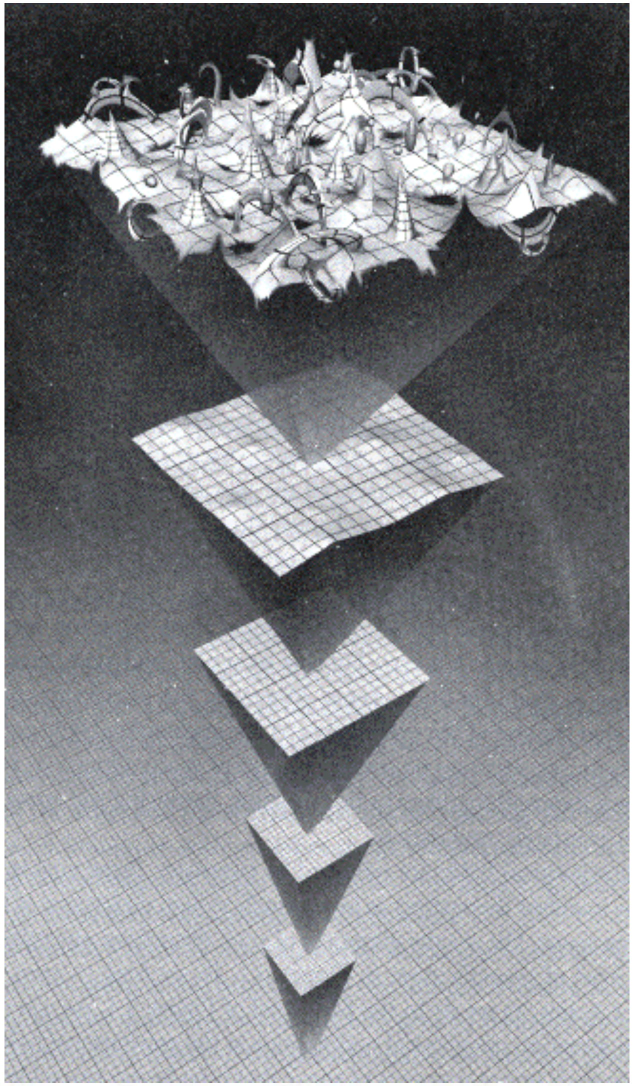
Quantum gravity constraints from the farthest quasars

Fabrizio Tamburini
CIVEN and
Dept. of Physics and Astronomy
University of Padova

Io stimo più il trovar un vero, benché di cosa leggiera, che 'l disputar lungamente delle massime questioni senza conseguir verità nissuna (Galileo Galilei).

Context

- Defining QG fluctuations limits
- Why is it so important?
- Spacetime foam concept



Context. Quantum gravity can be considered the Holy Grail of modern physics. Strings and other alternative theories describing the quantum properties of spacetime suggest that spacetime could present a foamy structure and also that, in certain cases, quantum gravity may manifest at energies much below the Planck scale. One of the observable effects could be the degradation of the diffraction images of distant sources.

QG. State of the art:

No theory of quantum gravity at all.

But we have some *(too many)* approaches:

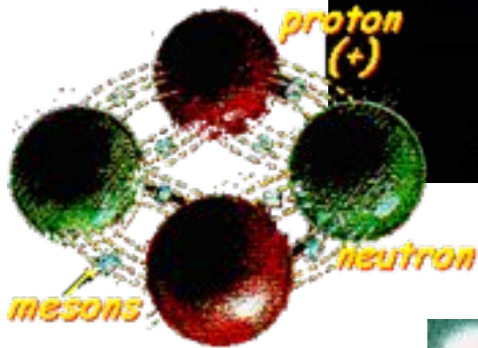
- String theory – no supersymmetric partner found @ LHC yet – Grand Unification
- Supergravity – low energy limit of strings (?)
- Loop Quantum Gravity – no superforce or unification aims, but a quantum description of gravity without background.
- Now a brief & sketchy summary…

Grand Unified Theories or "simply" quantum gravity?

We have 4 known forces:

- Electromagnetism

- Weak force



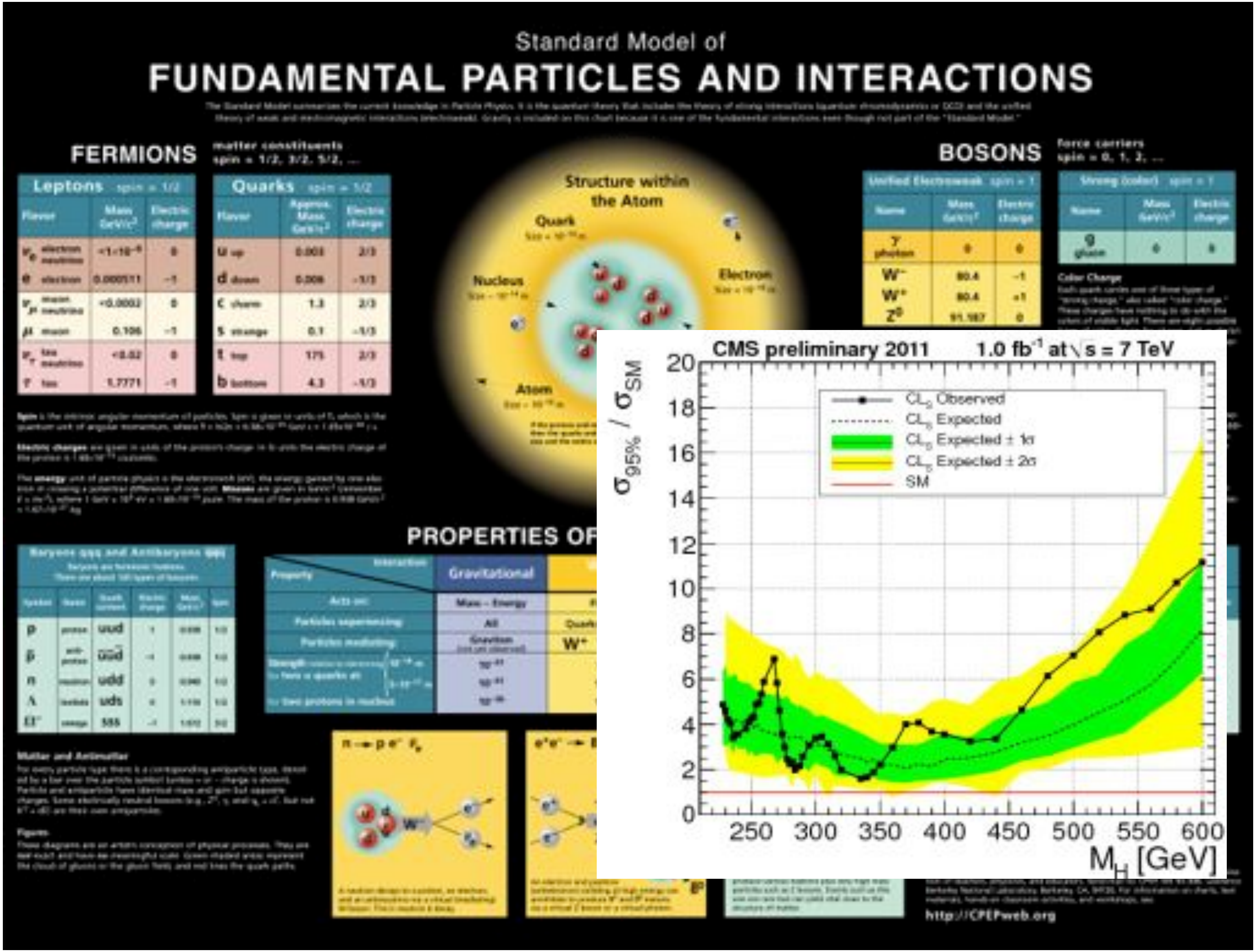
- Strong Nuclear Force

- Gravitation

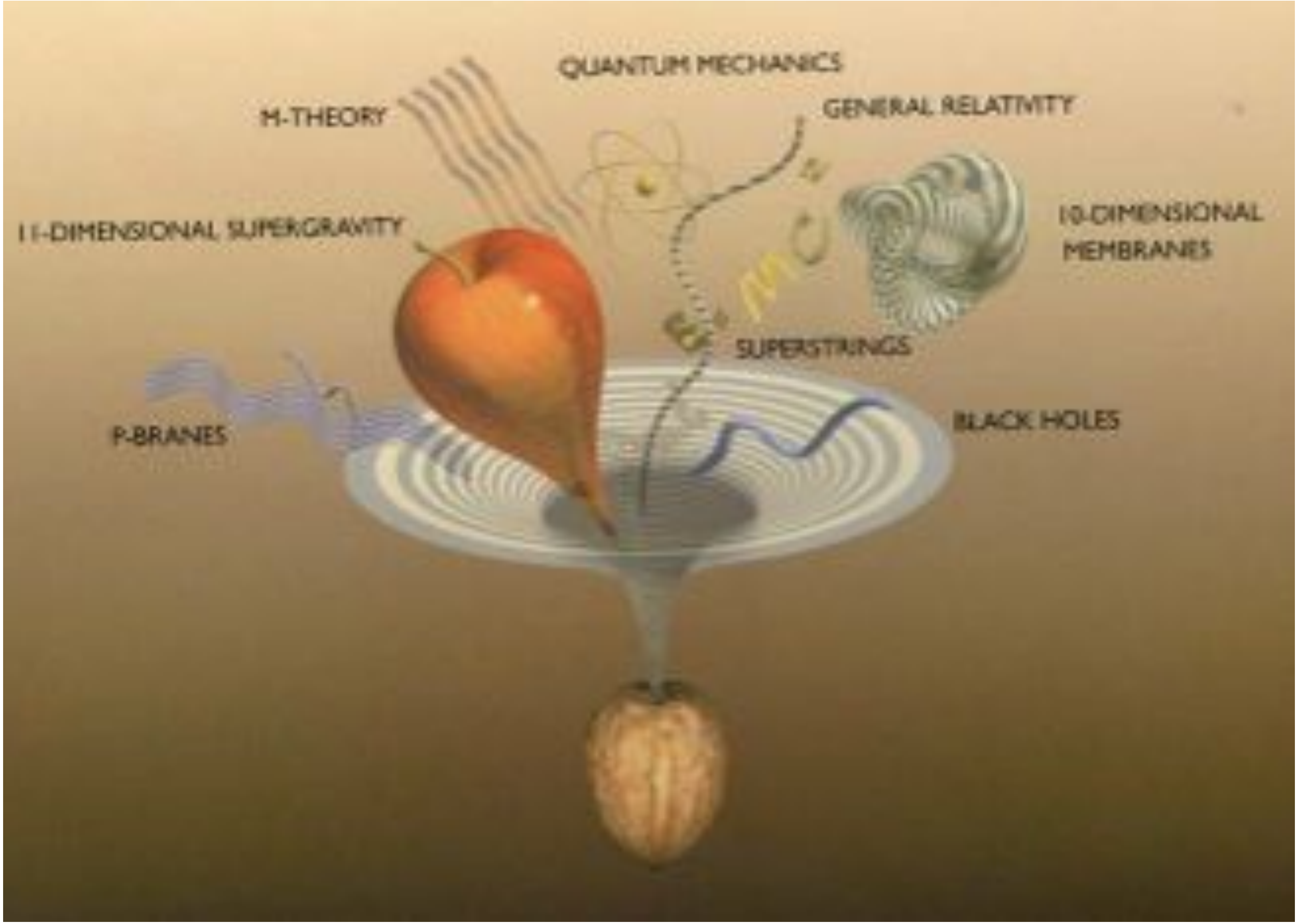
Coupling constants why there is not a perturbative or standard quantum theory

α_{em}	$\sim$	$1/137.0359895(61)$	OK – QED
α_{strong}	$\sim$	14	Difficult but numerically…
G_{weak}	$\sim$	$1.02 \times 10^{-5}/M_p^2$	No-go need another more complete theory Weinberg-Salam-Glashow
	$\sim$	$1.16639(2) \times 10^{-5}\mathrm{GeV}^{-2}$	
G_{Newton}	$\sim$	$5.9 \times 10^{-39}/M_p^2$	Quantum gravity
	$\sim$	$6.67259(85) \times 10^{-1}\mathrm{m}^3\mathrm{kg}^{-1}\mathrm{s}^{-2}$	

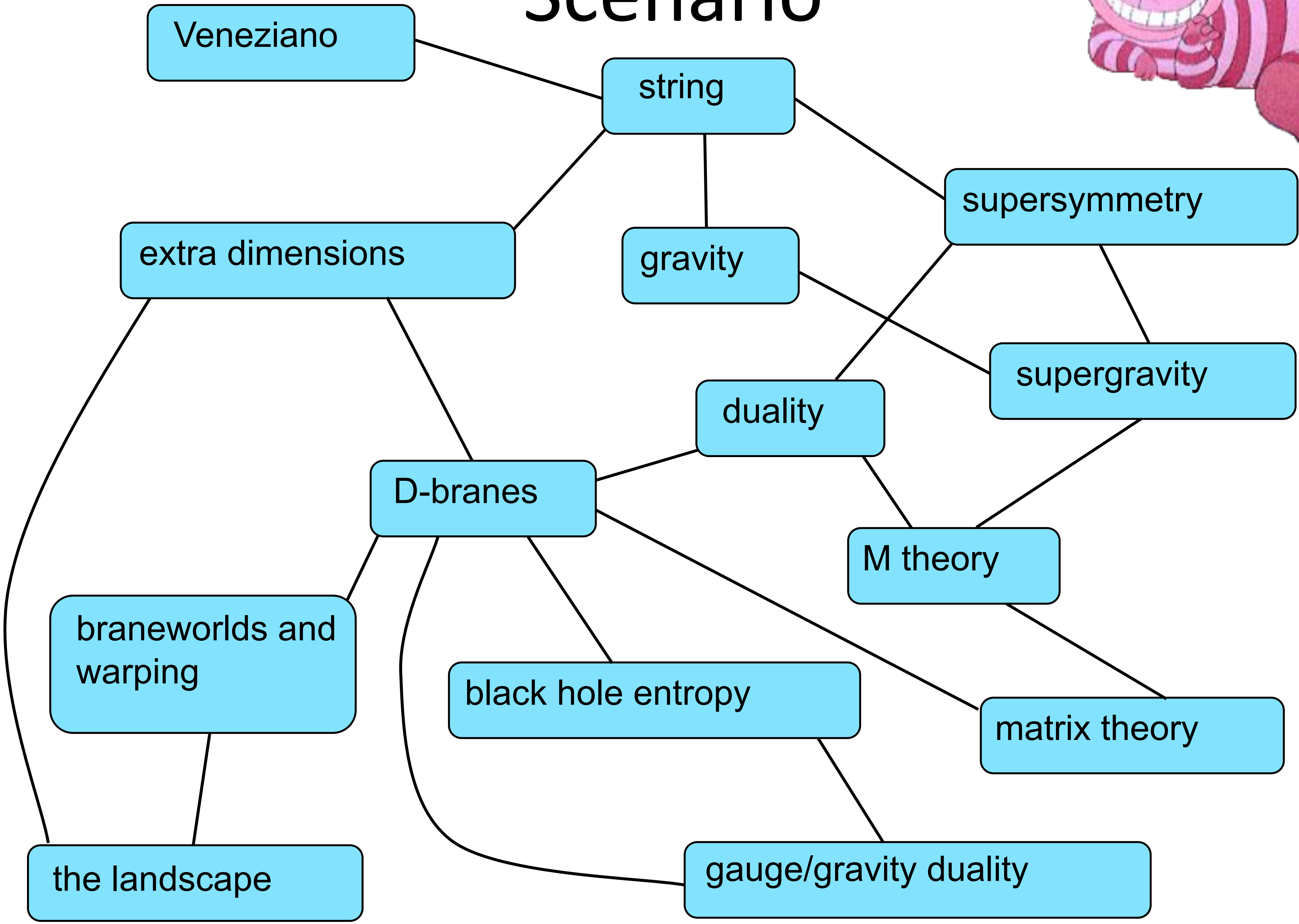
Inverse of a mass $\rightarrow$ non renormalizable with power expansion
no-go theorem, similar to Fermi's theory of weak interaction
No-go theorems.


Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
FERMIONS
BOSONS
Leptons
Quarks
Structure within the Atom
Quark
Nucleus
Electron
Atom
PROPERTIES OF
Gravitational
http://CPEPweb.org
CMS preliminary 2011
1.0 fb⁻¹ at √s = 7 TeV
σ95% / σSM
CLs Observed
CLs Expected
CLs Expected ± 1σ
CLs Expected ± 2σ
SM
MH [GeV]

QG in a nutshell



Scenario



Veneziano
string
supersymmetry
extra dimensions
gravity
supergravity
duality
D-branes
M theory
braneworlds and warping
black hole entropy
matrix theory
the landscape
gauge/gravity duality

Loop Quantum Gravity no superforce

- No background needed. Math similar to string theory. It derives from the same thoughts…
- In order to construct Quantum Gravity, we should fix our starting point at General Relativity.
- We quantize it while keeping all its principles intact: geodesic equation and Background Independence, path integral representation…

$$\delta \int ds = 0$$

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Is there one theory of quantum gravity or many? How to choose? Phenomenology – expected effects

• Many attempts of quantizing gravity give up **Lorentz invariance** at the start, and it has even been argued that this is a necessary feature of quantum gravity.
See e.g. the superluminal neutrino problem.

• It is hard to see how the successes of Special Relativity can then be maintained. E.g., the Standard Model would have ~20 extra parameters (and by tuning them you can set **different "speeds" of light** for every particle), and even **Planck-scale breaking** will feed down into the low energy Lagrangian.

Phenomenology will help the choice of the "better direction"

How to move in the jungle: a first step is phenomenology and then decide what to do

- It is not a QG theory, only a simple “rule of thumb” approach with known physics to determine the size of QG fluctuations.
- Each QG model predicts different space and time fluctuations, describing the graining of this “space-time foam”.

The Hitchhiker's Guide to QG

- What is the **characteristic scale** of quantum gravity? Why do we speak about a “scale”?
- Fluctuation scale of energy, momentum and space and time.
- How to determine it? Via *Heisenberg Principle* or else?
- Planck scale? (mks) it seems the most “natural”

$$l_p \simeq 1.616 \times 10^{-35}$$

$$t_p \simeq 5.391 \times 10^{-44}$$

- Larger-than Planck scale fluctuations or even sub-millimetric fluctuations of space and time?

Using photons as probes for QG

- A photon with energy E experiences energy fluctuations because of spacetime fluctuations occurring at **characteristic time scales** $t^* > t_P$.
- Power-law interpolation – uncertainty $t \geq t^*$

  $E = h\nu \quad \delta E/E \sim \delta p/p \sim (E/E_p)^\alpha$

  ST grains

  standard deviation for t $\sigma_t/t = f(t_p/t)$

  $f = (t_p/t)(a_0 + a_1(t_p/t) + a_2(t_p/t)^2 + \ldots) \approx a_0(t_p/t) \ll 1$

  the lowest-order fluctuations in Planck units a_0

  with E-p dependence $p^2 = E^2[1 \pm a_0(E/E_P)^\alpha]$

  and α is the "characteristic exponent".

What does it mean?

- The foamy structure of spacetime can be revealed by the modification it induces as <u>random perturbation</u> of the **photon dispersion arrival time of a bunch of photons** emitted by a distant source and affecting the phase coherence of the light
- *Classically*, one can see this as two differently fluctuating wave velocities that may systematically cumulate during the journey of each photon are generated and then *interfere* when entering an interferometer or, equivalently, a telescope aperture. Fringes/Airy rings are blurred away

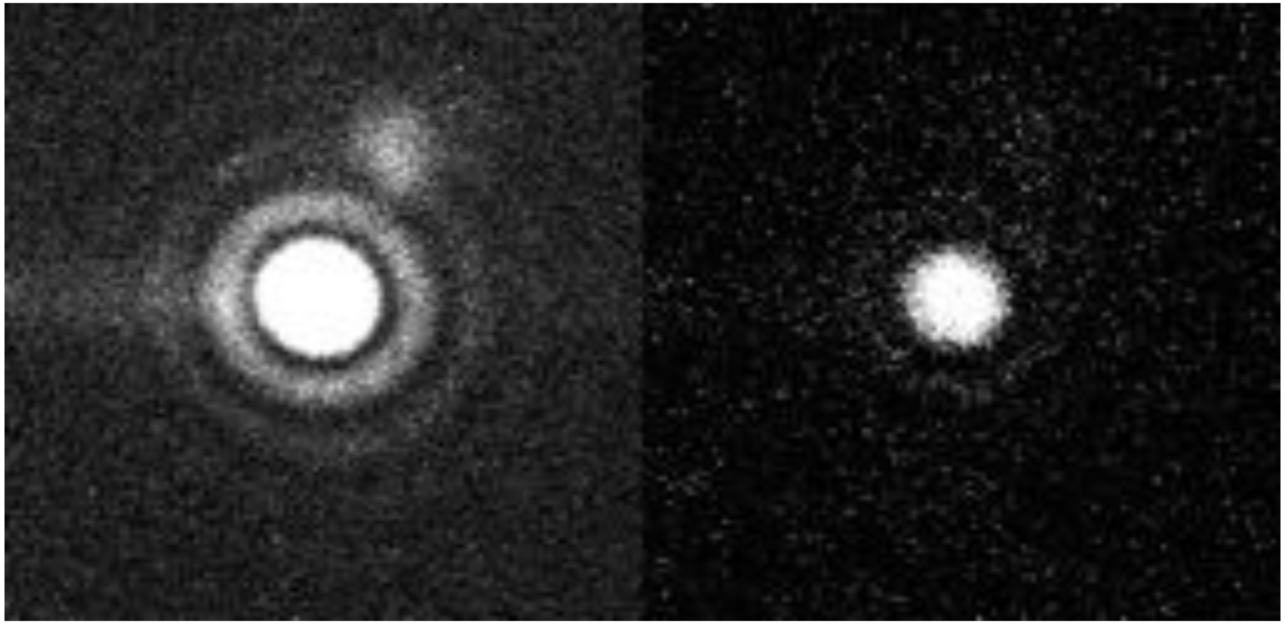
- Those effects can in principle be detected by analyzing possible modifications of the interference fringe structures through **stellar interferometry**.
- *Equivalently*, the cumulated phase variation can be detected also by imaging and analyzing, with a diffraction-limited telescope, the ring structure of Airy disks of cosmological point-like sources (*Ragazzoni et al., 2003*).

Airy rings are still observed if the cumulated phase is limited to the value $\delta\phi \leq 2\pi$.

The expected differences are quite small.

Aims of our work

Aims. We searched for this degradation effect, caused by Quantum Gravity fluctuations, in the light of the farthest quasars observed by the Hubble Space Telescope with the aim of setting new limits to the fluctuations of the spacetime foam and Quantum Gravity models.



QG fluctuations degrade the Airy ring of point-like QSOs – blurring like that of atmospheric seeing.

If blurring is measured one determines the fluctuation scale and properties

Finding QG energy fluctuation scales

- EM wave (*say, photon and its wavelength)* - as ruler
- Energy fluctuations = time of arrival fluctuations
- Loss of coherence from point-like sources
- The photon's wavelength λ is the smallest scale at which **group and phase velocities** can be defined.

$$t = \lambda / v_g \qquad \phi = 2\pi v_p / v_g$$

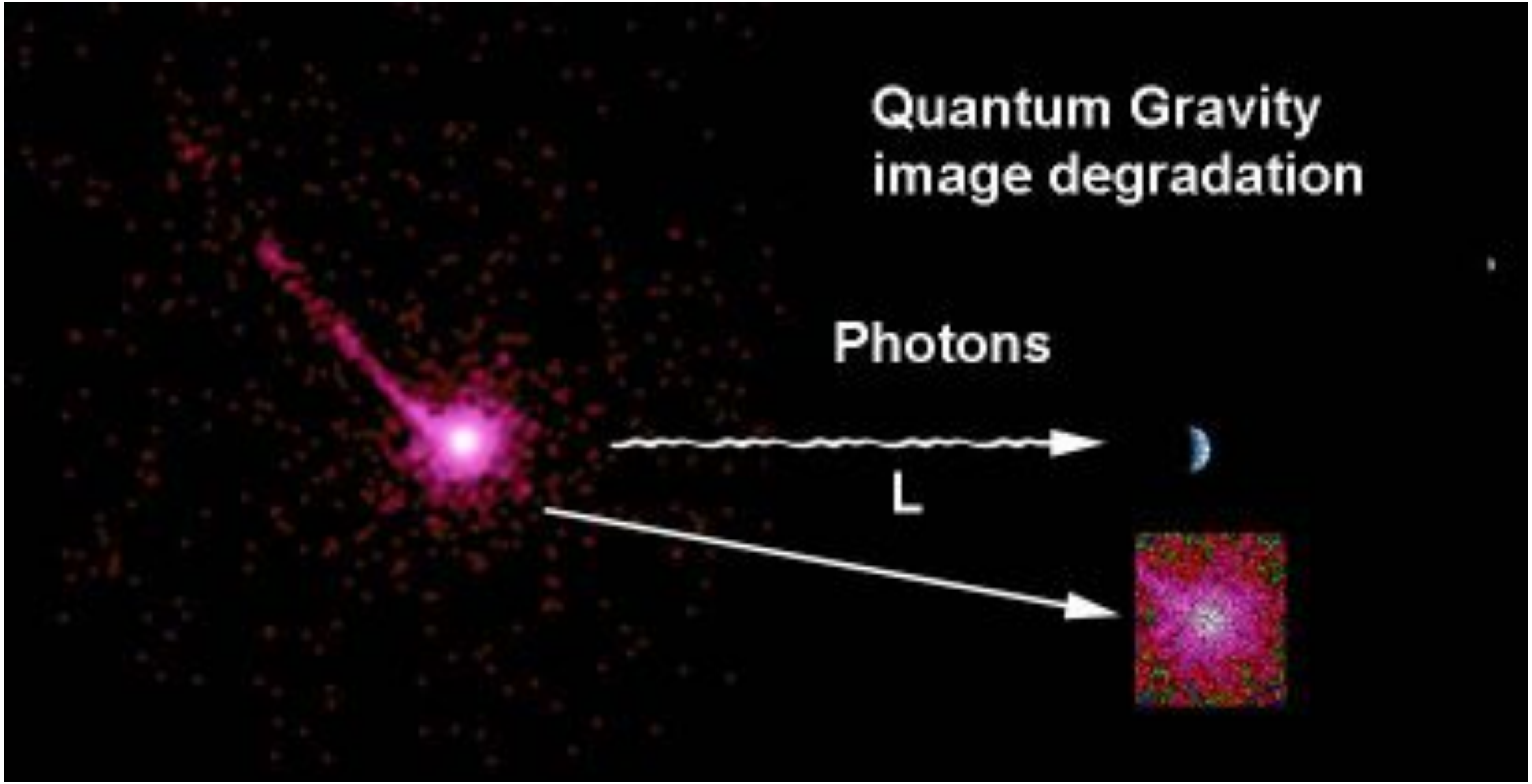
QG Phase indetermination

$a_0 \sim 1$ amplitude

$$(\Delta\phi_{QG})_{min} \sim 2\pi a_0 \frac{l_p^\alpha L^{1-\alpha}}{\lambda} \sim 2\pi \frac{L}{\lambda}\left[1 \pm \sqrt{2}\alpha \left(\frac{hc}{\lambda E_P}\right)^\alpha\right]$$

l_p^α Planck length $\quad L$ travelling distance e.g. from QSO to Earth

Cumulating QG fluctuations



PSF degradation - example

Phenomenological models of ST foam (blurring decreases if **α** increases)

- **Random-walk model: α = ½**, random perturbations of space-time add incoherently with a square root dependence or with a more general distribution function (G. Amelino-Camelia, 2000 and Ng & van Dam, 1994).
- **Holographic model: α = 2/3** Beckenstein-Hawking's holographic principle and black hole entropy (G. 't Hooft, 2003). Important for theoreticians…
- **Standard QG model: α = 1** the gravitational field fluctuations are on the order of the Planck scale (Smolin, 2003; Rovelli, 2004).

Methods – how to determine these small fluctuations

Methods. We developed a software that estimates and compares the phase variation in the interference patterns of the high redshift QSOs, taken from the snapshot survey of HST-SDSS, with those of stars that are expected to be not affected by Quantum Gravity effects. We used a two-parameter function to determine, for each test star and quasar, the *maximum* of the diffraction pattern and calculate the Strehl ratio.

Tiny Tim provides a good PSF for any single image of HRC camera, but it is not enough precise to detect new QG effects wrt those already present in the literature. **Provides corrections for the spectral differences to calibrate our software.**

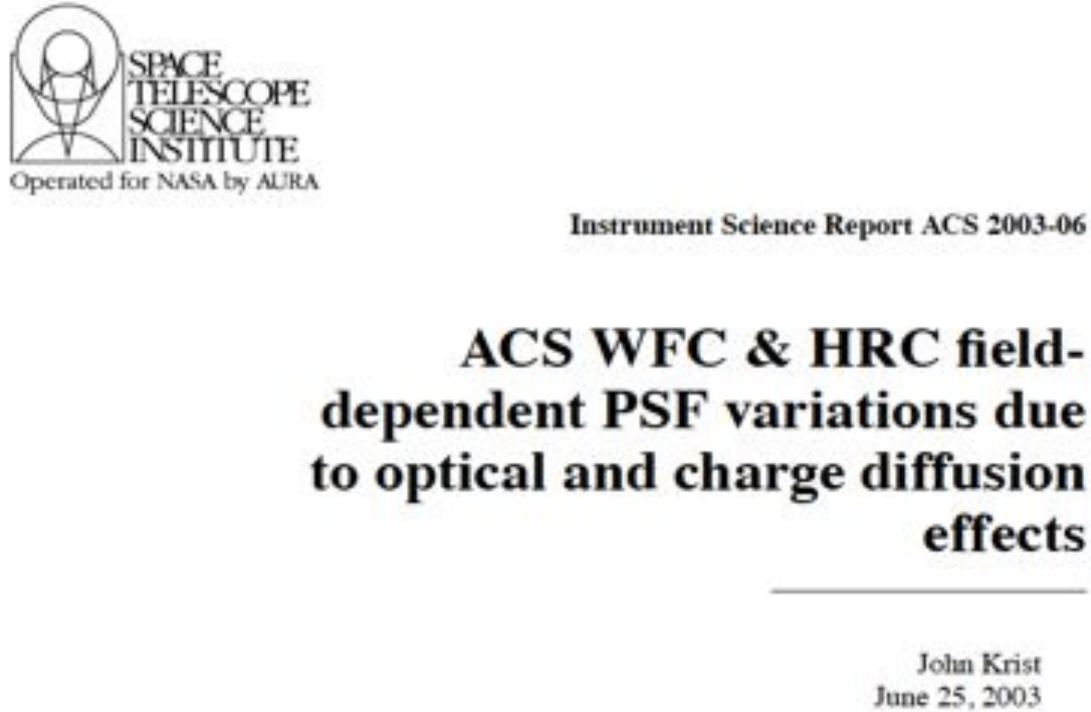
One has to reach the actual Strehl ratio of the telescope + HRC + filter(s) and manage the optical aberrations with a statistical mode, including, and averaging, the telescope random deformations (breathing) and apply a statistical approach to this problem. Much more measurements give a better precise final measurement with a smaller error.
In this way we were able to exclude most of the “Holographic models” and the Random-Walk models of spacetime foam.

Our Targets - farthest QSOs

- High redshift QSOs. Snapshot survey of HST-SDSS (Richards et al. 2006);
- **147** sources ($4 < z < 5.4$) +
  filter F775W (λ_c = 776.4 nm, bandwidth λ = 152.8 nm)
- **4** sources ($5.7 < z < 6.3$) +
  filter F850LP (λ_c = 944.5 nm, bandwidth λ = 122.9 nm)
- luminosity distances **L** from a concordance Universe model H_0 = 72 km/s/Mpc, $(\Omega_M,\Omega_\Lambda)$=(0.3, 0.7); (Krauss, 2002)
- small effects on λ due to the expansion of the Universe included in the calculations.

HST setup - characterization

- HRC/ACS: High-Resolution Channel (HRC)Advanced Camera for Surveys (ACS)
  HRC detector: 1024×1024 SITe CCD field-of-view (26"×29")
  spatial sampling (0.025" per pixel)
- **Field Dependent PSF variations!**
  Improving tiny tim without assuming a psf structure “a priori”



SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA

Instrument Science Report ACS 2003-06

ACS WFC & HRC field-dependent PSF variations due to optical and charge diffusion effects

John Krist
June 25, 2003

Improving sensitivity for a set of measurements

- We used drizzled (DRZ) images corrected for geometric effects and reduced in the standard manner, including their having been overscan-, bias- and dark-corrected, flat-fielded and photometrically calibrated. Corrected in color.
- Determination of the phase variations **from the Strehl ratio** (S), ratio btw the max peak intensities of the aberrated and unaberrated source

$$\Delta\phi \approx \frac{\lambda}{D}\sqrt{-ln(S)} \qquad S = \frac{(\mathrm{Max})_{\mathrm{source}}}{(\mathrm{Max})_{\mathrm{th}}} \sim \exp\left[-\left(\Delta\phi\frac{D}{\lambda}\right)^2\right]$$

Phase variations: causes

$$\Delta\phi(z)_{\mathrm{QSO}} = \Delta\phi_{\mathrm{ab}} + \Delta\phi(z)_{\mathrm{size}} + \Delta\phi(z)_{\mathrm{QG}}$$

$\Delta\phi_{\mathrm{ab}}$ is the phase variation due to the aberrations

$\Delta\phi_{\mathrm{QG}}$ those due to QG

$\Delta\phi_{\mathrm{size}}$ to the resolvability of QSOs

Test with galactic stars, pessimistic approach

$$\Delta\phi_{\mathrm{star}} = \Delta\phi_{\mathrm{ab}}$$

the effects of QG are negligible at non-cosmological distances.

$$(\Delta\phi(z)_{QSO})_{\mathrm{Corrected}} = \Delta\phi(z)_{\mathrm{QSO}} - \langle\Delta\phi\rangle_{\mathrm{star}}$$

$$\simeq \Delta\phi(z)_{\mathrm{size}} + \Delta\phi(z)_{\mathrm{QG}}$$

Model of the detector's distortions

Search for the PSF center

- Finding the position of the center and the maximum of the diffraction pattern for each source.
  The light intensity distribution is initially interpolated by a two-parameter function in a 3X3 pixel area.
- Recursive algorithm. Errors less than 1% in the estimate of the maximum of the diffraction pattern
- Center found; then with this recursive search one studies the PSF and builds the 7-parameter function *F* that fits the expected emipirical psf
- No resampling with the previous pixel scale
- 2 different procedures for the 2 different filters

Position of the maximum & PSF sampling: the recursive function *F*

Detector mapping from stars from different images

$$F\ (x, y, [mx, cx, cy, \epsilon, \theta, \sigma_1, \sigma_2]) = \frac{mx}{\sigma_1 + \sigma_2}$$

$$\times \sum_{n=1}^{2} \sigma_{3-n} \exp\left[-\frac{x_1^2(x, \cdots) - \epsilon x_1^2(x, \cdots) + y_1^2(x, \cdots)}{2\sigma_n^2(1-\epsilon)}\right]$$

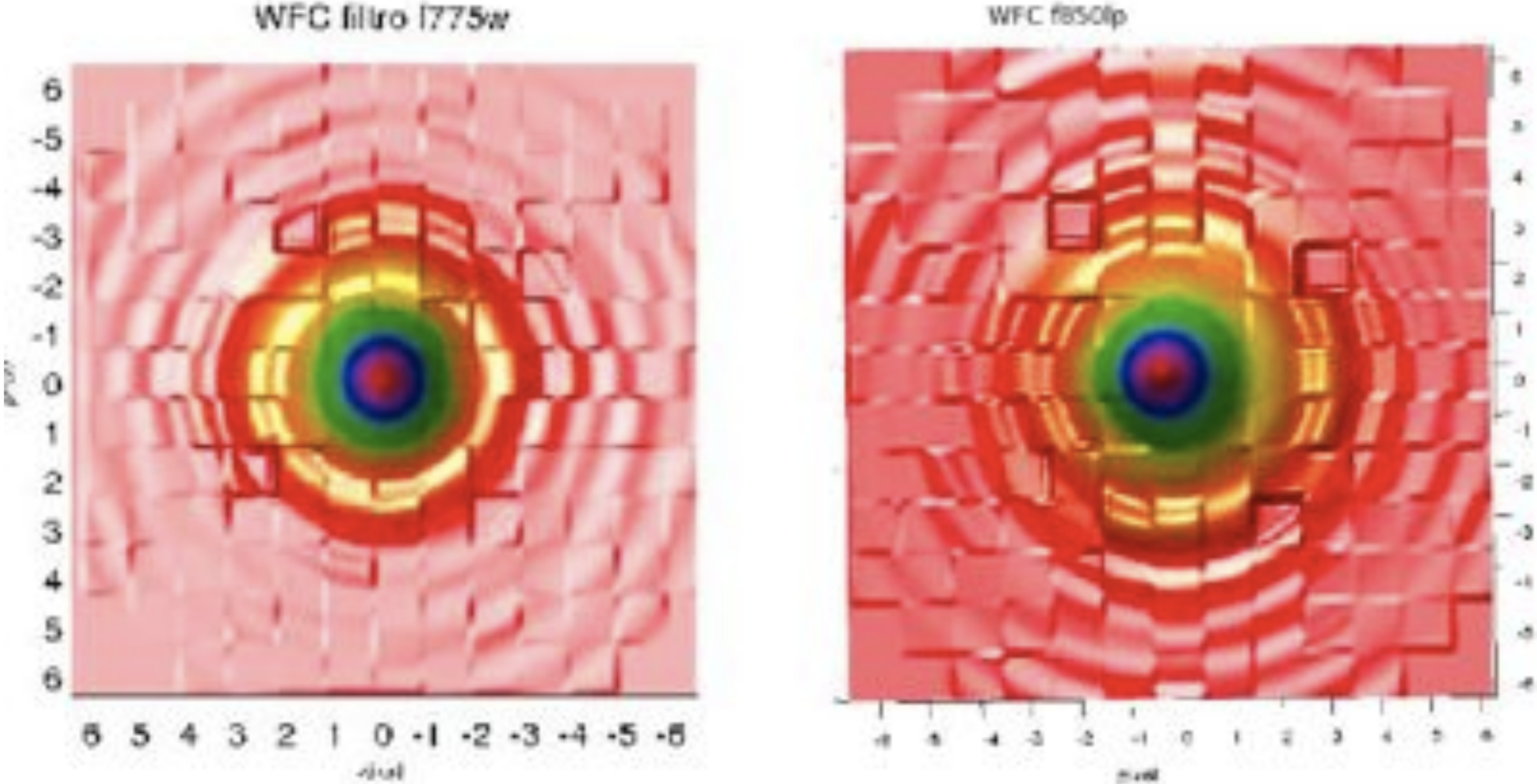
$$x_1(x, y, cx, cy, \theta) = (x - cx)\cos\theta - (y - cy)\sin\theta$$

$$y_1(x, y, cx, cy, \theta) = (x - cx)\sin\theta + (y - cy)\cos\theta$$

in a domain of elliptical sections of pixels with eccentricity ε

With a recursive procedure, we tune the values of the parameters $mx, cx, cy, \epsilon, \theta, \sigma_1, \sigma_2$ of the 2D function, F, until minimizing the difference between the measured and the fitted intensity of each pixel, on a 3 × 3 matrix centered around the brightest pixel. In the calculations each pixel is divided in 15 × 15 sub-pixels and for each of these divisions the procedure determines the intensity as a function of the position in the detector. At the end, we obtained both the position of the center and the intensity of the light pattern in the 3×3 area with a precision of 15×15 division for each pixel

A“raw” star with the 2 filters in the same CCD position



Phase variation of a sample of stars after *F*

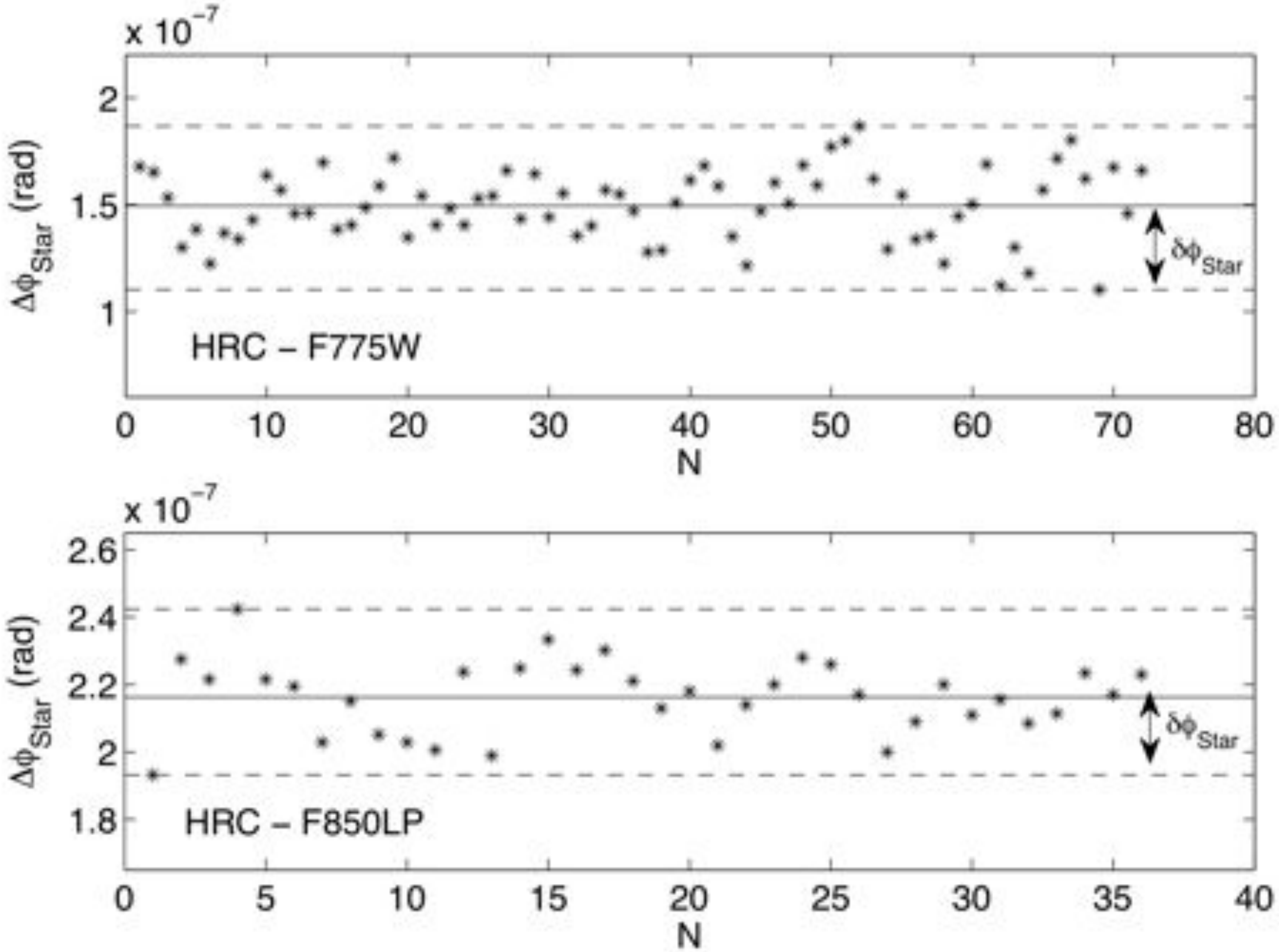
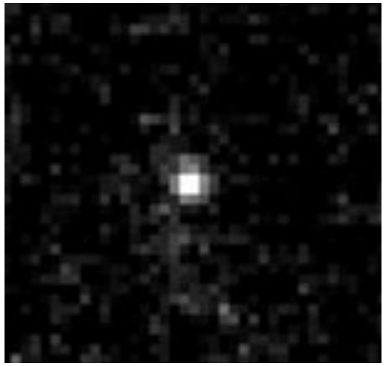
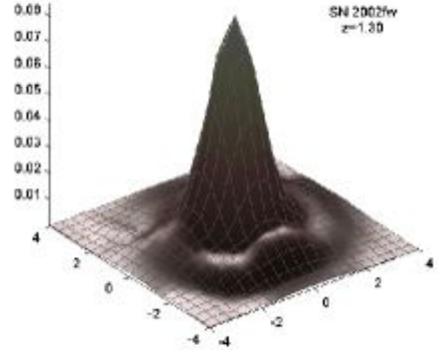


Fig. 3. Phase variation of 72 stars imaged with the High Resolution Camera with the filter F775W (upper panel) and 36 stars with the filter F850LP (bottom panel). We plot also the averaged value $\langle \Delta\phi_{star} \rangle$ (solid line) and the error $\delta\phi_{star}$. The dashed lines show the values $\langle \Delta\phi_{star} \rangle \pm \delta\phi_{star}$.

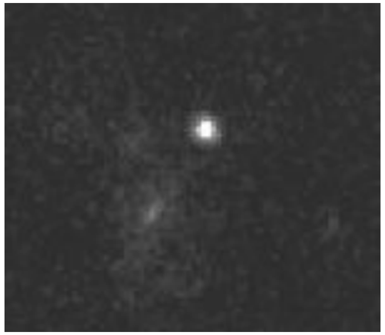
Tests: isolated SNe from Strolger et al. (2004)
Improving the function *F*

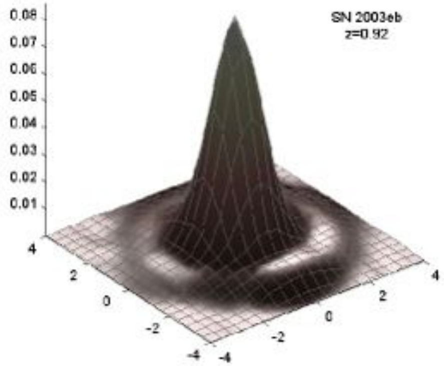
SN 2002fw
D ≈ 3900 Mpc



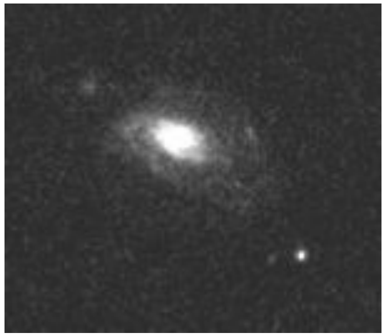


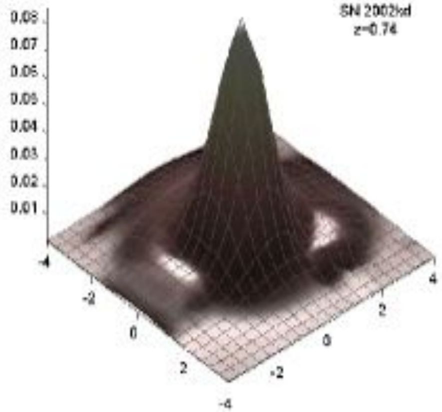
SN 2002eb
D ≈ 2700 Mpc



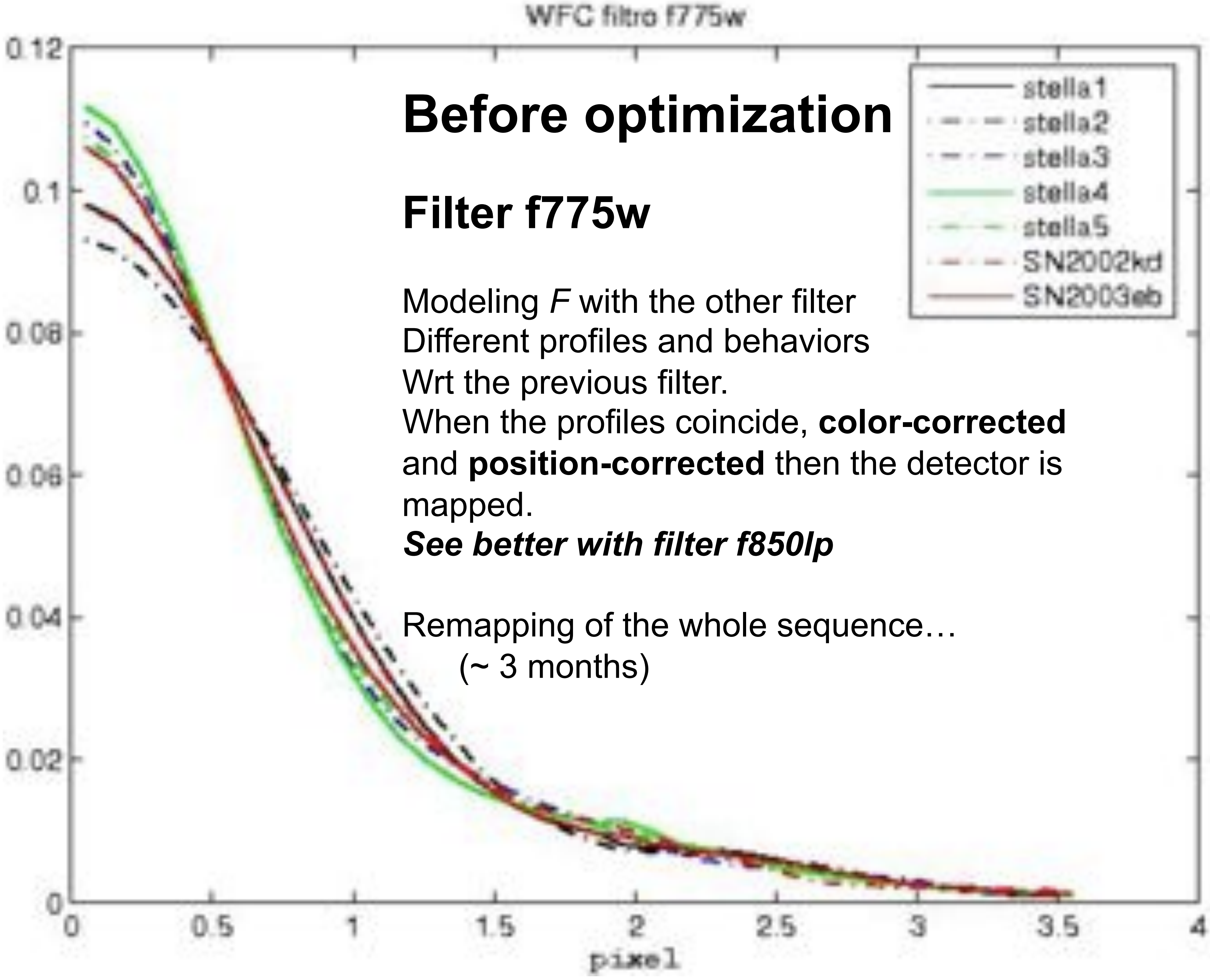


SN 2002kd
D ≈ 2200 Mpc





Airy rings are visible, calibration and characteristic exponent extimation



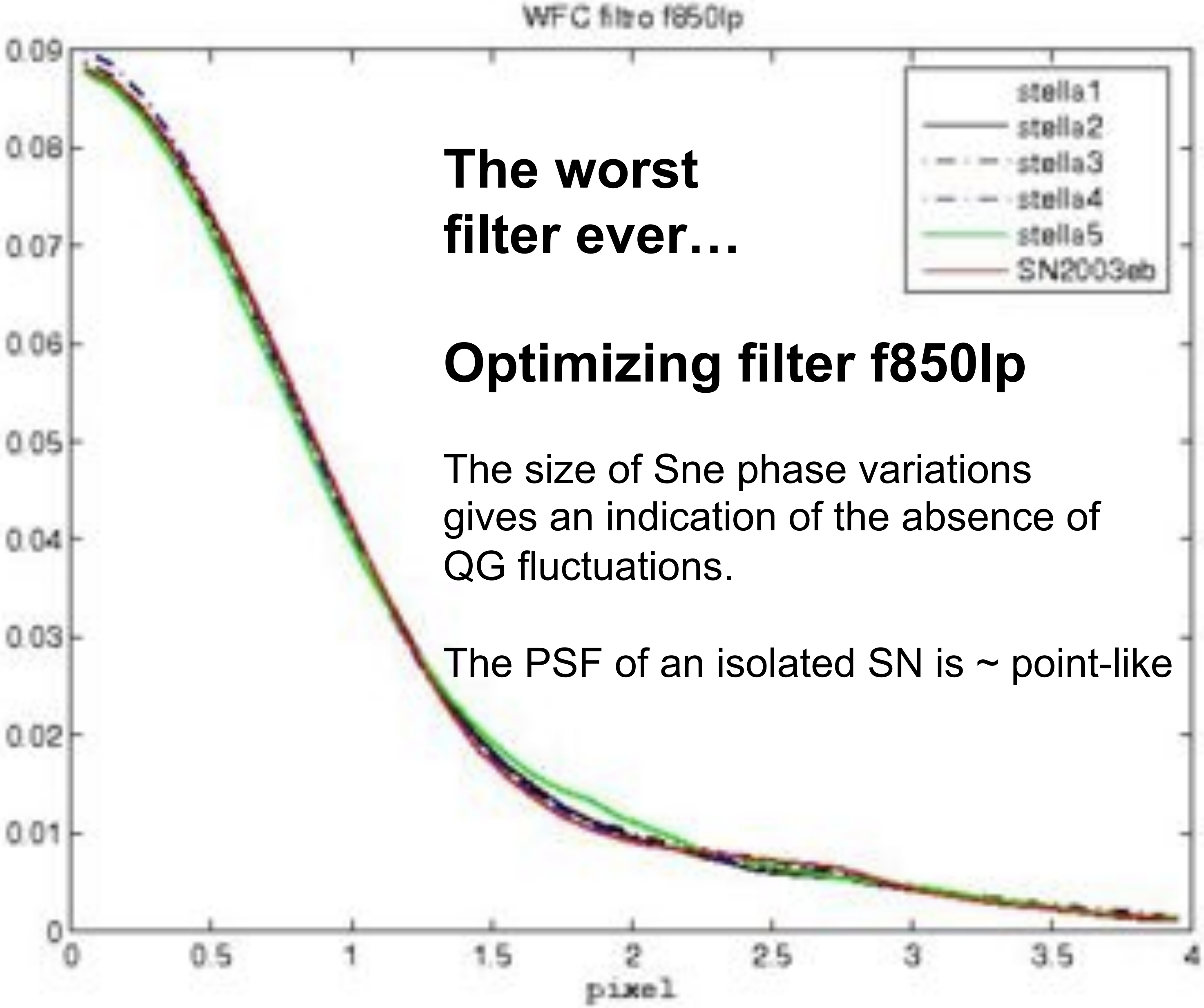
Before optimization

Filter f775w

Modeling *F* with the other filter
Different profiles and behaviors
Wrt the previous filter.
When the profiles coincide, **color-corrected** and **position-corrected** then the detector is mapped.
See better with filter f850lp

Remapping of the whole sequence…
(~ 3 months)

Profiles of 5 stars and of SN2003eb (z=0,9). The profiles have been normalized wrt the 4 test pixel area. Modelling the function *F* for each position of the CCD with sample stars and with the supernovae

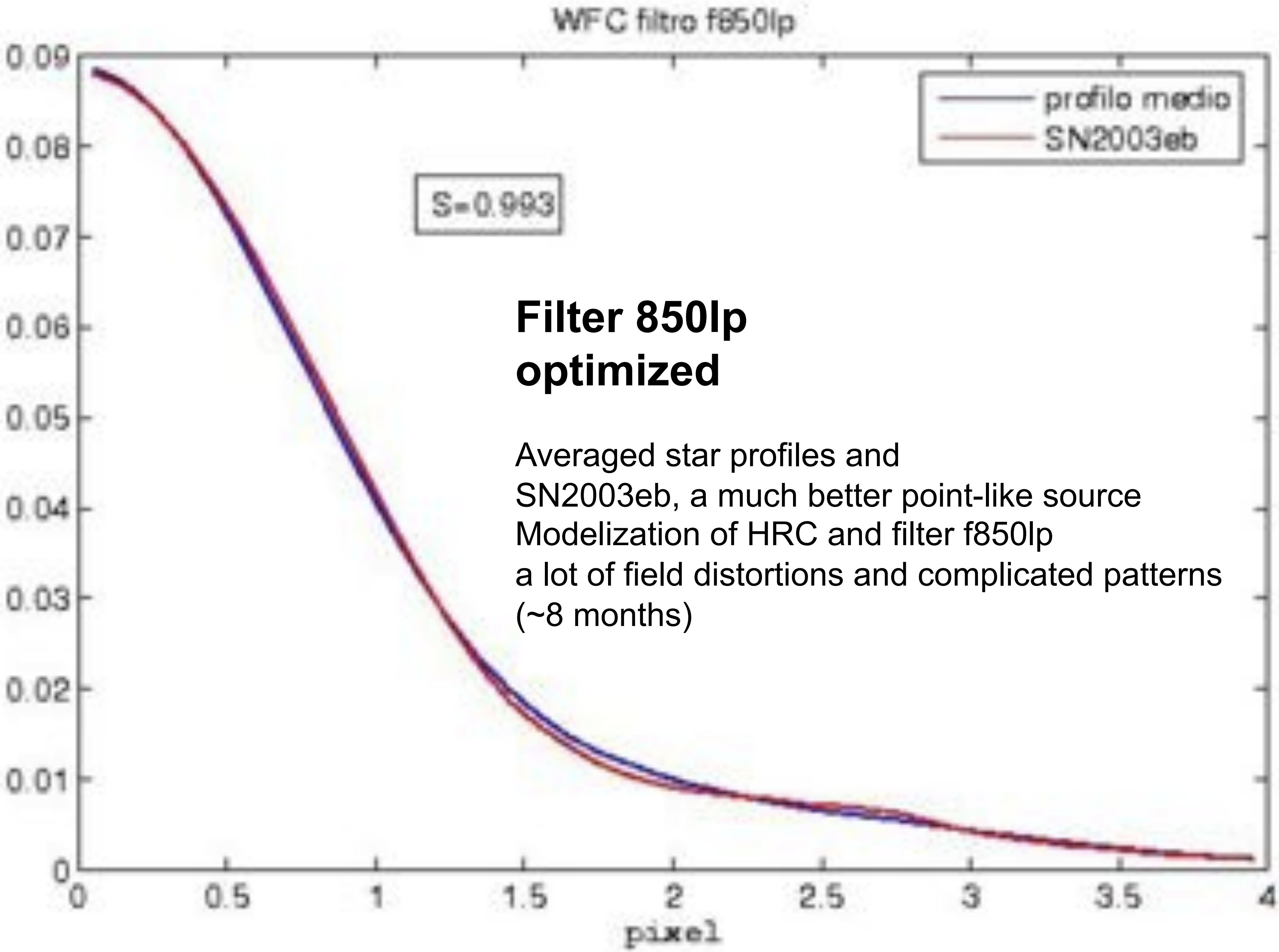


The worst filter ever…

Optimizing filter f850lp

The size of Sne phase variations gives an indication of the absence of QG fluctuations.

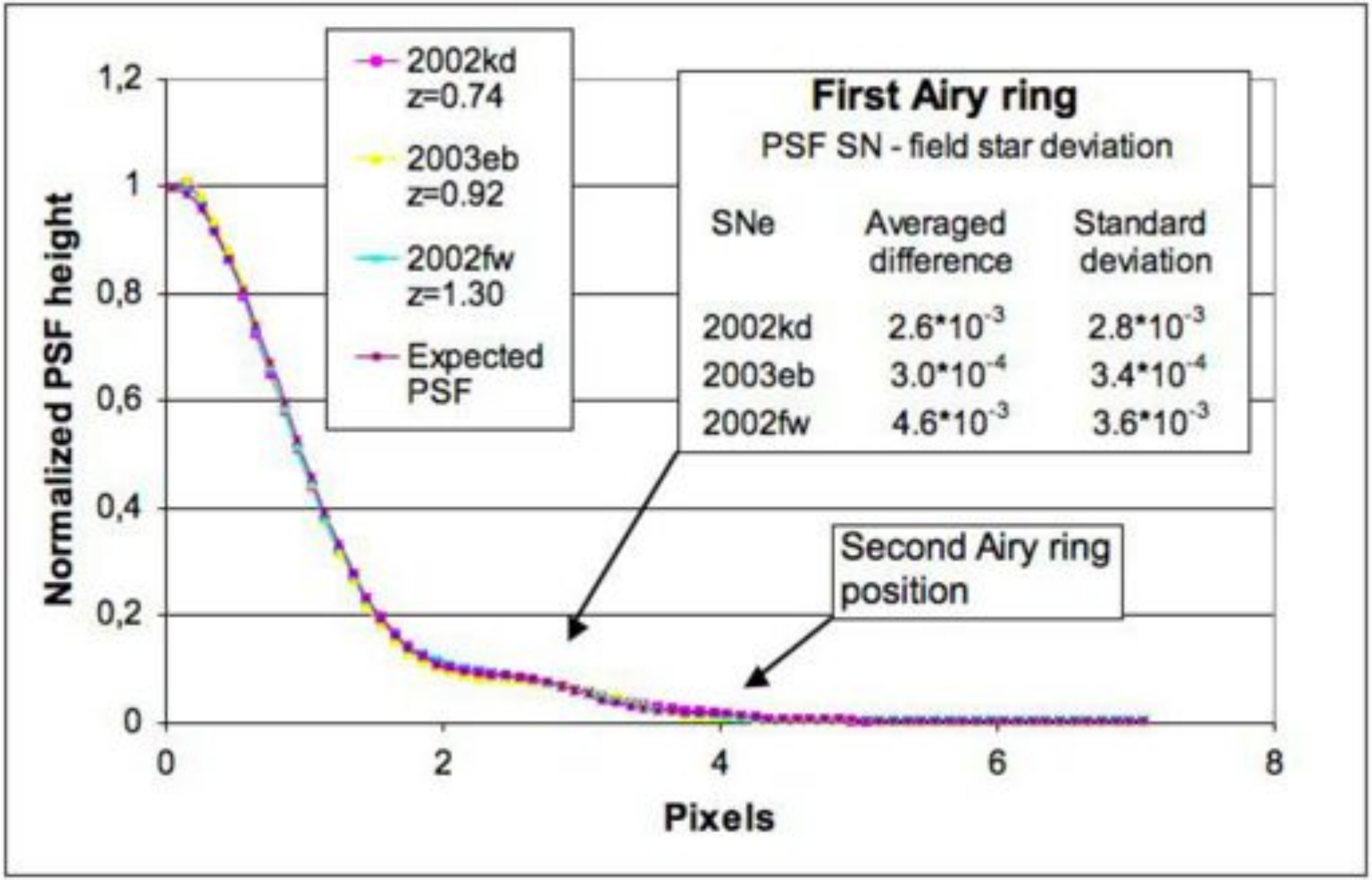
The PSF of an isolated SN is ~ point-like



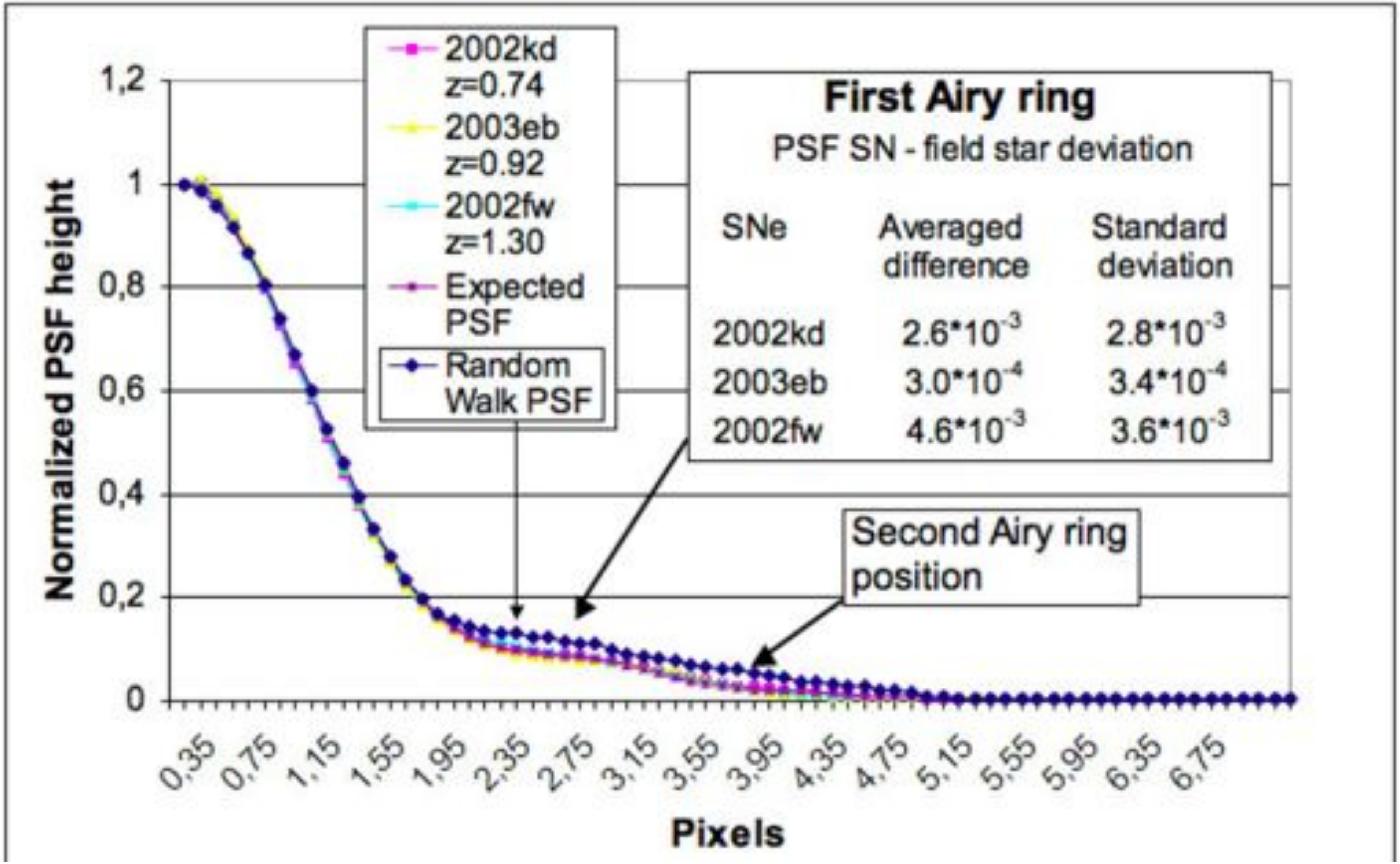
Filter 850lp optimized

Averaged star profiles and
SN2003eb, a much better point-like source
Modelization of HRC and filter f850lp
a lot of field distortions and complicated patterns
(~8 months)

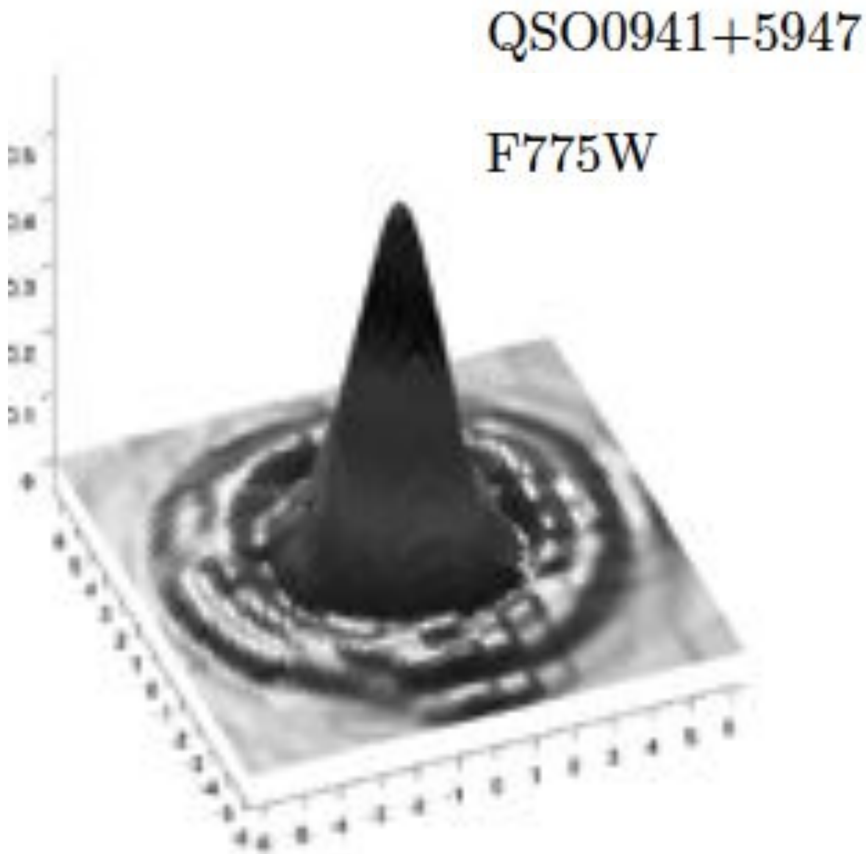
Improving a recursive empirical psf with isolated SNe – *F* test

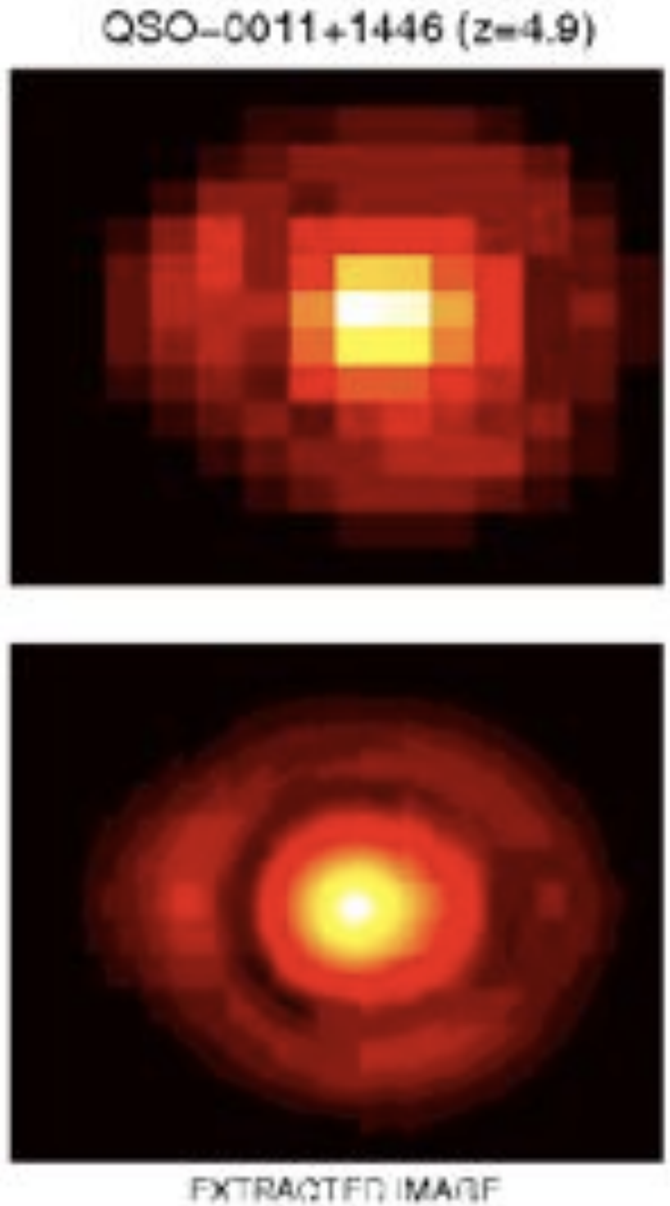


No visible QG effects with isolated SNe – random walk model out

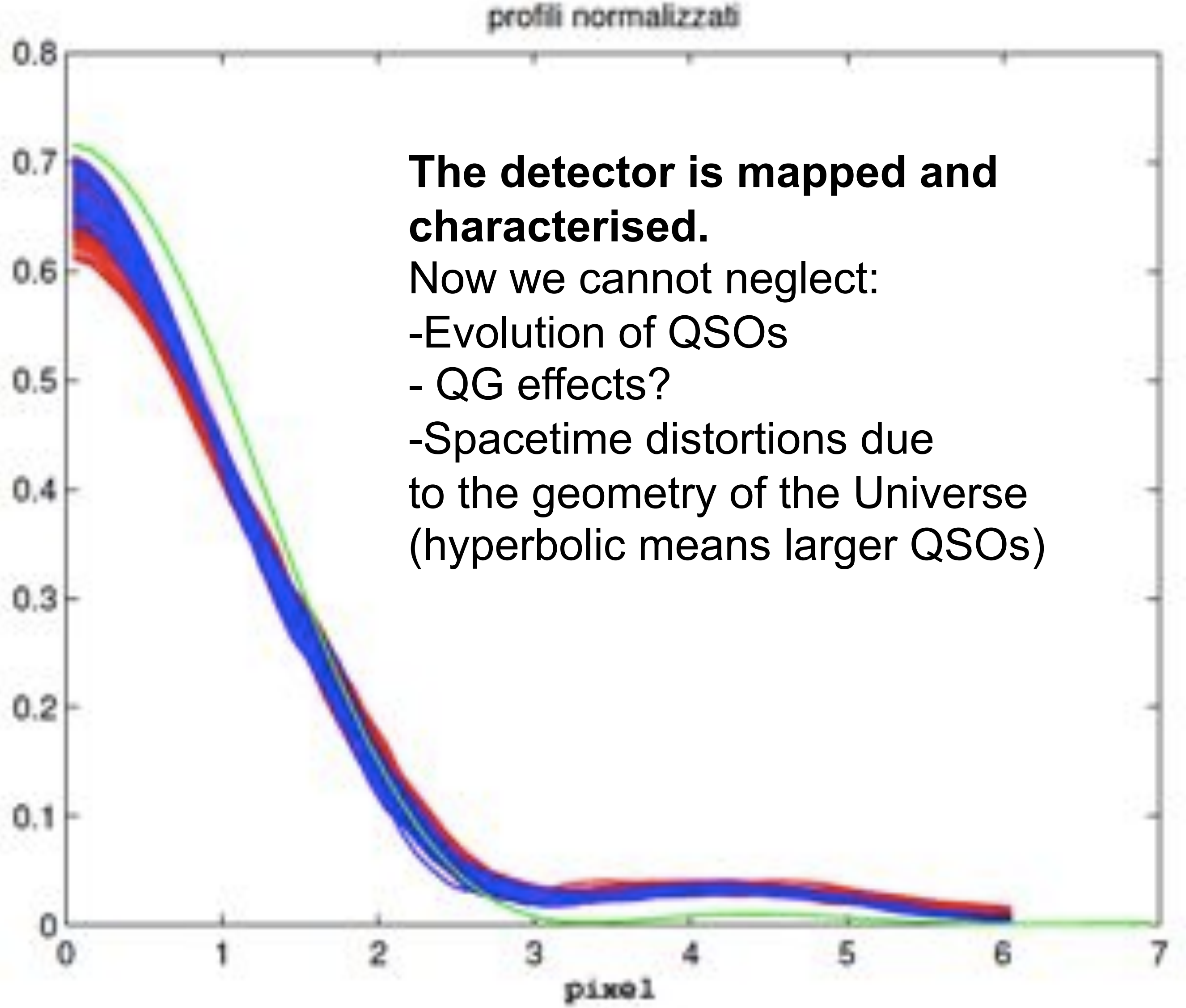


Tests with point-like QSOs





Stars & QSOs different PSF: evolutionary QSOs effects or QG?



The detector is mapped and characterised.

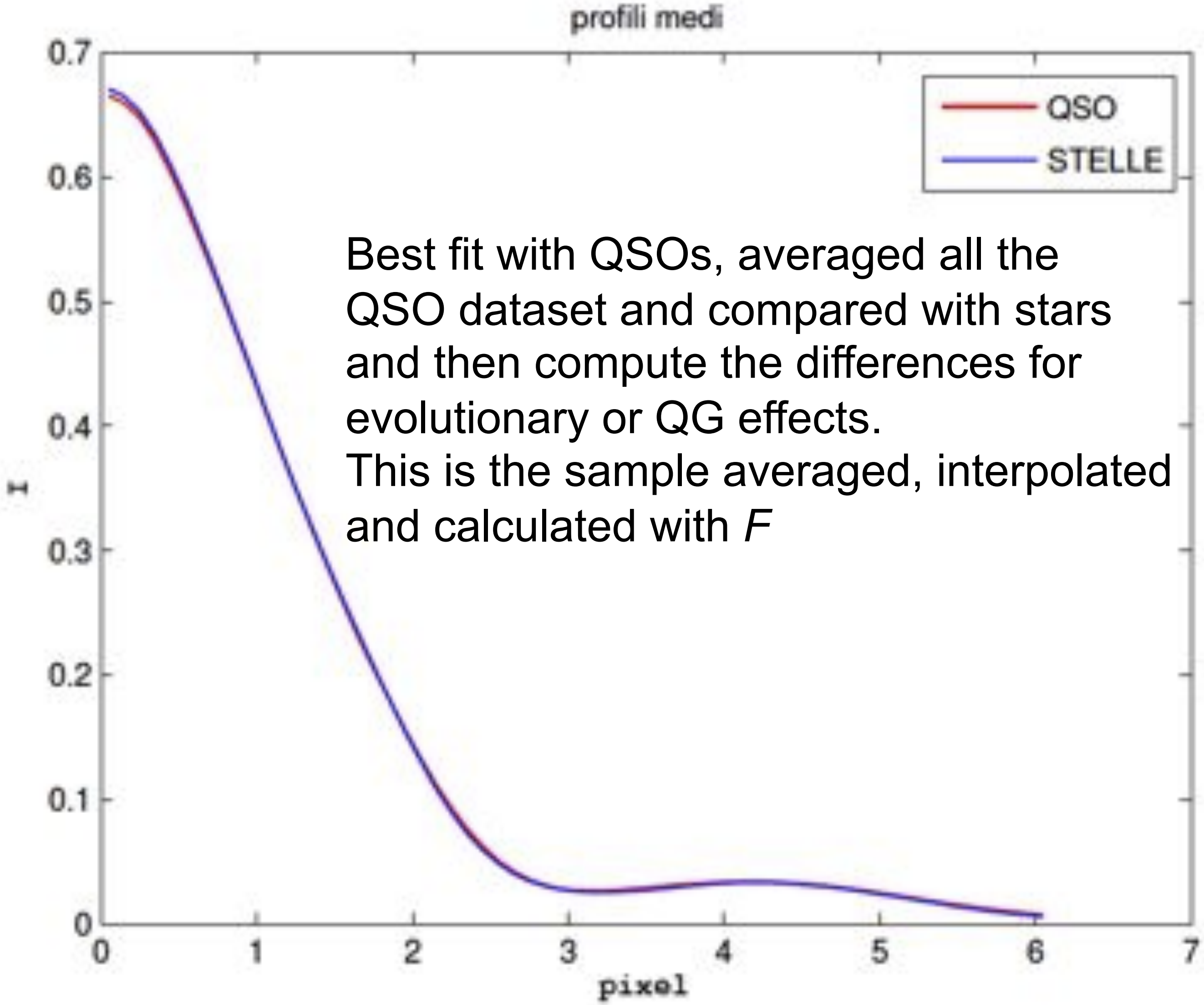
Now we cannot neglect:

-Evolution of QSOs

- QG effects?

-Spacetime distortions due to the geometry of the Universe (hyperbolic means larger QSOs)

Averaging QSOs: the farthest behave like stars



Best fit with QSOs, averaged all the QSO dataset and compared with stars and then compute the differences for evolutionary or QG effects.
This is the sample averaged, interpolated and calculated with *F*

QSO images
an example of data interpolation, fitting and reduction

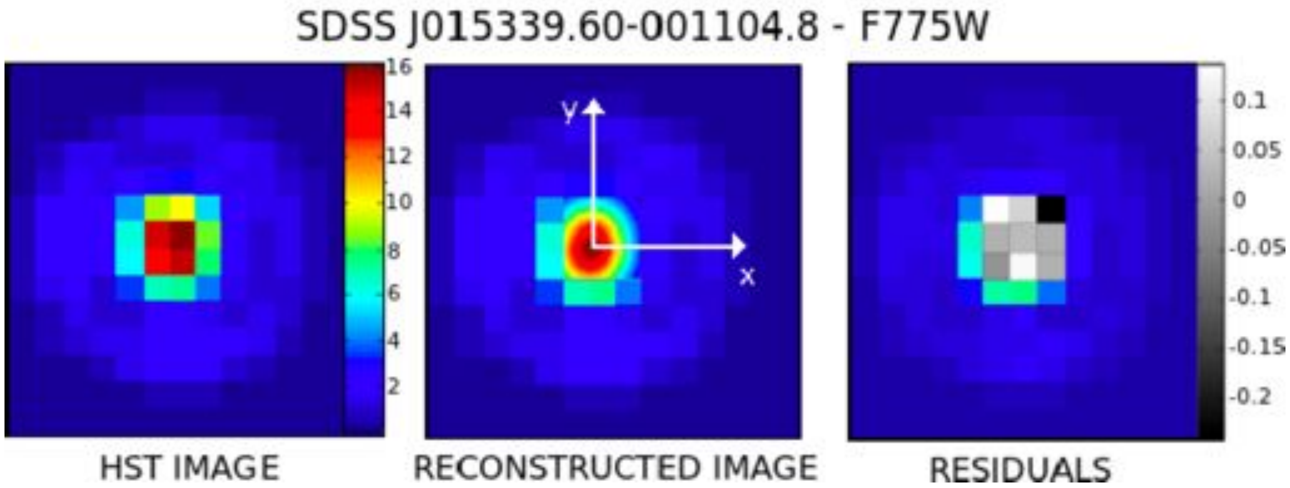


Fig. 1. *Left: HST image of the quasar QSO 0153-0011, IAU name SDSS J015339.60-001104.8 located at* $z = 4.205$. *The field of view is of* 15×15 *pixels. Center: we show the central region (*3×3 *pixels) reconstructed using the function F (Eq.9). We plot the cartesian axes centered on the maximum of the intensity pattern. Here* $\epsilon = 0.23$ *and* $\alpha = 0.14$ *rad. Each pixel of the analyzed area is divided into* 15×15 *sub–pixels. Right: we show the residuals of the central analyzed area (*3×3 *pixels).*

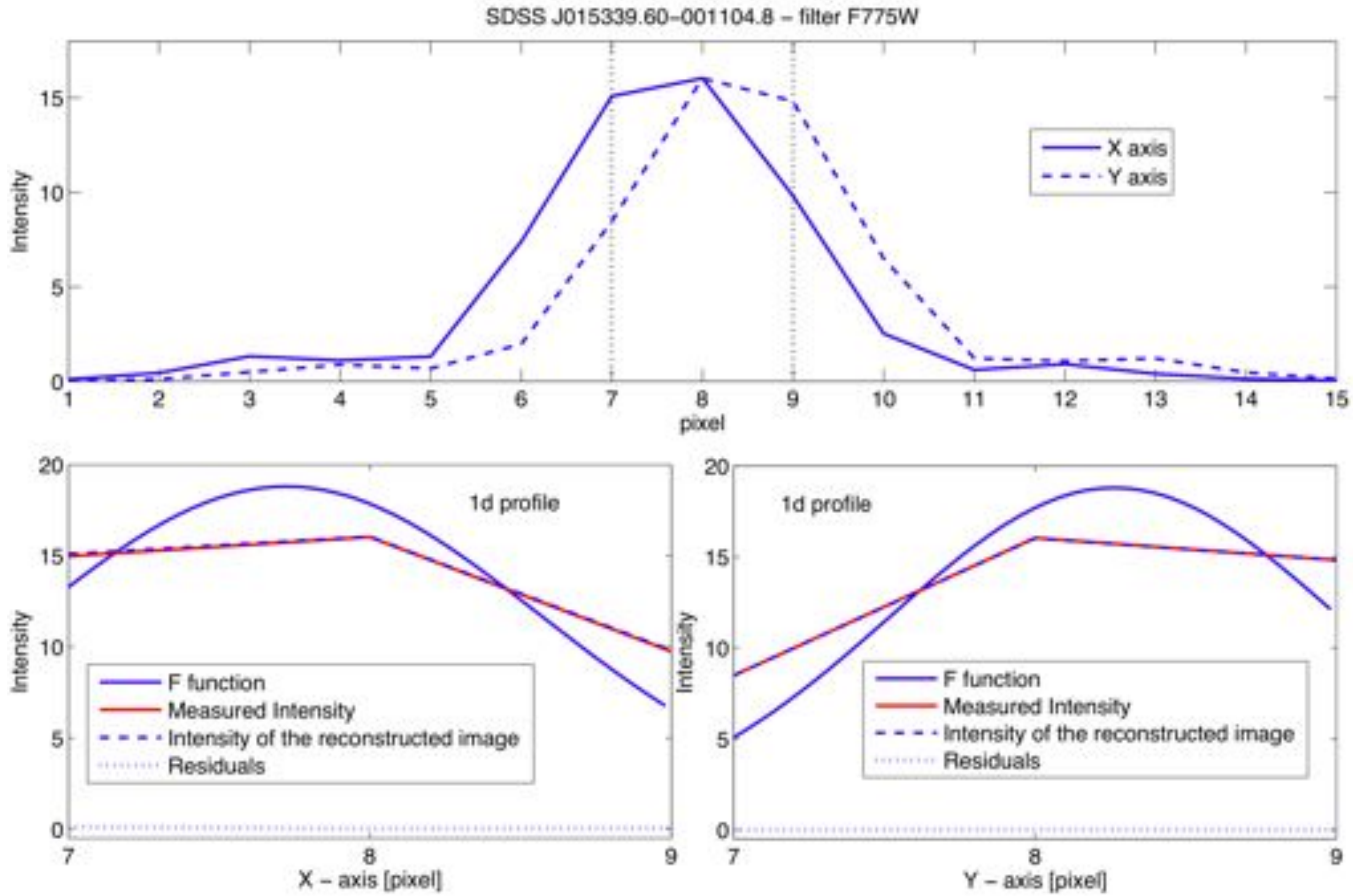


Fig. 2. *Top: 1d cut along the x–axis (solid line) and the y–axis (dashed line) of the measured intensity of QSO SDSS J015339.60-001104.8. We analyzed the area within the two dotted lines. Bottom: we show the measured intensity (red line), the interpolated function F (solid blue line), the intensity of the reconstructed image (dashed blu line) and the residuals (dotted blue line) of the 1-d cut along the x–axis (left) and the y–axis (right) of the central area (3×3 pixels).*

Phase from QSOs Strehl ratio
let us summarize

$$\Delta\phi \approx \frac{\lambda}{D}\sqrt{-ln(S)} \qquad S = \frac{(\mathrm{Max})_{\mathrm{source}}}{(\mathrm{Max})_{\mathrm{th}}} \sim \exp\left[-\left(\Delta\phi\frac{D}{\lambda}\right)^2\right]$$

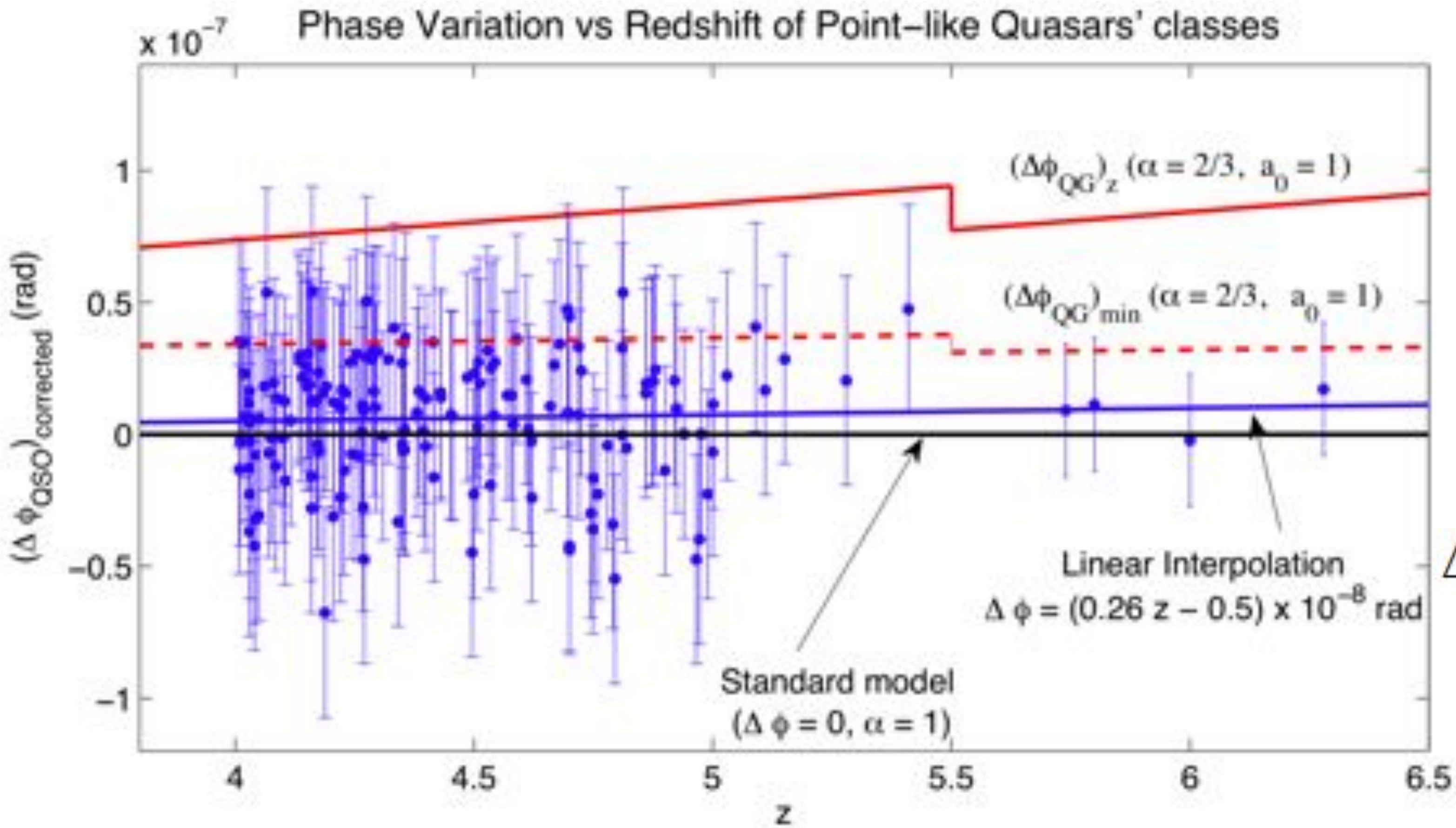
$$\Delta\phi(z)_{\mathrm{QSO}} = \Delta\phi_{\mathrm{ab}} + \Delta\phi(z)_{\mathrm{size}} + \Delta\phi(z)_{\mathrm{QG}} + \Delta\phi(z)_{\mathrm{lens}}$$

$$\Delta\phi_{\mathrm{star}} \simeq \Delta\phi_{\mathrm{ab}}$$

Corrected with stars and SNe

$$\begin{aligned}(\Delta\phi(z)_{QSO})_{\mathrm{Corrected}} &= \Delta\phi(z)_{\mathrm{QSO}} - \langle\Delta\phi\rangle_{\mathrm{star}} \\ &\simeq \Delta\phi(z)_{\mathrm{size}} + \Delta\phi(z)_{\mathrm{QG}} + \Delta\phi(z)_{\mathrm{lens}} \pm \delta\phi_{star}\end{aligned}$$

Why do we expect phase variations in QSOs?



a= 0.26±0.78

b= -0.5±3.5

$$\sigma_a = \delta\phi_{star}\sqrt{\frac{\sum z_i^2}{\Delta}}$$

$$\sigma_b = \delta\phi_{star}\sqrt{\frac{N}{\Delta}}$$

$$\Delta = N\sum z_i^2 - (\sum z_i)^2$$

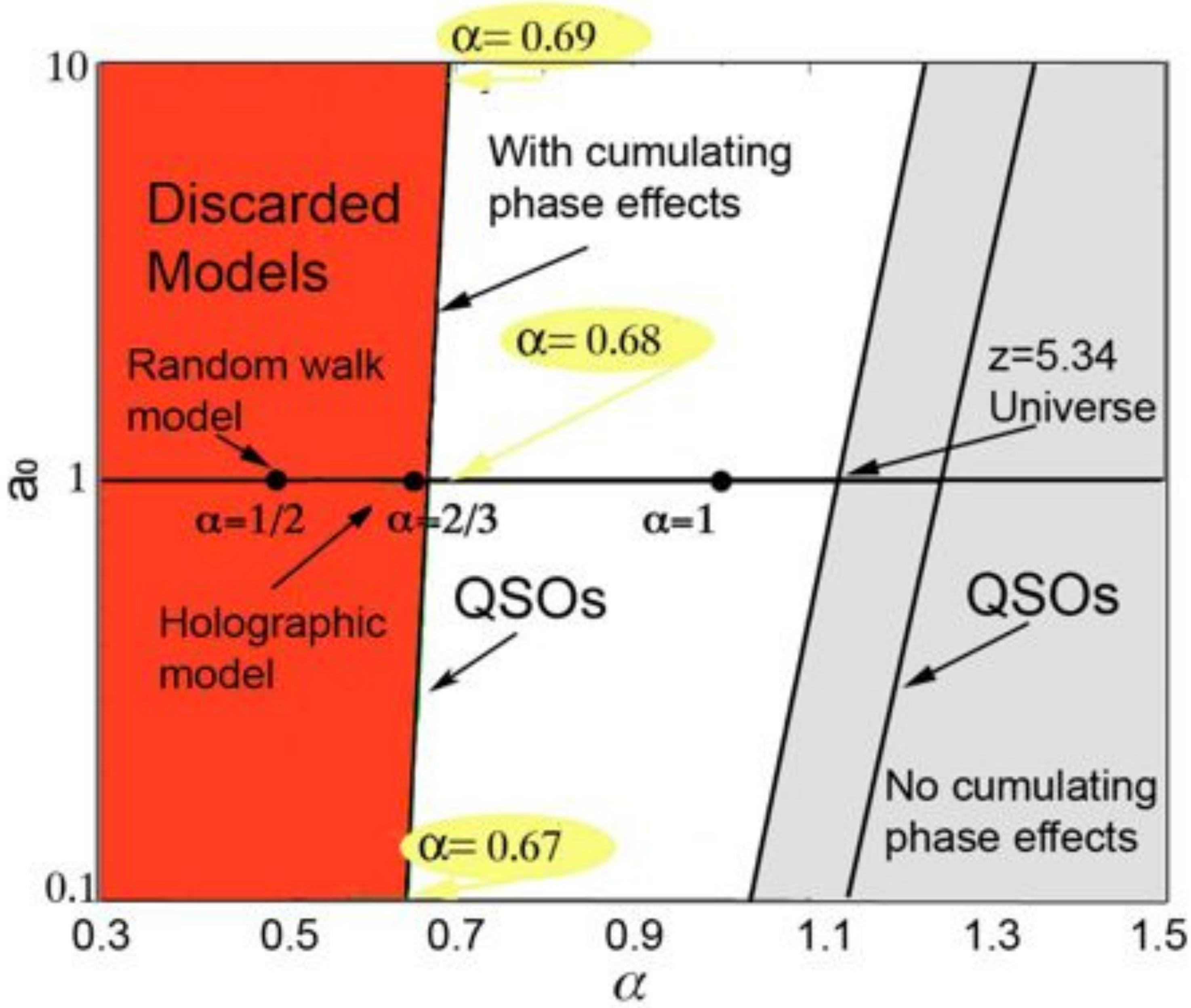
Fig. 4. Corrected phase variations of QSOs as a function of the redshift z. No blurring effects due to QG are observed. The linear interpolation of all the data sets show a positive trend, indicating the possible resolvability of the sources - blue solid line (color online). The red (color online) continuous and dashed "z"-shaped lines represent the expected growth of the phase variation, $\Delta\phi$, as a function of the redshift z. The break of the two curves indicating the limits of QG effects with (red solid line) and without cosmological redshift corrections (red dashed line), are due to the change of filters, F775W and F850LP. The phase variations observed are much smaller than those expected from the spacetime fluctuations described by the holographic principle model having $\alpha = 2/3$ and $a_0 = 1$.

Big errors but still below the value α=⅓

Results

Results. Our results go far beyond those already present in the literature. By adopting the most conservative approach where are taken into account the correction terms that describe the possibility for spacetime fluctuations of cumulating across long distances and partially compensate the effects of the phase variations, we exclude the random walk model and most of the holographic model of the spacetime foam. Without considering these correction terms, all the main Quantum Gravity scenarios are excluded. Finally, our results show the absence of any directional dependence of QG effects and the validity of Cosmological Principle with an independent method: viewed on large scale, the properties of the Universe are the same for all observers, including the effects of spacetime fluctuations.

QG theories - parameter space



Cumulating phase effects

and

non-cumulating phase effect

ST foam models

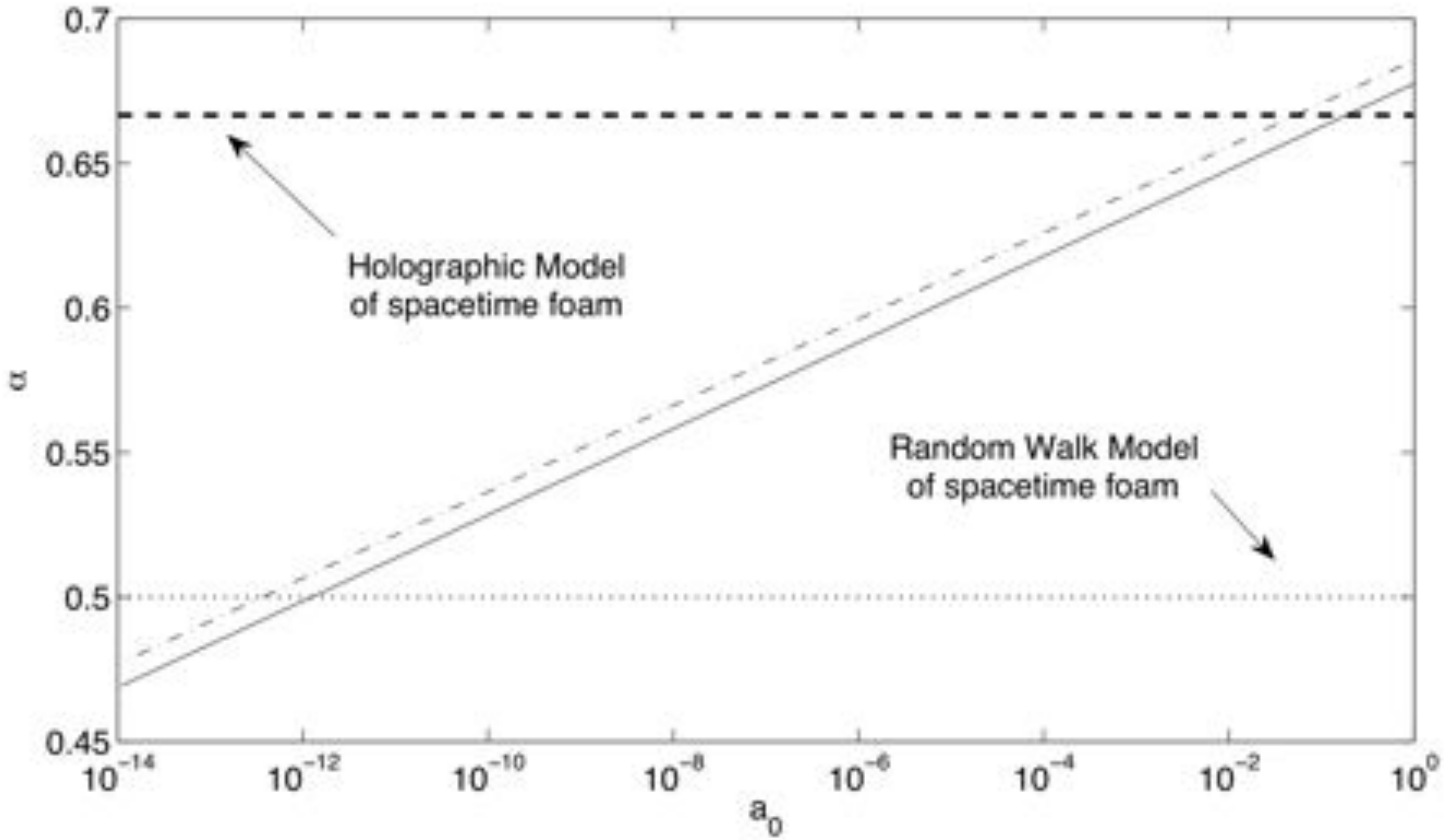


Fig. 6. Limitations to the parameters a_0 and α from QSOs. The excluded regions are below the dotted-dashed or the solid line depending on whether or not the photons redshifted to the observer wavelenghts, were taken in account, respectively. The holographic Model ($\alpha = 2/3$) of spacetime foam is preserved respectively for $a_0 \lesssim 5 \times 10^{-2}$ and $a_0 \lesssim 0.15$ (upper panel). The Random Walk Model ($\alpha = 1/2$) is preserved respectively for $a_0 \lesssim 10^{-13}$ and $a_0 \lesssim 10^{-12}$ (lower panel).

Conclusions

- We found **no blurring** that could be caused by the interaction of photons with quantum gravity fluctuations.
- Most of the models of space-time foam consistent with the holographic principle and, consequently, with black hole entropy, can be ruled out for most of the values of the fluctuation amplitude parameter a_0.
- No magnification of QSO images expected from the geometry of the Universe adopted: either the Universe is flat in the interval $4 < z < 6$ or QSOs may present some unknown evolutionary effects at large z.
- Absence of any directional dependence on QG effects
- Limited effects of intergalactic medium on the light across these cosmological distances in those observation bands.
- Confirmation of the cosmological principle for the ST foam on scales up to $z \sim 6$.