just an illusion

Stoccolma 27.6.2012

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Imagination ("just an illusion")

misleading inferences

19th century humans (Galilean/pre-Einsteinian) could have asked do we all share the same time?
(more technically: is time a relativistic invariant?)

but nobody asked

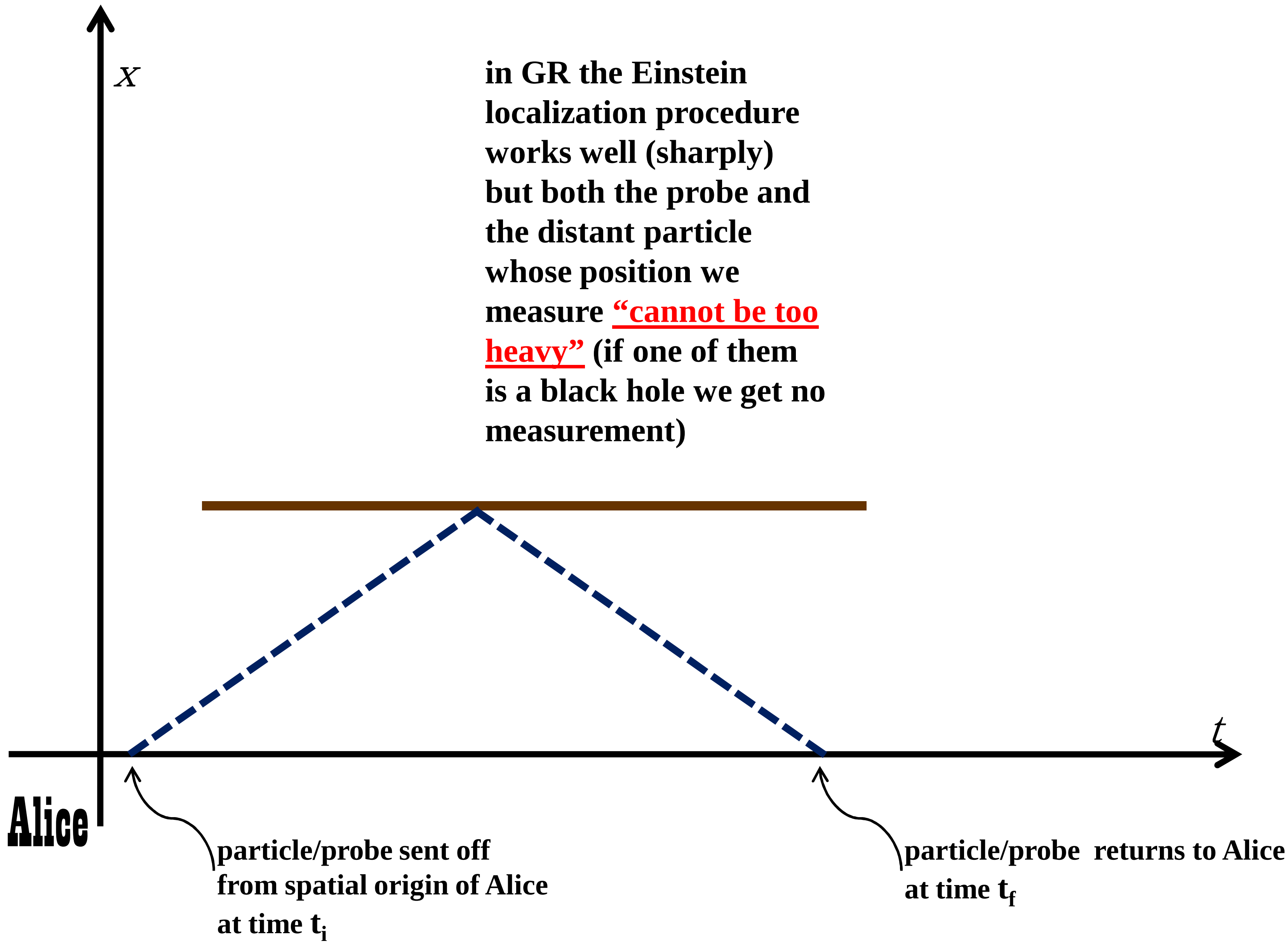
and if they happened to ask themselves this question they would answer “of course yes”

we now know the answer is NO

the key mission for fundamental physics:
which questions we are not even asking whose answer is NO???

Einstein localization procedure and Quantum Gravity

in GR the Einstein localization procedure works well (sharply) but both the probe and the distant particle whose position we measure "cannot be too heavy" (if one of them is a black hole we get no measurement)



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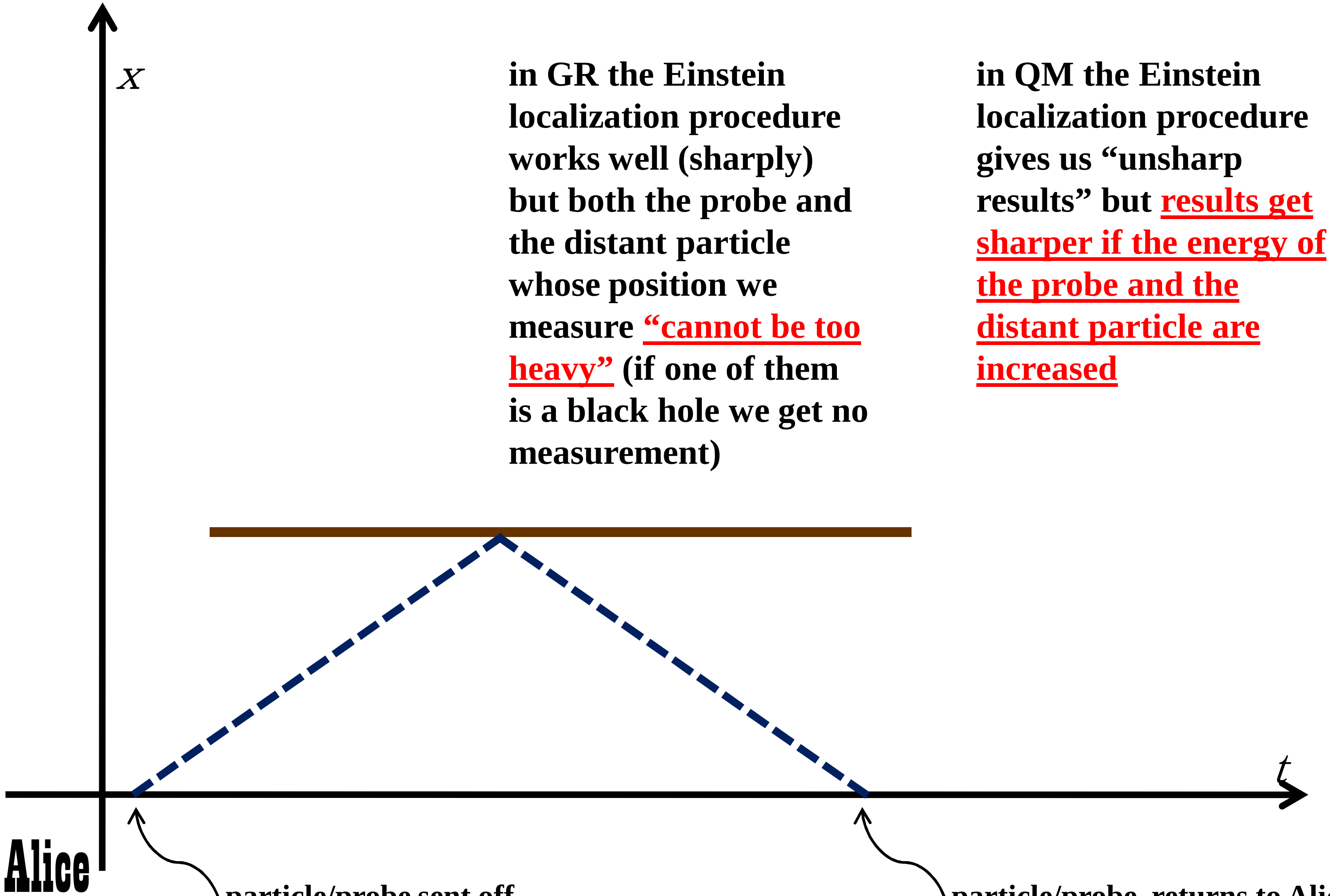
in QM the Einstein localization procedure gives us “unsharp results” but results get sharper if the energy of the probe and the distant particle are increased



particle/probe sent off from spatial origin of Alice at time t_i

particle/probe returns to Alice at time t_f

evidently no classical spacetime for quantum gravity

this is the "localization problem in quantum gravity" which has fascinated so many physicists

Mead, PhysRev135 (1964) B849
Padmanabhan, *ClassQuantGrav4*(1987)L107
Doplicher+Fredenhagen+Roberts, PhysLettB331(1994)39
Ng+VanDam, ModPhysLettA9(1994)335
GAC, ModPhysLettA9(1994)3415

and many others...
see reviews:
Garay, IntJournModPhysA10(1995)145
Hossenfelder,arXiv:1203.6191

which sort of weird notion of spacetime could we encounter in the quantum-gravity realm?

how weird could it get?

must be consistent with everything we know about spacetime!
so what is it that we know about spacetime?

Well let us start from the very beginning.
How do we first learn about spacetime?

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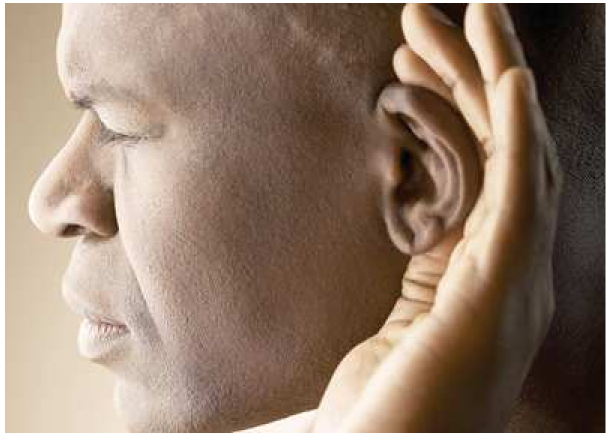

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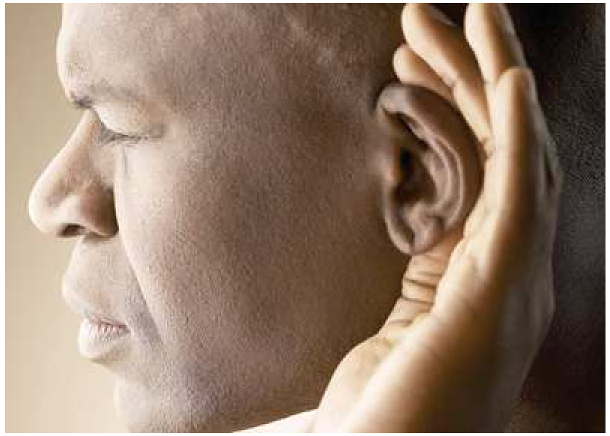
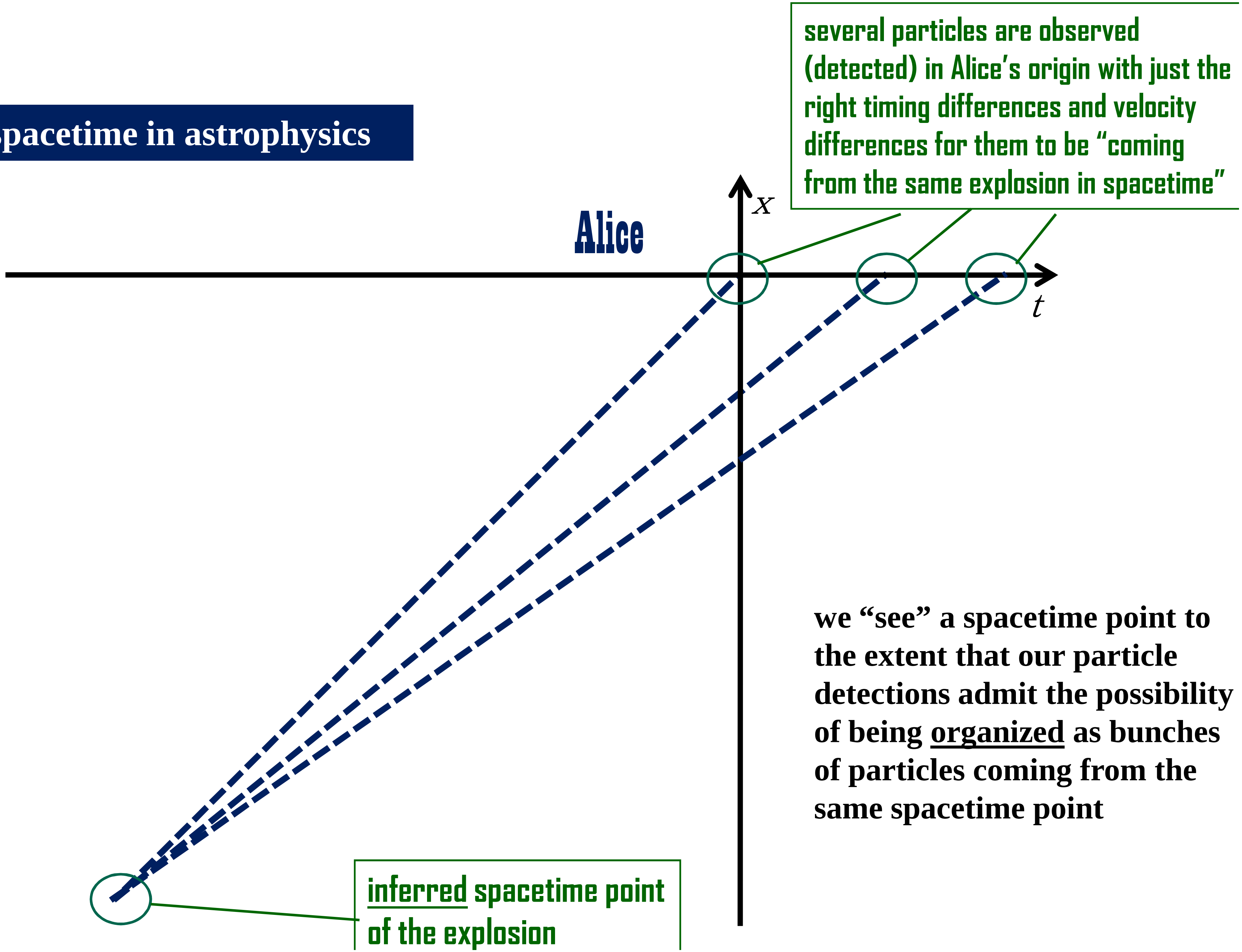




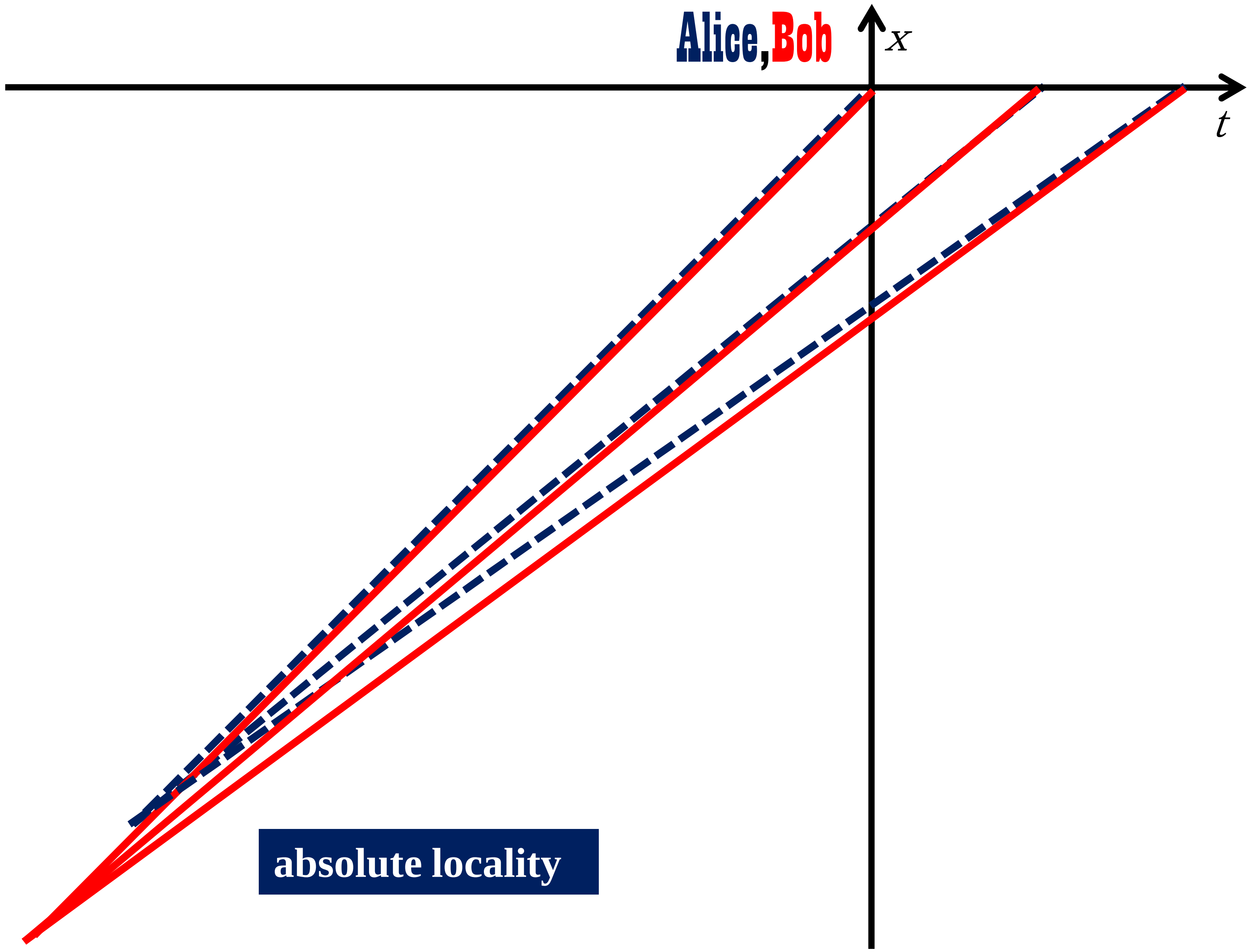
So our first encounters with spacetime are particle detections.
This suggests that we get into the habit of conceptualizing a spacetime because this notion is somehow a <u>useful organizing notion</u> for the particle detections by our "resident detectors"

spacetime in astrophysics



we "see" a spacetime point to the extent that our particle detections admit the possibility of being <u>organized</u> as bunches of particles coming from the same spacetime point

a remarkable fact: a boosted observer Bob describes the explosion somewhat differently <u>but still infers an explosion at a distant spacetime point</u>



main message from this: the observables physicists call "spacetime observables" are "less primitive" then the observables physicists associate to pure particle detections

one can describe a particle detection without any reference to a spacetime

one cannot perform a spacetime measurement without involving particle detections

why do we care? we don't
As long as the current experimental situation stands, allowing us to treat spacetime observables as no less tangible than particle detections, we do not care about these differences

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But is important to notice that the status of spacetime in contemporary physics resembles the status of the ether at the beginning of last century. Poincare’:

> “Whether the ether exists or not matters little - let us leave that to the metaphysicians; what is essential for us is, that everything happens as if it existed, and that this hypothesis is found to be suitable for the explanation of phenomena. After all, have we any other reason for believing in the existence of material objects? That, too, is only a convenient hypothesis; only, it will never cease to be so, while some day, no doubt, the ether will be thrown aside as useless.”

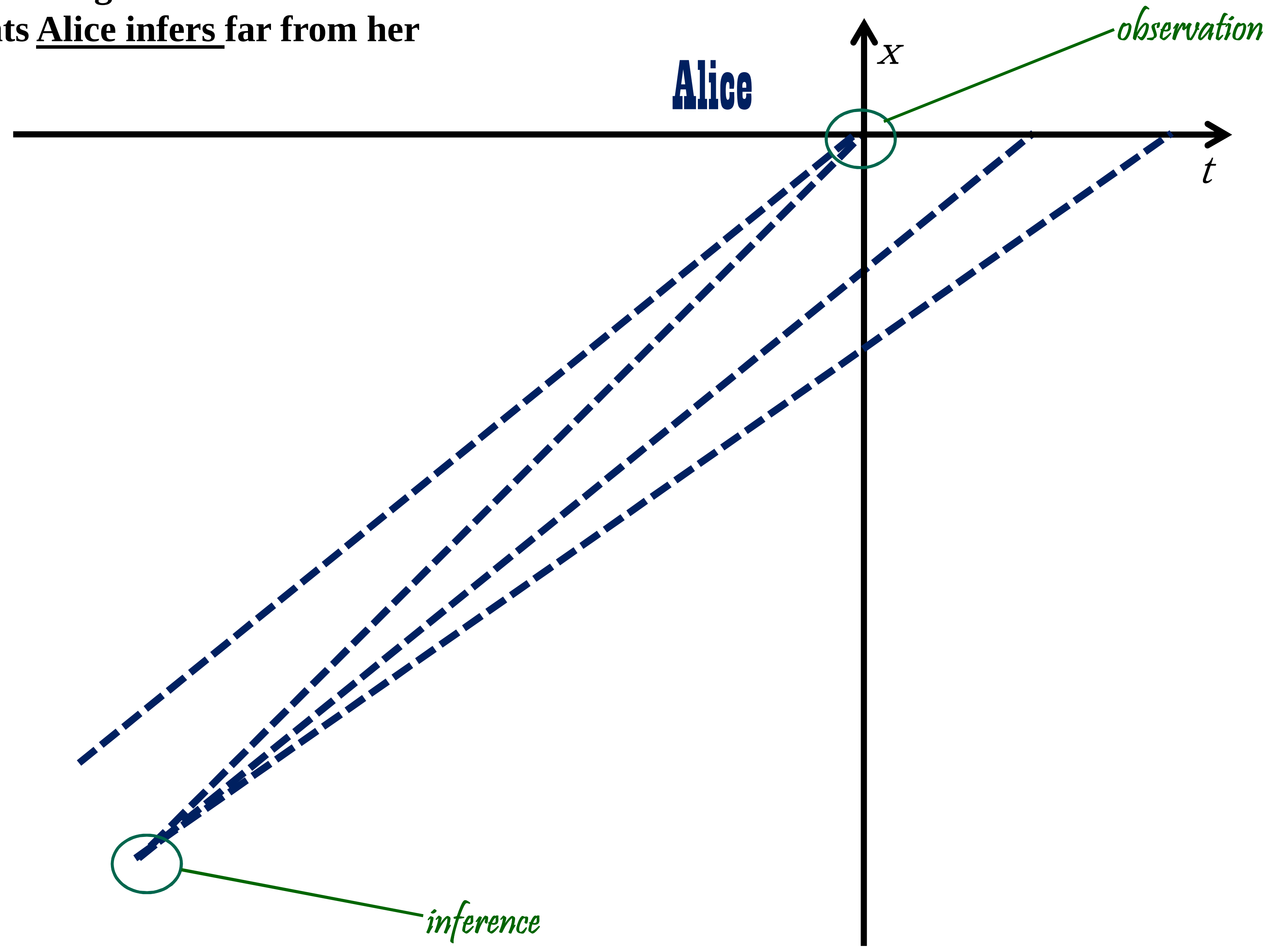
this awareness prepares us for possible "surprises"

of course it does not ensure that there will be any "surprises"

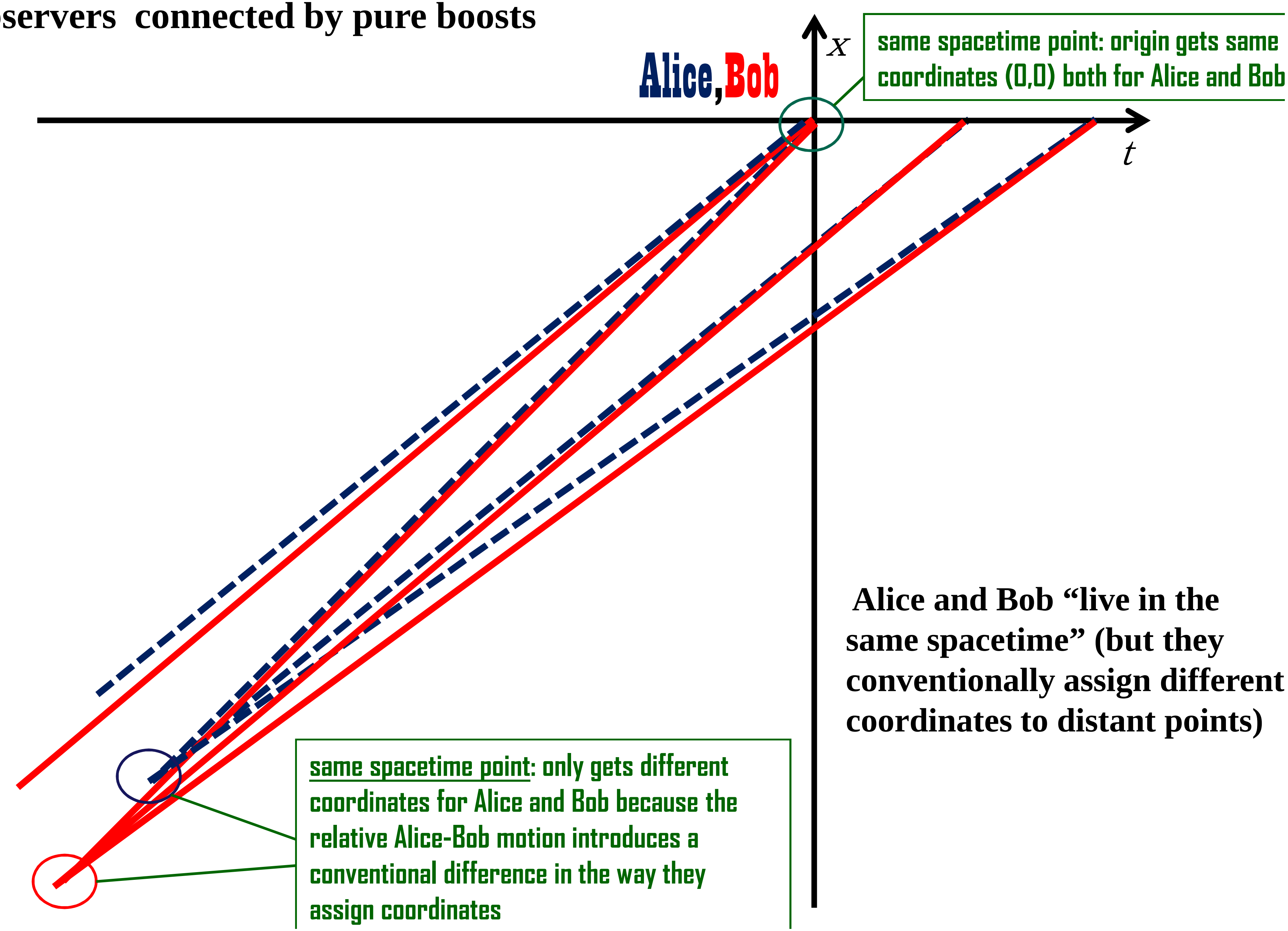
but, just in case, what is the weakest building block in our present conceptualization of spacetime?
by which of course I mean:
which aspect of our present conceptualization of spacetime relies on the most challengeable experimental basis?

<u>this weakest building block is the absolute locality of distant events</u>

in our current theories (therefore, evidently, within the experimental data gathered so far) coincidences of events <u>observed at Alice</u> appear to be no less robust/tangible than coincidences of events <u>Alice infers</u> far from her



story with local observations and distant inferences applies equally well to all observers connected by pure boosts



Alice and Bob "live in the same spacetime" (but they conventionally assign different coordinates to distant points)

do any of the theories that are currently studied challenge the notion of absolute locality of distant events?

one definite example are DSR-relativistic theories, where a large momentum scale plays the same relativistic role as the large velocity scale "c"

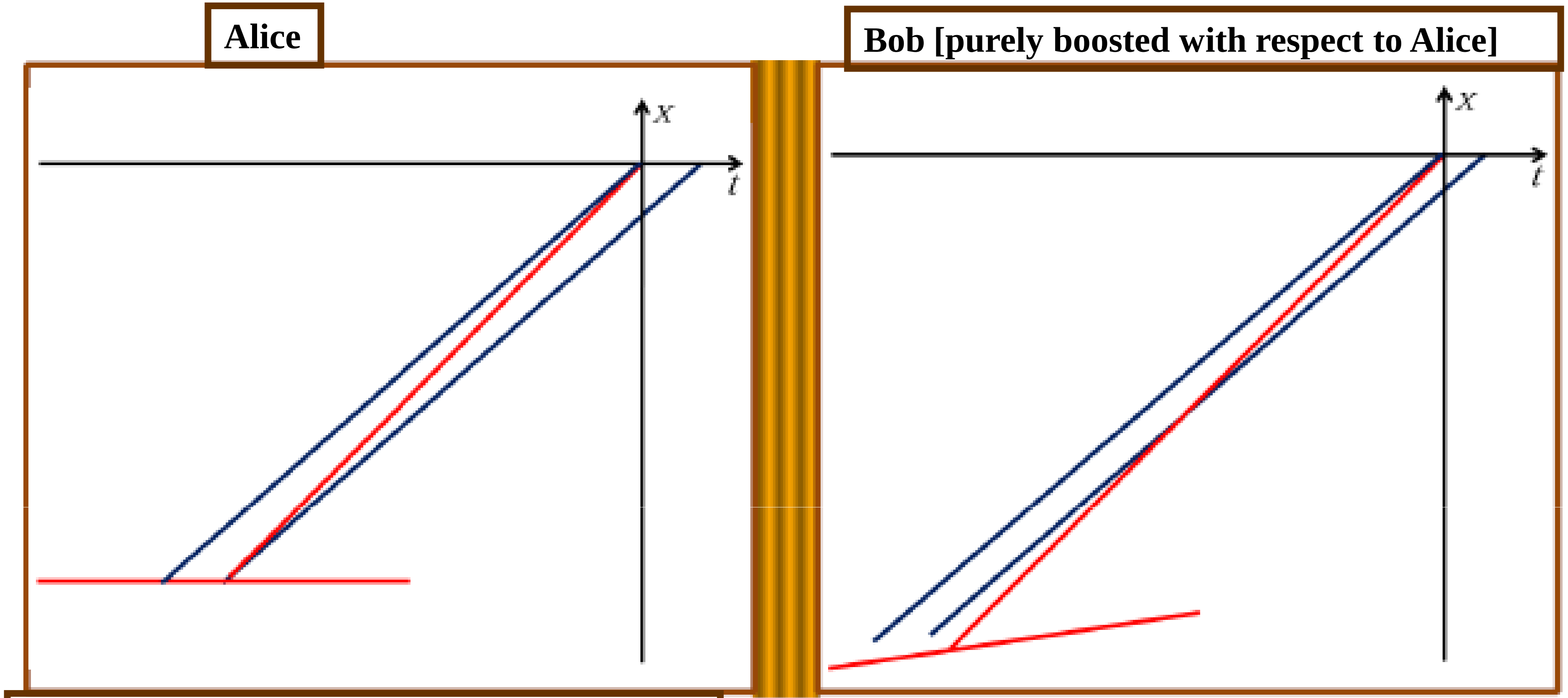
GAC, grqc0012051,IntJModPhysD11,35
hepth0012238,PhysLettB510,255
KowalskiGlikman,hepth0102098,PhysLettA286,391
Magueijo+Smolin, hepth0112090,PhysRevLett88,190403
GAC,grqc0207049,Nature418,34

it had been known for some time that DSR-relativistic theories produce striking paradoxes for locality

GAC,IntJModPhysD11(2002)1643
Schutzhold +Unruh, JETP Lett78 (2003) 431
DeDeo + PrescodWeinstein,arXiv:0811.1999
Hossenfelder,PhysRevLett104 (2010) 140402

the emerging understanding is that these paradoxes for locality in DSR case play a role analogous to the paradoxes for simultaneity (such as the "twin paradox") encountered in going from Galilean Relativity to Special Relativity:
relative locality stands to the introduction of the invariant momentum scale
just like relative simultaneity stands to the introduction of the invariant speed scale

in particular in DSR-relativistic theories the **locality of distant events is relative**



blue lines for "high-energy particles"
red lines for "low-energy particles"

GAC+Matassa+Mercati+Rosati,
arXiv:1006.2126; PhysRevLett106, 071301

more refined and more widely applicable formulations of this relativity of spacetime locality are now provided within the relative-locality curved-momentum-space framework (see Jurek's talk)

GAC+Freidel+Kowalski-Glikman+Smolin,arXiv:1104.2019, PhysRevD84,087702

with the curved-momentum-space setup one can formulate consistently relative locality even for theories that break Lorentz symmetry, rather than deforming Lorentz symmetry in the DSR sense

and specifically for the DSR scenarios the curved-momentum-space setup provides powerful geometric tools for describing the deformations of translation transformations that must accompany the DSR-deformations of boost transformations

GAC+Arzano+Kowalski-Glikman+Rosati+Trevisan, arXiv:1107.1724;ClassQuantGrav29,075007

NEW RESULTS!!!

GAC+Astuti+Rosati,arXiv:1206.3805

where is spacetime in (first-quantized) quantum mechanics?

what is observable about spacetime in quantum mechanics?

observables are self-adjoint operators on the Hilbert space

“x” is the position of a particle (so no spacetime observable without particle)

and actually “t” is the evolution parameter (it is not an observable)

NEW RESULTS!!!

GAC+Astuti+Rosati,arXiv:1206.3805

but this "standard setup" gives a limited perspective on spacetime in quantum mechanics

we need to examine these issues at the level of the covariant formulation of quantum mechanics

Reisenberger+Rovelli,PhysRevD65(2002)125016
Halliwell,PhysRevD64(2001)04408
Gambini+Porto,PhysRevD63(2001)105014

quantum version of the covariant formulation of classical mechanics of point particles

"t" (q_0) and "x" (q_1) are both operators acting on the Hilbert space

"Kinematical Hilbert space" is unconstrained

$$[\hat{\pi}_0, \hat{q}_0] = i \ , \qquad [\hat{\pi}_0, \hat{q}_1] = 0$$
$$[\hat{\pi}_1, \hat{q}_0] = 0 \ , \qquad [\hat{\pi}_1, \hat{q}_1] = -i$$

"Physical Hilbert space" obtained from the Kinematical Hilbert space by enforcing the Hamiltonian constraint, e.g. for free particles

$$[E^2 - p^2 - m^2]\,|\Psi\rangle = 0$$

enforcing Hamiltonian constraint means I have particles, so no "pure spacetime observables"

spacetime is the unphysical Kinematical Hilbert space

NEW RESULTS!!!

GAC+Astuti+Rosati,arXiv:1206.3805

this fits with my main message

and also sets the stage for addressing the most crucial long-standing issue for the study of the kappa-Minkowski (and other similar) noncommutative spacetime

$$[x_j, x_0] = i\ell x_j \qquad [x_j, x_k] = 0$$

what does it mean? [x,t]≠0? "t" is an evolution parameter!!!

well it does make sense on the kinematical Hilbert space of the covariant formulation of quantum mechanics

$$\hat{x}_0 = \hat{q}_0 \ , \qquad \hat{x}_1 = \hat{q}_1 e^{\ell \hat{\pi}_0}$$

with

$$[\hat{\pi}_0, \hat{q}_0] = i \ , \qquad [\hat{\pi}_0, \hat{q}_1] = 0$$
$$[\hat{\pi}_1, \hat{q}_0] = 0 \ , \qquad [\hat{\pi}_1, \hat{q}_1] = -i$$

NEW RESULTS!!! GAC+Astuti+Rosati,arXiv:1206.3805

similar representations of kappa-Minkowski on a Hilbert space had been tried, though without our covariant-quantum-mechanics interpretation and using different representations

most importantly they were missing the key ingredient for assessing the relativistic properties: the associated representation of the differential calculus

translations in kappa-Minkowski $x_\mu \to x_\mu + \varepsilon_\mu$

with $[\varepsilon_0, x_\mu] = 0; [\varepsilon_j, x_l] = 0; [\varepsilon_j, x_0] = i\lambda\varepsilon_j$ **differential calculus**

so that $[x_j + \varepsilon_j, x_0 + \varepsilon_0] = i\lambda[x_j + \varepsilon_j]$ $\quad [x_j + \varepsilon_j, x_k + \varepsilon_k] = 0$

our formulation gives a representation on the kinematical Hilbert space of covariant quantum mechanics also for the differential calculus

$$\varepsilon_j = e^{\ell \pi_0} a_j \qquad \varepsilon_0 = a_0$$

with a_j and a_0 ordinary real numbers

NEW RESULTS!!!

GAC+Astuti+Rosati,arXiv:1206.3805

and we also give a representation on our Hilbert space of the translation generators (which combine with the translation parameters to give the description of translation map between two observers)

$$P_\mu \triangleright [\hat{x}_1, \hat{x}_0] = i\ell P_\mu \triangleright \hat{x}_1$$

$$P_\mu \triangleright f(\hat{x})g(\hat{x}) = (P_\mu \triangleright f(\hat{x}))\, g(\hat{x}) + \left(e^{-\ell\delta^1_\mu P_0} \triangleright f(\hat{x})\right)(P_\mu \triangleright g(\hat{x}))$$

$$P_0 \triangleright f(\hat{x}_0, \hat{x}_1) \longleftrightarrow [\hat{\pi}_0, f(\hat{q}_0, \hat{q}_1 e^{\ell\hat{\pi}_0})]$$

$$P_1 \triangleright f(\hat{x}_0, \hat{x}_1) \longleftrightarrow e^{-\ell\hat{\pi}_0}[\hat{\pi}_1, f(\hat{q}_0, \hat{q}_1 e^{\ell\hat{\pi}_0})]$$

now take

$$Bob = [\mathbf{1} - i\varepsilon_\mu P^\mu]Alice$$

and specialize to the following "fuzzy point"

$$\Psi_{\overline{\pi}_\mu, \sigma_\mu, \overline{q}_\mu}(\pi_\mu) = N e^{-\frac{(\pi_0 - \overline{\pi}_0)^2}{4\sigma_0^2} - \frac{(\pi_1 - \overline{\pi}_1)^2}{4\sigma_1^2}} e^{i\pi_0\overline{q}_0 - i\pi_1\overline{q}_1}$$

relative locality in a quantum spacetime!!!

GAC+Astuti+Rosati,arXiv:1206.3805

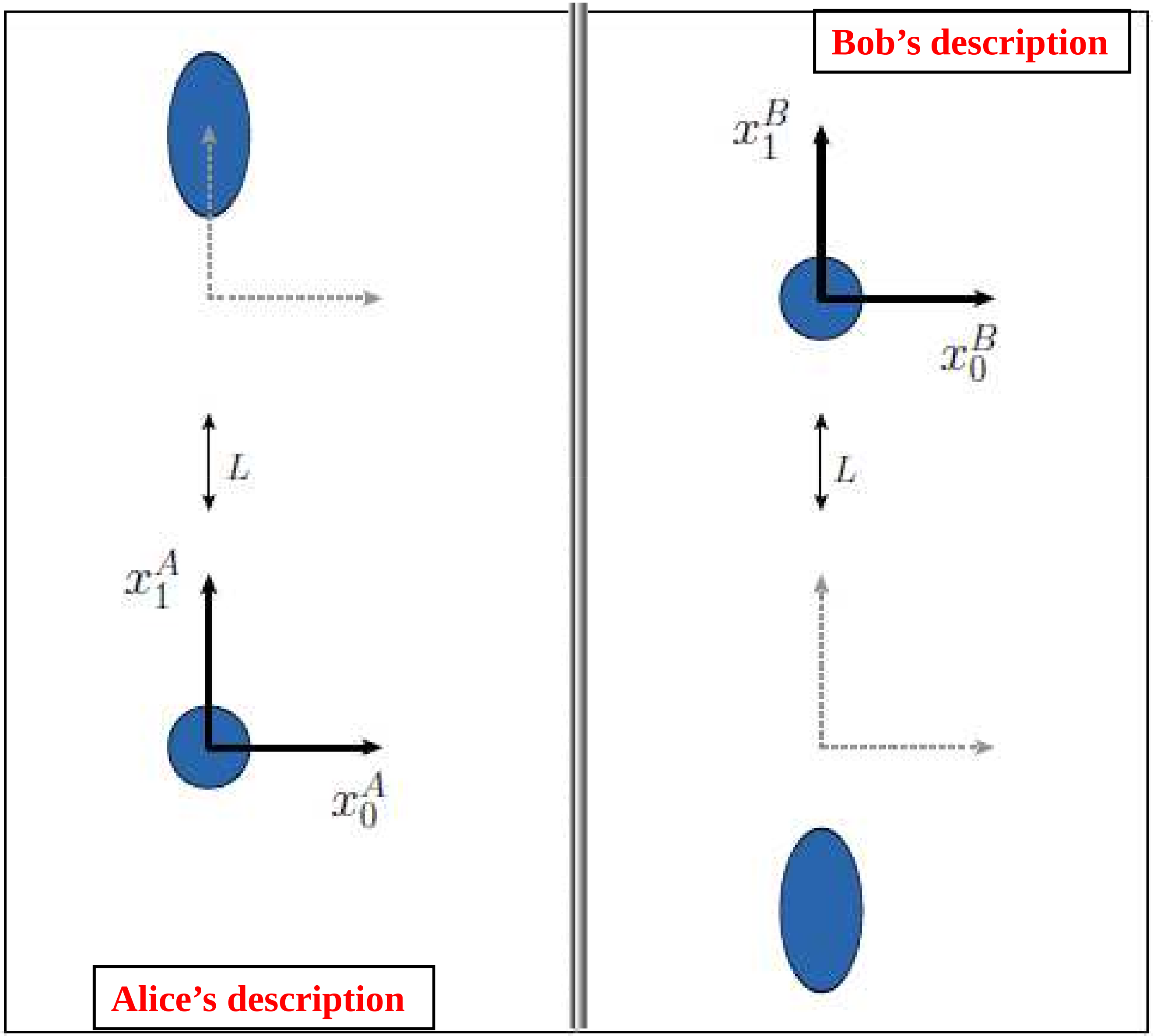


FIG. 1. We illustrate the features of relative locality we uncovered for the κ-Minkowski quantum spacetime by considering the case of two distant observers, Alice and Bob, in relative rest (with synchronized clocks). In figure we have only two points in κ-Minkowski, each described by a gaussian state in our Hilbert space. One of the points is at Alice (centered in the spacetime origin of Alice's coordinatization) while the other point is at Bob. The left panel reflects Alice's description of the two points, which in particular attributes to the distant point at Bob larger fuzziness than Bob observes (right panel). And in Alice's coordinatization the distant point is not exactly at Bob. Bob's description (right panel) of the two points is specular, in the appropriately relativistic fashion, to the one of Alice. The magnitude of effects shown would require the distance L to be much bigger than drawable. And for definiteness in figure we assumed $\bar{\pi}_0 \simeq 2\sigma_0$ and $\sigma_1 \simeq \sigma_0$.

same message emerges from doing the analysis on the physical Hilbert space

GAC+Astuti+Rosati,arXiv:1206.XXXX

is this allowed?
is this even possible?

of course it is allowed to the extent that it is consistent with what we know about spacetime

and for small enough values of the kappa-Minkowski deformation scale it obviously is consistent with what we know about spacetime

it turns out that if the kappa-Minkowski deformation scale is (the inverse of) the Planck scale this picture is consistent with available data and interestingly "safe by not a tremendously wide margin" (few orders of magnitude)

GAC+Astuti+Rosati,arXiv:1206.XXXX

Figure 1: Composite image created from the Sloan Digital Sky Survey and the UKIRT Infrared Deep Sky Survey. The quasar ULAS J1120+0641, at redshift of 7.1, appears as a faint red dot close to the center. Observations of quasars by ground telescopes must handle the effects of image blurring produced when light crosses the atmosphere. Even space telescopes would be affected by some image blurring, according to heuristic descriptions of gravity-induced foaminess of spacetime. Heuristics is however not providing reliable estimates of the

GAC+Astuti+Rosati,arXiv:1206.XXXX

summarizing

how do we know we all share the same spacetime?

GAC+Freidel+Kowalski-Glikman+Smolin,arXiv:1104.2019, PhysRevD84,087702

- ☐ stupid question
- ☐ question for philosophers
- ☒ experimental question

against spacetime

“I don’t see space. I see things”

Diego Rivera (1886-1957; renowned Mexican painter)