Title: Singular gauges and dS invariance of the graviton vacuum

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Abstract: There has been a long-running discussion as to whether free gravitons on dS have a dS-invariant state. On the one hand, de Sitter invariant states are clearly singular in gauges favored by cosmologists; e.g. transverse traceless synchronous gauge associated with the k=0 slicing of dS. However, Higuchi has constructed a dS-invariant state using a different gauge. We resolve this tension by showing that the above ÃÂƒÂ¢ÃÂ‚ÂÂ€ÃÂ‚ÂÂœcosmologists
gaugeÃÂƒÂ¢ÃÂ‚ÂÂ€ÃÂ‚ÂÂ• is in fact singular on global de Sitter space. This observation may prove useful in understanding the physics of calculations indicating large IR effects involving gravity in dS.

Singular gauges and dS invariance of the graviton vacuum

Donald Marolf, UCSB

10/27/2010

Work in progress with
Ian Morrison

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This talk: Gravitons!

Longstanding issue: The graviton propagator in dS is "large" in the IR.

Emphasized by: Starobinsky, Woodard, Antoniadis and Mottola, ...Giddings, ...

Classic example:

Consider TT synchronous gauge in k=0 slicing.

$$D = 3{+}1 \quad \langle 0|h_{ab}(x)h_{cd}(y)|0\rangle = \sum_s \int \frac{d^3k}{(2\imath k)^3} H^2(1+k^2\lambda^2)\epsilon^s_{ab}\epsilon^s_{cf}$$

Diverges!

Also, growth of graviton "variance" at late times in various gauges.

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Longstanding issue: The graviton propagator in dS is "large" in the IR.

E.g. Starobinsky, Woodard, Antoniadis and Mottola ... Giddings...

What is the *physics* of this phenomenon?

Might it be a gauge artifact, either entirely or in part?

Subtle question:

Weyl tensor correlators are well-defined, fall off at large separation and are dS invariant.

But is there more to the physics than this?

What happens at higher orders in perturbation theory? How to compute observables there?

With flat-potential scalars (inflation), leads to measurable tensor power spectrum.

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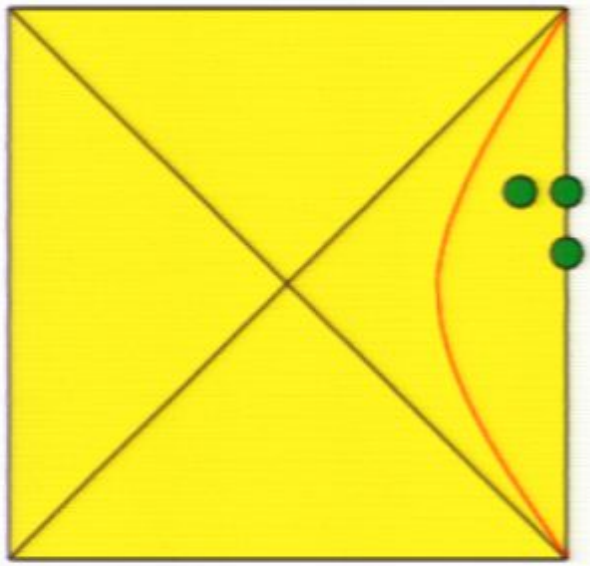
De Sitter invariance?

One probe of these issues is dS invariance.
A sharp gauge-invariant question.

In a dS-invariant vacuum, gauge-invariant correlators within the static patch must be invariant under t-translations. Cannot grow with time.



E.g., variance with small smearing, any n-point function at small separations.

dS invariance would constrain, but would not preclude, large IR effects. Can still grow with *separation*.

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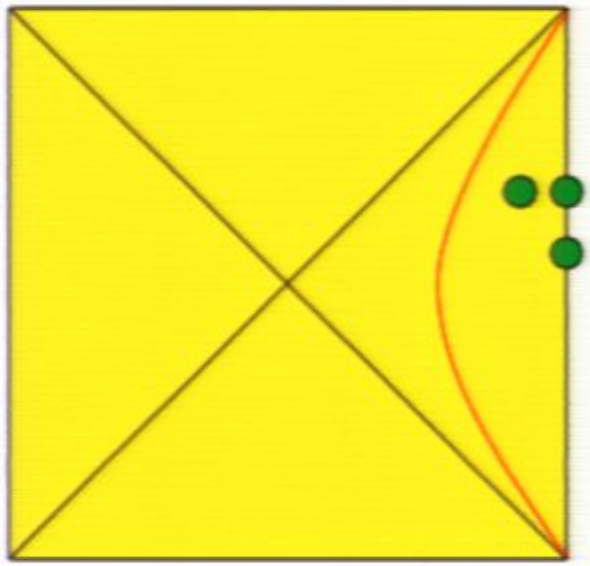

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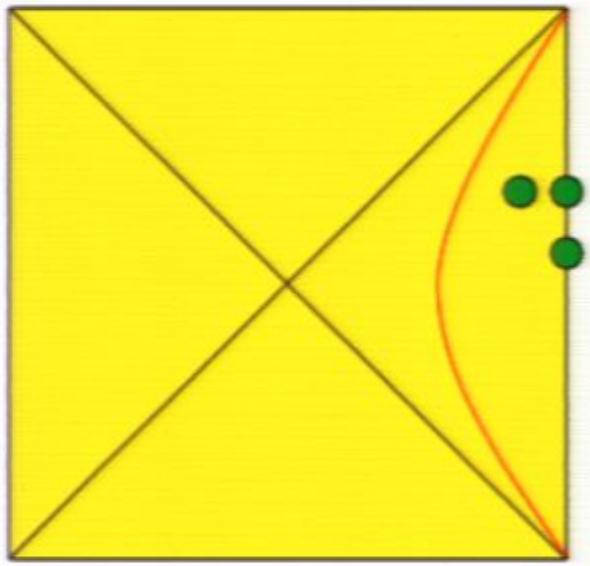

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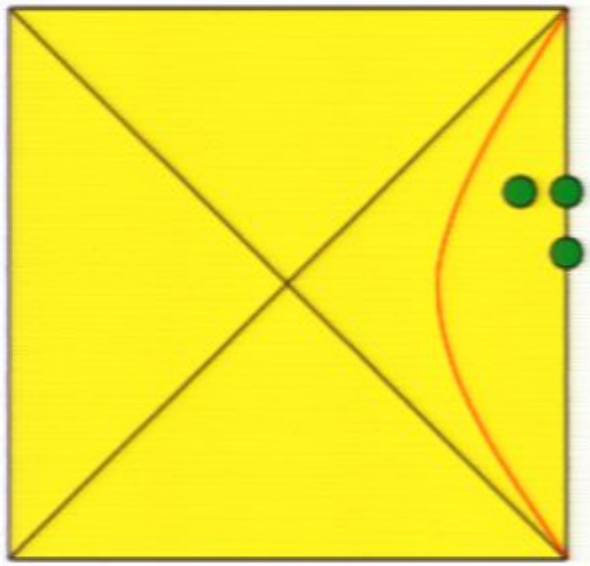

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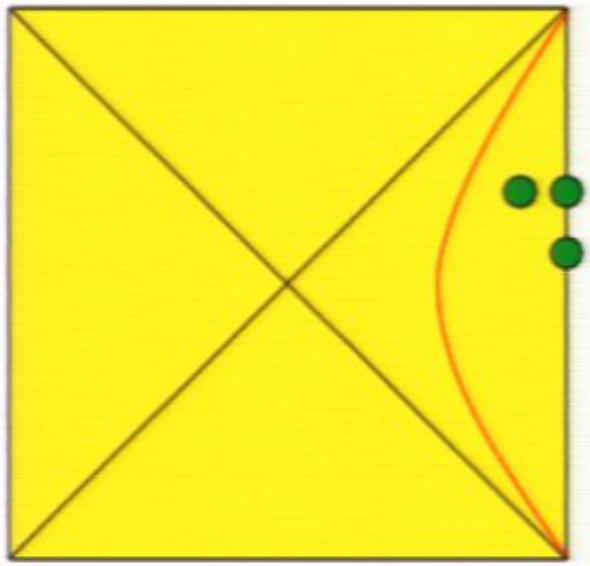

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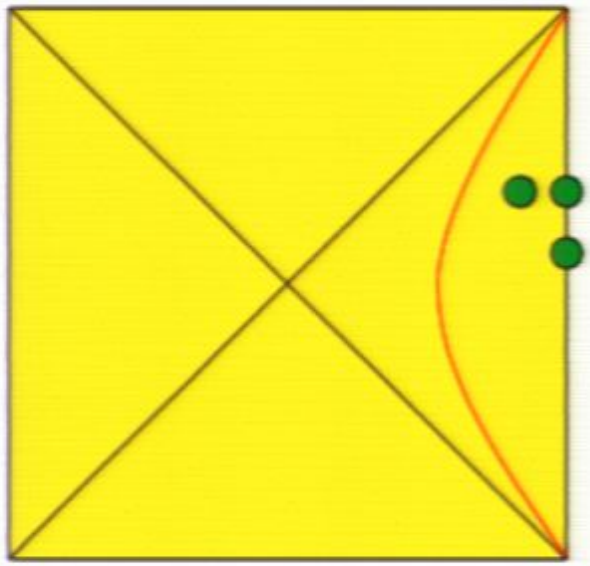

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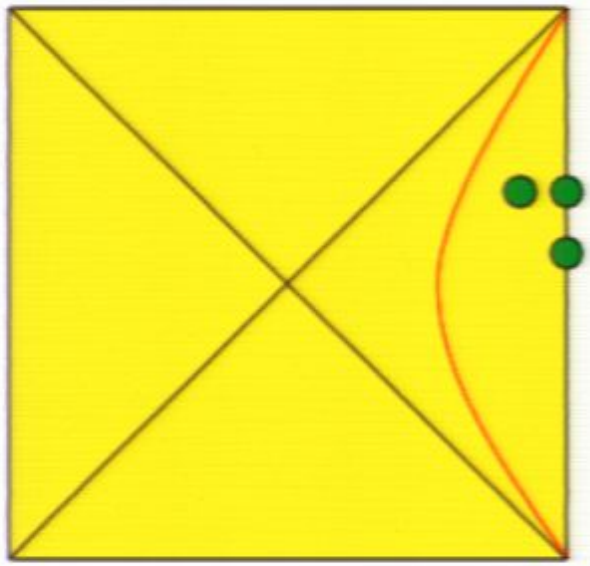

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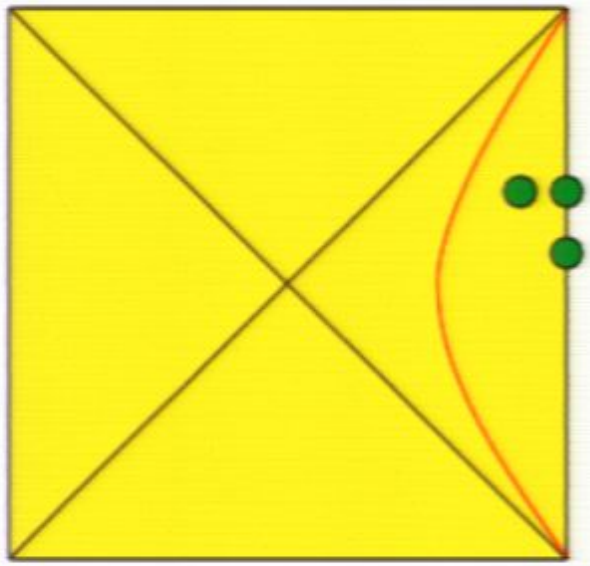

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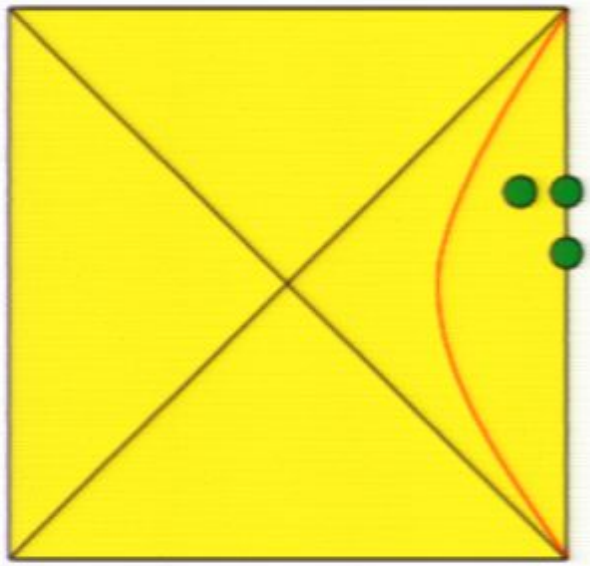

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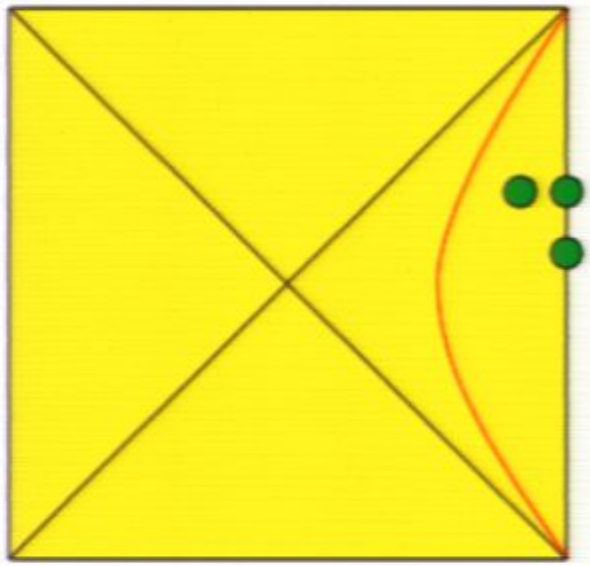

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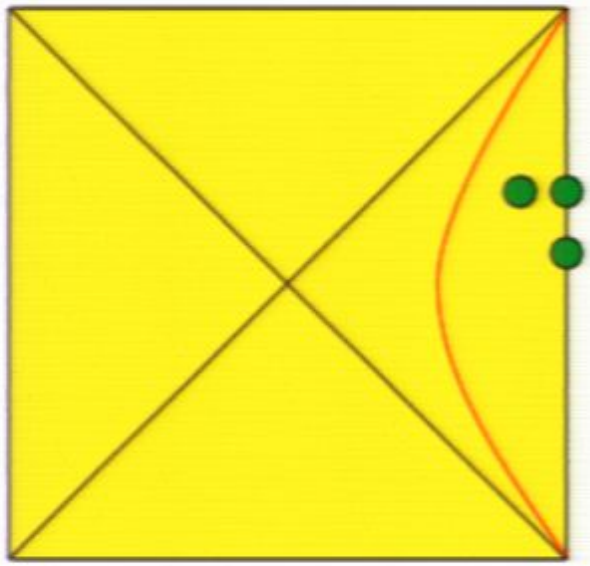

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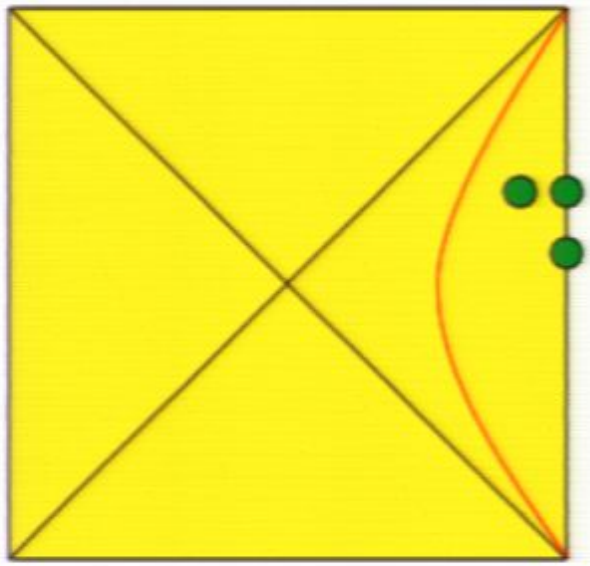

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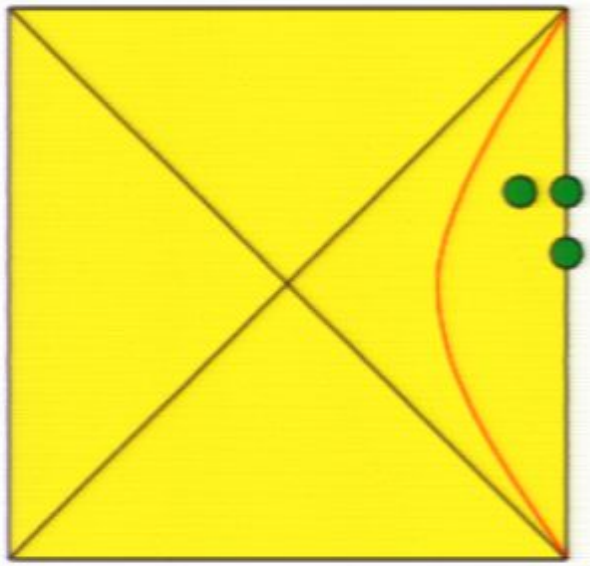

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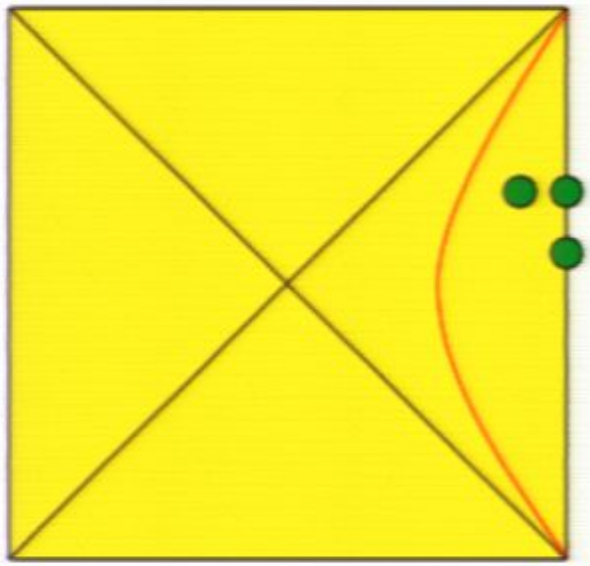

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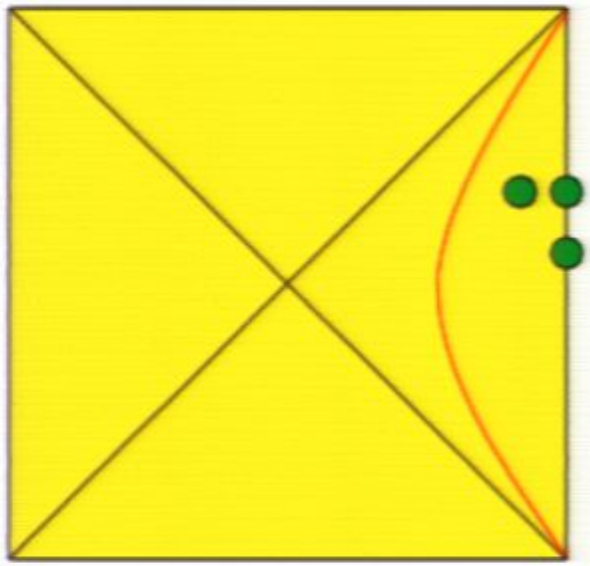

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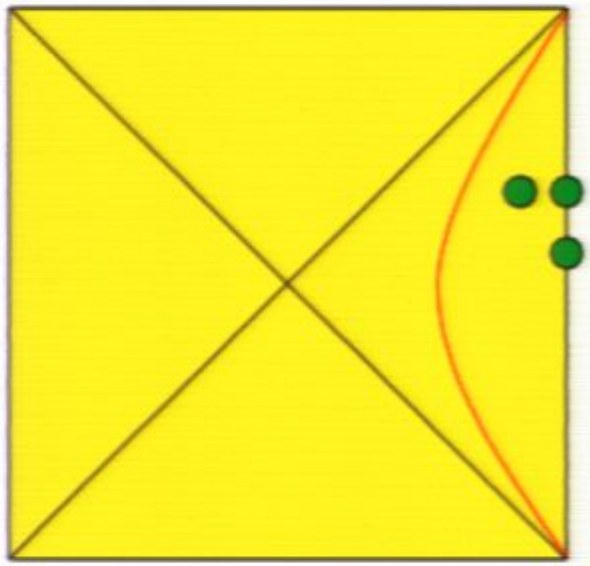

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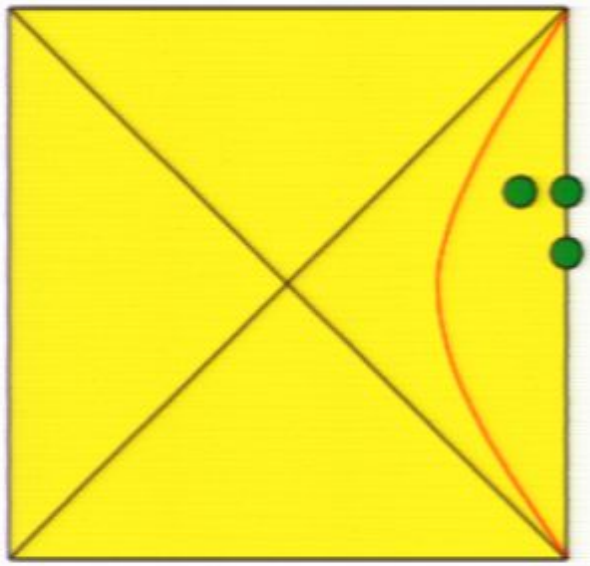

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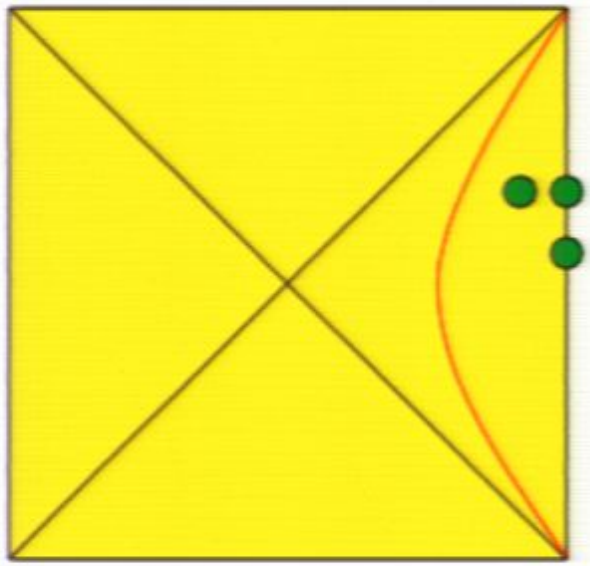

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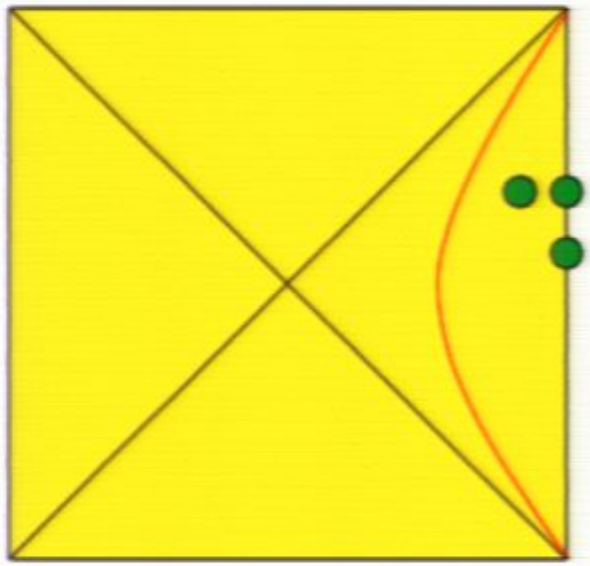

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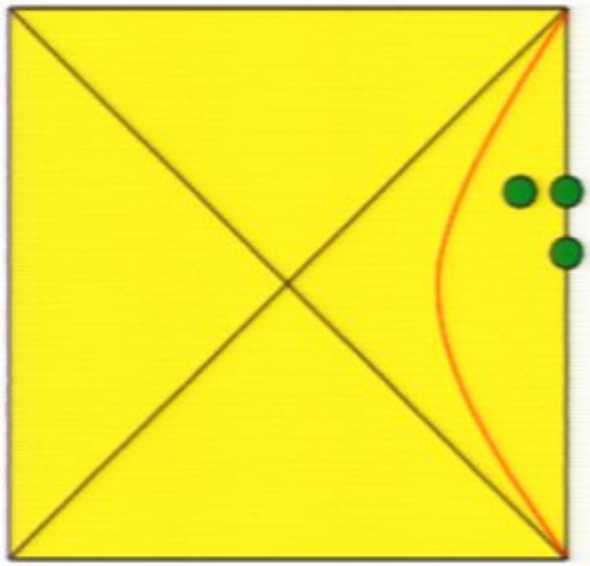

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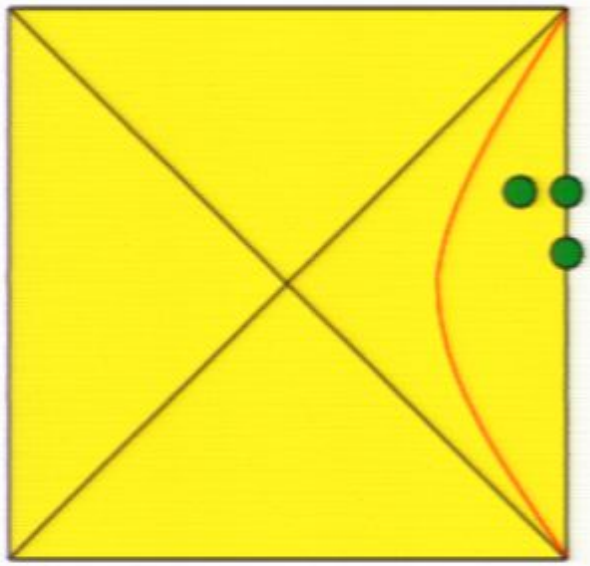

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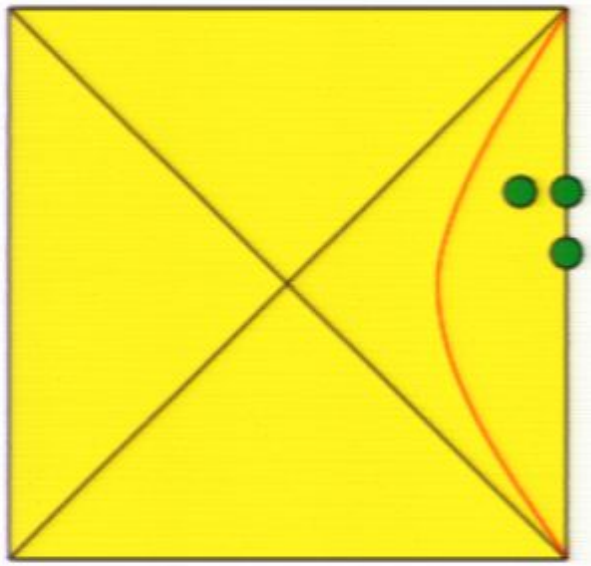

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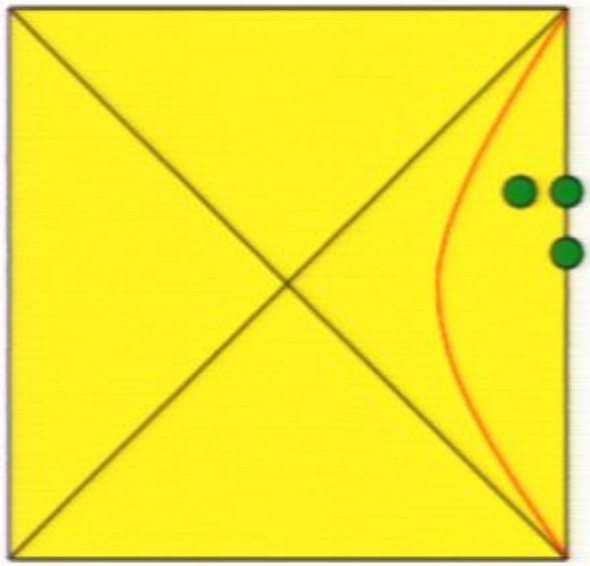

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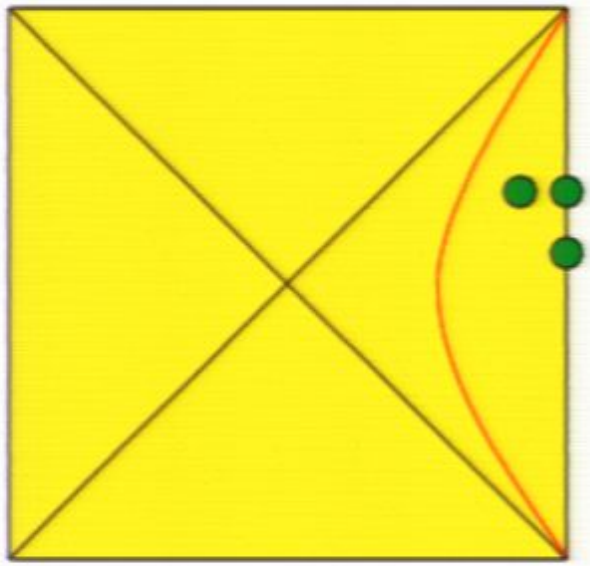

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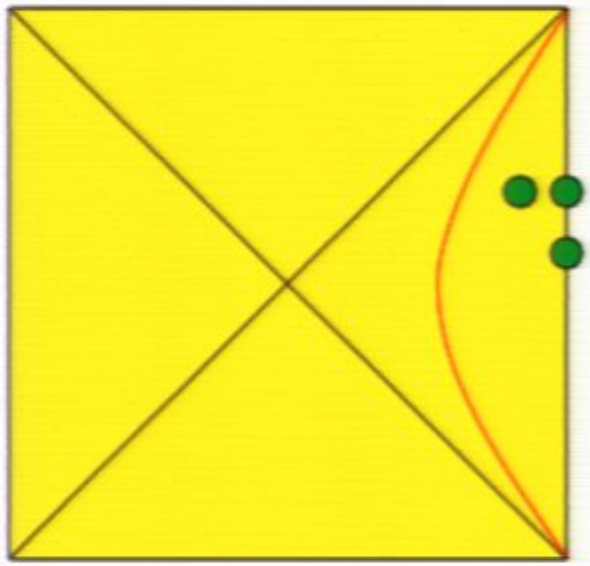

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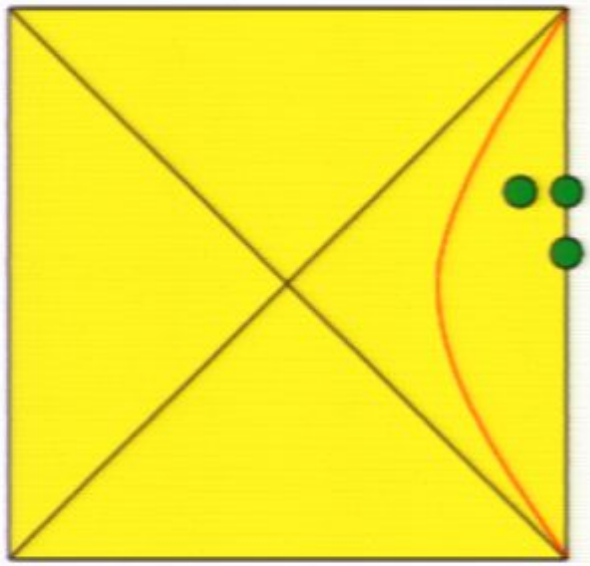

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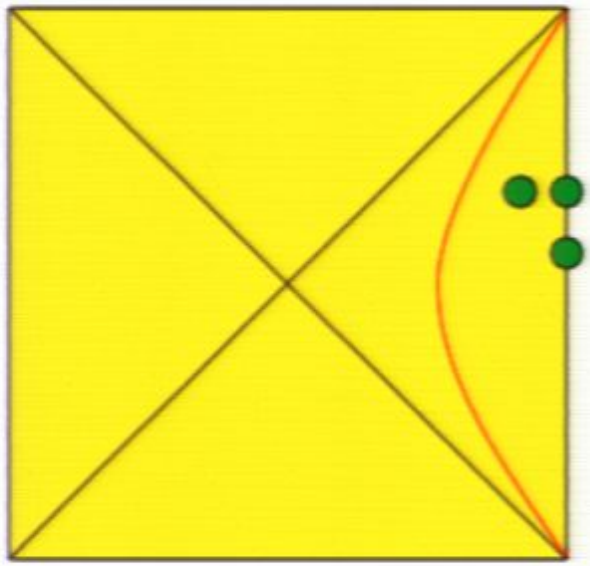

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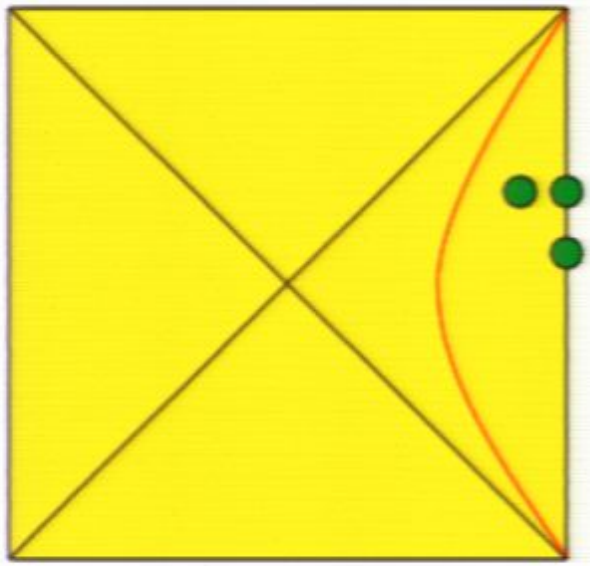

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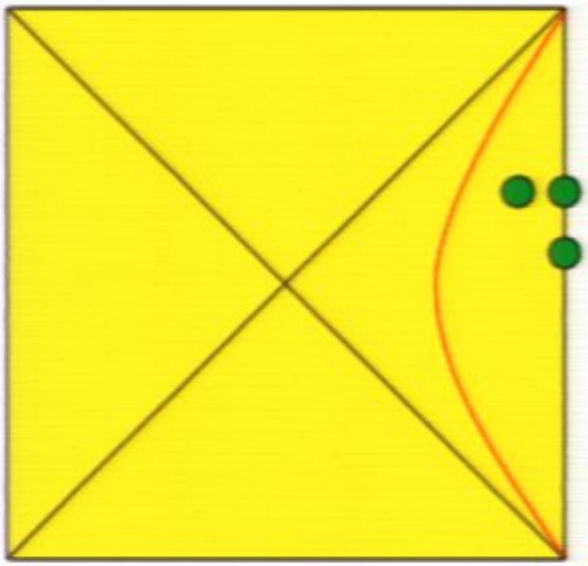

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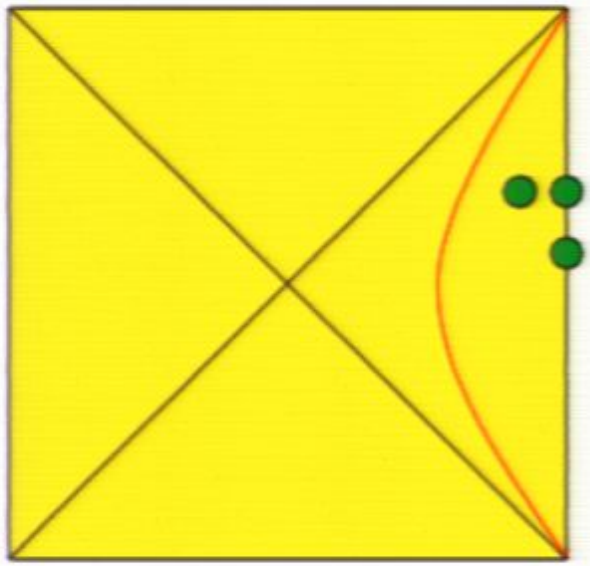

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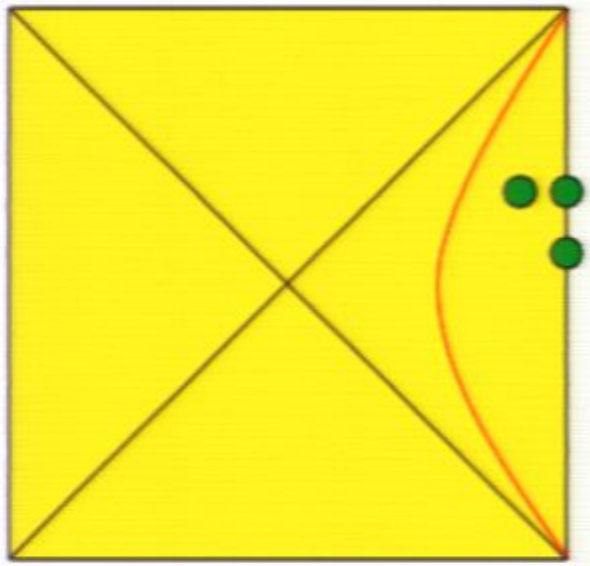

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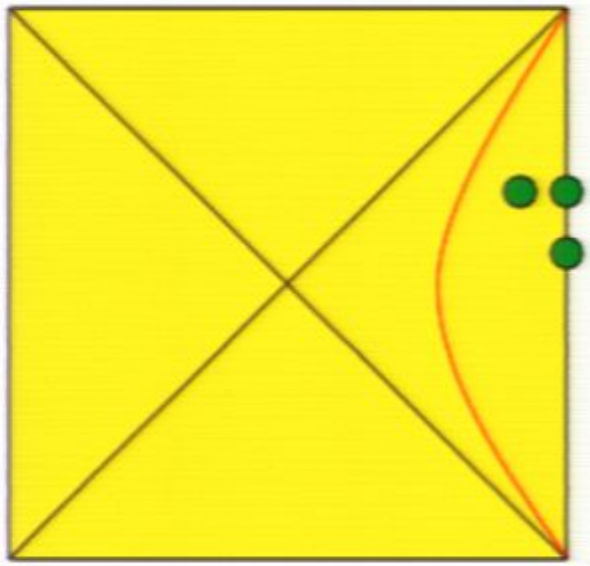

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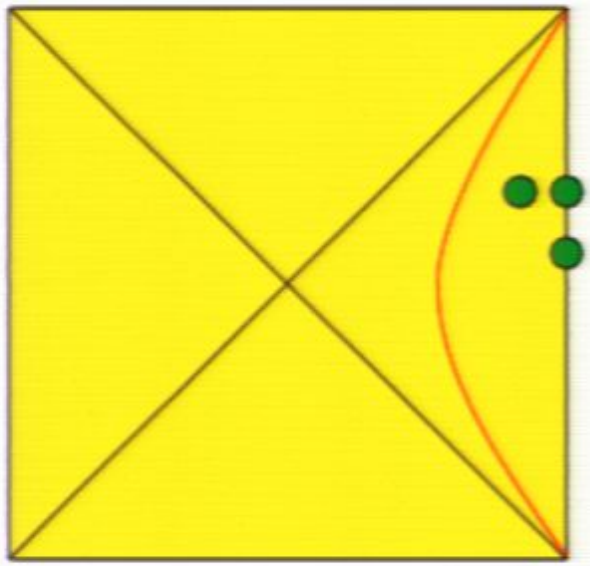

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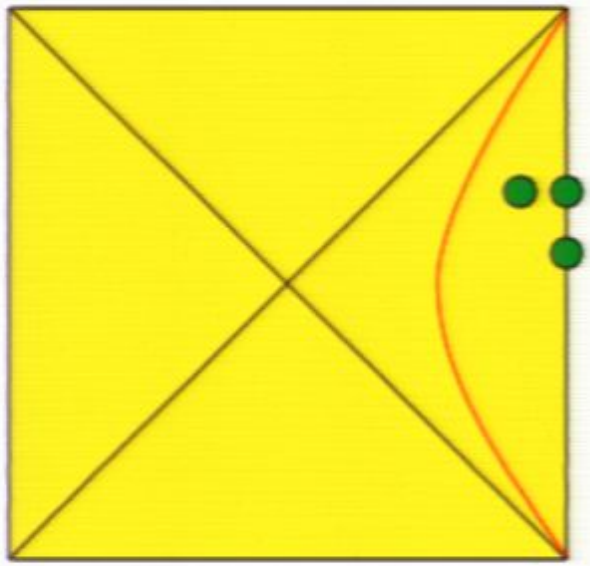

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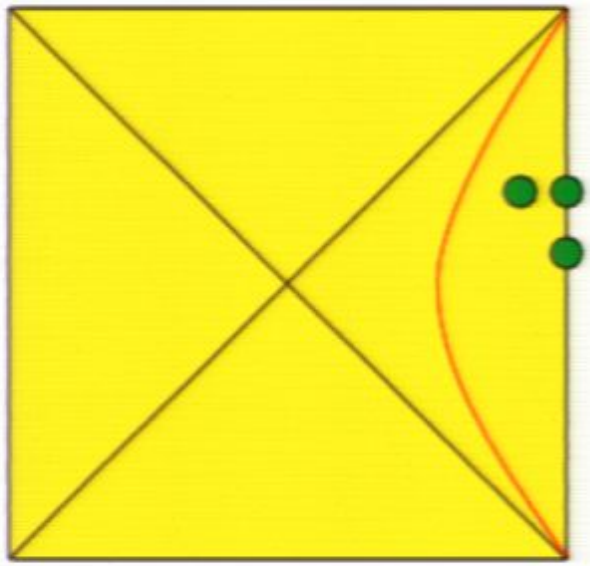

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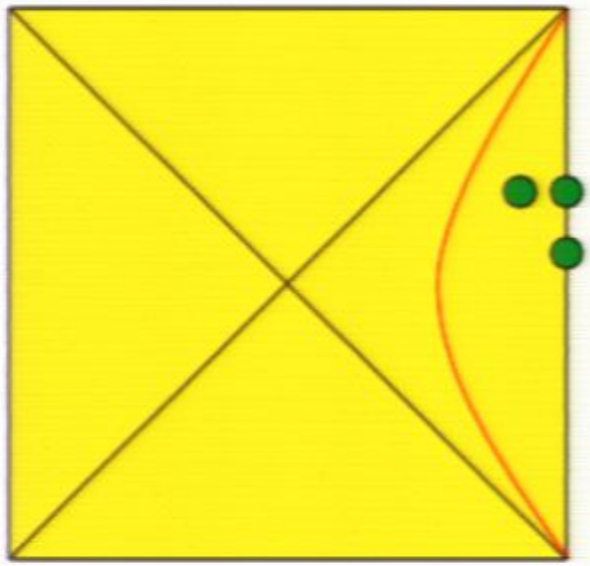

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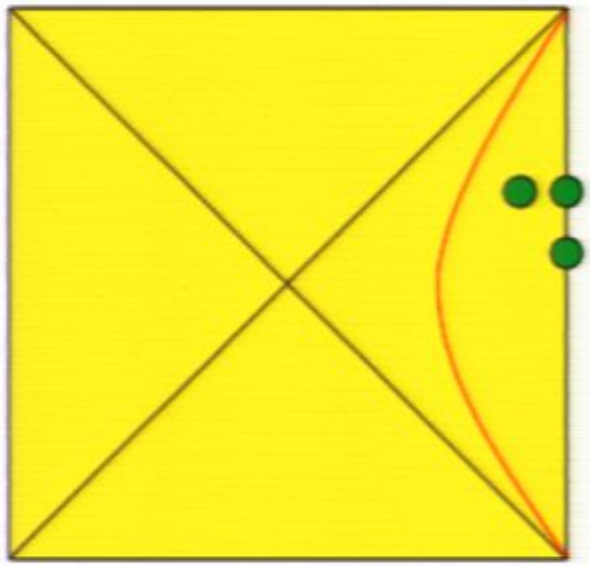

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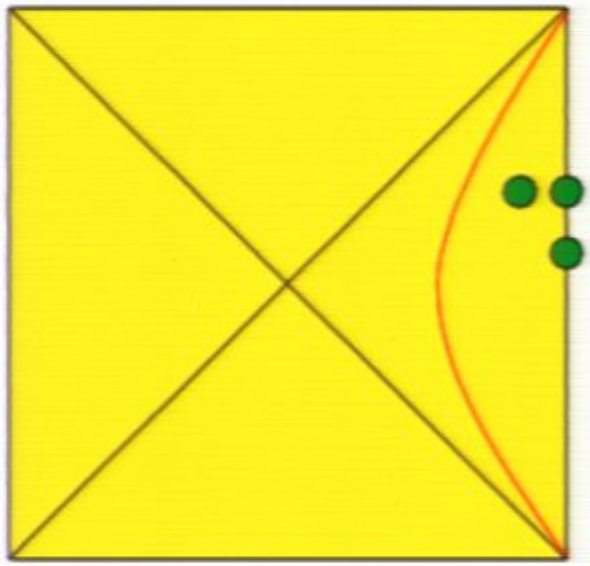

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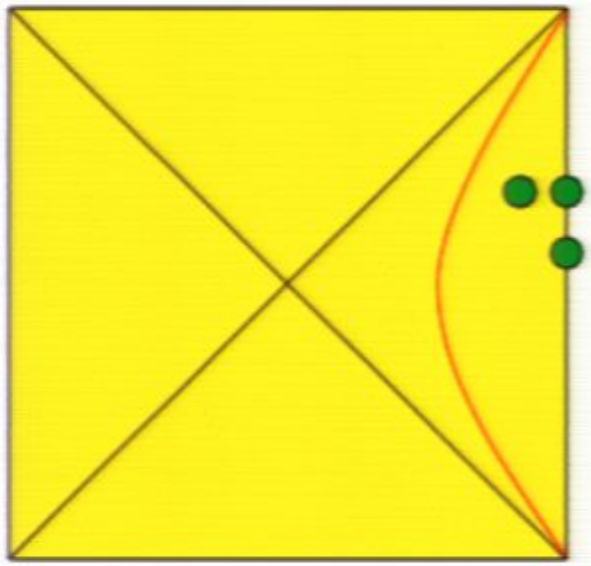

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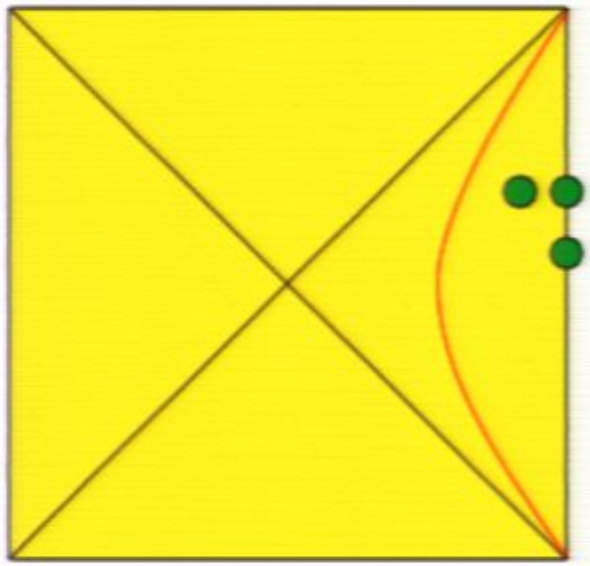

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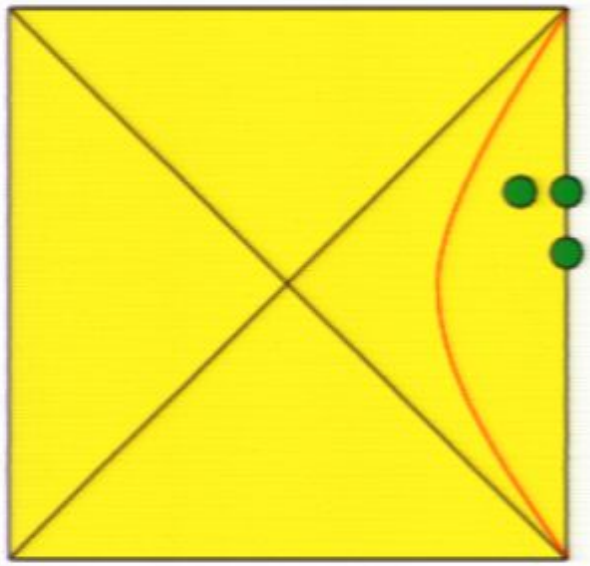

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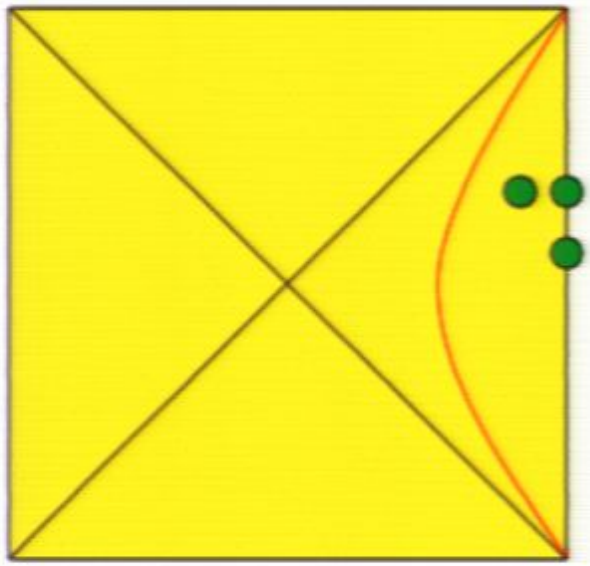

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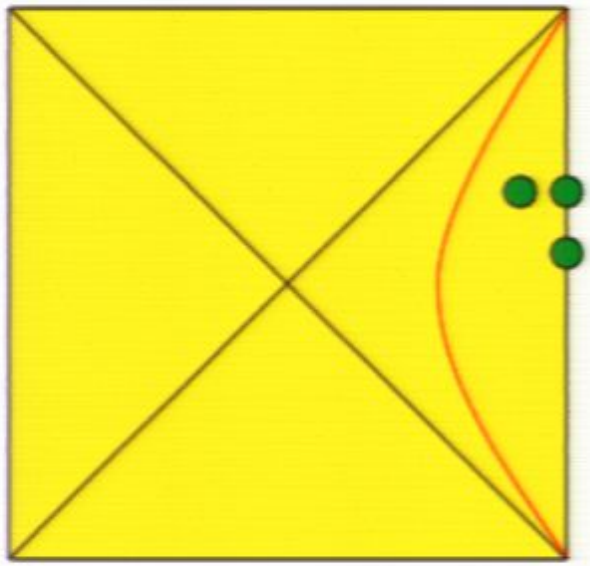

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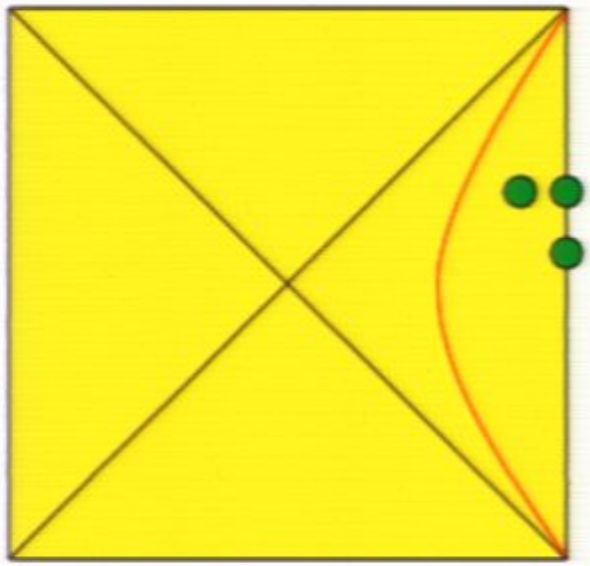

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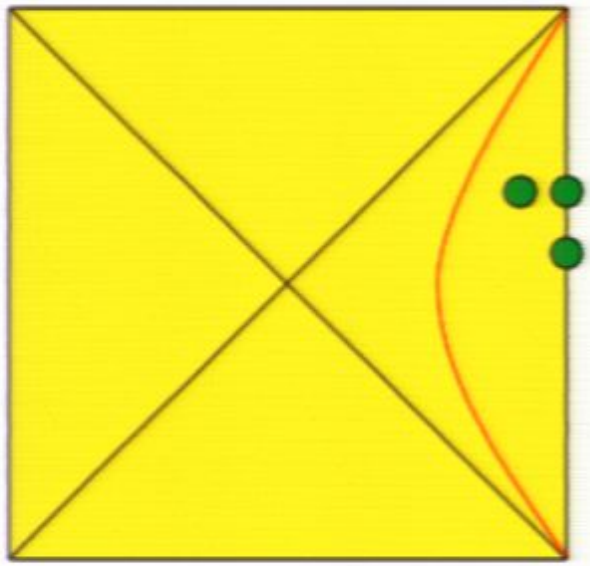

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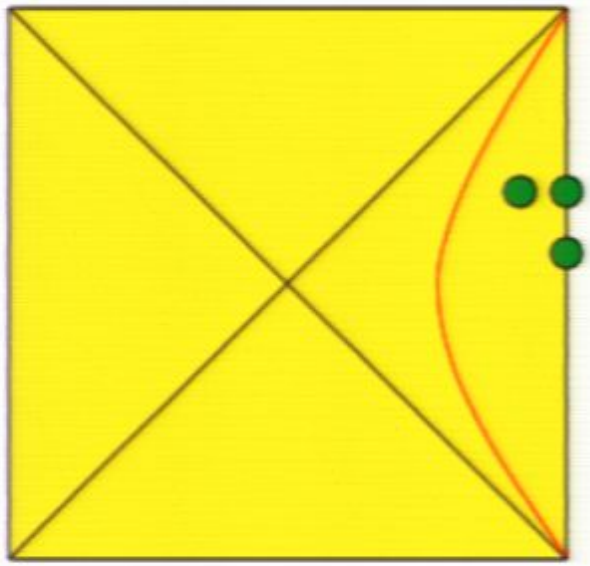

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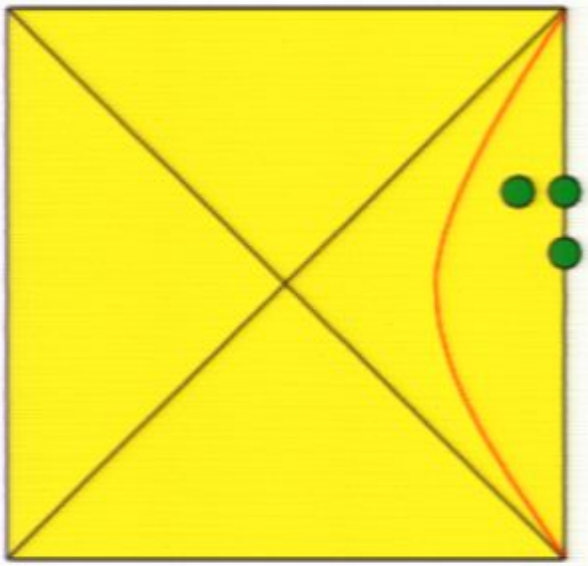

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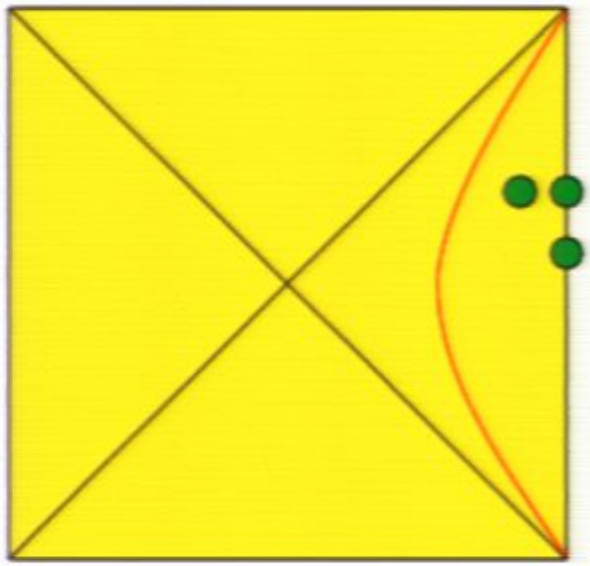

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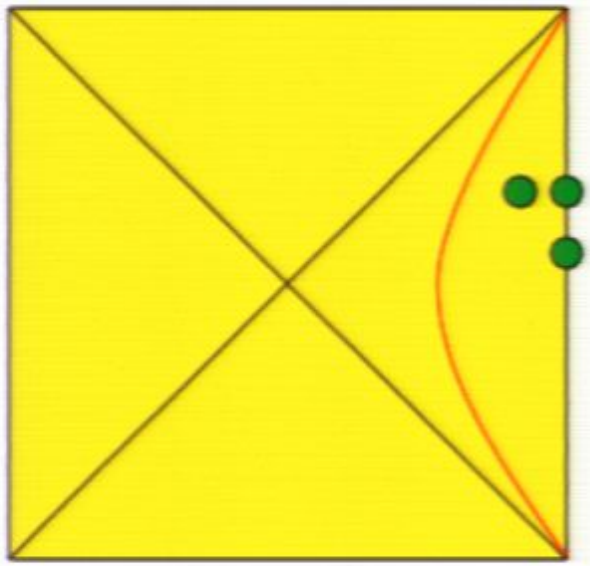

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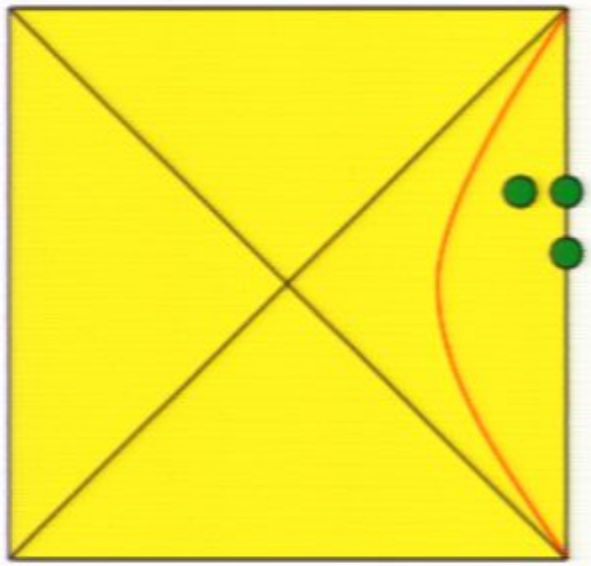

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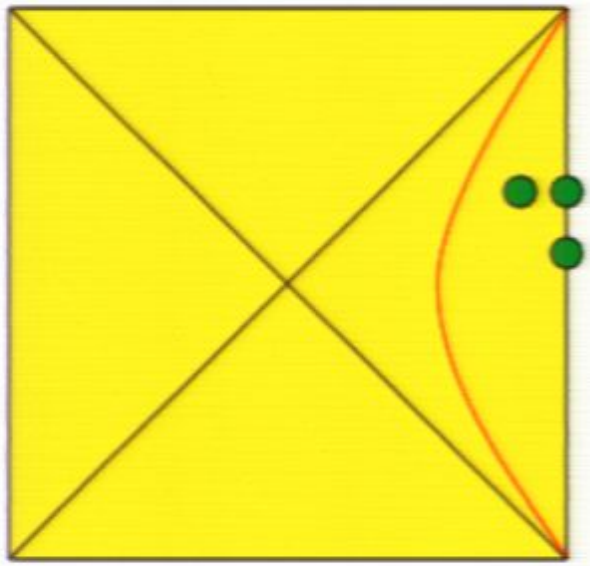

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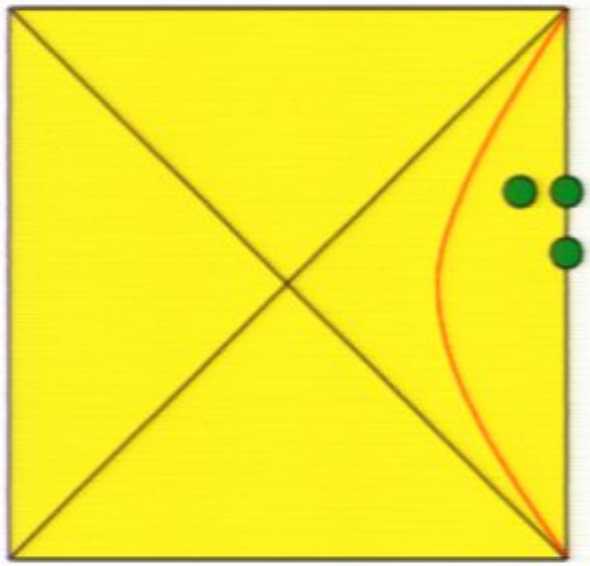

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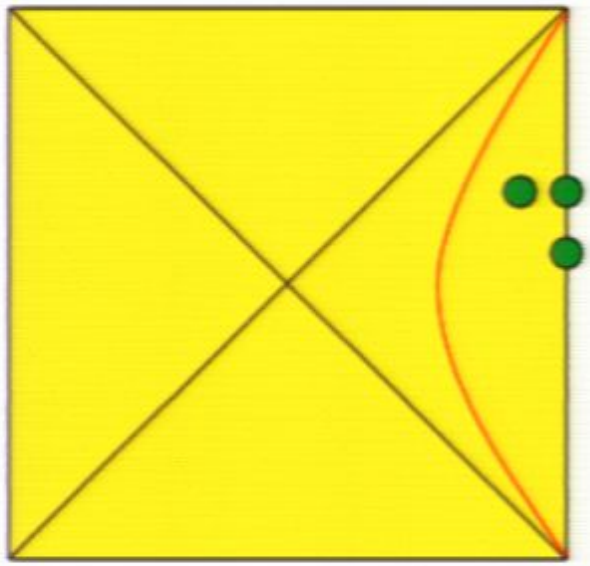

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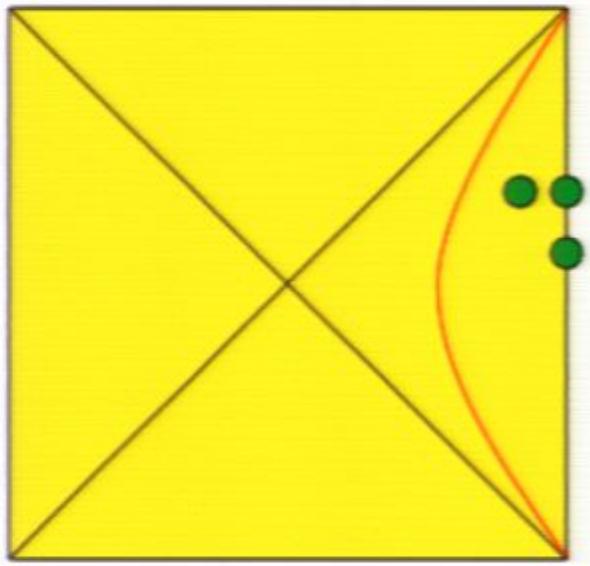

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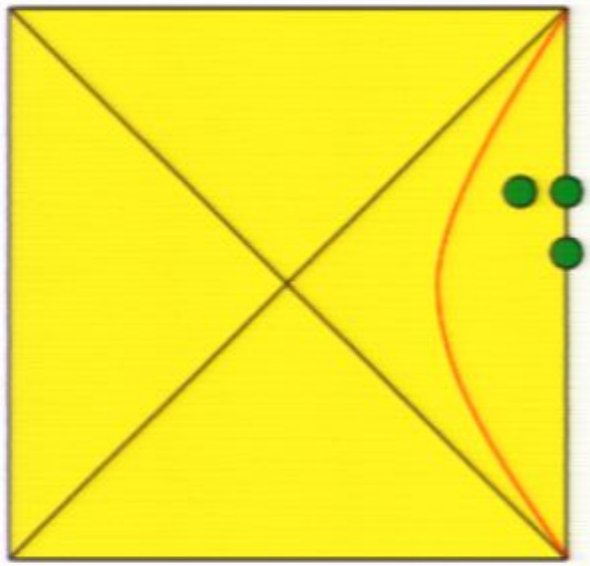

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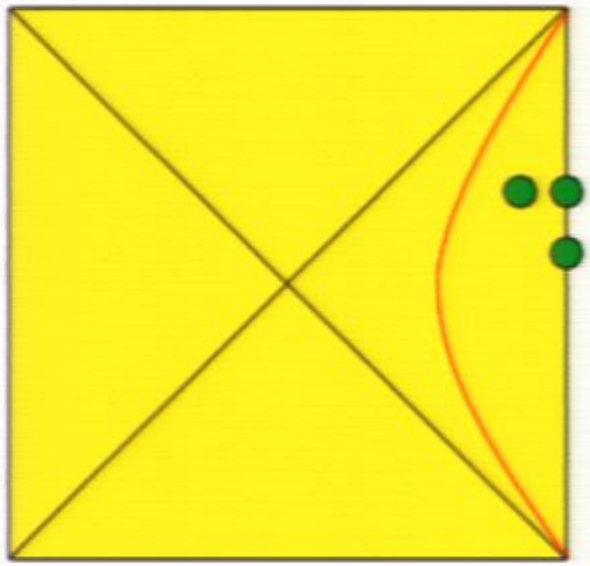

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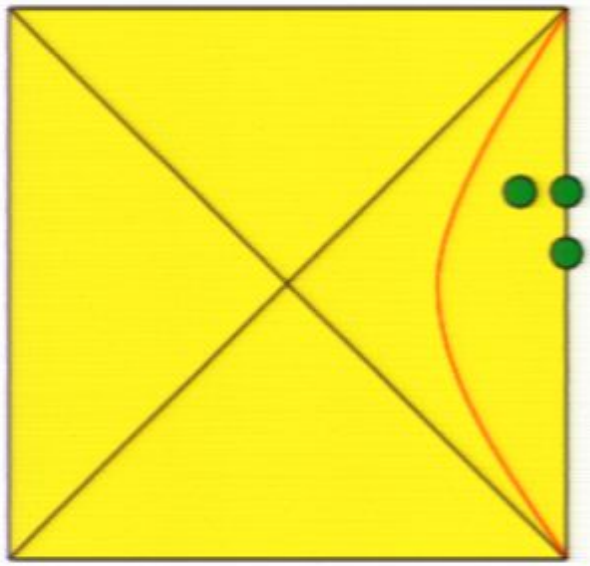

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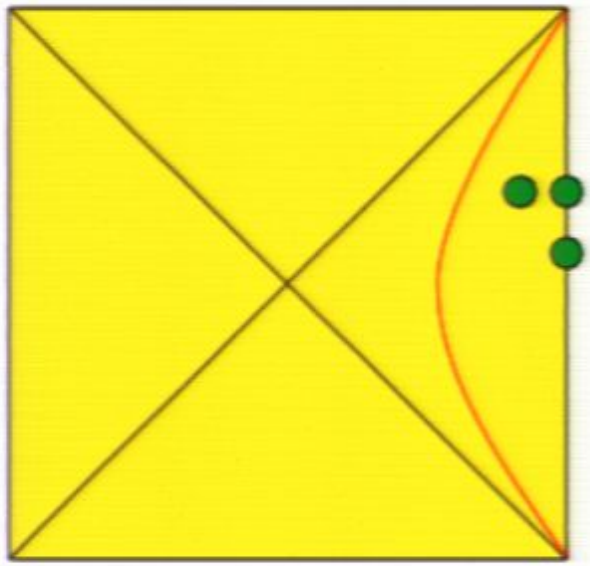

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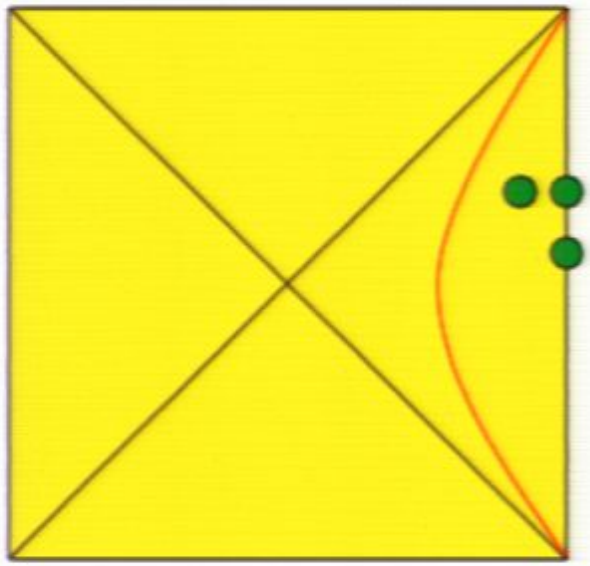

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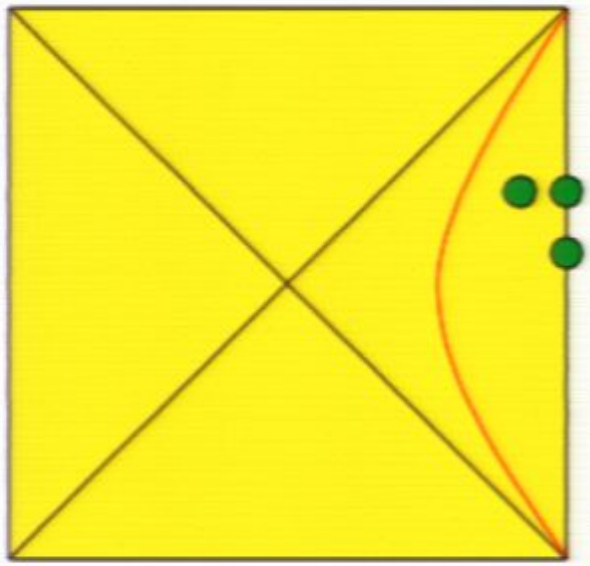

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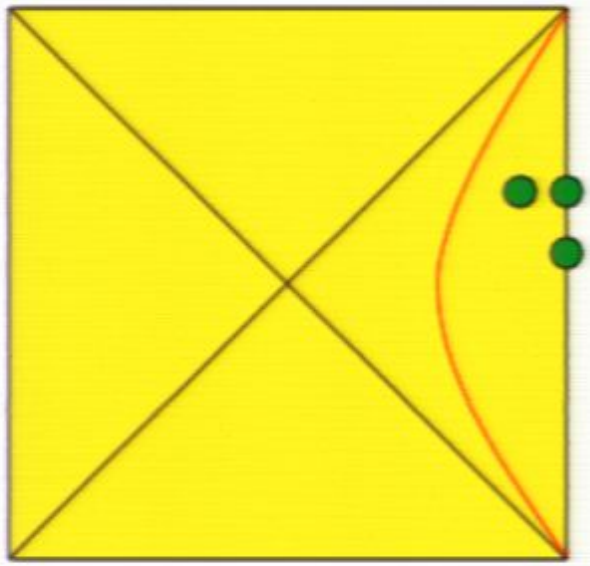

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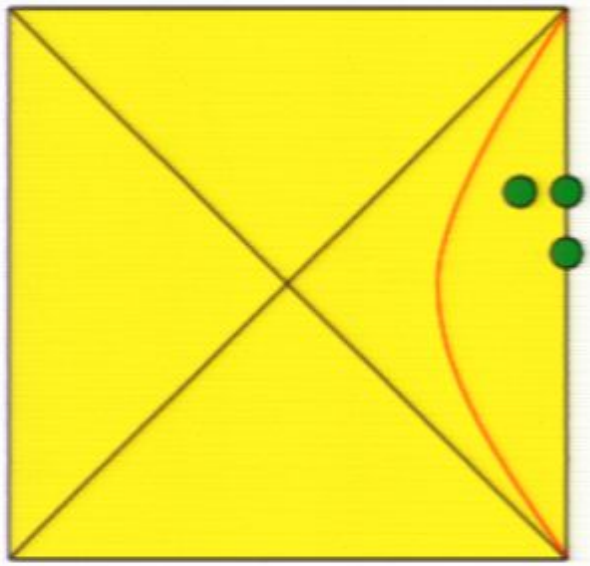

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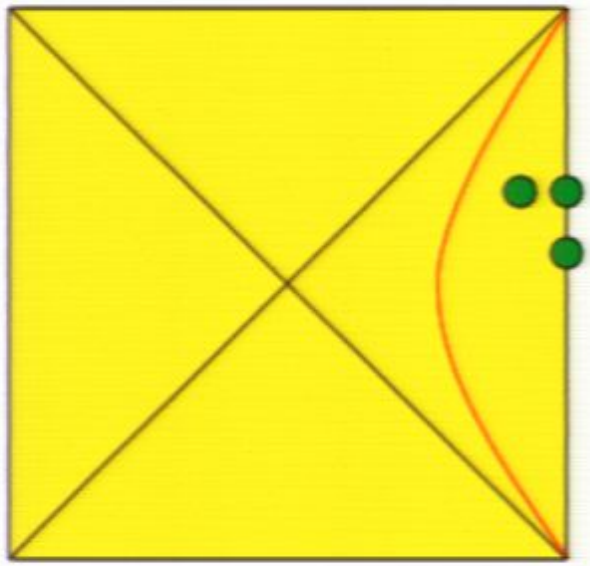

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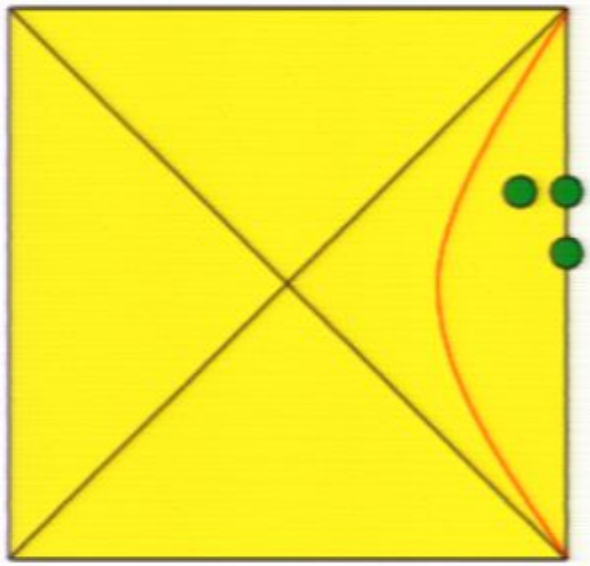

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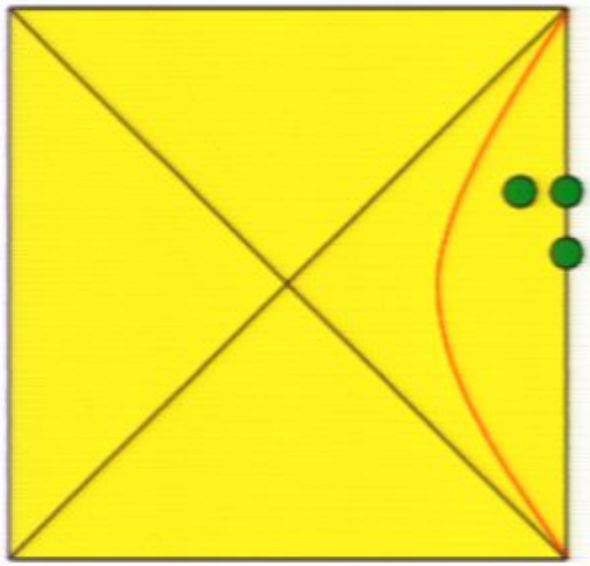

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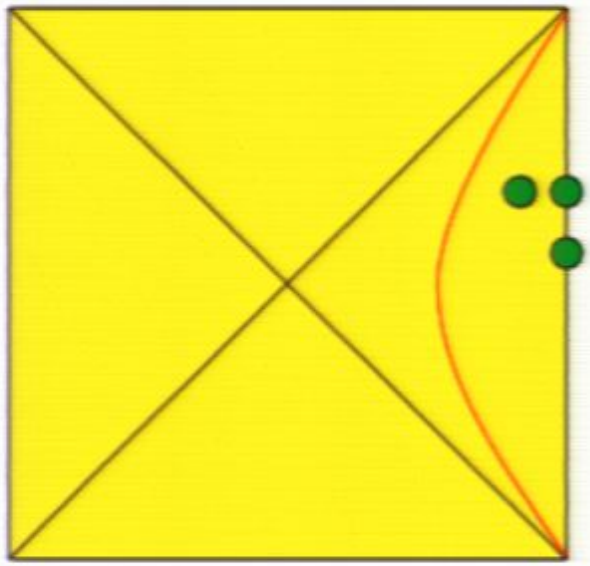

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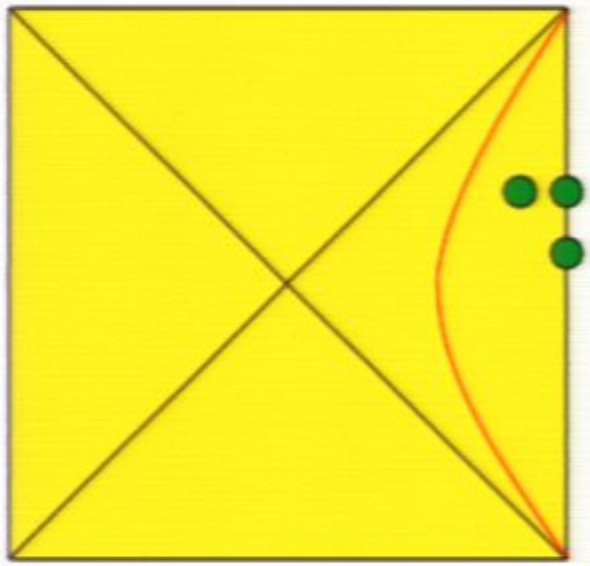

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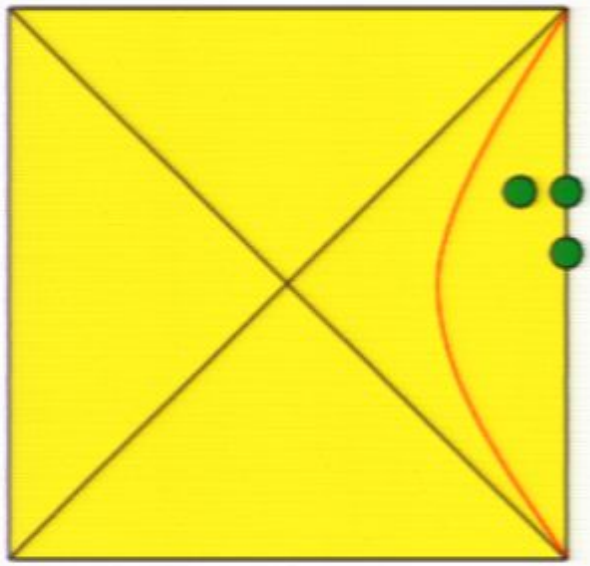

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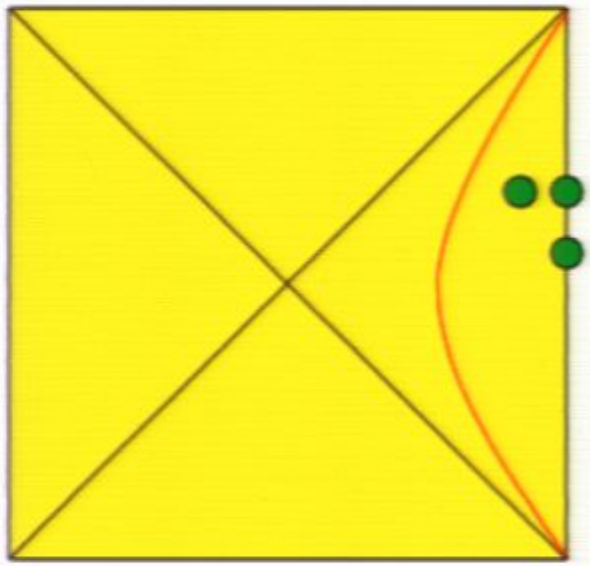

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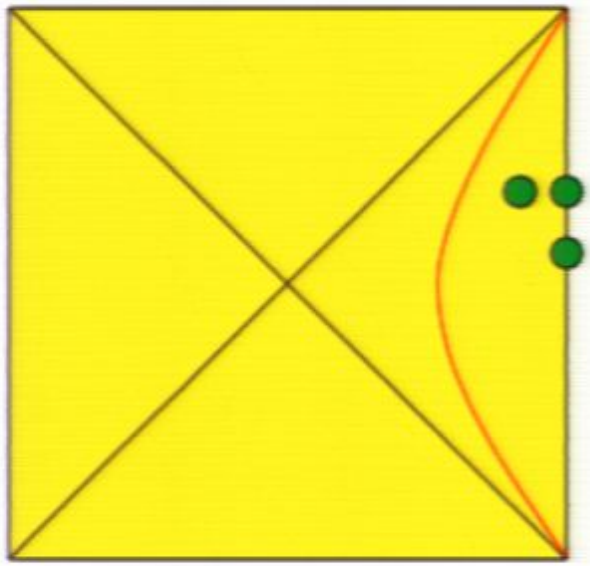

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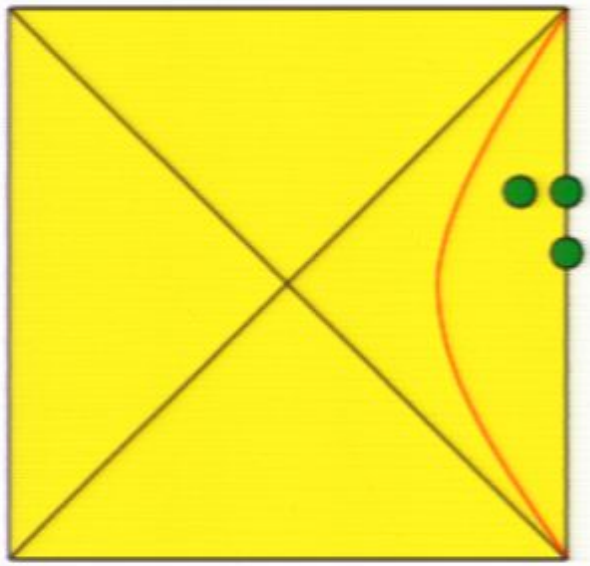

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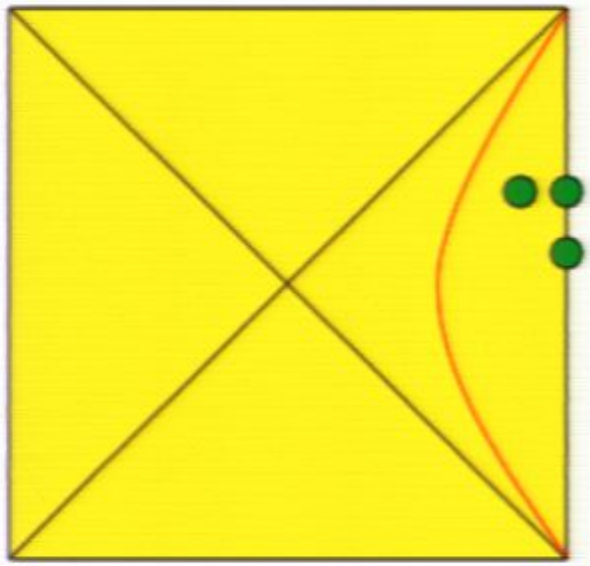

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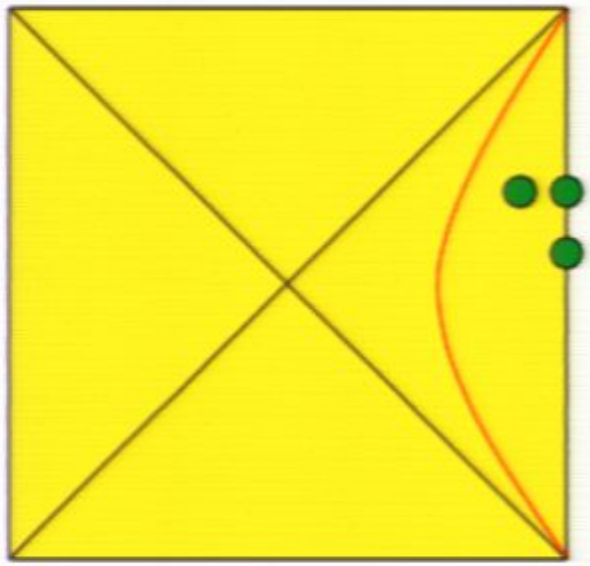

E.g., variance with small smearing, any n-point function at small separations.

dS invariance would constrain, but would not preclude, large IR effects. Can still grow with *separation*.

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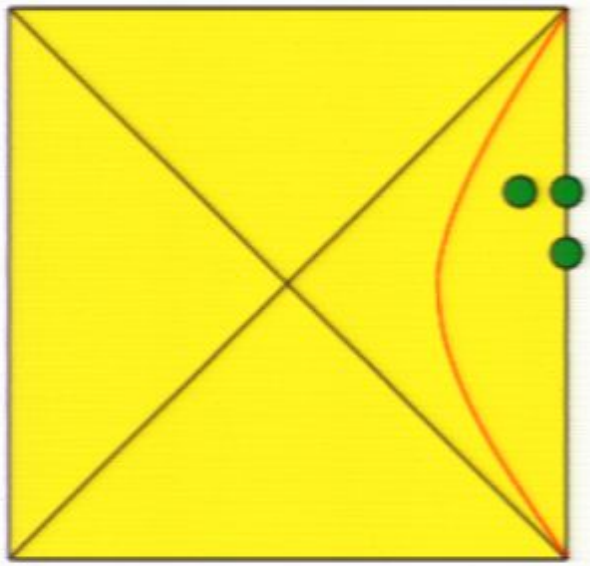

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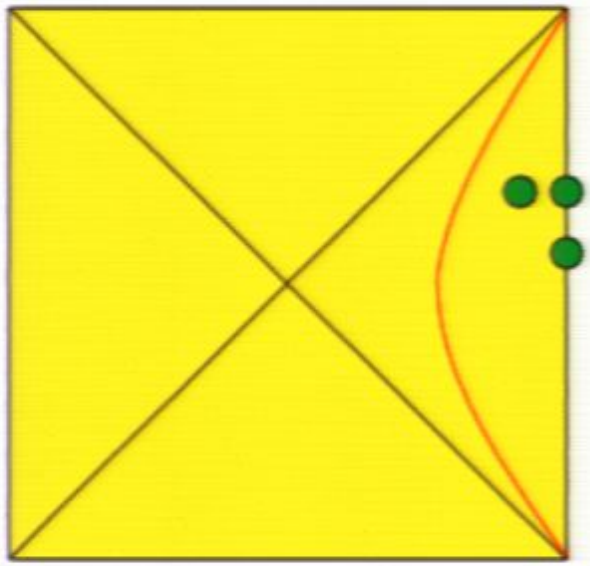

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Pro dS-invariance: Allen & Turyn, Higuchi & collaborators, Hawking, Hertog, & Turok

Focus on Kleppe vs Higuchi

Kleppe (1993): "Breaking of de Sitter invariance in quantum cosmological gravity"
No dS-invariant propagator in TT synchronous gauge in k=0 slicing.

Higuchi (1991) "Quantum linearization instabilities of de Sitter space-time. 2."

TT synchronous gauge in k=+1 slicing (global coords)

$$Q_i|0\rangle = 0$$

For every dS sym generator Q_i

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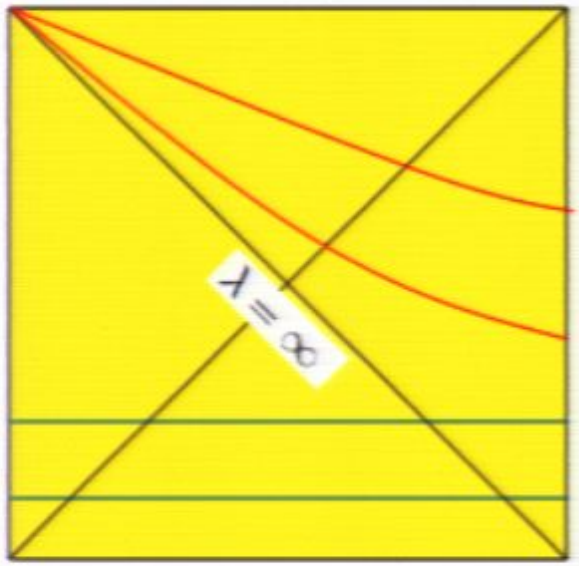
Might k=0 TTS gauge be singular on global dS?

Please let me know if this analysis is in the literature.

Given a general perturbation $\bar{h}_{ab}$ on global dS, can we find $h_{ab} = \bar{h}_{ab} + \nabla_a \xi_b + \nabla_b \xi_a$ satisfying

$$\nabla^a h_{ab} = 0, \; h_a{}^a = 0$$
$$h_{00} = h_{0i} = 0$$

in k=0 coordinates for smooth ξ_b?



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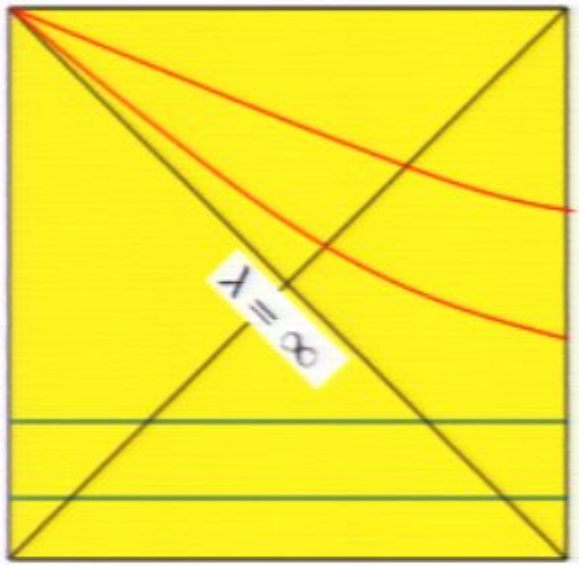

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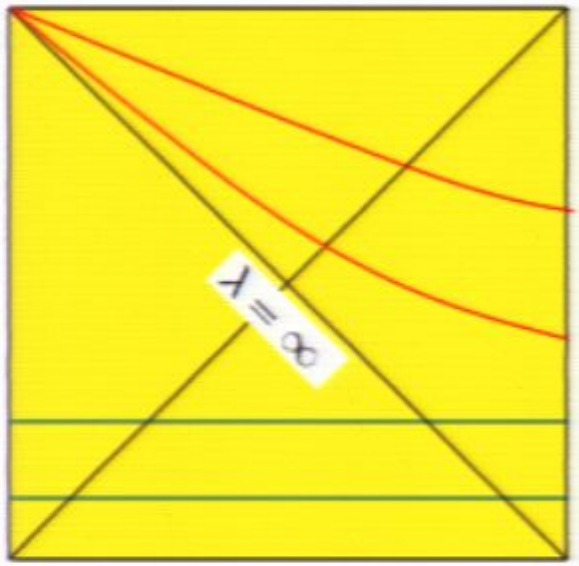

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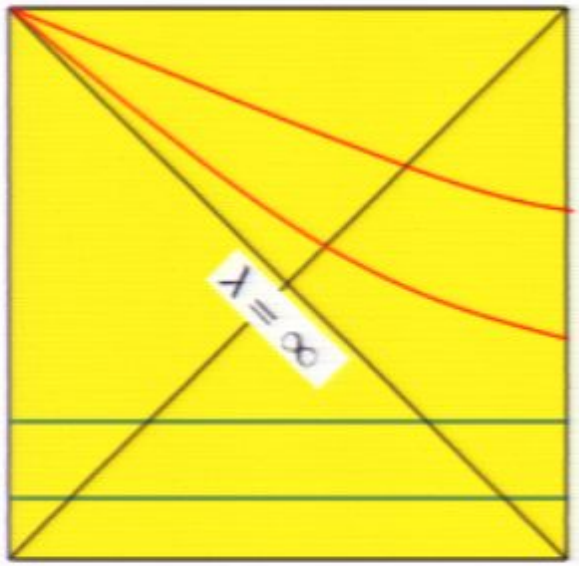

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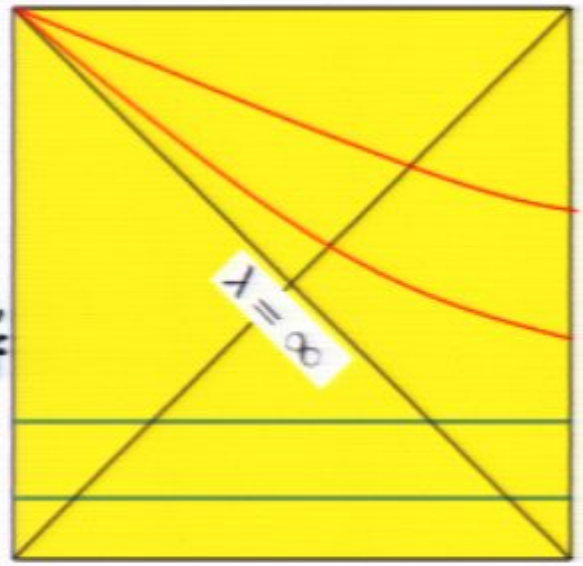
So assume $\bar{h}_{ab}$ is TT.
Use residual gauge trans to impose

$h_{00} = h_{0i} = 0, \dot{h}_{00} = \dot{h}_{0i} = 0$ for some λ

Elliptic PDE for $\xi_a, \dot{\xi}_a$.



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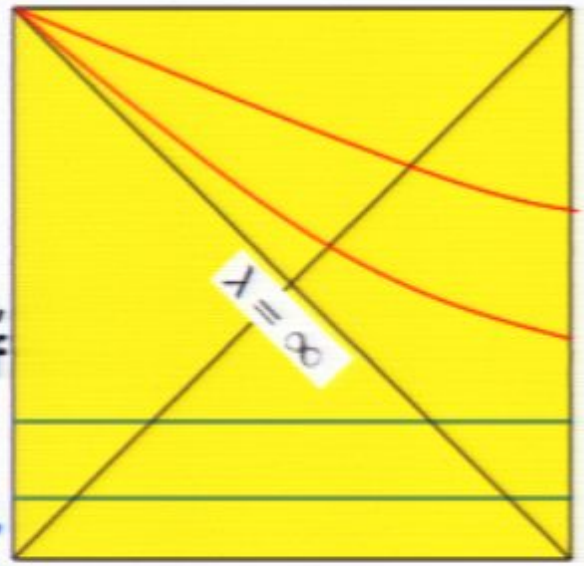

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By Euclidean and scaling symmetries, remaining elliptic PDE for ξ_i must be of the form

$$s_i = \partial_k \partial^k \xi_i + A\, \partial_i \partial^k \xi_k + \frac{B}{\lambda^2} \xi_i$$

where $s_i = \alpha \dot{h}_{0i} + \beta \partial_i h_{00} + \gamma \frac{h_{0i}}{\lambda}$

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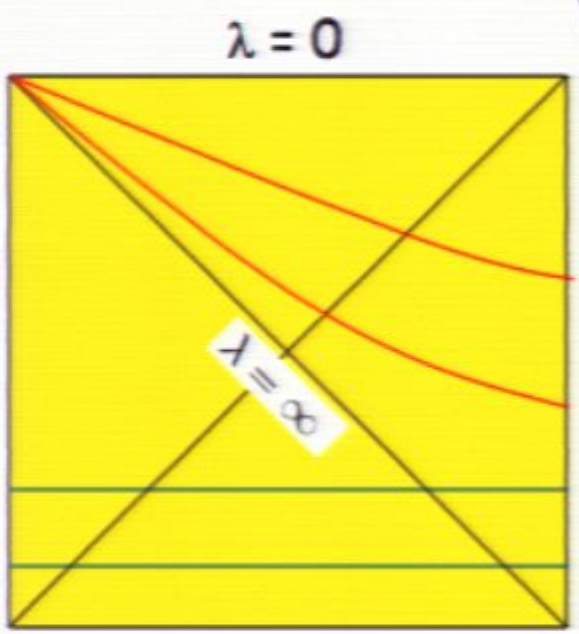


Calculations give:

A = (d-3)/(d-1), B =0, α = -1, β = 1/(d-1), γ = (d-2)

A > -1 ⇨ operator L is elliptic

$$\partial_k \partial^k + \frac{B}{\lambda^2} > L > (A+1)\partial_k \partial^k + \frac{B}{\lambda^2}$$

B =0 ⇨ operator L is *massless!*

⇨ G ~ $r^{-(d-3)}$; i.e., 1/r for d=4.

Measure is $d^{d-1}x$, so solutions exist only if $s_i \sim r^{-p}$ for p > 2.

Might k=0 TTS gauge be singular on global dS?

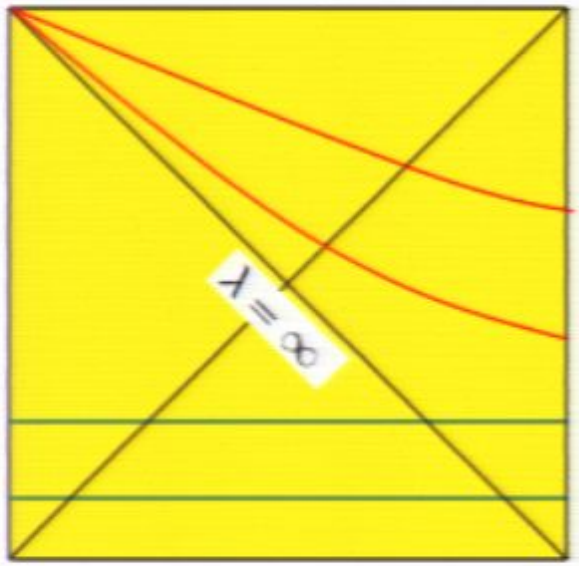
$$s_i = -\dot{h}_{0i} + \frac{1}{d-1}\partial_i h_{00} + (d-2)\frac{h_{0i}}{\lambda}$$

Solutions exist only if $s_i \sim r^{-3}$.

On global dS, any smooth solution is allowed. So choose a TT synchronous mode in *global* coordinates and convert to k=0; $(\theta,\tau)_{\text{global}} \to (r,\lambda)_{k=0}$

$h_{\tau\tau} = h_{\tau\theta} = 0$, but $h_{\theta\theta} = h(\text{angles})\, f(\tau)$

With $f \sim e^{-2\tau/\ell}$



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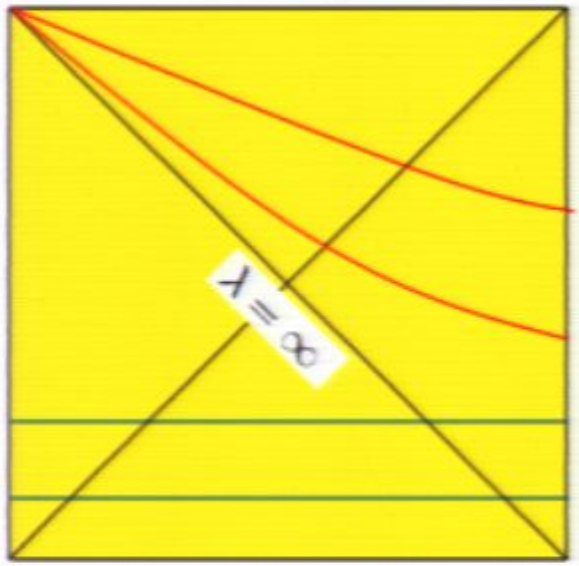
With $f \sim e^{-2\tau/\ell}$

At fixed λ, large r find

$e^{-2\tau/\ell} \sim r^2/2\lambda$,

$$\theta \sim \pi - \frac{2\ell}{r}\left(1 + \frac{\lambda^2 - \ell^2}{r^2} + \ldots\right)$$

$\lambda = 0$



$$h_{00} = \left(\frac{\partial\theta}{\partial\lambda}\right)^2 h_{\theta\theta} \sim \frac{\ell^2\lambda^2}{r^6}\frac{r^4}{\ell^2\lambda^2} \sim \frac{1}{r^2} \qquad h_{0i} \sim h_{0r} = \left(\frac{\partial\theta}{\partial\lambda}\right)\left(\frac{\partial\theta}{\partial r}\right) h_{\theta\theta} \sim \frac{1}{\lambda r}$$

$\Longrightarrow$ $s_i \sim 1/\lambda^2 r$ *No solution!*

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- TT Synchronous gauge in k=0 slicing is singular on global dS. Assuming TT leads to:

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- Generically, $s_i \sim 1/\lambda^2 r$, falls off too slowly.
- Note: no such problem w/ synchronous gauge on torus. Zero mode of s_i vanishes due to transversality.
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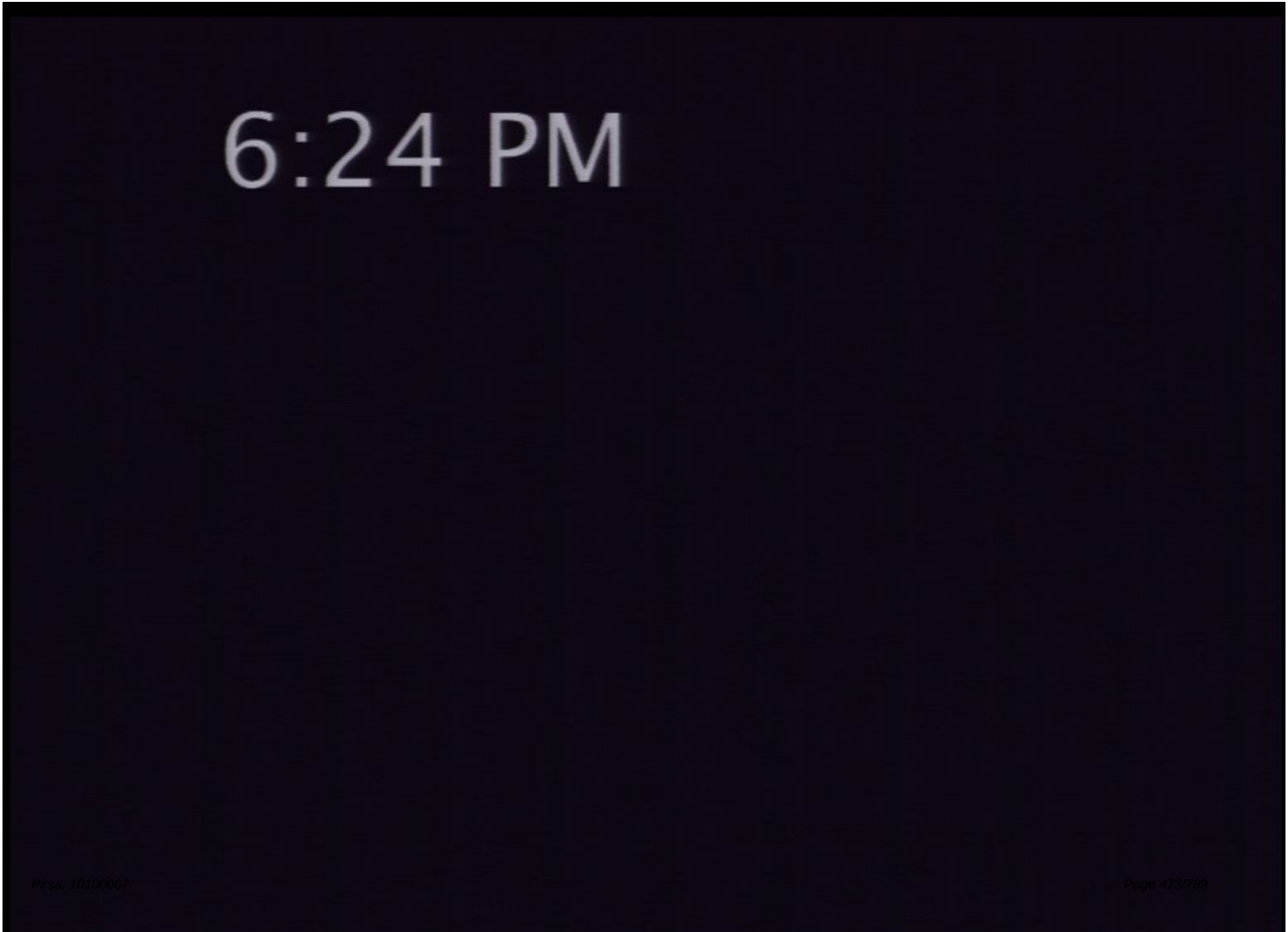
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$$s_i = \partial_k \partial^k \xi_i + \frac{d-1}{d-3}\,\partial_i \partial^k \xi_k \qquad s_i = -\dot{h}_{0i} + \frac{1}{d-1}\partial_i h_{00} + (d-2)\frac{h_{0i}}{\lambda}$$

- Generically, $s_i \sim 1/\lambda^2 r$, falls off too slowly.
- Note: no such problem w/ synchronous gauge on torus. Zero mode of s_i vanishes due to transversality.
- Resolves tension in literature. Supports argument that graviton vacuum is dS invariant.
- ⟹ No invariant large IR effects inside horizon (i.e., inside static patch), even at large times (w/o massless scalars).

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Might k=0 TTS gauge be singular on global dS?

$$s_i = -\dot{h}_{0i} + \frac{1}{d-1}\partial_i h_{00} + (d-2)\frac{h_{0i}}{\lambda}$$

Solutions exist only if $s_i \sim r^{-3}$.

On global dS, any smooth solution is allowed. So choose a TT synchronous mode in *global* coordinates and convert to k=0; $(\theta,\tau)_{\text{global}} \to (r,\lambda)_{k=0}$

$h_{\tau\tau} = h_{\tau\theta} = 0$, but $h_{\theta\theta} = h(\text{angles})\, f(\tau)$

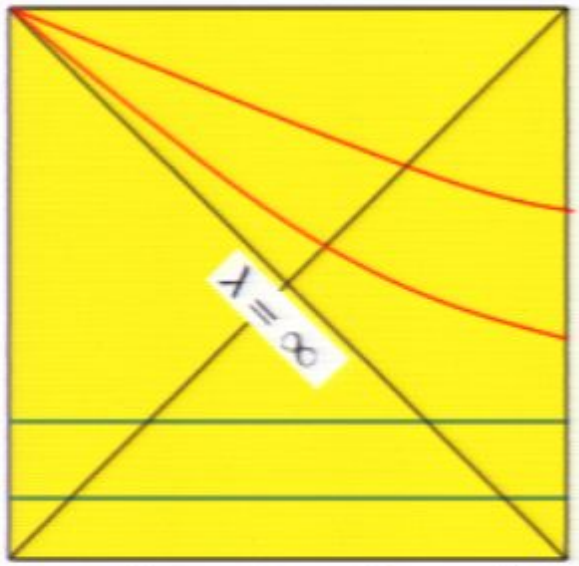
With $f \sim e^{-2\tau/\ell}$

At fixed λ, large r find

$e^{-2\tau/\ell} \sim r^2/2\lambda$,

$$\theta \sim \pi - \frac{2\ell}{r}\left(1 + \frac{\lambda^2 - \ell^2}{r^2} + \ldots\right)$$

$\lambda = 0$



$$h_{00} = \left(\frac{\partial\theta}{\partial\lambda}\right)^2 h_{\theta\theta} \sim \frac{\ell^2\lambda^2}{r^6}\frac{r^4}{\ell^2\lambda^2} \sim \frac{1}{r^2} \qquad h_{0i} \sim h_{0r} = \left(\frac{\partial\theta}{\partial\lambda}\right)\left(\frac{\partial\theta}{\partial r}\right) h_{\theta\theta} \sim \frac{1}{\lambda r}$$

$\Longrightarrow$ $s_i \sim 1/\lambda^2 r$ *No solution!*