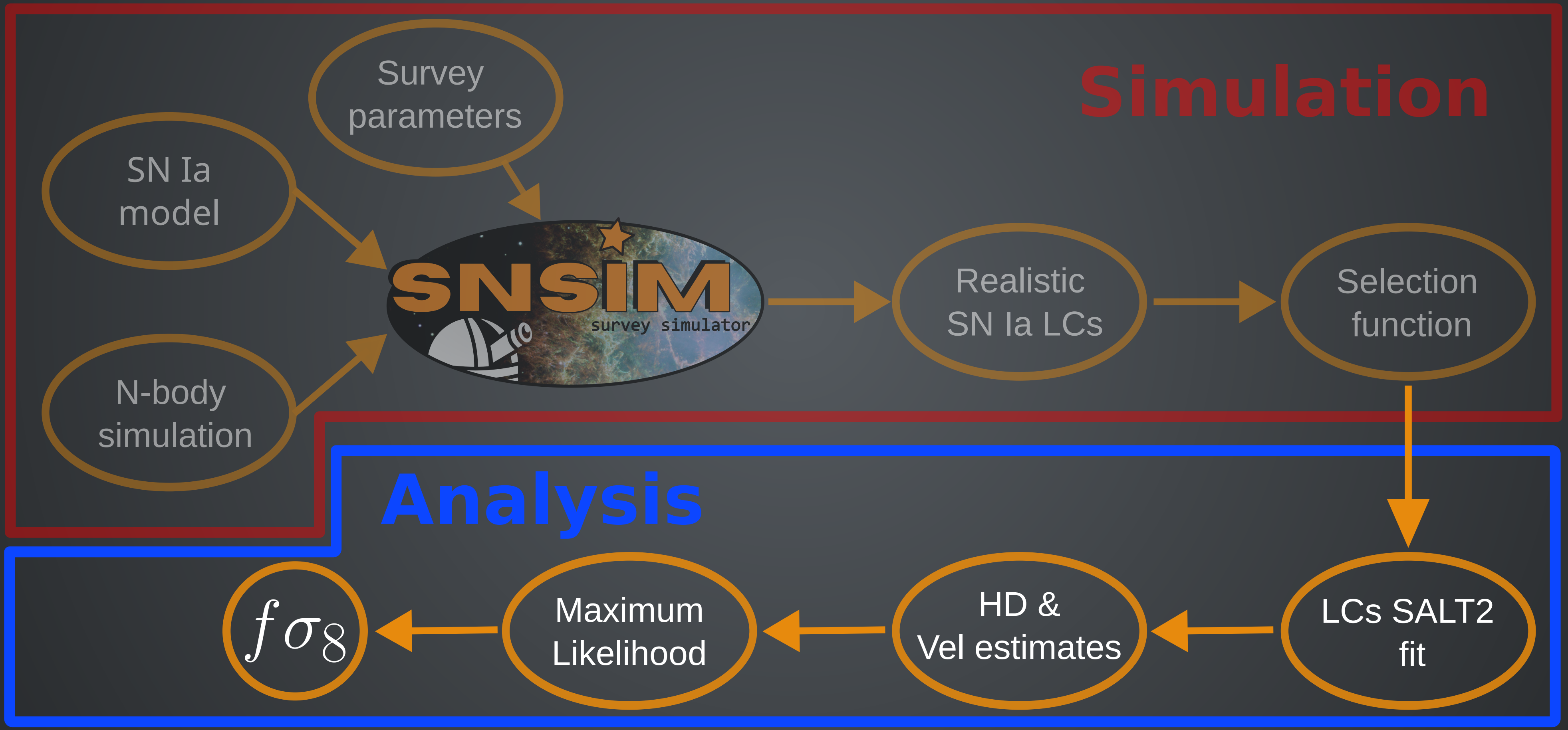


$f\sigma_8$ with SNe Ia peculiar velocities: the simulation and analysis pipeline



Analysis: lightcurves fit and cosmological cut

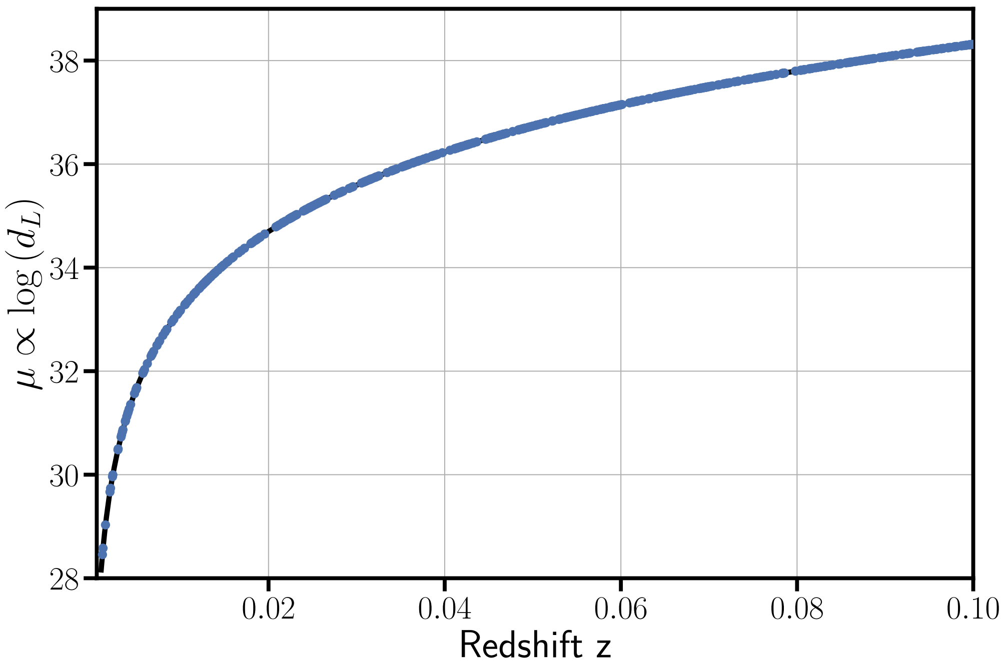
After SALT2 fit, we apply quality cuts:

Cuts	**Remains %**	**⟨N⟩ SNe Ia**
SALT2 fit success	88.7	3830
$P_{\text{fit}} > 95\%$	84.9	3664
3 epochs with $\lvert p \rvert < 10$	89.7	3873
$\lvert x_1 \rvert < 3$	89.5	3867
$\lvert c \rvert < 0.3$	88.8	3834
$\sigma_{t_0} < 1$	89.4	3862
$\sigma_{x_1} < 1$	89.3	3858
$z_{\text{obs}} > 0.02$	97.9	4228
All cuts	**81.5**	**3520**

Analysis: velocities from Hubble diagram residuals

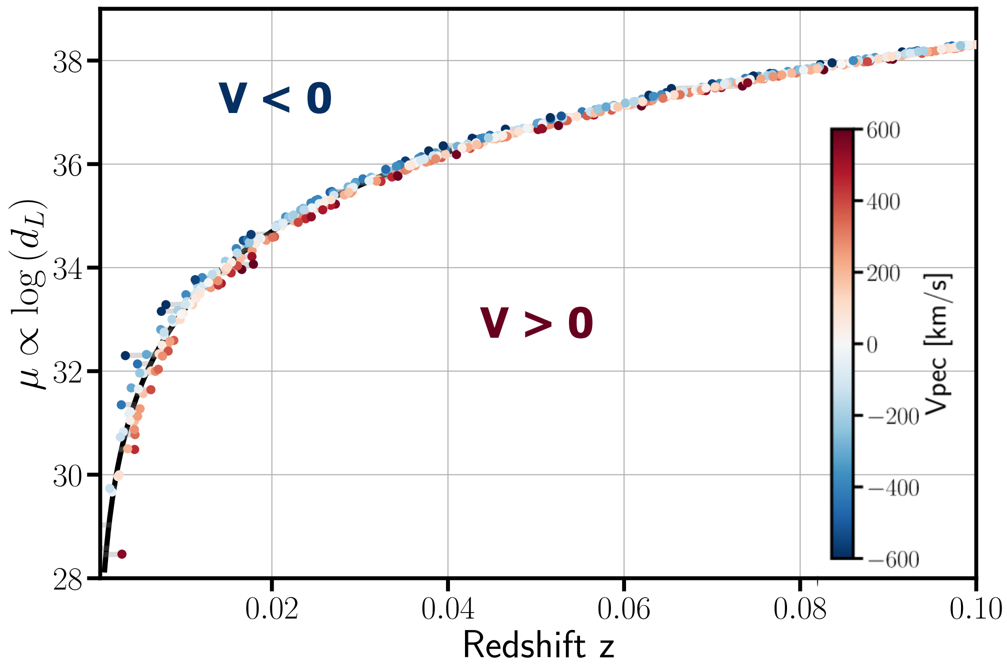
Analysis: velocities from Hubble diagram residuals

Standard candles



Analysis: velocities from Hubble diagram residuals

Standard candles + velocities

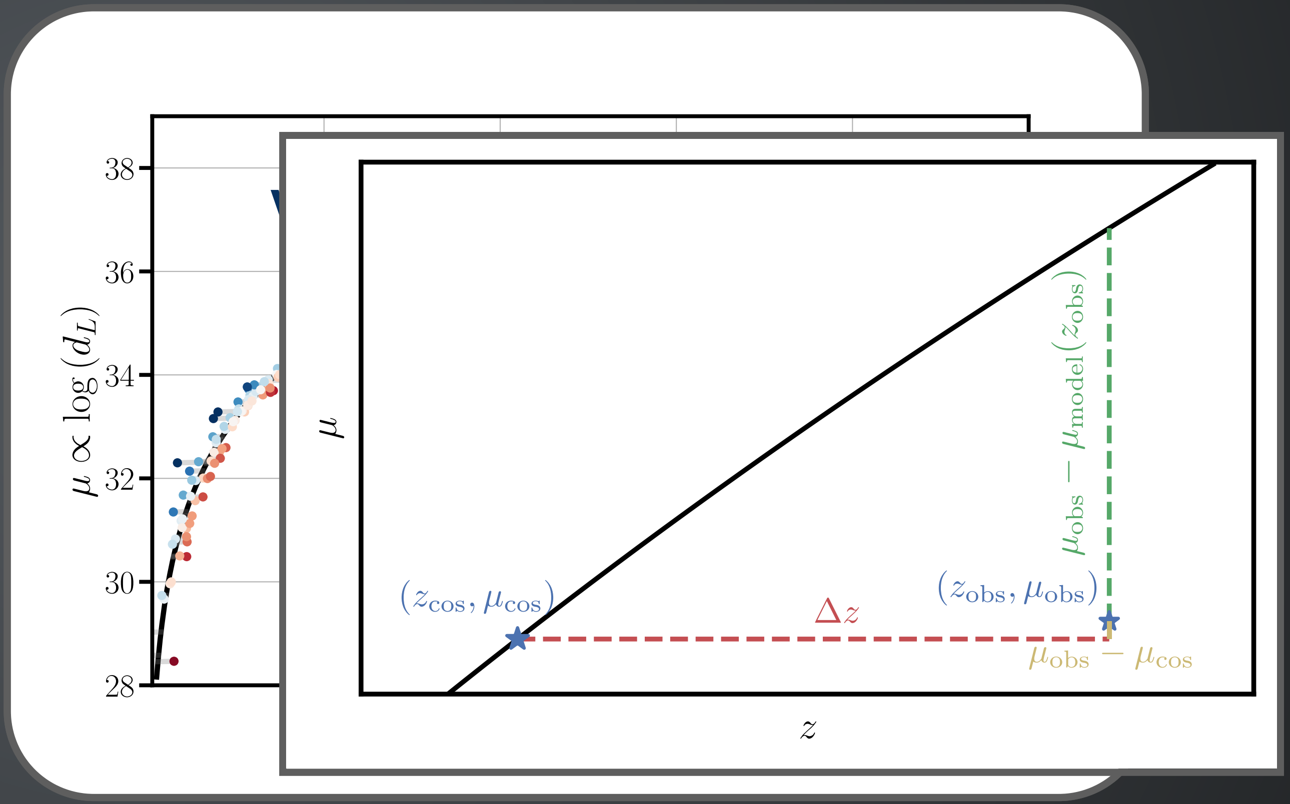


Analysis: velocities from Hubble diagram residuals

Standard candles + velocities

The velocity estimator:

$$\hat{v} = -\frac{\ln(10)c}{5}\left(\frac{(1+z)c}{H(z)r(z)} - 1\right)^{-1}\Delta\mu$$



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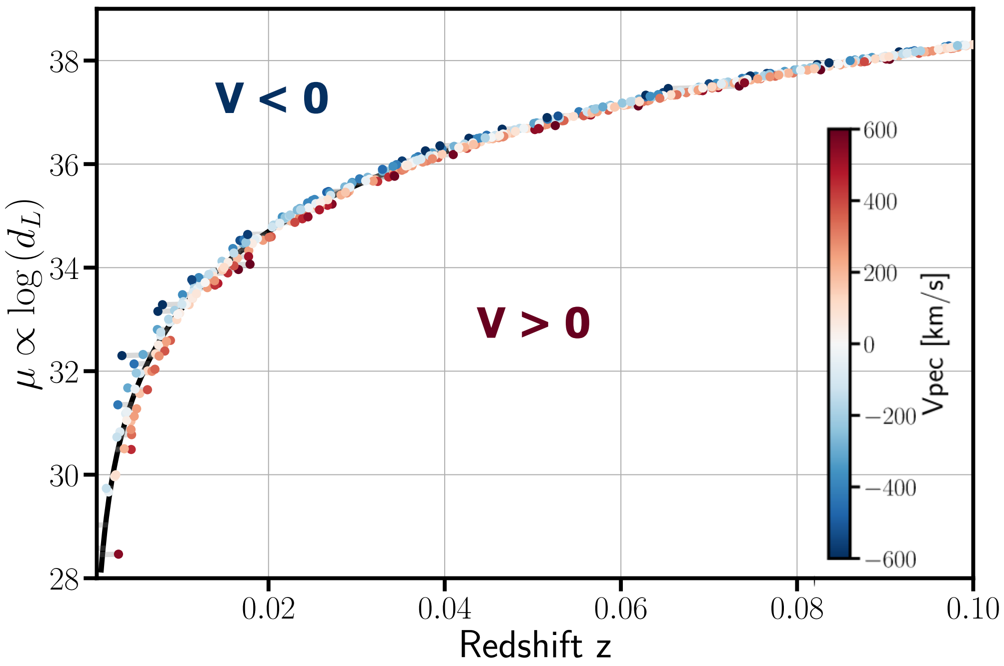


Analysis: velocities from Hubble diagram residuals

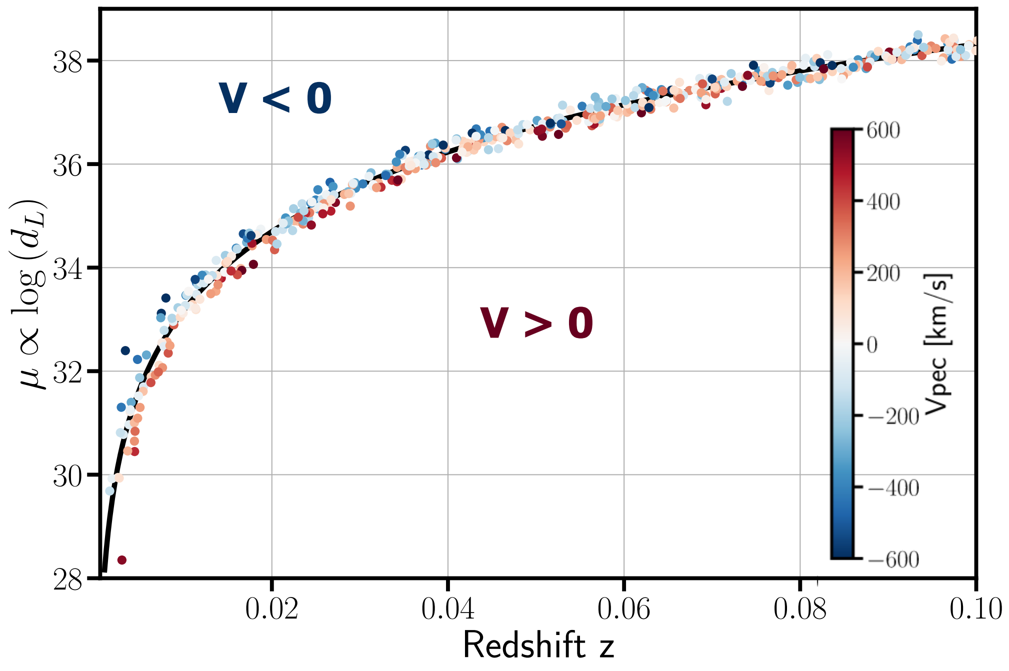
Standard candles + velocities + noise

The velocity estimator:

$$\hat{v} = -\frac{\ln(10)c}{5}\left(\frac{(1+z)c}{H(z)r(z)} - 1\right)^{-1}\Delta\mu$$

The velocity estimator error:

$$\sigma_{\hat{v}} = -\frac{\ln(10)c}{5}\left(\frac{(1+z)c}{H(z)r(z)} - 1\right)^{-1}\sigma_{\mu}$$



Analysis: the Maximum-Likelihood method

Method used with galaxy data in *Abate et al. 2010*, *Johnson et al. 2014* and *Howlett et al.* 2017

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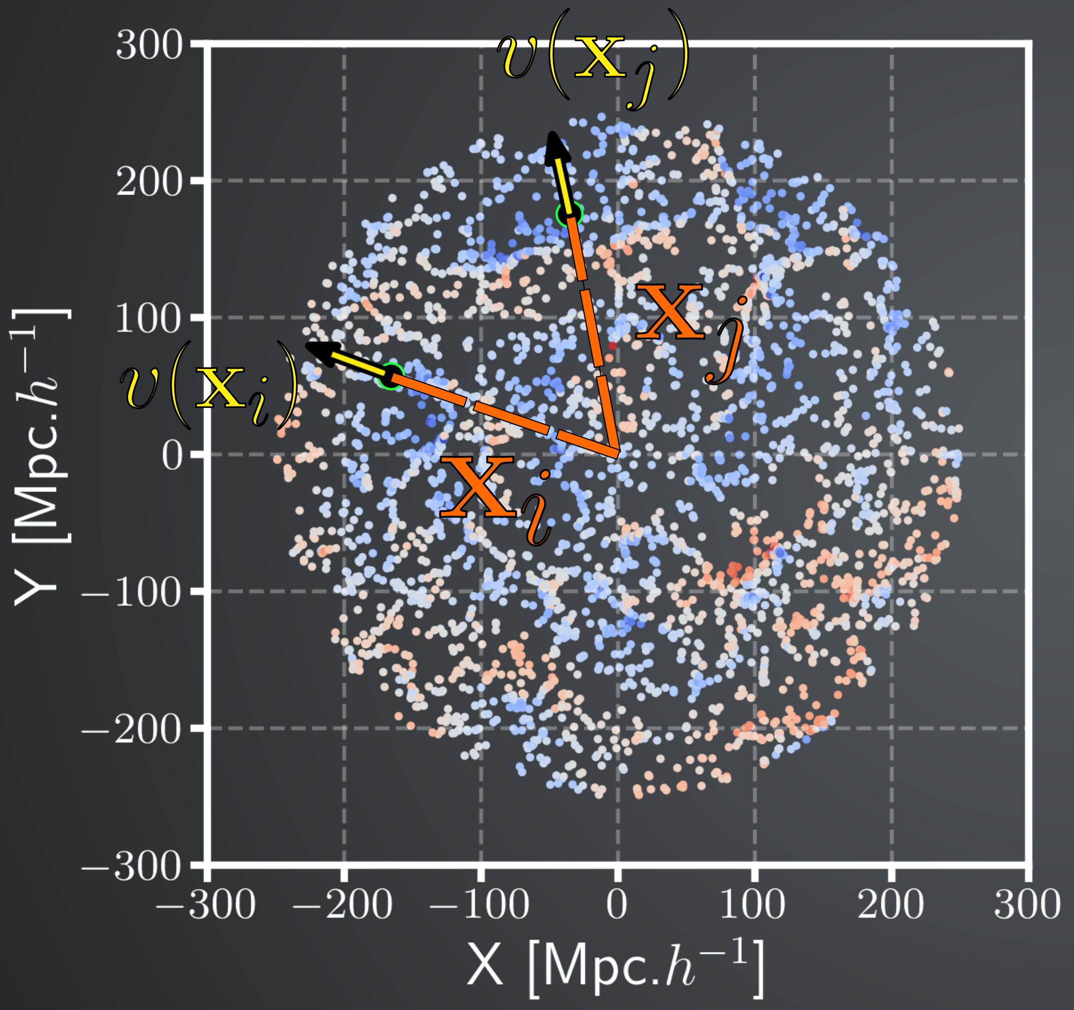
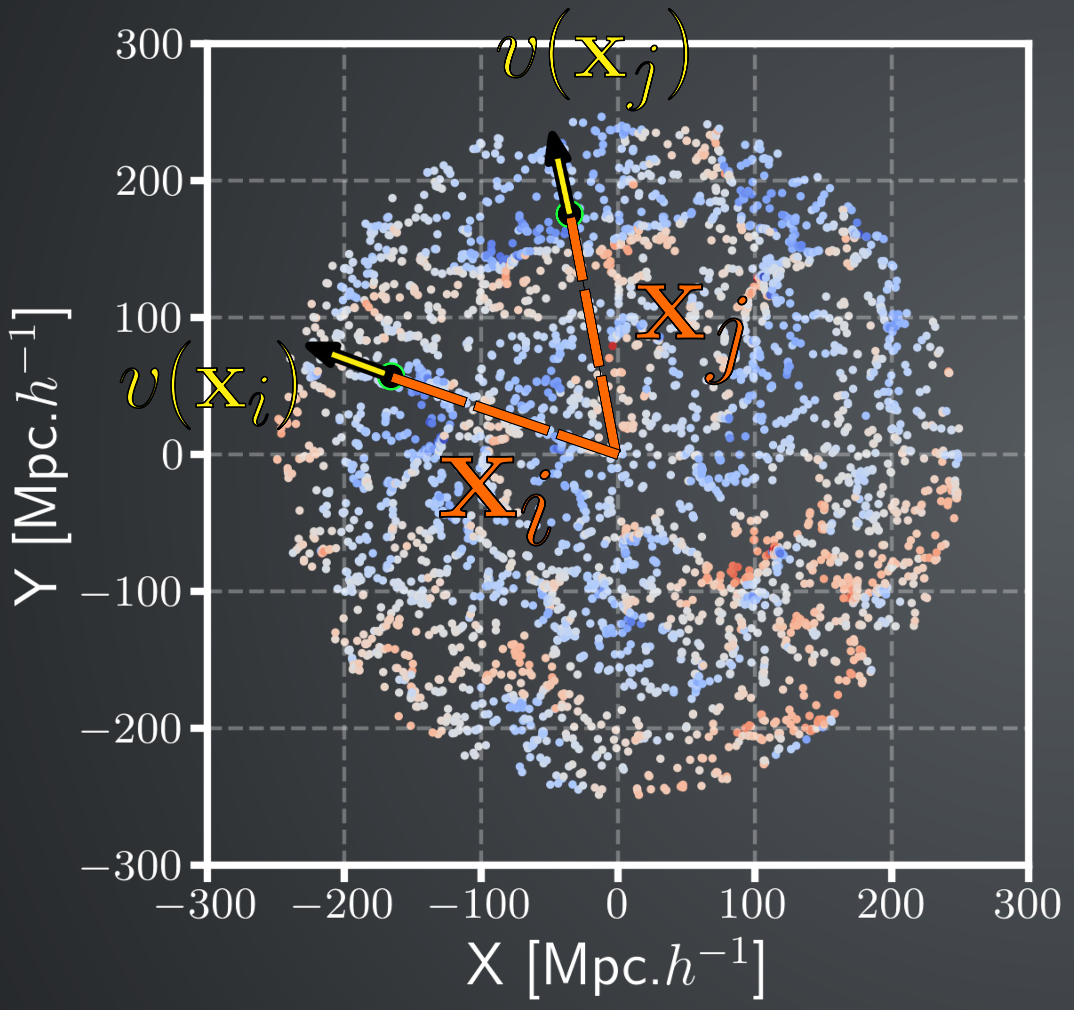


The correlation function depends on the **Power Spectrum**

Analysis: the Maximum-Likelihood method

Method used with galaxy data in *Abate et al. 2010*, *Johnson et al. 2014* and *Howlett et al.* 2017

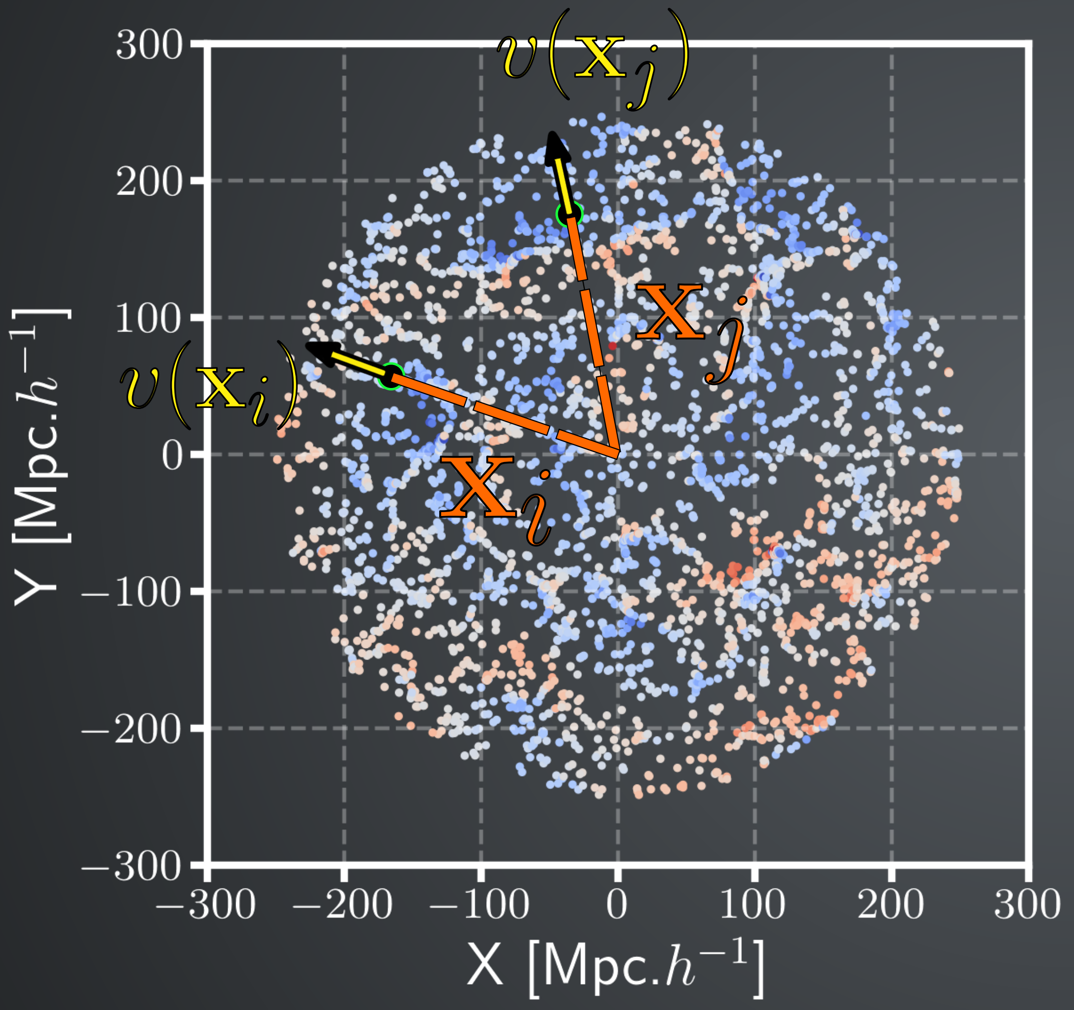


The correlation function depends on the **Power Spectrum**

$$\langle v(\mathbf{x}_i)v(\mathbf{x}_j)\rangle \propto (f\sigma_8)^2 \int dk\tilde{P}(k)W^{(v)}(k;\mathbf{x}_i,\mathbf{x}_j)$$

Analysis: the Maximum-Likelihood method

Method used with galaxy data in *Abate et al. 2010*, *Johnson et al. 2014* and *Howlett et al.* 2017



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It gives us a $f\sigma_8$ dependent model for our covariance matrix!

$$C_{ij}^{vv}(f\sigma_8) = \langle v(\mathbf{x}_i)v(\mathbf{x}_j)\rangle$$

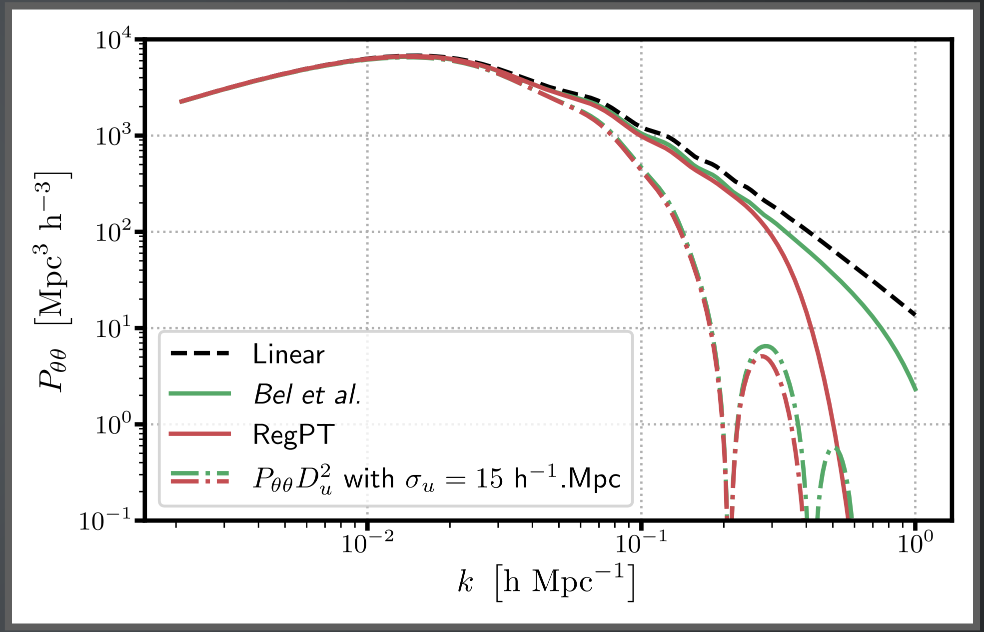
Analysis: the Maximum-Likelihood method

Method used with galaxy data in *Abate et al. 2010*, *Johnson et al. 2014* and *Howlett et al.* 2017

Two non-linear models of power spectra:

- One based on N-body simulaton fit from *Bel et al.* 2019
- One based on PT beyond order one from *Taruya et al.* 2012

Effect of redshift space distorsions taken into account with damping function $D_u(\sigma_u)$ (*Koda et al. 2014*)



Analysis: the Maximum-Likelihood method

Free parameters of the likelihood:

Growth-rate related parameters:

$\mathbf{p} = \{f\sigma_8, \sigma_u, \sigma_v\}$, $\sigma_u \equiv$ RSD, $\sigma_v \equiv$ non-linearities

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The likelihood:

$$\mathcal{L}(\mathbf{p}) \propto |C(\mathbf{p})|^{-\frac{1}{2}} \times \exp\left[-\frac{1}{2}\mathbf{v}^T C(\mathbf{p})^{-1}\mathbf{v}\right]$$

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The covariance:

$$C_{ij}(\mathbf{p}) = C_{ij}^{vv}(f\sigma_8, \sigma_u) + {\sigma_v}^2 \delta_{ij}^K + \sigma_{\hat{v}}^2 \delta_{ij}^K$$

$$C_{ij}^{vv}(f\sigma_8, \sigma_u) = \langle v(\mathbf{x}_i) v(\mathbf{x}_j)\rangle \propto (f\sigma_8)^2 \int dk P(k) W(k) D_u^2(k; \sigma_u)$$

Outline

- Introduction:
  - The ΛCDM standard model
  - Alternatives to Λ
- Growth rate of structure
  - What is the growth rate of structures?
  - How to measure it?
- Type Ia supernovae
  - SNe Ia for cosmology
  - The Zwicky Transient Facility
- The growth-rate analysis pipeline
  - Simulation
  - Analysis
- Results
  - The sample bias
  - ZTF 6-years forecast
  - How to improve the measurement?
- Other works
  - Systematic effect on H_0 due to velocities
  - What's next?
- Conclusion

Results: the selection bias (*Carreres et al. 2023*)

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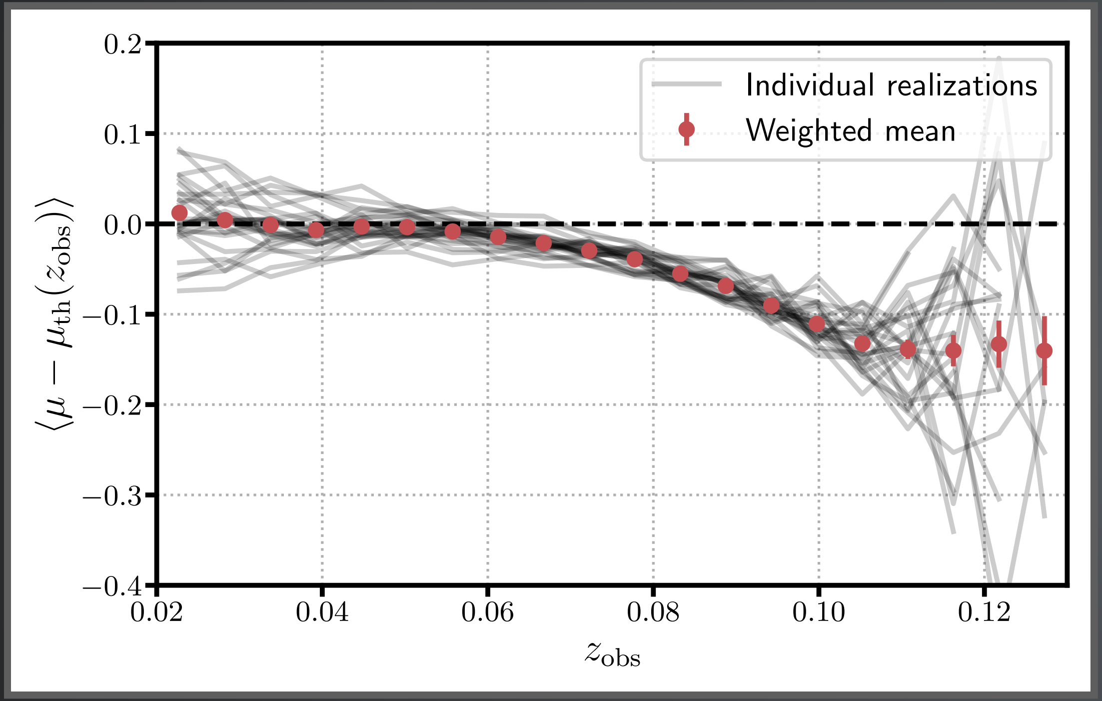
Bias on HD residuals



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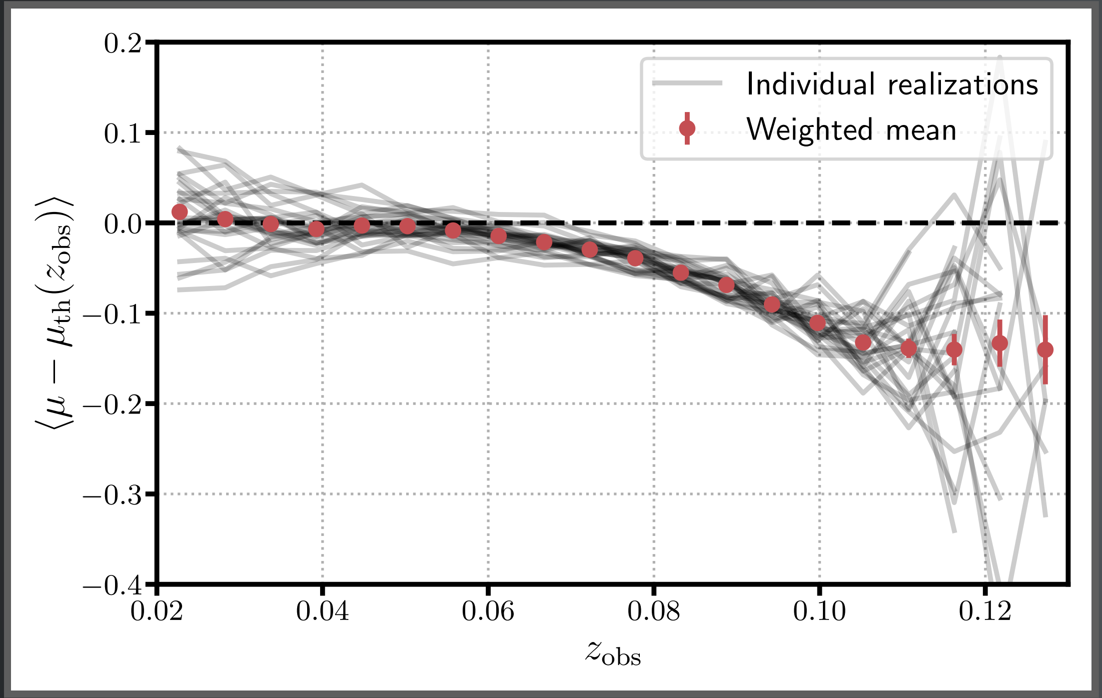
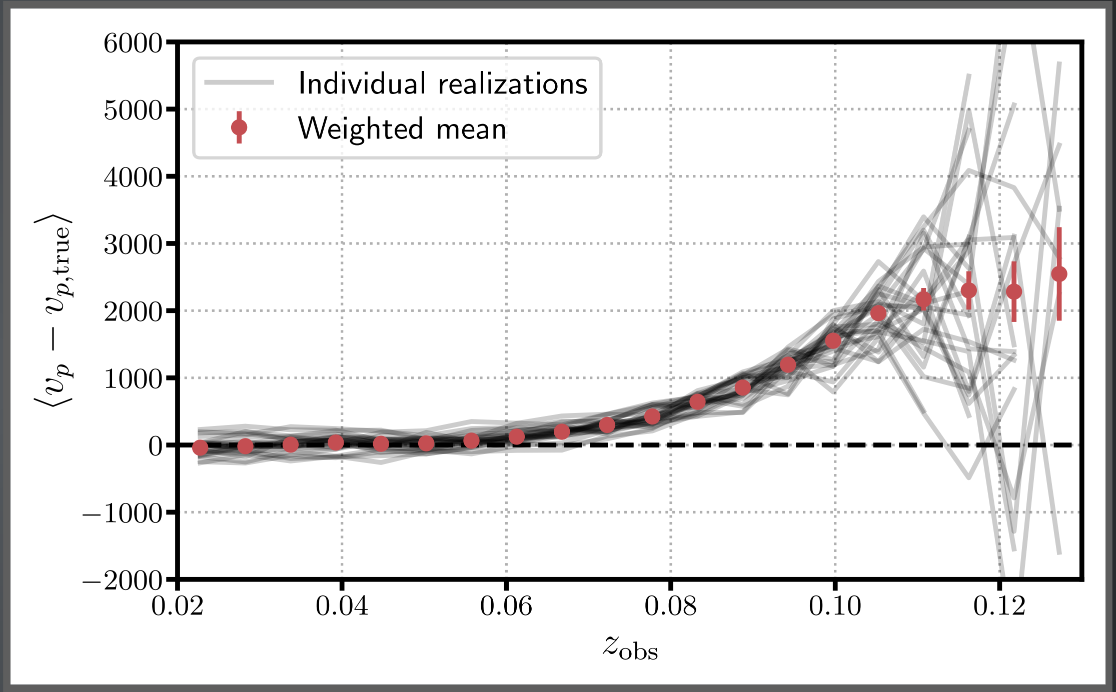


Bias on velocity estimates



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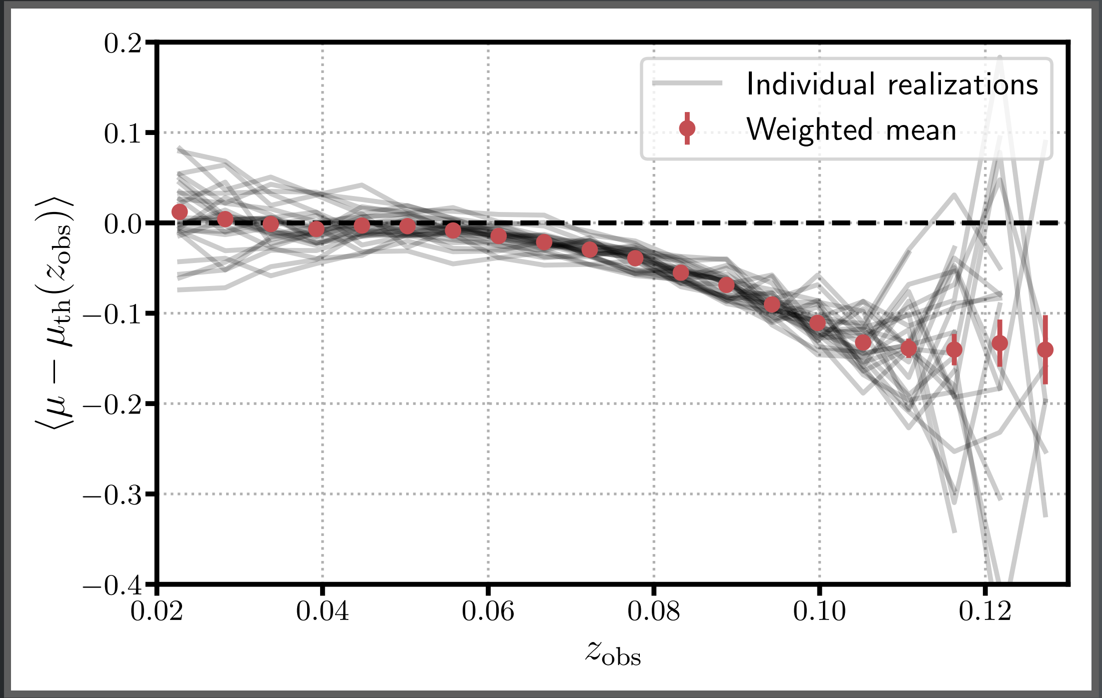

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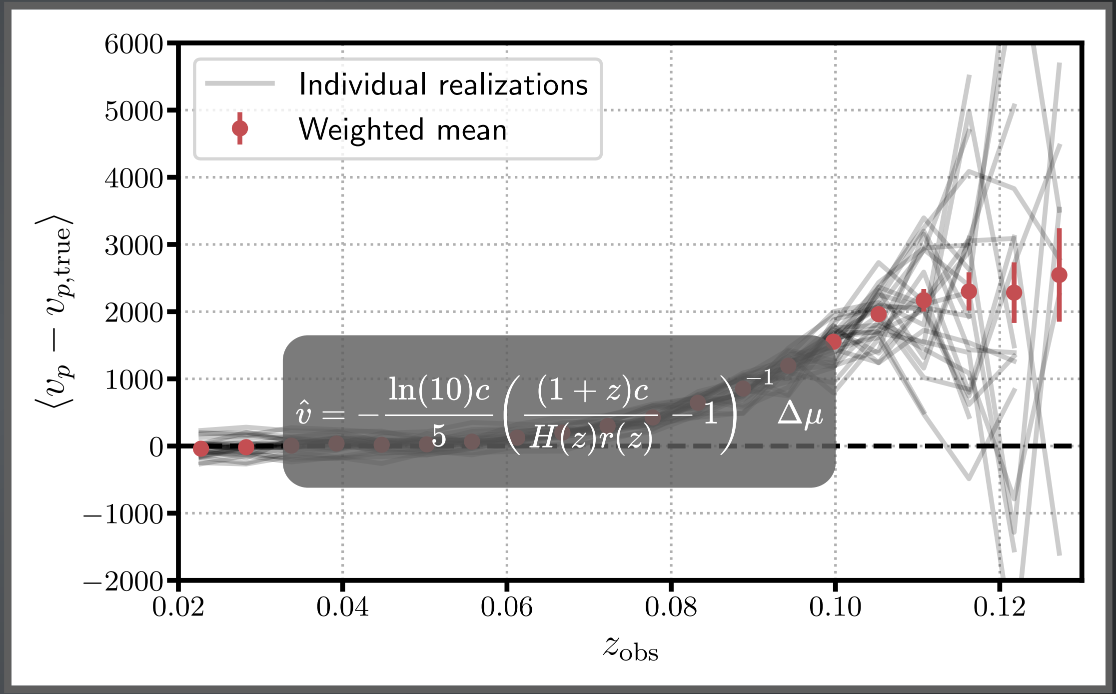

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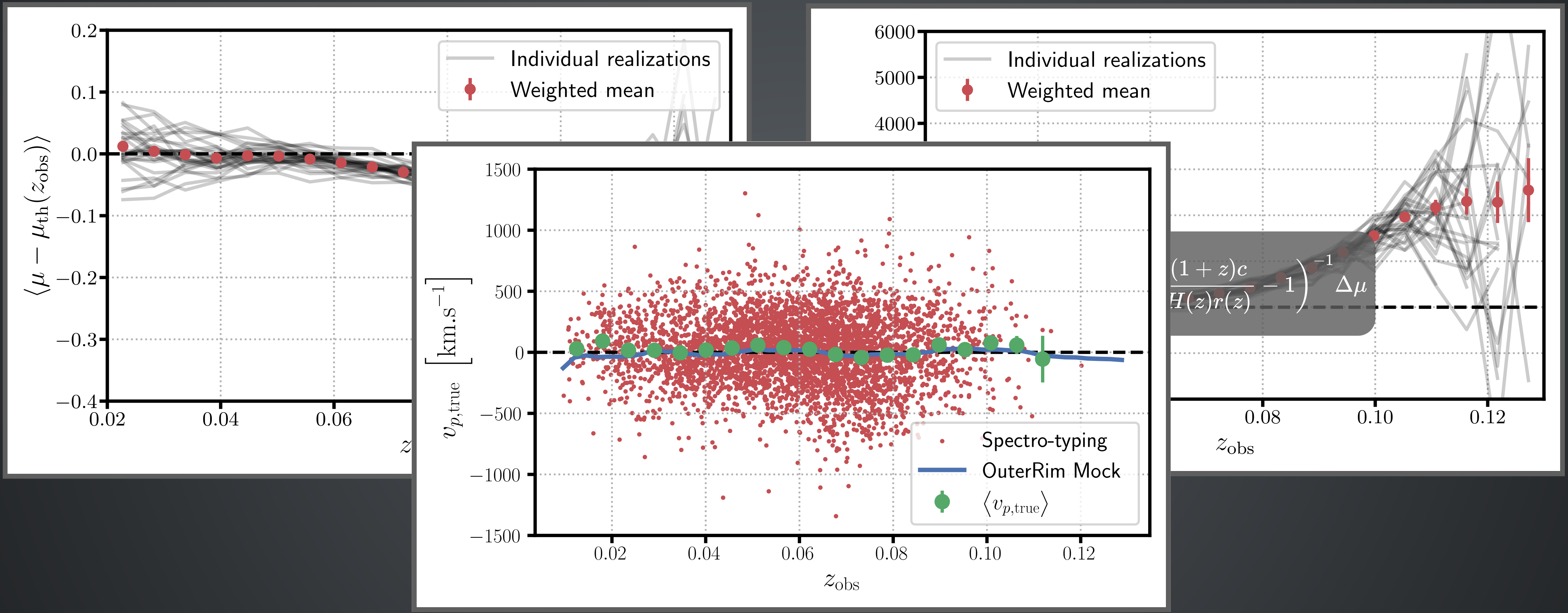
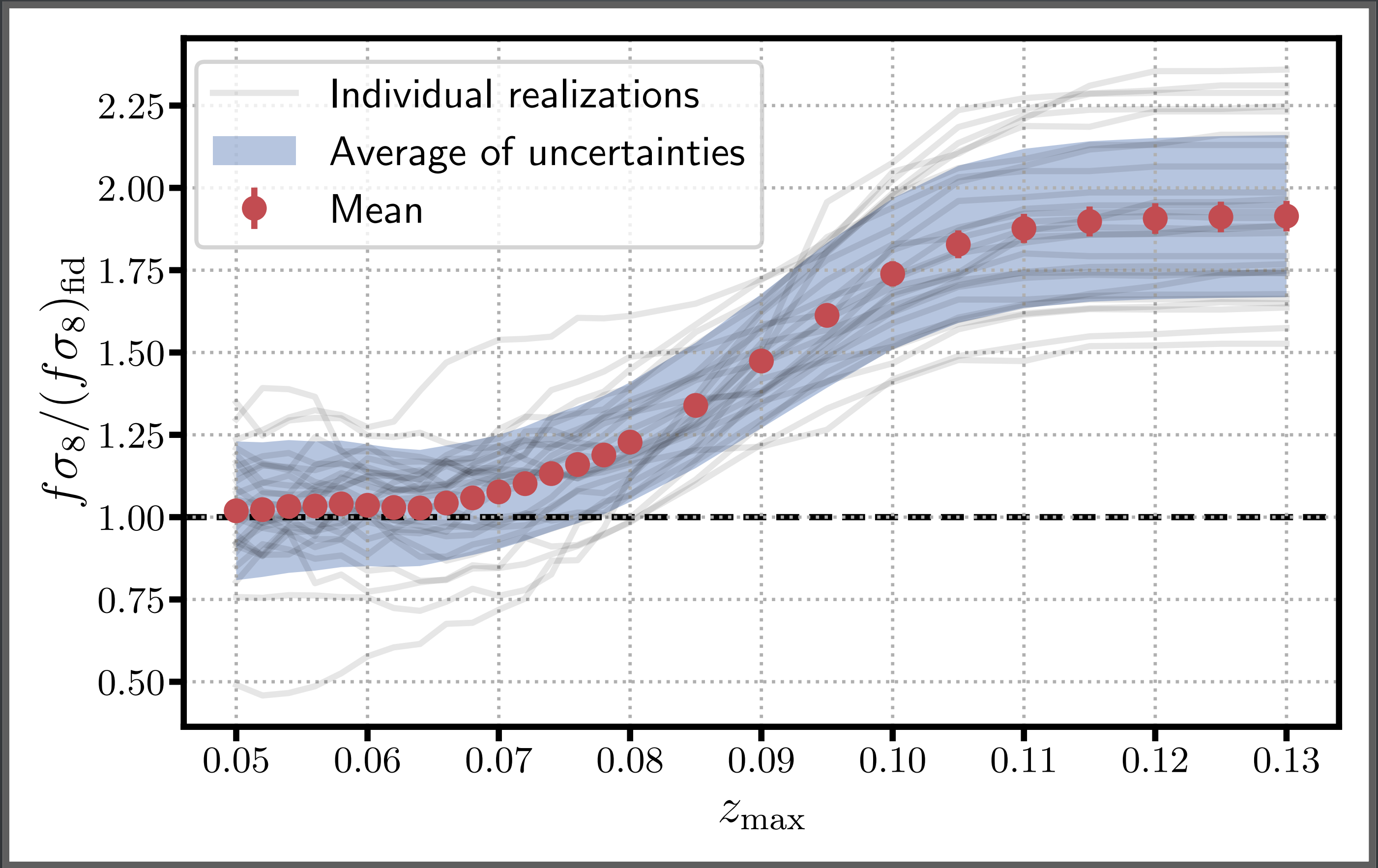


Only the estimated velocities are biased !!!

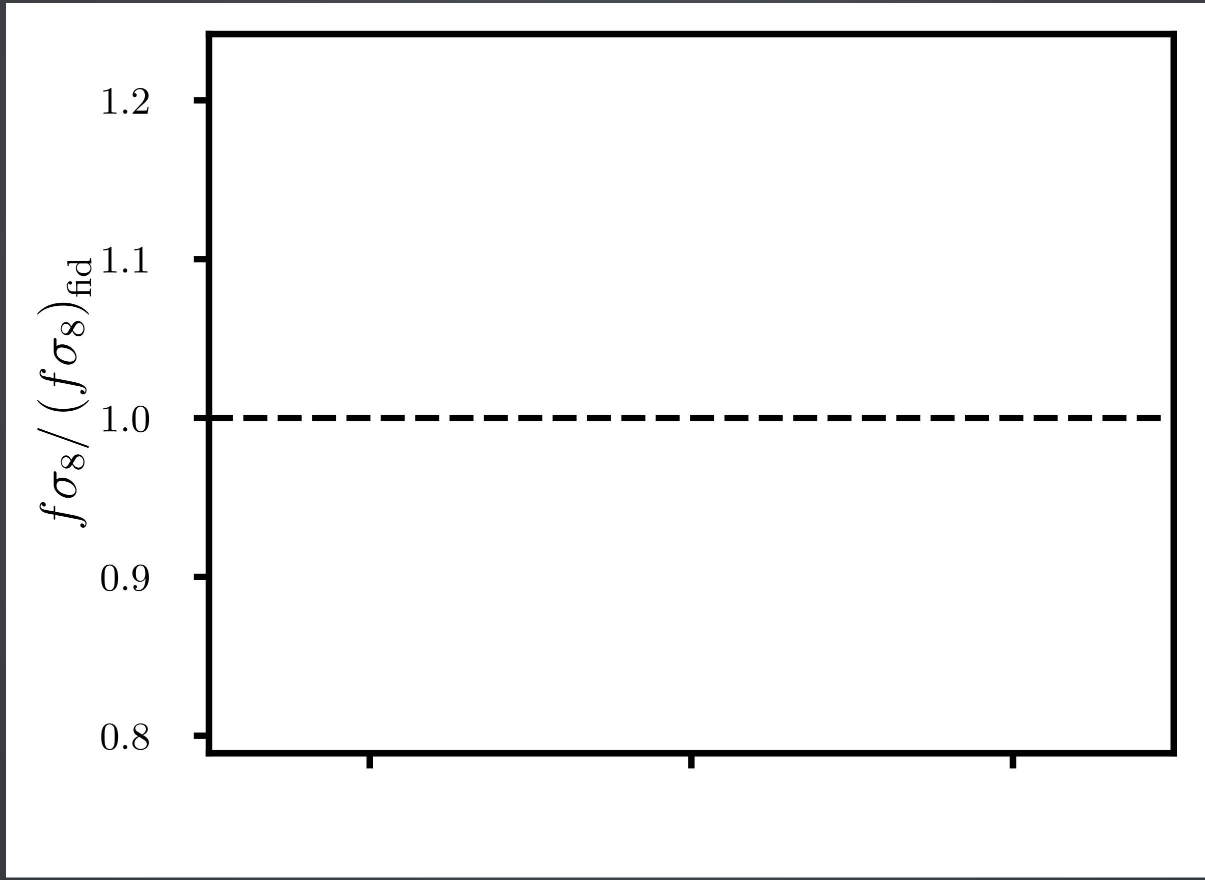
Results: the selection bias (*Carreres et al. 2023*)

Bias on $f\sigma_8$



Results: forecast for a ZTF 6-years complete sample (*Carreres et al. 2023*)

$z < 0.06 \Rightarrow \langle N_{\mathrm{SN}} \rangle \simeq 1600 \sim$ half of the sample



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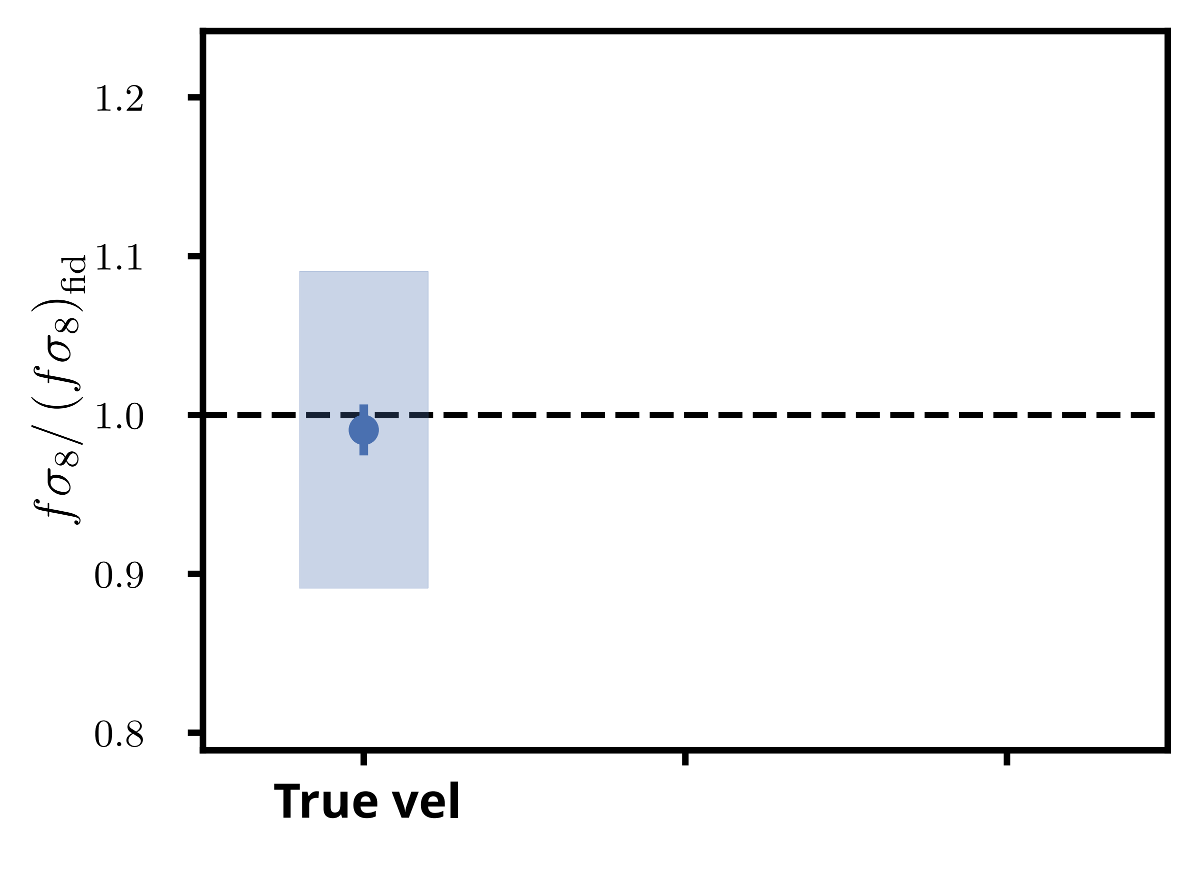

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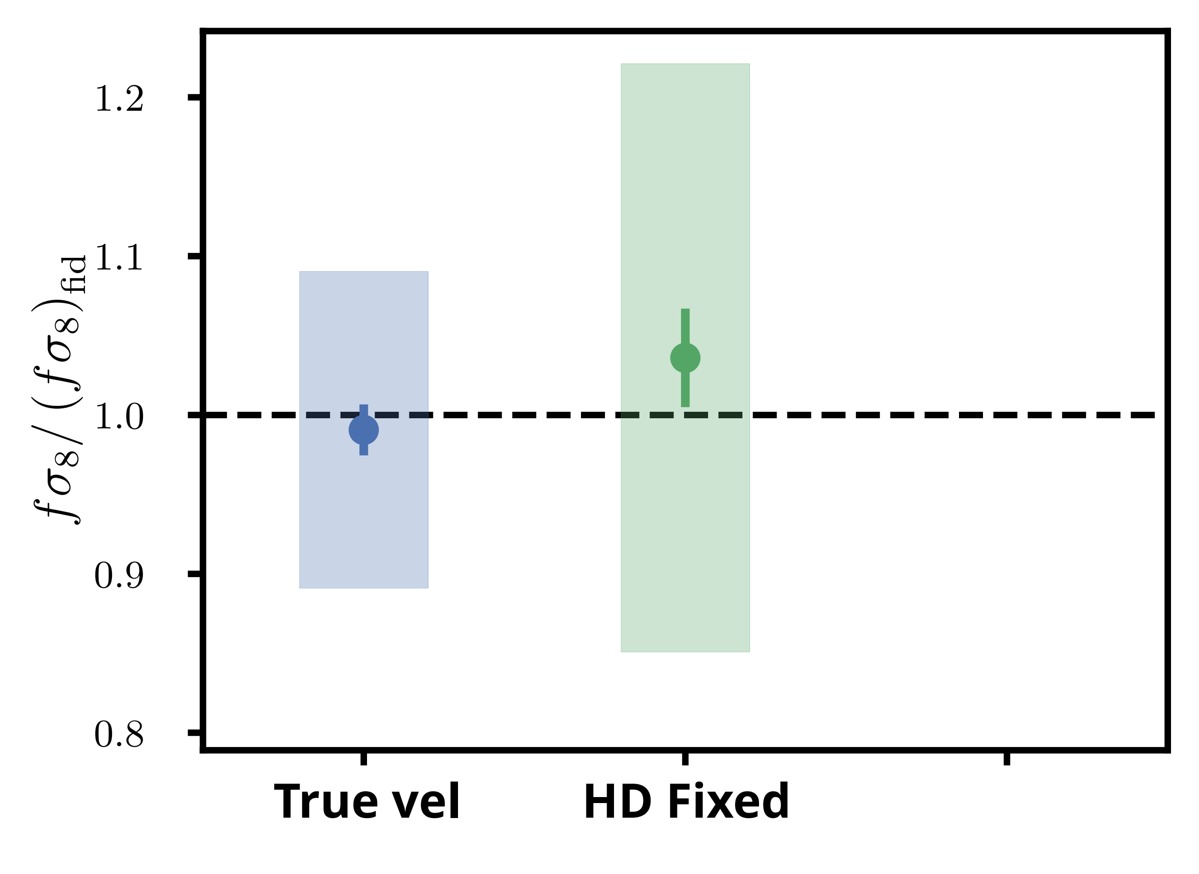

Analysis: joint fit

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Free parameters:

Growth-rate related parameters: $\mathbf{p} = \{f\sigma_8, \sigma_u, \sigma_v\}$

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Data vector

HD residuals: $\Delta\mu(\mathbf{p}_{\mathrm{HD}}) = m_B + \alpha x_1 - \beta c - M_0 - \mu_{\mathrm{model}}(z)$

$$\hat{v} \to \hat{v}(\mathbf{p}_{\mathrm{HD}}) = -\frac{\ln(10)c}{5}\left(\frac{(1+z)c}{H(z)r(z)} - 1\right)^{-1} \Delta\mu(\mathbf{p}_{\mathrm{HD}})$$

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Covariance

$$\sigma_{\hat{v}} \to \sigma_{\hat{v}}(\mathbf{p}_{\mathrm{HD}}) = \frac{\ln(10)c}{5}\left(\frac{(1+z)c}{H(z)r(z)} - 1\right)^{-1}\sigma_\mu(\mathbf{p}_{\mathrm{HD}})$$

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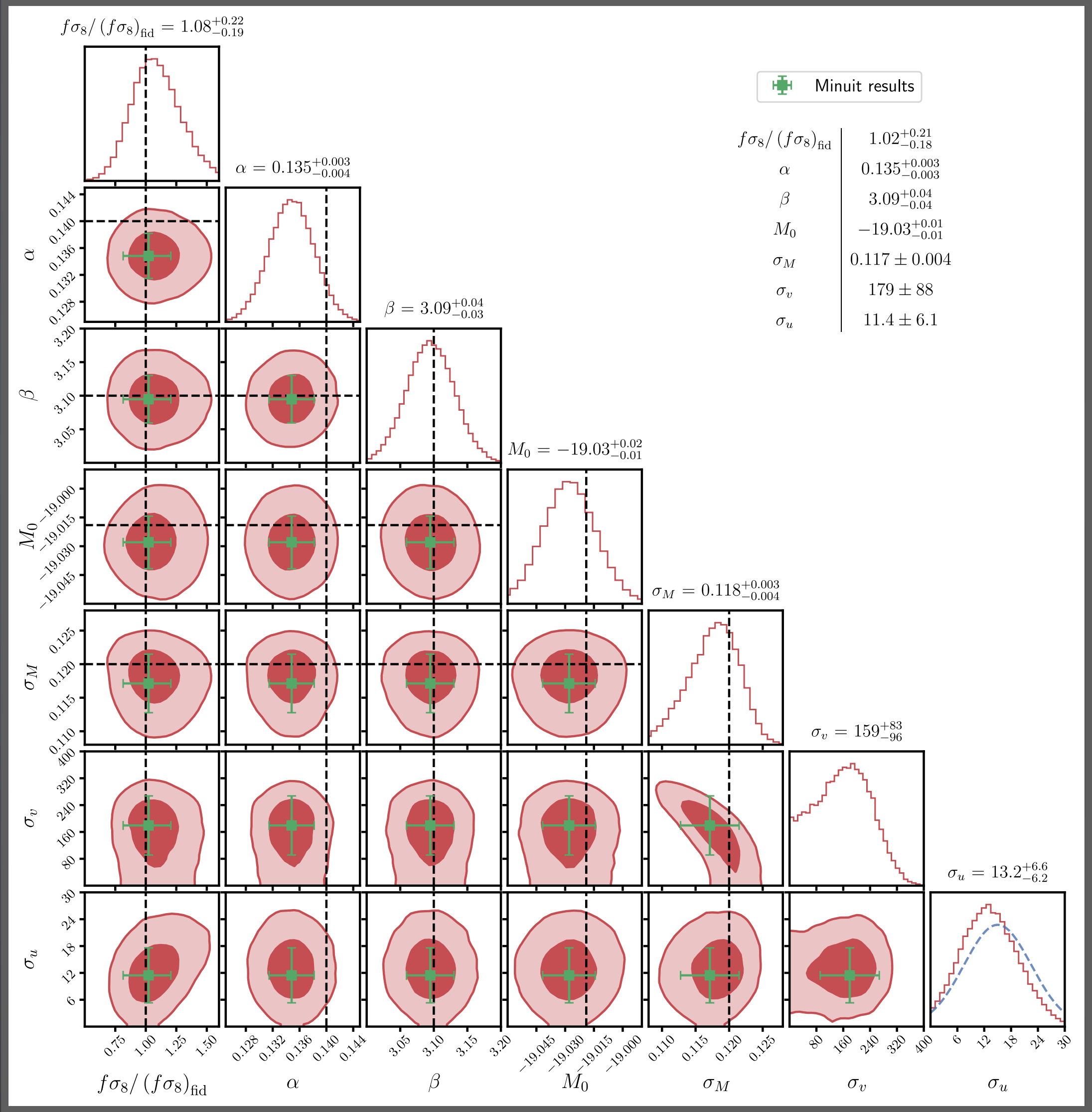

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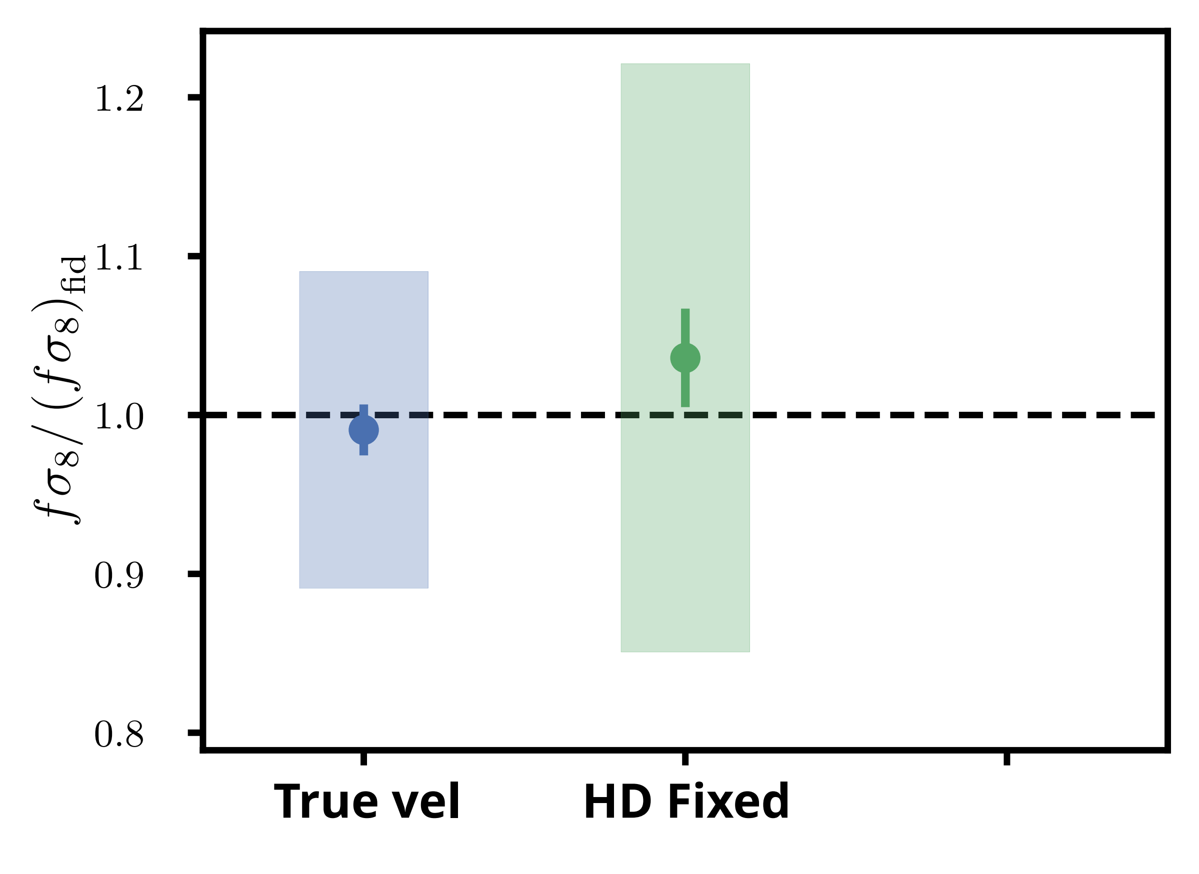

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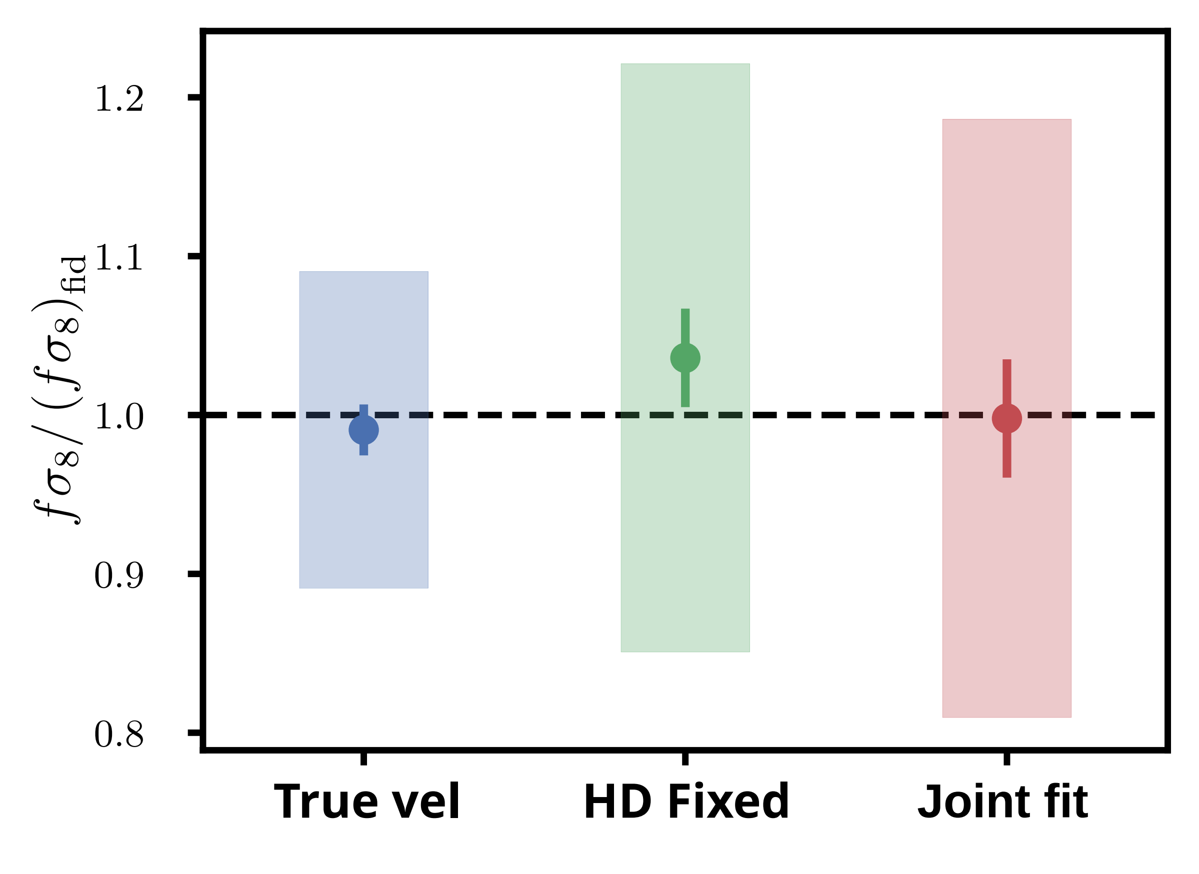
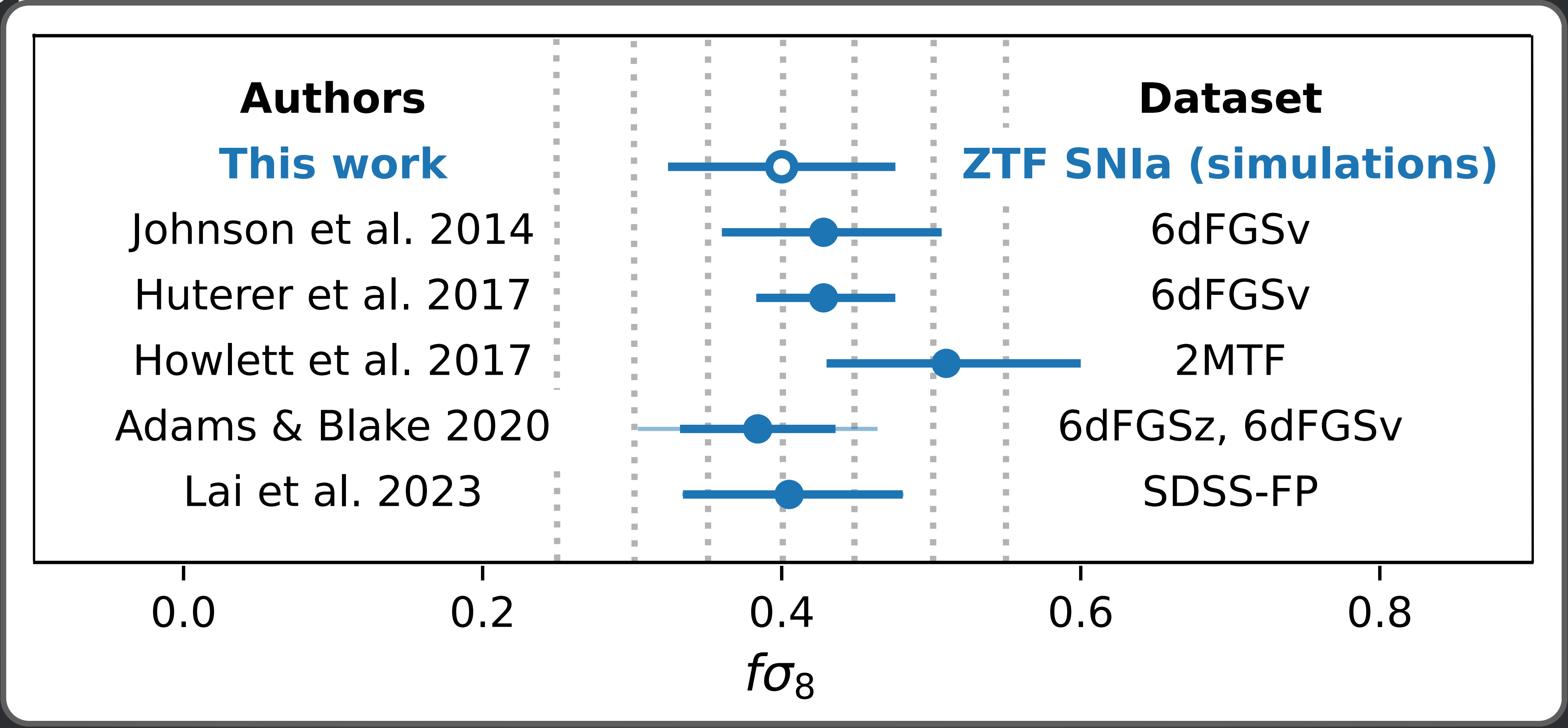


Results: comparison with existing measurements (*Carreres et al. 2023*)



With ~1600 SNe Ia, ZTF is at the same precision level as existing measurements with several thousands of galaxies

Results: could a bias correction improve the constraint? (*Carreres et al. 2023*)

Simulate a perfect correction of the bias: $v_{\mathrm{debias},i} \sim \mathcal{N}(v_{\mathrm{true}}, \sigma_{\hat{v},i})$

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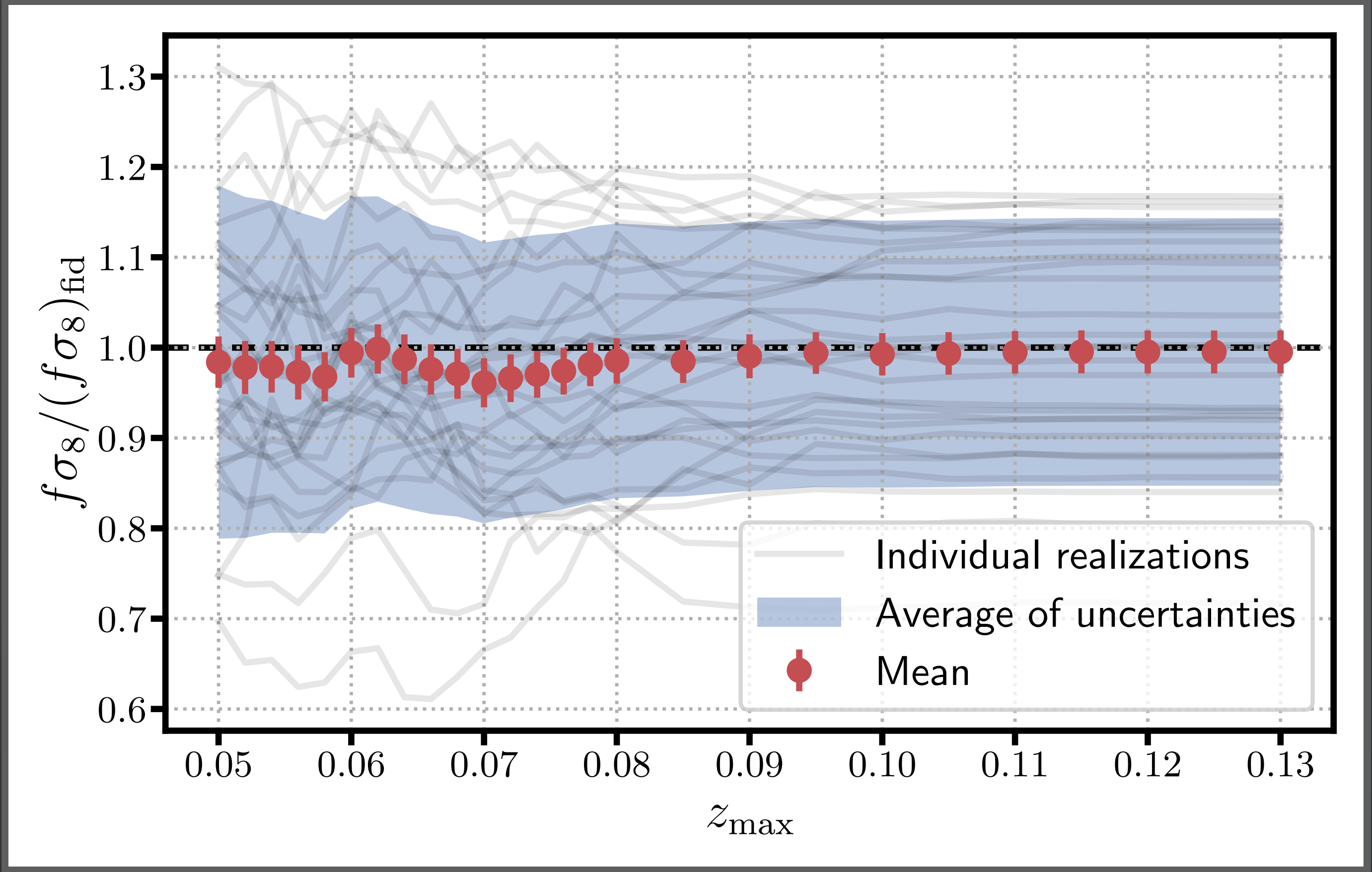

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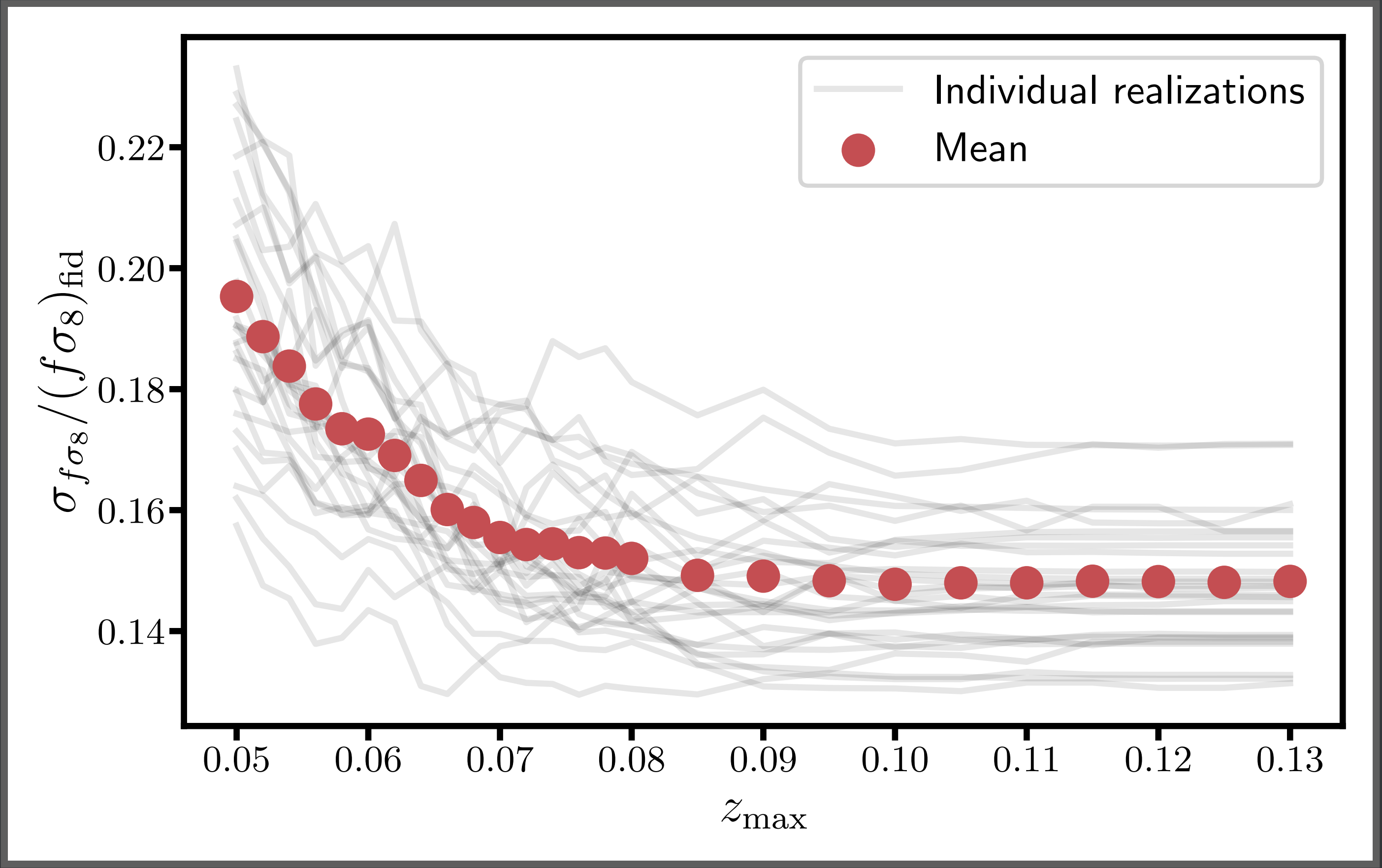

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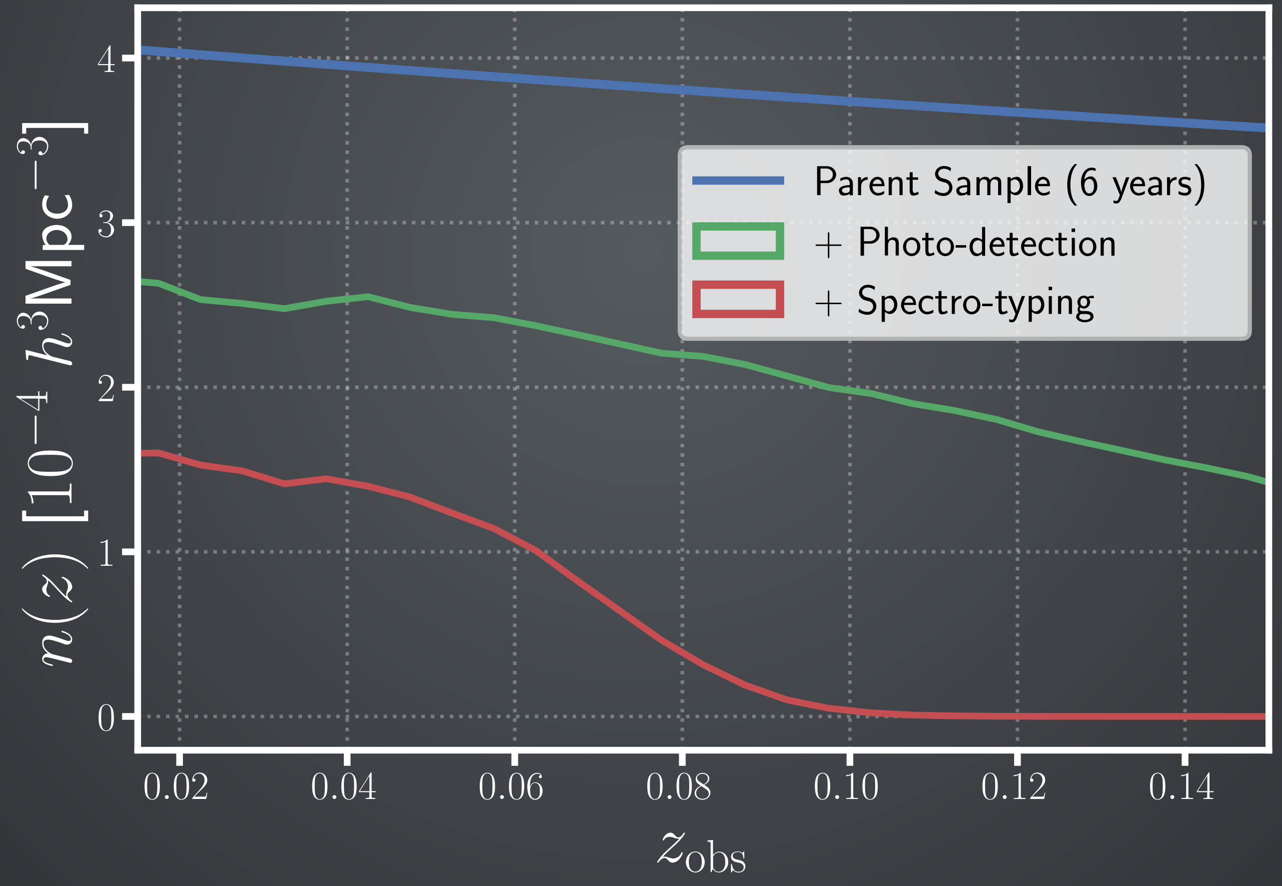

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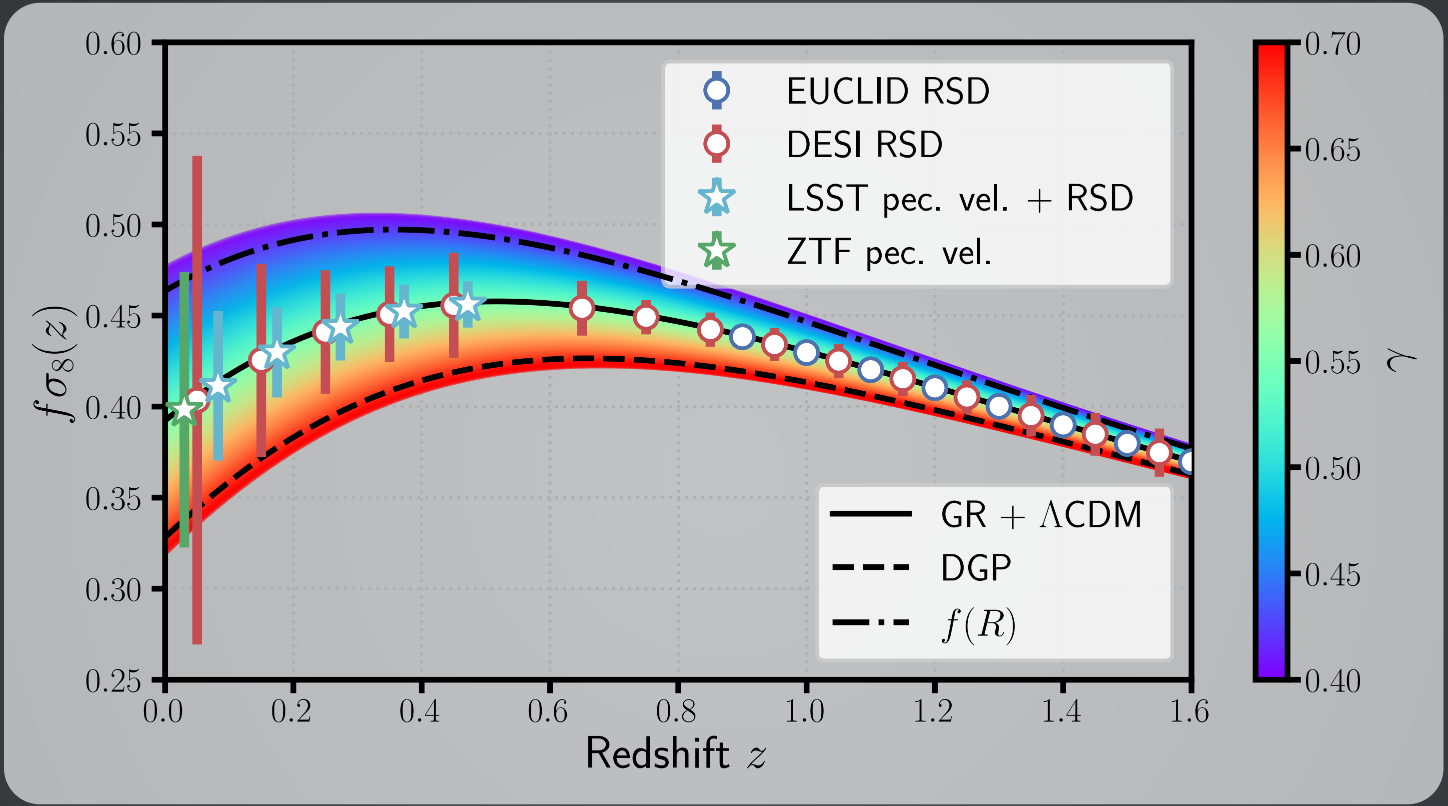
- Velocity $\times$ density measurements (e.g. ZTF + DESI)

Future surveys



Forecast credits: DESI arxiv:1611.00036, LSST arxiv:1708.08236, EUCLID arXiv:1606.00180

Outline

- Introduction:
  - The ΛCDM standard model
  - Alternatives to Λ
- Growth rate of structure
  - What is the growth rate of structures?
  - How to measure it?
- Type Ia supernovae
  - SNe Ia for cosmology
  - The Zwicky Transient Facility
- The growth-rate analysis pipeline
  - Simulation
  - Analysis
- Results
  - The sample bias
  - ZTF 6-years forecast
  - How to improve the measurement?
- Other works
  - Systematic effect on H_0 due to velocities
  - What's next?
- Conclusion

Systematic effect on H_0 due to velocities (paper in prep)

Hubble Diagram fit

$$\Delta\mu = m_B + \alpha x_1 - \beta c - M_0 - \mu_{\mathrm{model}}(z)$$

where M_0 **is degenerate with** H_0

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We use our 27 mocks from $\texttt{SNSim}$ that contain correlated velocities to evaluate velocities effect in Hubble diagram fit

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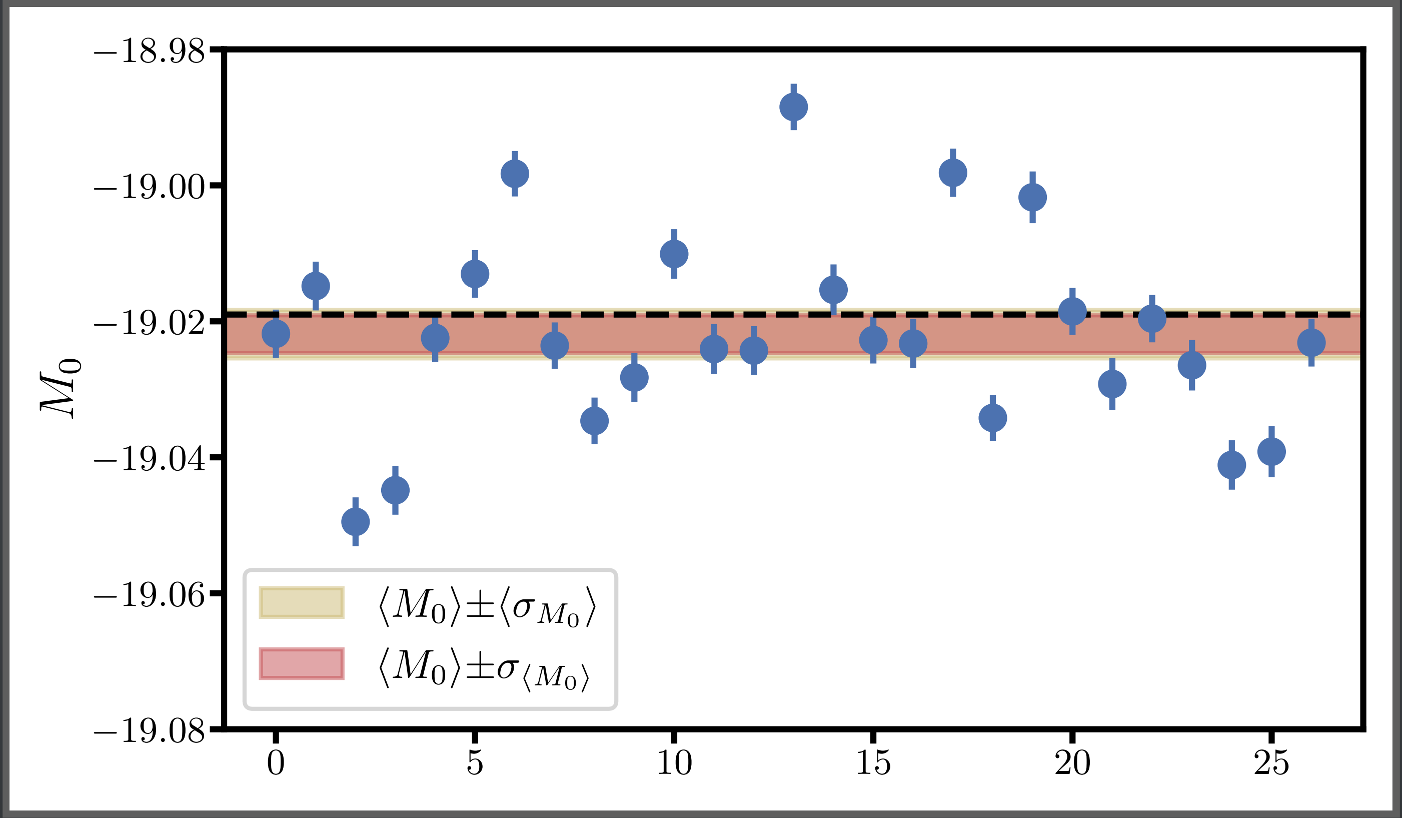
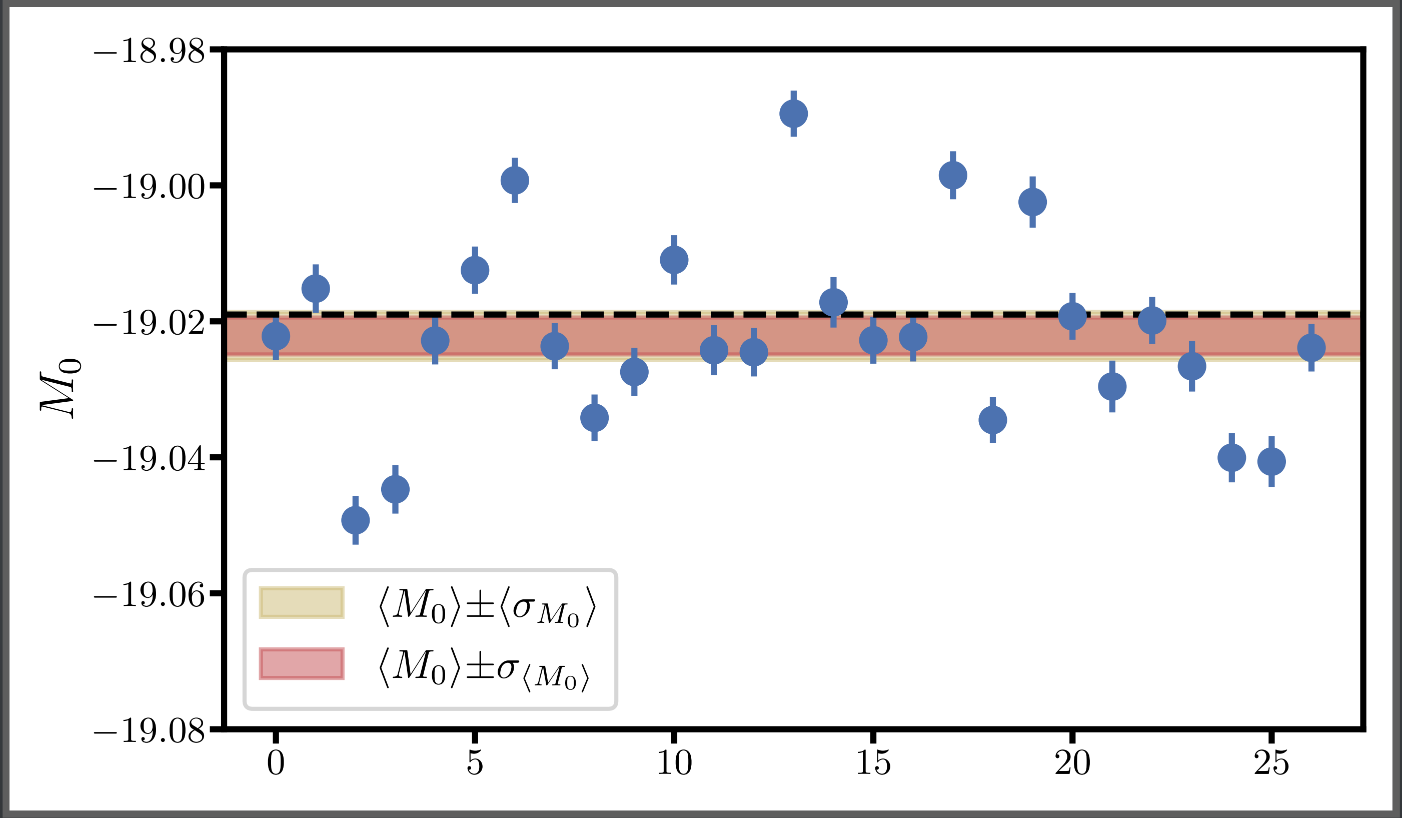
Velocities not taken into account



Systematic effect on H_0 due to velocities (paper in prep)

Diagonal term for velocity errors



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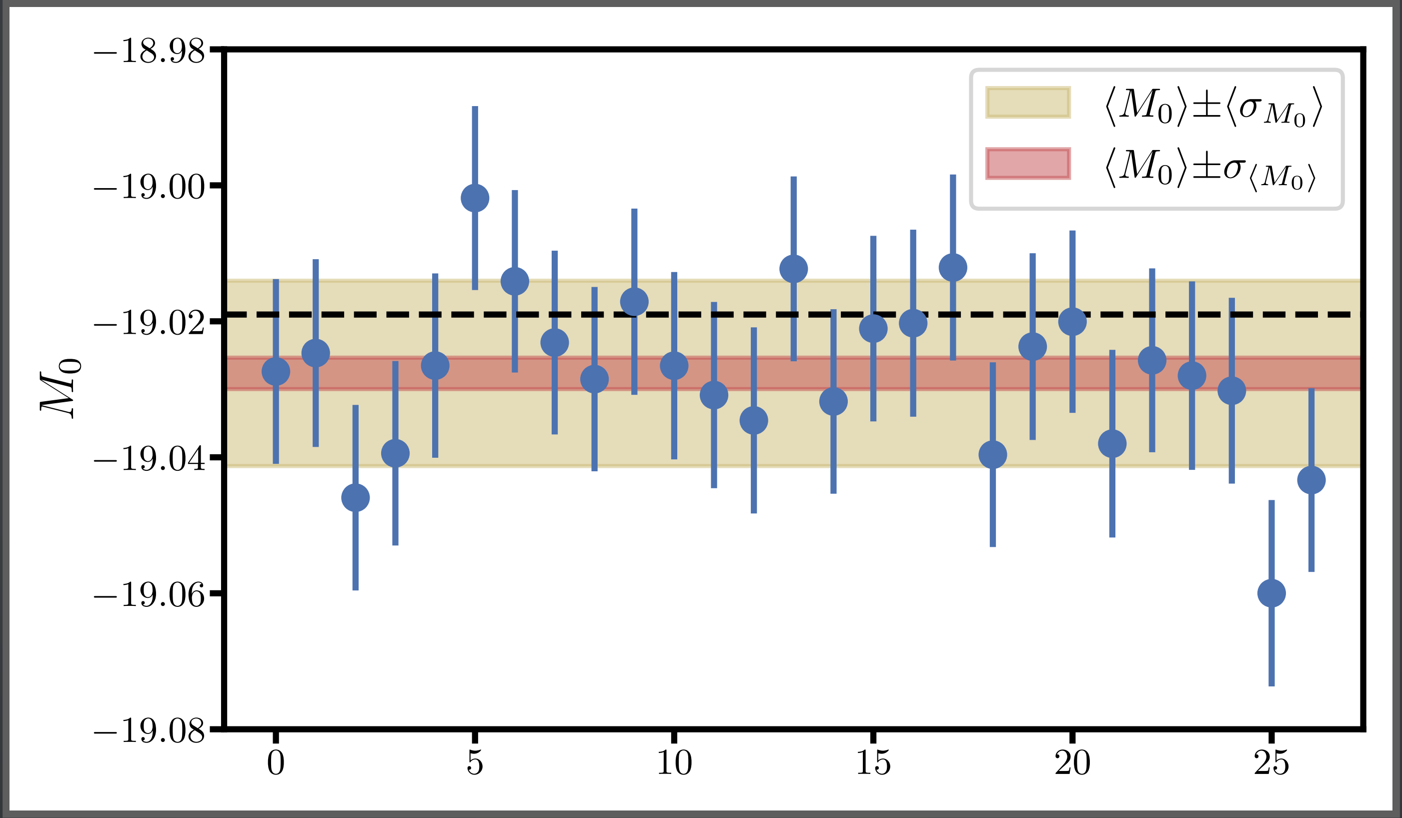
Full covariance matrix for velocities



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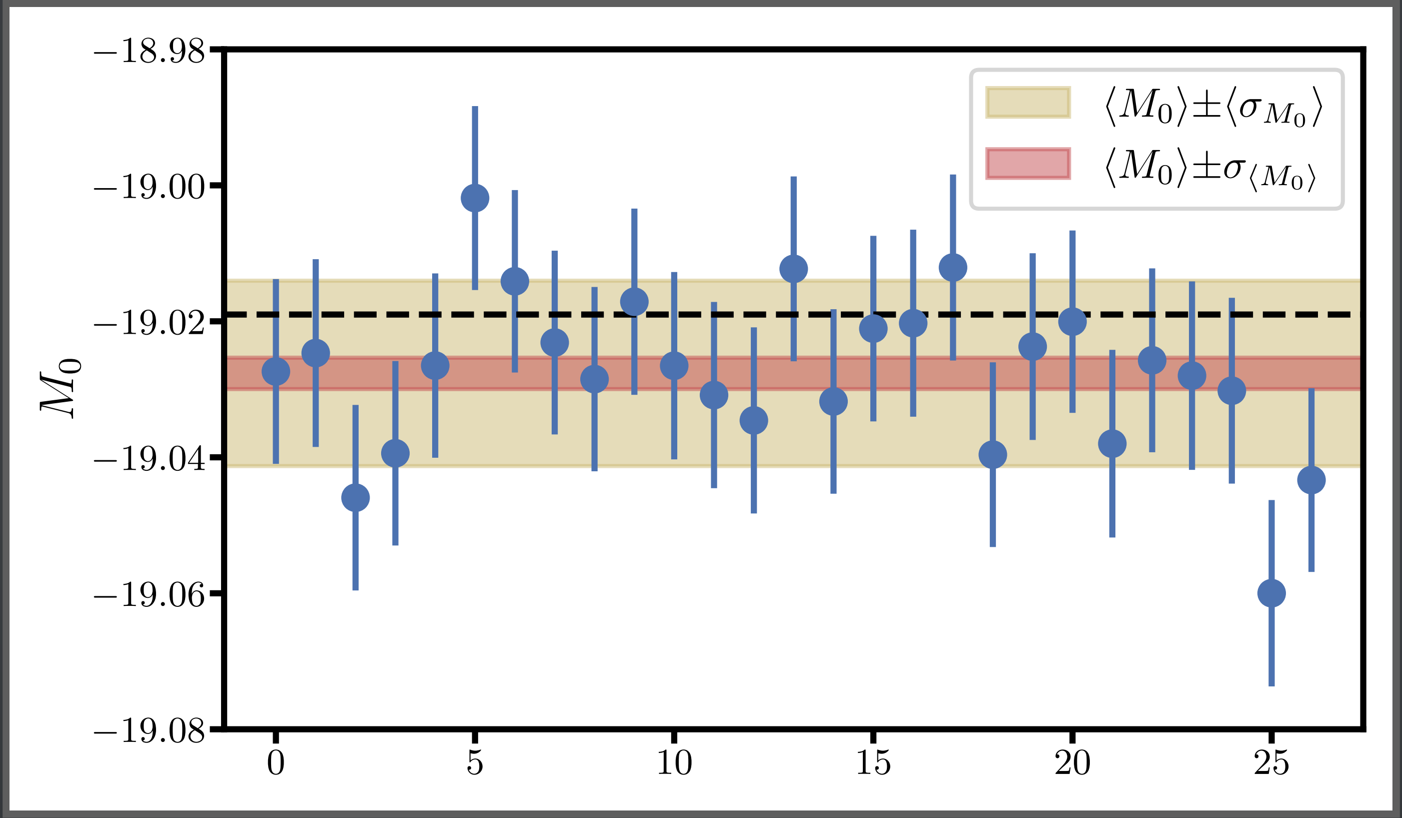

Preliminary results: using full covariance matrix multiplies by ~4 the error on M_0 on simulations. First test on ZTF DR2 data gives an error multiplied by ~2.

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- Application of the $f\sigma_8$ analysis to ZTF data

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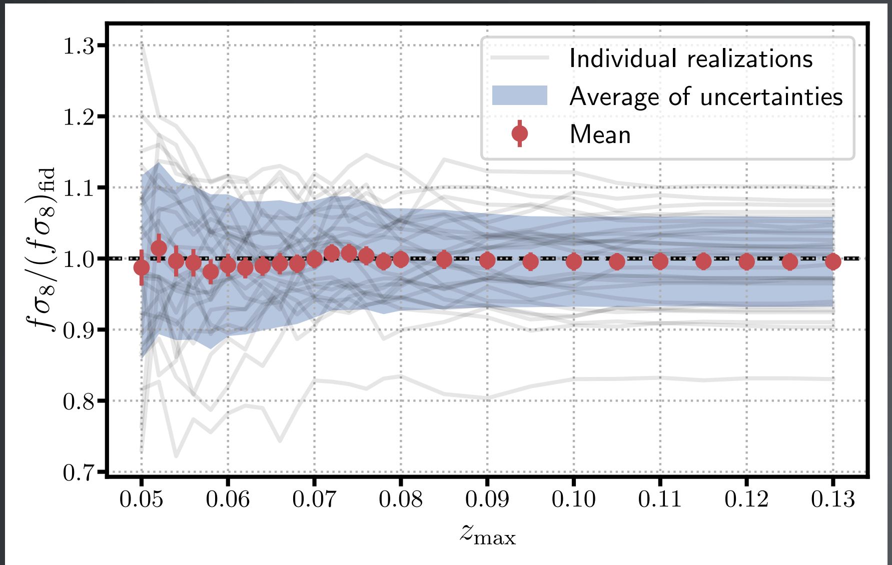
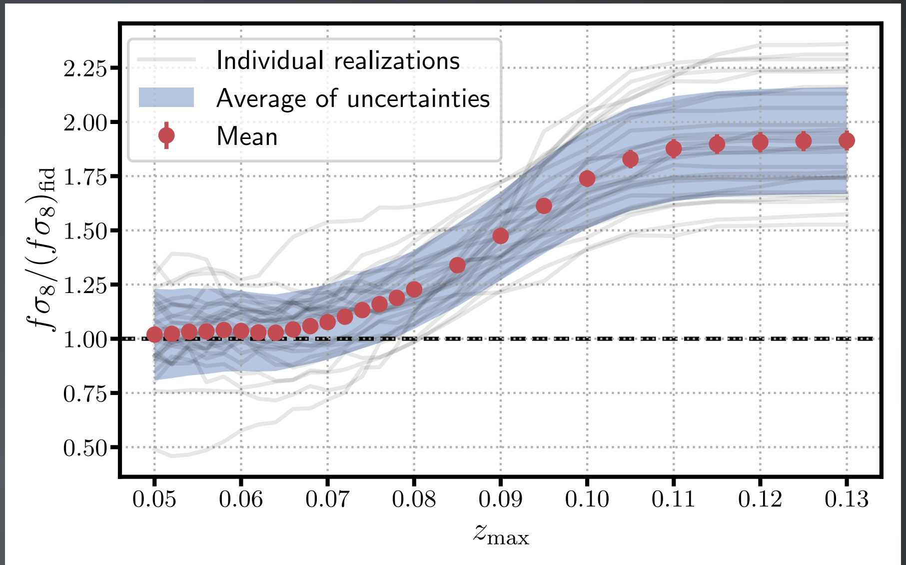
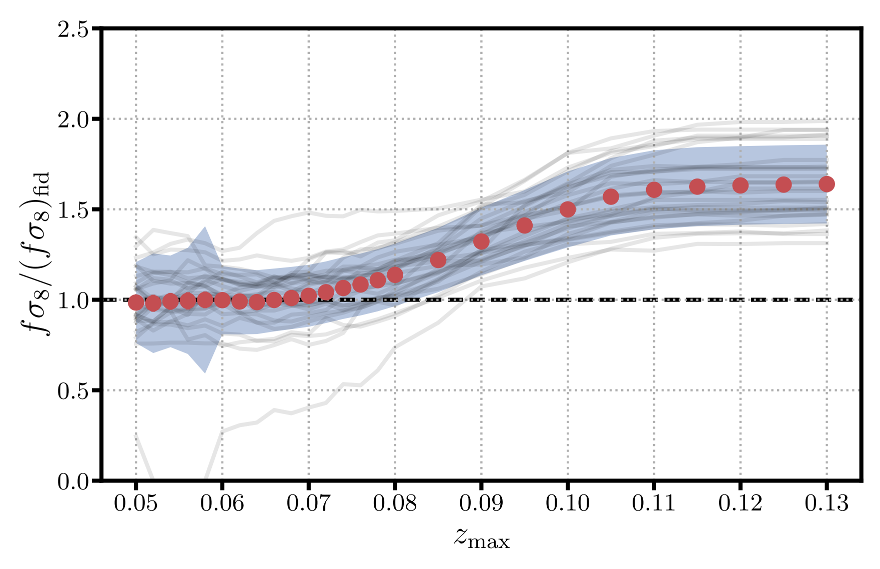
- We forecast that we will have a ~19% precision on a $f\sigma_8$ measurement with a 6-year ZTF SNe Ia spectro-identified sample with $z < 0.06$
- Improvements are expected from future work on photometric typing analysis and combination with density measurements

Backup slides

$f\sigma_8$ as a function of $z_{\max}$







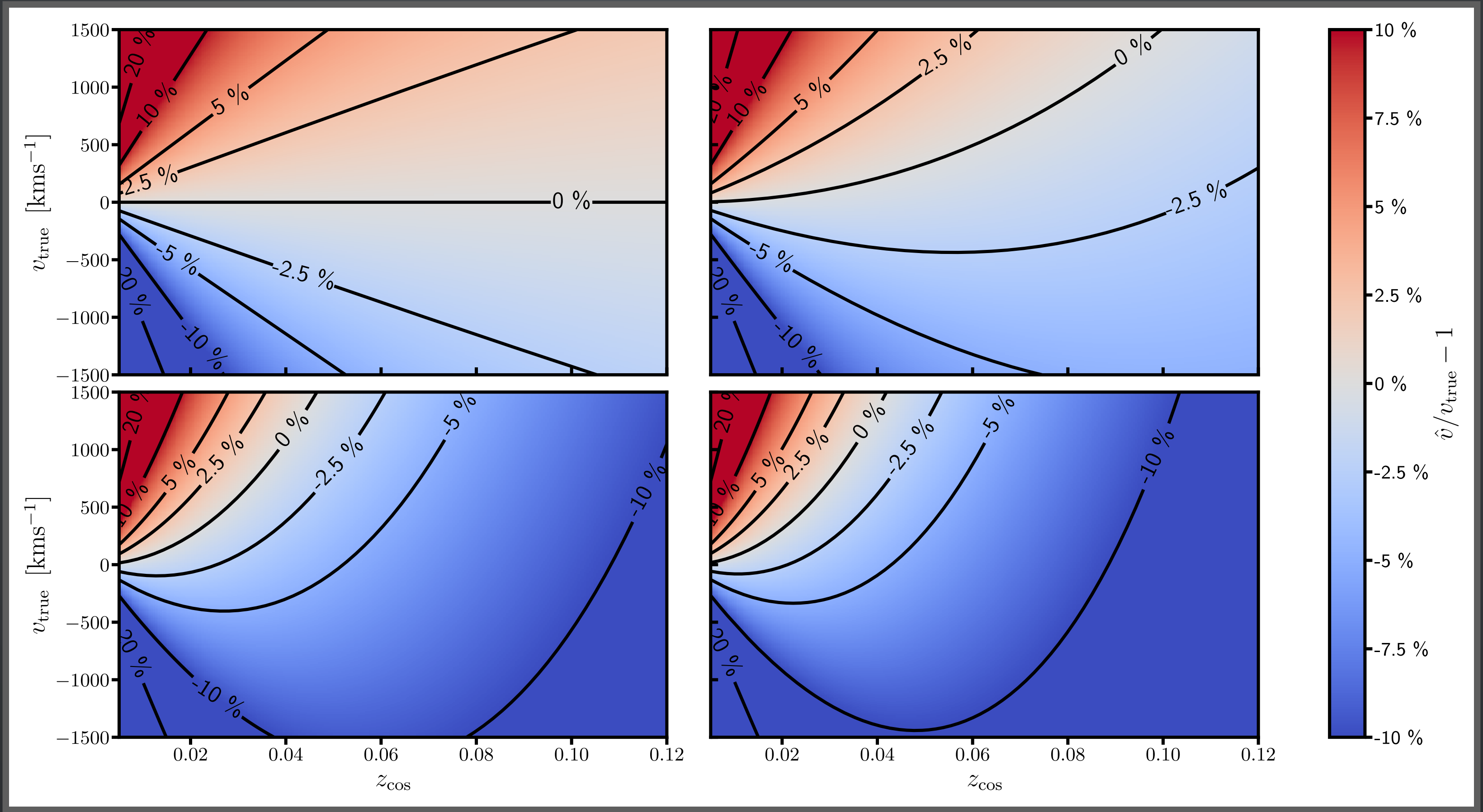
Velocity estimators biases

$$\hat{v}_1 = -\frac{\ln(10)c}{5}\left(\frac{(1+z)c}{H(z)r(z)} - 1\right)^{-1}\Delta\mu$$

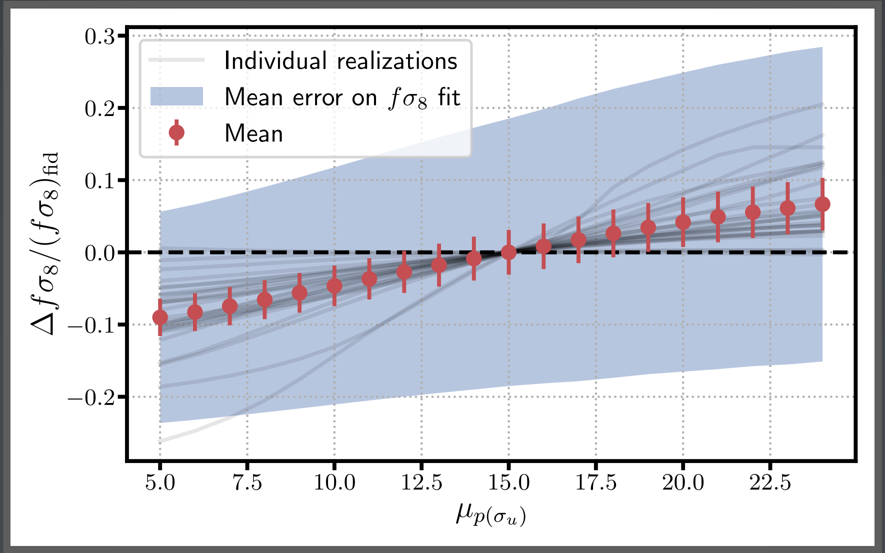
$$\hat{v}_3 = -\frac{\ln(10)c}{5}\left(\frac{1+z}{z} - 1\right)^{-1}\Delta\mu$$

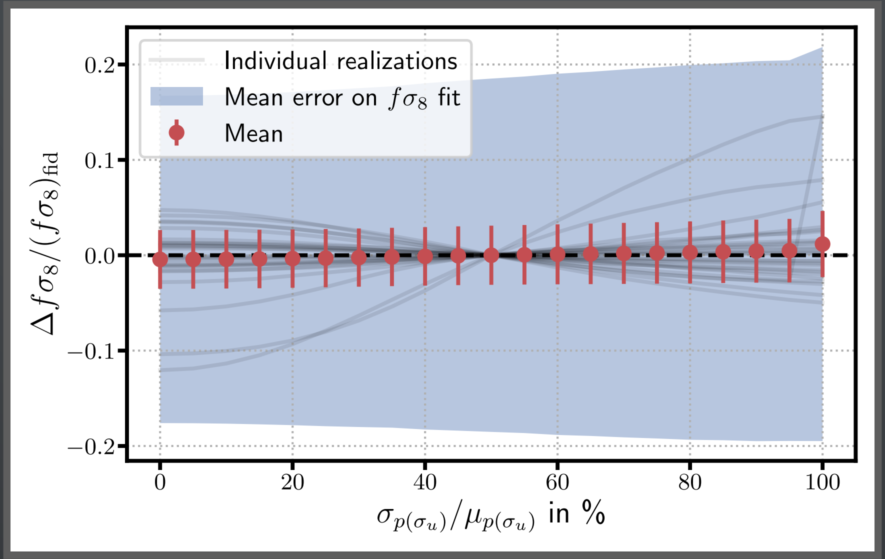
$$\hat{v}_2 = -\frac{\ln(10)}{5}\frac{H(z)r(z)}{(1+z)}\Delta\mu$$

$$\hat{v}_4 = -\frac{\ln(10)c}{5}\frac{z}{1+z}\Delta\mu$$



Gaussian prior on σ_u





ZTF H_0 budget erro(*Dhawan et al. 2021*)

Table 2. The contribution from individual terms in the error budget for measure H_0 with the current uniform distance ladder and the forecast with expected distances from JWST.

Quantity	Current Uncertainty (mag)	Expected Uncertainty (mag)
SN Ia intrinsic scatter	0.15	$0.1 / \sqrt{100} = 0.01$
TRGB absolute calibration	0.038	0.023
TRGB in SN Ia hosts	0.05	$0.05 / \sqrt{100} = 0.005$
Peculiar Velocity	0.02	0.01
Intercept of the Hubble diagram ($5a_B$)	0.013	0.004