Galactic-Scale Tests of Fundamental Physics

Cosmology/BCCP Seminar, Berkeley

12th October 2021

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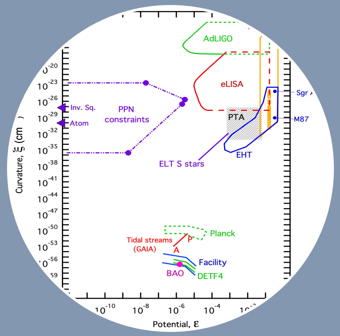
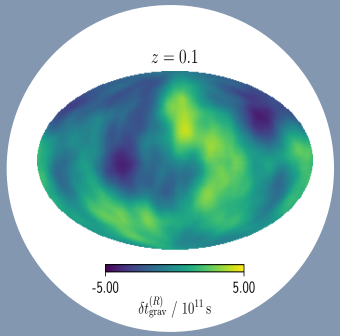
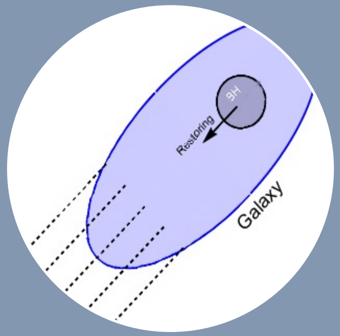
Outline



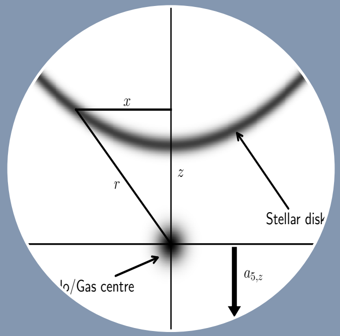
Why galaxies?



Photon dispersion relation



Black Holes and Galileons



Modeling the noise

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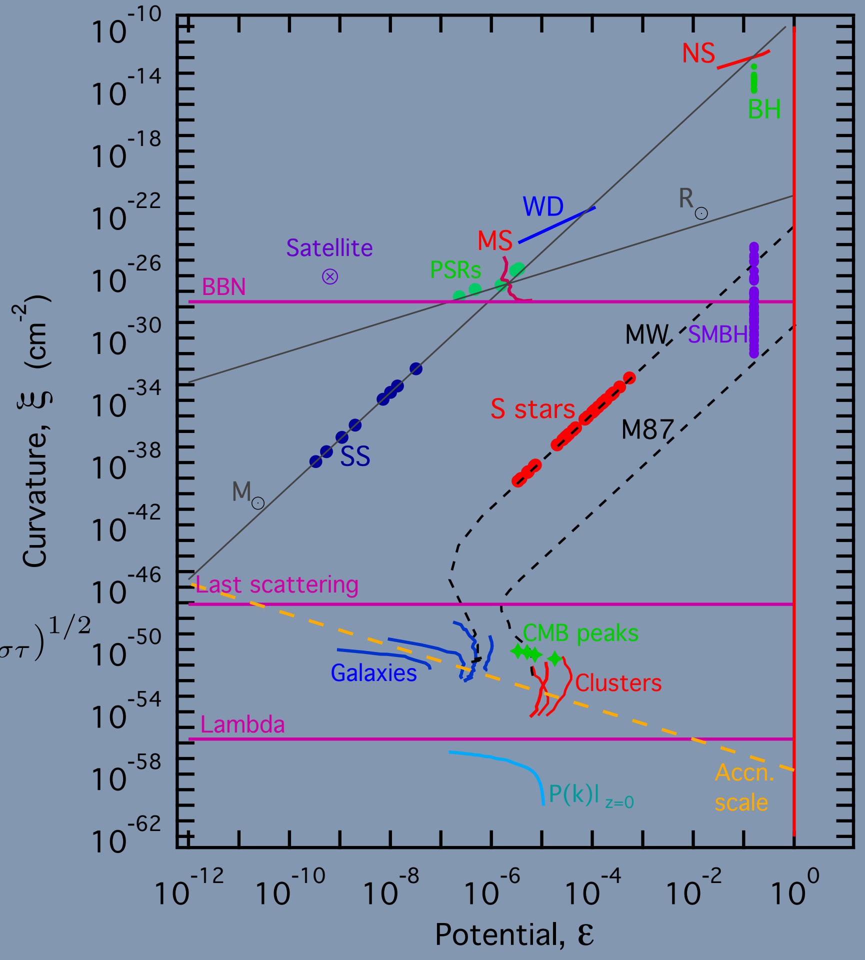
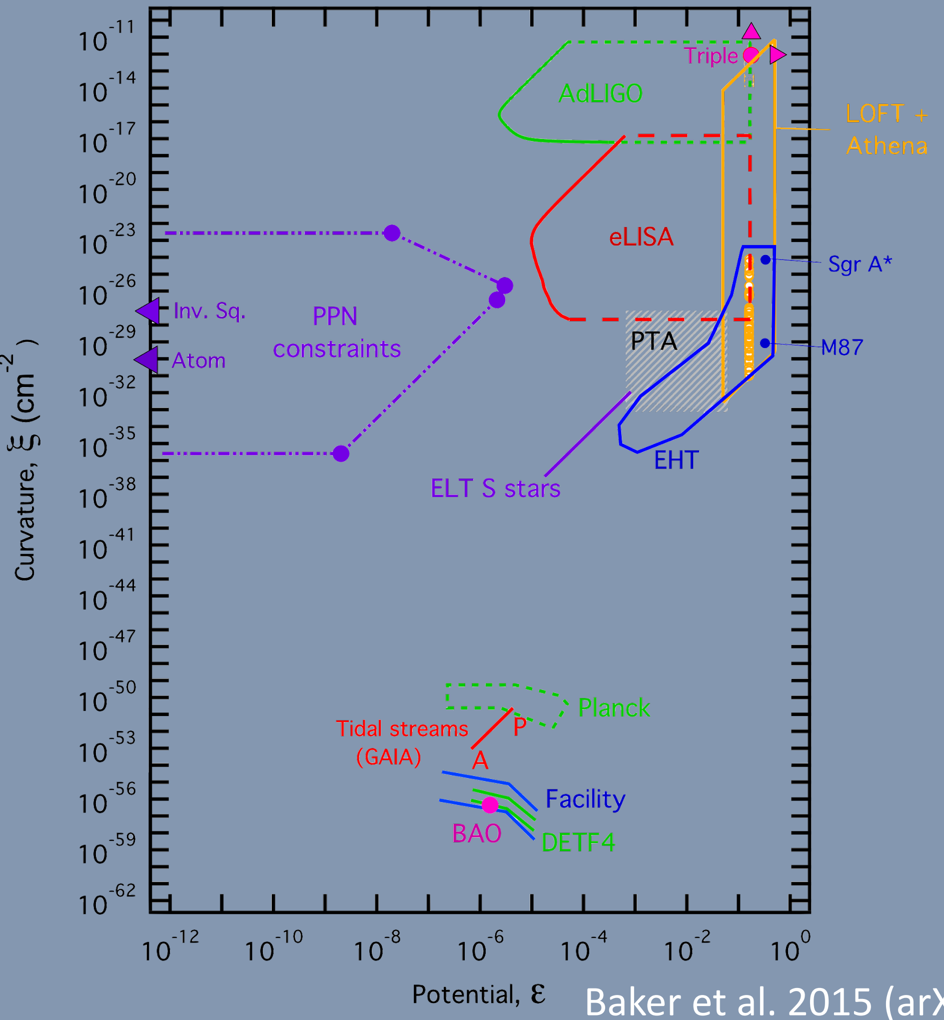
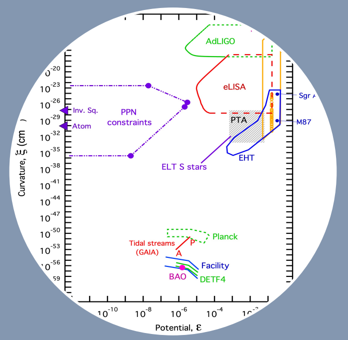
Why galaxies?

Astrophysics – An underexplored region of parameter space

$$\xi = (R^{\mu\nu\sigma\tau}R_{\mu\nu\sigma\tau})^{1/2}$$

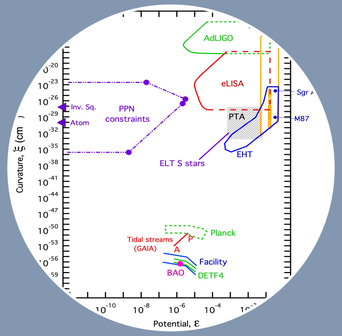






Baker et al. 2015 (arXiv:1412.3455)

Novel effects on astrophysical scales



- Fifth forces - screening
- Dark matter

- Lots of high quality data

- Usually assume a theory of gravity (GR or Newtonian) and then do astrophysics. Can we get a good enough handle on astrophysics to instead test the theory of gravity?

Galaxy-by-galaxy forward model

$$\mathcal{L} = \prod_g \int \mathcal{L}_g \left(r_{\rm pred} \right) \times \mathcal{L}_g \left(r_{\rm obs} | r_{\rm pred} \right) {\rm d} r_{\rm pred}$$

“Predicted Signal”

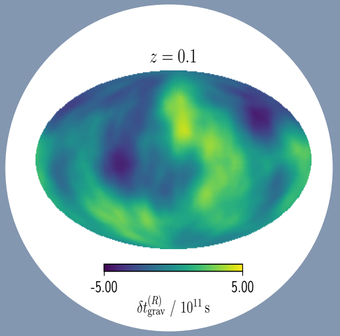
- “New physics” parameters
- Galactic properties
- Large scale structure (BORG)

“Noise Model”

- “Noise” parameters
- Other astrophysical processes
- Observational effects

Photon dispersion relation

Quantum Gravity



Qualitative argument (Wheeler 1998):

- On timescales $\Delta t \sim 1/E_P$, expect quantum-gravitational fluctuations in spacetime of energy $\Delta E \sim E_P$
- Spacetime would not look smooth on length scales $\Delta x \sim 1/E_P$ - "foamy" structure
- Non-trivial refractive index for empty space? Would be important at high energies.

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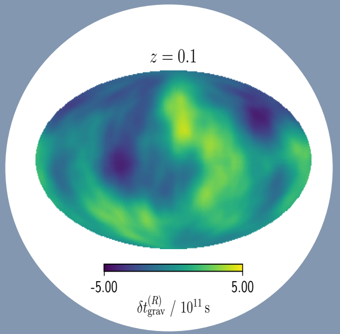


Energy Dependent Arrival Times: Quantum Gravity

$$\vec{p}^{\,2} = E^2 \left[1 + f\left(\frac{E}{E_{\rm QG}}\right)\right] = E^2 \left[1 + \xi \frac{E}{E_{\rm QG}} + \mathcal{O}\left(\frac{E^2}{E_{\rm QG}^2}\right)\right]$$

$$v = \frac{\partial E}{\partial p} \sim 1 - \xi \frac{E}{E_{\rm QG}}$$

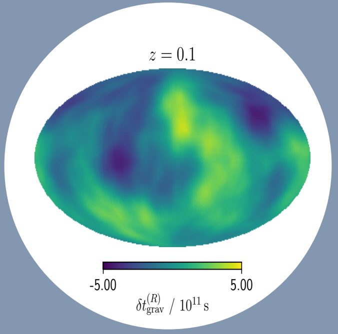
For two photons emitted simultaneously at redshift z and observed energies E_i and E_j,

$$\Delta t_{ij}^{\rm (QG)} = \xi \frac{E_i - E_j}{E_{\rm QG}} \int_0^z \frac{1+z'}{H\left(z'\right)} {\rm d}z'$$

Could be observed at high energies.

Amelino-Camelia et al. 1998 (arXiv:9712103), Jacob & Piran 2008 (arXiv:0712.2170)

Energy Dependent Arrival Times: Massive Photon



$$v = \sqrt{1 - \frac{m_\gamma^2}{E^2}} \approx 1 - \frac{1}{2}\frac{m_\gamma^2}{E^2}$$

$$\Delta t_{ij}^{(\mathrm{MP})} = \frac{m_\gamma^2}{2}\left(\frac{1}{E_i^2} - \frac{1}{E_j^2}\right)\int_0^z \frac{1}{H\left(z'\right)\left(1+z'\right)^2}\mathrm{d}z'$$

Would be important at low energies.

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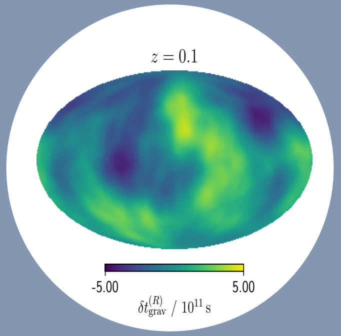
GRBs are ideal for this



$$\Delta t_{ij}^{(\mathrm{QG})} = \xi \frac{E_i - E_j}{E_{\mathrm{QG}}} \int_0^z \frac{1+z'}{H(z')} \mathrm{d}z'$$

$$\Delta t_{ij}^{(\mathrm{MP})} = \frac{m_\gamma^2}{2} \left(\frac{1}{E_i^2} - \frac{1}{E_j^2} \right) \int_0^z \frac{1}{H(z') (1+z')^2} \mathrm{d}z'$$

- Large z $\Rightarrow$ large integral $\Rightarrow$ tight constraints.
- Short duration and observed time delays $\Rightarrow$ any novel effect must be small.
- QG (massive photon) best at high (low) energy.
- Radio frequencies - dispersion by electrons has same energy dependence as for a massive photon.

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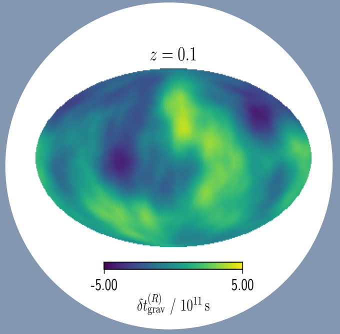
Challenges to Overcome



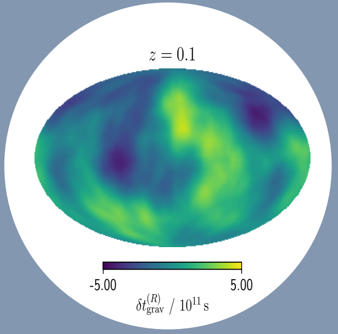
Some issues with previous constraints

- Do not propagate uncertainties in redshift of source.
- Simple (or no) model for other contributions to spectral lag.
- Only use a handful of GRBs.

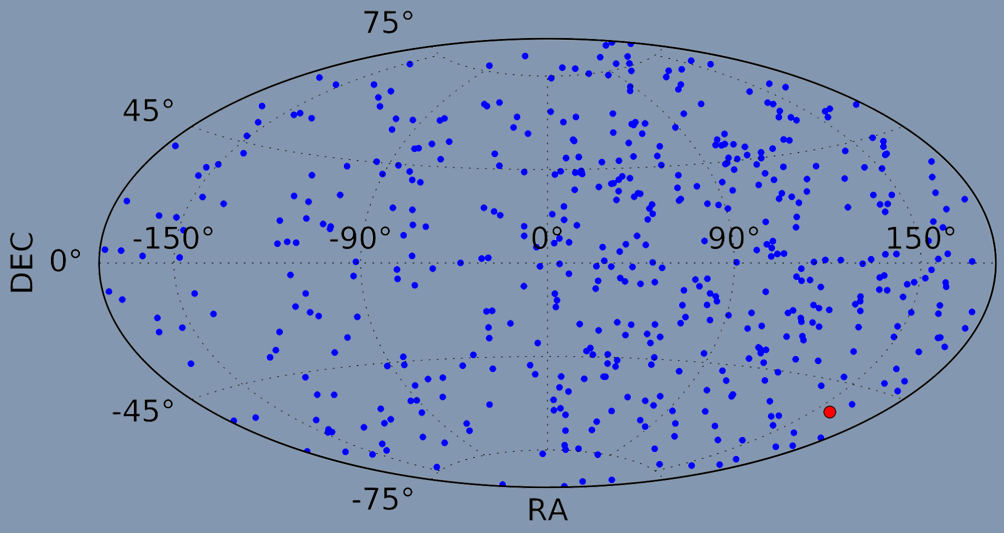
How to overcome this

- Forward model time delays with Monte Carlo procedure.
- Test a variety of models - compare performance and sensitivity of constraint.
- Use a larger sample.

GRB Data



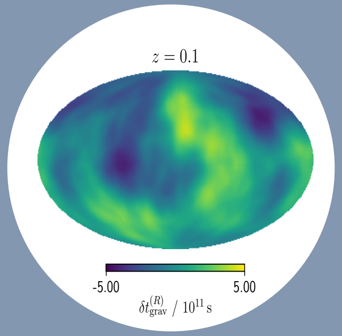
- 448 GRBs (BATSE)
- Time delay data for 4 energy channels (25 – 325 keV)
- Pseudo-redshifts (with uncertainty) from spectral peak energy-peak luminosity relation:



$$\log L \propto \log\left(E_{\rm p}\left(1+z\right)\right)$$

Yu, Xi & Wang 2018 (arXiv:1708.02396)

Forward Model the Time Delays



$$\Delta t_{ij}^{(\mathrm{QG})} = \xi \frac{E_i - E_j}{E_{\mathrm{QG}}} \int_0^z \frac{1+z'}{H\left(z'\right)} \mathrm{d}z'$$

- Draw E_i and E_j from distribution proportional to spectrum between band's limits
- Draw redshift from two-sided Gaussian with upper and lower redshift errors
- Calculate $\Delta t_{ij}^{(QG)}$ for some fiducial $\ell_{QG} \equiv \xi / E_{QG}$

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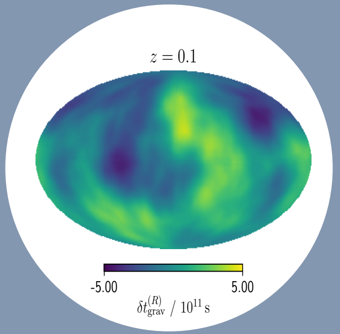
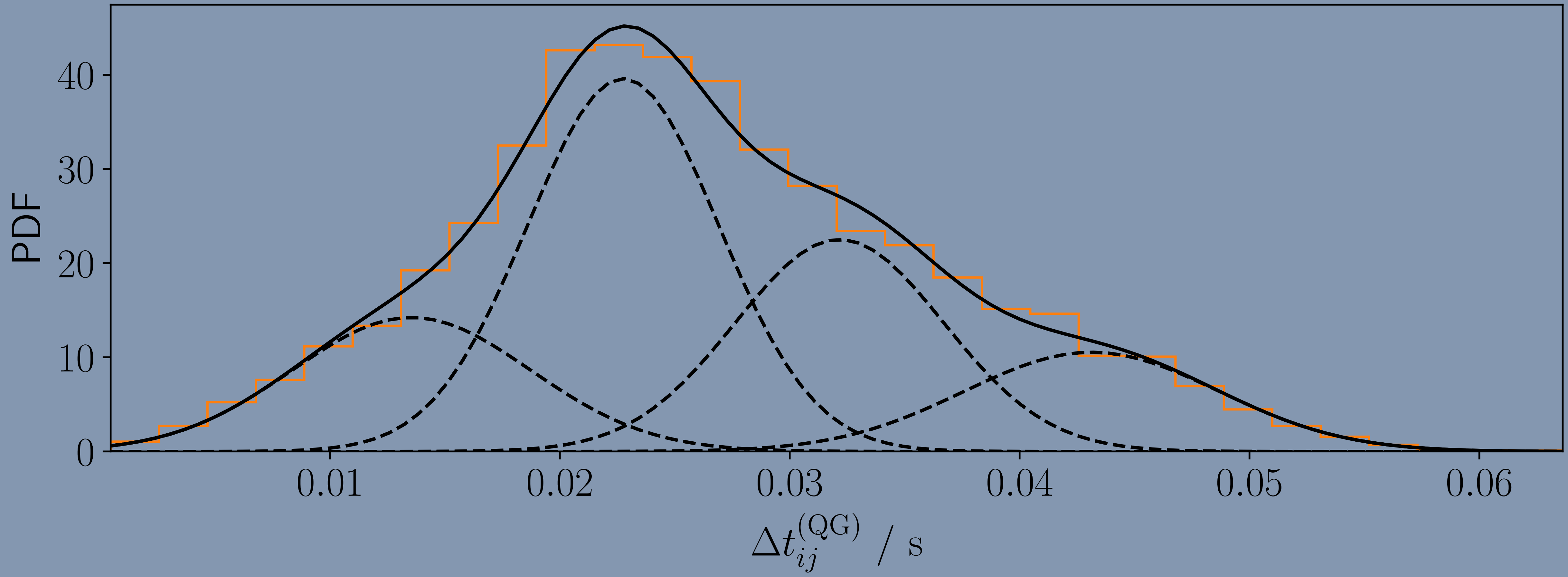
Forward Model the Time Delays



Take samples and fit to a Gaussian Mixture Model



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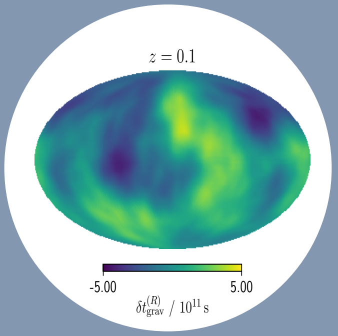
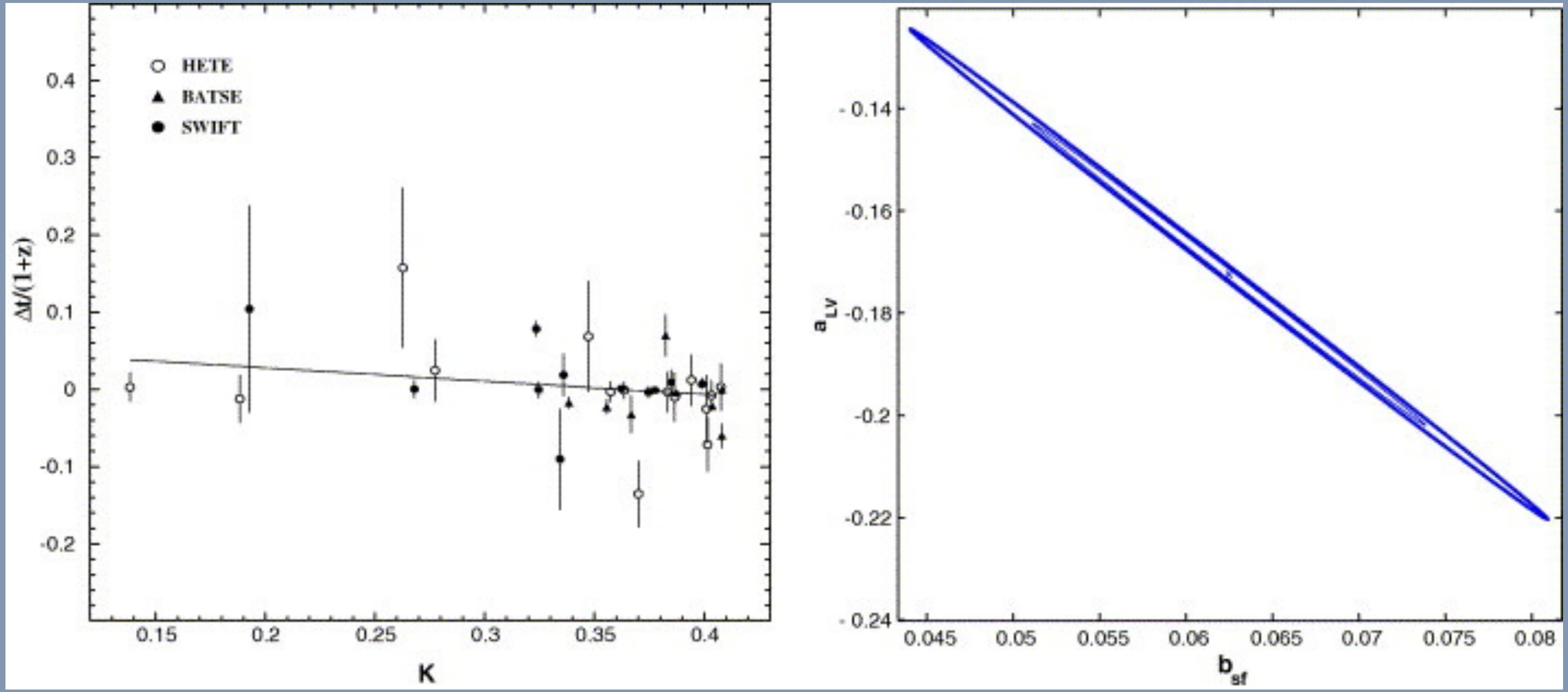


Other contributions to the time delay

$$\Delta t_{ij}^{(\rm obs)} = \Delta t_{ij}^{(\rm th)} + B_{ij}$$

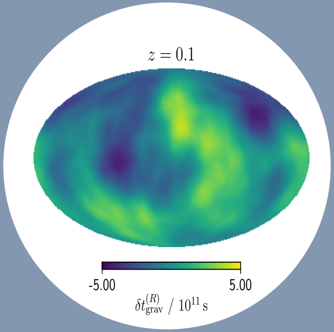
First approach: Suppose B_{ij} intrinsic to source and same for all GRBs

$$\mathcal{L}\left(B_{ij}\right) = \delta\left(B_{ij} - b_{ij}\left(1+z\right)\right)$$



Ellis et al. 2006 (arXiv:0510172)

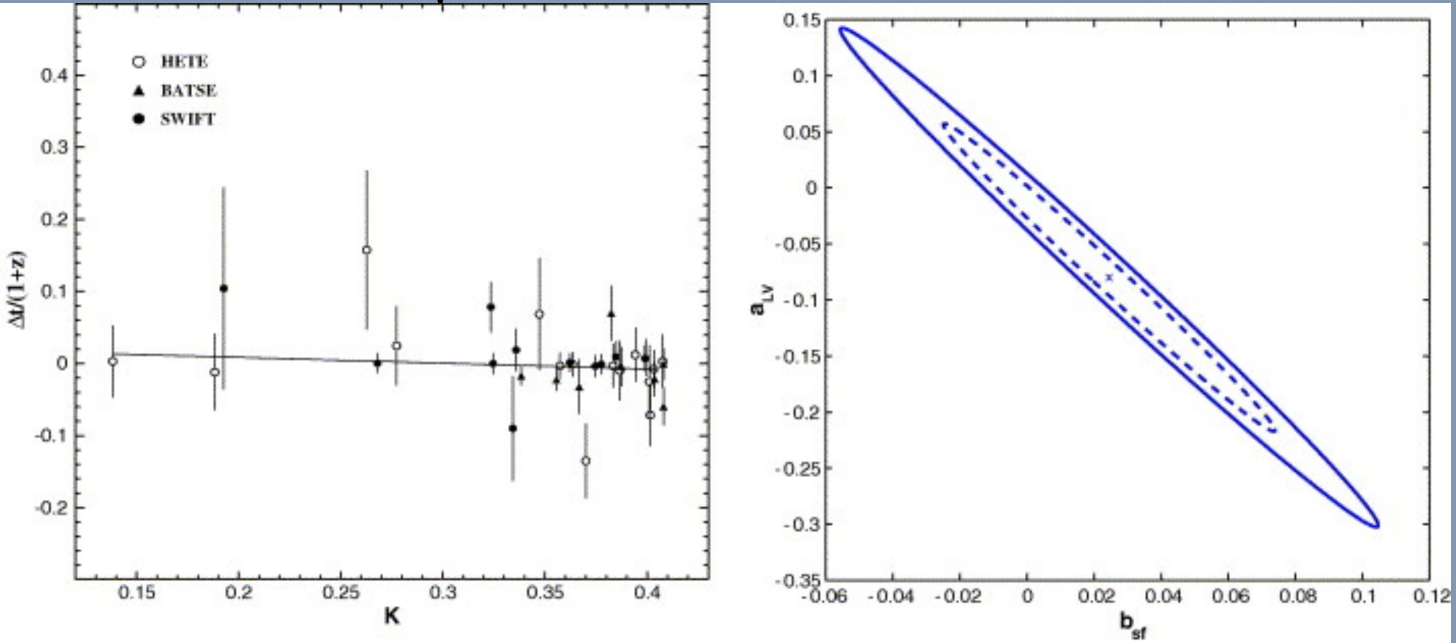
Other contributions to the time delay



$$\Delta t_{ij}^{(\rm obs)} = \Delta t_{ij}^{(\rm th)} + B_{ij}$$

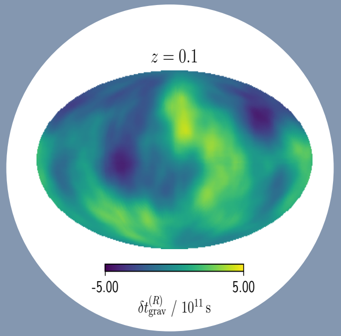
Second approach: Suppose B_{ij} intrinsic to source and stochastic

$$\mathcal{L}\left(B_{ij}\right) = \frac{1}{\sqrt{2\pi\sigma_{ij}^2}} \exp\left(-\frac{\left(B_{ij} - b_{ij}\left(1+z\right)\right)^2}{2\sigma_{ij}^2}\right)$$



Ellis et al. 2006 (arXiv:0510172)

Our approach – try several models



Ideally want

- Try different B_{ij} models - model comparison
- Results to be (relatively) insensitive to how one models the noise

For just observational noise:

$$\mathcal{L}\left(B_{ij}\right) = \sum_{\beta} \frac{\omega_{ij}^{(\beta)}}{\sqrt{2\pi}\sigma_{ij}^{(\beta)}} \exp\left[-\frac{\left(B_{ij} - \mu_{ij}^{(\beta)}\right)^2}{2{\sigma_{ij}^{(\beta)}}^2}\right]$$

Can add in intrinsic contributions by allowing some Gaussians to depend on redshift, e.g.

$$\mu_{ij}^{(\beta)} \to \mu_{ij}^{(\beta)}\left(1 + z_s\right), \quad \sigma_{ij}^{(\beta)} \to \sigma_{ij}^{(\beta)}\left(1 + z_s\right)$$

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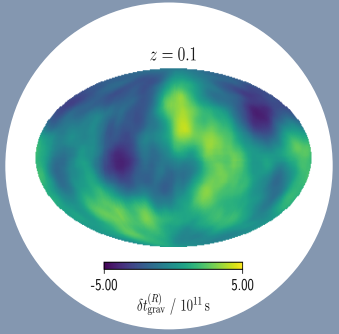
Recap



$$\Delta t_{ij}^{(\mathrm{obs})} = \Delta t_{ij}^{(\mathrm{th})} + B_{ij}$$

$$\mathcal{L}_s \left(\Delta t_{ij}^{(\mathrm{QG})} \right) = \sum_{\alpha} \frac{w_{sij}^{(\alpha)}}{\sqrt{2\pi} \tau_{sij}^{(\alpha)}} \exp \left[- \frac{\left(\Delta t_{ij}^{(\mathrm{QG})} - \lambda_{sij}^{(\alpha)} \right)^2}{2 {\tau_{sij}^{(\alpha)}}^2} \right]$$

$$\mathcal{L} \left(B_{ij} \right) = \sum_{\beta} \frac{\omega_{ij}^{(\beta)}}{\sqrt{2\pi} \sigma_{ij}^{(\beta)}} \exp \left[- \frac{\left(B_{ij} - \mu_{ij}^{(\beta)} \right)^2}{2 {\sigma_{ij}^{(\beta)}}^2} \right]$$

$$\mathcal{L} \left(\mathcal{D} | \vec{\theta} \right) = \prod_{sij} \mathcal{L}_s \left(\Delta t_{ij}^{(\mathrm{obs})} \right)$$

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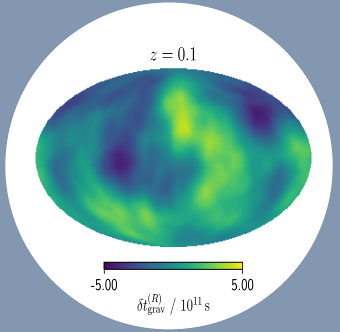
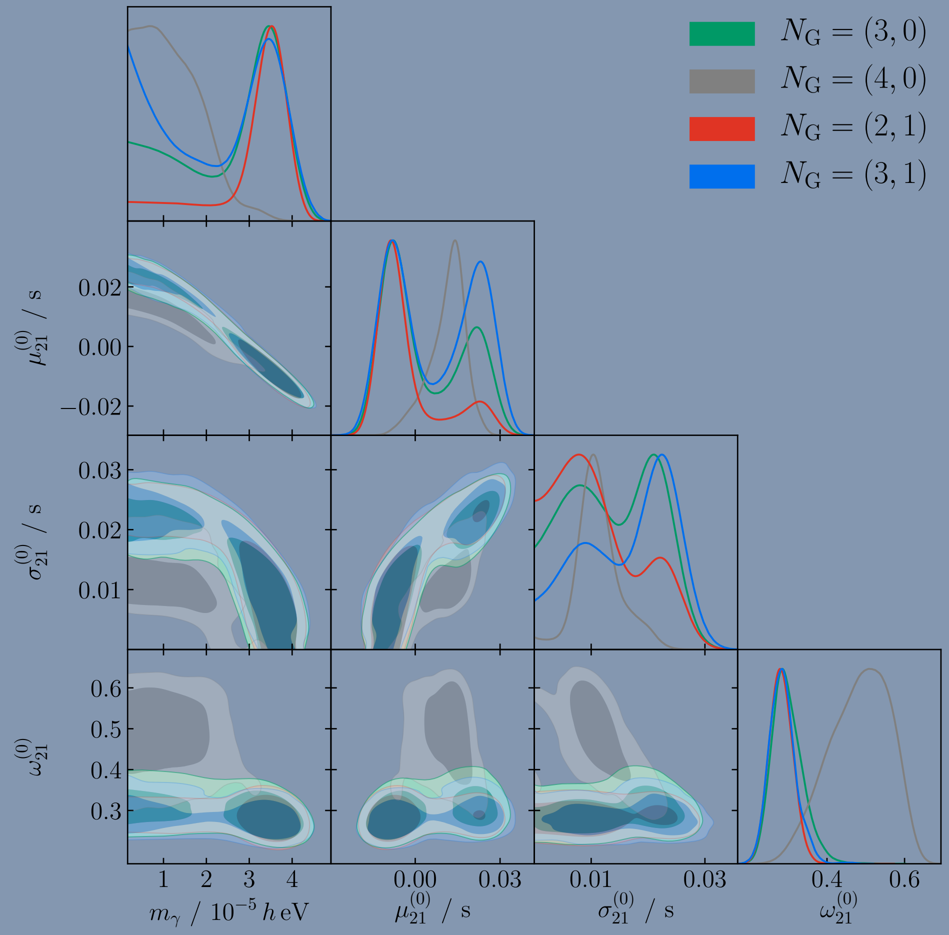
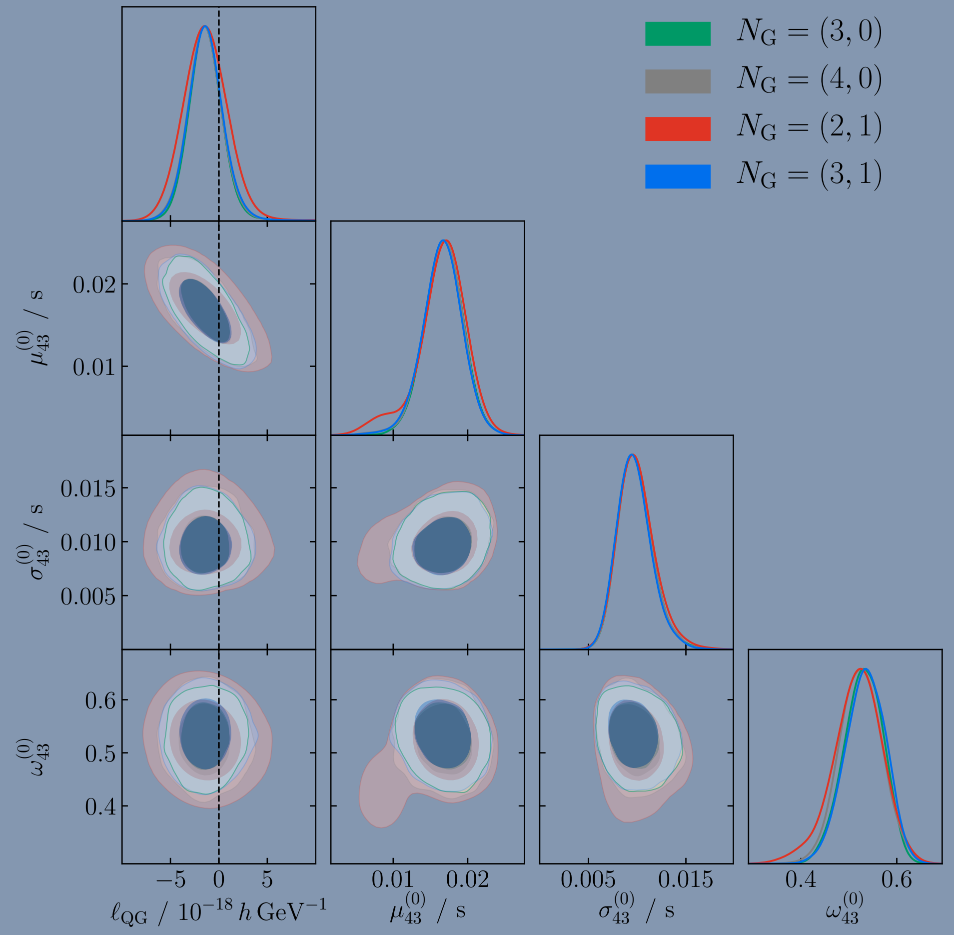
Results





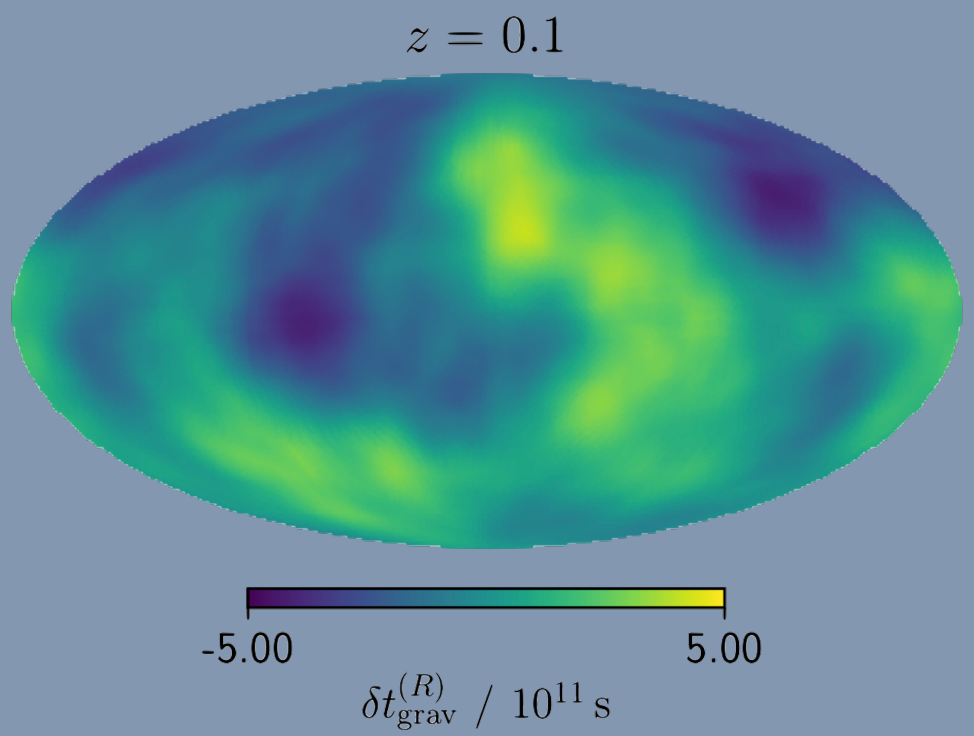


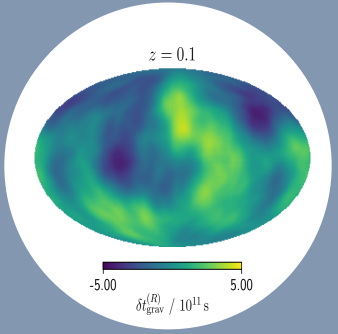
$$m_\gamma < 4.0 \times 10^{-5}\, h\, \mathrm{eV}/c^2 \;(95\%\ \mathrm{confidence})$$

$$|\ell_{\rm QG}| < 5.3 \times 10^{-18}\, h\ \mathrm{GeV}^{-1} \;(95\%\ \mathrm{confidence})$$

Bartlett, Desmond, Ferreira & Jasche 2021 (arXiv:2109.07850)

Other tests?





Shapiro time delays

$$\mathrm{d}s^2 = -\left(1 + 2\delta\phi\right)\mathrm{d}t^2 + a^2\left(t\right)\left(1 - 2\gamma\delta\phi\right)\mathrm{d}\vec{r}^{\,2}$$

$$t_{\mathrm{grav}} = -\left(1+\gamma\right)\int_0^{r_s} \mathrm{d}r\,\delta\phi_0(\vec{r})D(r)$$

Here can use spatial variation

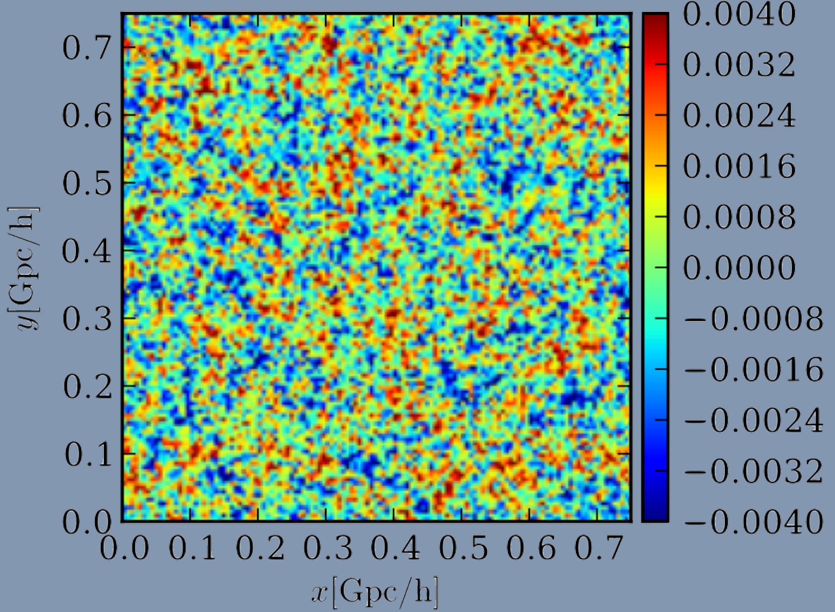
Bartlett, Bergsdal, Desmond, Ferreira & Jasche 2021 (arXiv:2106.15290)

BORG - Bayesian Origin Reconstruction from Galaxies

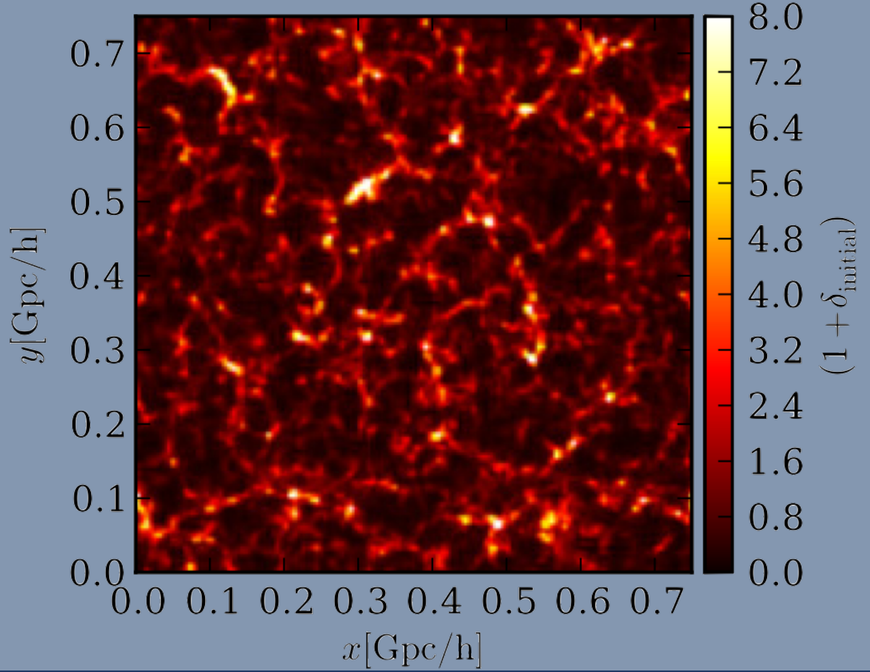
$$\mathcal{P}\left(\delta|\mathbf{s}\right) = \prod_i \delta^{\mathrm{D}}\left(\delta_i - G_i\left(\mathbf{s}\right)\right)$$

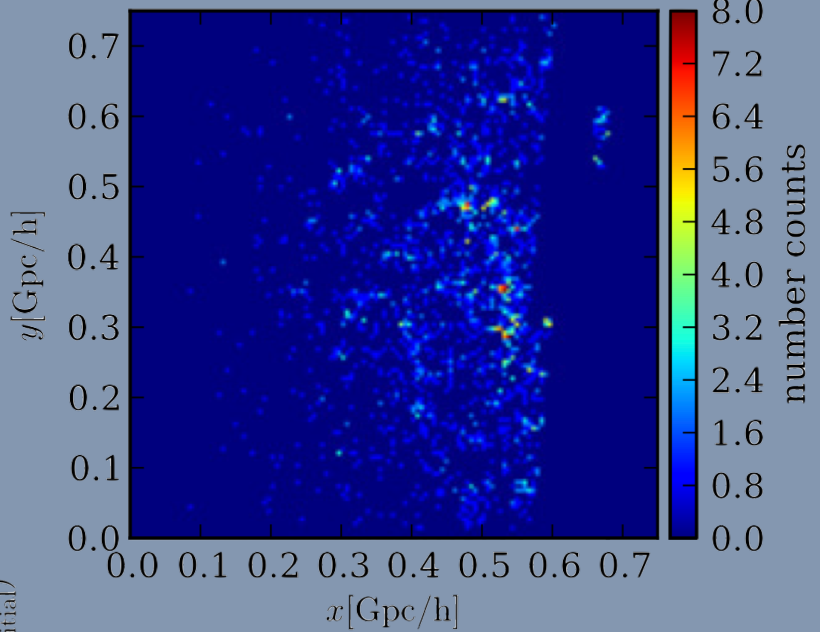
$$\frac{\mathrm{d}\vec{x}}{\mathrm{d}a} = \frac{\vec{p}}{\dot{a}a^2}, \qquad \frac{\mathrm{d}\vec{p}}{\mathrm{d}a} = -\frac{\nabla_{\vec{x}}\Phi}{aH\left(a\right)}$$

$$\nabla^2_{\vec{x}}\Phi = \frac{3}{2}H_0^2\Omega_{\mathrm{m},0}\frac{\delta_m\left(\vec{x}\right)}{a}$$



$$\mathcal{P}\left(\mathbf{s}|\mathbf{S}\right) = \frac{e^{-\frac{1}{2}\mathbf{s}^{\mathrm{T}}\mathbf{S}^{-1}\mathbf{s}}}{\sqrt{\det\left(2\pi\mathbf{S}\right)}}$$



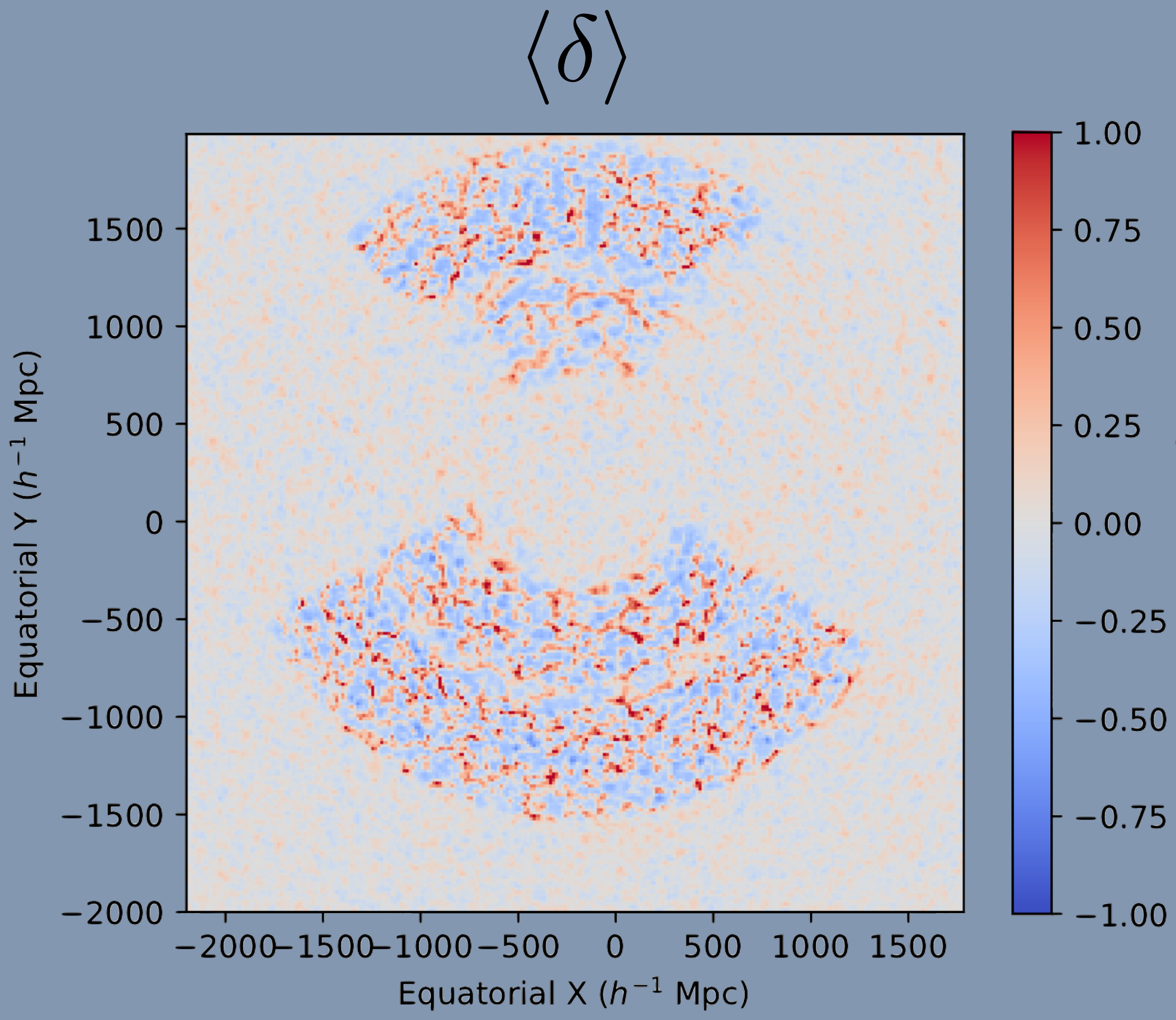


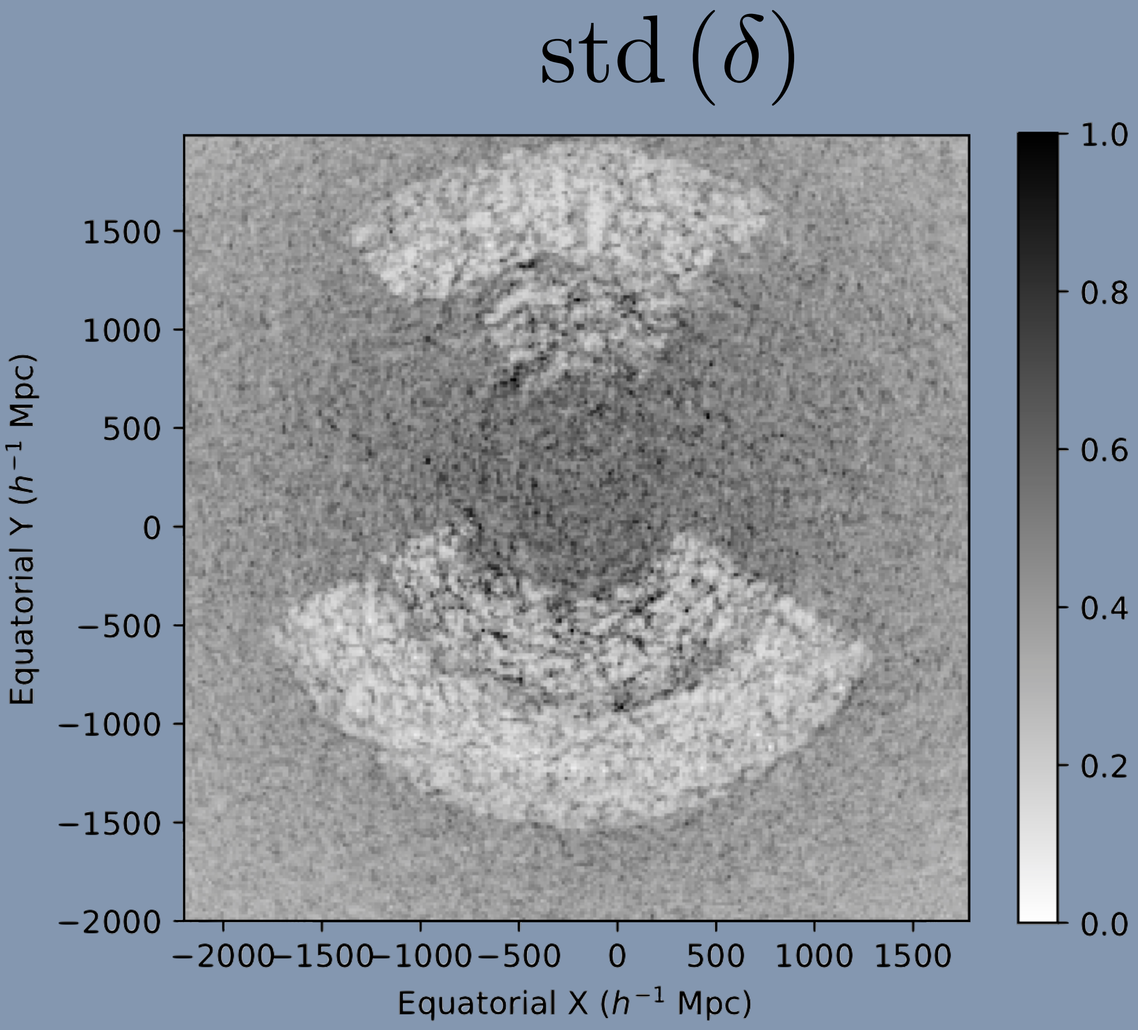
$$\mathcal{P}\left(\mathbf{N}|\lambda\left(\delta\right)\right) = \prod_i \frac{e^{-\lambda_i}\lambda_i^{N_i}}{N_i!}$$

+ galaxy bias model $\lambda(\delta)$

Jasche & Wandelt 2012 (arXiv: 1203.3639)
Jasche & Lavaux 2019 (arXiv: 1806.11117)

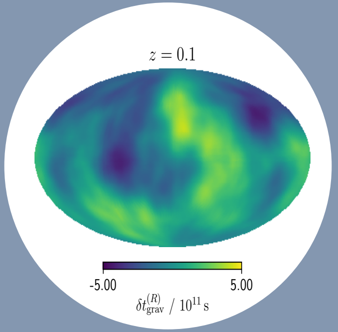
BORG - Bayesian Origin Reconstruction from Galaxies

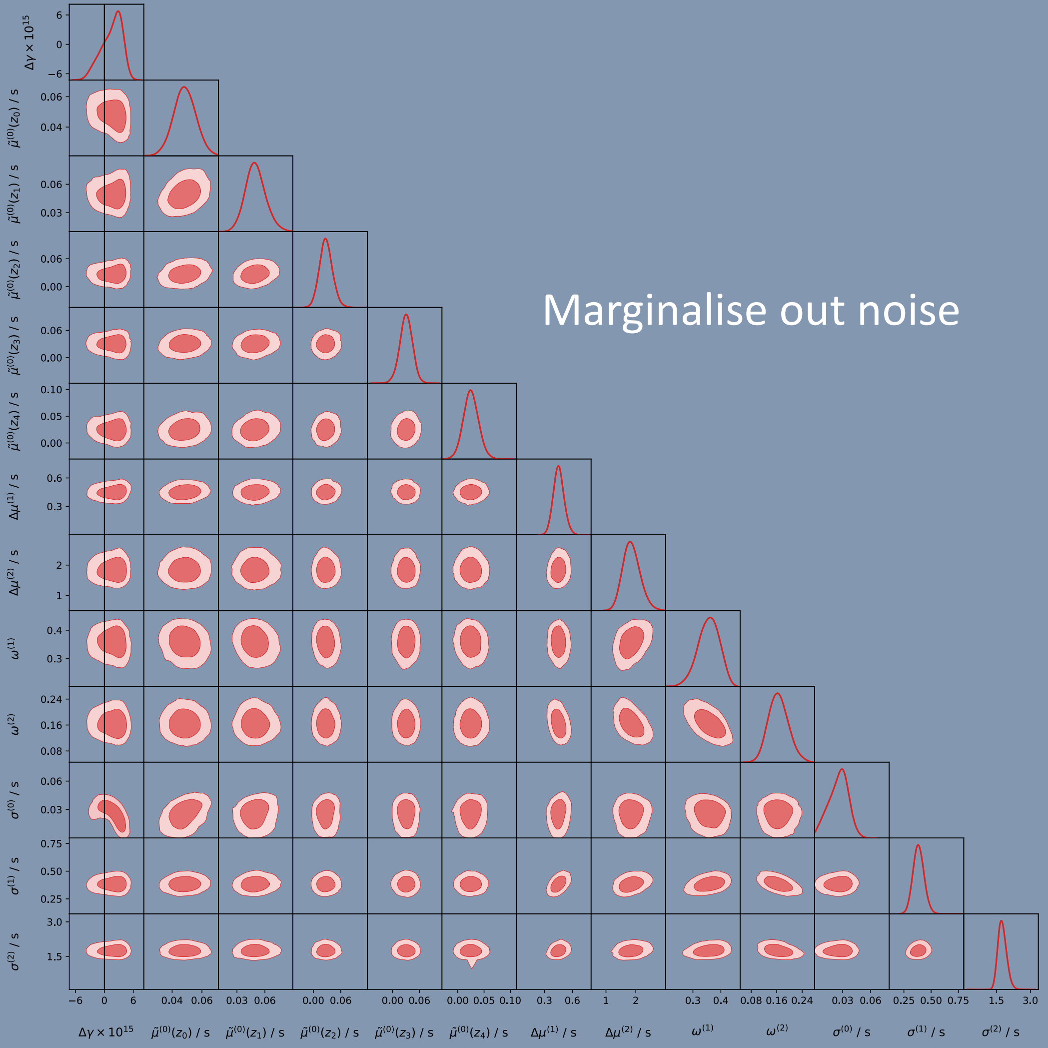




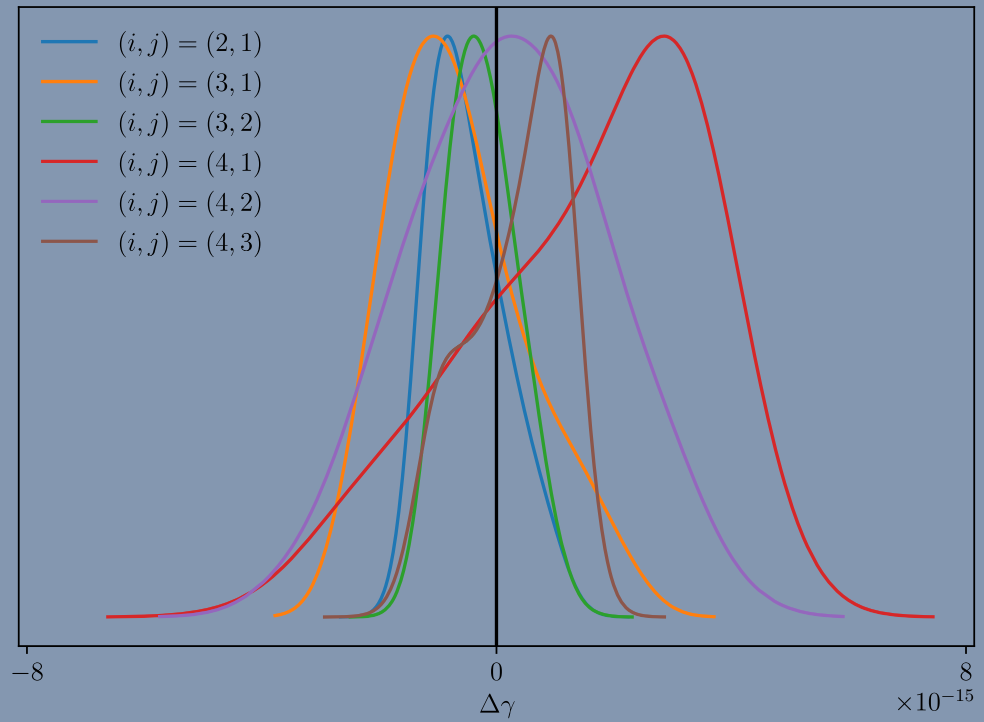
Lavaux, Jasche & Leclercq 2019 (arXiv:1909.06396)

Tightest constraints on $\Delta\gamma$





Marginalise out noise



$$E_{\rm QG} \gtrsim 10^{11}\ {\rm GeV}\ (1\sigma\ {\rm confidence})$$

Bartlett, Bergsdal, Desmond, Ferreira & Jasche 2021 (arXiv:2106.15290)

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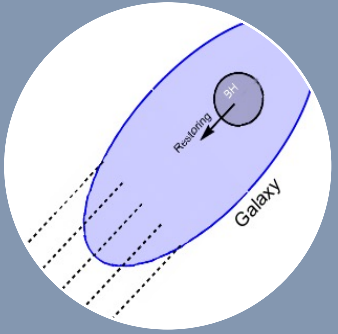
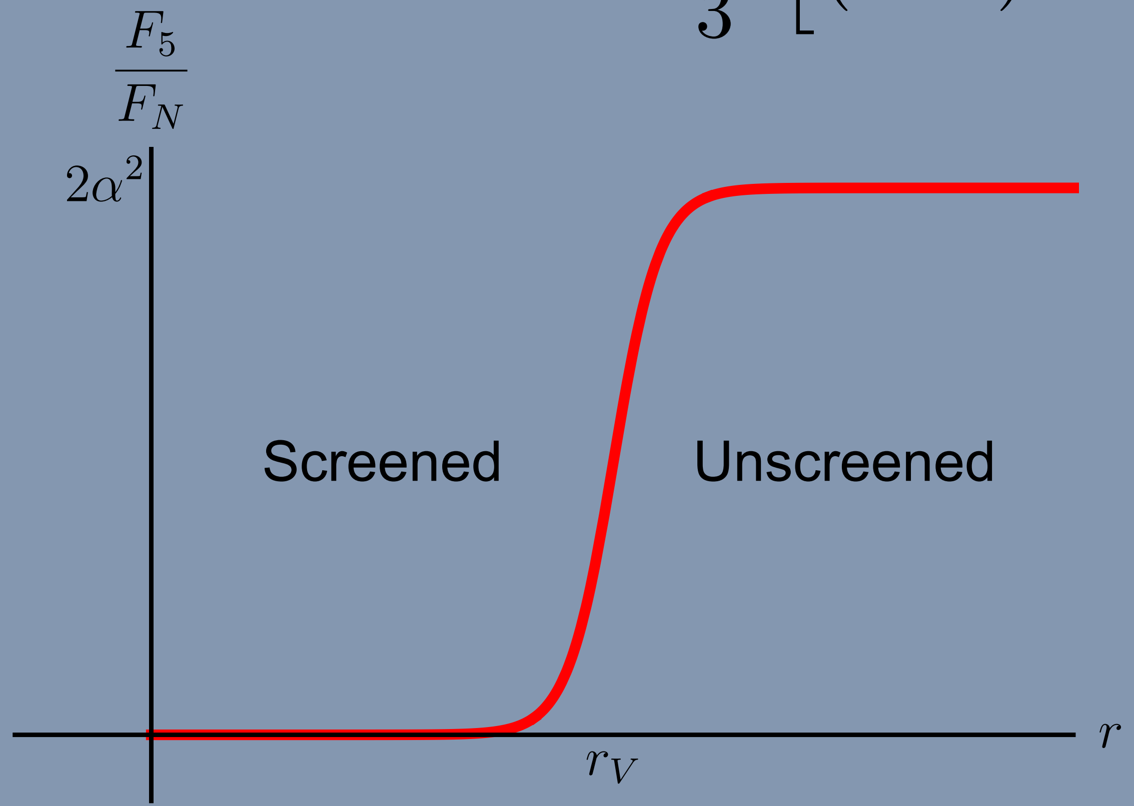
Black Holes and Galileons



Galileons result in a screened fifth force

$$\nabla^2\phi + \frac{r_{\rm C}^2}{3}\left[\left(\nabla^2\phi\right)^2 - \nabla_i\nabla_j\phi\nabla^i\nabla^j\phi\right] = 8\pi\alpha G_{\rm N}\bar{\rho}\Delta$$



$$M\ddot{\vec{x}} = \vec{F}_{\rm N} + \vec{F}_5 = -M\vec{\nabla}\Phi - \alpha Q\vec{\nabla}\phi$$

$$r_{\rm V} = \left(\tfrac{4}{3}\alpha G_{\rm N} M r_{\rm C}^2\right)^{\frac{1}{3}}$$

$$r_{\rm V,Sun} \sim 100\,{\rm pc}$$

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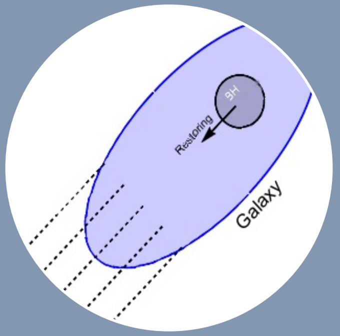
Large scale structure sources Galileon field



Problem: Black holes and stars within Vainshtein radius of host

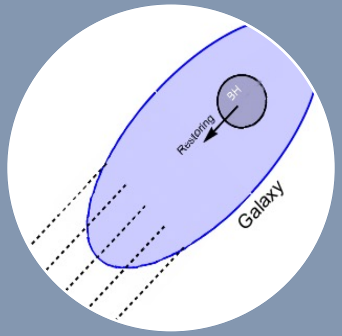
Solution: Galileon Symmetry

$$\phi \to \phi + b + c_\mu x^\mu$$

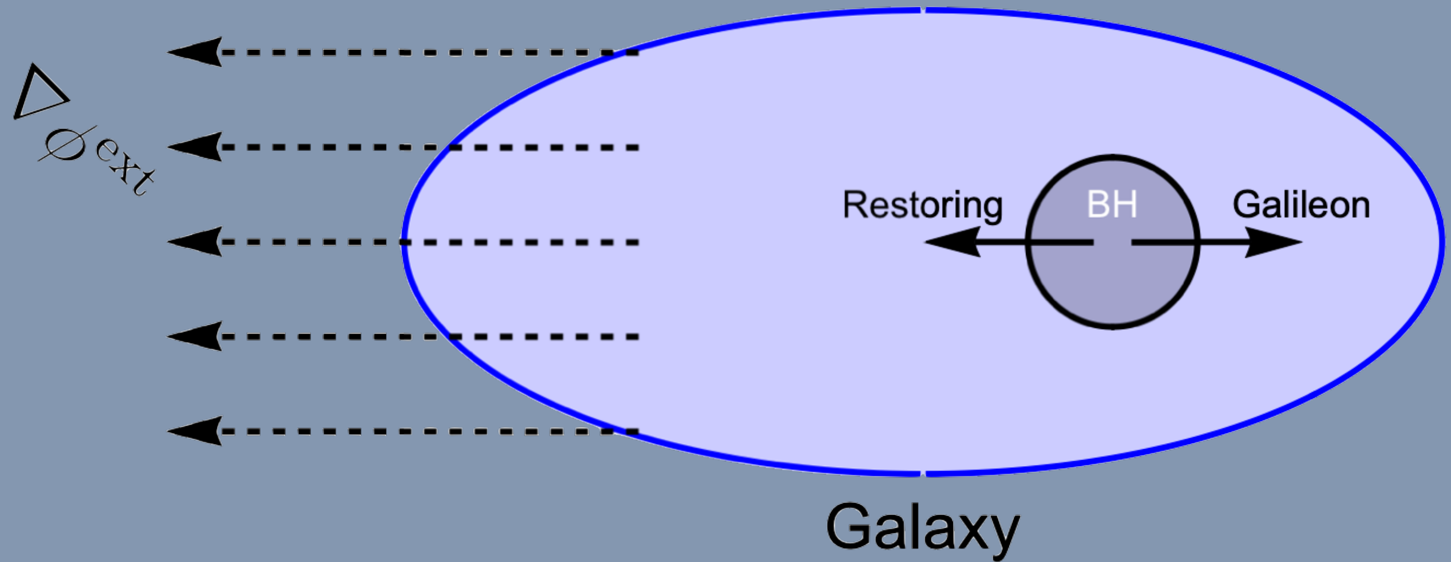
Can feel long wavelength modes, i.e. from large scale structure

$$M\ddot{\vec{x}} = -M\vec{\nabla}\Phi - \alpha Q \vec{\nabla}\phi_{\rm lss}$$

BHs do not feel a fifth force - offset BHs



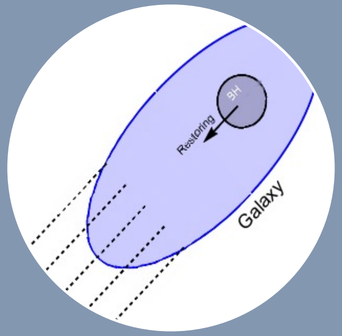
$$\text{Stars, gas, dark matter: } Q = M \qquad \text{Black holes: } Q = 0$$



$$r_{\bullet} = 0.1\,\mathrm{kpc}\left(\frac{2\alpha^2}{1}\right)\left(\frac{|g_{\rm lss}|}{20\,(\mathrm{km s^{-1}})^2\,\mathrm{kpc^{-1}}}\right)\left(\frac{0.01\,\mathrm{M_\odot pc^{-3}}}{\rho_0}\right)$$

Hui & Nicolis 2012 (arXiv:1201.1508)

Properties, Environment & Astrophysics



$$\ddot{r} = -\frac{GM\left(<r\right)}{r^2} - \alpha\vec{\nabla}\phi_{\mathrm{lss}}$$

1. Galaxy properties - $M(< r)$
2. Large scale structure - ϕ_{lss}
3. Knowledge of non-Galileon effects

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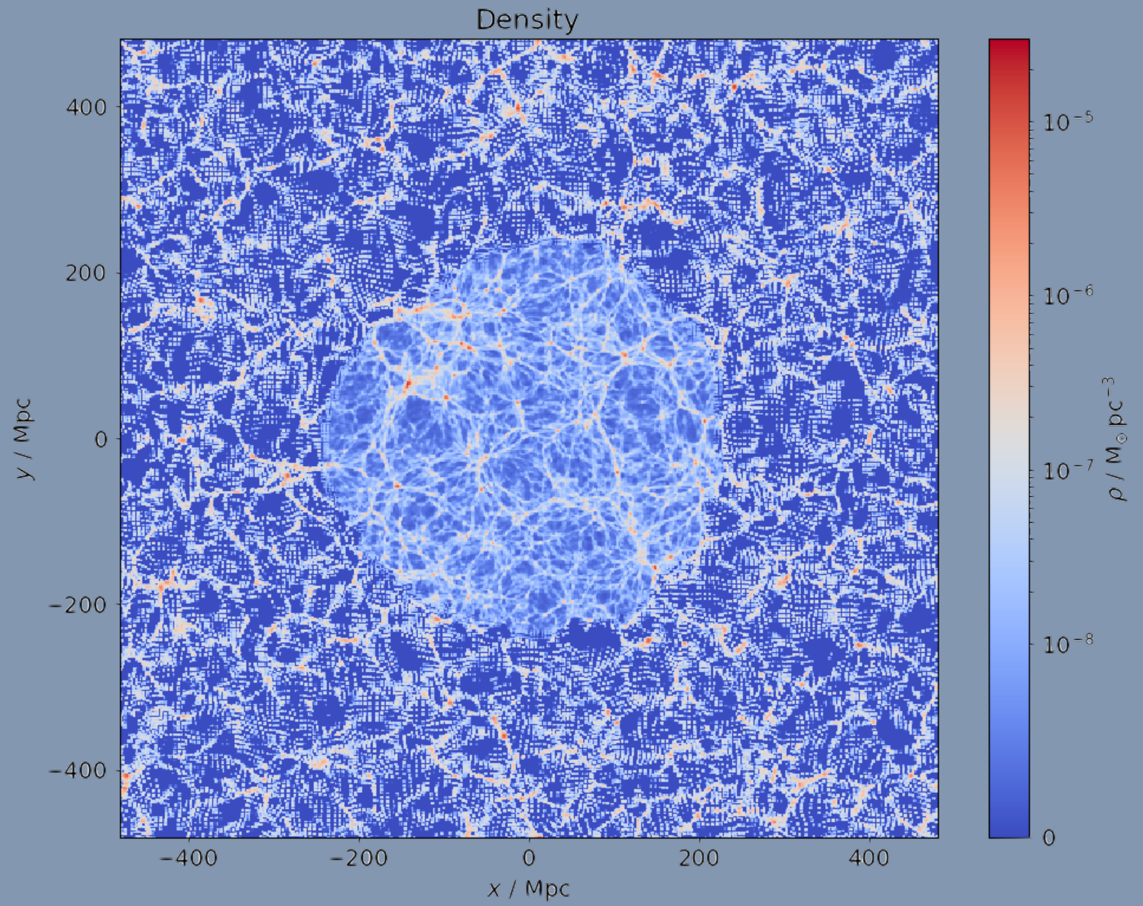
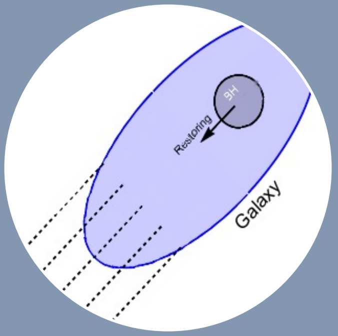
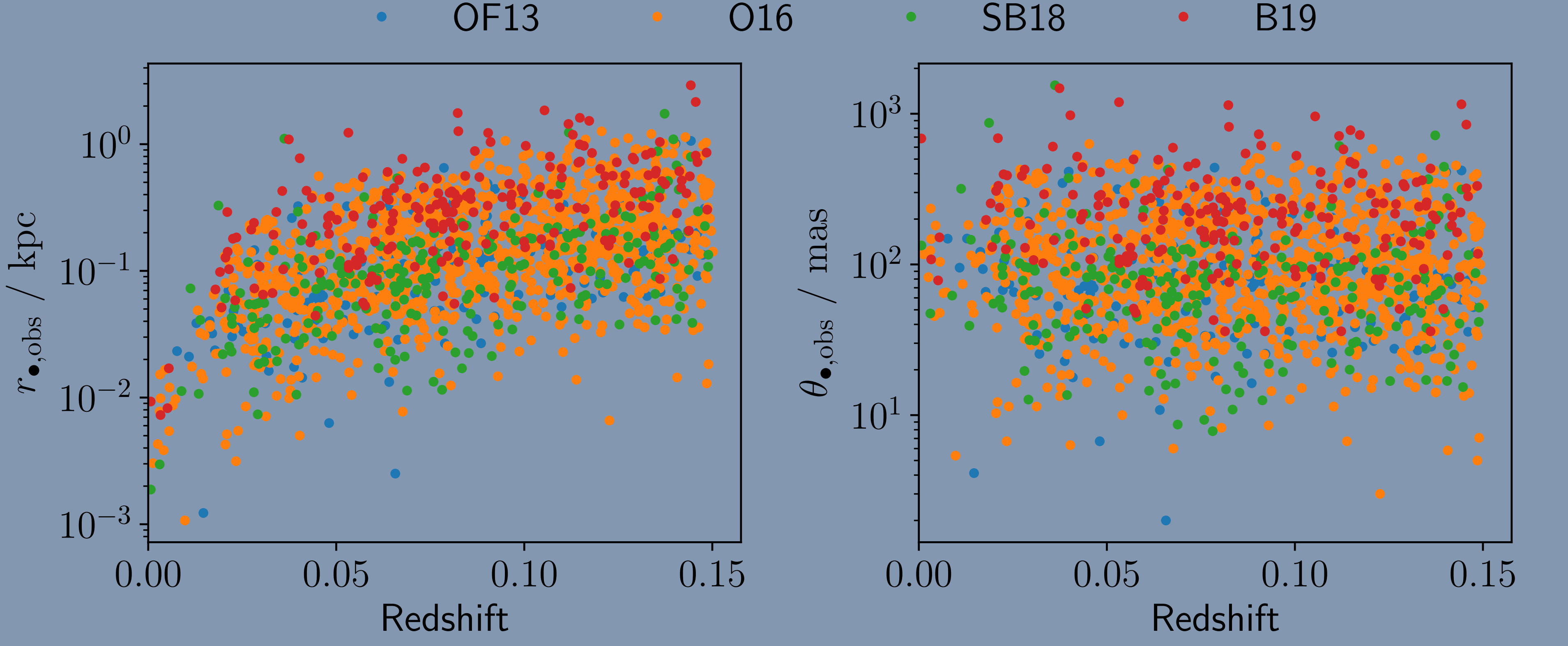
CSiBORG – Constrained Simulations in BORG

- Suite (100) of DM-only simulations - marginalize
- Initial conditions (z=69) from BORG reconstruction of 2M++
- Mass resolution $4.4 \times 10^8 \; M_\odot$
- Density field → gravitational field
- Filter out high k modes to mimic Vainshtein mechanism ($k_V = 2\pi/r_V$)
- Add in unconstrained small k modes



MC Sample galactic and LSS properties → Gaussian Mixture Model $\mathcal{L}(\mathrm{r_{pred}})$ → Convolve with noise model $\mathcal{L}(\mathrm{r}_{obs})$ → Compare to data (MCMC)





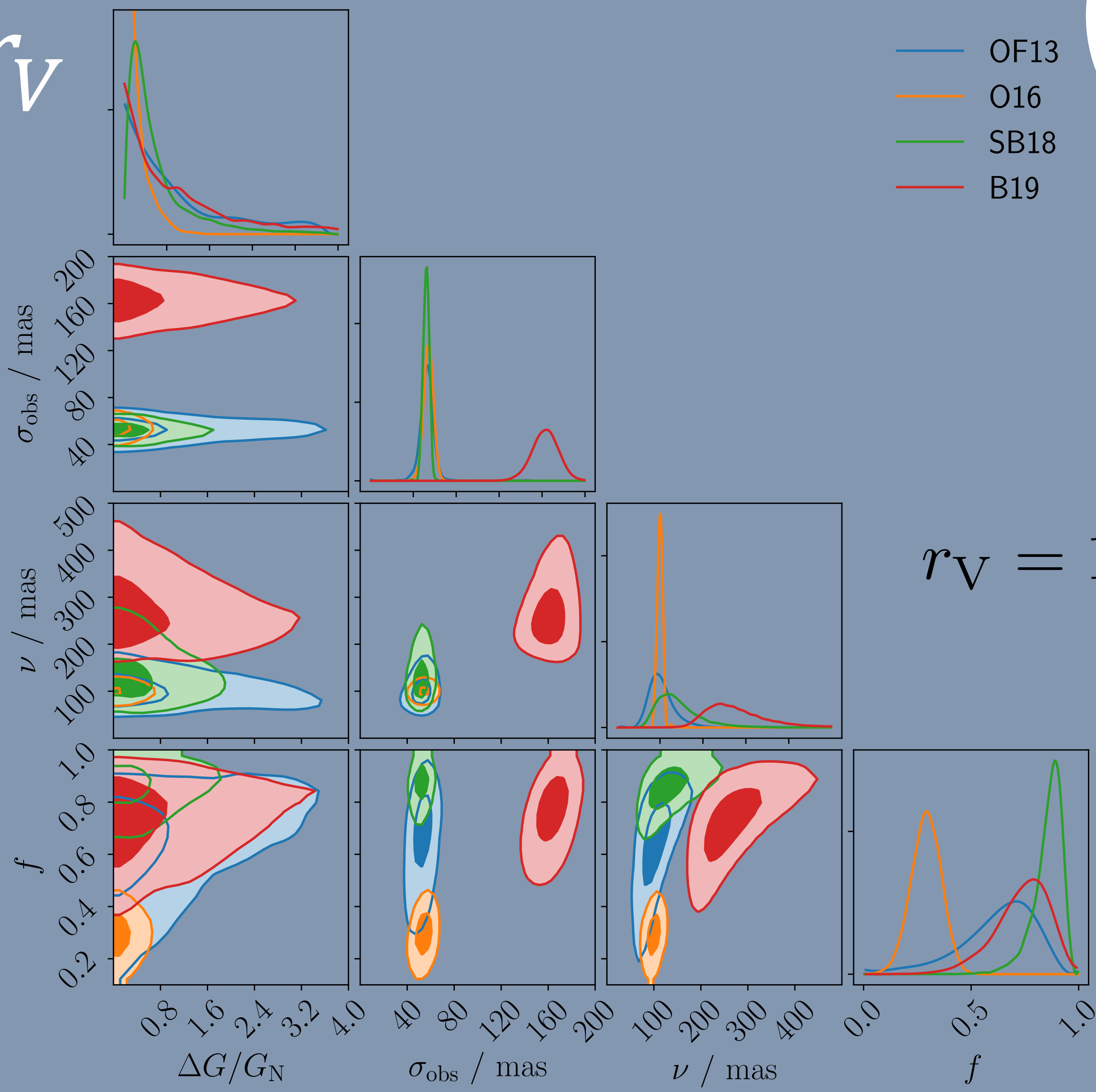
Bartlett, Desmond & Ferreira (arXiv:2010.05811)

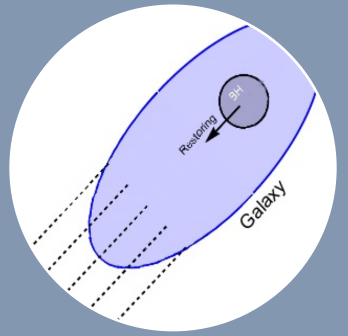
Constrain at fixed r_V

$$\mathcal{L}_{\rm g}\left(\theta_{\alpha,{\rm obs}}|\theta_{\alpha,{\rm pred}}\right) = \frac{f}{\sqrt{2\pi}\sigma_{\rm obs}} \exp\left(-\frac{\left(\theta_{\alpha,{\rm obs}}-\theta_{\alpha,{\rm pred}}\right)^2}{2\sigma_{\rm obs}^2}\right) + \frac{1-f}{2\nu}\exp\left(-\frac{\left|\theta_{\alpha,{\rm obs}}-\theta_{\alpha,{\rm pred}}\right|}{\nu}\right)$$

Can include intrinsic contribution:

$$\sigma_{\rm obs} \to \sqrt{\sigma_{\rm obs}^2 + \left(\frac{\sigma_{\rm int}}{d_{\rm A}}\right)^2}$$





$$r_{\rm V} = 100\,{\rm Mpc}$$

Bartlett, Desmond & Ferreira 2021 (arXiv:2010.05811)

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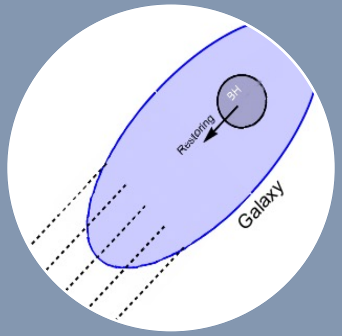
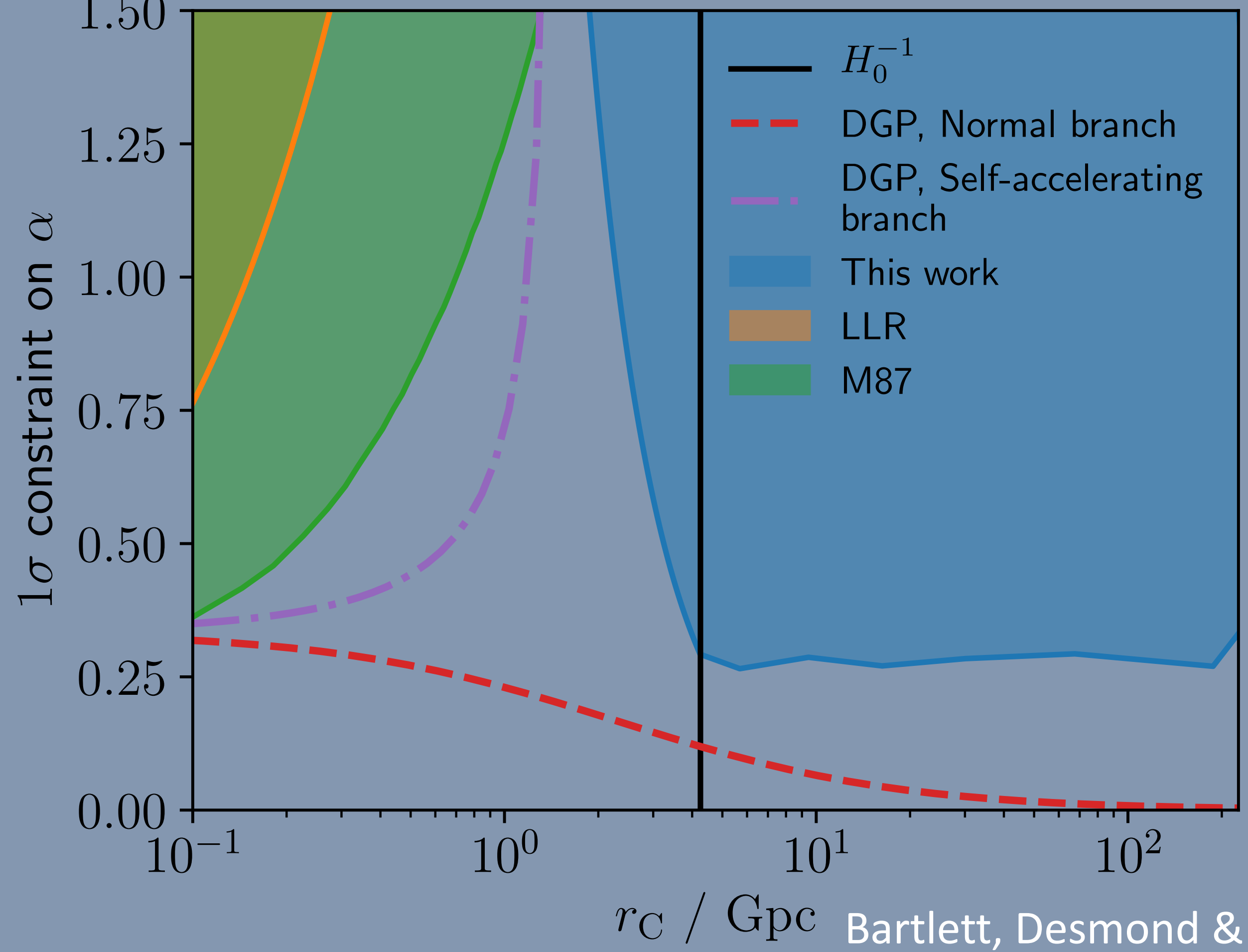
Constrain $\frac{\Delta G}{G_N} < 0.16$ at 1σ



$$\frac{\Delta G}{G_{\mathrm{N}}} \equiv 2\alpha^2$$



Bartlett, Desmond & Ferreira 2021 (arXiv:2010.05811)

Modeling the noise

Recap

MC Sample galactic and LSS properties → Gaussian Mixture Model $\mathcal{L}(\mathrm{r}_{\mathrm{pred}})$ → Convolve with noise model $\mathcal{L}(\mathrm{r}_{obs})$ → Compare to data (MCMC)

- Noise model – simple and empirical
- Astrophysics is messy – could be degenerate with my signal
- How do I know I can trust what I’ve done?

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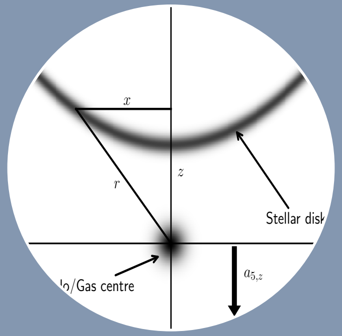
What questions should I ask?



$$y_i = \bar{y}_i + \text{noise}$$

$$\mathcal{L}_i\left(y_i \middle| \bar{y}_i\right) = \frac{1}{\sqrt{2\pi}\sigma_{y,i}} \exp\left(-\frac{\left(y_i - \bar{y}_i\right)^2}{2\sigma_{y,i}^2}\right)$$

1. Am I missing any correlations?
2. How significant are these correlations?
3. Is my model for $\bar{y}_i$ sufficient?

Bartlett, Desmond & Ferreira 2021 (arXiv:2103.10356)

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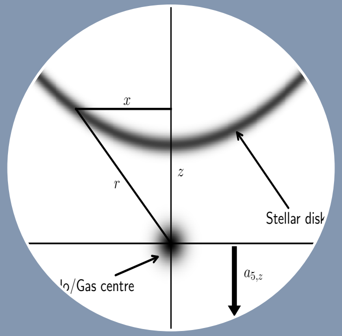

Example – Screened Fifth Forces

$$S = \int \mathrm{d}^4 x \sqrt{-g} \frac{R + f(R)}{16 \pi G_{\mathrm{N}}} + S_{\mathrm{m}}$$

Object unscreened if

$$|\Phi| < \chi = \frac{3}{2} f_{R0} = \frac{3}{2} \times 10^{-8} \left(\frac{\lambda_{\mathrm{c}}}{0.32\,\mathrm{Mpc}} \right)^2$$

and thus feel fifth-force

$$G_{\mathrm{N}} \to G_{\mathrm{N}} \left(1 + \frac{\Delta G}{G_{\mathrm{N}}} \right)$$

Stars will be “self-screened” for $\chi \lesssim 10^{-6}$

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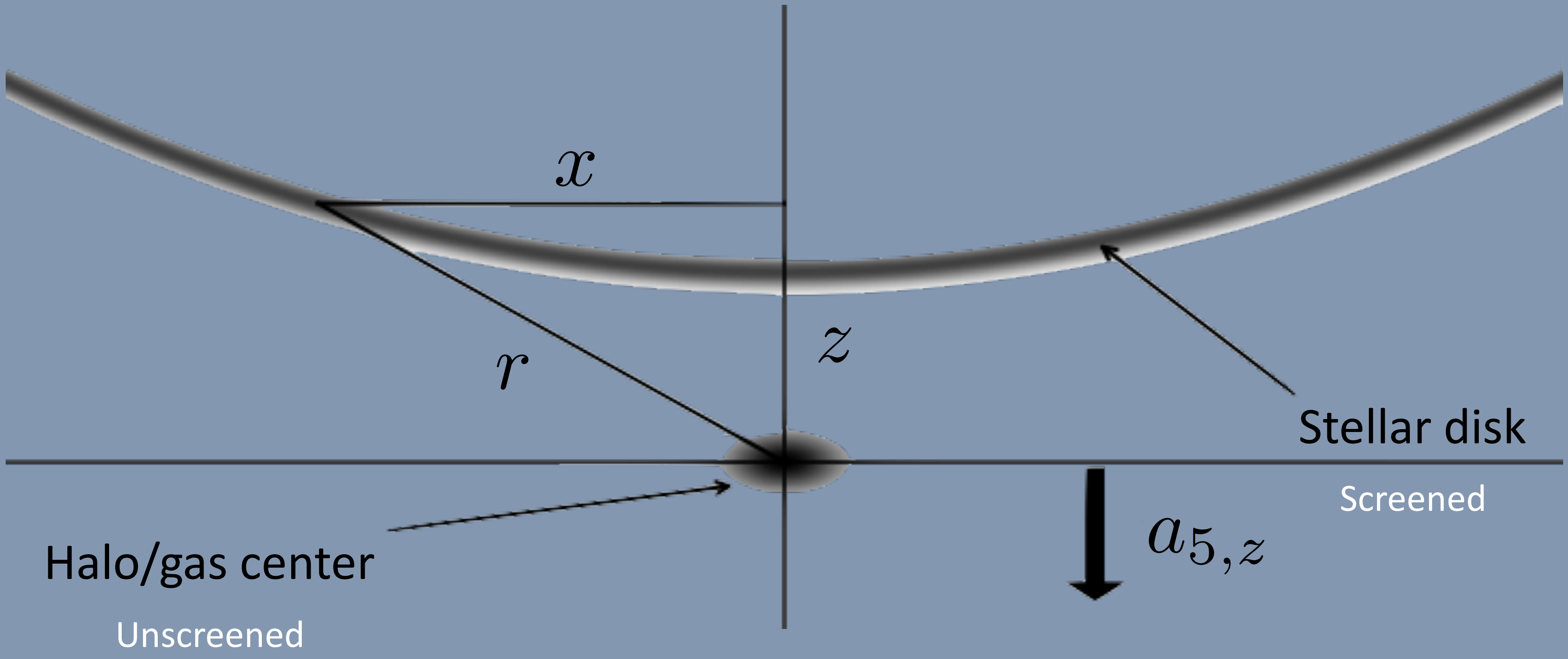
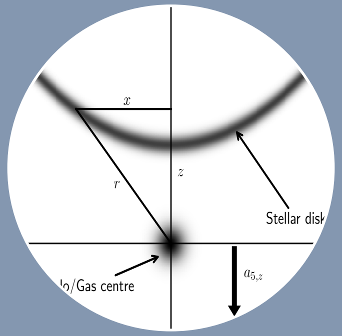
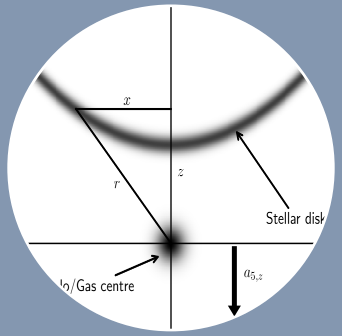
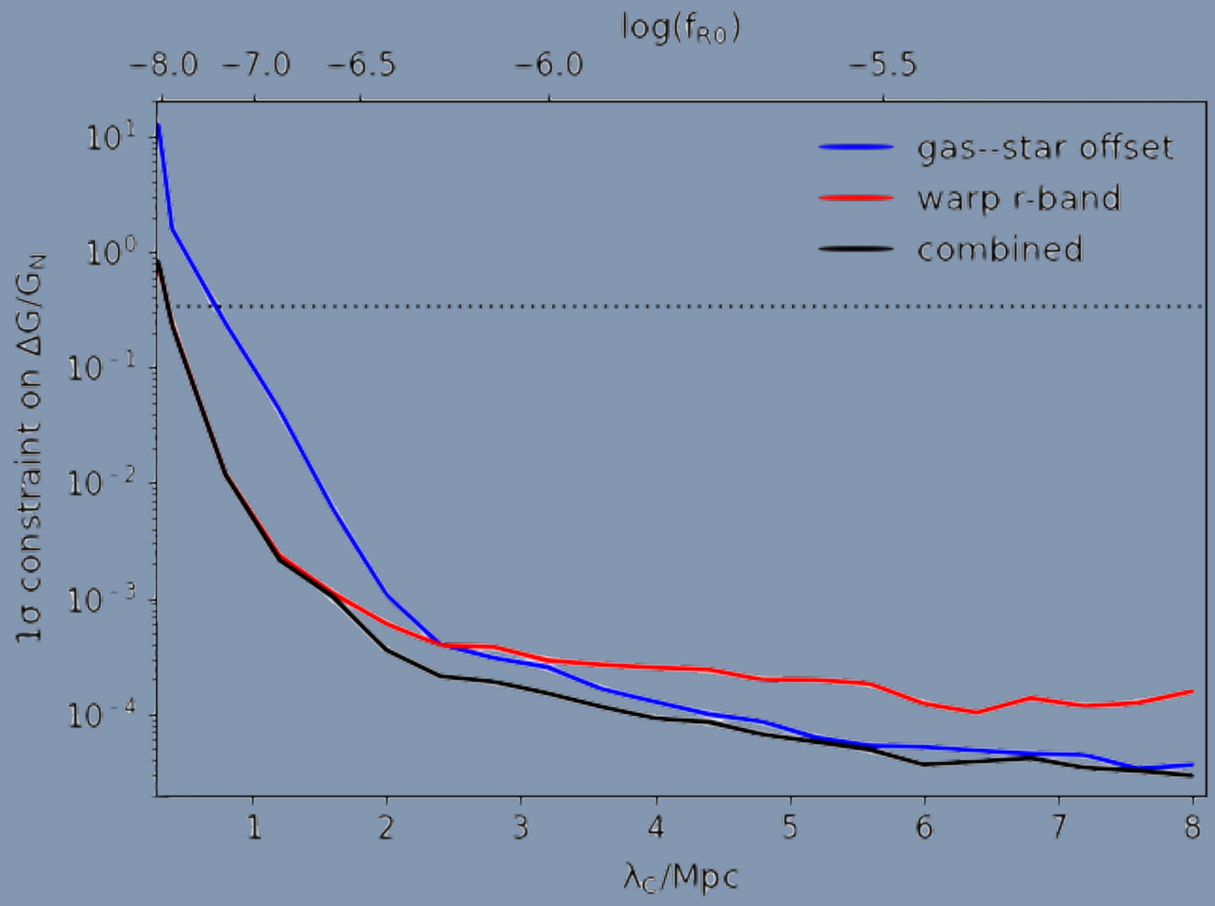
Gas-star offsets and galaxy warps

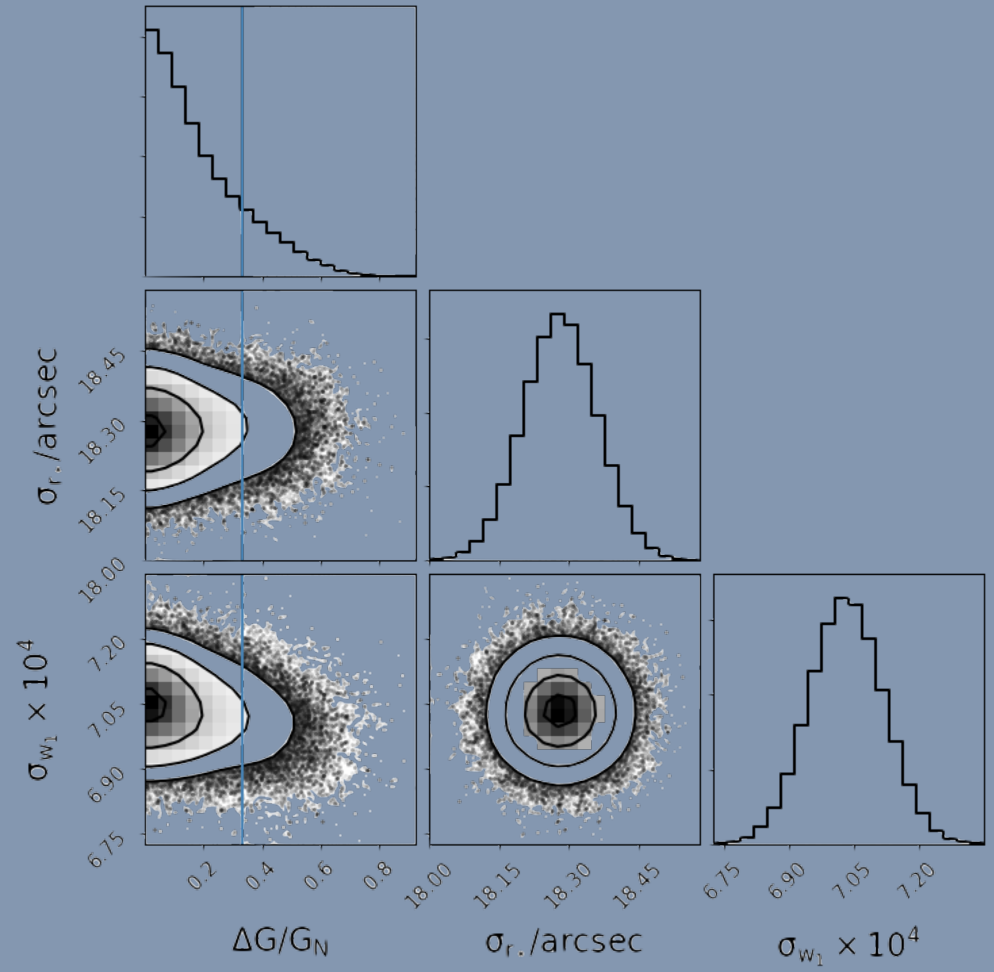




Astrophysically Relevant Hu-Sawicki $f(R)$ ruled out







Desmond & Ferreira 2020 (arXiv:2009.08743)

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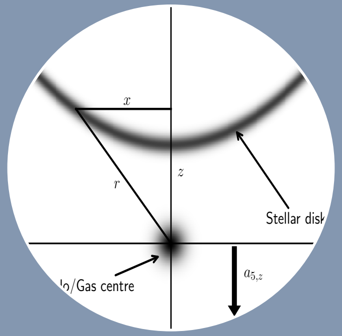
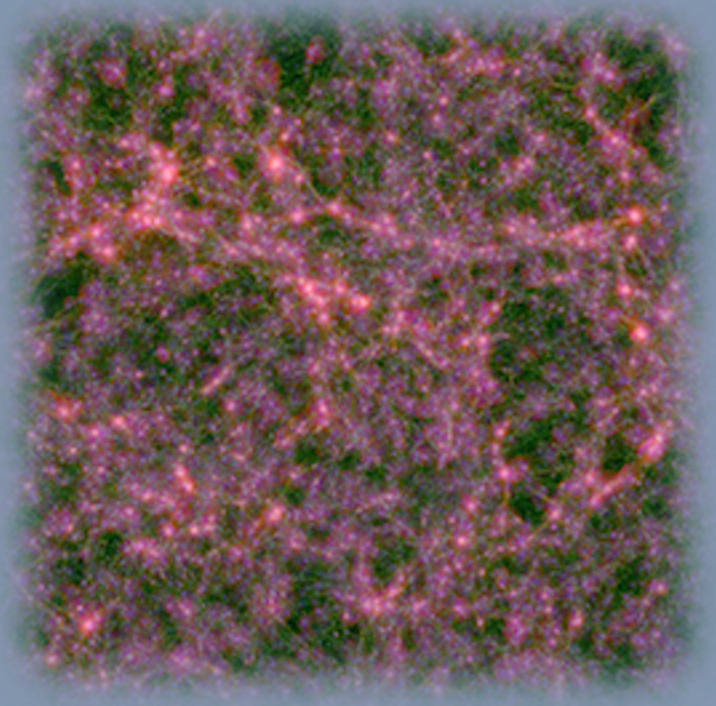
Use a hydrodynamical simulation to test model



1. We know exactly what the theoretical parameters and implementation of baryonic physics are in the simulation
2. We have more information available there than we do observationally

- Horizon-AGN simulation: (100 Mpc/h)^3, 126,361 galaxies, baryonic effects
- ΛCDM – should get no fifth-force detection



http://www.horizon-simulation.org/about.html

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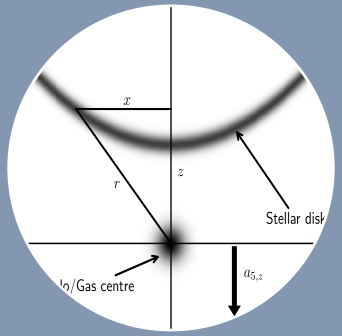
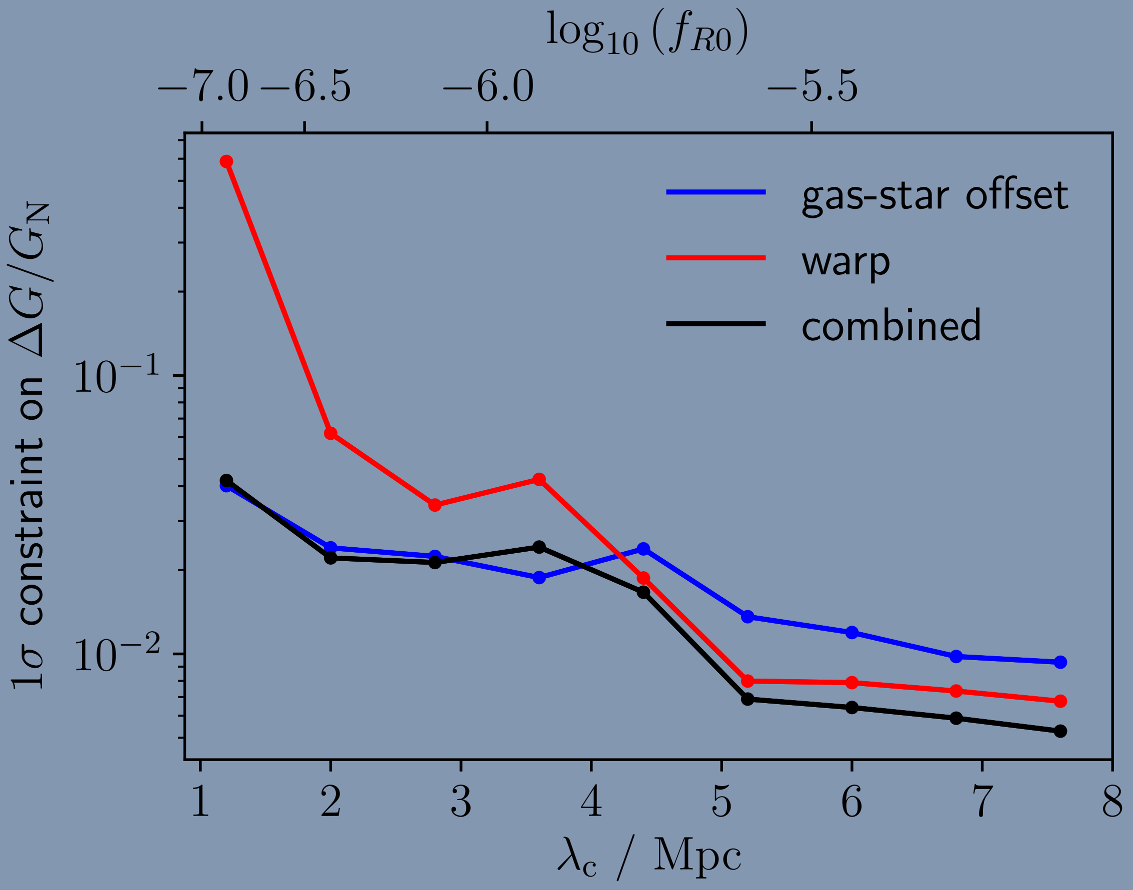
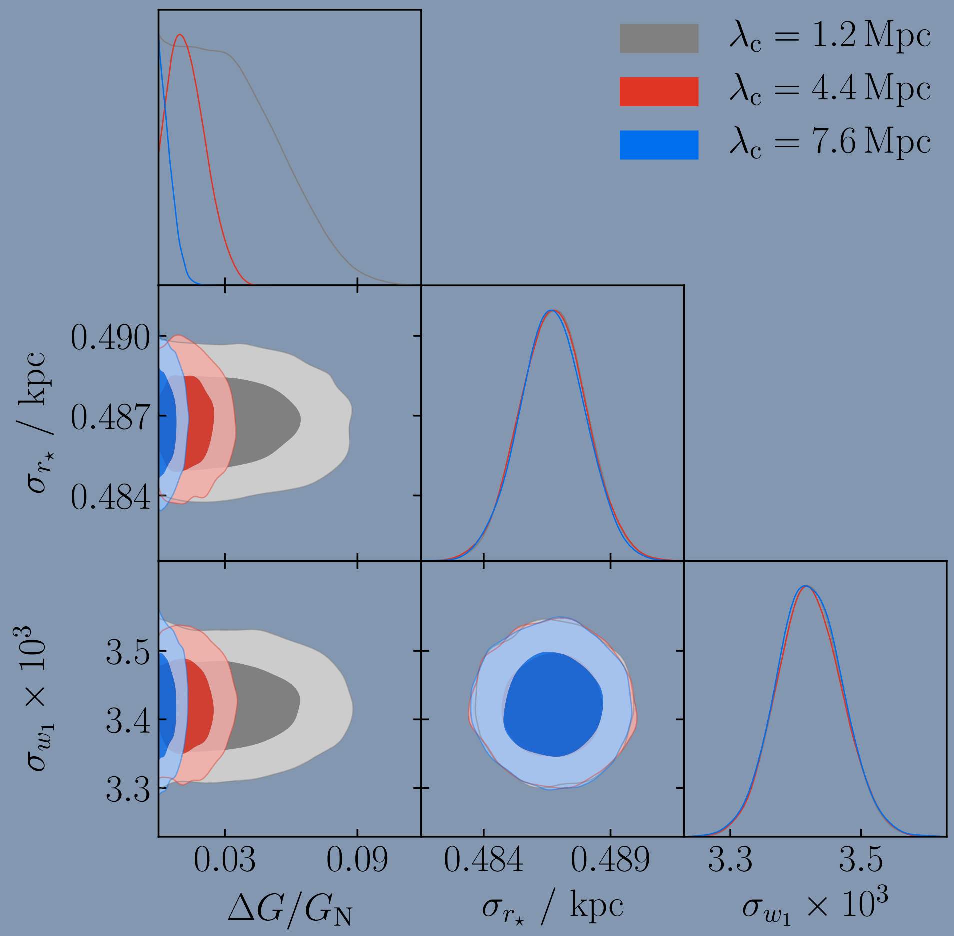
First check you don't get a detection

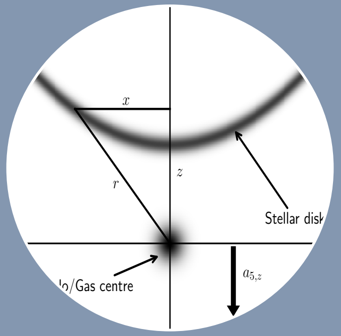




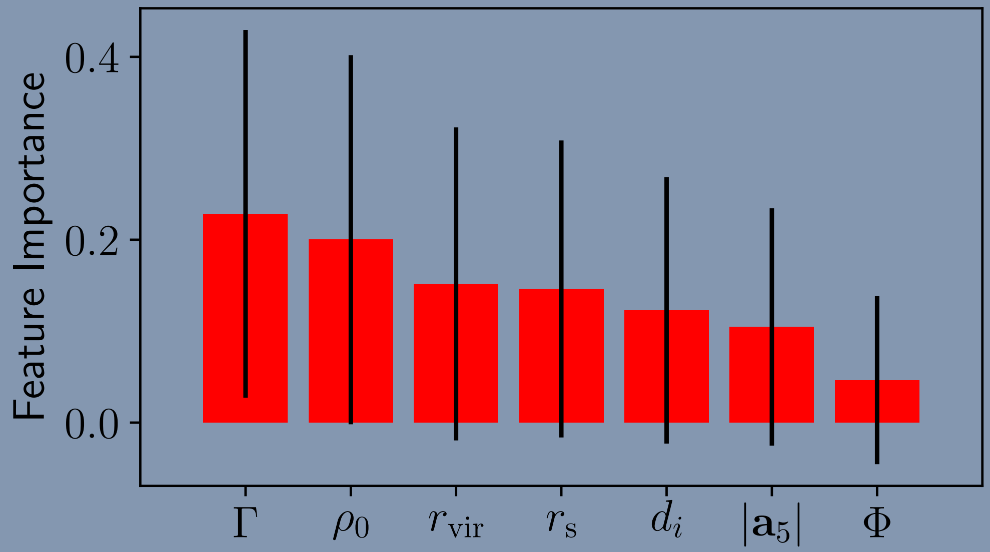


Bartlett, Desmond & Ferreira 2021 (arXiv:2103.10356)

1. Am I missing any correlations?

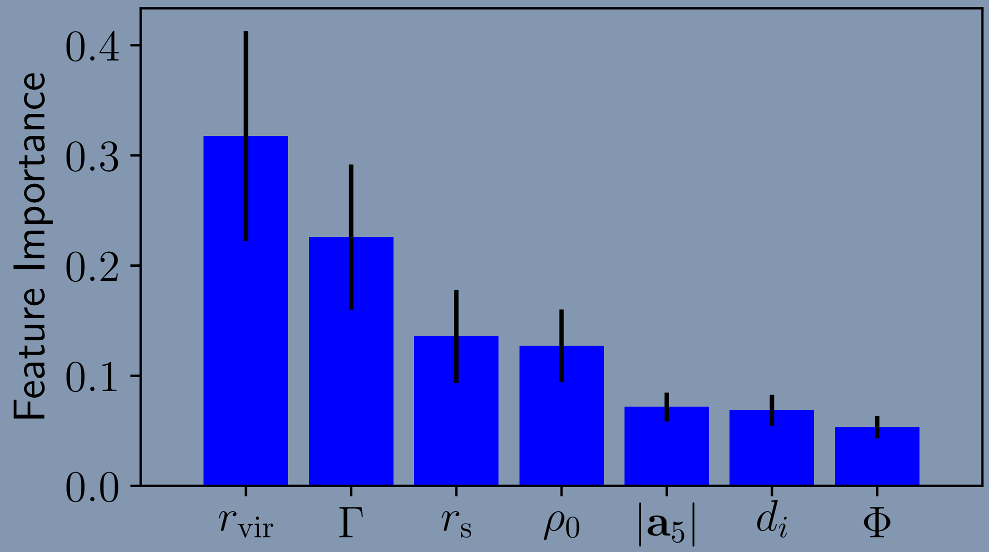


Galaxy warp



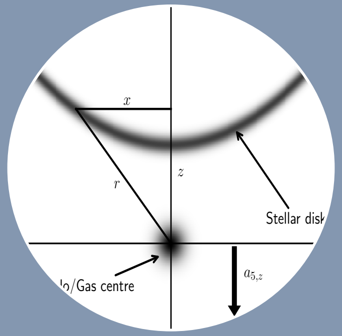
Cannot predict → Noise model should be sufficient

Gas-star offset



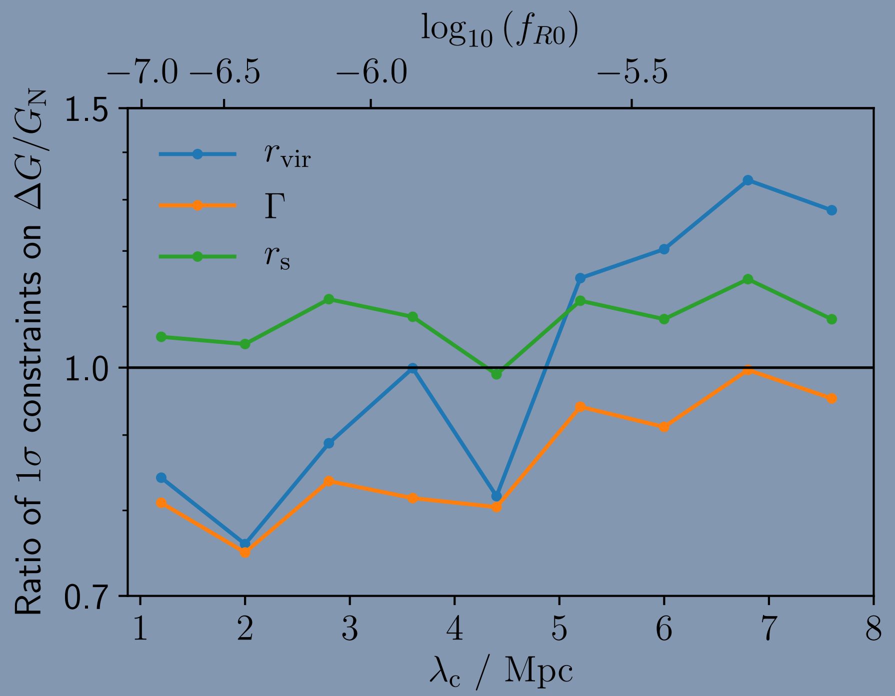
Can predict → Need to do more

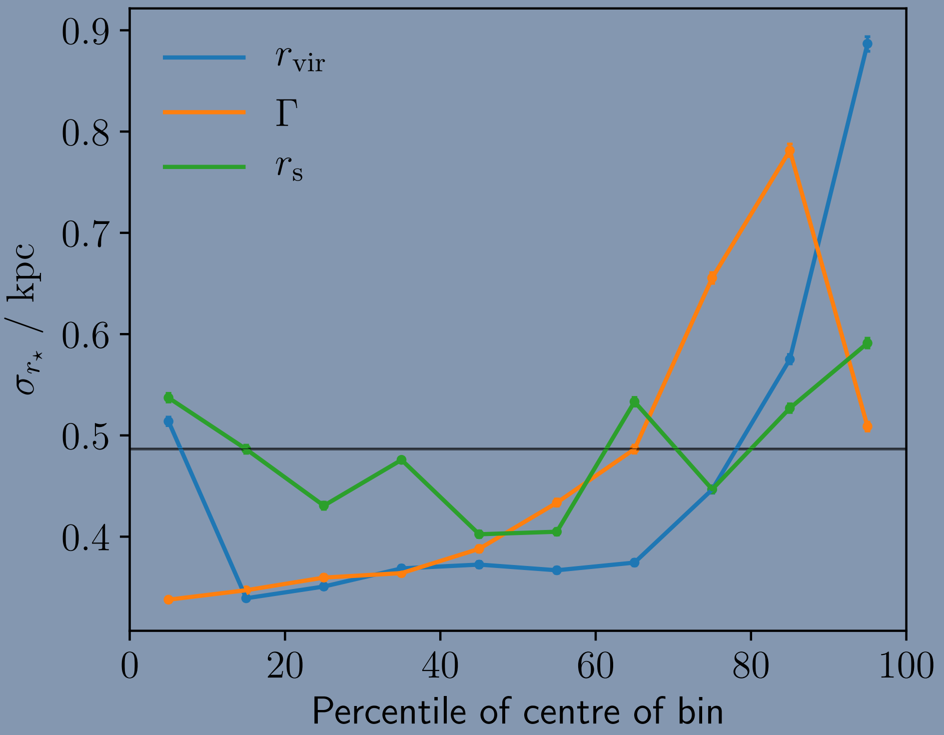
Bartlett, Desmond & Ferreira 2021 (arXiv:2103.10356)



2. How significant are these correlations?

- Bin galaxies based on properties
- Assign different noise parameters to each bin





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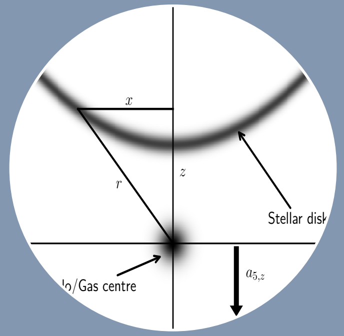
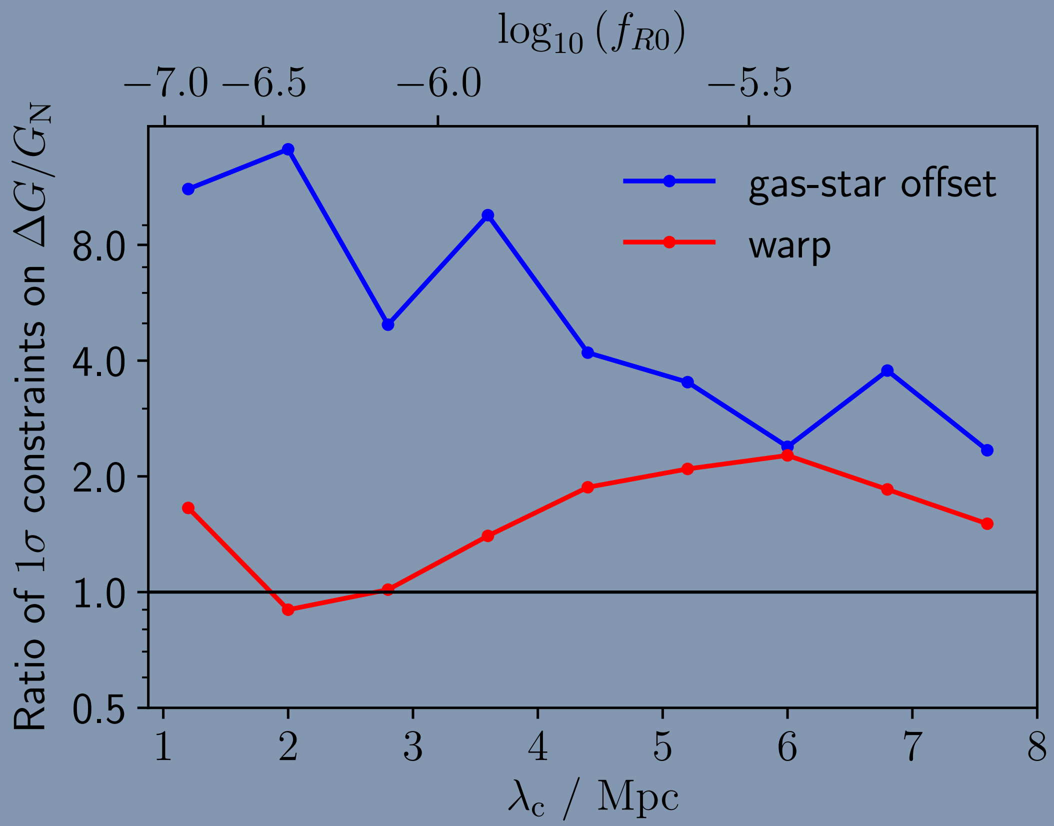
3. Is my model for $\bar{y}_i$ sufficient?



- With real data, had to assume the inner power-law slope of halo density profile
- We can measure this in the simulation
- Gas-star offsets far more sensitive than warps

- Conclusions depend on how much you trust your simulation



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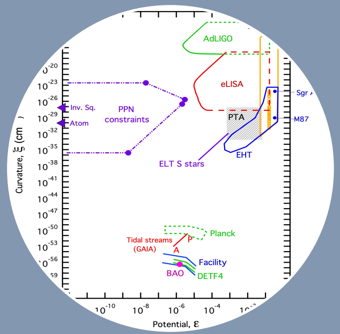
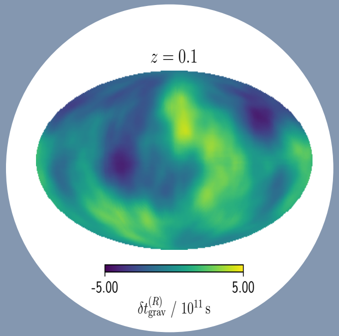
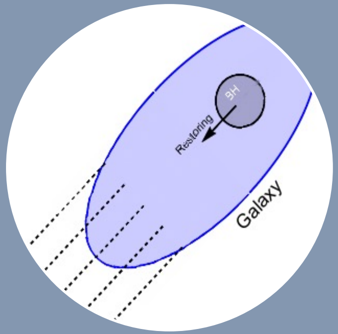
Summary



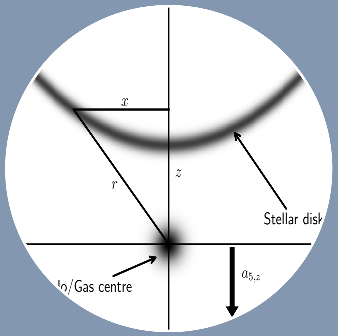
- Under-explored region of parameter space
- Lots of data



- Importance of noise
- $\Delta\gamma$ constraint 30 times stronger than previous attempts



- Tight constraints on fifth-force
- Improve non-linear modeling



- Astrophysics messy – should test your noise model

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