The Roles of Structure Formation and Λ in Black Hole Universes

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Based on arXiv:1610.05635 (Class. Quant. Grav. 34 065009) and arXiv:1707.xxxxx
Also arXiv:1705.01892 (Gen. Rel. Grav. 49: 98)

Motivation

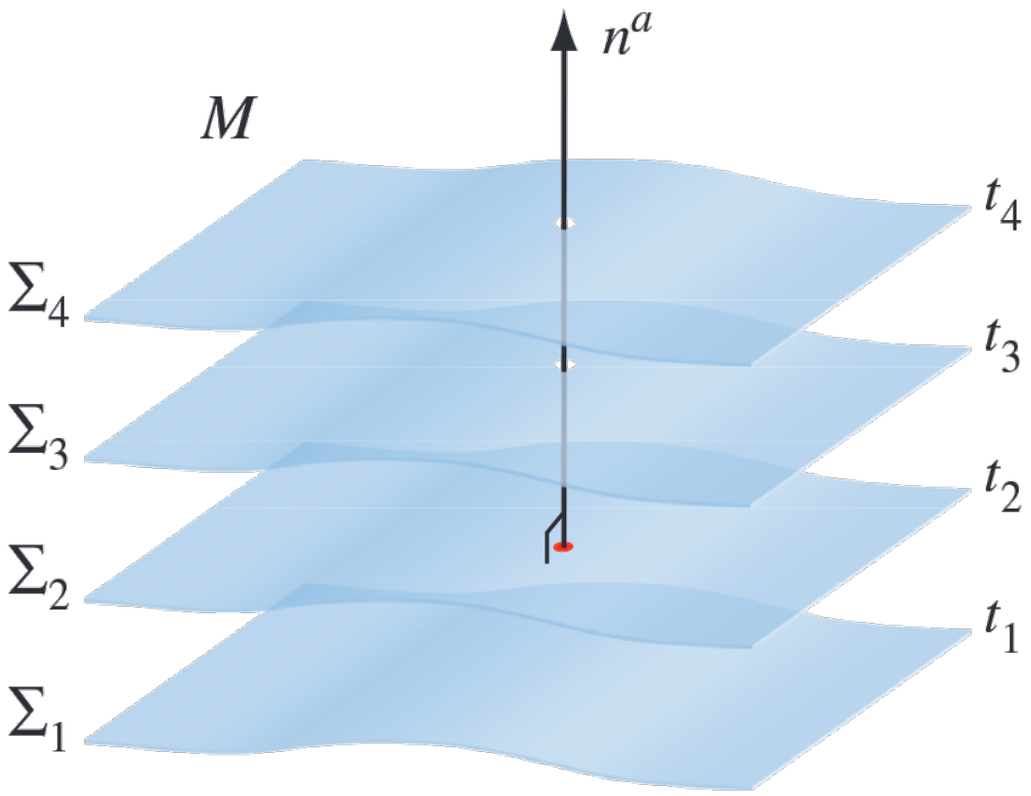
Cosmological principle: homogeneous and isotropic. Wish to *test* whether large scale expansion of space is that of FLRW.

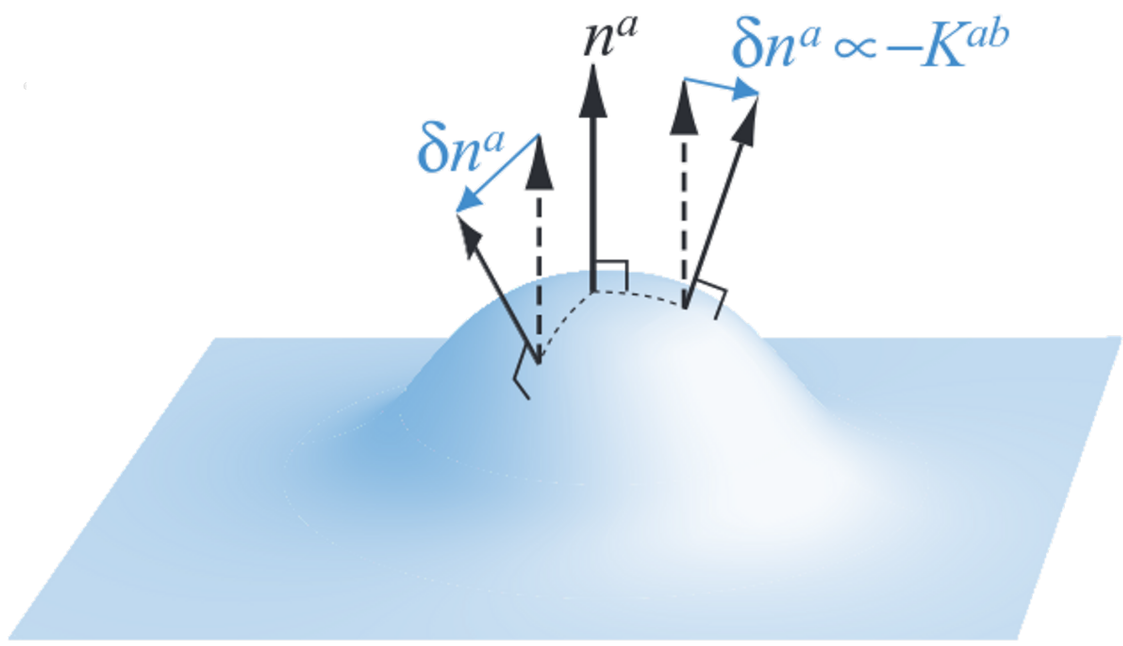
- **Theoretical:** ∃ non-commutativity in EFE's ⇒
    - small scale inhomogeneities may affect large scale dynamics (backreaction problem).

- **Observational:** homogeneity scale, effects on observables, precision cosmology.

Initial Data

- Full GR difficult to solve! Use 3 + 1 decomposition to instead get *constraint equations,* and specify the following:





Baumgarte & Shapiro, Numerical Relativity (2010)

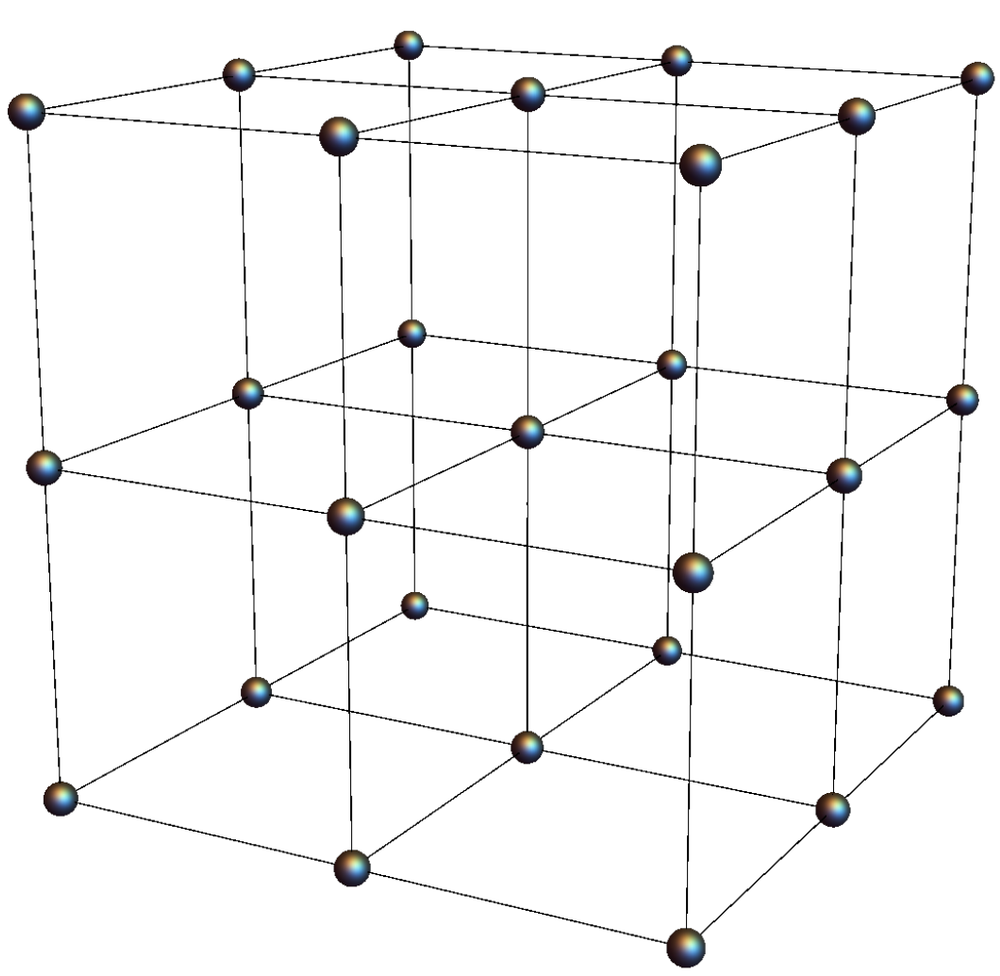
Hypersurface Σ_i, metric h_{ij}

Extrinsic curvature $K_{\mu\nu}$

Initial data

The Solution

- Exploit linearity that arises from conformally flat Schwarzschild solution. Superpose many Schwarzschild masses together - represents discretised matter content of Universe.



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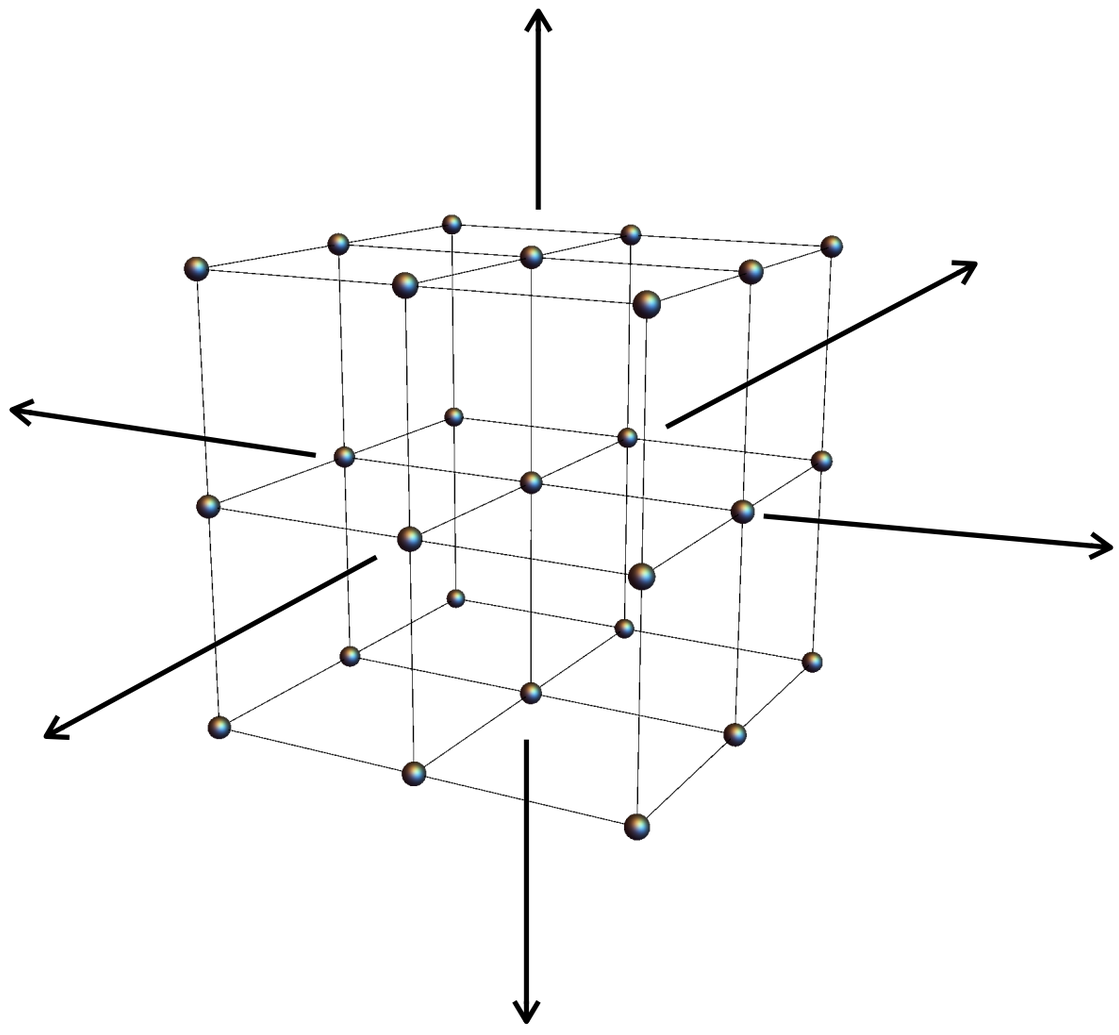
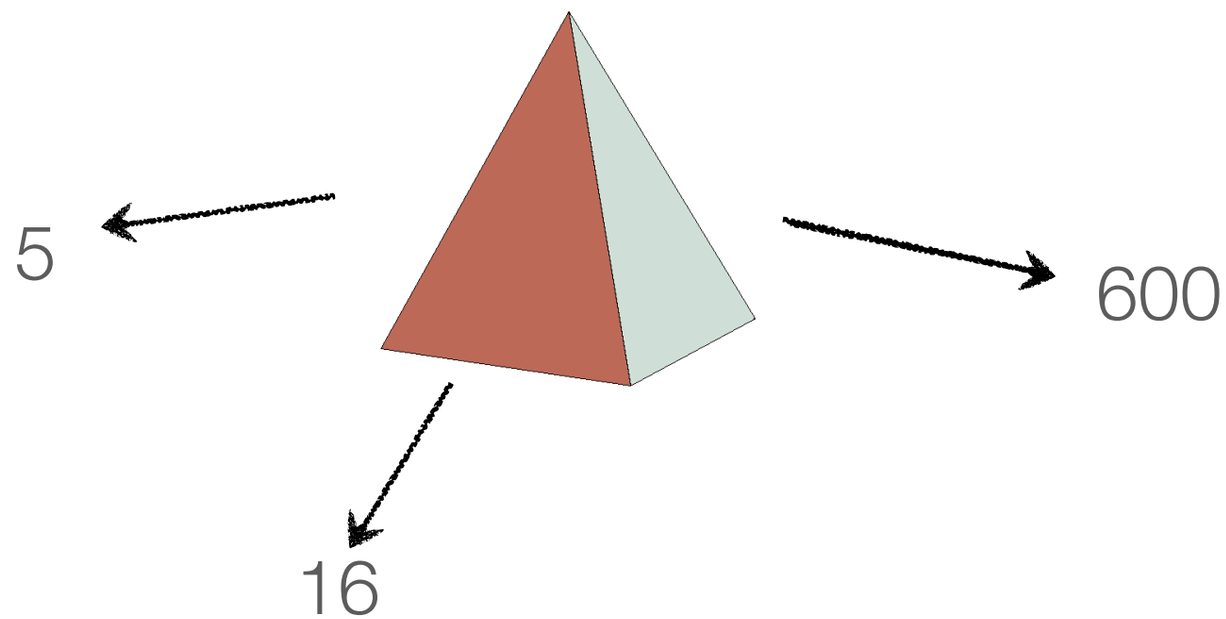


The Solution

- NB: Want **exact** solutions. Tile 3-sphere with identical polyhedra, and place Schwarzschild mass at centre of each ∴ closed cosmological model. 6 ways of doing this:

>1 way to arrange:

Tetrahedra



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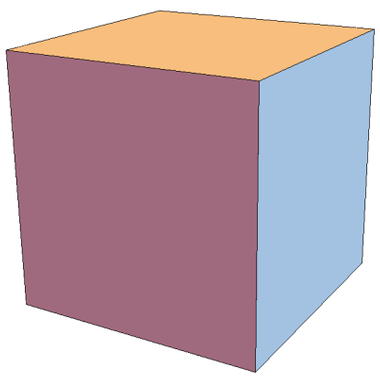
Only one way to arrange:

Cubes



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The Solution

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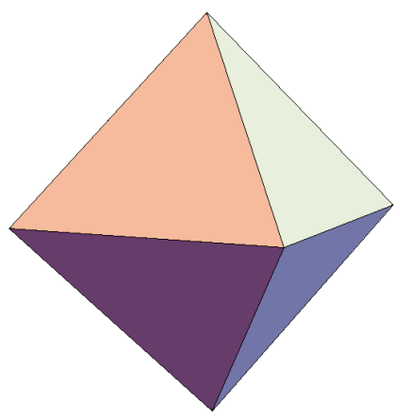
Only one way to arrange:

Octahedra



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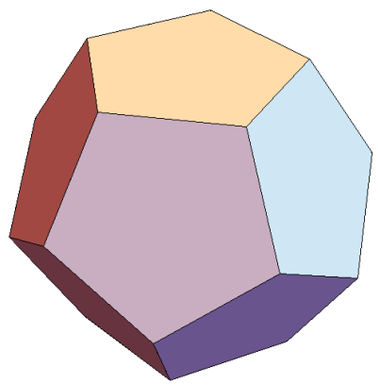
The Solution

- NB: Want **exact** solutions. Tile 3-sphere with identical polyhedra, and place Schwarzschild mass at centre of each ∴ closed cosmological model. 6 ways of doing this:

Only one way to arrange:

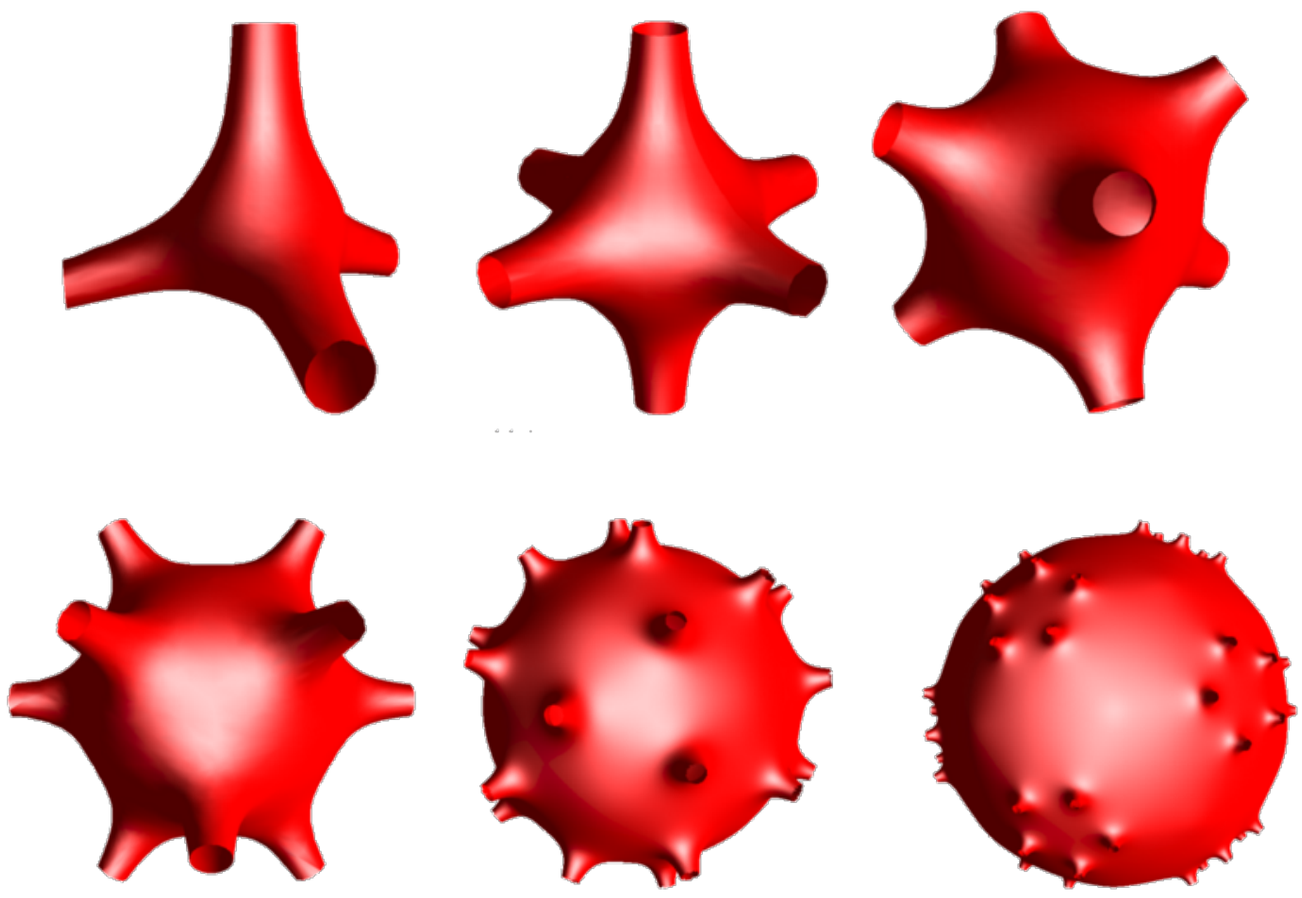
Dodecahedra



120

The Solution

- NB: Want **exact** solutions. Tile 3-sphere with identical polyhedra, and place Schwarzschild mass at centre of each ∴ closed cosmological model. 6 ways of doing this:

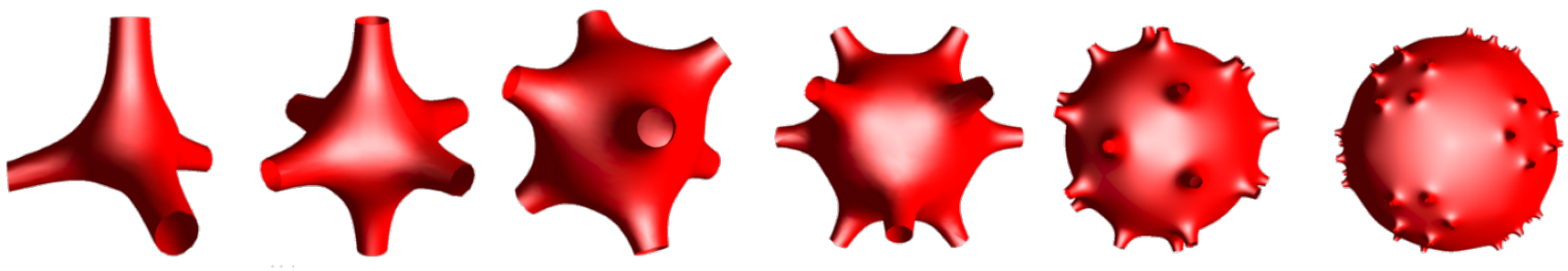


Clifton et al, Phys Rev D 86 043506 (2012)

Adding Λ

- Now looking at slice through Schwarzschild-de Sitter.
- $K_{\mu\nu}$ non-vanishing (no longer time symmetric).
- Appropriate choice: $K^2 = 3\Lambda$ to solve constraint eq^{n}s.
- ∴ looking at CMC foliation.

Intrinsic geometry identical to previous slice through Schwarzschild



Adding Λ

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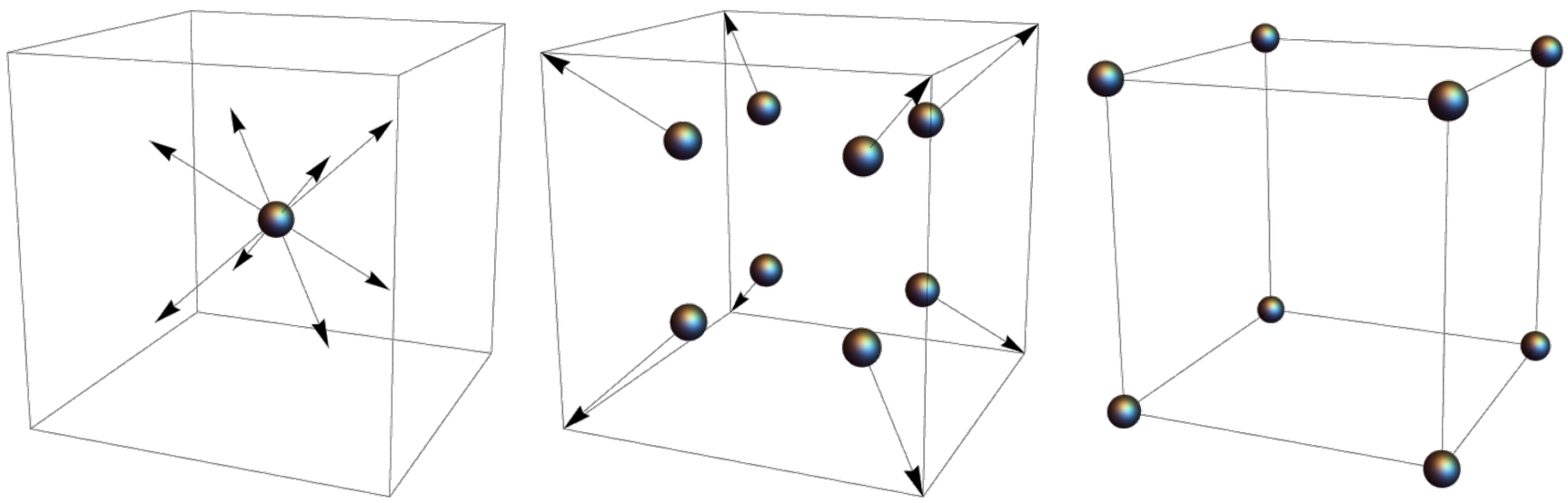
Eternal expansion if $\Omega_\Lambda > 4/27\ \Omega_m$.

Adding Structure

- Split each mass at centre of cell into number of vertices of that cell, and move towards these vertices.

$$v(\lambda) = v_{original} + \lambda v_{dual} - \lambda v_{original}$$



(a) $\lambda = 0$.

(b) $\lambda = 0.5$.

(c) $\lambda = 1$.

Adding Structure

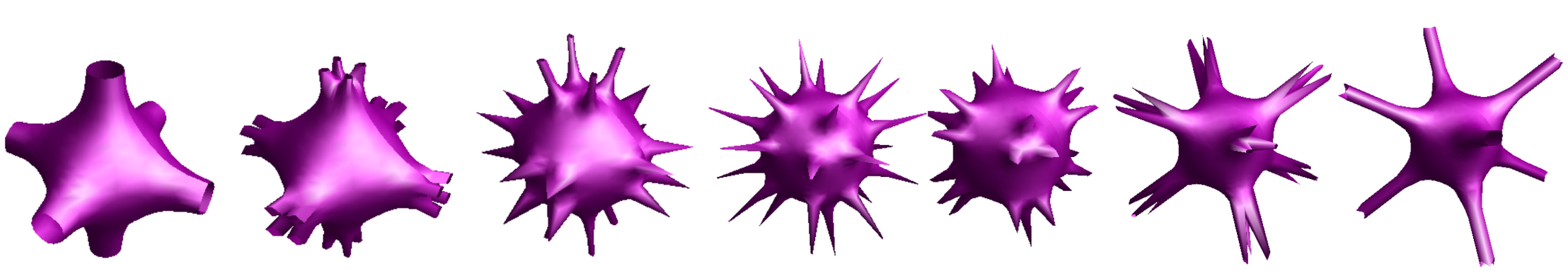
- Split each mass at centre of cell into number of vertices of that cell, and move towards these vertices.

Original nº.	Cell shape	No. vertices	Total no.	Dual no.
5	Tetrahedron	4	20	5
8	Cube	8	64	16
16	Tetrahedron	4	64	8
24	Octahedron	6	144	24
120	Dodecahedron	20	2400	600
600	Tetrahedron	4	2400	120

Adding Structure

- Split each mass at centre of cell into number of vertices of that cell, and move towards these vertices.

Intrinsic geometries now differ:



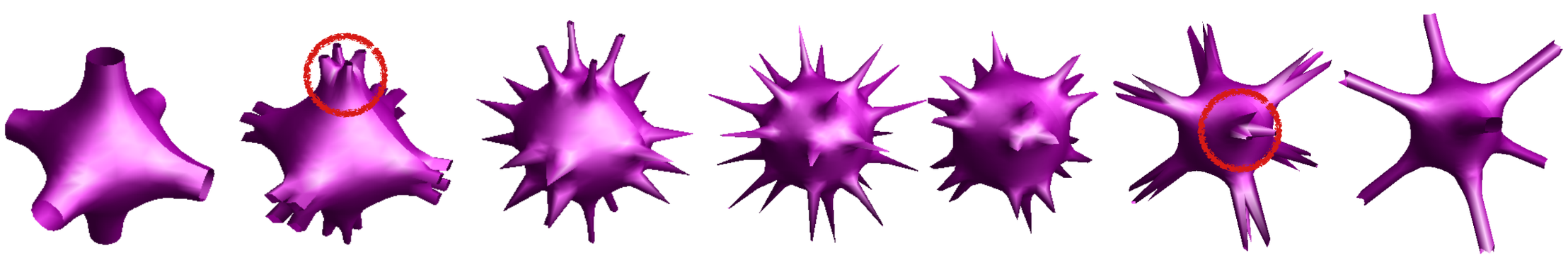
N=8 N=64 N=16

Increasing λ

Adding Structure

- Split each mass at centre of cell into number of vertices of that cell, and move towards these vertices.

Intrinsic geometries now differ:



Structures…

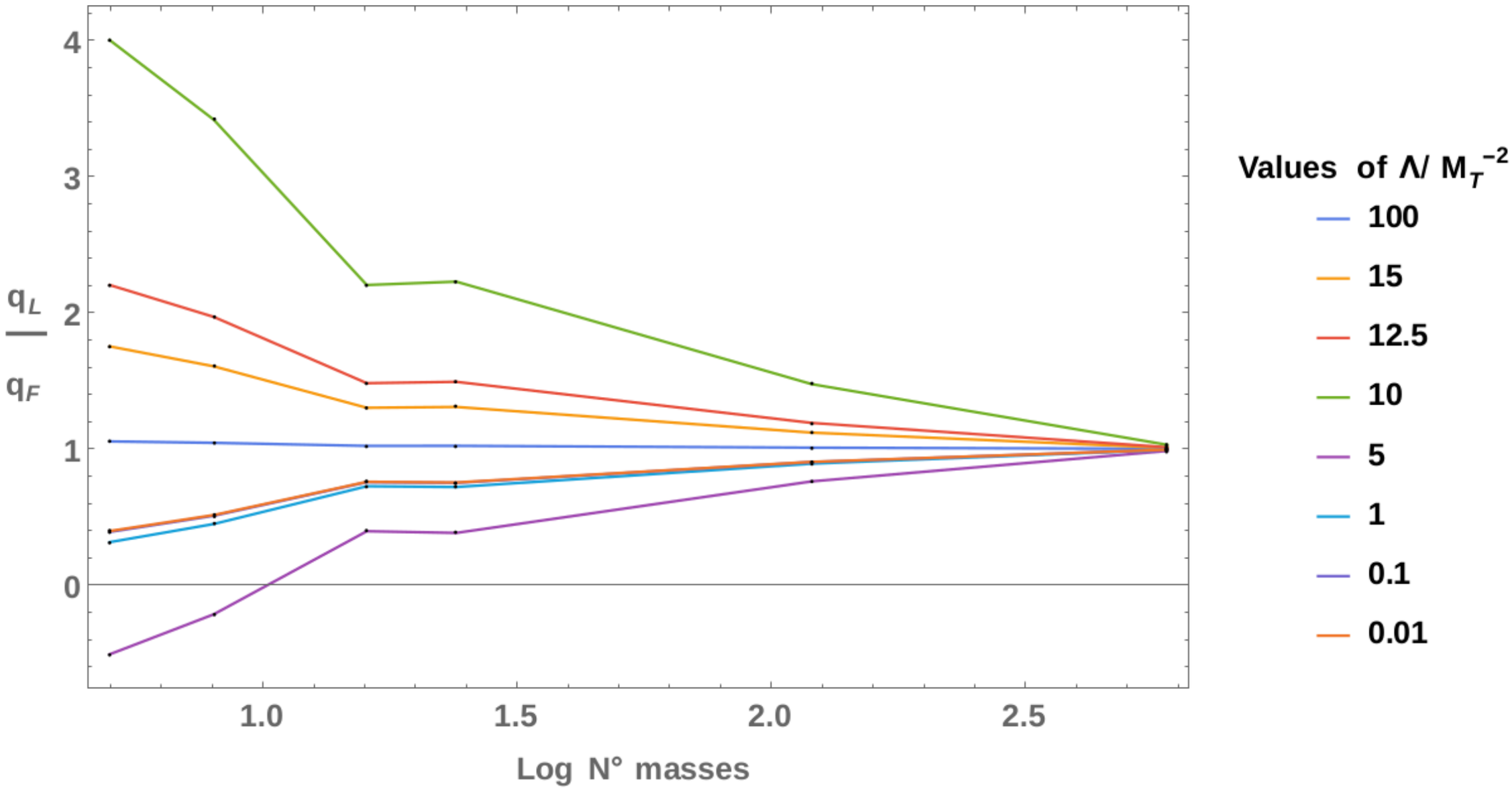
Horizons

- Horizons are marginally trapped surfaces with vanishing expansion. Use electric part of Weyl tensor to locate.

	Λ	Structure formation
Locating equation	$\mathbf{e}_1(E^{11}) = \alpha_1\alpha_2(3\Lambda)^{1/2}\, E^{11}$	$\mathbf{e}_1(E^{11}) = 0$
Type	Cosmological and black hole	Individual and collective black hole
Interesting results?	$\exists$ upper bound on Λ for horizons to exist. Large N, approaches SdS value of 1/9.	Collective only exists during clustering, for $\lambda \sim 0$ (or 1). Large N, λ_{crit} decreases.

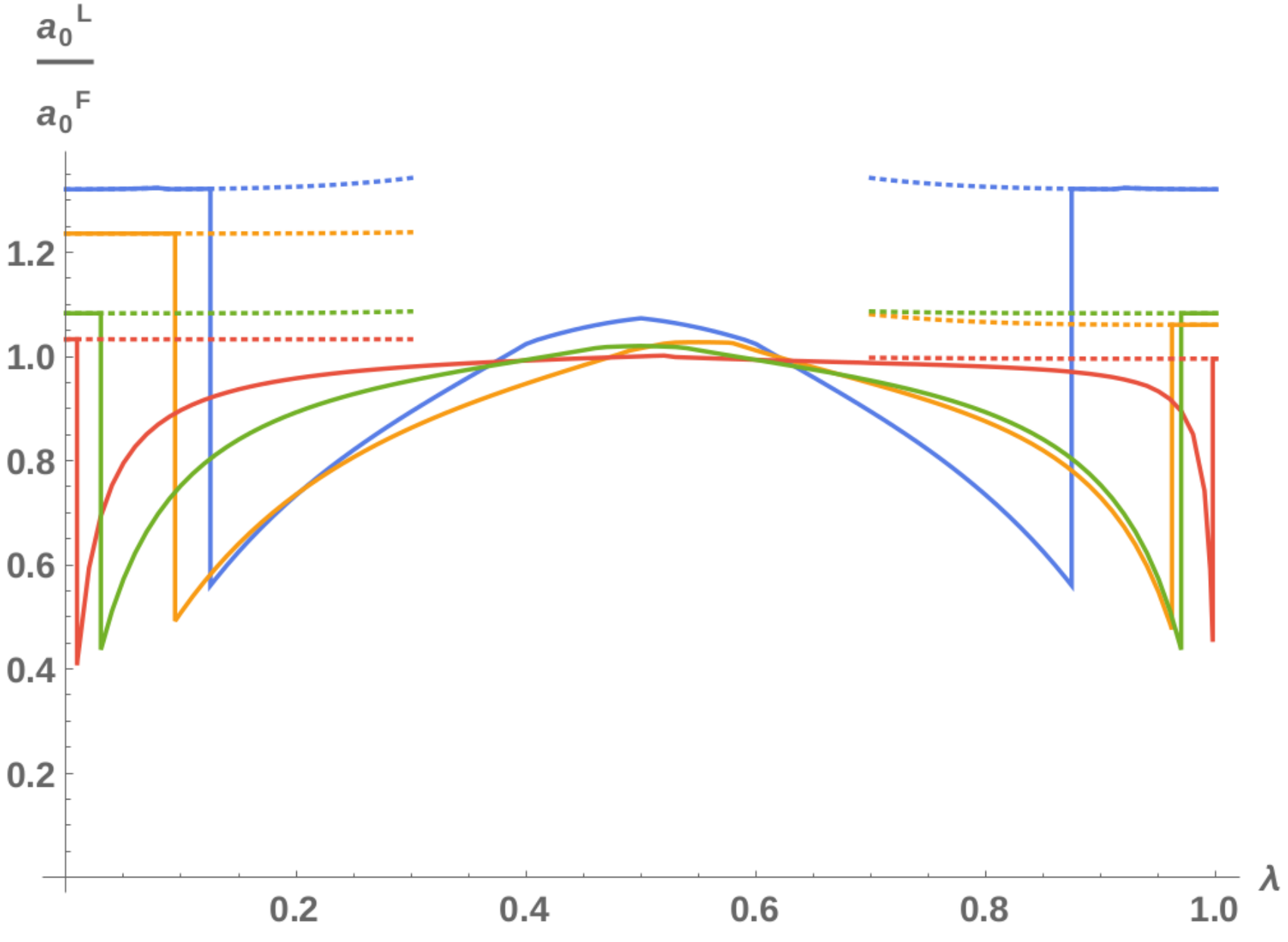
Comparison with FLRW Cosmology

- Deceleration parameter q with Λ:



Comparison with FLRW Cosmology

- Scale factors a_o with structure formation:



Summary and Future Work

- Black hole lattices provide exact analytic test of backreaction.
- Generalised existing models to include Λ and clusters of masses.
- As N increases → FLRW.
- Interaction energies appear to be important for masses close together.

Plans:

- Numerically evolve models with Λ.
- Split masses up further to create layers of substructures.

Thank you for listening