USING THREE-POINT FUNCTIONS OF GALAXIES AND MATTER TO TEST GALAXY MODELS AND COSMOLOGY

GCCL Seminar

Laila Linke

Based on work in collaboration with:
Peter Schneider,
Patrick Simon,
Sven Heydenreich,
And many KiDS members!

Argelander-Institut für Astronomie

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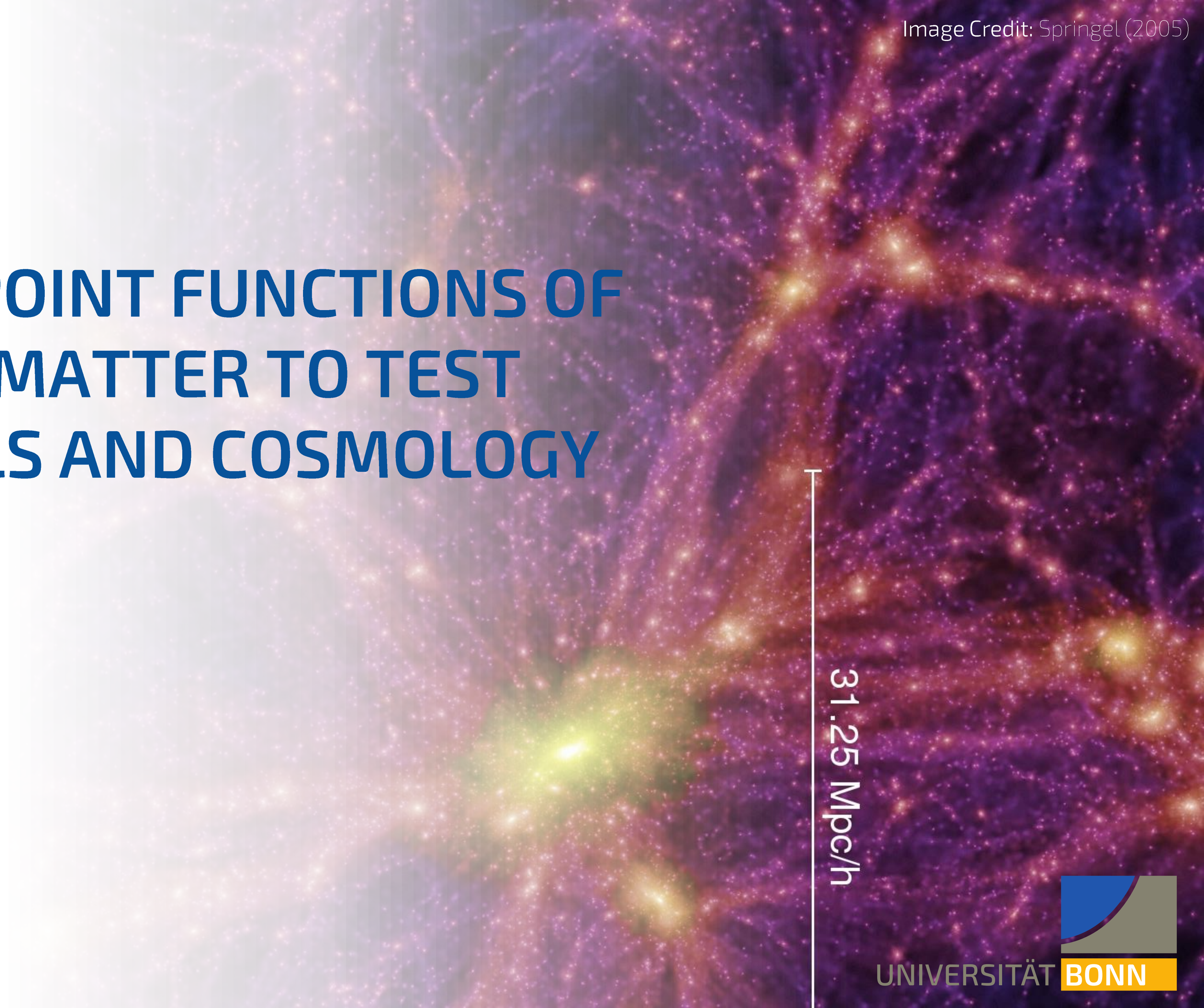


Image Credit: Springel (2005)

Some „big questions“…

Which cosmological model* best describes the evolution and structure of the Universe?

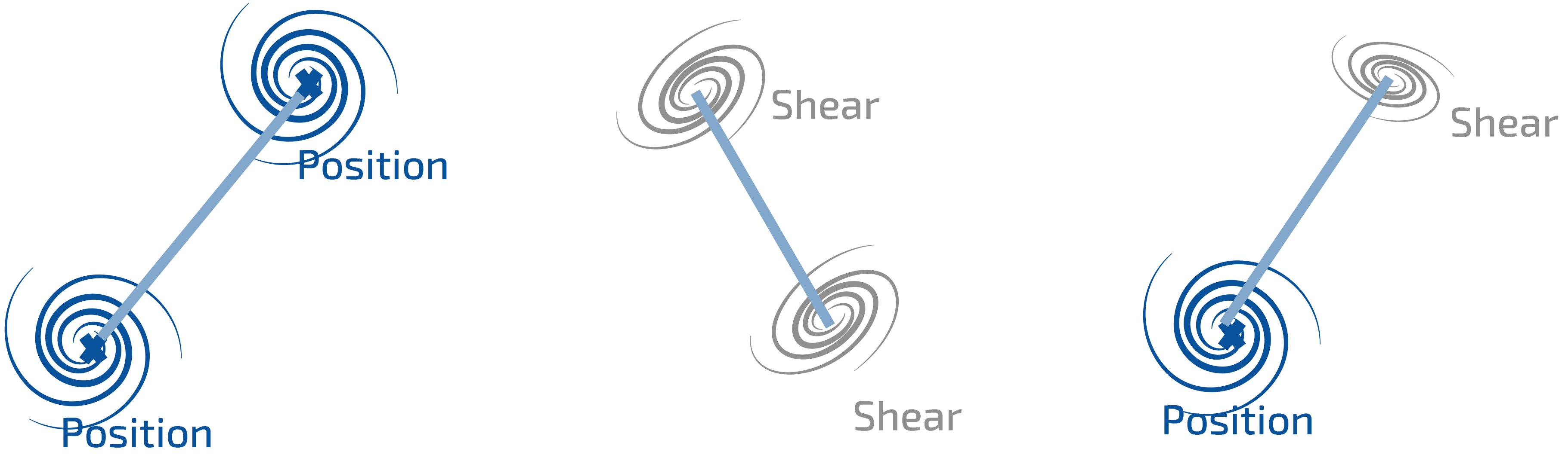
Which galaxy model best describes the evolution and distribution of Galaxies?

*: including Beyond-wCDM models, beyond-GR models, …

… And our tools to answer them!

Two-Point Statistics are not the only tool to constrain cosmology and galaxy models

Two- Point Statistics → Cosmology | Galaxy models



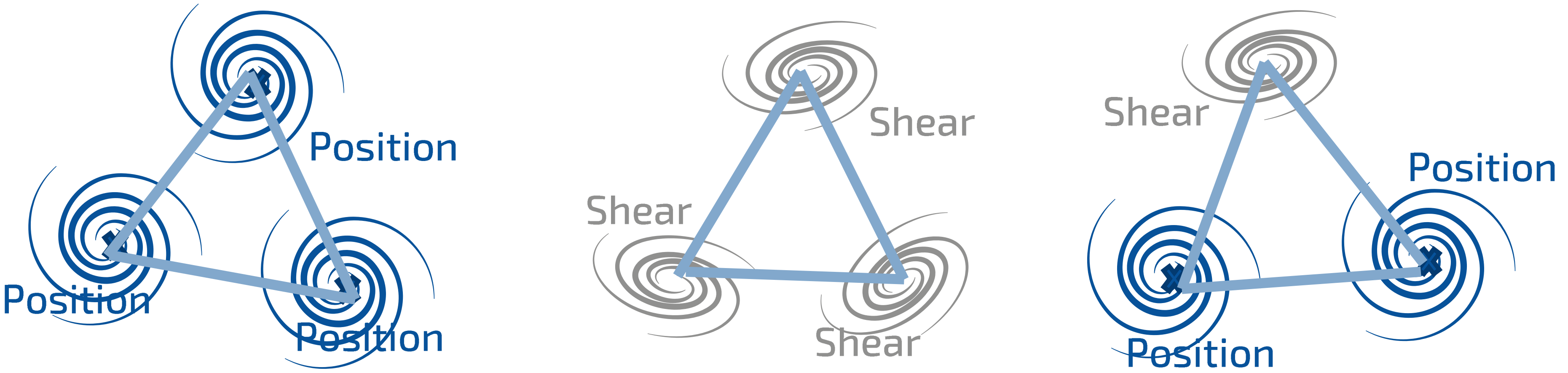
Galaxy Clustering | Cosmic Shear | Galaxy-Galaxy-Lensing

… And our tools to answer them!

Two-Point Statistics are not the only tool to constrain cosmology and galaxy models

Two- Point Statistics			Cosmology
Galaxy Clustering	Cosmic Shear	Galaxy-Galaxy-Lensing	Galaxy models

Three- Point Statistics			Cosmology
			Galaxy models



Third-Order Galaxy Clustering	Third-Order Shear	Galaxy-Galaxy-Galaxy-Lensing (G3L)

… And our tools to answer them!

Two-Point Statistics are not the only tool to constrain cosmology and galaxy models

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Three- Point Statistics			Cosmology
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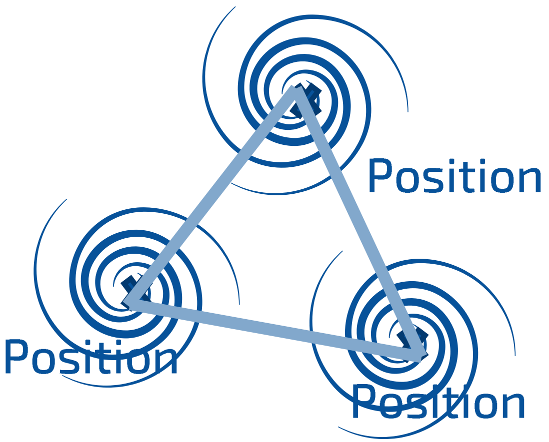
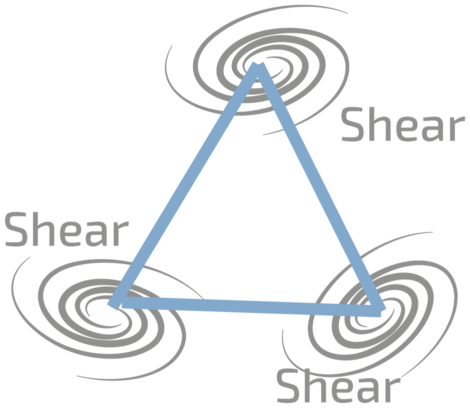
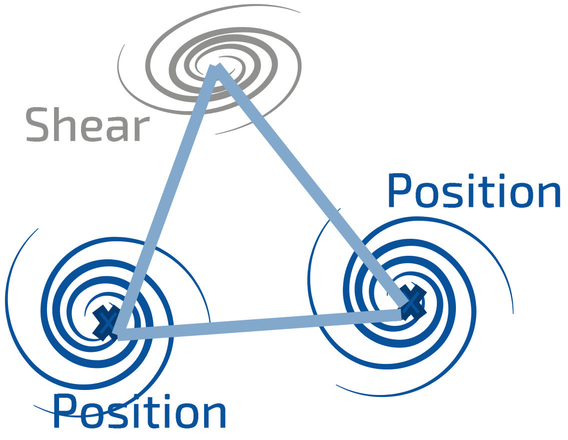


Third-Order Galaxy Clustering



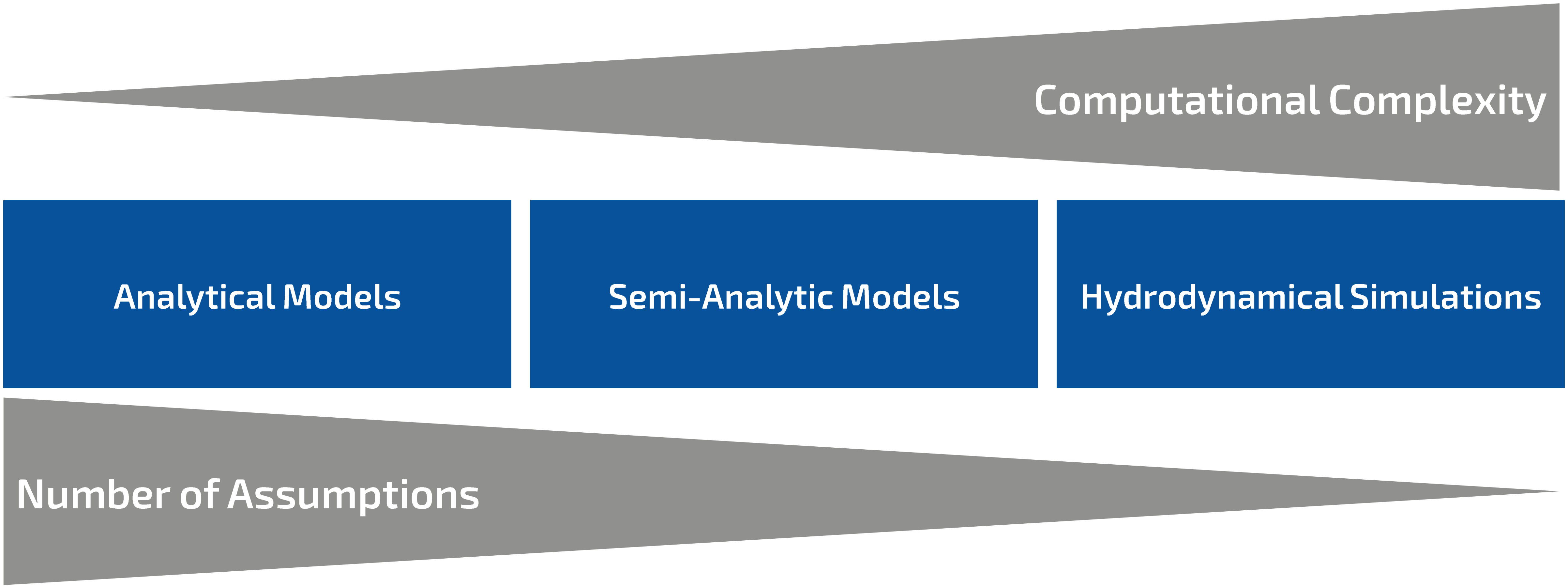
Third-Order Shear



Galaxy-Galaxy-Galaxy-Lensing (G3L)

Overview of Models of Galaxy Formation and Evolution

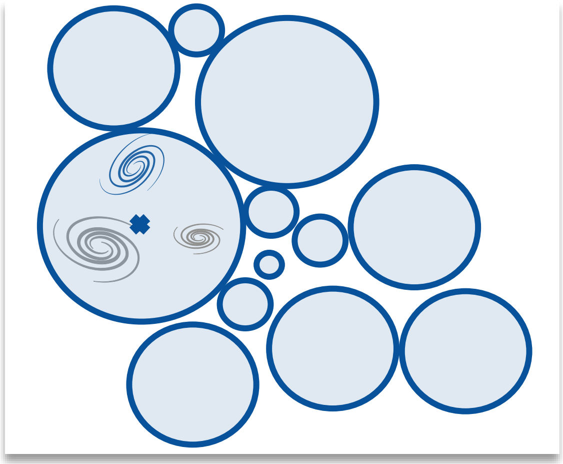
Galaxy models can be divided into three categories



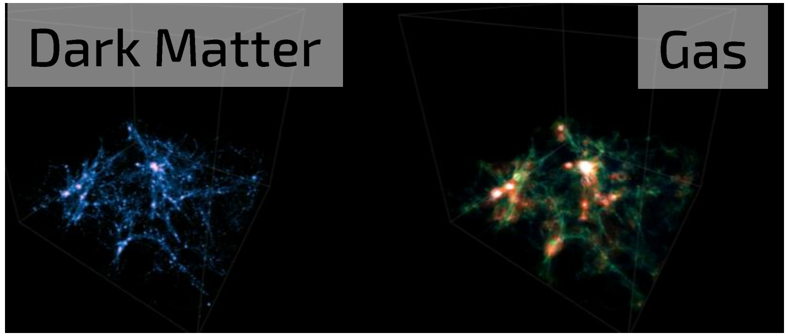
Overview of Models of Galaxy Formation and Evolution

Galaxy models can be divided into three categories

Analytical Models	Semi-Analytic Models	Hydrodynamical Simulations



- Star formation
- Chemical evolution
- Feedback
- Galaxy/Gas interactions
- ...



Computational Complexity

Number of Assumptions

Image Credit: Springel + (2005), **Video Credit:** Illustris Collaboration

Overview of Galaxy-Galaxy-Galaxy-lensing

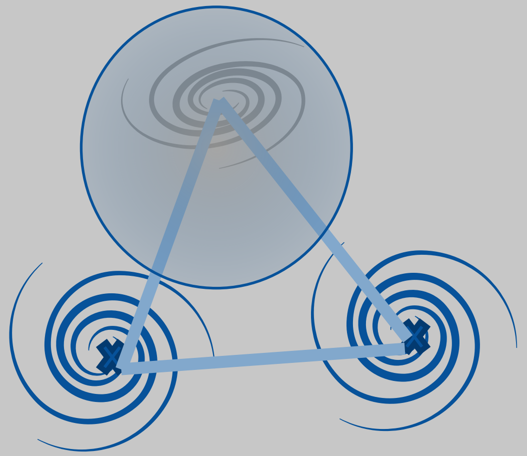
We use G3L to test galaxy models

OBSERVABLES

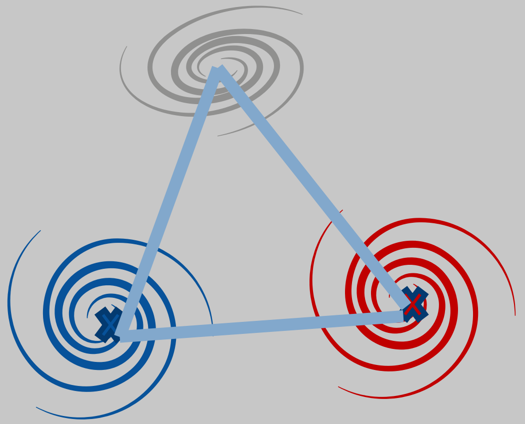
- G3L Correlation Functions $\tilde{\mathcal{G}}(\vec{\vartheta}_1, \vec{\vartheta}_2) = \frac{1}{\bar{n}^2}\langle n(\vec{\theta} + \vec{\vartheta}_1)\, n(\vec{\theta} + \vec{\vartheta}_2)\gamma(\vec{\theta})\rangle$
- Aperture Statistics $\langle N^2 M_{\mathrm{ap}}\rangle$

BENEFITS COMPARED TO 2-PT STATISTICS:

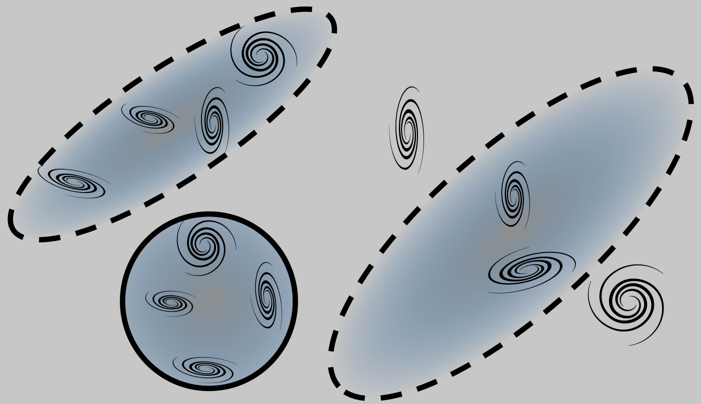
Galaxy-Matter-Bispectrum



Correlations of galaxy populations



Alignment of galaxy pairs and matter



Overview of Models of Galaxy Formation and Evolution

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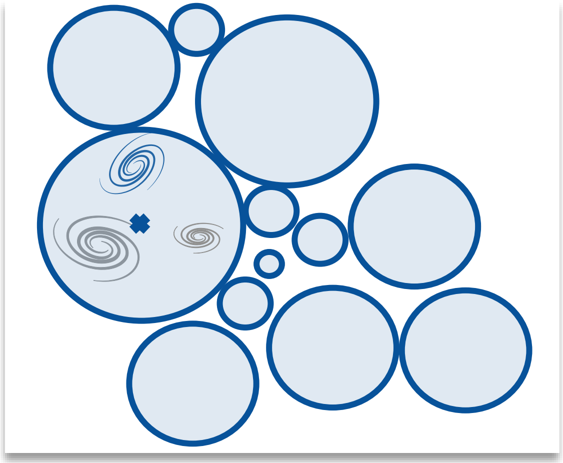
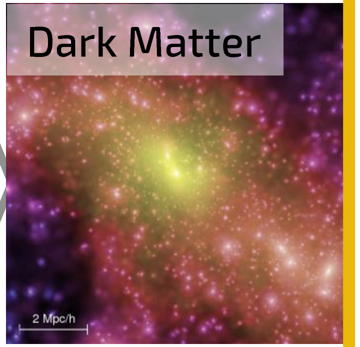
Analytical Models

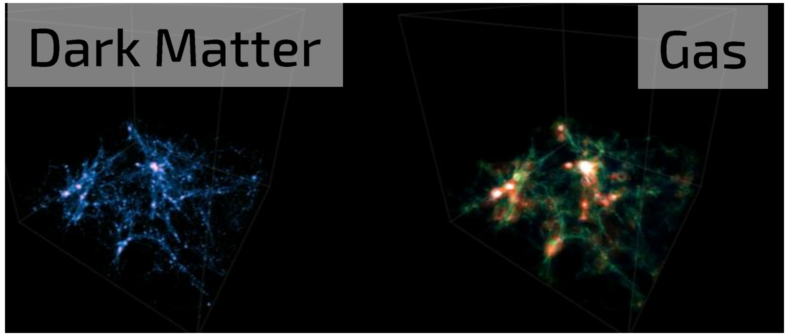


Semi-Analytic Models

- Star formation
- Chemical evolution
- Feedback
- Galaxy/Gas interactions
- ...



Hydrodynamical Simulations



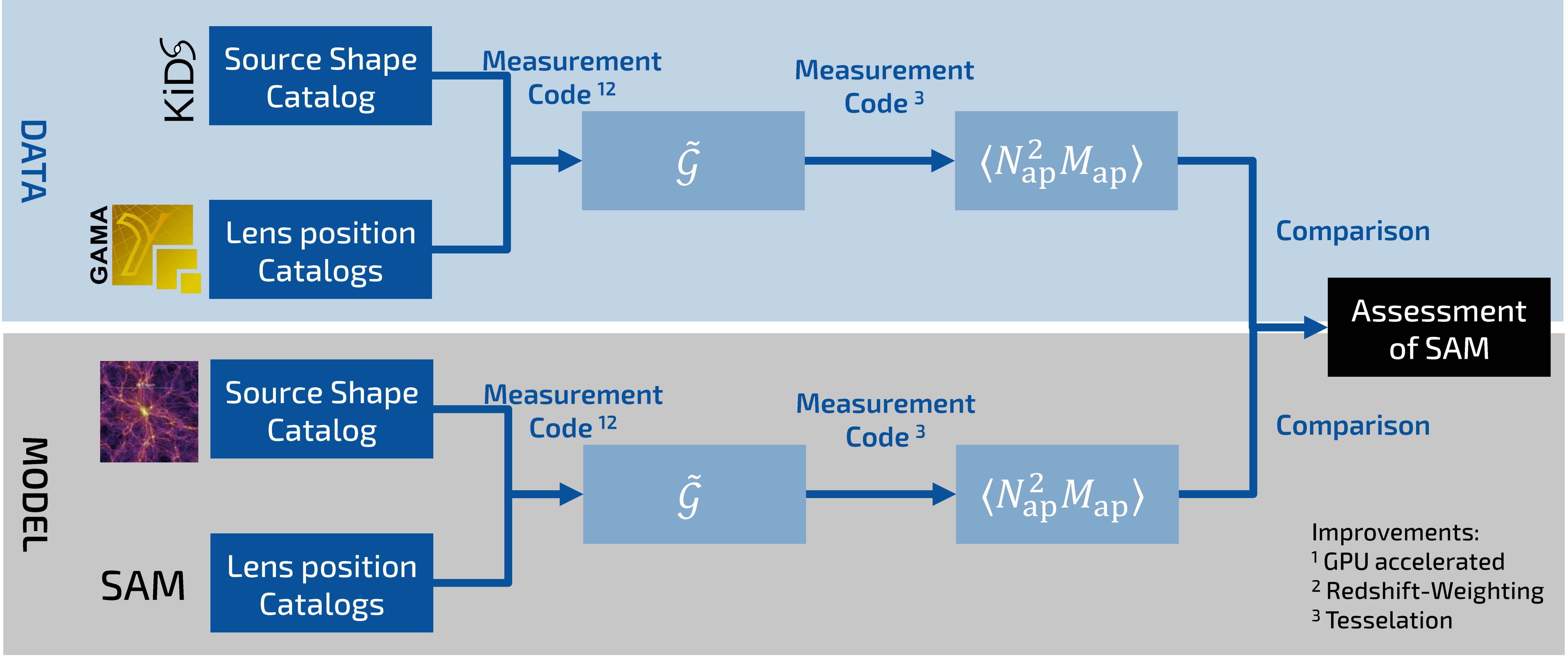
Computational Complexity

Number of Assumptions

Image Credit: Springel + (2005), **Video Credit:** Illustris Collaboration

Pipeline for testing SAMs with G3L

We test two SAMs by comparing their G3L predictions to observations



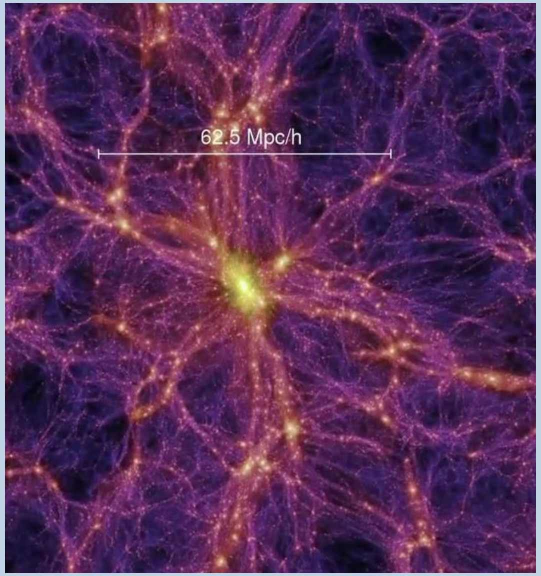
More Info at **LL, Simon, Schneider & Hilbert (2020):** *Astronomy & Astrophysics*, 634:A13, arXiv: 1909.06190;
Code available at **github.com/llinke1/G3LConGPU**.

Observational and Simulational Data for SAM test

We test two SAMs by comparing their G3L predictions to observations

Simulation

Millennium Run with models by Henriques+ (2015; H15) and Lagos+(2012; L12)



- 64 x 16 deg^2 realizations
- Source shear from multiple-lens-plane algorithm (Hilbert+ 2009)
- Lens stellar masses and colours from SAM

Observation

Overlap of KiDS, VIKING and GAMA

KiDS

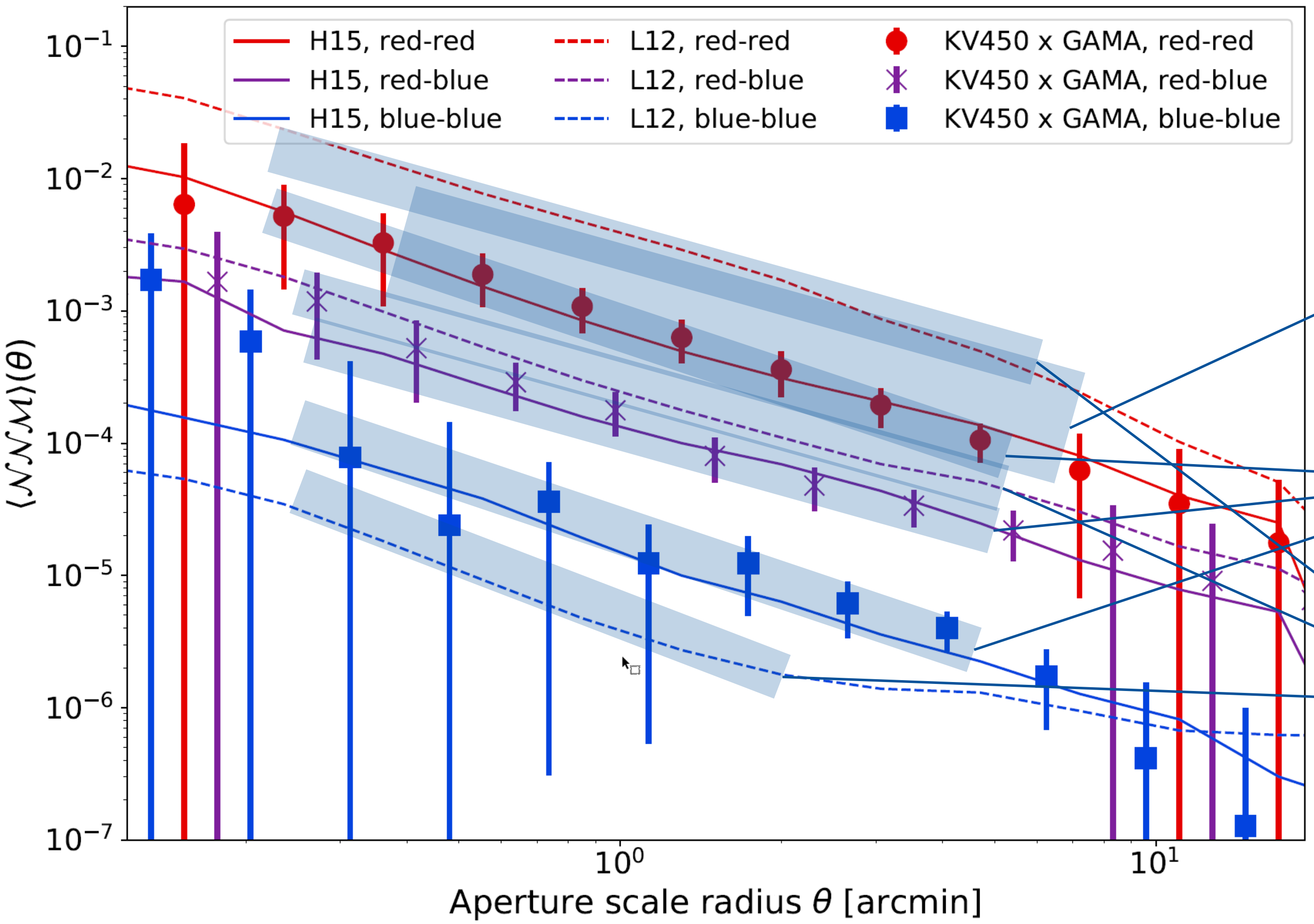
GAMA

- 180 deg^2 survey area with spectroscopy and photometry
- Source shapes from KiDS + VIKING (Wright+ 2019)
- Lens redshifts, stellar masses and colours from GAMA (Liske+ 2015, Wright+ 2017)

Image Credits:

G3L measurements for red and blue lenses

The H15 model agrees, the L12 model disagrees with the observations



Largest signal for red-red pairs ➔ large galaxy bias

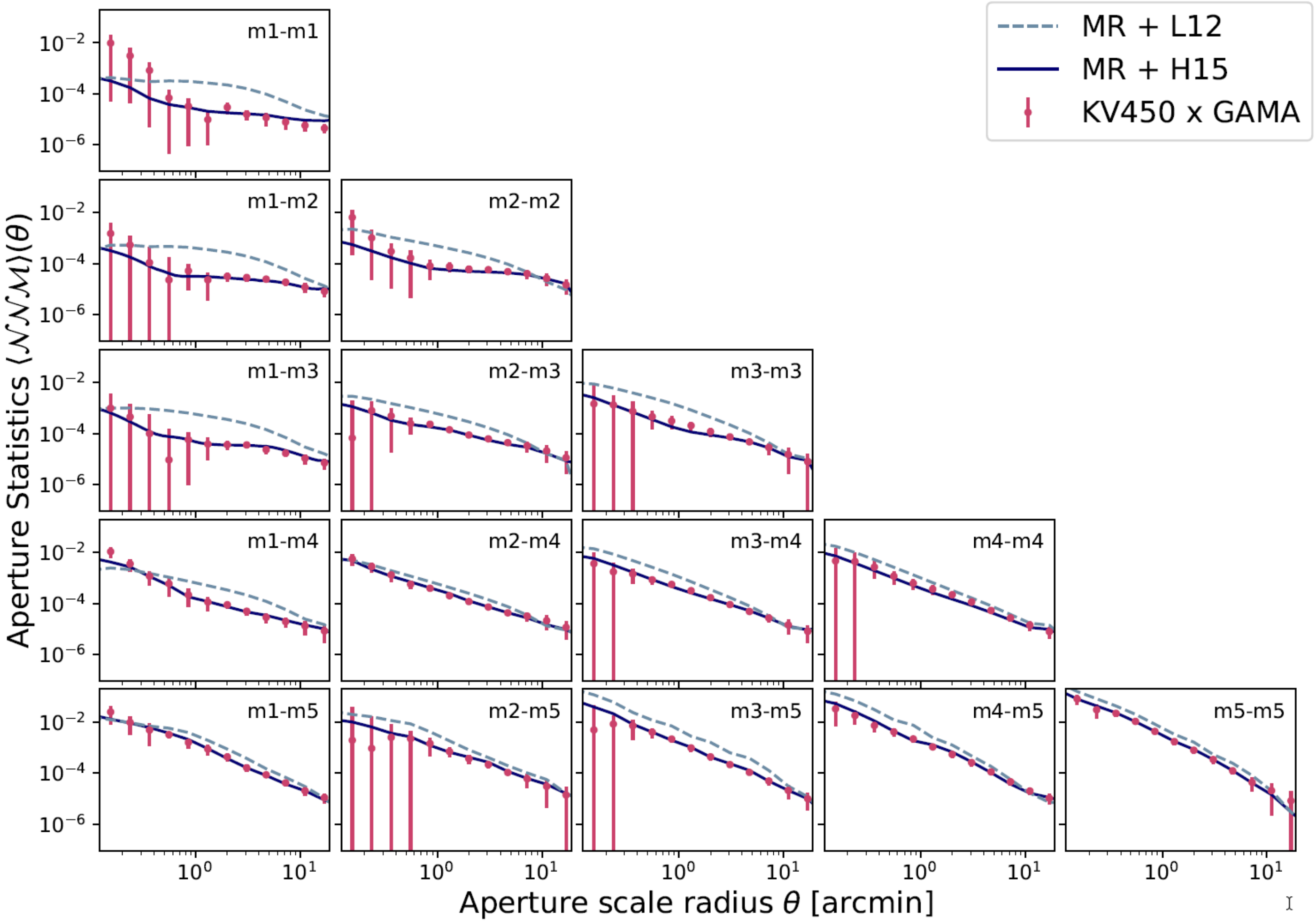
H15 model agrees with observations

L12 model disagrees with observations

More Info at LL, Simon, Schneider et al. (2020), *Astronomy & Astrophysics*, 640:A59, arXiv: 2005.02419

G3L measurements for lenses with different stellar masses

The H15 model agrees, the L12 model disagrees with the observations



- H15 model agrees with observations
- L12 model differs from observations
- Potential reasons: Too strong ram pressure stripping / Tidal interactions, different dust and IMF models

More Info at LL, Simon, Schneider et al. (2020), *Astronomy & Astrophysics*, 640:A59, arXiv: 2005.02419

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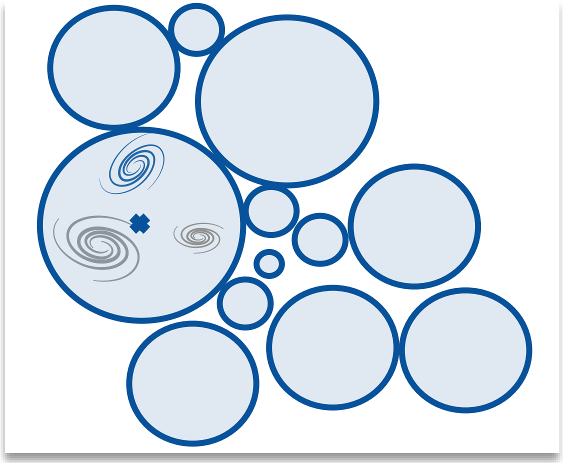


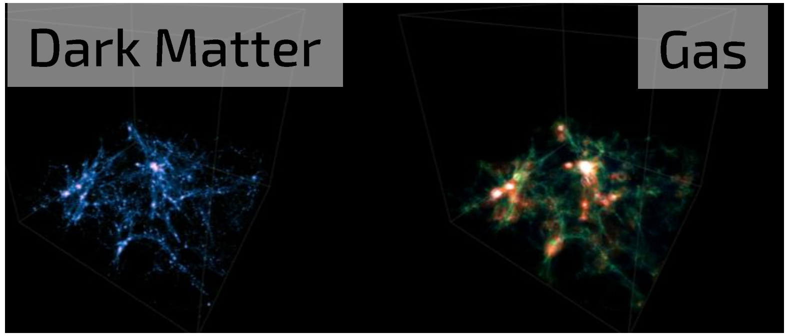
Star formation

Chemical evolution

Feedback

Galaxy/Gas interactions

...



Computational Complexity

Number of Assumptions

Image Credit: Springel + (2005), **Video Credit:** Illustris Collaboration

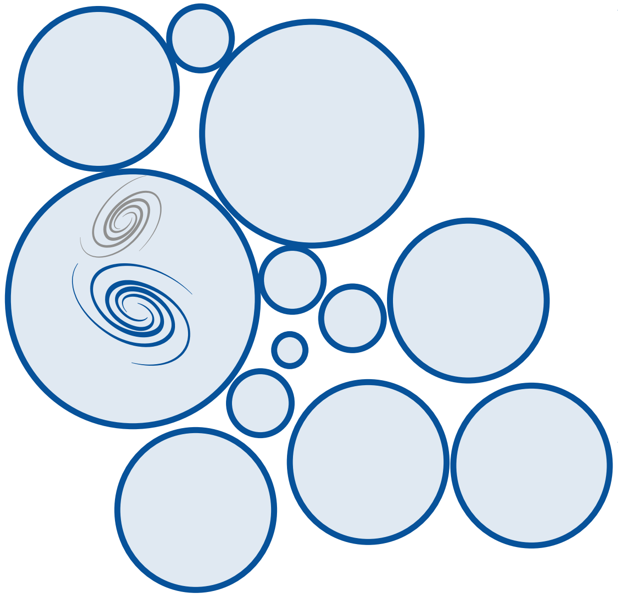
Overview of G3L halo model

Halo models rely on several assumptions

Halo Mass Function (HMF)
What mass are the halos?

Halo Occupation Distribution (HOD)
How many galaxies are in each halo?

Halo Model for G3L



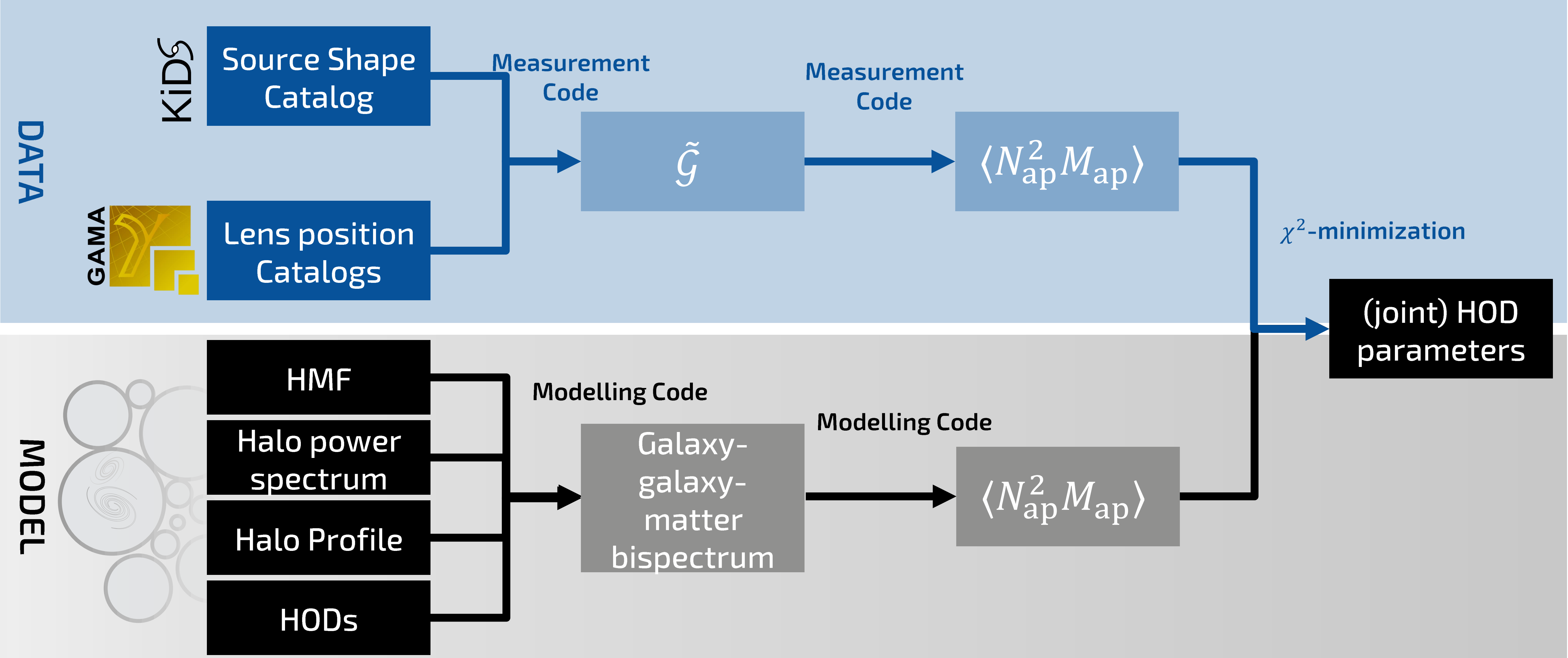
Halo Power- and Bispectrum
Where are the halos?

Halo Profile
What is the halo density?

Cosmology

Pipeline for testing the G3L halo model

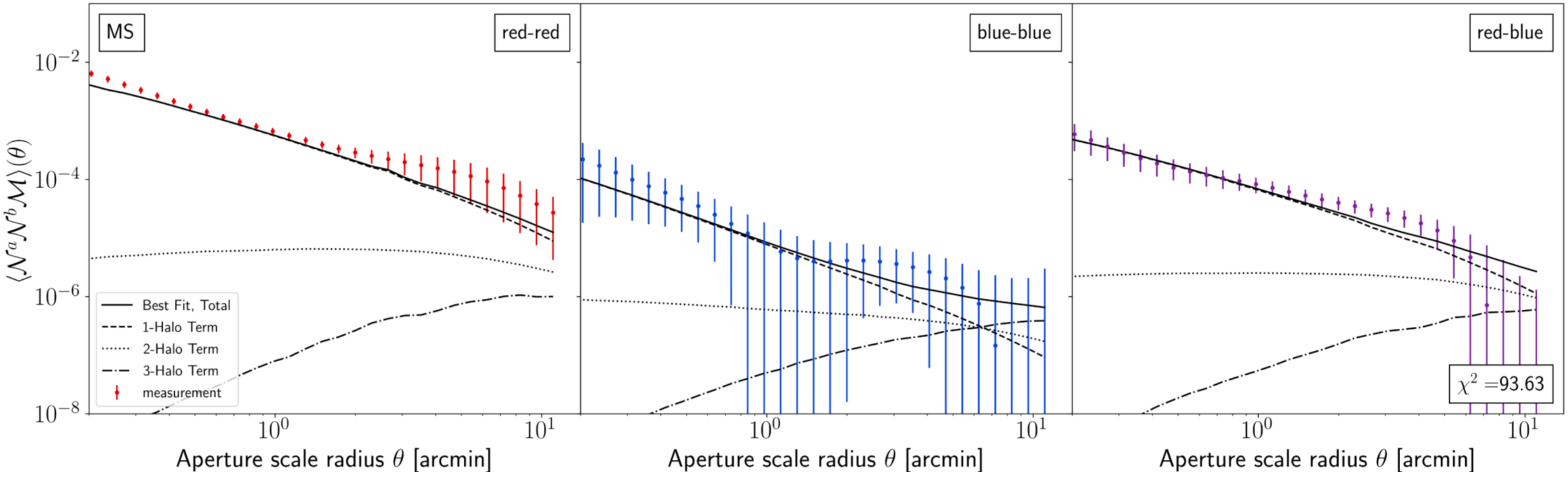
We fit HOD parameters with the observed G3L signal



Code available at **github.com/llinke1/G3LHalo**

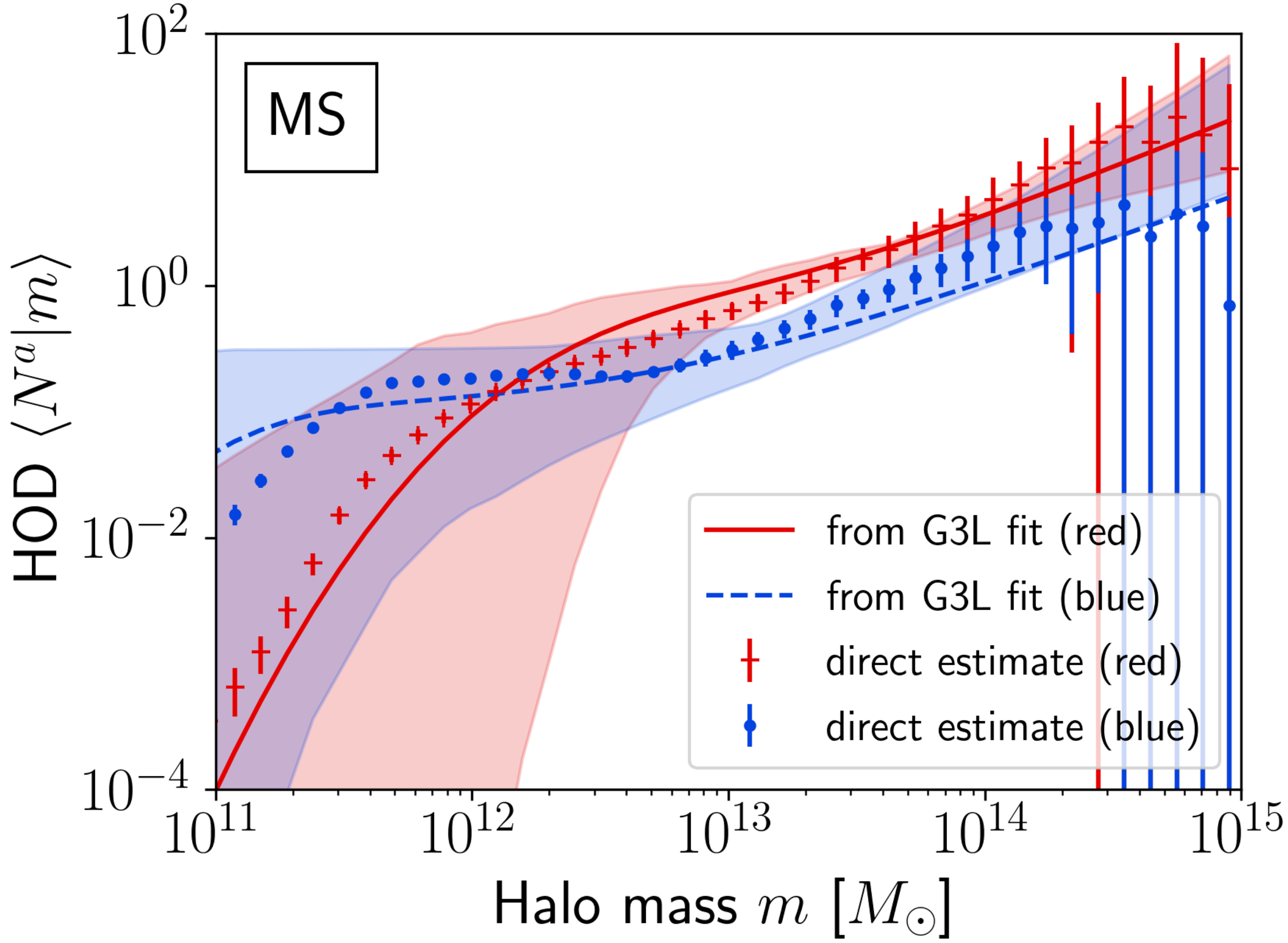
Result of Halo Model Fit to Millennium Simulation

Best-fitting model agrees with the Millennium Simulation at the 95% Confidence Level



Comparison of HODs from G3L fit and actual HODs

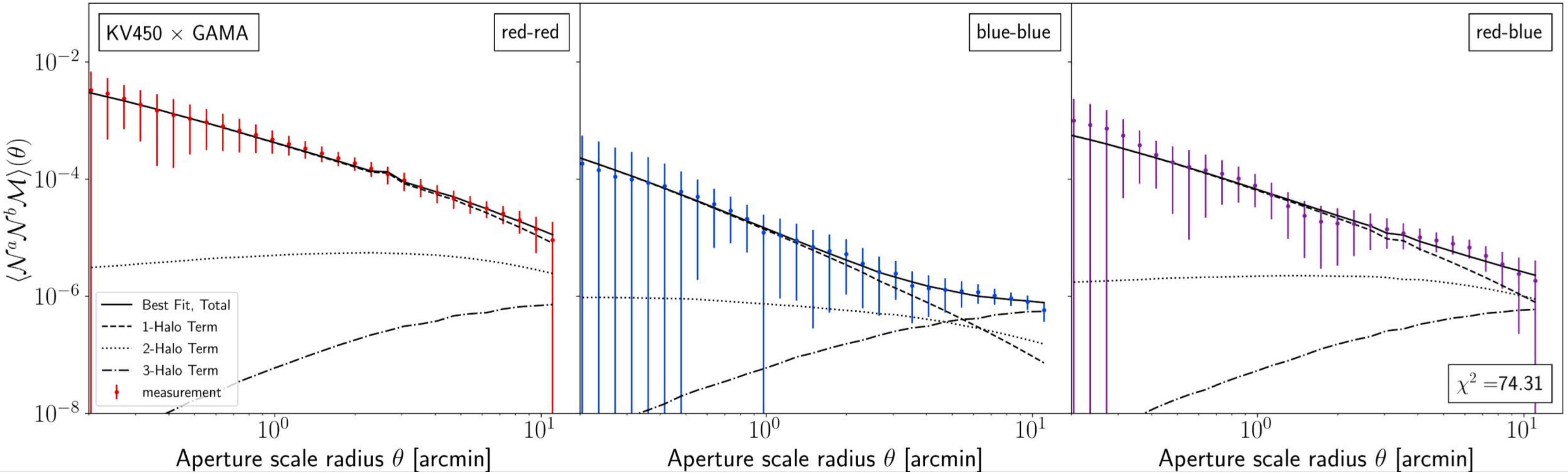
The G3L fit recovers the HODs of red and blue simulated galaxies



- G3L fit recovers HODs of red and blue galaxies
- Fit has large uncertainties at small halo masses, better constraints for medium to large halo masses
- Similar results for stellar-mass selected lenses

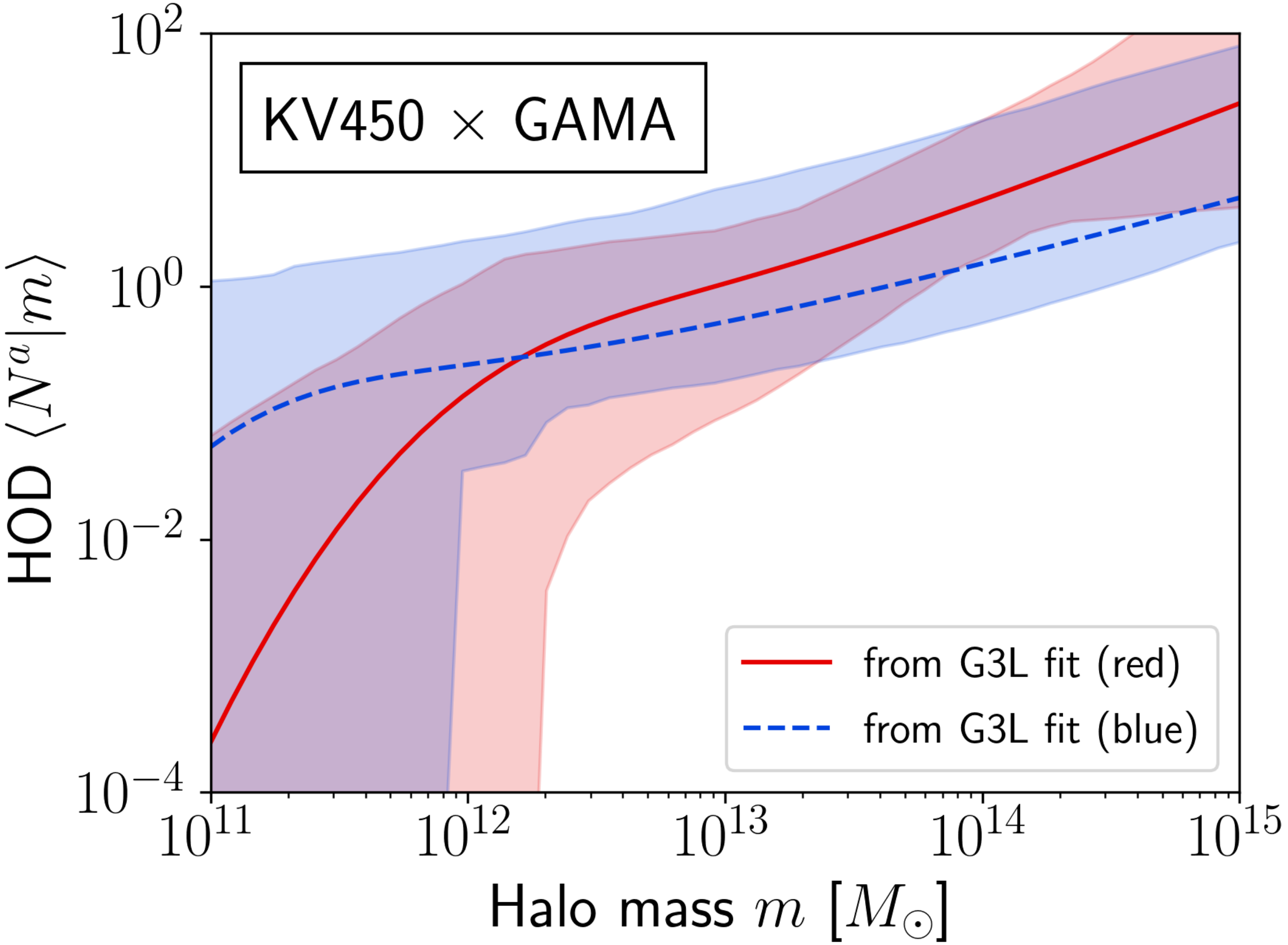
Result of Halo Model Fit to KV450 x GAMA

Best-fitting model agrees with the Observation at the 95% Confidence Level



HODs and from G3L fit to KV450 x GAMA

The HODs of GAMA galaxies are similar to the simulated ones



- G3L fit gives HODs similar to the HODs in the simulation
- Fit has large uncertainties at small halo masses

… And our tools to answer them!

Two-Point Statistics are not the only tool to constrain cosmology and galaxy models

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Three- Point Statistics			Cosmology
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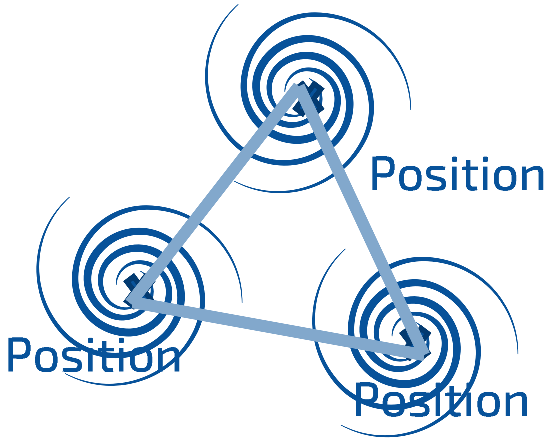
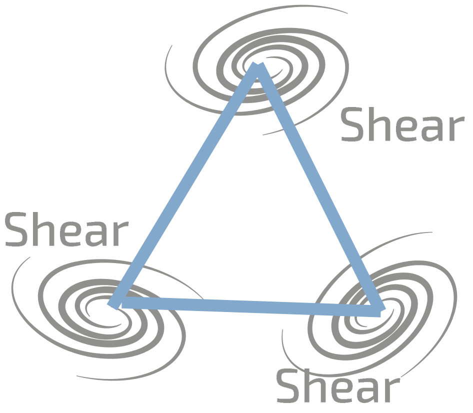
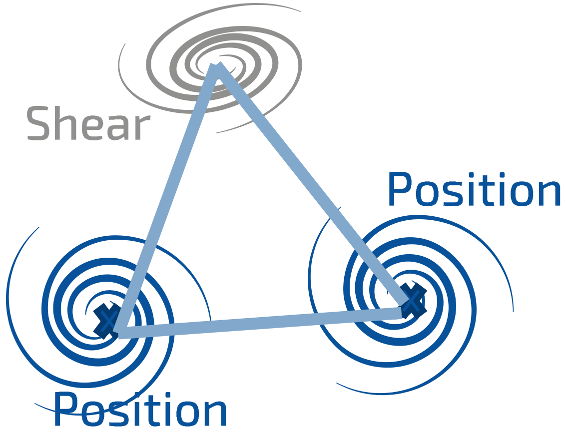


Third-Order Galaxy Correlation



Third-Order Shear



Galaxy-Galaxy-Galaxy-Lensing (G3L)

Overview of third-order shear analysis

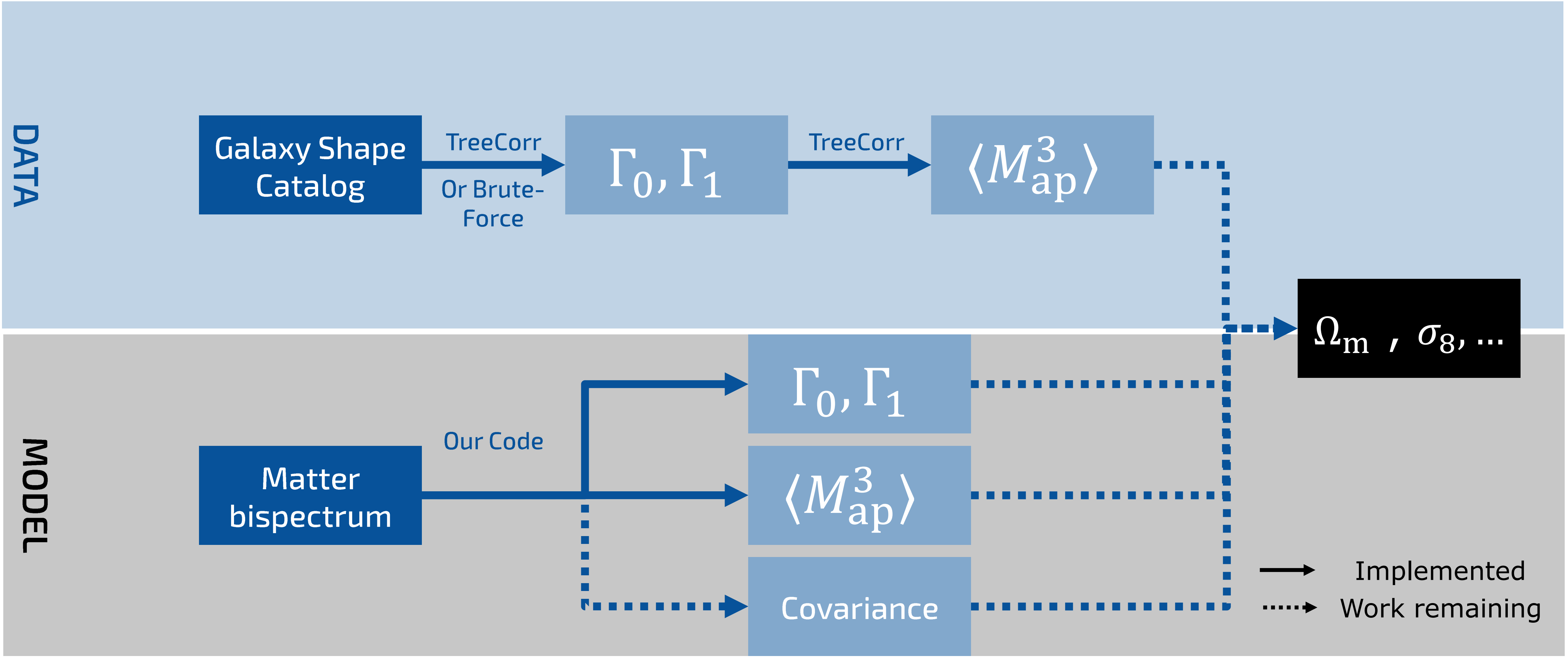
OBSERVABLES

- Third-Order Shear Correlation Functions Γ_0, Γ_1
- Aperture Statistics $\langle M_{\mathrm{ap}}^3 \rangle(\theta_1, \theta_2, \theta_3)$, $\langle M_{\perp}^2 M_{\mathrm{ap}} \rangle(\theta_1, \theta_2, \theta_3)$

BENEFITS COMPARED TO 2PT STATISTICS / OTHER HOS:

- Break $\Omega_{\mathrm{m}} - \sigma_8$ degeneracy (e.g. Kilbinger & Schneider, 2005)
- Potential for self-calibration of nuisance parameters (Pyne & Joachimi, 2021)
- Can be directly used on shear catalogues and deals easily with masks
- Automatically includes systematics check with B-Modes
- Direct modelling eases inclusion of systematics

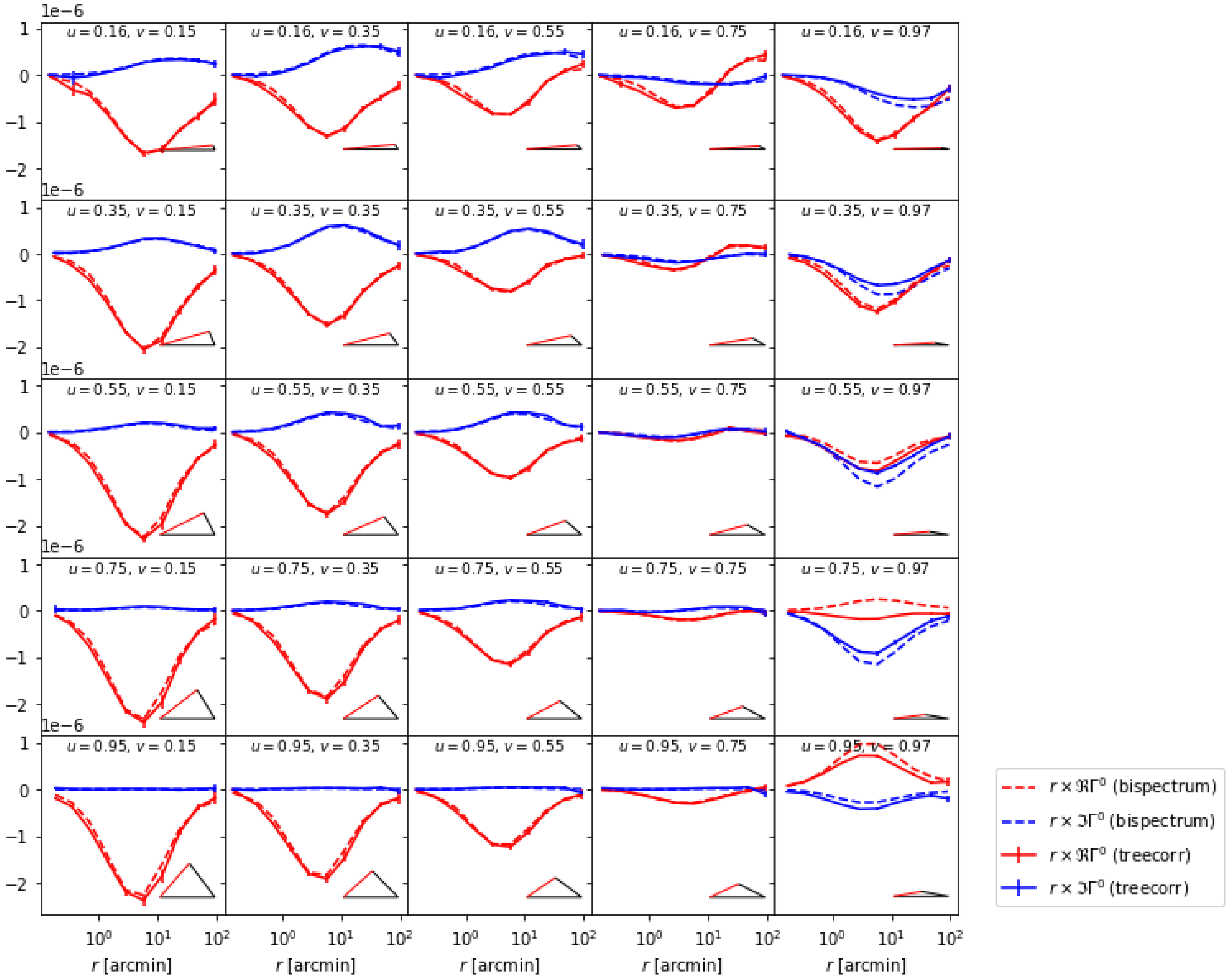
Measurement and modelling pipeline for third order shear



In collaboration with Sven Heydenreich

Comparison of 3pcf of model and Millennium simulation

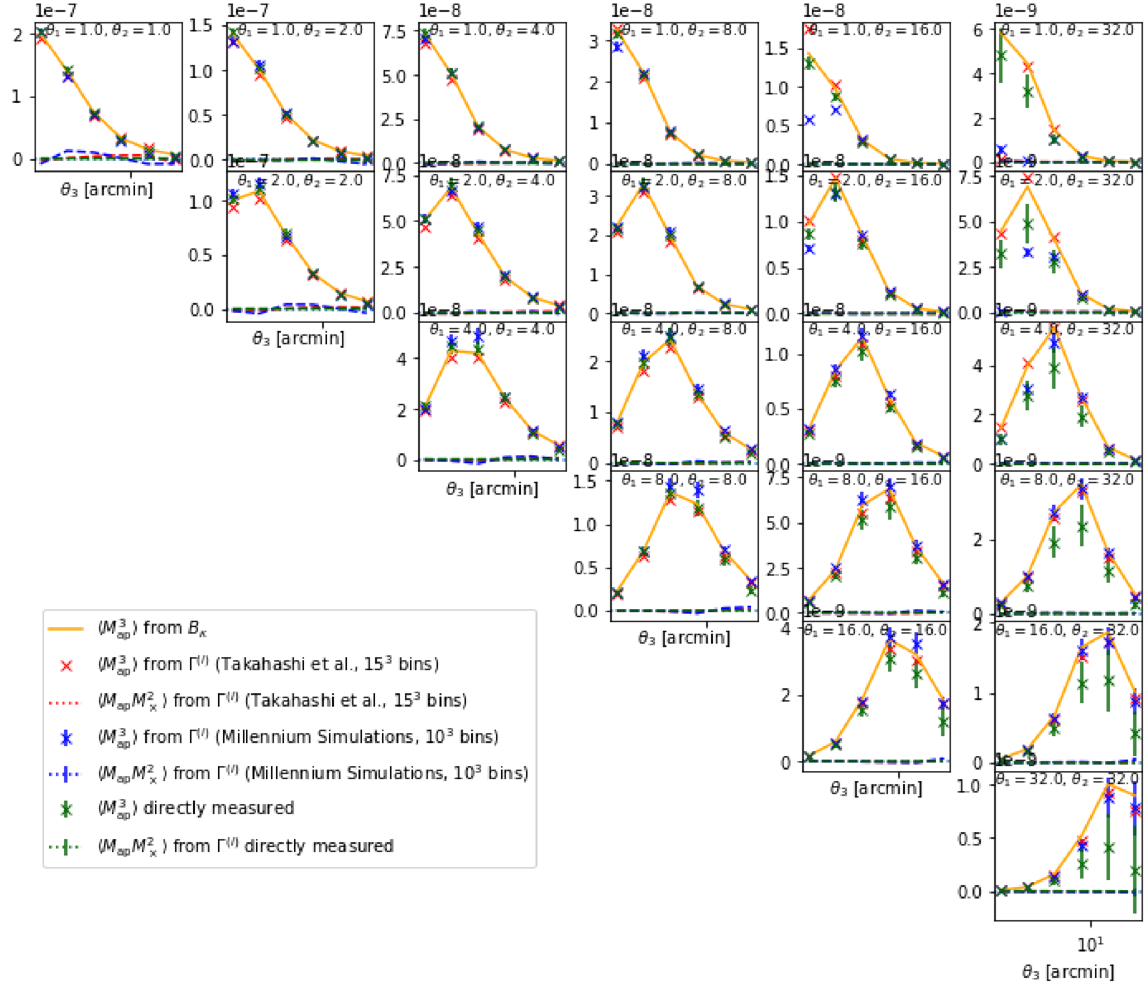
The 3pcf of the model agrees with the simulation



- Model agrees with Millennium simulation for all triangle configurations
- Modelling of 3pcf is computationally more expensive than modelling of aperture statistics
- Data vector for 3pcf is larger

Comparison of $\langle M_{\mathrm{ap}}^3 \rangle$ of model and Millennium simulation

The modelled aperture statistics agree with the simulation

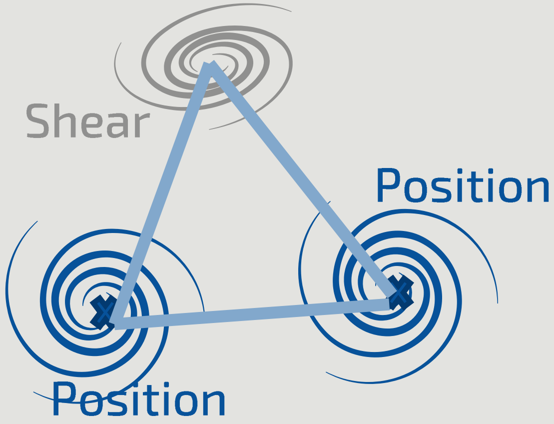


- Modelled and directly measured aperture masses agree remarkably well
- Conversion from 3pcf to aperture statistics is accurate only if the 3pcf is measured in ~15x15x15 bins or more
- E/B-mode leakage is small (in contrast to two-point statistics)

In collaboration with Sven Heydenreich

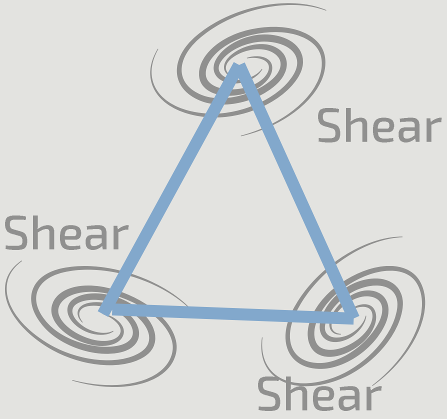
Conclusion

Three-Point statistics are worthwhile!



G3L can be used to test galaxy models

- Not all SAMs predict the correct G3L signal
- Halo Models can describe G3L with realistic HOD parameters
- G3L halo model showed that HODs of red and blue galaxies are positively correlated



Third-order-shear can be used to complement cosmological analyses

- Modelling of third-order shear correlation function and aperture statistics is possible
- Models agree with Millennium Simulation

THANK YOU!


Image Credit: ESA/NASA

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