Paolo Creminelli, ICTP (Trieste)

Robustness of primordial tensor mode predictions

with J. Gleyzes, J. Noreña and F. Vernizzi, 1407.8439 (PRL)

with L. Bordin, M. Mirbabayi and J. Noreña, in progress

Moriond - March 24th 2016

Compare with scalars

- It is easy to play with scalar perturbations:

  1. choice of potential
  2. many scalars (effects on late Universe)
  3. speed of propagation c_S

  Room for alternatives to inflation

Compare with scalars

• It is easy to play with scalar perturbations:

1. choice of potential
2. many scalars (effects on late Universe)
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Room for alternatives to inflation

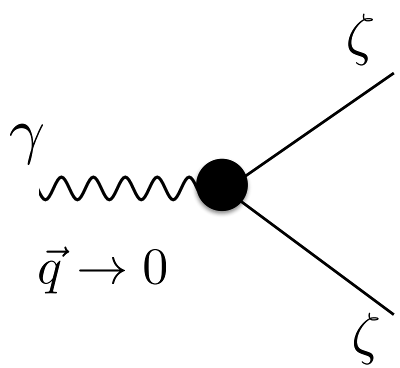
• It is not easy to play with gravity ! GWs are direct probes of H

Two observables

1. Tensor power spectrum: $\Delta_h^2(k) = \frac{2}{\pi^2}\frac{H^2}{M_{\rm pl}^2}$

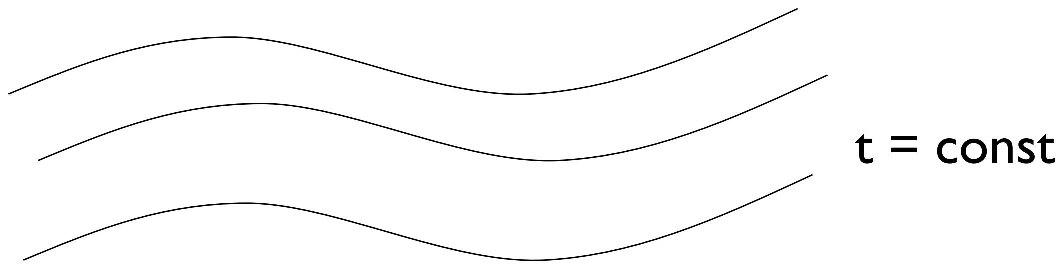
   Can we modify it by non-trivial speed c_T ?

2. Consistency relation with soft tensor mode: $\lim_{\vec{q}\to 0}\langle \gamma_{\vec{q}}\, \zeta_{\vec{k}_1} \zeta_{\vec{k}_2}\rangle$



Speed of gravity

Effective field theory of inflation:



Parametrize the most general dynamics compatible with symmetries

Cheung, PC, Fitzpatrick, Kaplan, Senatore 07

$$S = \int d^4x \sqrt{-g} \frac{M_{\rm Pl}^2}{2} \left[R - 2(\dot{H} + 3H^2) + 2\dot{H} g^{00} - \underline{\underline{\left(1 - c_T^{-2}(t)\right)\left(\delta K_{\mu\nu} \delta K^{\mu\nu} - \delta K^2\right)}} \right]$$

$$K_{ij} = \frac{1}{2N}\left(\dot{h}_{ij} - \nabla_i N_j - \nabla_j N_i\right)$$

$$S_{\gamma\gamma} = \frac{M_{\rm Pl}^2}{8} \int d^4x a^3 c_T^{-2} \left[\dot{\gamma}_{ij}^2 - c_T^2 \frac{(\partial_k \gamma_{ij})^2}{a^2} \right] \longrightarrow \Delta_T^2 = \frac{2}{\pi^2} \frac{H^2}{M_{\rm Pl}^2} \cdot \frac{1}{c_T(t)}$$

Speed of gravity

$$\Delta_T^2 = \frac{2}{\pi^2} \frac{H^2}{M_{\rm Pl}^2} \cdot \frac{1}{c_T(t)}$$

- Scale invariance without H ~ const.
- P_T does not measure energy scale
- $n_T \neq 2\dot{H}/H^2 < 0$

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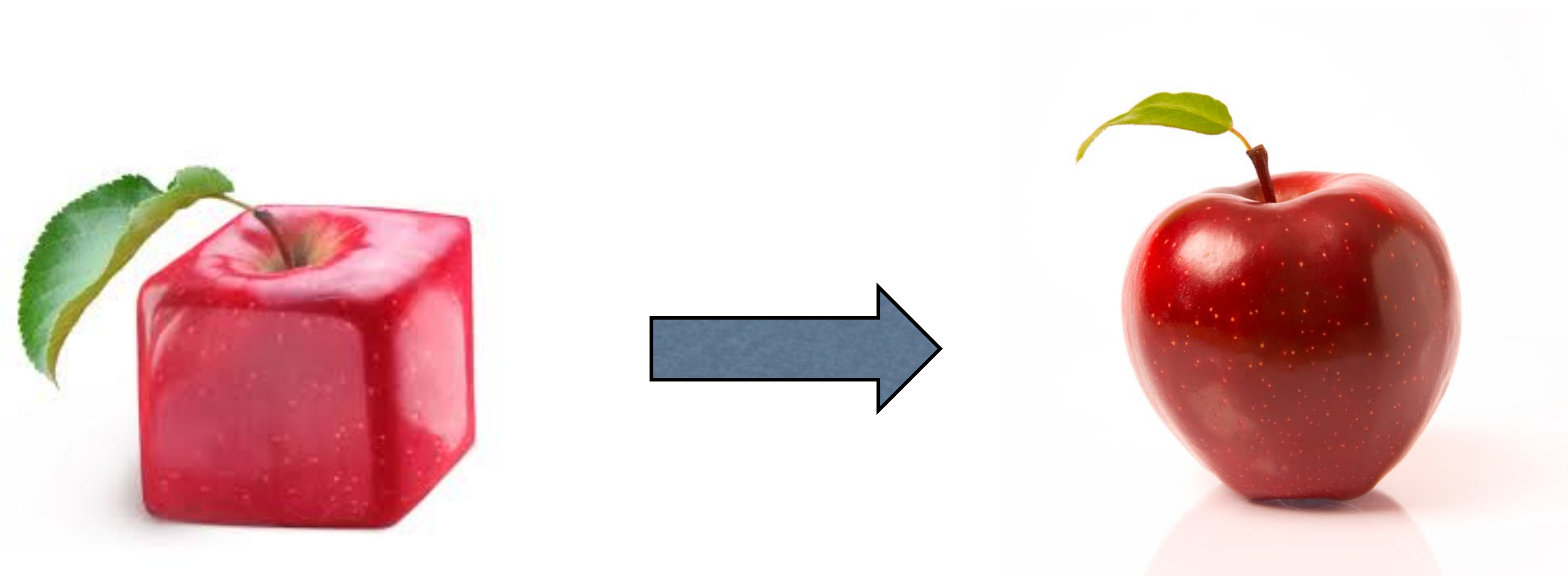

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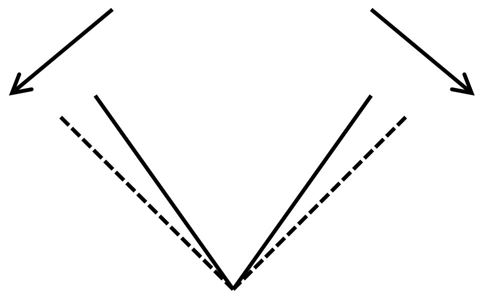
Disformal transformation:

$$g_{\mu\nu} \mapsto g_{\mu\nu} - (1 - c_T^2)\partial_\mu\phi\partial_\nu\phi/(\partial\phi)^2$$



$$g_{\mu\nu} \mapsto c_T^{-1}(t)\, g_{\mu\nu}$$

$$\tilde t \equiv \int c_T^{1/2}(t){\rm d}t\ , \qquad \tilde a(\tilde t) \equiv c_T^{-1/2} a(t)$$

$$\dot c_T = 0$$

$$\int {\rm d}^4x\sqrt{-\tilde g}\frac{M_{\rm Pl}^2}{2}\left\{\tilde R - 2(\dot{\tilde H} + 3\tilde H^2) + 2\dot{\tilde H}\tilde g^{00} + 2(1-c_T^2)\dot{\tilde H}\times\left(1-\sqrt{-\tilde g^{00}}\right)^2\right\}$$

$$\tilde c_s = 1/c_T$$

NG in original frame beyond decoupling!

Disformed away

$$S = \int \mathrm{d}\tilde{t}\mathrm{d}^3x\sqrt{-\tilde{g}}\frac{M_{\rm Pl}^2}{2}\Big\{\tilde{R} - 2(\dot{\tilde{H}} + 3\tilde{H}^2) + 2\dot{\tilde{H}}\tilde{g}^{00} + \Big[2(1-c_T^2)\dot{\tilde{H}} - \quad \tfrac{3}{2}\alpha^2 -$$

$$c_T^2\Big(\dot{\alpha} + \tilde{H}\alpha + \frac{1}{2}\alpha^2\Big)\Big] \times \Big(1 - \sqrt{-\tilde{g}^{00}}\Big)^2 + 2\alpha\,\delta\tilde{K}\Big(1 - \sqrt{-\tilde{g}^{00}}\Big)\Big\}$$

$$\alpha \equiv \dot{c_T}/c_T$$

Blue tilt using c_T → Stable $\dot{\tilde{H}} > 0$ (NEC violation) with operator $\delta N \delta K$

PC, Luty, Nicolis, Senatore 06

No loss of generality in taking $c_T = 1$
(even multifield or alternatives to inflation)

Exceptions: 1. Different symmetry pattern (solid inflation, gauge-flation…)

e.g Cannone, Tasinato, Wands 14

2. GWs not produced as vacuum fluctuations

Domcke + Ben-Dayan talks

Spectrum and 3pf corrections

- Corrections to spectrum start with 3 derivative operators:

$$\varepsilon^{ijk}\partial_i\dot{\gamma}_{jl}\dot{\gamma}_{lk}\ , \qquad \varepsilon^{ijk}\partial_i\partial_m\gamma_{jl}\partial_m\gamma_{lk}$$

$$4\int \mathrm{d}^4x\ \varepsilon^{0ijk}\nabla_i\delta K_{jl}\delta K_{lk} \qquad -4\int \mathrm{d}^4x\ \varepsilon^{ijk}\left(\frac{1}{2}{}^3\Gamma^p_{iq}\partial_j{}^3\Gamma^q_{kp}+\frac{1}{3}{}^3\Gamma^p_{iq}{}^3\Gamma^q_{jr}{}^3\Gamma^r_{kp}\right)$$

Parity violation: different power spectrum for each elicity

$$\langle\gamma^{\pm}_{\vec{k}}\gamma^{\pm}_{\vec{k}'}\rangle=(2\pi)^3\delta(\vec{k}+\vec{k}')\frac{H^2}{2M^2_{\mathrm{Pl}}k^3}\left(1\pm\beta\frac{\pi}{2}\frac{H}{\Lambda}\right)$$

For r ~ 0.1 we can observe a 50% difference between the two polarizations

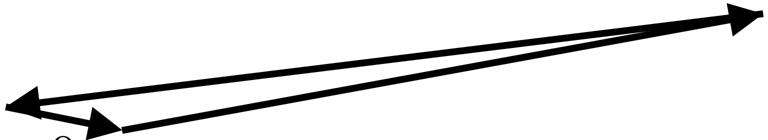
Gluscevic, Kamionkowski 10
Ferte, Grain 14

- Not only spectrum, also $\langle\gamma\gamma\gamma\rangle$ cannot be modified at leading order in derivatives

Single-field consistency relation for 3pf

Maldacena 03
PC, Zaldarriaga 04

Squeezed limits



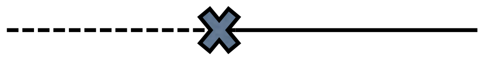
$\vec{q} \to 0$

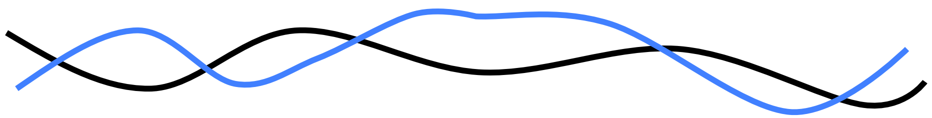
$$\phi(t,\vec{x}) = \phi_0(t) \qquad\qquad h_{ij} = e^{2\zeta(t,\vec{x})}\left(e^{\gamma(t,\vec{x})}\right)_{ij}$$

The long mode is already classical when the other freeze
and acts simply as a rescaling of the coordinates

$$\lim_{\vec{q}\to 0}\langle \zeta_{\vec{q}}\, \zeta_{\vec{k}_1} \zeta_{\vec{k}_2}\rangle' = -\langle \zeta_{\vec{q}}\, \zeta_{-\vec{q}}\rangle' \langle \zeta_{\vec{k}_1} \zeta_{-\vec{k}_1}\rangle' \frac{\mathrm{d}\ \log k_1^3 \langle \zeta_{\vec{k}_1} \zeta_{-\vec{k}_1}\rangle'}{\mathrm{d}\log k_1}$$

Violated in multifield:

σ  ζ



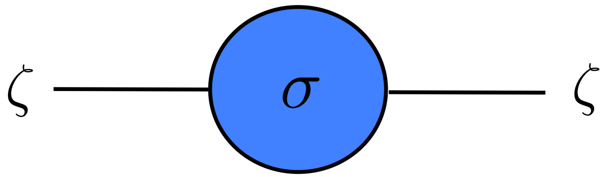
f_{NL}^{local} as smoking gun for multifield models

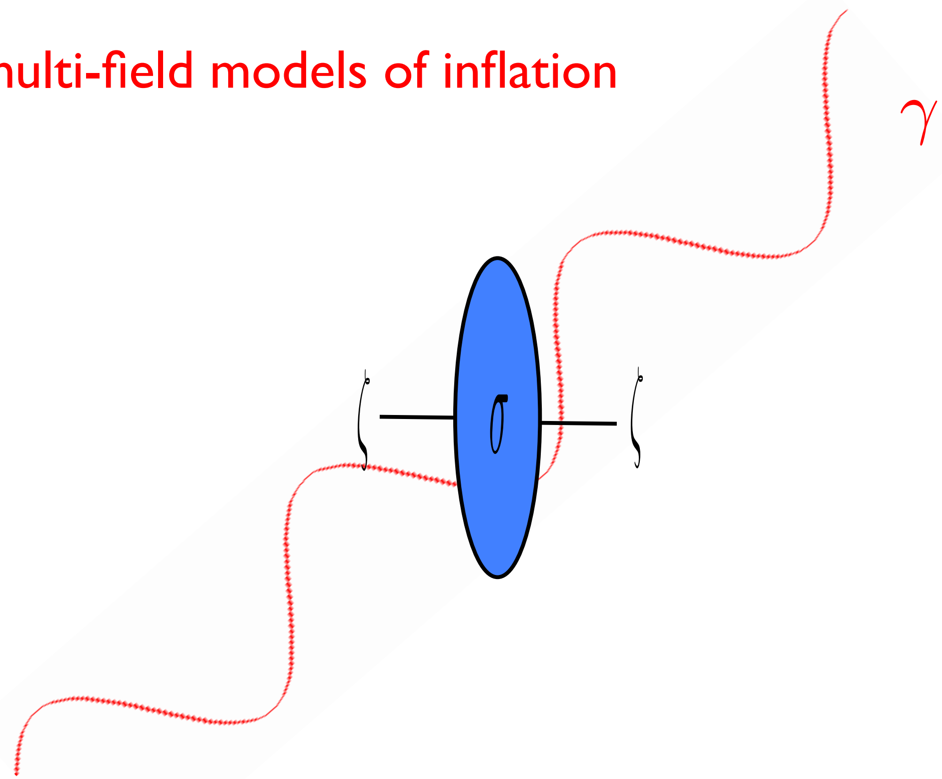
Tensor consistency relation for 3pf

Same logic leads to

$$\lim_{\vec{q}\to 0}\langle\gamma^s_{\vec{q}}\,\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\rangle' = -\langle\gamma^s_{\vec{q}}\,\gamma^s_{\vec{-q}}\rangle'\epsilon^s_{ij}k^i_1 k^j_1\frac{\partial}{\partial k_1^2}\langle\zeta_{\vec{k}_1}\zeta_{-\vec{k}_1}\rangle'$$

But this is valid also for multi-field models of inflation





Violated if there are extra tensors

see also Dimastrogiovanni, Fasiello, Kamiokowski 15

Higuchi bound

Higuchi 87

Spin-2 particles in de Sitter with $m^2 < 2H^2$ are forbidden (besides the graviton)

- Group theoretical statement
- In Pauli-Fierz action, longitudinal component becomes a ghost
- Symmetries on 2pf

Arkani-Hamed, Maldacena 15

$$\mathcal{O}_{ij} \sim \eta^{\Delta} \qquad \Delta_{\pm} = \frac{3}{2} \pm \sqrt{\left(s - \frac{1}{2}\right)^2 - \frac{m^2}{H^2}}$$

$$\langle \epsilon^2 . O_{\vec{k}} \tilde{\epsilon}^2 . O_{-\vec{k}} \rangle' \propto k^{2\Delta - 3} \left[e^{-2i\chi} + \frac{4(3-\Delta)}{\Delta} e^{-i\chi} + \frac{6(3-\Delta)(2-\Delta)}{(\Delta-1)\Delta} + \frac{4(3-\Delta)}{\Delta} e^{i\chi} + e^{2i\chi} \right]$$

Becomes negative
for $\Delta < 1$

For example one cannot have KK gravitons with a small mass

Composite operators

Does Higuchi bound apply to composite operators? E.g. $\partial_i\phi\partial_j\phi - \frac{1}{3}(\partial\phi)^2\delta_{ij}$

No!

- Only if $\mathcal{O}_{\mu\nu} \sim \eta^{\Delta}$
- Only for conformal primaries

$$(2\Delta+1)(\partial_i\phi\partial_j\phi - \frac{1}{3}\delta_{ij}(\partial\phi)^2) - \Delta\left[\partial_i(\phi\partial_j\phi) - \frac{1}{3}\delta_{ij}\partial_k(\phi\partial_k\phi)\right]$$

Descendants

Cannot rule out the existence of operators below Higuchi, though one has probably to face tachyons

Ways out

- Coupling with inflaton breaks dS isometry: can make helicity-2 healthy
- Bigravity theories have a reference metric different from dS

Hinterbichler's talk

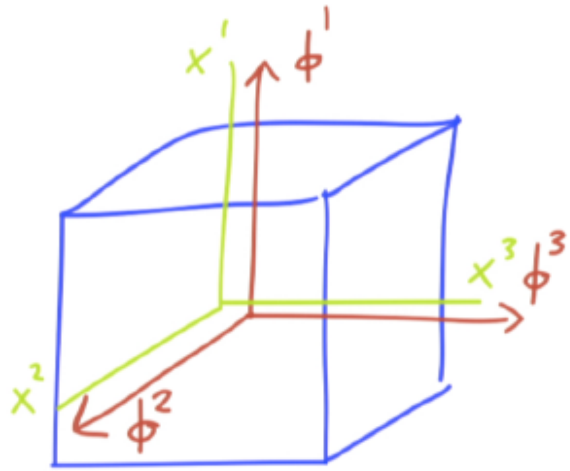
- Models with a different symmetry pattern

Piazza's talk

E.g. Solid inflation (also Gauge-flation, Chromo-Natural...)

CR rescaling argument fails
+ extra tensors

$$\langle \gamma^{\lambda}_{\vec{q}\to 0}\zeta_{\vec{k}}\zeta_{-\vec{k}}\rangle' = -\frac{10}{9}\,\frac{F_Y}{F}\,P_\gamma(q)P_\zeta(k)\,\frac{1}{c_L^2\epsilon}\,\left(\hat{k}^i\hat{k}^j\epsilon^{\lambda}_{ij}\right)$$

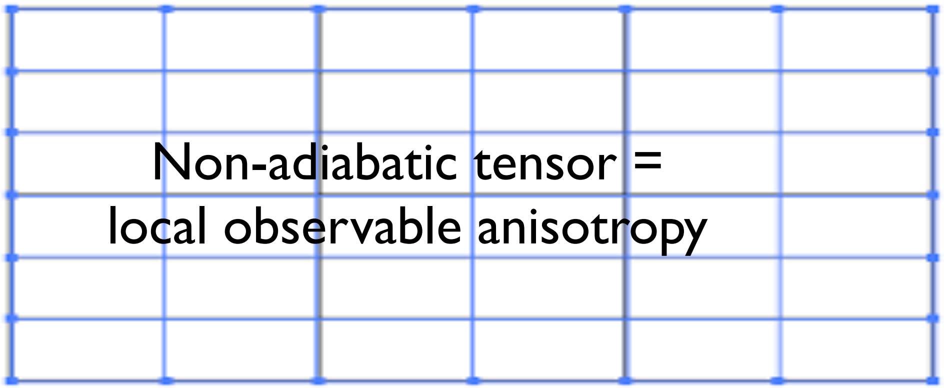


Anisotropy

Violation of tensor CR $\longleftrightarrow$ (Light) Non-adiabatic tensor mode

Non-adiabatic scalar just changes local homogeneous values

VS



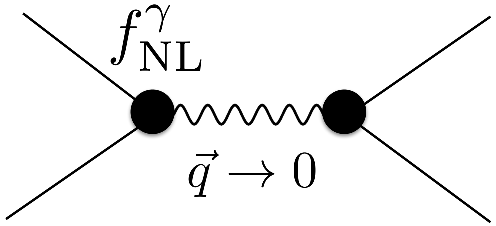
Universe does not isotropize quickly during inflation

We ask inflation to make the Universe flat and homogeneous, not isotropic

Notari's talk

Experimental signatures

$\langle BTT \rangle$ Meerburg, Meyers, van Engelen, Ali Haimoud 16 NEXT TALK!!



If tensor CR holds:

1. Super-H γ does nothing
2. Inside-H γ induces space-dependent quadrupolar power spectrum (fossil)

e.g. Schmidt, Pajer, Zaldarriaga 13

If tensor CR is broken:

1. Quadrupolar modulation of power spectrum: $P_\zeta(k)\left[1+\mathcal{Q}_{ij}\hat{k}_i\hat{k}_j\right]$

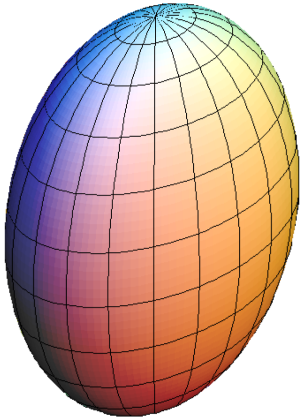
$\mathcal{Q} \lesssim 10^{-2}$ Planck 15

$$P_\zeta(\vec{k}) = P_\zeta(k)\left[1 + f^{\gamma}_{\rm NL}\epsilon^s_{ij}(\vec{q})\hat{k}_i\hat{k}_j\gamma^s_q\right]$$

$$\mathcal{Q}^2 \simeq \frac{8\pi}{15} f^{\gamma\,2}_{\rm NL}\, r P_\zeta \cdot \Delta N$$

Sensitive to number of e-folds

Experimental signatures



Statistics of Gaussian Q_{ij} completely fixed by its variance

Different from axisymmetric: $P_\zeta(k)\left[1+(\vec{E}\cdot\hat{k})^2\right]$

(like models with vector in background)

Probability same eigenvalues at 10% is ~ 0.7%

2. 4-point function in countercollinear limit

$$\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\zeta_{\vec{k}_4}\rangle' = \frac{{f_{\rm NL}^{\gamma}}^2}{4}P_\gamma(q)P_\zeta(k_1)P_\zeta(k_3)\cos 2\chi_{12,34}$$

No analysis so far. Similar to $\tau_{\rm NL}$ but orthogonal

Maybe GWs are already in the data!

Conclusions

- Robustness of $\Delta_h^2(k) = \frac{2}{\pi^2}\frac{H^2}{M_{\rm pl}^2}$

- Robustness of tensor consisteny relations

- Violations would be extremely interesting: different symmetry pattern

Backup slides