Looking for Geons

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UNI GRAZ
NAWI Graz
Natural Sciences

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  - Propagating particle-like gravitational wave
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- If massive: Dark matter candidate
  - Similar (equal?) to primordial black holes

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  - What does particle-like mean?
  - What are admissible states?
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  - What are admissible states?
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- Answers probably depend on theory!
  - Here: Path-integral version of Einstein Hilbert, assuming its existence and equivalence to CDT
- Take a cue from experiment
  - “Propagating, massive particle” is a useful concept over many orders of magnitude

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- Hints for a geon from CDT
  - Particle-like, potentially massive

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- Hints for a geon from CDT
  - Particle-like, potentially massive
- Spin and supergravity

Setup

- QFT setting – no strings or other non-QFT structures

Setup

$$Z = \int_{\Omega} Dg_{\mu\nu} D\phi^a e^{iS[\phi, e] + iS_{EH}[e]}$$

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- QFT setting – no strings or other non-QFT structures
- Diffeomorphism is like a gauge symmetry [Hehl et al.'76]
    - Arbitrary local choices of coordinates do not affect observables – pure passive formulation

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- Integration variable currently arbitrary choice
  - Manifold topolgies when factoring out diffeomorphisms
  - Other choices (e.g. vierbein) possible when integrating over diffeomorphism orbits

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Standard gravity coupling

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Other fields

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- Integration variable currently arbitrary choice
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- Setup of FRG/Asymptotic safety, CDT, EDT

Dynamical formulation

$$\langle O \rangle = \int_{\Omega} Dg_{\mu\nu} D\phi^a O\, e^{iS[\phi,e]+iS_{EH}[e]}$$

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Needs to be invariant

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- Locally under Diffeomorphism
- Locally under Lorentz transformation

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- Locally under Diffeomorphism
- Locally under Lorentz transformation
- Locally under gauge transformation
- Globally under custodial,… transformation

to be non-zero

Observables

[Ambjorn et al.'12,19, Maas'19]

- Average metric vanishes: $\langle g_{\mu\nu}(x) \rangle = 0$
  - No preferred events, maximally symmetric

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  - Average space-time is an observation from invariants like the curvature scalars
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    - E.g. again curvature scalars
  - Arguments/distances need to be invariants
    - E.g. geodesic distances [Ambjorn et al.'12, Schaden '15, Maas'19]

Space-time structure

[Maas'19]

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$$\frac{\langle \int d^d x \sqrt{\det g}\, R(x)\rangle}{\langle \int d^d x \sqrt{\det g}\rangle} = const$$

- No preferred events
  - Space-time on average homogenous and isotropic
  - Relevant space-time is flat or (anti-)de Sitter for Einstein-Hilbert gravity
  - Invariants identify the particular type

Simpelst object: Scalar

- Consider a scalar particle
  - E.g. described by a scalar field
  - Completely invariant

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Completely scalar: Invariant under all symmetries

- Consider a scalar particle
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Simpelst object: Scalar

Argument is the event, not the coordinate

Result depends on events

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- Consider a scalar particle
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  - Completely invariant
  - Events not a useful argument

Simpelst object: Scalar

[Ambjorn et al.'12, Schaden'15]

Some distance function

$$\langle O(x)O(y)\rangle = D(r(x,y))$$

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- Distance is a quantum object: Expectation value
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$$\langle O(x) O(y) \rangle = D(r(x,y))$$

$$r(x,y) = \langle min_z \int_x^y d\lambda \, g_{\mu\nu} \frac{dz^\mu}{d\lambda} \frac{dz^\nu}{d\lambda} \rangle$$

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Select geodesic

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$$\langle O(x) O(y) \rangle = D(r(x,y))$$

Separate calculation

$$r(x,y) = \langle min_z \int_x^y d\lambda\, g_{\mu\nu} \frac{dz^\mu}{d\lambda} \frac{dz^\nu}{d\lambda} \rangle$$

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Simpelst object: Scalar

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Reduces the full dependence: Definition
Dependence on events will only vanish if all events on the average are equal – probably true

$$\langle O(x)O(y)\rangle = D(r(x,y))$$

$$r(x,y) = \langle min_z \int_x^y d\lambda\, g_{\mu\nu} \frac{dz^\mu}{d\lambda}\frac{dz^\nu}{d\lambda}\rangle$$

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- Distance is a quantum object: Expectation value
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- Generalization of flat-space arguments

Causal Dynamical Triangulation

[Ambjorn et al.'12,19]

$$\langle O \rangle = \int_{\Omega} Dg_{\mu\nu} D\phi^a O e^{iS[\phi,e]+iS_{EH}[e]}$$

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Toplogy of manifold
– diffeomorphism invariant!

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Restricted to foliable,
pseudo-Riemannian manifolds
with fixed global structure

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[Ambjorn et al.'12,19]

$$\langle O \rangle = \sum_{\Omega} D\, d\left(X_i, Y_j\right) O\, e^{iS_{EH}[e]}$$

Replaced with a finite, discrete triangulation
by simplices – basically tetrads
(Regge calculus)

Causal Dynamical Triangulation

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Wick rotation allows use of standard Monte-Carlo (lattice) techniques

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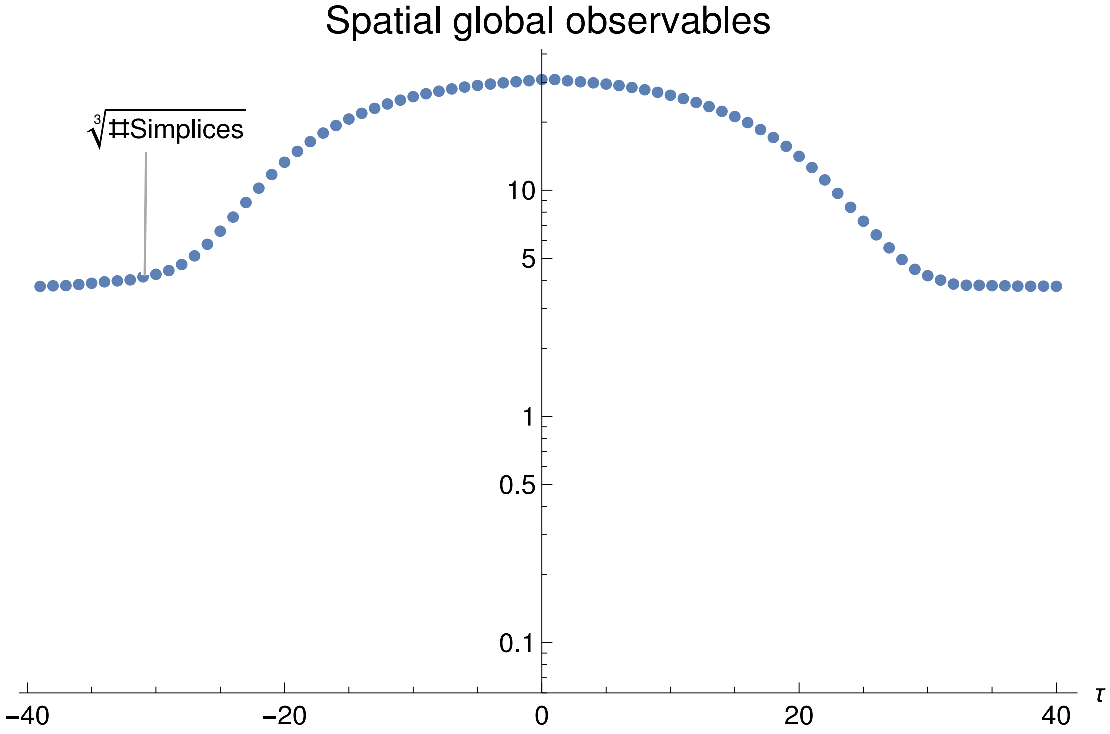
Here: Periodic in time, spatially spherical, (N_T,#Simplices)

Space-time in CDT

[Ambjorn et al.'12,'19
Maas, Plätzer, Pressler'25]



Space-time in CDT

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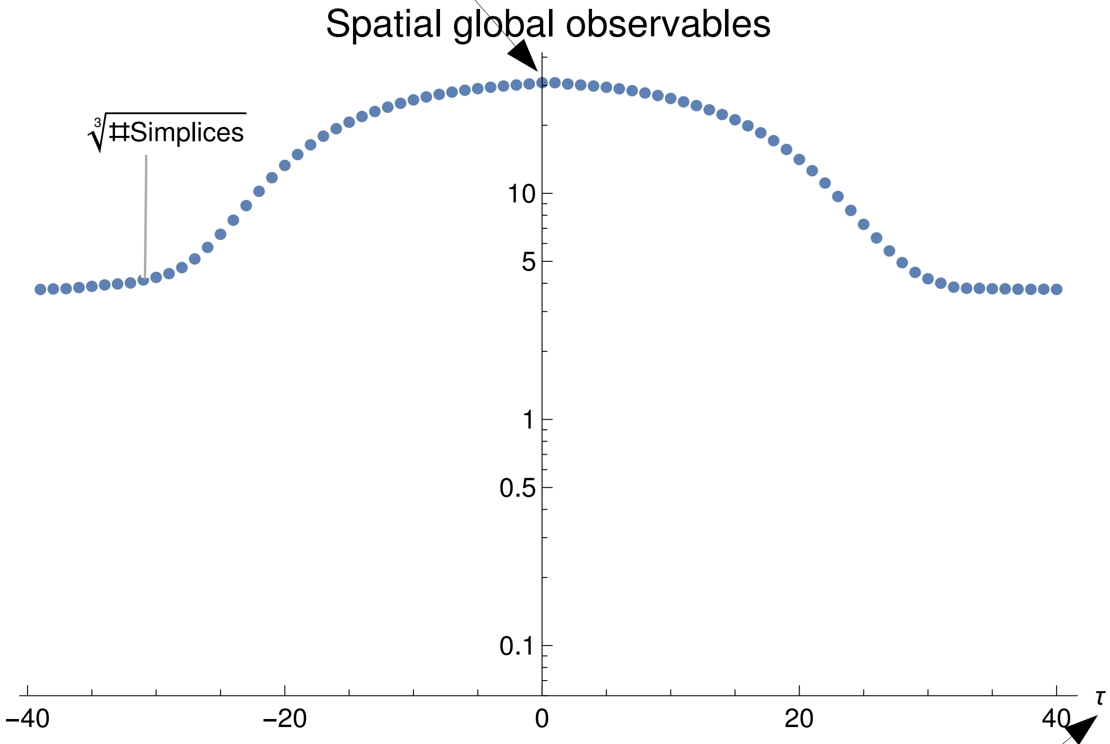
Maximum volume
constrained by finite size



Cosmological time
defined with respect
to maximal extension

Space-time in CDT

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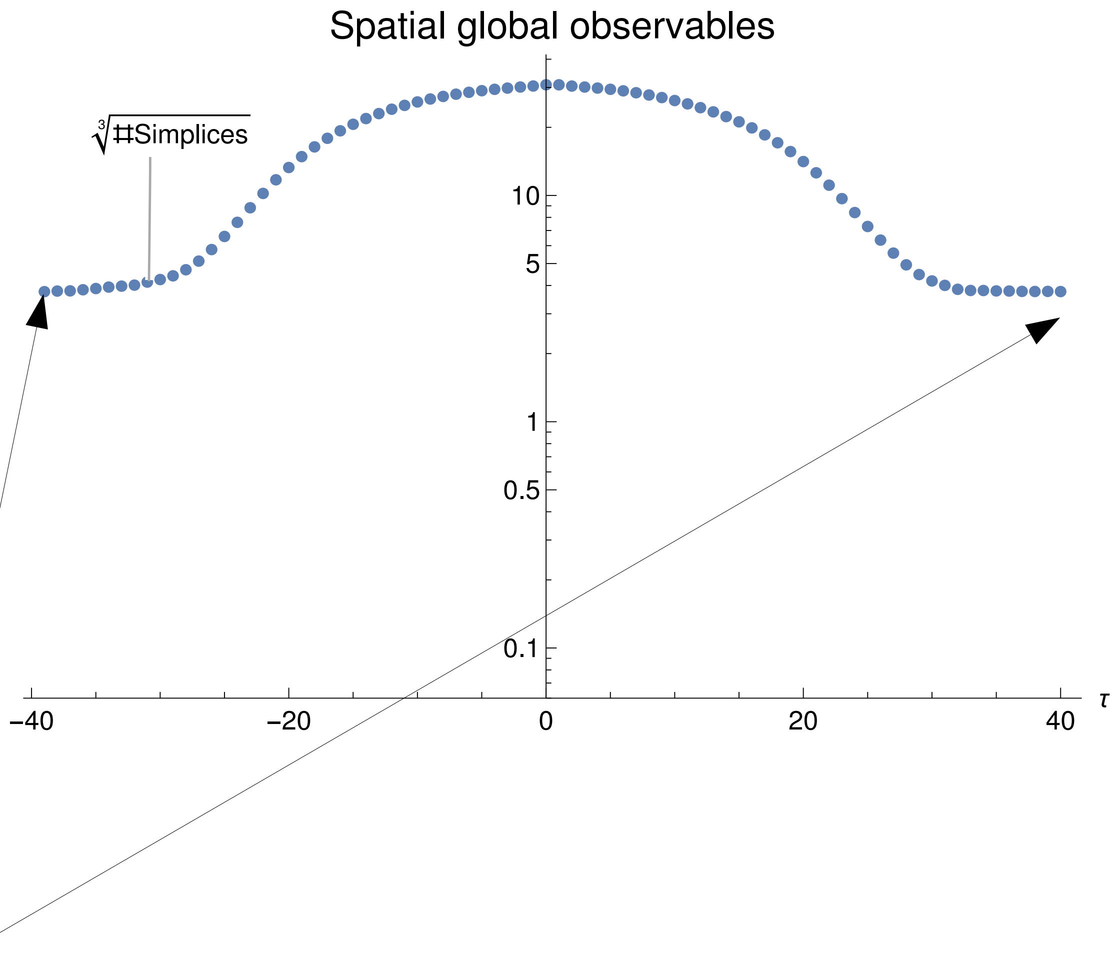

Periodicity
by boundary conditions

Space-time in CDT

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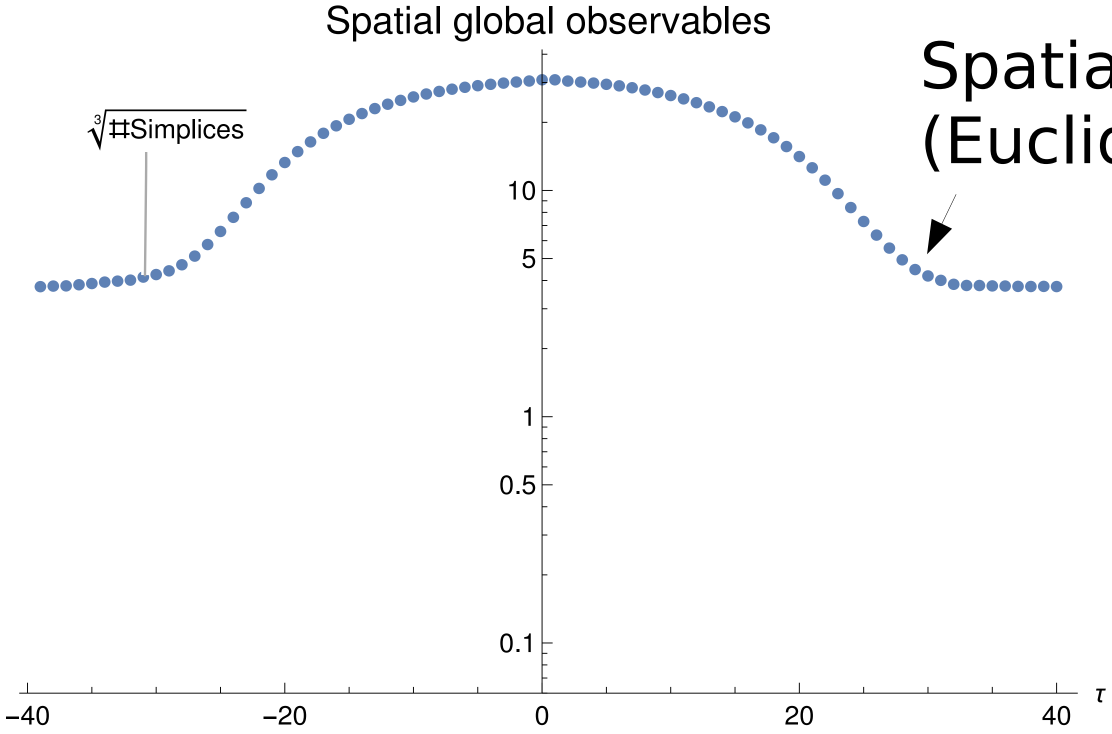

Spatial profile consistent with (Euclidean) de Sitter ~ radius

Space-time in CDT

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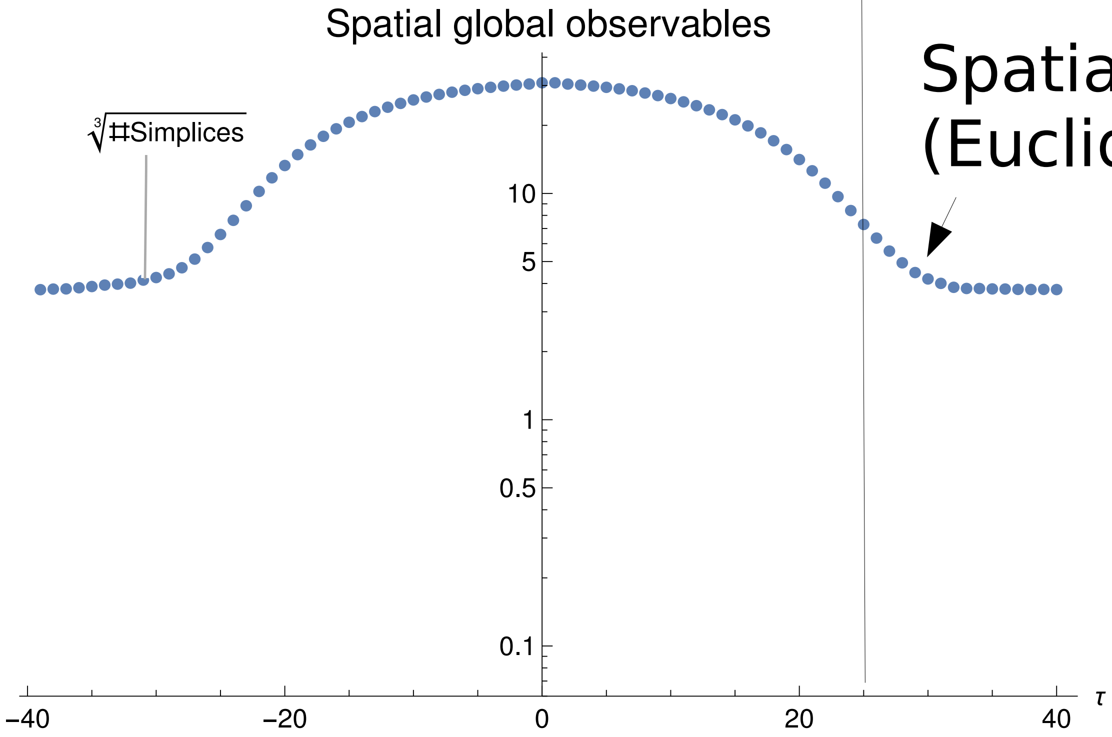
Rapid expansion

Spatial profile consistent with (Euclidean) de Sitter ~ radius



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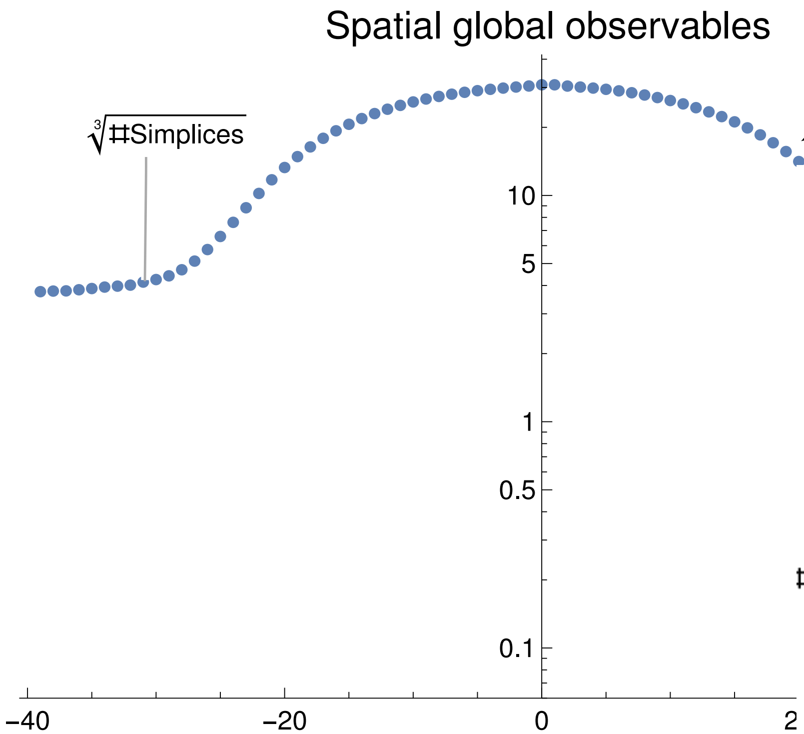
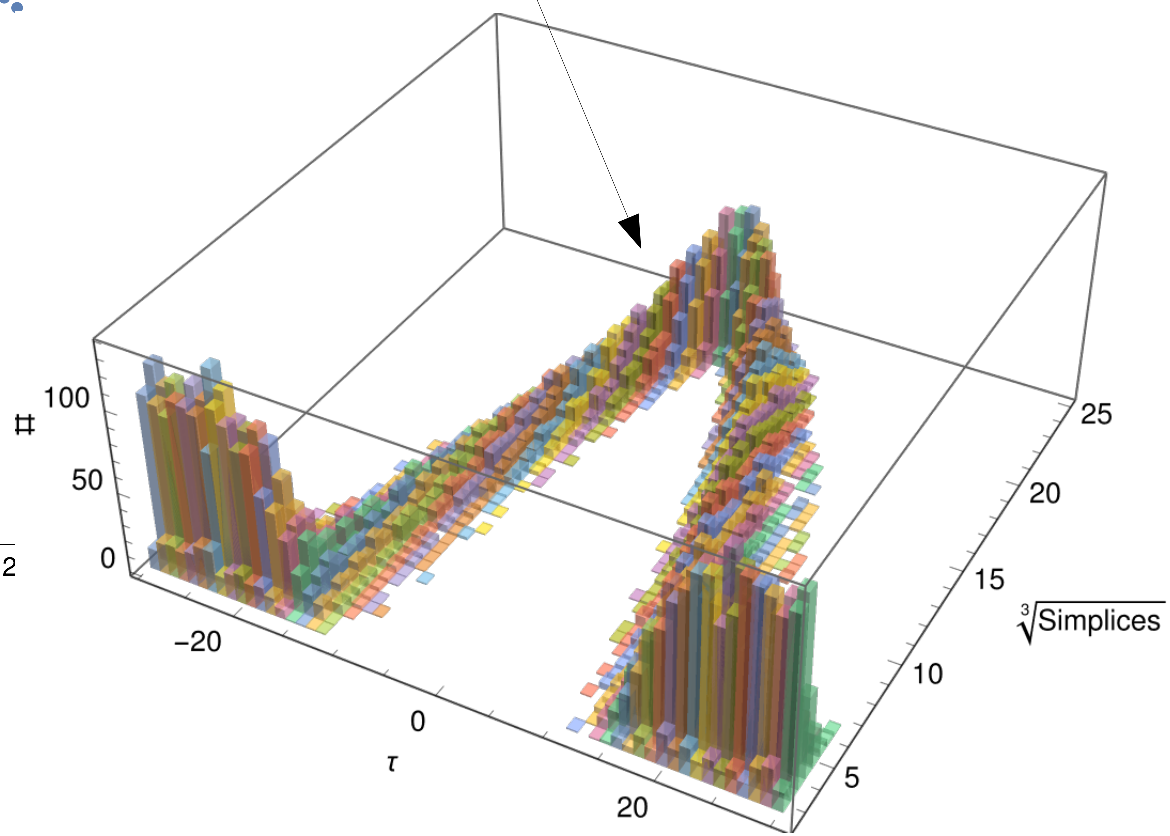
Per configuration histogram of the size
- relatively similar, no large fluctuations





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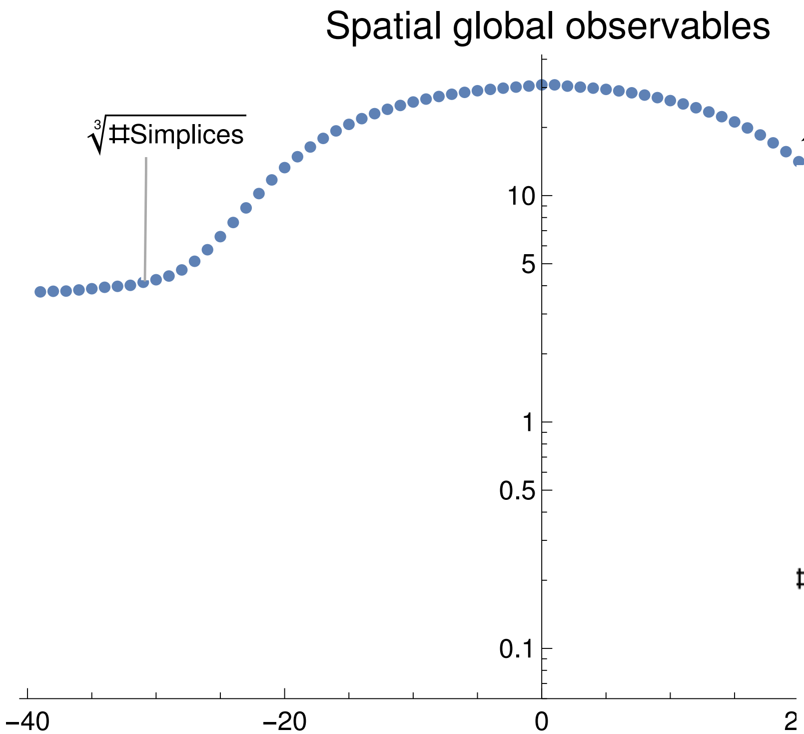

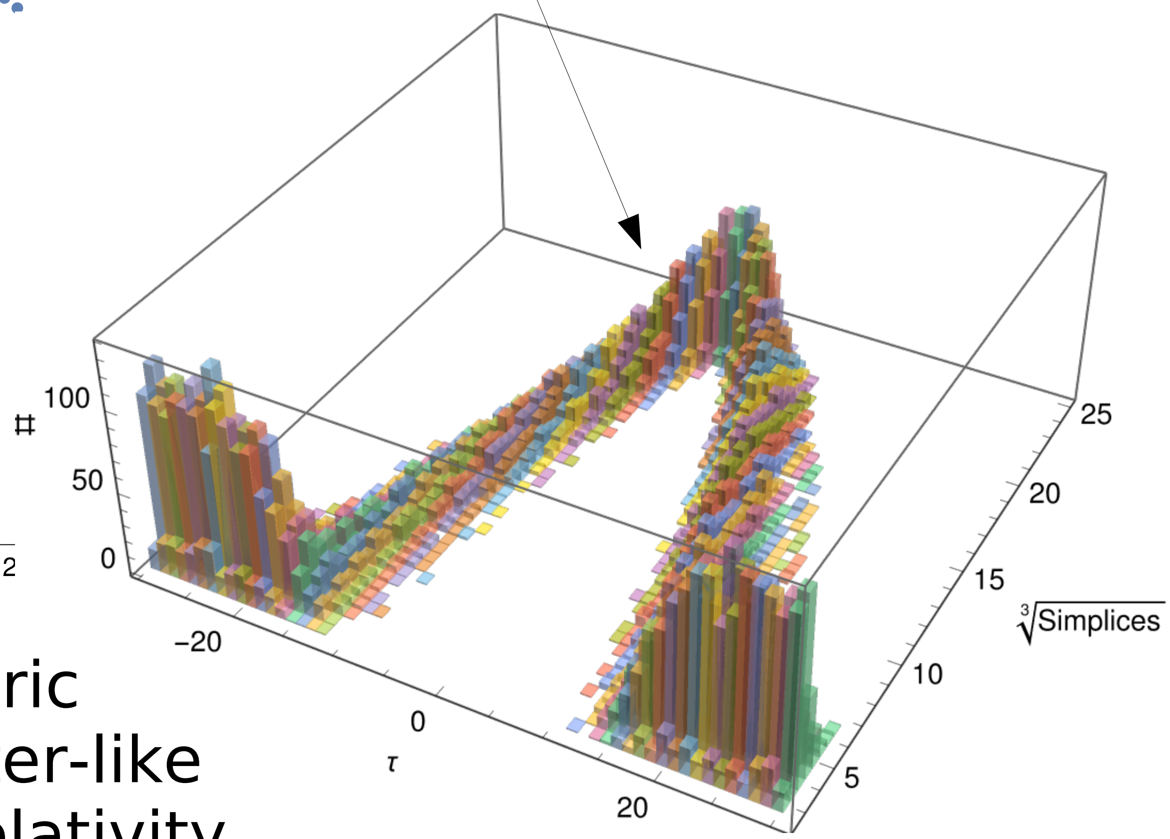

An average gauge-fixed metric would be close to the de Sitter-like
→ Like in classical general relativity

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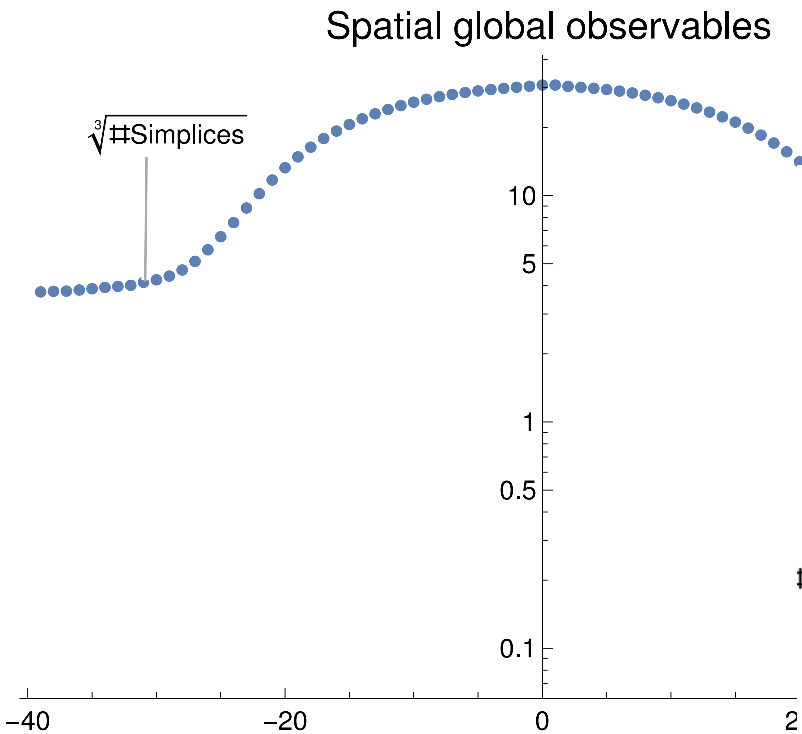

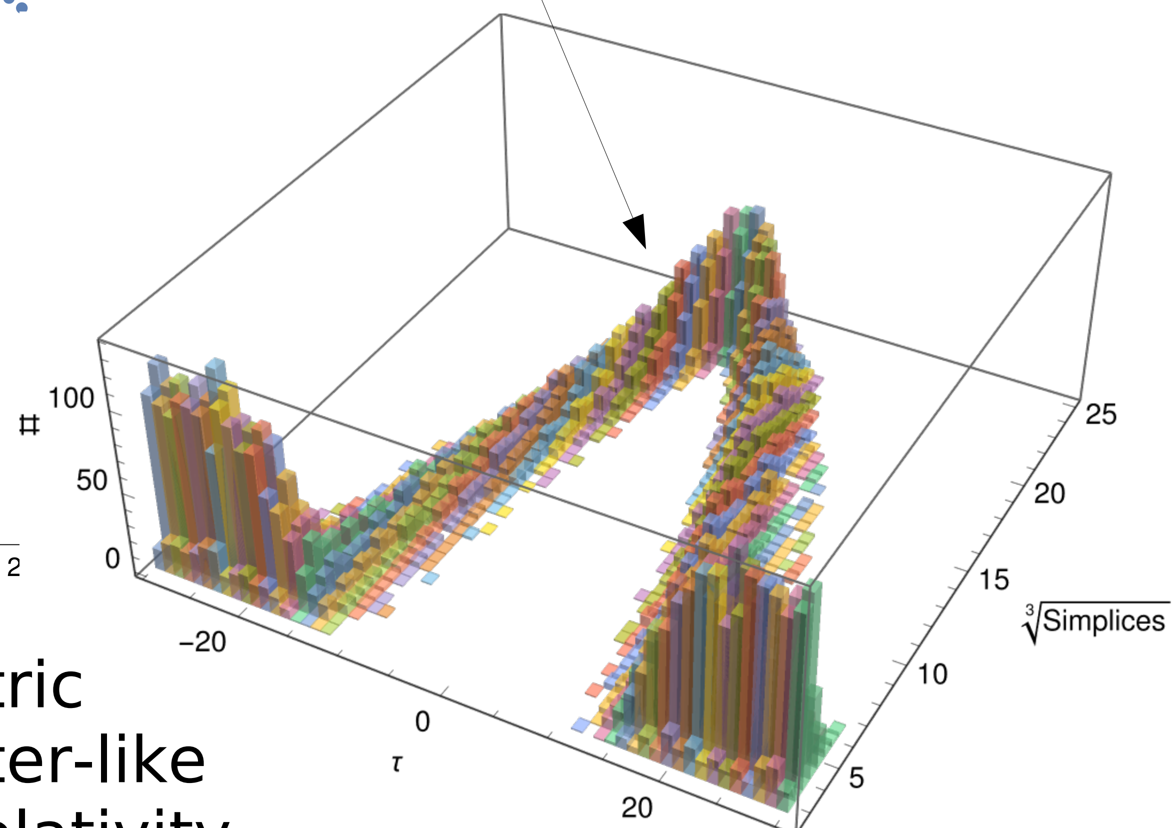

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Metric fluctuations small: Brout-Englert-Higgs effect!

Space-time in CDT

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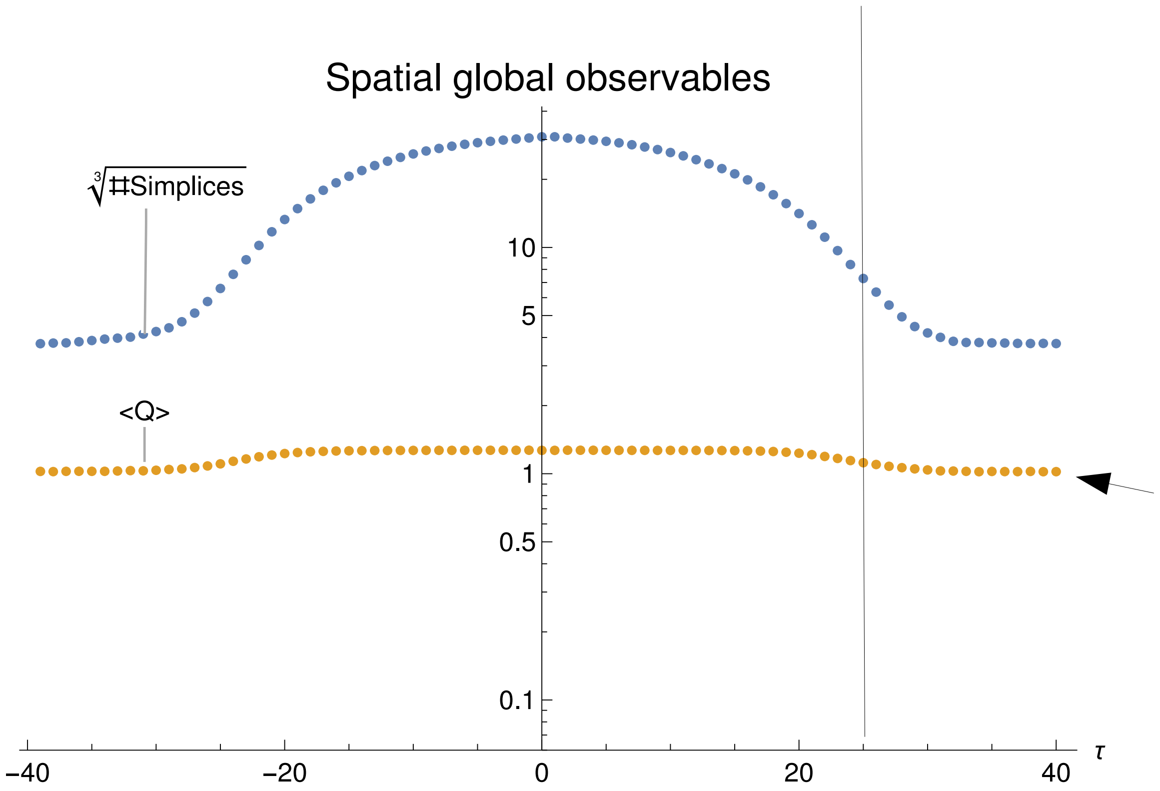
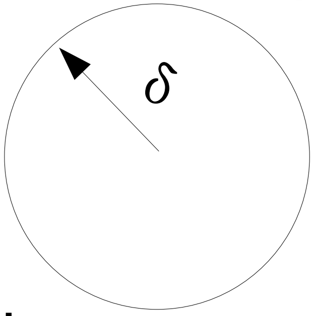


Quantum curvature Q

Basically area of surface with the same distance to a point



Can be compared to flat-space sphere

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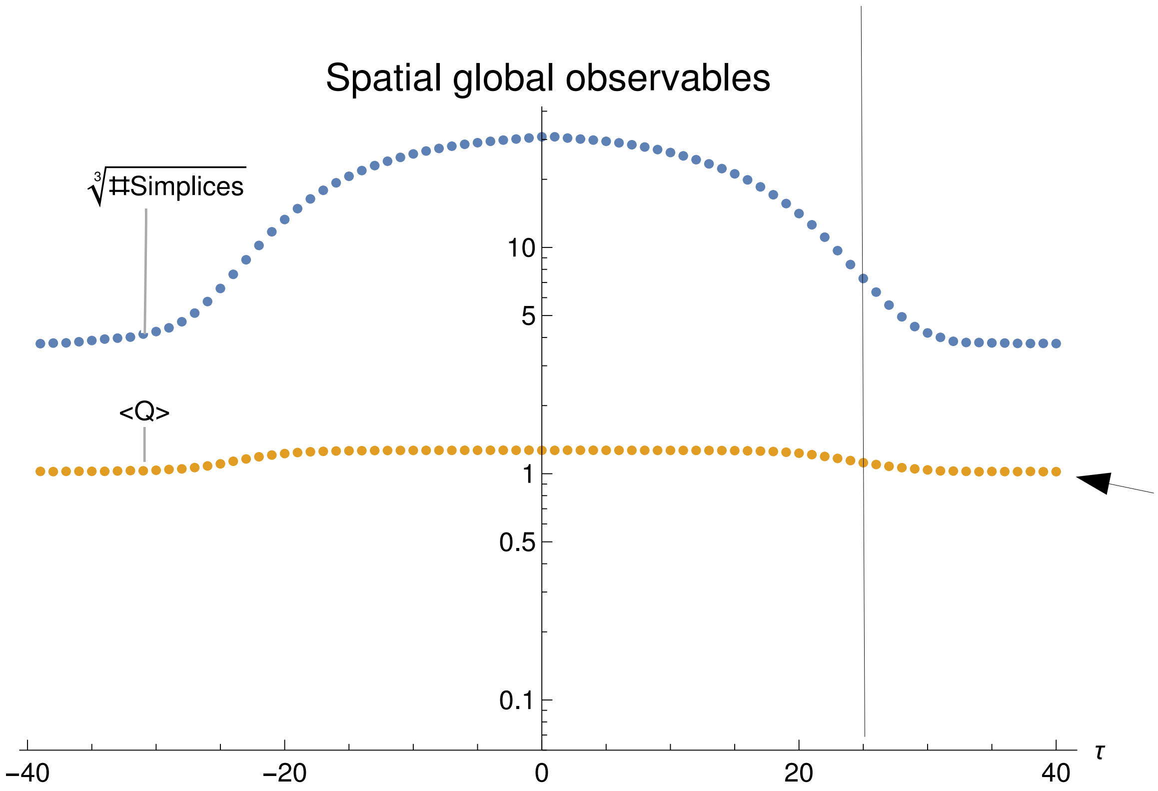

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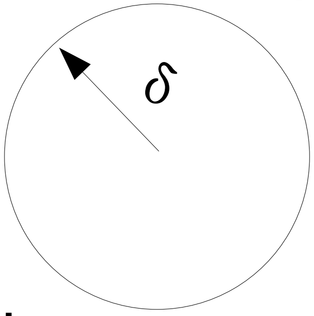

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Continuum limit:

$$Q=q_1-\delta^2 q_2 R+O(\delta^3)$$

Curvature scalar as physical information

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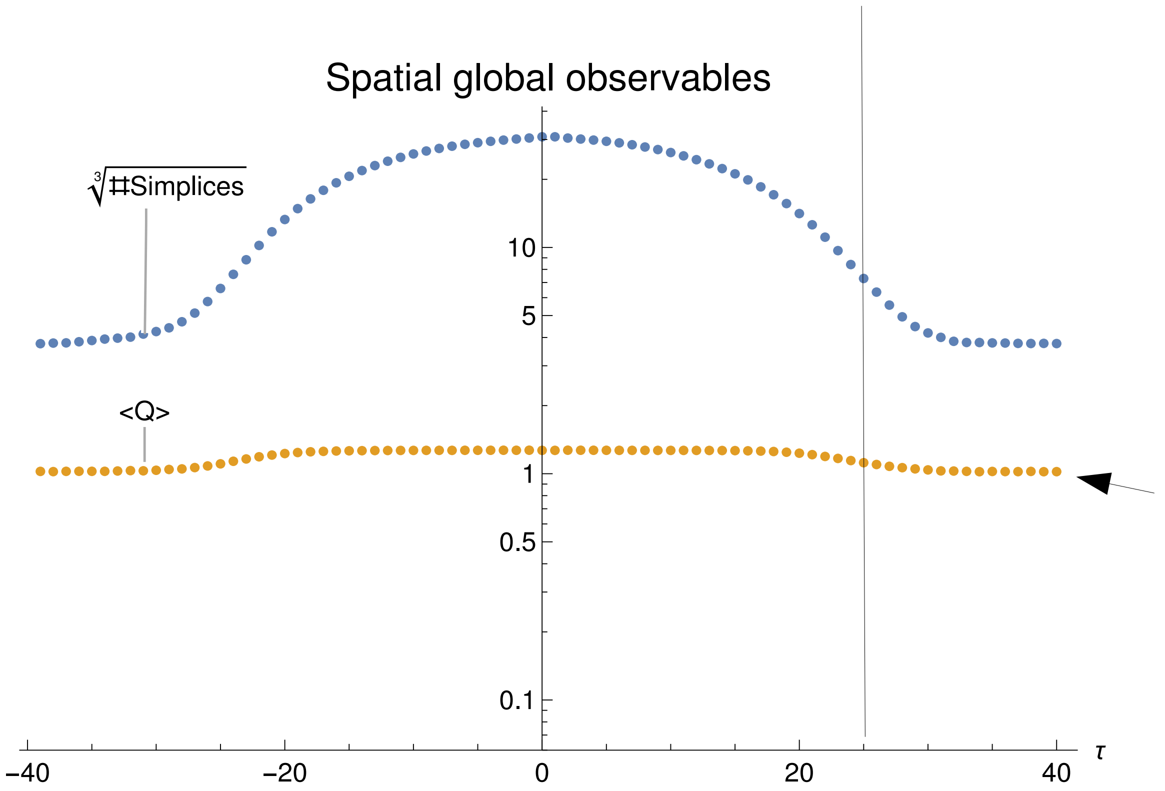

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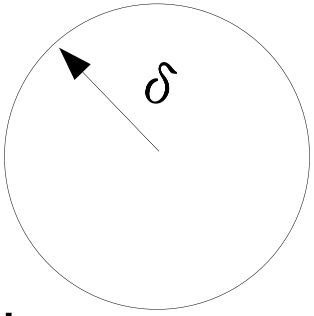

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Here: $\delta = 6a$

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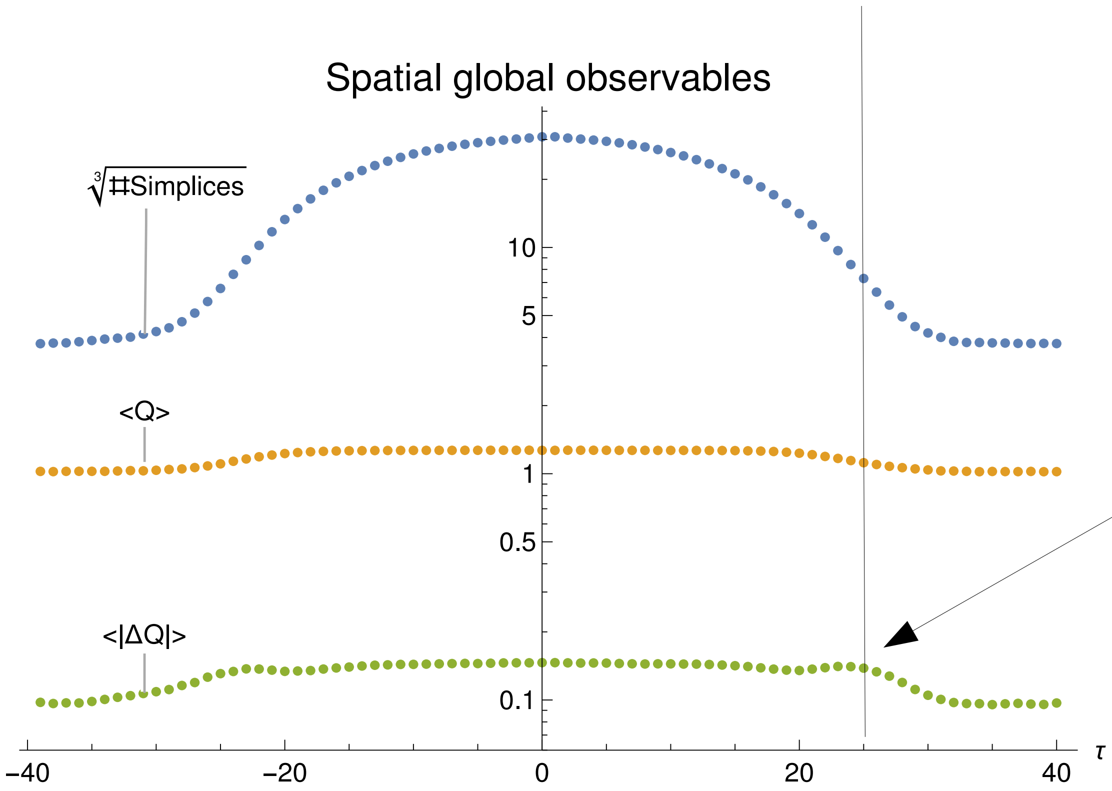

Quantum curvature fluctuations peak around fastest expansion

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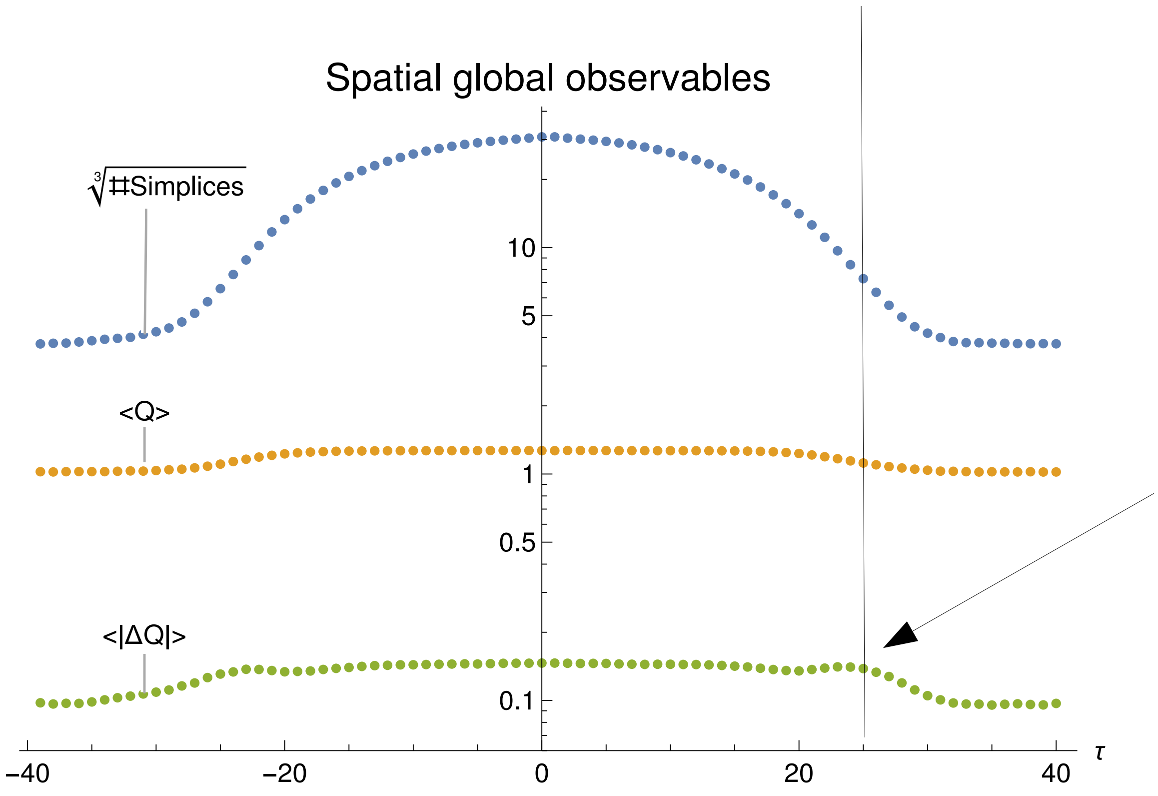

Quantum curvature fluctuations peak around fastest expansion

Only cosmological constant, no inflation!

What about cosmology?

[Maas et al.'22]

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$$\langle O(x)P(x)\ldots Q(y_1)\ldots R(y_n)\rangle$$

  - Originate at same event: Big bang
  - Distances between x and y_i future time-like
  - Distances between y_i space-like
  - Evolution of a matter/curvature concentration

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    - Preceived life-time in an eigenframe at one y_i
  - A universe is a scattering process

Particles

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  - Independent of operators

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  - Use the BEH effect to do so

Fröhlich-Morchio-Strocchi mechanism

[Fröhlich et al.'80,'81
Review: Maas'17]

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- Fröhlich-Morchio-Strocchi mechanism
  - Expand expectation values in quantum fluctuations
    - Not a background field approach
  - Suppression for more fluctuation fields expected
  - Works well in flat-space quantum field theory

Applying FMS to gravity

- CDT universe is well-approximated by a classical metric
  - Due to the parameter values – special!
  - Small quantum fluctuations at large scales
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- FMS split after (convenient) gauge fixing
  - $g_{\mu\nu} = g^c_{\mu\nu} + \gamma_{\mu\nu}$
  - Classical part g^c is a metric, chosen, e.g., to give exact (observed) curvature
  - Quantum part is small

Details (and challenges)

[Maas et al.'22]

- Classical metric needs to be useful
  - Should not have special events
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  - Simple choice: Haywood gauge $g^{\mu\nu}\partial_\nu g_{\mu\rho}=0$
  - Inverse fluctuation satisfies Dyson equation

$$\gamma^{\mu\nu}=-\left(g^c\right)^{\mu\sigma}\gamma_{\sigma\rho}\left(\left(g^c\right)^{\rho\nu}+\gamma^{\rho\nu}\right)$$

  - Infinite series at tree-level

Distance

$$r(x,y) = \langle min_z \int_x^y d\lambda \, g_{\mu\nu} \frac{dz^\mu}{d\lambda} \frac{dz^\nu}{d\lambda} \rangle$$

- Application to distance between two events

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Quantum corrections

- Application to distance between two events
  - Yields to leading order classical distance
    - Yields at leading-order classical space-time
  - Quantum corrections depends on events

Propagators

[Maas'19]

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Leading term is
flat space propagator

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[Maas et al.'22]

- Pure gravity excitation: Curvature-curvature correlator: Geon

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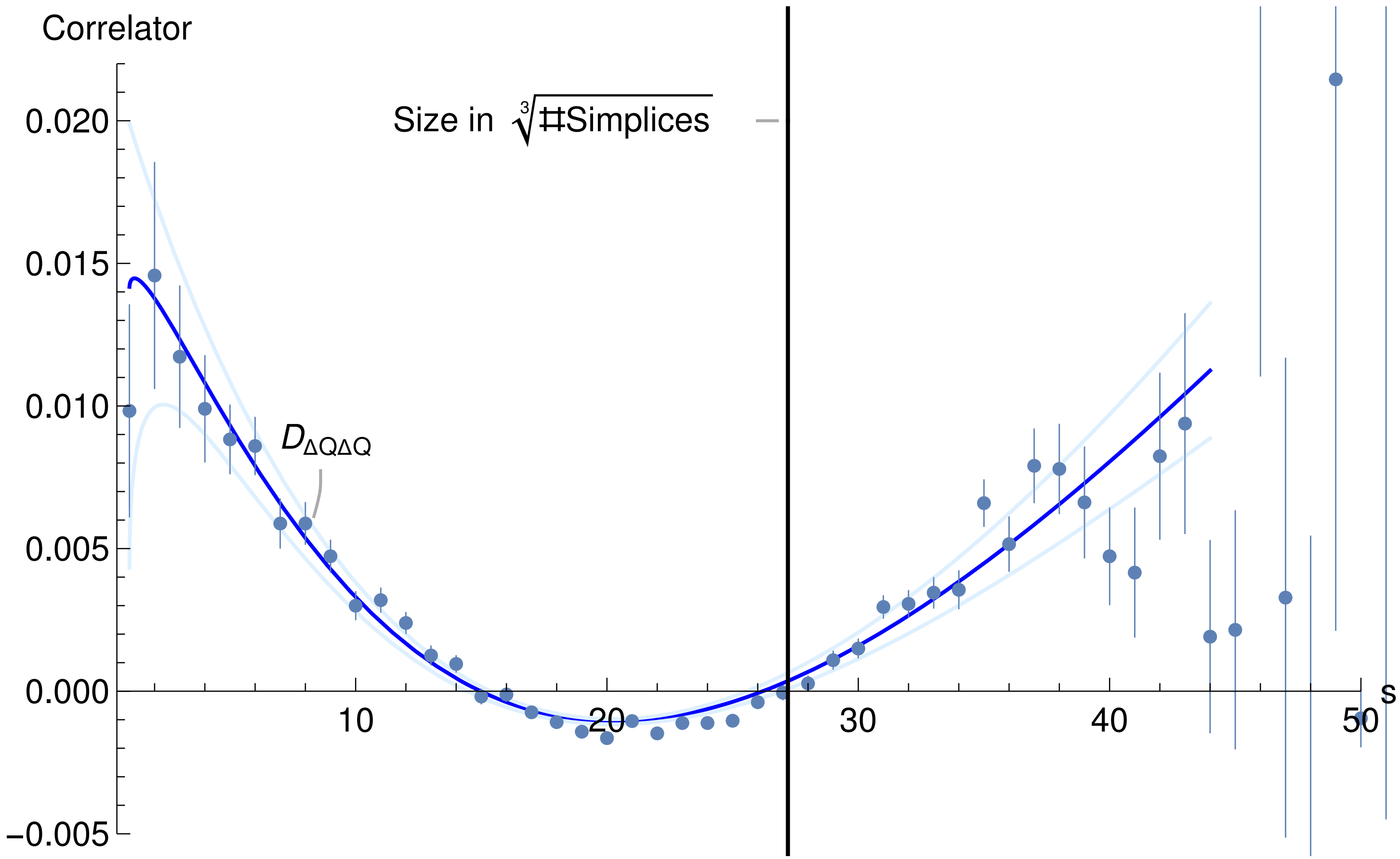

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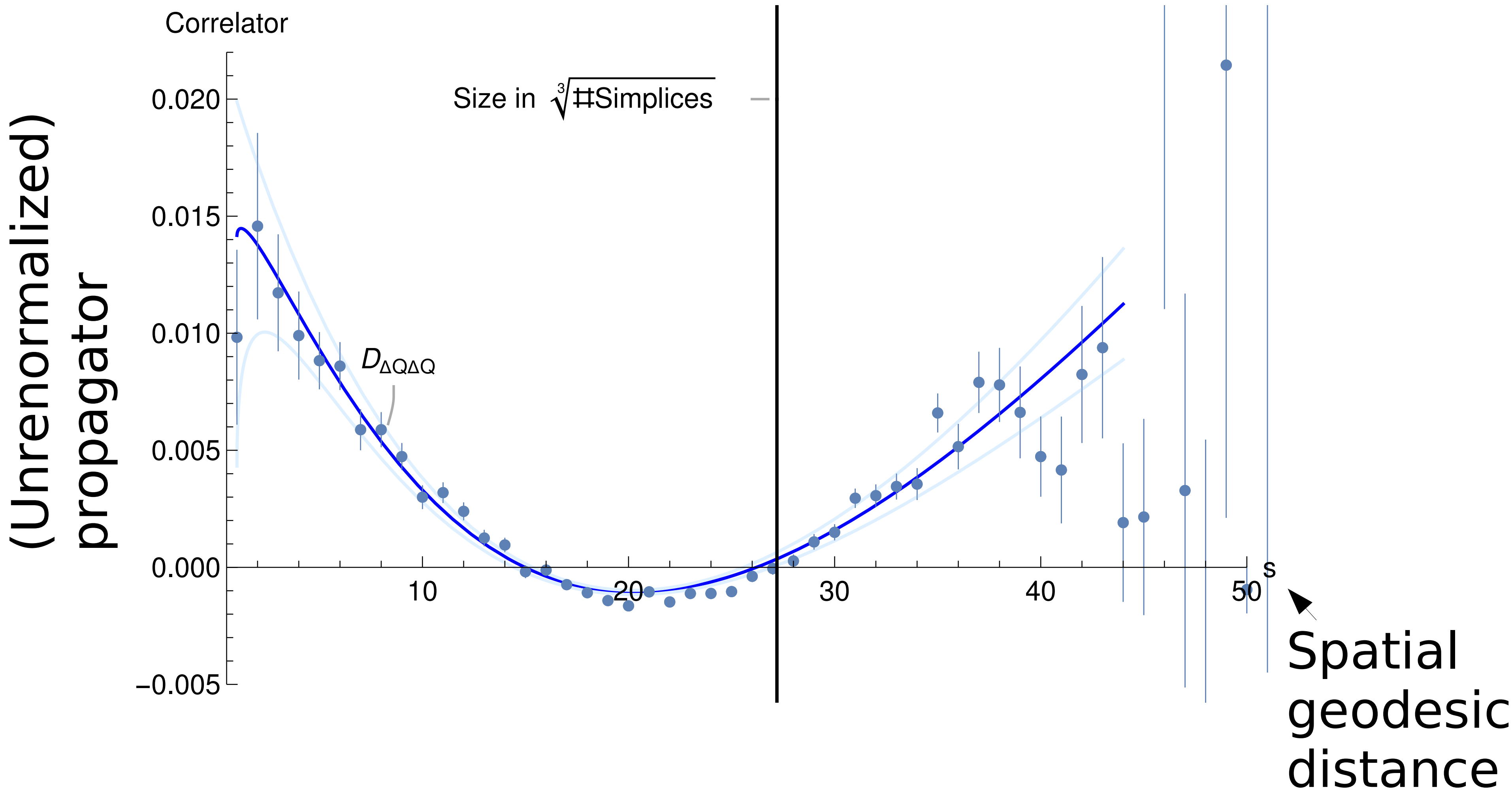

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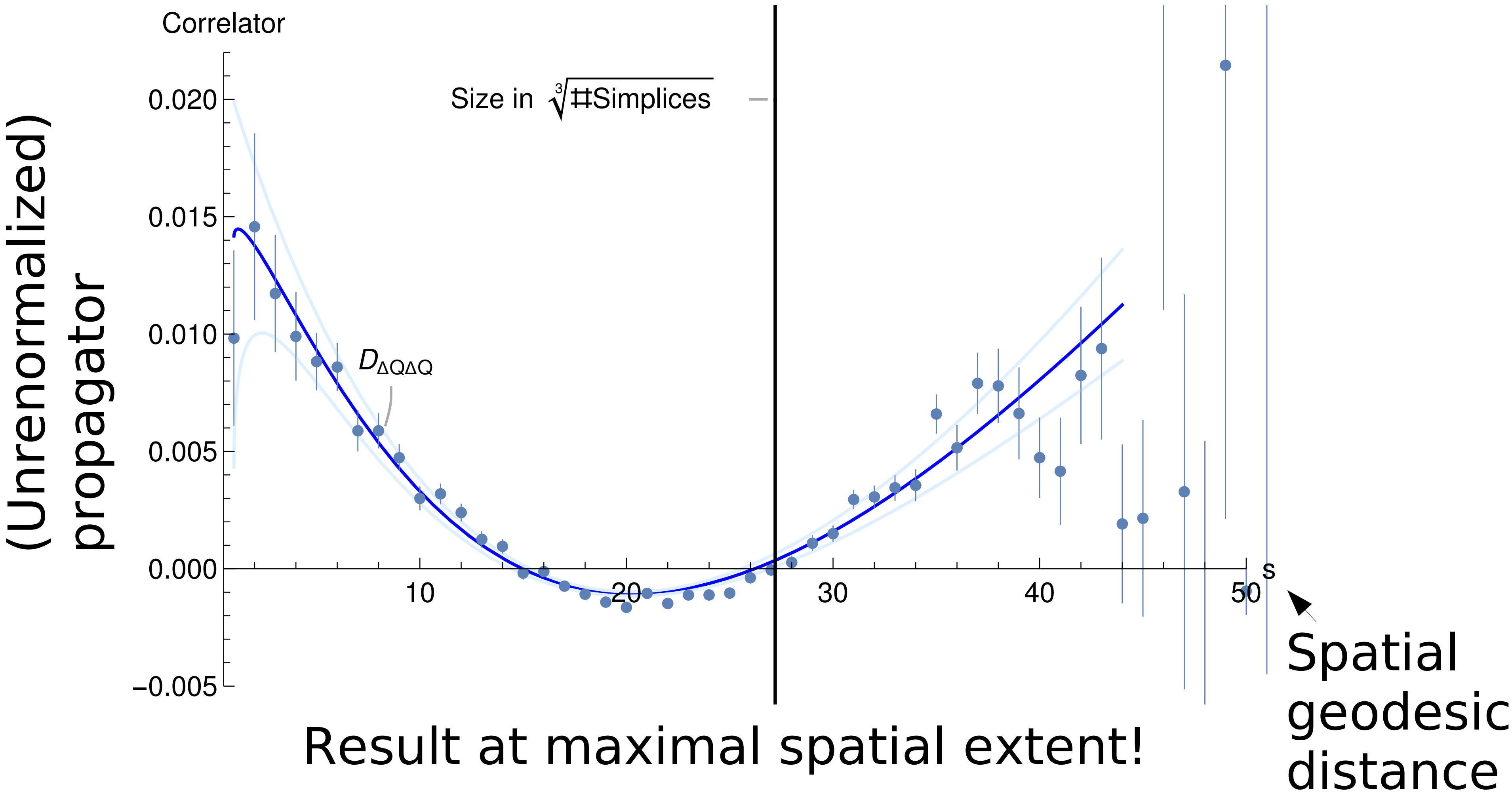

Result at maximal spatial extent!

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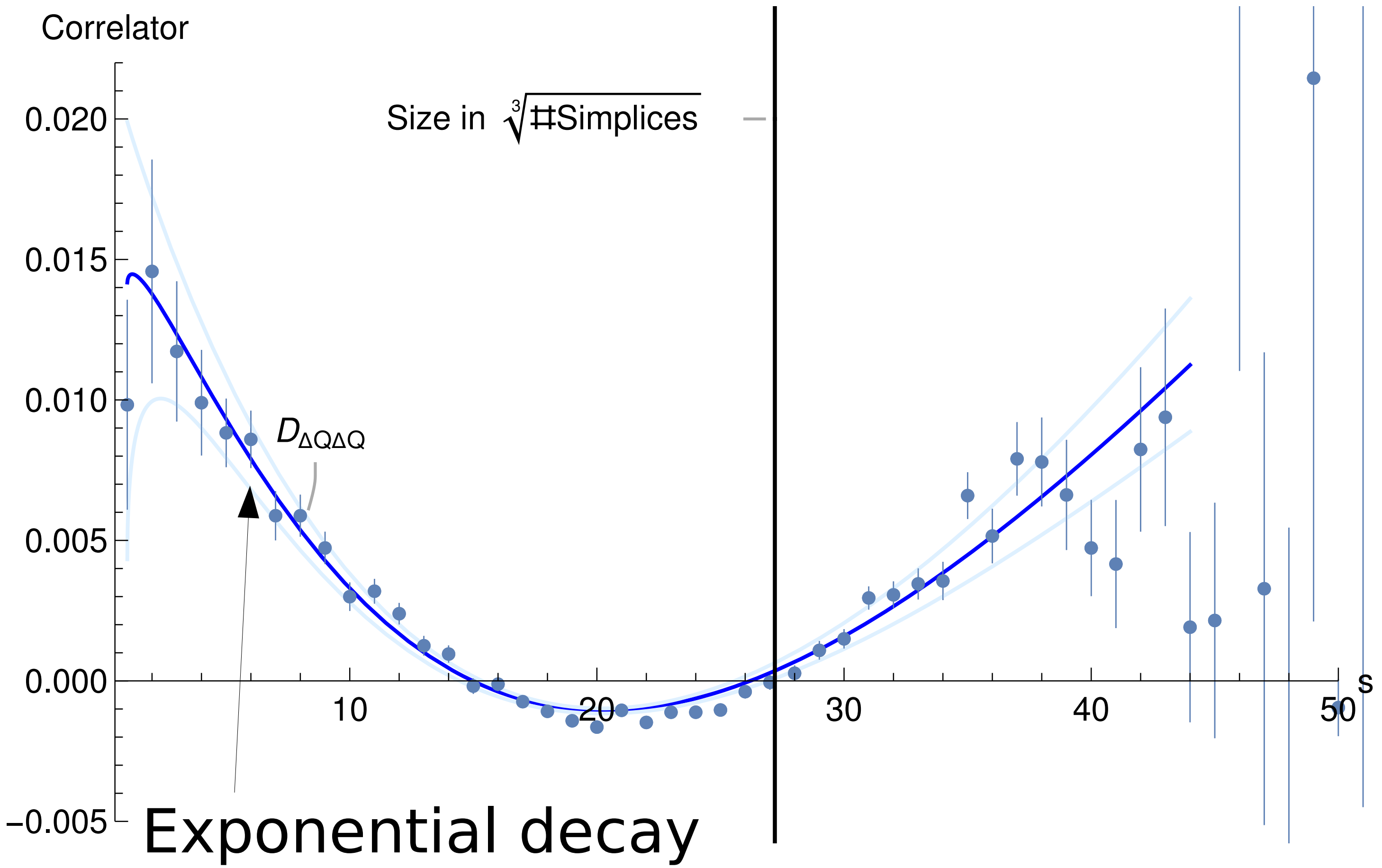

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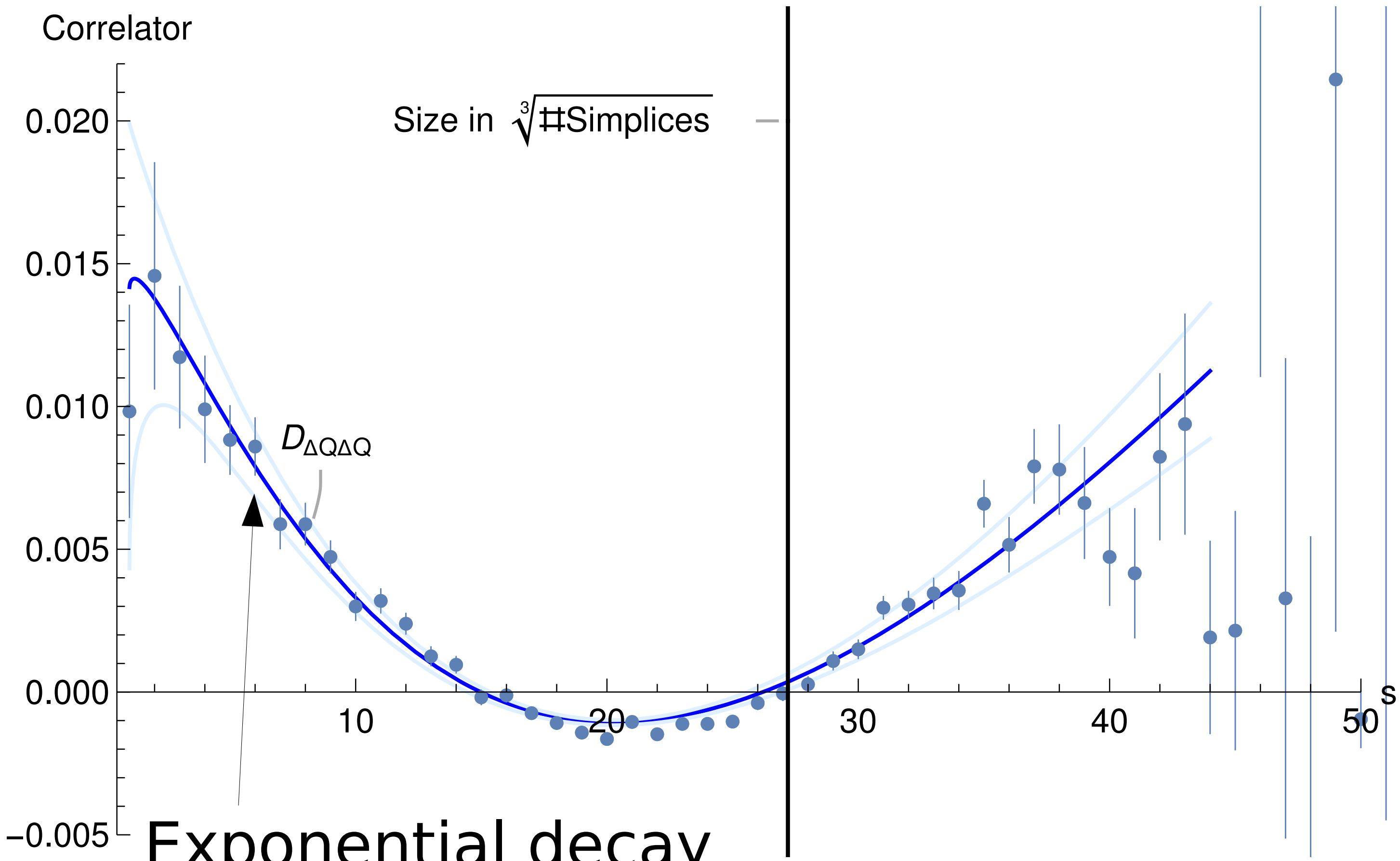

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- as in flat space-time for a massive particle

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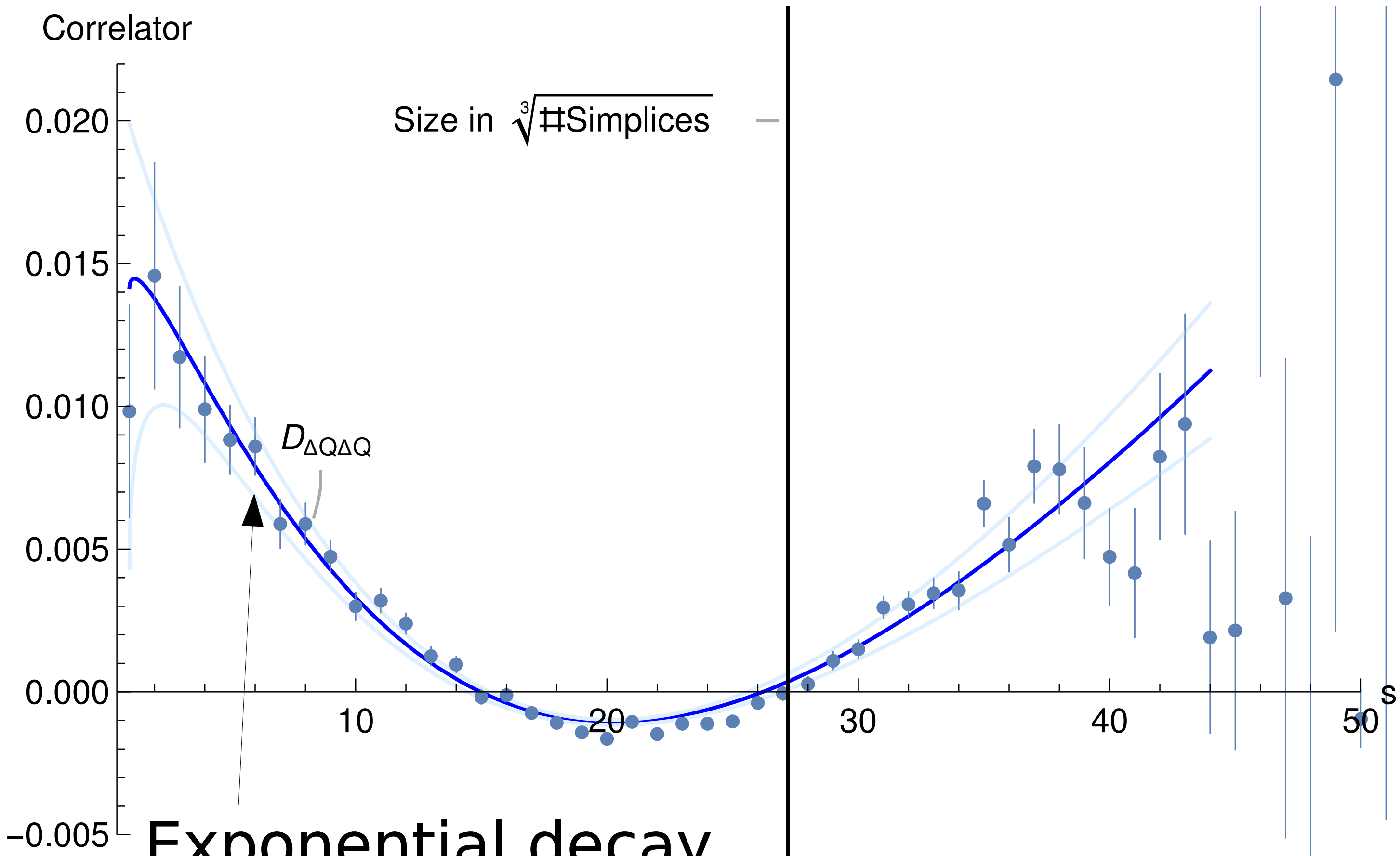

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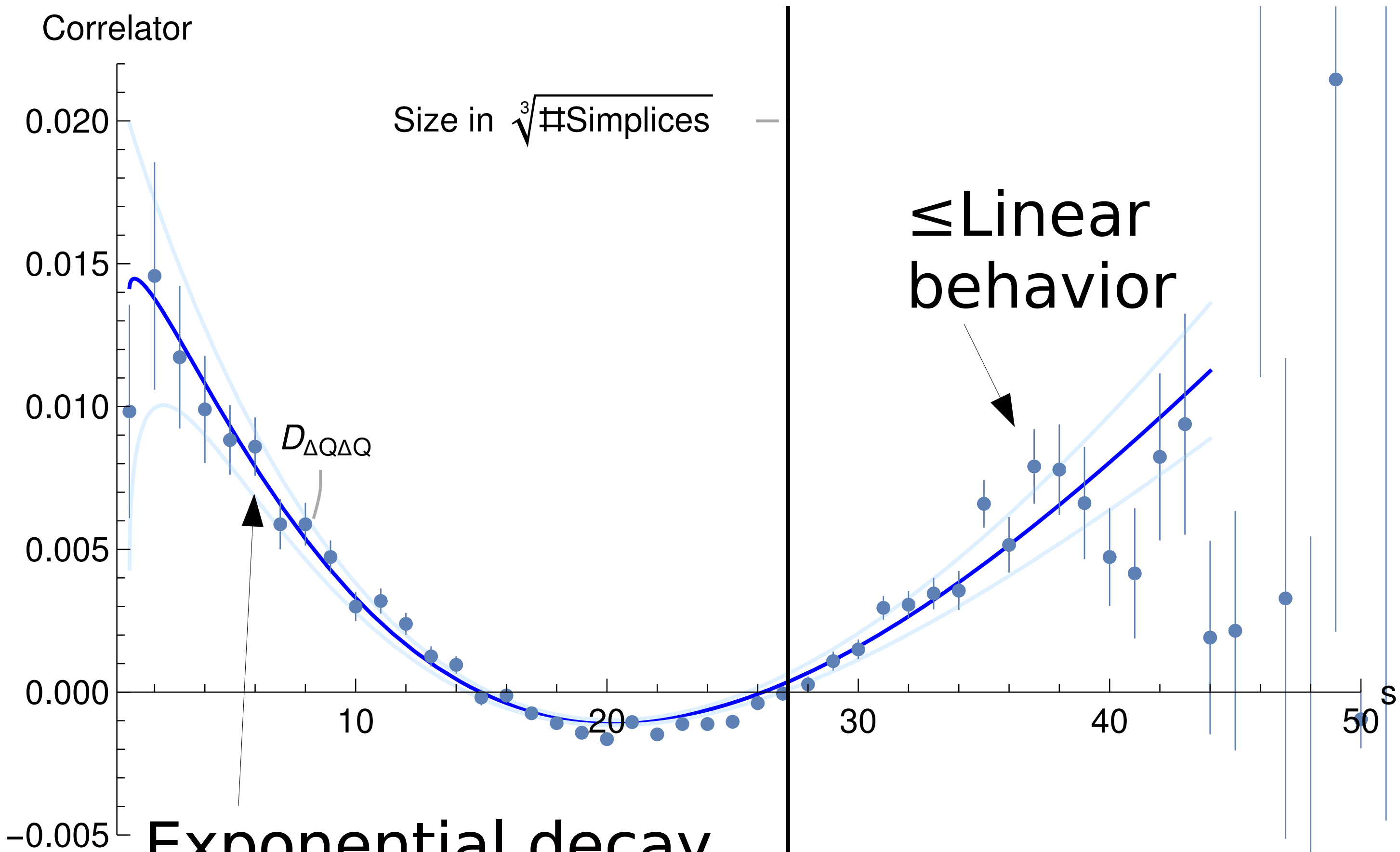

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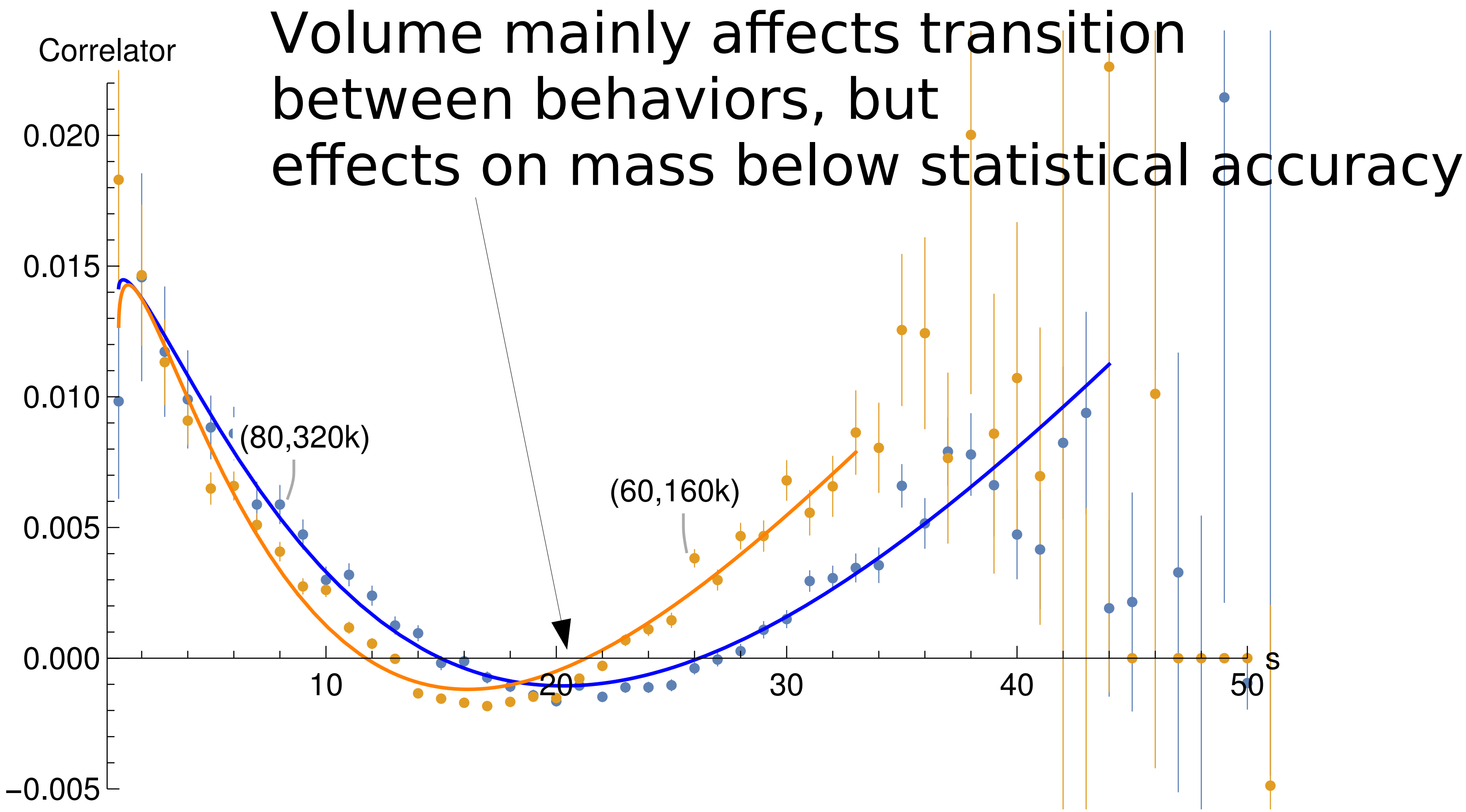

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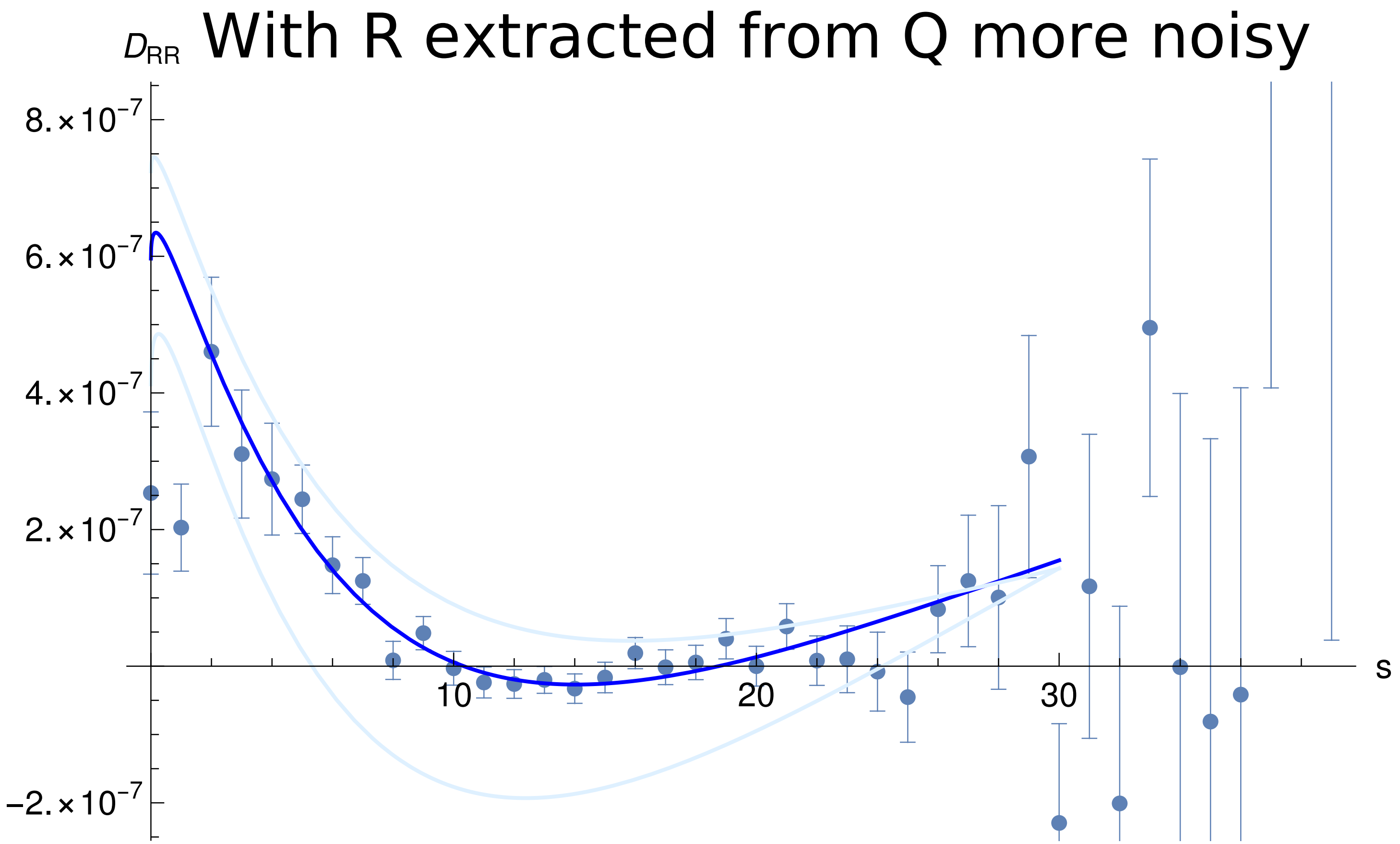

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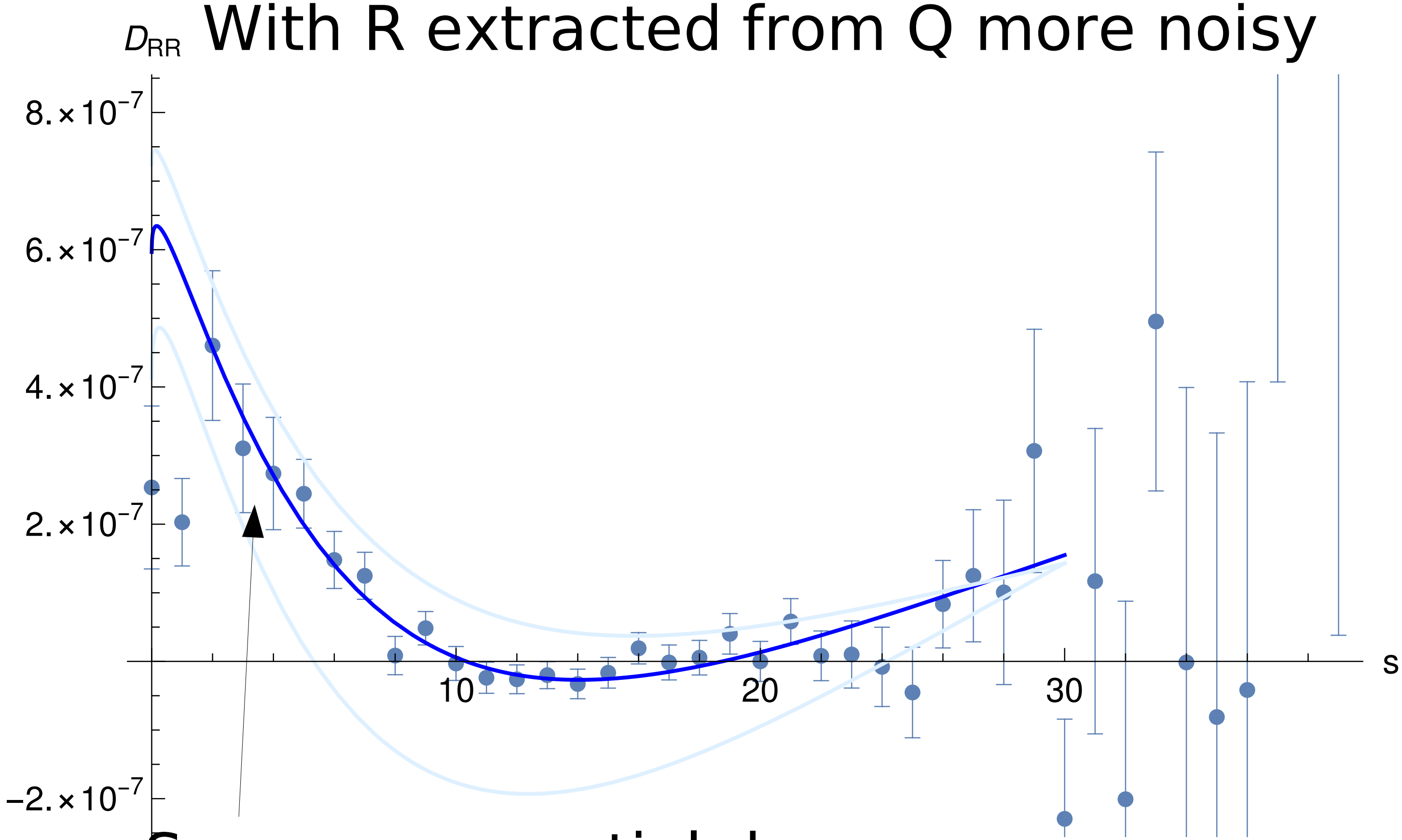
With R extracted from Q more noisy



Same exponential decay
Smaller volume: Earlier zero crossing

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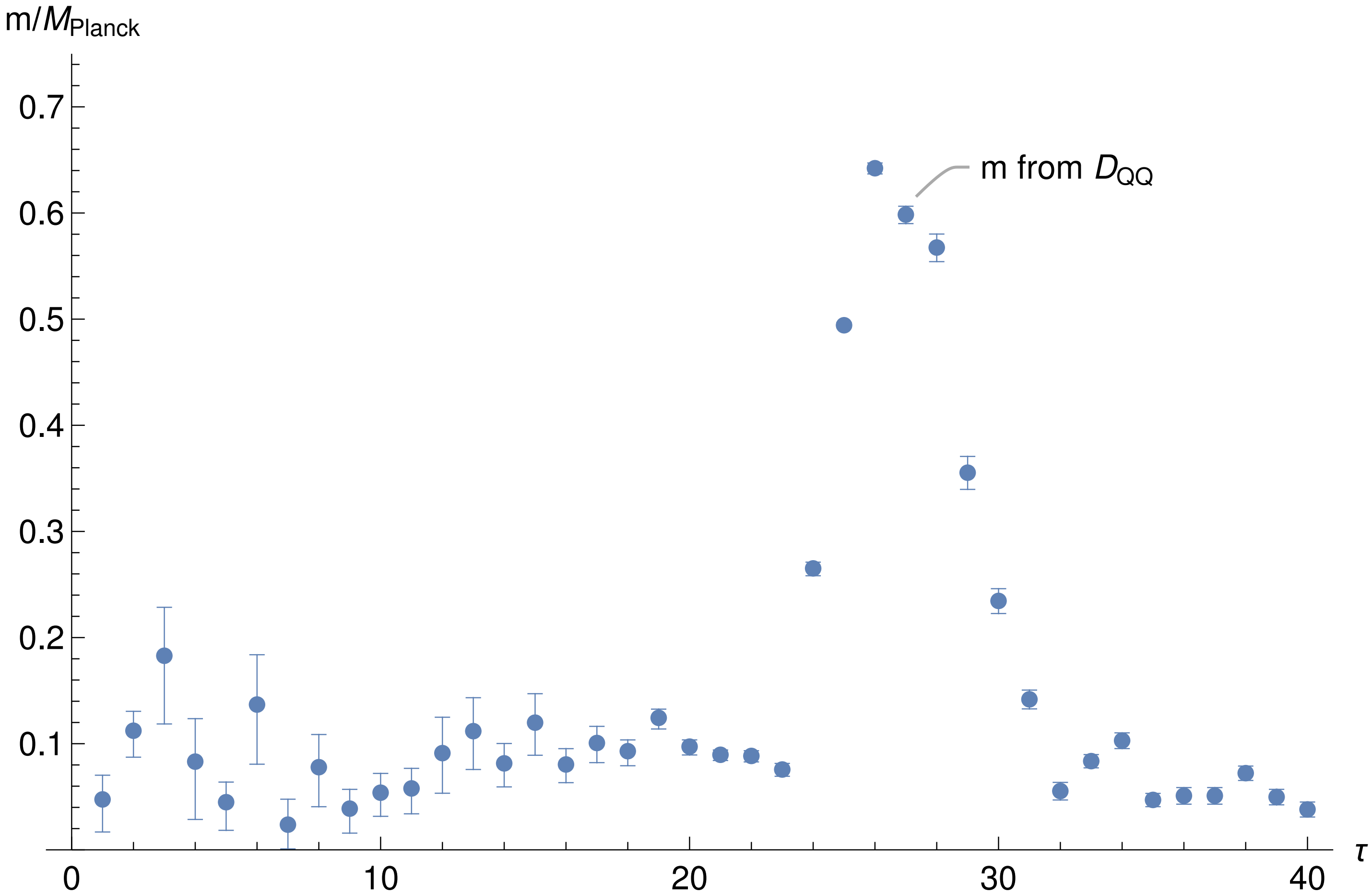

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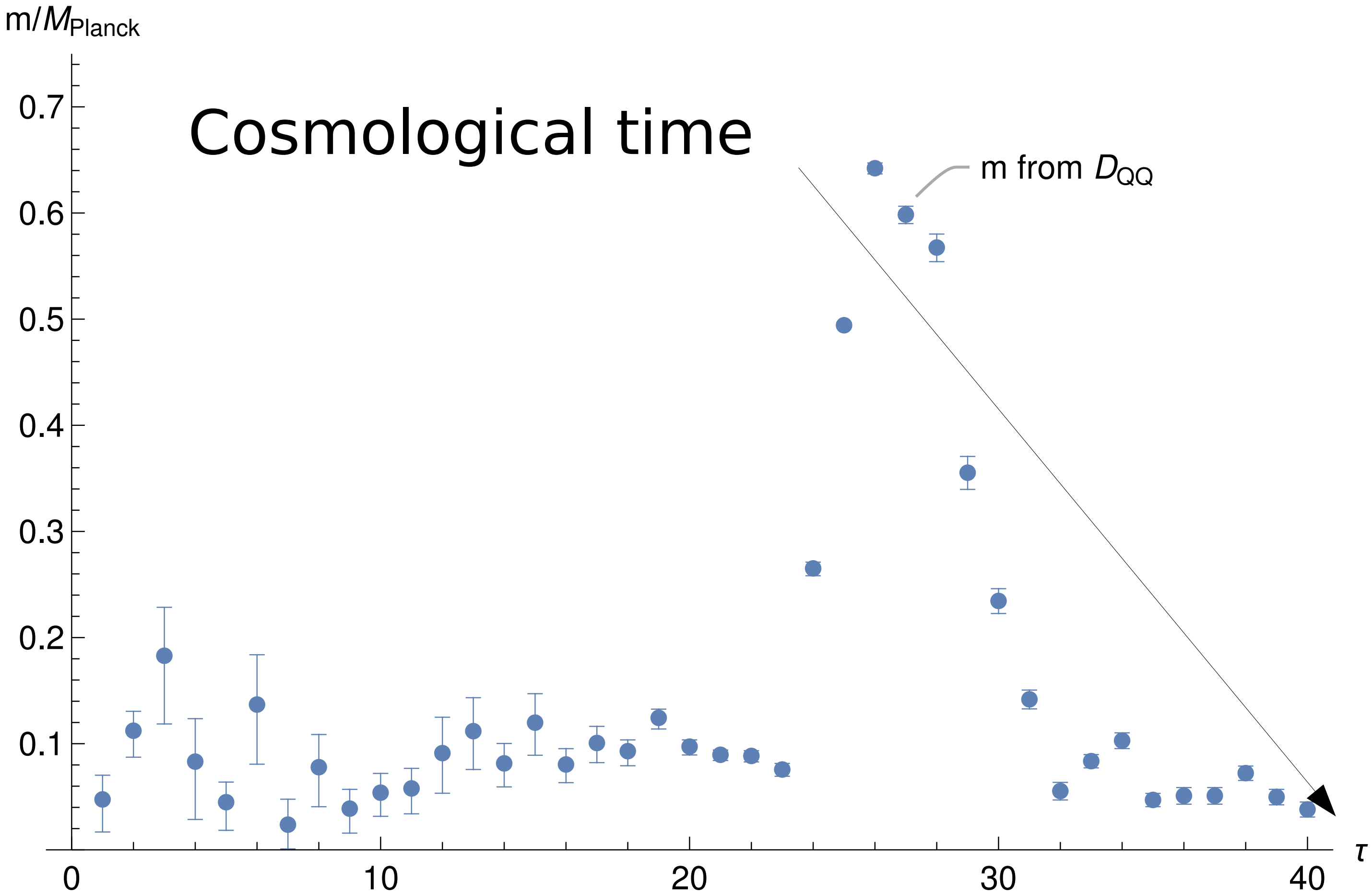

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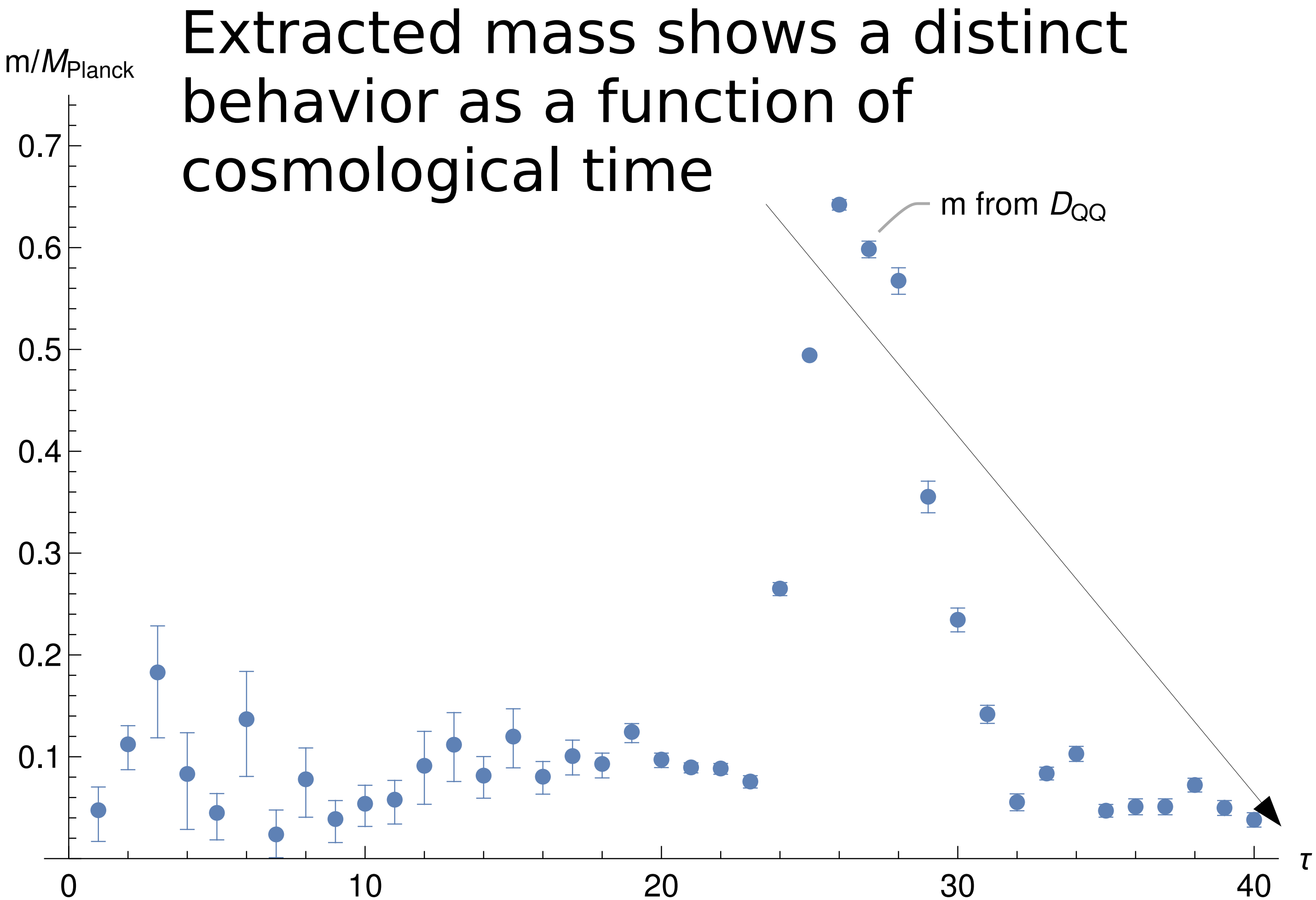

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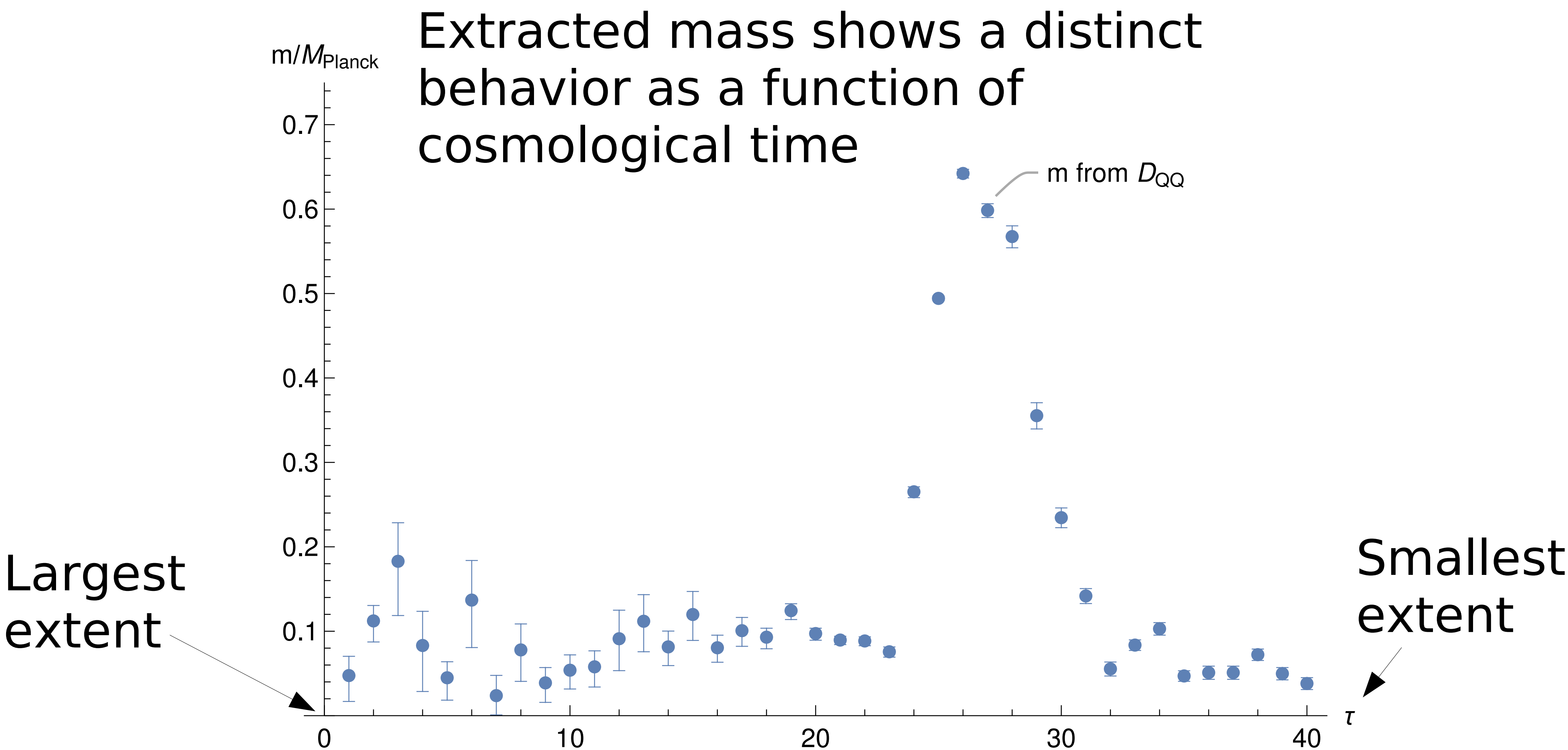

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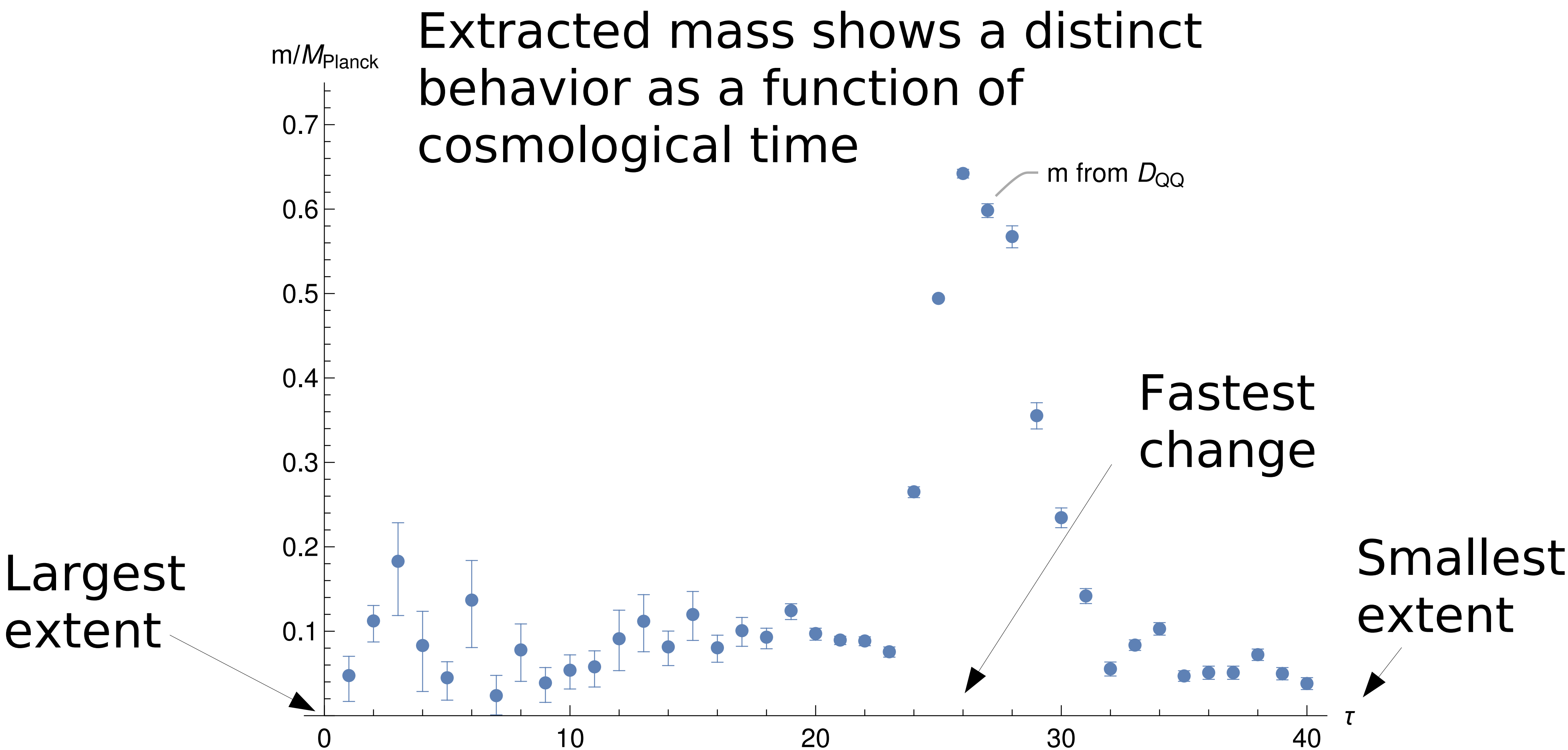

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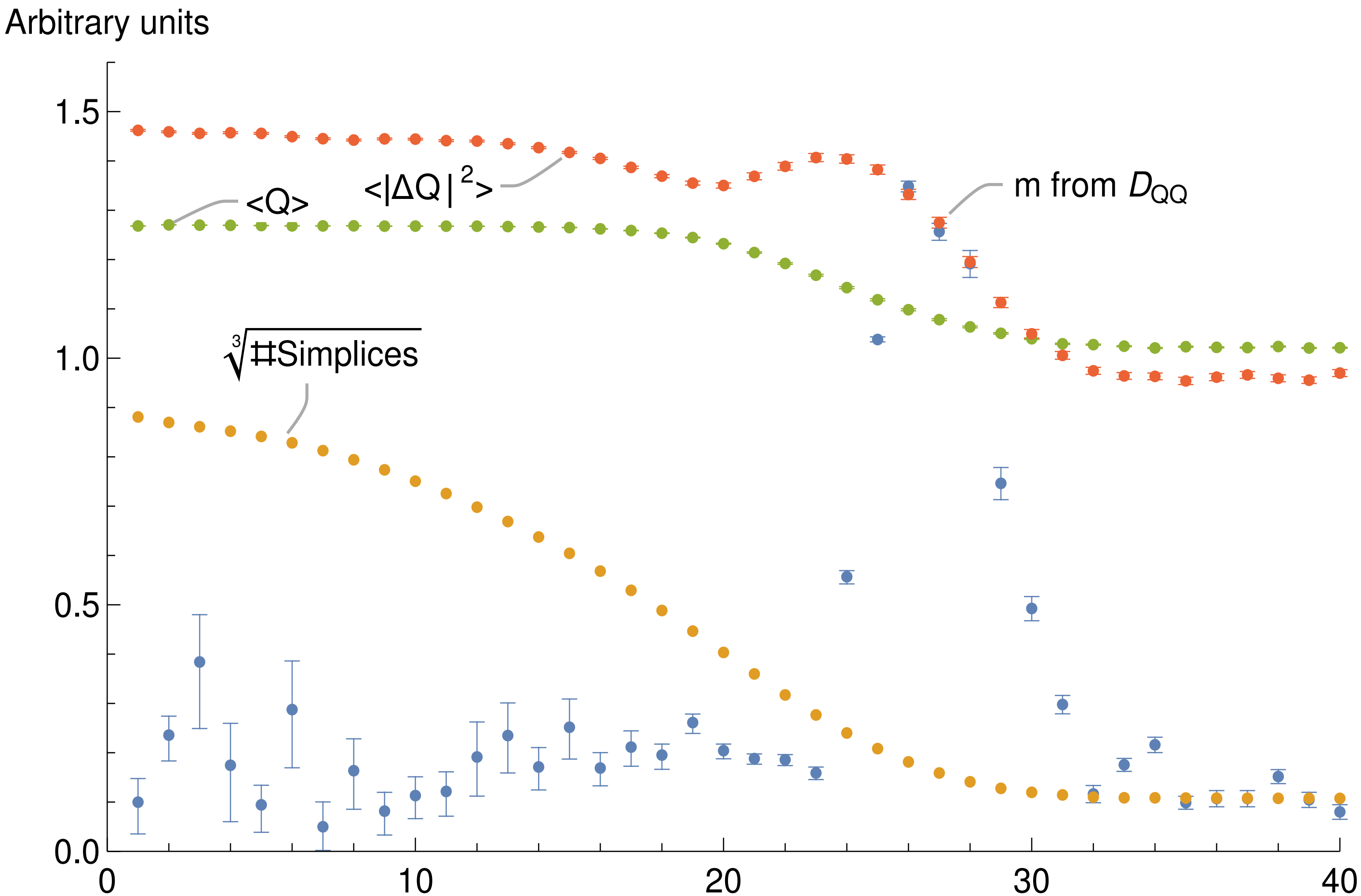

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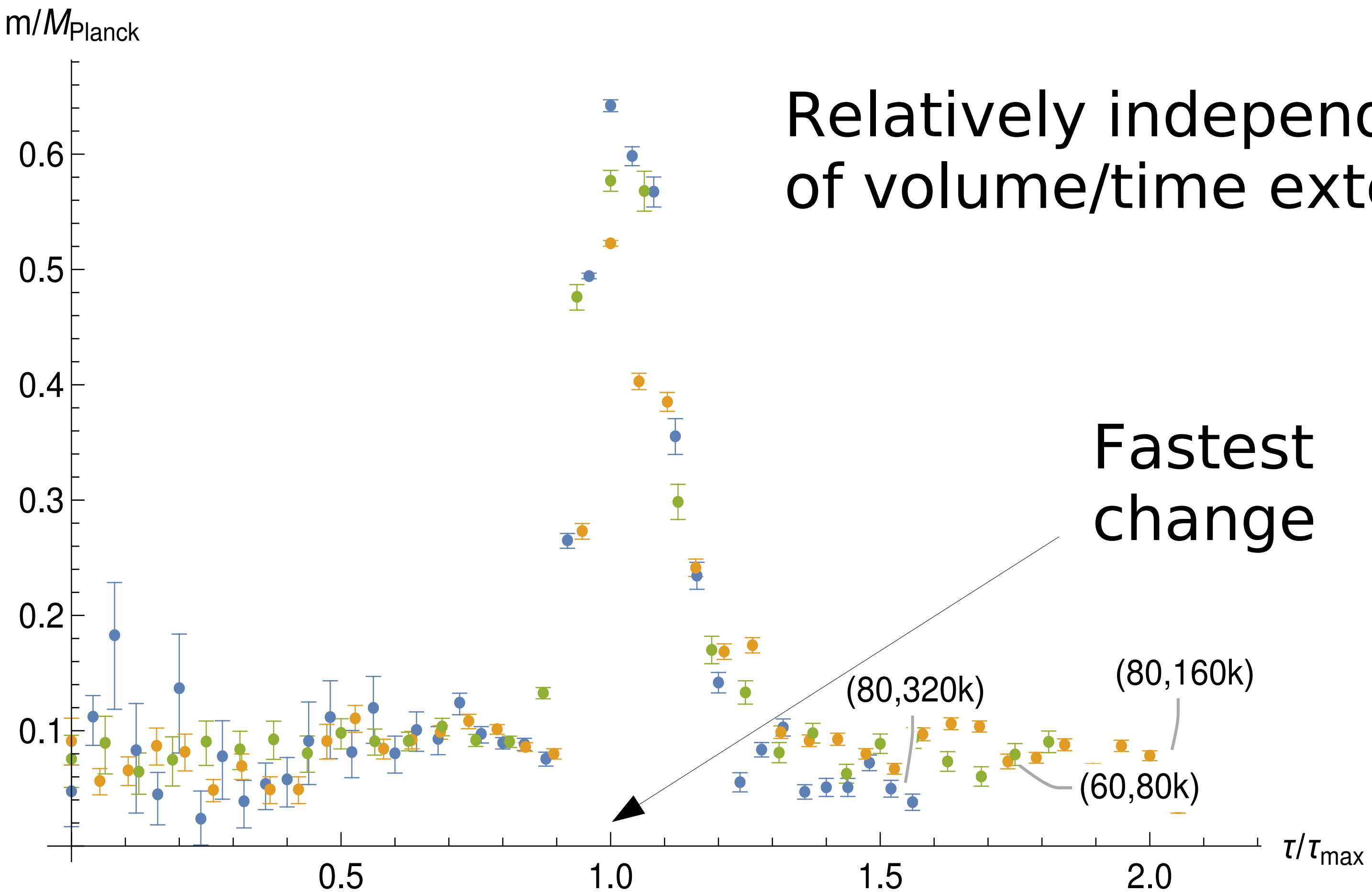

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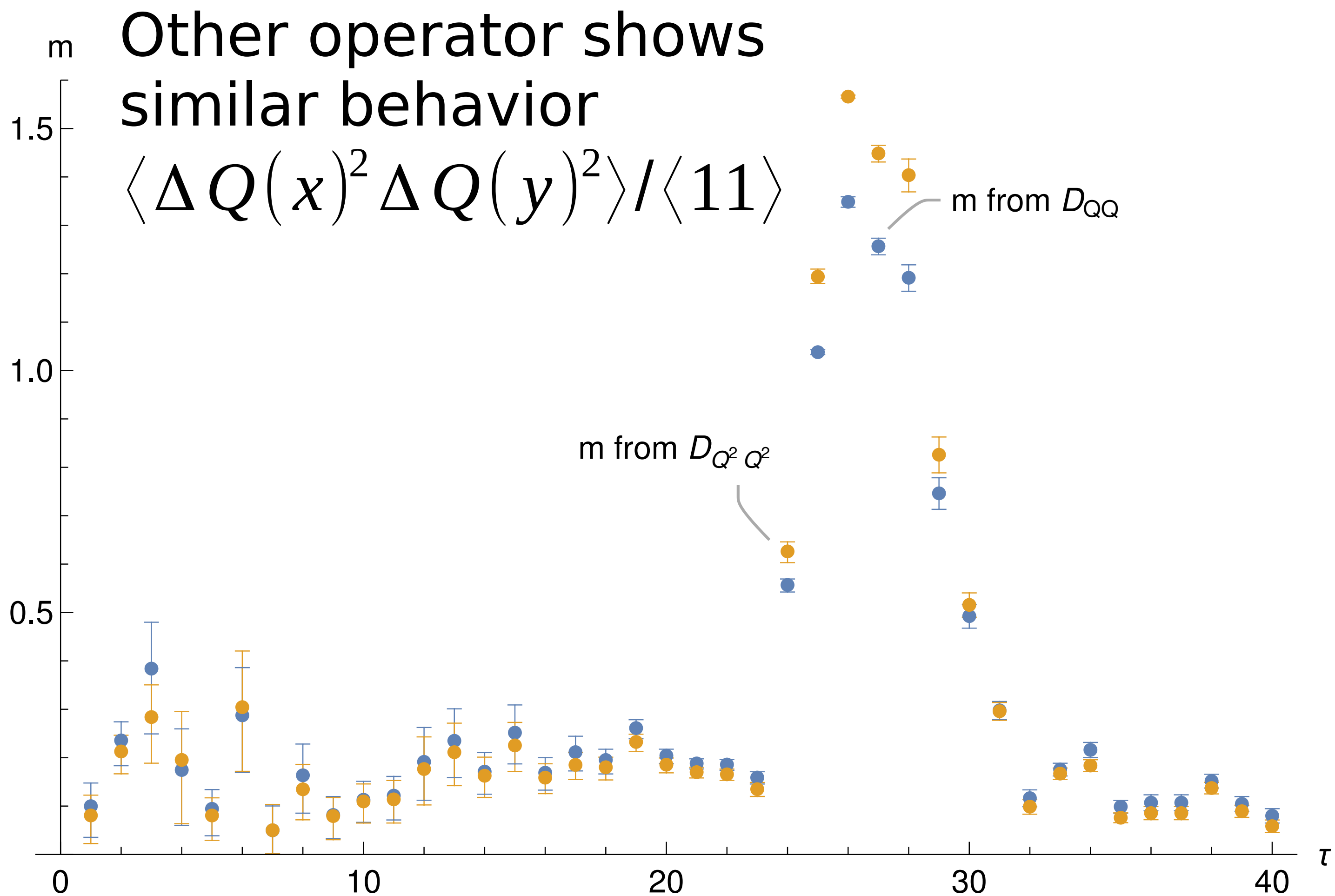

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Speculative phenomenology

[Maas ’19]

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  - If mass really changes during an inflationary phase, this could be a completely different scenario
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- Would evade all (in)direct detection bounds
- What happens with the long-distance behavior in a spatially flat universe?

Speculative phenomenology

[Maas ’19]

- Macroscopic gravitational objects need to be build in the same way

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Spin

[Maas '19]

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Supergravity

[Maas'23
Maas, Pressler, Plätzer'25]

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- CDT simulations hints that these create reasonable physical degrees of freedom
  - Self-bound gravitons with a mass: Geons
- Observed BEH effect and FMS mechanism allow access to all scales