Transverse coherence of a seeded Free-Electron Laser:
the case of FERMI@Elettra

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Situation

How do FEL's compare with other coherent light sources?
Is the single-pass FEL really a laser?

State of the art of transverse coherence measurements on FEL's:

- FLASH, TESLA test facility, etc. [A. Singer et al., *Phys. Rev. Lett.* **101**, 254801 (2008); A. Singer et al., Opt. Express. **20**, 16 (2012); etc.]
- LCLS [I. A. Vartanyants et al., *Phys. Rev. Lett.* **107**, 144801 (2011)]
- MAX-Lab Test-FEL J. Schwenke, *talk and proceedings of FEL 2011*

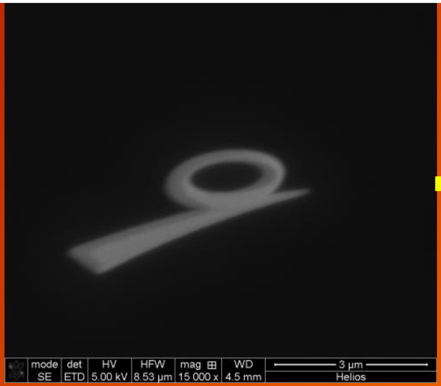
Purpose of measurements at FERMI@Elettra:

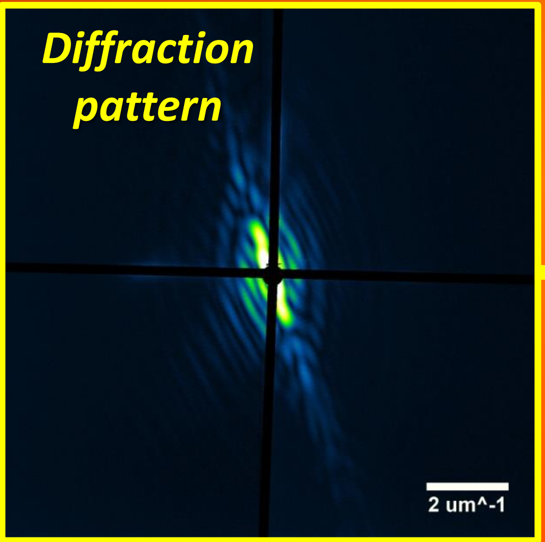
- **Characterize a new kind of user-dedicated FEL source (seeded, harmonic generation, extreme-ultraviolet)**
- **Compare seeded and SASE FEL configurations**
- **Characterize the light for users**

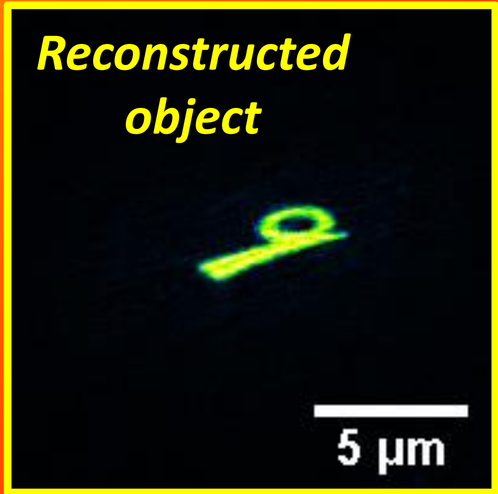
Motivation

Applications requiring a high degree of coherence such as diffraction imaging

Result on FERMI@Elettra







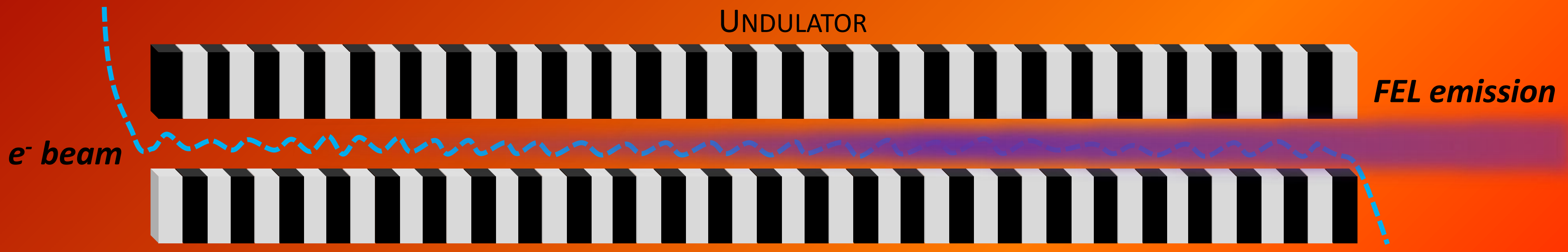
Courtesy of F. Capotondi

→ *Outline:*

1. *Description of the experiment and direct results*
2. *Comparison of transverse coherence with other sources*
3. *Predictions for a Gauss-Schell Model beam*

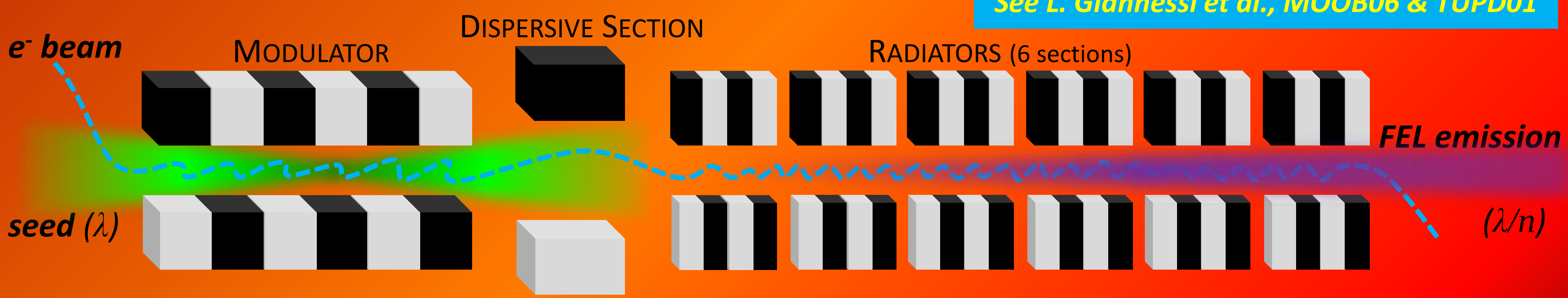
FEL configuration

Self-Amplified Spontaneous Emission – SASE (SACLA, LCLS, FLASH)



Seeding and harmonic generation/amplification (FERMI@Elettra)

See L. Giannessi et al., MOOB06 & TUPD01

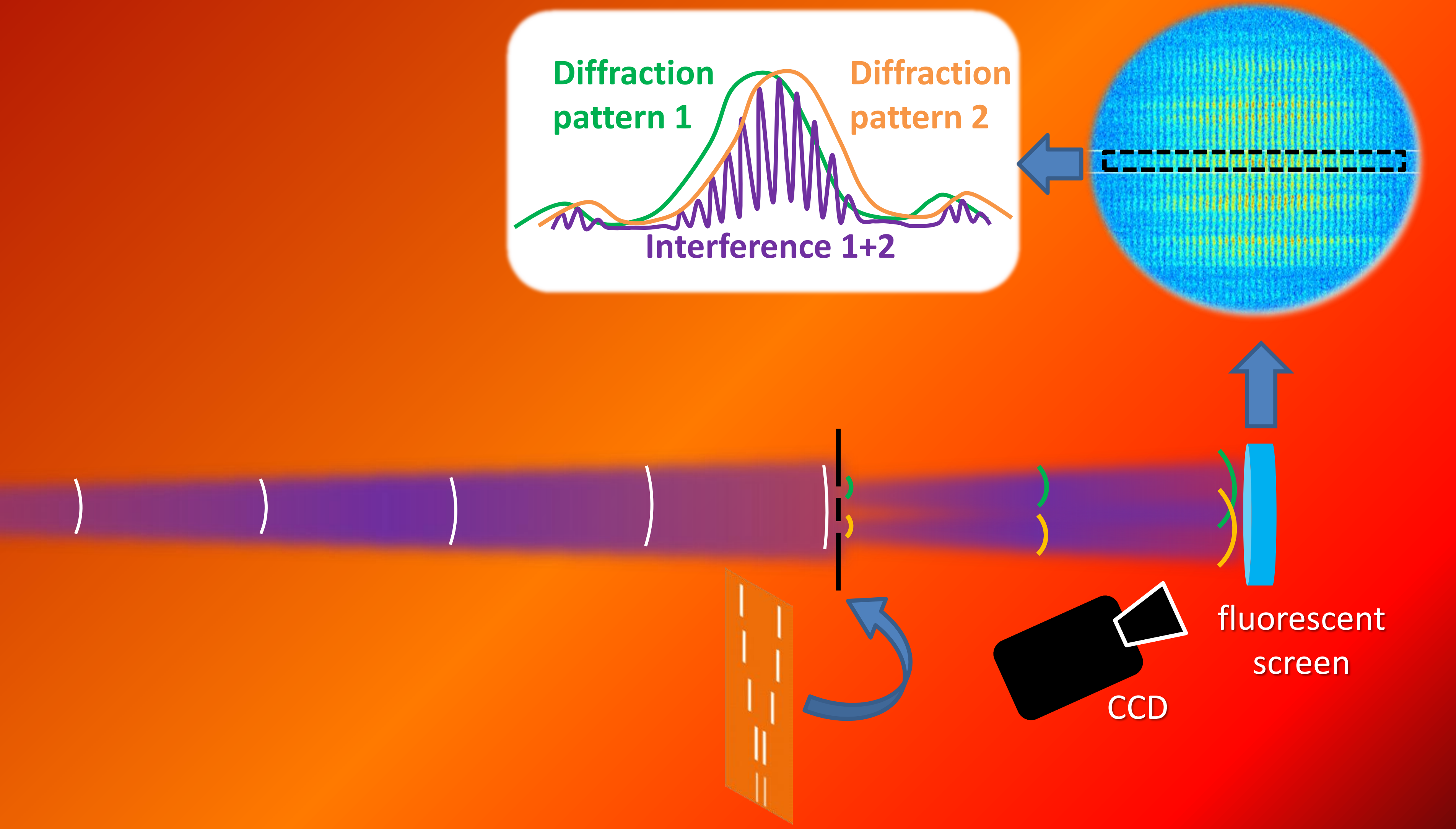


FEL emission = « copy » of the seed (spectrum and time)

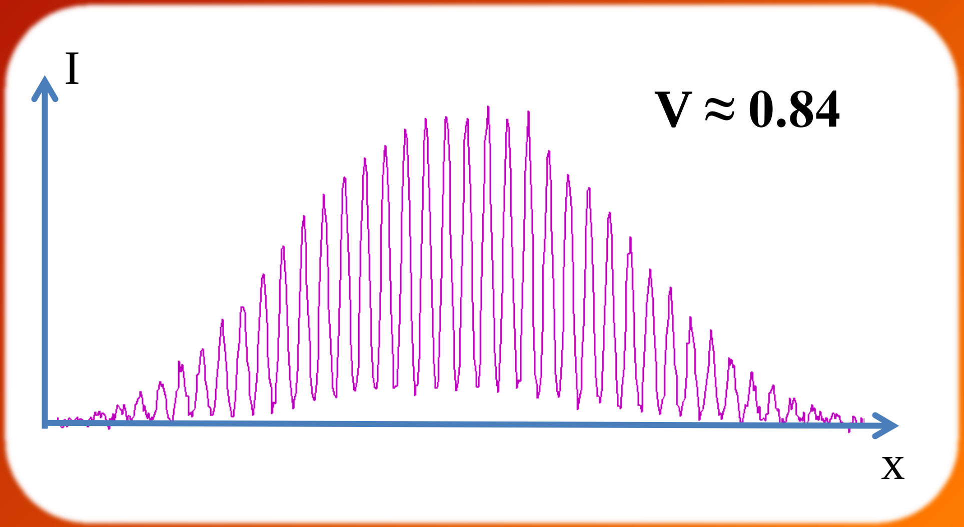
Is it also true for transverse properties? (intensity, wavefront, coherence)

Setup for Young's experiment

Setup design: C. Svetina & S. Gerusina



Principle



Coherence of light: ability to interfere

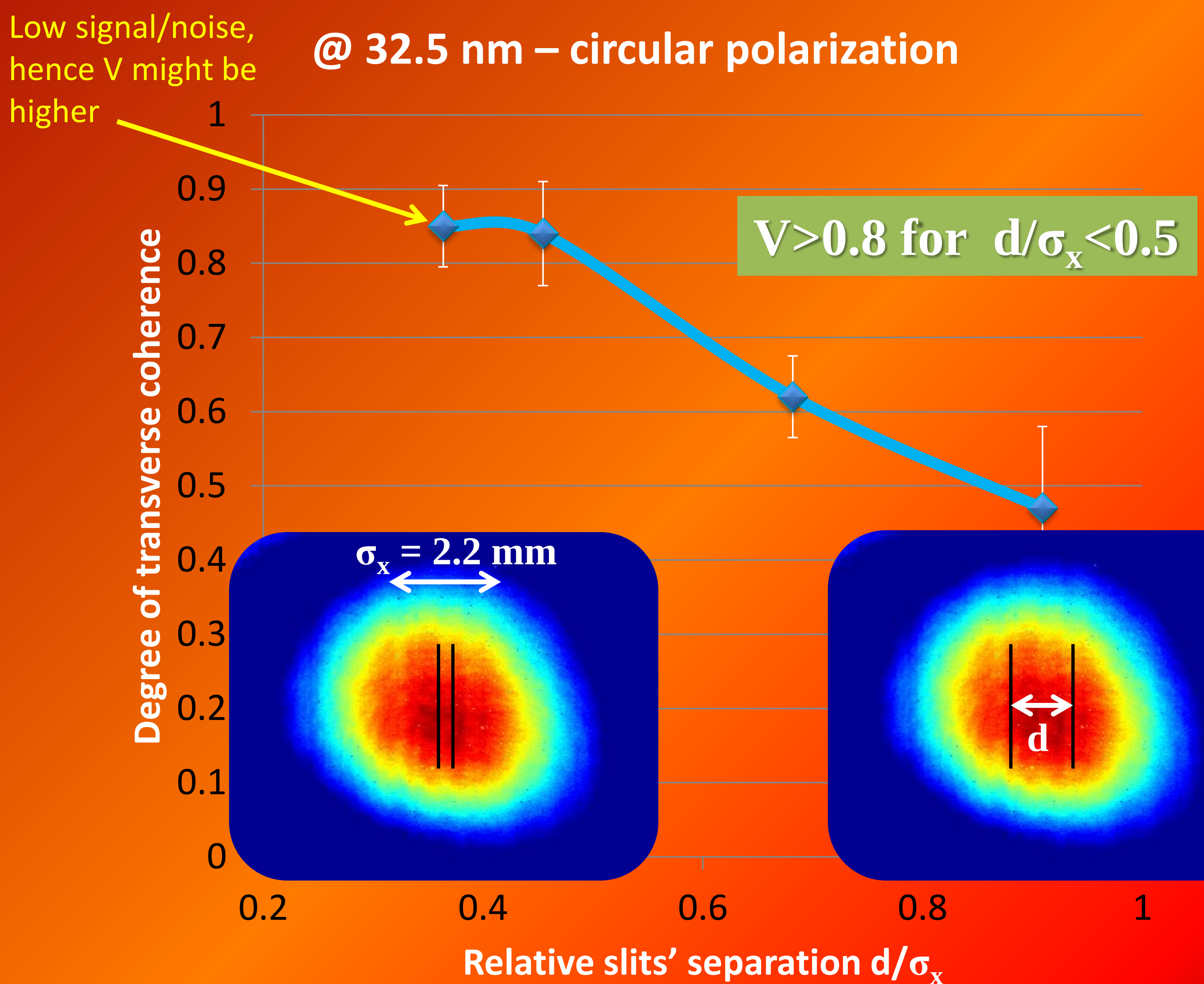
__Degree of coherence__
→ « quality » of the interference
→ visibility V of the fringes

IF:
1) the spectrum is narrow enough
2) the intensities from both slits are equal
3) the temporal coherence does not affect the quality of the interference

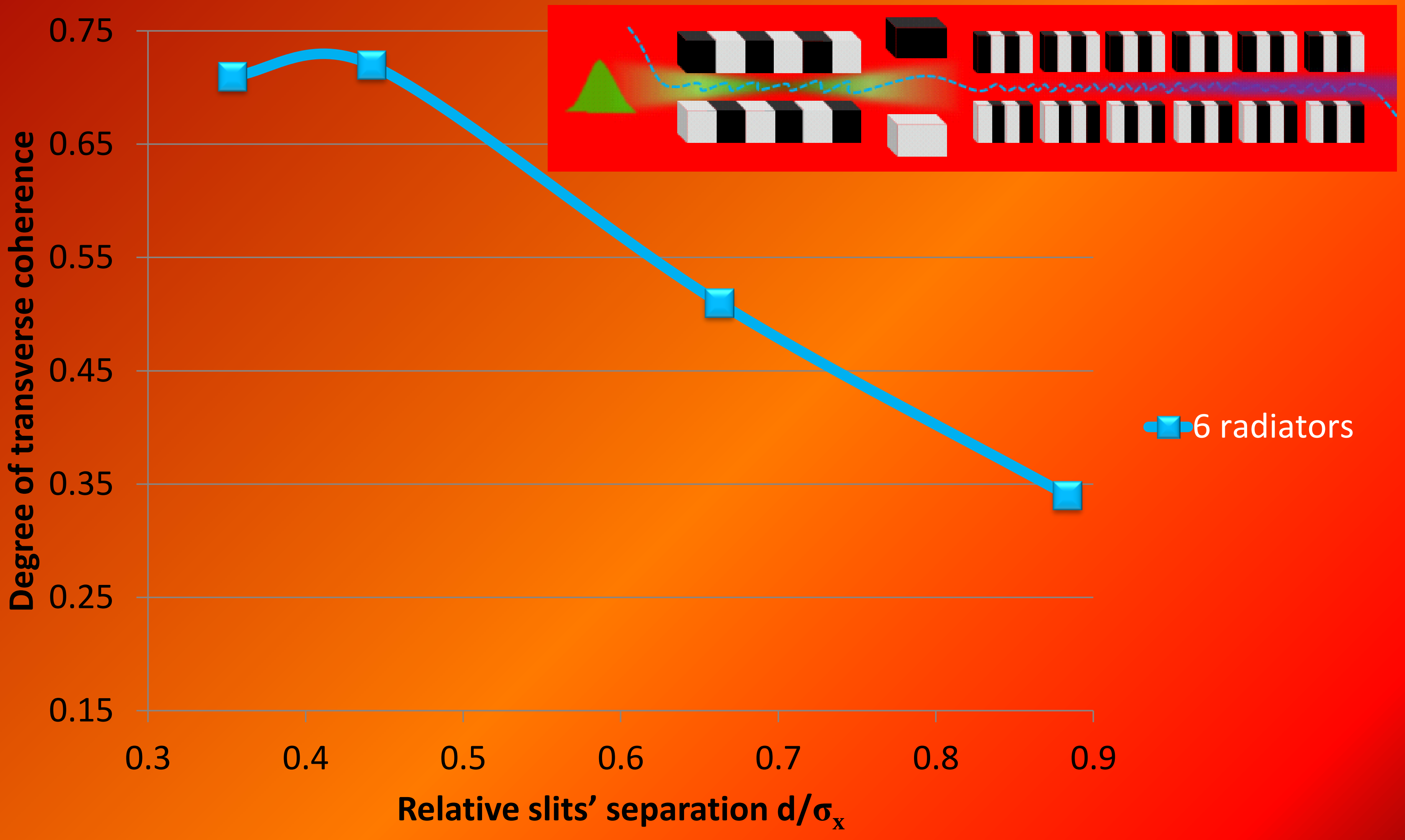
THEN: $$\text{Degree of transverse coherence} = V(x) = \frac{I_{max}(x) - I_{min}(x)}{I_{max}(x) + I_{min}(x)}$$

V = 1 → full coherence (e.g., single-mode lasers)
V = 0 → incoherent light

Experimental results in standard conditions



Effect of amplification length and saturation



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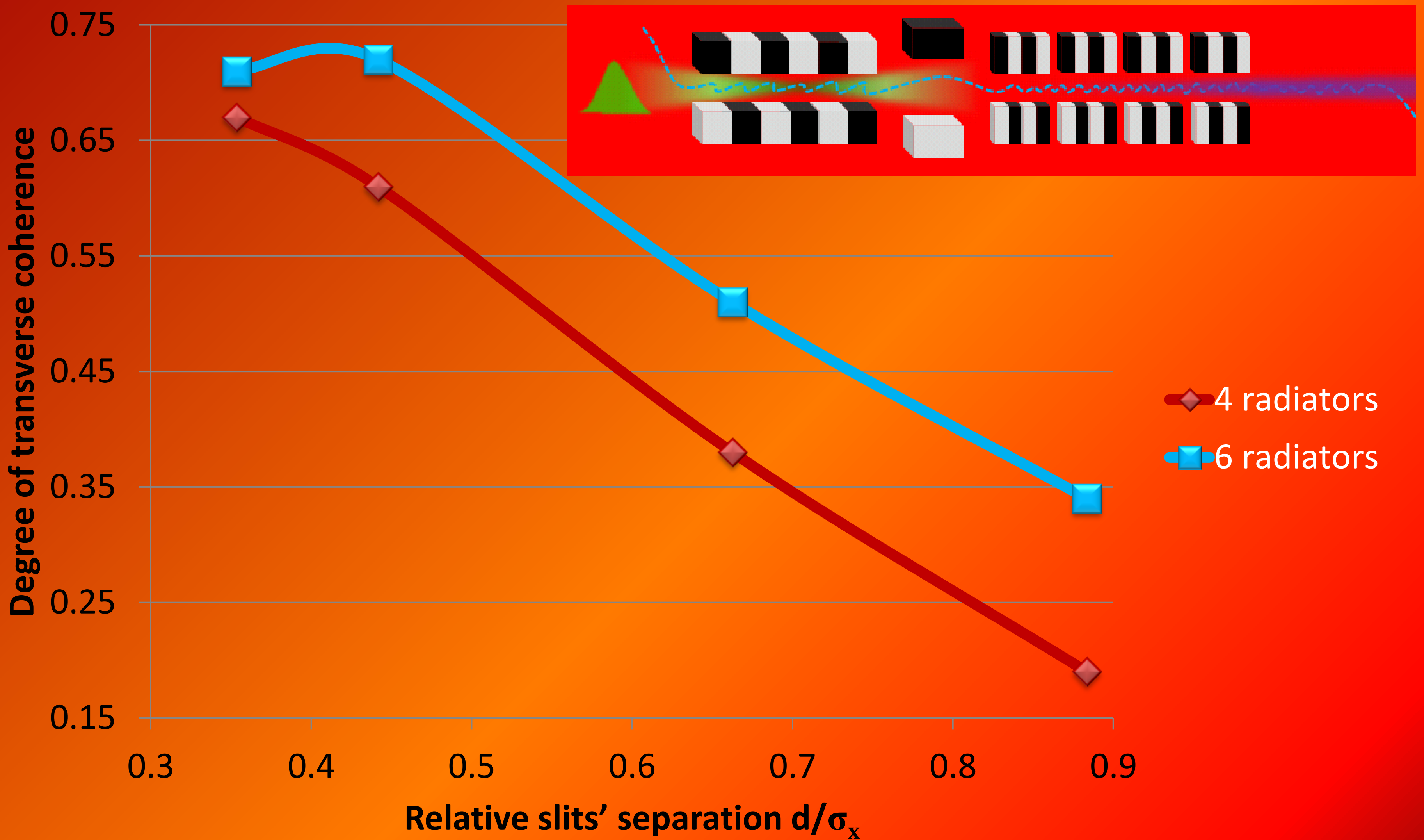

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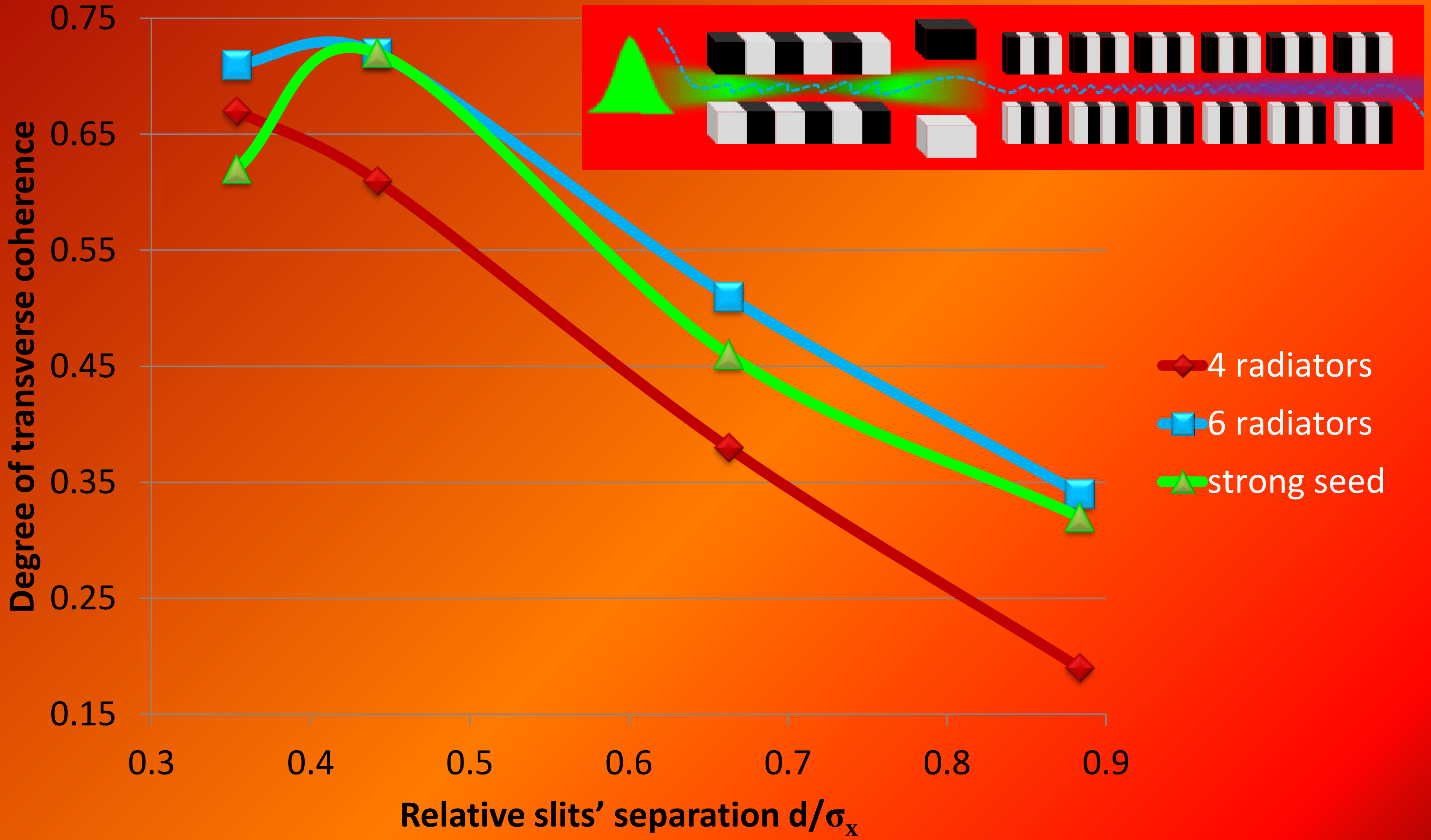

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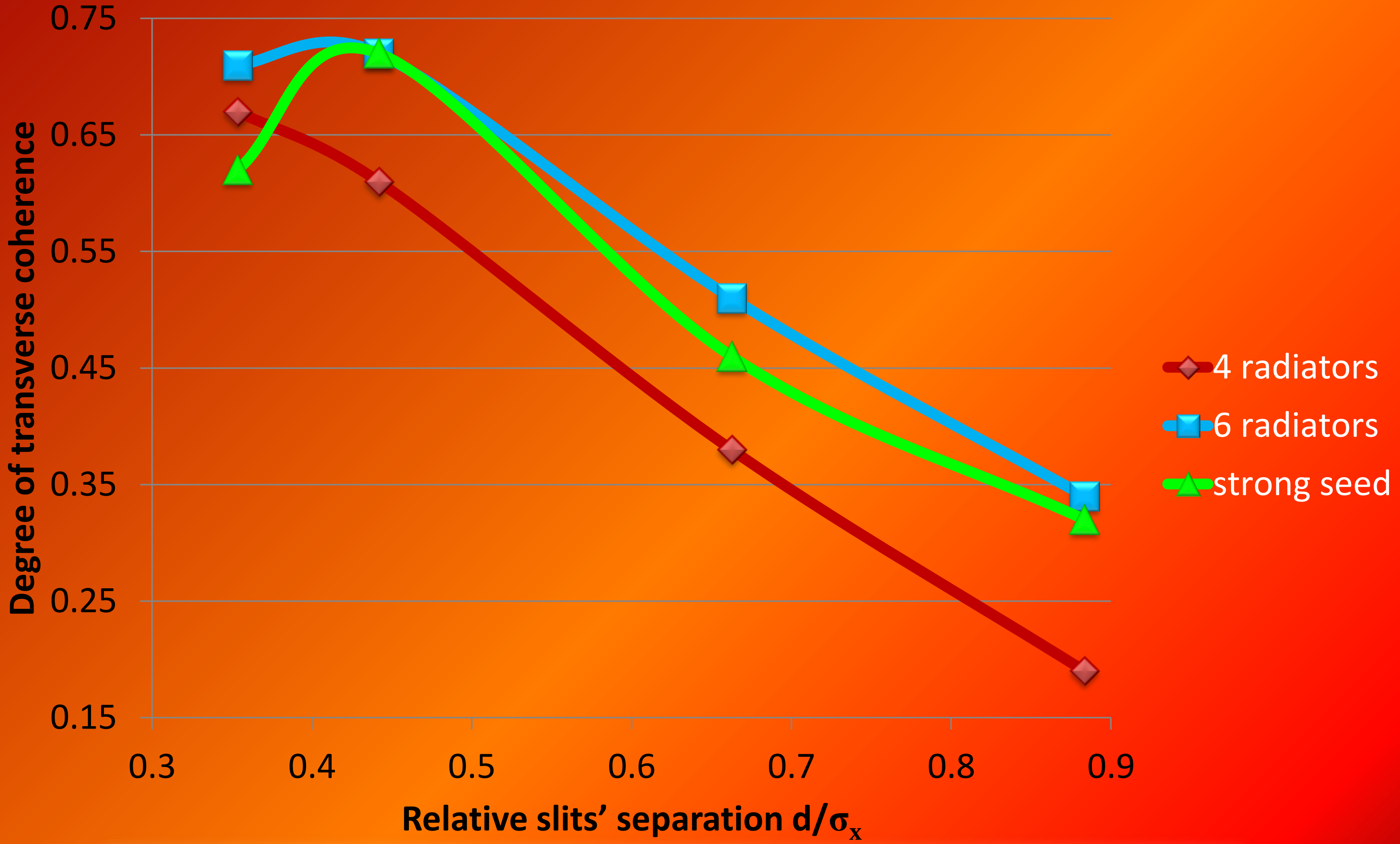
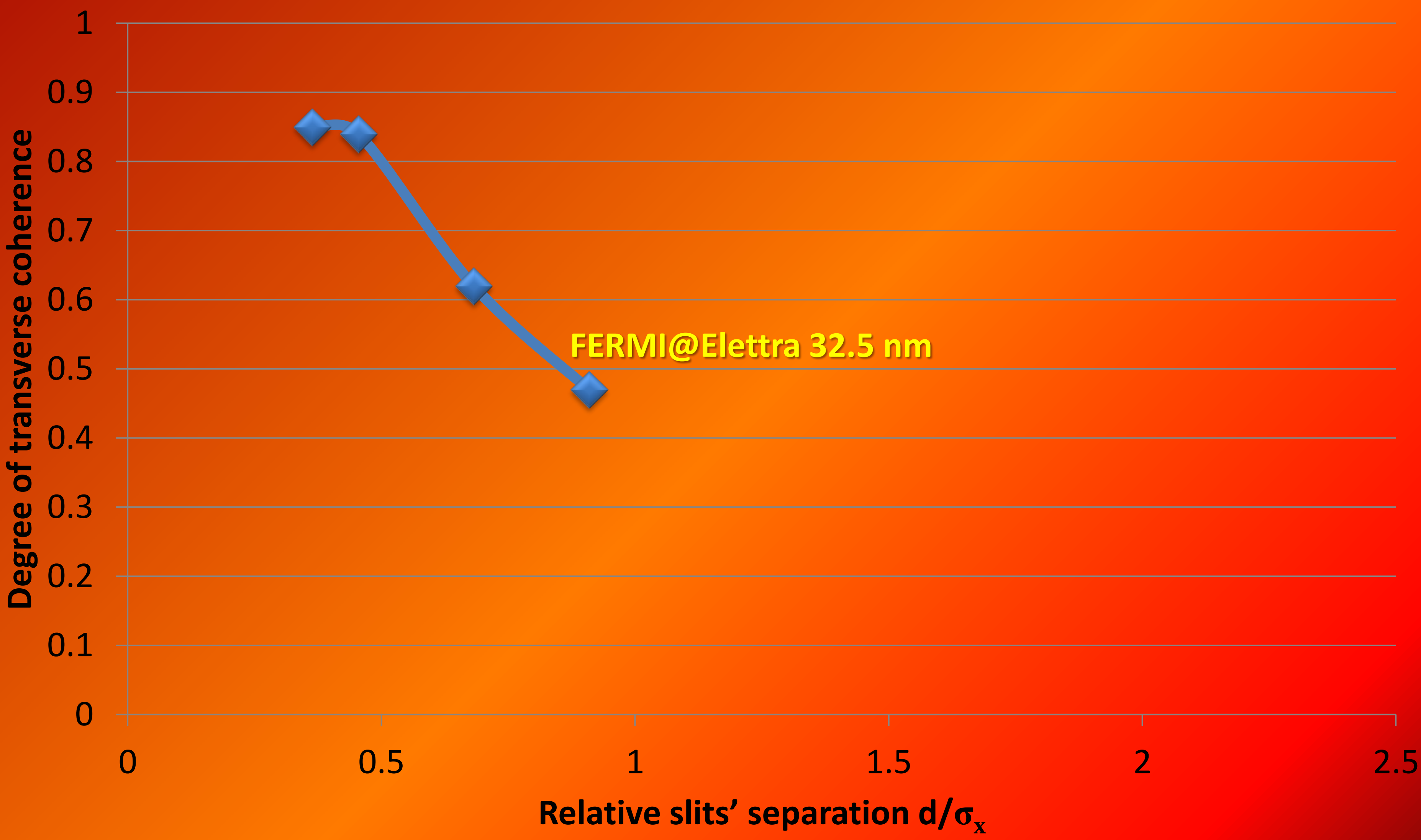


➢ LOWERING THE AMPLIFICATION LENGTH OR GOING INTO OVERBUNCHING DECREASES THE TRANSVERSE COHERENCE.

Comparison with other femtosecond EUV sources



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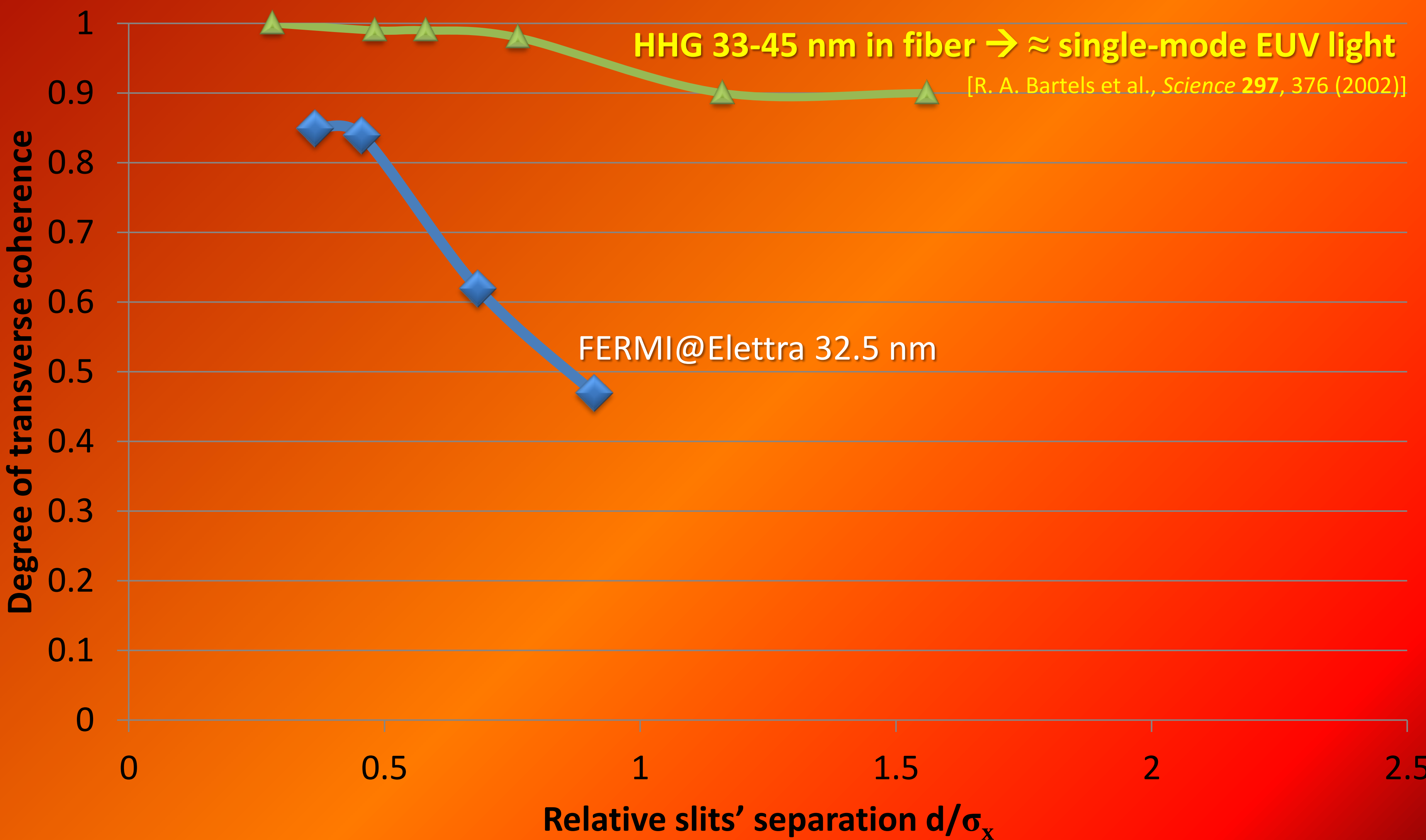

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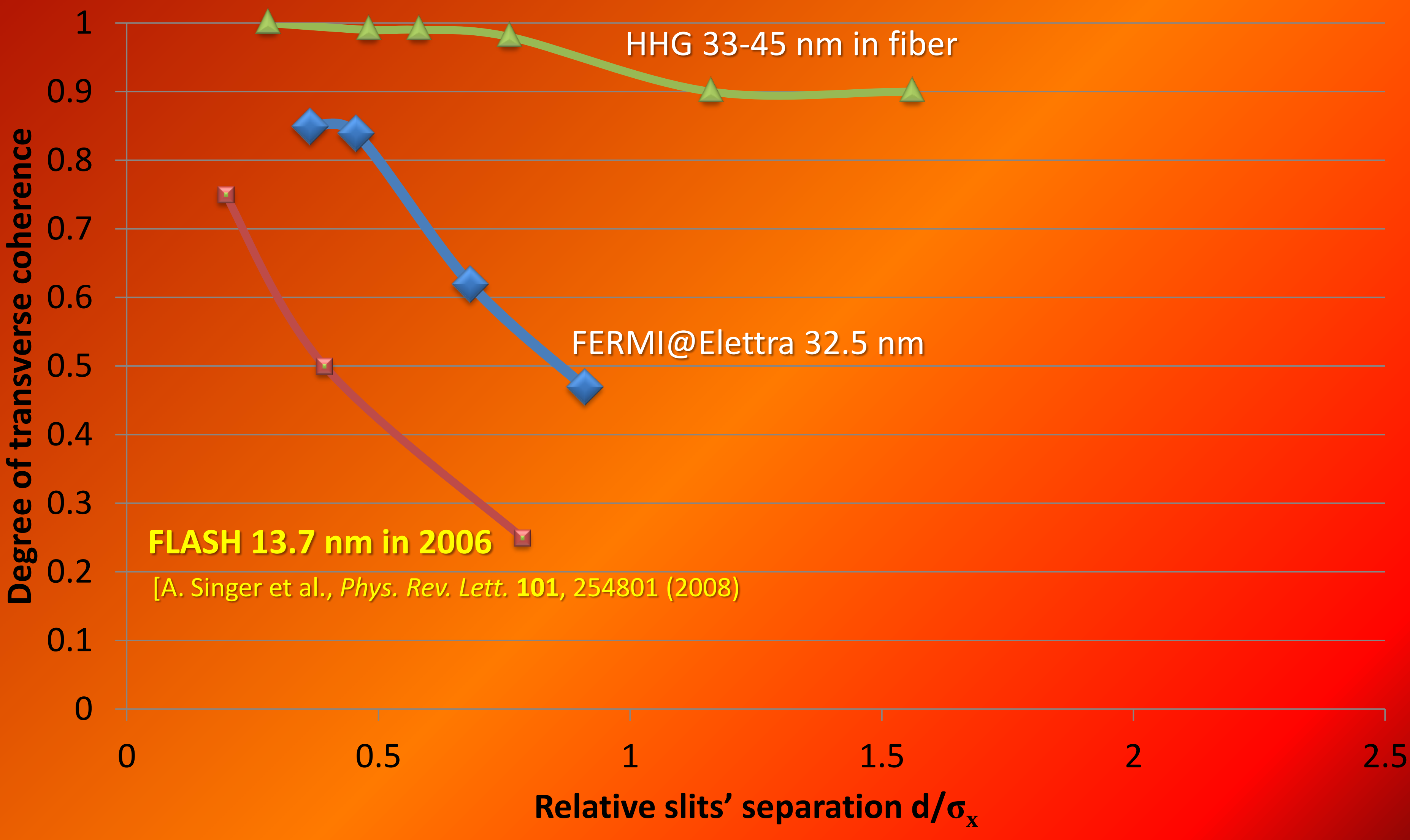

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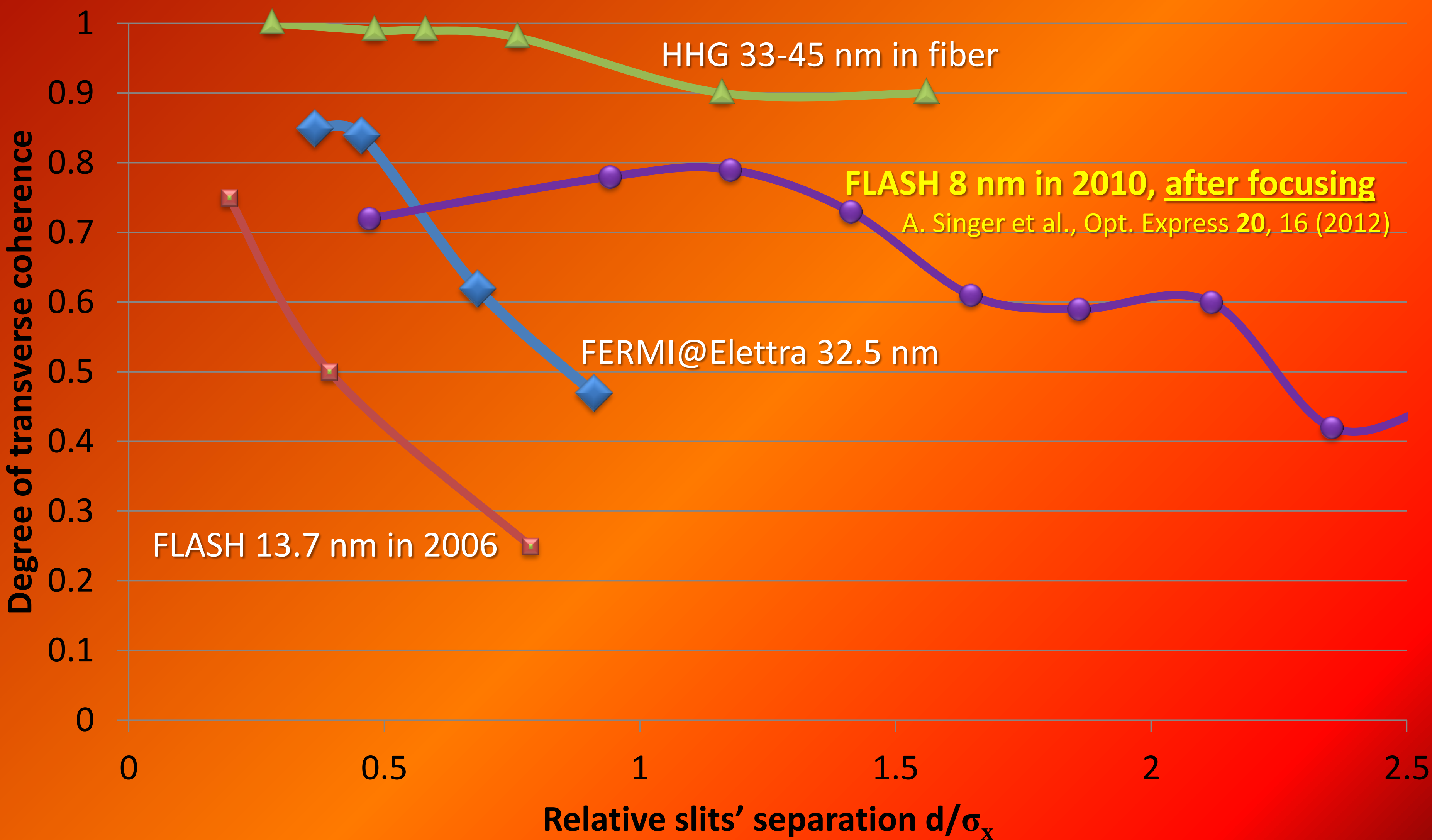

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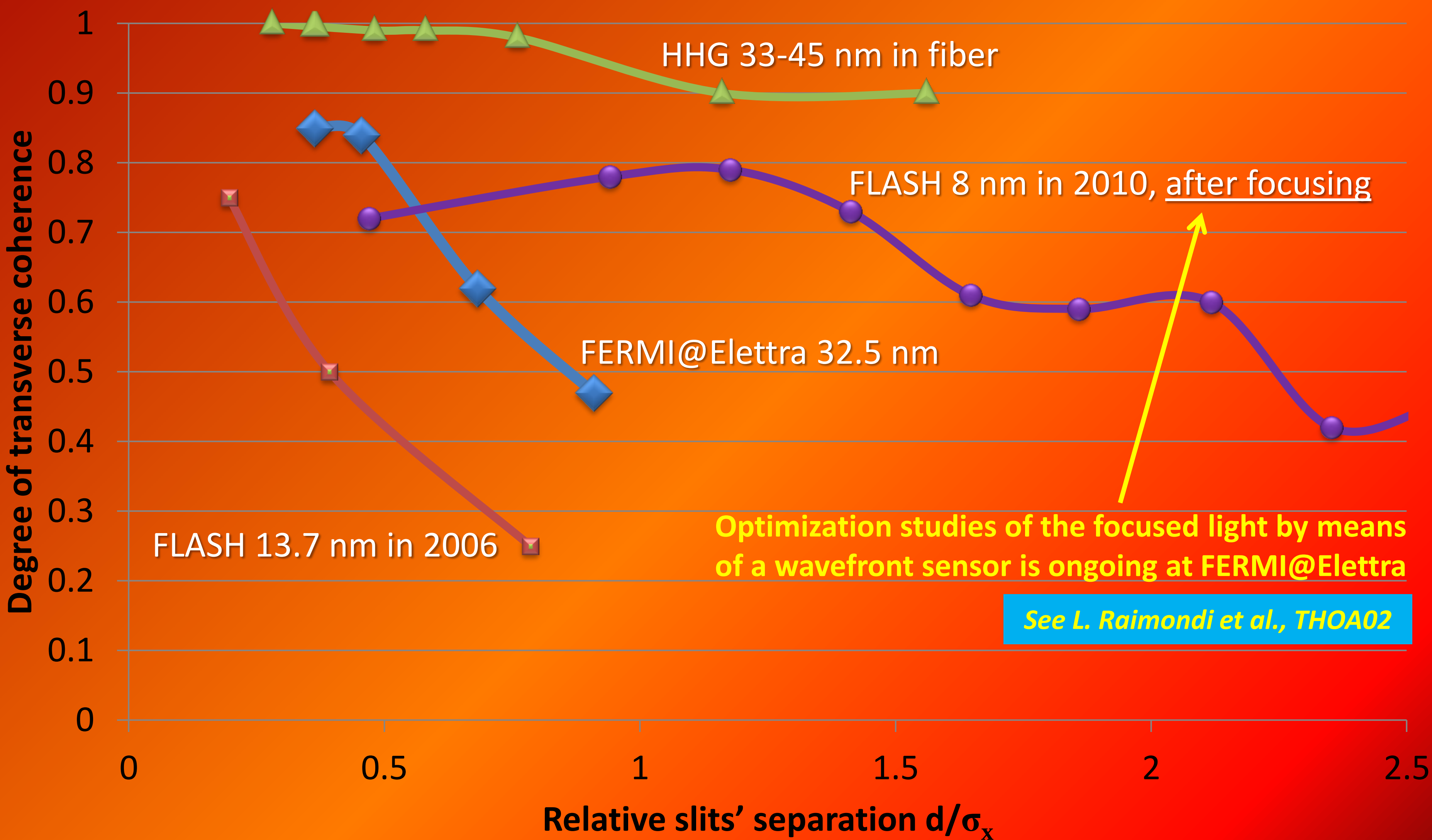


Transverse coherence of a Gauss-Schell Model (GSM) beam

For GSM at source

$= \sqrt{I(x_1)} \times \sqrt{I\,(x_2)} \times degree\ of\ transverse\ coherence(x_1, x_2)$

$I(x)$ **and the degree of transverse coherence are Gaussians.**

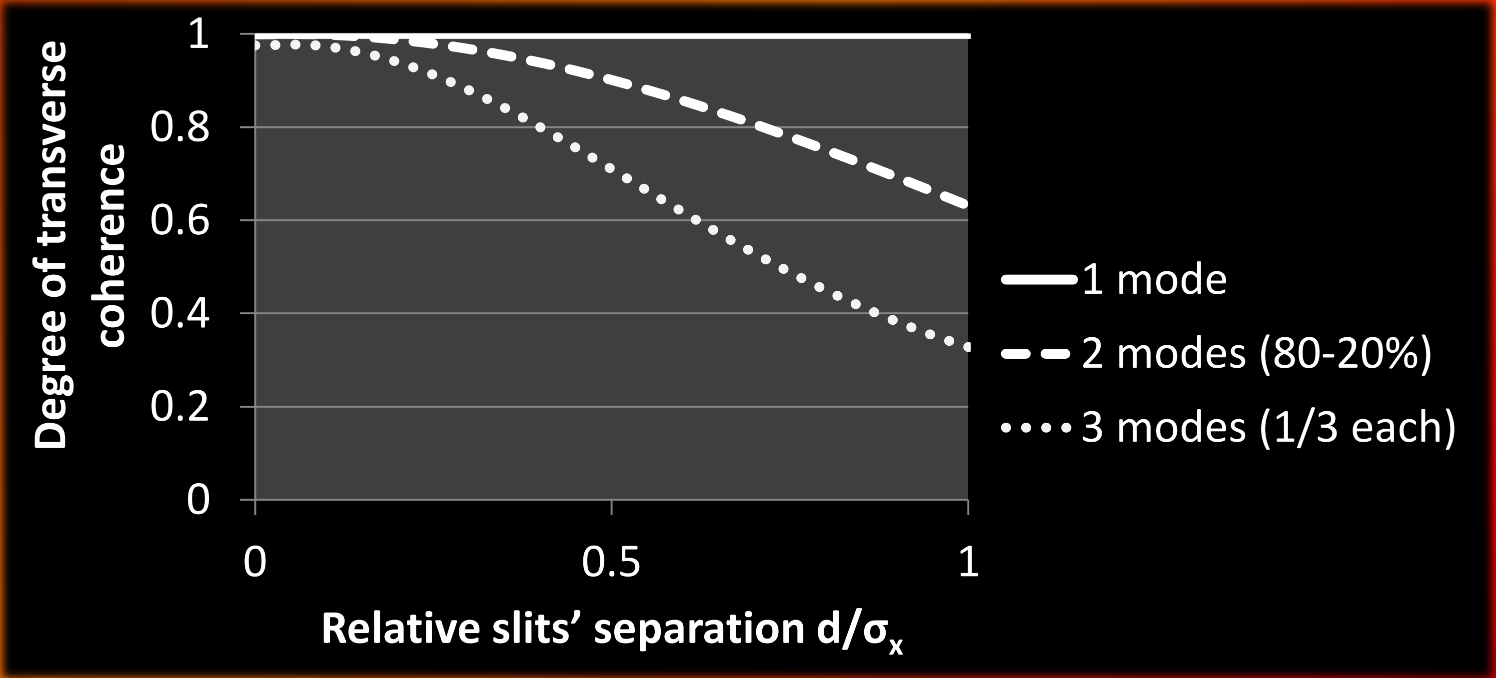
CROSS-SPECTRAL DENSITY

[L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics*]

In general

$= \sum_j \beta_j \phi_j \phi_j^*$ **ϕ_j are Hermite-Gauss functions (TEM modes) of weight β_j**

- **RETRIEVAL OF THE DEGREE OF TRANSVERSE COHERENCE AT ANY POSITION** z

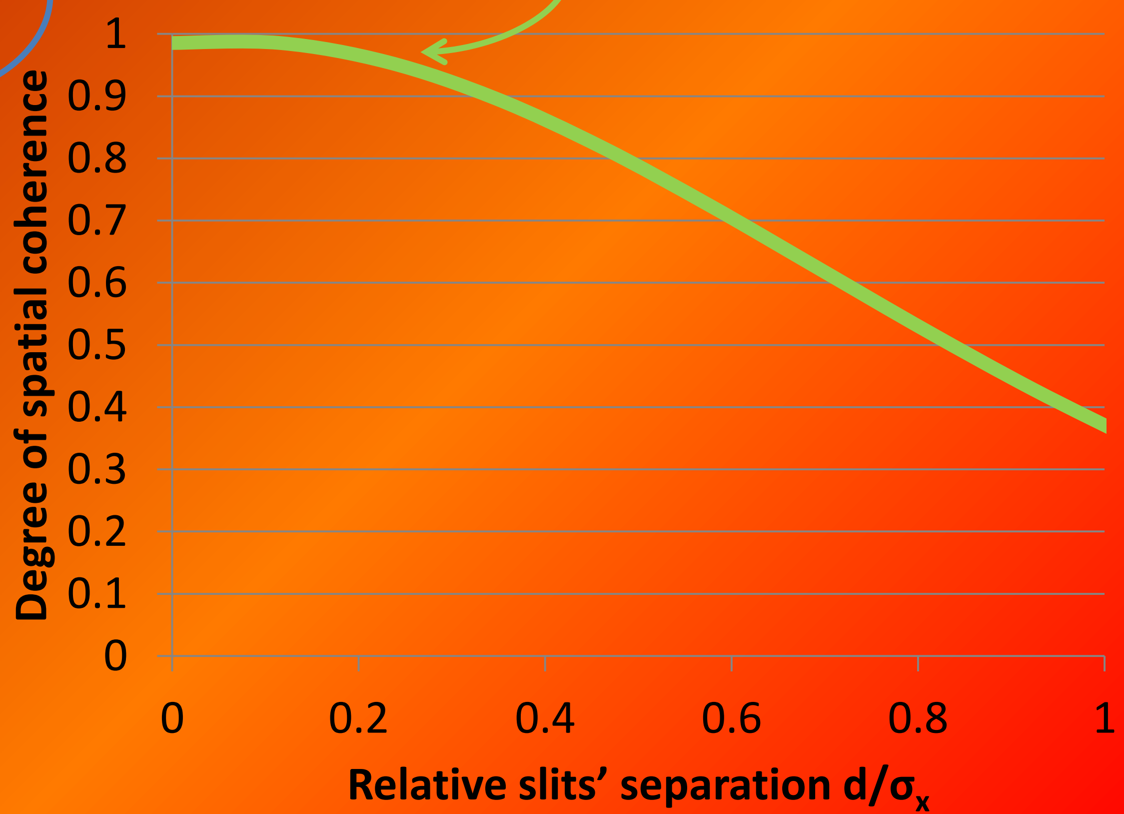


Comparison with GSM: modes & coherence at z = 65 m

Assumption: FERMI@Elettra = GSM source (size and divergence measured)

→Theoretical mode proportions and degree of transverse coherence

j	β_j
0	39.5%
1	23.9%
2	14.5%
3	8.7%
4	5.3%



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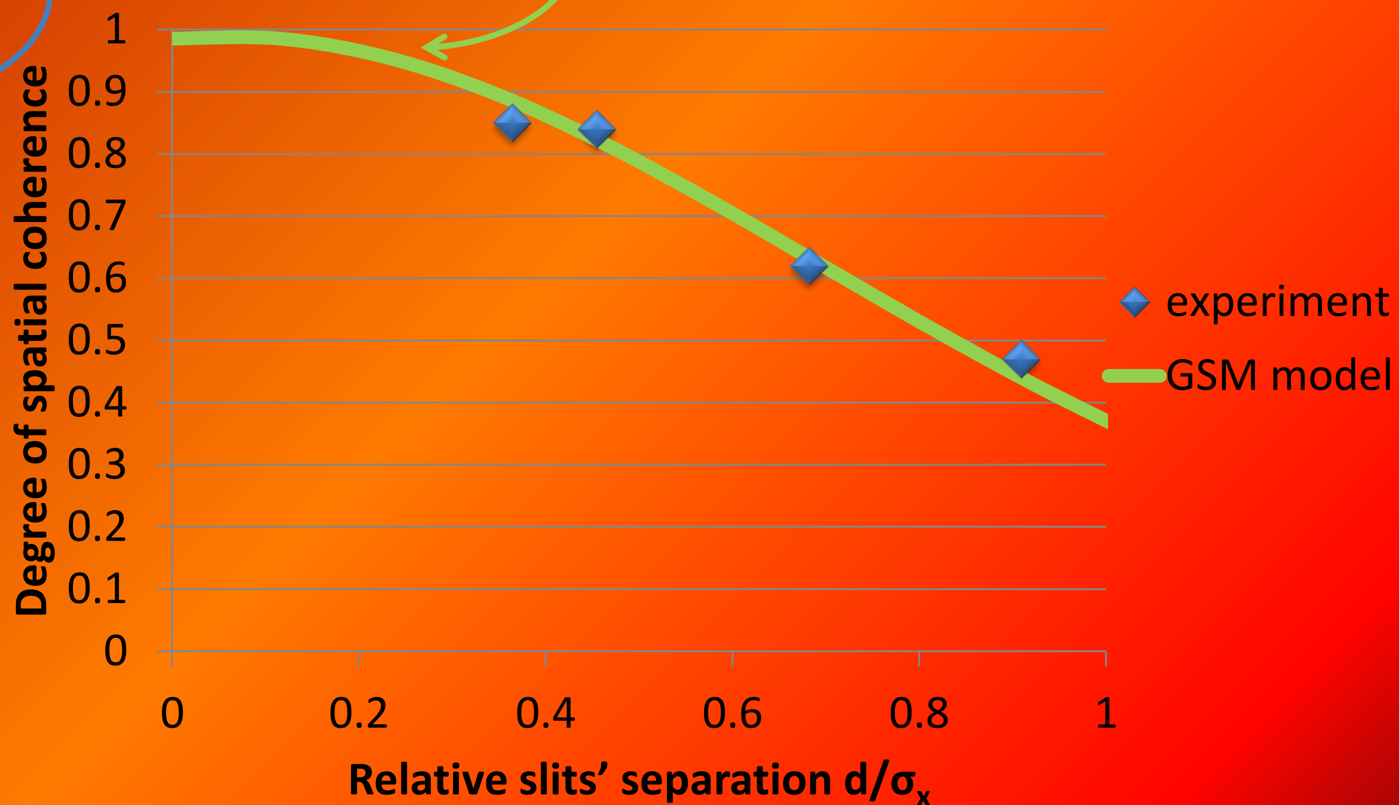
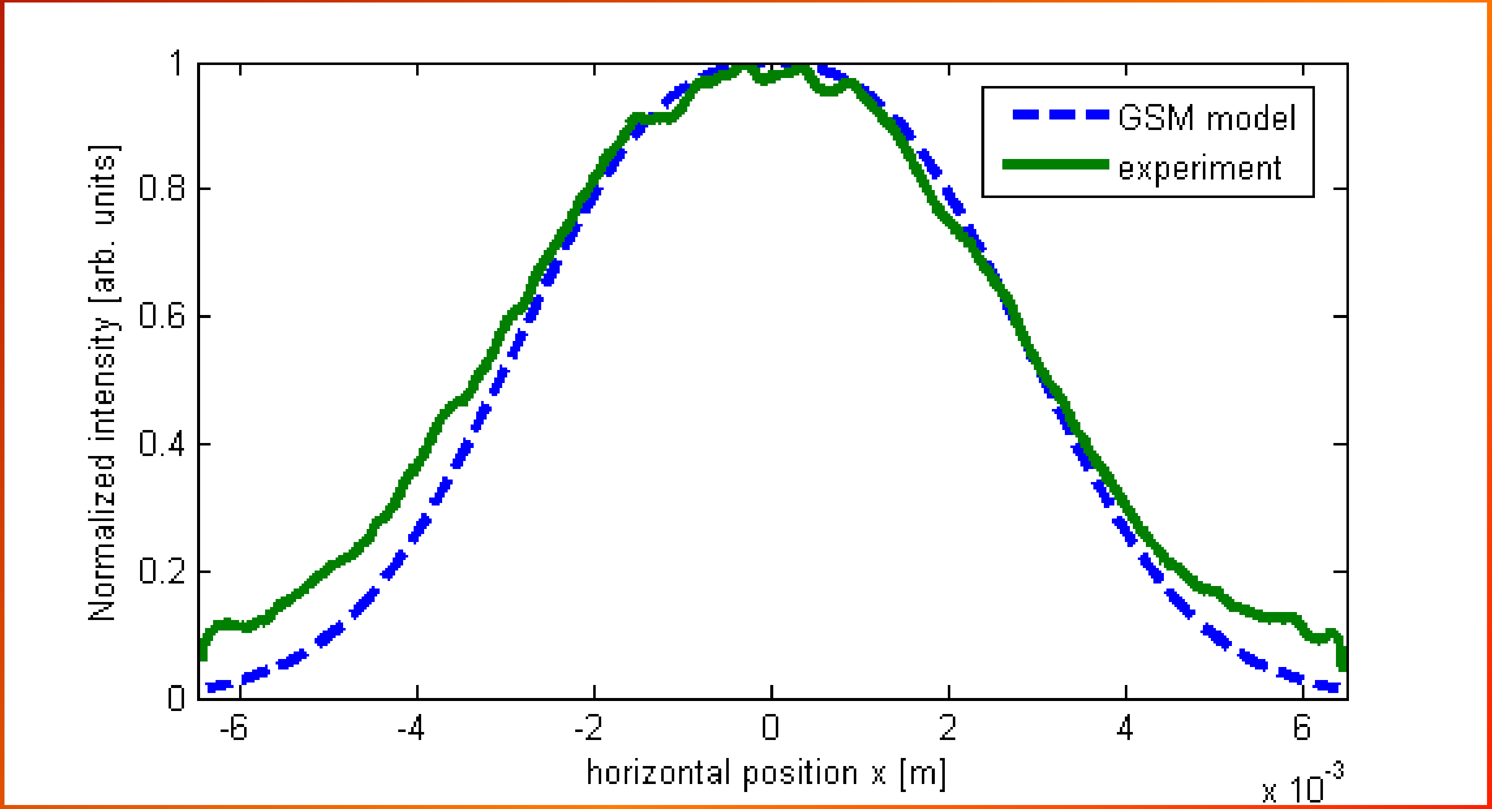


Comparison with GSM: intensity at z = 73.5 m



	Radius σ_x [mm]
GSM	2.3
experiment	2.4 +/- 0.06

- **The GSM is in good agreement with the FERMI@Elettra measurements @32.5nm for transverse coherence and intensity distributions**

Conclusion

- **« Good » transverse coherence of FERMI@Elettra**

- **Possibility to consider its light as a Gauss-Schell model beam**

- **Extend studies to recent Shack-Hartman measurements**

- **Difference found between seeded and SASE FEL's.**

  → Comparison has to be pushed i.e., do measurements with similar setups on different facilities

  Possible to try in SASE mode on FERMI@Elettra! ***See E. Allaria et al., TUOB02***

  → How could the seed act for improving transverse qualities?

- **More generaly, how to manage the spatial characteristics of the FEL light? (spatial quality / emittance of the electron beam, etc.)**

Acknowledgements

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- **Flavio Capotondi** **and the whole DIPROI beamline**

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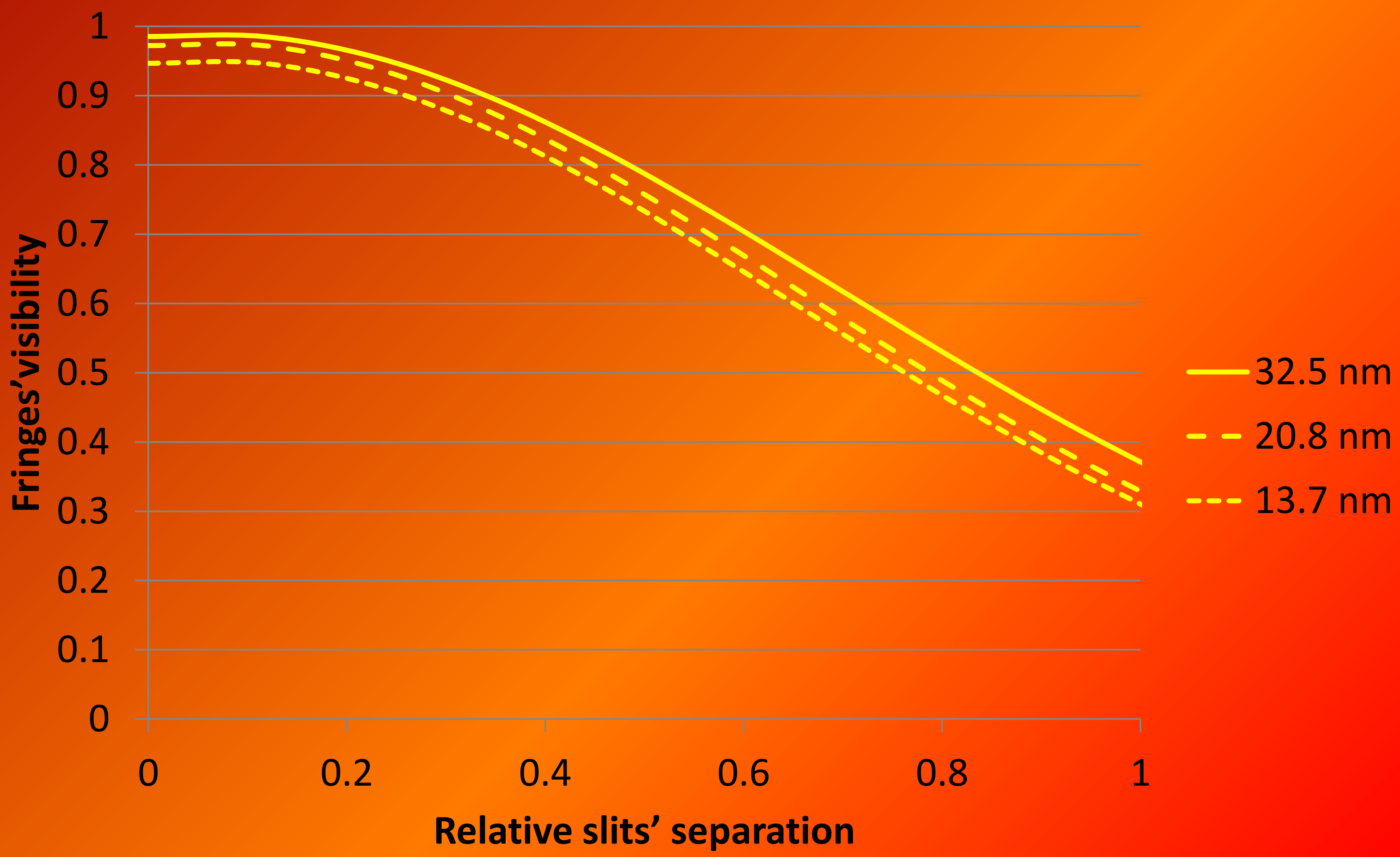
And thank you for your attention!

ありがとうございます **arigatō gozaimasu**

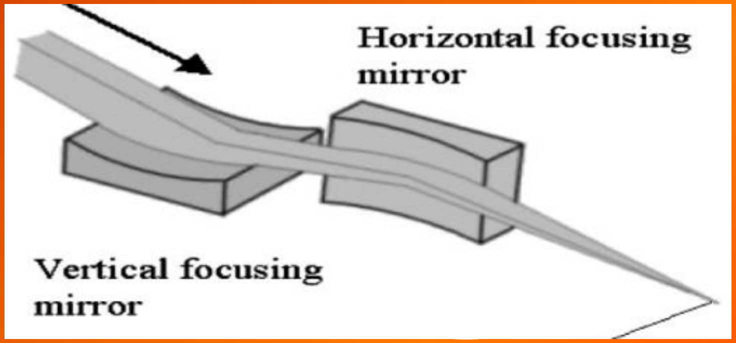
Prediction of Gauss-Schell Model @ 20.8 and 13.7 nm

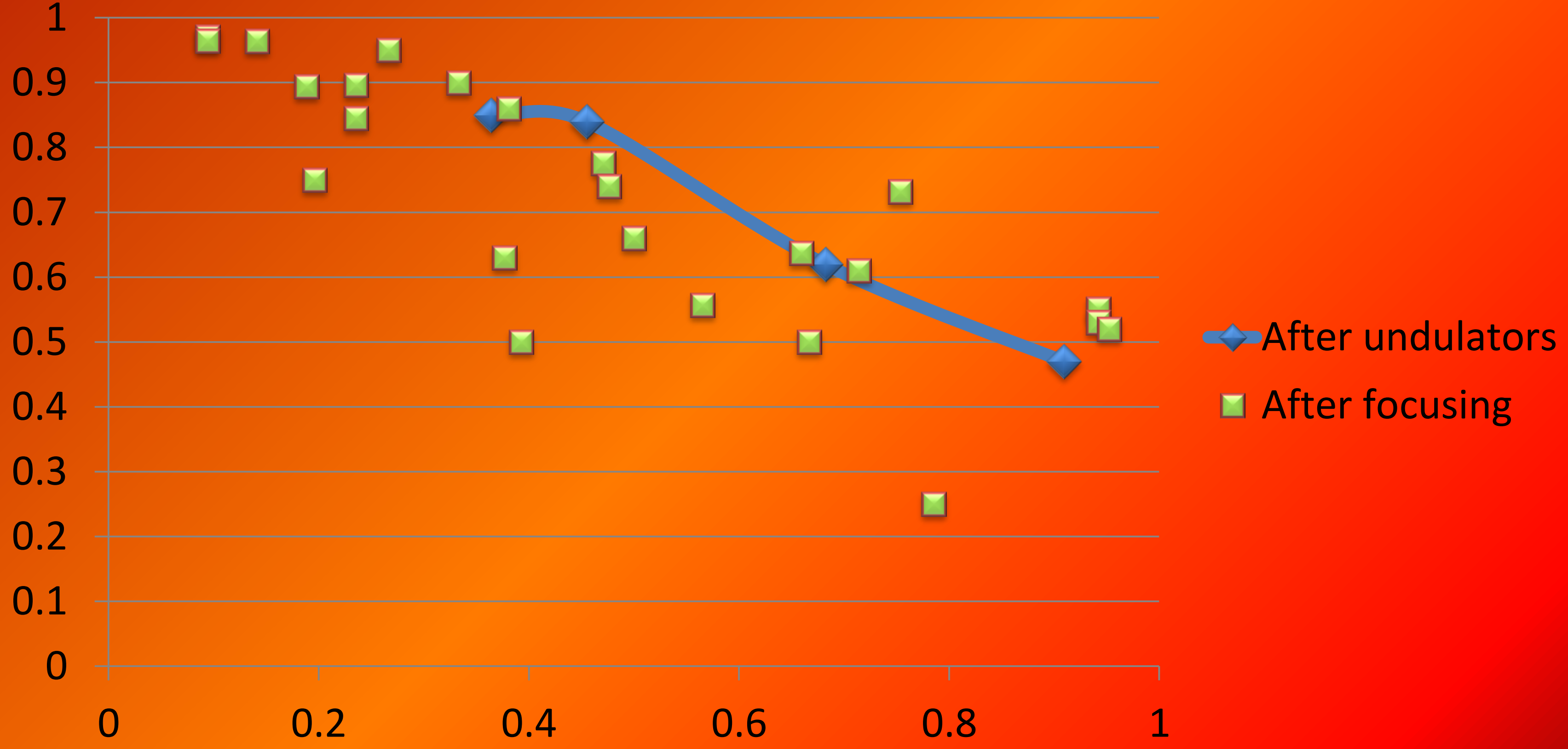


- **Assuming that the model applies well also to other wavelengths, the decrease of spatial coherence vs. wavelength is very slow.**

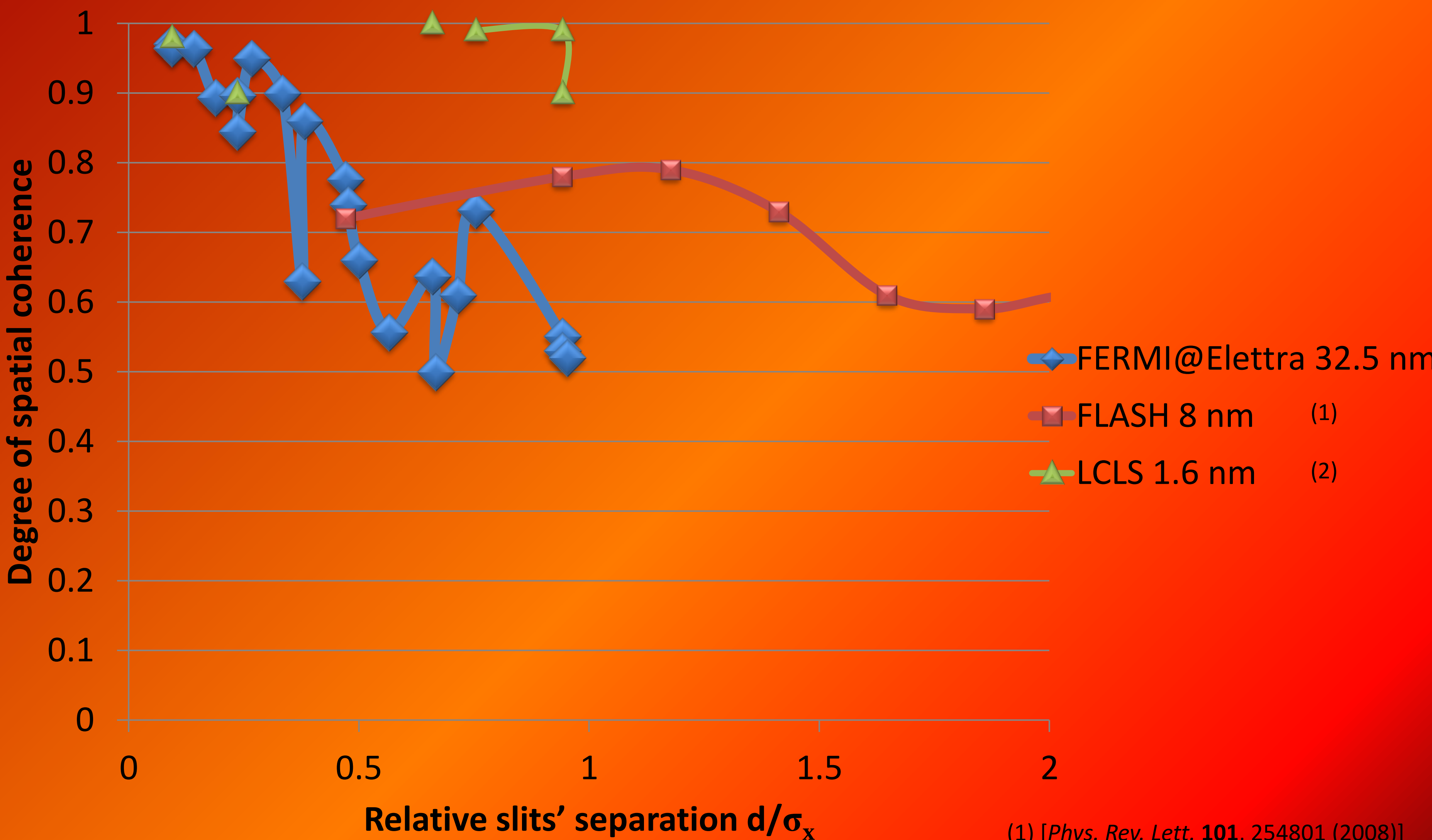
Comparison after focusing

Focusing by bendable mirrors in Kirkpatrick-Baez configuration (f=1.2m)



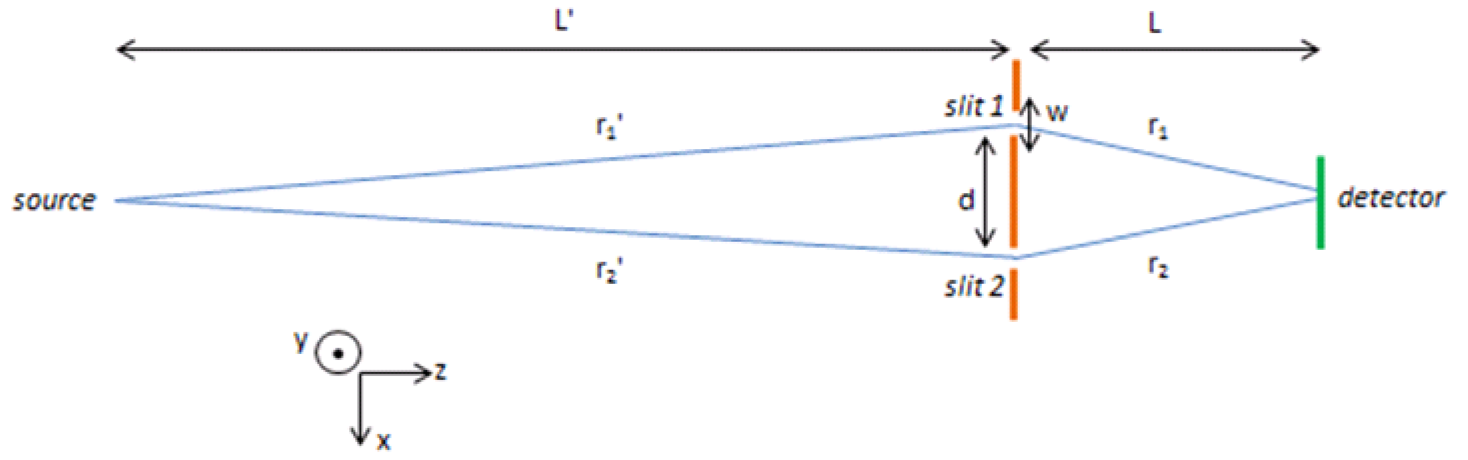


After focusing



(1) [*Phys. Rev. Lett.* **101**, 254801 (2008)]

(2) [*Science* **297**, 376 (2002)]

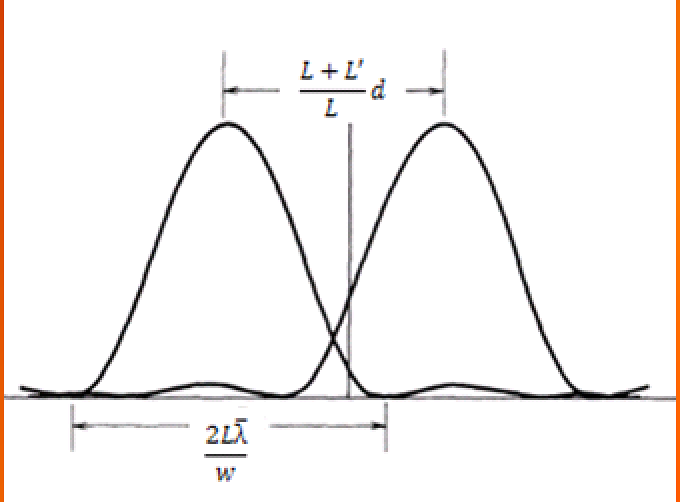


d [mm]	w [µm]
0.8	20
1	40
1.5	40
2	40
4	40

$$w = z\theta_f = z\lambda/d$$

$$I(\theta) \propto \cos^2\left[\frac{\pi d \sin\theta}{\lambda}\right] \ \mathrm{sinc}^2\left[\frac{\pi b \sin\theta}{\lambda}\right]$$

$$|\mu_{12}| = \frac{I_1(M) + I_2(M)}{2\sqrt{I_1(M) I_2(M)}} V$$



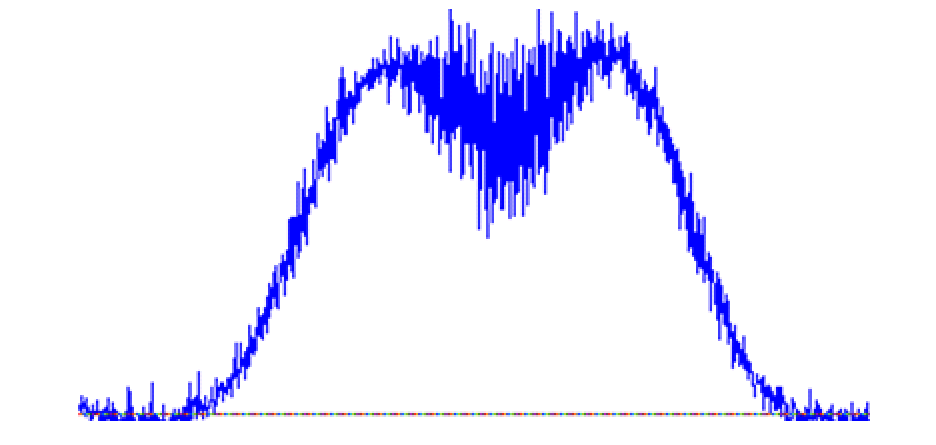


Figure 6: pattern observed on CCD_pos.01 for the couple of slits d=4mm.

The second order correlations of the wave fields are described in the theory of coherence by the mutual coherence function (MCF) $\Gamma_{12}(\tau)$, that defines the correlations between two complex values of the electric field $E(\mathbf{r}_1, t)$ and $E^*(\mathbf{r}_2, t+\tau)$ at different points $\mathbf{r}_1$ and $\mathbf{r}_2$ and separated by the time interval τ

$$\Gamma(\mathbf{r}_1, \mathbf{r}_2, \tau) = \langle E(\mathbf{r}_1, t) E^*(\mathbf{r}_2, t+\tau) \rangle, \tag{1}$$

where the brackets $\langle\rangle$ indicate the ensemble average. Correlations of the field in the spatial-frequency domain are determined by the cross-spectral density function (CSD) $W(\mathbf{r}_1, \mathbf{r}_2, \omega)$, which is a Fourier transform of the MCF

$$W(\mathbf{r}_1, \mathbf{r}_2, \omega) = \int_{-\infty}^{\infty} \Gamma_{12}(\tau) e^{-i\omega\tau} d\tau. \tag{2}$$

The spectral density of the field $S(\mathbf{r}, \omega)$ is defined as the CSD function taken at the same position $S(\mathbf{r}, \omega) = W(\mathbf{r}, \mathbf{r}, \omega)$. The normalized versions of the two functions (1) and (2) are the complex degree of coherence $\gamma(\mathbf{r}_1, \mathbf{r}_2, \tau)$ and the spectral degree of coherence $\mu(\mathbf{r}_1, \mathbf{r}_2, \omega)$, respectively.

- « Good » degree of coherence (>0.8 for d/σ_x<0.5) & spatial shape ajouter surf(Bsum) et sigma+/-std