Title: The Beauty and Basics of BAO

Date: Jul 31, 2009 11:00 AM

URL: http://pirsa.org/09070039

Abstract: The Baryon Acoustic Oscillations (BAO) are the latest weapon in the quest for precision cosmology and dark energy. Many presentations on BAO are complicated and unclear and I will therefore present BAO with particular emphasis on trying to give the simplest theoretical description, both at the linear and nonlinear level, and will describe some of the observational challenges to measuring BAO.

Baryon Acoustic Oscillations

Bruce Bassett (SAAO/UCT)

Based on review with Renee Hlozek (Oxford), appearing in the book ***Dark Energy*** *(C*

Overview

Overview

- Statistical Standard Rulers

Overview

- Statistical Standard Rulers
- Origins, uses & measurements of BAO

Overview

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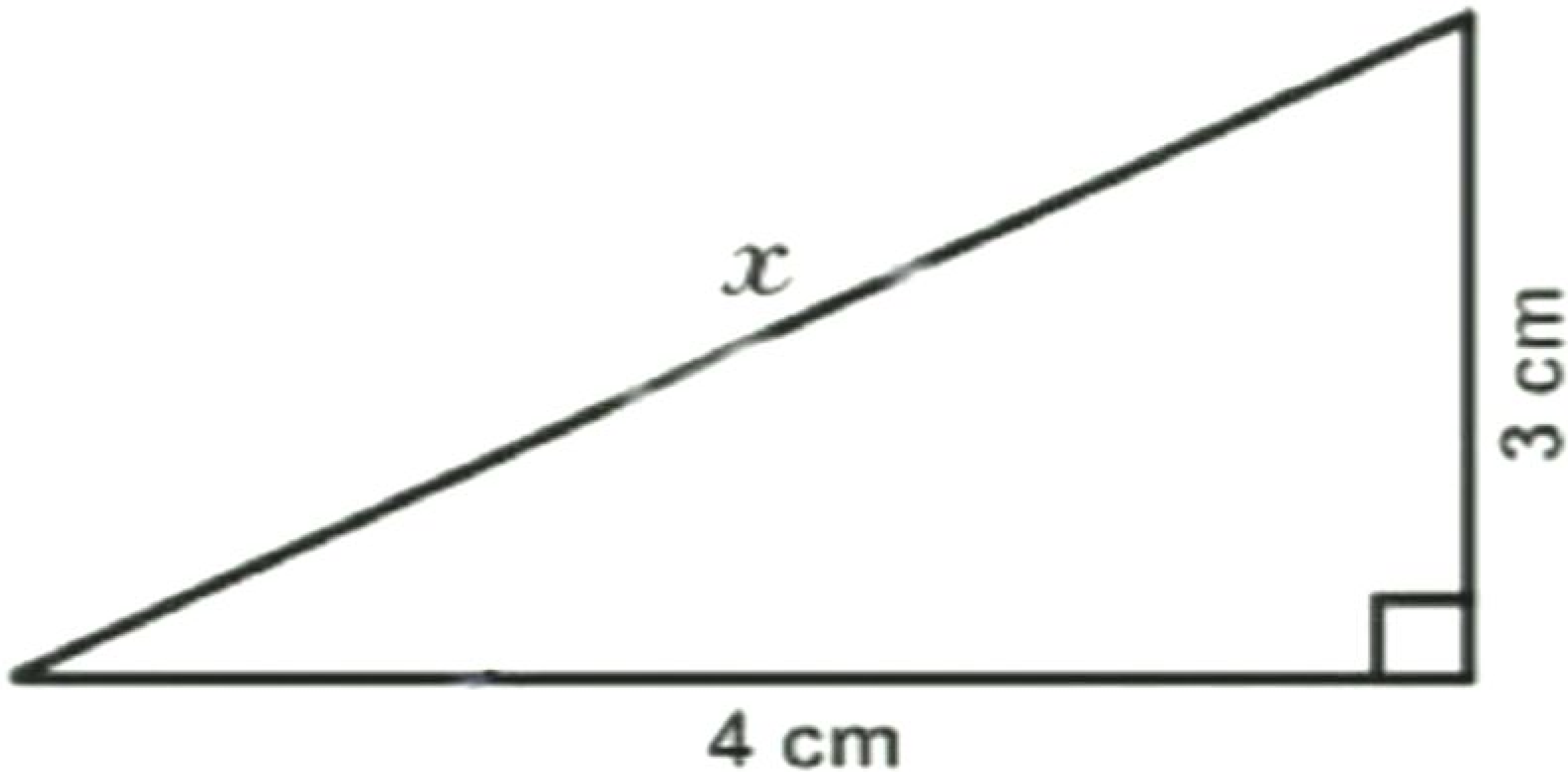
- Origins, uses & measurements of BAO
- Targets for BAO surveys

Overview

- Statistical Standard Rulers
- Origins, uses & measurements of BAO
- Targets for BAO surveys
- Complications
  - Nonlinearities
  - Photometric vs spectroscopic surveys

3. Find x.



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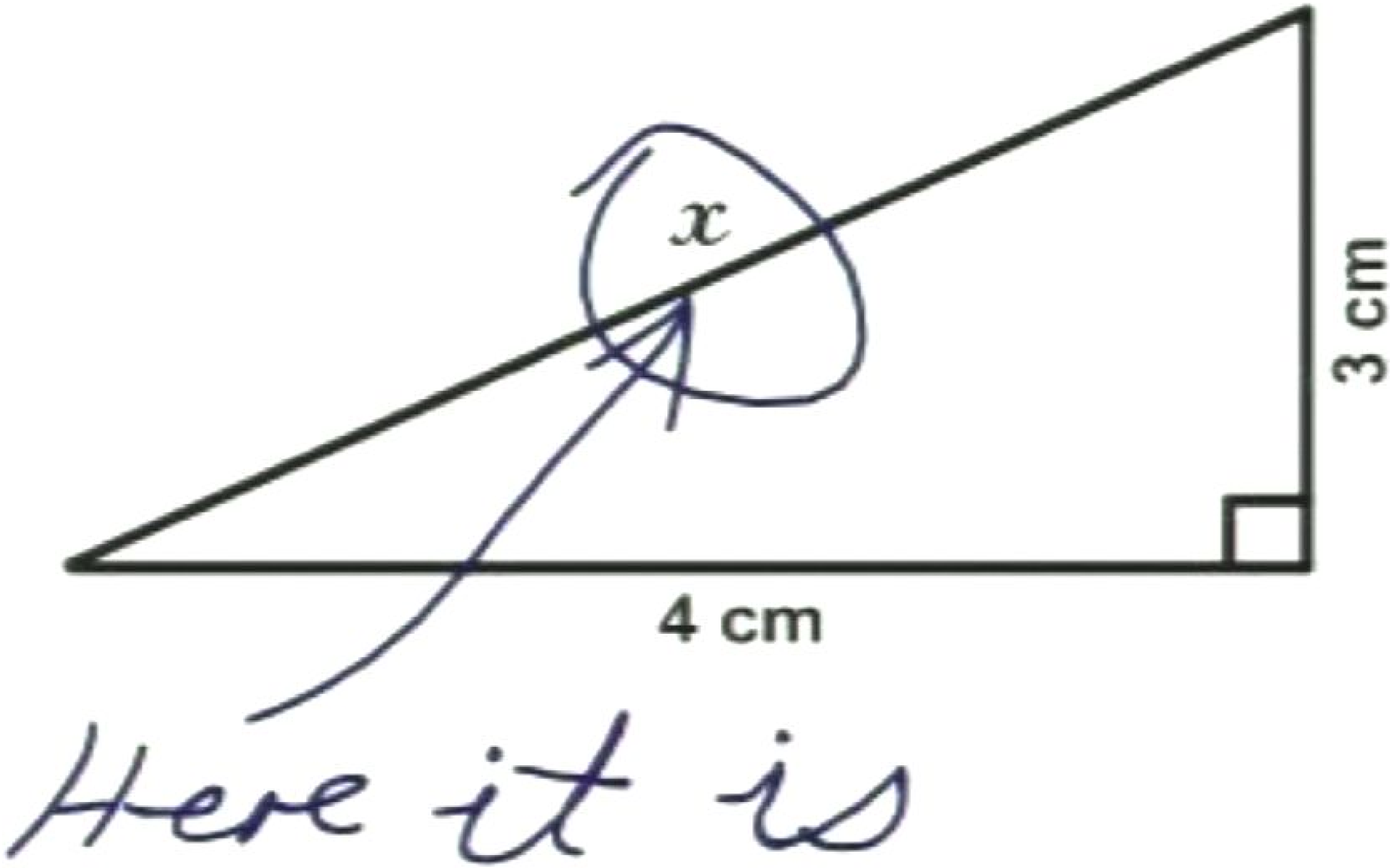

The Importance of Communication in Scienc

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DiabetesCare

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ARTICLES

A mathematical model for the determination of total area under glucose tolerance and other metabolic curves

MM Tai
Obesity Research Center, St. Luke's-Roosevelt Hospital Center, New York, New York.

OBJECTIVE--To develop a mathematical model for the determination of total areas under curves from various metabolic studies. RESEARCH DESIGN AND METHODS--In Tai's Model, the total area under a curve is computed by dividing the area under the curve between two designated values on the X-axis (abscissas) into small segments (rectangles and triangles) whose areas can be accurately calculated from their respective geometrical formulas. The total sum of these individual areas thus represents the total area under the curve. Validity of the model is established by comparing total areas obtained from this model to these same areas obtained from graphic method (less than +/- 0.4%). Other formulas widely applied by researchers under- or overestimated total area under a metabolic curve by a great margin. RESULTS--Tai's model proves to be able to 1) determine total area under a curve with precision; 2) calculate area with varied shapes that may or may not intercept on one or both X/Y axes; 3) estimate total area under a curve plotted against varied time intervals (abscissas), whereas other formulas only allow the same time interval; and 4) compare total areas of metabolic curves produced by different studies. CONCLUSIONS--The Tai model allows flexibility in experimental conditions, which means, in the case of the glucose-response curve, samples can be taken with differing time intervals and total area under the curve can still be determined with precision.

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Bruce Bassett (SAAO/UCT) BAO

114 citations

(Statistical) Standard Rulers

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“Standard” is a Crucial Ingredient

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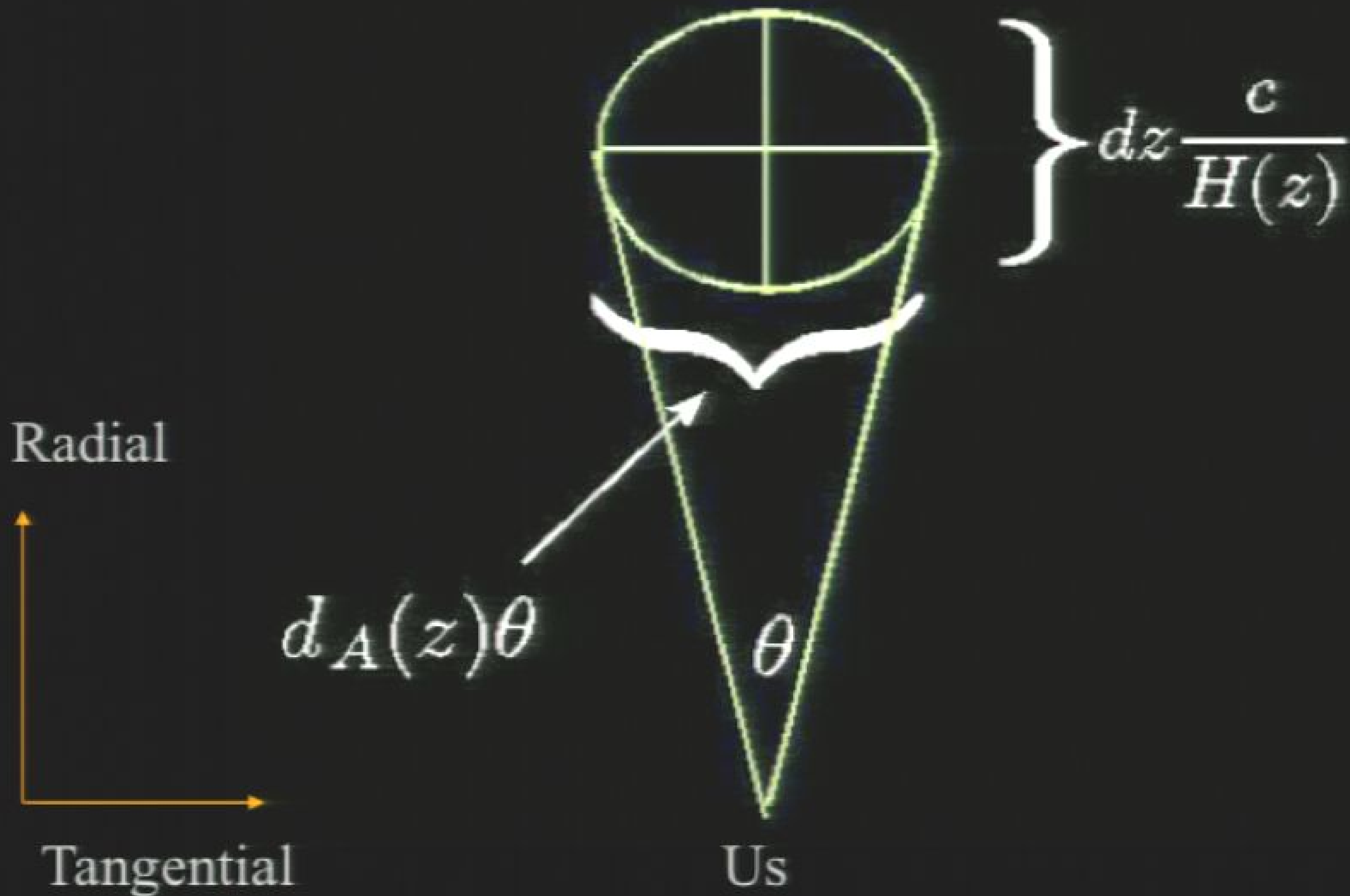
“Standard” is a Crucial Ingredient

The Beauty of Standard Volumes



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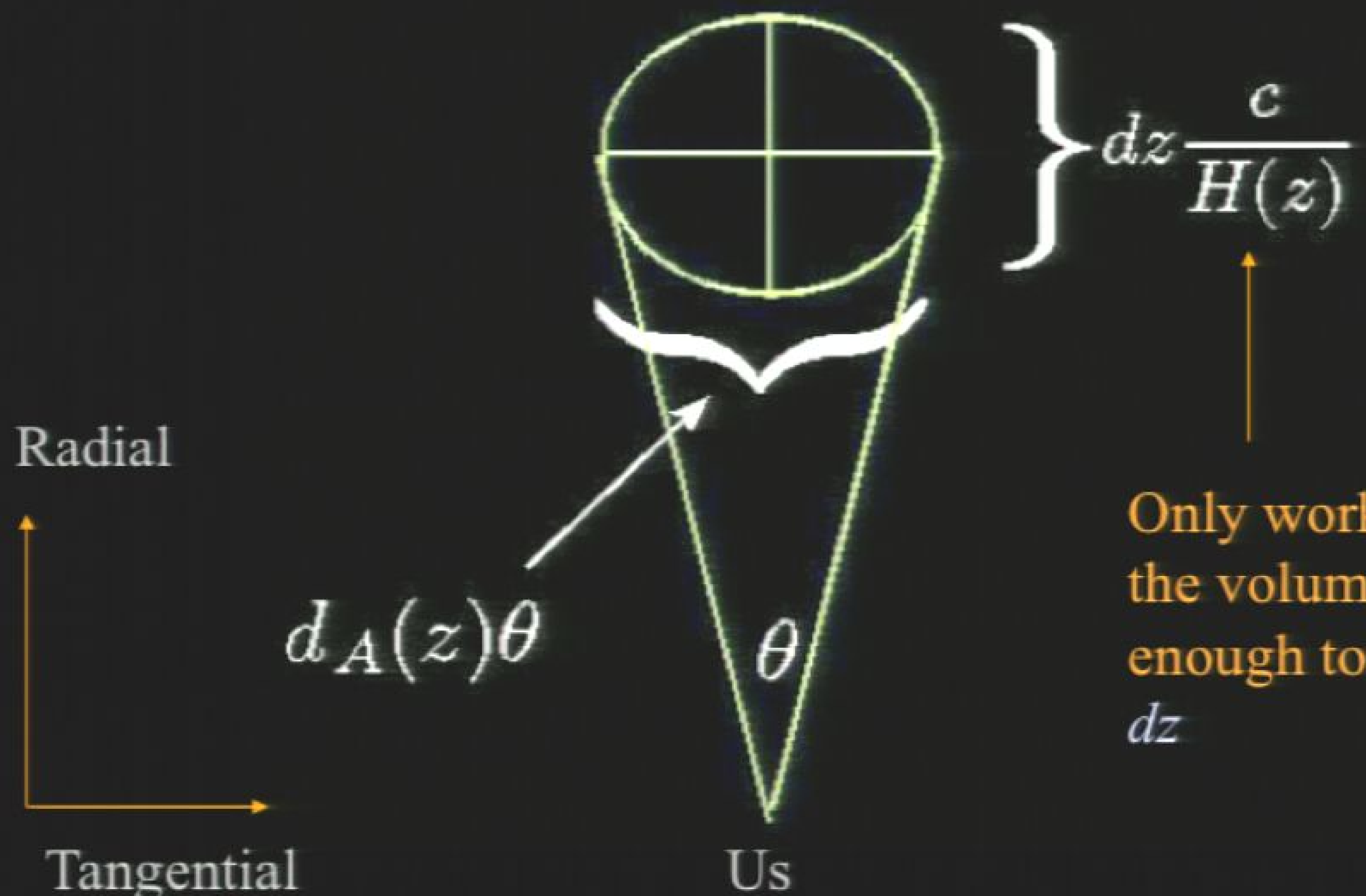
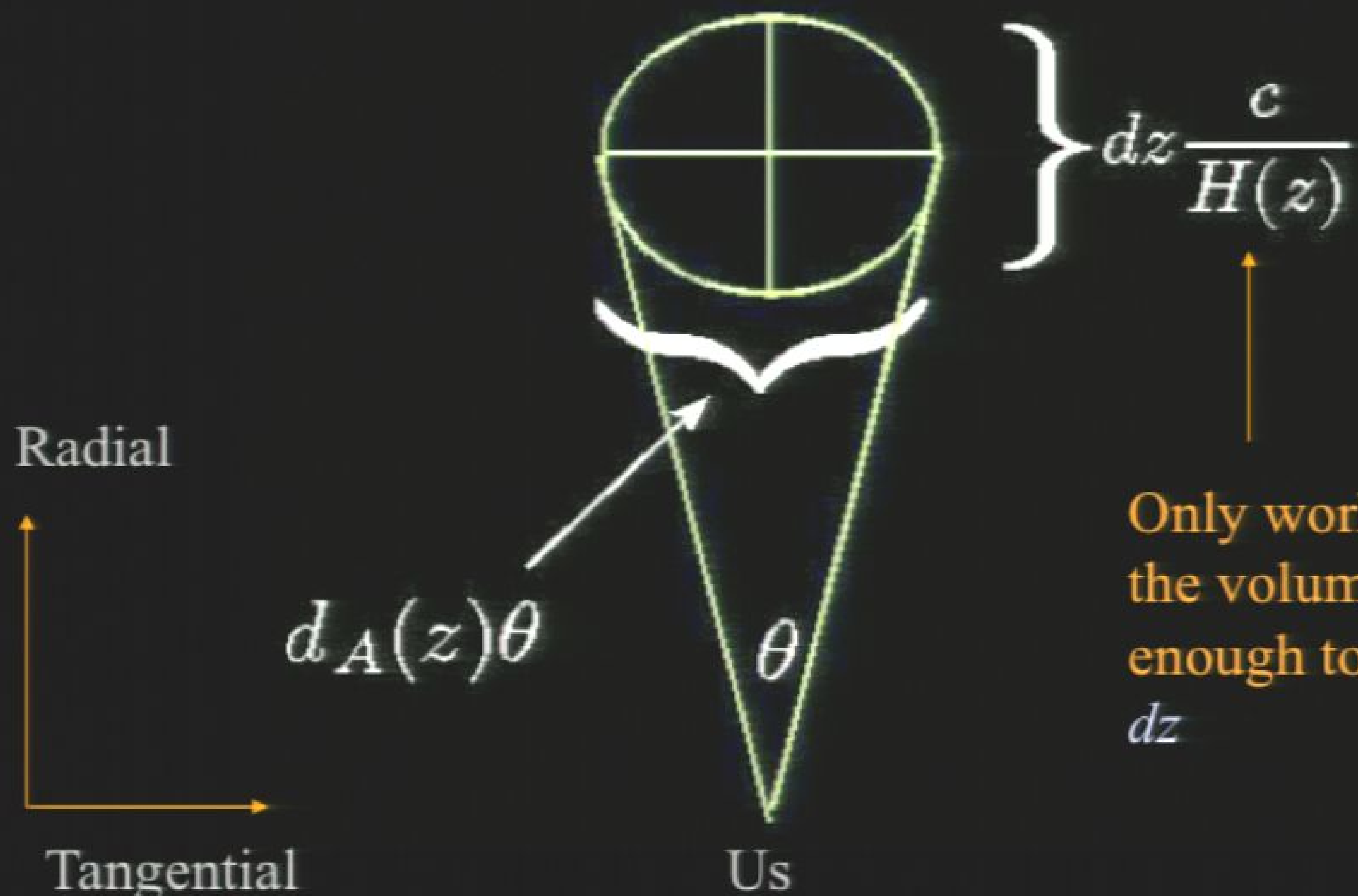


Only works if the volume is big enough to measure dz

BAO and AP

The Beauty of Standard Volumes



Only works if the volume is big enough to measure *dz*

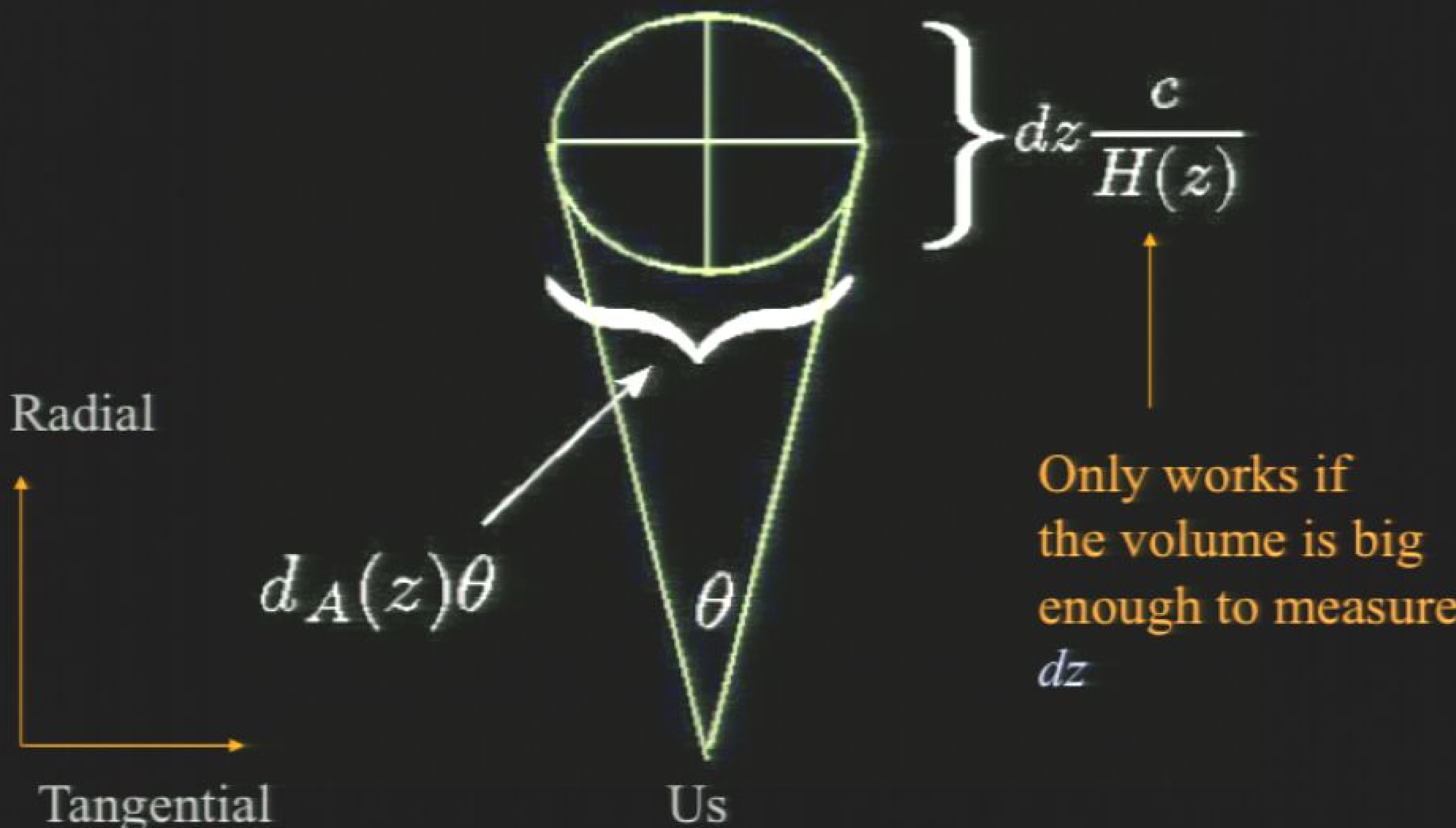
BAO and AP

BAO and AP

- If we *only* know the volume is spherical, then we constrain the product $H(z)\, d_A(z)$ (the Alcock-Paczynski (AP) test)

BAO and AP

The Beauty of Standard Volumes



BAO and AP

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- If we also know the *absolute* sizes in both radial and tangential directions (like with BAO), we constrain both $d_A(z)$ and $H(z)$ separately.

BAO and AP

- If we *only* know the volume is spherical, then we constrain the product $H(z)\, d_A(z)$ (the Alcock-Paczynski (AP) test)
- If we also know the *absolute* sizes in both radial and tangential directions (like with BAO), we constrain both $d_A(z)$ and $H(z)$ separately.
- BAO thus provide an *absolute* AP test.

$$d_A(z) = \frac{c}{H_0\sqrt{-\Omega_k}(1+z)} \sin\left(\sqrt{-\Omega_k}\int_0^z \frac{H_0}{H(z')} dz'\right)$$

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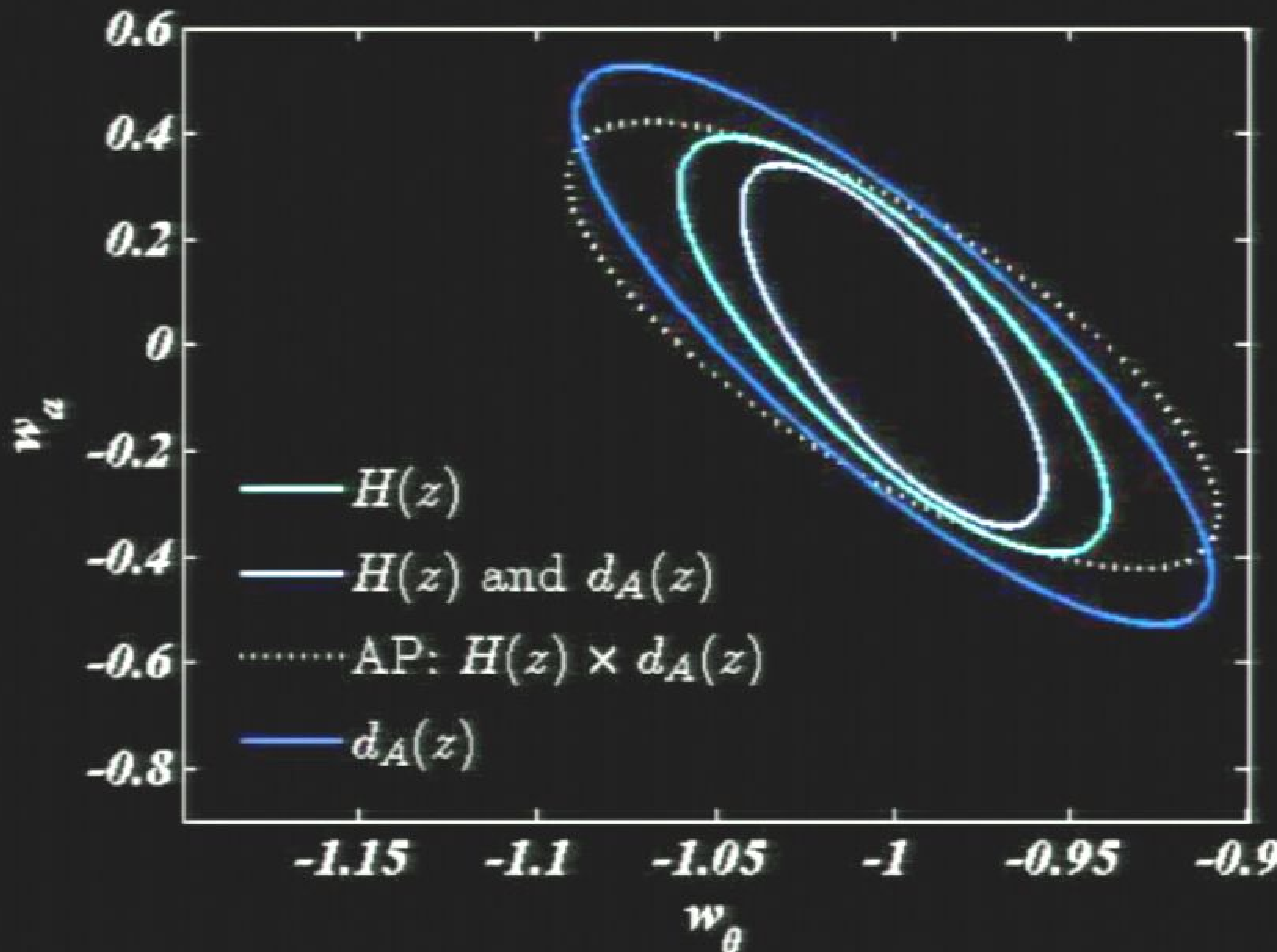

0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
w_a
$H(z)$
$H(z)$ and $d_A(z)$
AP: $H(z) \times d_A(z)$
$d_A(z)$
-1.15
-1.1
-1.05
-1
-0.95
-0.9
w_0

Testing the Copernican Principle

- Test isotropy of gravitational collapse via comparison of BAO with other probes (e.g. SNIa)

- Compare curvature at different redshifts using

$$\Omega_k = \frac{[H(z)D'(z)]^2 - 1}{[H_0 D(z)]^2}$$

arXiv:0712.3457

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What are BAO and why do we think they are standard rulers?

3D Green's Function for Φ

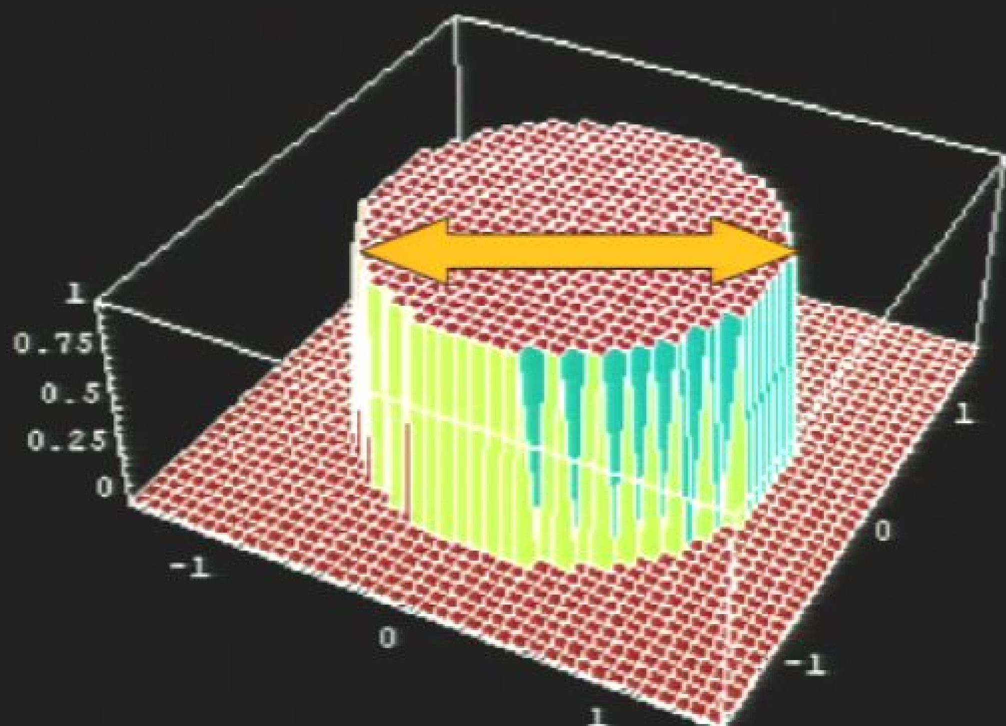
Speed of Sound

$$\phi^{(3)}(r,\tau) = \frac{3}{4\pi}(c_s\tau)^{-3}\,\theta(c_s\tau - r)$$

Sound Horizon

Bashinsky and Bertschinger, 20

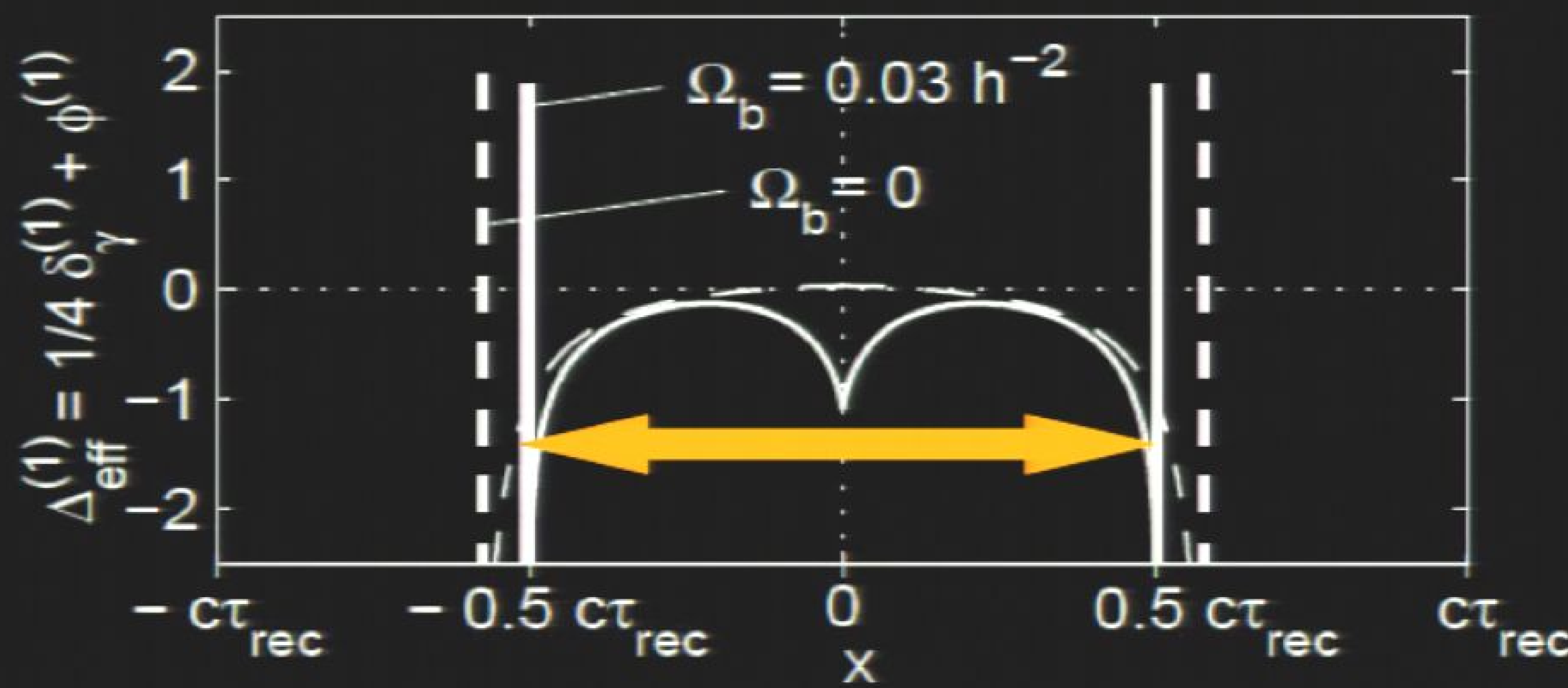
$$\phi^{(3)}(r,\tau) = \frac{3}{4\pi}(c_s\tau)^{-3}\,\theta(c_s\tau - r)$$



Light travels faster than sound. This is why some people appear bright until you hear them speak.

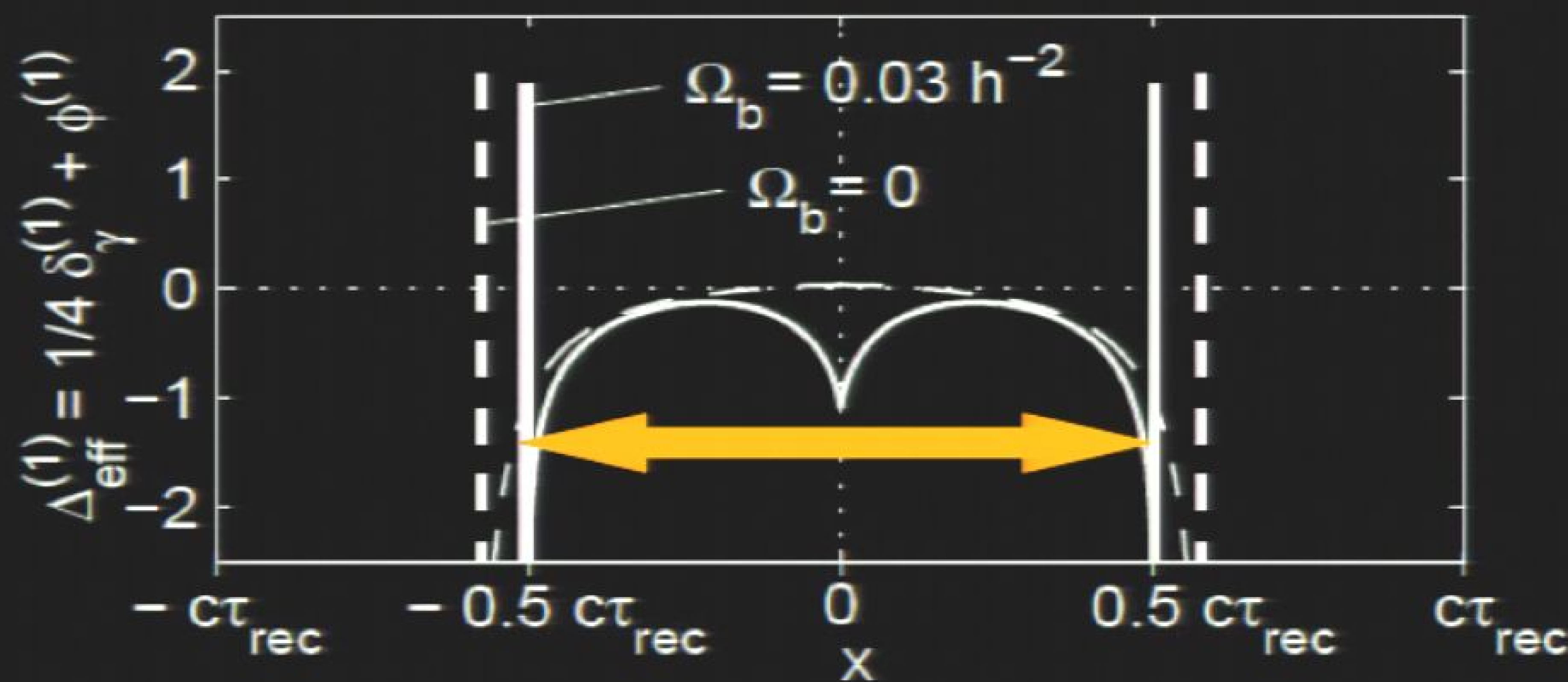
…. only partially true before decoupling

Real Space Transfer Function



Bashinsky and Bertschinger, 2

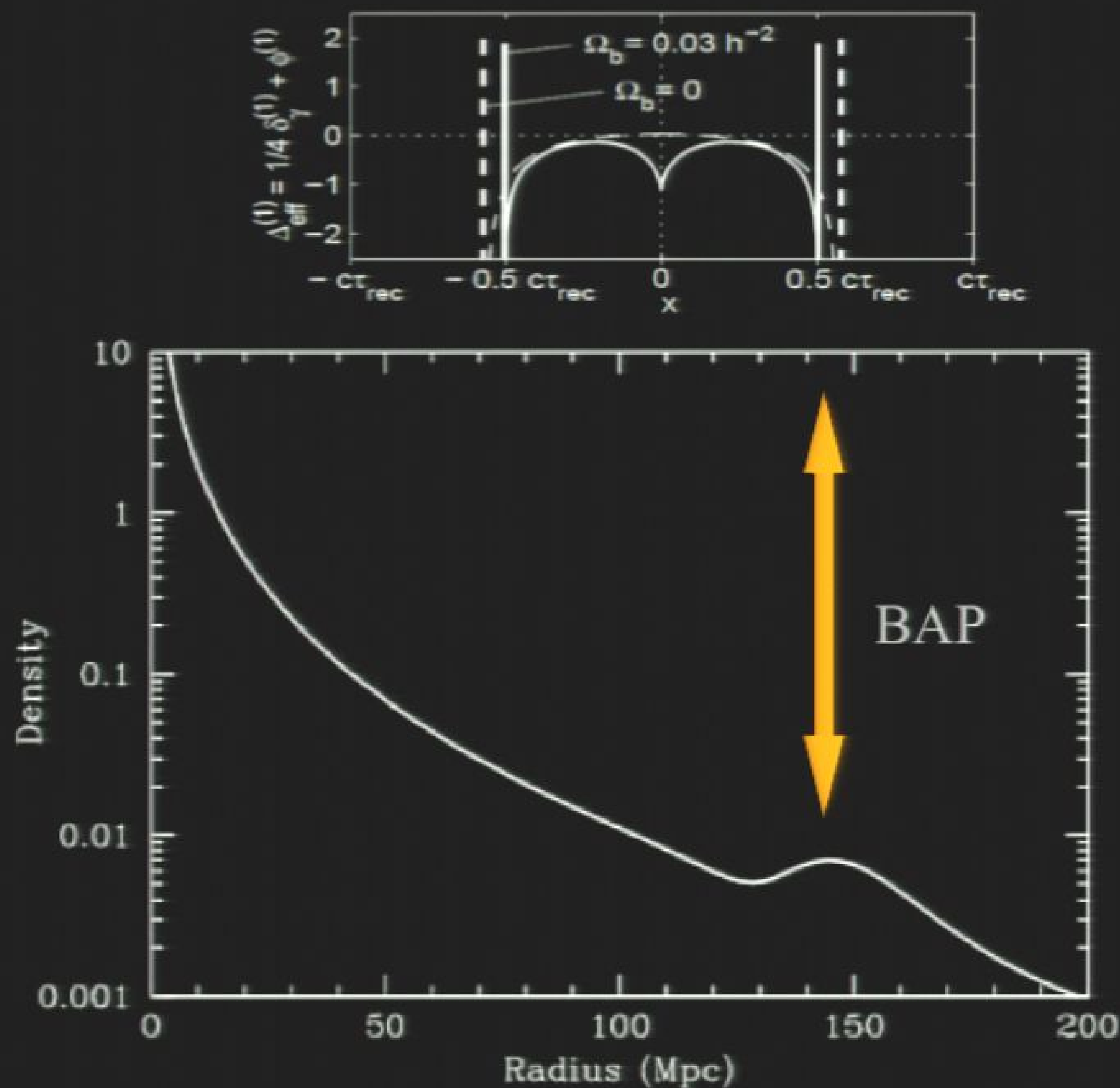
Real Space Transfer Function



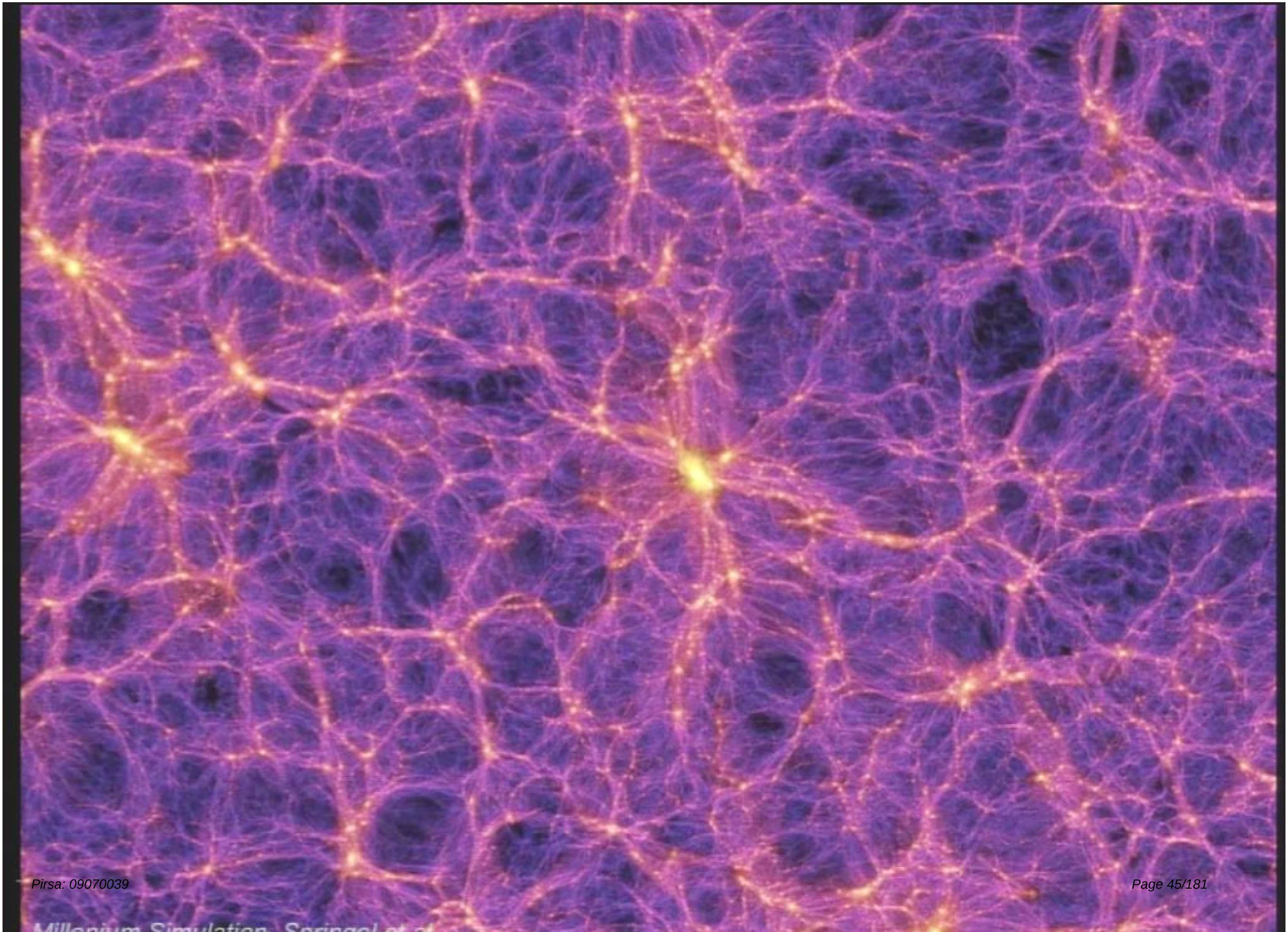
$$c_s^2 = (1/3)/[1 + (3\rho_b)/(4\rho_\gamma)]$$

Bashinsky and Bertschinger, 2

It is the same standard ruler that suggests the cosmos is flat

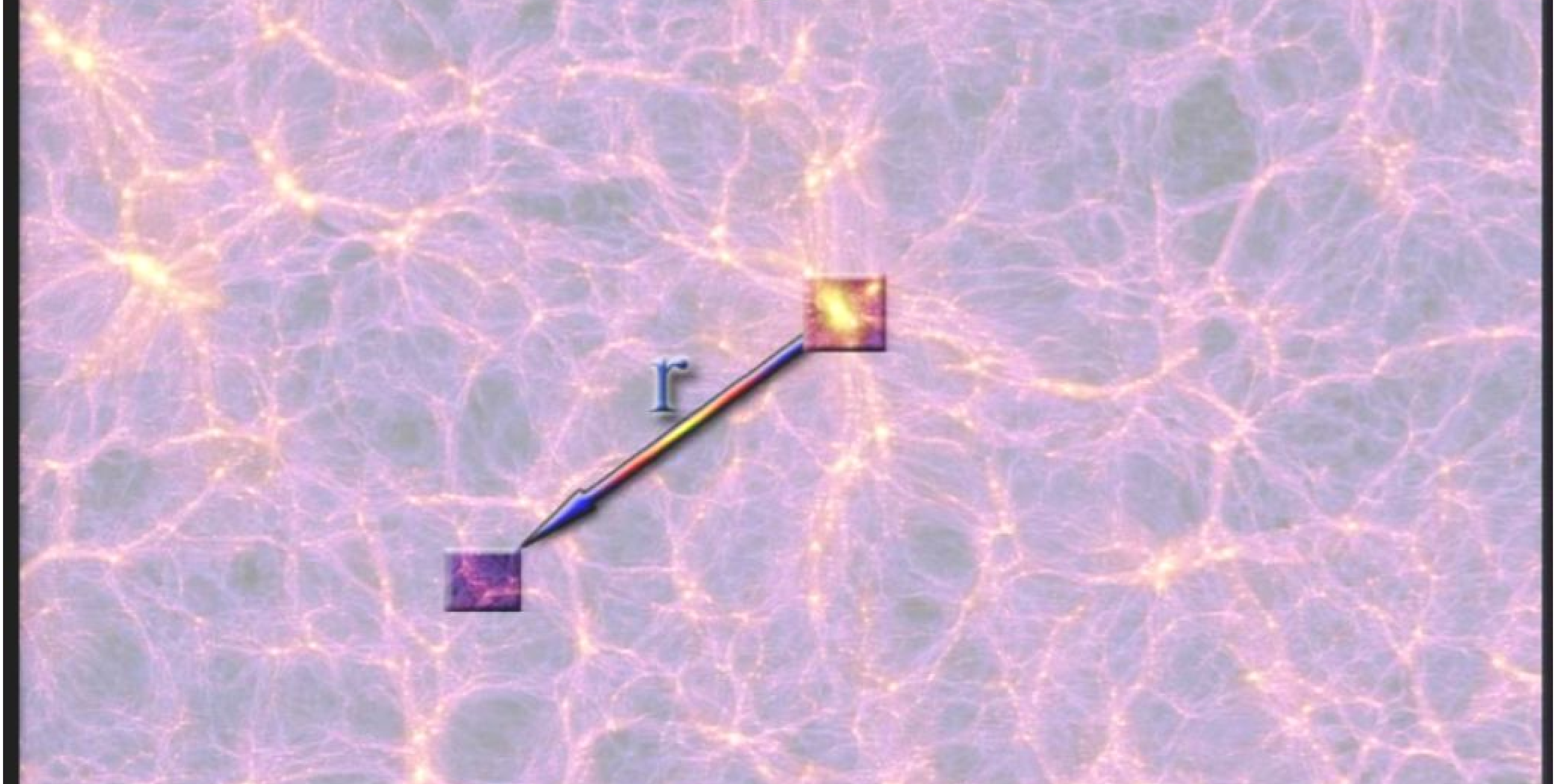


Bruce Bassett (SAAO/UCT) BAO


Millenium Simulation, Springel

2-point Correlation function

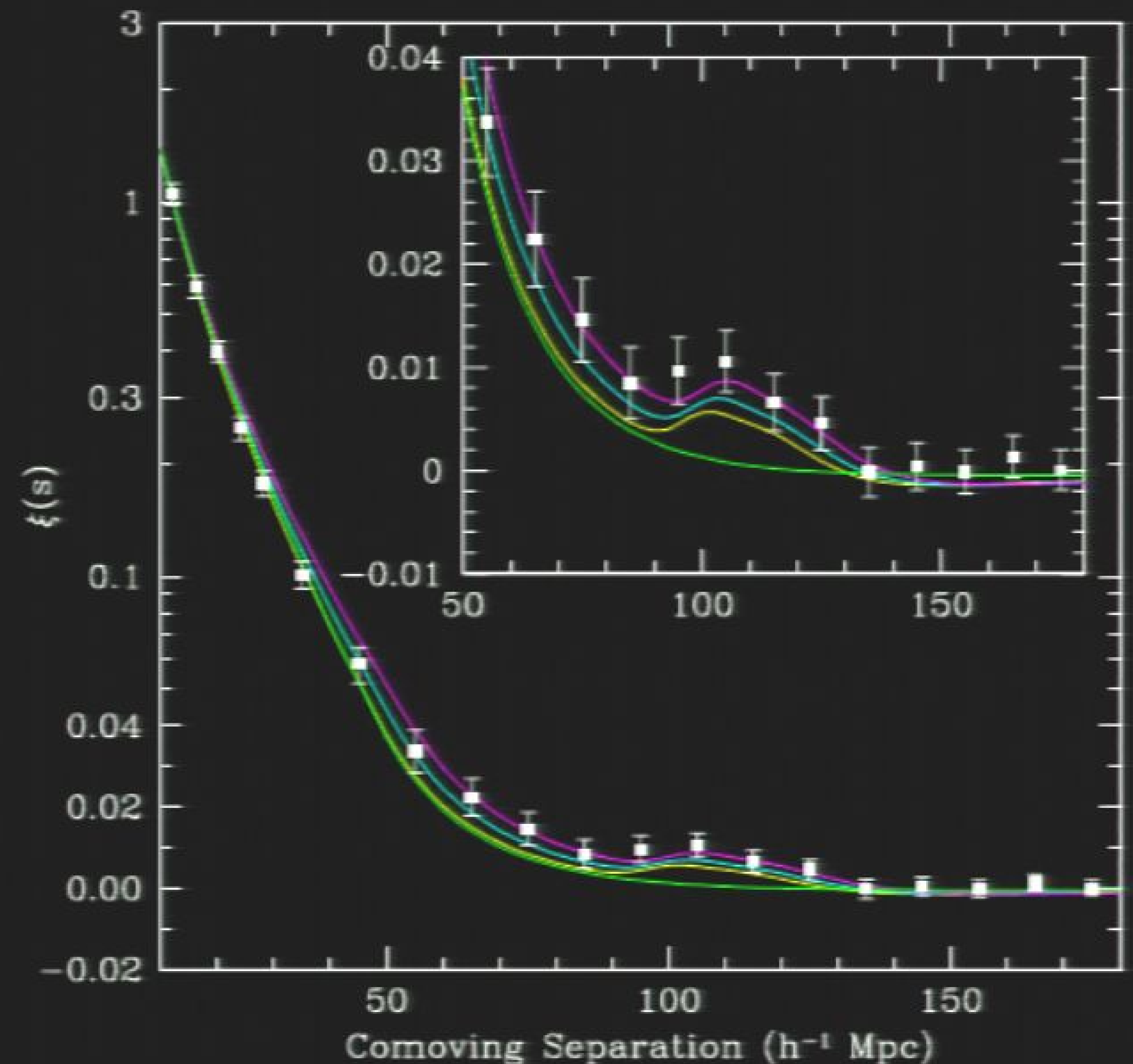
$\xi(r)$



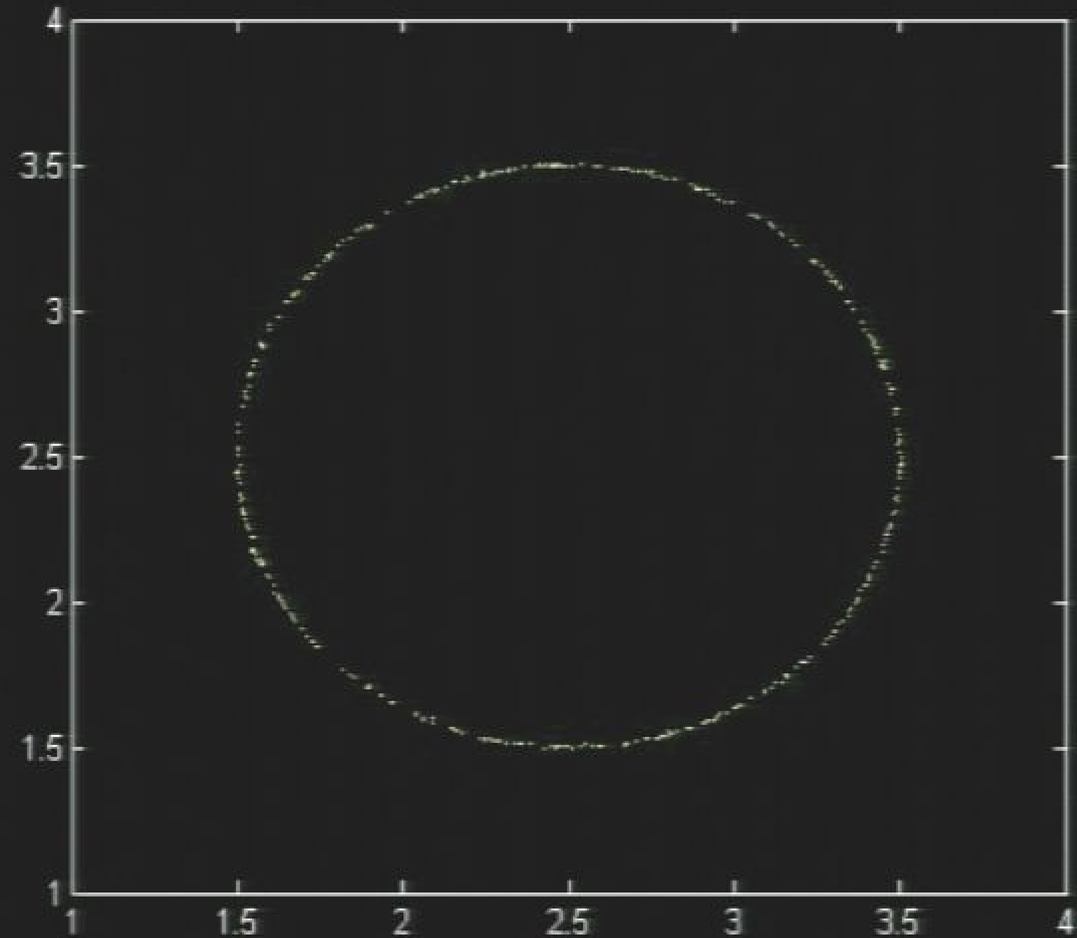
2-point Correlation function

$\xi(r)$

We expect to see an increase in $\xi(r)$ at $r \sim 100$ *Mpc*



Eisenstein et al, SDSS LR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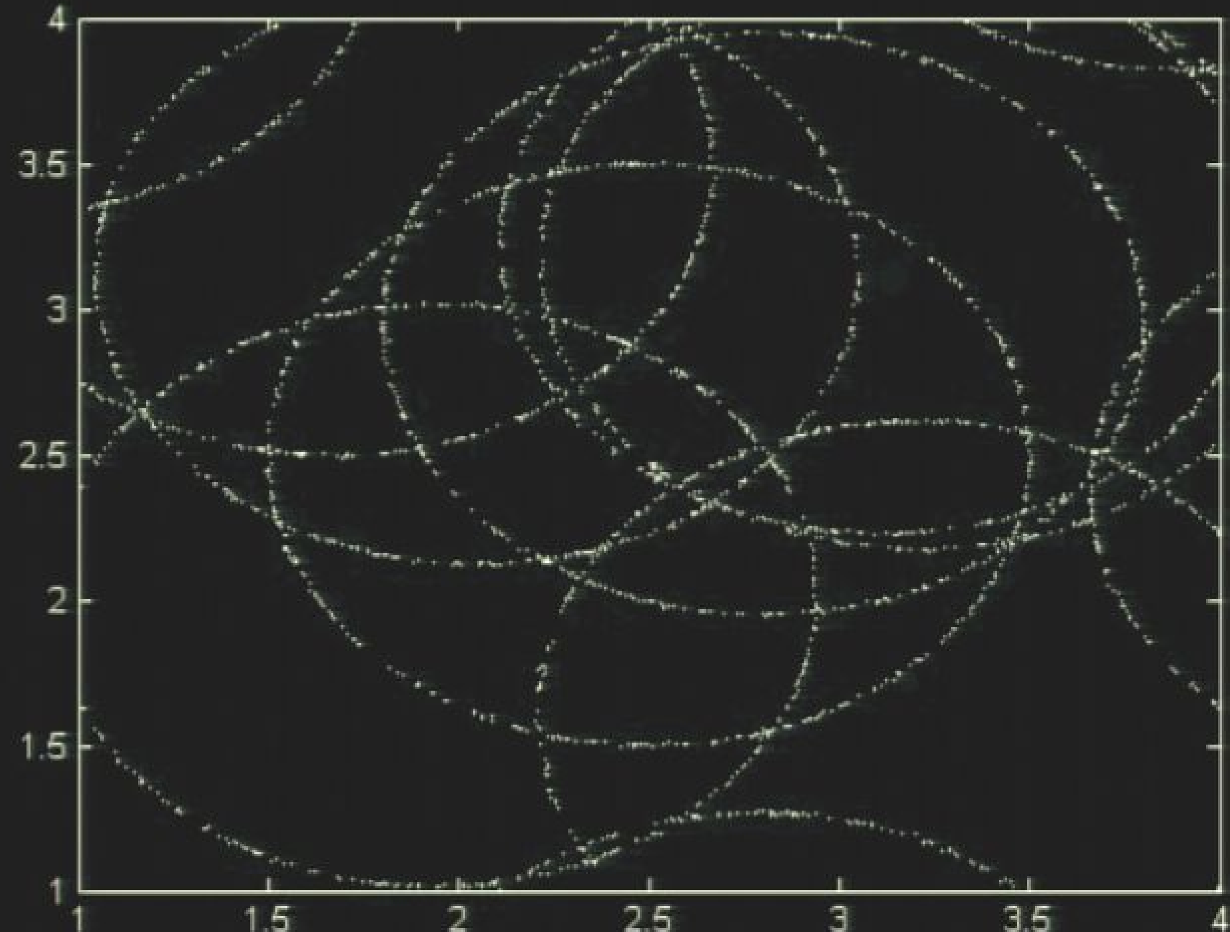
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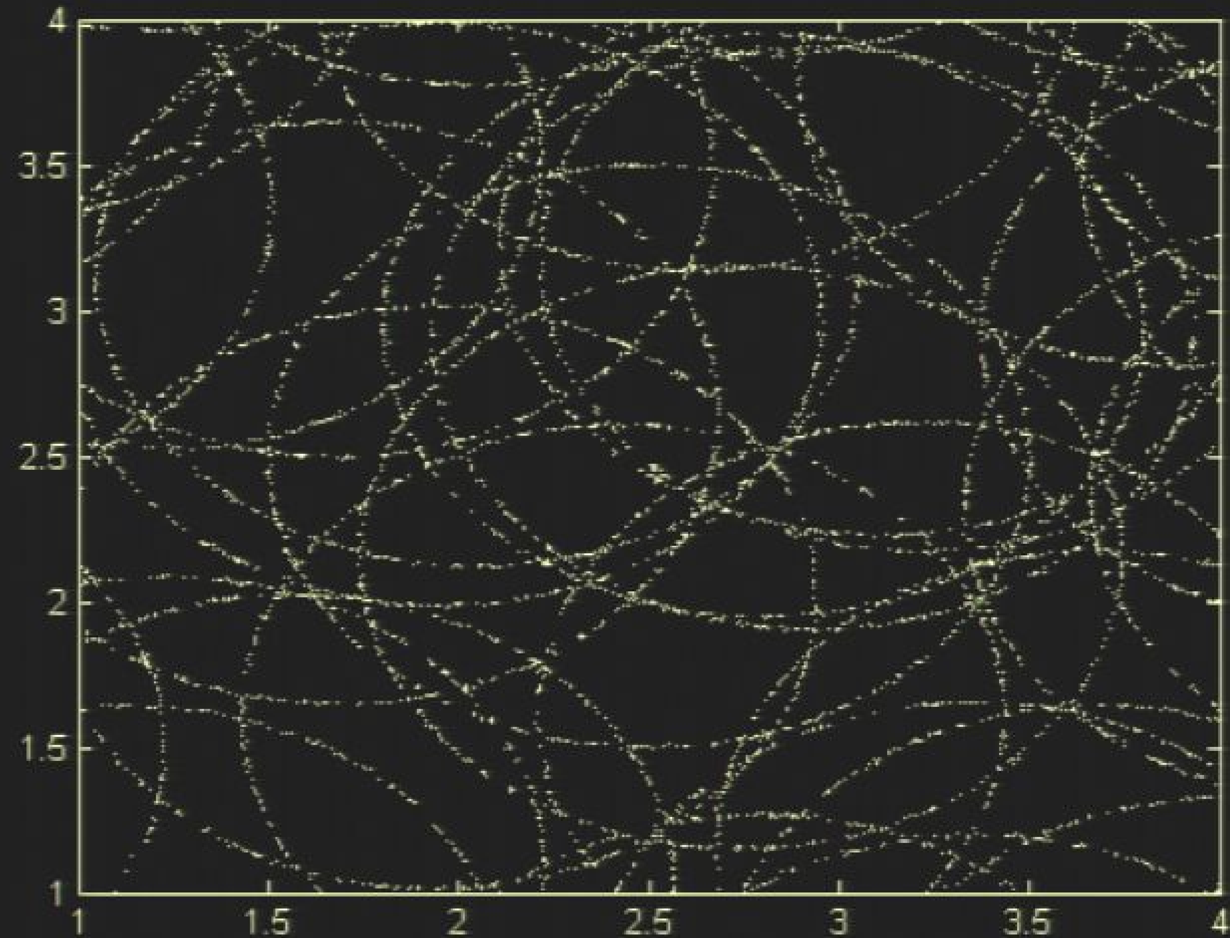

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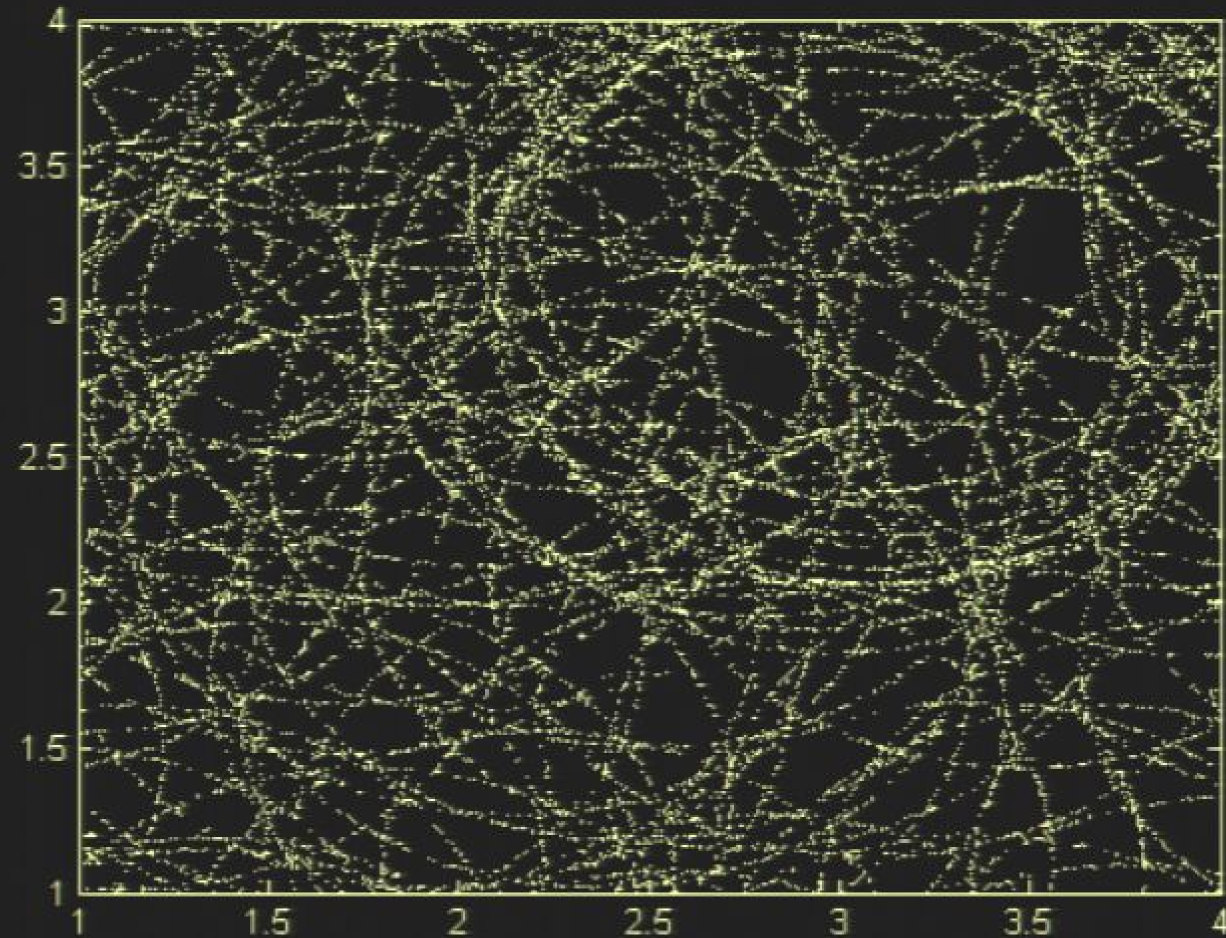
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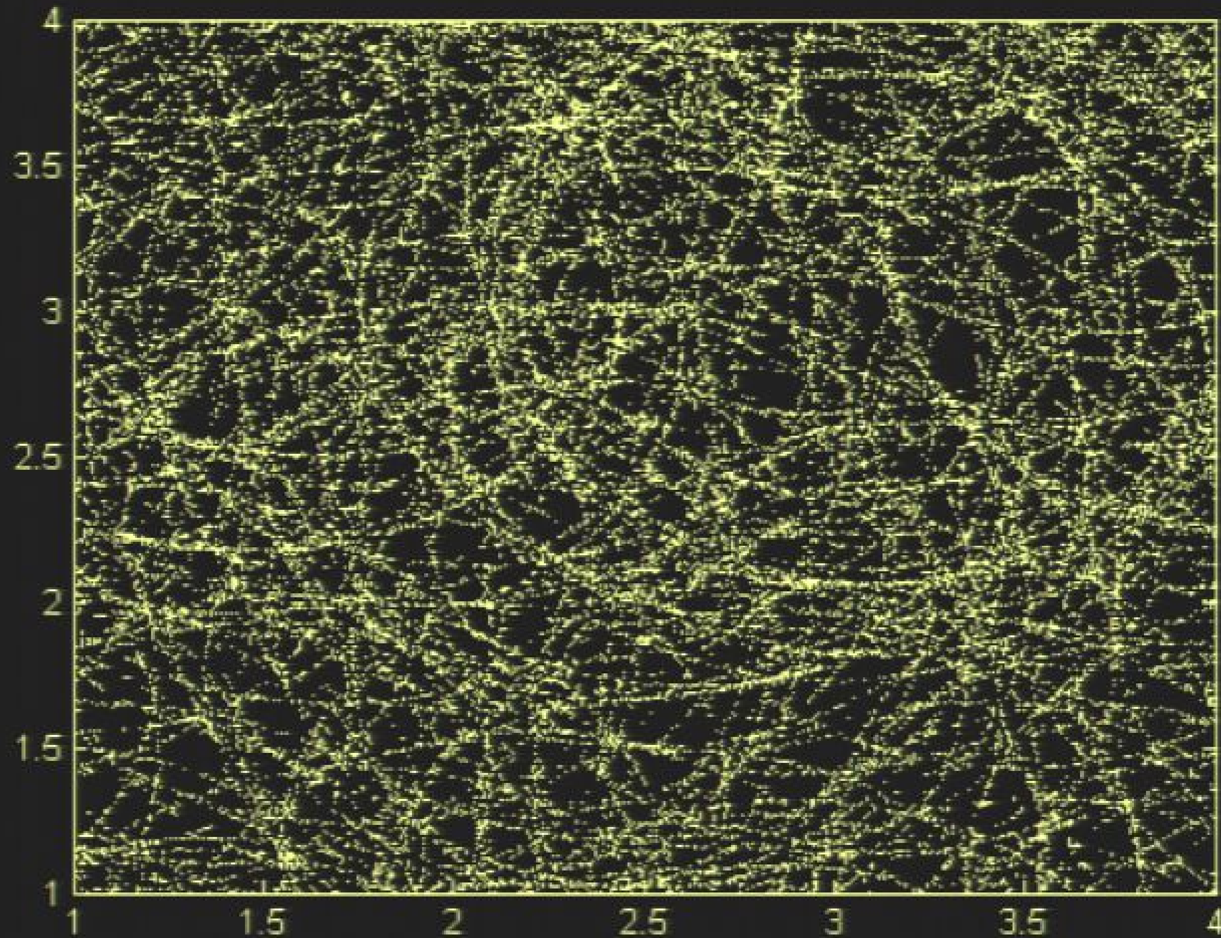
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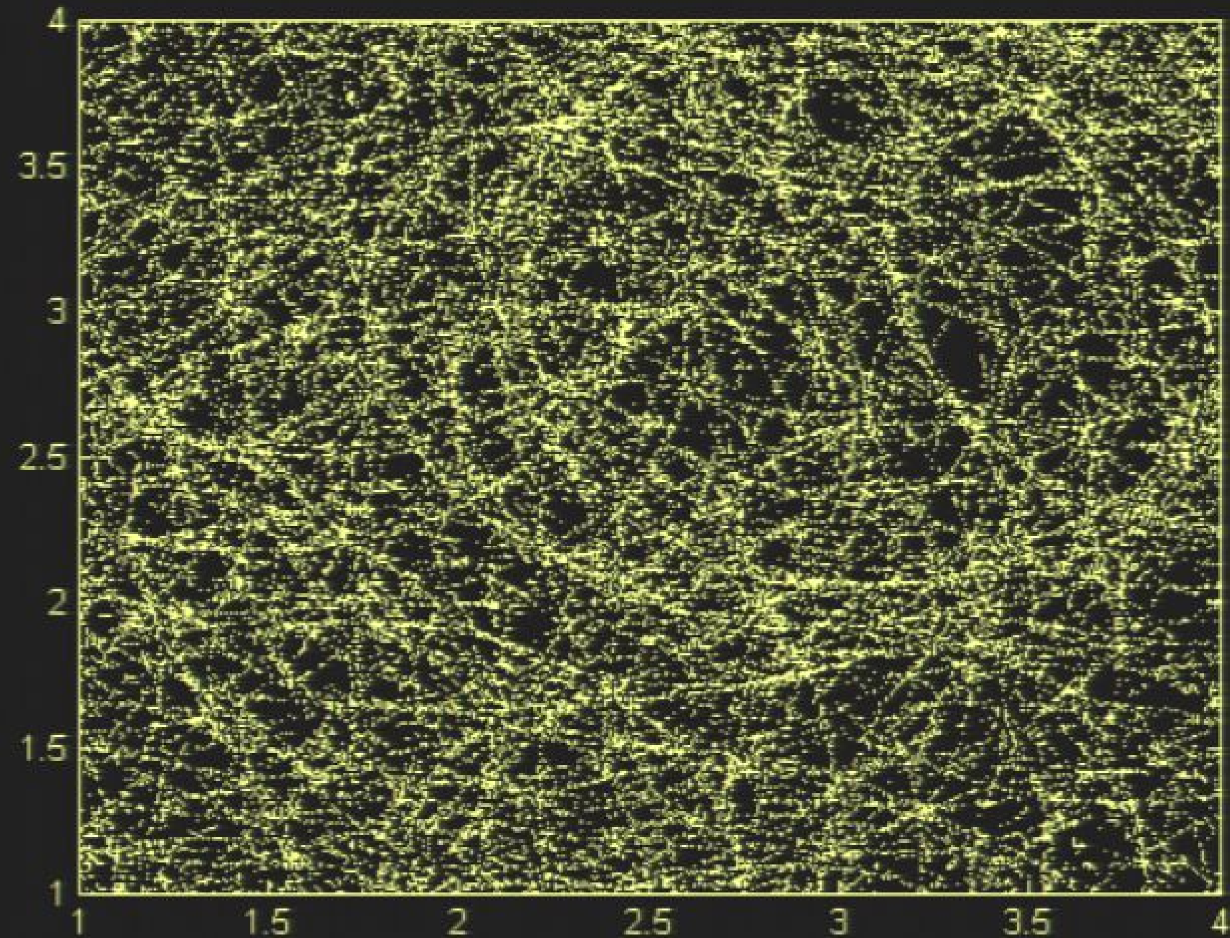

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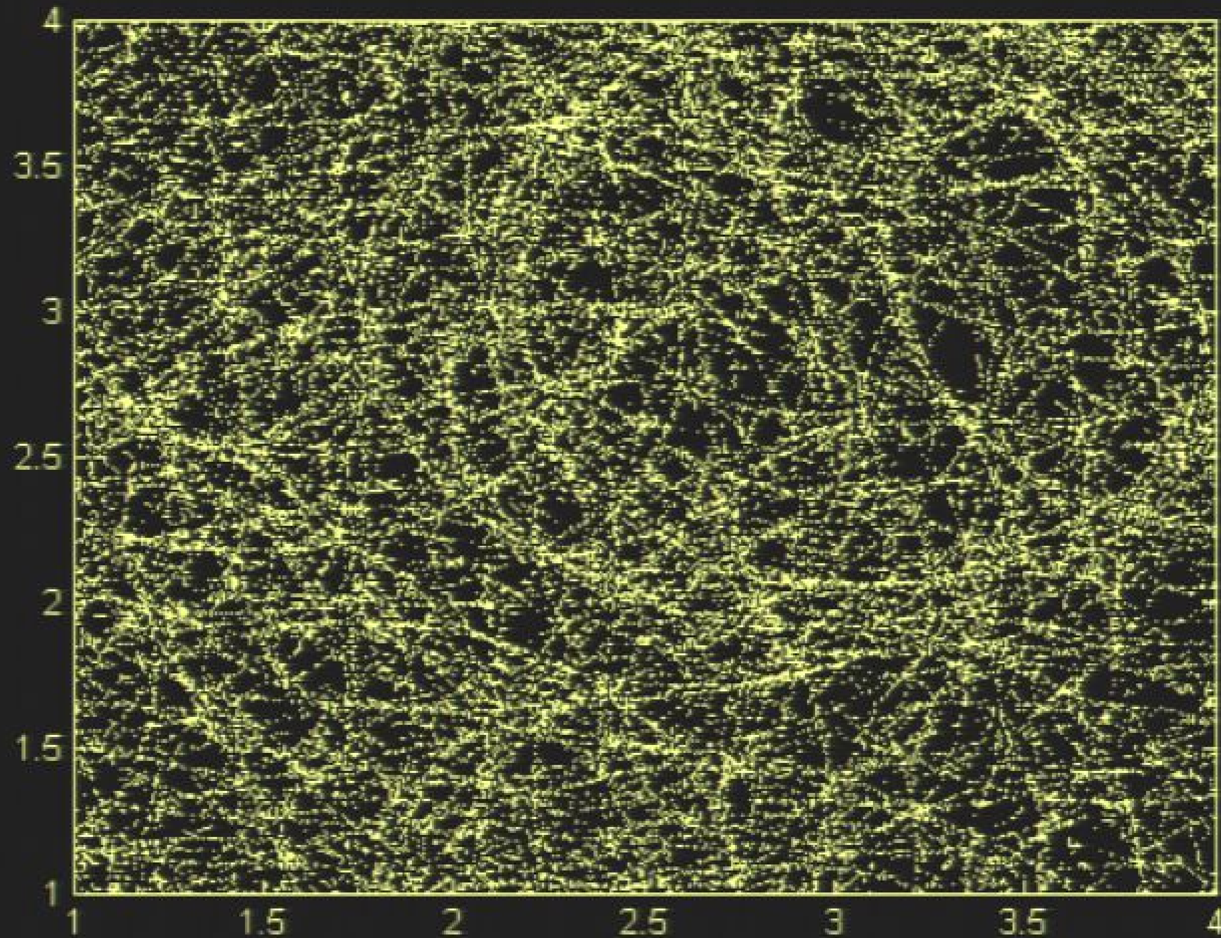

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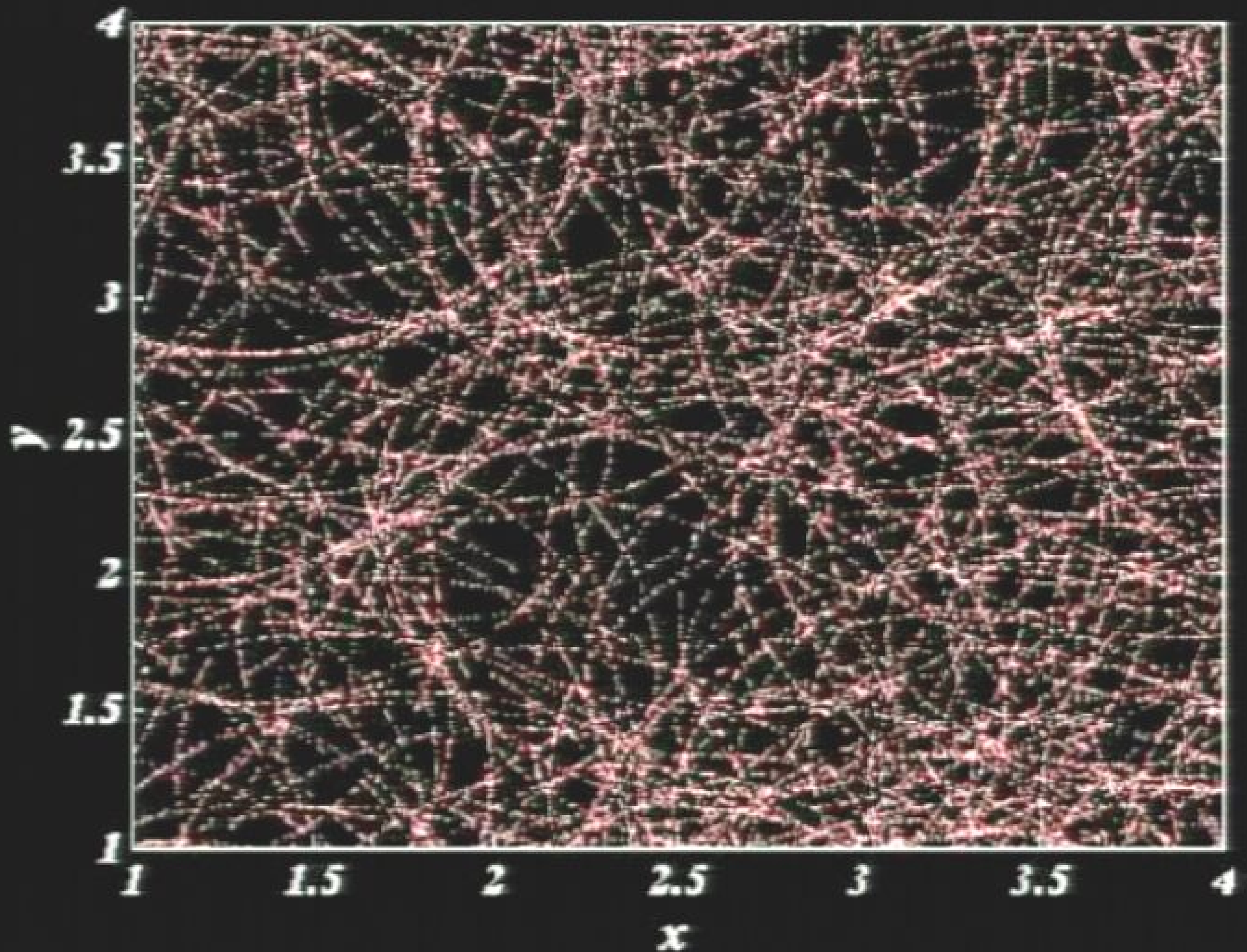
Statistical Standard Rulers



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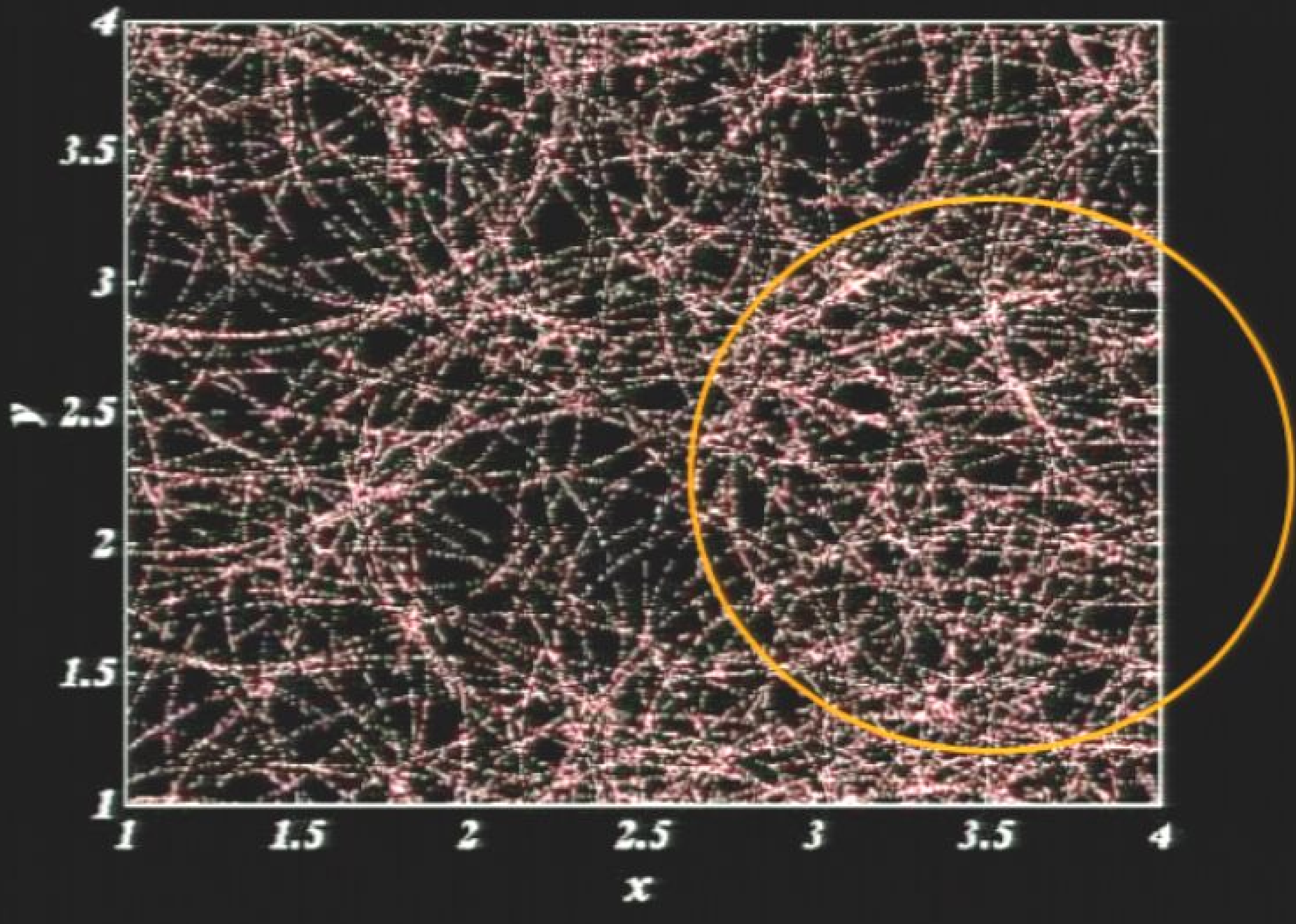

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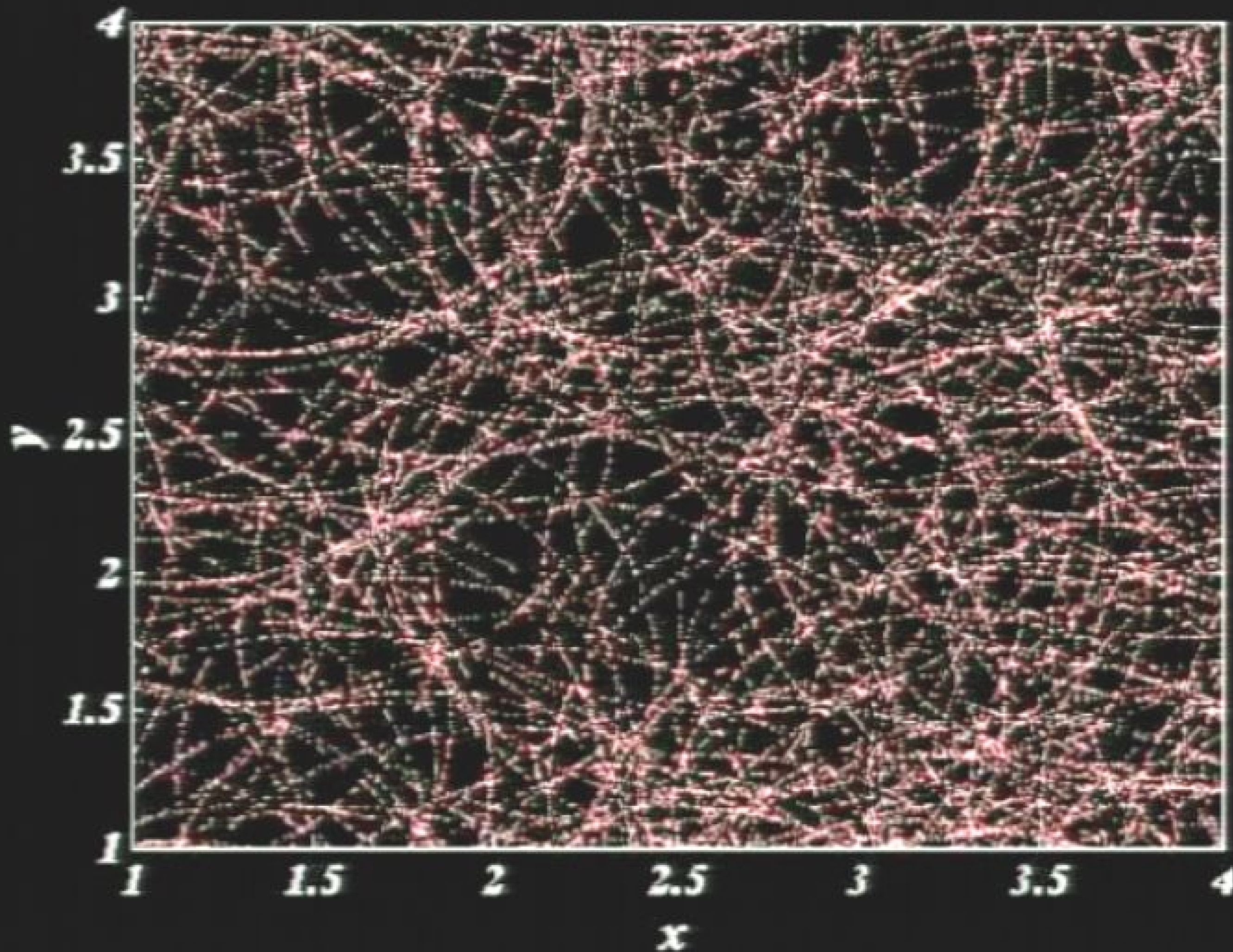

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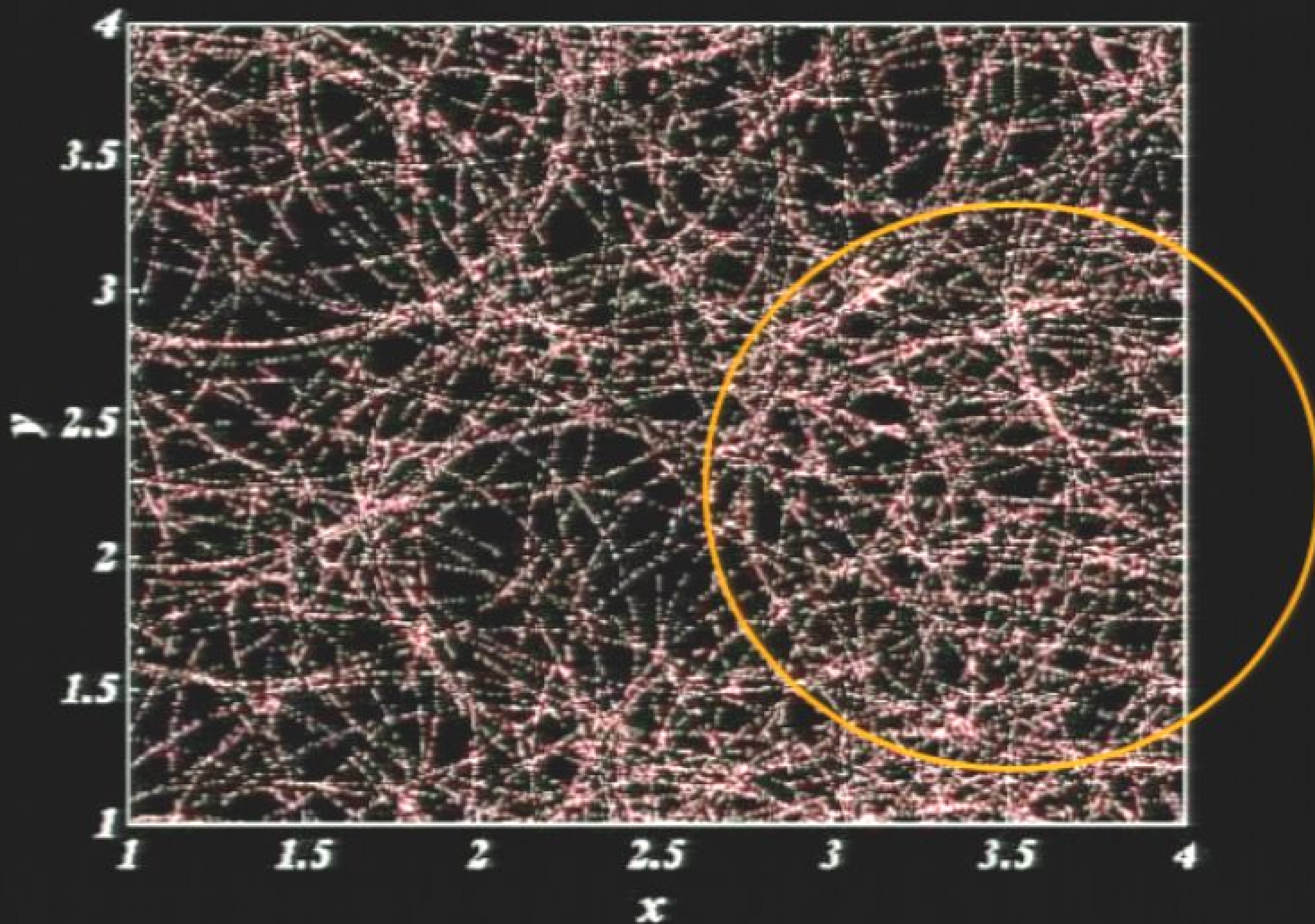

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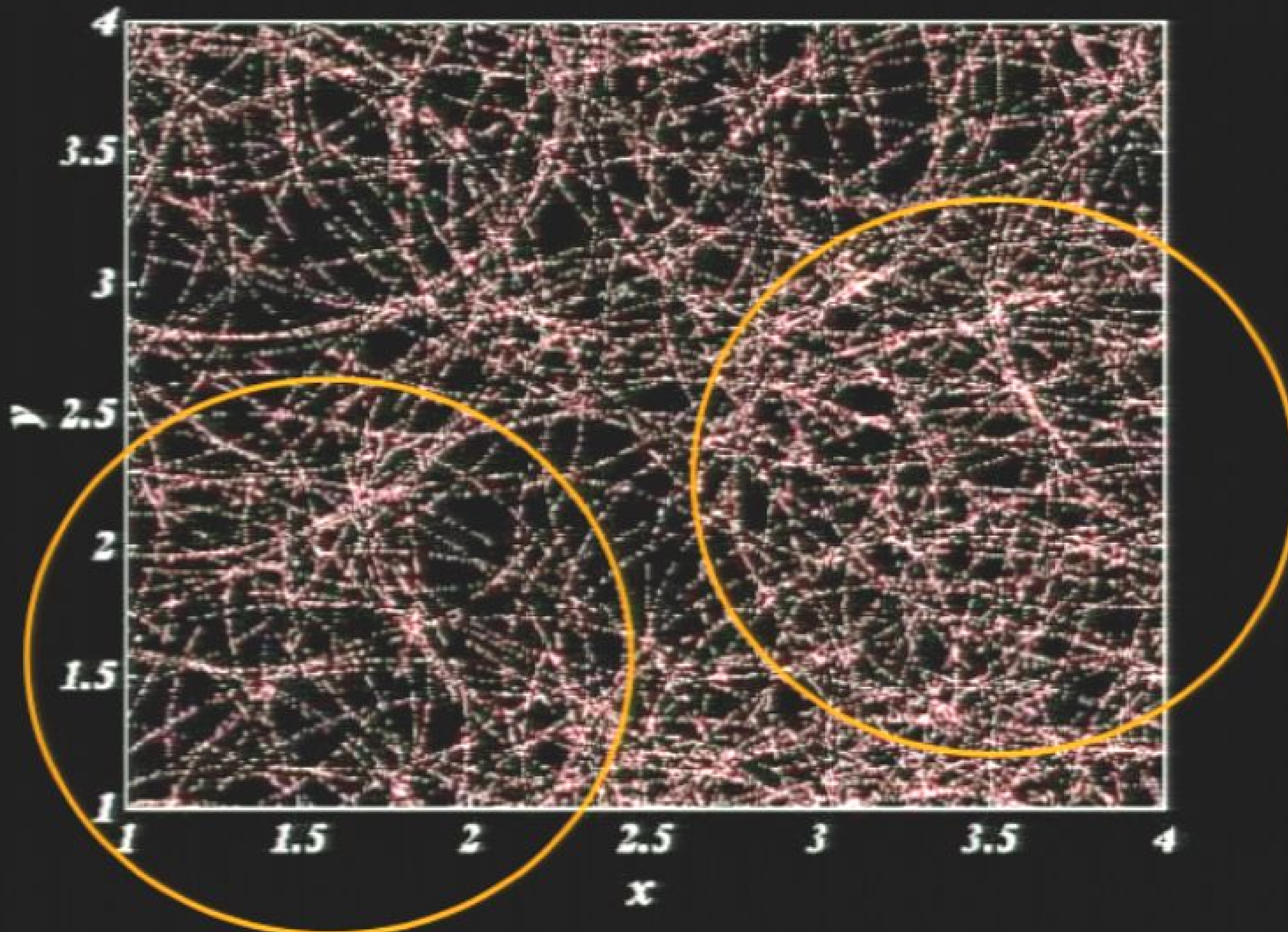

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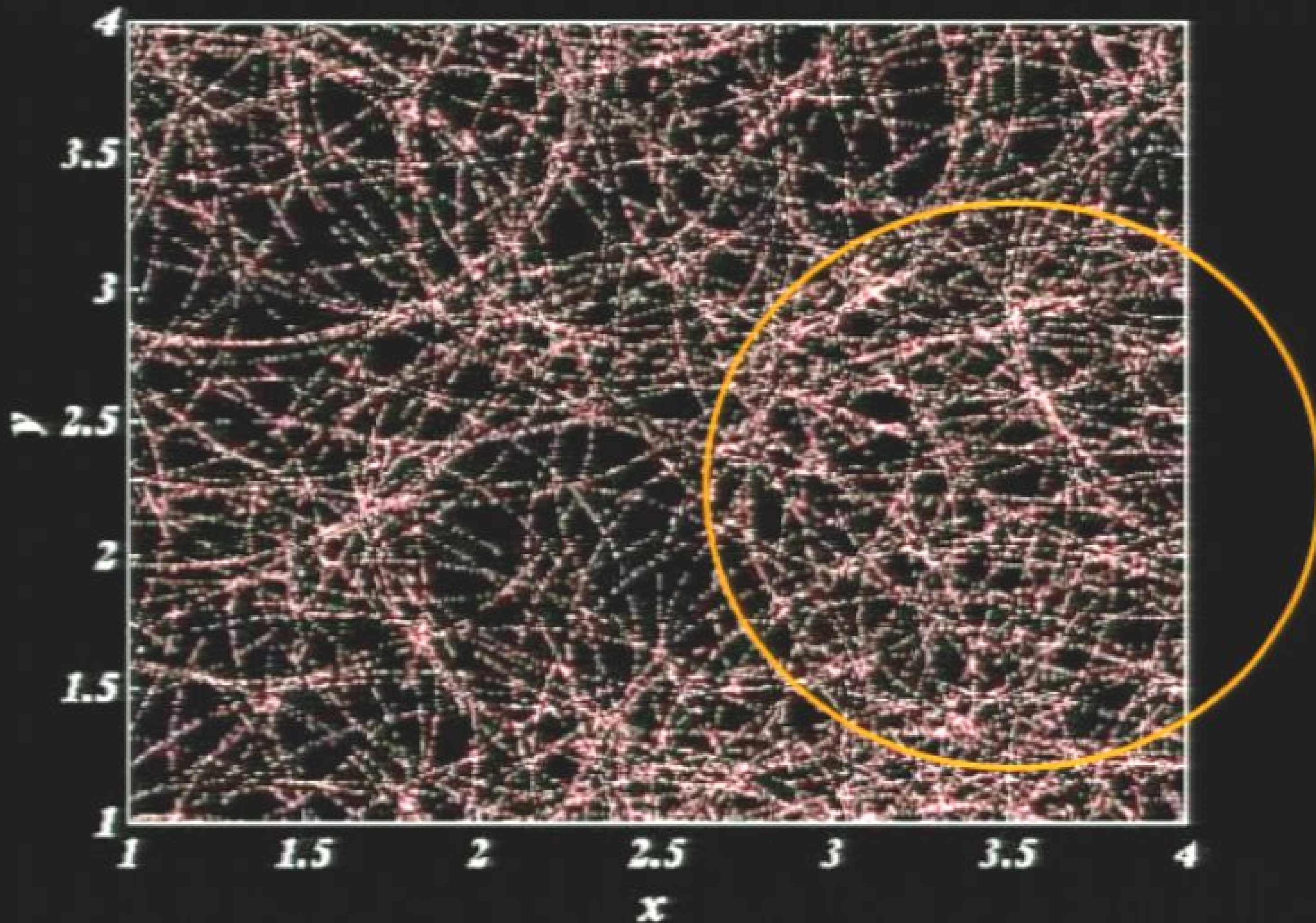

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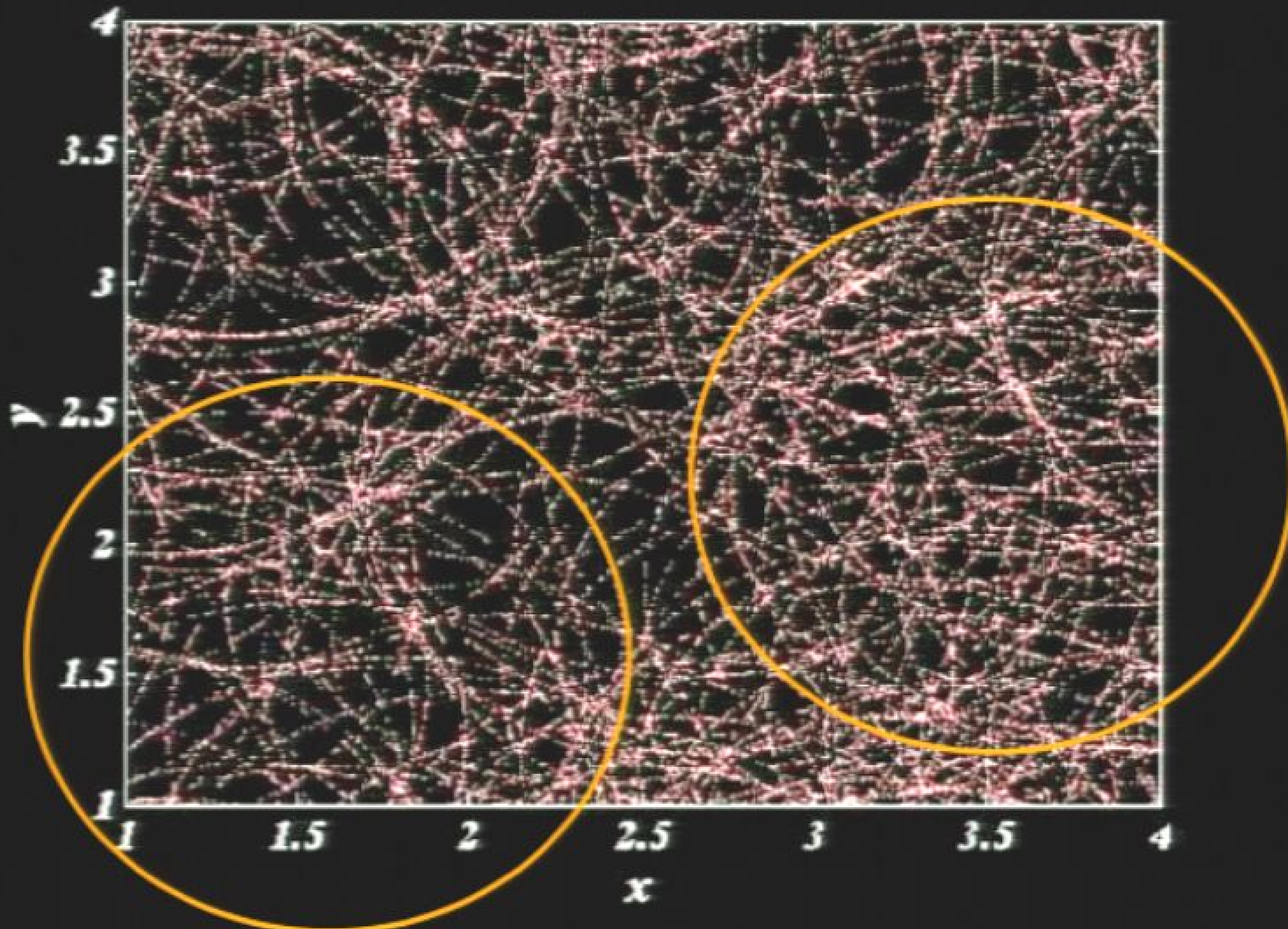
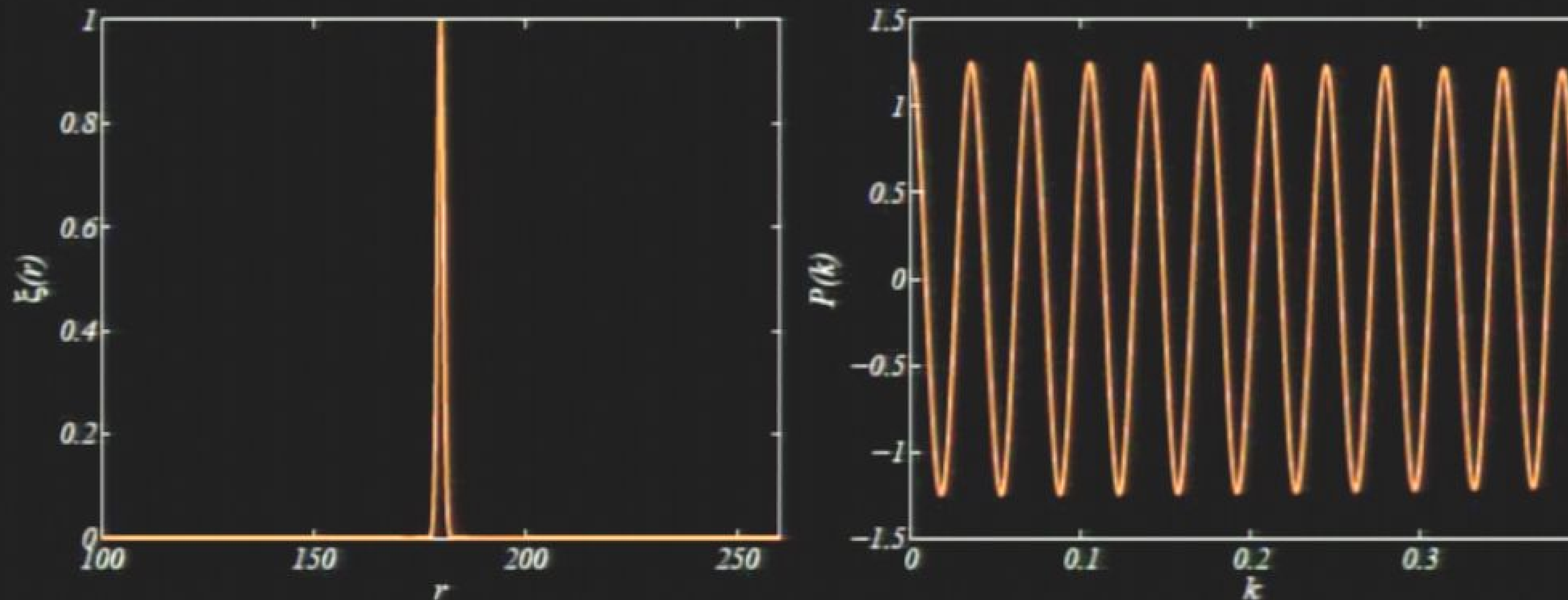
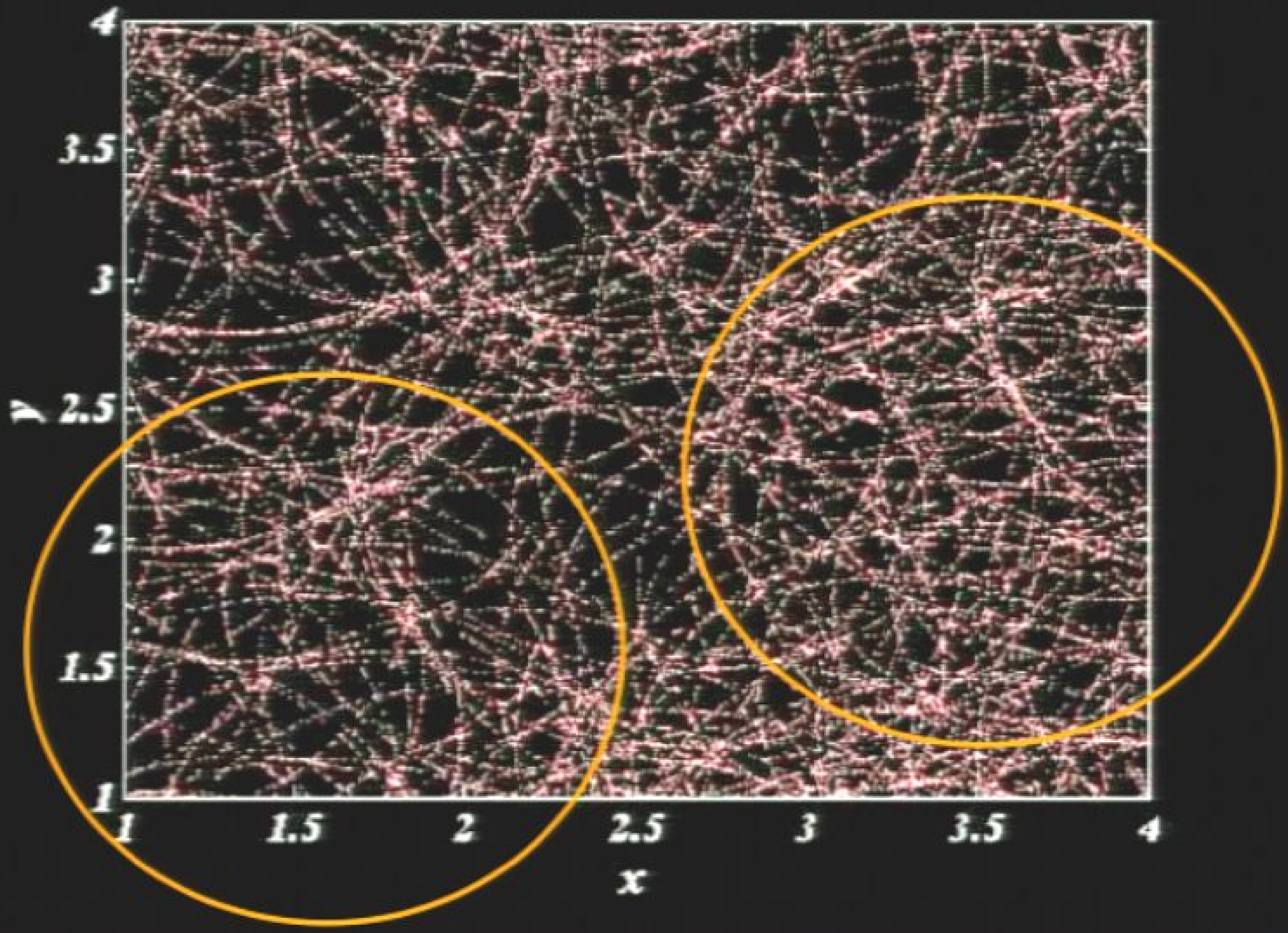


Where are the oscillations in BAO?



$\xi(r) \longleftrightarrow P(k)$

Statistical Standard Rulers



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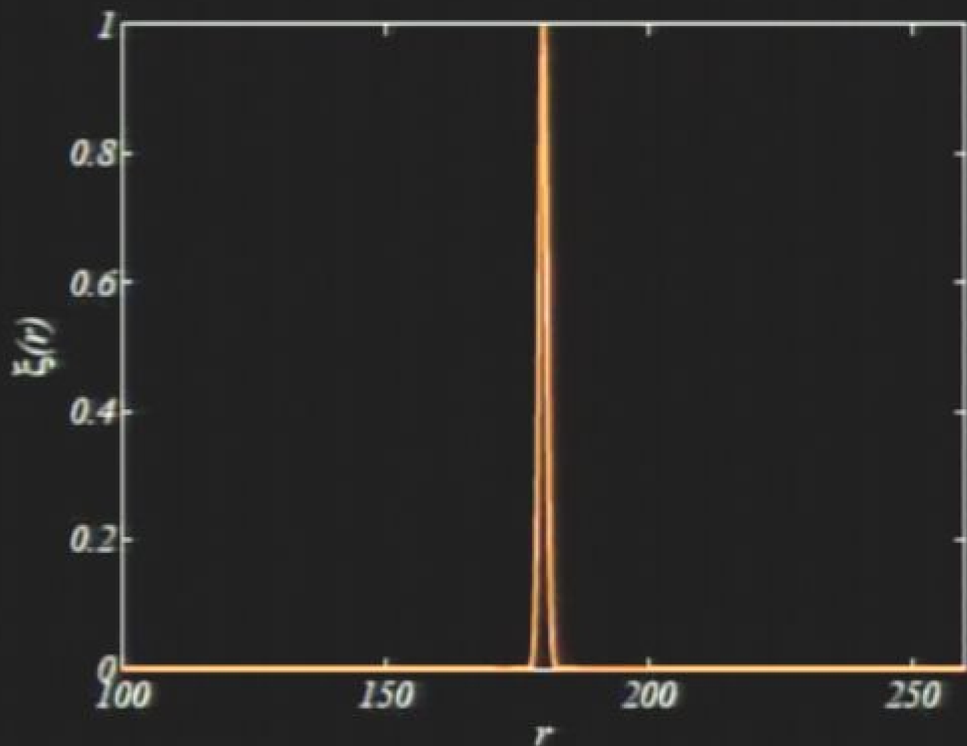

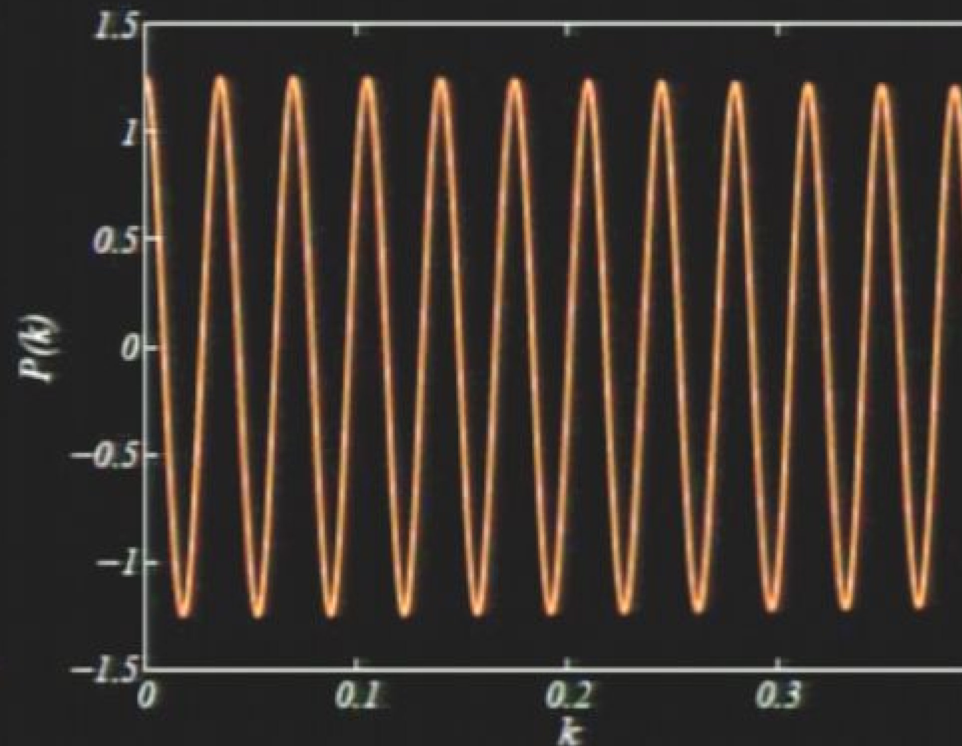

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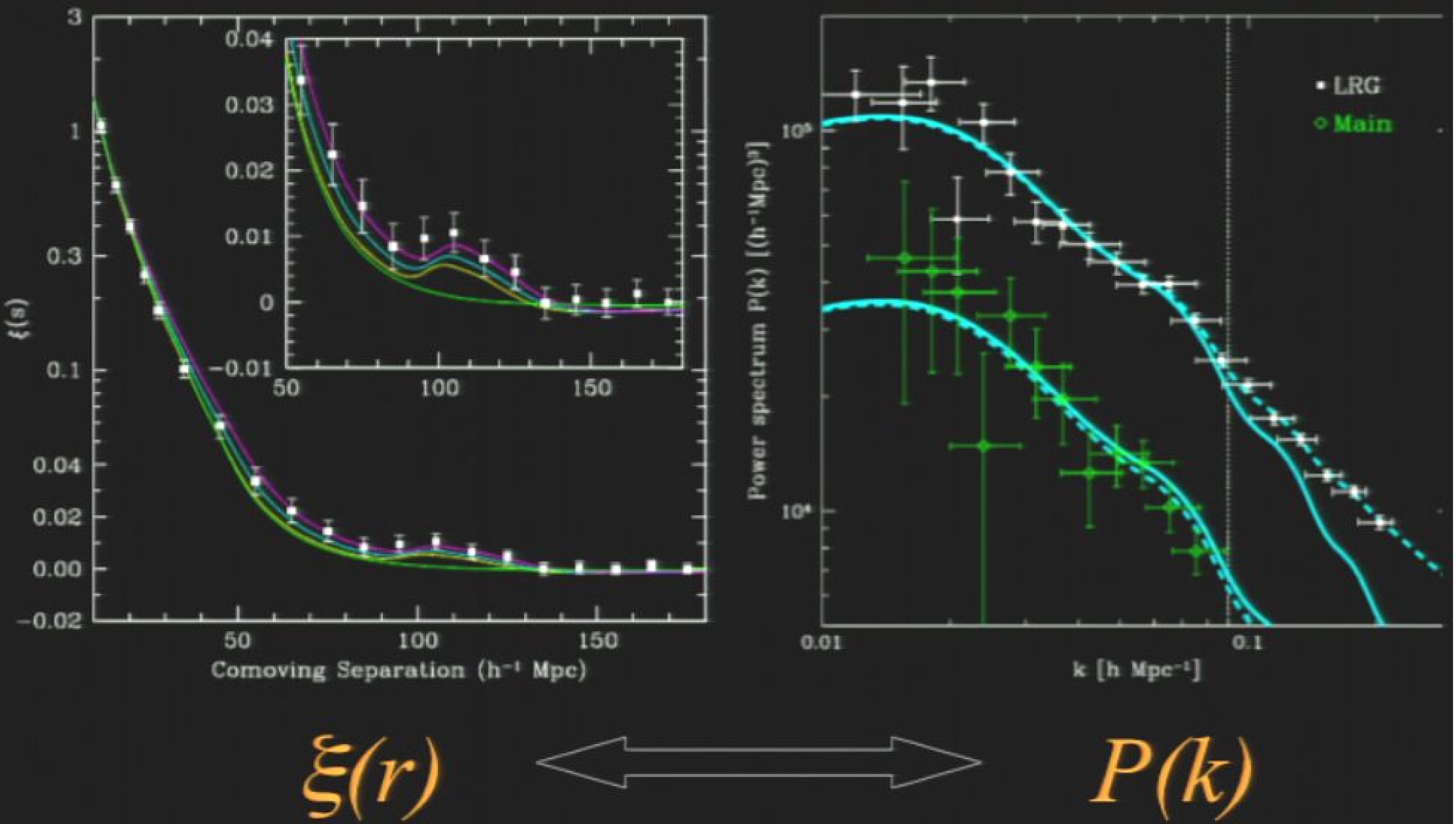

ξ(s)
Comoving Separation (h⁻¹ Mpc)
Power spectrum P(k) [(h⁻¹Mpc)³]
k [h Mpc⁻¹]
LRG
Main
ξ(r)
P(k)

BAP Detection Is Hard!

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- Consider a typical LRG. How many LRGs do we expect in a BAP shell around it?

BAP Detection Is Hard!

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- n $\sim 10^{-4}\, h^3\, Mpc^{-3}$
- Volume = 20 Mpc x $100^2\, Mpc^2$ x 5 $\sim 10^6\, h^{-3}\, Mpc^3$

BAP Detection Is Hard!

- Consider a typical LRG. How many LRGs do we expect in a BAP shell around it?
- n ~10^{-4} h^3 Mpc^{-3}
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  → 100 LRGs from purely uniform distribution

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- BAP in $\xi(r)$ gives ~1% excess probability

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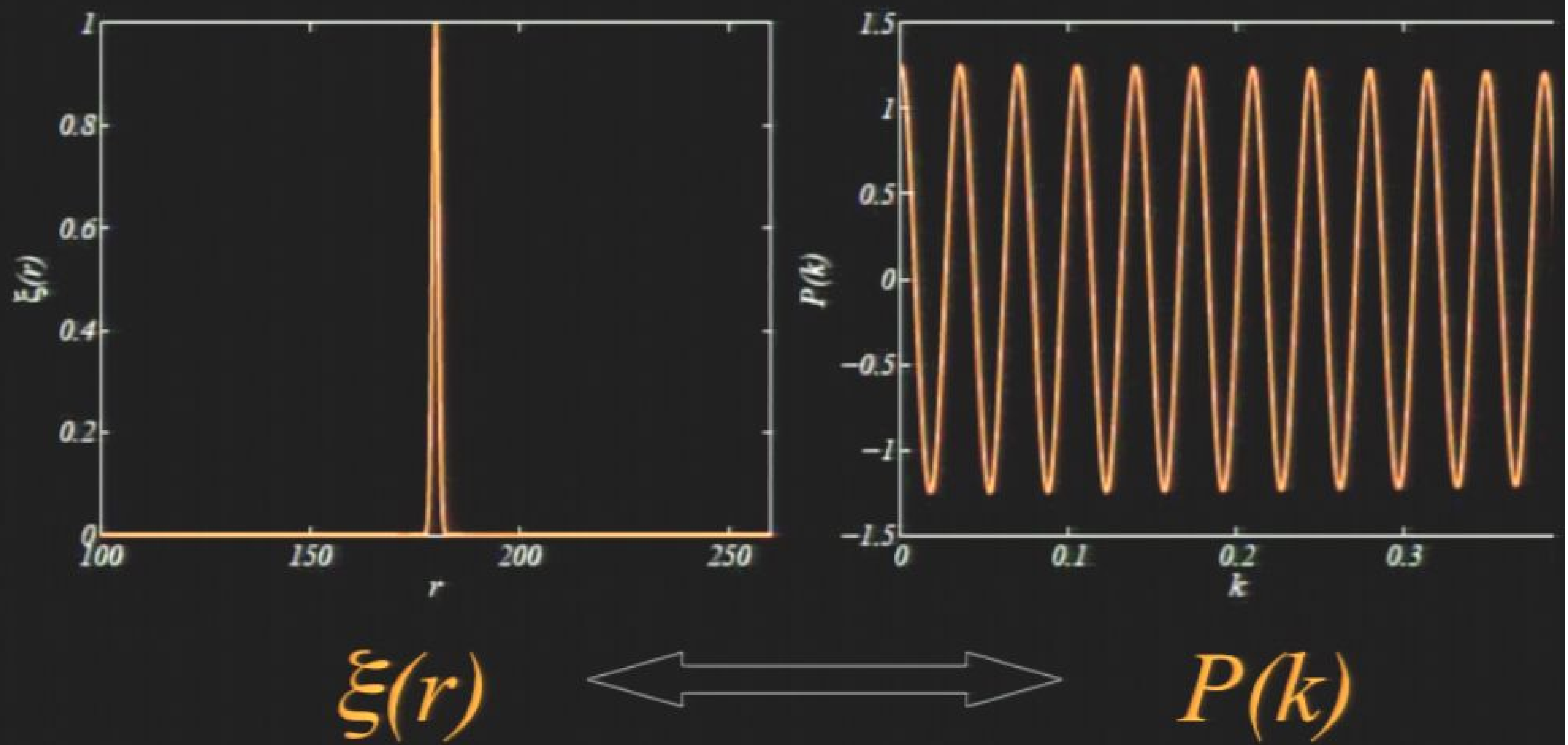

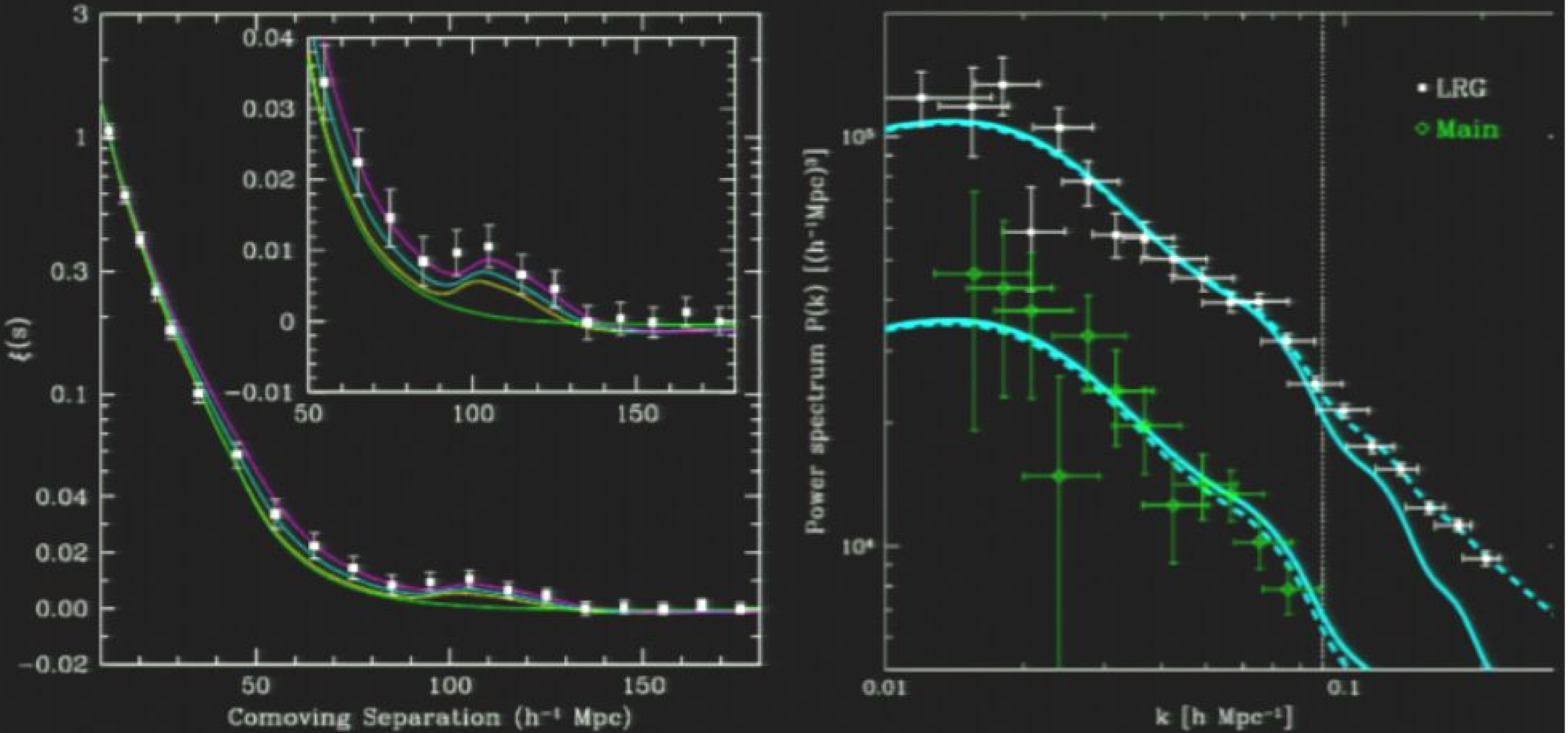

Comoving Separation (h^{-1} Mpc)
$\xi(s)$
Power spectrum P(k) [(h^{-1}Mpc)^3]
k [h Mpc^{-1}]
LRG
Main

$\xi(r)$ ⟺ $P(k)$

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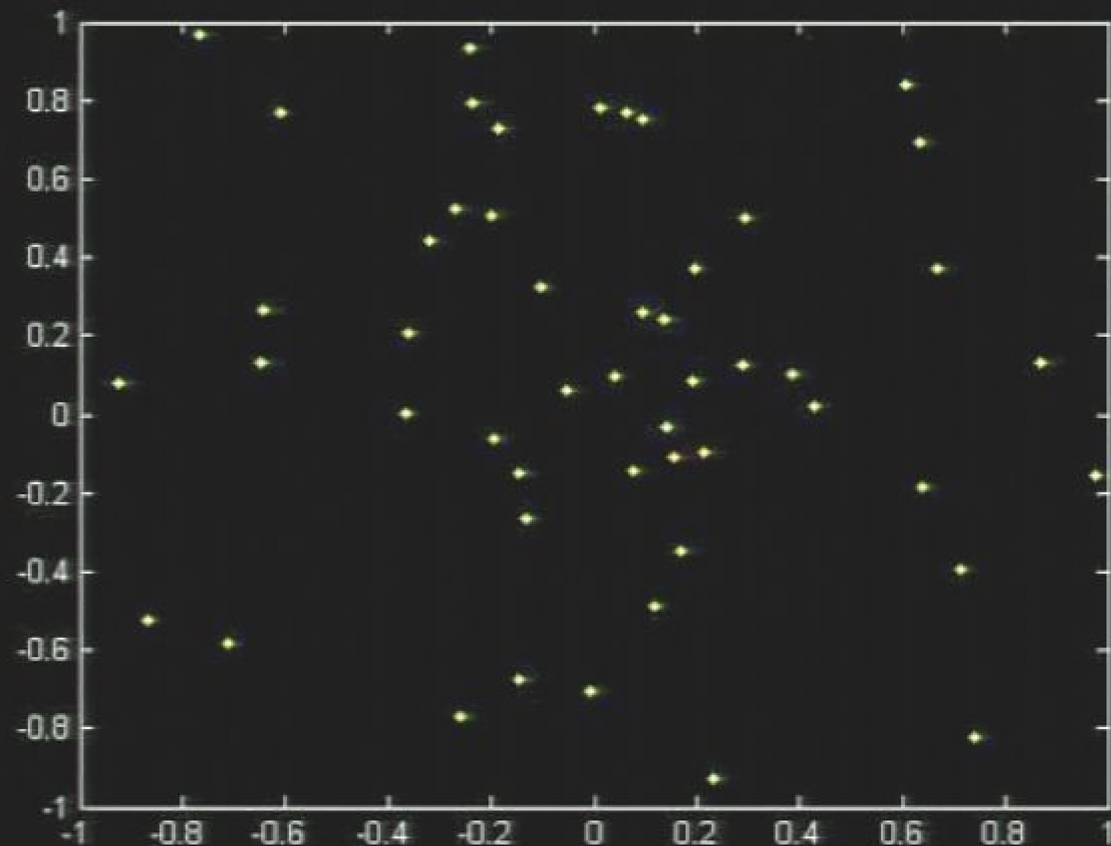
- n ~10^{-4} h^3 Mpc^{-3}

Power Spectrum Errors

$$\frac{\delta P}{P} = \frac{1}{\sqrt{m}}\left(1 + \frac{1}{nP}\right)$$

Shot Noise



Fixed Volume

50 points

Power Spectrum Errors

$$\frac{\delta P}{P} = \underbrace{\frac{1}{\sqrt{m}}}_{\text{Cosmic Variance}} \left(1 + \underbrace{\frac{1}{nP}}_{\text{Shot Noise}}\right)$$

m = number of Fourier modes measured in the survey
n = mean galaxy number density in the survey

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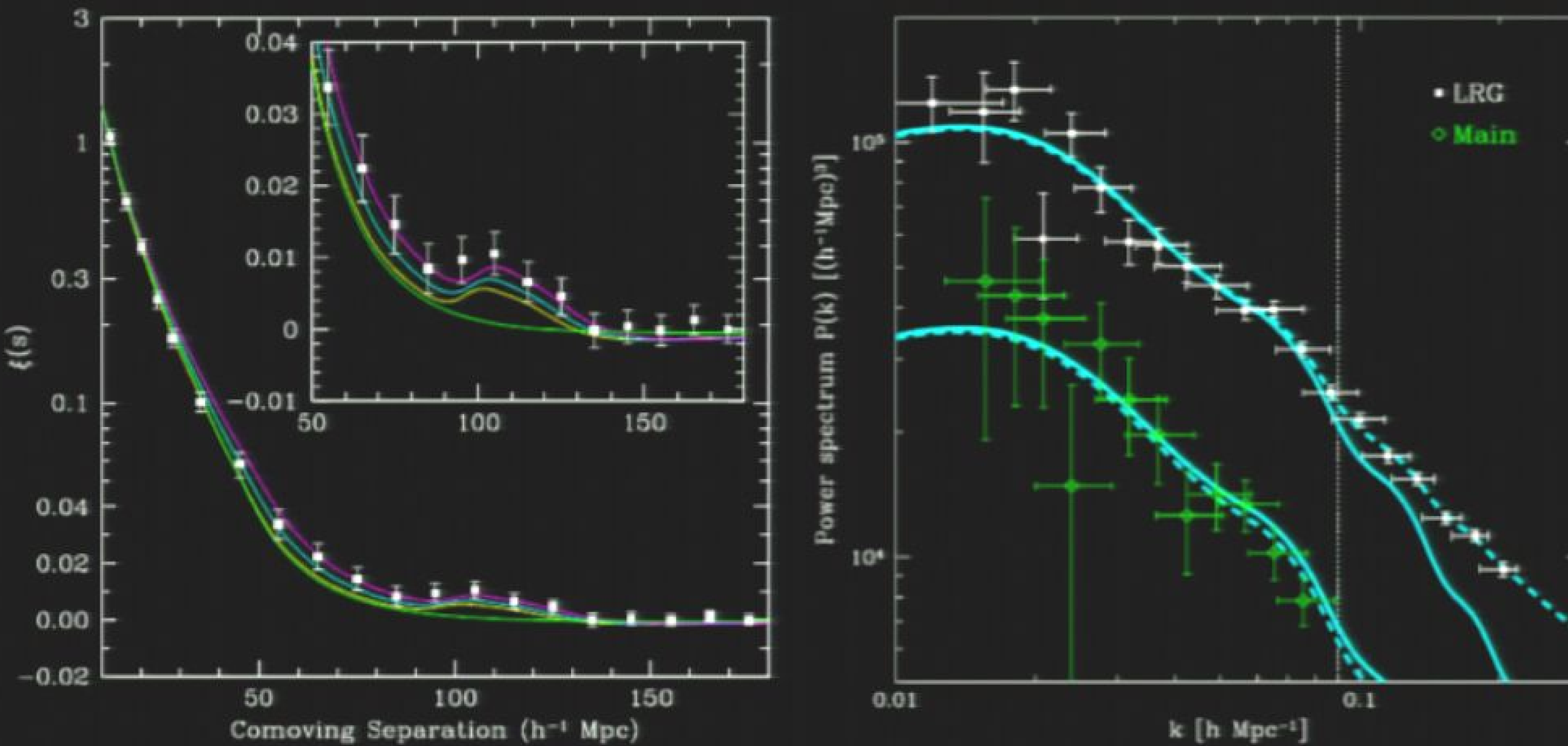
- Volume = 20 *Mpc* x 100^2 Mpc^2 x 5 ~ 10^6 h^{-3} Mpc^3

  → 100 LRGs from purely uniform distribution
- BAP in $\xi(r)$ gives ~1% excess probability
- So gives a *single extra LRG* on average.
- Need lots of volume and large numbers of galaxies…so we can see the extra galaxy on average!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Cosmic Variance Shot Noise

m = number of Fourier modes measured in the survey

Power Spectrum Errors

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Cosmic Variance — $\frac{1}{\sqrt{m}}$

Shot Noise — $\frac{1}{nP}$

BAP Detection Is Hard!

- Consider a typical LRG. How many LRGs do we expect in a BAP shell around it?
- n ~10^{-4} h^3 Mpc^{-3}
- Volume = 20 *Mpc* x 100^2 Mpc^2 x 5 ~ 10^6 h^{-3} Mpc^3

  → 100 LRGs from purely uniform distribution
- BAP in $\xi(r)$ gives ~1% excess probability
- So gives a *single extra LRG* on average.
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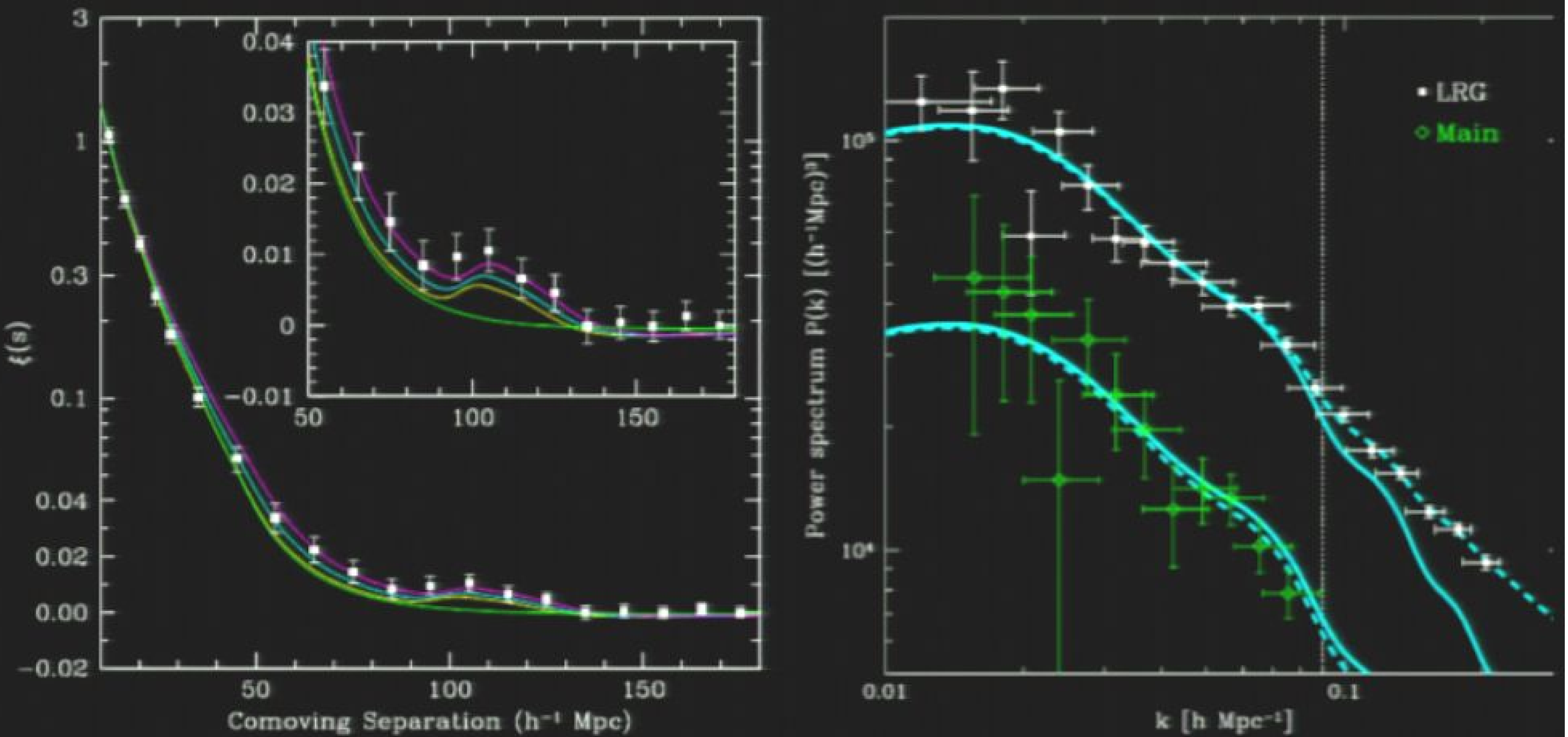
ξ(s)
Comoving Separation (h⁻¹ Mpc)
Power spectrum P(k) [(h⁻¹Mpc)³]
k [h Mpc⁻¹]
LRG
Main

$\xi(r)$ ⟷ $P(k)$

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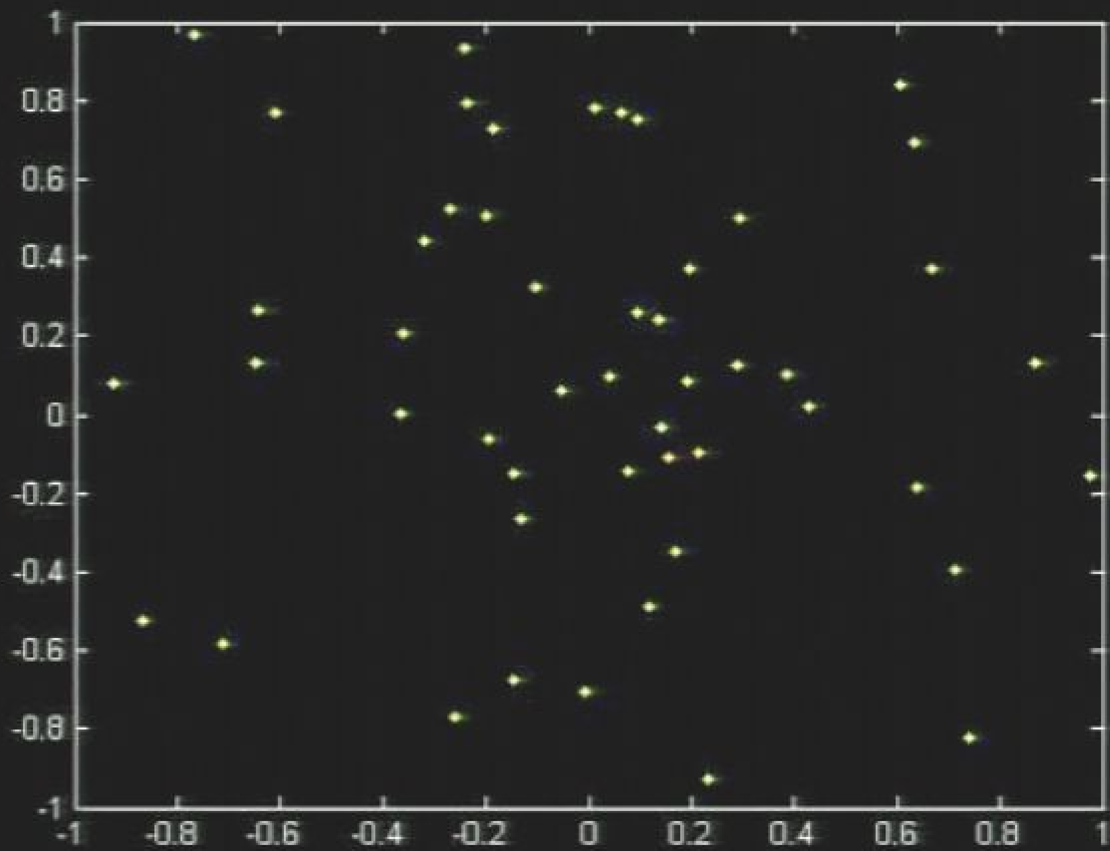
n = mean galaxy number density in the survey

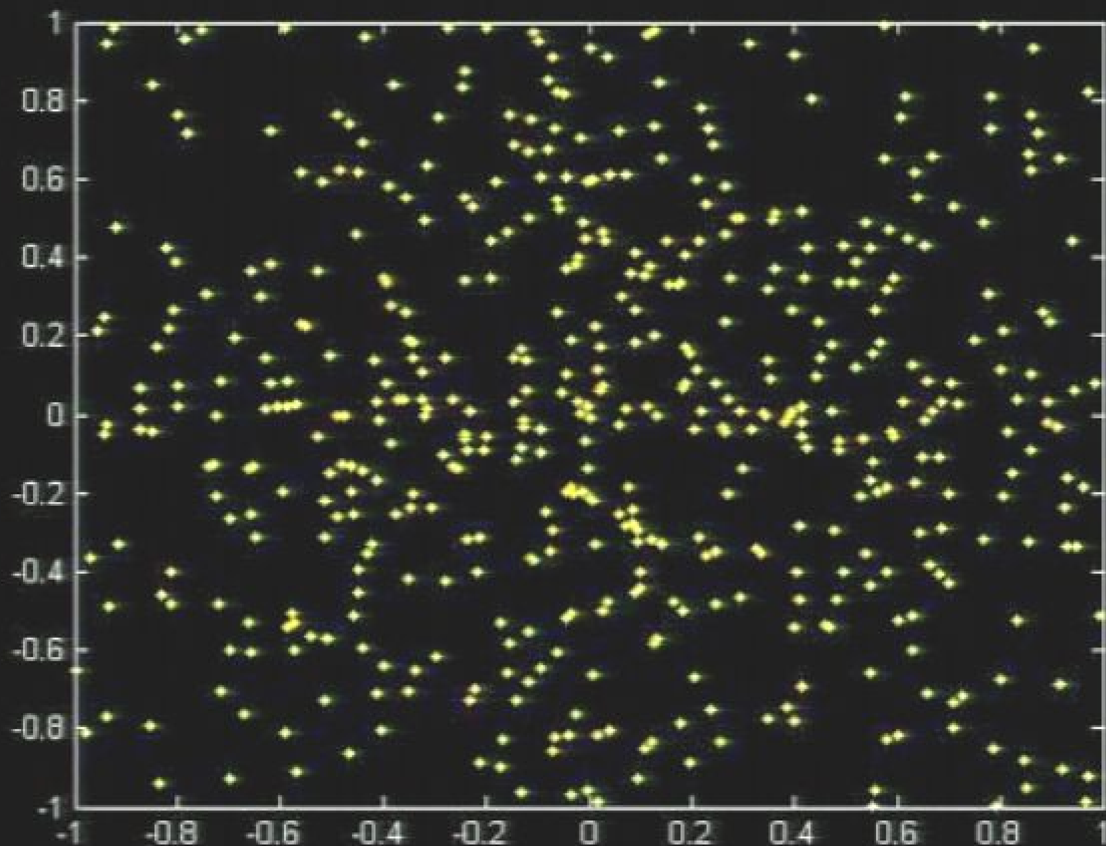
Shot Noise



Fixed Volume

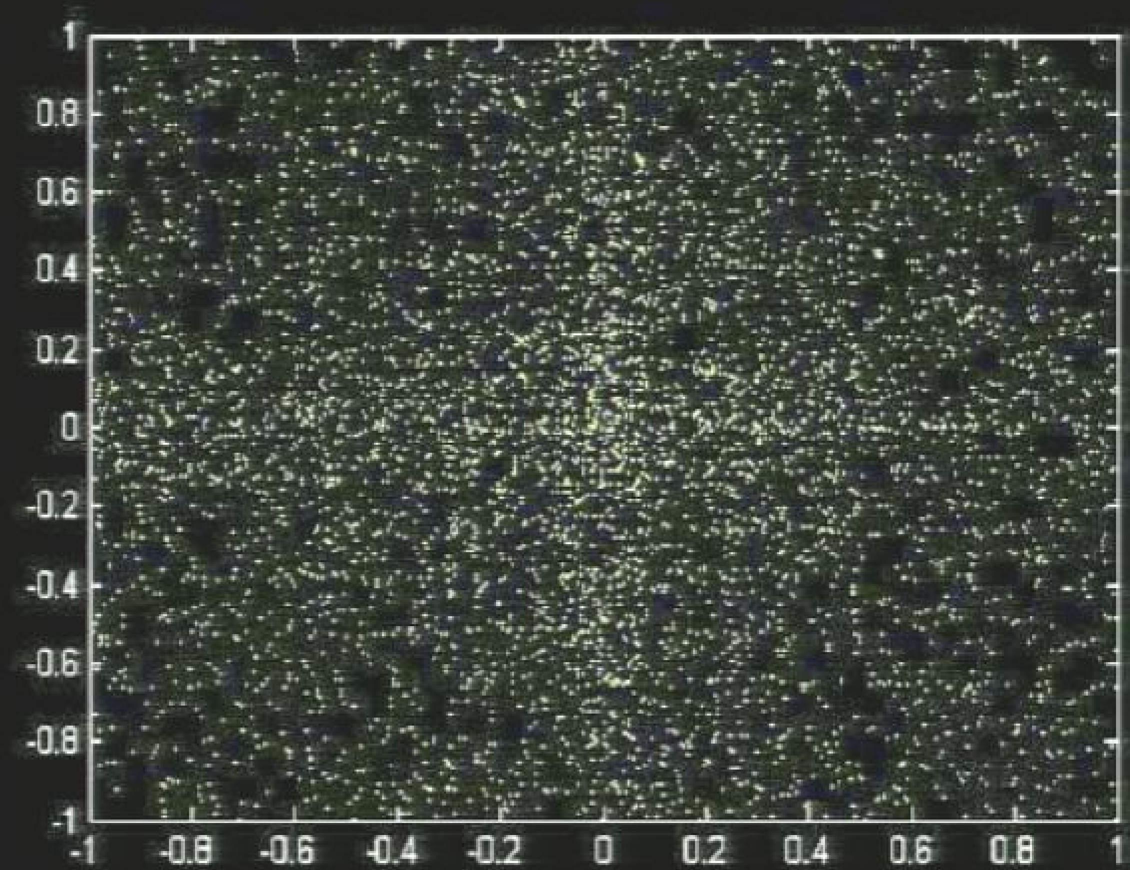
50 points

Shot Noise



Fixed Volume 500 points

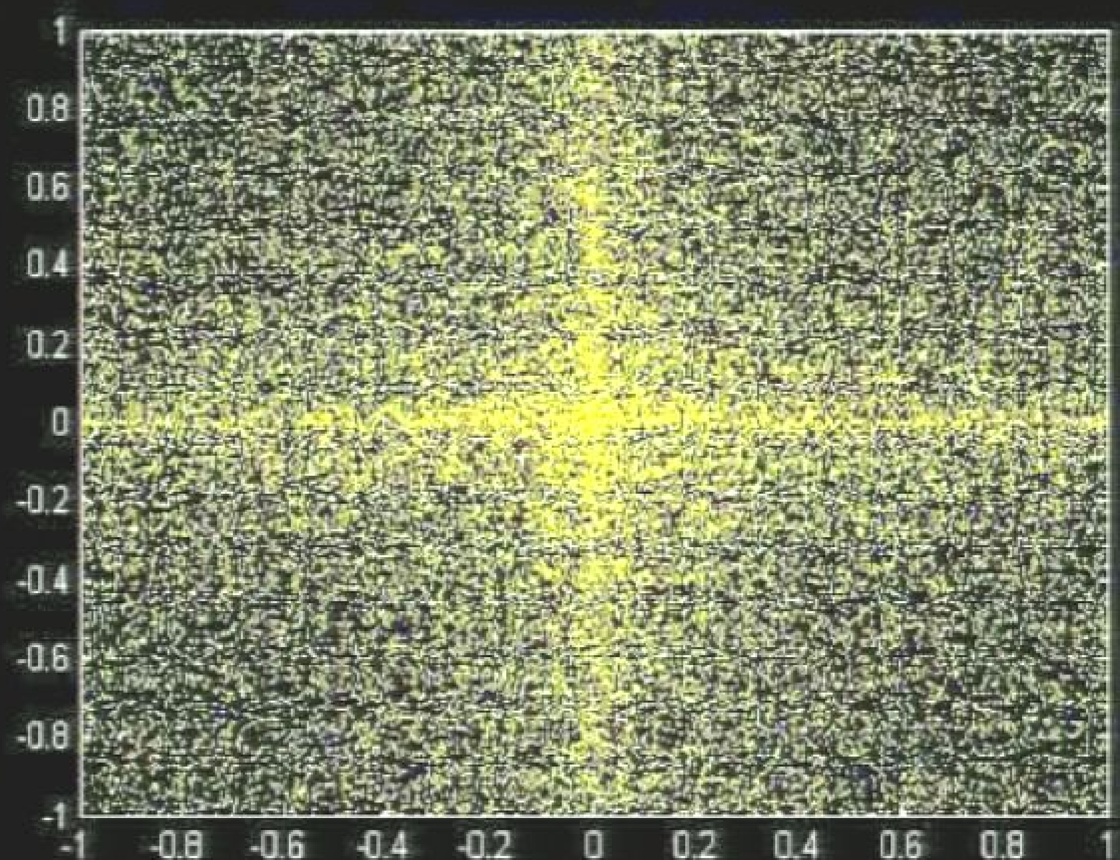
Shot Noise



Fixed Volume

5000 points

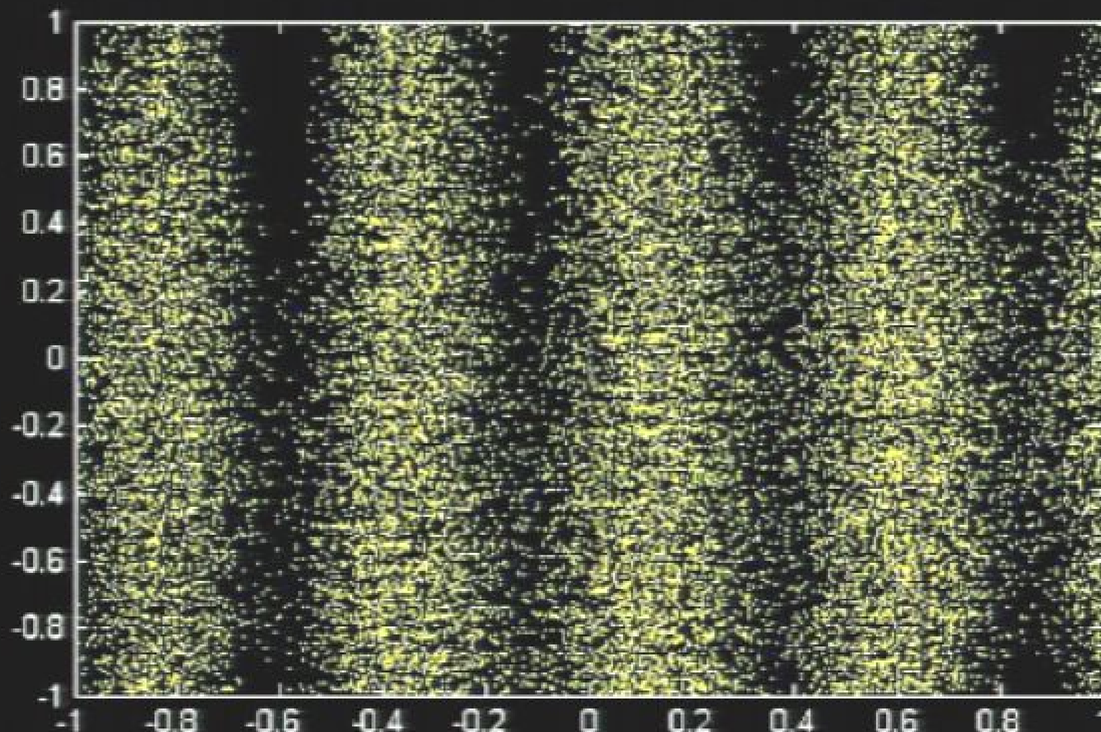
Shot Noise



Fixed Volume

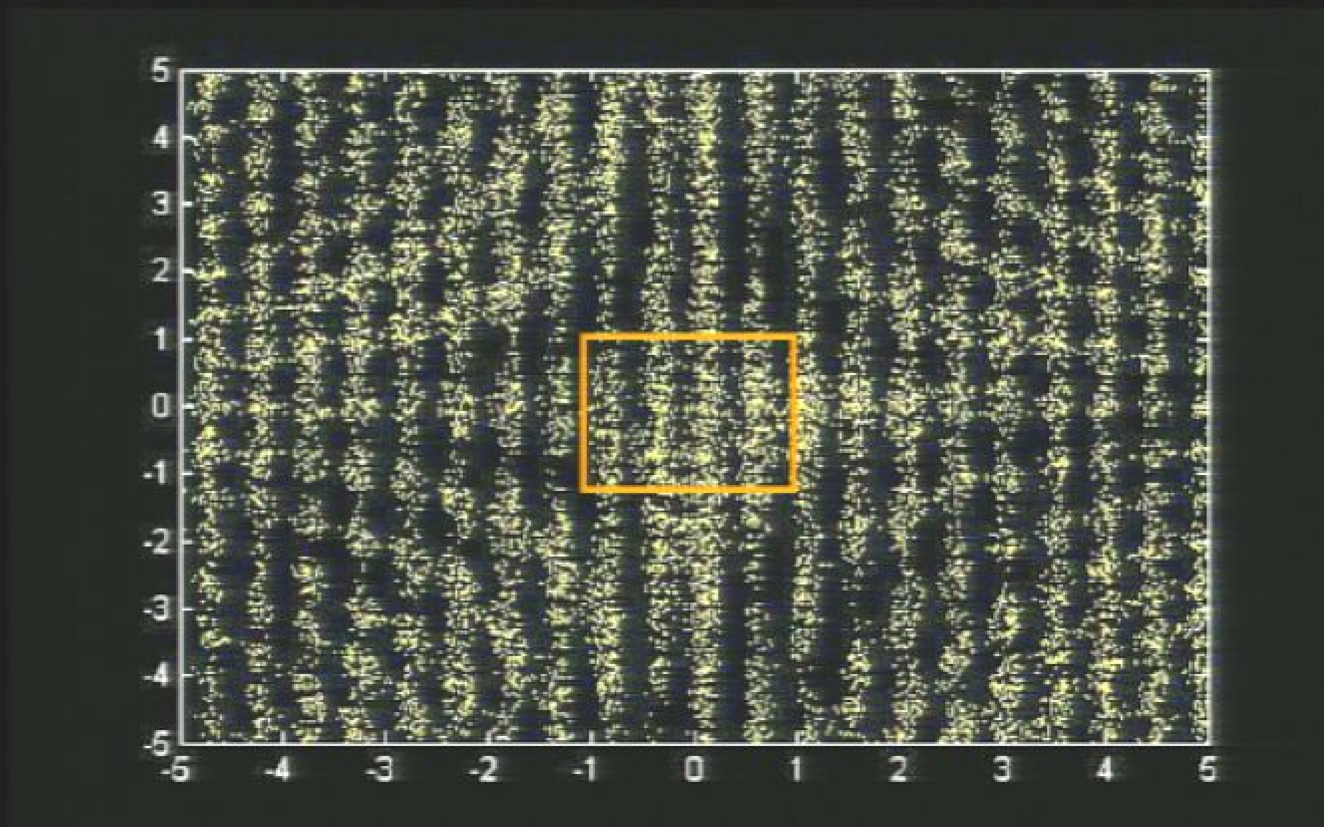
50k points

Cosmic Variance



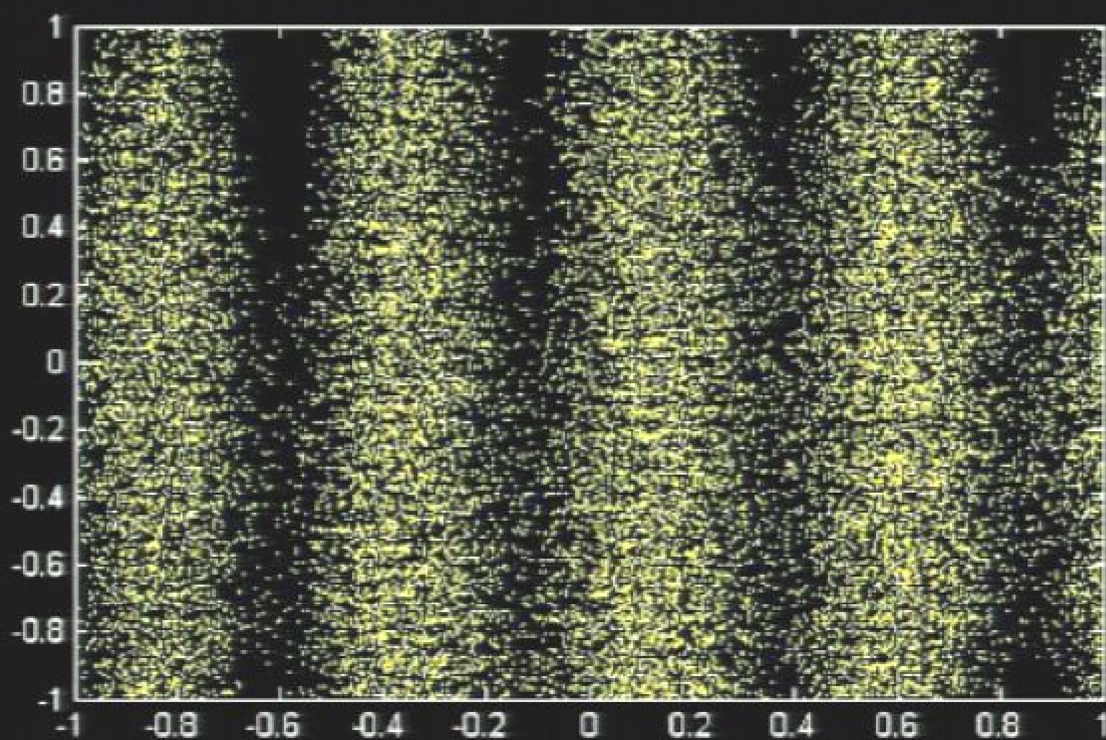
1 x Volume   Fixed 50k points

Cosmic Variance



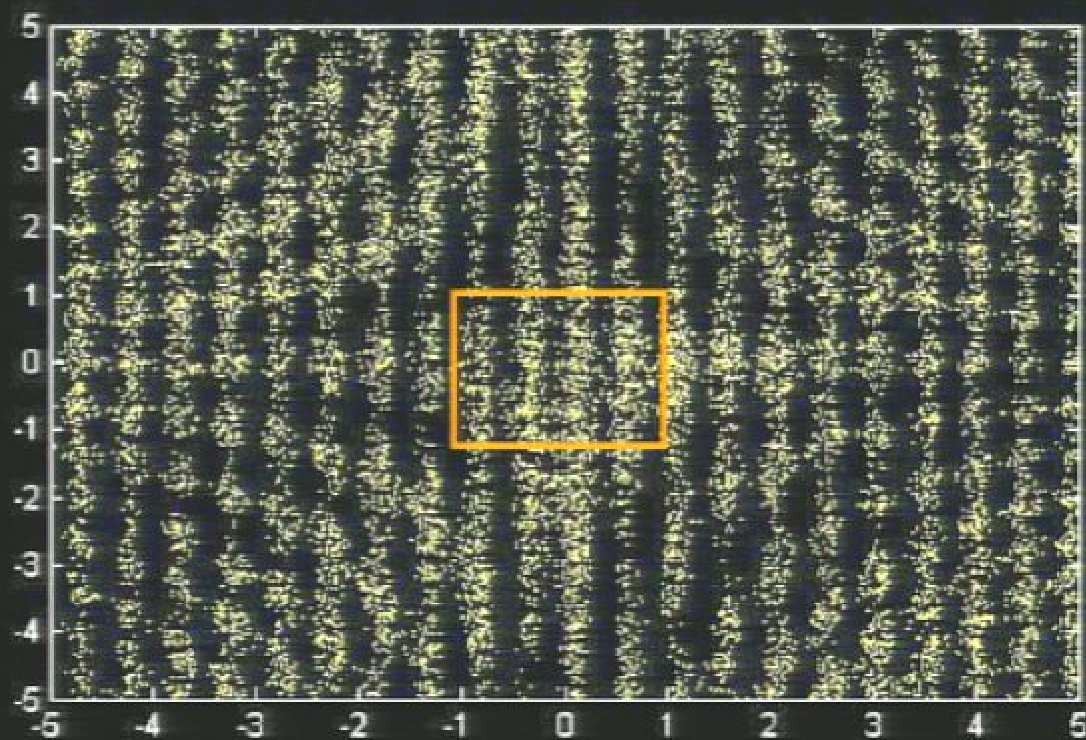
25 x Volume Fixed 50k points

Cosmic Variance



1 x Volume Fixed 50k points

Cosmic Variance



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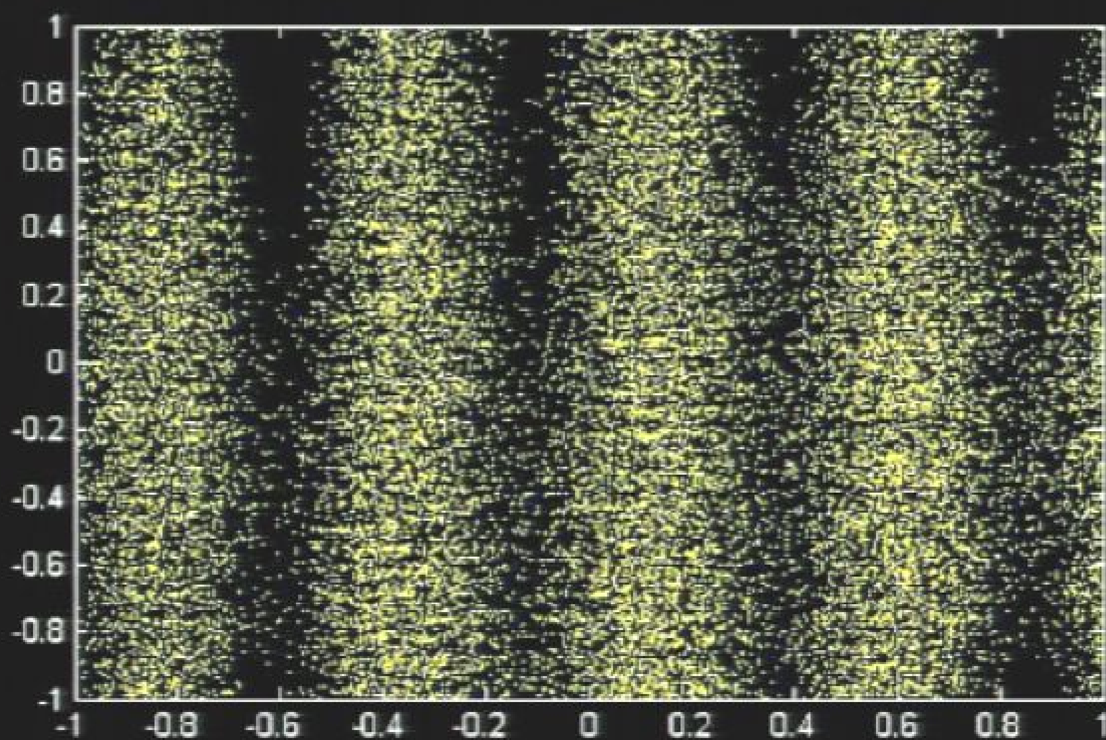
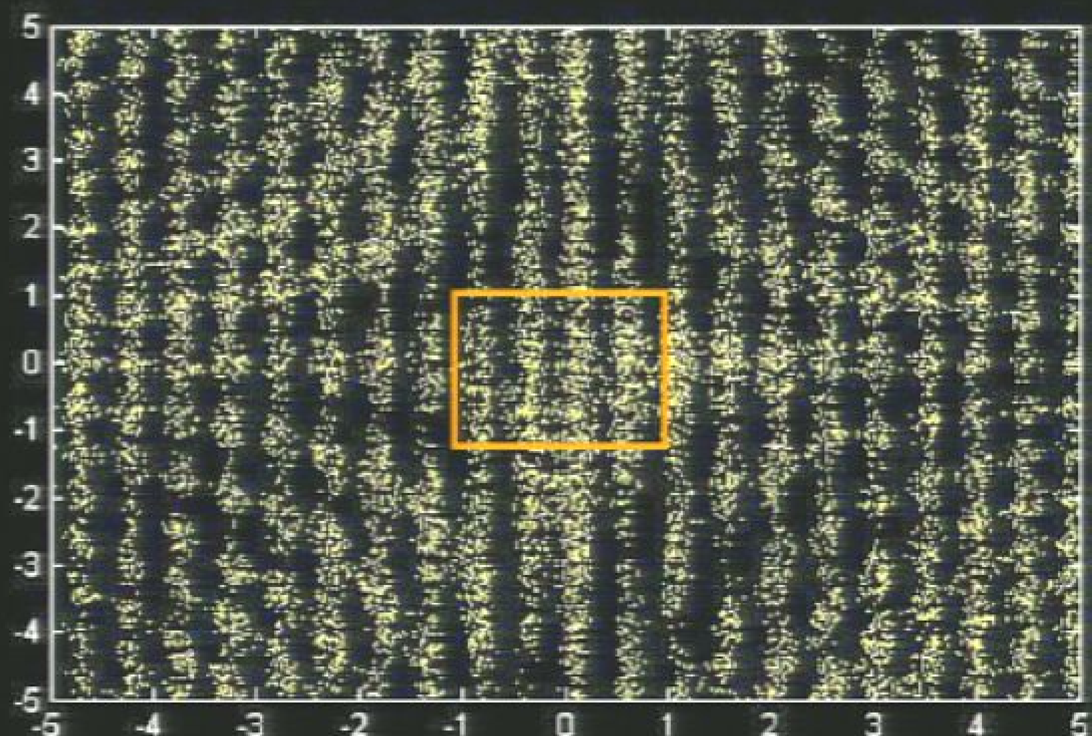
Cosmic Variance



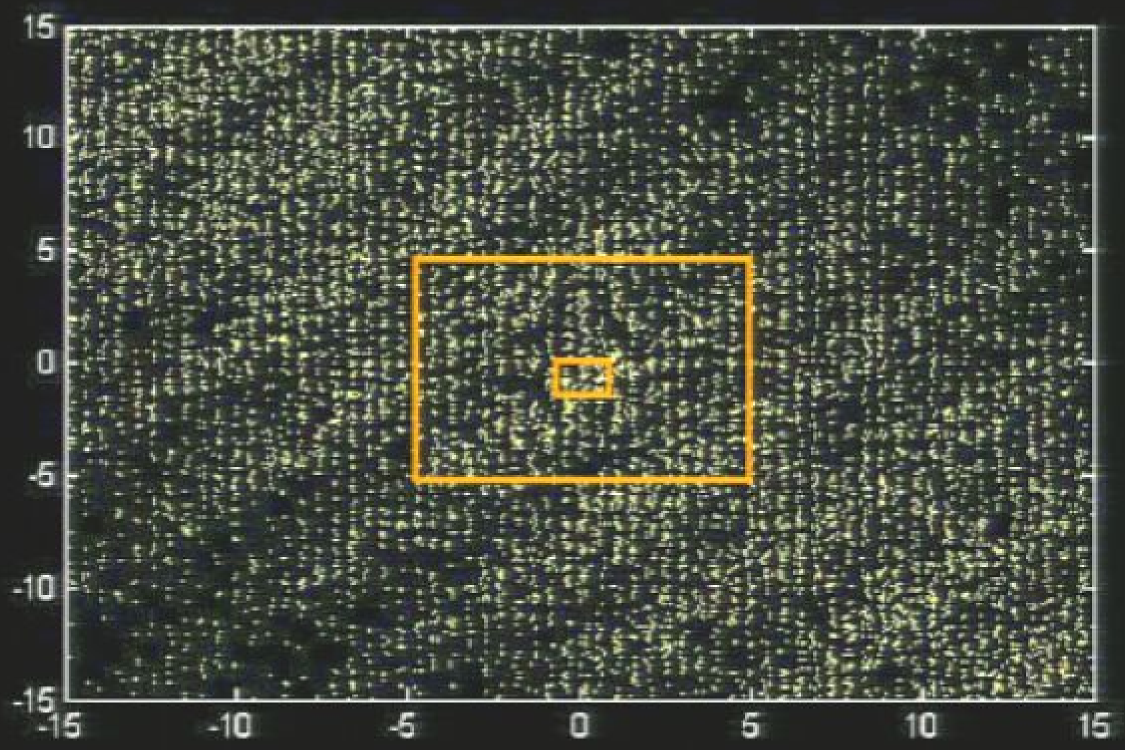
1 x Volume   Fixed 50k points

Cosmic Variance



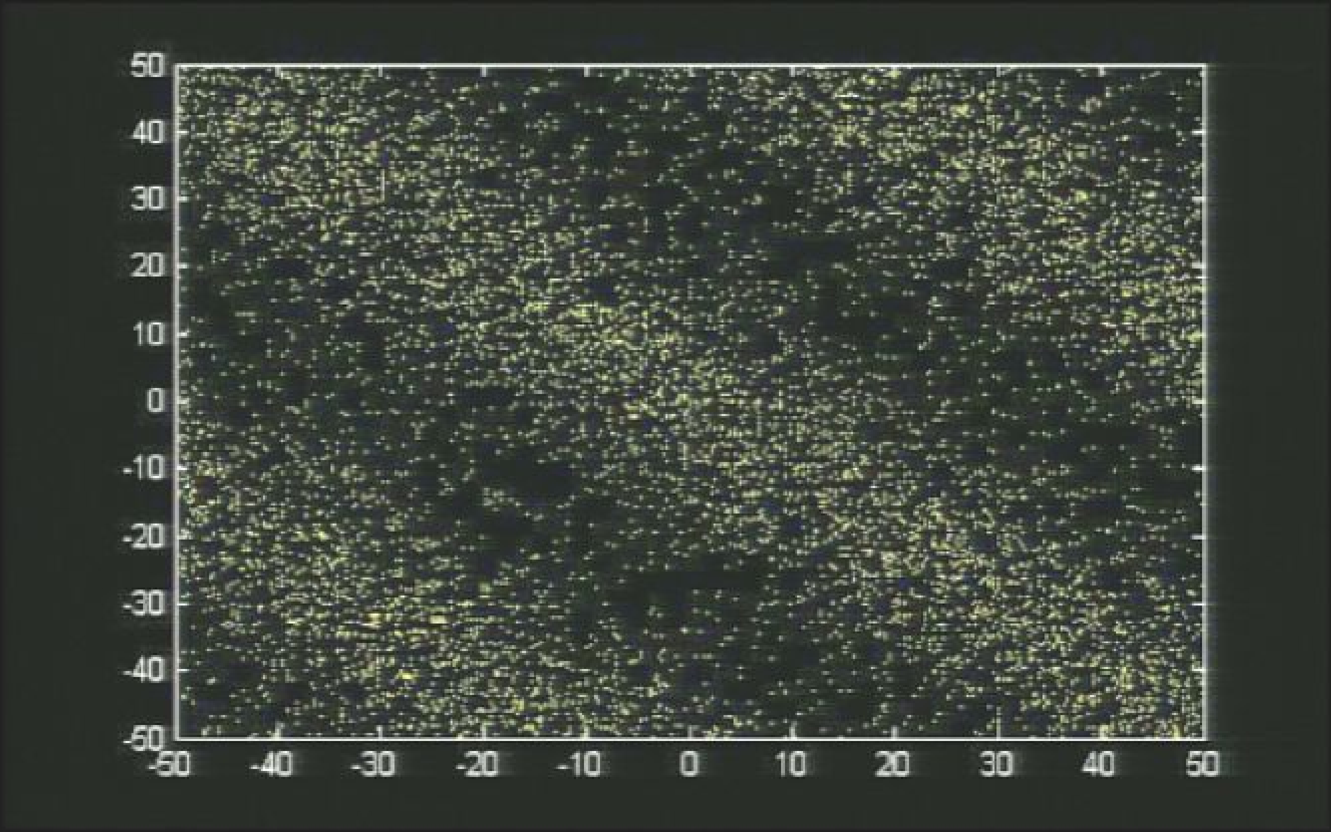
25 x Volume　　Fixed 50k points

Cosmic Variance



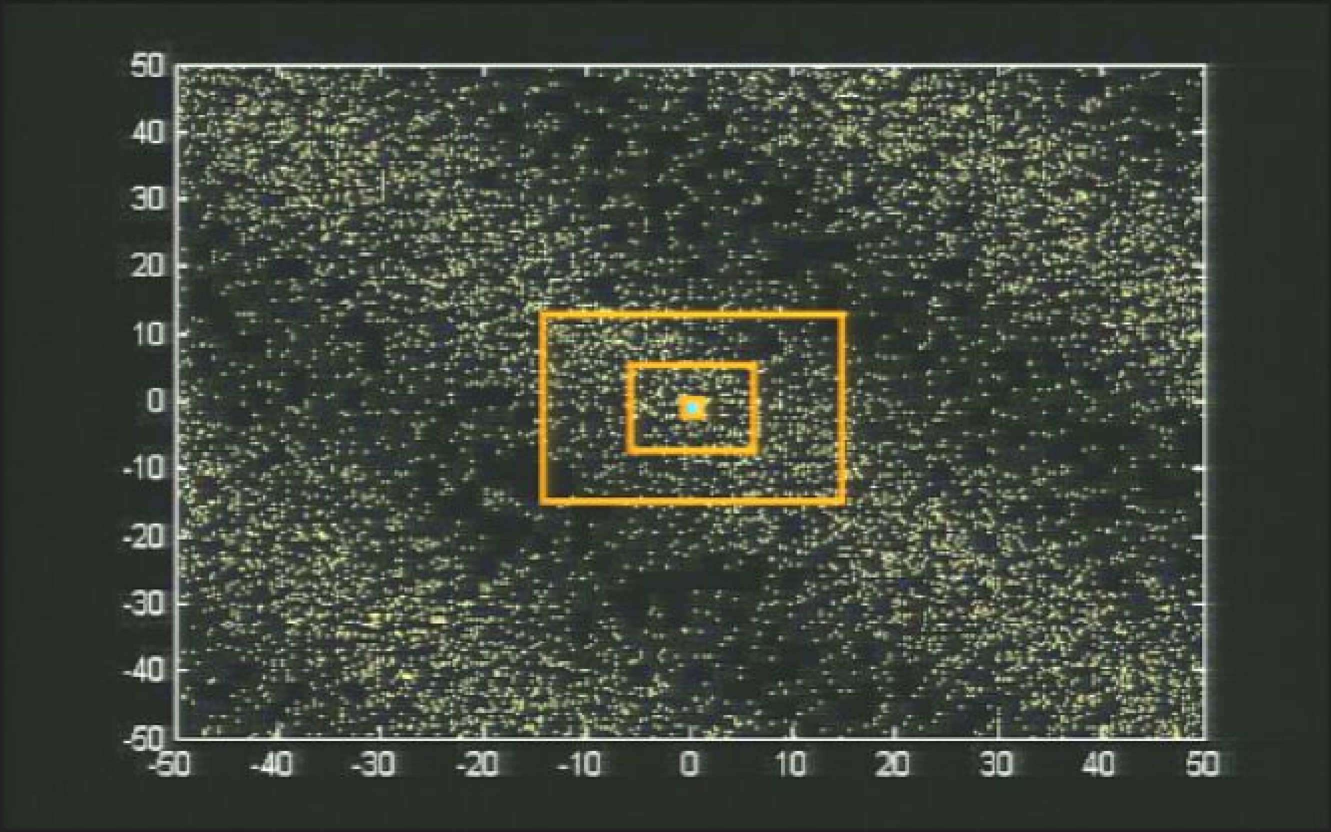
225 x Volume   Fixed 50k points

Cosmic Variance



2200 x Volume   Fixed 50k points

Cosmic Variance

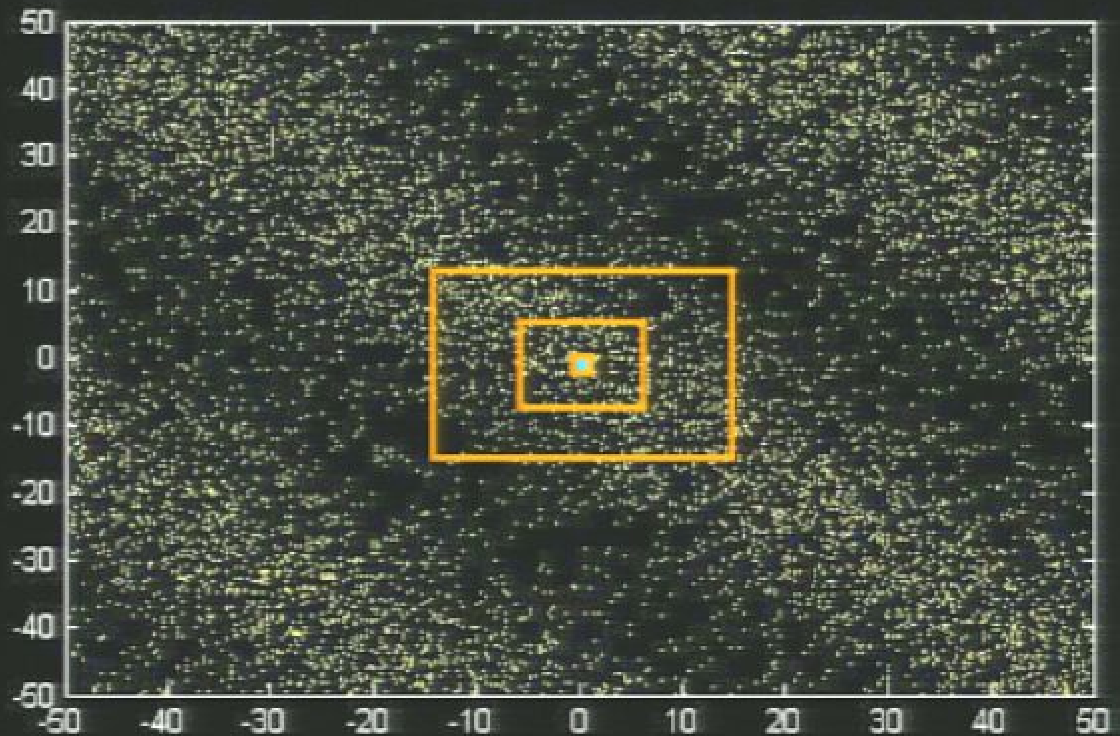


2200 x Volume Fixed 50k points

Optimal Survey Design

- What is the optimal sampling of a page of text?
- Depends what information you want.
- E.g. what language it is written in…
- E.g. what page layout is being used…
- Trade-off between the two…
- $nP \sim 1\text{-}5$ is optimal

Cosmic Variance



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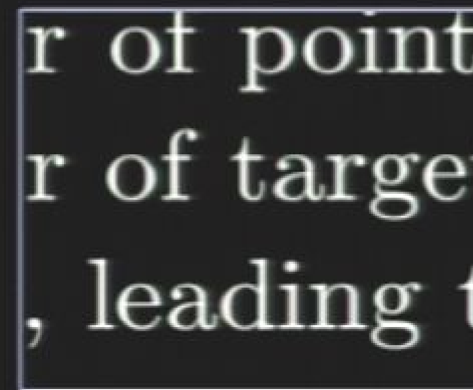

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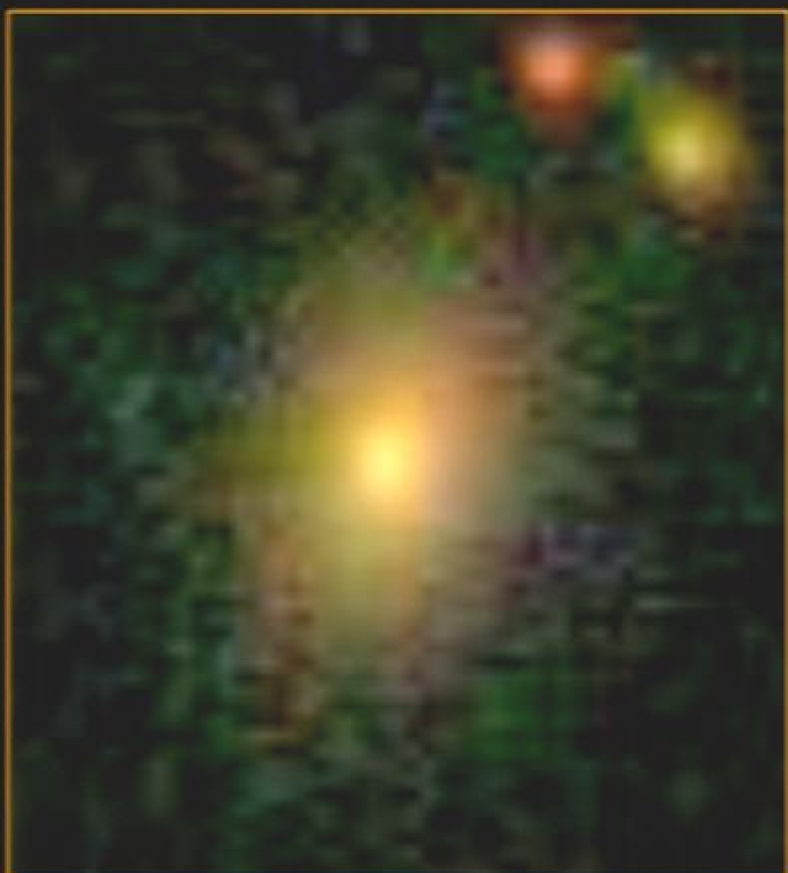
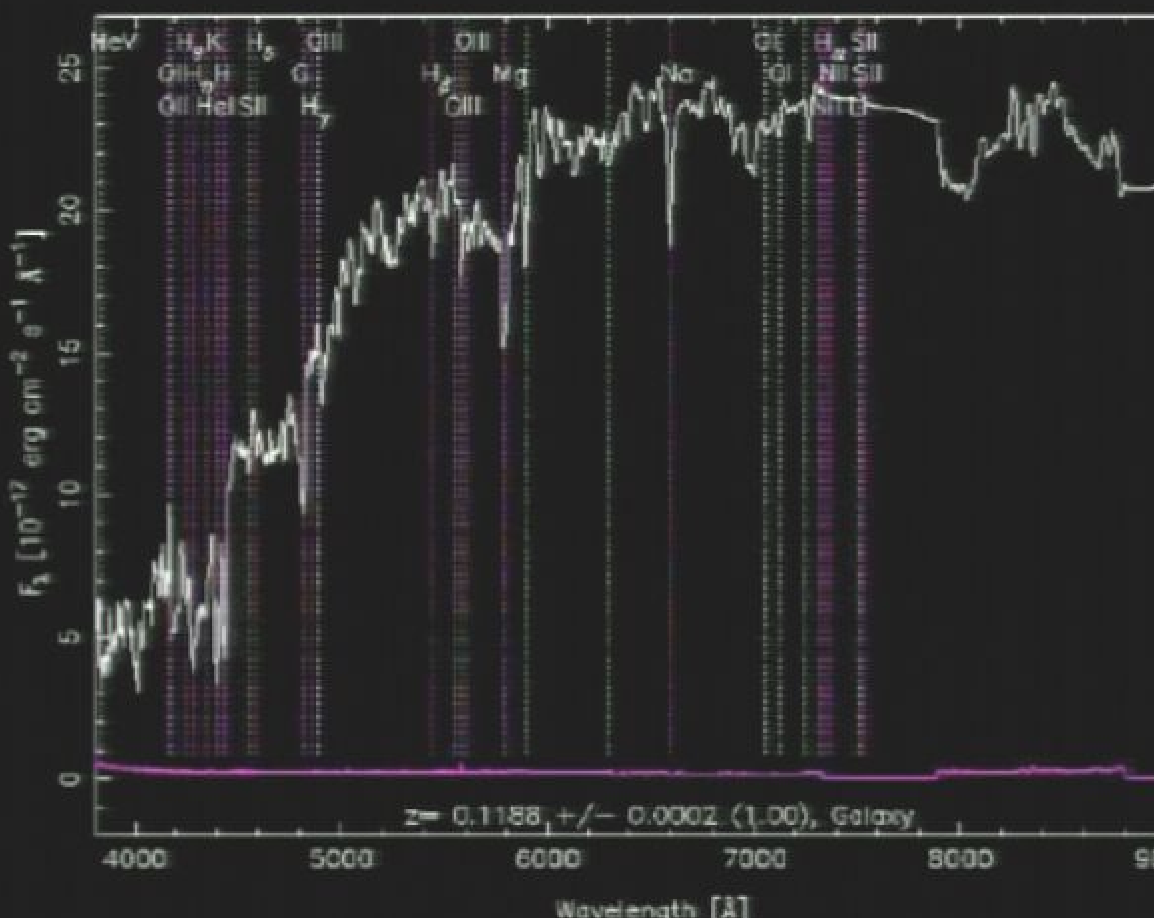
BAO Targets

What targets should one use for measuring the BAO? Options are:

- Luminous Red Galaxies (LRGs)
- Star-forming galaxies (blue)
- Neutral Hydrogen (HI)
- Lyman alpha forest

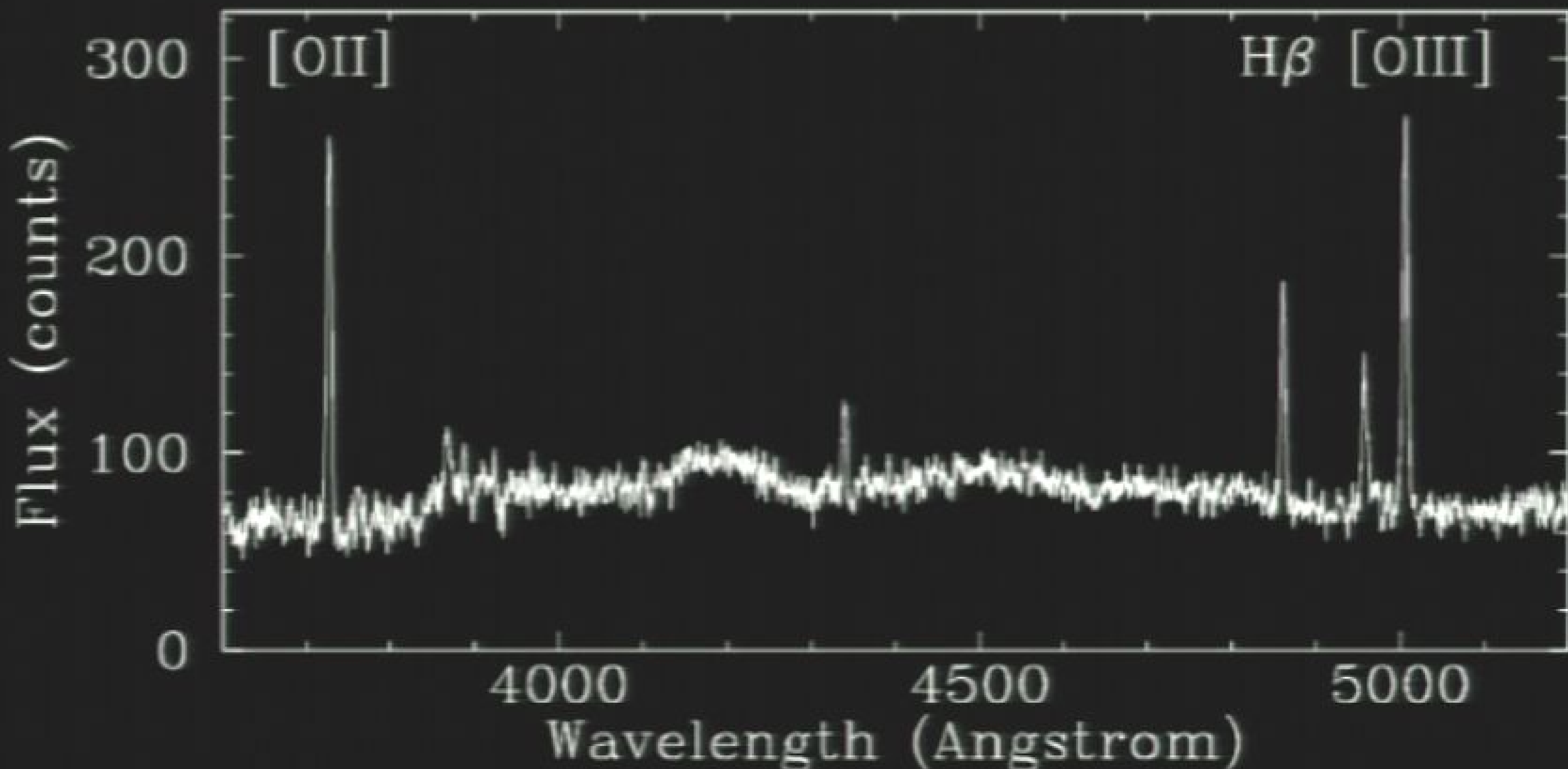
LRGs





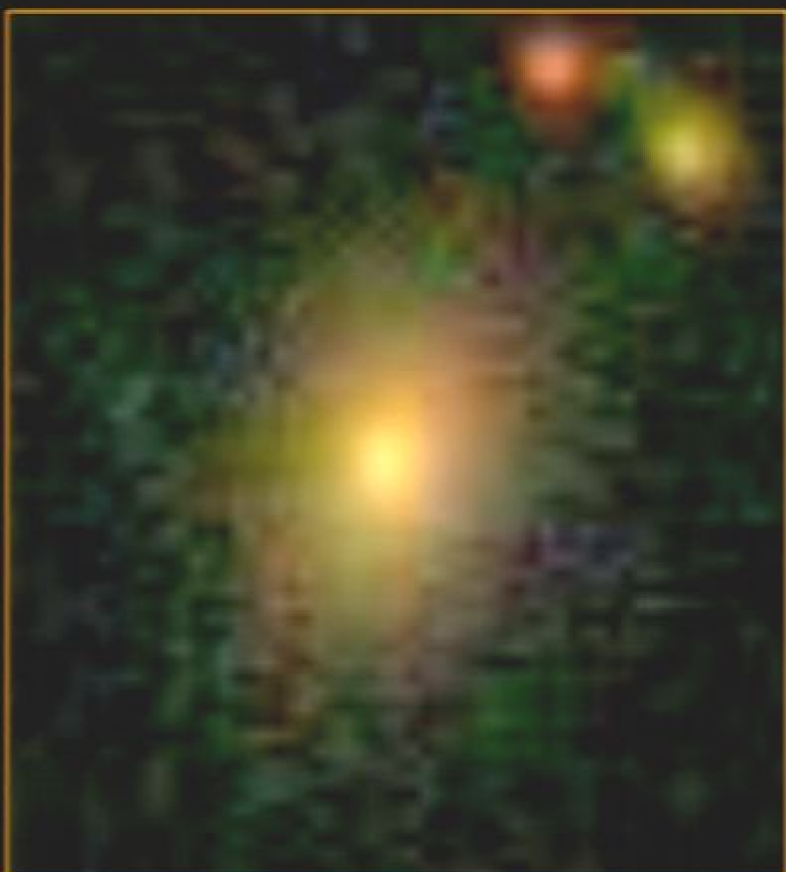
- Used by SDSS, BOSS and LAMOST

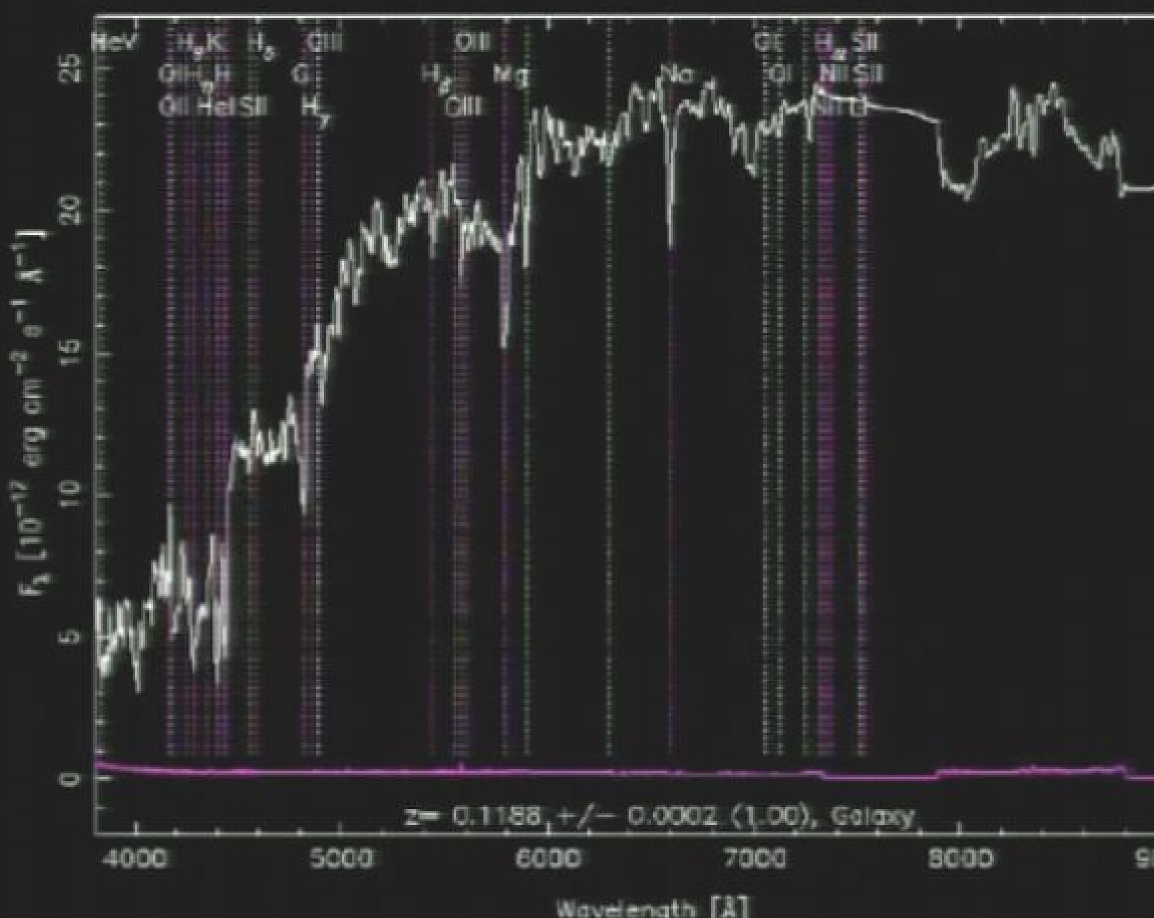
Blue, star-forming galaxies



- Used by WiggleZ, preferred for 8m class

LRGs





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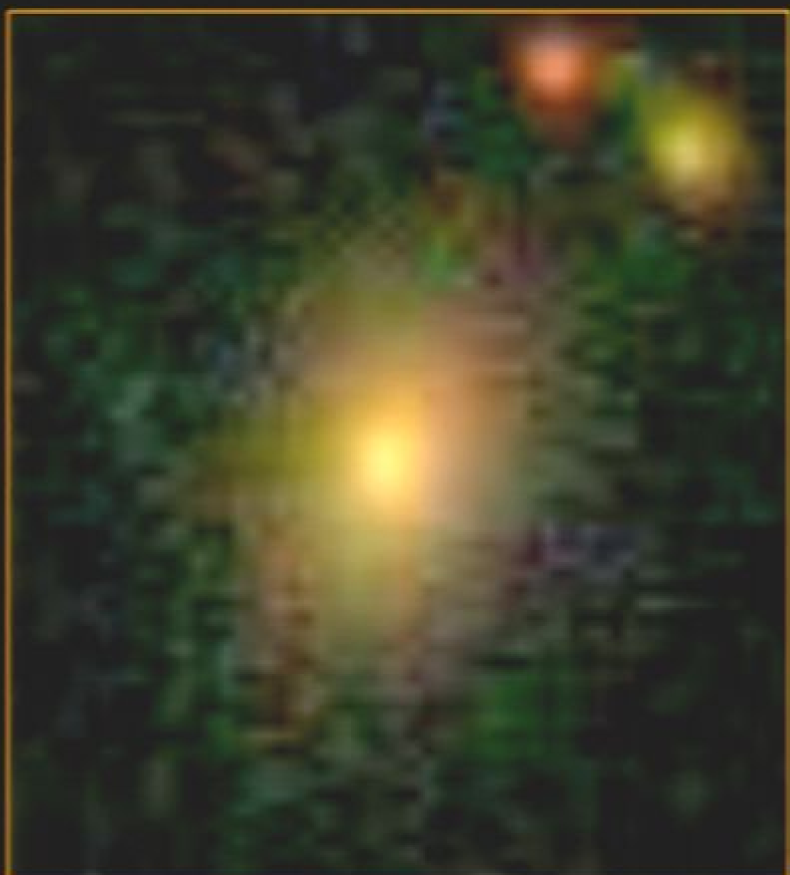

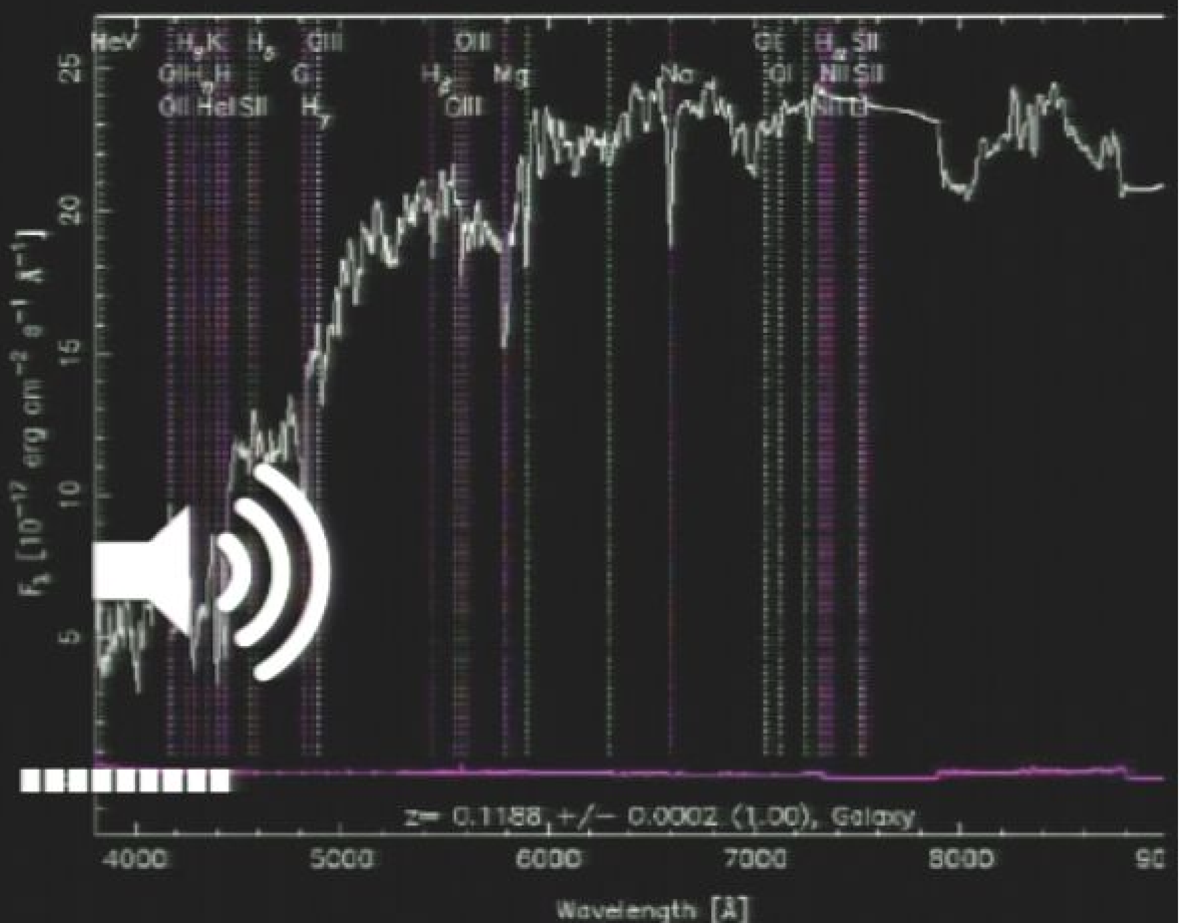

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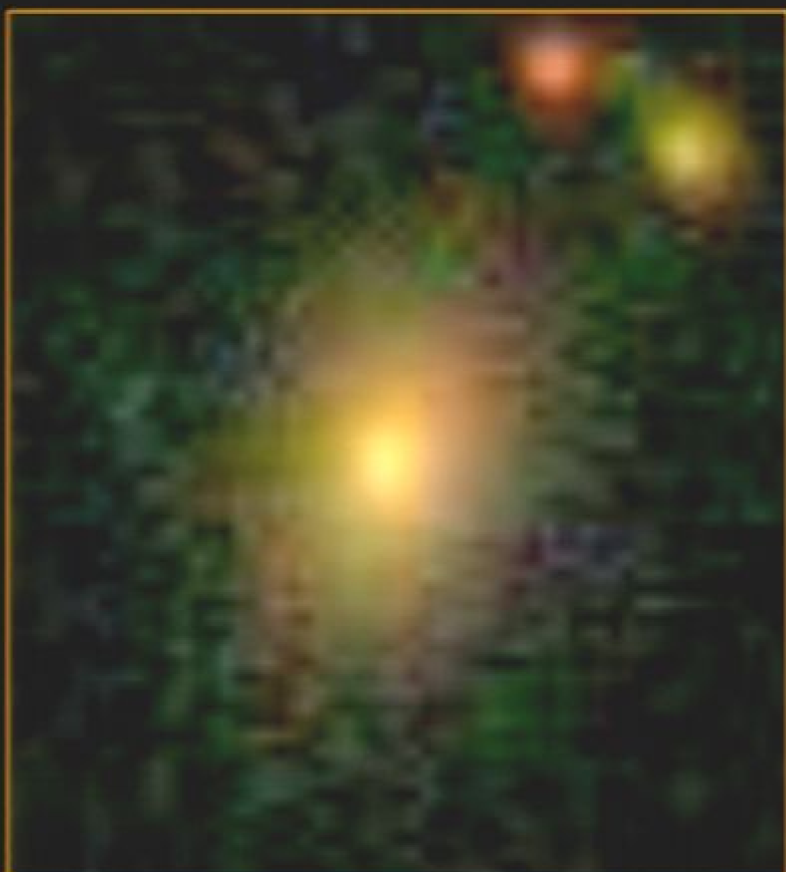

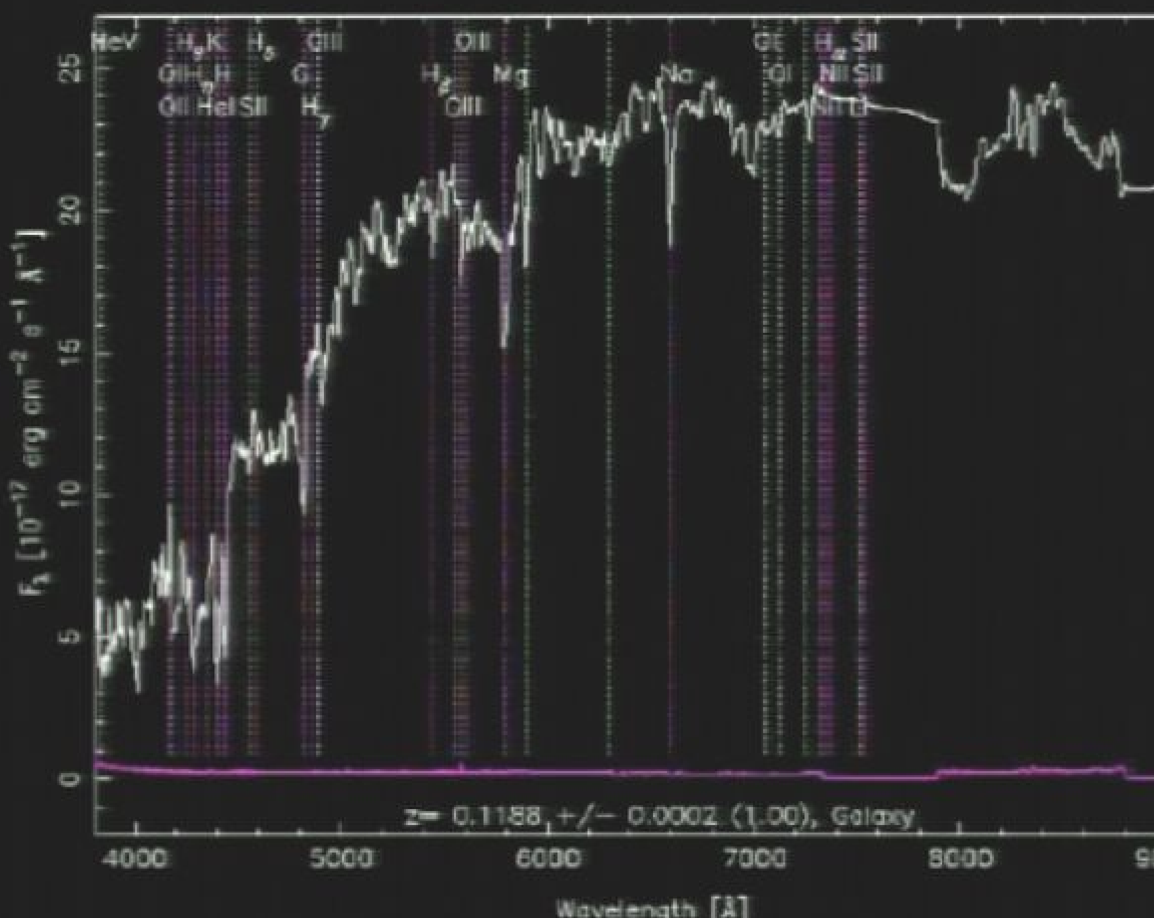

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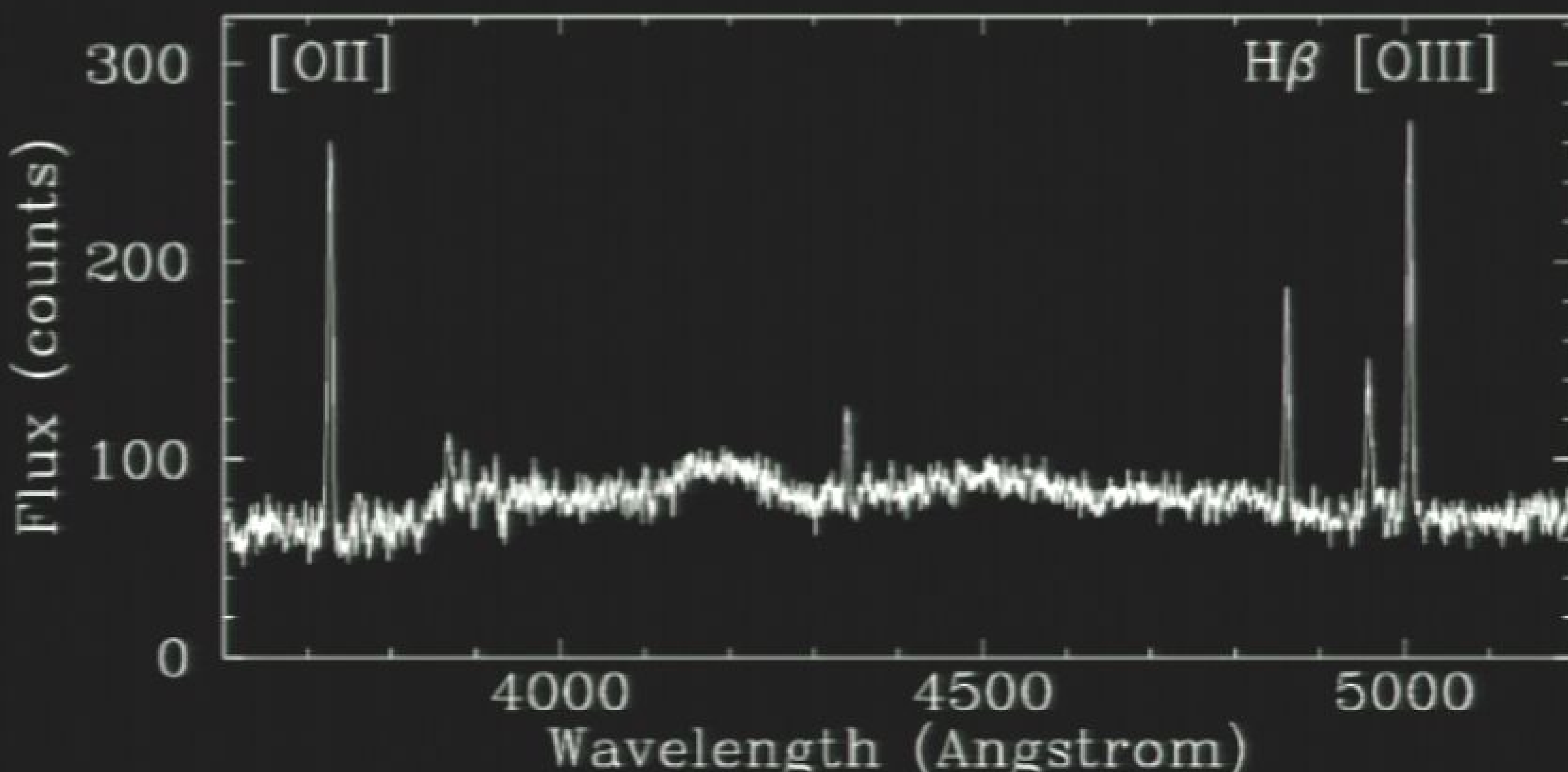

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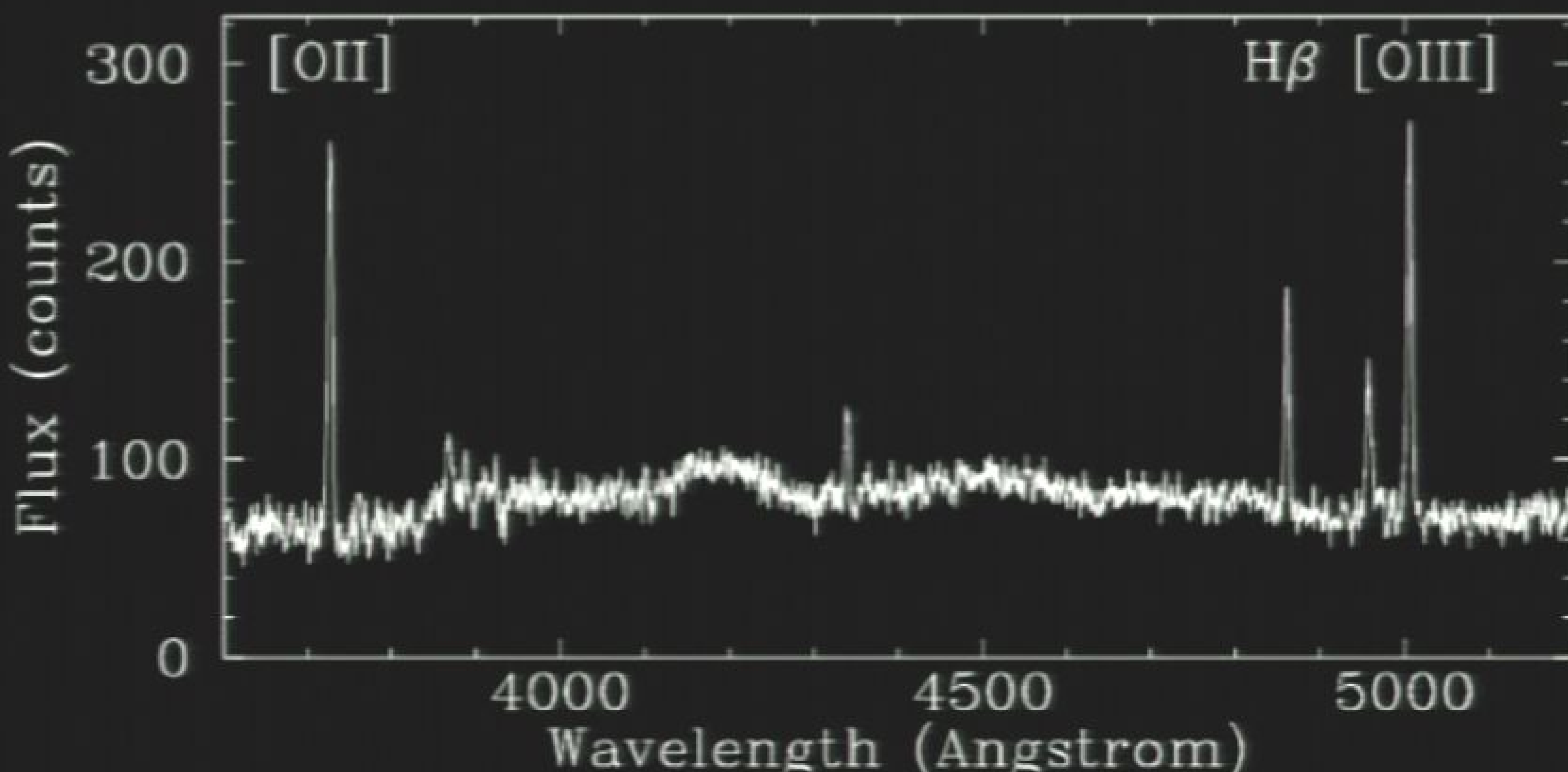

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Neutral Hydrogen (HI) and Lyman Alpha Forest

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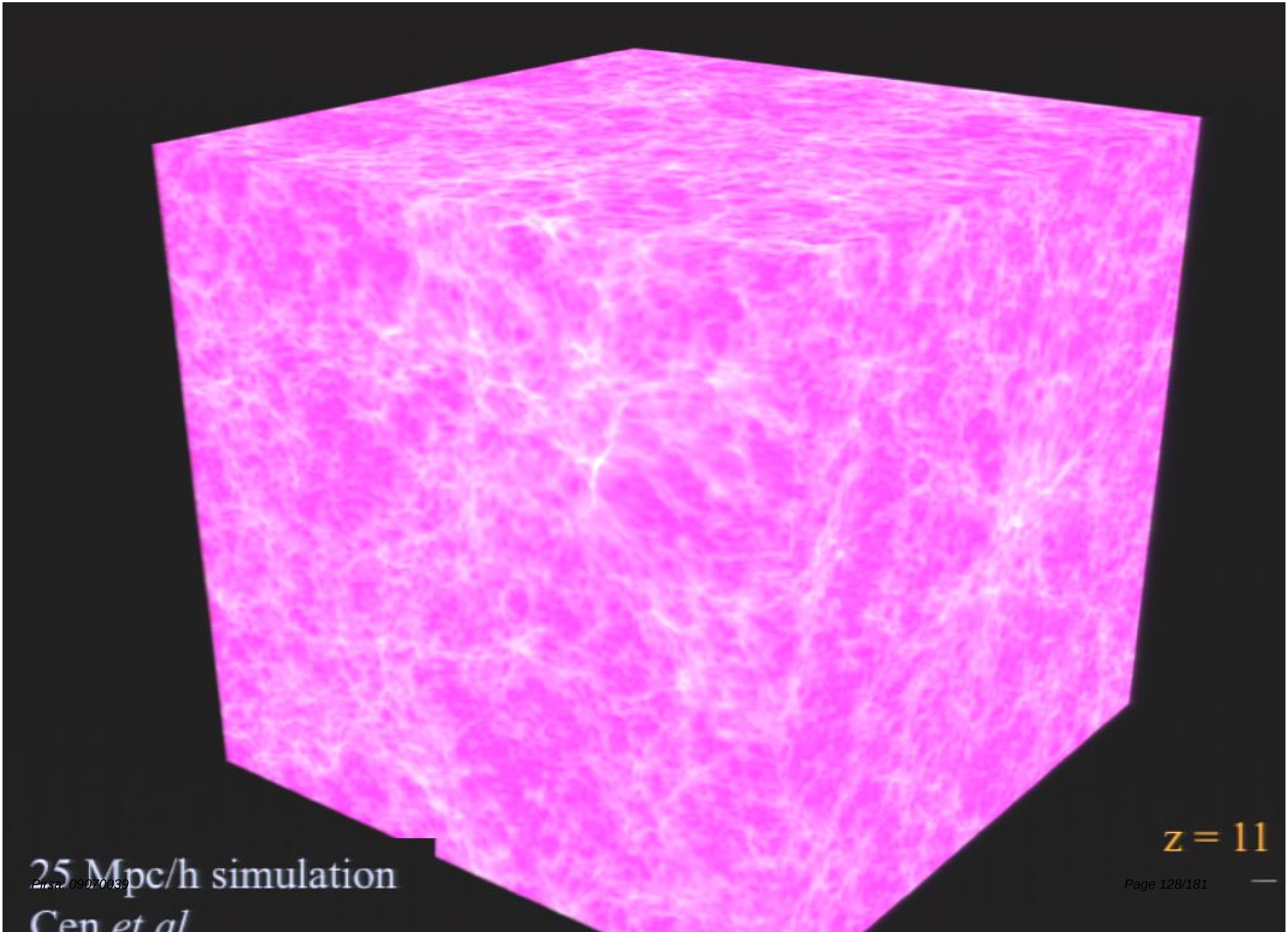
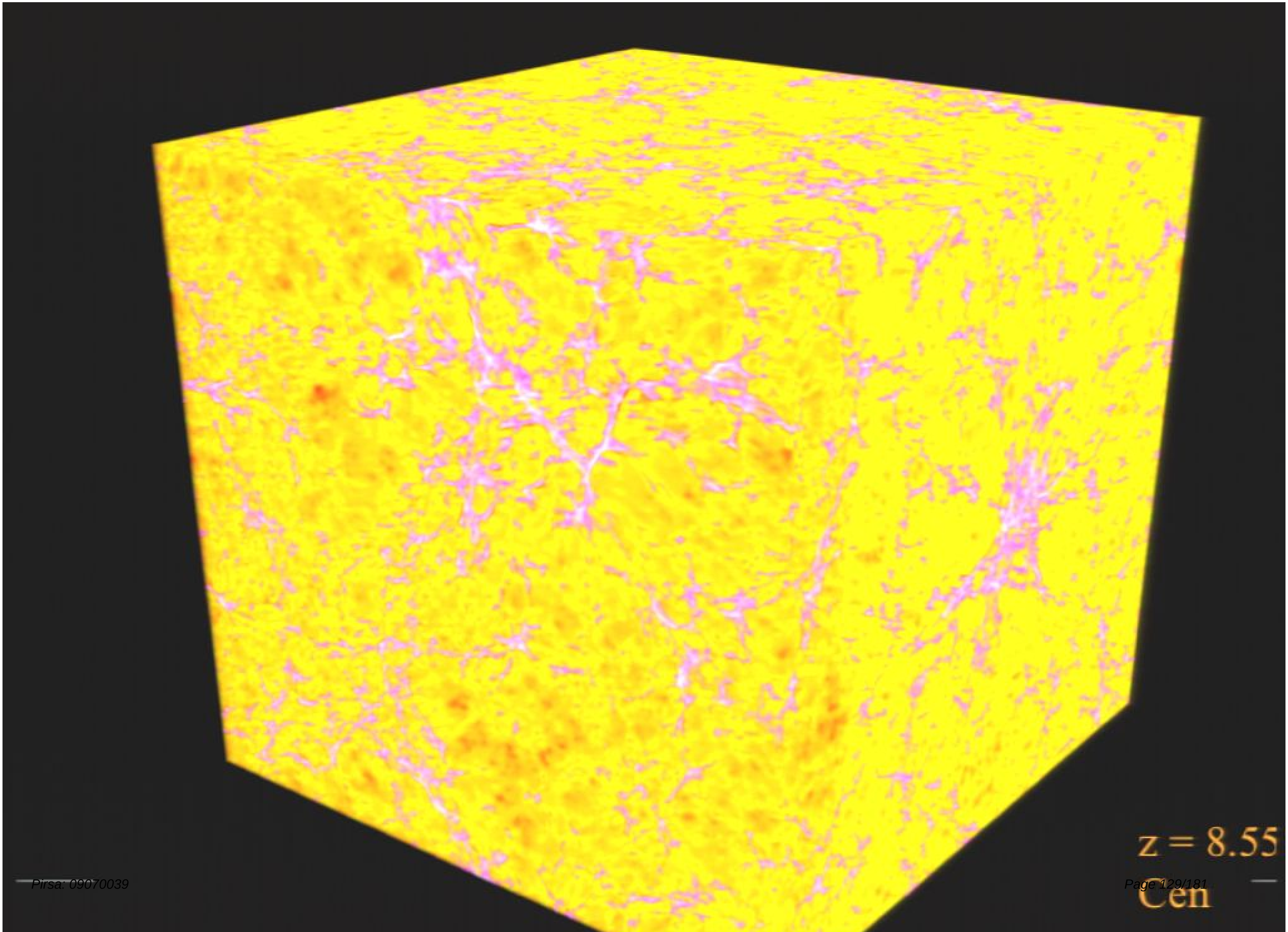
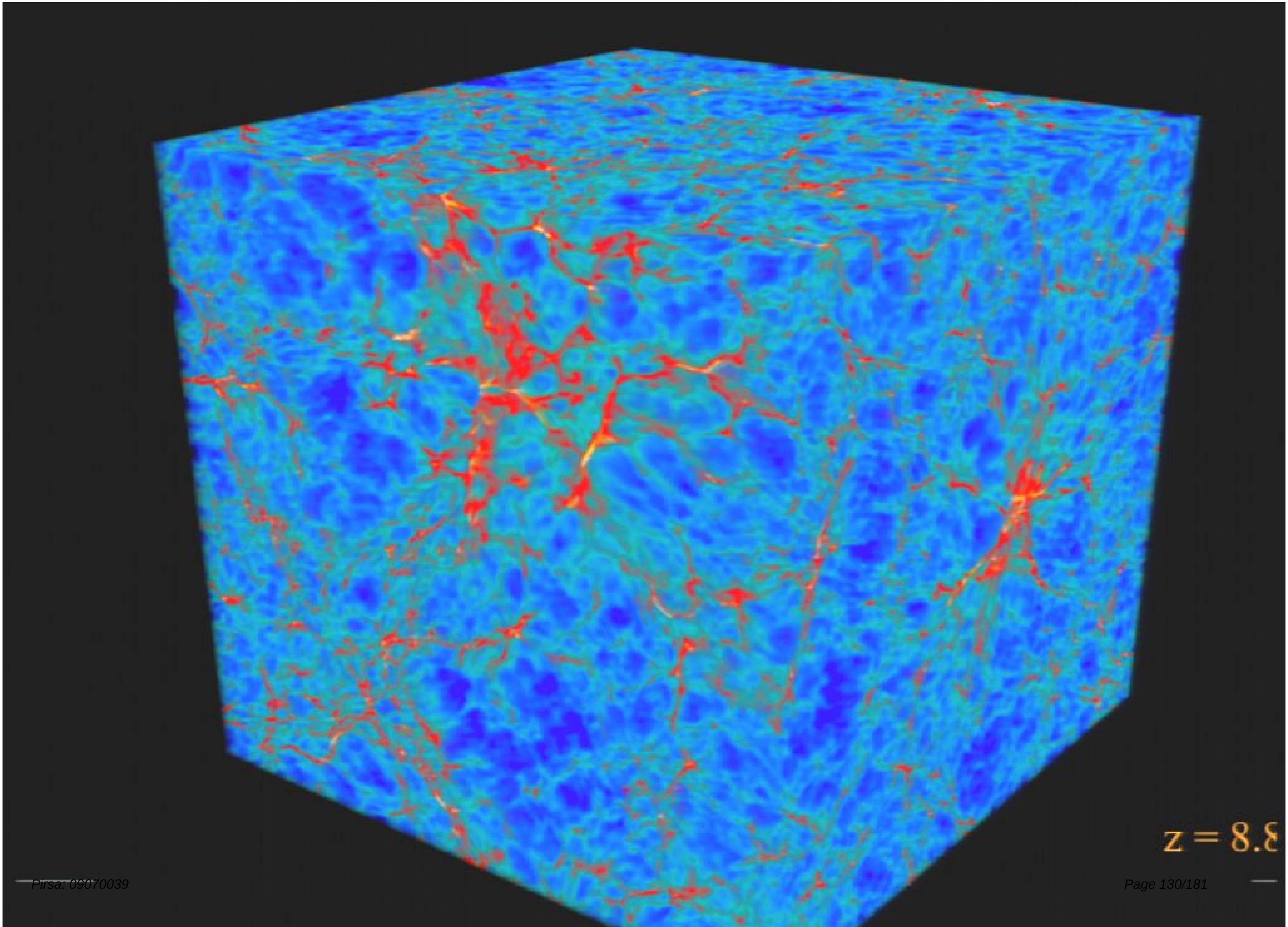
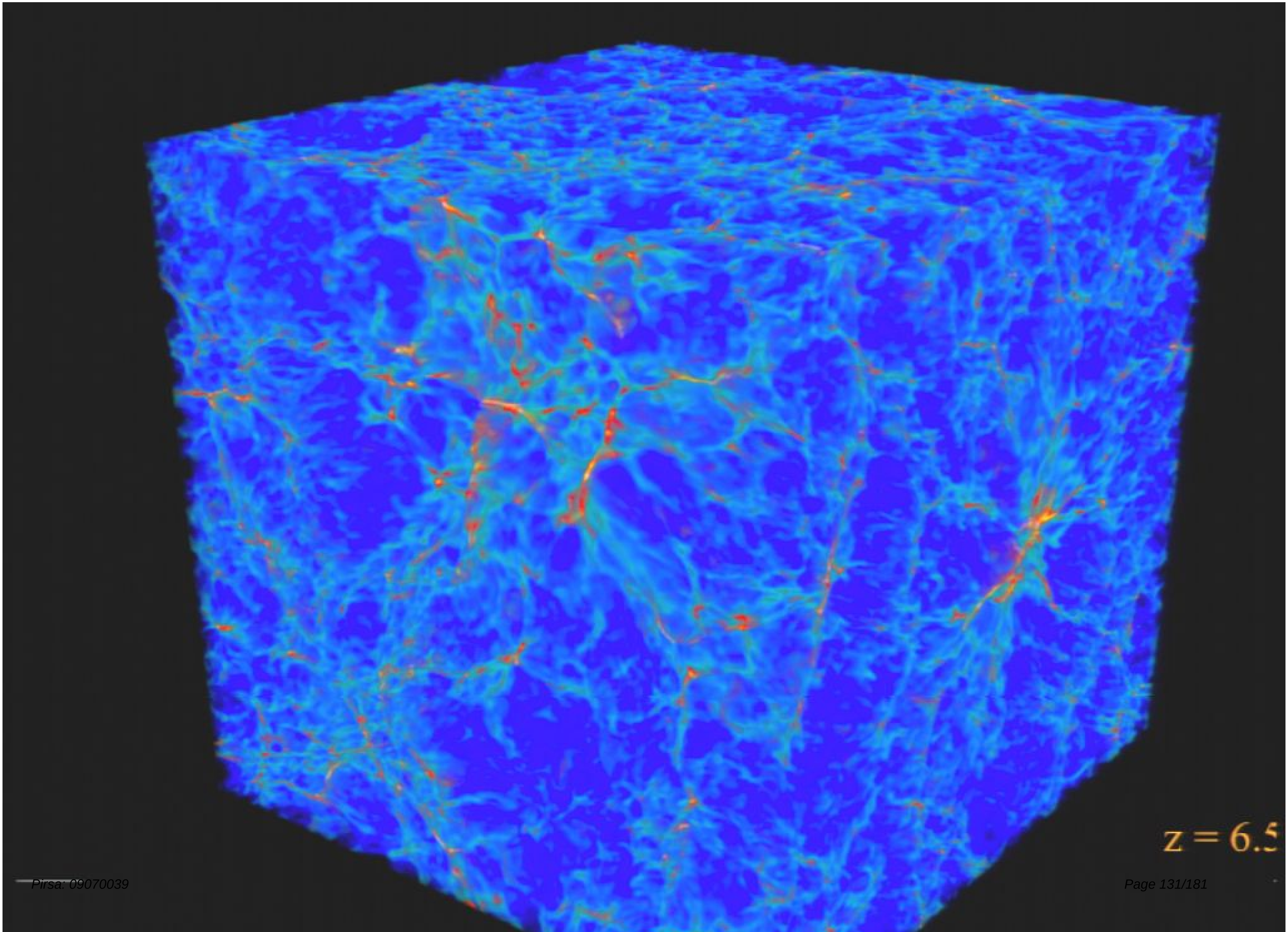
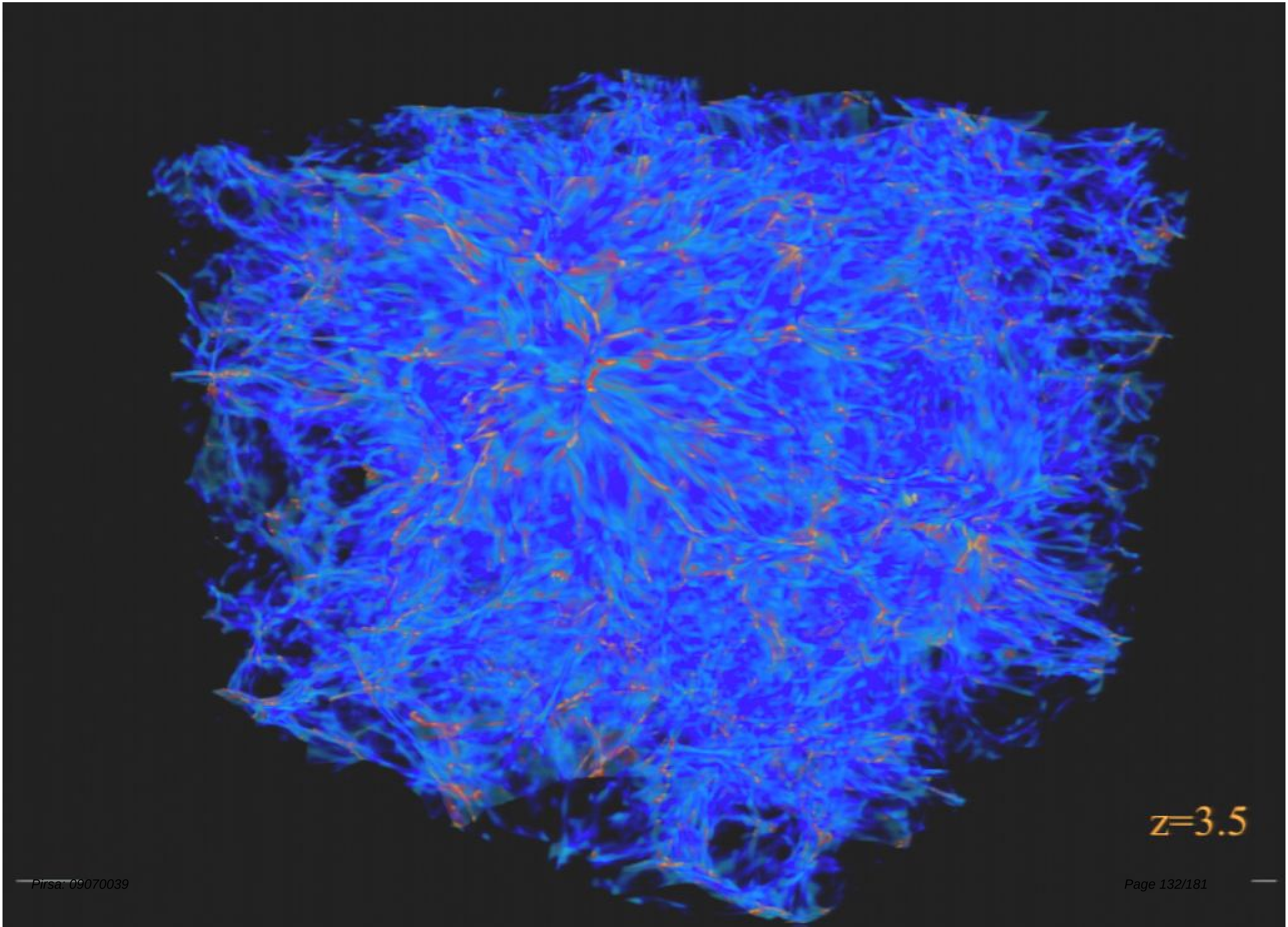
- Both of these can be used to map neutral hydrogen when the nonlinear scale was very small.

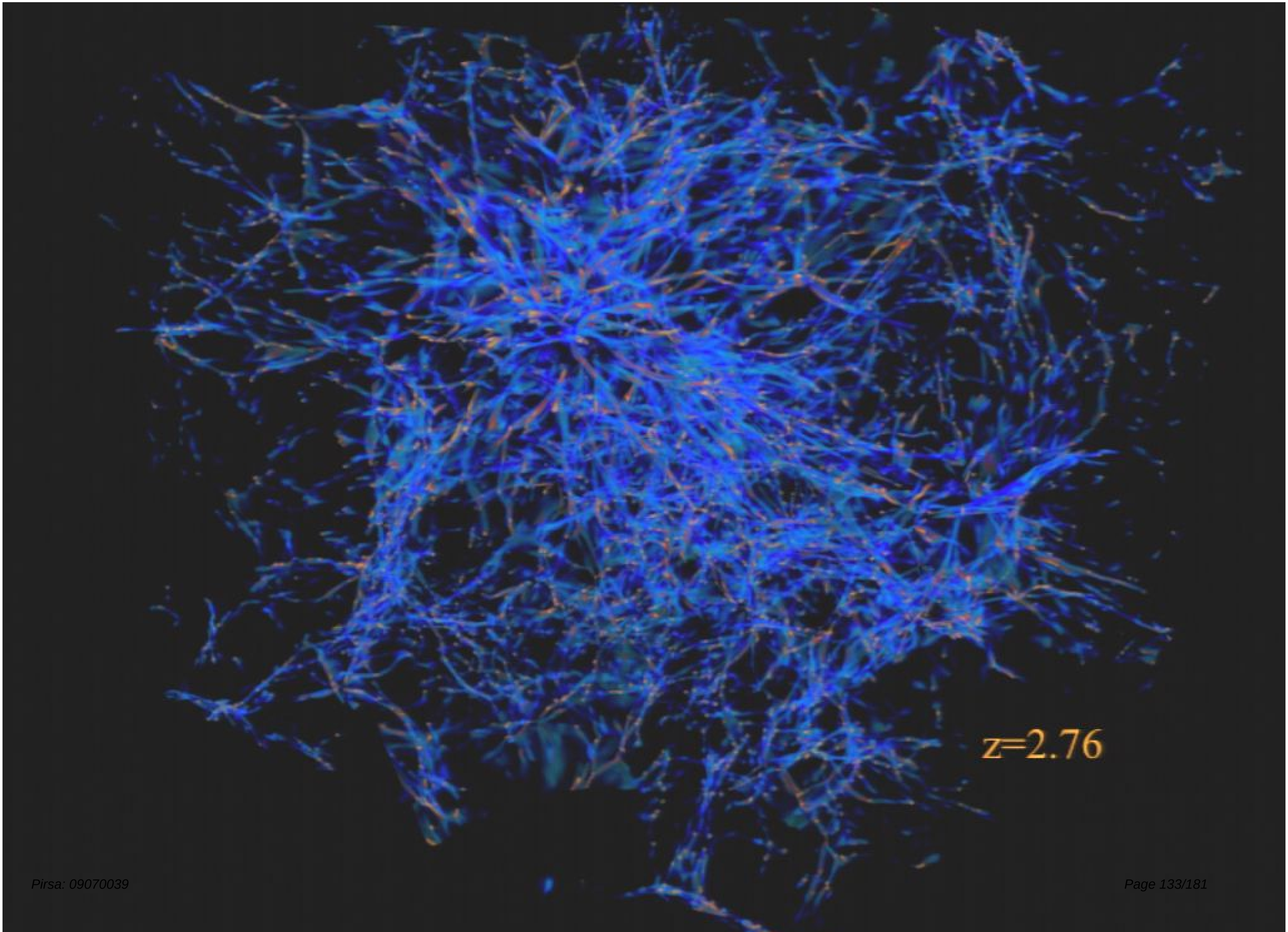

z = 11
25 Mpc/h simulation
Cen *et al*


z = 8.55
Cen

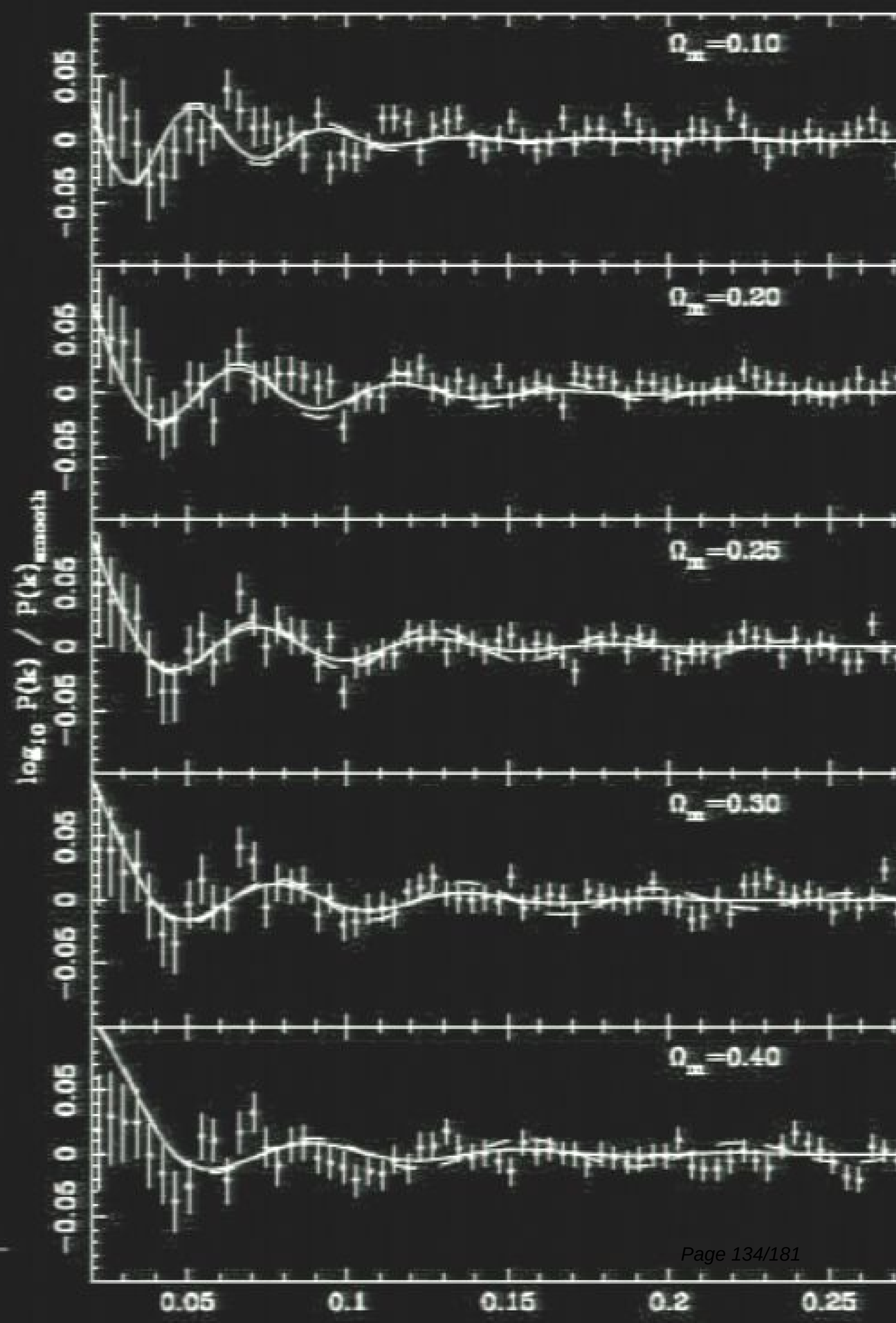

z = 8.8


z = 6.5


z=3.5


z=2.76

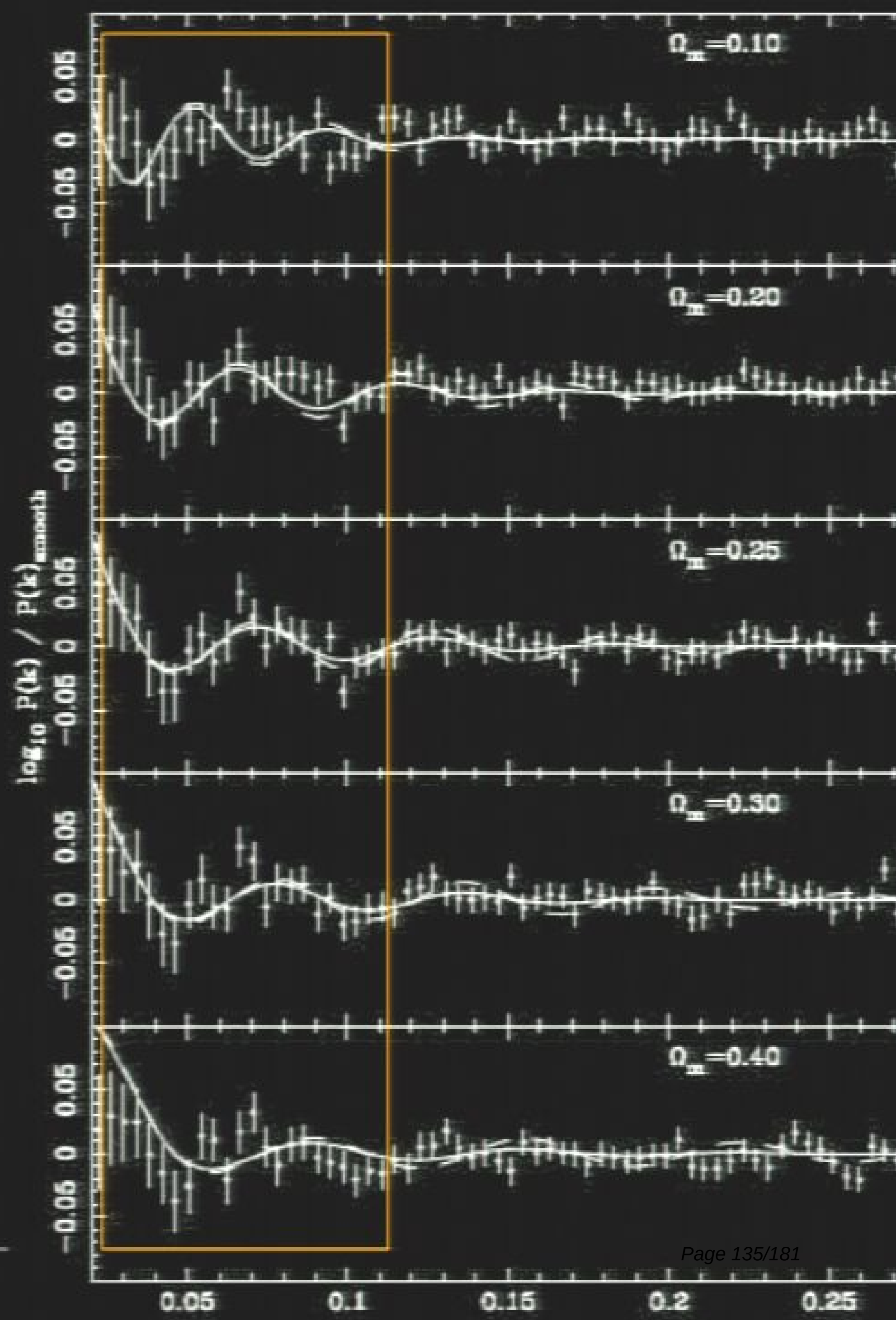
Current Data



Percival *et. al.* '07

Current Data

- Just the BAO wiggles
- Produced for SDSS + 2df galaxies combined



Percival *et. al.* '07

BAO

have provided the *first* ever cosmic distance measure based on *linear* physics

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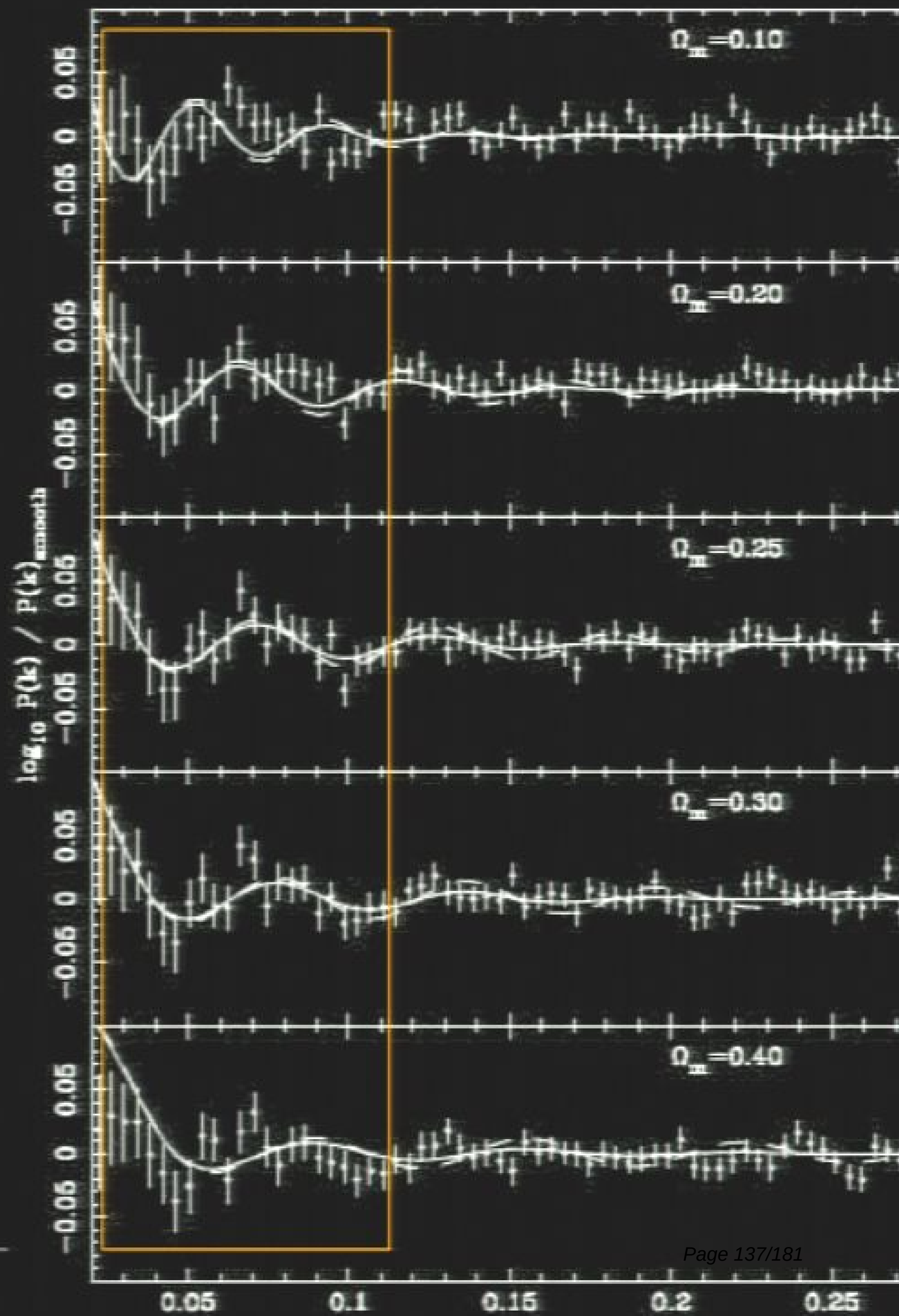

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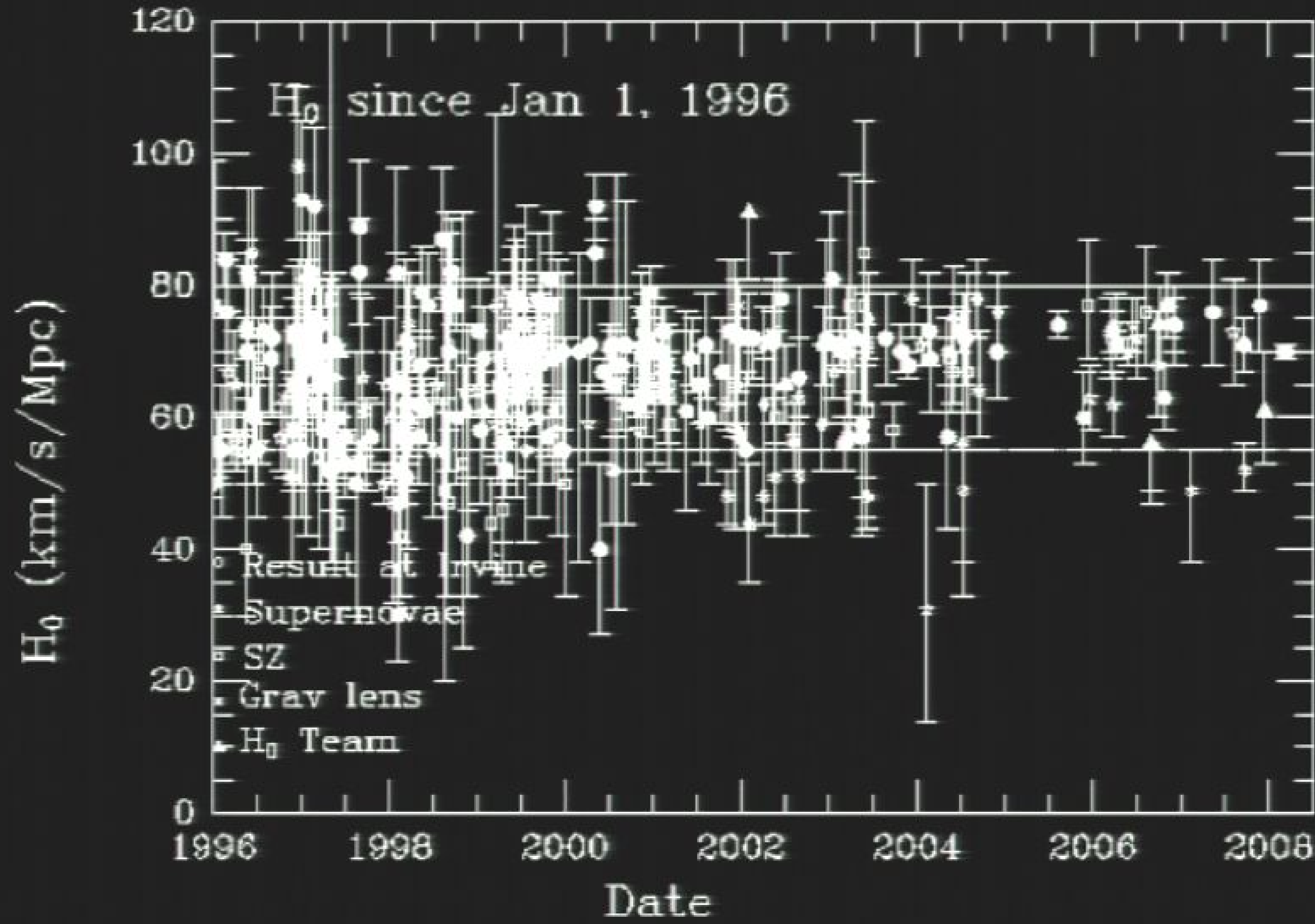

H0 since Jan 1, 1996
H0 (km/s/Mpc)
Date
Result at Irvine
Supernovae
SZ
Grav lens
H0 Team
120
100
80
60
40
20
0
1996
1998
2000
2002
2004
2006
2008

J. Huchra

Complications

A man falls from a window and on the way down someone asks…``*how's it going*''?

The man replies: "*So far so good!*"

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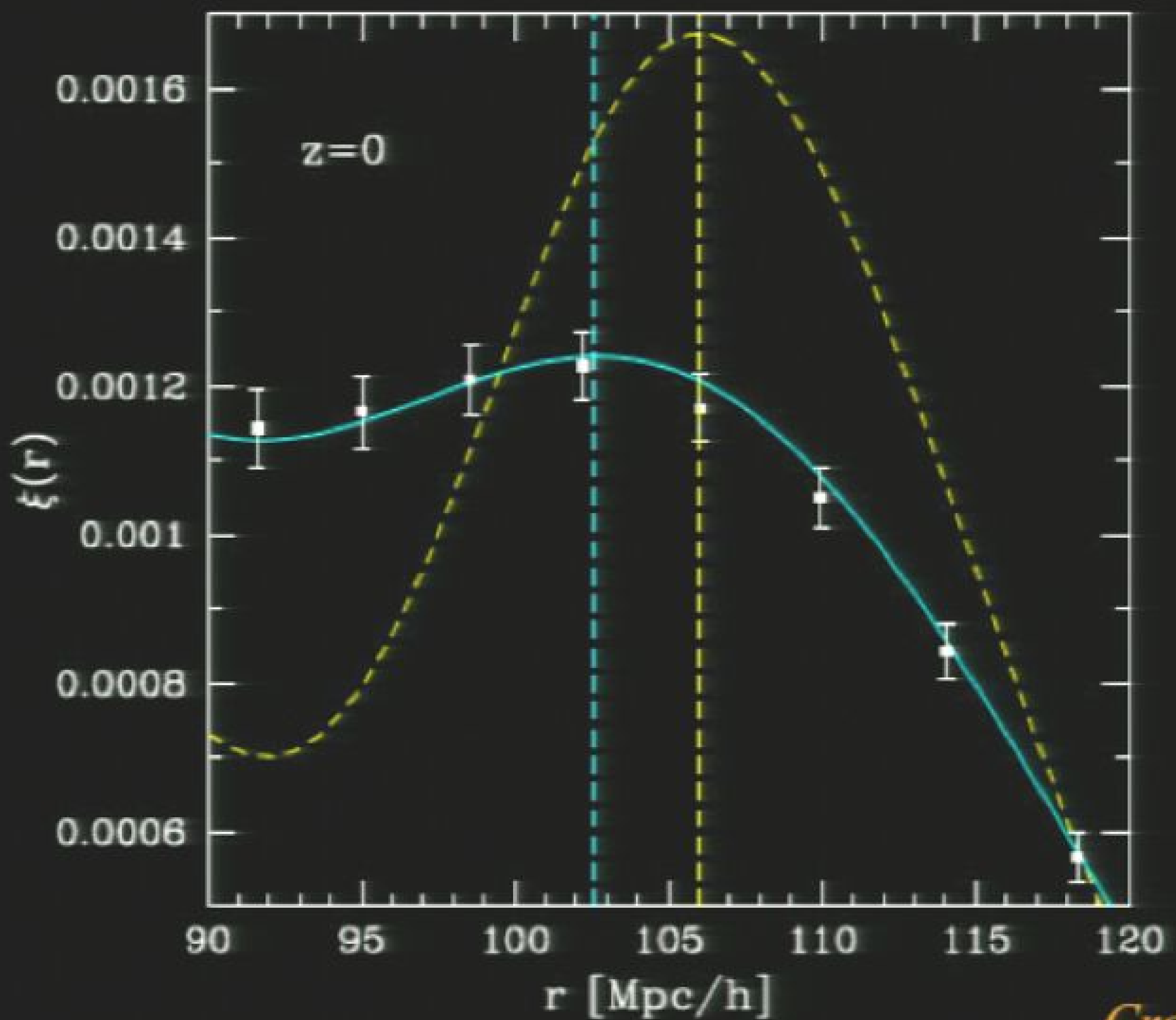
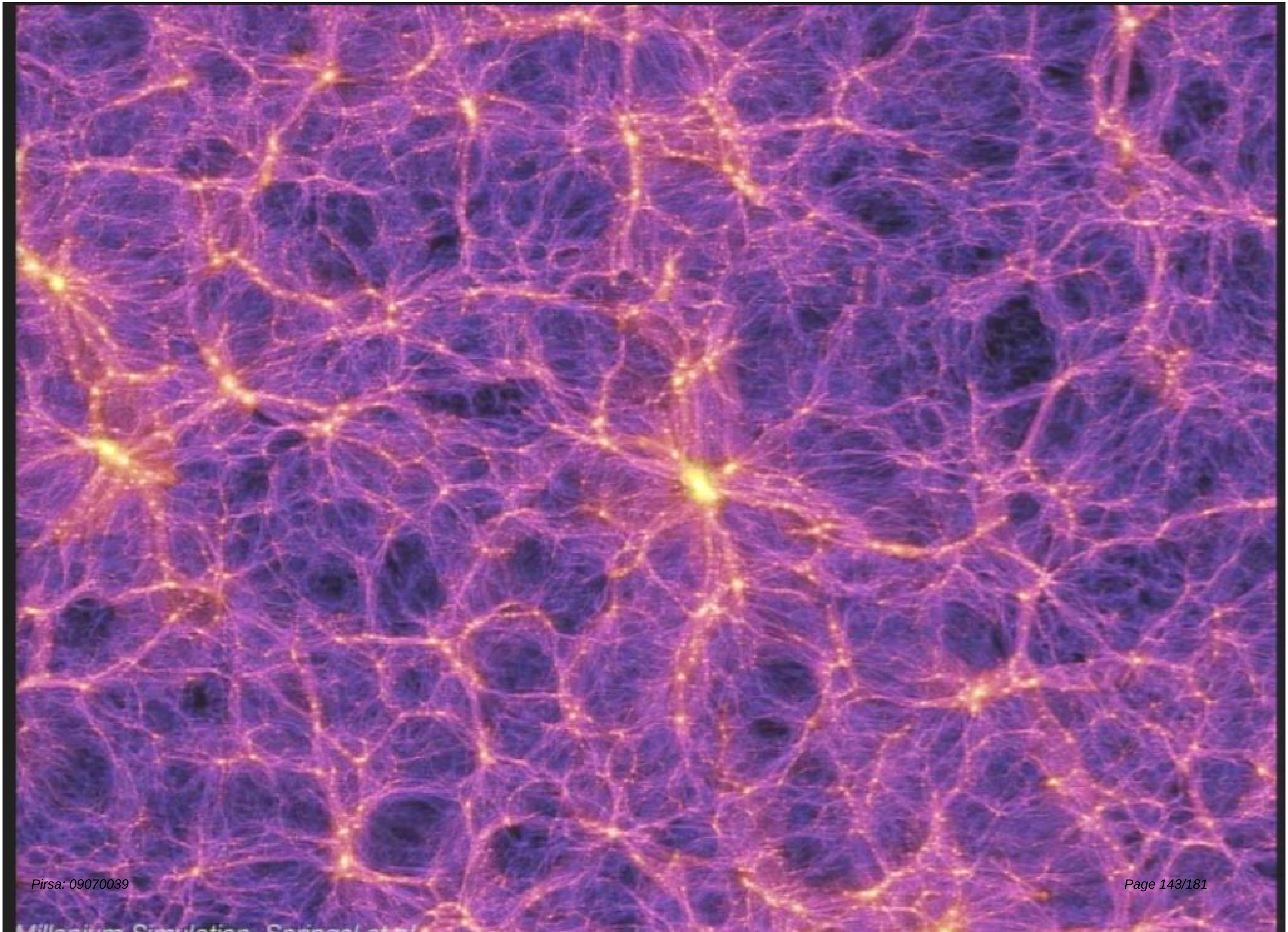
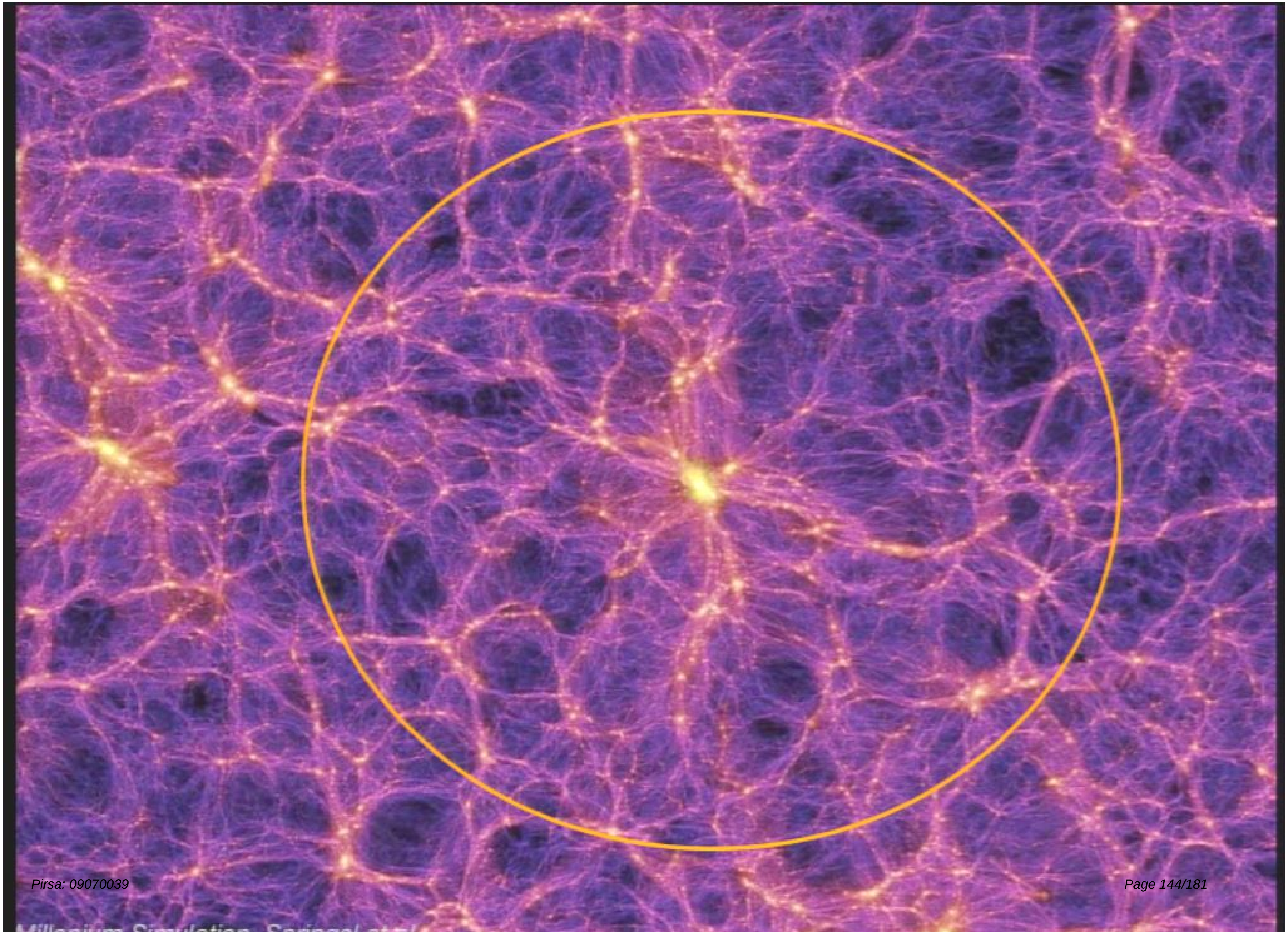
Cosmological Methods are similar – they have a free-fall zone and a hard, systematic "floor" where things get tough

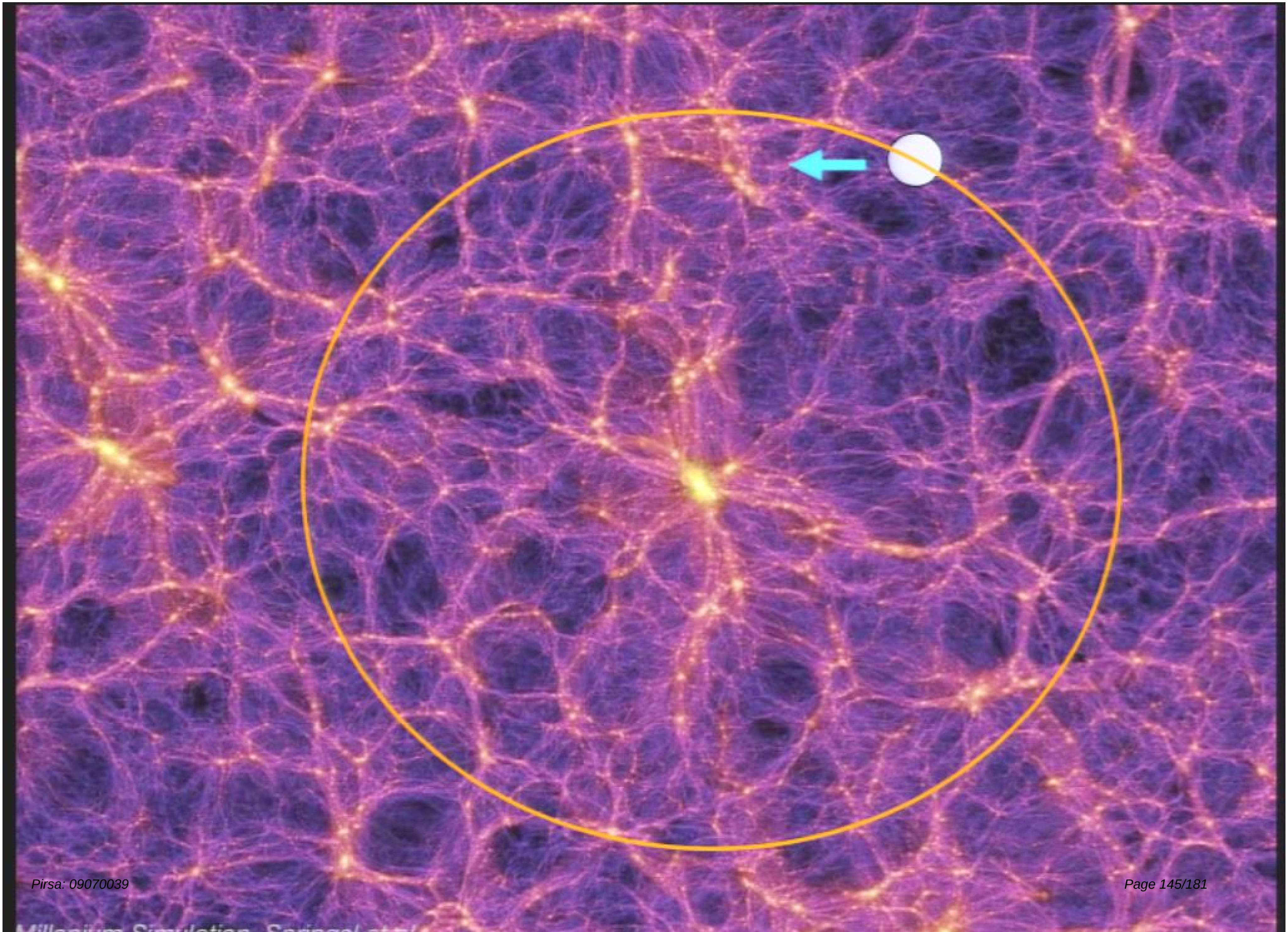
BAO and Nonlinearity

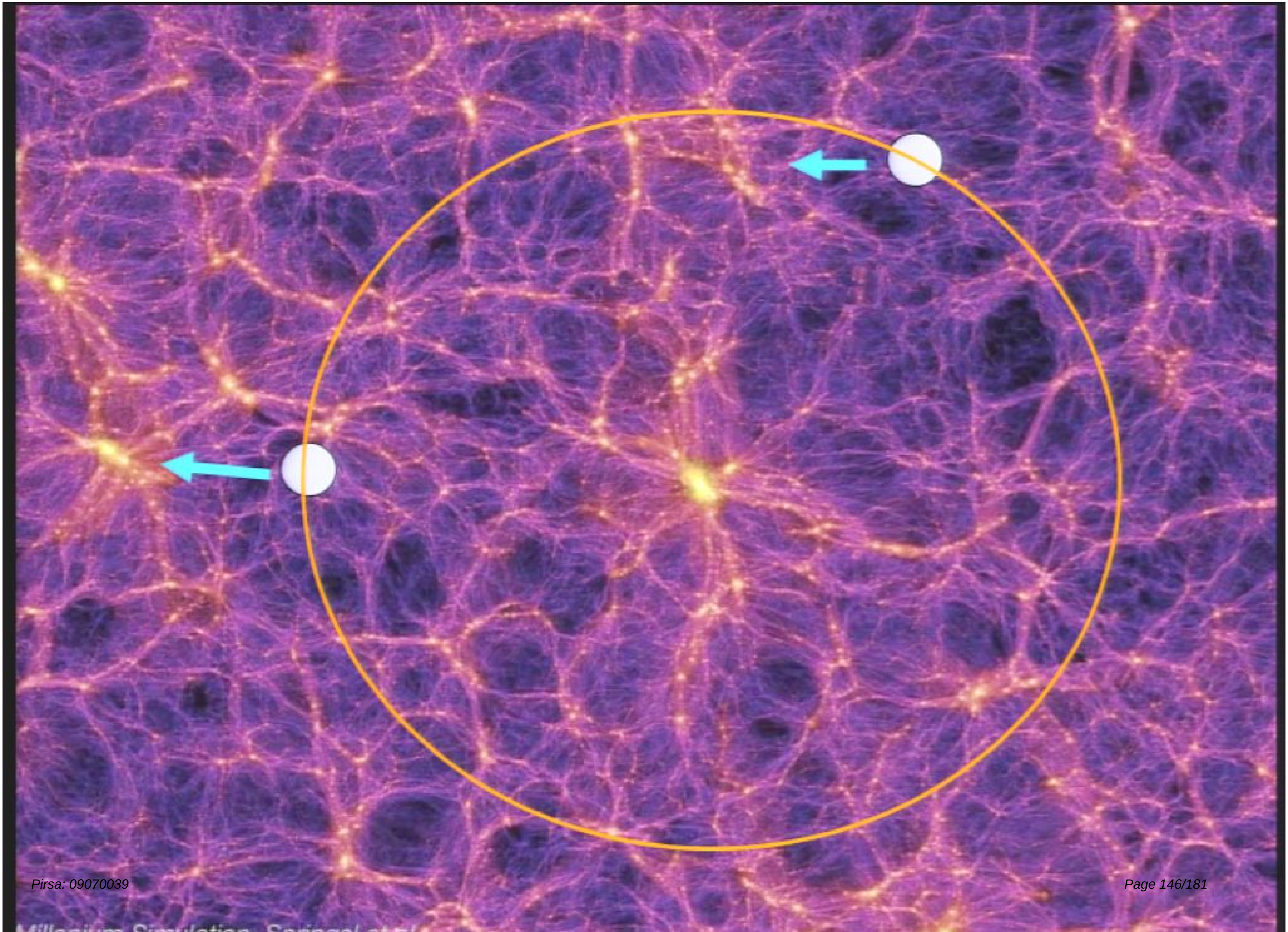


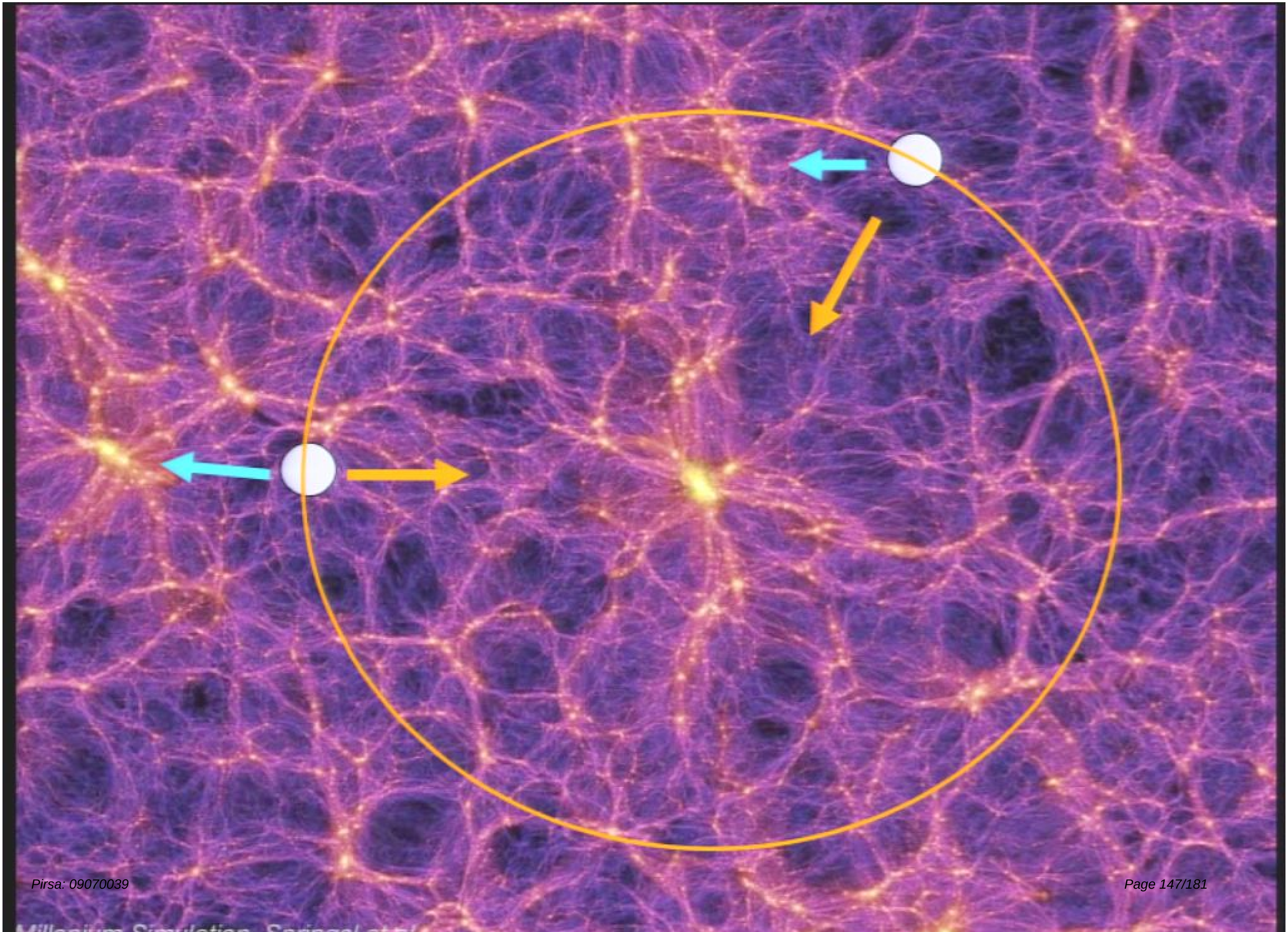
Crocce et al

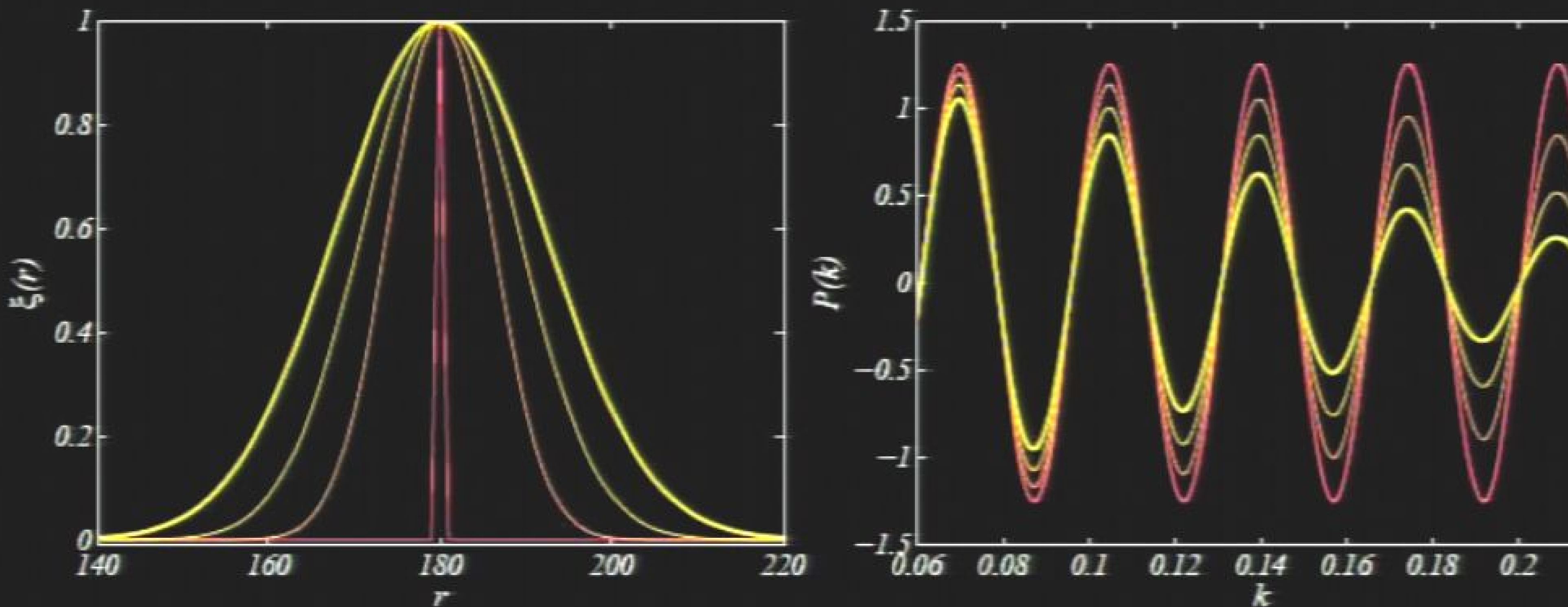




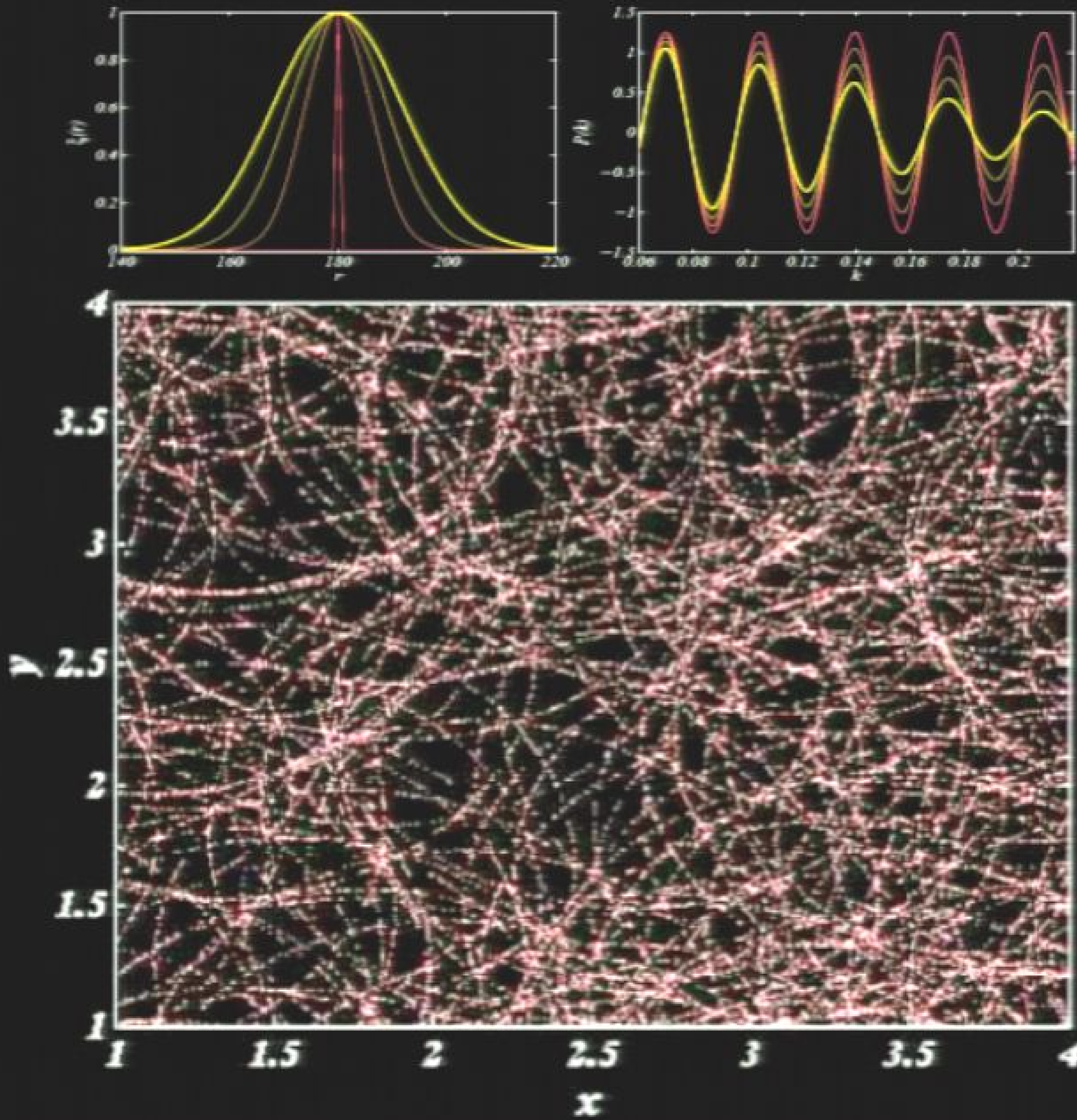




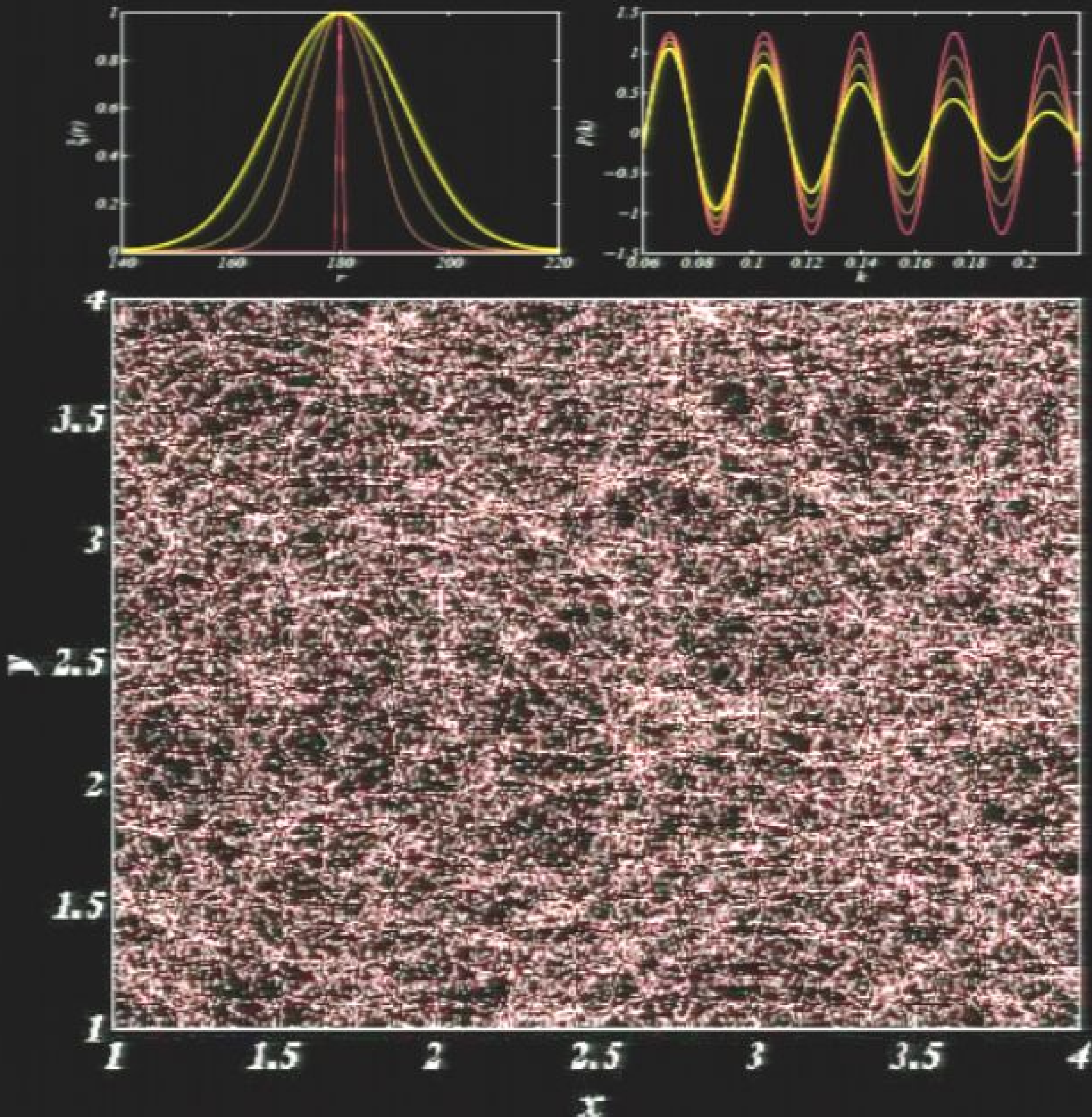




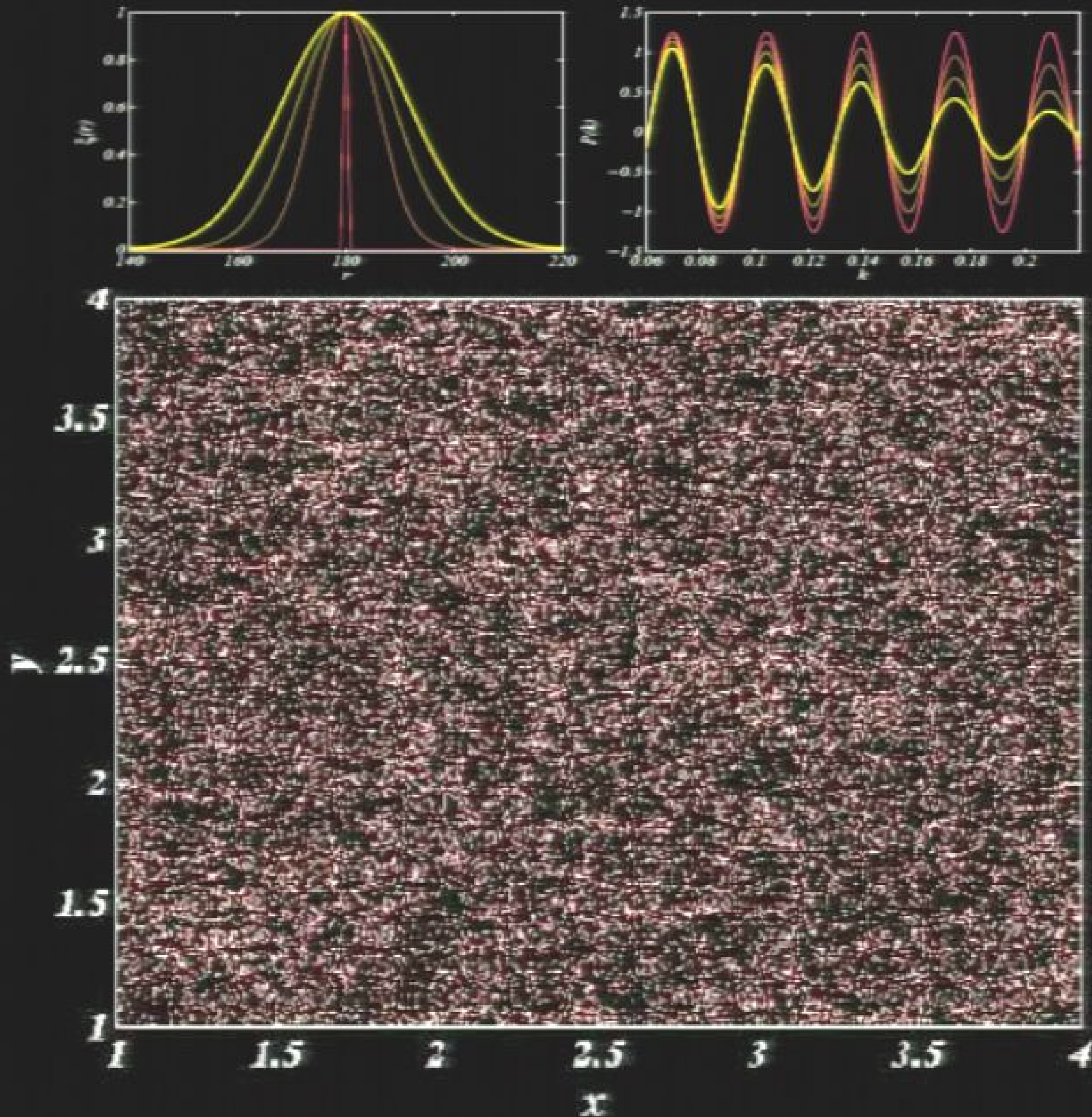
$\xi(r) \Longleftrightarrow P(k)$



140
160
180
200
220
r
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
k
1
1.5
2
2.5
3
3.5
4
x
y



y
x



ξ(r)
r
P(k)
k
y
x

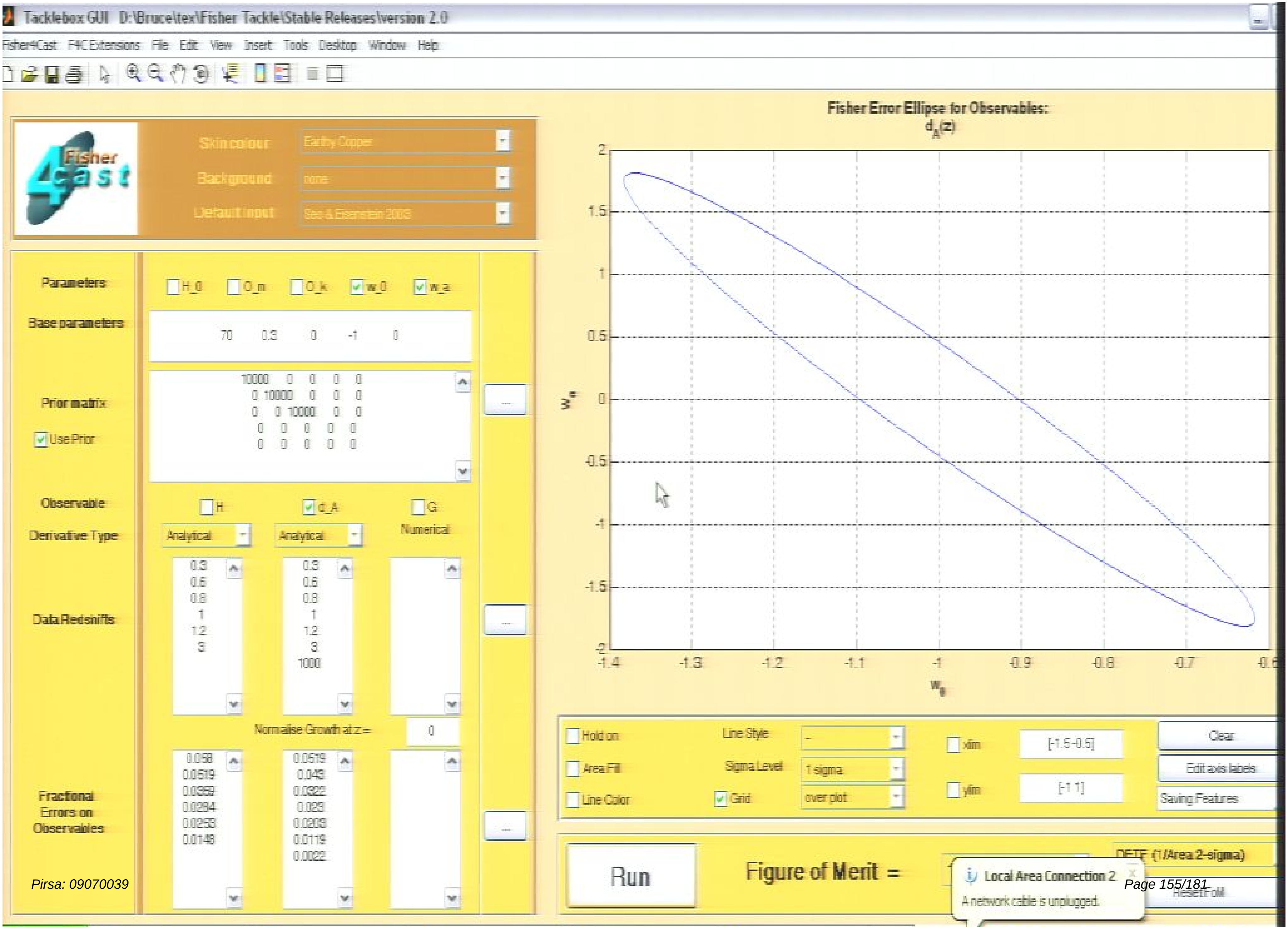
Calibrating Nonlinearity

- Although it is (weakly) nonlinear, gravity is still quite clean (compare turbulent MHD in strong gravitational field)
- Good reasons to believe the nonlinear effects can be calibrated at the 1% level for BAO/BAP
- Still needs more theoretical and numerical study
- Only true if background is FLRW … what do we do in LTB?

Photometric BAO Surveys

It is tempting to want to just do an imaging survey instead of taking spectra

Photometric BAO surveys primarily sacrifice $H(z)$ information and need much larger volume to compete.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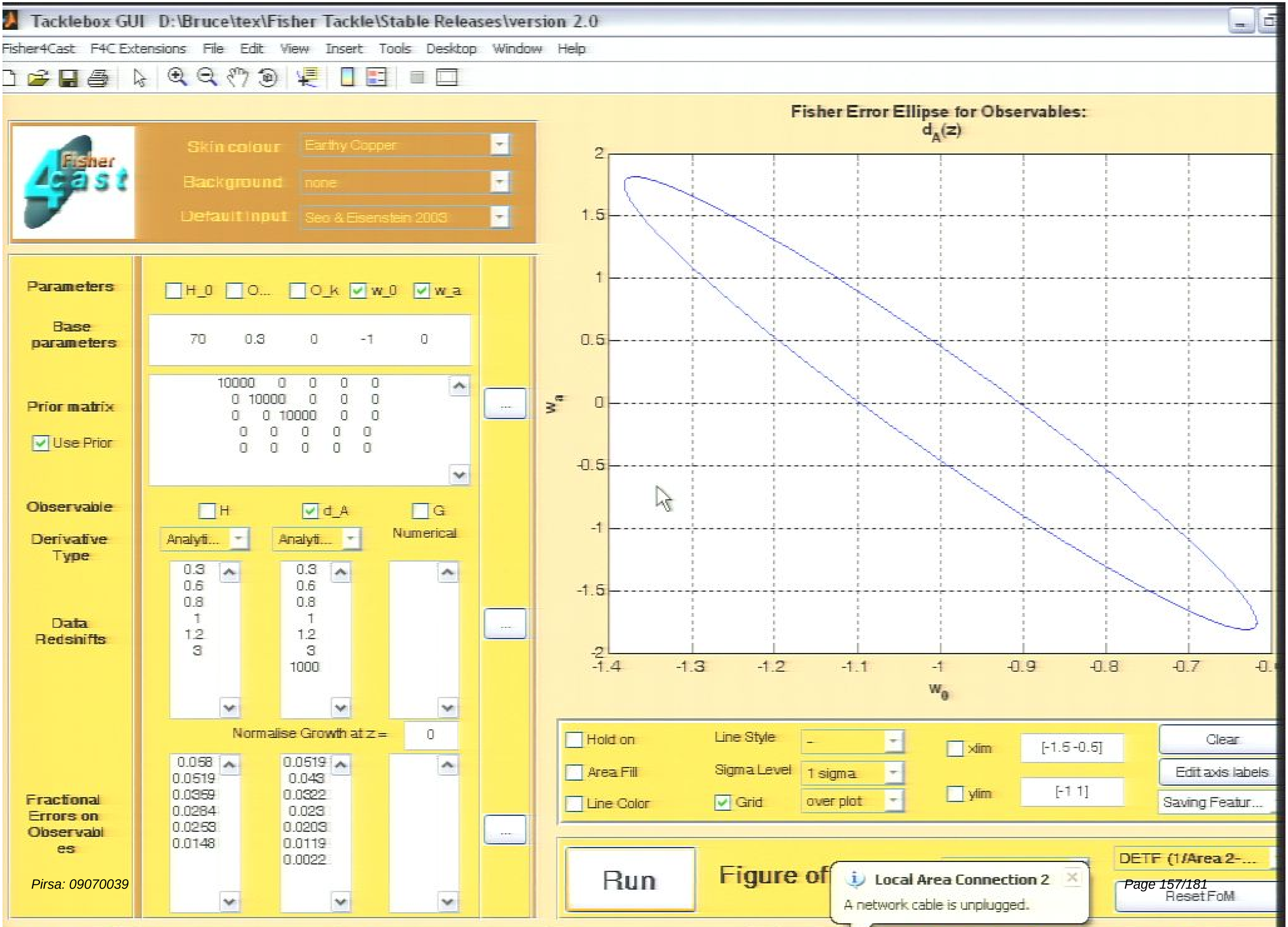
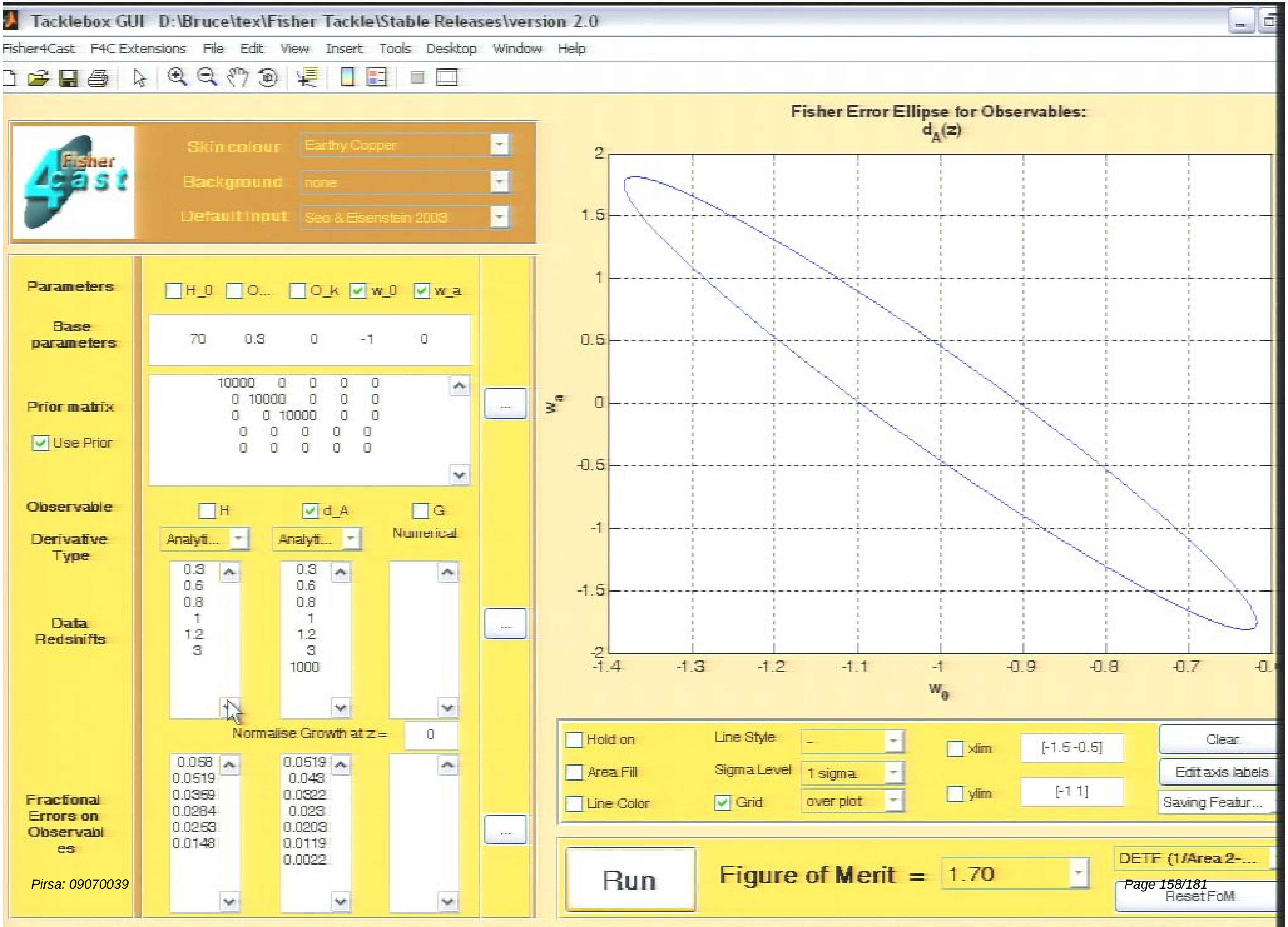
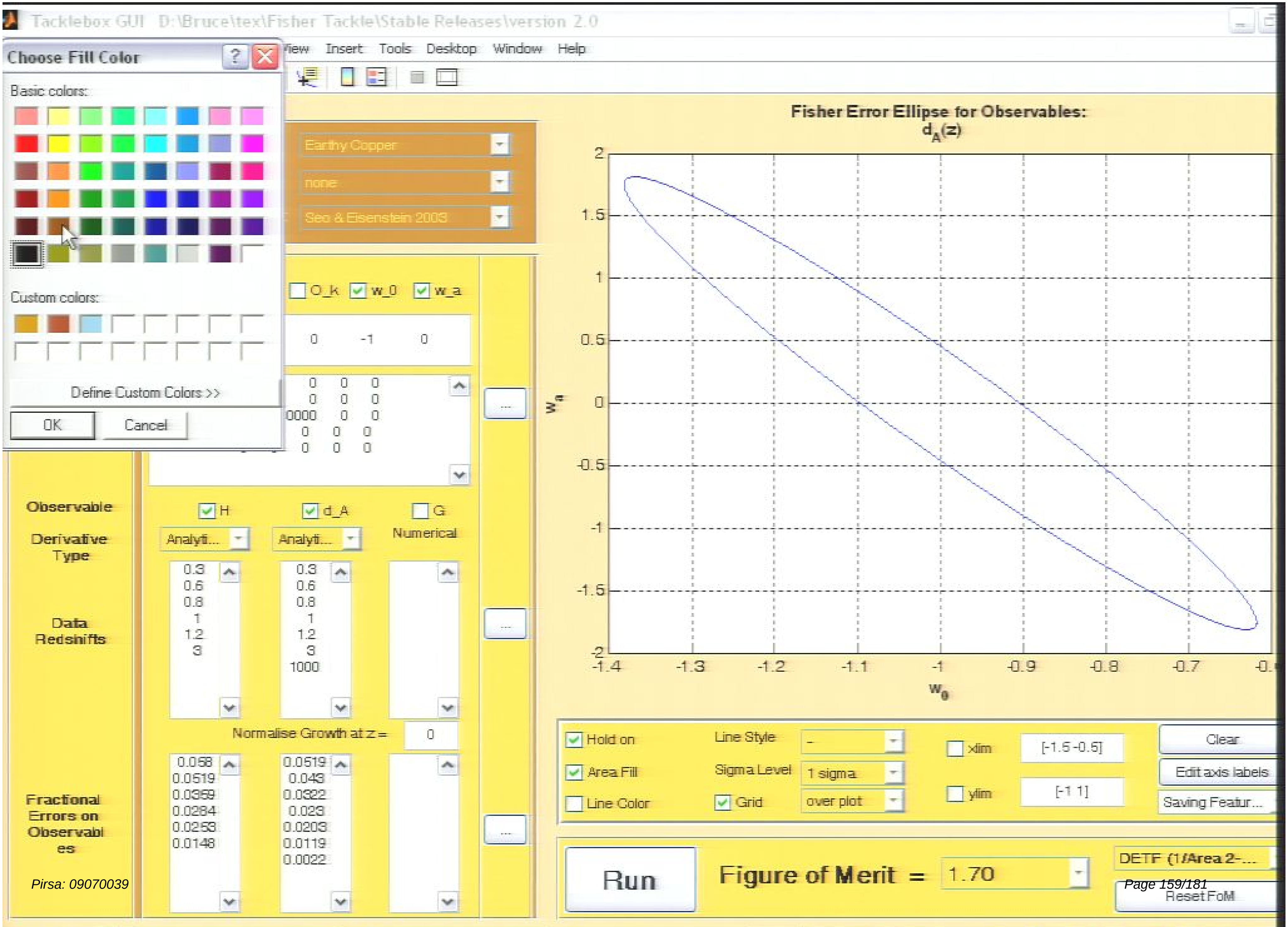
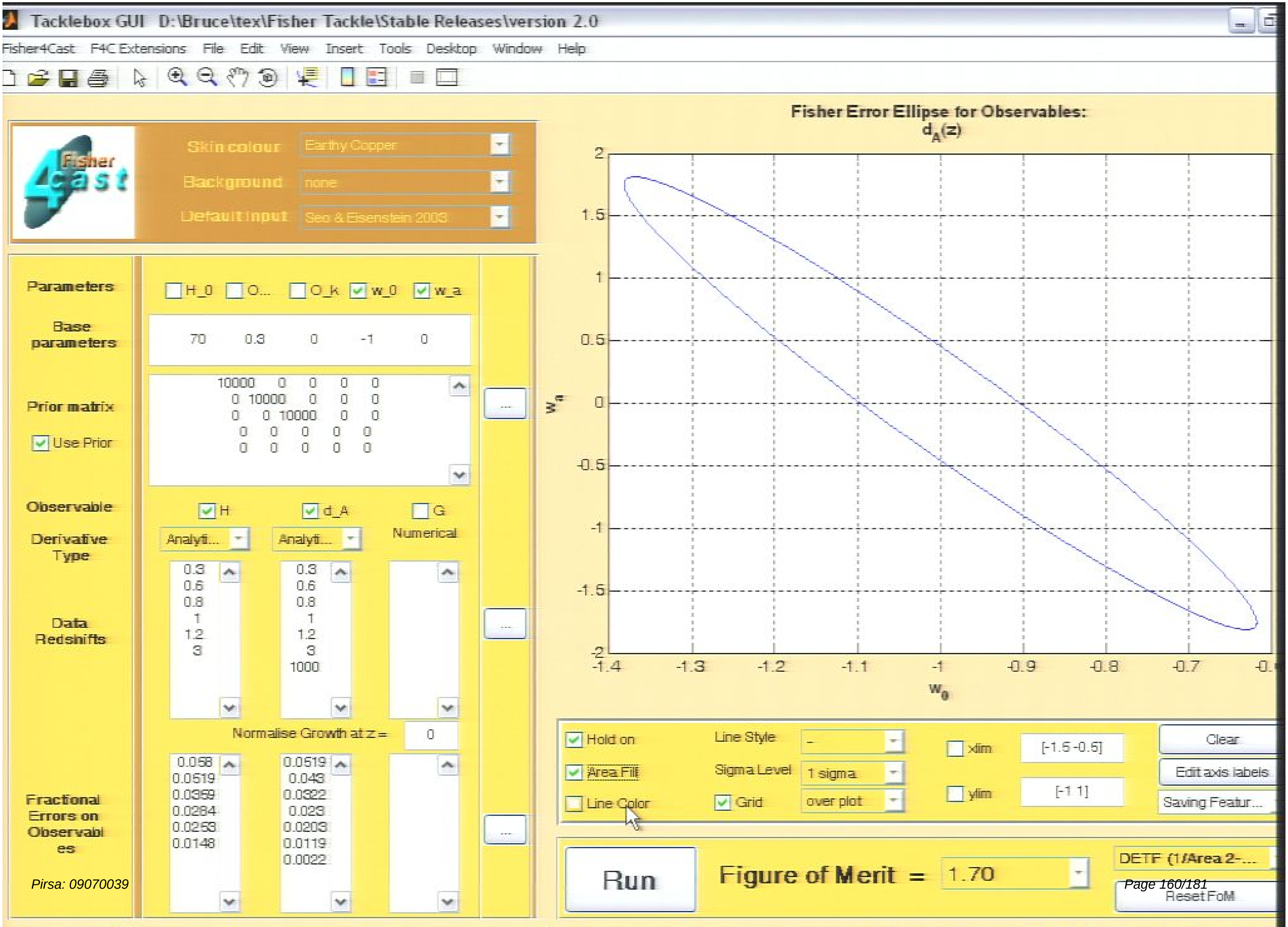
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Skin colour Earthy Copper
Background none
Default input Seo & Eisenstein 2003
Parameters H_0 O_m O_k w_0 w_a
Base parameters 70 0.3 0 -1 0
Prior matrix
Use Prior
Observable H d_A G
Derivative Type Analytical Analytical Numerical
Data Redshifts
Normalise Growth at z = 0
Fractional Errors on Observables
Fisher Error Ellipse for Observables:
d_A(z)
Hold on
Area Fill
Line Color
Line Style
Sigma Level 1 sigma
Grid over plot
xlim [-1.5 -0.5]
ylim [-1 1]
Clear
Edit axis labels
Saving Features
Run
Figure of Merit =
DETF (1/Area 2-sigma)
Local Area Connection 2
A network cable is unplugged.

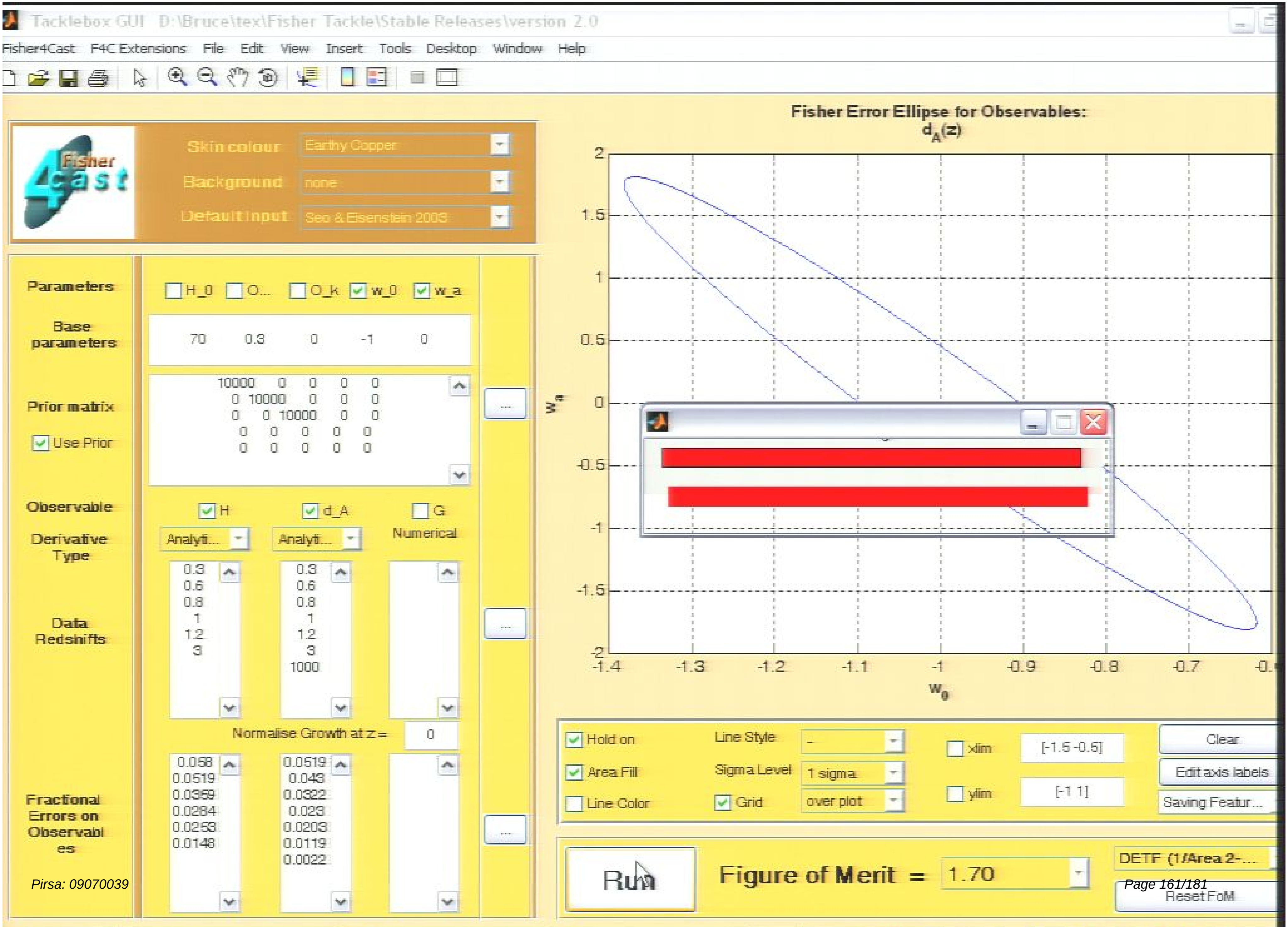

Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Skin colour
Earthy Copper
Background
none
Default input
Seo & Eisenstein 2003
Parameters
H_0 O... O_k w_0 w_a
Base parameters
70 0.3 0 -1 0
Prior matrix
10000 0 0 0 0
0 10000 0 0 0
0 0 10000 0 0
0 0 0 0 0
0 0 0 0 0
Use Prior
Observable
H d_A G
Derivative Type
Analyti... Analyti... Numerical
Data Redshifts
0.3 0.6 0.8 1 1.2 3
0.3 0.6 0.8 1 1.2 3 1000
Normalise Growth at z = 0
Fractional Errors on Observables
0.058 0.0519 0.0359 0.0284 0.0253 0.0148
0.0519 0.043 0.0322 0.023 0.0203 0.0119 0.0022
Fisher Error Ellipse for Observables:
d_A(z)
w_a
w_0
Hold on
Area Fill
Line Color
Line Style
Sigma Level
1 sigma
Grid
over plot
xlim
[-1.5 -0.5]
ylim
[-1 1]
Clear
Edit axis labels
Saving Featur...
Run
Figure of
DETF (1/Area 2-...
Reset FoM
Local Area Connection 2
A network cable is unplugged.

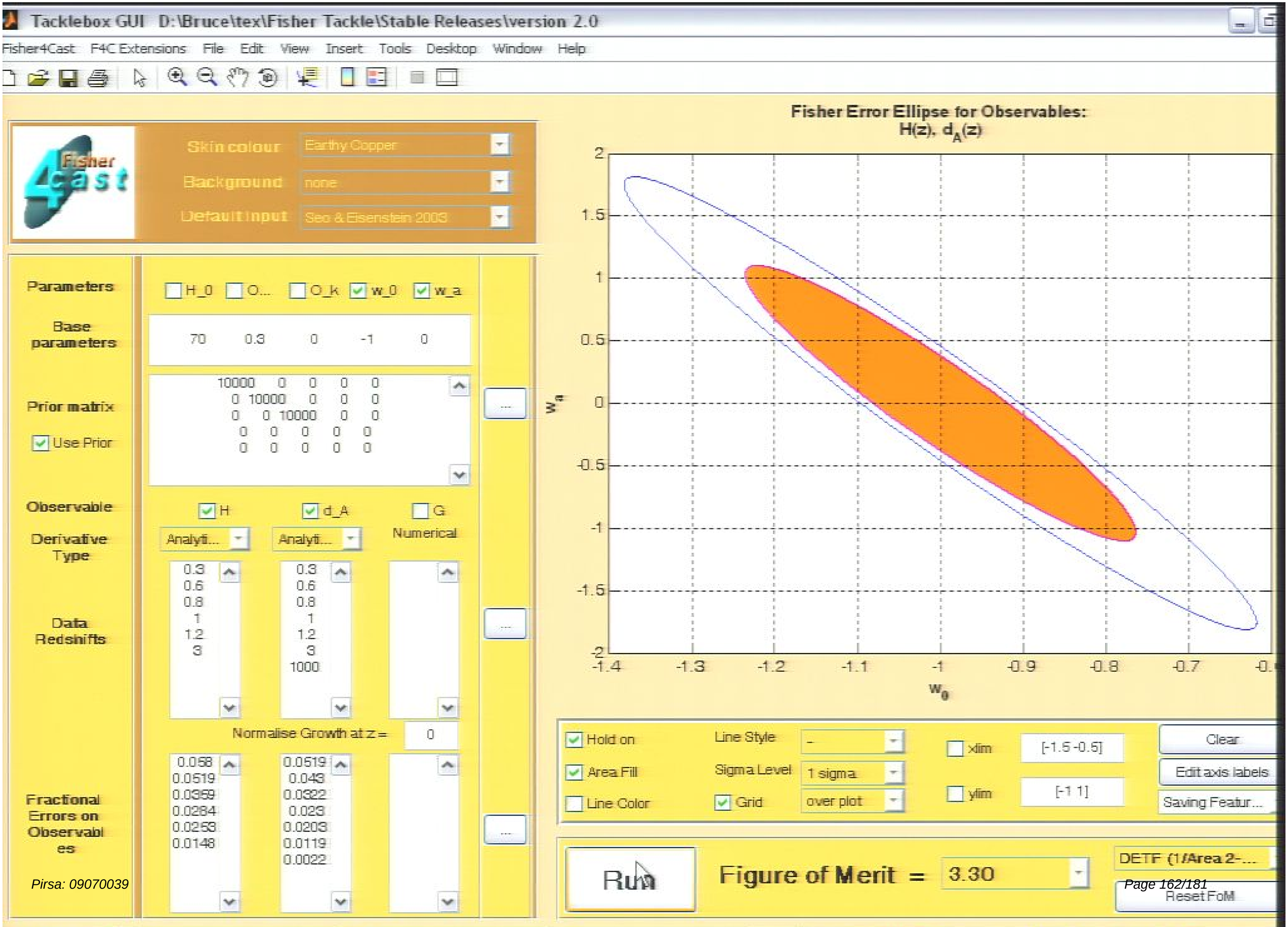

Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Fisher 4cast
Skin colour
Earthy Copper
Background
none
Default input
Seo & Eisenstein 2003
Parameters
H_0 O... O_k w_0 w_a
Base parameters
70 0.3 0 -1 0
Prior matrix
10000 0 0 0 0
0 10000 0 0 0
0 0 10000 0 0
0 0 0 0 0
0 0 0 0 0
Use Prior
Observable
H d_A G
Derivative Type
Analyti... Analyti... Numerical
Data Redshifts
0.3 0.6 0.8 1 1.2 3
0.3 0.6 0.8 1 1.2 3 1000
Normalise Growth at z = 0
Fractional Errors on Observables
0.058 0.0519 0.0359 0.0284 0.0253 0.0148
0.0519 0.043 0.0322 0.023 0.0203 0.0119 0.0022
Fisher Error Ellipse for Observables:
d_A(z)
w_a
w_0
Hold on
Area Fill
Line Color
Line Style
Sigma Level
1 sigma
Grid
over plot
xlim
[-1.5 -0.5]
ylim
[-1 1]
Clear
Edit axis labels
Saving Featur...
Run
Figure of Merit = 1.70
DETF (1/Area 2-...
Reset FoM

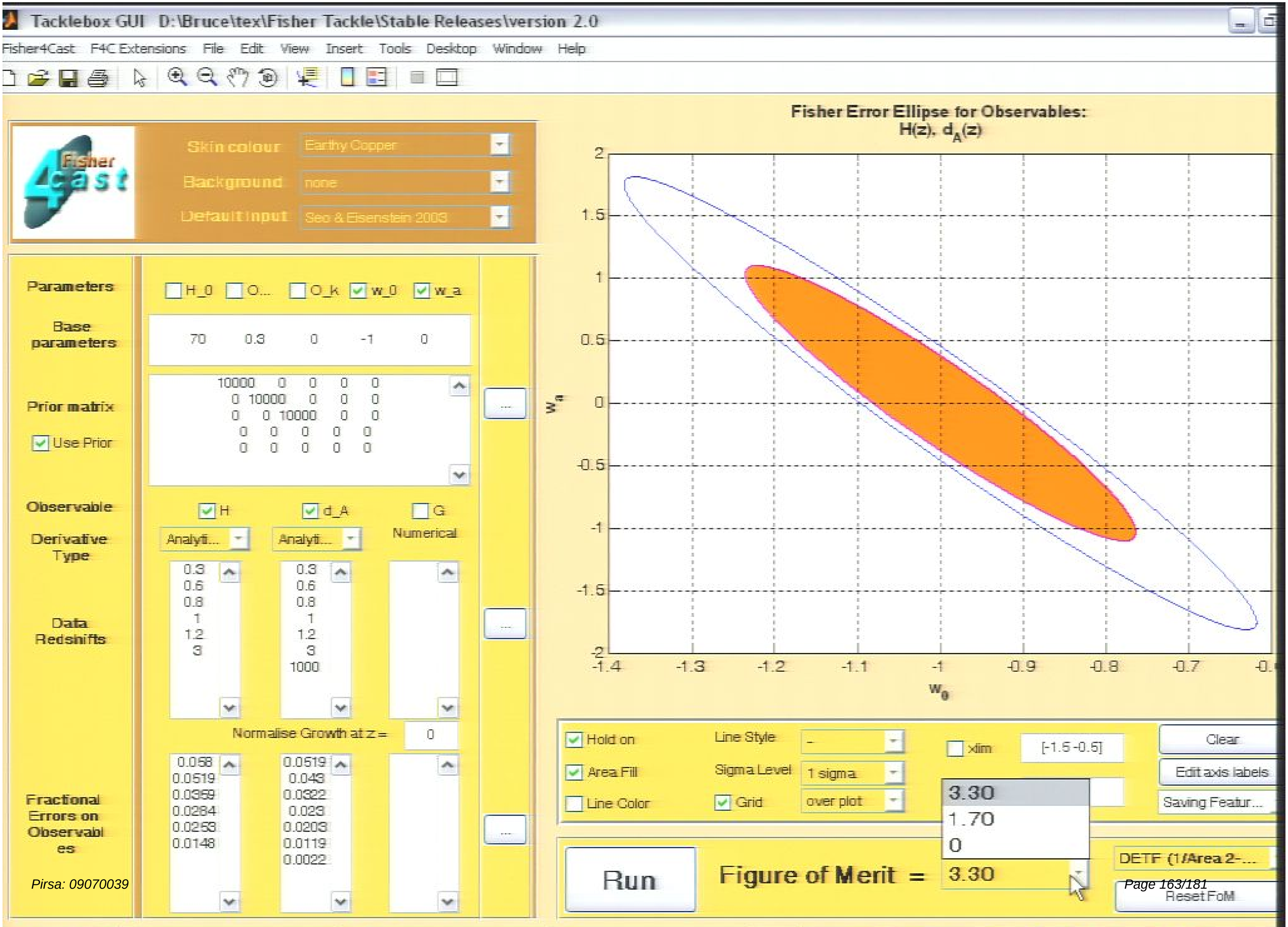

Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
View Insert Tools Desktop Window Help
Choose Fill Color
Basic colors:
Custom colors:
Define Custom Colors >>
OK
Cancel
Earthy Copper
none
Seo & Eisenstein 2003
O_k w_0 w_a
Fisher Error Ellipse for Observables:
d_A(z)
w_a
w_0
Observable
H
d_A
G
Derivative Type
Analyti...
Numerical
Data Redshifts
Normalise Growth at z =
Fractional Errors on Observables
Hold on
Area Fill
Line Color
Line Style
Sigma Level
1 sigma
Grid
over plot
xlim
ylim
[-1.5 -0.5]
[-1 1]
Clear
Edit axis labels
Saving Featur...
Run
Figure of Merit =
1.70
DETF (1/Area 2-...
Reset FoM

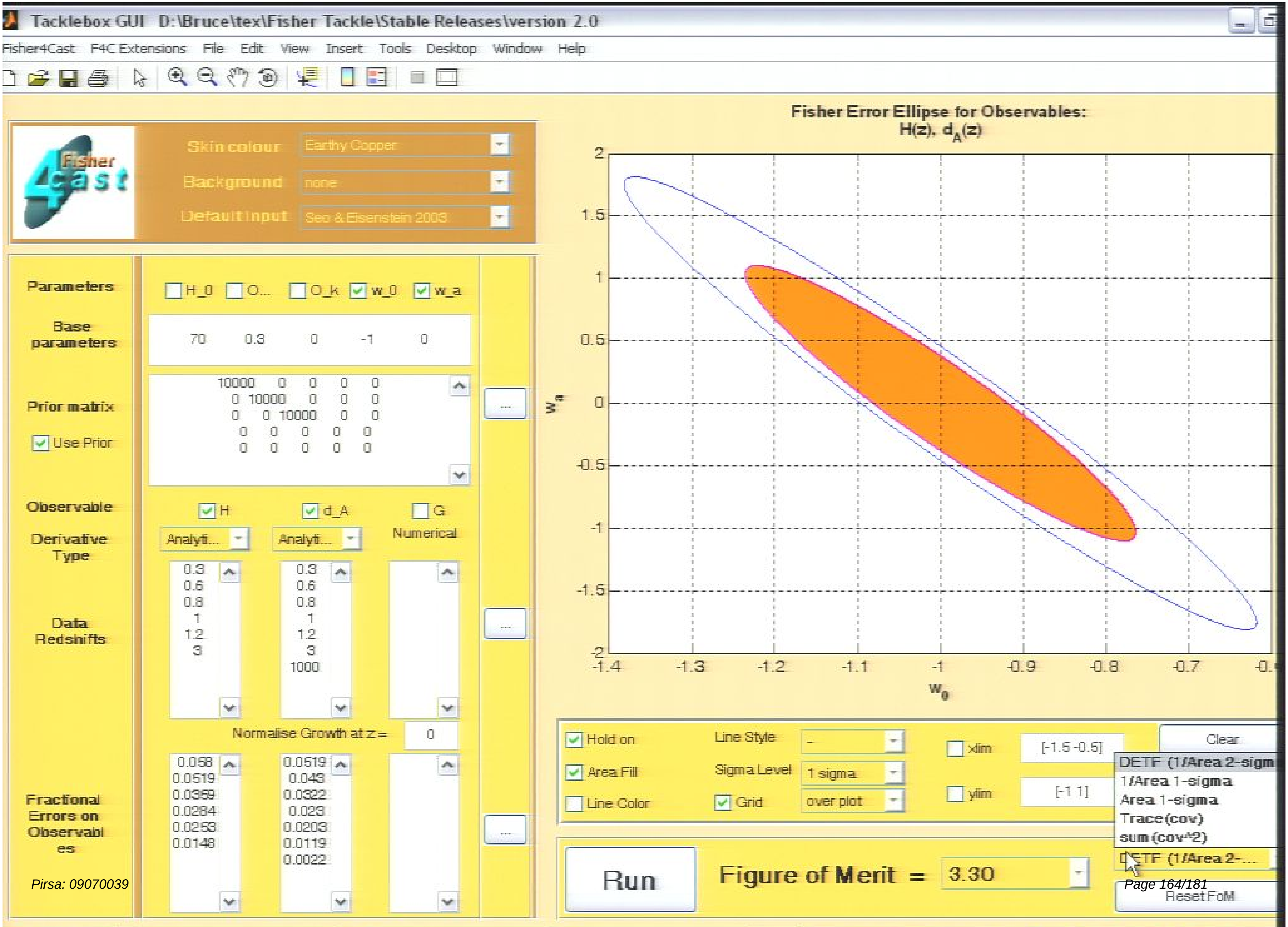


Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Skin colour
Earthy Copper
Background
none
Default input
Seo & Eisenstein 2003
Parameters
H_0 O... O_k w_0 w_a
Base parameters
70 0.3 0 -1 0
Prior matrix
Use Prior
10000 0 0 0 0
0 10000 0 0 0
0 0 10000 0 0
0 0 0 0 0
0 0 0 0 0
Observable
H d_A G
Derivative Type
Analyti... Analyti... Numerical
Data Redshifts
0.3 0.6 0.8 1 1.2 3
0.3 0.6 0.8 1 1.2 3 1000
Normalise Growth at z = 0
Fractional Errors on Observables
0.058 0.0519 0.0359 0.0284 0.0253 0.0148
0.0519 0.043 0.0322 0.023 0.0203 0.0119 0.0022
Fisher Error Ellipse for Observables:
$d_A(z)$
w_a
w_0
Hold on
Area Fill
Line Color
Line Style
Sigma Level
1 sigma
Grid
over plot
xlim
[-1.5 -0.5]
ylim
[-1 1]
Clear
Edit axis labels
Saving Featur...
Run
Figure of Merit = 1.70
DETF (1/Area 2-...
Reset FoM

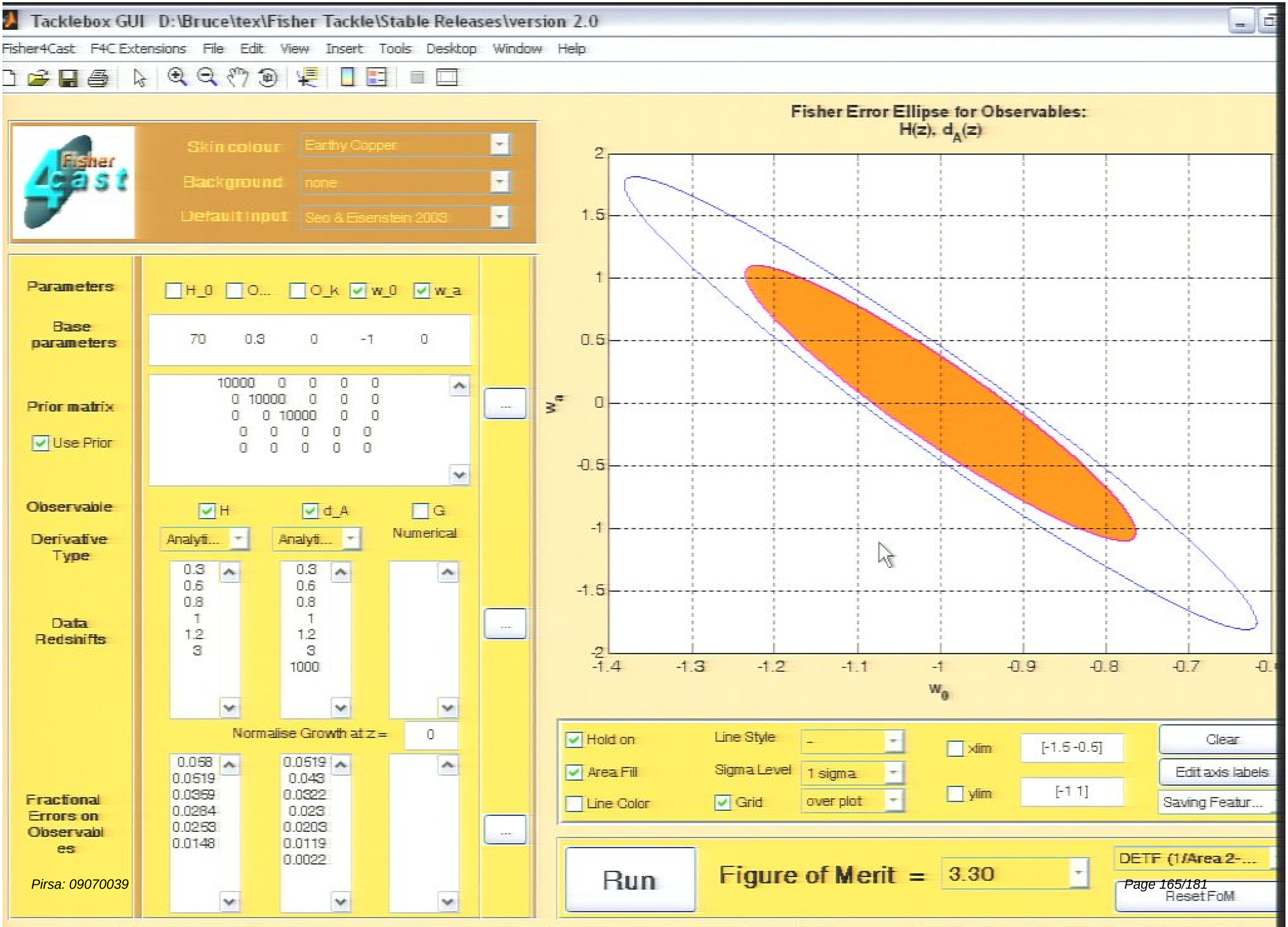

Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Fisher 4cast
Skin colour Earthy Copper
Background none
Default input Seo & Eisenstein 2003
Parameters
H_0 O... O_k w_0 w_a
Base parameters
70 0.3 0 -1 0
Prior matrix
Use Prior
10000 0 0 0 0
0 10000 0 0 0
0 0 10000 0 0
0 0 0 0 0
0 0 0 0 0
Observable
H d_A G
Derivative Type
Analyti... Analyti... Numerical
Data Redshifts
0.3 0.6 0.8 1 1.2 3
0.3 0.6 0.8 1 1.2 3 1000
Normalise Growth at z = 0
Fractional Errors on Observables
0.058 0.0519 0.0359 0.0284 0.0253 0.0148
0.0519 0.043 0.0322 0.023 0.0203 0.0119 0.0022
Fisher Error Ellipse for Observables:
d_A(z)
w_a
w_0
Hold on
Area Fill
Line Color
Line Style
Sigma Level 1 sigma
Grid over plot
xlim [-1.5 -0.5]
ylim [-1 1]
Clear
Edit axis labels
Saving Featur...
Run
Figure of Merit = 1.70
DETF (1/Area 2-...
Reset FoM

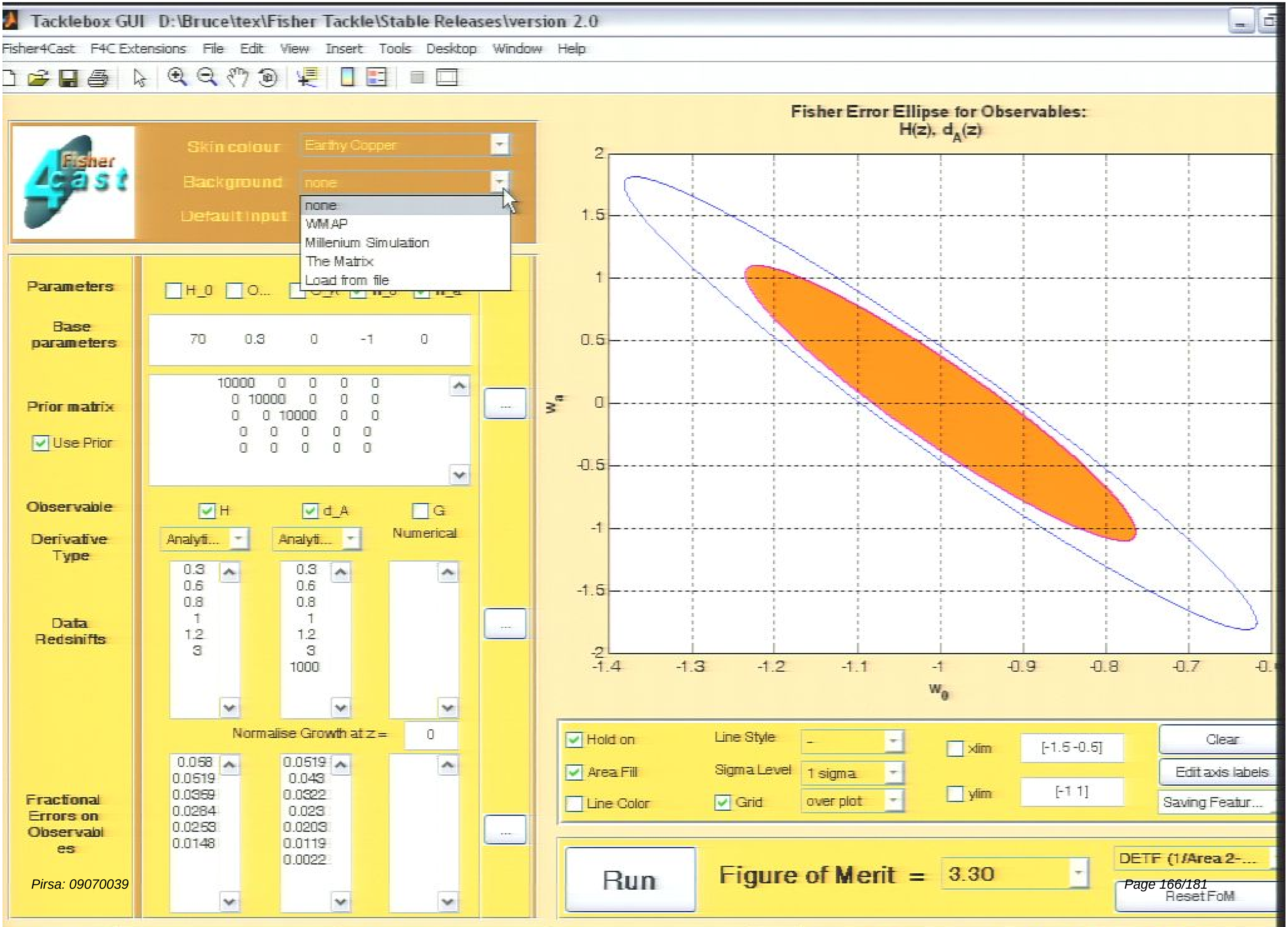

Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Skin colour
Earthy Copper
Background
none
Default input
Seo & Eisenstein 2003
Parameters
H_0 O... O_k w_0 w_a
Base parameters
70 0.3 0 -1 0
Prior matrix
Use Prior
Observable
H d_A G
Derivative Type
Analyti... Analyti... Numerical
Data Redshifts
Normalise Growth at z = 0
Fractional Errors on Observables
Fisher Error Ellipse for Observables:
H(z), d_A(z)
w_a
w_0
Hold on
Area Fill
Line Color
Line Style
Sigma Level
1 sigma
Grid
over plot
xlim
[-1.5 -0.5]
ylim
[-1 1]
Clear
Edit axis labels
Saving Featur...
Run
Figure of Merit = 3.30
DETF (1/Area 2-...
Reset FoM


Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Skin colour
Earthy Copper
Background
none
Default Input
Seo & Eisenstein 2003
Parameters
H_0 O... O_k w_0 w_a
Base parameters
70 0.3 0 -1 0
Prior matrix
Use Prior
Observable
H d_A G
Derivative Type
Analyti... Analyti... Numerical
Data Redshifts
Normalise Growth at z =
Fractional Errors on Observables
Fisher Error Ellipse for Observables:
H(z), d_A(z)
Hold on
Area Fill
Line Color
Line Style
Sigma Level
1 sigma
Grid
over plot
xlim
[-1.5 -0.5]
Clear
Edit axis labels
Saving Featur...
Run
Figure of Merit =
3.30
1.70
DETF (1/Area 2-...
Reset FoM

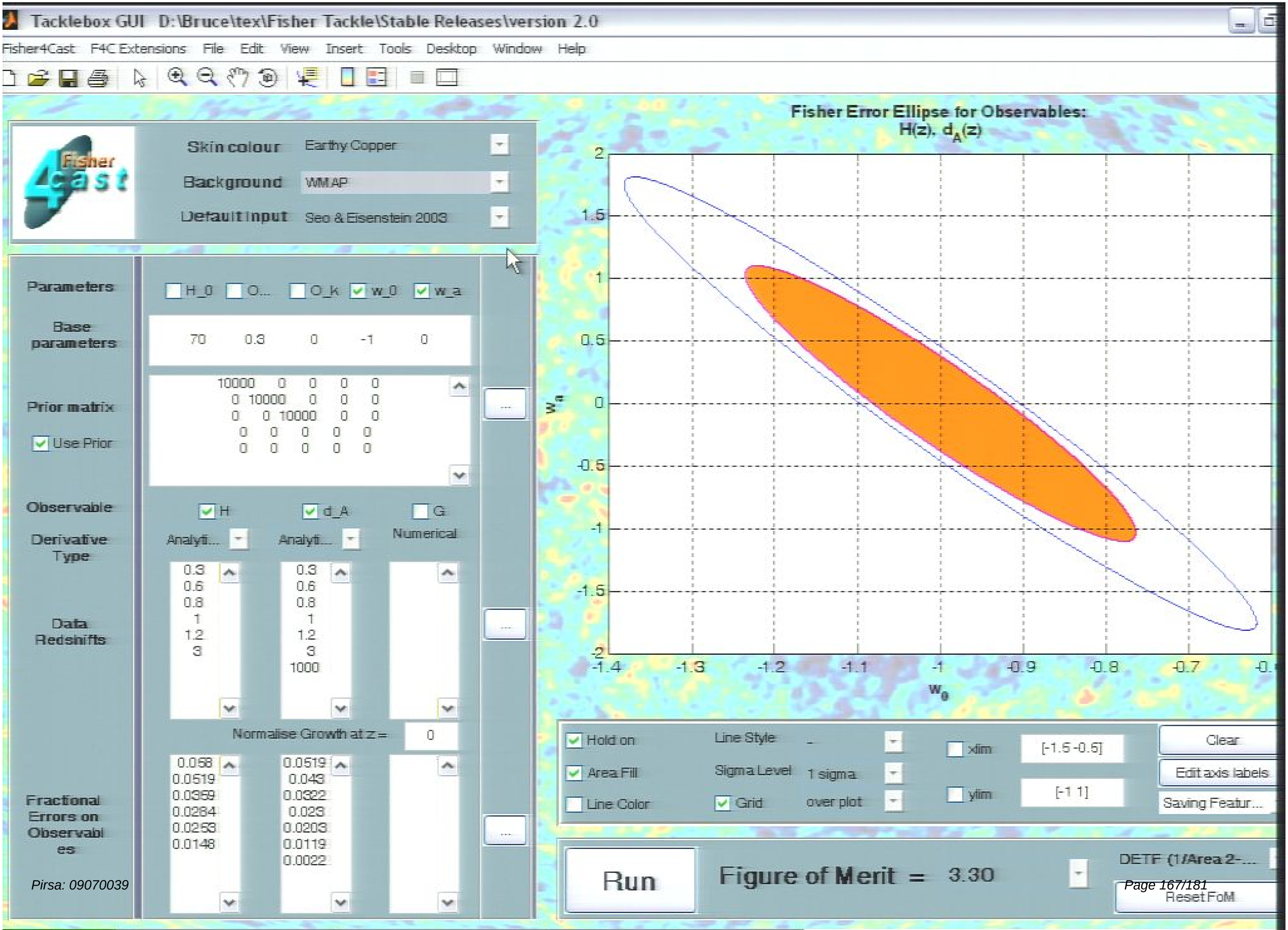


Pirsa: 09070039

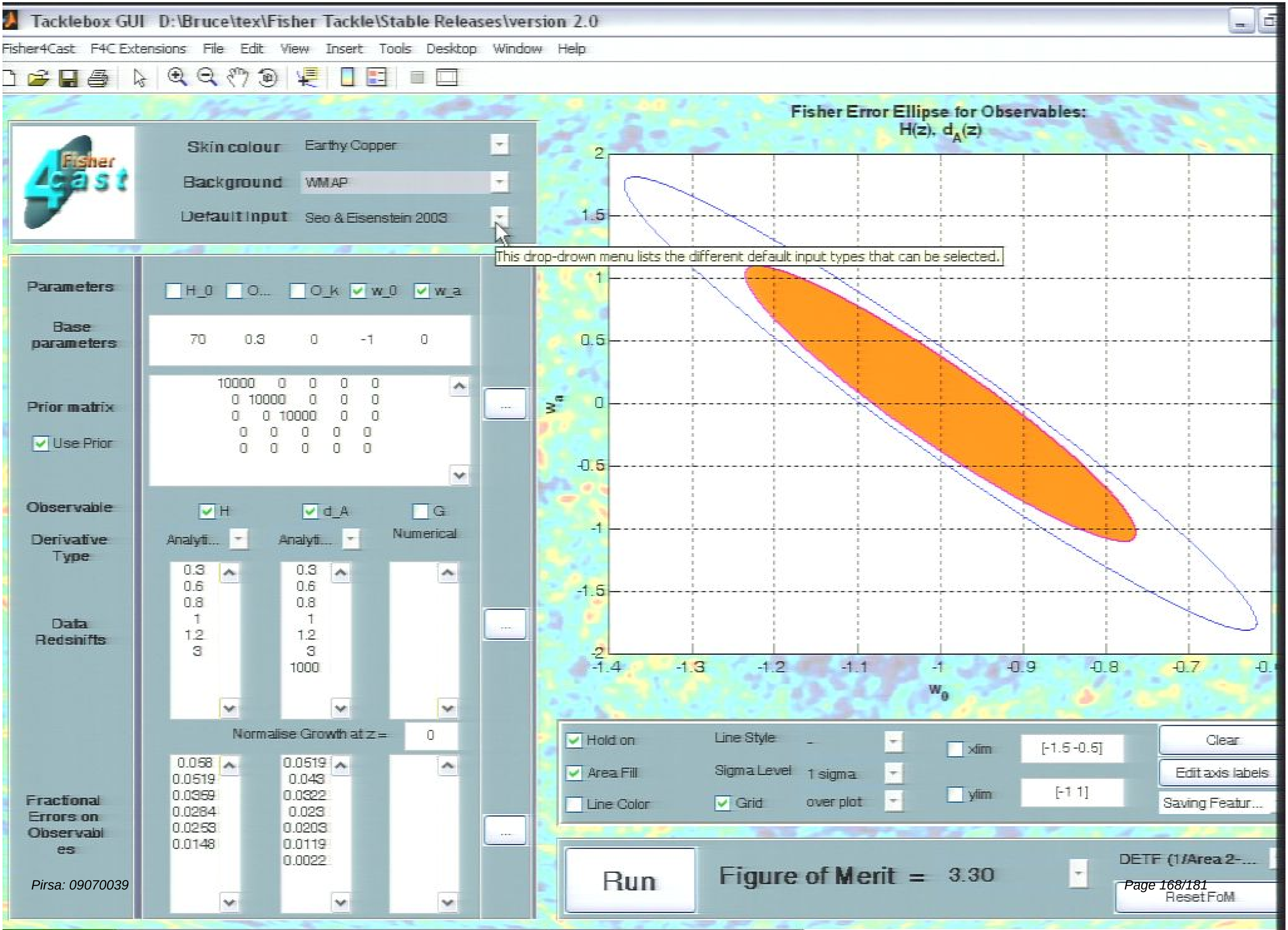

Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Skin colour
Earthy Copper
Background
none
Default Input
Seo & Eisenstein 2003
Parameters
H_0 O... O_k w_0 w_a
Base parameters
70 0.3 0 -1 0
Prior matrix
10000 0 0 0 0
0 10000 0 0 0
0 0 10000 0 0
0 0 0 0 0
0 0 0 0 0
Use Prior
Observable
H d_A G
Derivative Type
Analyti... Analyti... Numerical
Data Redshifts
0.3 0.6 0.8 1 1.2 3
0.3 0.6 0.8 1 1.2 3 1000
Normalise Growth at z = 0
Fractional Errors on Observables
0.058 0.0519 0.0359 0.0284 0.0253 0.0148
0.0519 0.043 0.0322 0.023 0.0203 0.0119 0.0022
Fisher Error Ellipse for Observables:
H(z), d_A(z)
w_a
w_0
Hold on
Area Fill
Line Color
Line Style
Sigma Level
1 sigma
Grid
over plot
xlim
[-1.5 -0.5]
ylim
[-1 1]
Clear
Edit axis labels
Saving Featur...
Run
Figure of Merit = 3.30
DETF (1/Area 2-...
Reset FoM

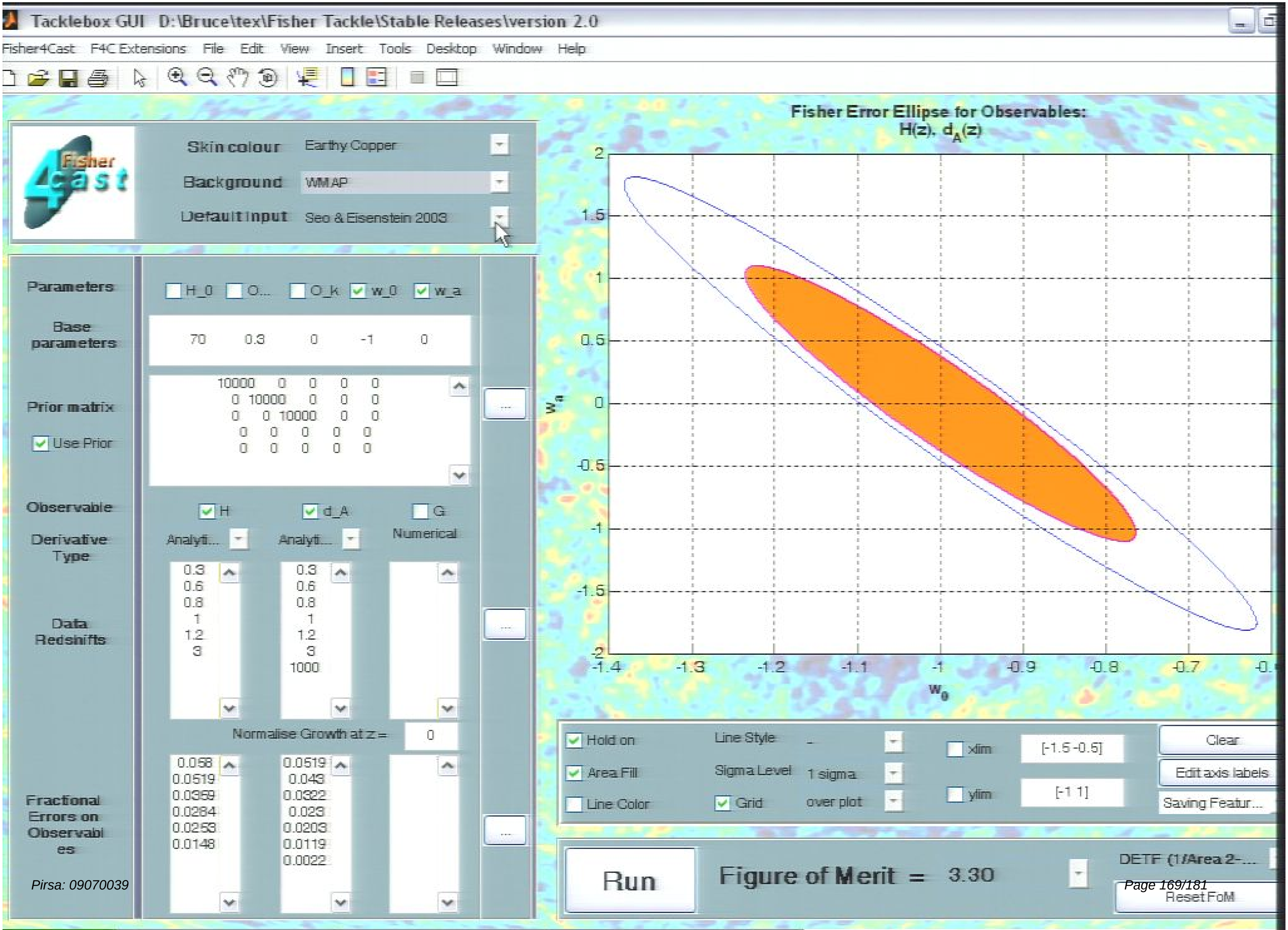


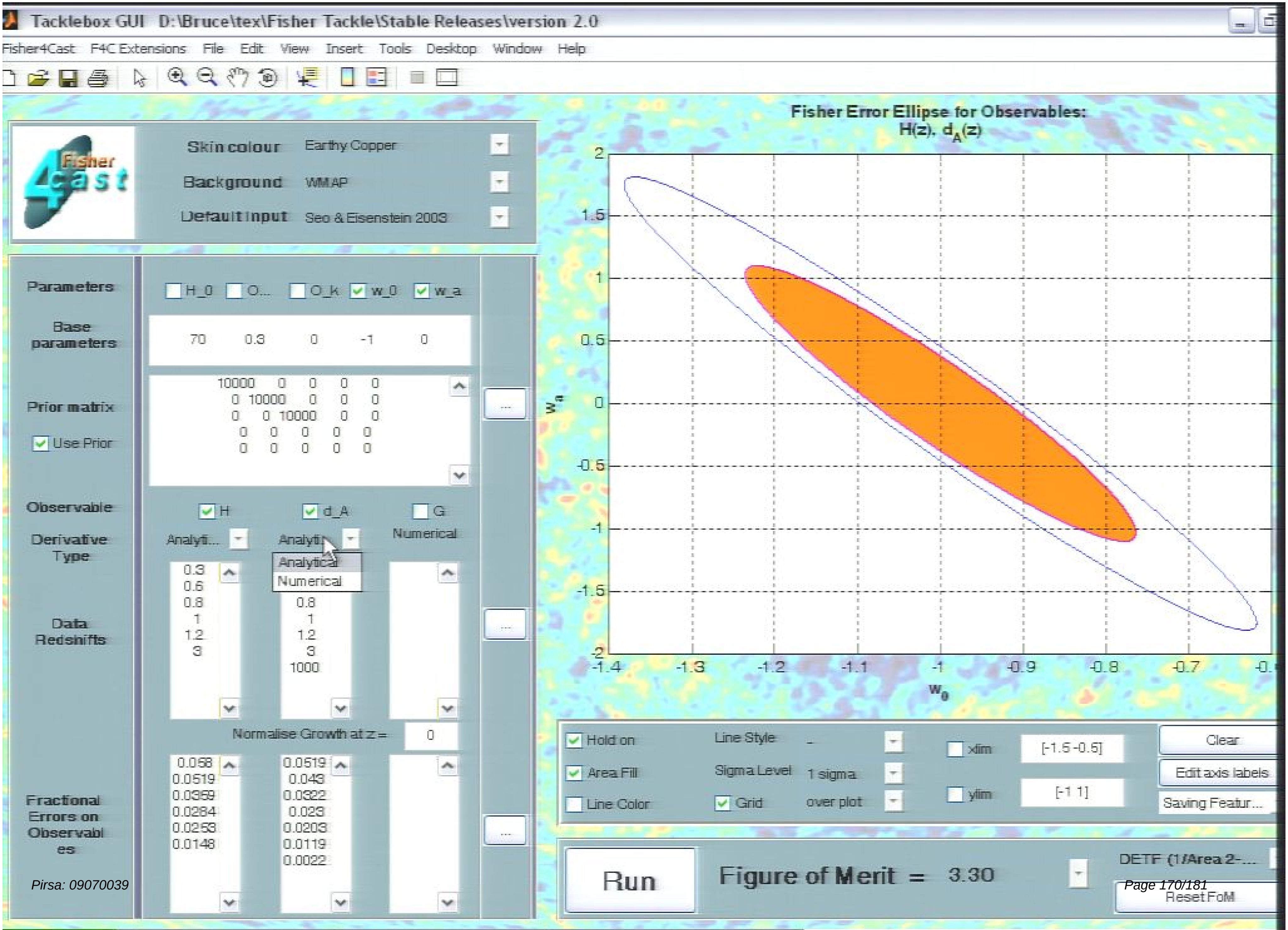
Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Fisher 4cast
Skin colour
Earthy Copper
Background
none
Default input
none
WMAP
Millenium Simulation
The Matrix
Load from file
Parameters
H_0
O...
Base parameters
70 0.3 0 -1 0
Prior matrix
10000 0 0 0 0
0 10000 0 0 0
0 0 10000 0 0
0 0 0 0 0
0 0 0 0 0
Use Prior
Observable
H
d_A
G
Derivative Type
Analyti...
Analyti...
Numerical
Data Redshifts
0.3 0.6 0.8 1 1.2 3
0.3 0.6 0.8 1 1.2 3 1000
Normalise Growth at z = 0
Fractional Errors on Observables
0.058 0.0519 0.0359 0.0284 0.0253 0.0148
0.0519 0.043 0.0322 0.023 0.0203 0.0119 0.0022
Fisher Error Ellipse for Observables:
H(z), $d_A(z)$
w_a
w_0
Hold on
Area Fill
Line Color
Line Style
Sigma Level
1 sigma
Grid
over plot
xlim
[-1.5 -0.5]
ylim
[-1 1]
Clear
Edit axis labels
Saving Featur...
Run
Figure of Merit = 3.30
DETF (1/Area 2-...
Reset FoM



Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Skin colour Earthy Copper
Background WMAP
Default Input Seo & Eisenstein 2003
Parameters H_0 O... O_k w_0 w_a
Base parameters 70 0.3 0 -1 0
Prior matrix
10000 0 0 0 0
0 10000 0 0 0
0 0 10000 0 0
0 0 0 0 0
0 0 0 0 0
Use Prior
Observable H d_A G
Derivative Type Analyti... Analyti... Numerical
Data Redshifts
0.3 0.6 0.8 1 1.2 3
0.3 0.6 0.8 1 1.2 3 1000
Normalise Growth at z = 0
Fractional Errors on Observables
0.058 0.0519 0.0359 0.0284 0.0253 0.0148
0.0519 0.043 0.0322 0.023 0.0203 0.0119 0.0022
Fisher Error Ellipse for Observables: H(z), $d_A(z)$
w_a
w_0
Hold on
Area Fill
Line Color
Line Style
Sigma Level 1 sigma
Grid over plot
xlim [-1.5 -0.5]
ylim [-1 1]
Clear
Edit axis labels
Saving Featur...
Run
Figure of Merit = 3.30
DETF (1/Area 2-...
Reset FoM


Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Fisher 4cast
Skin colour
Earthy Copper
Background
WMAP
Default Input
Seo & Eisenstein 2003
This drop-drown menu lists the different default input types that can be selected.
Parameters
H_0 O... O_k w_0 w_a
Base parameters
70 0.3 0 -1 0
Prior matrix
10000 0 0 0 0
0 10000 0 0 0
0 0 10000 0 0
0 0 0 0 0
0 0 0 0 0
Use Prior
Observable
H d_A G
Derivative Type
Analyti... Analyti... Numerical
Data Redshifts
0.3 0.6 0.8 1 1.2 3
0.3 0.6 0.8 1 1.2 3 1000
Normalise Growth at z = 0
Fractional Errors on Observables
0.058 0.0519 0.0359 0.0284 0.0253 0.0148
0.0519 0.043 0.0322 0.023 0.0203 0.0119 0.0022
Fisher Error Ellipse for Observables:
H(z), d_A(z)
w_a
w_0
Hold on
Area Fill
Line Color
Line Style
Sigma Level
1 sigma
Grid
over plot
xlim
ylim
[-1.5 -0.5]
[-1 1]
Clear
Edit axis labels
Saving Featur...
Run
Figure of Merit = 3.30
DETF (1/Area 2-...
Reset FoM


Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Fisher 4cast
Skin colour Earthy Copper
Background WMAP
Default Input Seo & Eisenstein 2003
Parameters H_0 O... O_k w_0 w_a
Base parameters 70 0.3 0 -1 0
Prior matrix
10000 0 0 0 0
0 10000 0 0 0
0 0 10000 0 0
0 0 0 0 0
0 0 0 0 0
Use Prior
Observable H d_A G
Derivative Type Analyti... Analyti... Numerical
Data Redshifts
0.3 0.6 0.8 1 1.2 3
0.3 0.6 0.8 1 1.2 3 1000
Normalise Growth at z = 0
Fractional Errors on Observables
0.058 0.0519 0.0359 0.0284 0.0253 0.0148
0.0519 0.043 0.0322 0.023 0.0203 0.0119 0.0022
Fisher Error Ellipse for Observables: H(z), d_A(z)
w_a
w_0
Hold on
Area Fill
Line Color
Line Style
Sigma Level 1 sigma
Grid
over plot
xlim [-1.5 -0.5]
ylim [-1 1]
Clear
Edit axis labels
Saving Featur...
Run
Figure of Merit = 3.30
DETF (1/Area 2-...
Reset FoM



Tacklebox GUI D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0
Fisher4Cast F4C Extensions File Edit View Insert Tools Desktop Window Help
Skin colour Earthy Copper
Background WMAP
Default input Seo & Eisenstein 2003
Parameters H_0 O... O_k w_0 w_a
Base parameters 70 0.3 0 -1 0
Prior matrix
Use Prior
Observable H d_A G
Derivative Type Analyti... Analytical Numerical
Data Redshifts
Normalise Growth at z = 0
Fractional Errors on Observables
Fisher Error Ellipse for Observables: H(z), d_A(z)
w_a
w_0
Hold on
Area Fill
Line Color
Line Style
Sigma Level 1 sigma
Grid over plot
xlim [-1.5 -0.5]
ylim [-1 1]
Clear
Edit axis labels
Saving Featur...
Run
Figure of Merit = 3.30
DETF (1/Area 2-...
Reset FoM

Editor - D:\Bruce\tex\Fisher Tackle\Stable Releases\version 2.0\FM_GUI.m

File Edit Text Cell Tools Debug Desktop Window Help

Stack: Base

```
% -----------------------------------------------------------------------
% Copyright (C) 2008-2009
% Bruce Bassett Yabebal Fantaye  Renee Hlozek  Jacques Kotze
%
%
%
% This file is part of Fisher4Cast.
%
% Fisher4Cast is free software: you can redistribute it and/or modify
% it under the terms of the Berkeley Software Distribution (BSD) license.
%
% Fisher4Cast is distributed in the hope that it will be useful,
% but WITHOUT ANY WARRANTY; without even the implied warranty of
% MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
% BSD license for more details.
% -----------------------------------------------------------------------
%
% FM_GUI sets a Gui for the Fisher matrix tacklebox.
%
% It excutes the callbacks which are
% USERIN- the input for the GUI. During the first
% initialisation of this function, USERIN is zero
% which opens the new GUI window. All buttons and controls follow a specific
% format as outlined in the Matlab Help files, and indentation is key in
% this code. The GUI also contains floating help to aid the user.
% For more information on GUI's, please see the Matlab documentation.


function FM_GUI(USERIN)

global axis_spec tacklebox


if nargin==0
```

FM_GUI.m | isoFoM_movie2.m | isoFoM.m | isoFoM_movie.m

FM_GUI Ln 20 Col 39

Editor - D:\Bruce\tex\Fisher Tackle\Papers\isoFoM_movie.m

File Edit Text Cell Tools Debug Desktop Window Help

Stack: Base

```
function isoFoM_movie
% movie of iso FoM surface - either slice or isosurface
% BB 1 June 09

close all
%load v_30_new.mat; old data
load new_detf_fom_vol_out.mat  % new DETF FoM data
%v = v_30_new;
v = fom_vol;
H=linspace(0.1,5,30); da=linspace(0.1,5,30); G=linspace(0.1,5,30);
[x y z] = meshgrid(H,da,G);

xmin = 0.1;
xmax = 5;
ymin = 0.1;
ymax = 5;
zmin = 0.1;
zmax = 5;
minv = min(min(min(v)));
maxv = max(max(max(v)));

figure(2)
whitebg('white')  % colour of background
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
n = 75;  % number of threshold steps
step = (maxv-minv)./n;  % union step in threshold
thresh = minv:step:maxv;   % threshold vector
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

slice_flag = 1;  % 1 if slice animation, 0 if union

nslice = 50;
```

FM_Col.m × isoFoM_movie2.m × isoFoM.m × isoFoM_movie.m ×

isoFoM_movie Ln 24 Col 79

Editor - D:\Bruce\tex\Fisher Tackle\Papers\isoFoM_movie.m

File Edit Text Cell Tools Debug Desktop Window Help

Stack: Base

```
function isoFoM_movie
% movie of iso FoM surface - either slice or isosurface
% BB 1 June 09

close all
%load v_30_new.mat; old data
load new_detf_fom_vol_out.mat  % new DETF FoM data
%v = v_30_new;
v = fom_vol;
H=linspace(0.1,5,30); da=linspace(0.1,5,30); G=linspace(0.1,5,30);
[x y z] = meshgrid(H,da,G);

xmin = 0.1;
xmax = 5;
ymin = 0.1;
ymax = 5;
zmin = 0.1;
zmax = 5;
minv = min(min(min(v)));
maxv = max(max(max(v)));

figure(2)
whitebg('white')  % colour
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
n = 75;  % number of threshold steps
step = (maxv-minv)./n;  % union step in threshold
thresh = minv:step:maxv;   % threshold vector
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

slice_flag = 1;  % 1 if slice animation, 0 if union

nslice = 50;
```

MATLAB Editor

File D:\...tex\Fisher Tackle\Papers\isoFoM_movie.m is not found in the current directory or on the MATLAB path.

To run this file, select one of the following

- (•) Change MATLAB current directory
- ( ) Add directory to the top of the MATLAB path
- ( ) Add directory to the bottom of the MATLAB path

OK | Cancel

FM_Cal.m × isoFoM_movie2.m × isoFoM.m × isoFoM_movie.m ×

isoFoM_movie Ln 24 Col 79

Editor - D:\Bruce\tex\Fisher Tackle\Papers\isoFoM_movie.m

File Edit Text Cell Tools Debug Desktop Window Help

Figure 2

File Edit View Insert Tools Desktop Window Help

```
function isoFoM_movie
% movie of iso FoM surface - either slice o
% BB 1 June 09

close all
%load v_30_new.mat; old data
load new_detf_fom_vol_out.mat  % new DETF F
%v = v_30_new;
v = fom_vol;
H=linspace(0.1,5,30); da=linspace(0.1,5,30)
[x y z] = meshgrid(H,da,G);

xmin = 0.1;
xmax = 5;
ymin = 0.1;
ymax = 5;
zmin = 0.1;
zmax = 5;
minv = min(min(min(v)));
maxv = max(max(max(v)));

figure(2)
whitebg('white')  % colour of background
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
n = 75;  % number of threshold steps
step = (maxv-minv)./n;  % union step in threshold
thresh = minv:step:maxv;   % threshold vector
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

slice_flag = 1;  % 1 if slice animation, 0 if union

nslice = 50;
```

FM_Od.m × isoFoM_movie2.m × isoFoM.m × isoFoM_movie.m ×

isoFoM_movie Ln 24 Col 79

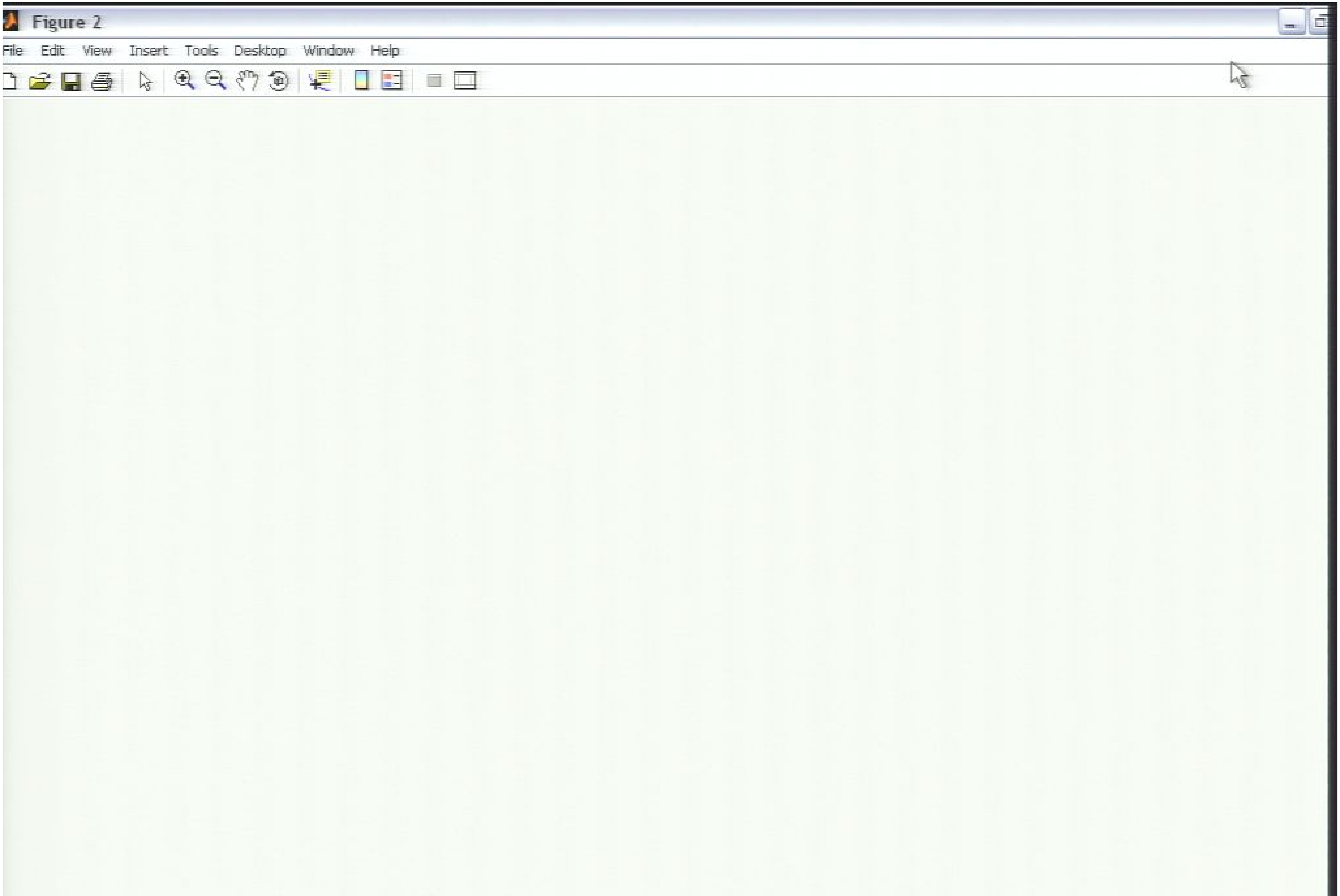


Figure 2
File Edit View Insert Tools Desktop Window Help

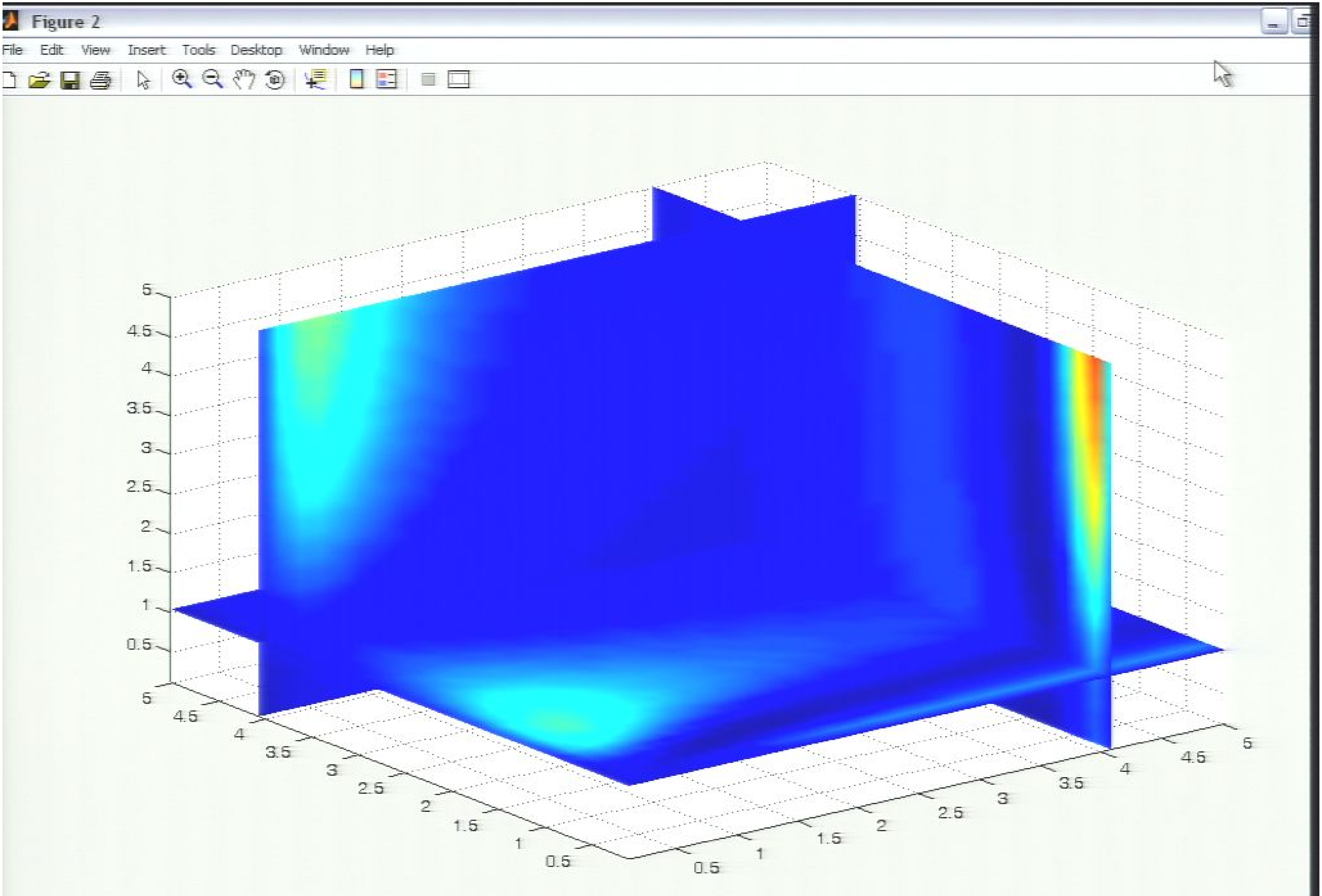


Figure 2
File Edit View Insert Tools Desktop Window Help
5
4.5
4
3.5
3
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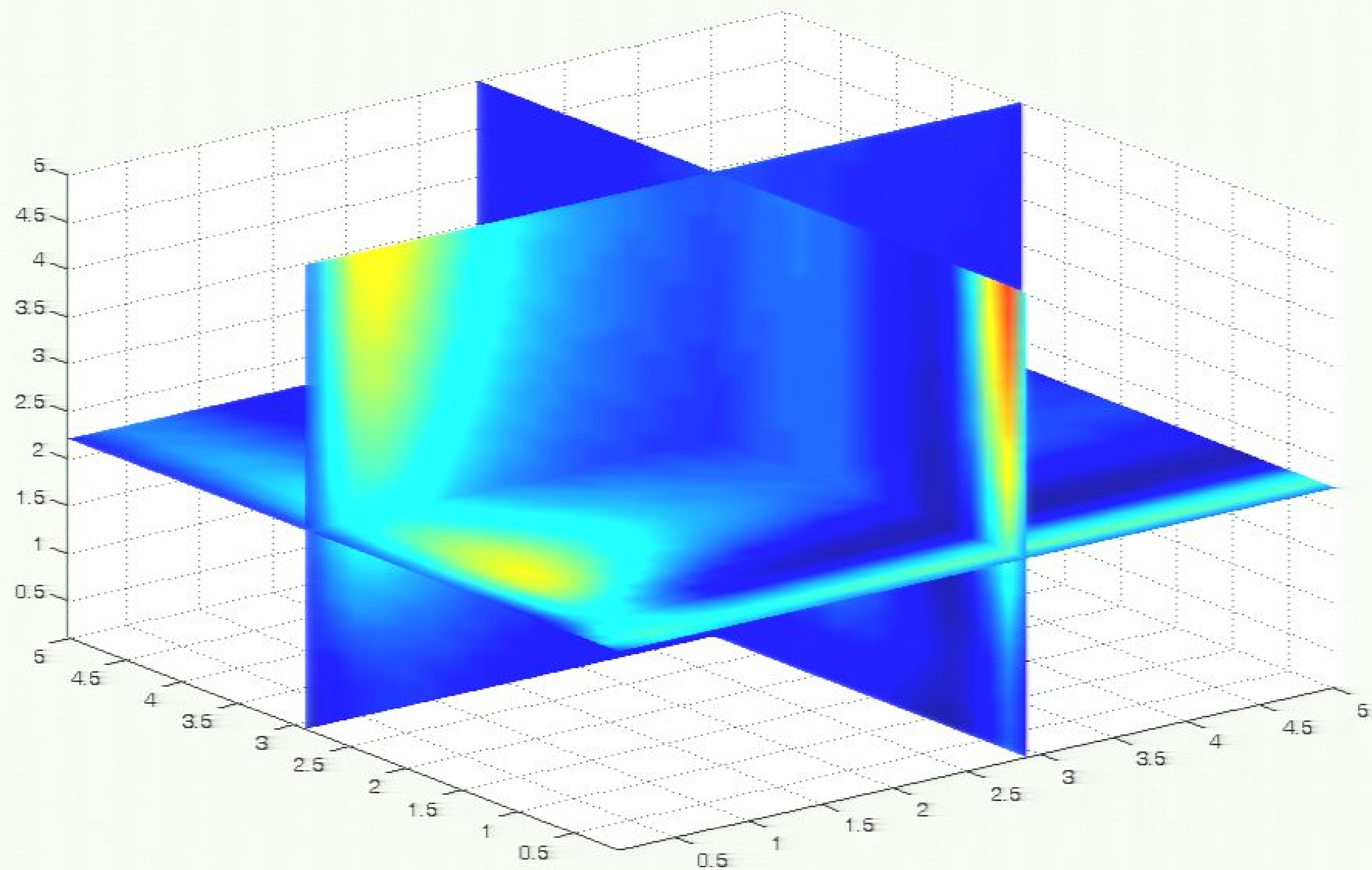
Figure 2

File Edit View Insert Tools Desktop Window Help



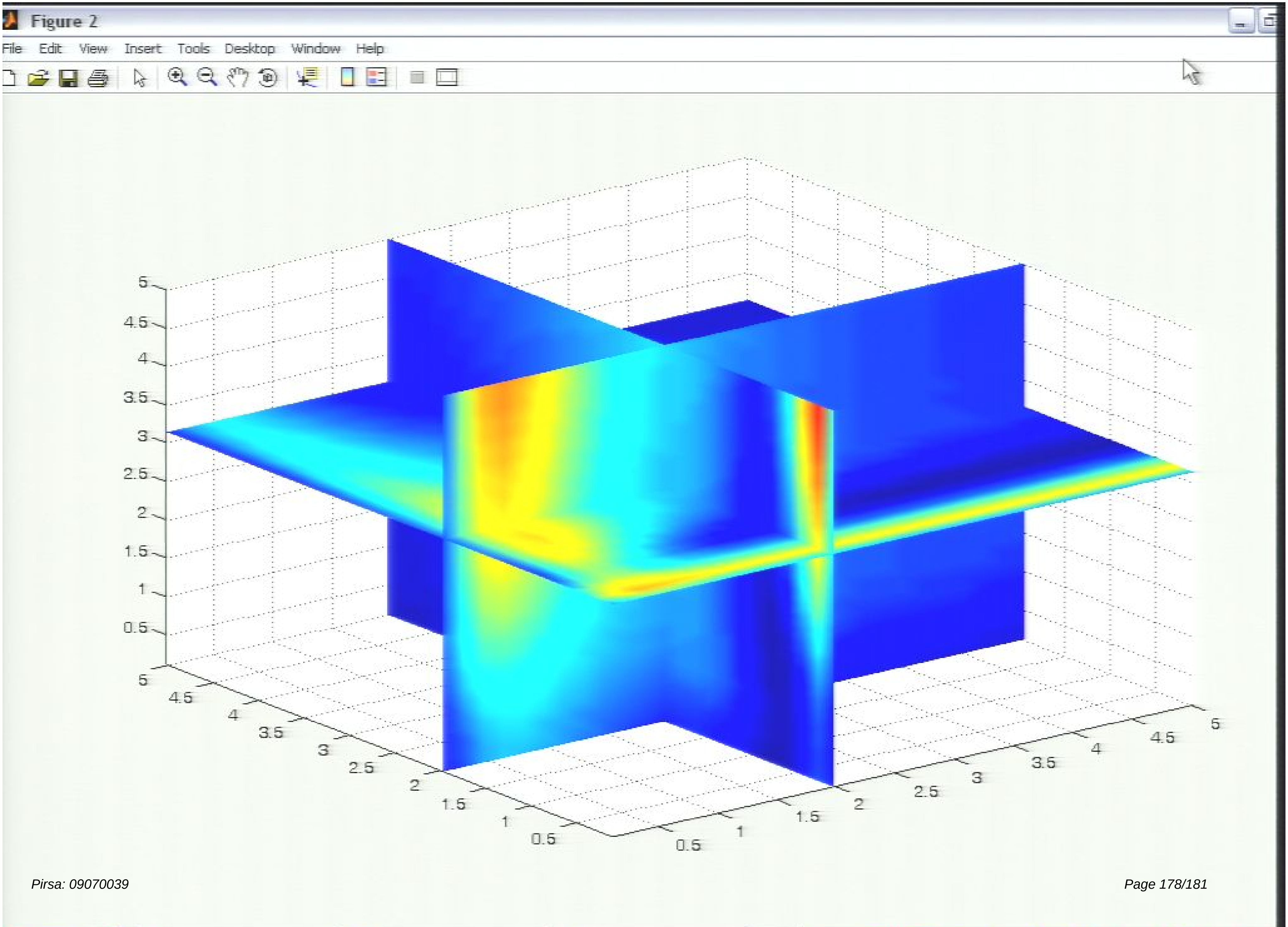


Figure 2
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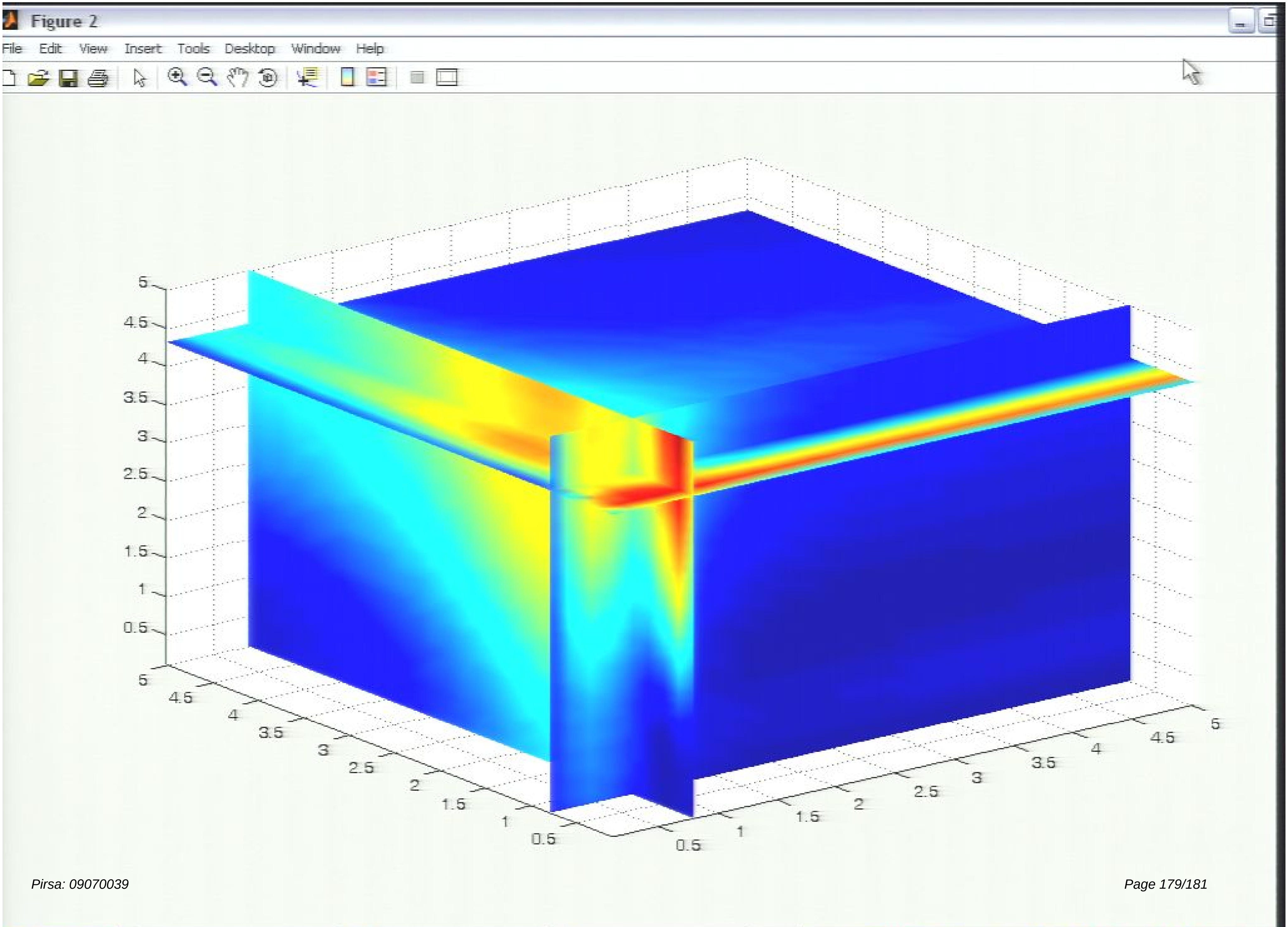
Figure 2
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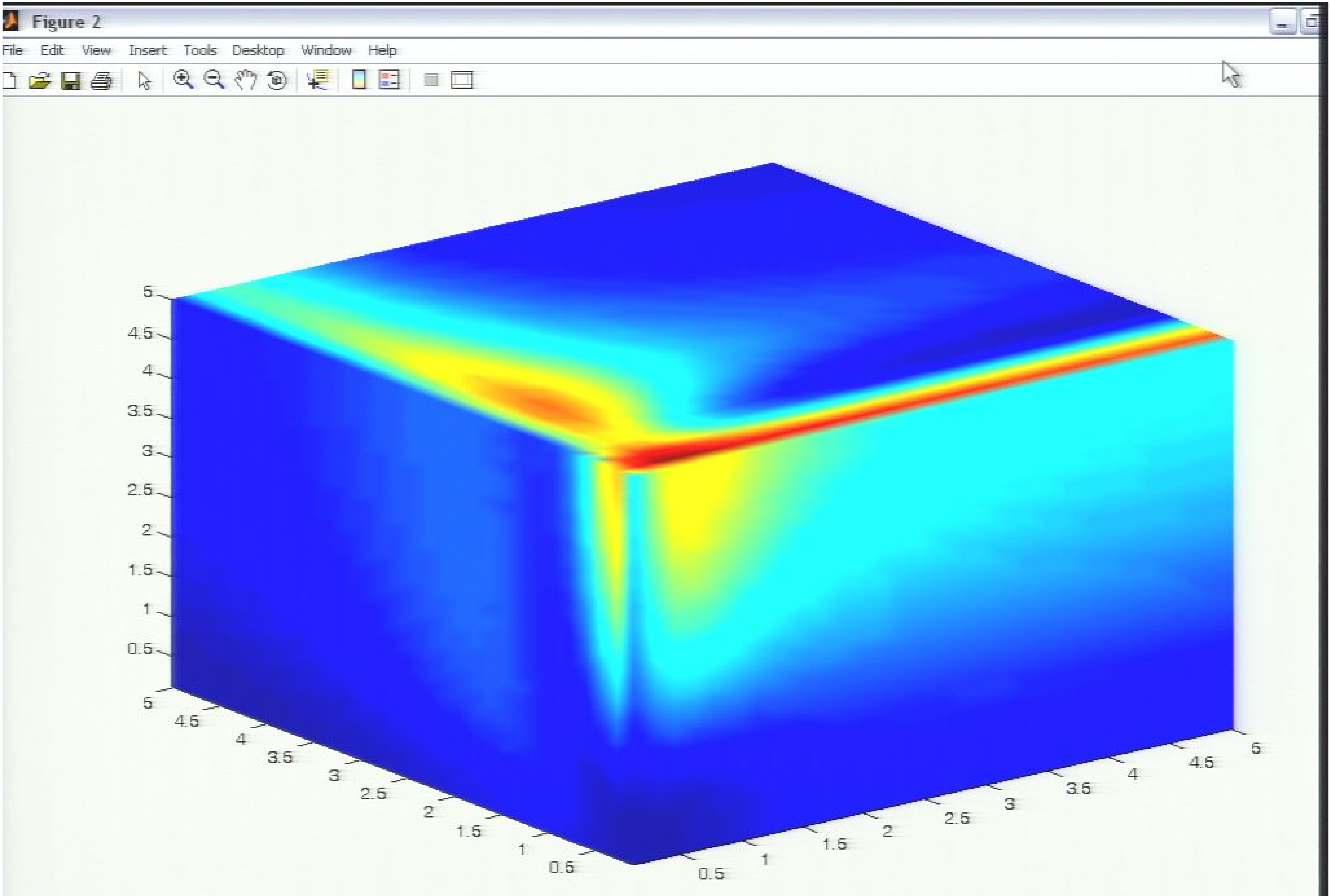

Figure 2
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Editor - D:\Bruce\tex\Fisher Tackle\Papers\isoFoM_movie.m

File Edit Text Cell Tools Debug Desktop Window Help

Stack: Base

```
function isoFoM_movie
% movie of iso FoM surface - either slice or isosurface
% BB 1 June 09

close all
%load v_30_new.mat; old data
load new_detf_fom_vol_out.mat  % new DETF FoM data
%v = v_30_new;
v = fom_vol;
H=linspace(0.1,5,30); da=linspace(0.1,5,30); G=linspace(0.1,5,30);
[x y z] = meshgrid(H,da,G);

xmin = 0.1;
xmax = 5;
ymin = 0.1;
ymax = 5;
zmin = 0.1;
zmax = 5;
minv = min(min(min(v)));
maxv = max(max(max(v)));

figure(2)
whitebg('white')  % colour of background
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
n = 75;  % number of threshold steps
step = (maxv-minv)./n;  % union step in threshold
thresh = minv:step:maxv;   % threshold vector
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

slice_flag = 1;  % 1 if slice animation, 0 if union

nslice = 50;
```

FM_Cal.m × isoFoM_movie2.m × isoFoM.m × isoFoM_movie.m ×

isoFoM_movie Ln 24 Col 79