

# 1-point lensing statistics in cosmology



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# Ioav's Students in 2006



loav was instrumental in my career



*Working with Ioav was a pleasure*

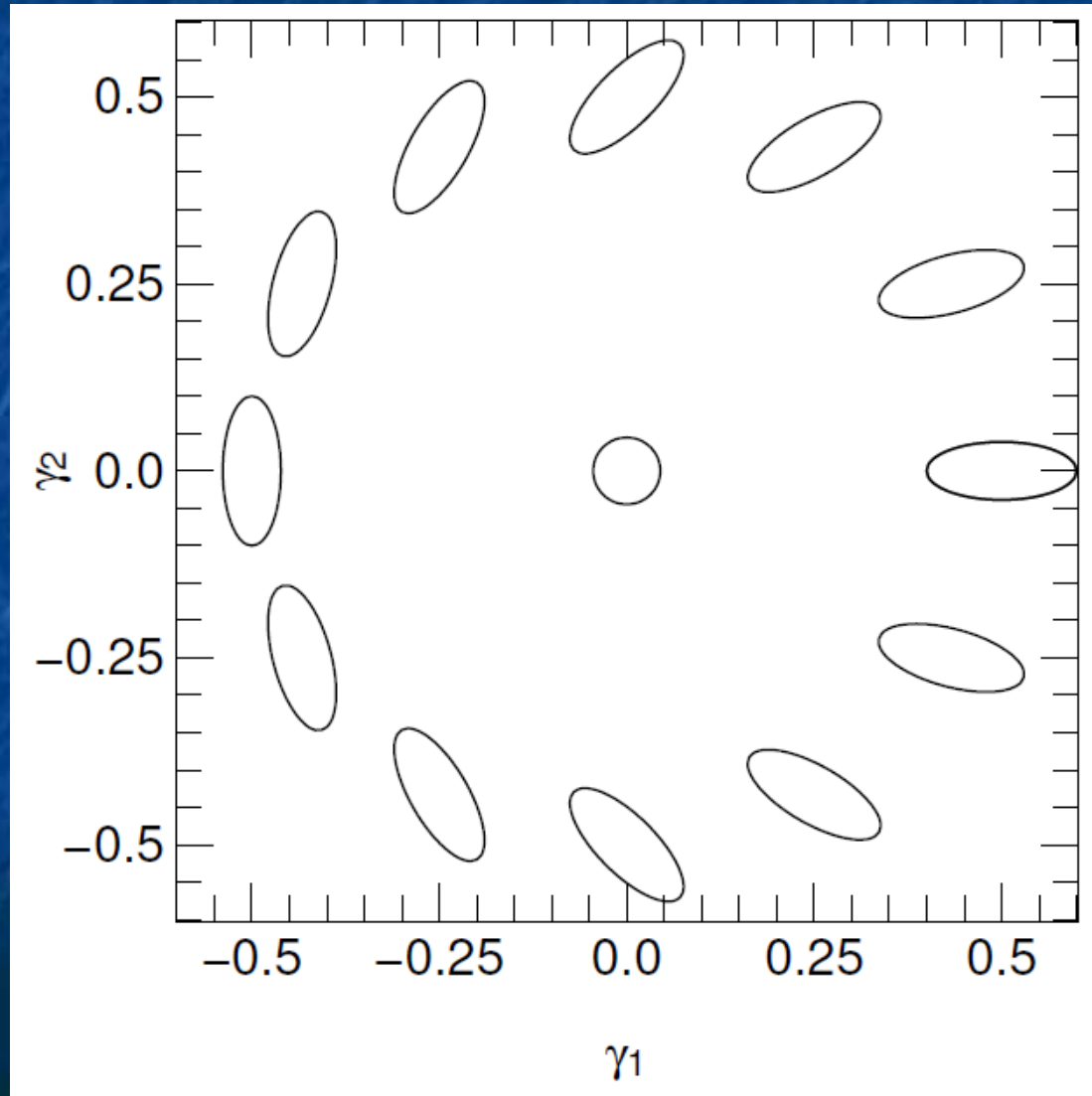


# Cosmic Shear

- Lensing changes galaxies ellipticities
- In the weak-lensing regime  $\rightarrow$  only the shear ( $\gamma$ ) matters
- Shear can only be observed statistically.
  - Typical values:

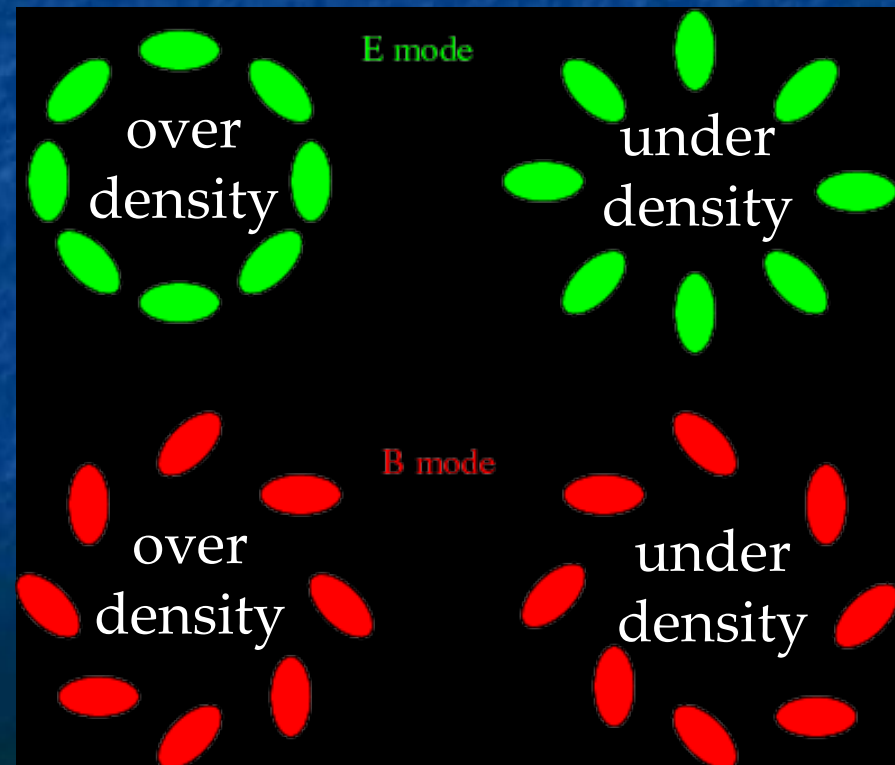
$$\gamma \sim 0.03$$

$$\sigma_\varepsilon \langle |\varepsilon|^2 \rangle^{1/2} \sim 0.3$$



# Cosmic Shear

- **Cosmic Shear** → coherent distortions to light-bundles in the weak-lensing regime
  - Measured in the 2-point shear correlation function
    - Shear power-spectrum
  - Like in the CMB and EM, there are **E** and **B**-modes in weak-lensing
  - E-modes have larger S/N and are easier to observe



# Cosmic Shear

- Cosmic shear faces several challenges (see Kilbinger 1411.0115)
  - Intrinsic alignment of galaxies
  - Dependence on non-linear scales in the  $P(k)$ 
    - Requires simulations to understand
    - Introduces non-Gaussianities in the  $\kappa$  distribution
- Difficult astrophysical systematics
  - E.g.: correlations between weak-lens. selection function and background density
  - E.g.: background galaxies obscured by massive foreground ones

# Lensing PDFs

- Cosmic shear is not the only important lensing statistic
- The 1-point statistic (the lensing PDFs of  $\kappa$ ,  $\gamma$  and  $\mu$ ) are also very important. They:
  - are simpler to work with
  - provide complementary information
  - can be used to understand observational selection functions and Malmquist bias
    - E.g.: number counts of sub-mm galaxies are subject to large biases due to strong-lensing

*Negrello et al., 2010, Science, 330*

- can be used to model **lensing of standard candles** (SNe) and standard sirens (GWs)

# The Inverse Lensing Problem

- Lensing is usually treated as noise in SNe & GW
- Can we turn this noise into signal?
  - Can we learn about cosmology from the scatter of supernovae in the Hubble diagram?
  - Answer: **YES!** We can constrain **the matter power spectrum  $P(k)$**  and/or **halo mass function!**
  - It is a new observable & good **cross-check**

*Dodelson & Vallinotto (astro-ph/0511086, PRD)*

*Quartin, Marra & Amendola (1307.1155, PRD)*

*Ben-Dayan, & Kalaydzhyan (1309.4771, PRD)*

*Castro, Marra & Quartin (1605.07548, MNRAS)*



# The Method of the Moments (MeMo)

- Parametrize the  $\mu$  PDF with its first 4 moments

$$L_{\text{MeMo}}(\text{cosmo}, \text{nuisance}) \propto \prod_j^{\text{z bins}} \frac{1}{|\Sigma_j|} \exp \left( -\frac{1}{2} \chi_j^2 \right)$$

$$\chi_j^2 = (\boldsymbol{\mu} - \boldsymbol{\mu}_{\text{fid}})^t \Sigma_j^{-1} (\boldsymbol{\mu} - \boldsymbol{\mu}_{\text{fid}})$$

$$\boldsymbol{\mu} = \{\mu'_1, \mu_2, \mu_3, \mu_4\}$$

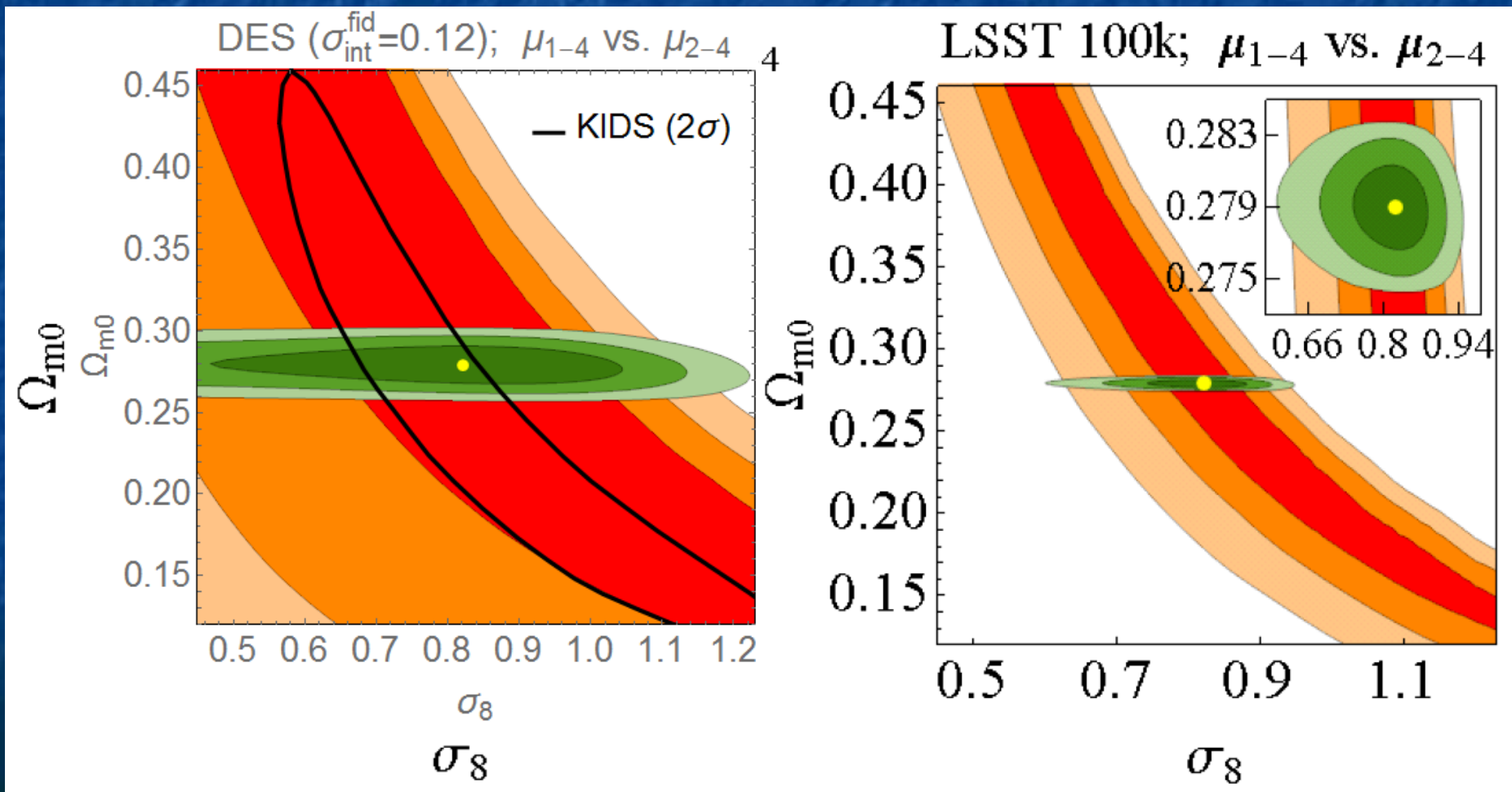
- Very complicated covariance matrix
  - There is reason to believe it is under control

*Quartin, Marra & Amendola (1307.1155, PRD)*

*Macauley, Davis et al., (1607.03966, MNRAS)*

# The Inverse Lensing Problem (2)

- DES (LSST)  $\rightarrow \sigma_8$  with  $\sim 30\%$  ( $\sim 6\%$ ) precision!



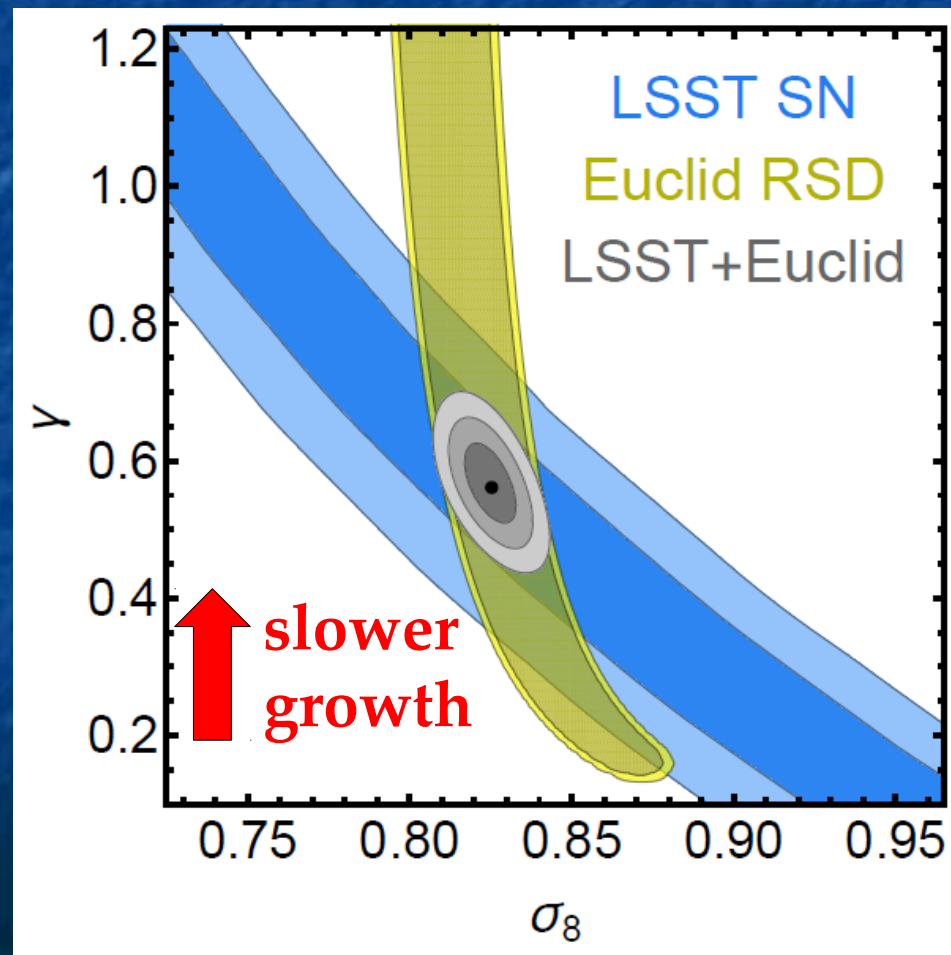
# Modified Gravity

- SNe lensing can also measure **growth** of structures
- Mod. gravity models often exhibit a distinct growth

$$f_g \equiv \frac{-d \ln G}{d \ln 1+z} \approx [\Omega_m(z)]^\gamma$$

$$\text{GR} \rightarrow \gamma = \frac{6}{11} \simeq 0.55$$

*Amendola, Castro, Marra & Quartin (1412.3703, MNRAS)*



# Back to the Lensing PDFs

- As mentioned, SNe lensing is a complicated problem
  - What are the possible systematics in these results?
- The most obvious candidate are baryons
  - Baryons affect structure formation mostly in the high-density regions ( $\kappa > 0.5$ )
  - We thus conducted a full ray-tracing analysis on a suite of Hydro simulations (the *Magneticum Pathfinder* – [www.magneticum.org](http://www.magneticum.org))



*Castro, Quartin, Giocoli, Borgani, Dolag – 1711.10017*

# Baryonic Lensing PDFs

| Box<br>name | $L_{\text{box}}$<br>(Mpc/h) | $\epsilon_{\text{soften.}} (\text{kpc}/h)$ |      |       | $N_{\text{particles}}$ | $m_{\text{DM}}$<br>( $M_{\odot}/h$ ) |
|-------------|-----------------------------|--------------------------------------------|------|-------|------------------------|--------------------------------------|
|             |                             | DM                                         | Gas  | Stars |                        |                                      |
| 4/uhr       | 48                          | 1.4                                        | 1.4  | 0.7   | $2 \times 576^3$       | $3.6 \times 10^7$                    |
| 4/hr        | 48                          | 3.75                                       | 3.75 | 2.0   | $2 \times 216^3$       | $6.9 \times 10^8$                    |
| 3/hr        | 128                         | 3.75                                       | 3.75 | 2.0   | $2 \times 576^3$       | $6.9 \times 10^8$                    |
| 2/hr        | 352                         | 3.75                                       | 3.75 | 2.0   | $2 \times 1584^3$      | $6.9 \times 10^8$                    |

- Ray-tracing requires **very high mass-resolution** runs
  - These in turn limit the size of the boxes to  $\sim 200$  Mpc
- To understand the effect of baryons, each Hydro run was accompanied by a DM-only run
- We also must test numerical convergence for each variable (boxsize, resolution, number of snapshots)

$z = 1$

DM-only 1.76 arcsec

DM-only 7.04 arcsec

AGN-Hydro 1.76 arcsec

DM-only

AGN-Hydro

H1

H2

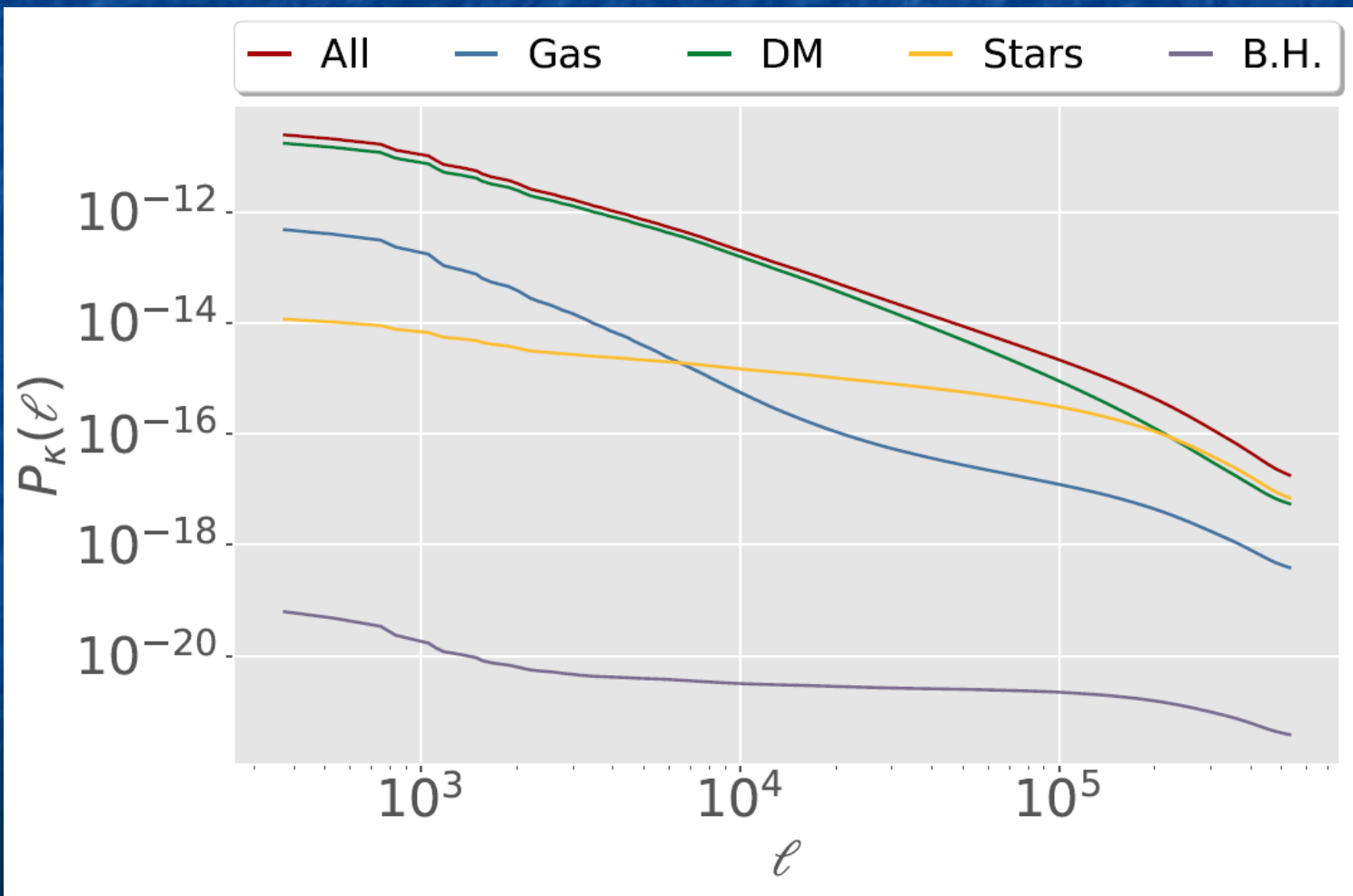
H1

H2

-0.02 0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14

# Baryonic Lensing PDFs

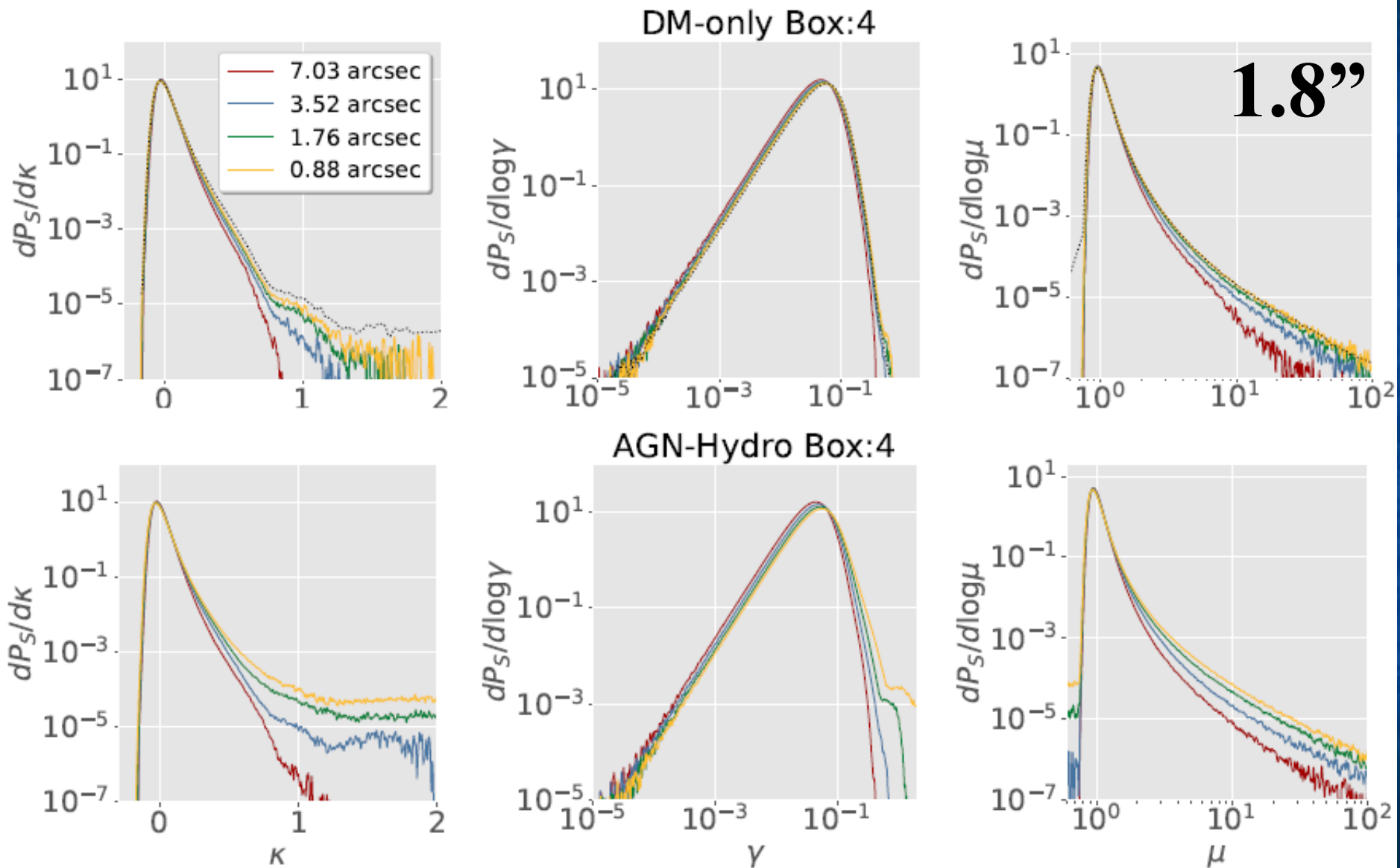
## ■ Convergence power spectrum



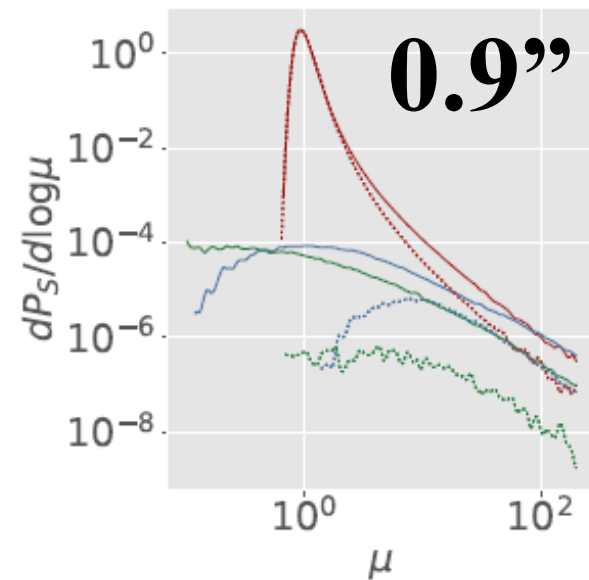
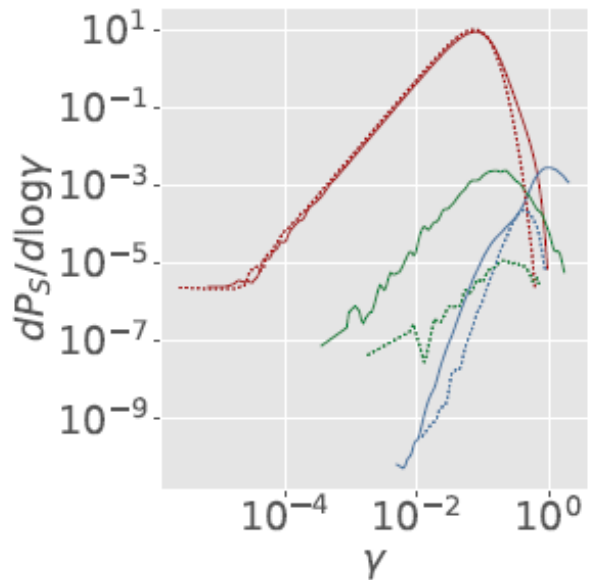
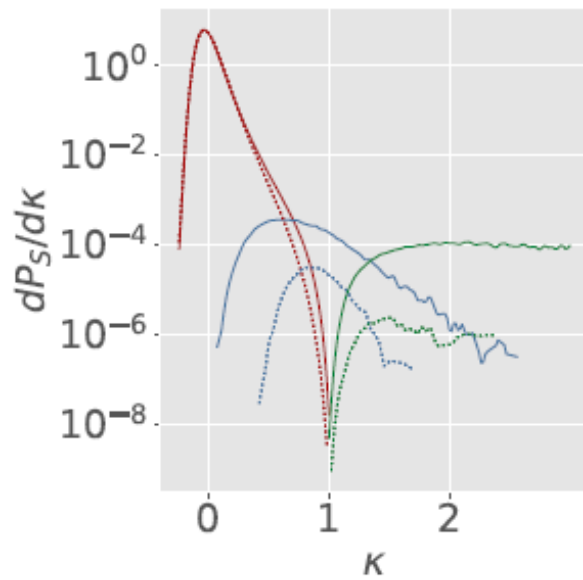
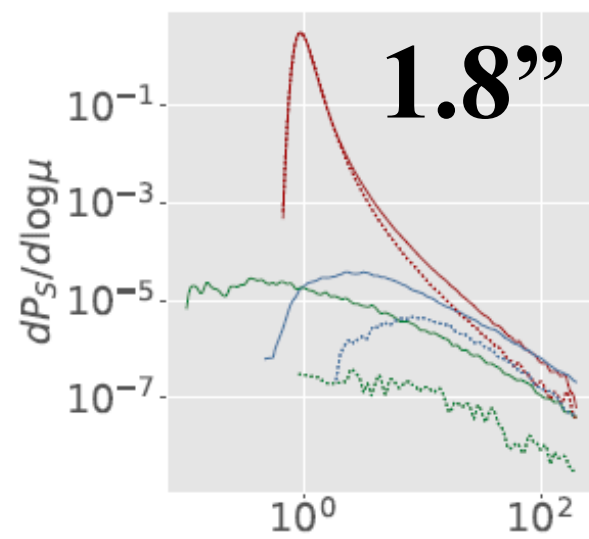
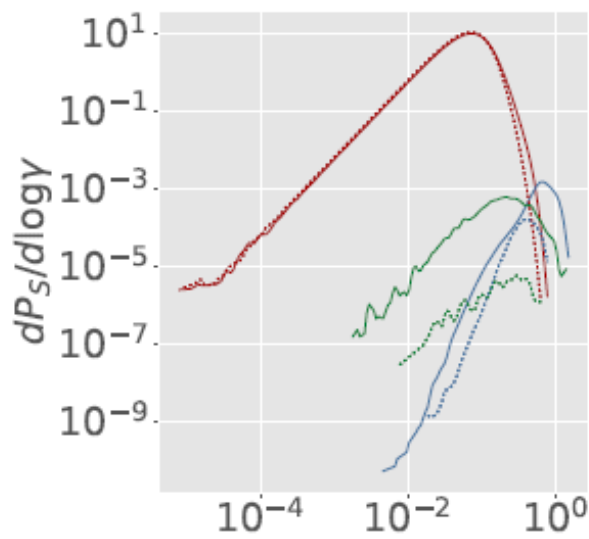
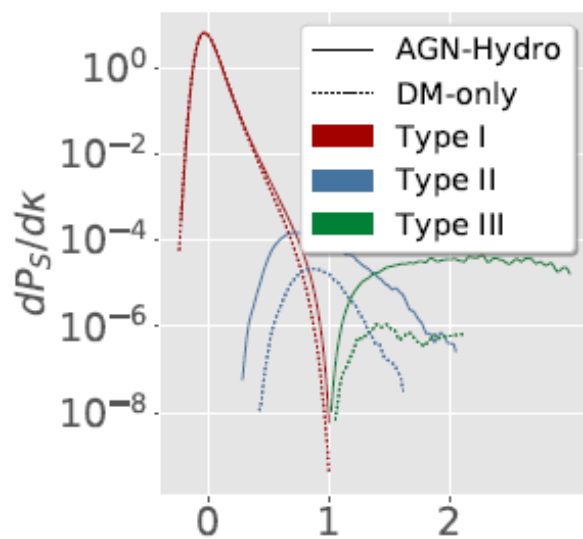
# Baryonic Lensing PDFs

- Previous ray-tracing analyses → cut the projected density maps into a grid of fixed size → fixed spatial resolution
  - However, what is more relevant observationally are the **angular** scales
  - We thus computed the different PDFs for **fixed angular scales**
  - *Magneticum* resolutions allow at most  $0.9 - 1.8''$
  - Best ground surveys have angular resolution  $\sim 0.8''$ 
    - Euclid will achieve  $0.2''$  (!)
- We also computed PDFs @  $3.5''$ ,  $7''$  &  $14''$ 
  - Direct results for objects of different sizes
    - i.e.: average magnification of galaxies @  $z = 2$

$$z = 3$$



$$z = 5$$



# Strong Lensing

- Baryons make a **huge** difference for strong lensing
- Caveat: these numbers may change in runs with higher mass resol.

| $\theta_{\text{grid}}$ (arcsec) | Multi-image prob. ( $\times 10^6$ ) |         |         |         |
|---------------------------------|-------------------------------------|---------|---------|---------|
|                                 | $z = 1$                             | $z = 2$ | $z = 3$ | $z = 5$ |
| DM-only                         |                                     |         |         |         |
| 7.04                            | —                                   | —       | 0.016   | 0.11    |
| 3.52                            | 0.0003                              | 0.13    | 0.59    | 1.8     |
| 1.76                            | 0.039                               | 1.2     | 3.6     | 9.0     |
| 0.88                            | 0.090                               | 1.9     | 5.5     | 14      |
| 0.44                            | 0.12                                | 2.3     | 6.5     | 17      |
| AGN-Hydro                       |                                     |         |         |         |
| 7.04                            | 0.0024                              | 0.071   | 0.17    | 0.50    |
| 3.52                            | 1.0                                 | 4.9     | 9.4     | 17      |
| 1.76                            | 11                                  | 47      | 85      | 150     |
| 0.88                            | 32                                  | 140     | 260     | 480     |
| 0.44                            | 59                                  | 300     | 610     | 1200    |

# Strong Lensing

- These numbers can be confronted with data
- We need a catalog:
  - Of distant objects
  - Collected blindly
  - Without selection biases (like Malmquist bias)
- SDSS quasar catalog fits all these (Inada+ 1203.1087)
  - Mean  $z = 1.56$
  - There's a "statistical sample"
  - 26 QSOs have multiple images out of ~51k
    - 510 in a million
- Our hydro sims predict (@ 0.44") 160 in a million
  - The DM-only run predicts only 1.4 in a million

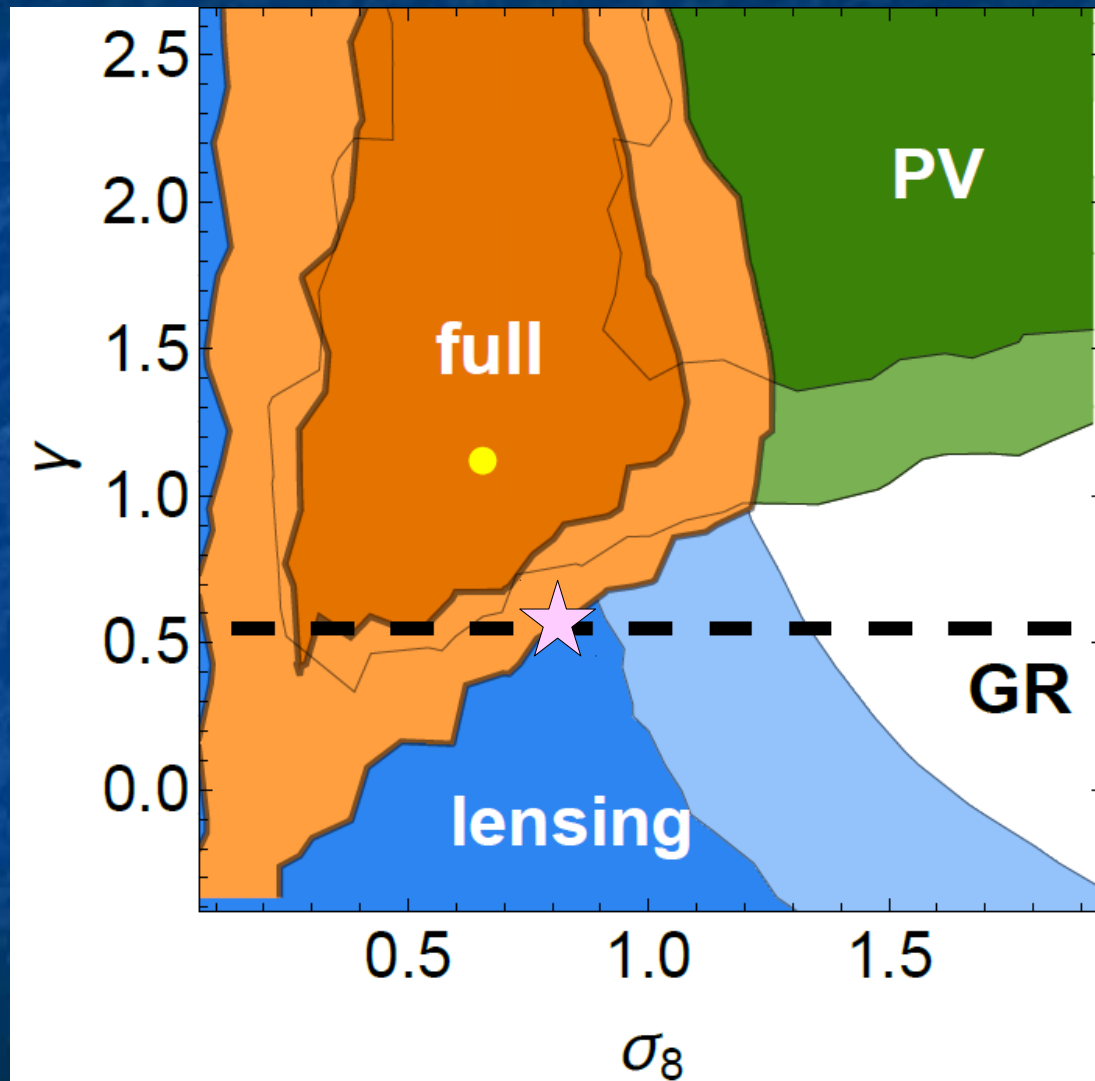
# Strong Lensing

- Ray-tracing in simulations have limitations:
  - No hope for angular resolutions better than  $0.1''$
  - QSO light bundles  $\rightarrow$  angular sizes of  $<\sim 10^{-4}''$
  - SNe light bundles  $\rightarrow$  " " "  $<\sim 10^{-6}''$
  - May stars & BH introduce important corrections?
  - The solution to this question must come from analytical or semi-analytical modeling
- See e.g. Fleury+ (1302.5308 + 1508.07903)
- Zumalacarregui & Seljak 1712.02240  $\rightarrow$  current SNe data already exclude primordial BH DM models
  - García-Bellido+ (1712.06574) claim otherwise
  - Tough problem to resolve!

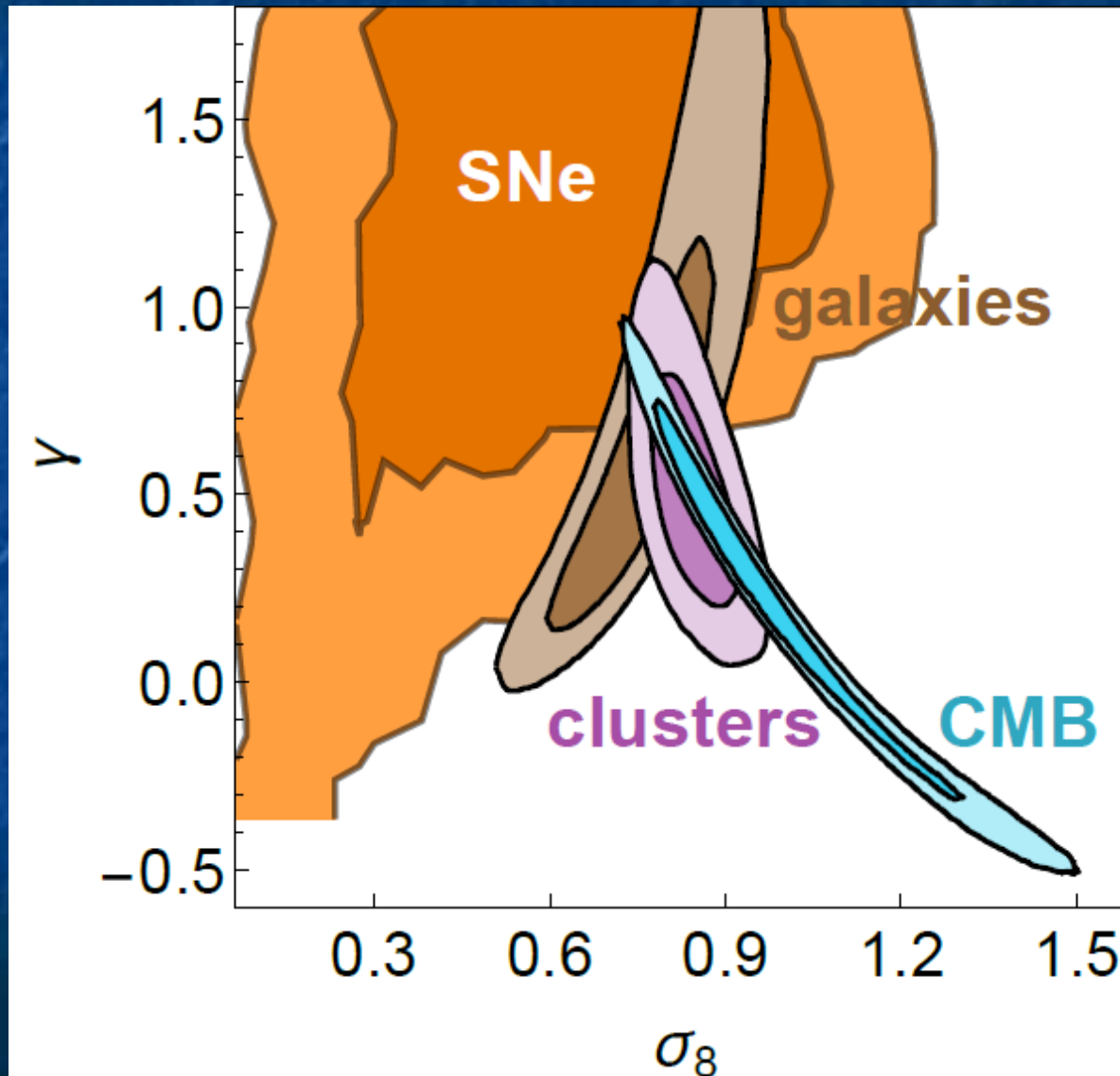
# SN Peculiar Velocity

- Lensing only affects far SNe ( $z \geq 0.4$ )
- At low redshift ( $z \leq 0.2$ ) another effect becomes relevant
  - “Peculiar velocities” (PV) in cosmology refers to velocities outside of the “Hubble flow” (i.e., expansion)
  - Typical PV @  $z = 0 \rightarrow \sim 600 \text{ km/s}$  ( $v / c \sim 0.002$ )
    - “extra blue/redshift”
  - These *perturbations* are high for low  $z$  (large relative error)
- **Crucial point:** these velocities are correlated
  - Correlations  $\rightarrow$  linear matter power spectrum
  - We can measure them & infer the power spectrum!

# JLA SN constraints (lens+PecVel)



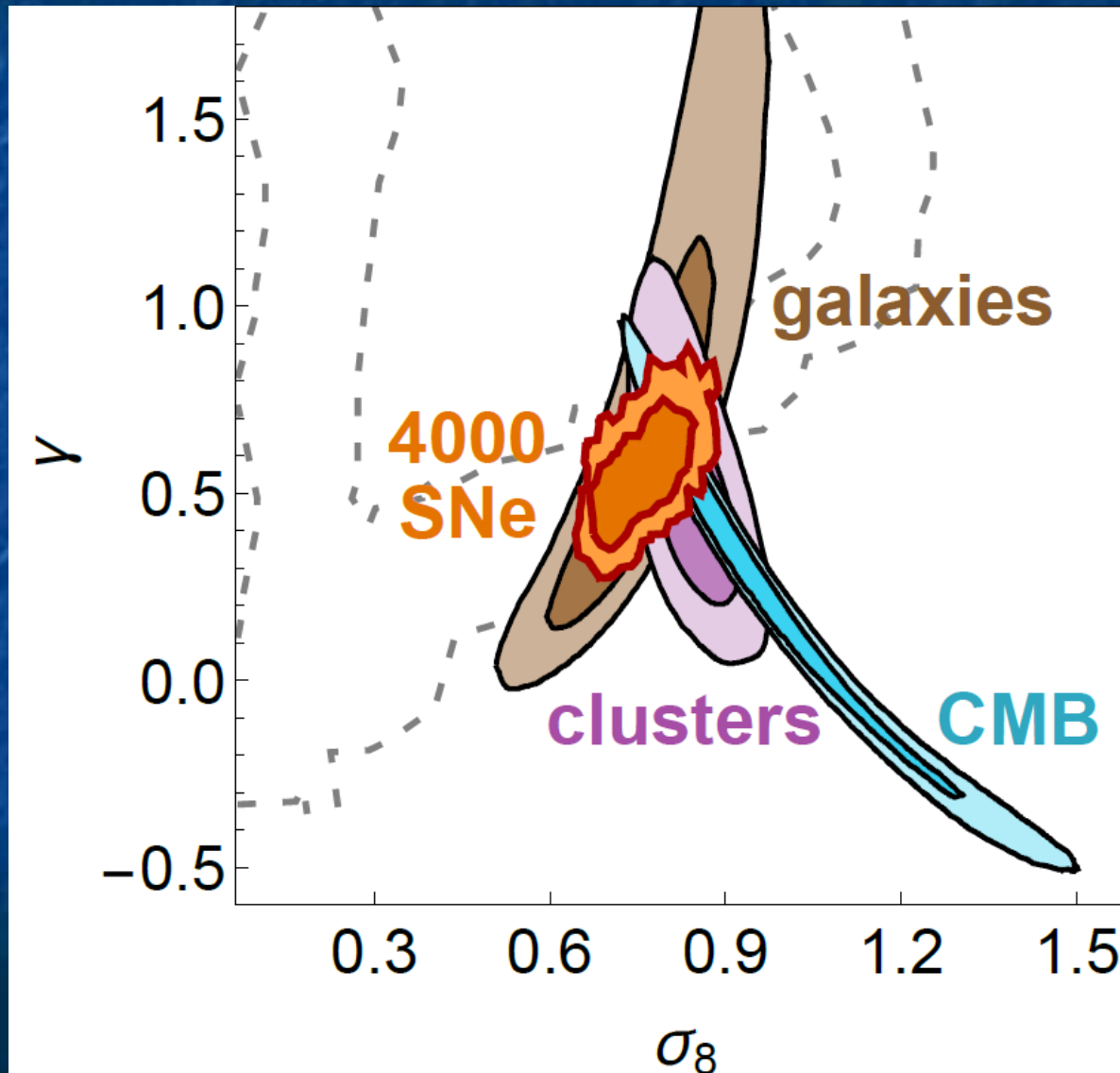
# Comparing with other data



*Castro, Quartin &  
Benitez (1511.08695,  
PhysDarkUniv)*

*Mantz, von der  
Linden et al.,  
(1407.4516, MNRAS)*

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# Conclusions

- Ray-tracing is best done at **fixed angular scales**
- Baryons affect the PDFs in high density regions ( $\kappa > 0.5$ )
  - Huge impact on strong lensing
- SNe lensing and pec. vel. very complementary
  - lensing:  $z > 0.4 \rightarrow$  **non-Gaussianity** in the Hub. diag.
  - P.V.:  $z \leq 0.25 \rightarrow$  **correlations** in the Hub. diag.
  - sub-grid scales contribution (e.g. PBH) still unclear
- It is a nice **cross-check** of  $\Lambda$ CDM

*Obrigado!*

