Adventures in the microlensing cloud

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Quasars and Supermassive black holes

Quasars and Supermassive black holes

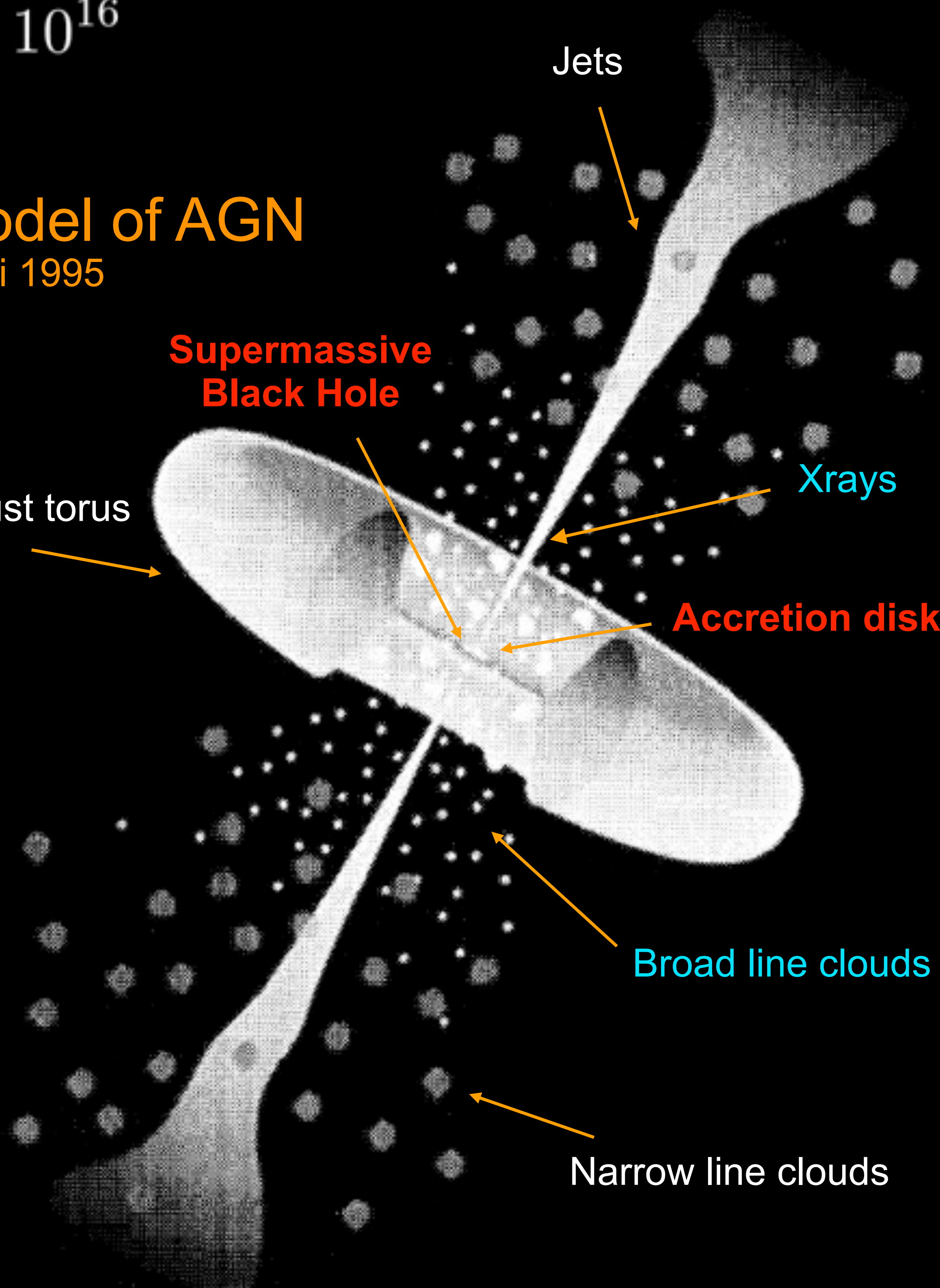
Quasars → feedback → galaxy formation and evolution

Quasar luminosities : $10^{11} < L/L_{\odot} < 10^{16}$

Quasars and Supermassive black holes

Quasars ➔ feedback ➔ galaxy formation and evolution

Quasar luminosities : $10^{11} < L/L_{\odot} < 10^{16}$



CAS, Swinburne

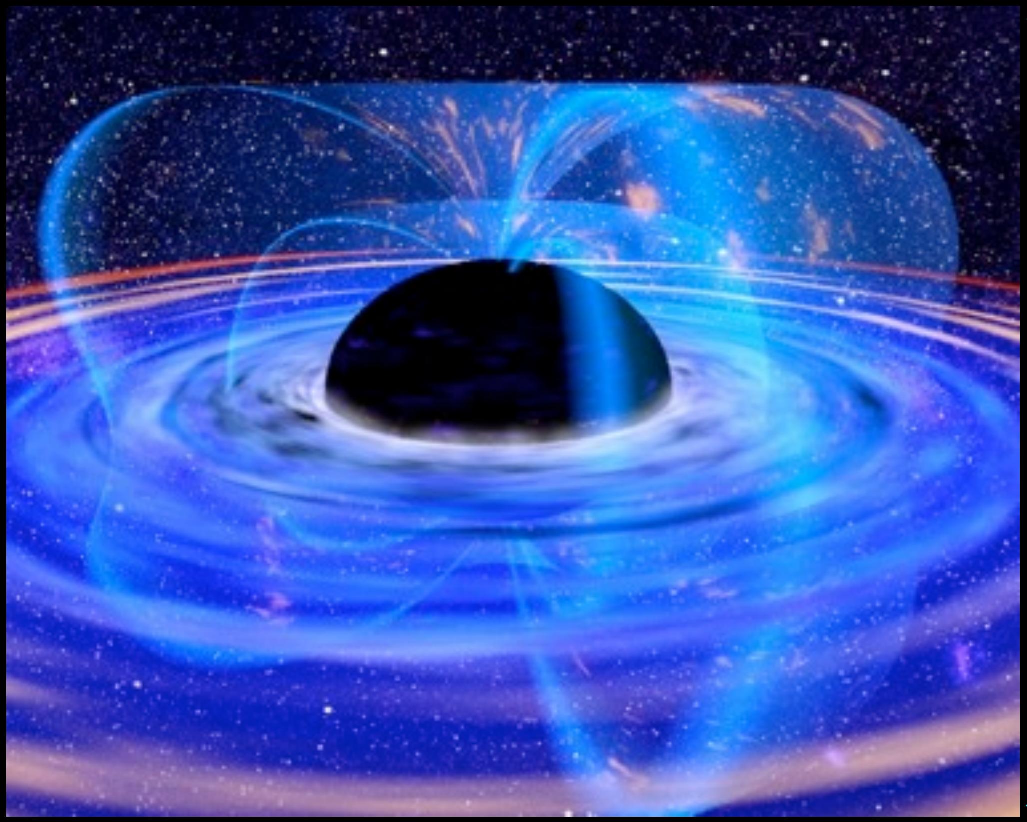
Quasars and Supermassive black holes

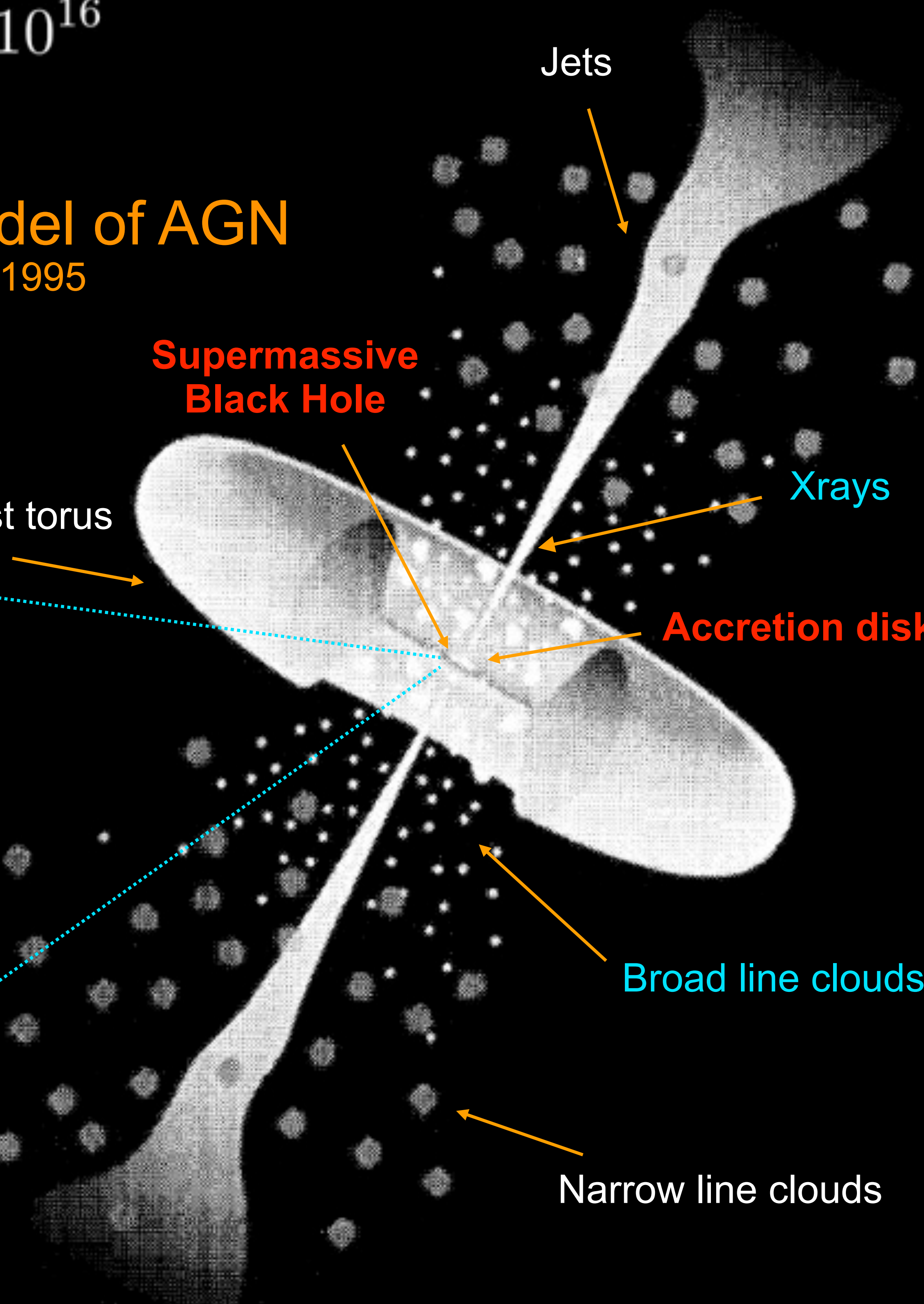
Quasars → feedback → galaxy formation and evolution

Quasar luminosities : $10^{11} < L/L_{\odot} < 10^{16}$

Unified model of AGN
Urry & Padovani 1995

Accretion disc **+** *Black hole* **=**
Energy





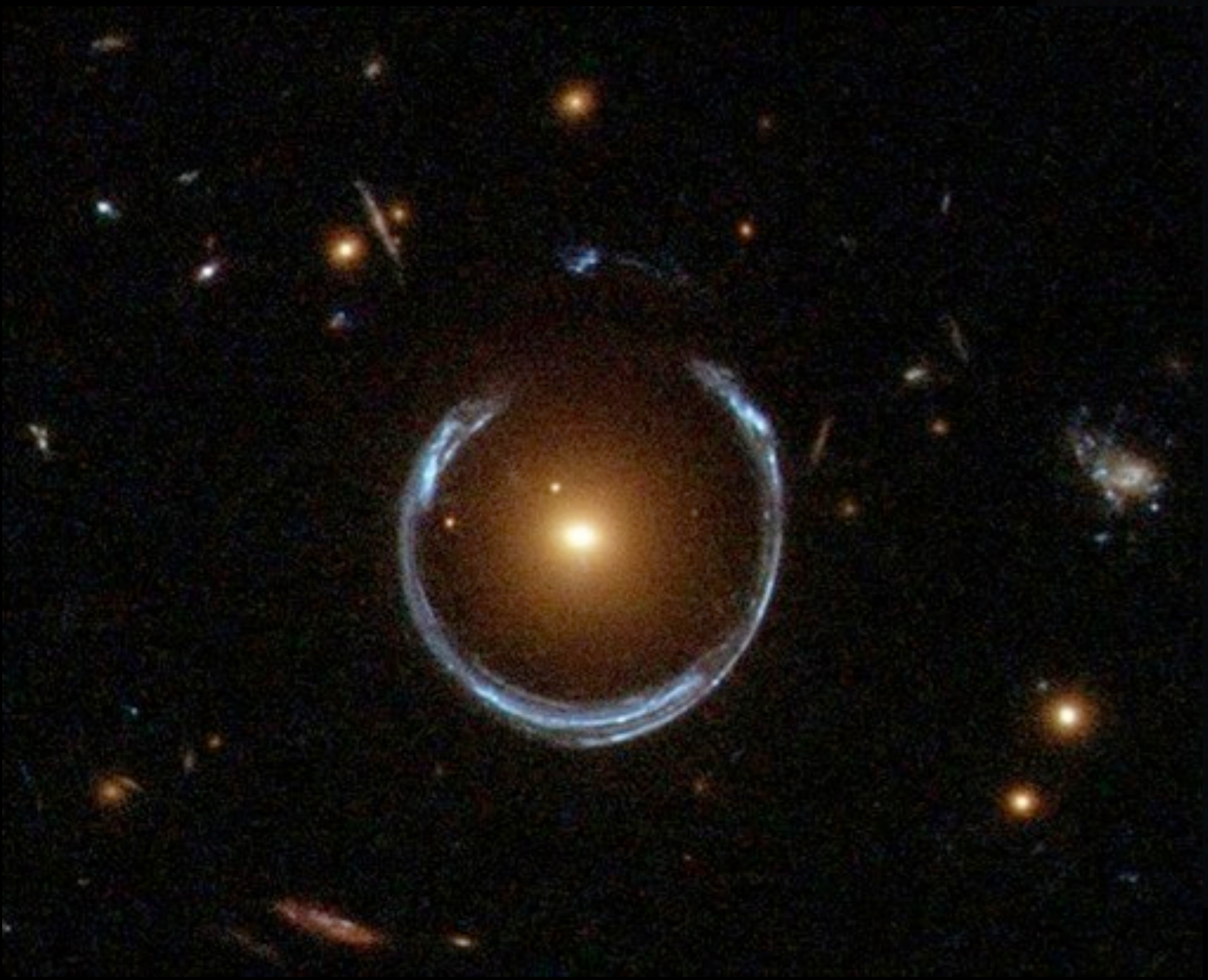
CAS, Swinburne


B
You are here
1
EURO


B
You are here
1
EURO


B
You are here
1
EURO

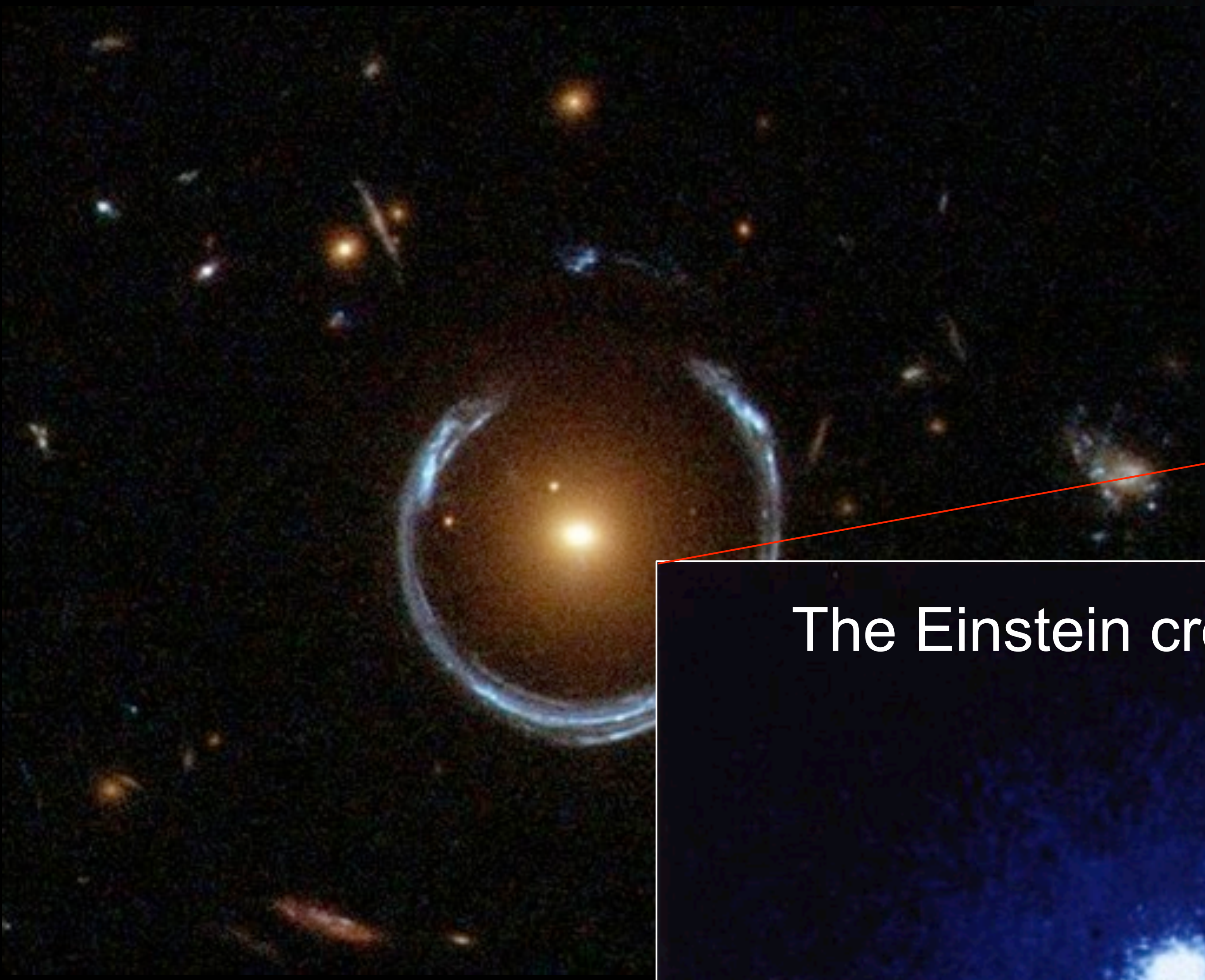
(Strong) gravitational lensing

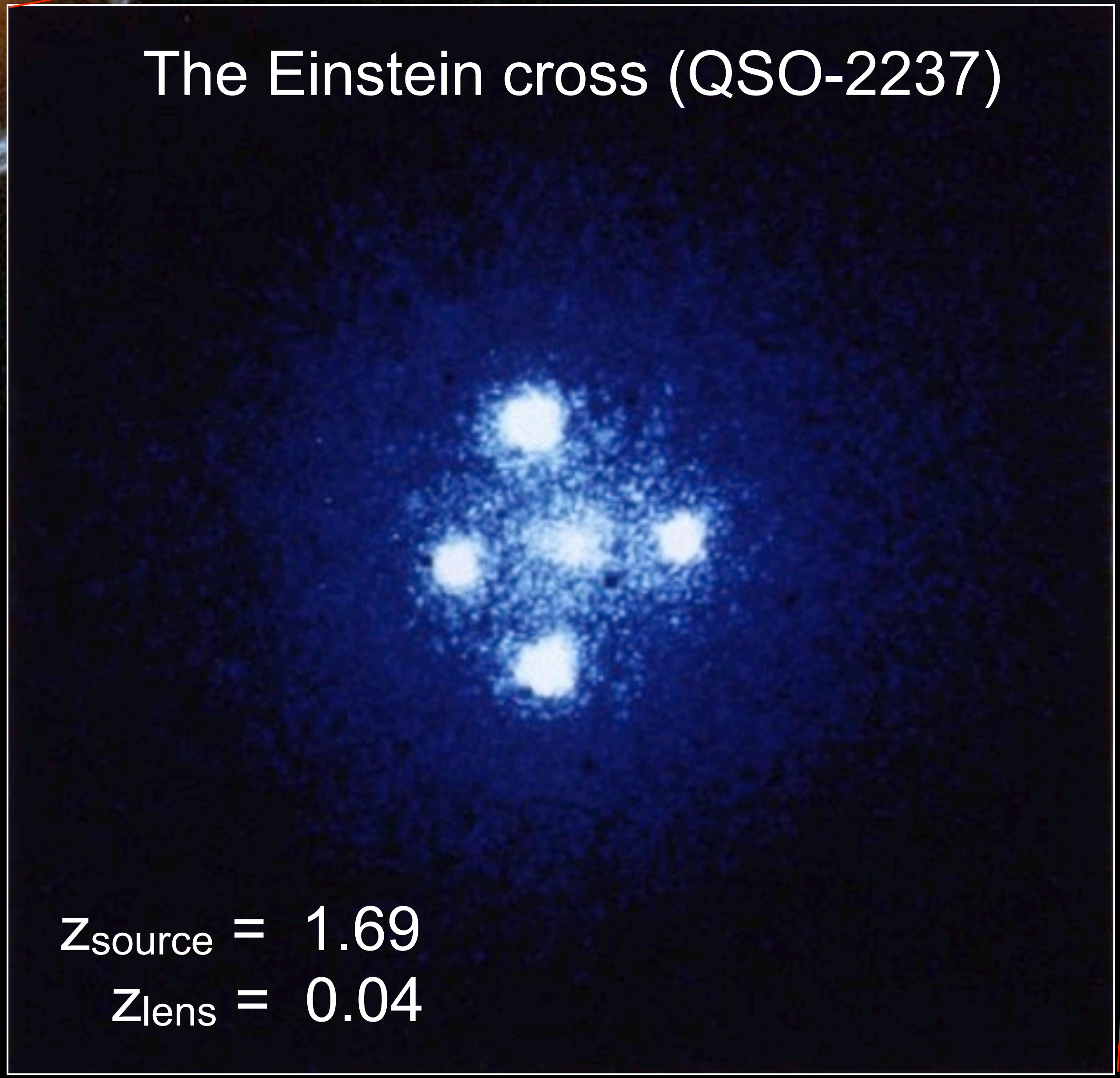


Images : HST NASA/ESA

Einstein rings, arcs, multiple images, magnifications...

(Strong) gravitational lensing





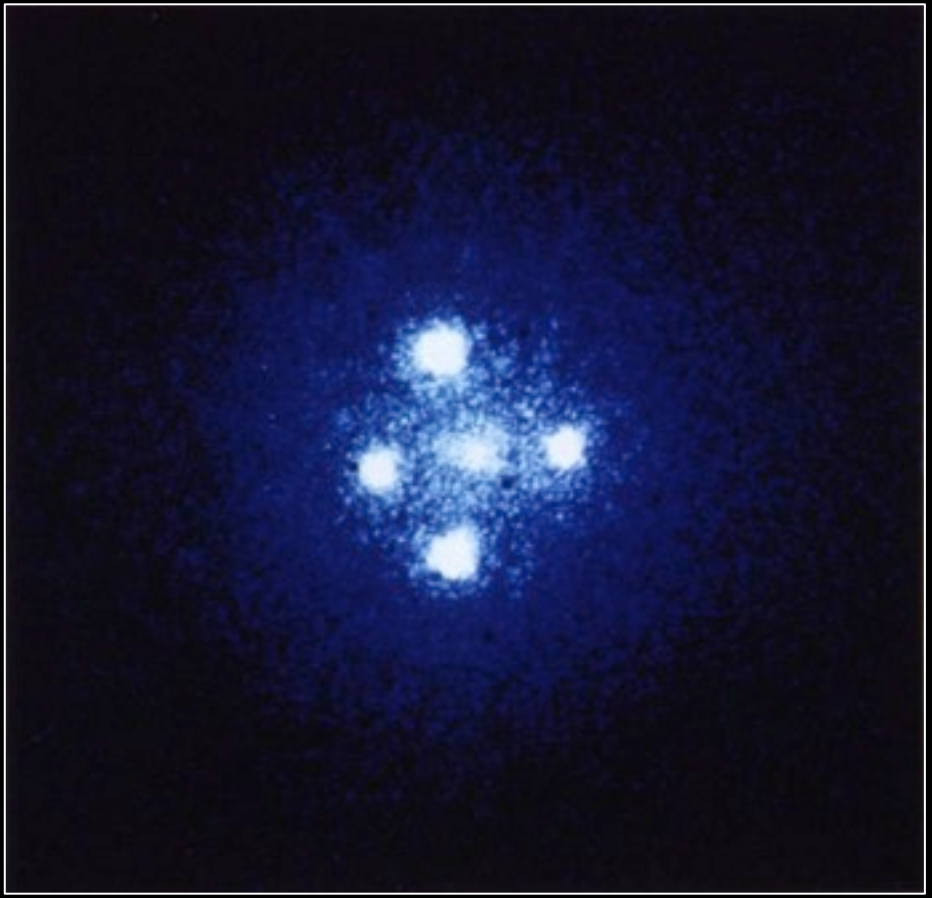
Images : HST NASA/ESA

lensing models part 1 (macro)

Solve lens equation
for ***mass distribution***

Input
(Observables)

Position of images
Image fluxes
(Time delays)
...



Output

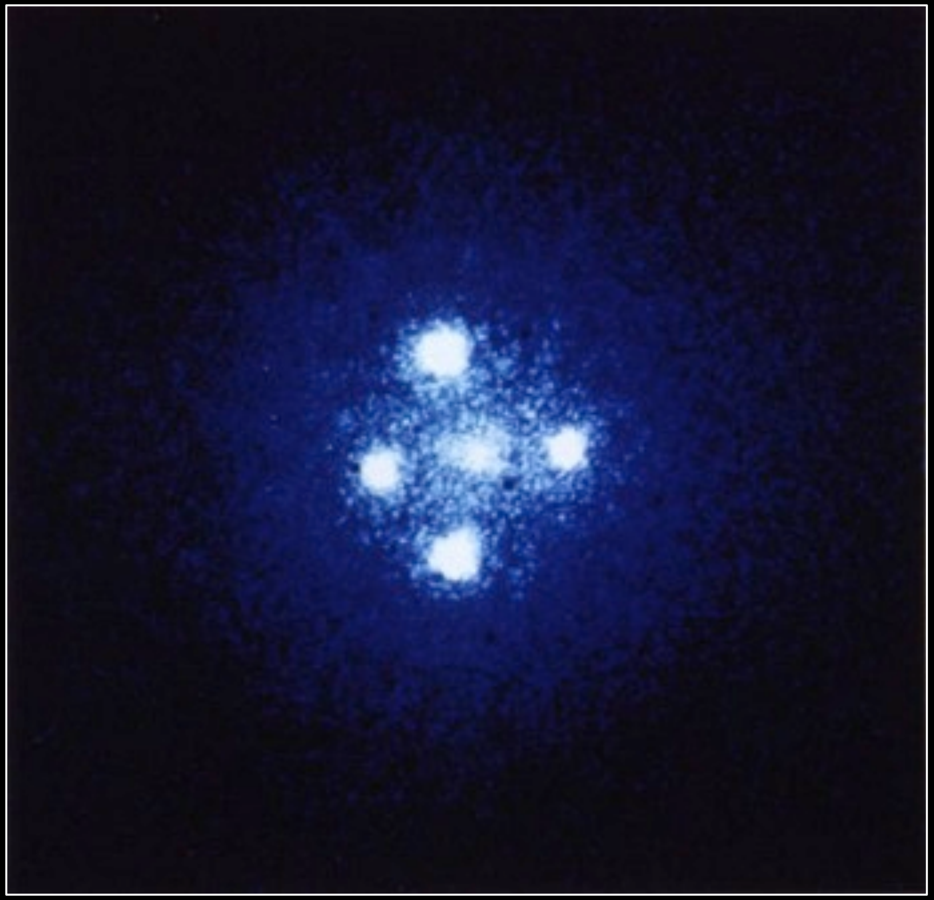
magnifications
κ : convergence
γ : shear
...

lensing models part 1 (macro)

Input
(Observables)

Position of images
Image fluxes
(Time delays)
...

Solve lens equation
for ***mass distribution***



Output

magnifications
κ : convergence
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...

Ready to :

study structure and substructure of the lens galaxy
study high redshift sources
perform cosmological measurements
...

lensing models part 1 (macro)

Solve lens equation
for ***mass distribution***

Input
(Observables)

Position of images
Image fluxes
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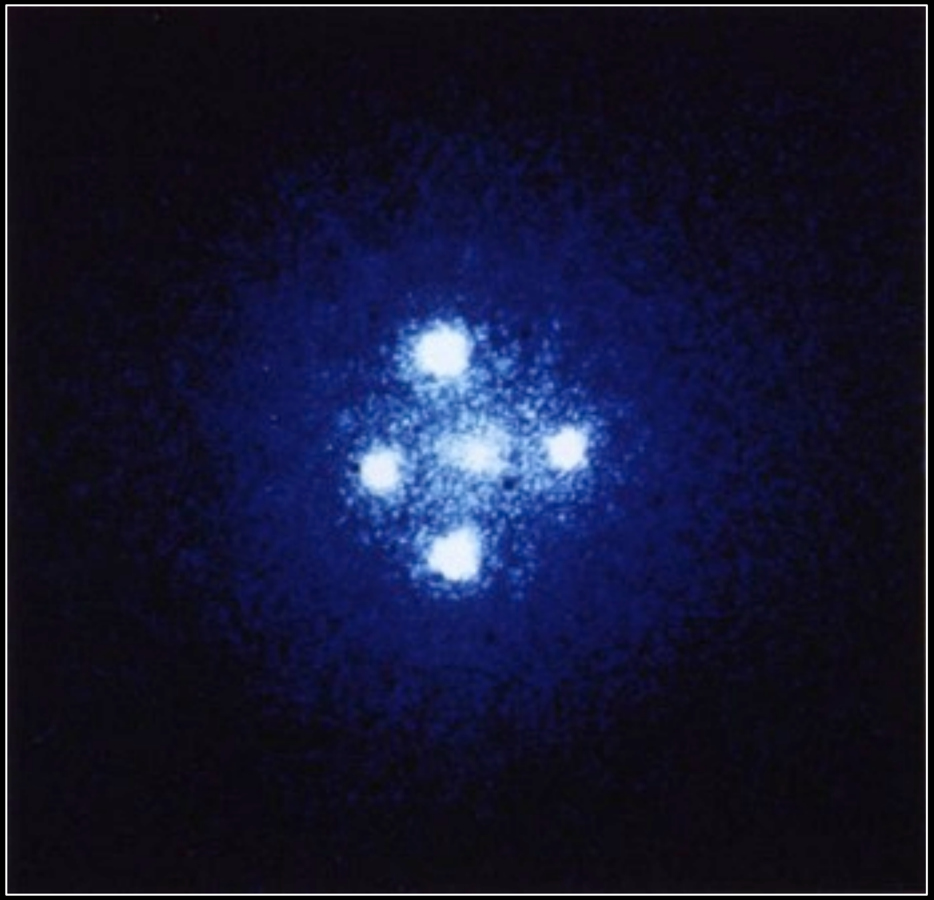


Output

magnifications
κ : convergence
γ : shear
...

Ready to :

study structure and substructure of the lens galaxy
study high redshift sources
perform cosmological measurements
...

But not the accretion disc yet!

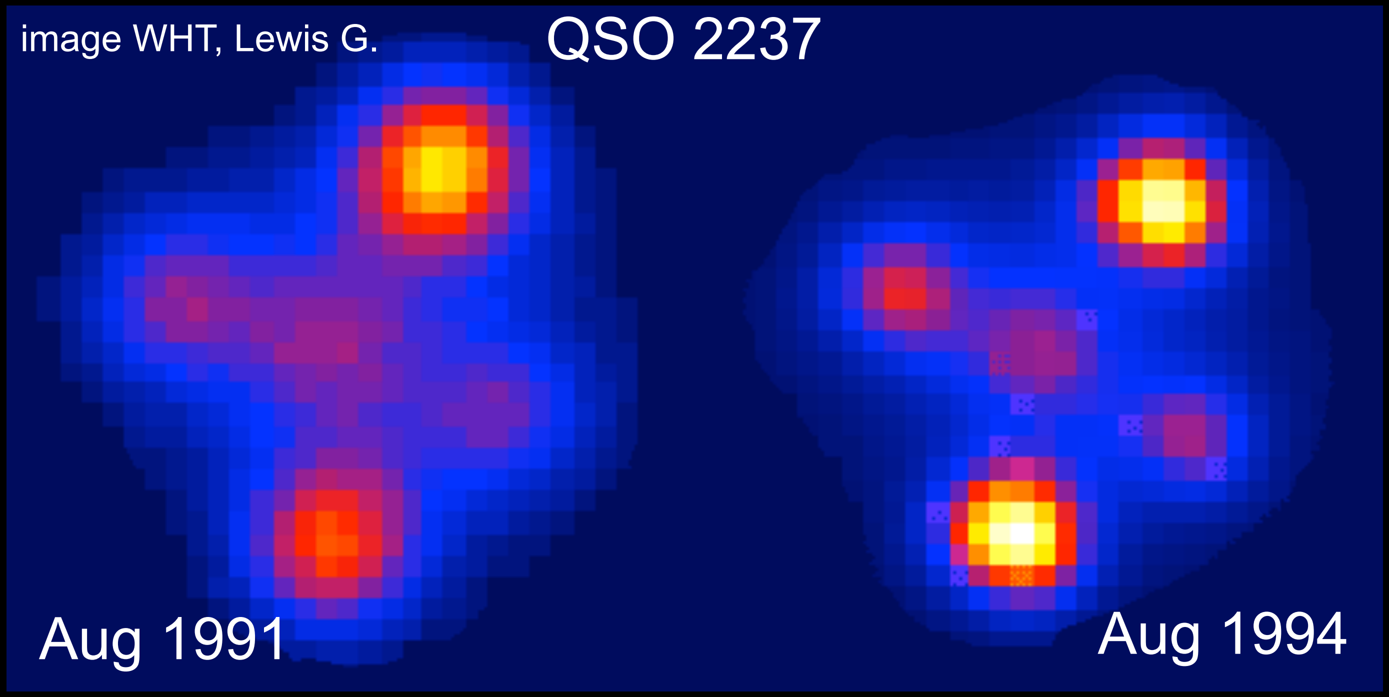
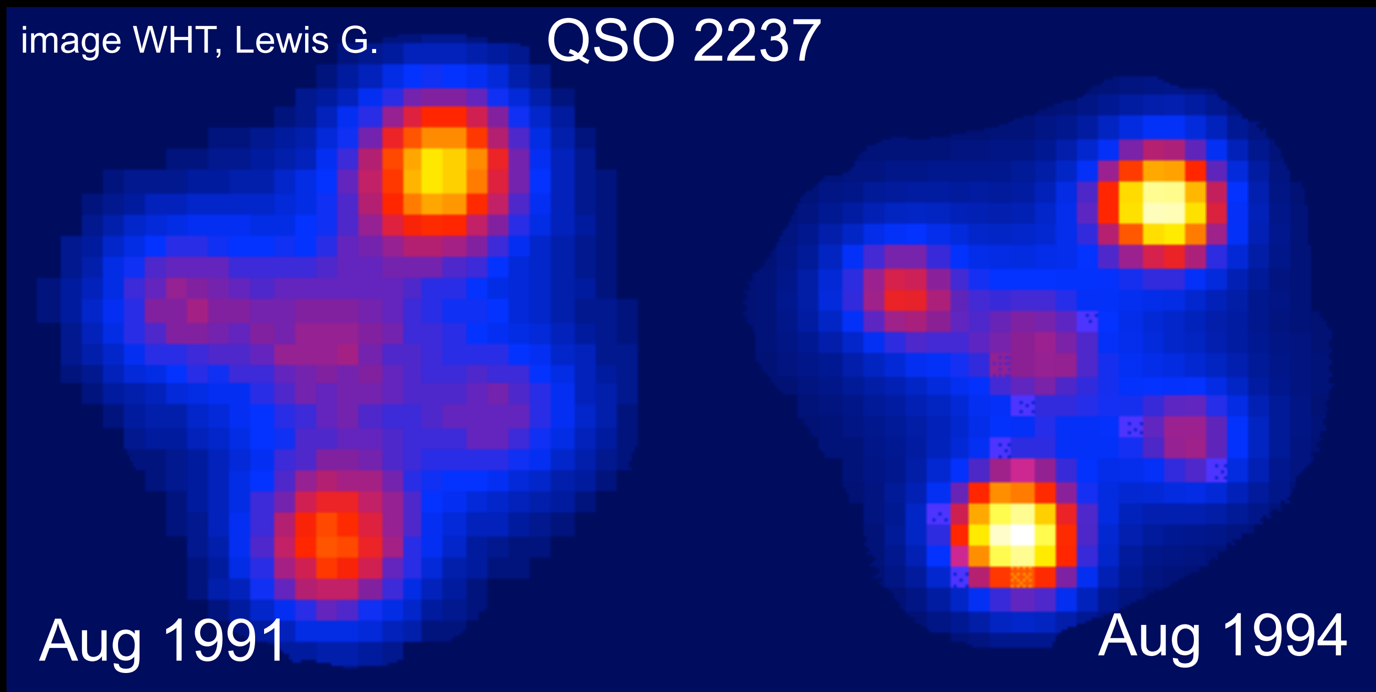


image WHT, Lewis G.
QSO 2237
Aug 1991
Aug 1994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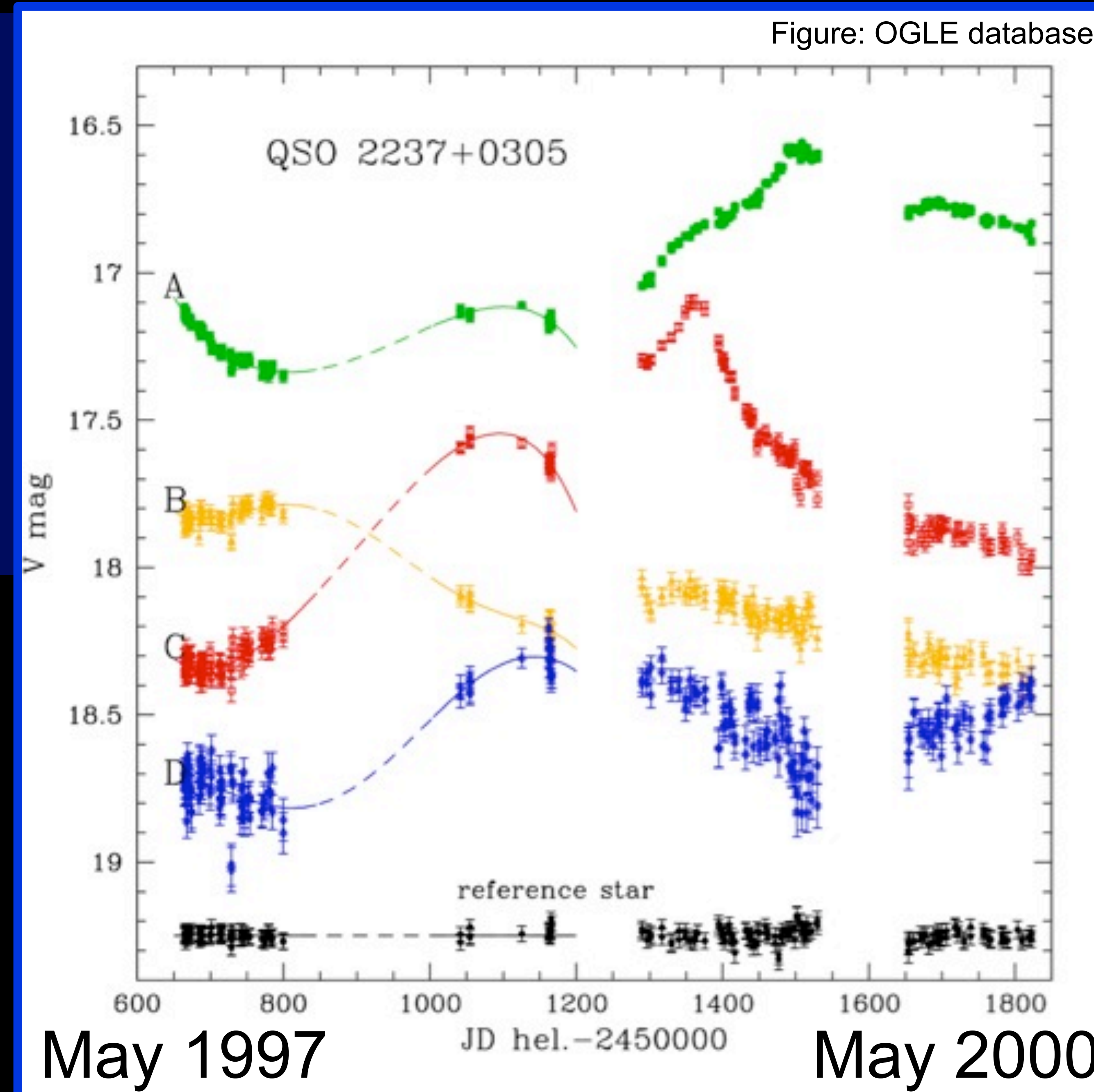
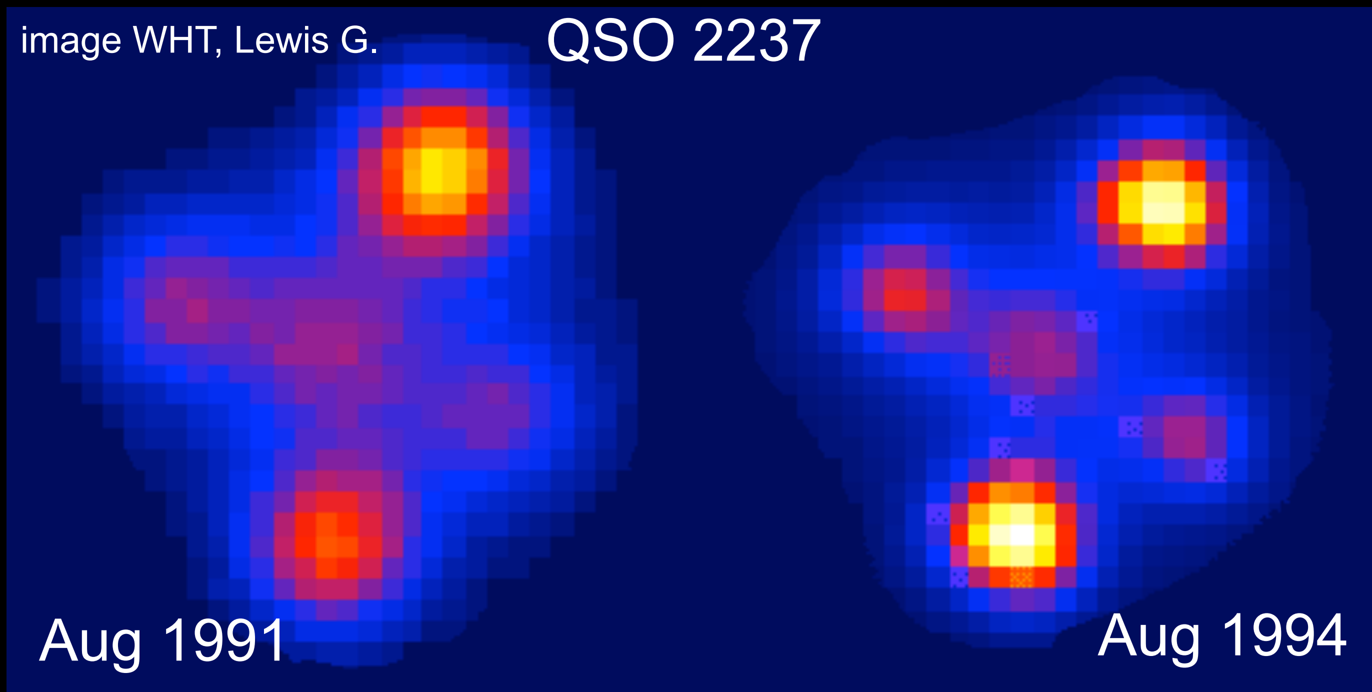
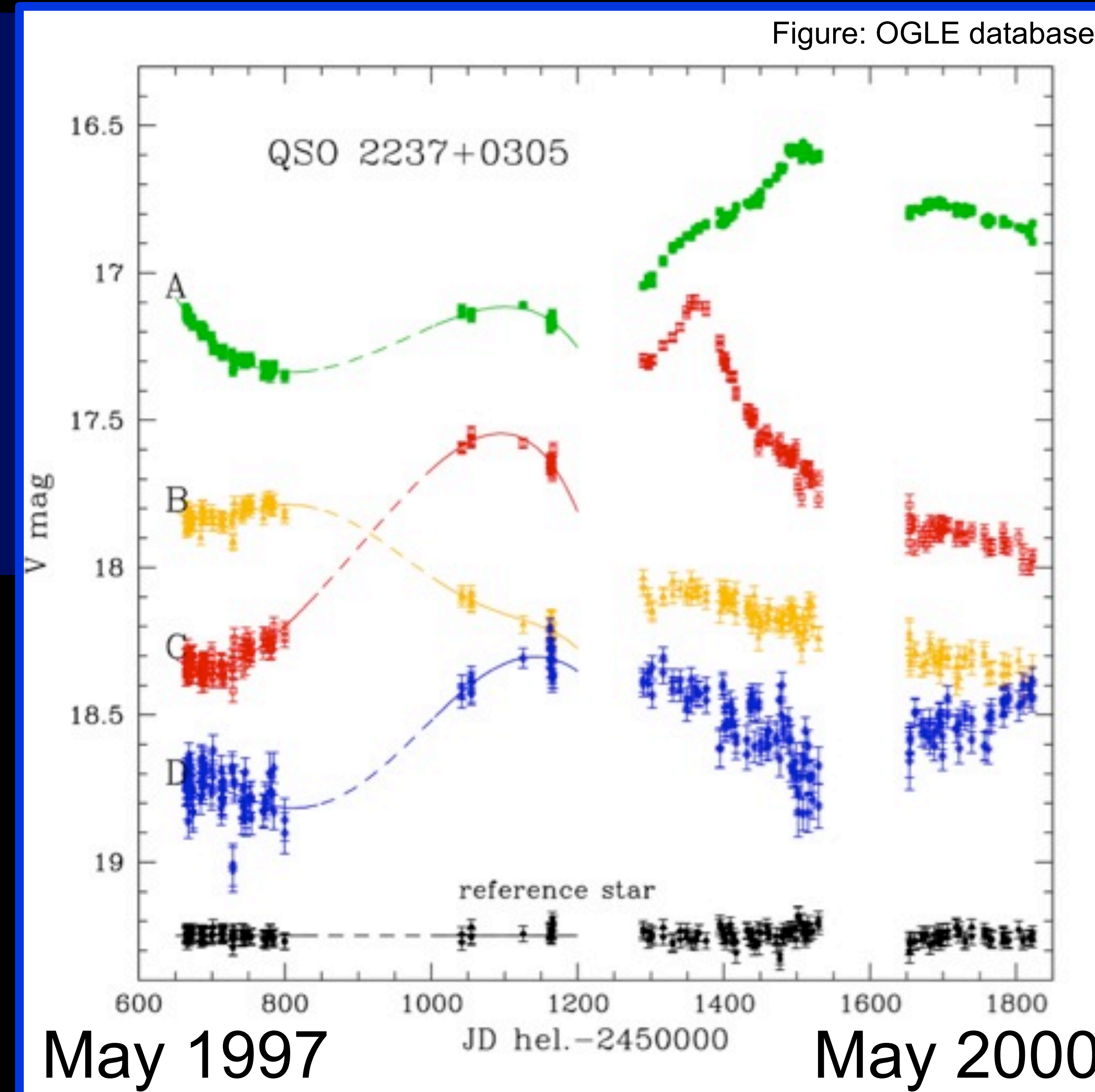
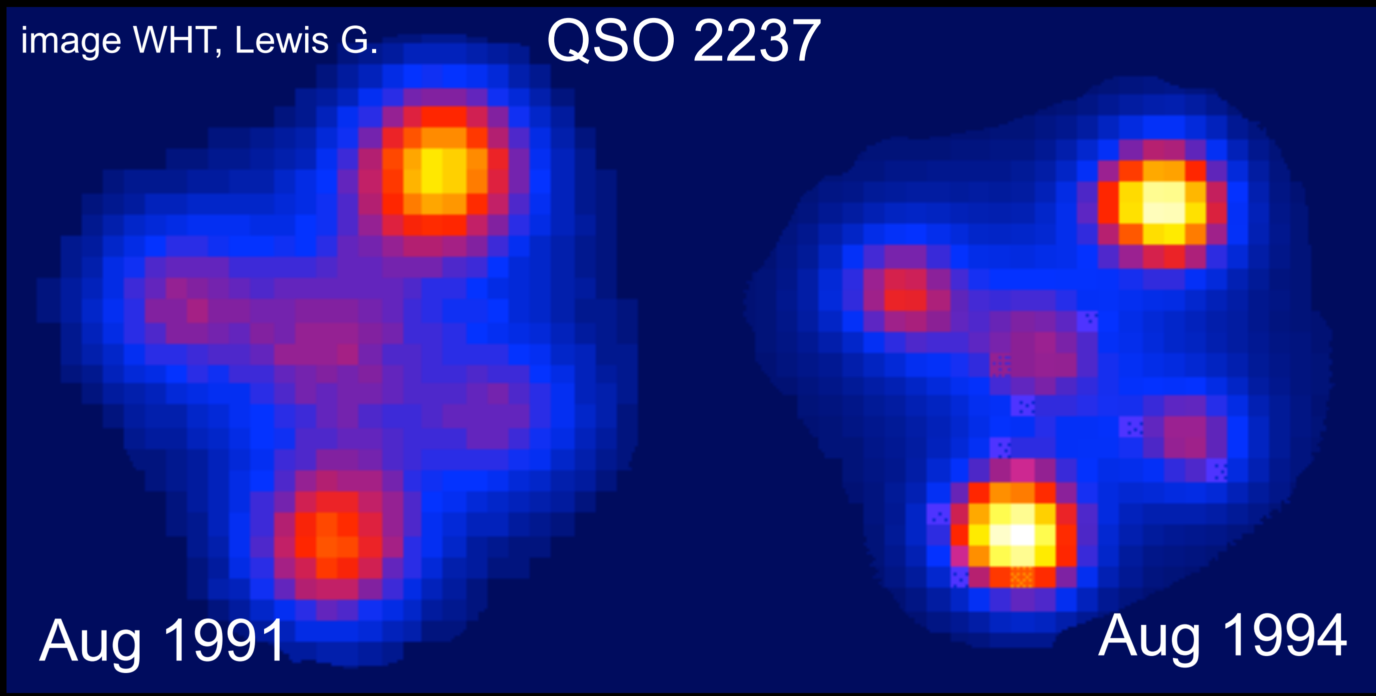


Figure: OGLE database
QSO 2237+0305
A
B
C
D
reference star
V mag
JD hel.−2450000
May 1997
May 2000





- *uncorrelated variability due to the lens*
- *models predict constant magnification*
- *we assumed smooth matter only...*



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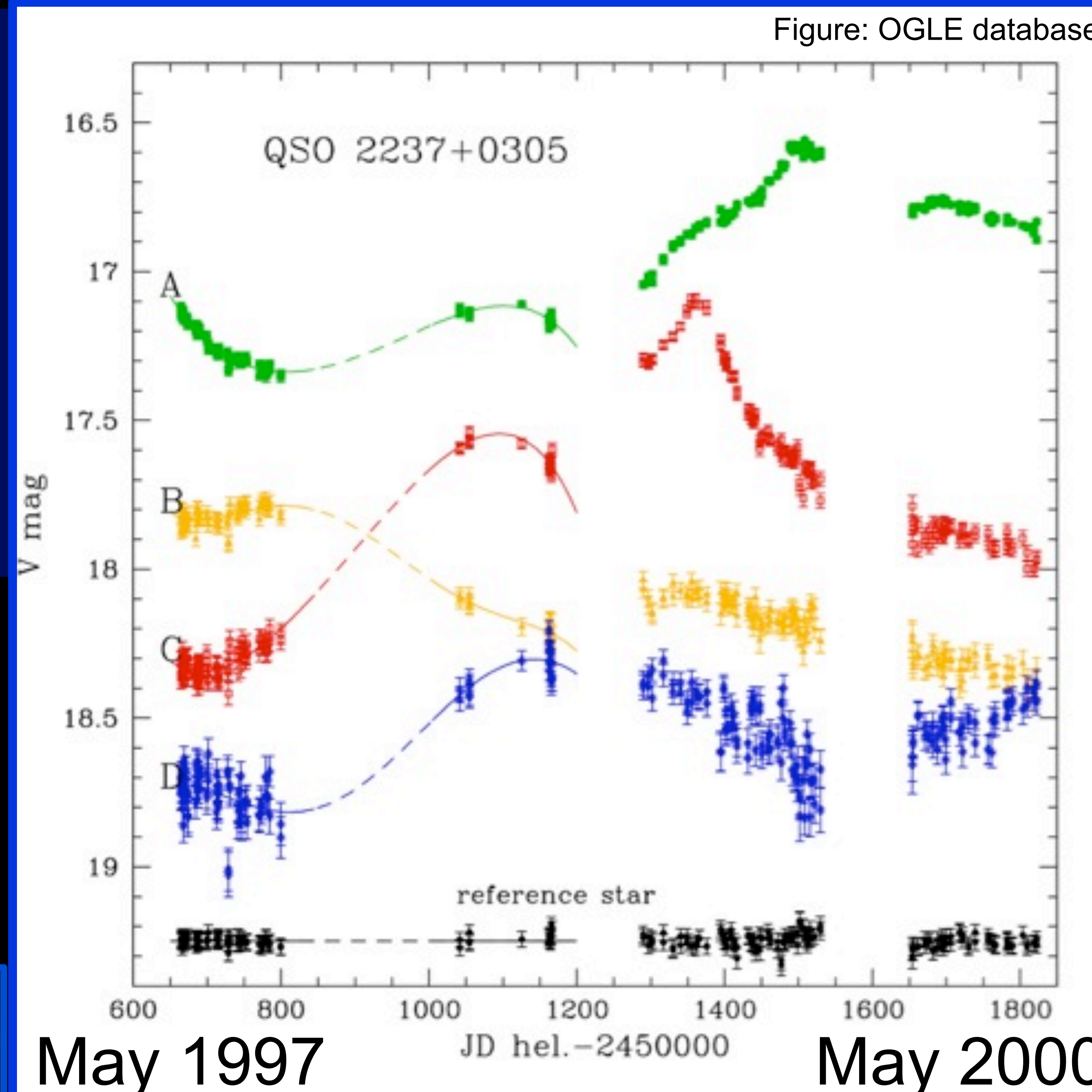

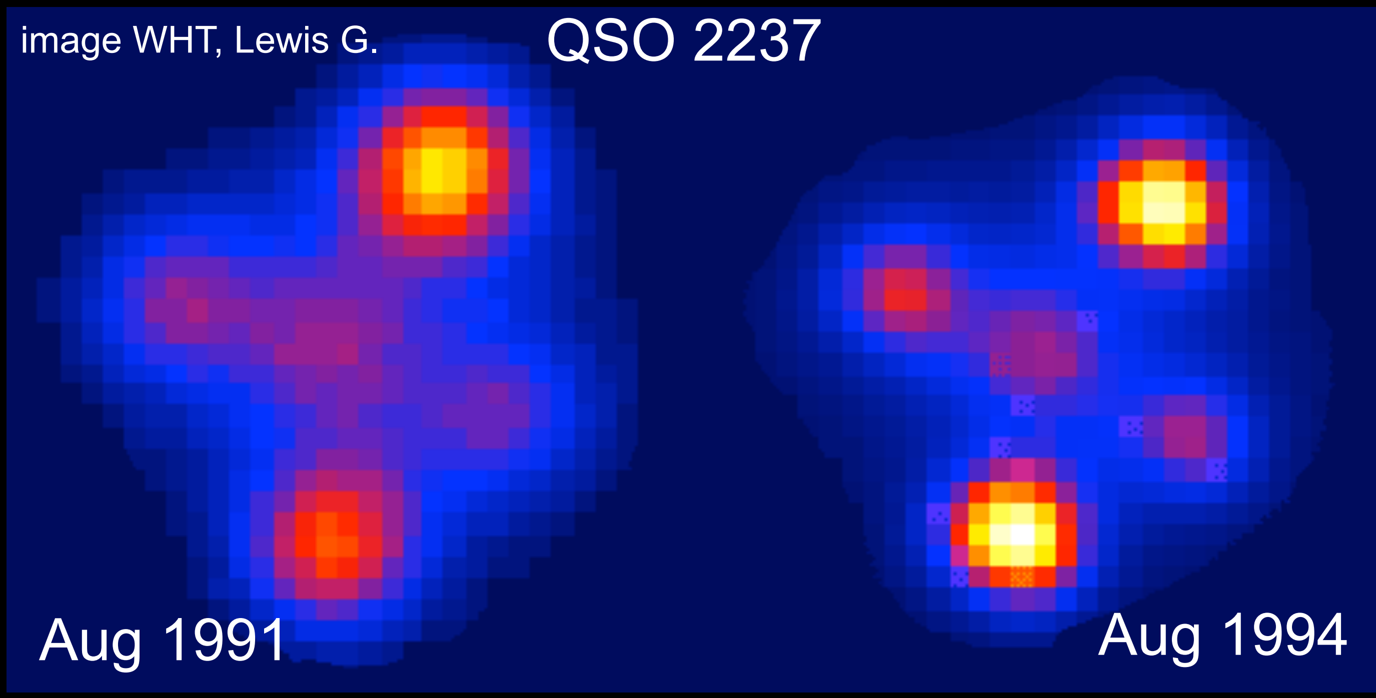

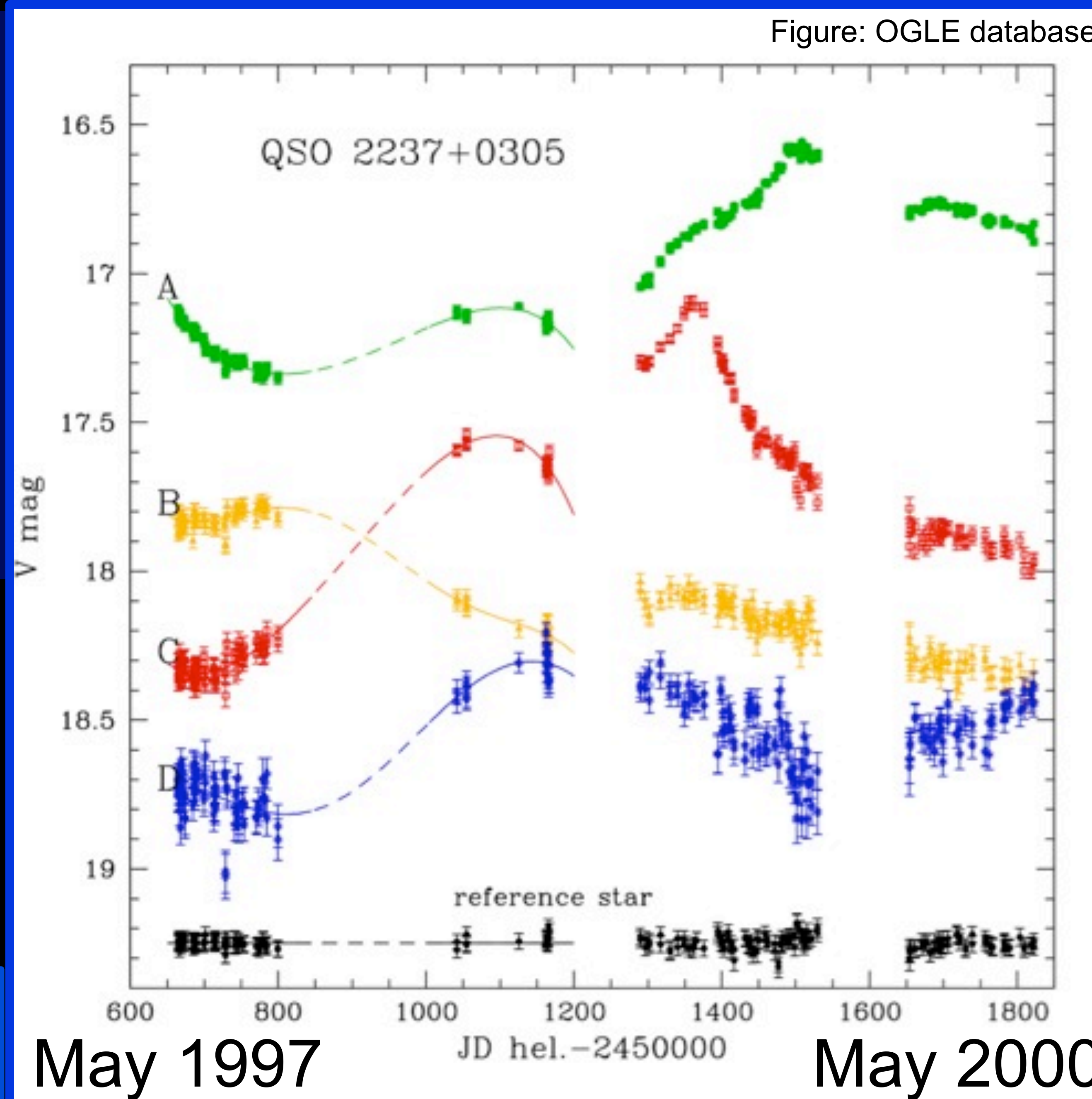

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compact objects
near the line of sight
+
relative motion
+
accretion disc size

Quasar microlensing

Quasar microlensing : present

Single Objects

- Mass function, stellar mass fraction (lens galaxy)
  (Poindexter et al. 2010, Mediavilla et al. 2009, Pooley et al. 2009)

- Size of the broad line region, X-ray emission
  (Floyd et al. 2012, Sluse et al. 2011, Dai et al. 2010)

- **Accretion disk size** and **profile**, **black-hole**
  (Blackburne et al. 2011, Morgan et al. 2010)

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Currently there are ~90 known lensed quasars *(CASTLES)*
~23 systems have been studied using microlensing

Number of systems is low due to difficulties in observing
(continuous monitoring, multi-wavelength)

Quasar microlensing : future

Future synoptic all-sky surveys, like ***LSST,***
are expected to find ***~8000*** new multiply imaged quasars
~3000 of which might be suitable for microlensing *(Oguri et al 2010)*

SINGLE OBJECTS

⬇

STATISTICAL SAMPLES

Quasar microlensing : future

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SINGLE OBJECTS

⬇

STATISTICAL SAMPLES

- *Can microlensing constrain accretion discs in the future?*

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SINGLE OBJECTS

↓

STATISTICAL SAMPLES

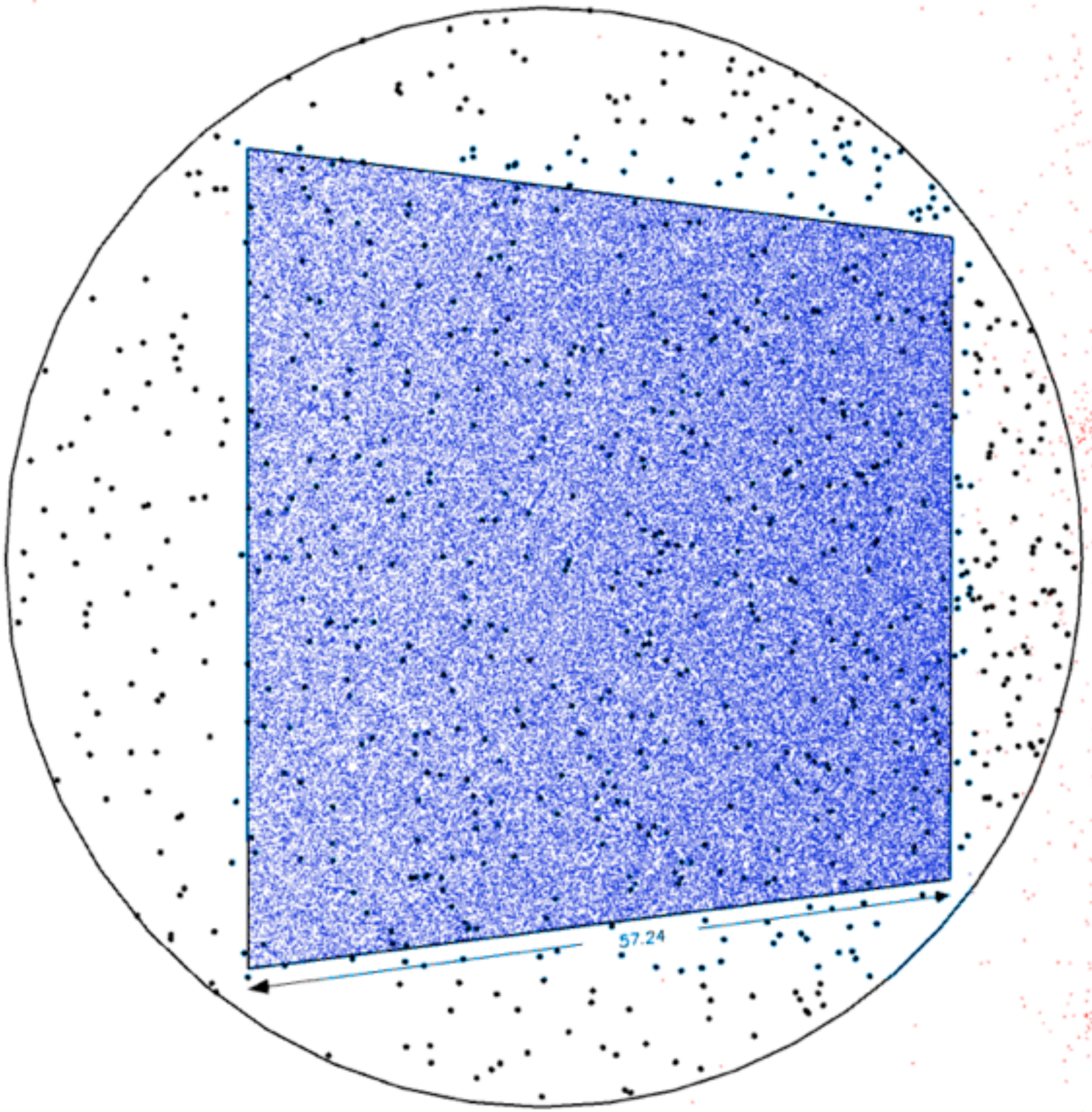
- *Can microlensing constrain accretion discs in the future?*

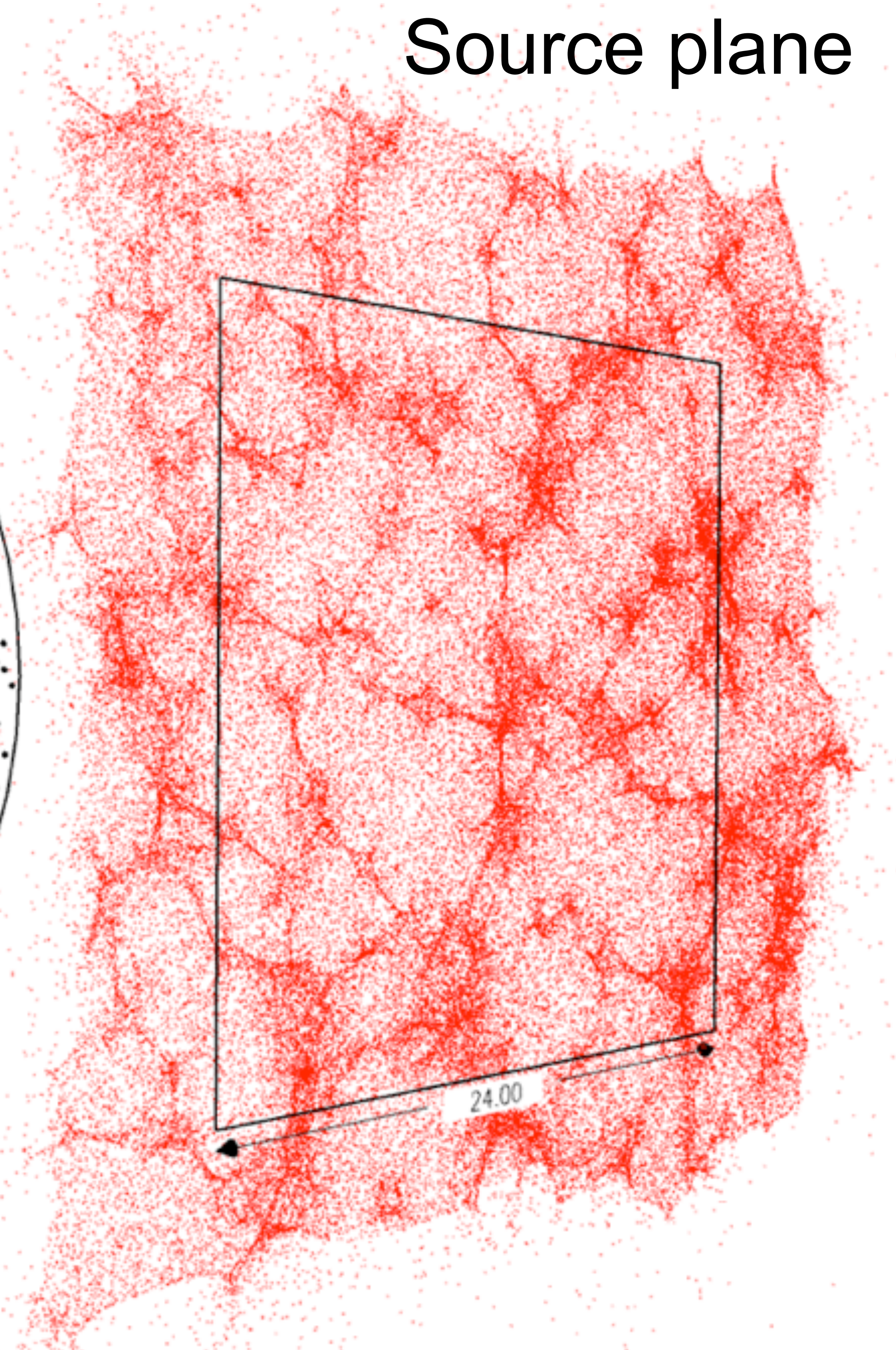
➥ *a lot of computational power needed !!!*

lensing models part 2 (micro)

Lens plane

Source plane





Images: C. Fluke

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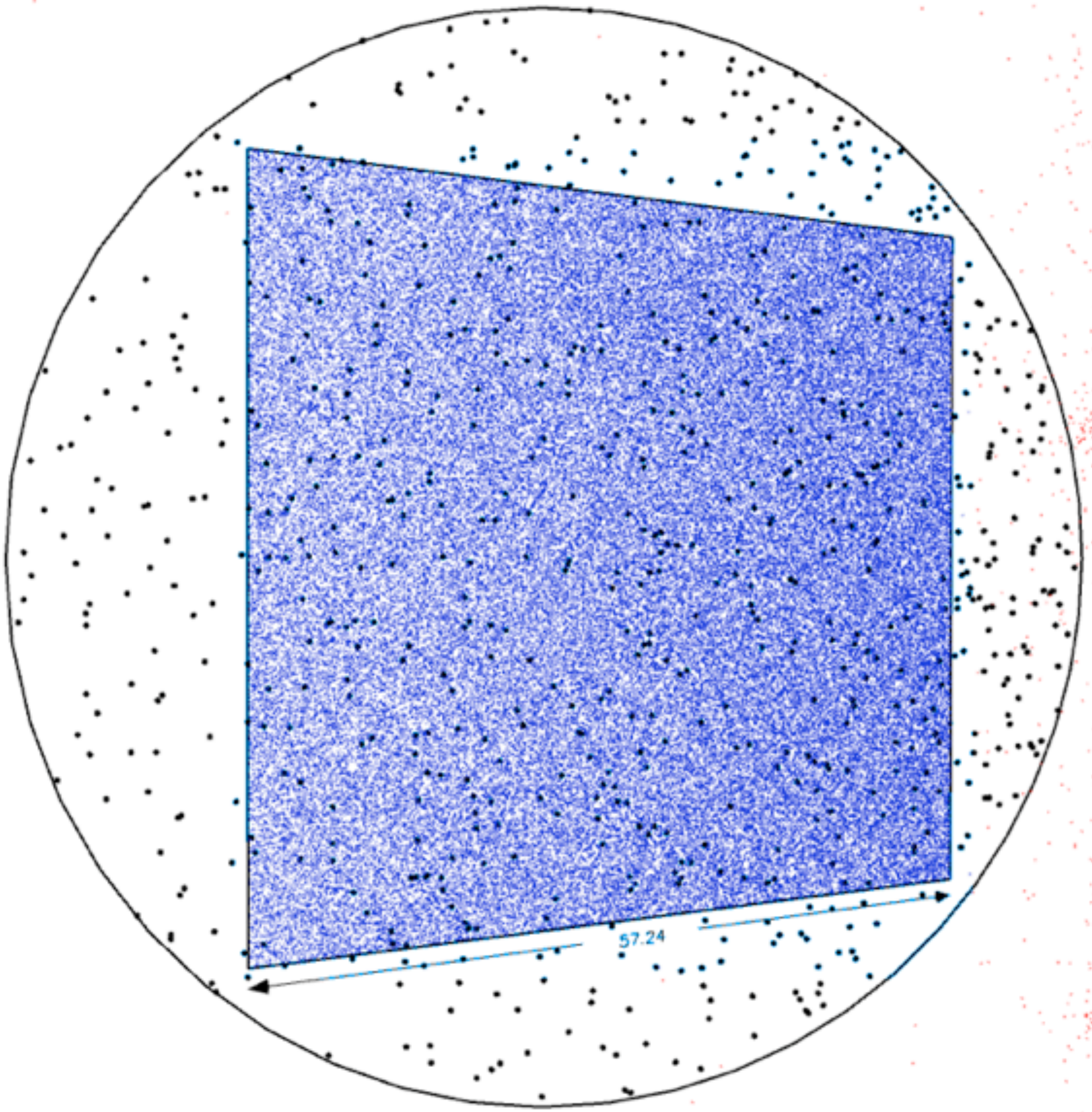

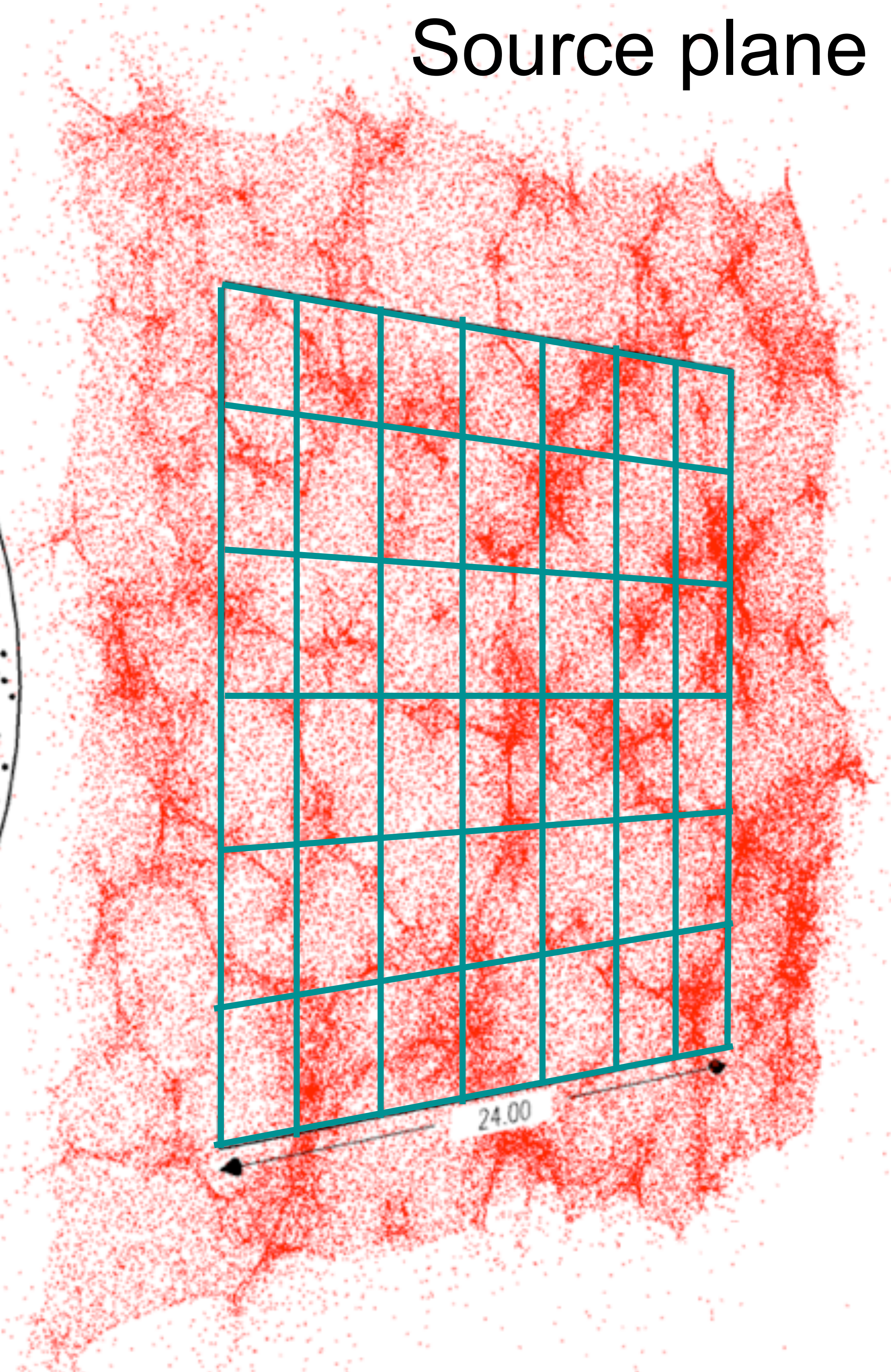

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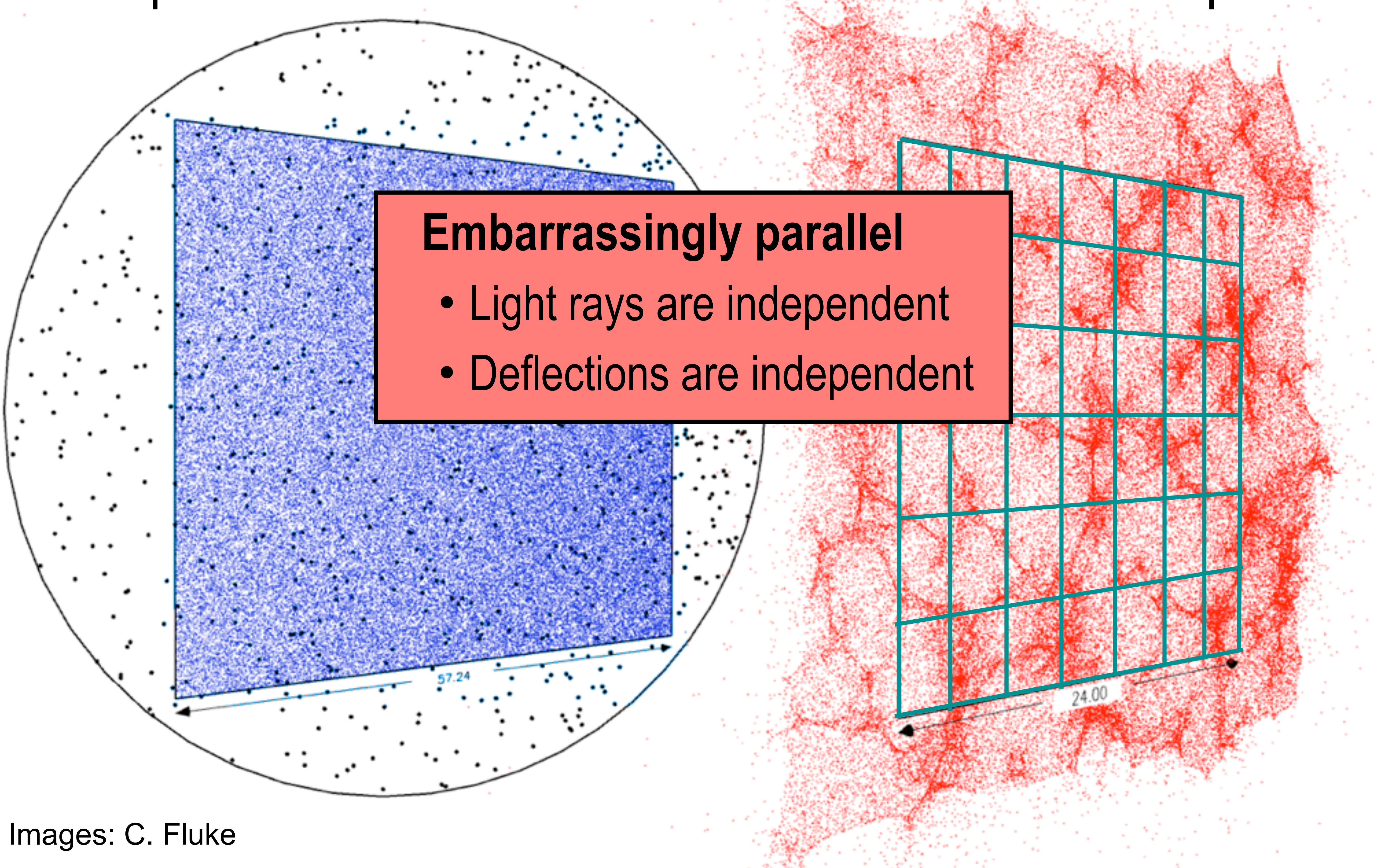
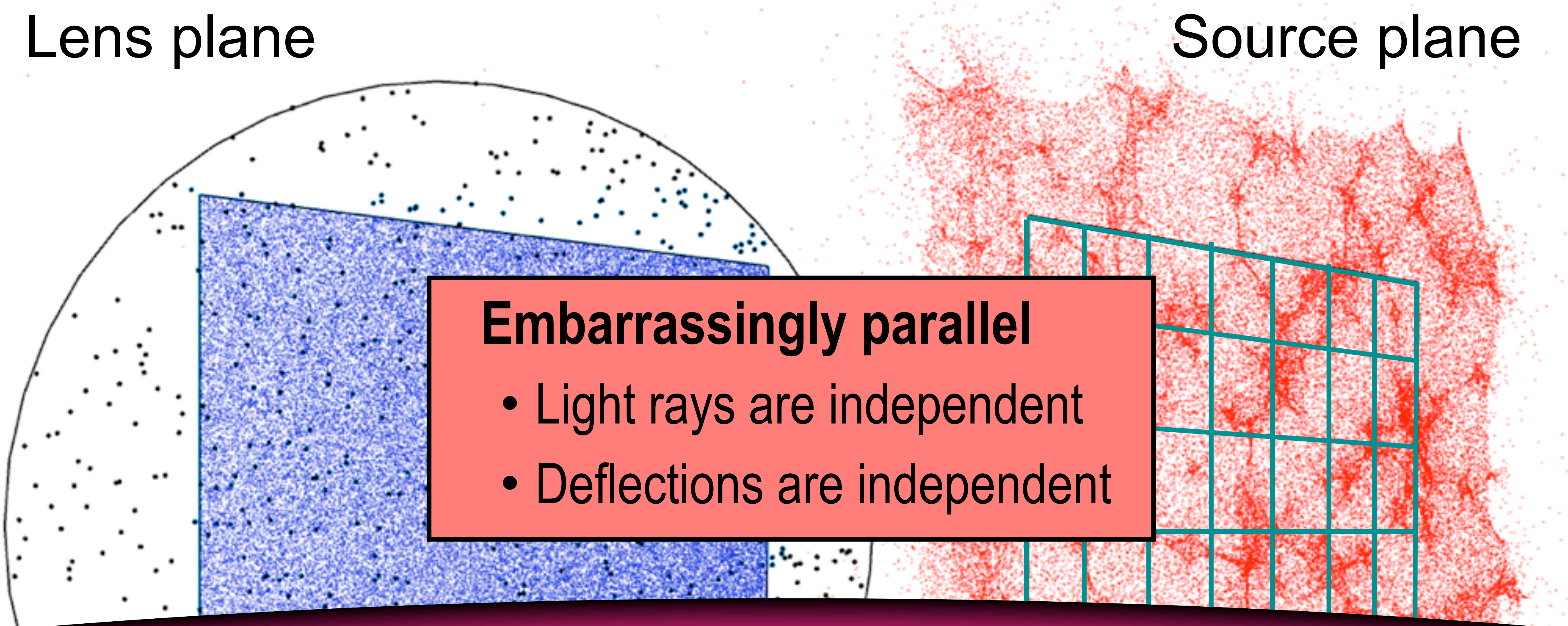


Embarrassingly parallel

- Light rays are independent
- Deflections are independent

Images: C. Fluke

lensing models part 2 (micro)



Embarrassingly parallel

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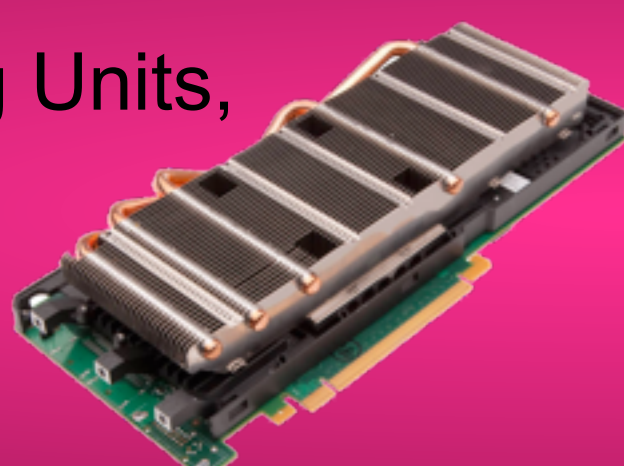
Direct inverse ray-shooting technique

(Thompson et al. 2010, Bate et al. 2010)

Graphics Processing Units, **GPUs**



GPU supercomputers
(like gSTAR)

CAS, Swinburne

Understanding the microlensing parameter space

	Wambsganss 1992	Lewis & Irwin 1995	**GERLUMPH* 2013**
method	tree code	contours	direct
pixels	512	-	10000
Total	**64**	**61**	**~50000**

** GPU-Enabled High-Resolution Micro-Lensing parameter survey*

(Bate & Fluke 2012)

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Convergence, κ	*describes the focusing power of the lenses*
Shear, γ	*distortion applied by external mass*

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External	**Convergence, κ**	*describes the focusing power of the lenses*
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Microlensing	mass of the microlenses	*(Wambsganss 1992, Lewis & Irwin 1995)*
	positions of the microlenses	*(Vernardos & Fluke 2013)*
	map width	*(Vernardos & Fluke 2013)*
	including smooth matter	*(Vernardos et al. 2013, refereed)*
Accretion disc	*size*	
	temperature profile	*in progress...*
	other...	

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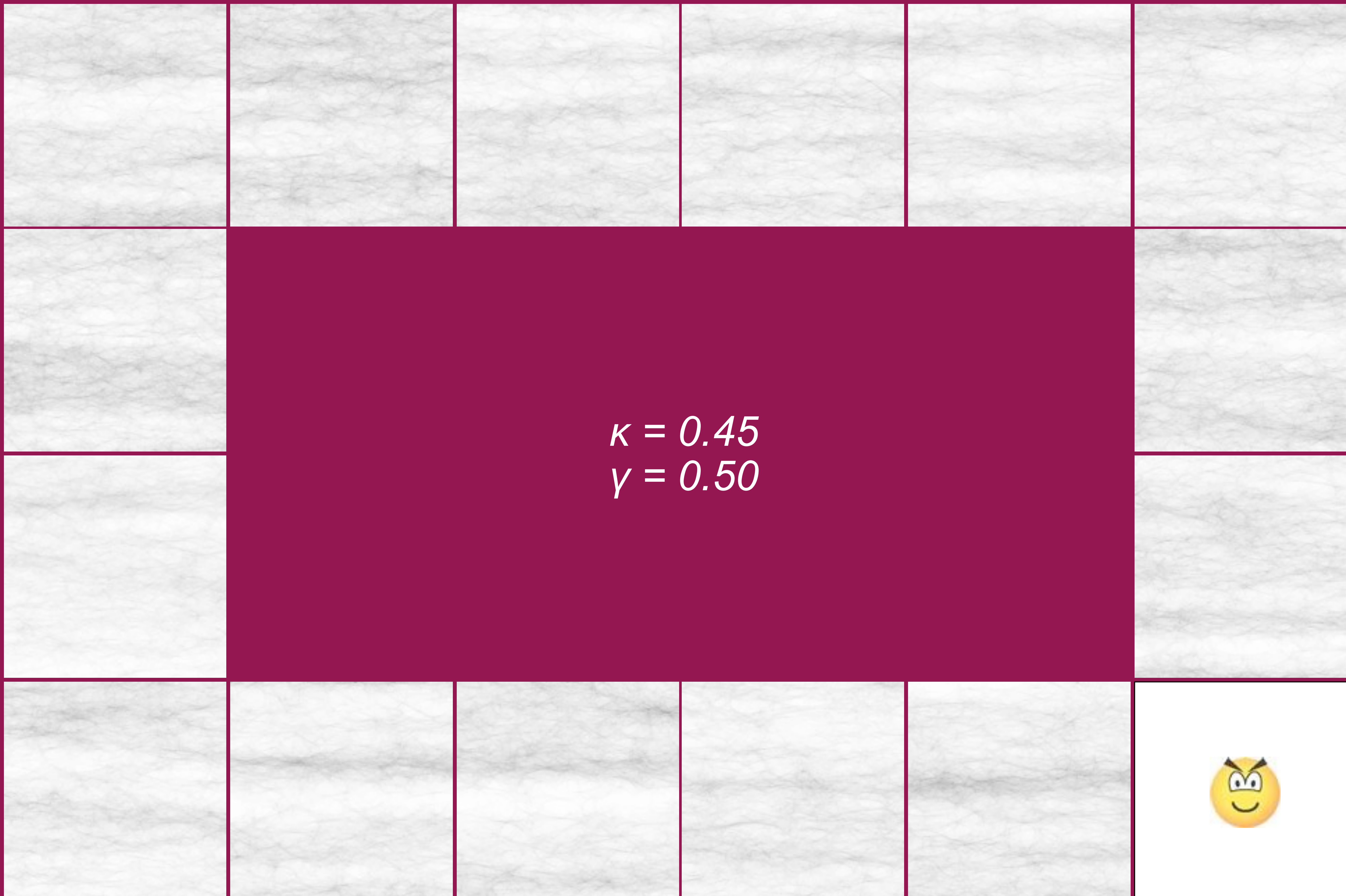
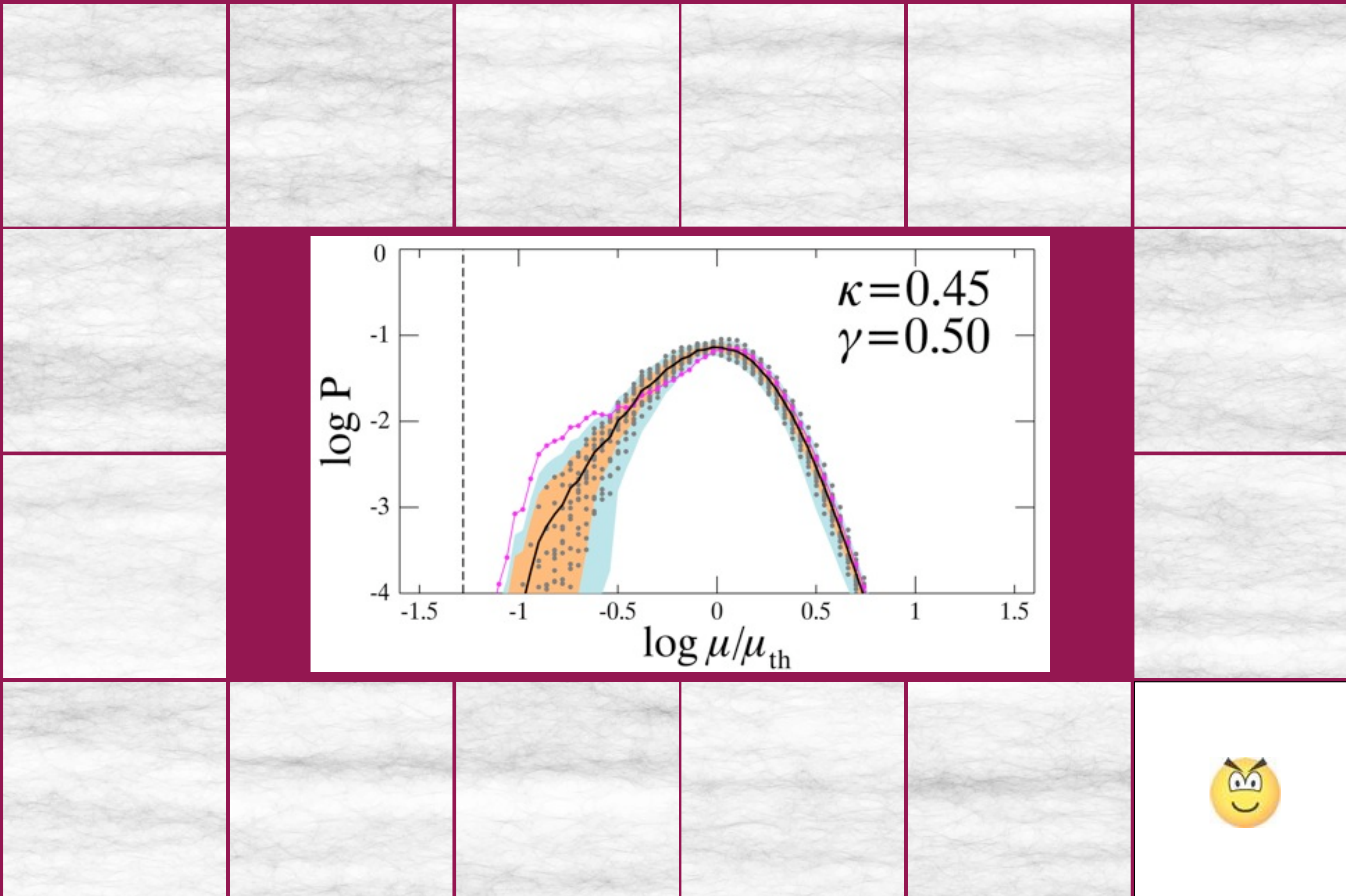

κ = 0.45
γ = 0.50

Magnification Probability Distribution (MPD)



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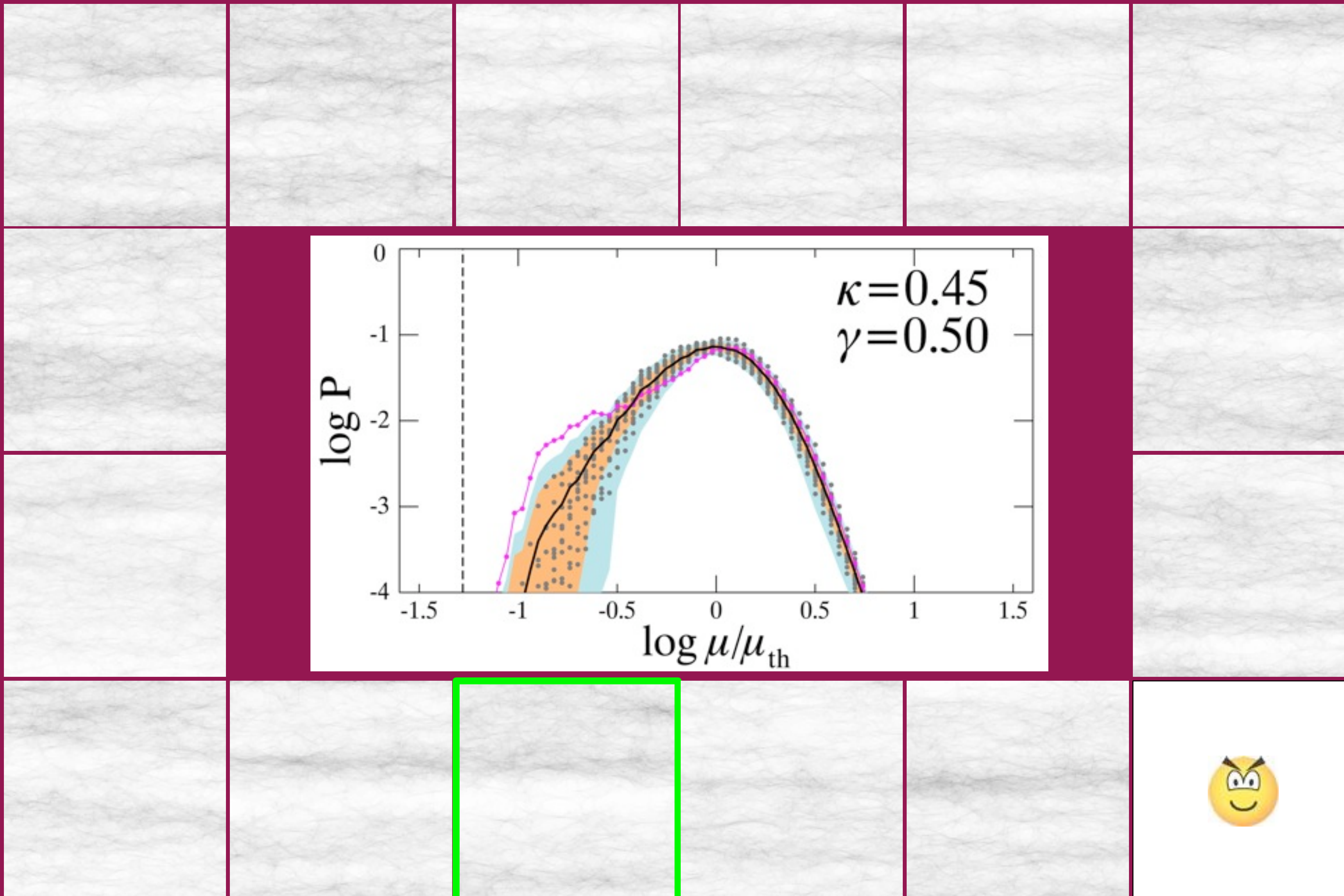
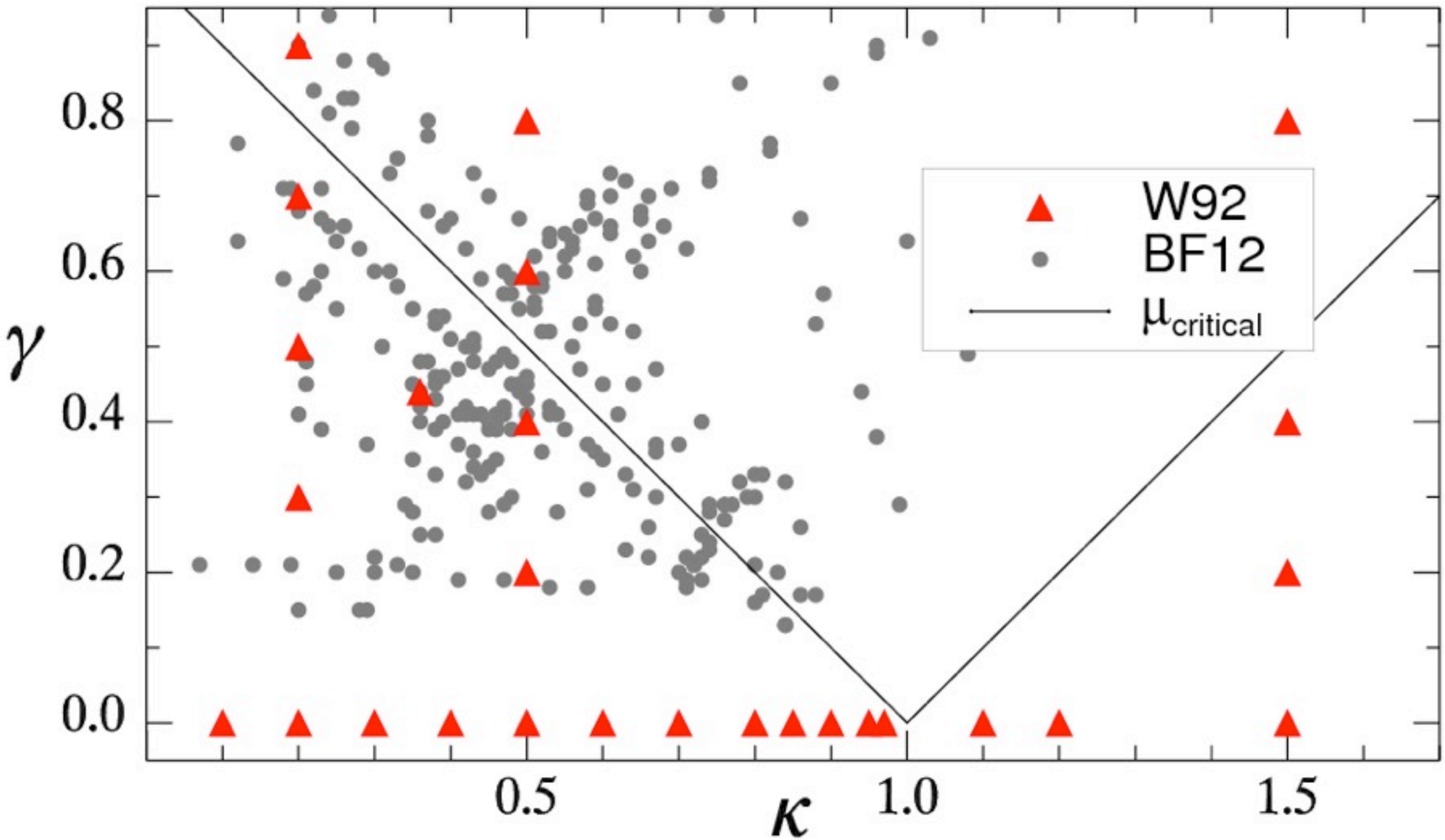
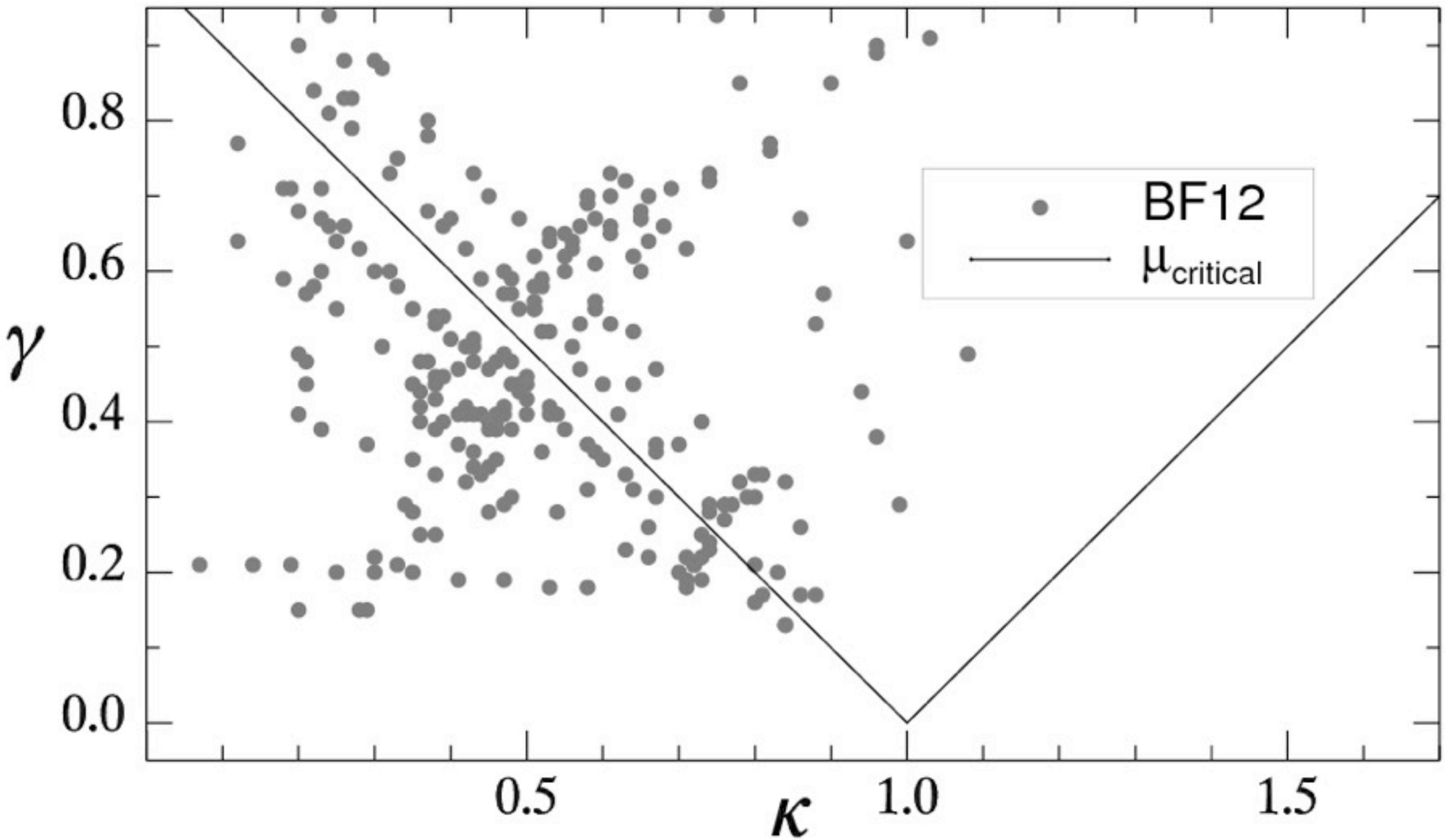


κ,γ parameter space

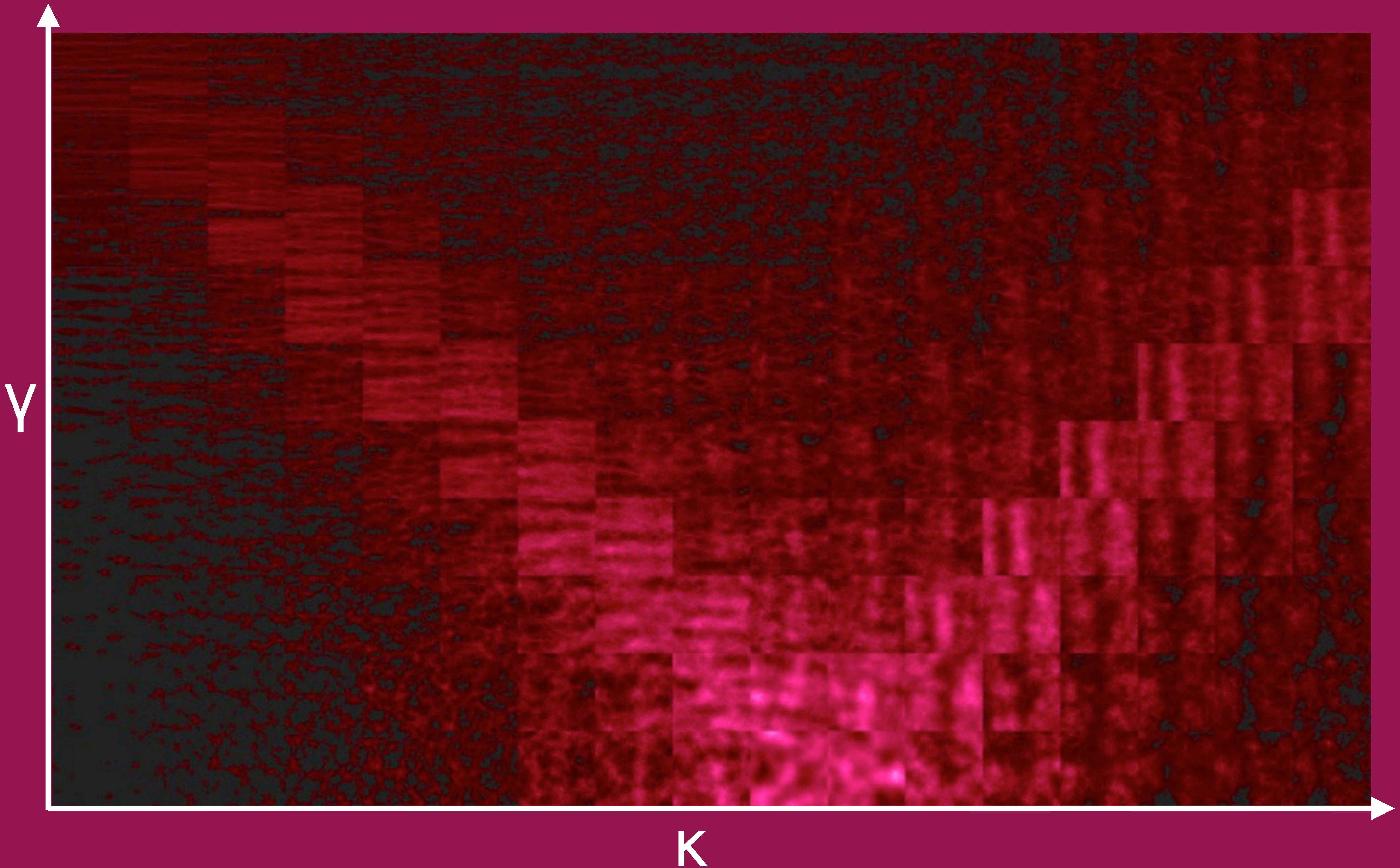


23 systems 256 κ,γ pairs	27 κ,γ pairs 64 individual maps

κ,γ parameter space

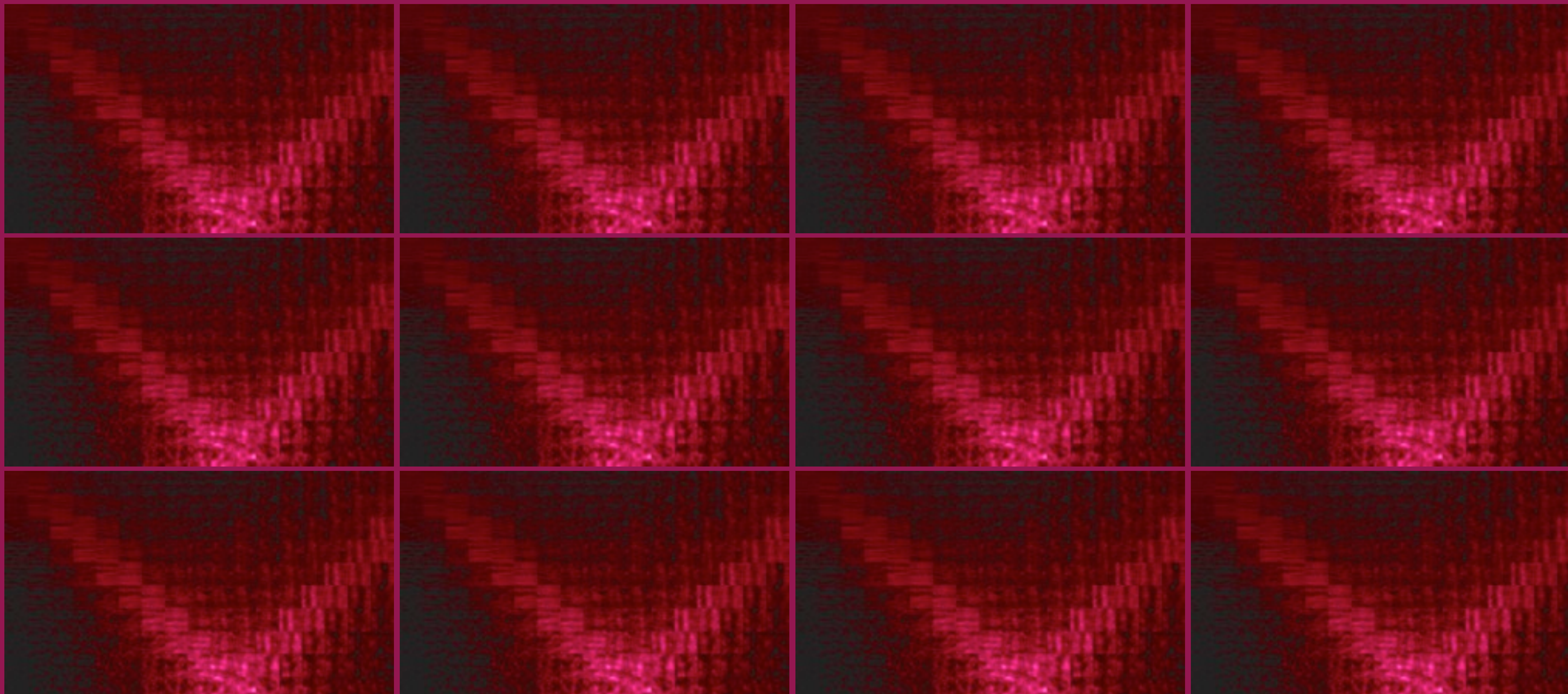


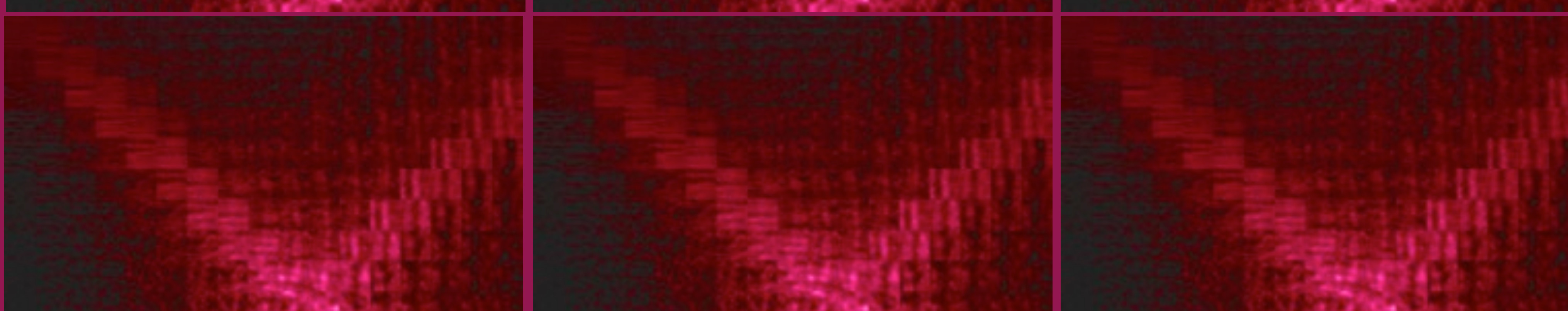
23 systems
256 κ,γ pairs



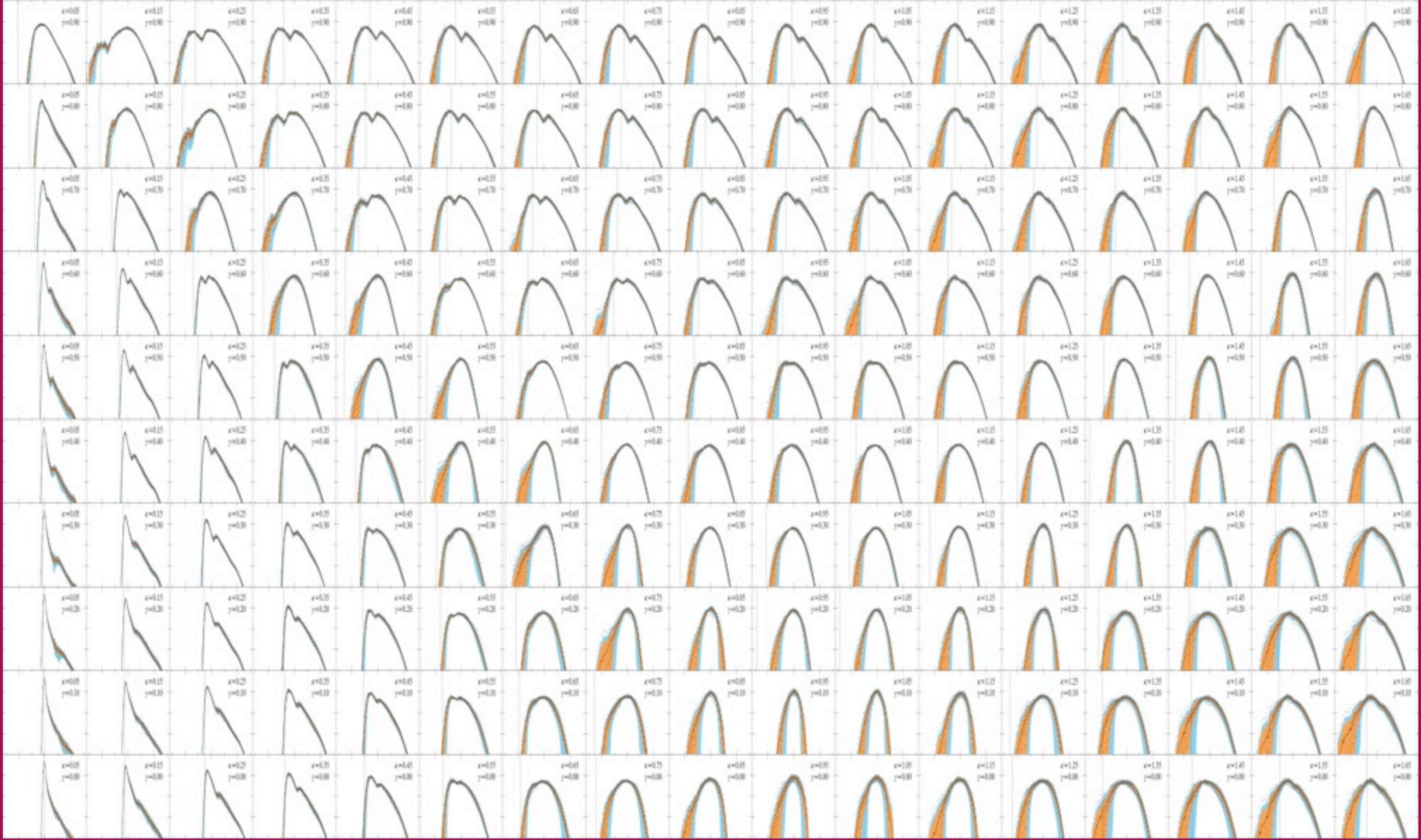
170 maps, 14 GPU days

GERLUMPH 0: 15 different random realizations





2550 maps
4096^2 pixels
213 GPU days
0.16 TB

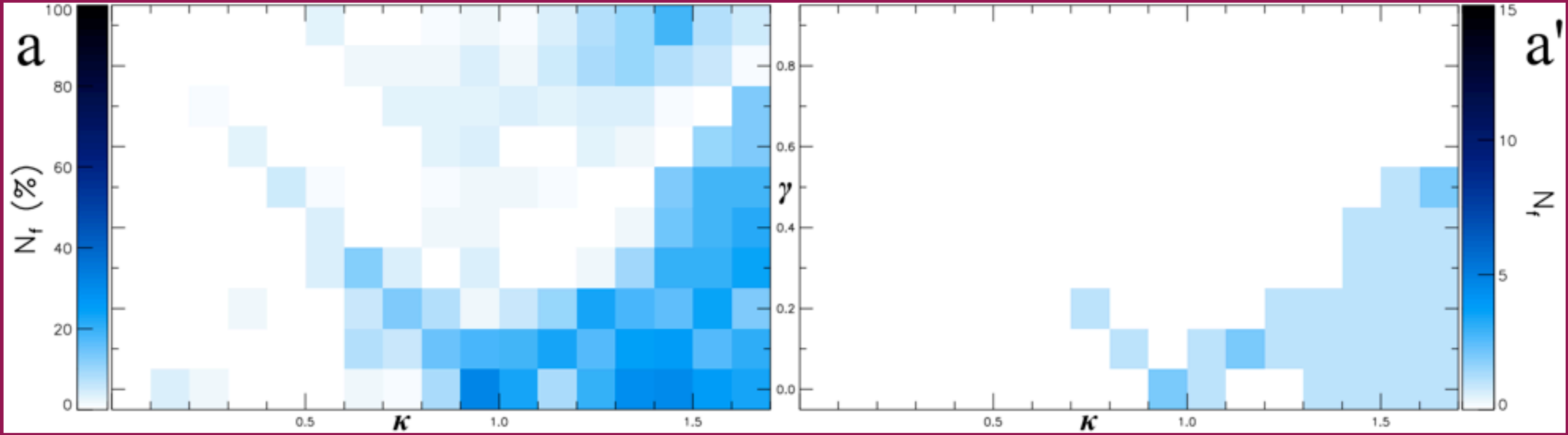


Vernardos & Fluke 2013

Kolmogorov-Smirnov tests

Null hypothesis : same distributions
failed test : p value < 0.05

Pairs of MPDs MPDs and the mean



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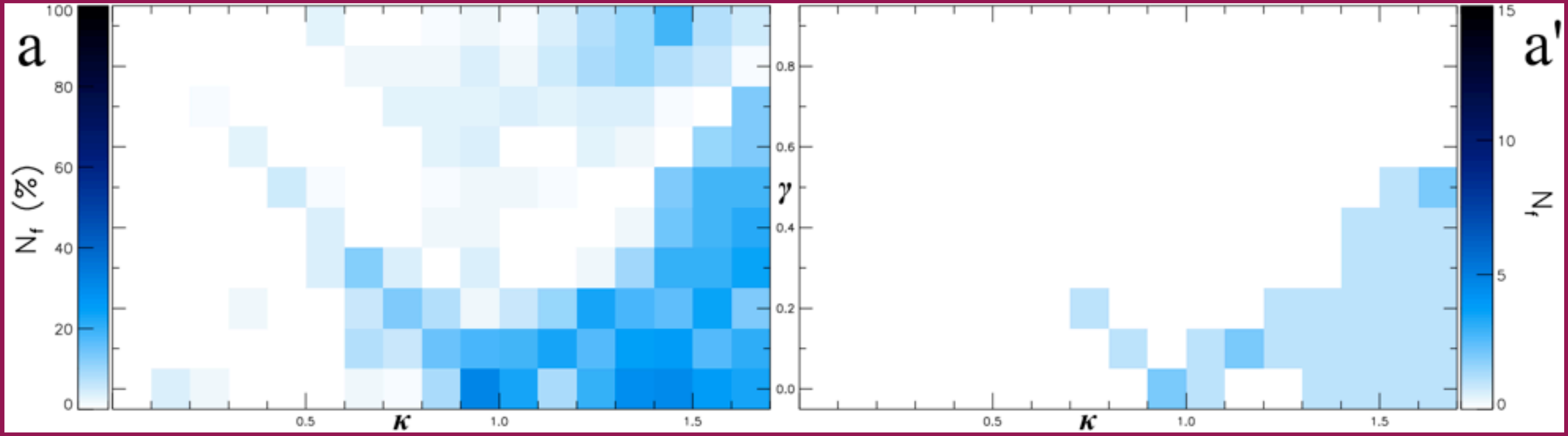


Vernardos & Fluke 2013

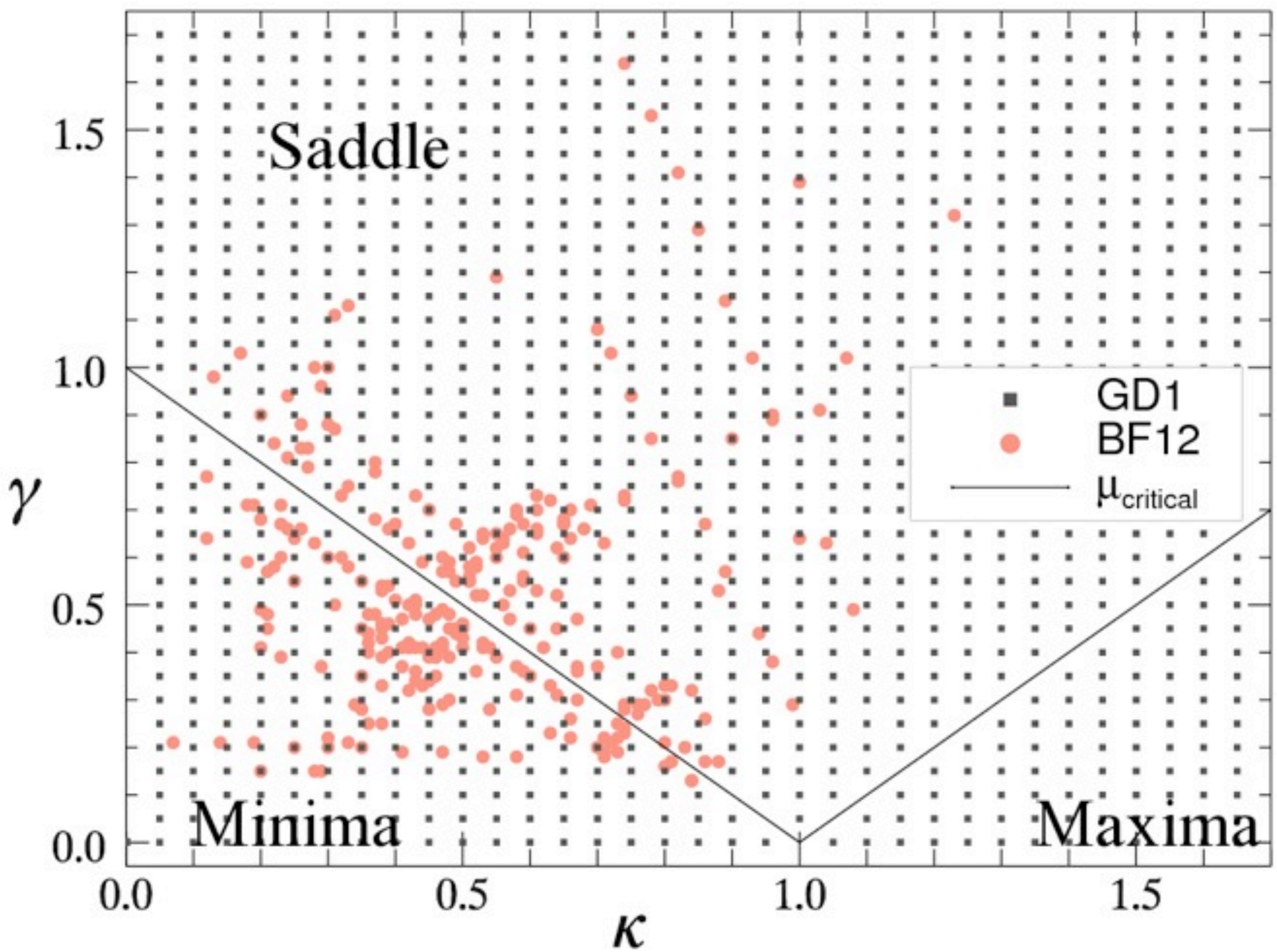
There are areas of parameter space where one map may not be representative convergence, κ : → compact / → smooth

extra parameter: smooth matter fraction

GERLUMPH I: Compact and smooth matter

convergence, κ : → compact, → smooth

extra parameter: smooth matter fraction

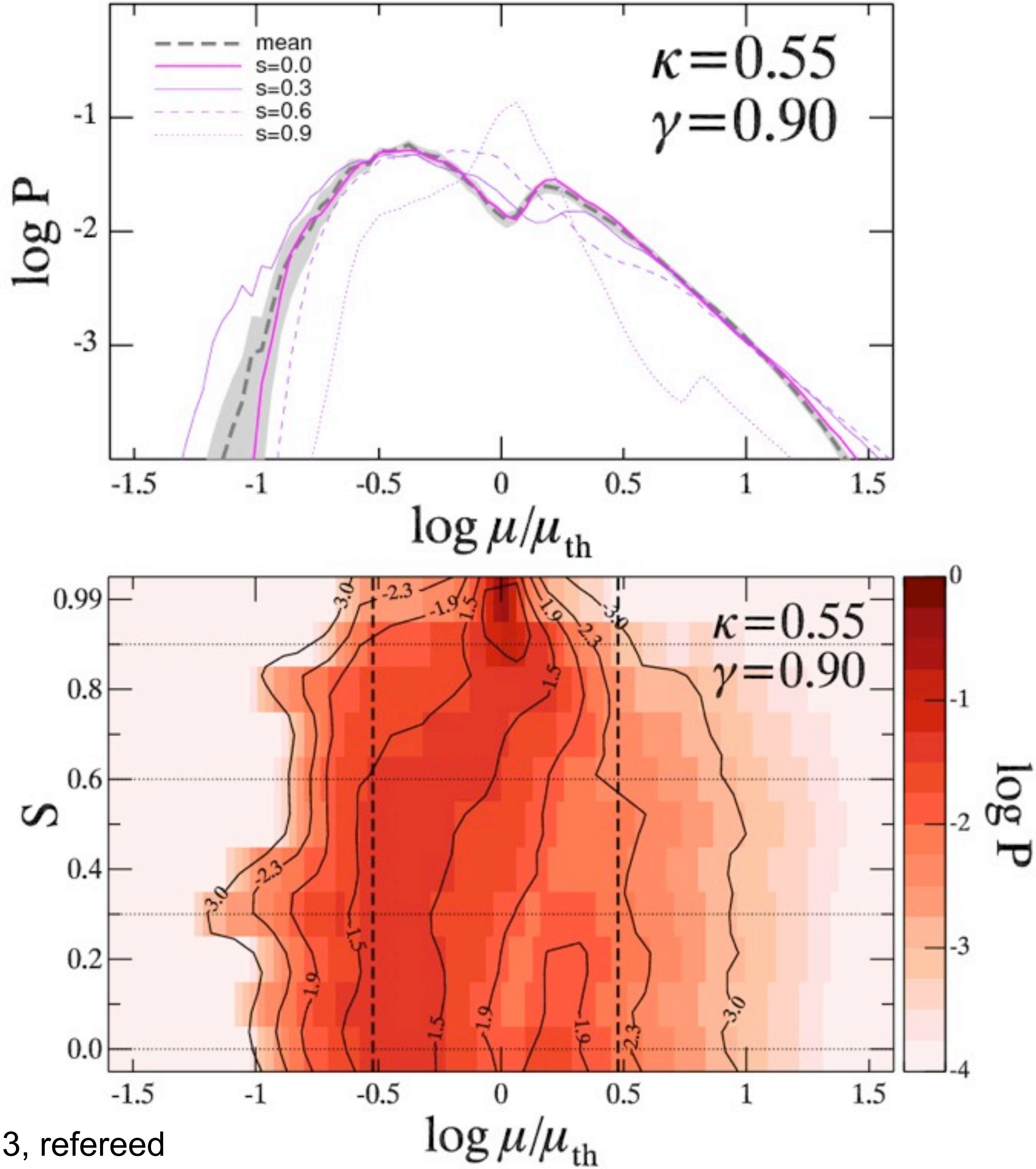


12342 maps

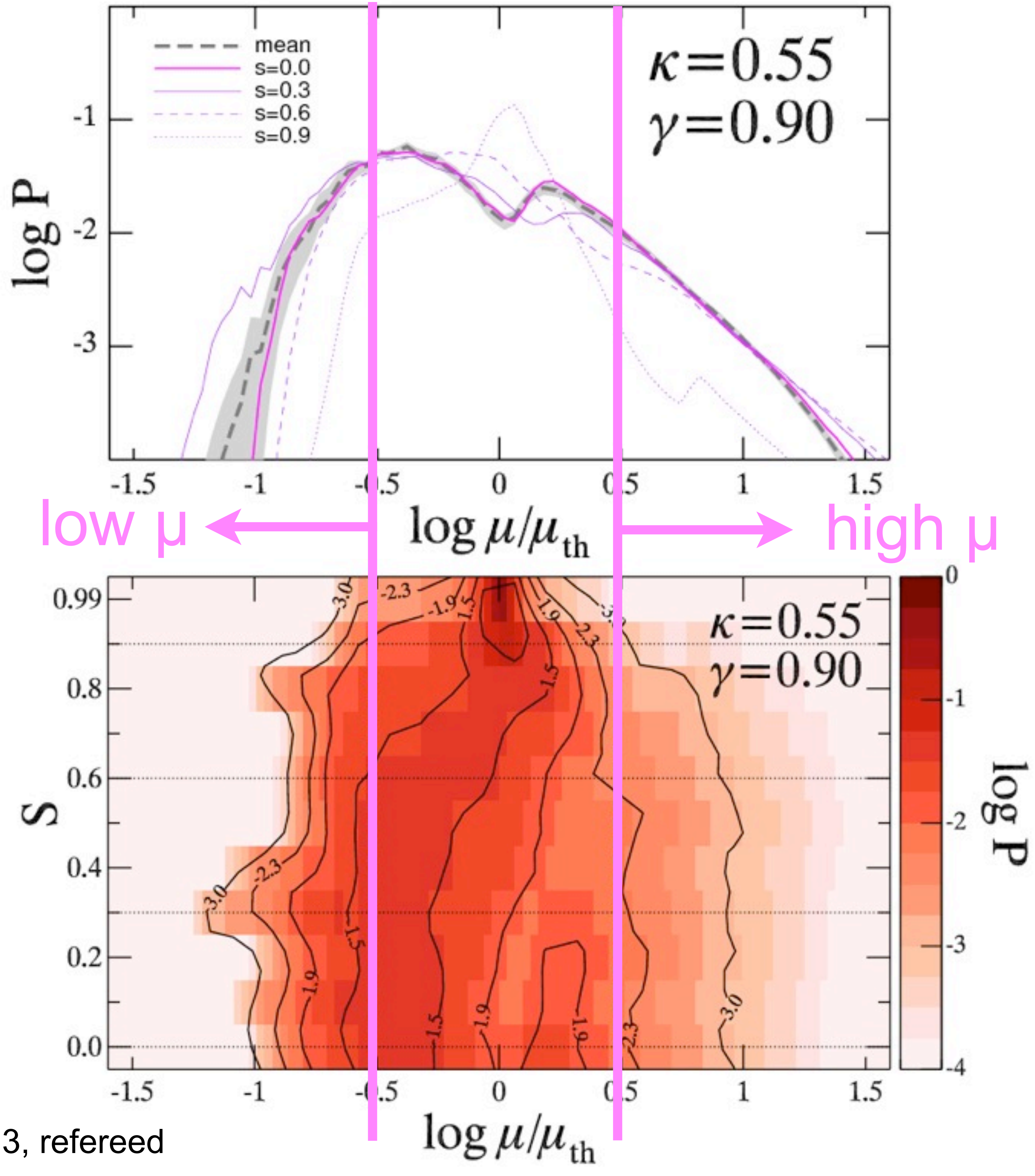
10000^2 pixels

2902 GPU days

4.5 TB

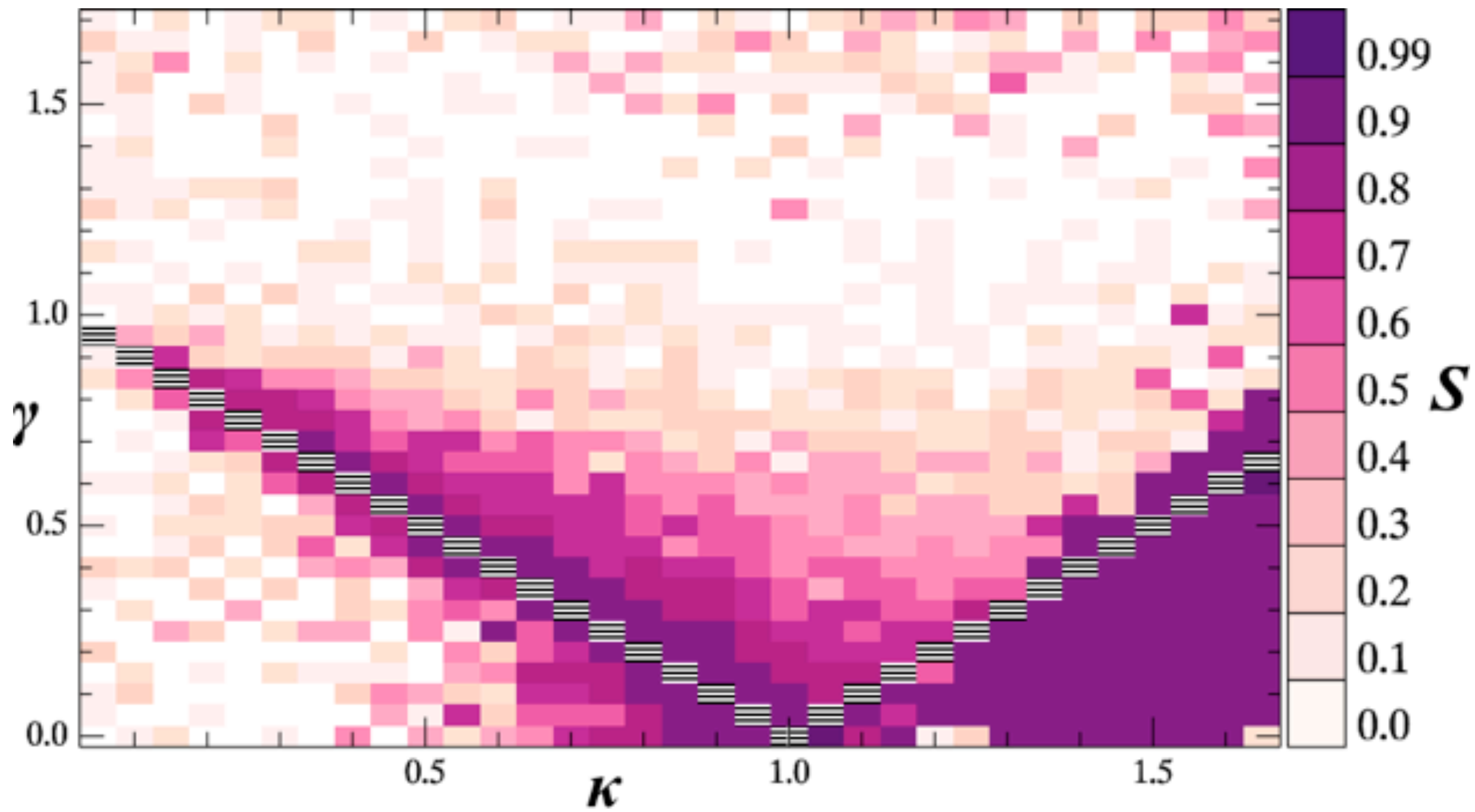


Vernardos et al. 2013, refereed

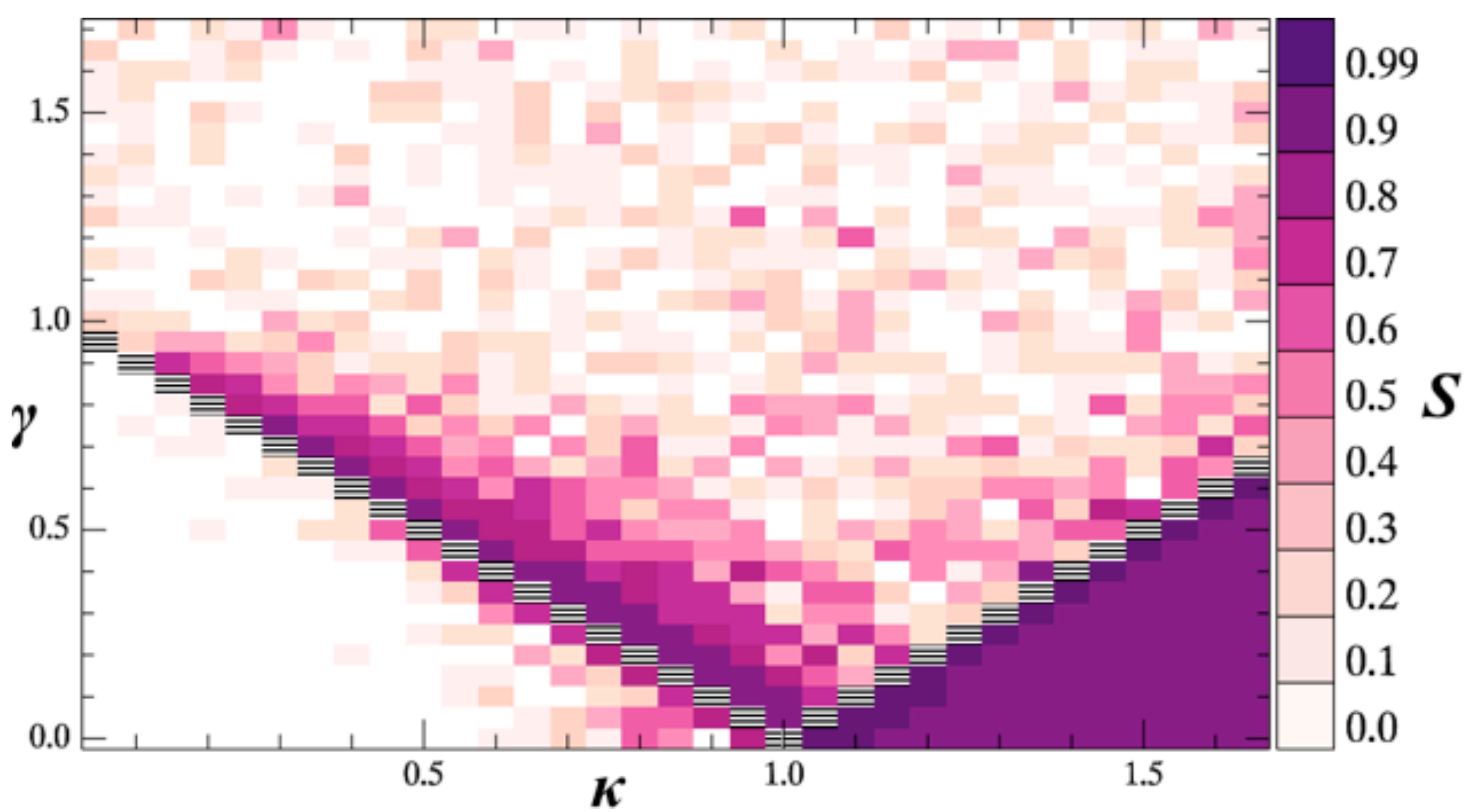


Vernardos et al. 2013, refereed

P_{max} for high μ



P_{max} for low μ



What’s next?

	GERLUMPH 0	GERLUMPH I	GERLUMPH II
(κ,γ)	170	1122	3753
s	1	11	11
lens positions	15	1	1
resolution	4096	10000	10000
total	**2550**	**12342**	**45705**

	GERLUMPH 0	GERLUMPH I	GERLUMPH II
(κ,γ)	170	1122	3753
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GERLUMPH I

Can microlensing constrain accretion discs in the future?

(predictions in the κ,γ parameter space)

GERLUMPH II

Is all of quasar microlensing correct?

(perturbations in the κ,γ)

	GERLUMPH 0	GERLUMPH I	GERLUMPH II
(κ,γ)	170	1122	3753
s	1	11	11
lens positions	15	1	1
resolution	4096	10000	10000
total	**2550**	**12342**	**45705**
status	complete	complete	*ongoing*
size (TB)	0.16	4.5	*16.9*
GPU time	213 days	2902 days	*15805 days*

GERLUMPH I

Can microlensing constrain accretion discs in the future?

(predictions in the κ,γ parameter space)

GERLUMPH II

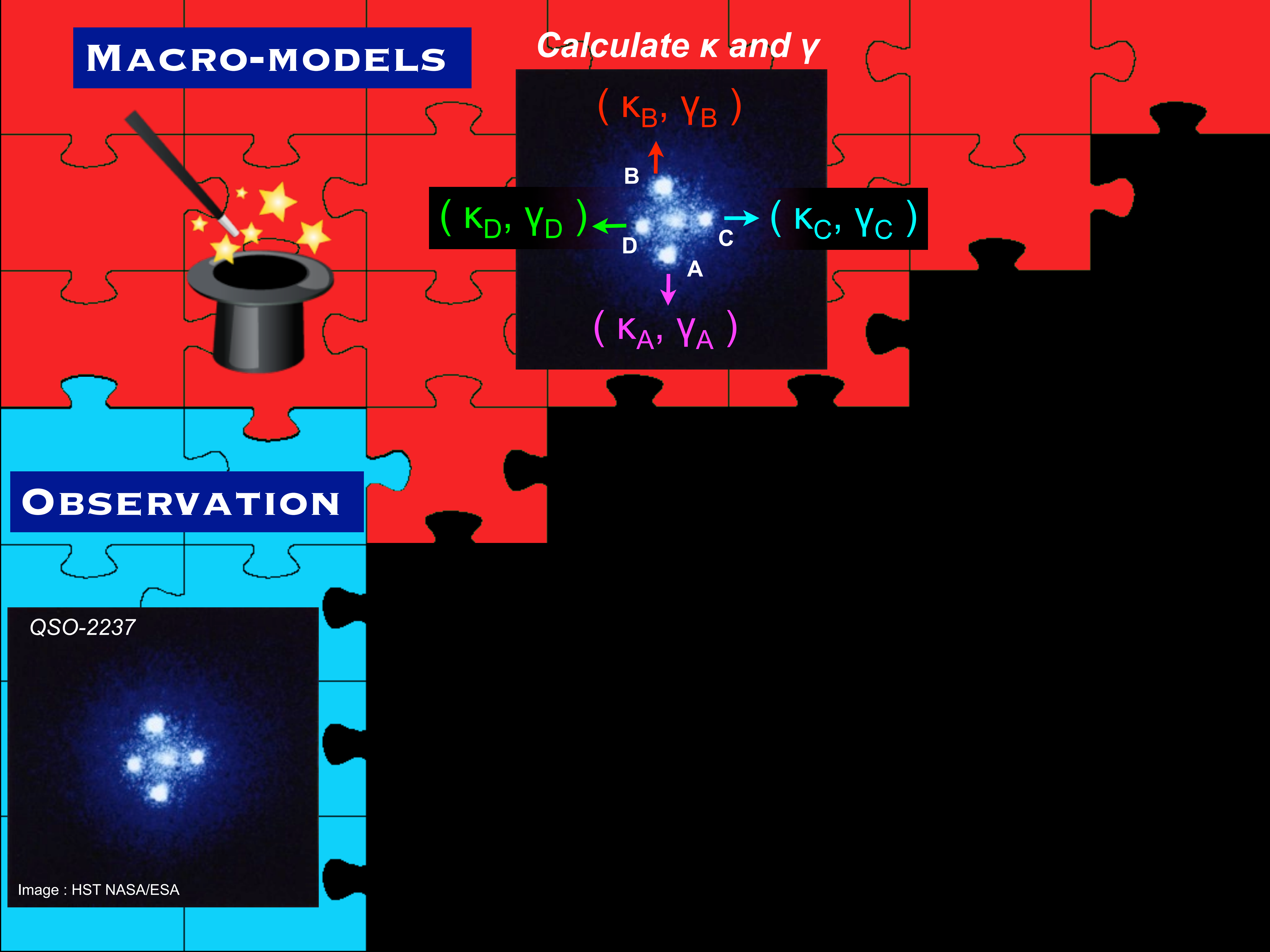
Is all of quasar microlensing correct?

(perturbations in the κ,γ)

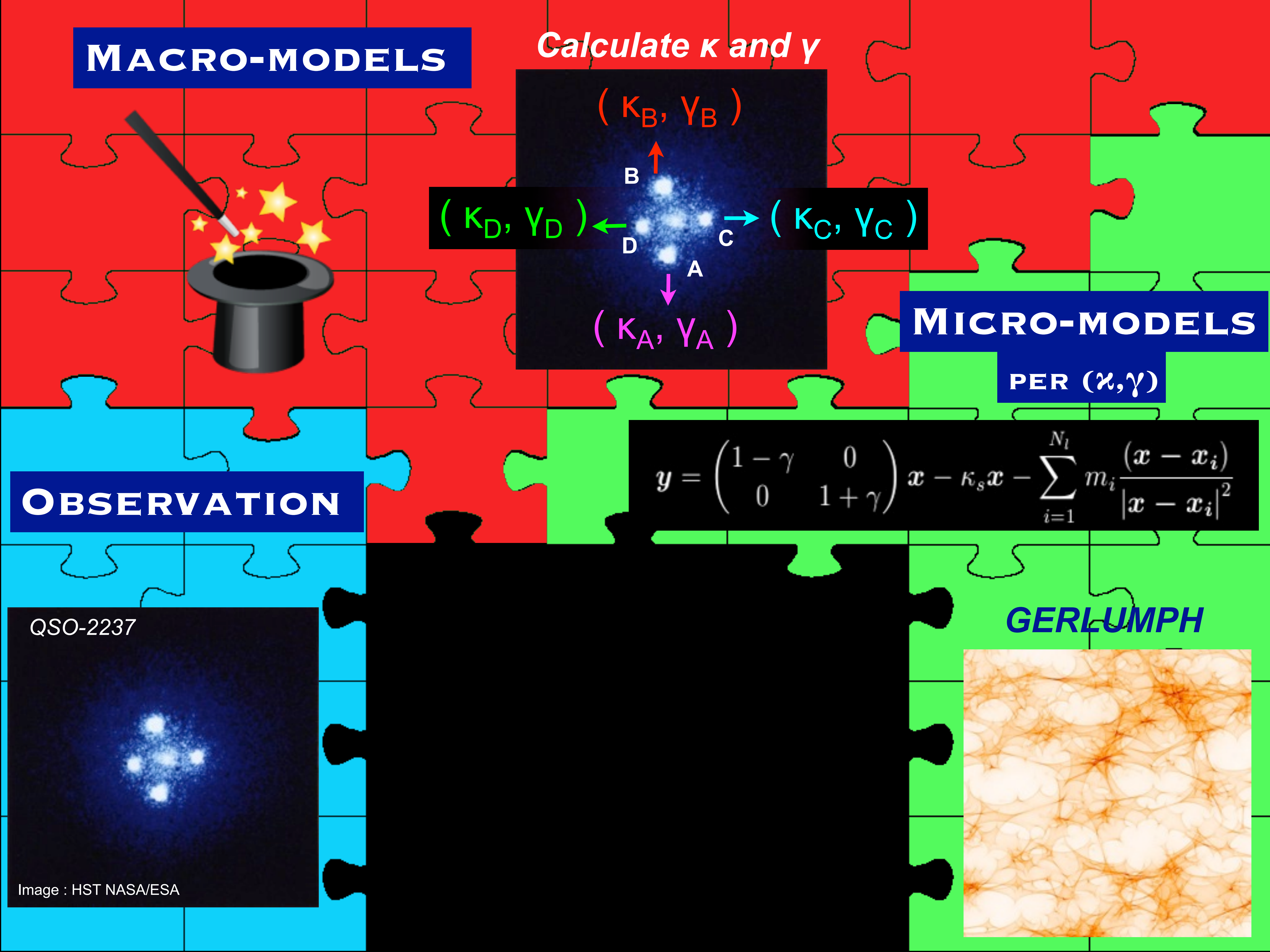
eResearch

Observation

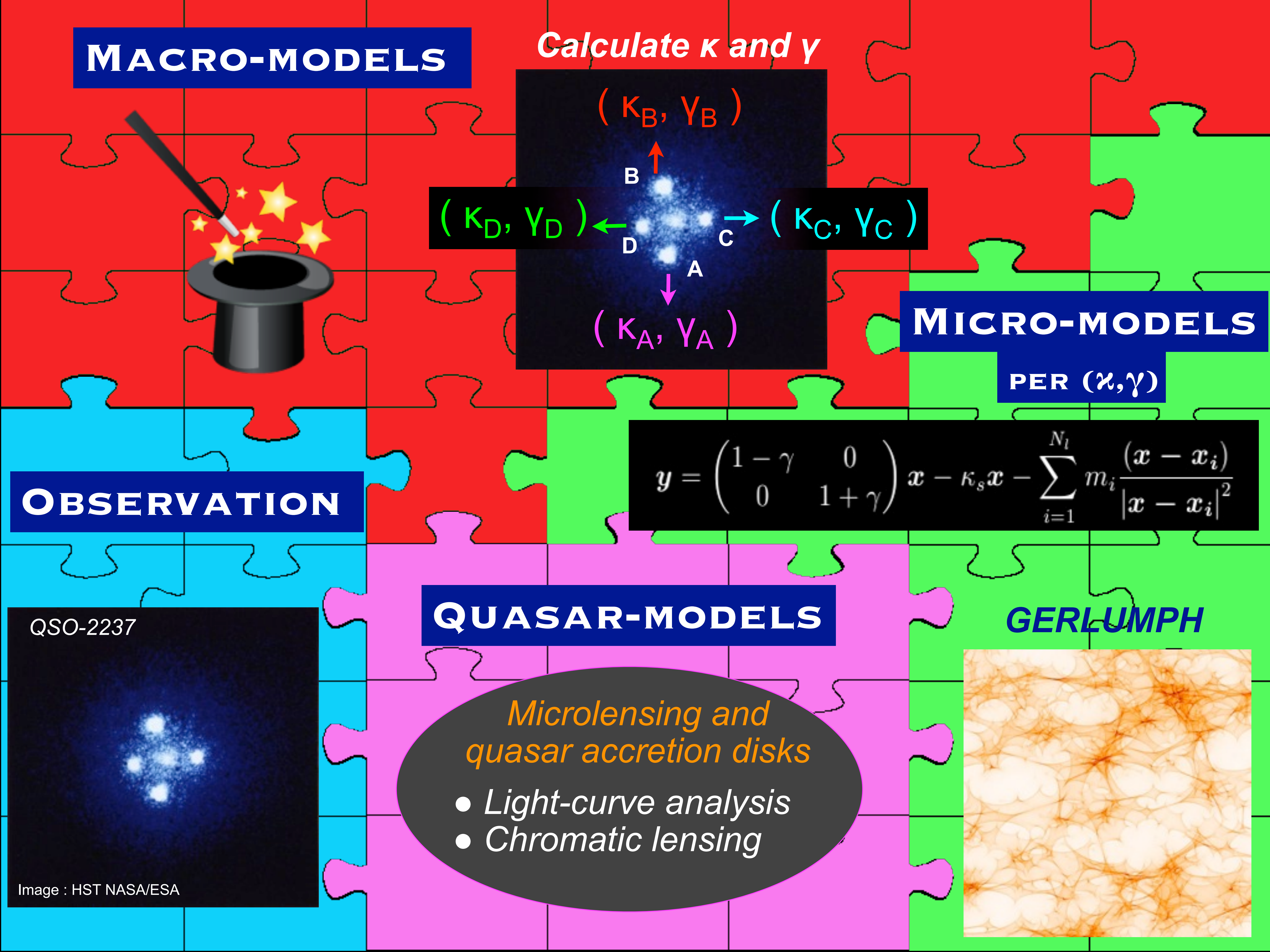
Image : HST NASA/ESA



Macro-models
Calculate κ and γ
(κB, γB)
B
(κD, γD)
D
C
(κC, γC)
A
(κA, γA)
Observation
QSO-2237
Image : HST NASA/ESA



Macro-models
Calculate κ and γ
(κB, γB)
B
(κD, γD)
D
C
(κC, γC)
A
(κA, γA)
Micro-models
per (κ,γ)
$y = \begin{pmatrix} 1-\gamma & 0 \\ 0 & 1+\gamma \end{pmatrix} x - \kappa_s x - \sum_{i=1}^{N_l} m_i \frac{(x - x_i)}{|x - x_i|^2}$
Observation
QSO-2237
Image : HST NASA/ESA
GERLUMPH



Macro-models
Calculate κ and γ
(κ_B, γ_B)
B
(κ_D, γ_D)
D
C
(κ_C, γ_C)
A
(κ_A, γ_A)
Micro-models
per (ϰ,γ)
$y = \begin{pmatrix} 1-\gamma & 0 \\ 0 & 1+\gamma \end{pmatrix} x - \kappa_s x - \sum_{i=1}^{N_l} m_i \frac{(x - x_i)}{|x - x_i|^2}$
Observation
QSO-2237
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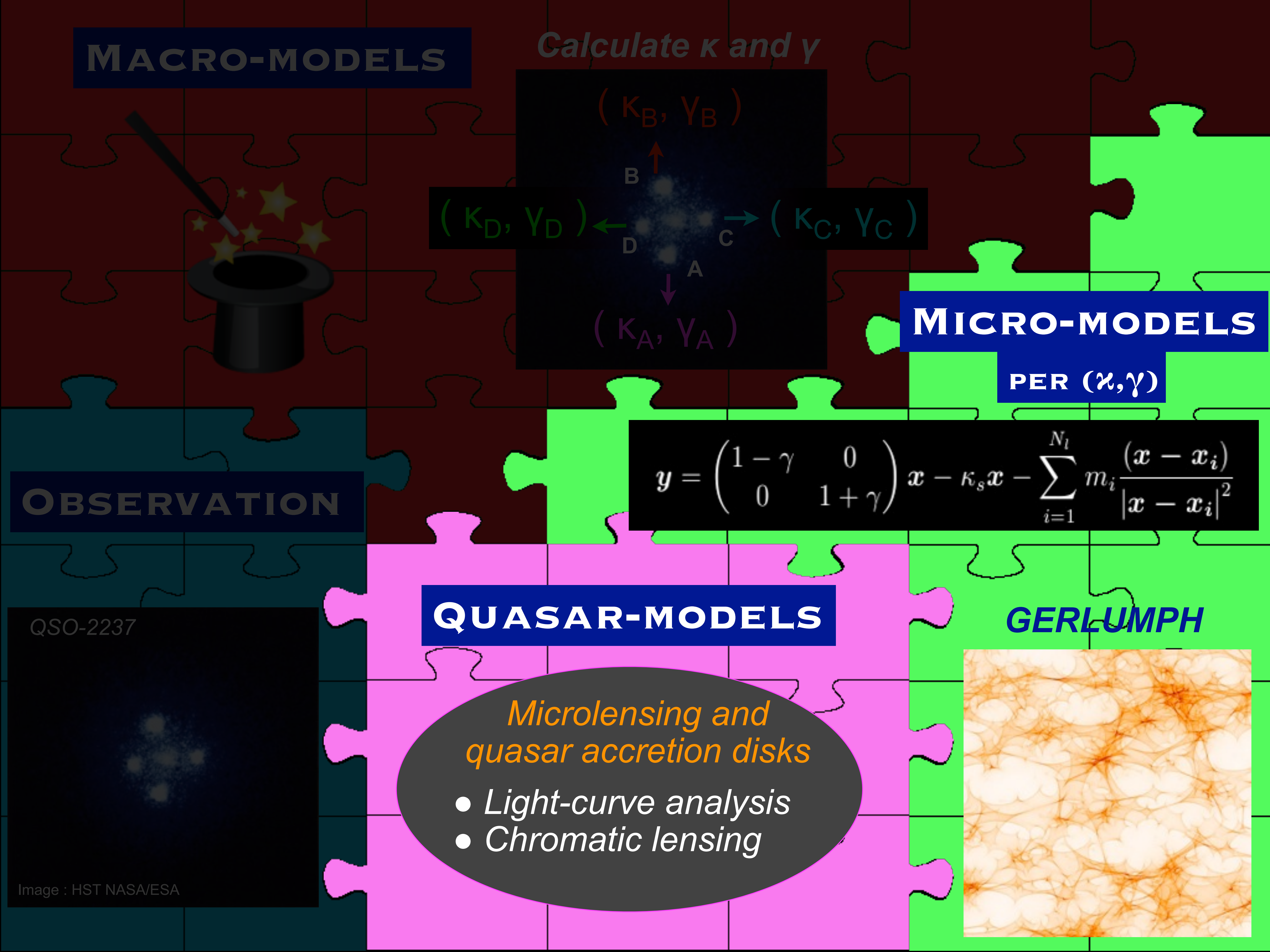
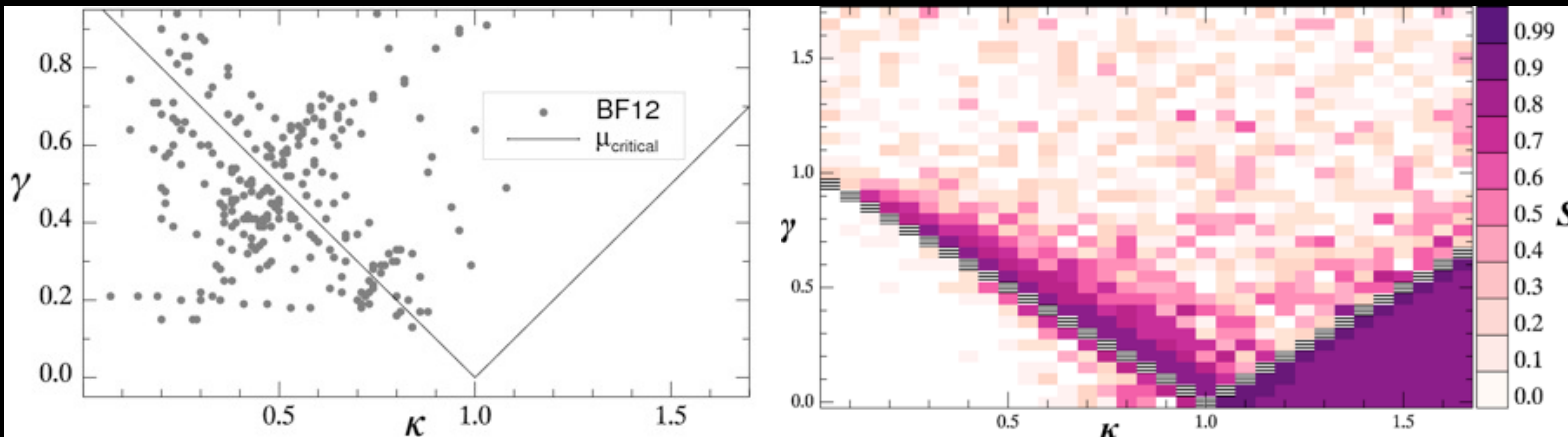
Quasar-models
Microlensing and quasar accretion disks
• Light-curve analysis
• Chromatic lensing
GERLUMPH



Macro-models
Calculate κ and γ
(κ_B, γ_B)
B
(κ_D, γ_D)
D
C
(κ_C, γ_C)
A
(κ_A, γ_A)
Micro-models
per (κ,γ)
$$y = \begin{pmatrix} 1-\gamma & 0 \\ 0 & 1+\gamma \end{pmatrix} x - \kappa_s x - \sum_{i=1}^{N_l} m_i \frac{(x - x_i)}{|x - x_i|^2}$$
Observation
QSO-2237
Image : HST NASA/ESA
Quasar-models
Microlensing and quasar accretion disks
● Light-curve analysis
● Chromatic lensing
GERLUMPH

Conclusions

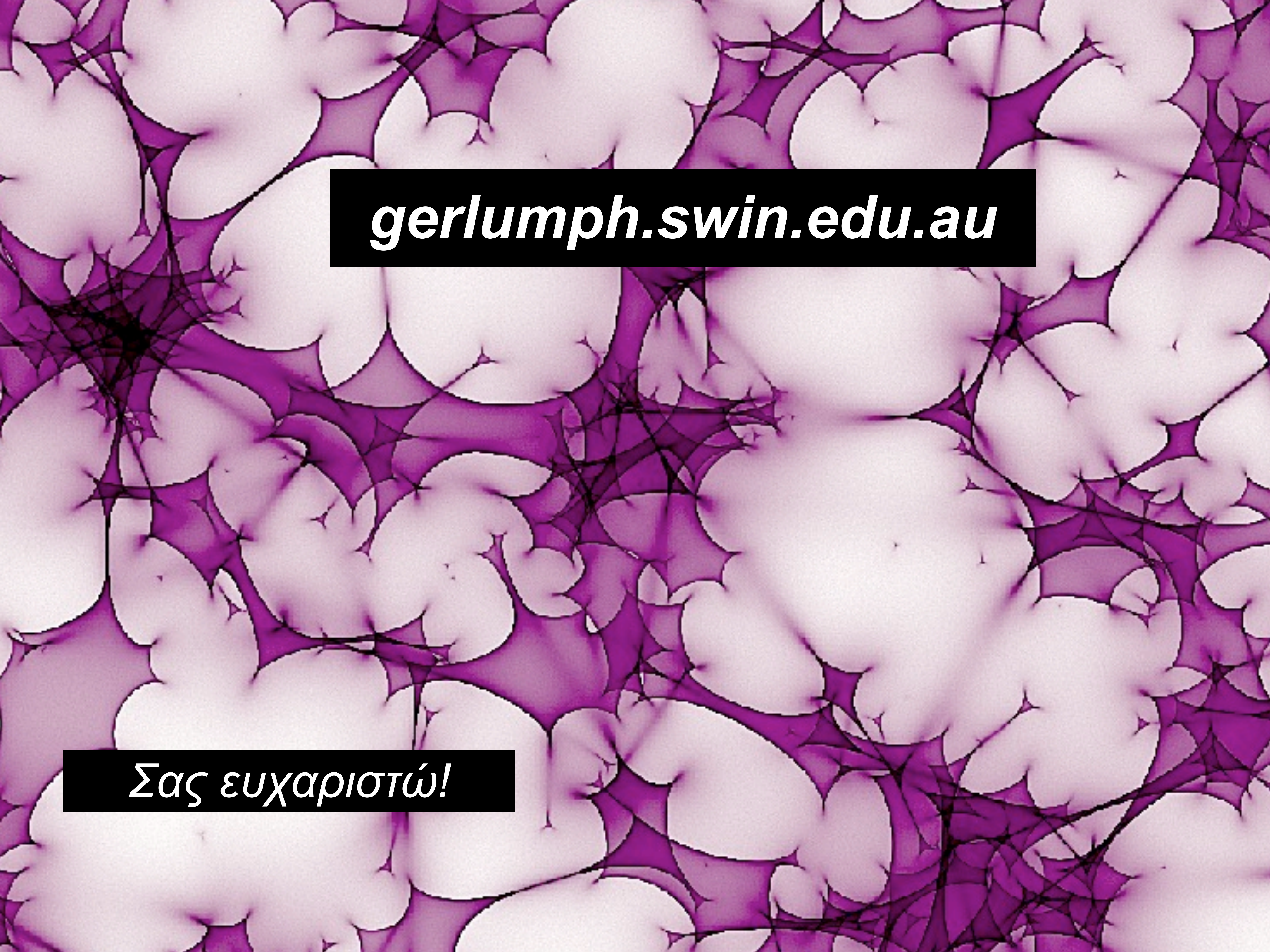
Microlensing parameter space



a few systems now (23), thousands in the future

eResearch

Much easier to test a variety of alternative accretion disc/SMBH models once we have statistically significant samples


gerlumph.swin.edu.au
Σας ευχαριστώ!

Science with magnification maps:
Light-curve analysis

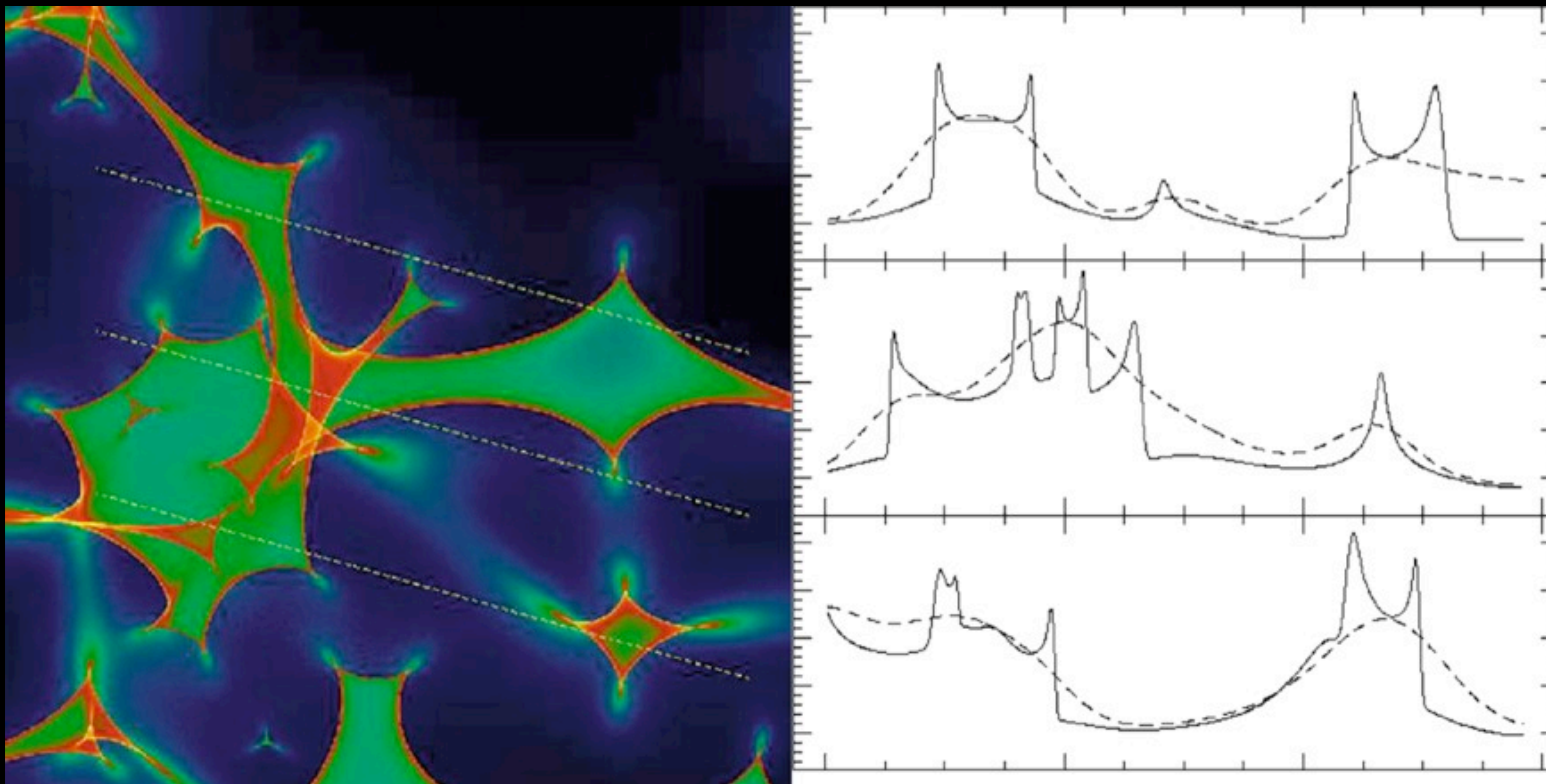


Figure : Schmidt & Wambsganss 2010

Smaller sources appear more magnified

Science with magnification maps:
Chromatic lensing

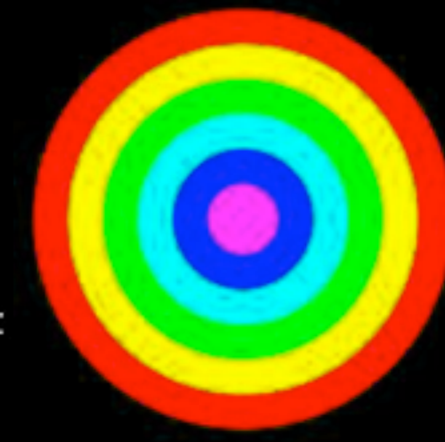
$\lambda_1, \lambda_2, \lambda_3$

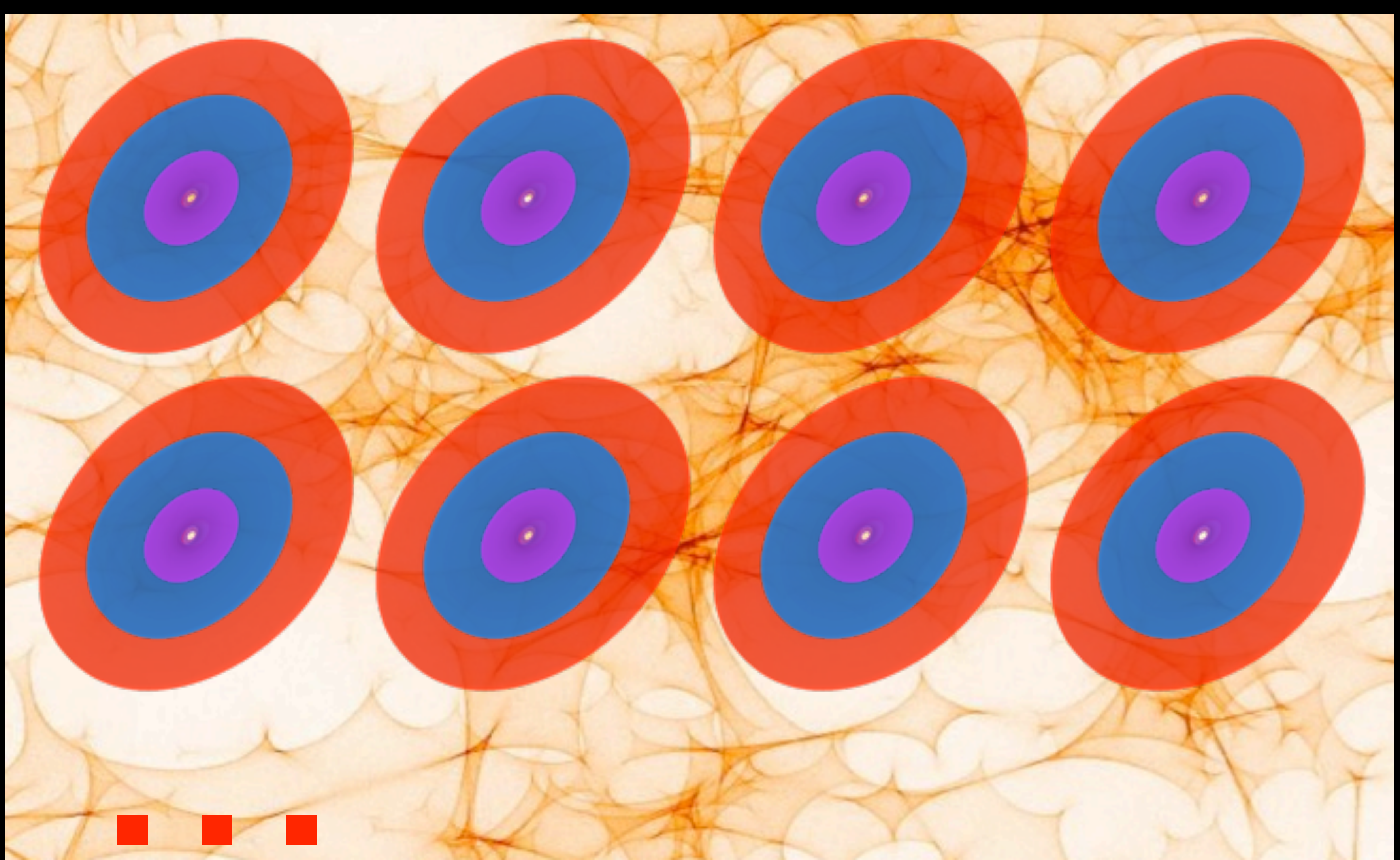
↓

R_1, R_2, R_3

Thin disk model
Shakura Sunyaev 1973

$$T \propto R^{\beta}, \beta = -3/4$$





$$= \begin{matrix} p(F_{12}) \\ p(F_{13}) \\ p(F_{23}) \end{matrix}$$

Science with magnification maps:
Chromatic lensing

$\lambda_1, \lambda_2, \lambda_3$

↓

R_1, R_2, R_3

Thin disk model
Shakura Sunyaev 1973

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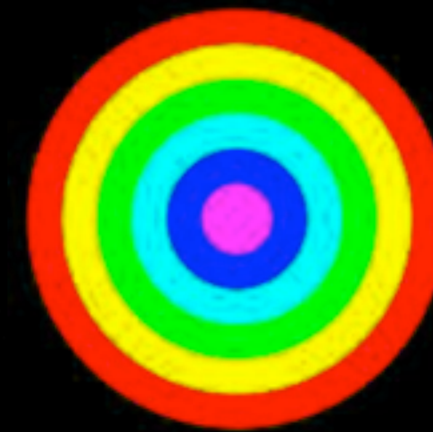
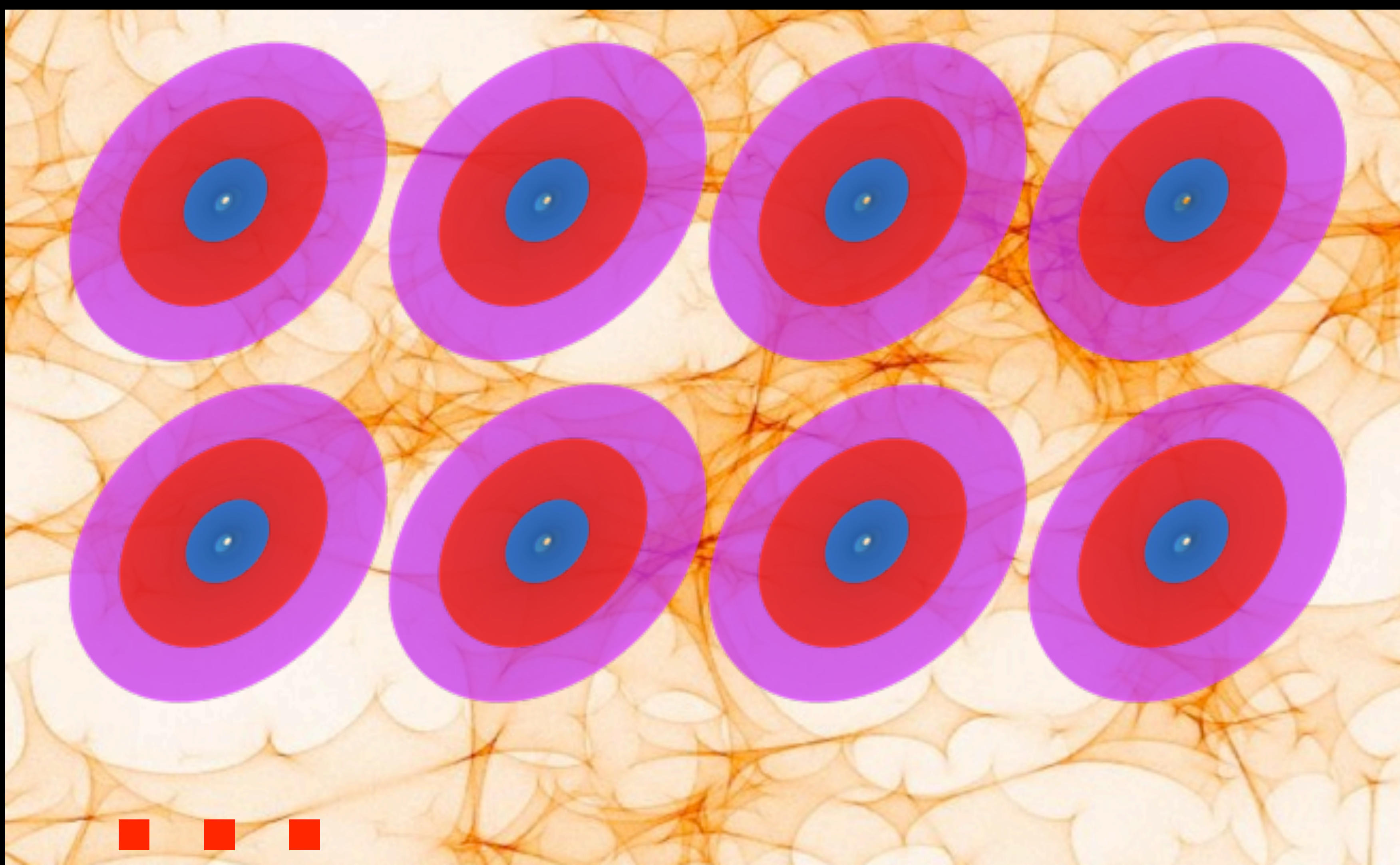
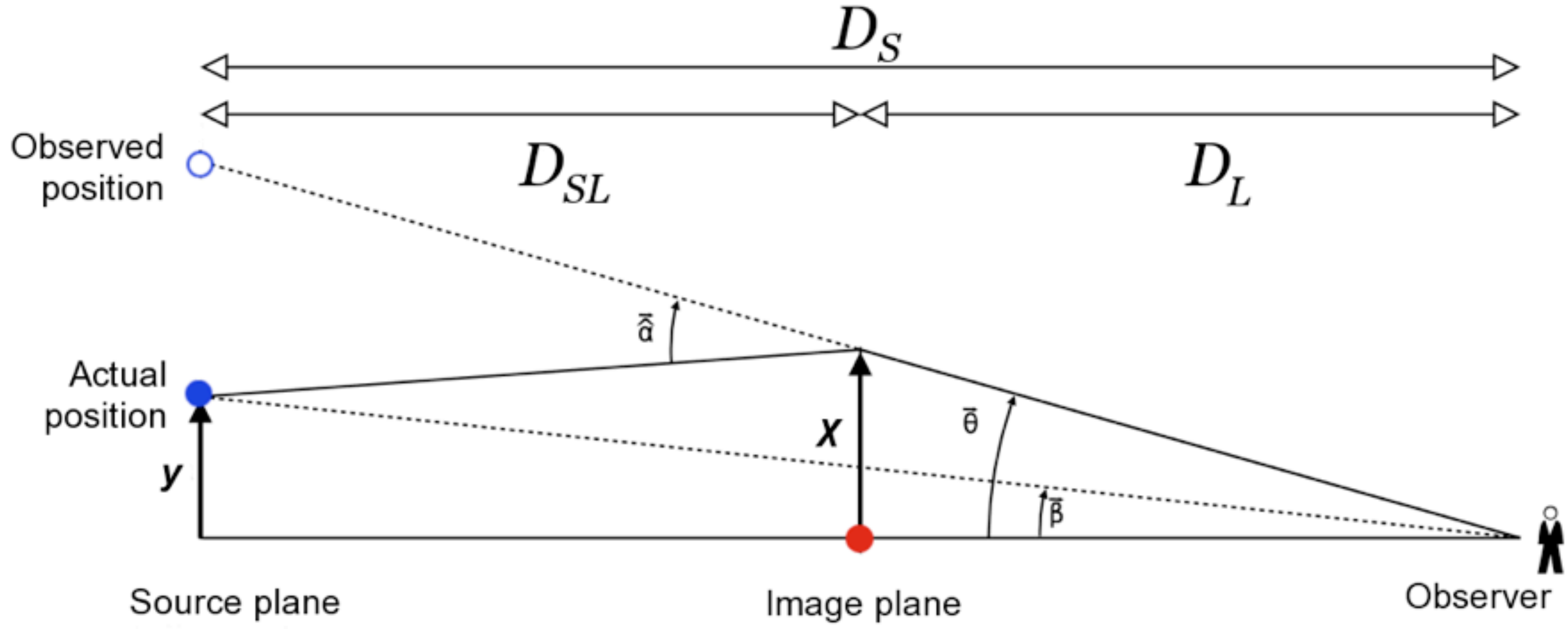




$$p'(F_{12})$$
$$= p'(F_{13})$$
$$p'(F_{23})$$

$$\boldsymbol{y} = \begin{pmatrix} 1-\gamma & 0 \\ 0 & 1+\gamma \end{pmatrix} \boldsymbol{x} - \kappa_s \boldsymbol{x} - \sum_{i=1}^{N_l} m_i \frac{(\boldsymbol{x} - \boldsymbol{x_i})}{|\boldsymbol{x} - \boldsymbol{x_i}|^2}$$

$$R_\lambda^{theory} = 9.7 \times 10^{15} \left(\frac{\lambda_{rest}}{\mu m} \right)^{4/3} \left(\frac{M_{BH}}{10^9 M_\odot} \right)^{2/3} \left(\frac{L}{\eta L_E} \right)^{1/3} cm$$



$$\hat{\alpha}(\theta) = \frac{4GM}{c^2}\frac{1}{\theta} \qquad \beta(\theta) = \theta - \frac{D_{LS}}{D_L D_S}\frac{4GM}{c^2}\frac{1}{\theta}$$

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}} \quad , \quad \begin{array}{c} z_L = 0.5 \\ z_S = 2 \\ H = 50 kms^{-1} Mpc^{-1} \\ D_{LS} \neq D_S - D_L \end{array} \quad \rightarrow \quad \theta_E = 1.8\sqrt{\frac{M}{10^{12} M_\odot}} arcsec$$

For objects with $M \sim M_\odot \Rightarrow \theta_E \sim \mu$ arcsec:

the projected R_{Ein} is comparable to the accretion disc size

Micro-models

from *Macro*-models

κ : ***convergence***
(compact,smooth)
γ : ***shear***

N_l is of the order of 10^6

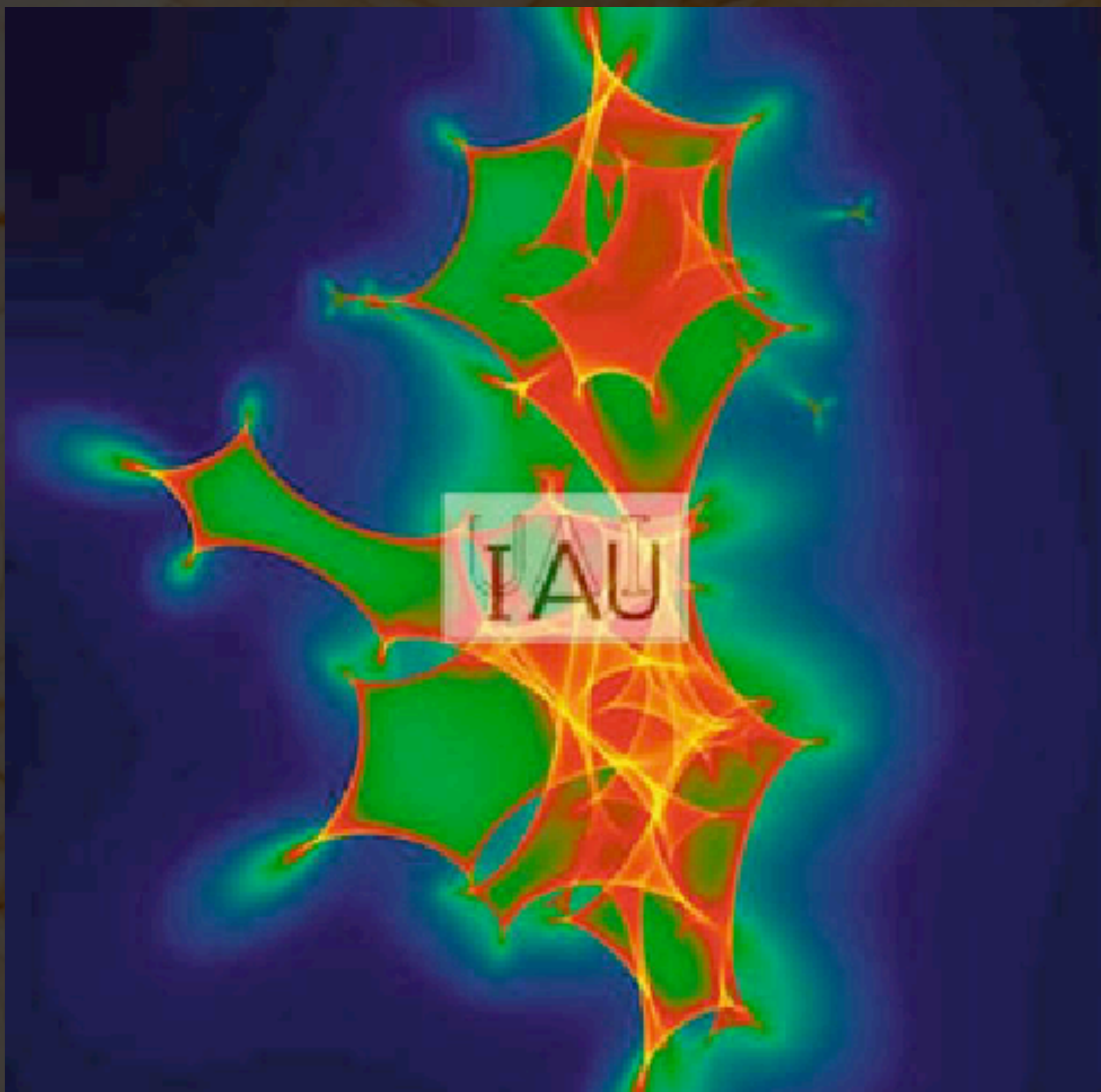
$$N_l = \frac{\kappa_l S}{\pi \langle M \rangle}$$

$$\boldsymbol{y} = \begin{pmatrix} 1-\gamma & 0 \\ 0 & 1+\gamma \end{pmatrix} \boldsymbol{x} - \kappa_s \boldsymbol{x} - \sum_{i=1}^{N_l} m_i \frac{(\boldsymbol{x}-\boldsymbol{x}_i)}{|\boldsymbol{x}-\boldsymbol{x}_i|^2}$$

has to be solved numerically

Direct inverse ray-shooting
"Ridiculously parallelizable problem"

\+ GPUs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