Michigan Tech
Michigan Technological University

Gamma-Ray Bursts as Cosmological Tools

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Outline

- ✓ *A brief history of time & the Universe*
- ✓ *Introduction to Astrophysical notions & definitions*
- ✓ *Gamma-Ray Bursts (GRBs)*
- ✓ *Can GRBs serve as standard candles?*

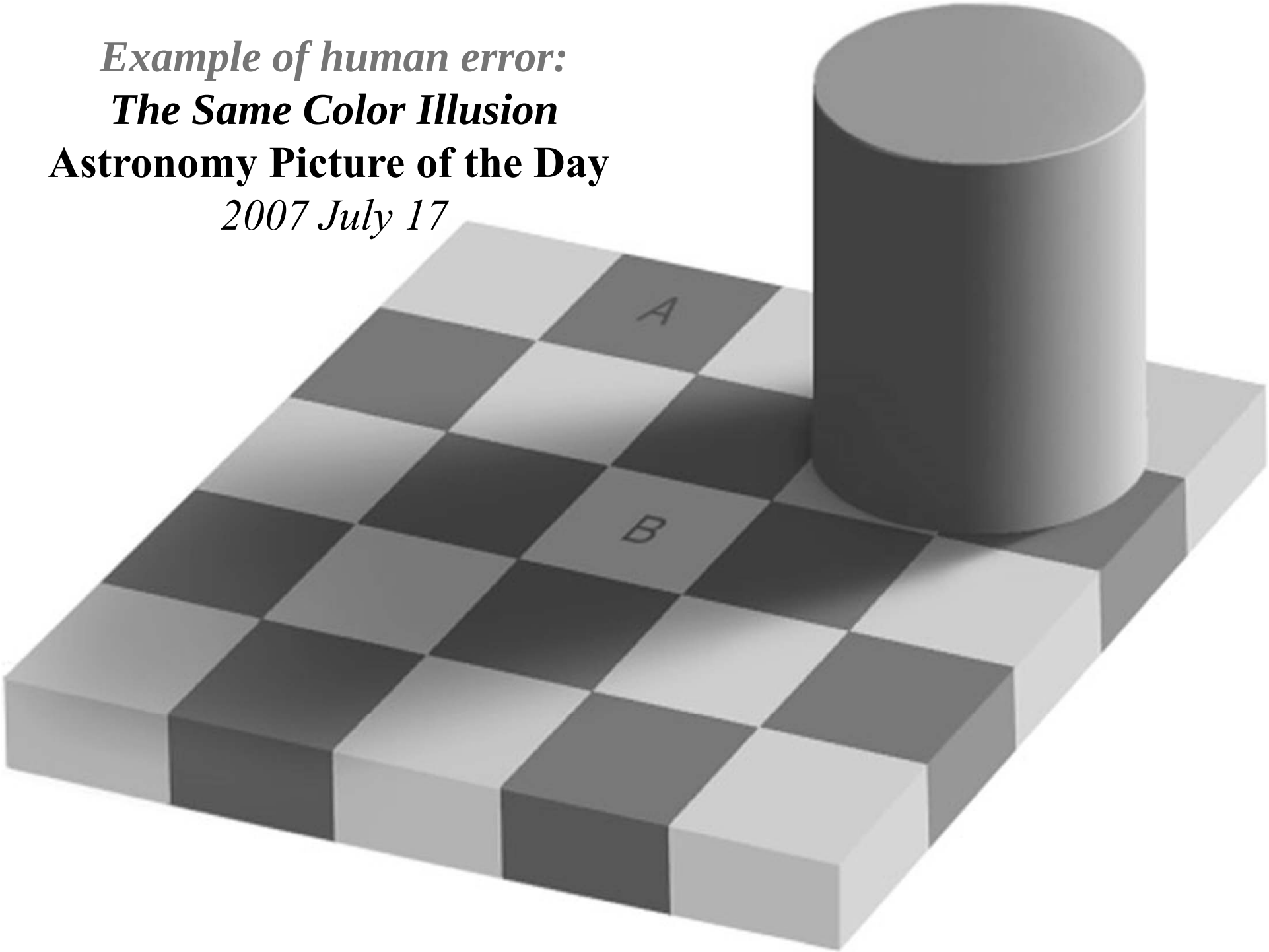
  - *Shahmoradi & Nemiroff, The Possible Impact of GRB Detectors on Cosmological Standard Candles, MNRAS, 2009, arXiv:0904.1464v1*
  - *Shahmoradi & Nemiroff, Hardness as a Spectral Peak Estimator for Gamma-Ray Bursts, MNRAS, 2010, arXiv:0912.2148v2*

Example of human error:

The Same Color Illusion

Astronomy Picture of the Day

2007 July 17



Example of human error:

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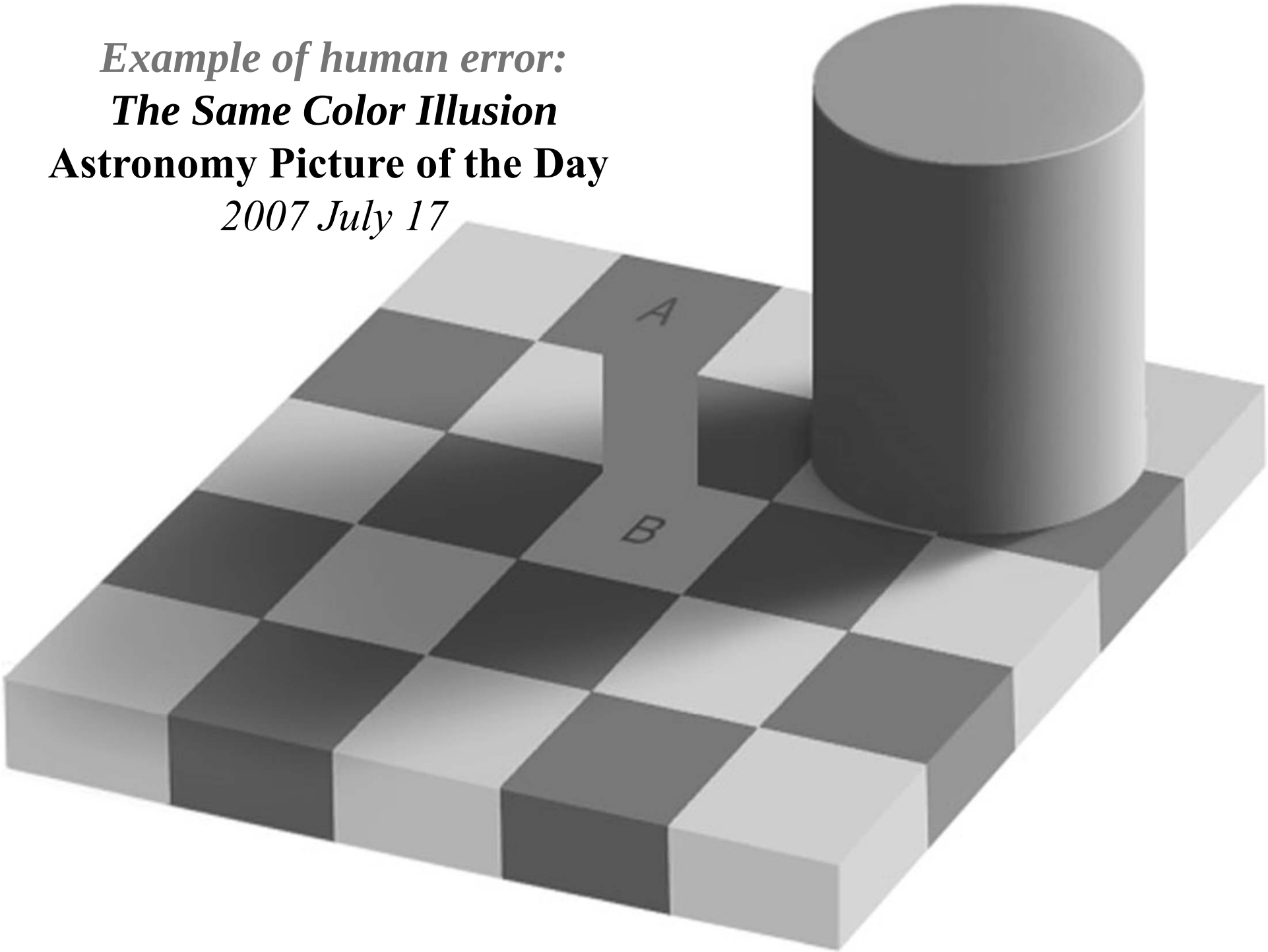
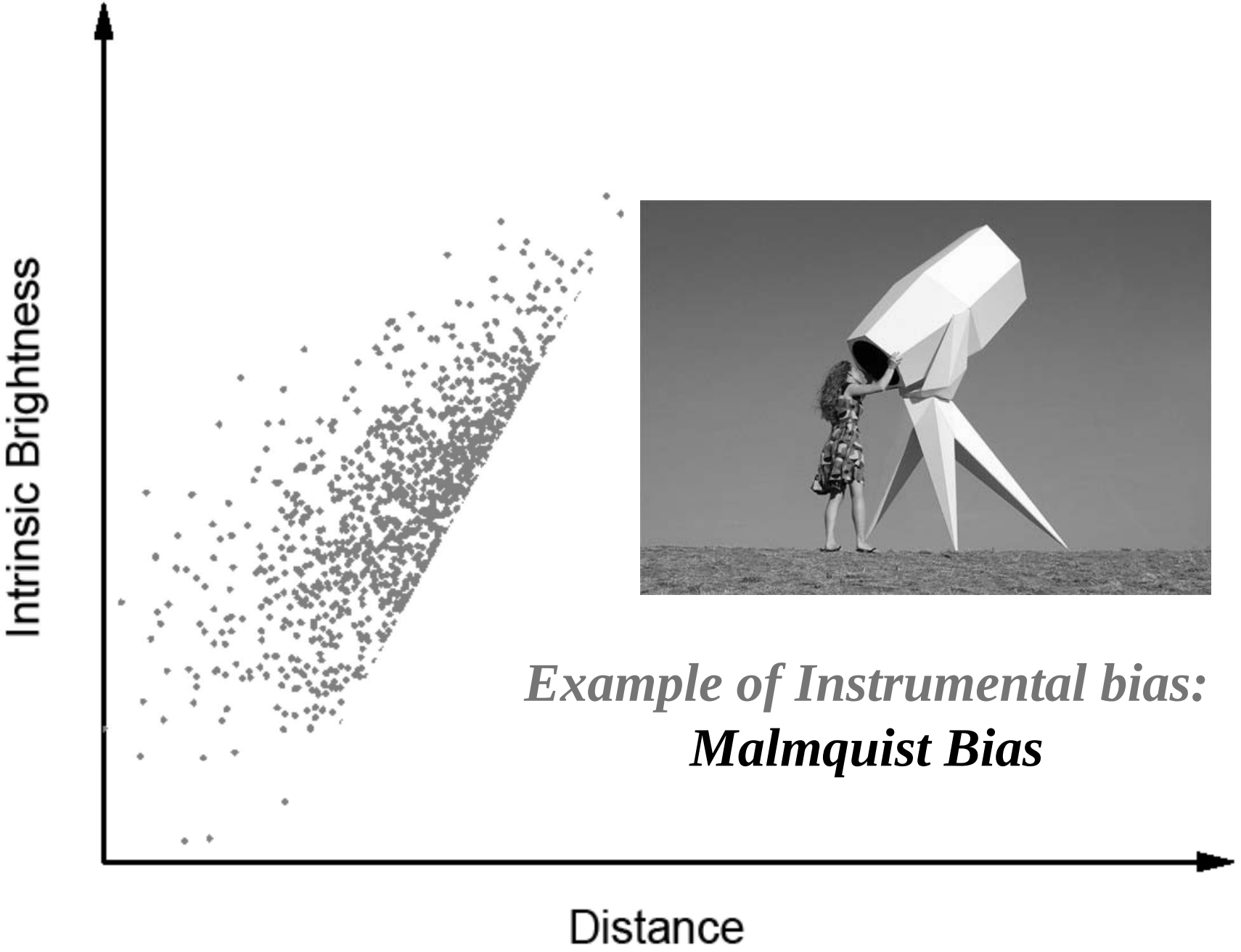
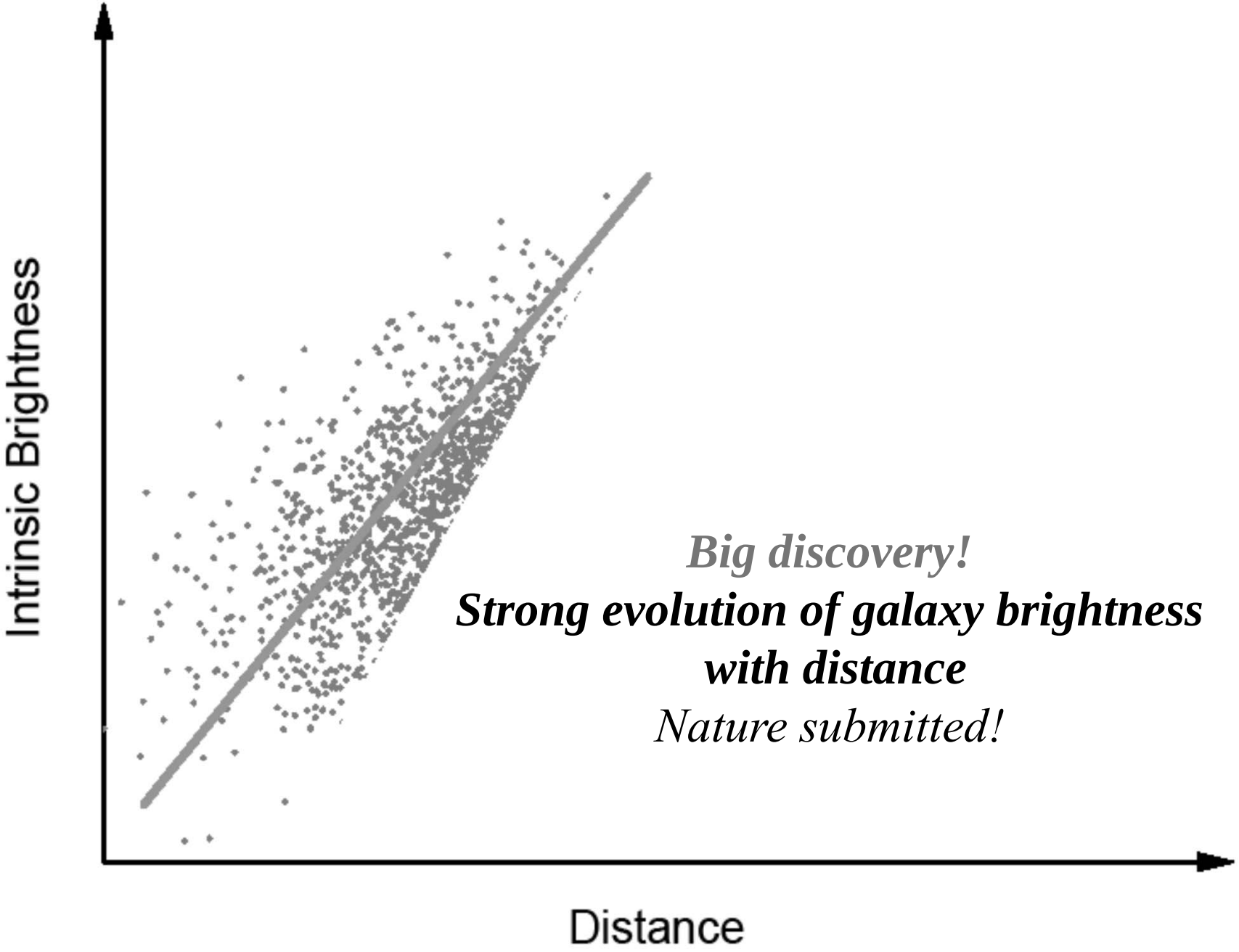
2007 July 17





Example of Instrumental bias:

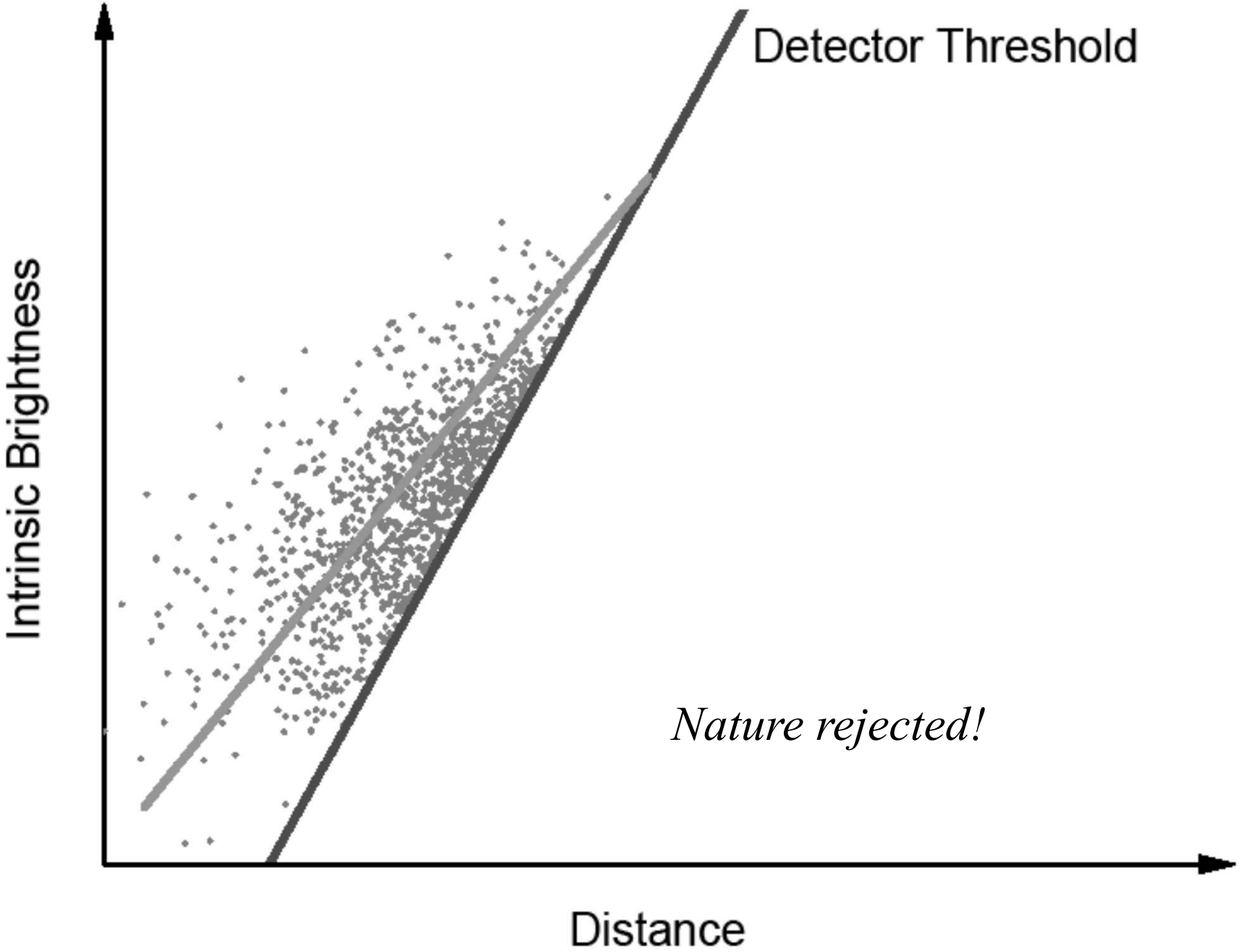
Malmquist Bias

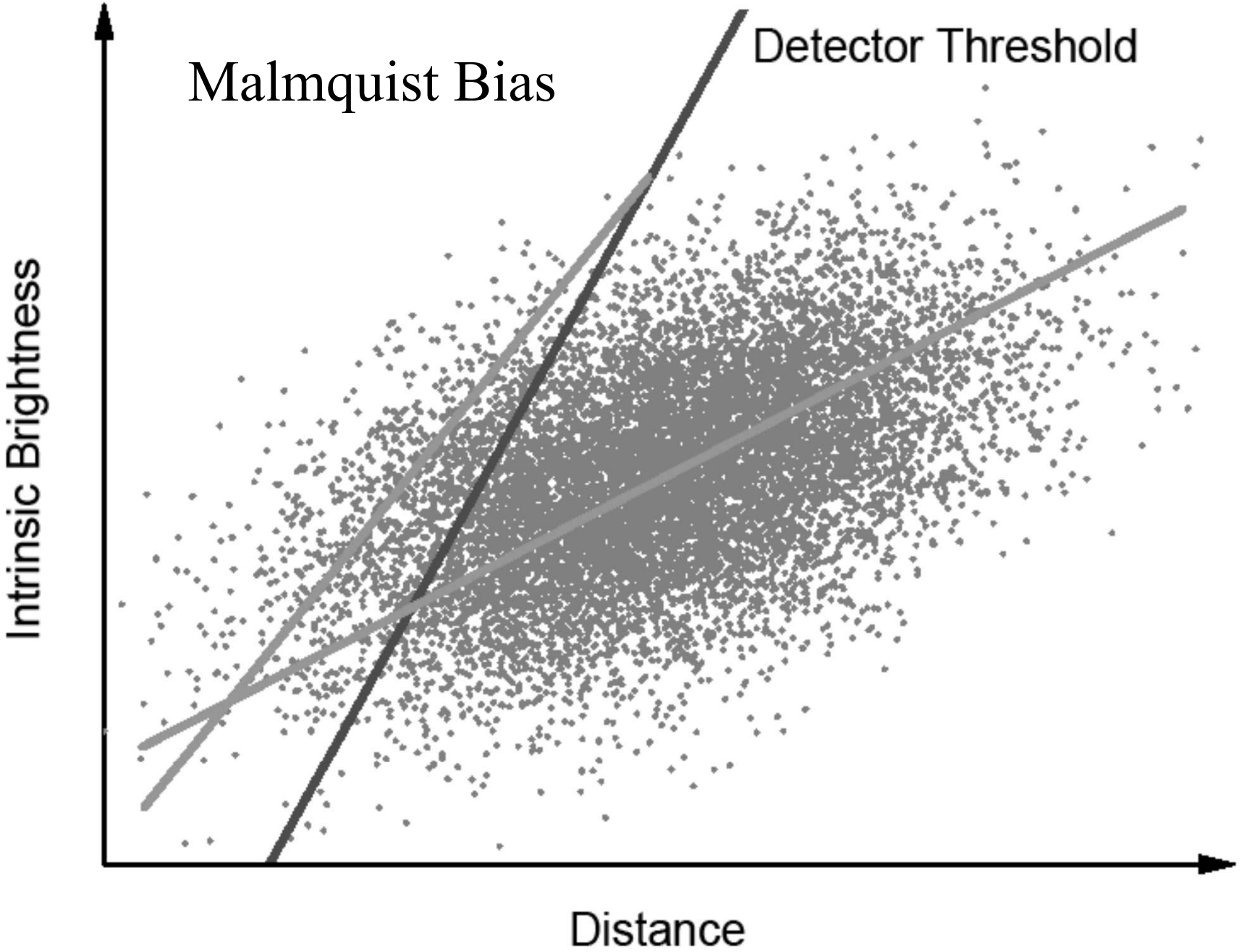


Big discovery!

Strong evolution of galaxy brightness with distance

Nature submitted!


Detector Threshold
Intrinsic Brightness
Distance
Nature rejected!


Malmquist Bias
Detector Threshold
Intrinsic Brightness
Distance

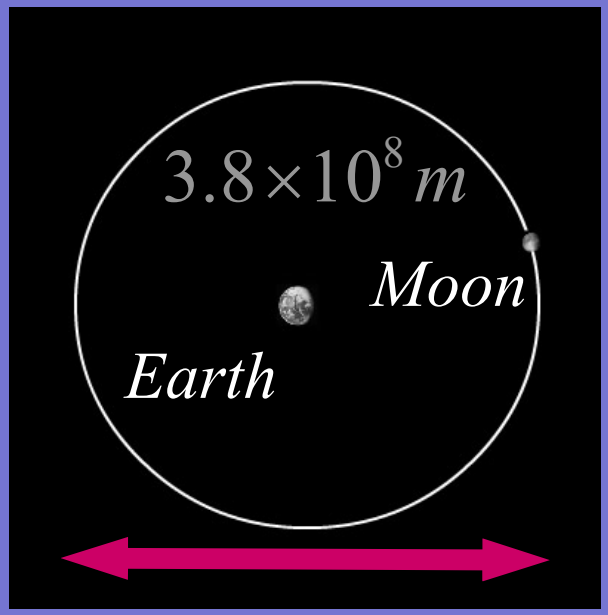
Edwin Hubble, Astronomer, 1925

- ✓ *The Universe is unimaginably huge*
- ✓ *The Universe is expanding*
  - ✓ *It had a beginning 13.7 billion years ago*
- ✓ *The visible size of the universe:*

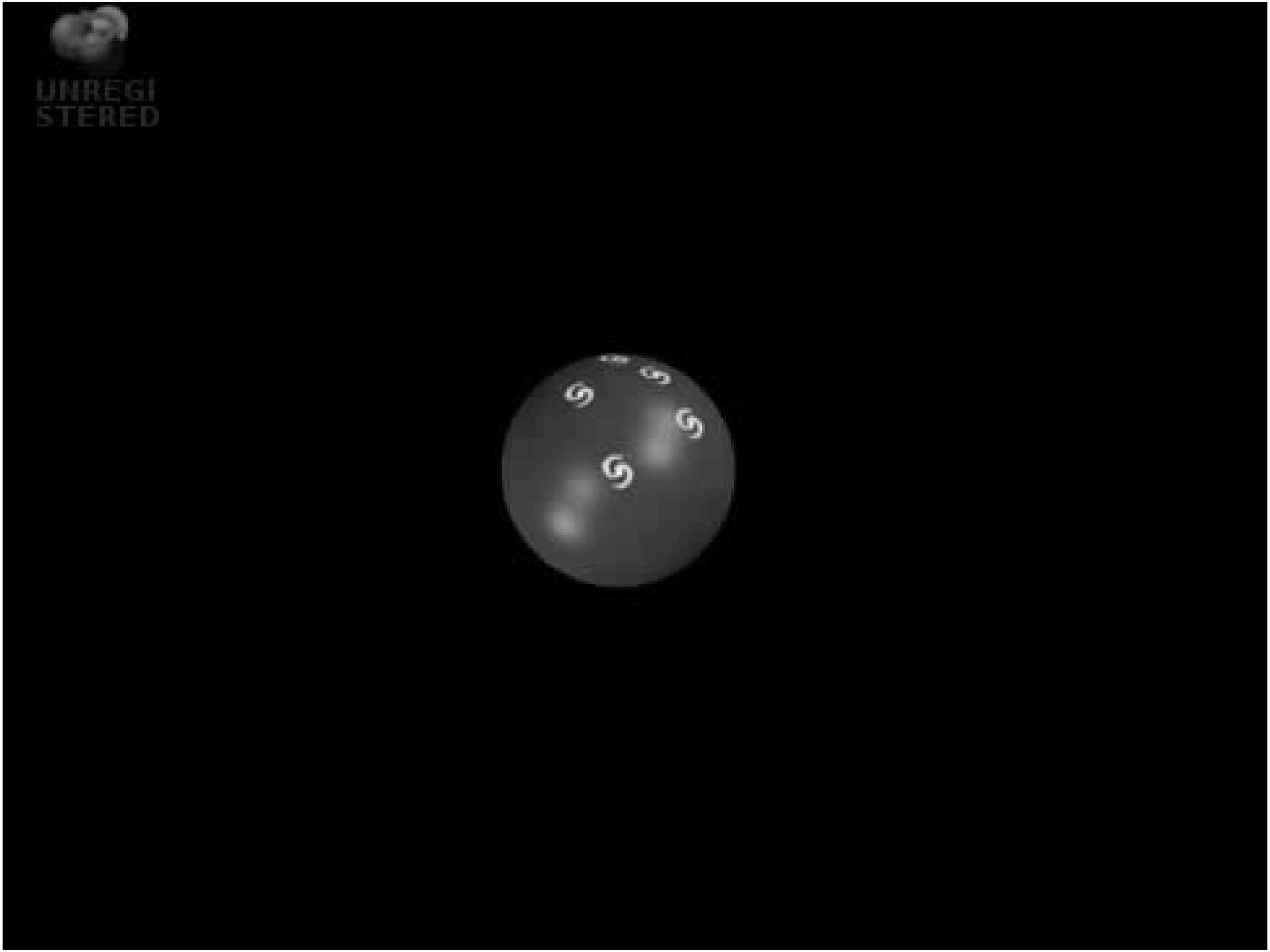
13.75±0.11 *billion light years*

or

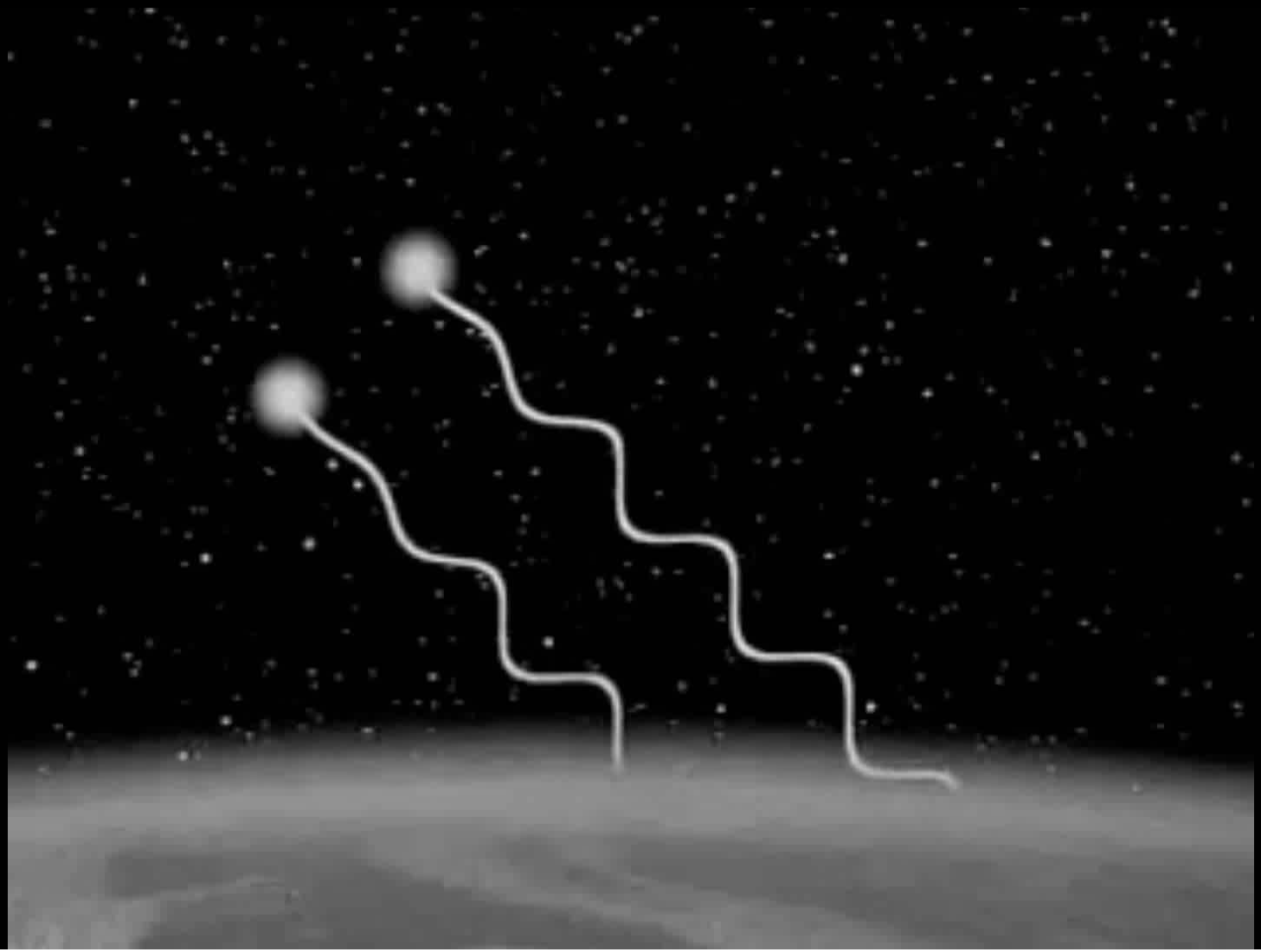
$\approx 1.3\times10^{26}\,m$

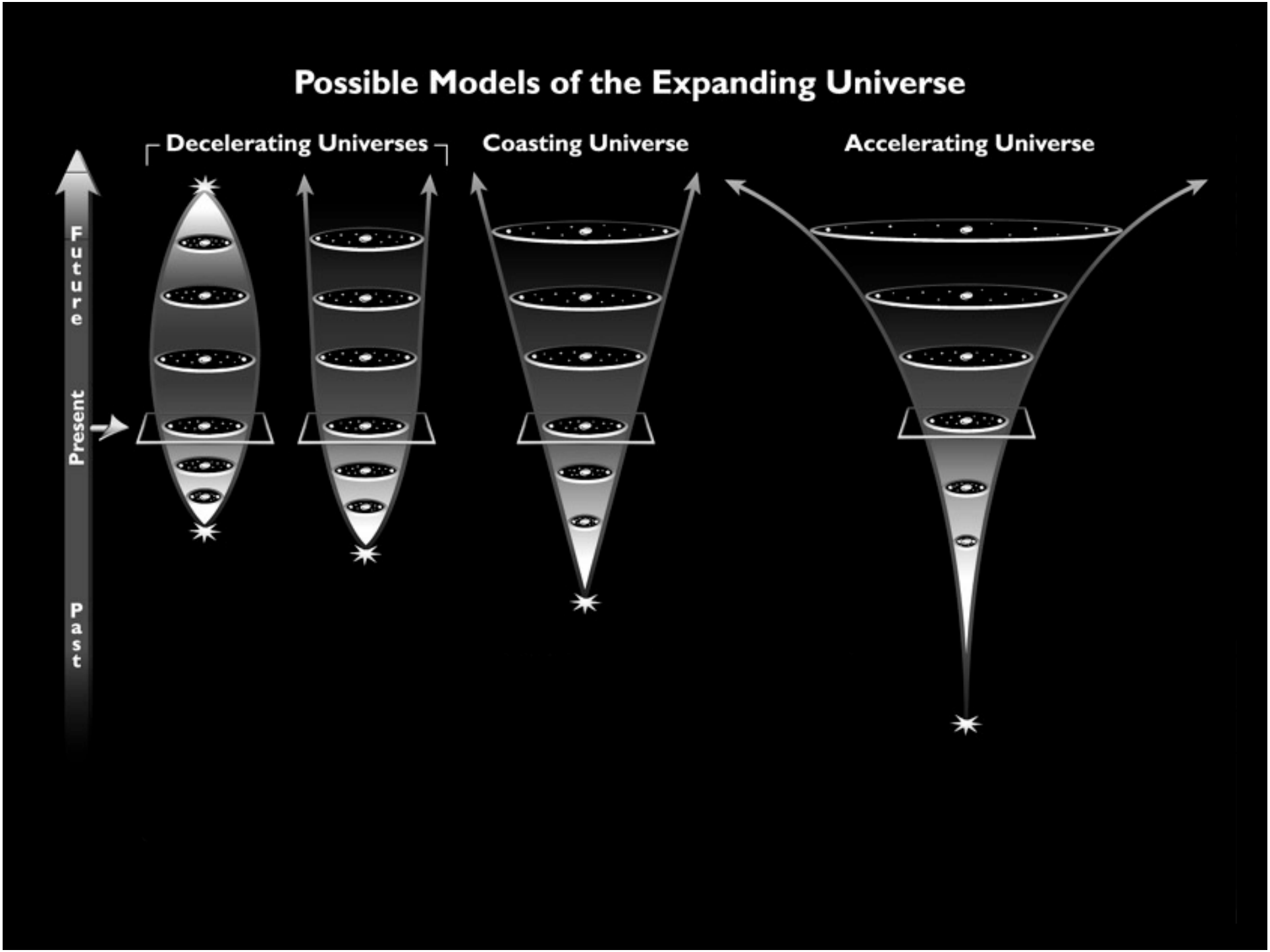


2 light seconds


UNREGI
STERED

How did Hubble discover the expansion of the Universe?




Possible Models of the Expanding Universe
Decelerating Universes
Coasting Universe
Accelerating Universe
Future
Present
Past

How to find the correct cosmological model?

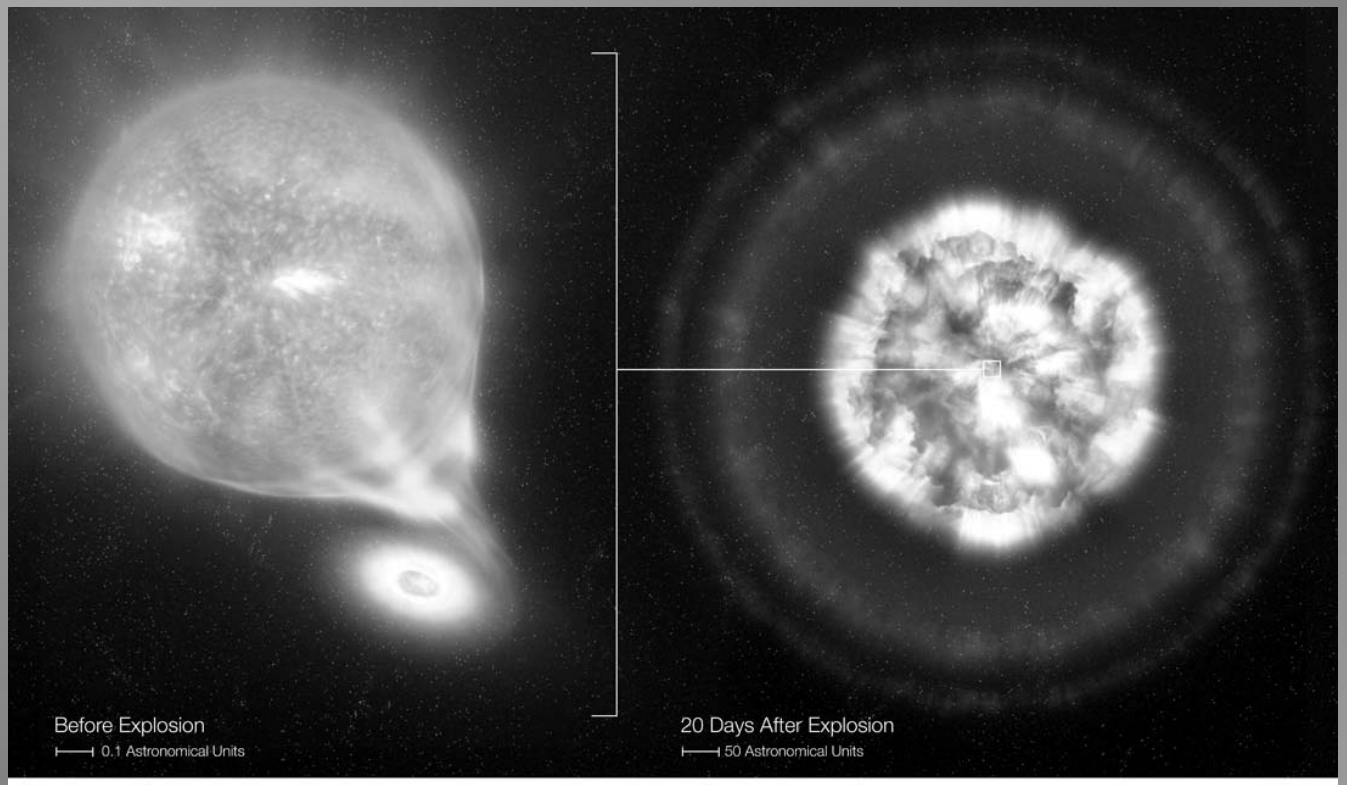
- ✓ *Cosmological Standard Candle*
  - ✓ *Constant Luminosity known*
  - ✓ *Spectroscopic Redshift known*

$$D_L = \sqrt{\frac{1}{4\pi}\frac{\text{Intrinsic Luminosity}}{\text{observed brightness}}}$$

- ✓ *Different cosmological models lead to different definitions of distance,*

$$D_L = \frac{C}{H_0}(1+z)\int_0^z dz'\left[(1+z')^3\Omega_M + \Omega_\Lambda\right]^{-1/2}$$

Type-Ia Supernovae as Cosmological Standard Candles



SN 2006X, before and after the Type Ia Supernova Explosion
(Artist Impression)

ESO Press Photo 31b/07 (12 July 2007)

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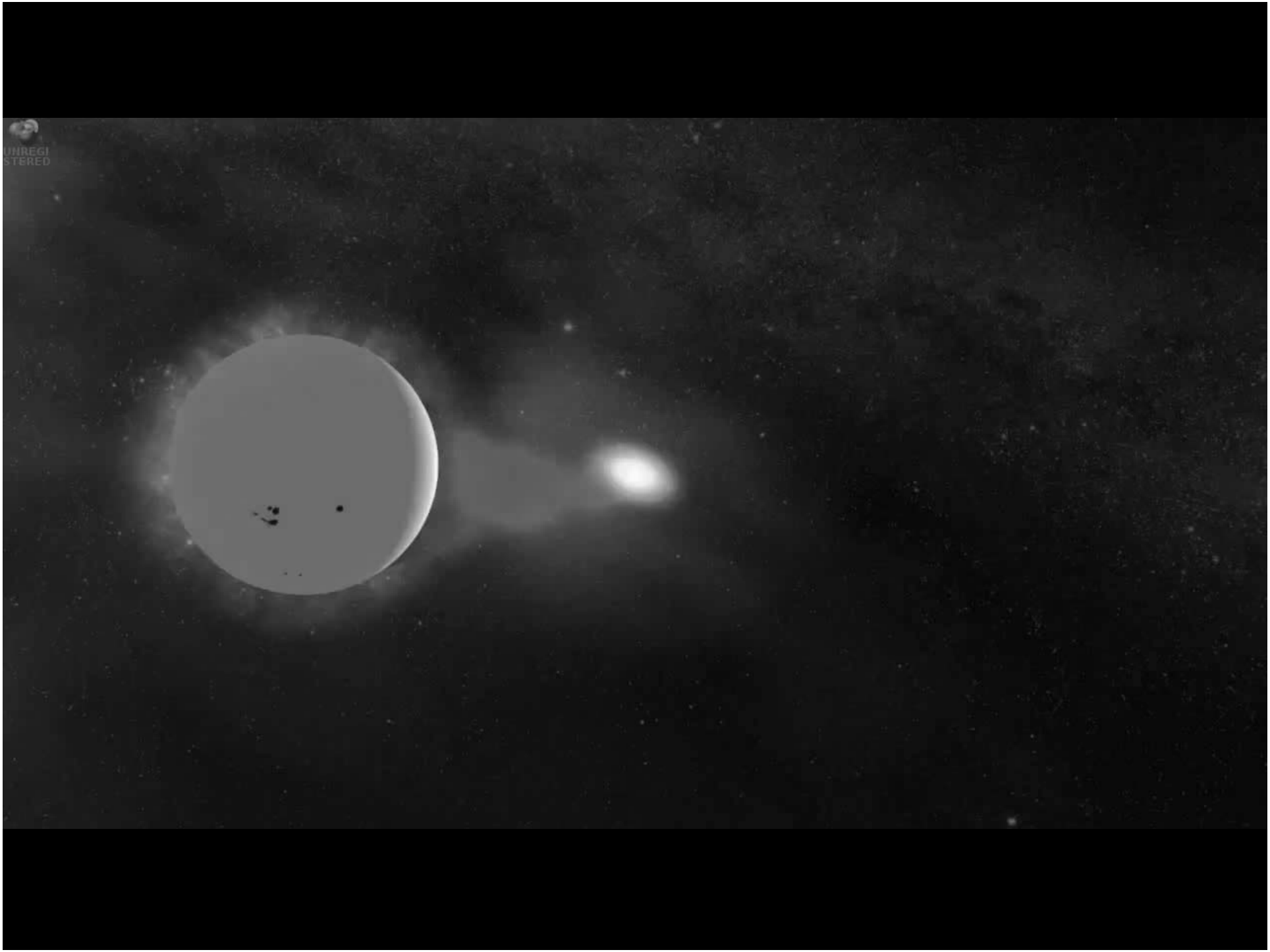
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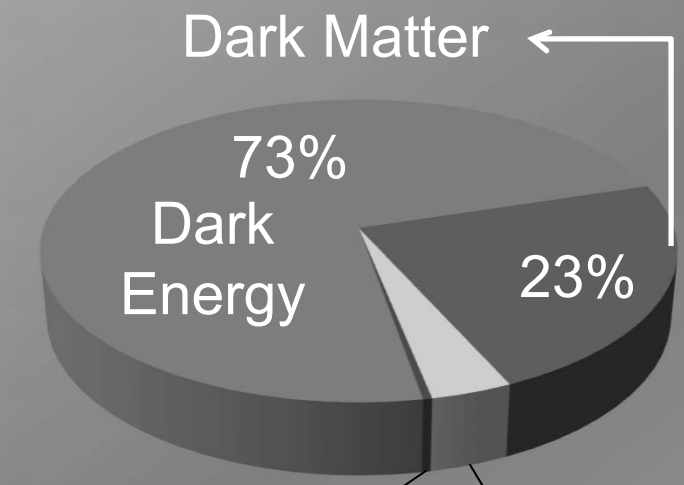
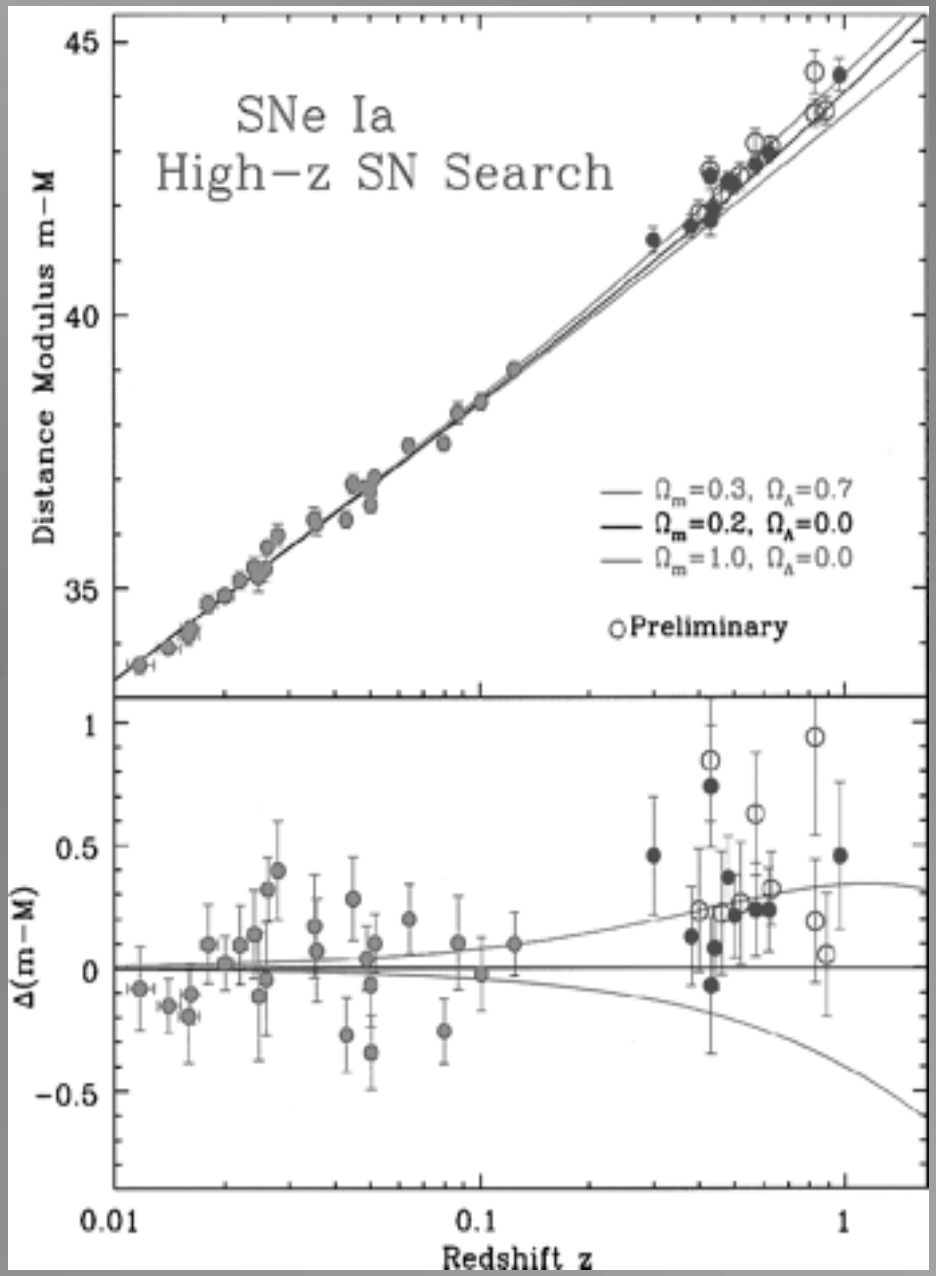
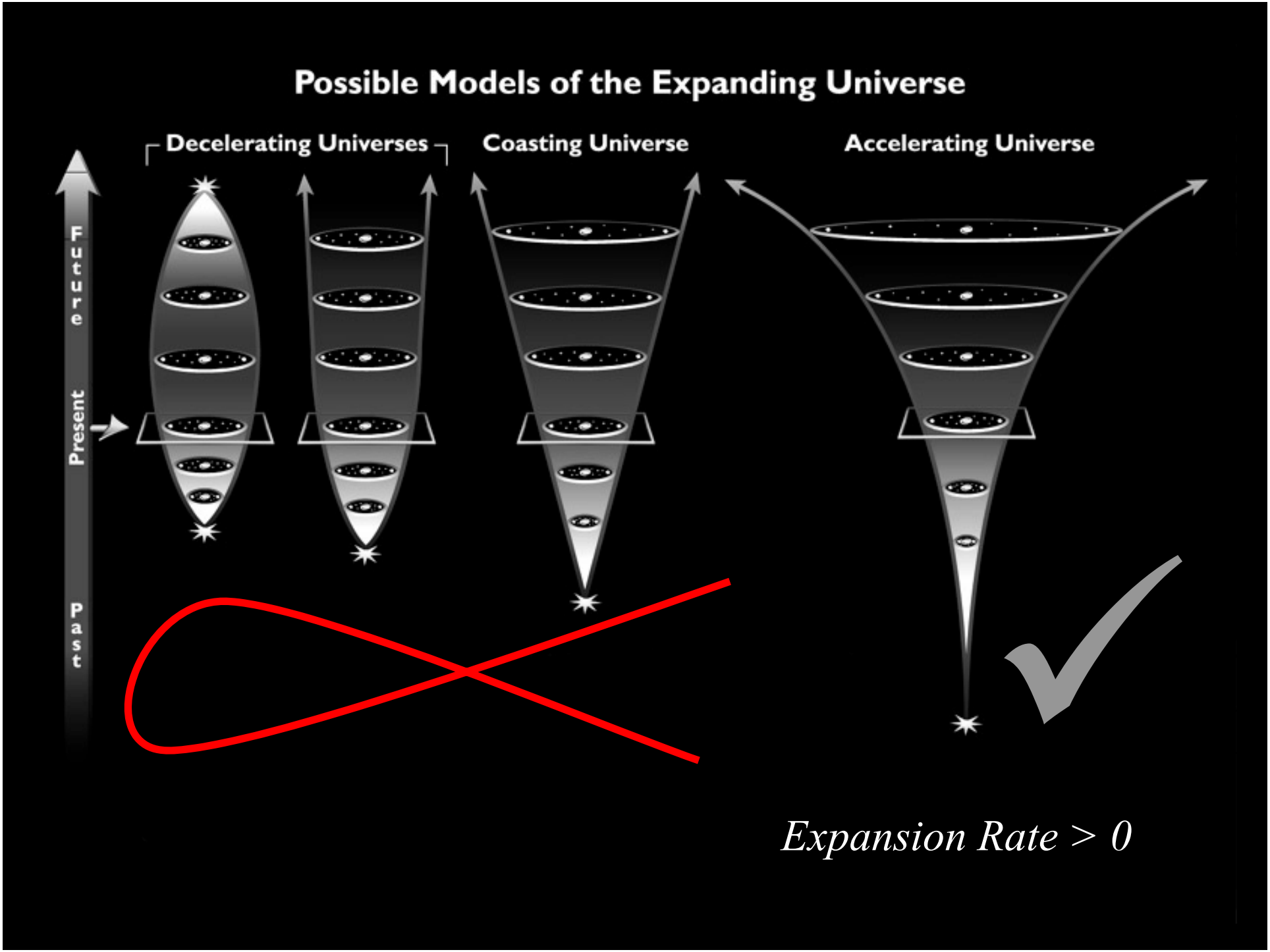
Supernovae Hubble diagram,

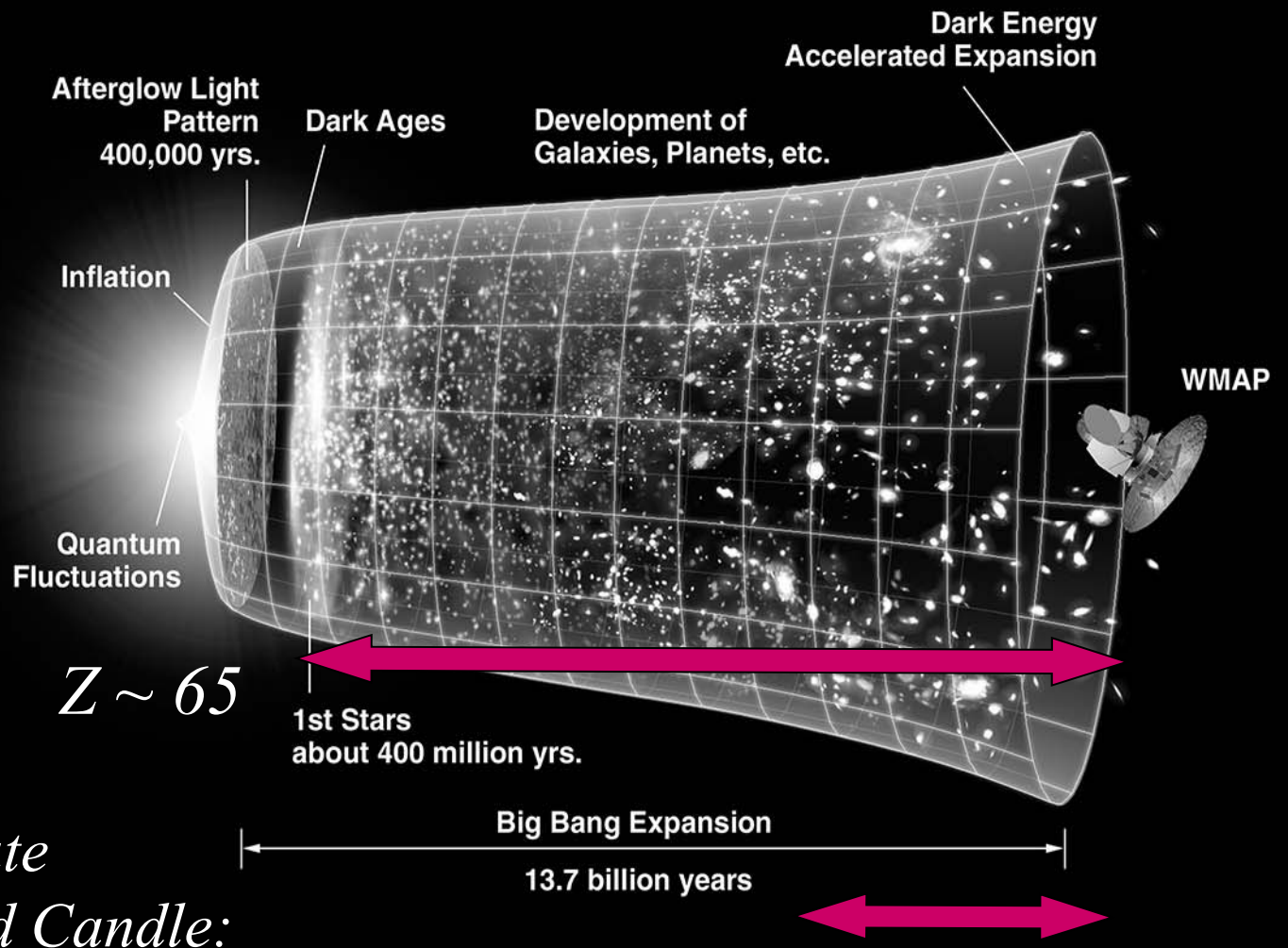
Kirshner 1999, PNAS, 96, 4224






Possible Models of the Expanding Universe
Decelerating Universes
Coasting Universe
Accelerating Universe
Future
Present
Past
Expansion Rate > 0

How to constrain the expansion rate of the universe in the distant universe?



Candidate Standard Candle: Gamma-Ray Bursts (GRBs)

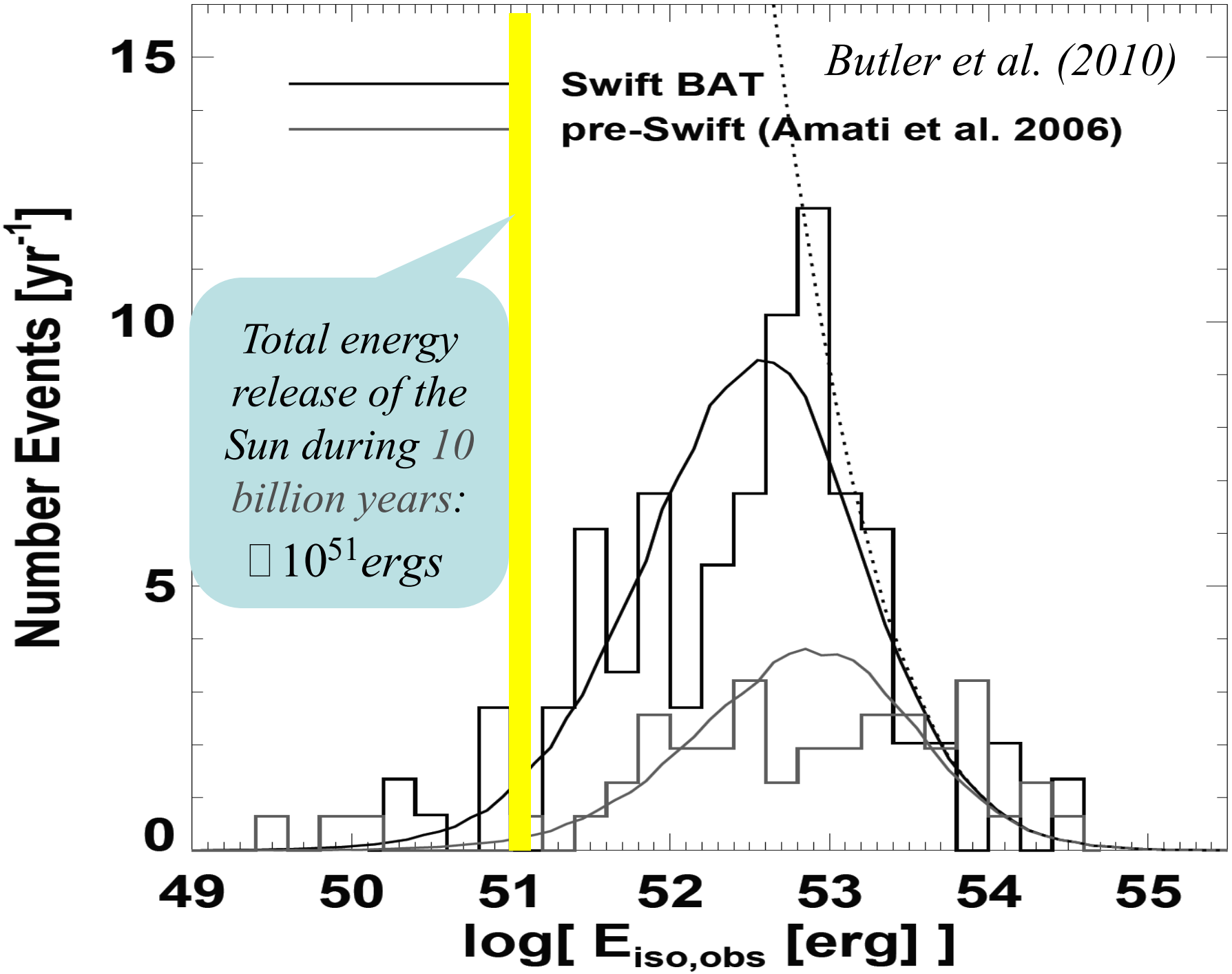
Supernovae projects: Z < 1.7

Gamma-Ray Bursts (GRBs)

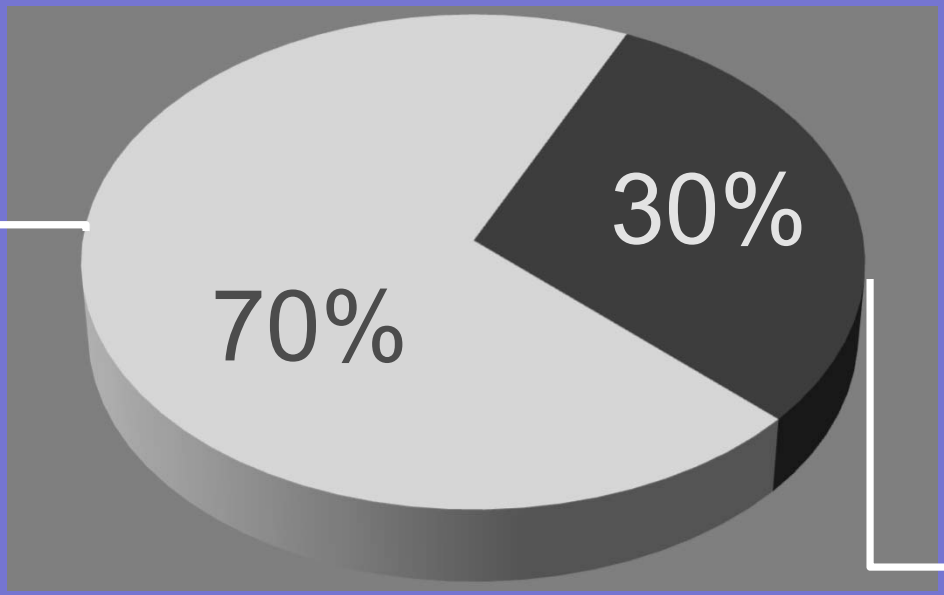
- ✓ *Discovered by Vela nuclear test detection satellite (1960s) , Top-Secret project before the collapse of USSR*

- ✓ *The most powerful explosions in the Universe*

$$10^{47} ergs < E_{iso} < 10^{55} ergs$$


Butler et al. (2010)
Swift BAT
pre-Swift (Amati et al. 2006)
Total energy release of the Sun during 10 billion years:
$\sim 10^{51}$ ergs
Number Events [yr^{-1}]
0
5
10
15
49
50
51
52
53
54
55
log[$E_{iso,obs}$ [erg]]

GRB types

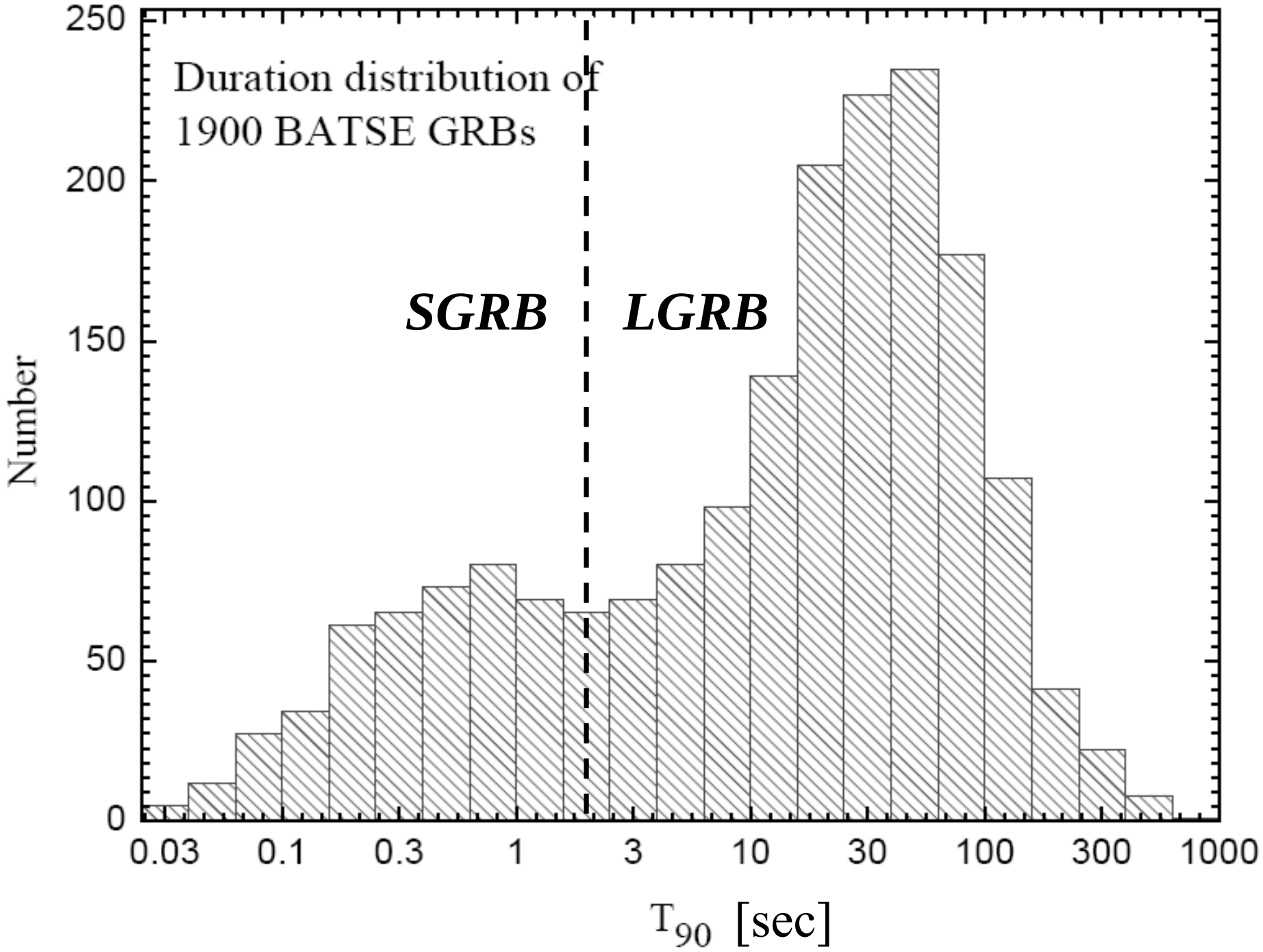


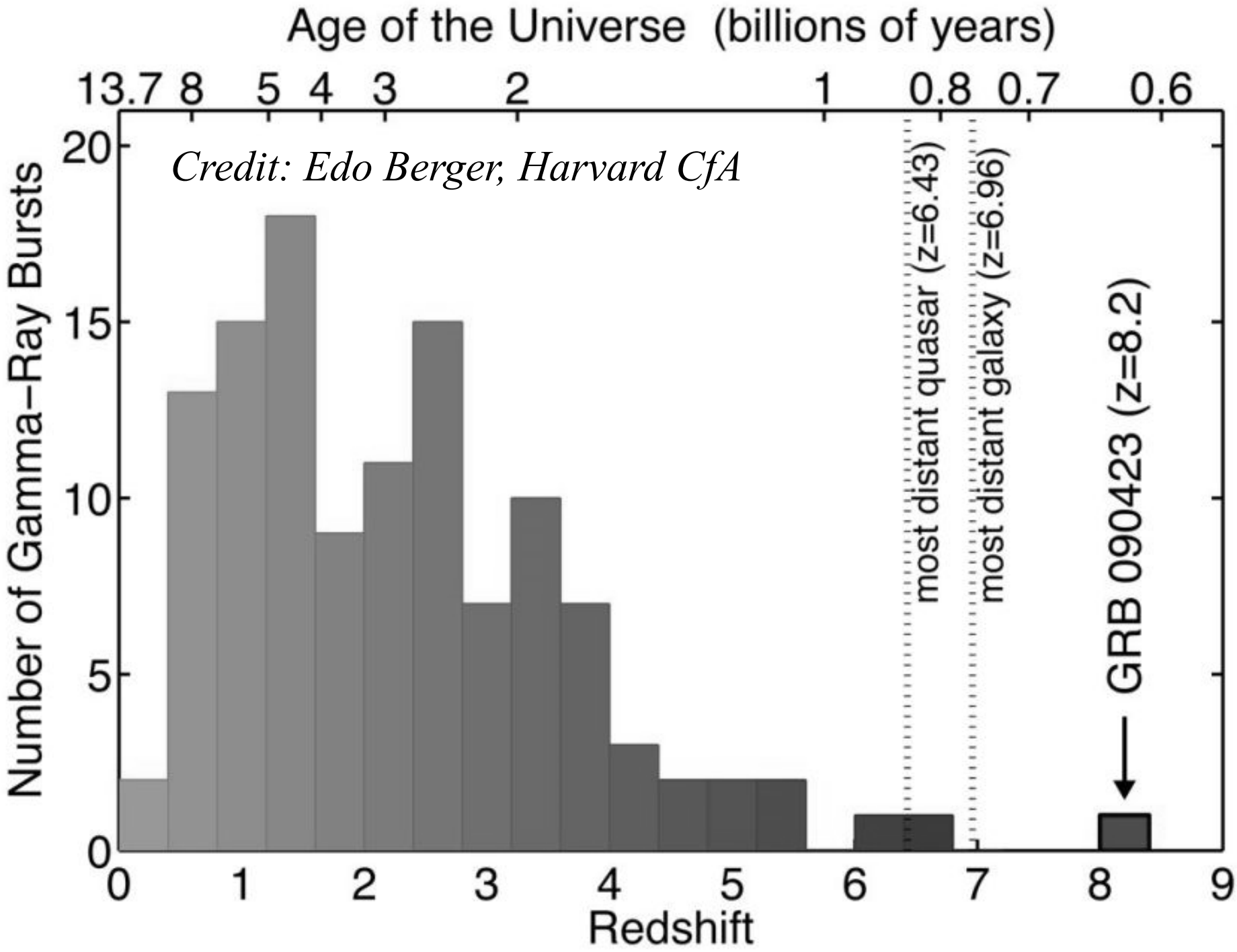
*Long-duration GRBs (**LGRB**s):*
possibly related to the death of supermassive stars

*Short-duration GRBs (**SGRB**s):*
possibly the merger of binary neutron stars

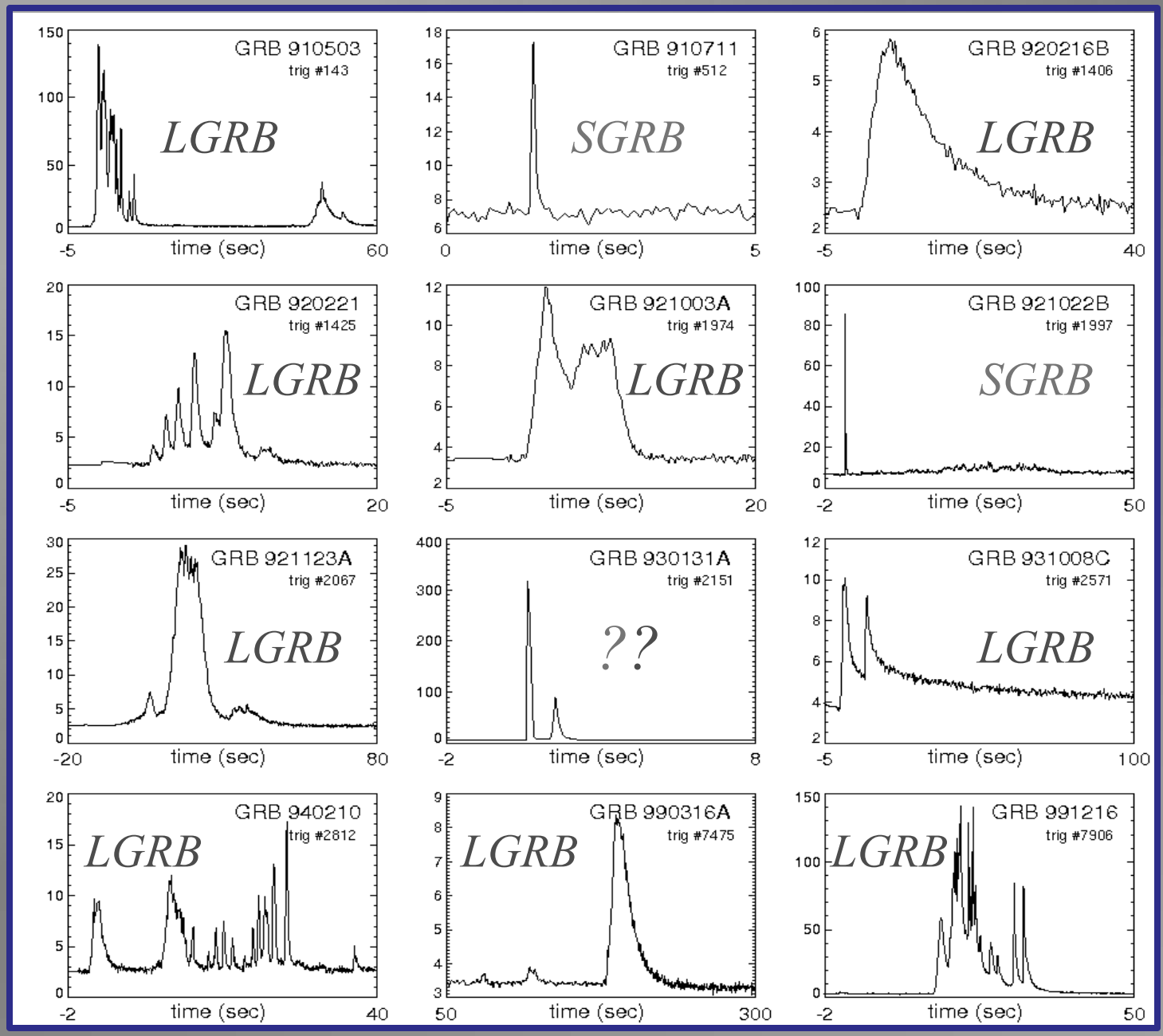
Long-duration GRB (LGRB)

Short-duration GRB (SGRB)

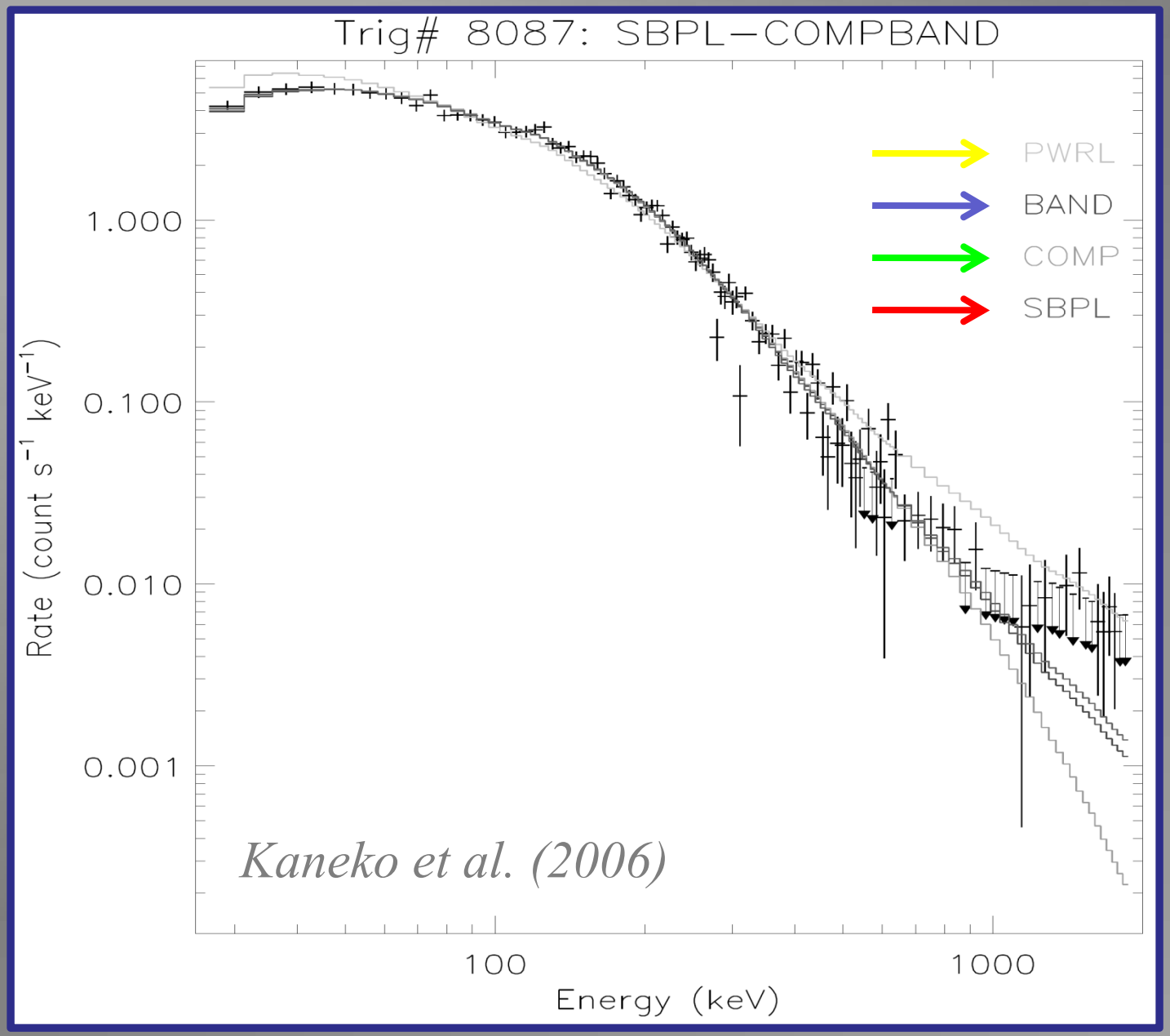

Duration distribution of
1900 BATSE GRBs
SGRB
LGRB
Number
250
200
150
100
50
0
0.03
0.1
0.3
1
3
10
30
100
300
1000
T90 [sec]


Age of the Universe (billions of years)
13.7
8
5
4
3
2
1
0.8
0.7
0.6
Credit: Edo Berger, Harvard CfA
Number of Gamma−Ray Bursts
0
5
10
15
20
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
0
1
2
3
4
5
6
7
8
9
Redshift

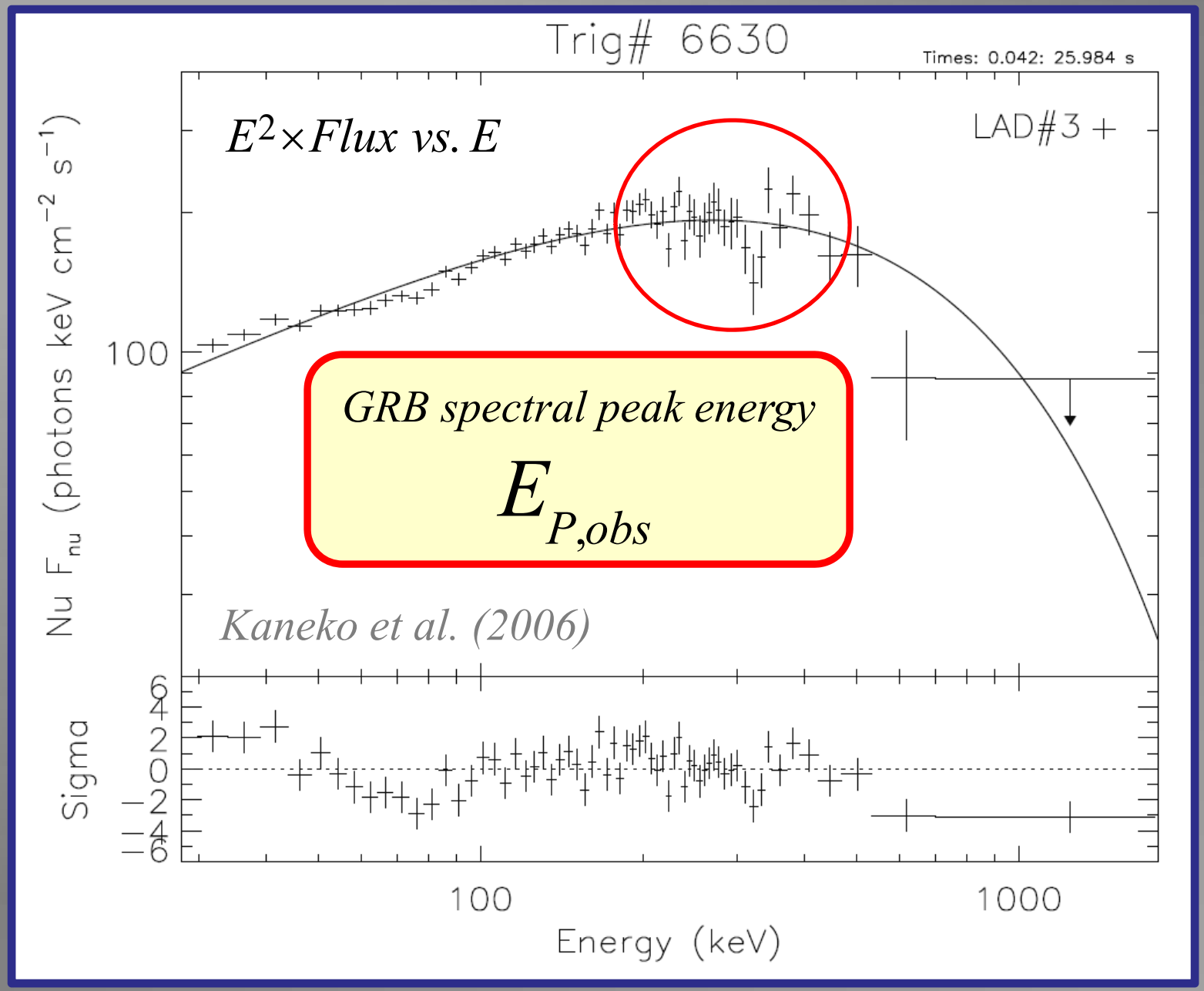
GRB light-curve diversity

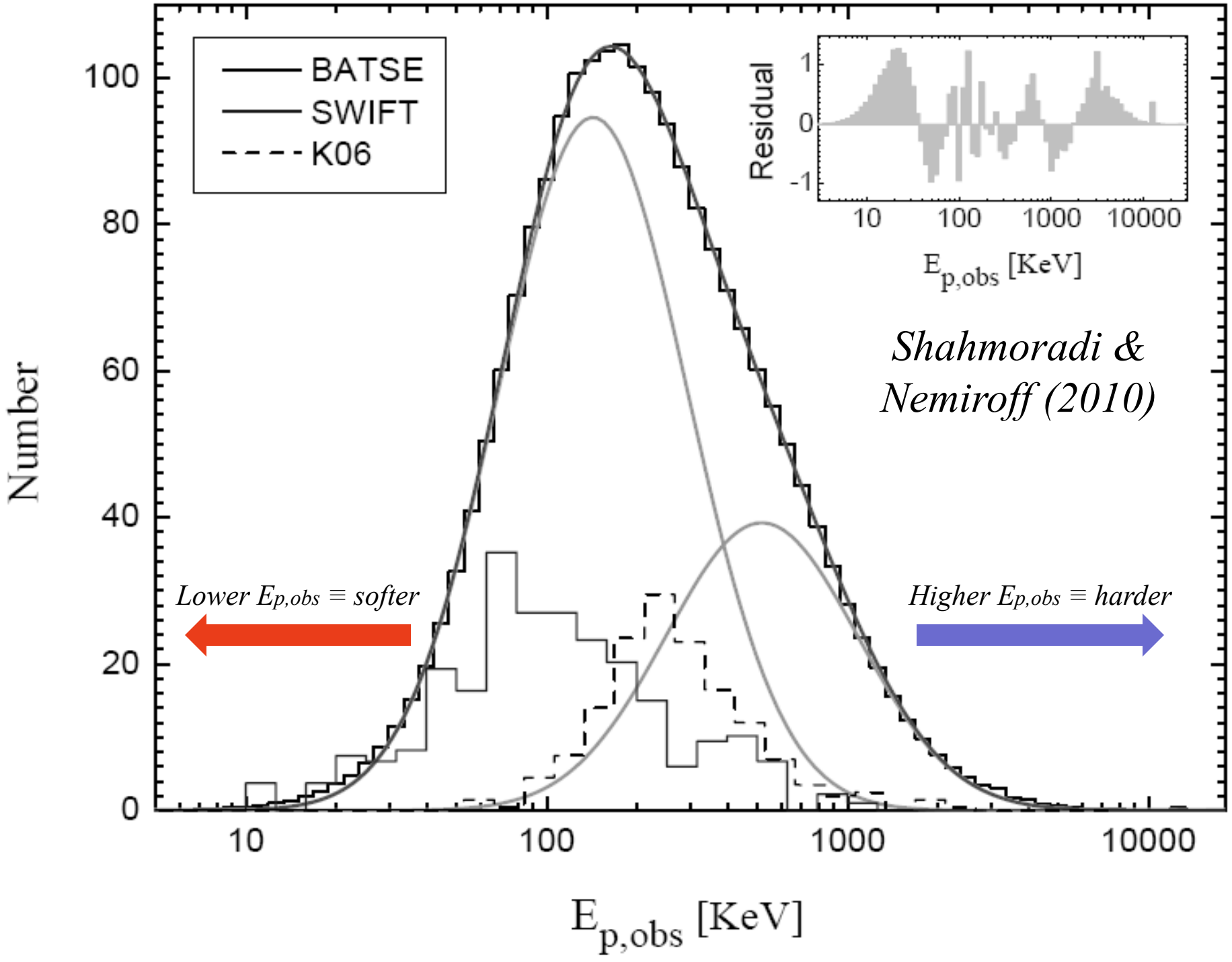


Example of GRB Spectrum

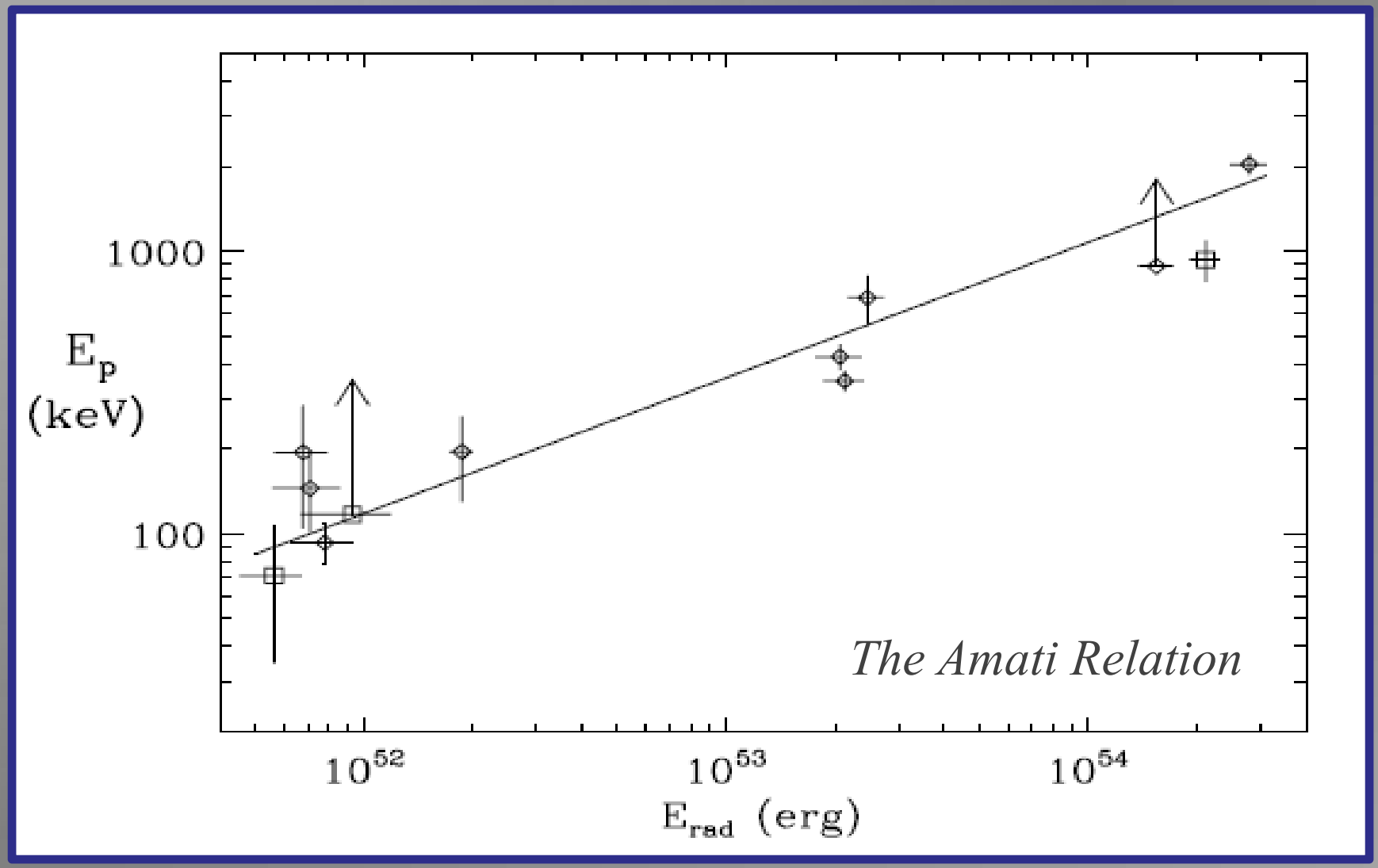


Example of GRB Power Spectrum



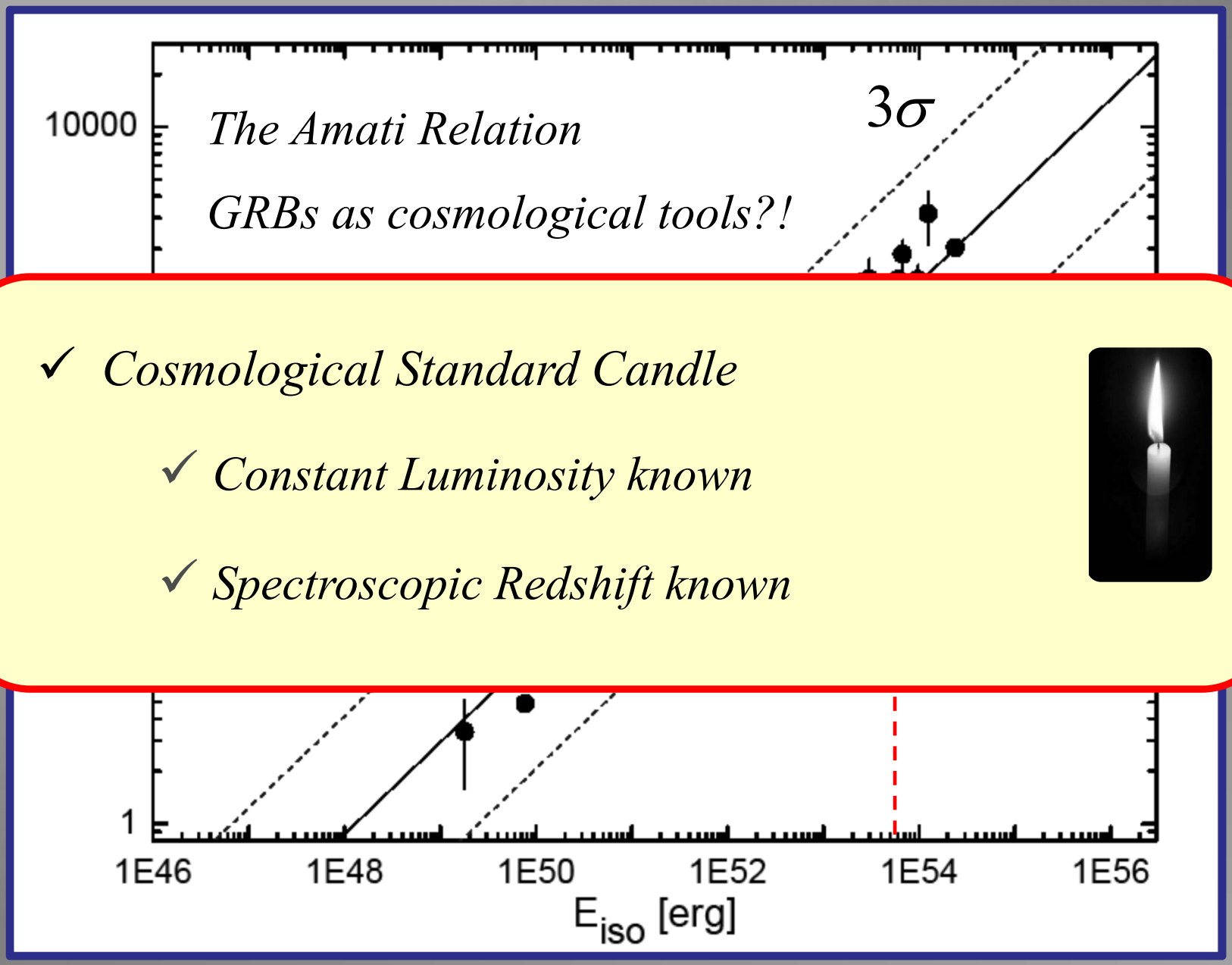

BATSE
SWIFT
K06
Residual
1
0
-1
10
100
1000
10000
$E_{p,obs}$ [KeV]
Shahmoradi & Nemiroff (2010)
Lower $E_{p,obs}$ ≡ softer
Higher $E_{p,obs}$ ≡ harder
Number
100
80
60
40
20
0
10
100
1000
10000
$E_{p,obs}$ [KeV]

Amati (2002)



The Amati Relation

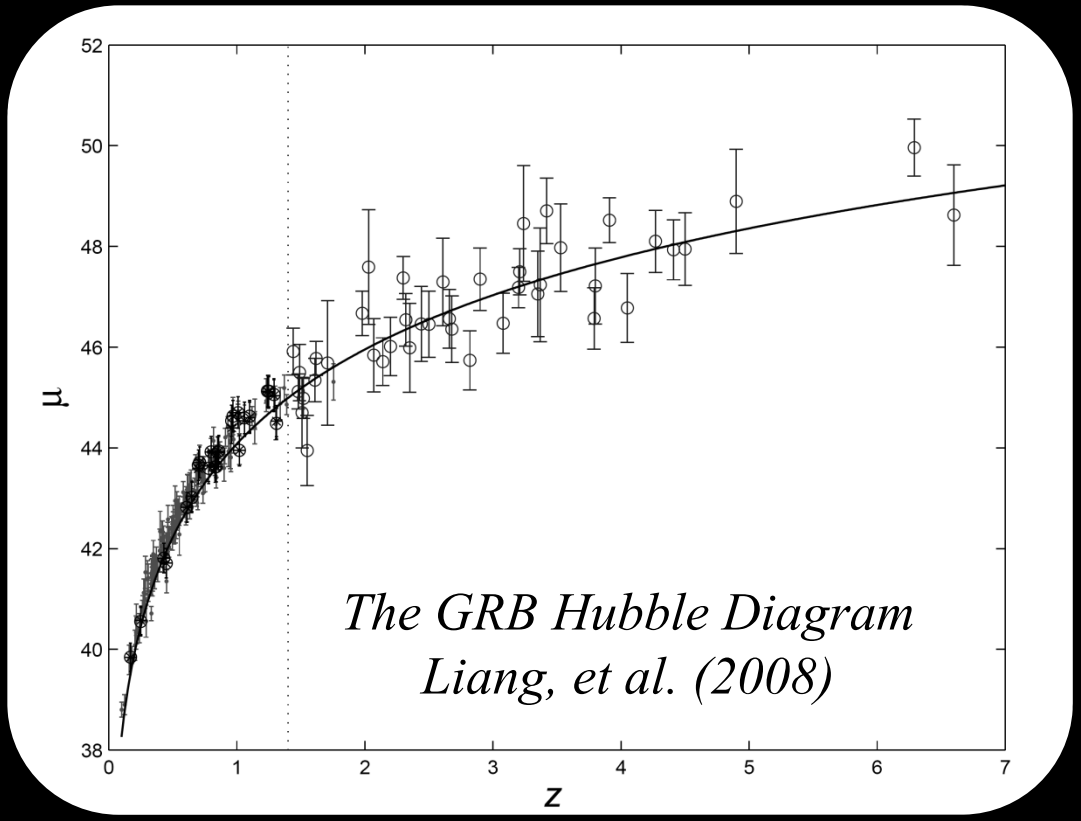
GRBs as cosmological tools?!



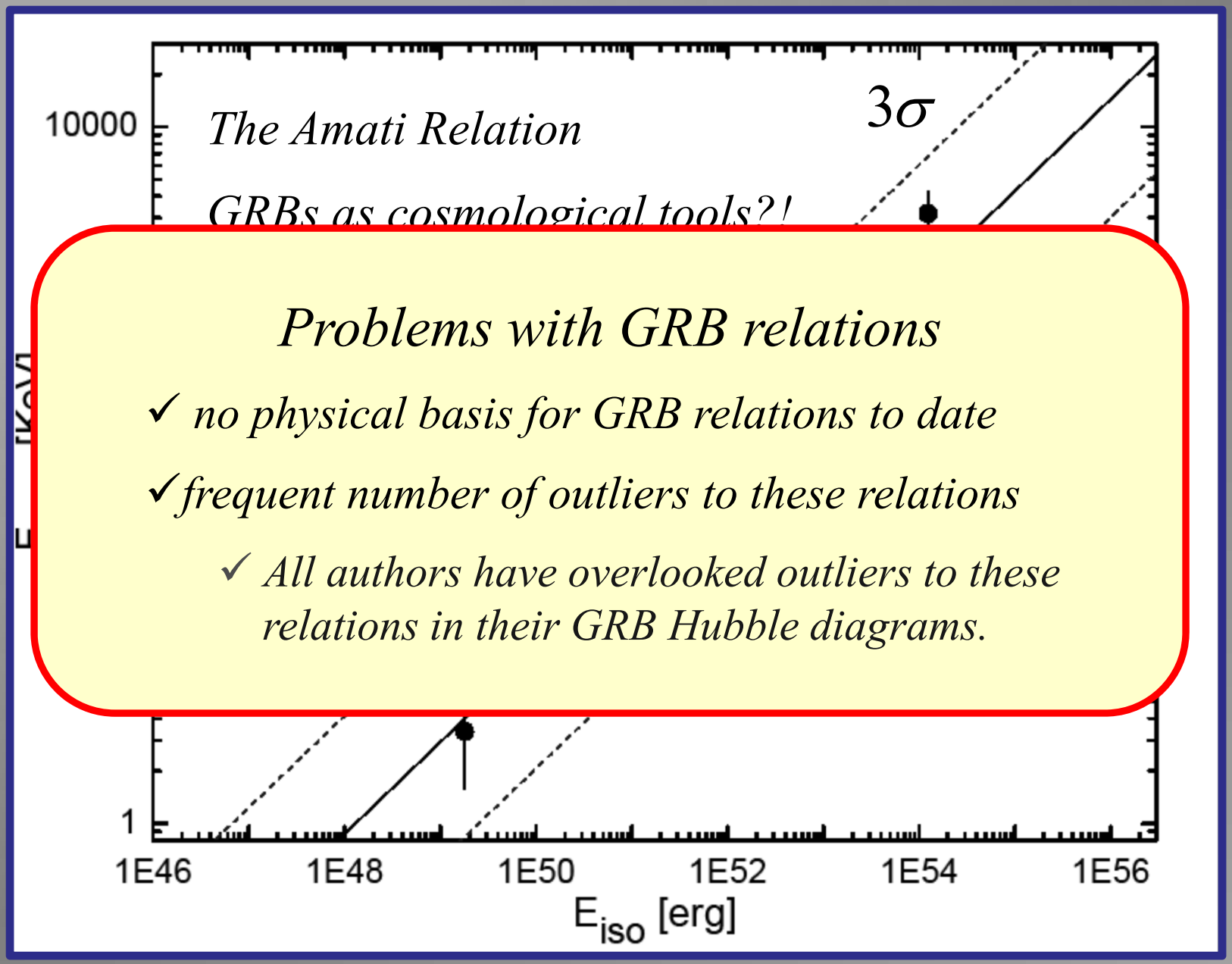
- ✓ *Cosmological Standard Candle*
  - ✓ *Constant Luminosity known*
  - ✓ *Spectroscopic Redshift known*

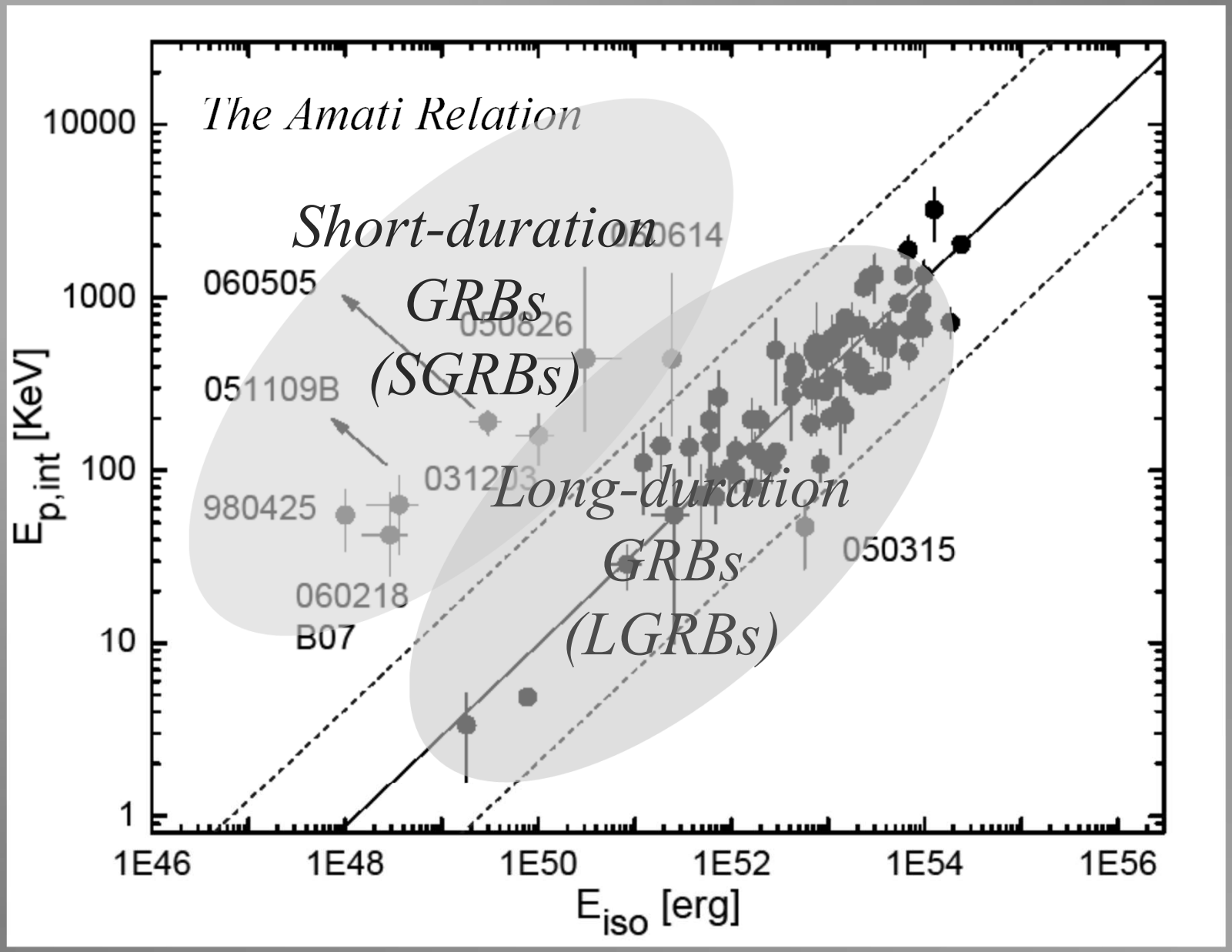
$$D_{\mathrm{L,obs}} = \sqrt{\frac{1}{4\pi}\frac{\mathrm{E_{iso}}(E_{p,\mathrm{int}})}{\mathrm{S_{bol}}}}$$

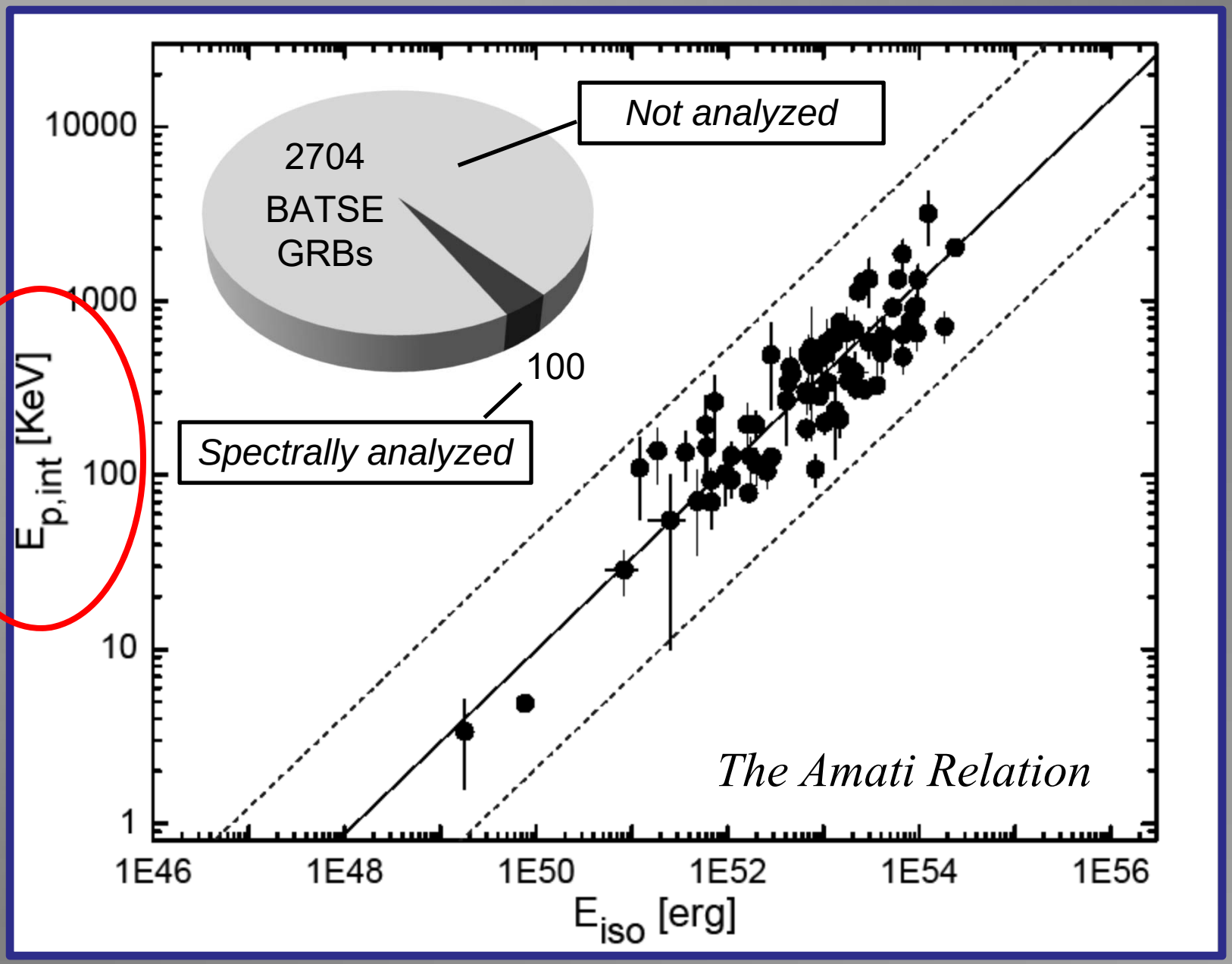
Standard Candle *Observer*

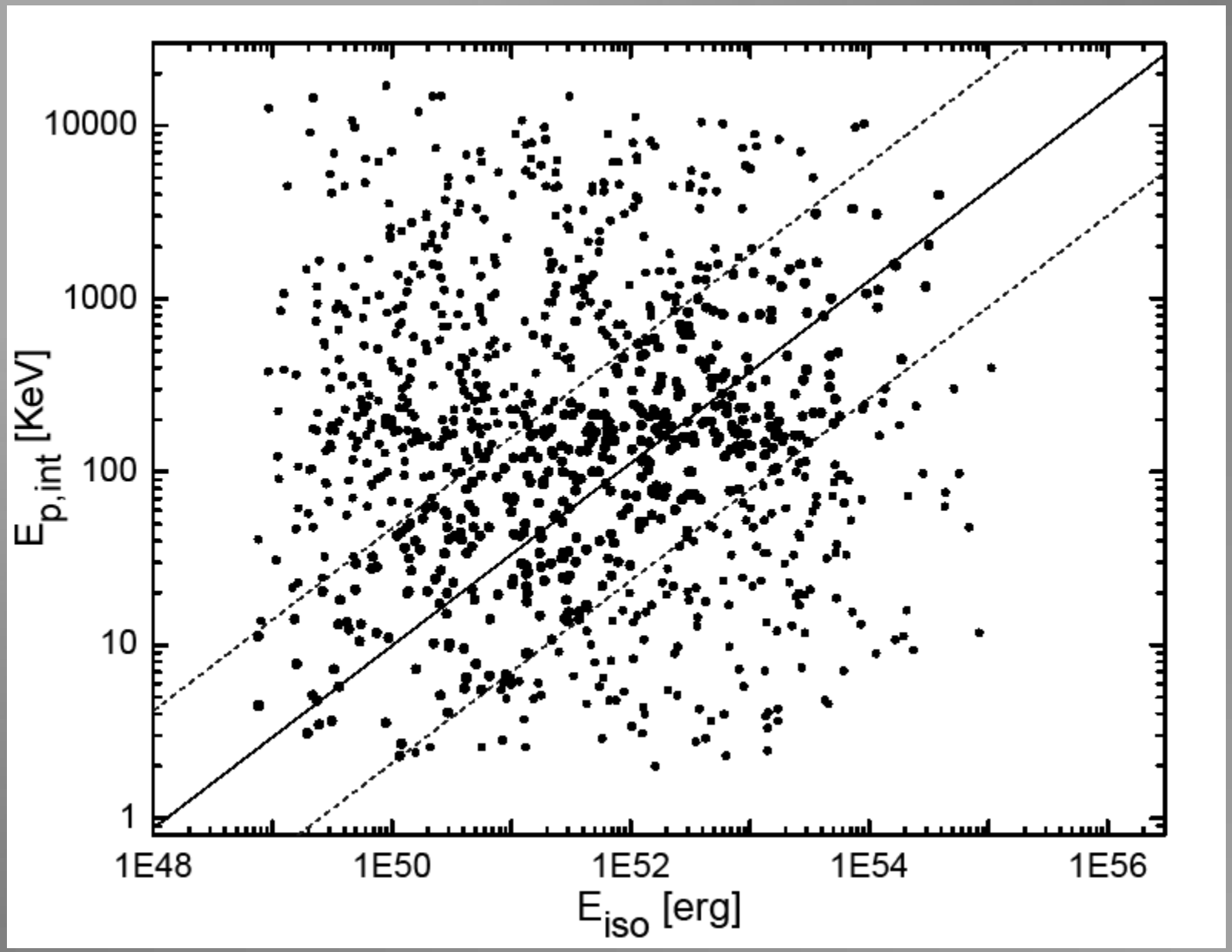


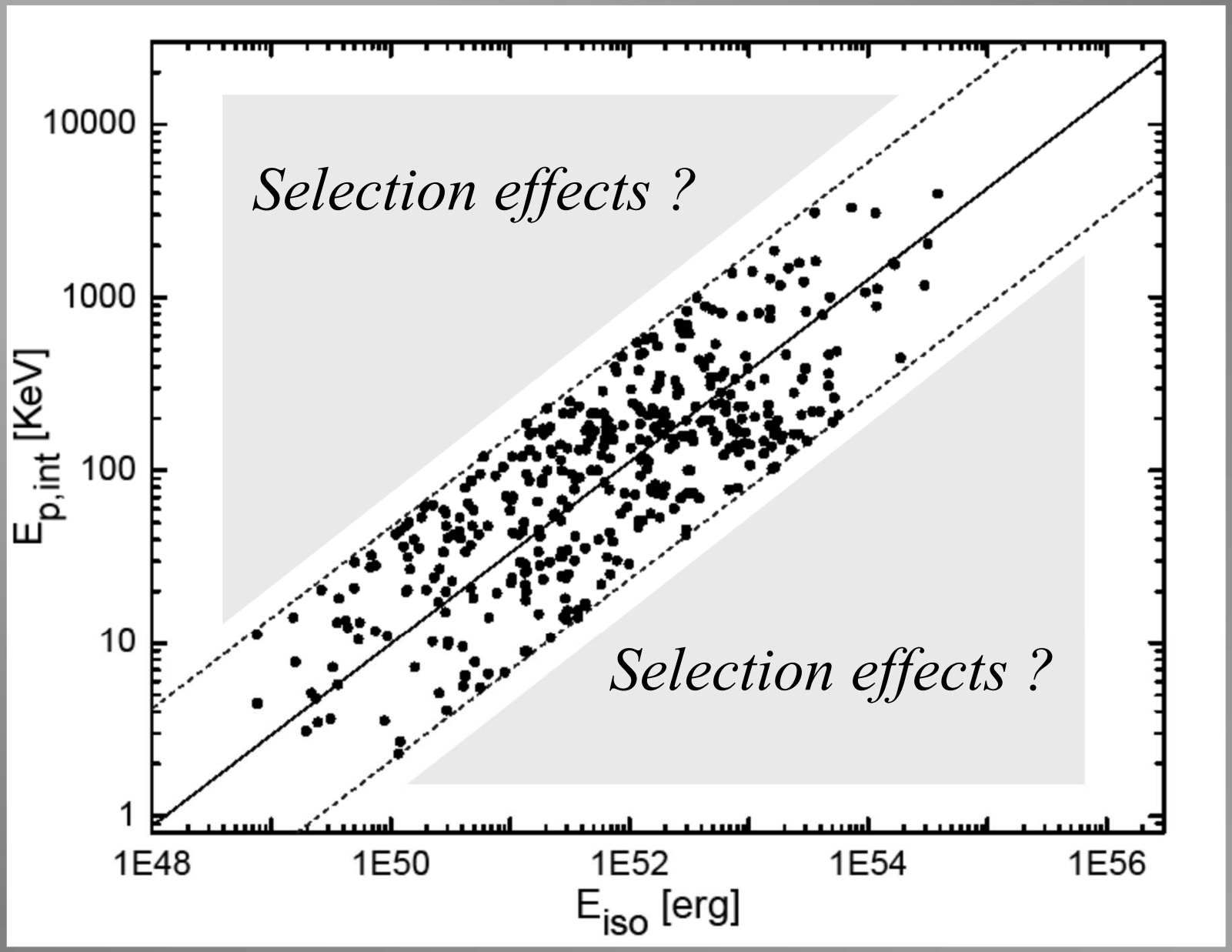
The GRB Hubble Diagram
Liang, et al. (2008)

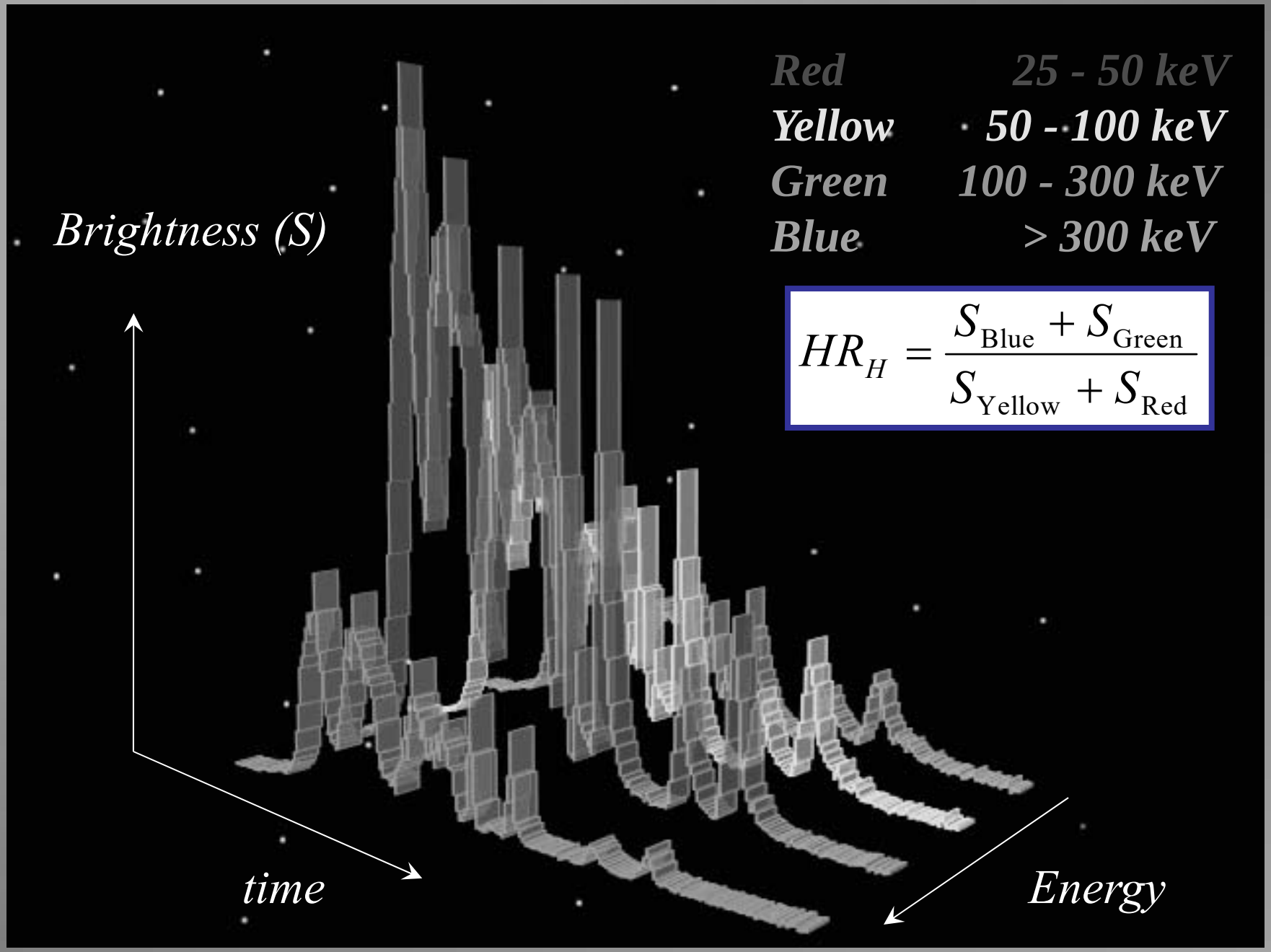

10000
1
1E46
1E48
1E50
1E52
1E54
1E56
E_{iso} [erg]
3σ
The Amati Relation
GRBs as cosmological tools?!
Problems with GRB relations
✓ no physical basis for GRB relations to date
✓ frequent number of outliers to these relations
✓ All authors have overlooked outliers to these relations in their GRB Hubble diagrams.

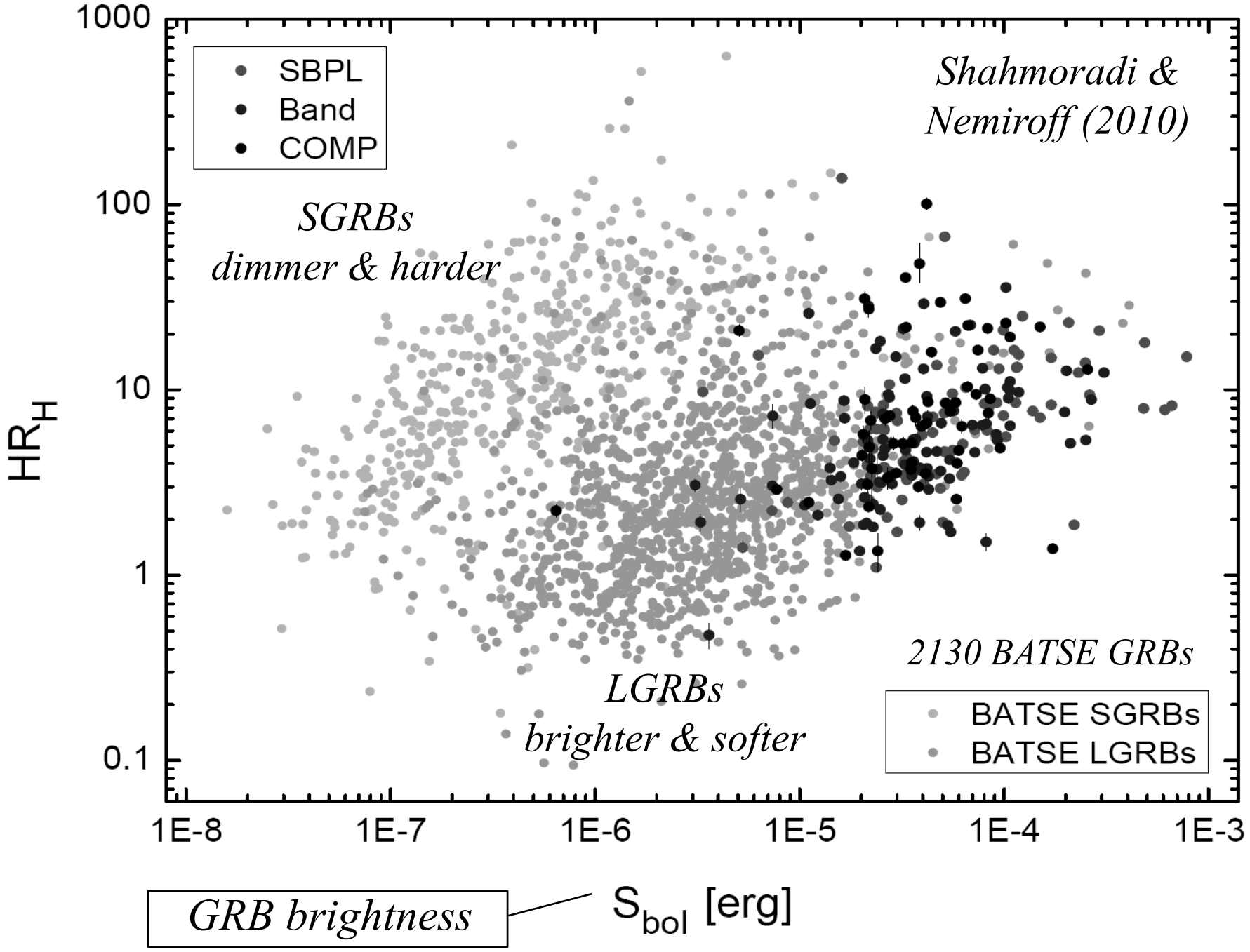

The Amati Relation
Short-duration GRBs (SGRBs)
Long-duration GRBs (LGRBs)
060505
051109B
980425
060218
B07
050826
050315
10000
1000
100
10
1
1E46
1E48
1E50
1E52
1E54
1E56
$E_{p,int}$ [KeV]
E_{iso} [erg]

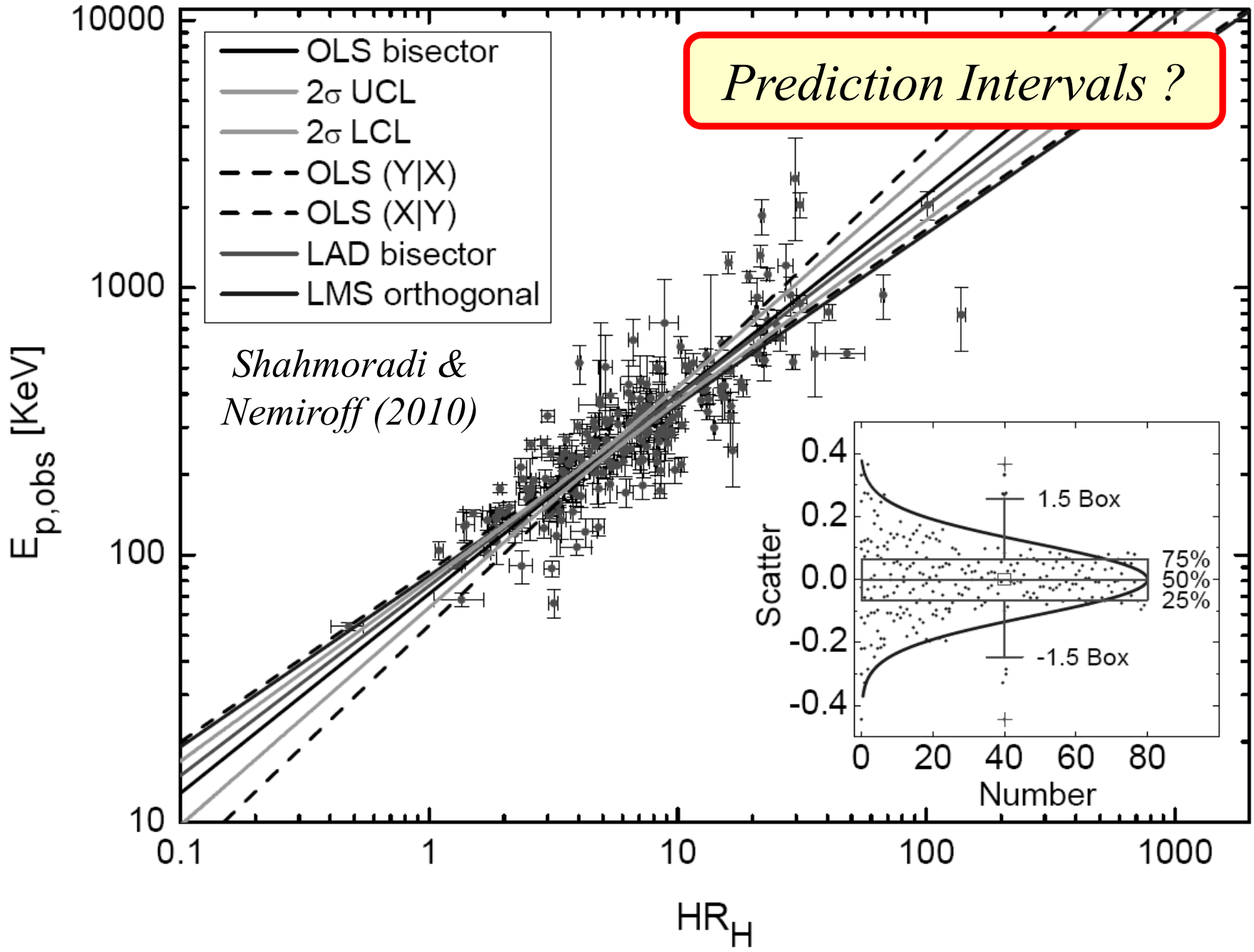

Not analyzed
2704
BATSE
GRBs
100
Spectrally analyzed
10000
1000
100
10
1
$E_{p,int}$ [KeV]
1E46
1E48
1E50
1E52
1E54
1E56
E_{iso} [erg]
The Amati Relation


10000
1000
100
10
1
$E_{p,int}$ [KeV]
1E48
1E50
1E52
1E54
1E56
E_{iso} [erg]

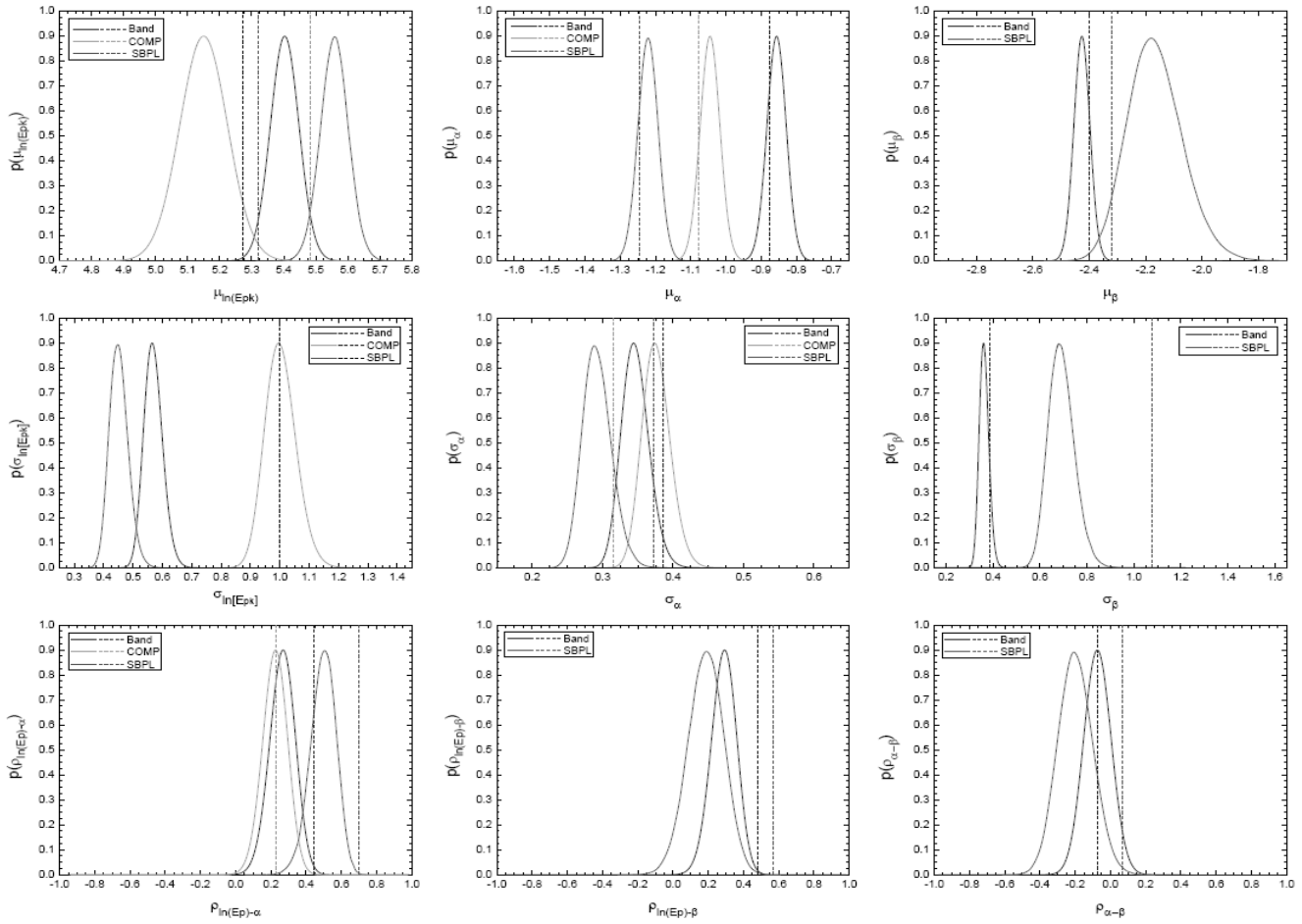

Selection effects ?
Selection effects ?
10000
1000
100
10
1
$E_{p,int}$ [KeV]
1E48
1E50
1E52
1E54
1E56
E_{iso} [erg]


Red 25 - 50 keV
Yellow 50 - 100 keV
Green 100 - 300 keV
Blue > 300 keV
$HR_H = \frac{S_{\text{Blue}} + S_{\text{Green}}}{S_{\text{Yellow}} + S_{\text{Red}}}$
Brightness (S)
time
Energy


1000
100
10
1
0.1
HR_H
SBPL
Band
COMP
Shahmoradi &
Nemiroff (2010)
SGRBs
dimmer & harder
LGRBs
brighter & softer
2130 BATSE GRBs
BATSE SGRBs
BATSE LGRBs
1E-8
1E-7
1E-6
1E-5
1E-4
1E-3
GRB brightness
S_bol [erg]


OLS bisector
2σ UCL
2σ LCL
OLS (Y|X)
OLS (X|Y)
LAD bisector
LMS orthogonal
Prediction Intervals ?
Shahmoradi & Nemiroff (2010)
$E_{p,obs}$ [KeV]
HR_H
10000
1000
100
10
0.1
1
10
100
1000
Scatter
0.4
0.2
0.0
-0.2
-0.4
1.5 Box
-1.5 Box
75%
50%
25%
0
20
40
60
80
Number

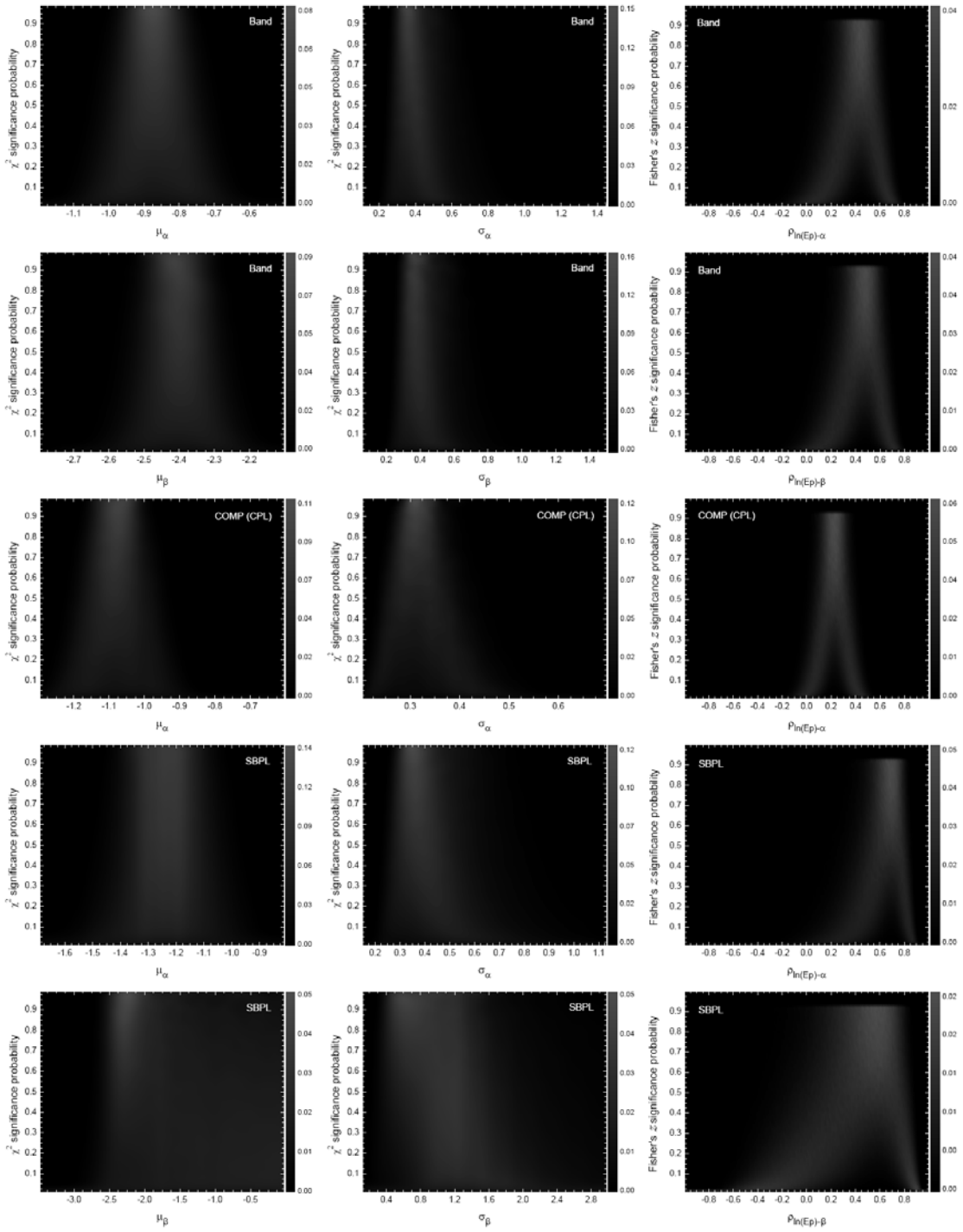
Parameter estimation based on
Bayes Theorem and Markov Chain Monte Carlo techniques.

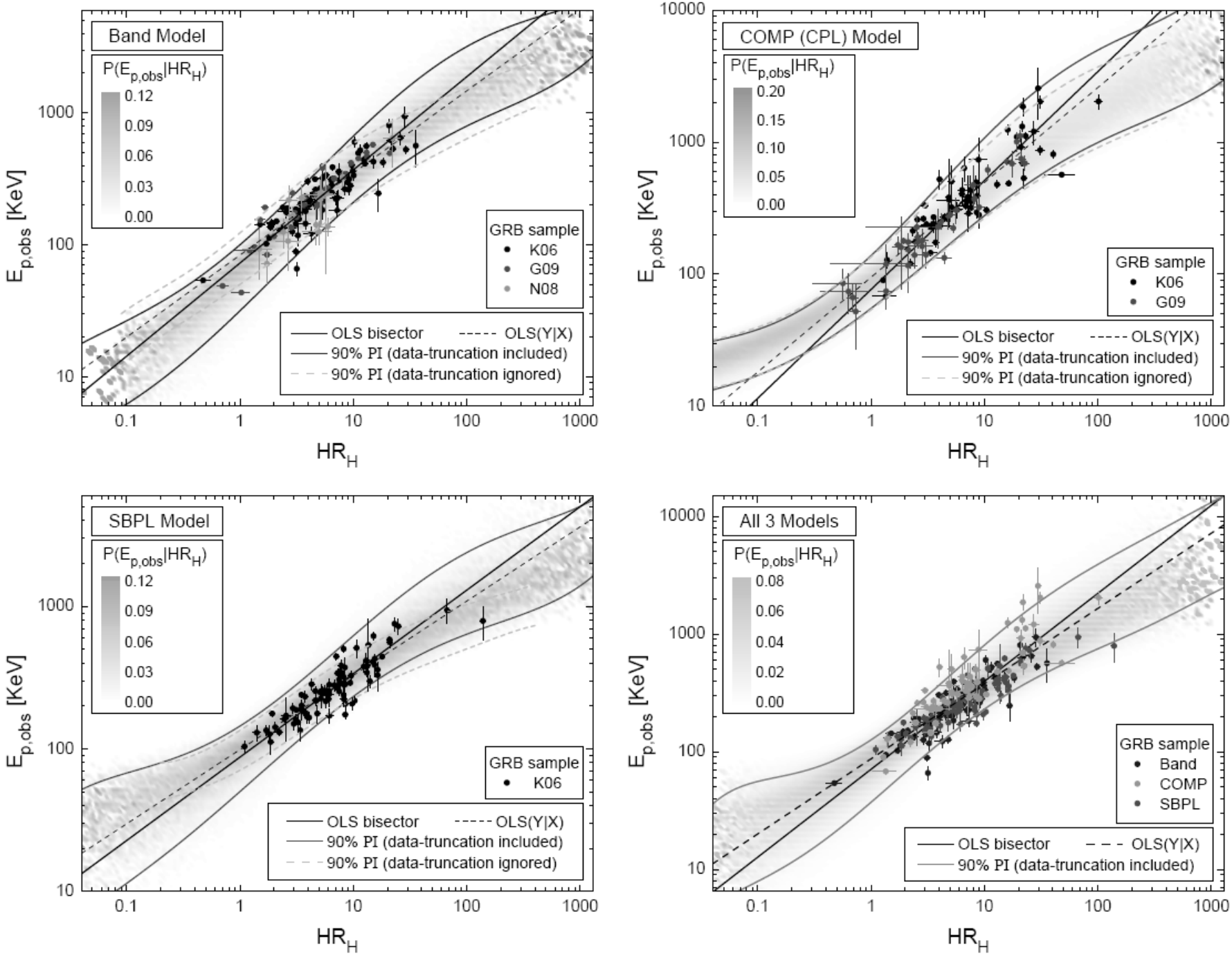


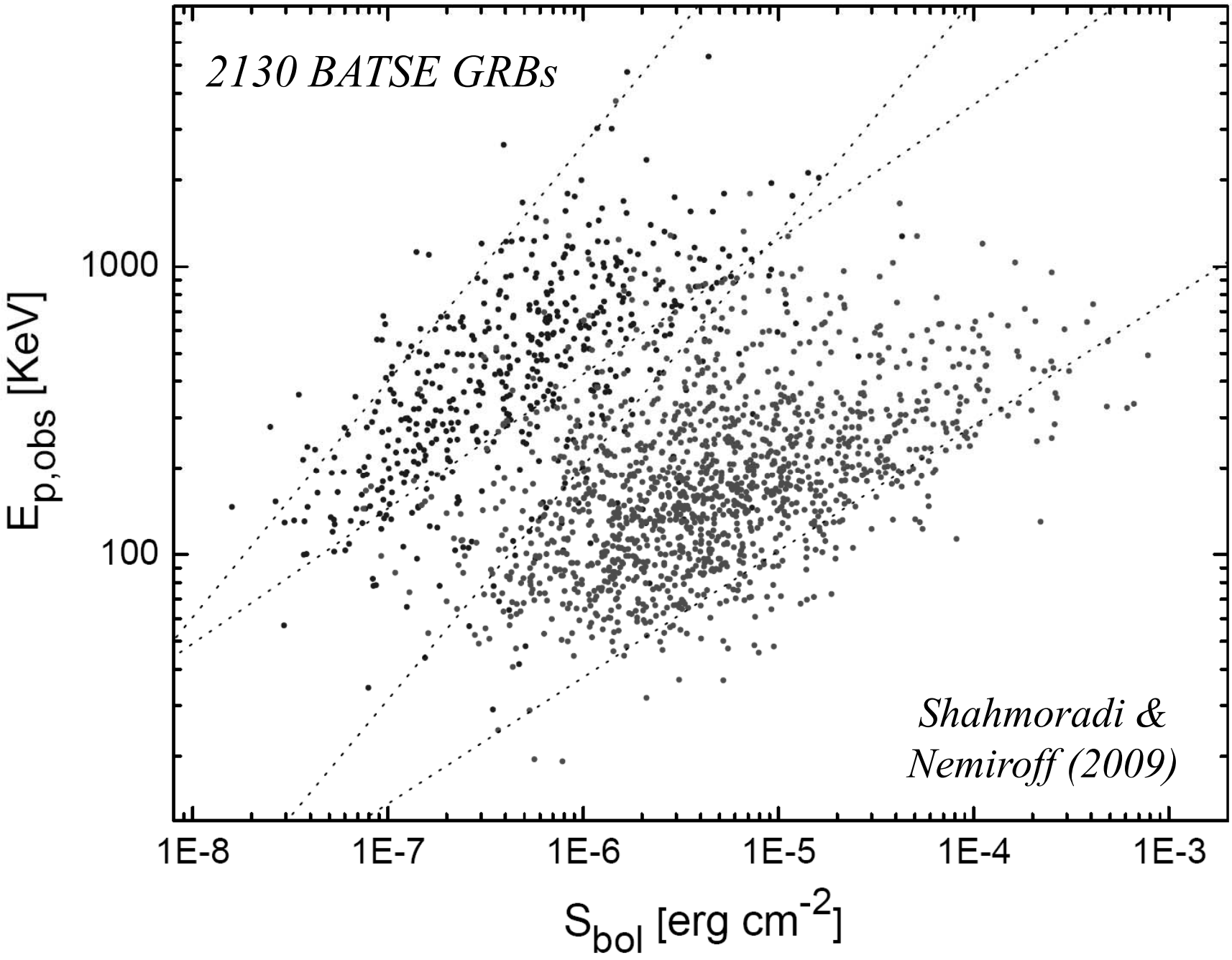
Posterior distributions of the parameters of the truncated multivariate normal distributions considered for the spectral parameters of the 3 GRB models: Band, COMP(CPL) & SBPL.

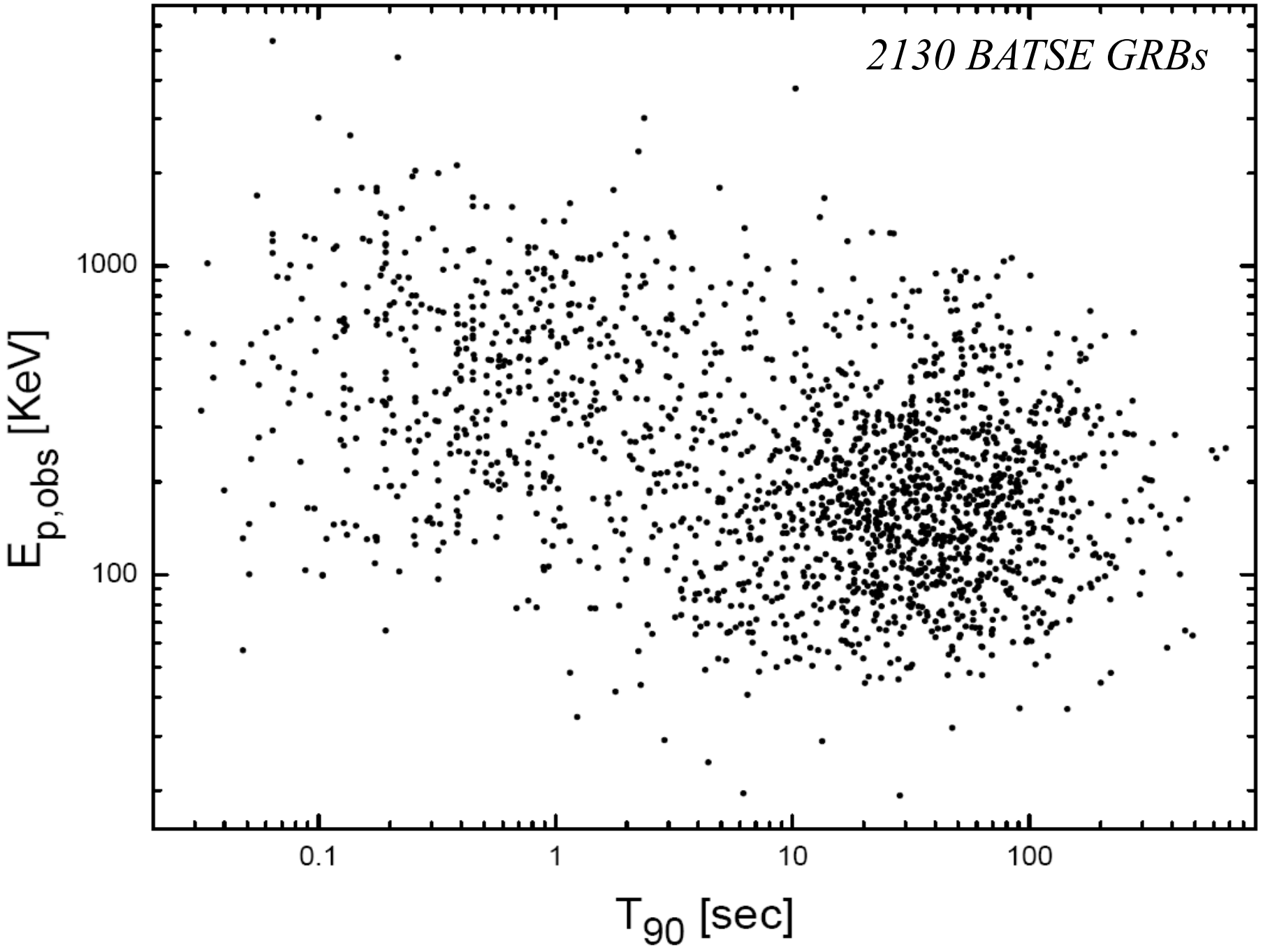
Parameter estimation based on Minimum χ2 & Mimimum Kolmogorov-Smirnov distance techniques.

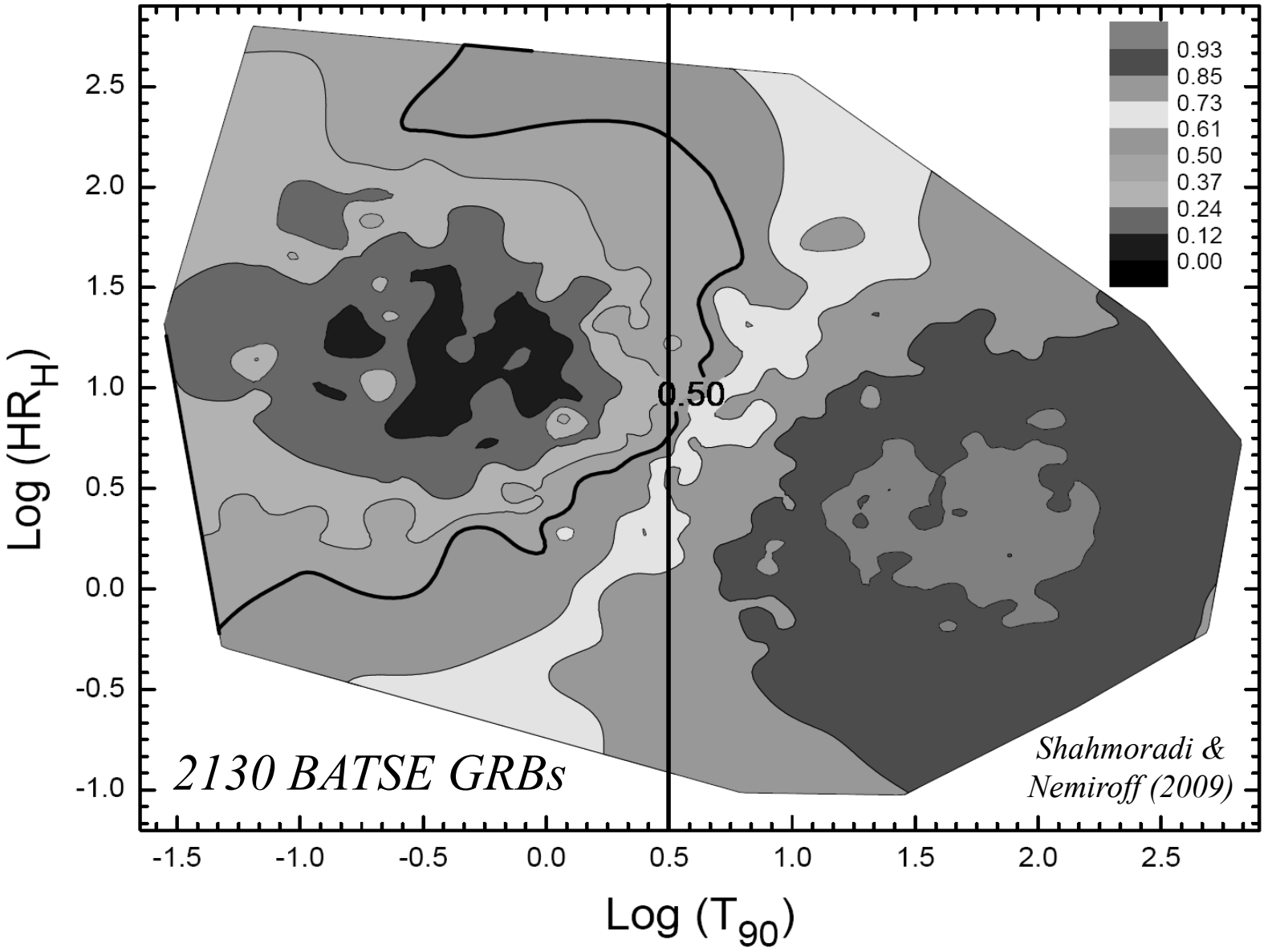
Marginalized likelihood contour plots of the observed data given different parameter values of the truncated multivariate normal distribution assumed for the spectral parameters of the three GRB models.




Band Model
P(E_p,obs|HR_H)
0.12
0.09
0.06
0.03
0.00
GRB sample
K06
G09
N08
OLS bisector
OLS(Y|X)
90% PI (data-truncation included)
90% PI (data-truncation ignored)
E_p,obs [KeV]
HR_H
COMP (CPL) Model
P(E_p,obs|HR_H)
0.20
0.15
0.10
0.05
0.00
GRB sample
K06
G09
OLS bisector
OLS(Y|X)
90% PI (data-truncation included)
90% PI (data-truncation ignored)
E_p,obs [KeV]
HR_H
SBPL Model
P(E_p,obs|HR_H)
0.12
0.09
0.06
0.03
0.00
GRB sample
K06
OLS bisector
OLS(Y|X)
90% PI (data-truncation included)
90% PI (data-truncation ignored)
E_p,obs [KeV]
HR_H
All 3 Models
P(E_p,obs|HR_H)
0.08
0.06
0.04
0.02
0.00
GRB sample
Band
COMP
SBPL
OLS bisector
OLS(Y|X)
90% PI (data-truncation included)
E_p,obs [KeV]
HR_H

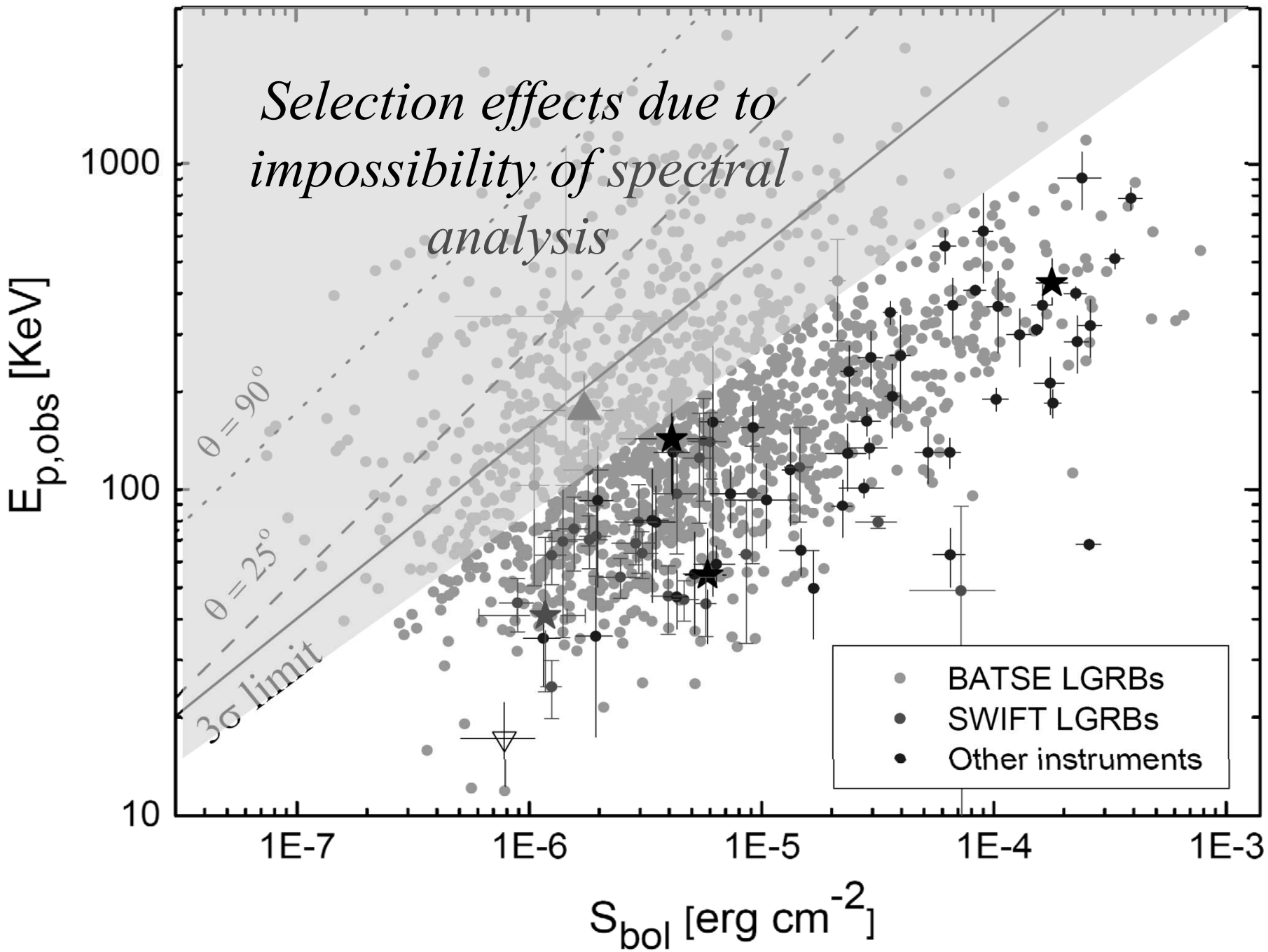

2130 BATSE GRBs
1000
100
$E_{p,obs}$ [KeV]
1E-8
1E-7
1E-6
1E-5
1E-4
1E-3
S_{bol} [erg cm^{-2}]
Shahmoradi &
Nemiroff (2009)


2130 BATSE GRBs
1000
100
$E_{p,obs}$ [KeV]
0.1
1
10
100
T_{90} [sec]



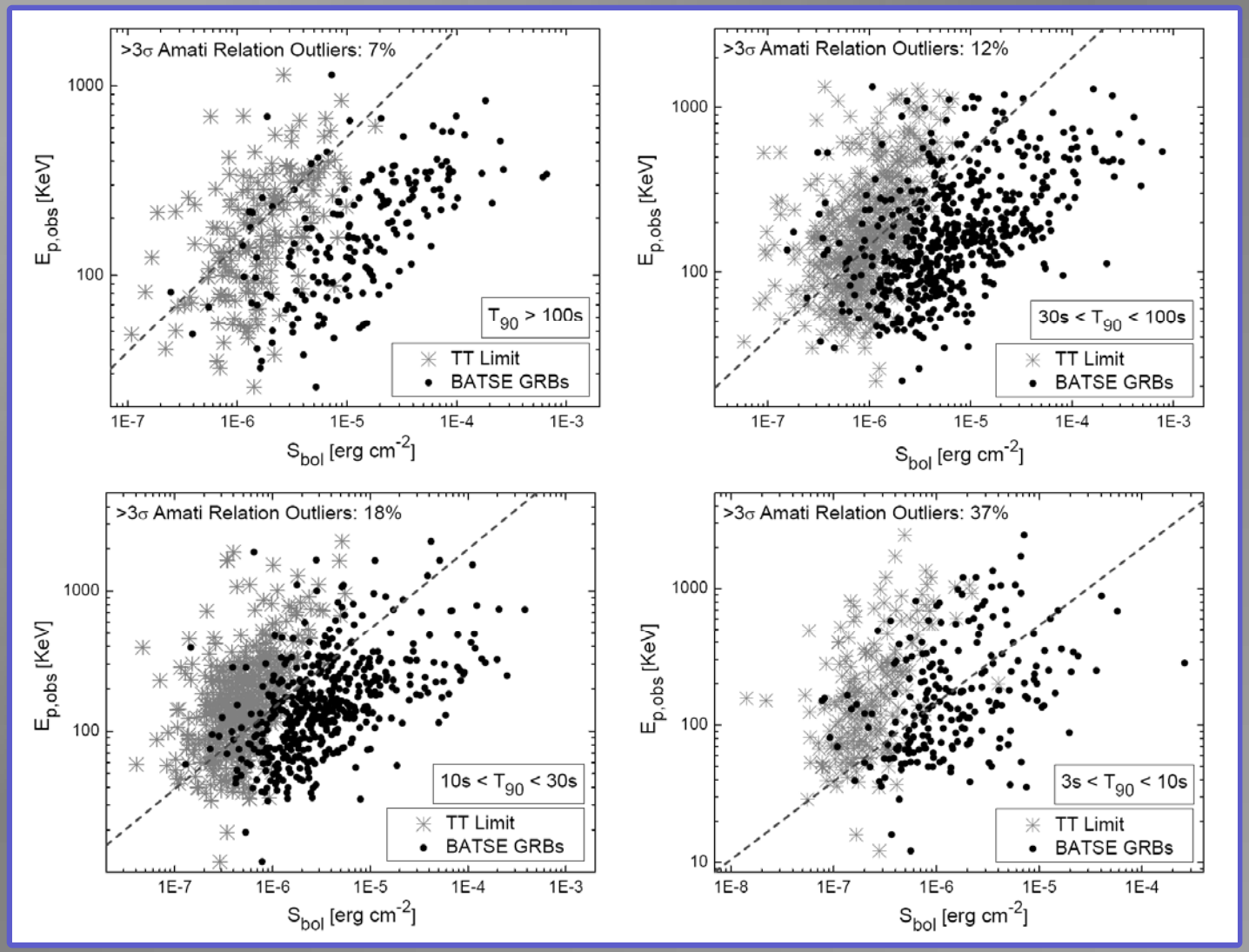
Fuzzy Cluster Analysis

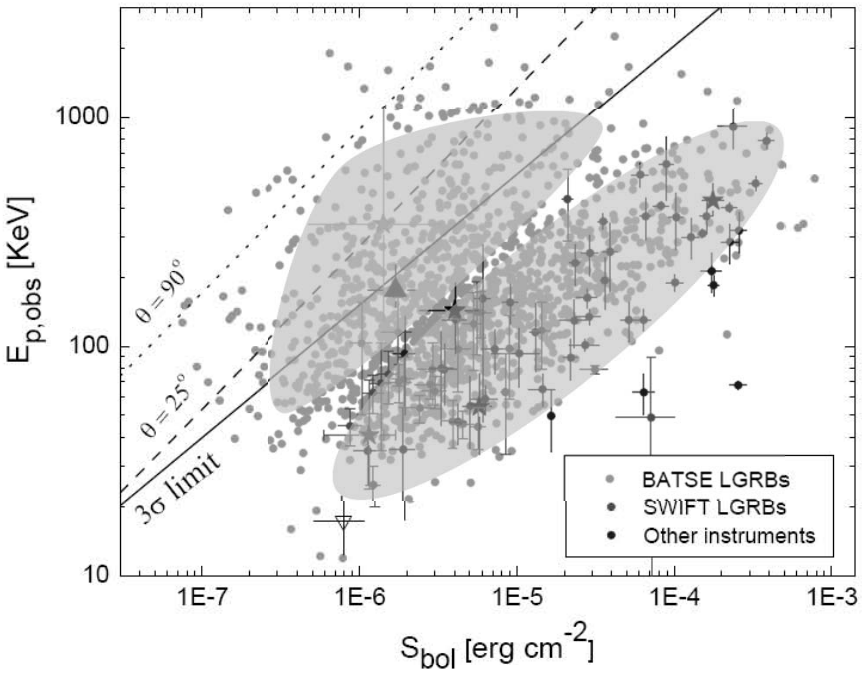
Sum of All Normalized Determinants (SAND), Rousseeuw et al. (1996)

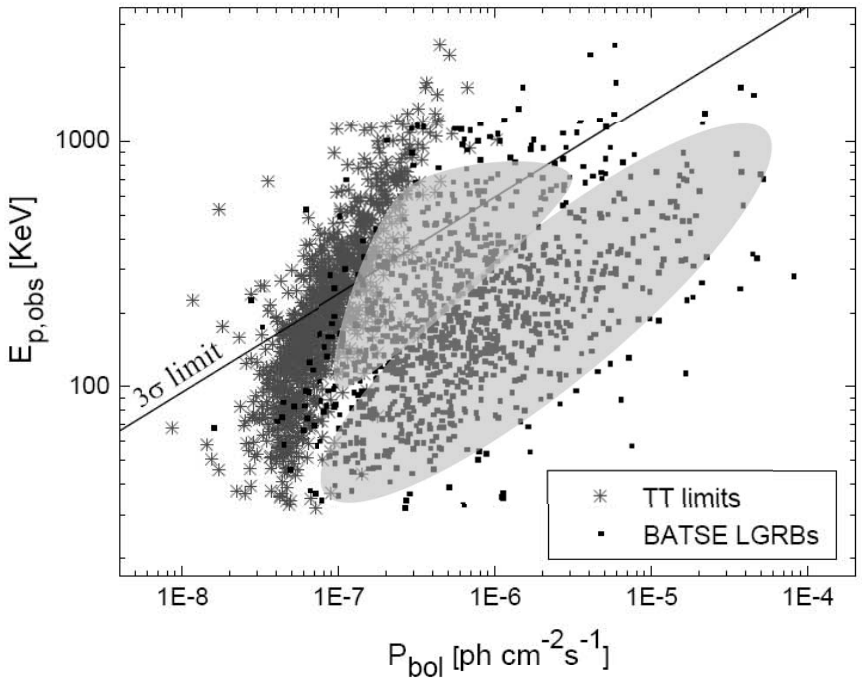

Selection effects due to impossibility of spectral analysis
θ=90°
θ=25°
3σ limit
BATSE LGRBs
SWIFT LGRBs
Other instruments
1000
100
10
1E-7
1E-6
1E-5
1E-4
1E-3
E_p,obs [KeV]
S_bol [erg cm^-2]

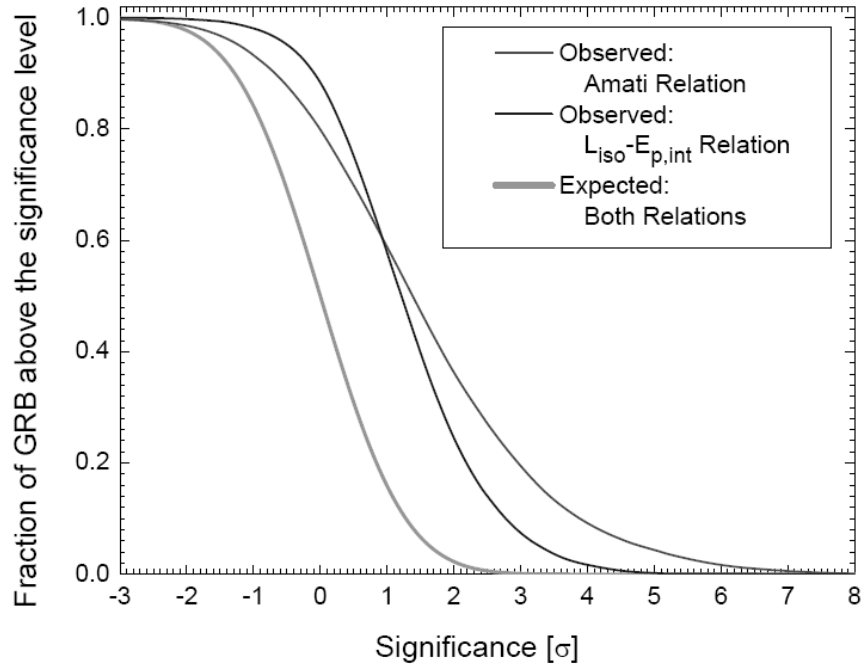
Selection Effects due to GRB Detectors?

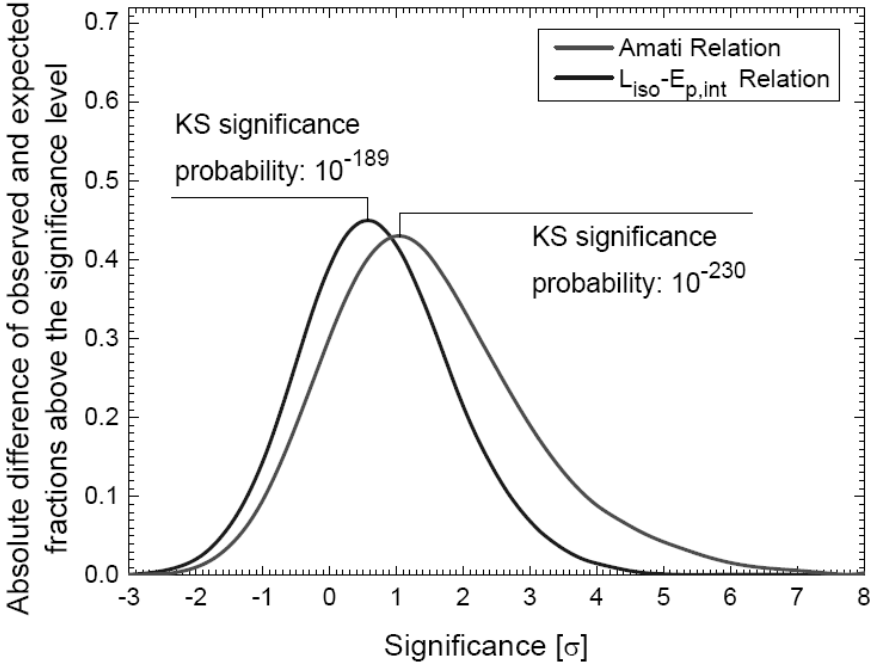
✓ *BATSE (1990-2000)*

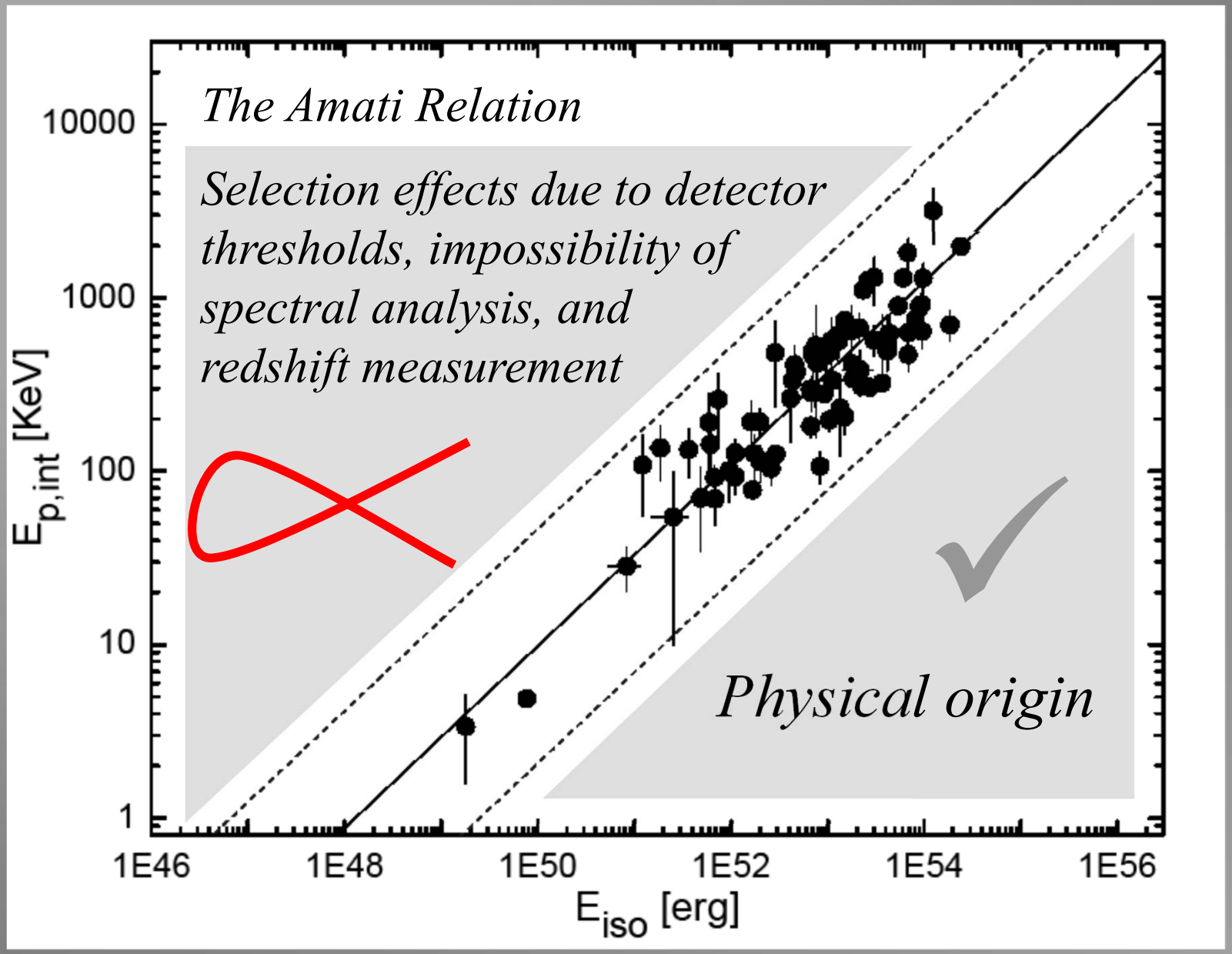



1000
100
10
$E_{p,obs}$ [KeV]
1E-7
1E-6
1E-5
1E-4
1E-3
S_{bol} [erg cm^{-2}]
θ = 90°
θ = 25°
3σ limit
BATSE LGRBs
SWIFT LGRBs
Other instruments


1000
100
$E_{p,obs}$ [KeV]
1E-8
1E-7
1E-6
1E-5
1E-4
P_{bol} [ph cm^{-2}s^{-1}]
3σ limit
TT limits
BATSE LGRBs


1.0
0.8
0.6
0.4
0.2
0.0
Fraction of GRB above the significance level
-3
-2
-1
0
1
2
3
4
5
6
7
8
Significance [σ]
Observed:
Amati Relation
Observed:
L_{iso}-$E_{p,int}$ Relation
Expected:
Both Relations


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Absolute difference of observed and expected fractions above the significance level
-3
-2
-1
0
1
2
3
4
5
6
7
8
Significance [σ]
Amati Relation
L_{iso}-$E_{p,int}$ Relation
KS significance
probability: 10^{-189}
KS significance
probability: 10^{-230}



✓ *Shahmoradi & Nemiroff, 2009, MNRAS*

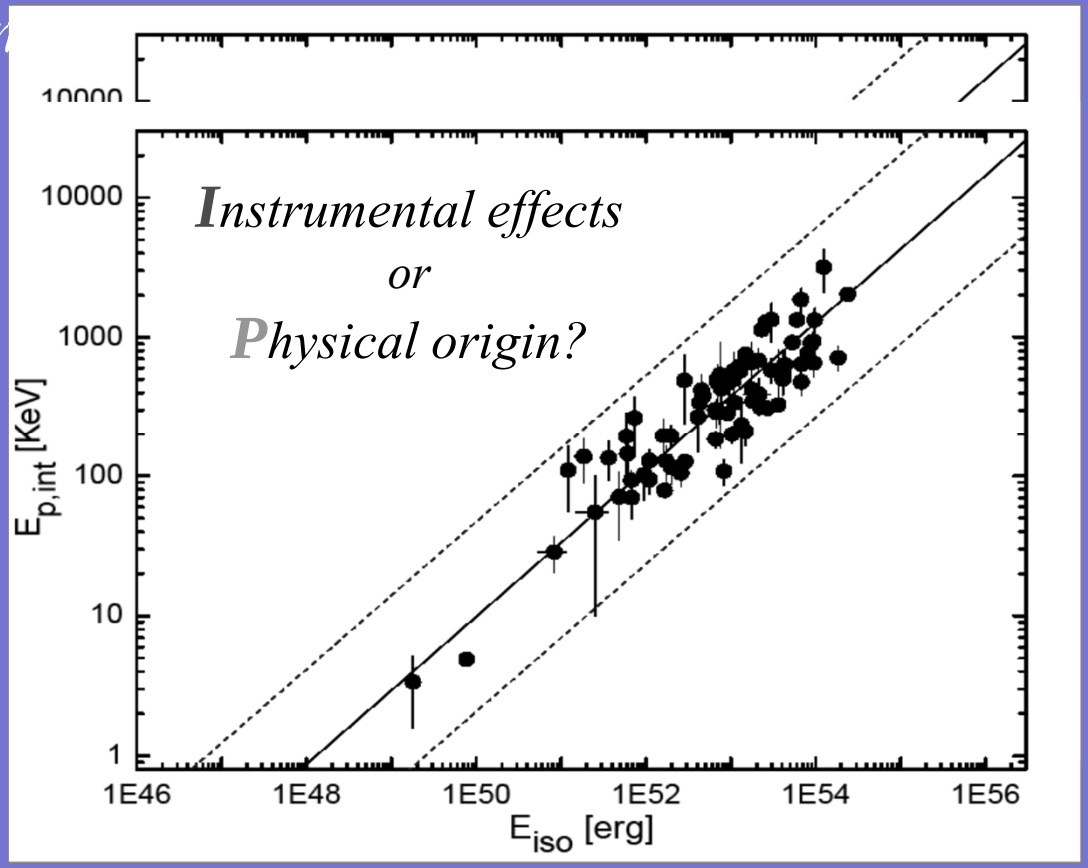
Summary & Conclusions

- ✓ *Gamma-Ray Bursts are the most powerful events of the Universe, possibly related to the death of super-massive stars.*
- ✓ *Several correlations among the spectral parameters of GRBs have been proposed, such as the Amati relation.*
- ✓ *Numerous attempts has been made by different authors to use these relations to construct the Hubble diagram*
- ✓ *The result of our analyses, however, provide the first direct evidence that the Amati & Ghirlanda relations do not have physical origins and to our estimates, these relations hold as inequalities.*
- ✓ *Although the utility of the Amati relation in cosmology is questioned, GRBs -- expected to be detectable out to $z \sim 65$ – might still hold the promise as the unique probes of the early universe. Further analysis coming up soon…*

General Conclusions

(Applicable to any field of Science)

- ✓ *Outliers! Take them seriously in data analysis.*
- ✓ *Strong Correlation, No Outlier! Then why should there be such stron*



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- ✓ *Dr. Robert Nemiroff, Astrophysicist, MTU / NASA*
  - ✓ *Continuous support during the past 3 years.*
  - ✓ *Absolute freedom in research.*
  - ✓ *How to do scientific research rather than what to do.*

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  author={Shahmoradi, Amir and Nemiroff, Robert J},
  journal={Monthly Notices of the Royal Astronomical Society},
  volume={451},
  number={1},
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  title={On the similarities of the prompt gamma-ray emissions in Short and Long Gamma-Ray Busts},
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  title={Hardness as a spectral peak estimator for gamma-ray bursts},
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  journal={Monthly Notices of the Royal Astronomical Society},
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}

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  title={VizieR Online Data Catalog: Gamma-ray bursts spectral peak estimator (Shahmoradi+, 2010)},
  author={Shahmoradi, A and Nemiroff, RJ},
  journal={VizieR Online Data Catalog},
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  year={2011}
}

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  title={The possible impact of gamma-ray burst detector thresholds on cosmological standard candles},
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  volume={411},
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  title={A Multivariate Fit Luminosity Function and World Model for Long Gamma-Ray Bursts},
  author={Shahmoradi, Amir},
  journal={The Astrophysical Journal},
  volume={766},
  number={2},
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  publisher={IOP Publishing}
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  booktitle={American Astronomical Society Meeting Abstracts\# 223},
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Thank you!
Questions?
Photo: Alborz Mountain,
Northern Persia