How Real Detector Thresholds Create False Standard Candles

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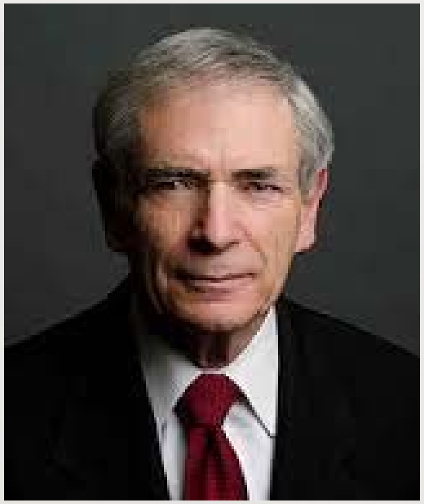

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Cognitive biases are everywhere in human life

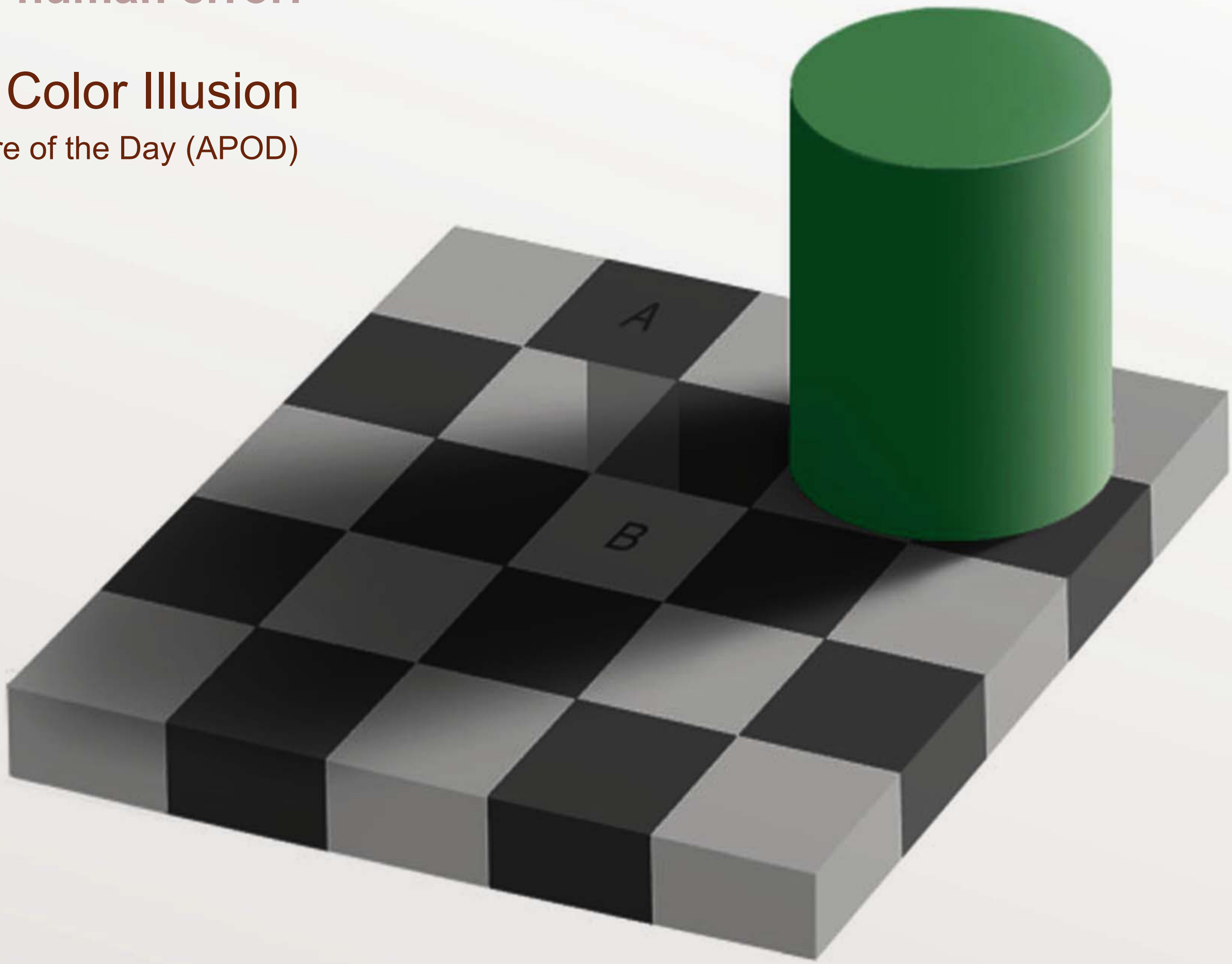
Example of human error:

The Same Color Illusion

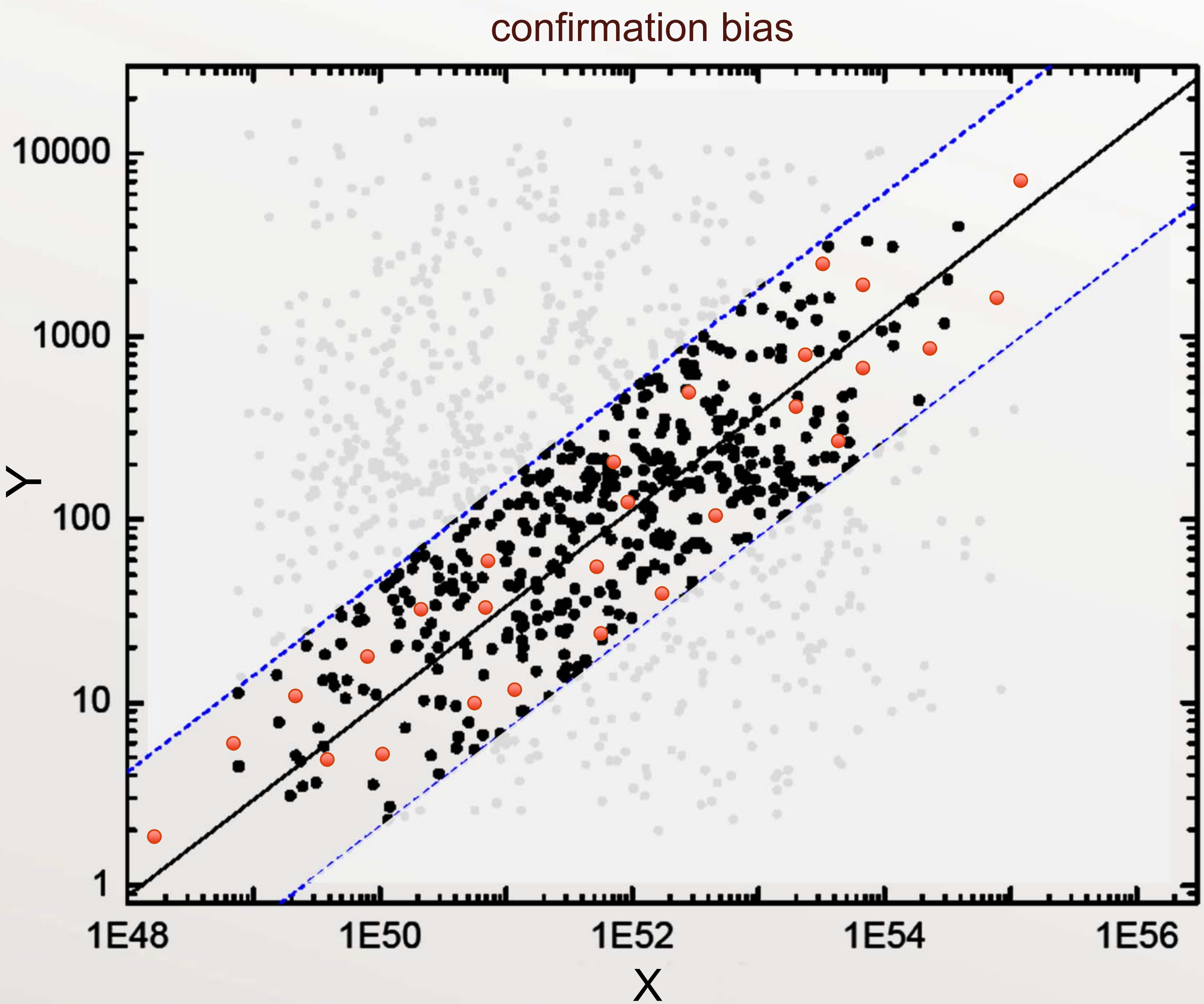
Astronomy Picture of the Day (APOD)

2007 July 17

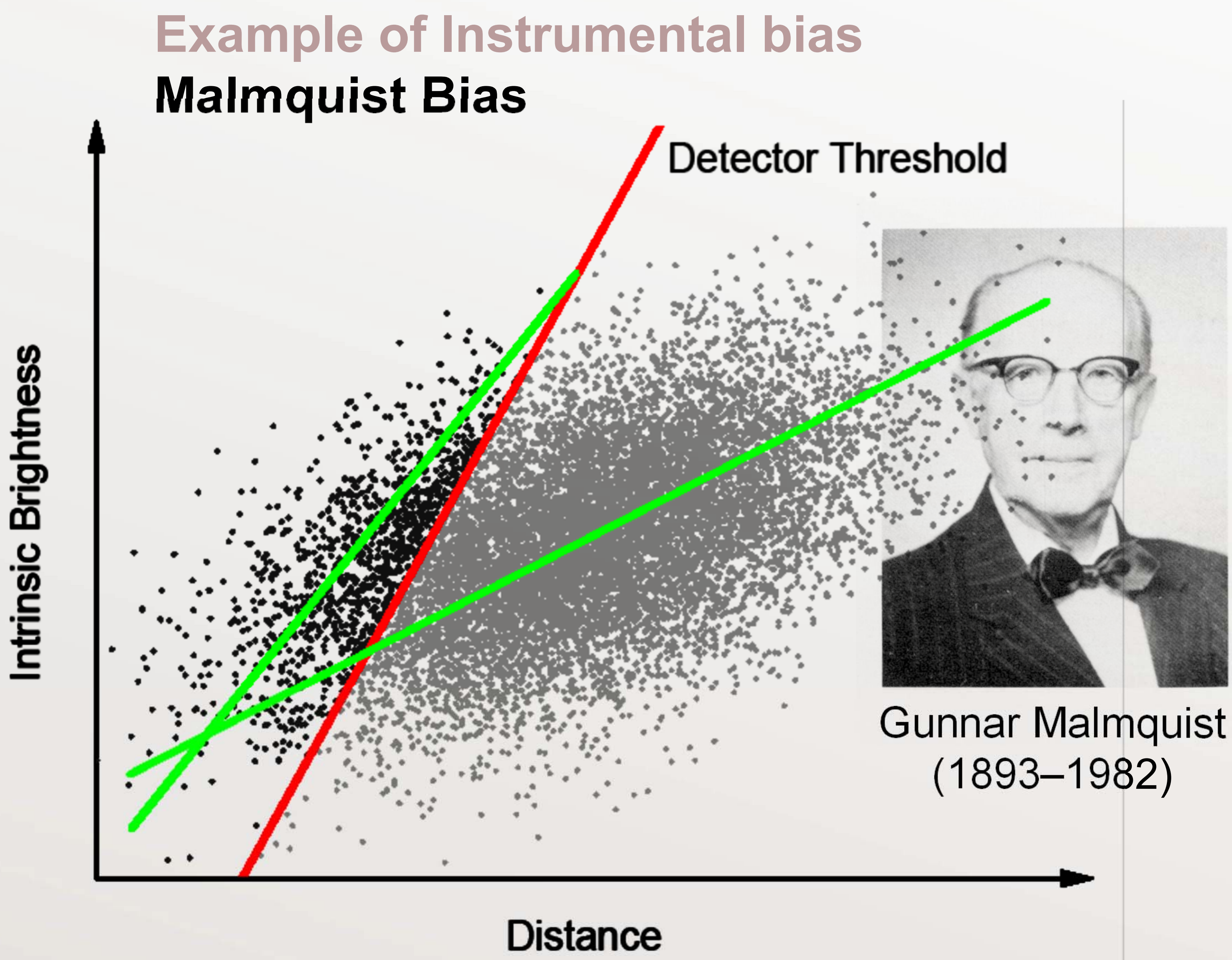
half full? or
half empty?



Statistical tests are often unable to capture human/instrumental biases



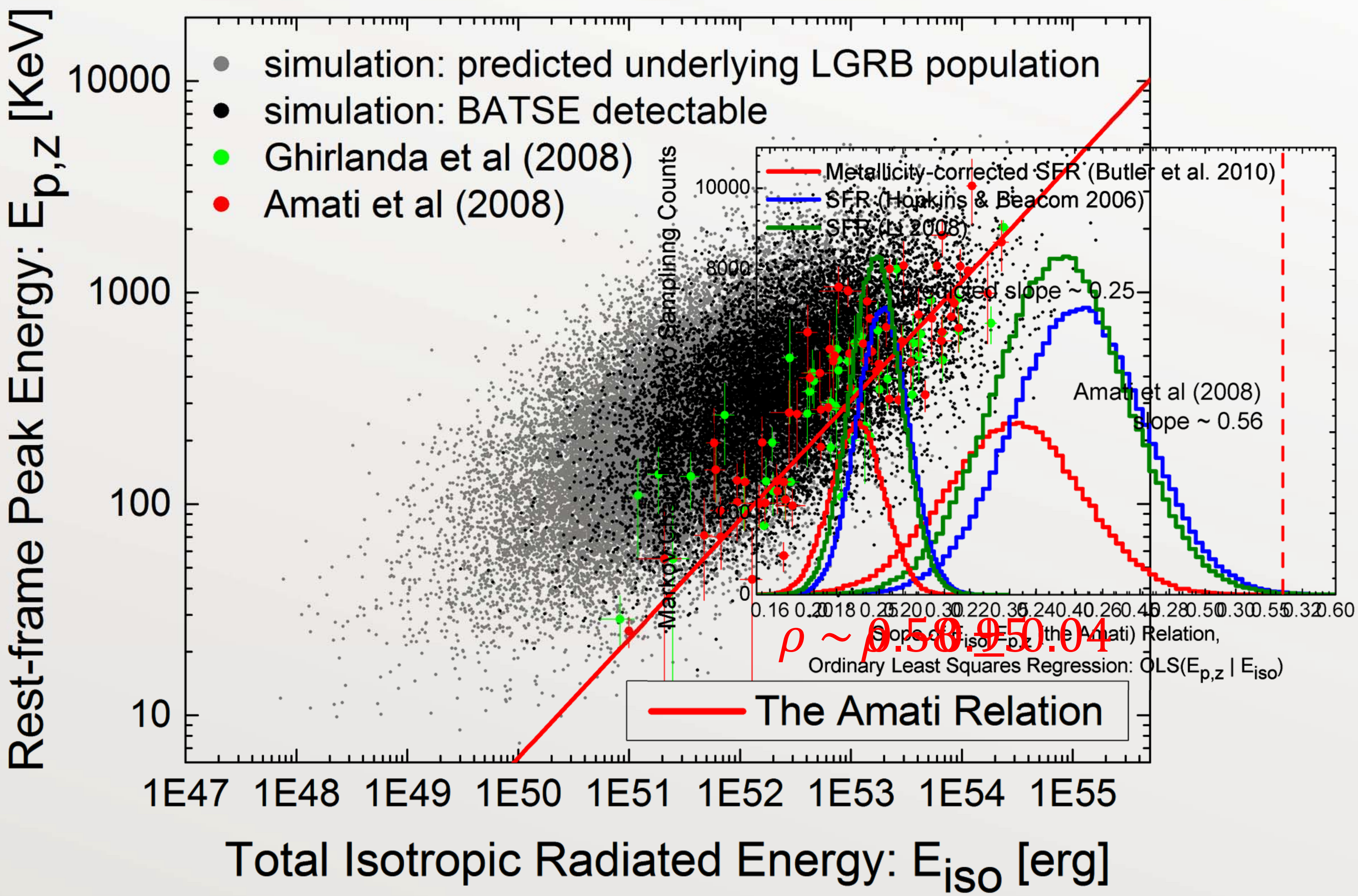
Instrumental bias: well-known in the field of Astronomy



Gunnar Malmquist
(1893–1982)

The Amati Relation

A combination of human biases, gamma-ray detector limitations, and sample incompleteness, as well as some real physics behind it.



Overview

I. Why are Gamma-Ray Bursts (GRBs) of interest to cosmologists?

II. What are Gamma-Ray Bursts?

III. Can we use GRBs as standard candles in cosmology?

IV. Take-home message for all scientists in any field of science

I. Why are Gamma-Ray Bursts (GRBs) of interest to cosmologists?

Short answer:

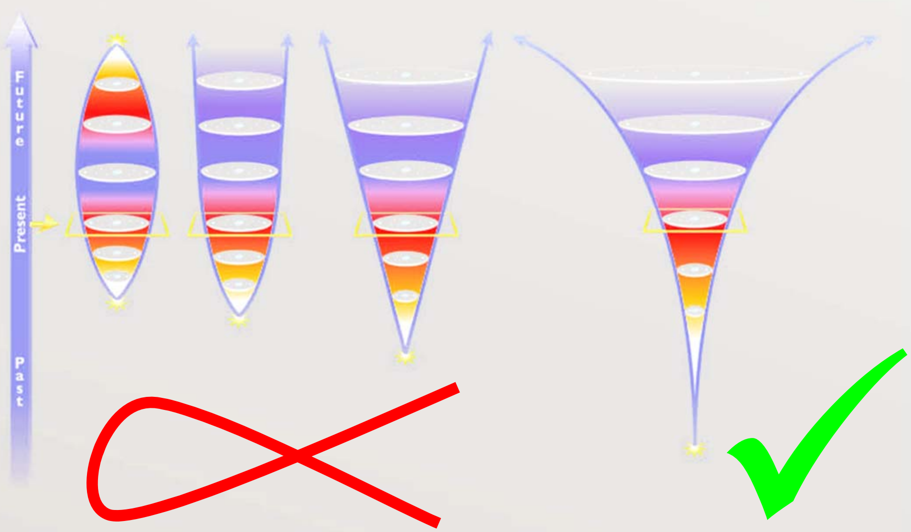
Since GRBs can be **potentially** used to test and validate cosmological models.

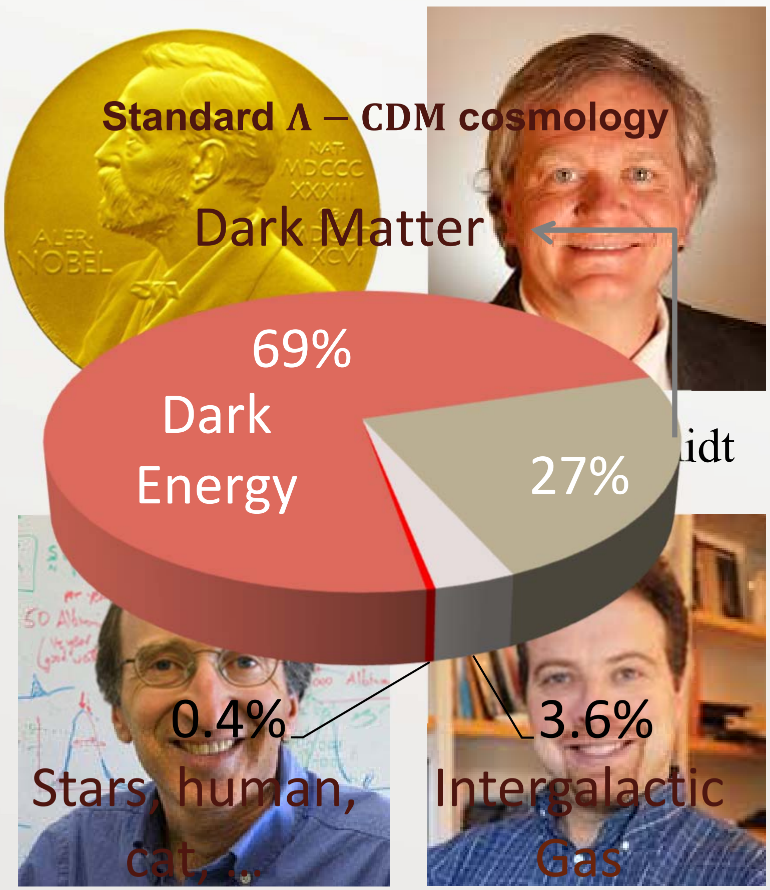
2011 Nobel Prize in Physics

The discovery of the **accelerating** expansion of the Universe

- Riess et al., 1998, ApJ, **116**, 1009-1038
- Perlmutter, 1999, ApJ, **517**, 565-586

Possible models of expanding universe





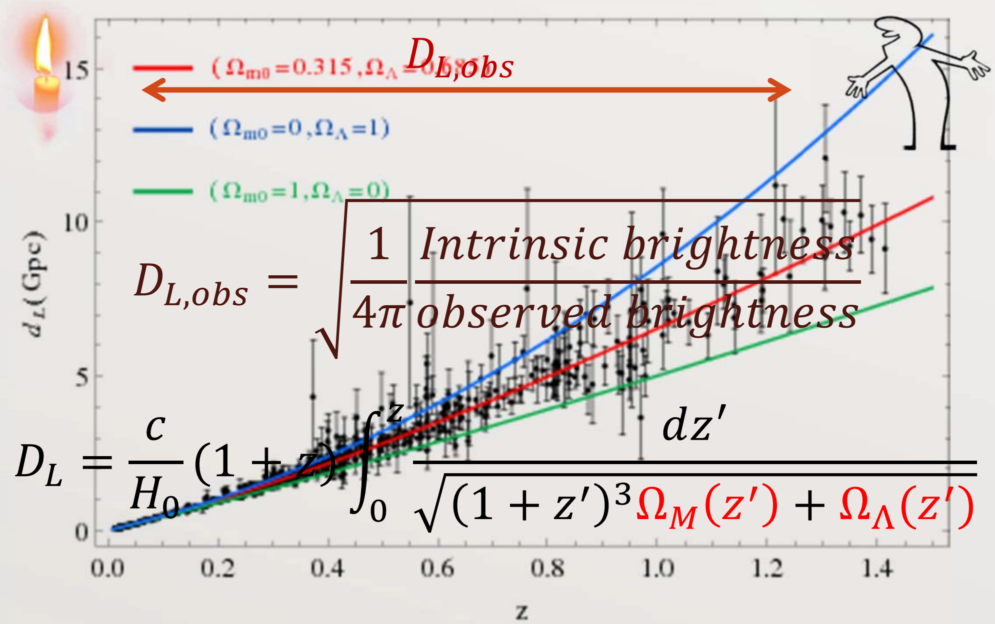
Saul Perlmutter

Adam Riess

2011 Nobel Prize in Physics

What did these gentlemen do to get the Nobel prize?

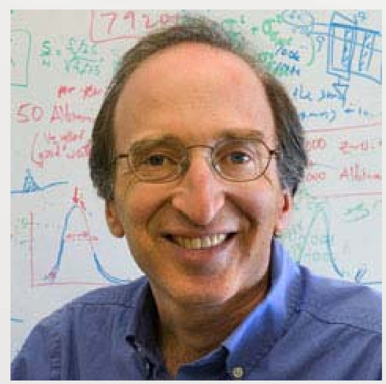
1. Find a cosmological standard candle (supernova Ia).
2. Measure their distances from the earth ($D_{L,obs}$).
3. Measure their redshifts (z), as well.
4. Given their redshifts and a cosmological model, calculate their theoretical distance (D_L) from the earth.
5. Compare D_L with $D_{L,obs}$.



$$D_{L,obs} = \sqrt{\frac{1}{4\pi}\frac{Intrinsic\ brightness}{observed\ brightness}}$$

$$D_L = \frac{c}{H_0}(1+z)\int_0^z \frac{dz'}{\sqrt{(1+z')^3\Omega_M(z') + \Omega_\Lambda(z')}}$$

Brian Schmidt

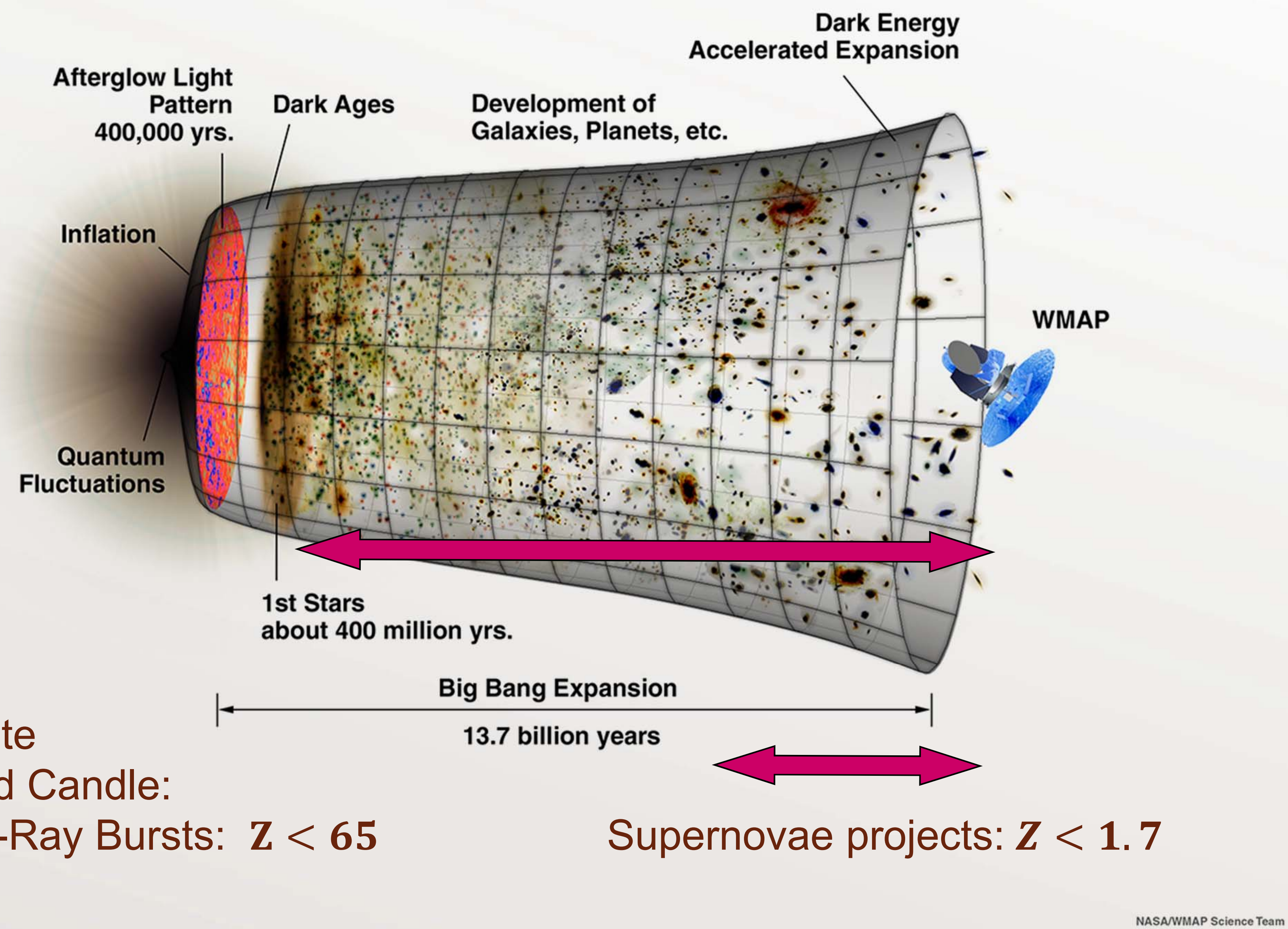


Saul Perlmutter

Adam Riess

Major problem with supernovae-Ia as standard candles?

Limited detectability out to $z \sim 1.7$



Candidate
Standard Candle:
Gamma-Ray Bursts: $\mathbf{Z < 65}$

Supernovae projects: $\boldsymbol{Z < 1.7}$

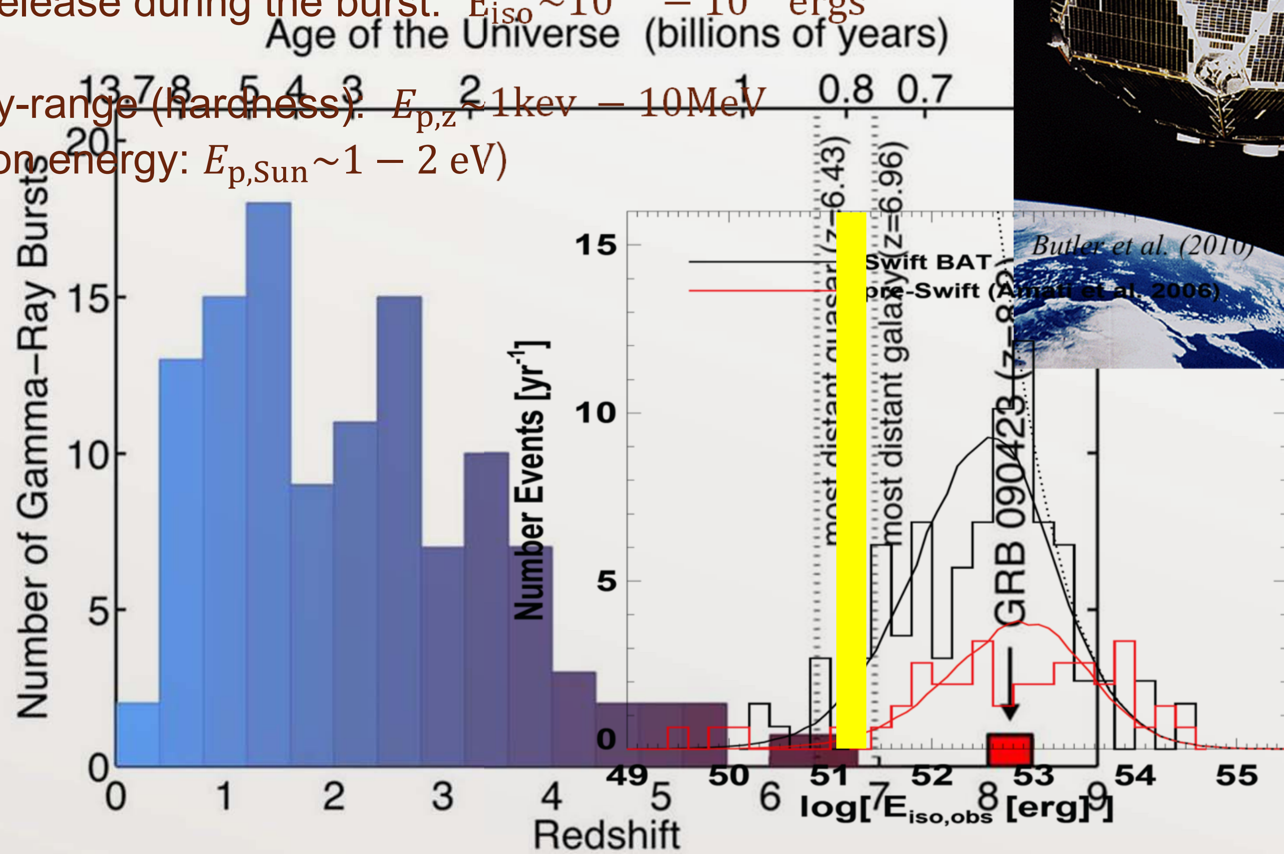
II. What are Gamma-Ray Bursts (GRBs)?

Short answer:

The brightest most powerful electromagnetic explosions in the universe, ever observed by humans.

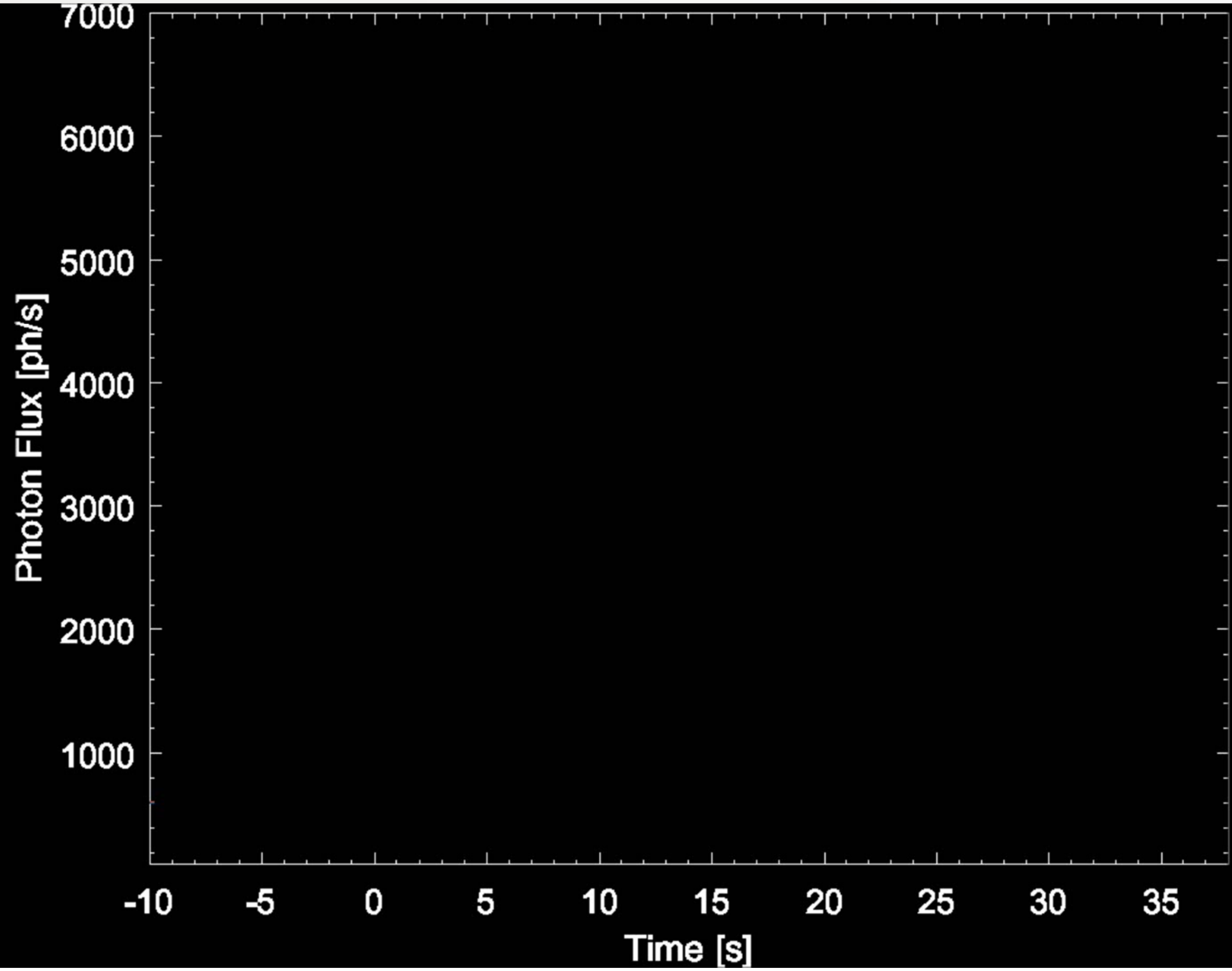
Gamma-ray bursts are flashes of gamma rays associated with extremely energetic explosions that have been observed in distant galaxies.

- First discovered by the Vela satellites in 1967.
- Most distant single object detected in the universe: $z \in [0.1 - 10]$
- Total energy release during the burst: $\mathrm{E_{iso}} \sim 10^{48} - 10^{55} \mathrm{ergs}$
- Photon energy-range (hardness): $E_{\mathrm{p,z}} \sim 1\mathrm{kev} - 10\mathrm{MeV}$
  (Sun's photon energy: $E_{\mathrm{p,Sun}} \sim 1 - 2\ \mathrm{eV}$)



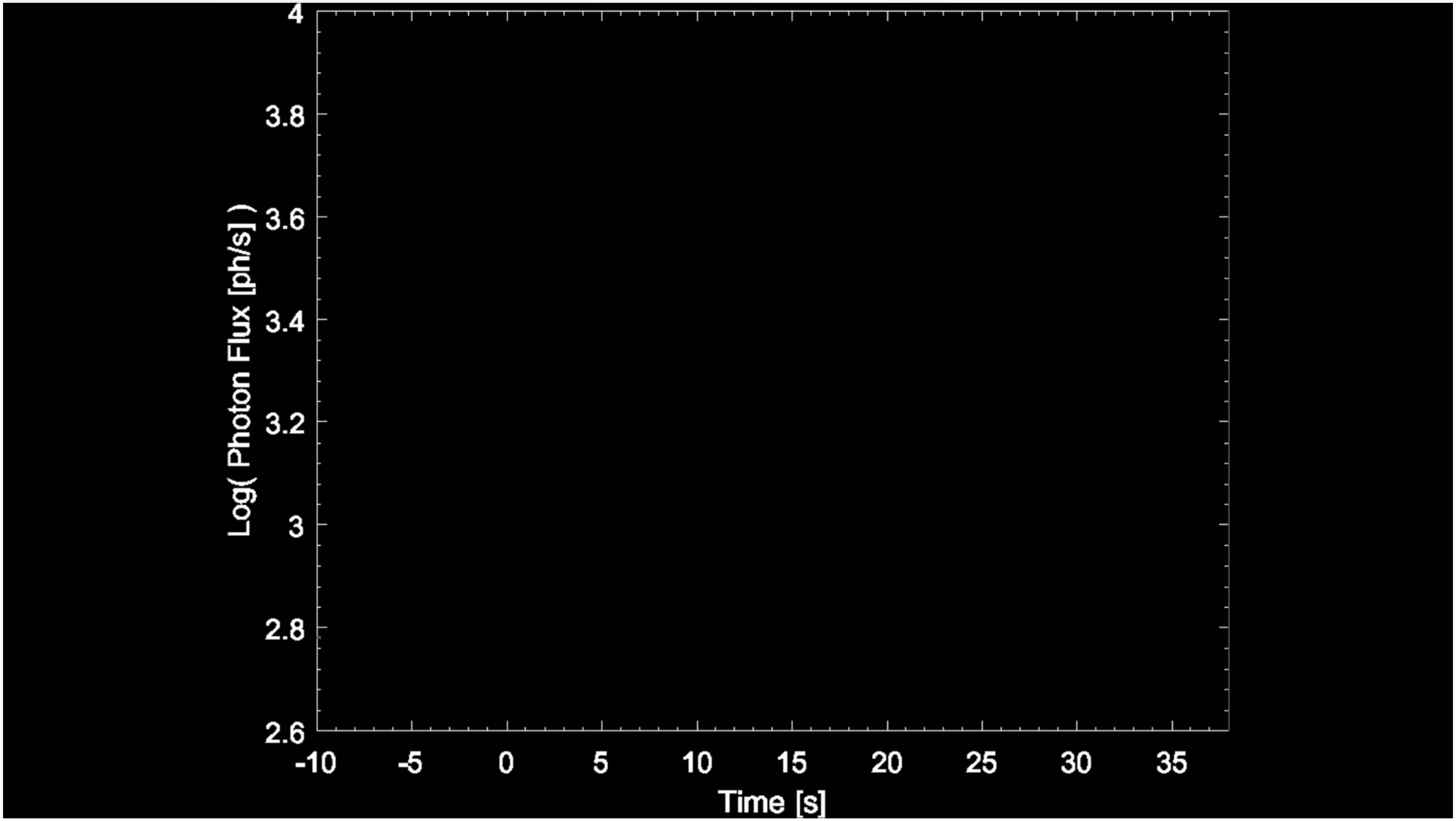
Example GRB lightcurve and spectrum

(BATSE GRB trigger 1085)



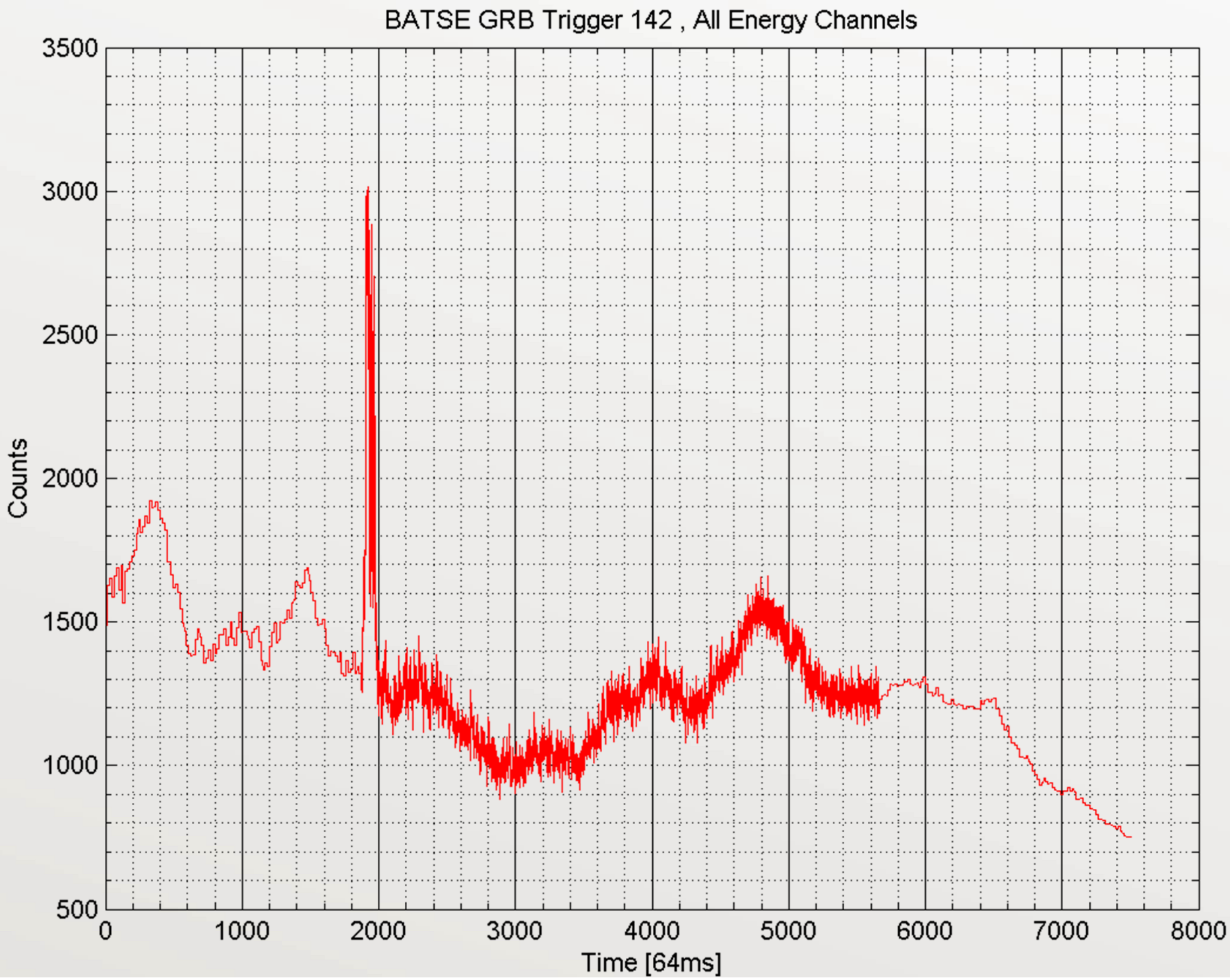
Example GRB lightcurve and spectrum

(BATSE GRB trigger 1085)



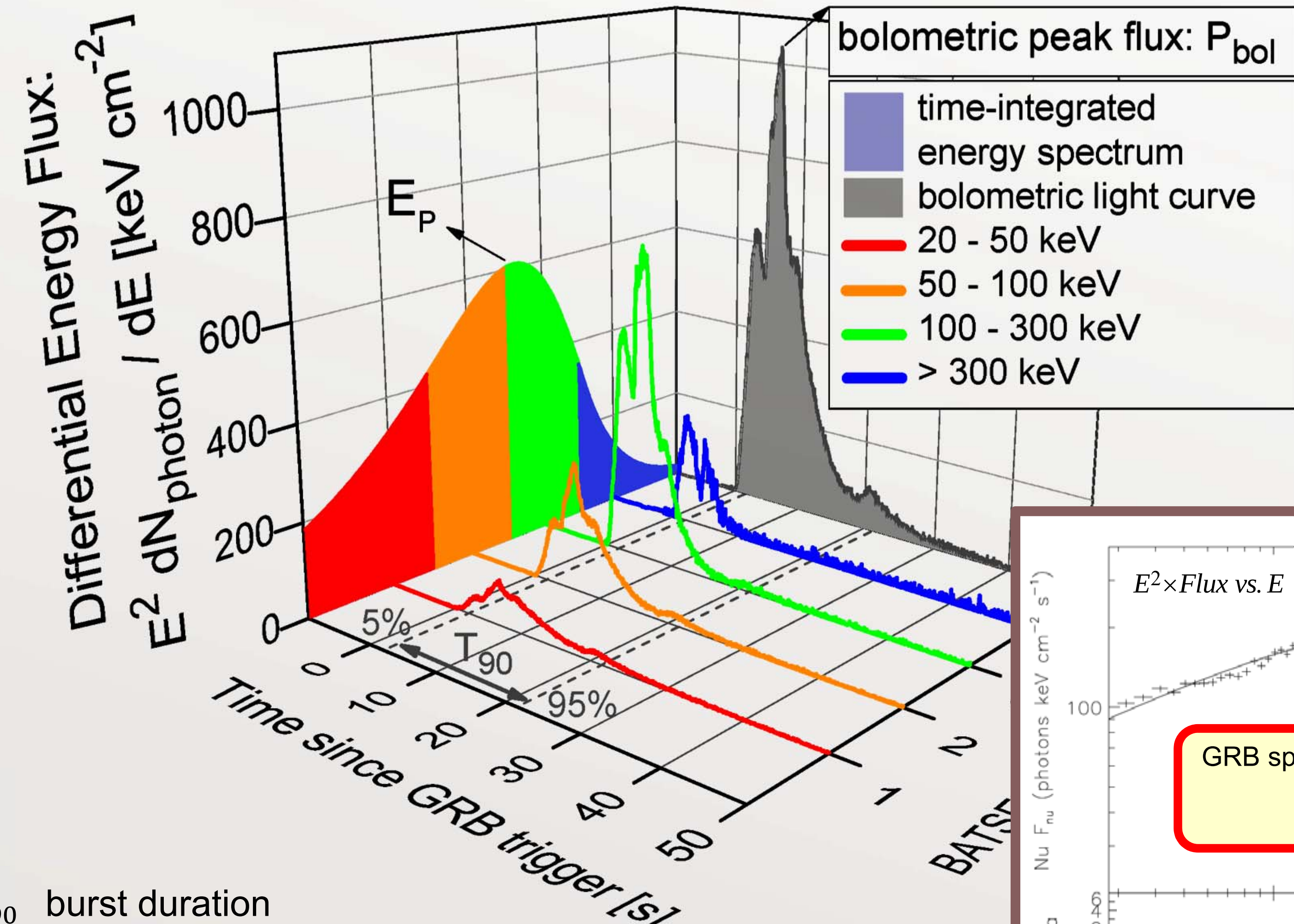
Example GRB lightcurve and spectrum

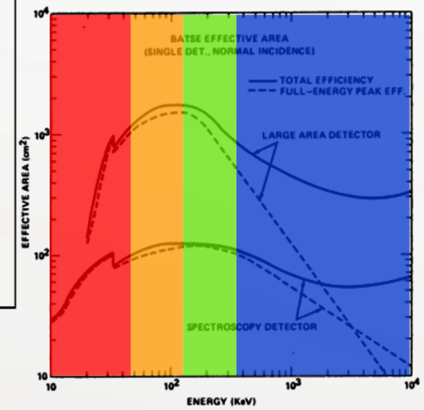
(BATSE GRB trigger 142)

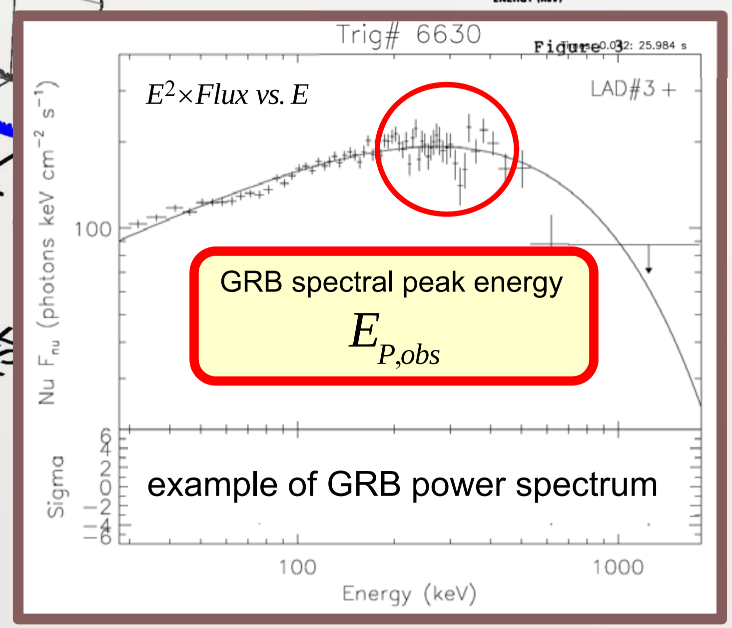


Example GRB light-curve and spectrum

and the four most important characteristics of GRBs







T_{90} burst duration

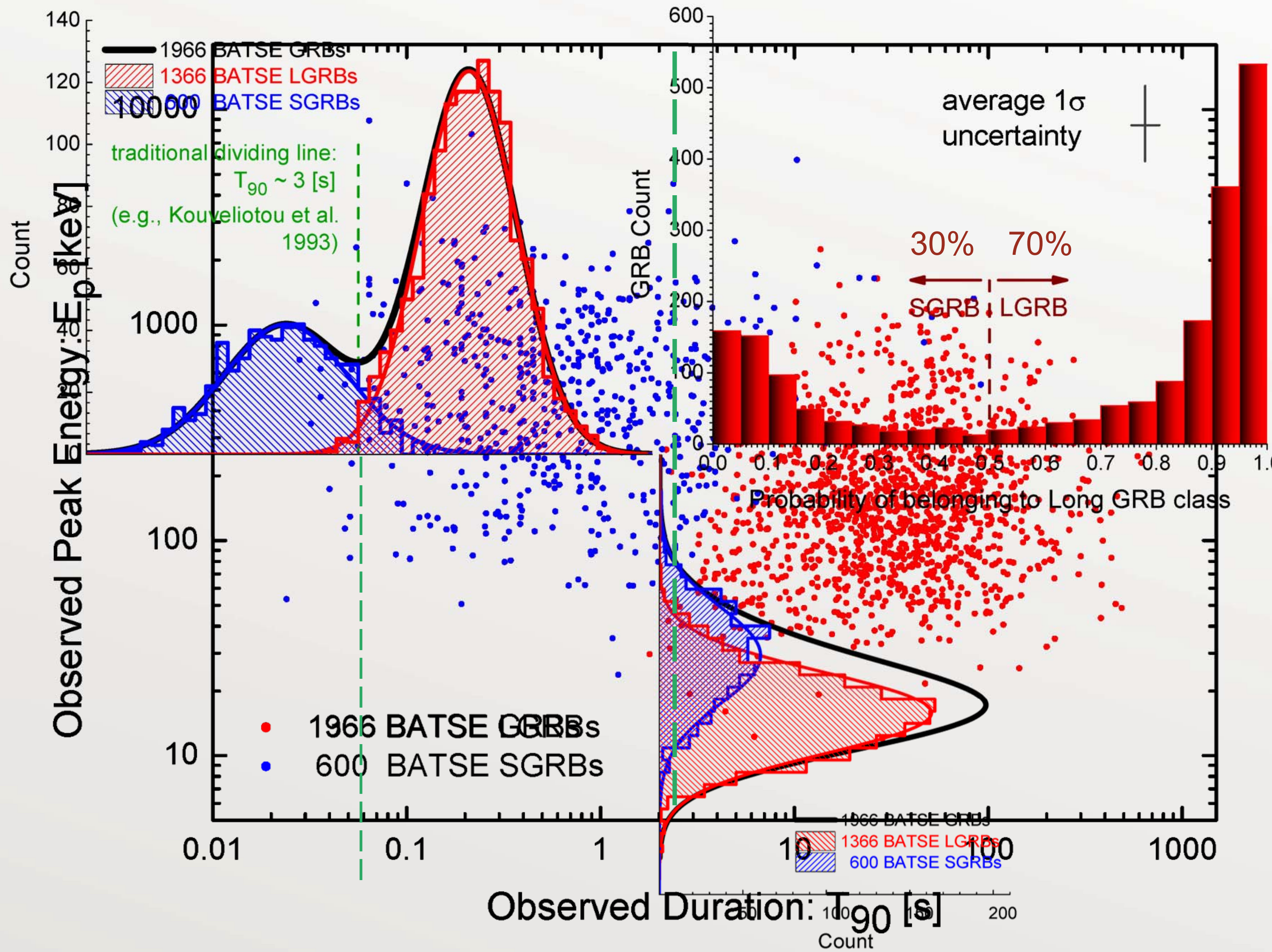
P_{bol} burst peak photon flux

S_{bol} burst total energy (received on earth)

E_p burst spectral peak energy

Classification of BATSE GRBs: fuzzy clustering vs. cutoff line

(Shahmoradi & Nemiroff, 2011, MNRAS, **411**, 1843–1856)



There are two types of Gamma-Ray Bursts (GRBs)

Short-duration class

Long-duration class

Discovery of Gravitational Wave Radiation in Feb 2016
Predicted by Albert Einstein in 1916

Each and every GRB has two sets of properties

Observer-frame

GRB observed duration: T_{90}

GRB peak photon flux: P_{bol}

GRB total observed energy: S_{bol}

GRB observed peak energy: E_p

z transformation

Rest-frame

GRB intrinsic duration: $T_{90,z} = \frac{T_{90}}{1+z}$

GRB peak luminosity: $L_{iso} = 4\pi D_L\ (z)^2\ P_{bol}$

GRB total energy release $E_{iso} = 4\pi D_L\ (z)^2\ S_{bol}$

GRB intrinsic peak energy: $E_{p,z} = E_p(1+z)$

III. Can we use GRBs as standard candles in cosmology?

Short answer:

No, at the moment. Maybe yes in future.

A&A 390, 81–89 (2002)
DOI: 10.1051/0004-6361:20020722
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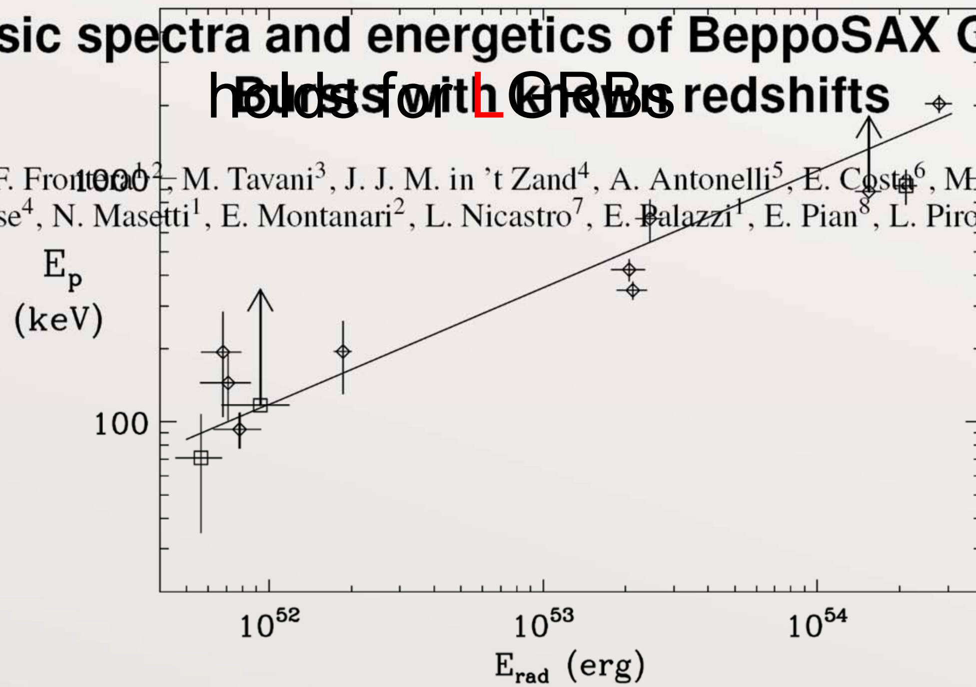
Astronomy & Astrophysics

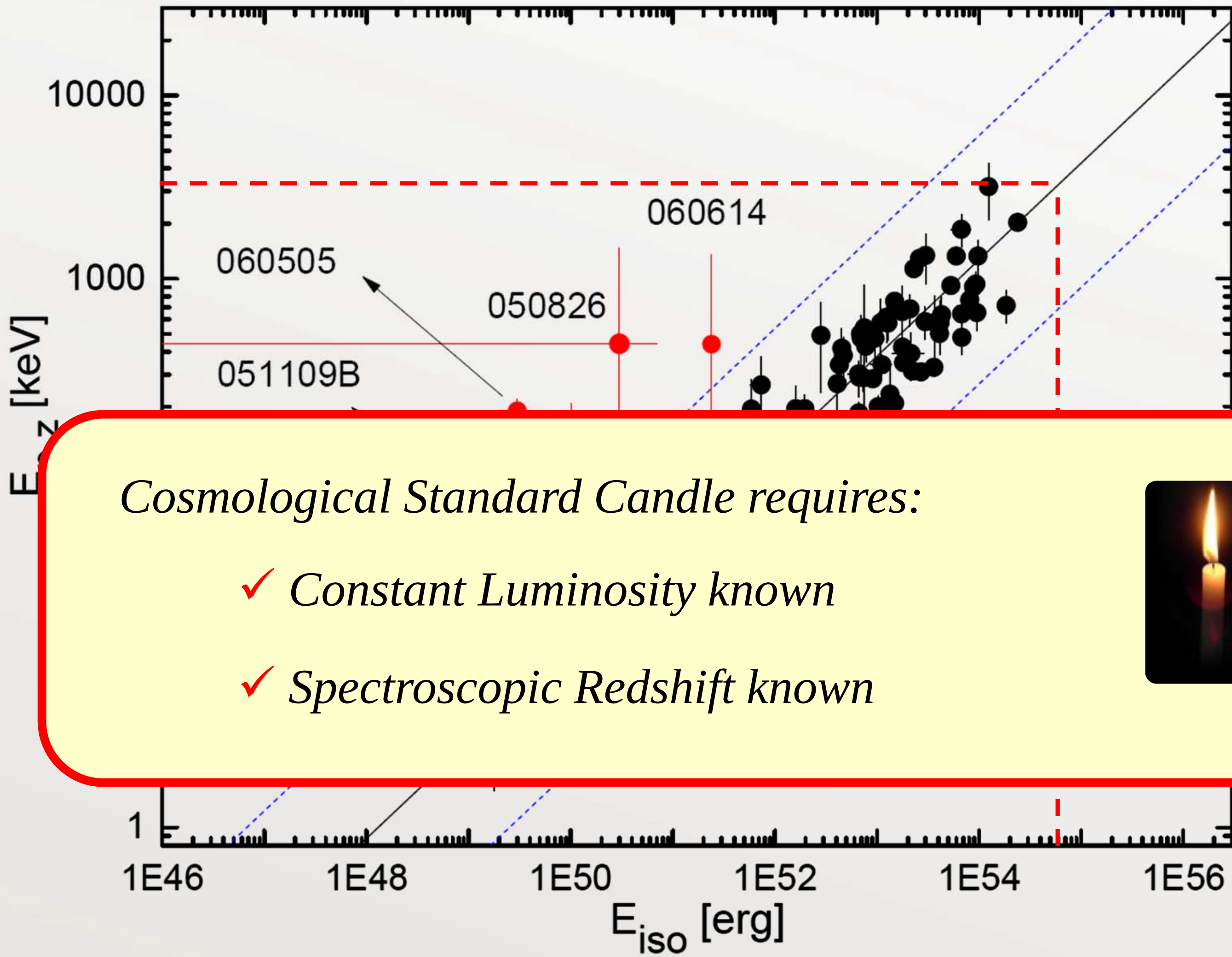
Intrinsic spectra and energetics of BeppoSAX Gamma–Ray Bursts with known redshifts

L. Amati[1], F. Frontera[1,2], M. Tavani[3], J. J. M. in 't Zand[4], A. Antonelli[5], E. Costa[6], M. Feroci[6], C. Guidorzi[2], J. Heise[4], N. Masetti[1], E. Montanari[2], L. Nicastro[7], E. Palazzi[1], E. Pian[8], L. Piro[6], and P. Soffitta[6]

holds for L GRBs



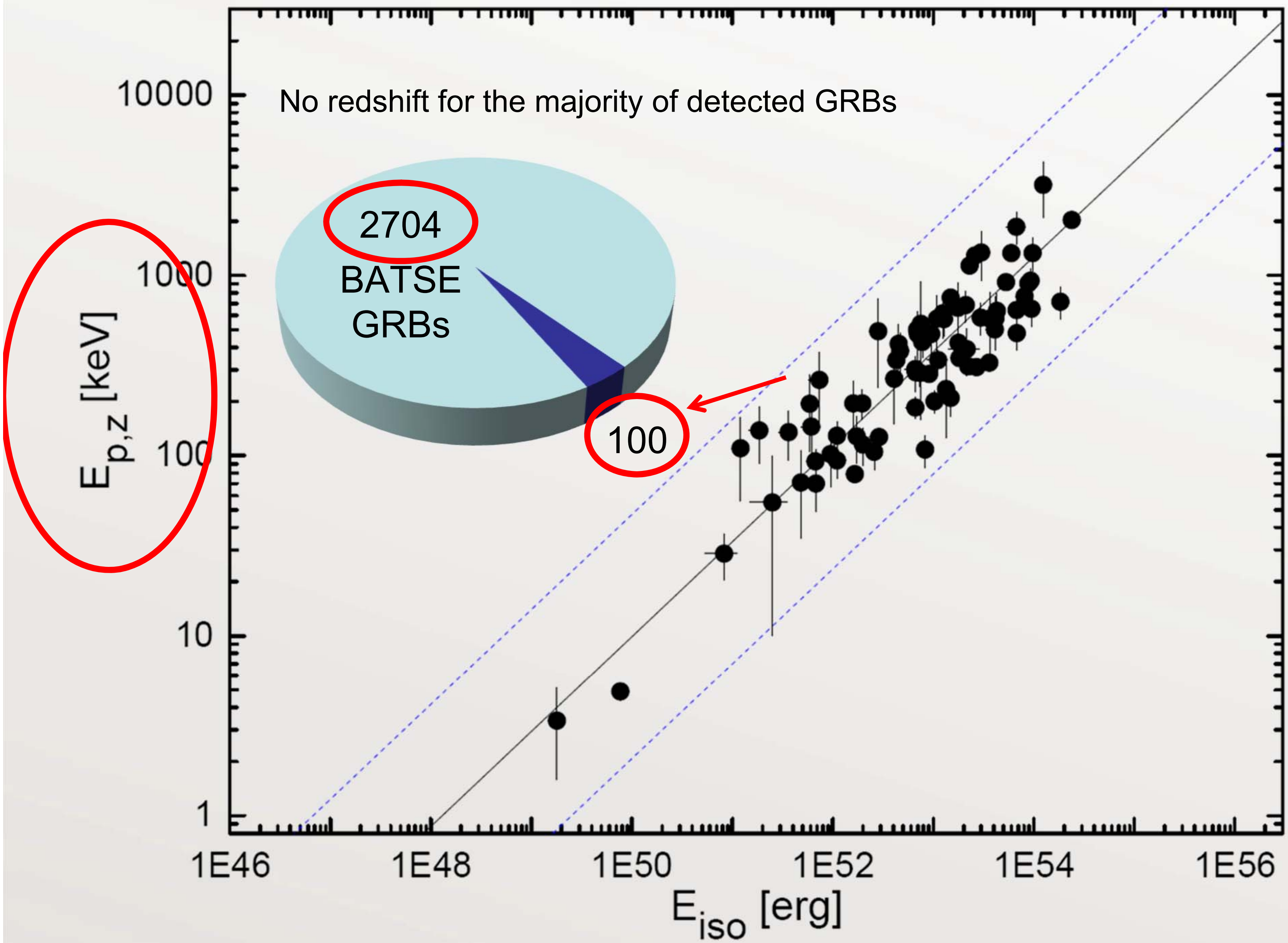
The spectral peak energy ($E_{p,z}$) of GRBs can be a standard candle, thanks to the Amati relation



Cosmological Standard Candle requires:

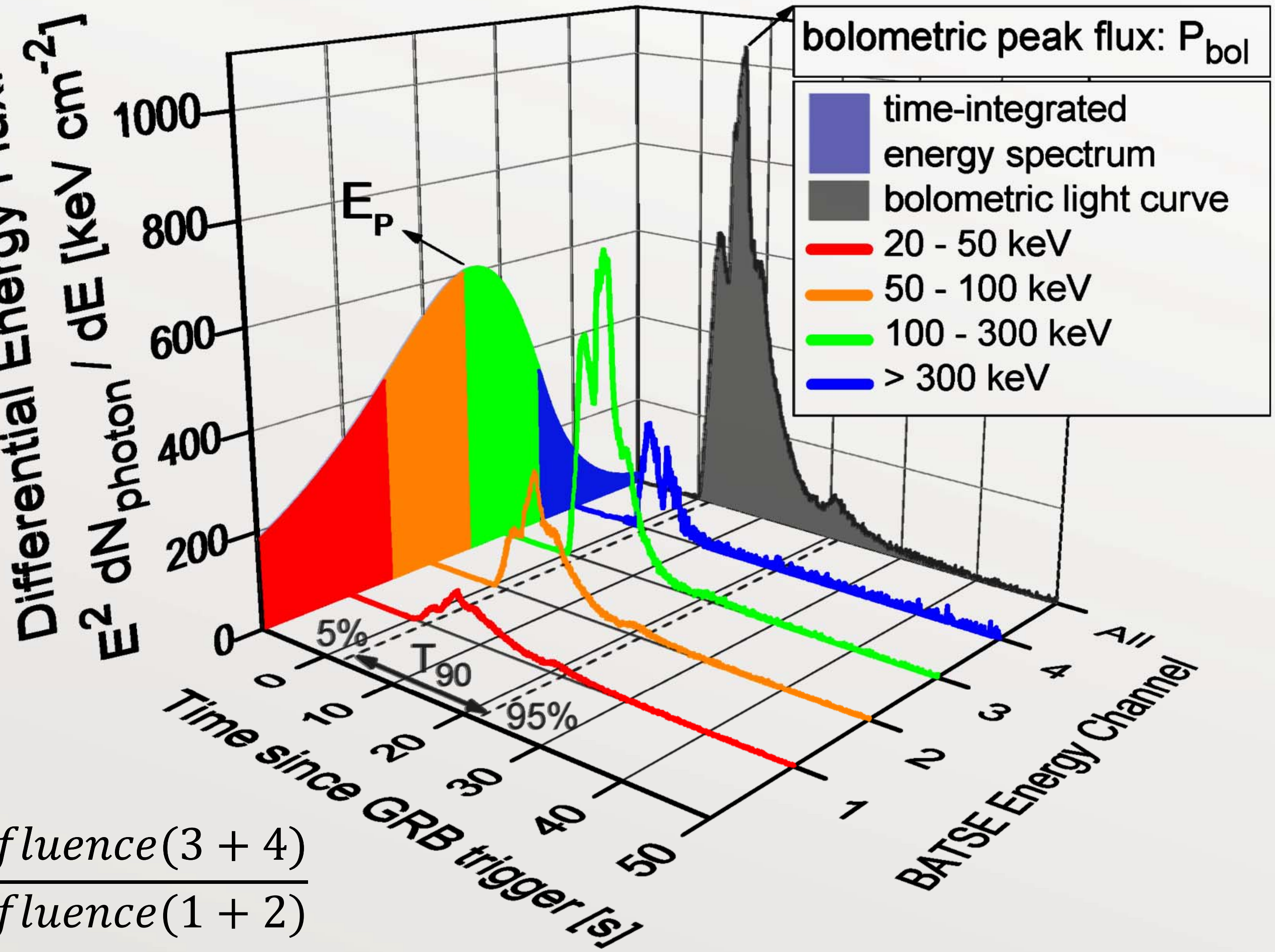
- ✓ *Constant Luminosity known*
- ✓ *Spectroscopic Redshift known*

The Amati relation has been constructed by less than 10% of all GRBs detected by all gamma-ray satellites



Example GRB lightcurve and spectrum

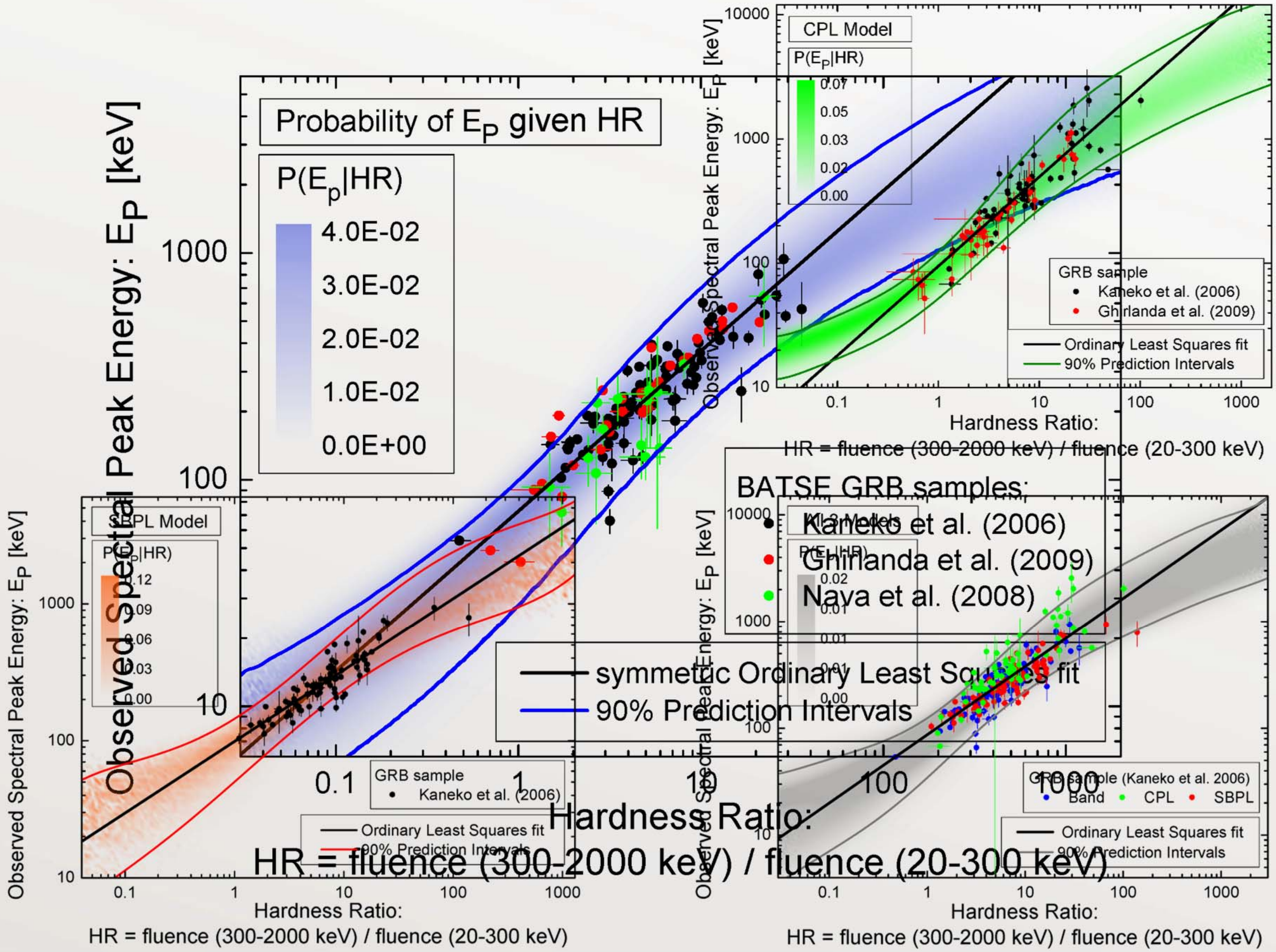
(BATSE GRB trigger 1085)



$$HR = \frac{fluence(3+4)}{fluence(1+2)}$$

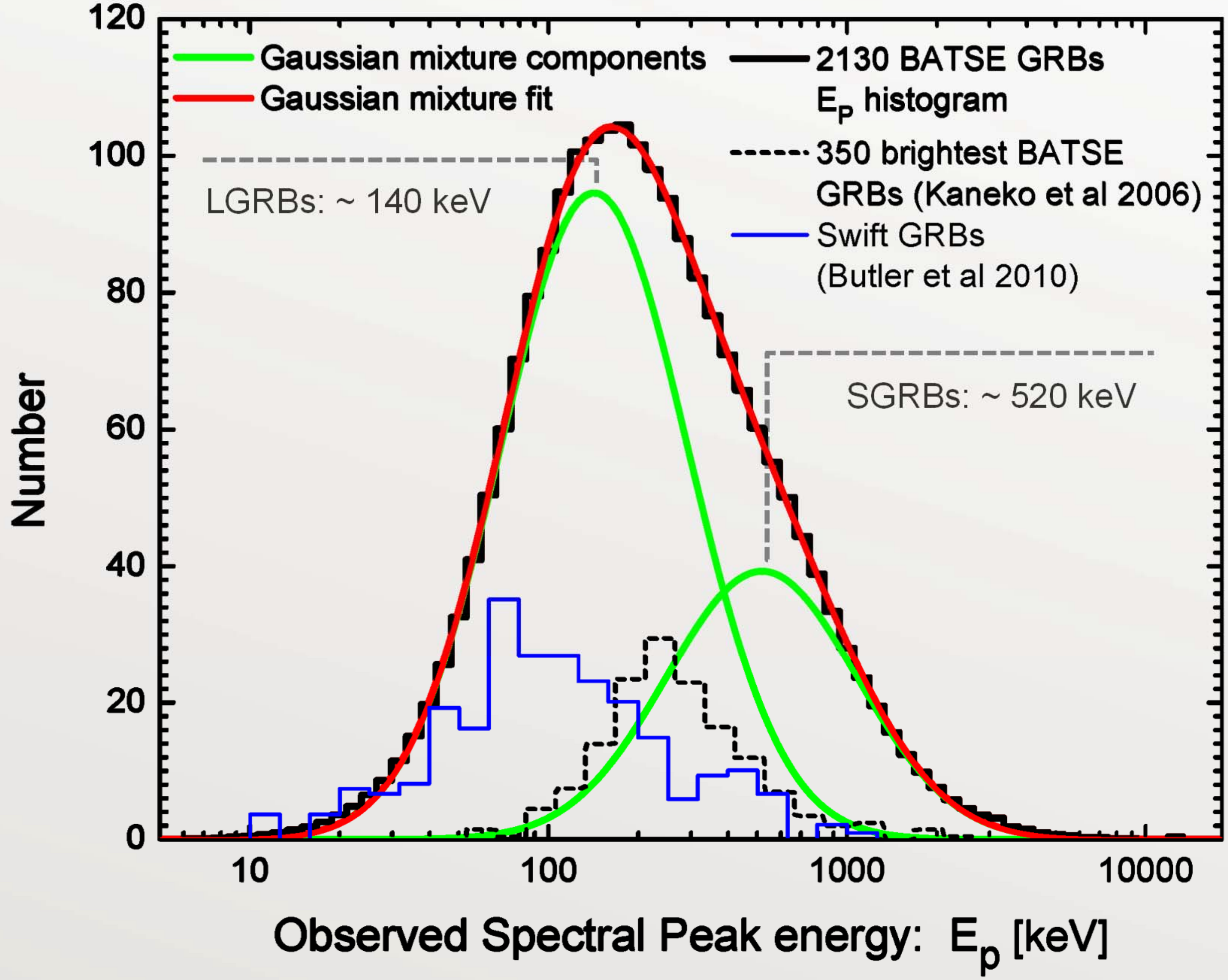
Hardness is a proxy measure of spectral peak energy of GRBs

(Shahmoradi & Nemiroff, 2010, MNRAS, **407**, 2075–2090)

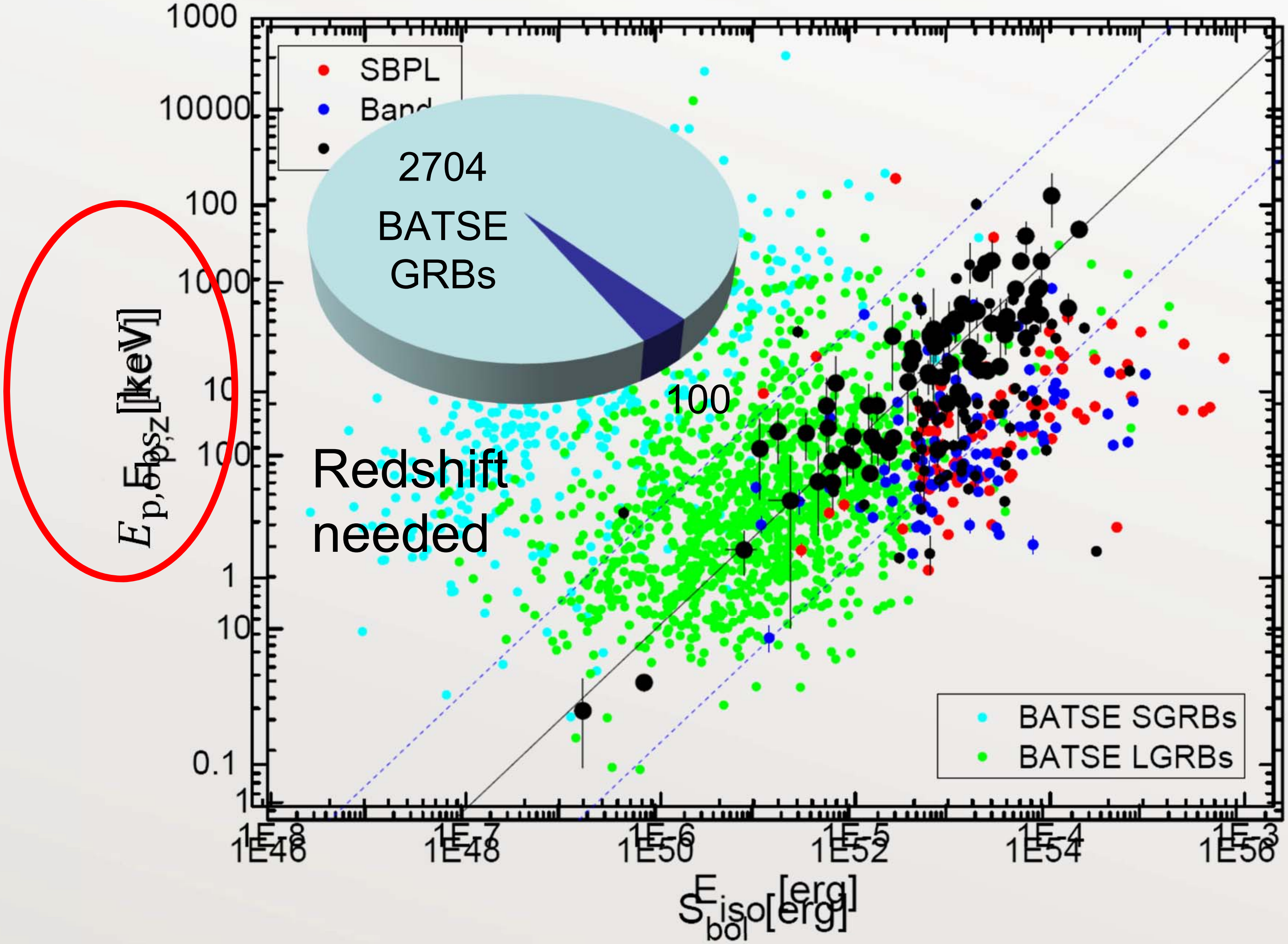


The peak energy distribution of 2130 BATSE GRBs

(Shahmoradi & Nemiroff, 2010, MNRAS, **407**, 2075–2090)



GRB astronomers are only seeing the tip of the iceberg

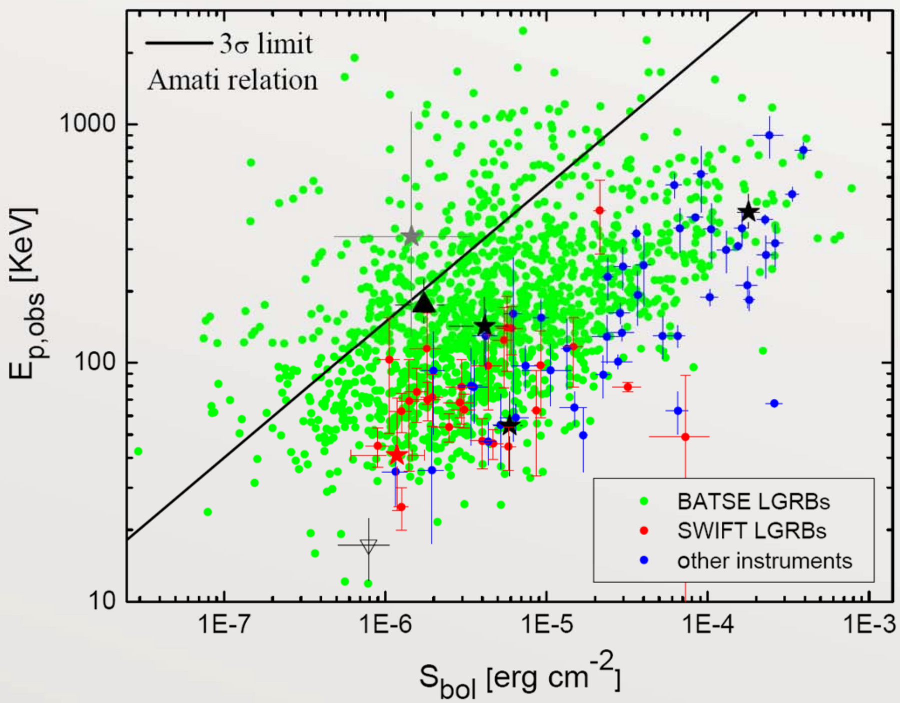


The Amati relation is heavily affected by sample incompleteness bias

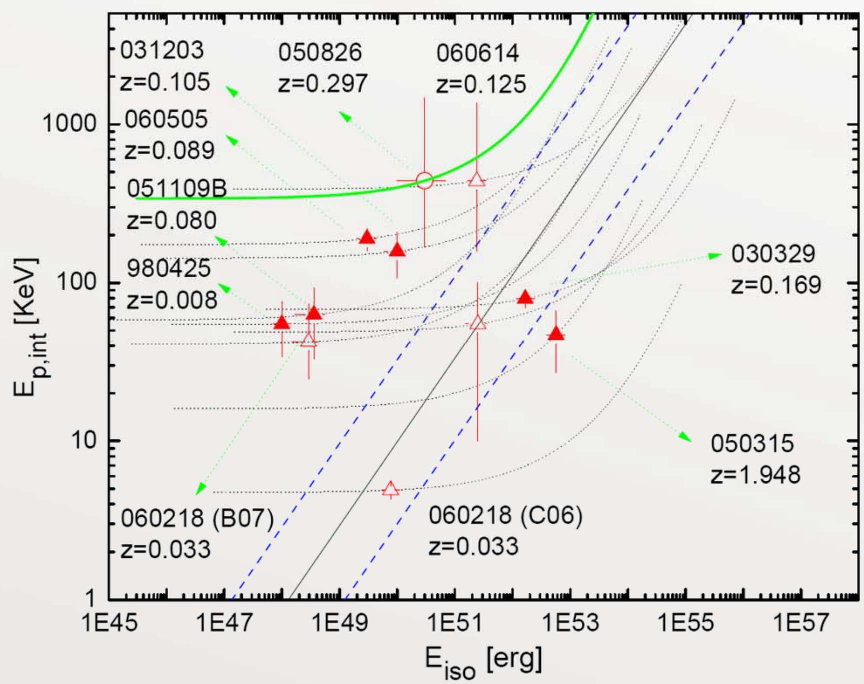
At least 19% of all detected GRBs with no redshift are not consistent with the Amati relation at $> 3\sigma$ significance level.

z transform

observer-frame

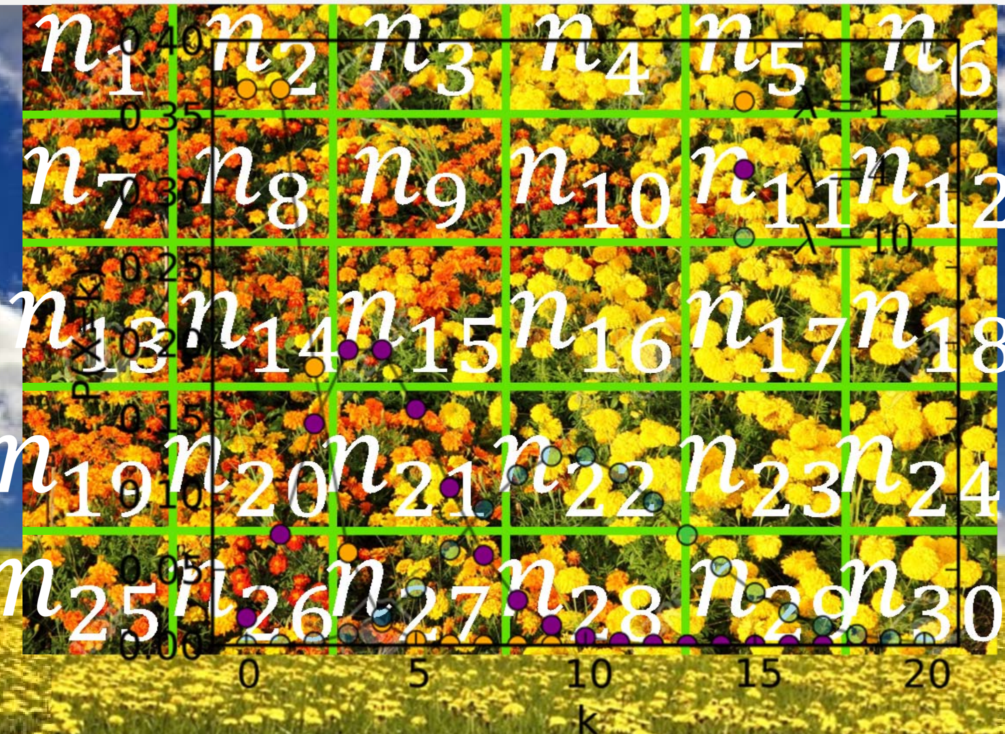


rest-frame



Is there also a sample incompleteness bias due to gamma-ray detector threshold?

Poisson distribution: The distribution of counts of independent events within a given interval of time, space, …



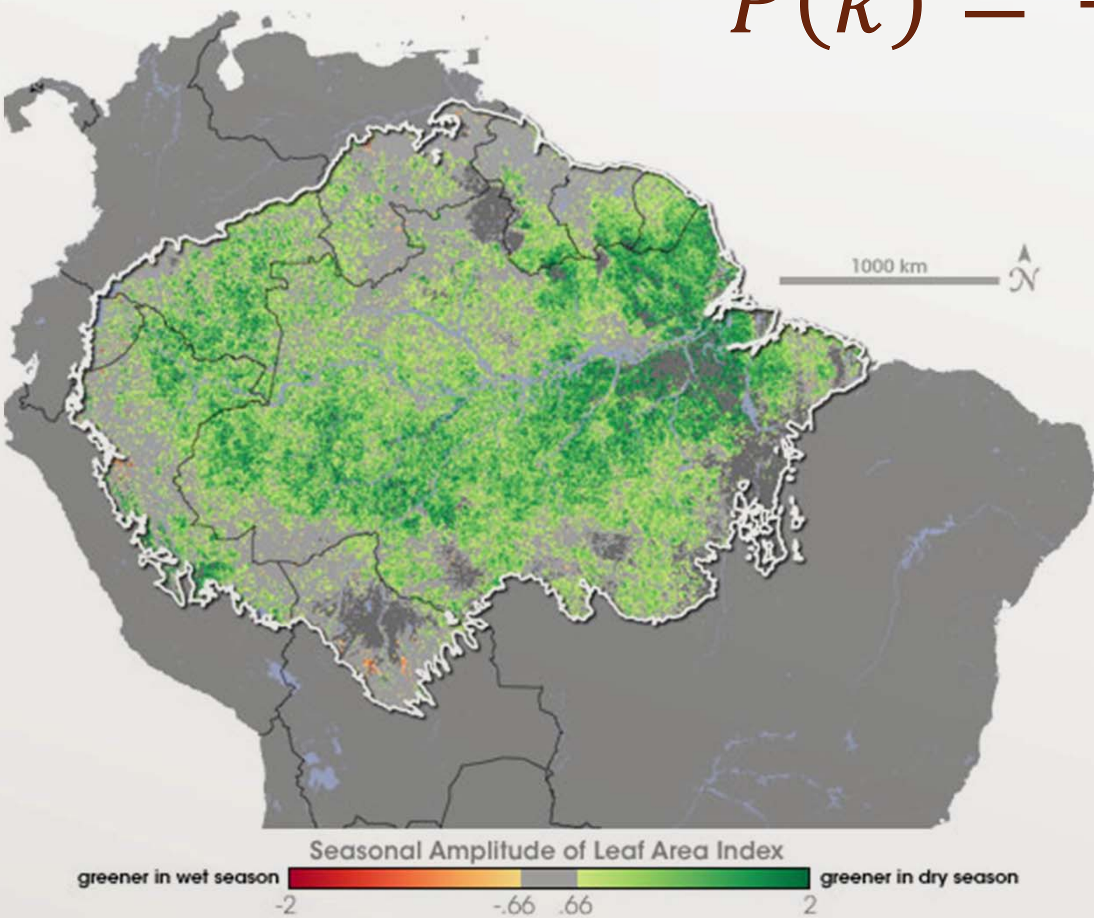
$$\lambda = \frac{1}{N}\sum_{N=0}^{N=30} n_i$$

$$P(k) = \frac{\lambda^k}{k!}e^{-\lambda}$$

Non-homogeneous spatial-temporal Poisson point process:

A Poisson point process with a Poisson parameter λ set as some location-dependent function in the underlying space on which the Poisson process is defined.

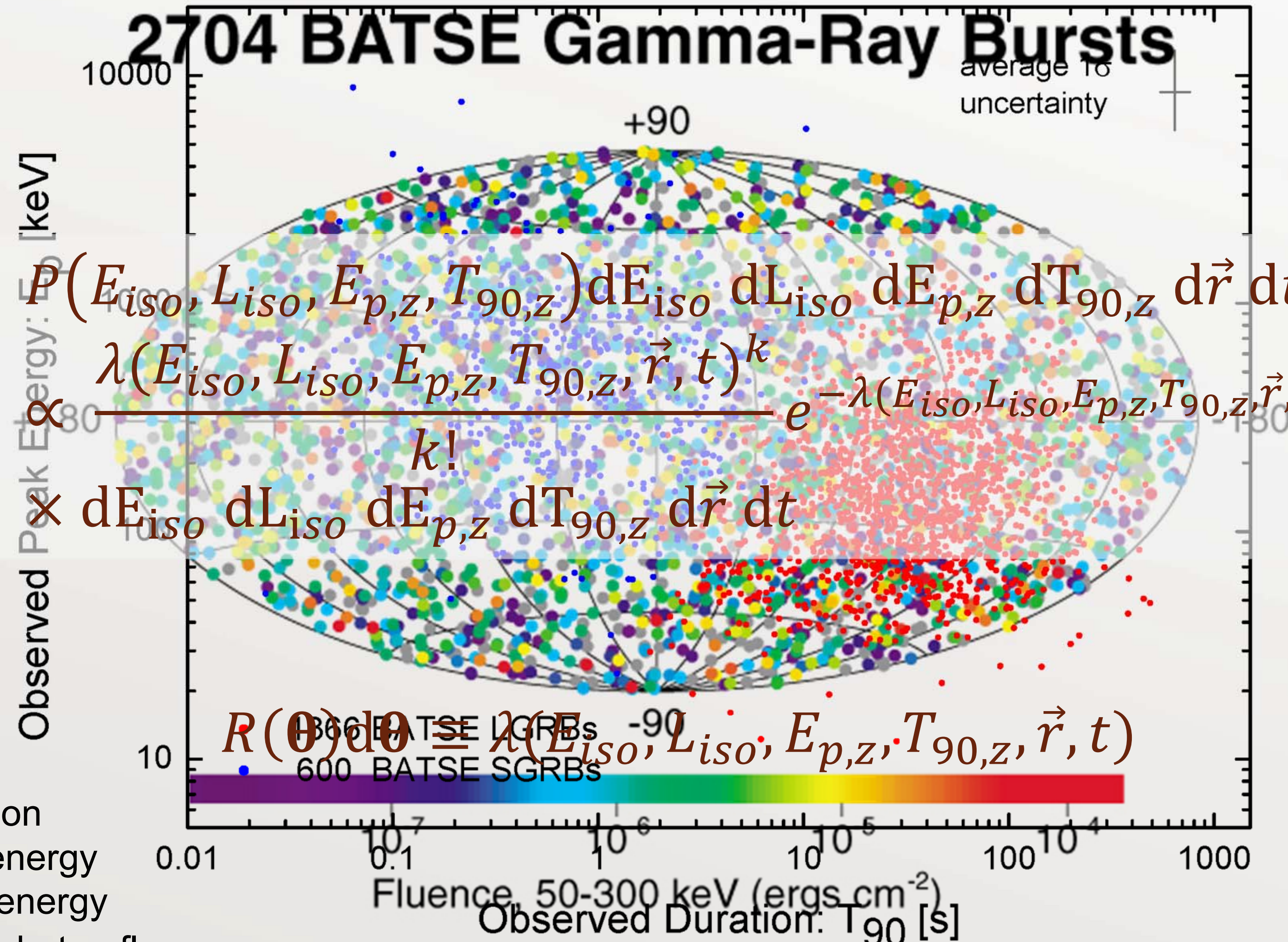
$$P(k) = \frac{\lambda(\vec{r},t)^k}{k!} e^{-\lambda(\vec{r},t)}$$



Poisson processes are additive!

GRB detection process can be modeled as a non-homogenous Poisson process

What is the rate of occurrence of GRBs as a function of their distance and properties, $R(\theta)$?

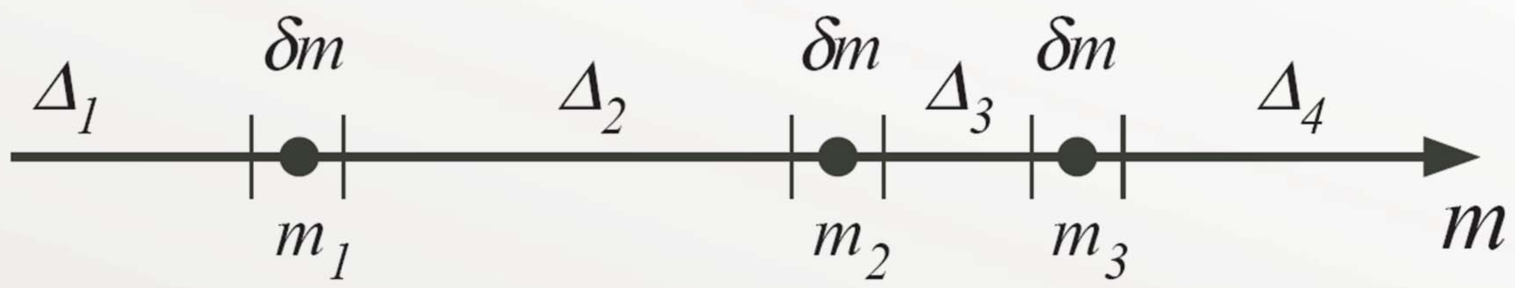


$$P\left(E_{iso}, L_{iso}, E_{p,z}, T_{90,z}\right)\mathrm{dE_{iso}\ dL_{iso}\ dE_{p,z}\ dT_{90,z}}\ \mathrm{d}\vec{r}\ \mathrm{d}t$$
$$\propto \frac{\lambda(E_{iso}, L_{iso}, E_{p,z}, T_{90,z}, \vec{r}, t)^k}{k!} e^{-\lambda(E_{iso}, L_{iso}, E_{p,z}, T_{90,z}, \vec{r}, t)}$$
$$\times\ \mathrm{dE_{iso}\ dL_{iso}\ dE_{p,z}\ dT_{90,z}}\ \mathrm{d}\vec{r}\ \mathrm{d}t$$

$$R(\boldsymbol{\theta})\mathrm{d}\boldsymbol{\theta} \equiv \lambda(E_{iso}, L_{iso}, E_{p,z}, T_{90,z}, \vec{r}, t)$$

T_{90} duration
S_{bol} total energy
E_p peak energy
P_{bol} peak photon flux
z redshift (distance from earth)

With a statistical model in hand, we can proceed to construct the likelihood function of the model to estimate model parameters



$$P(k) = \frac{\lambda(m)^k}{k!} e^{-\lambda(m)} \qquad P_0(m) = \frac{(R(m)\Delta m)^0}{0!} e^{-R(m)\Delta m} = e^{-R(m)\Delta m}$$

$$P_1(m) = \frac{(R(m)\Delta m)^1}{1!} e^{-R(m)\Delta m} = R(m)\Delta \mathrm{m}\, e^{-R(m)\Delta m}$$

$$L\big(\mathrm{DATA}|R(m)\big) = \prod_{i=1}^{N} P_1(m_i) \prod_{j=1}^{M} P_0(m_j) = (\Delta m)^N \left[\prod_{i=1}^{N} R\,(m_i)\right]\left[e^{-\sum_{j=1}^{N+M} R(m_j)\Delta \mathrm{m}}\right]$$

$$= (\Delta m)^N \left[\prod_{i=1}^{N} R\,(m_i)\right] \exp\left(-\int_M R(m)\mathrm{dm}\right)$$

How about the likelihood function for the non-homogenous Poisson process of GRB detection?

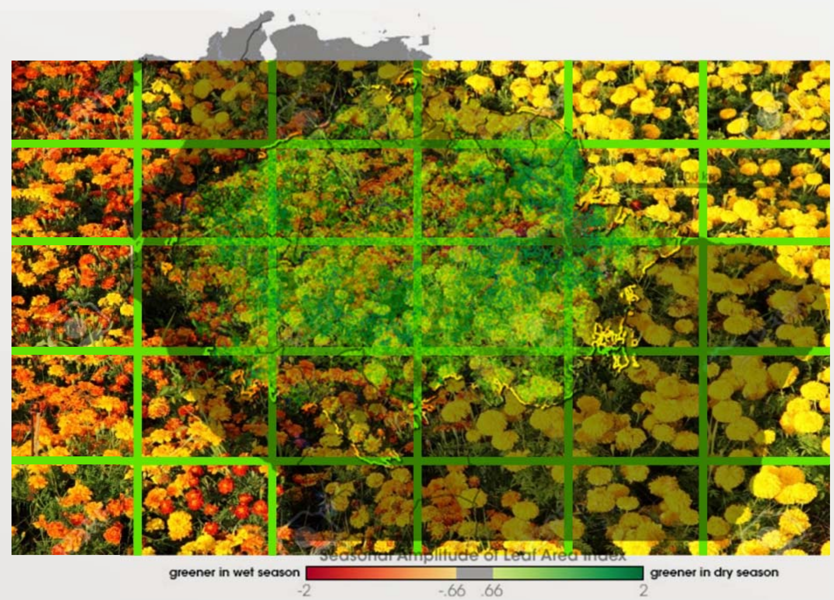
$$L\big(\mathrm{DATA}|R(m)\big) = (\Delta m)^N \left[\prod_{i=1}^{N} R\,(m_i)\right] \exp\left(-\int_M R(m)\mathrm{d}m\right)$$

$$L\big(\mathrm{GRB\ DATA}|R(\boldsymbol{\theta})\big) = (\Delta \boldsymbol{\theta})^N \left[\prod_{i=1}^{N} R\,(\boldsymbol{\theta}_i)\right] \exp\left(-\int_{\boldsymbol{\theta}} R(\boldsymbol{\theta})\mathrm{d}\boldsymbol{\theta}\right)$$

$$\boldsymbol{\theta} \equiv \vec{\theta} \equiv \left[E_{iso}, L_{iso}, E_{p,z}\,, T_{90,z}\,, z, t\right]$$

Now that we have the likelihood function, what is the most appropriate model for GRB rate as a function of GRB parameters?

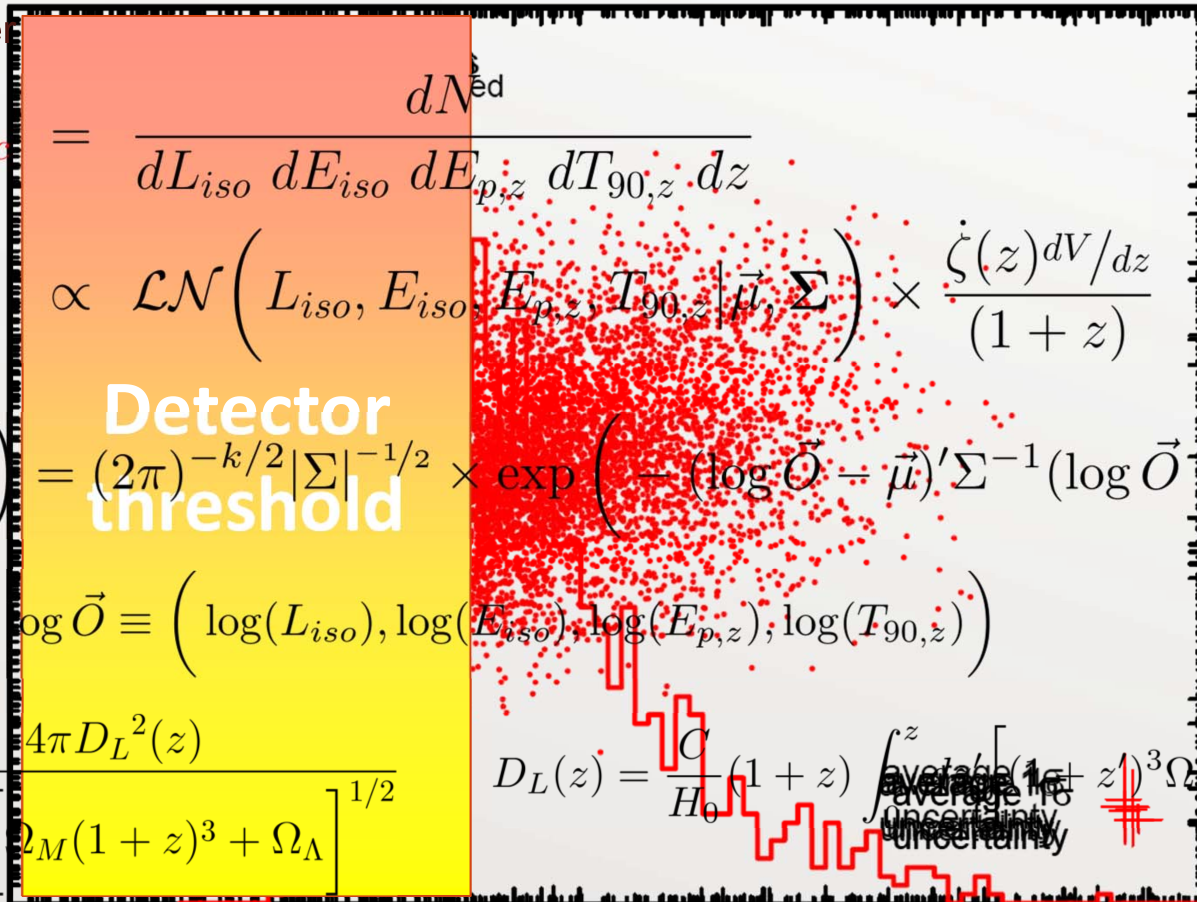
$$R\,(\boldsymbol{\theta}) = ?$$



Multivariate Log-normal distribution

The simplest most natural model of GRB occurrence rate R_{cosmic} as a function of GRB properties ($E_{iso}, L_{iso}, E_{p,z}, T_{90,z}, z$)

The rate parameter



$$\mathcal{R}_{cosmic} = \frac{dN}{dL_{iso}\ dE_{iso}\ dE_{p,z}\ dT_{90,z}\ dz}$$

$$\propto \mathcal{LN}\left(L_{iso}, E_{iso}, E_{p,z}, T_{90,z} \,\middle|\, \vec{\mu}, \Sigma\right) \times \frac{\dot{\zeta}(z)^{dV/dz}}{(1+z)}$$

$$\mathcal{N}\left(\log \vec{O} \,\middle|\, \vec{\mu}, \Sigma\right) = (2\pi)^{-k/2}|\Sigma|^{-1/2} \times \exp\left(-(\log \vec{O} - \vec{\mu})'\Sigma^{-1}(\log \vec{O} - \vec{\mu})/2\right)$$

$$\log \vec{O} \equiv \left(\log(L_{iso}), \log(E_{iso}), \log(E_{p,z}), \log(T_{90,z})\right)$$

$$\frac{dV}{dz} = \frac{C}{H_0}\frac{4\pi D_L{}^2(z)}{(1+z)^2\left[\Omega_M(1+z)^3 + \Omega_\Lambda\right]^{1/2}}$$

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

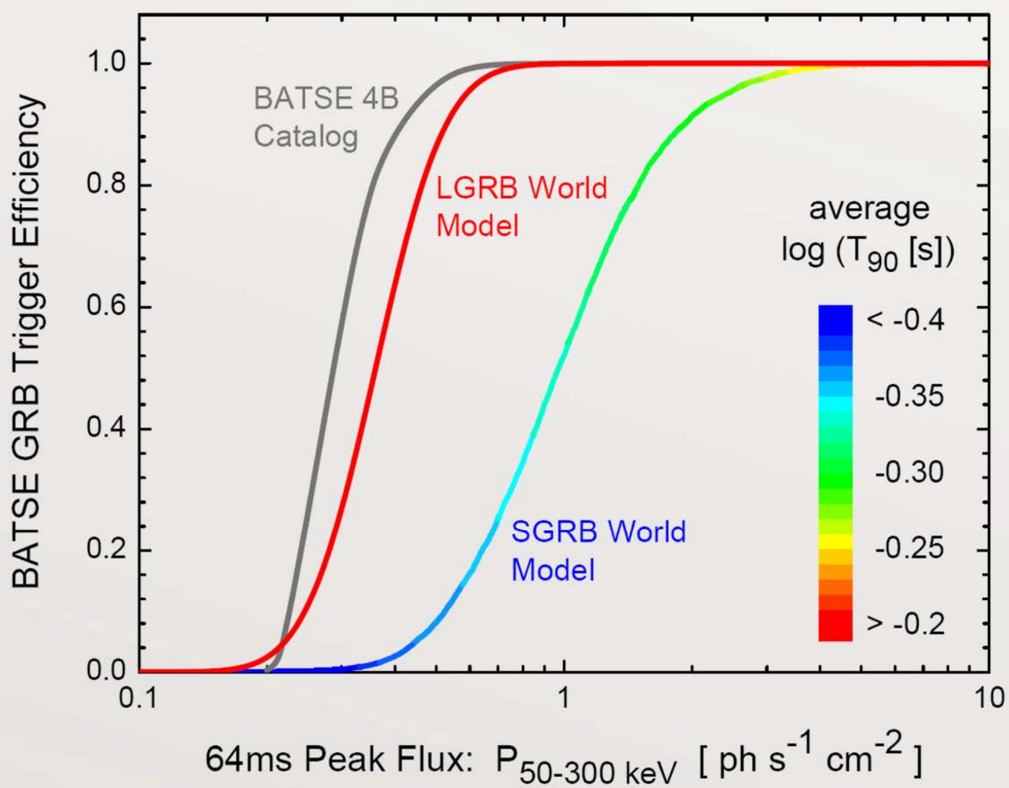
$$\dot{\zeta}(z) \propto \mathcal{SFR}(z) \propto \begin{cases} (1+z)^{\gamma_0} & z < z_0 \\ (1+z)^{\gamma_1} & z_0 < z < z_1 \\ (1+z)^{\gamma_2} & z > z_1, \end{cases}$$

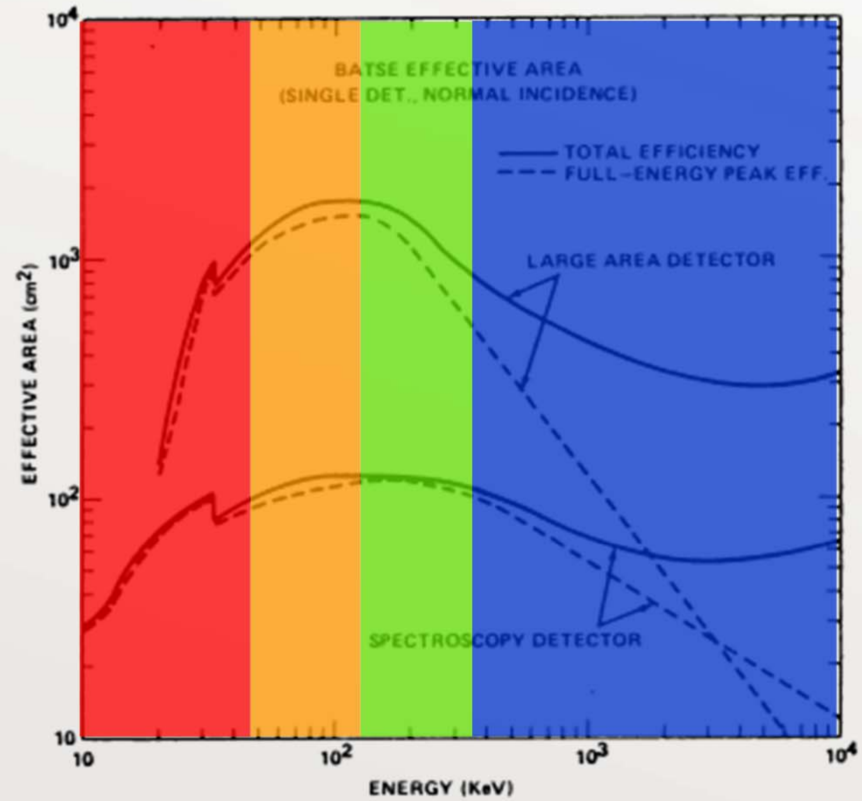
$$\mathcal{R}_{obs} = \eta(L_{iso}, E_{p,z}, T_{90,z}, z) \times \mathcal{R}_{cosmic}$$

GRB detection is therefore a Poisson process with mean $\lambda = R_{obs}(\boldsymbol{\theta})\mathrm{d}\boldsymbol{\theta}$

$$\mathcal{R}_{obs} = \eta(L_{iso}, E_{iso}, E_{p,z}, T_{90,z}, z|\mu_{\mathrm{thresh}}, \sigma_{\mathrm{thresh}}) \times \mathcal{R}_{cosmic}$$

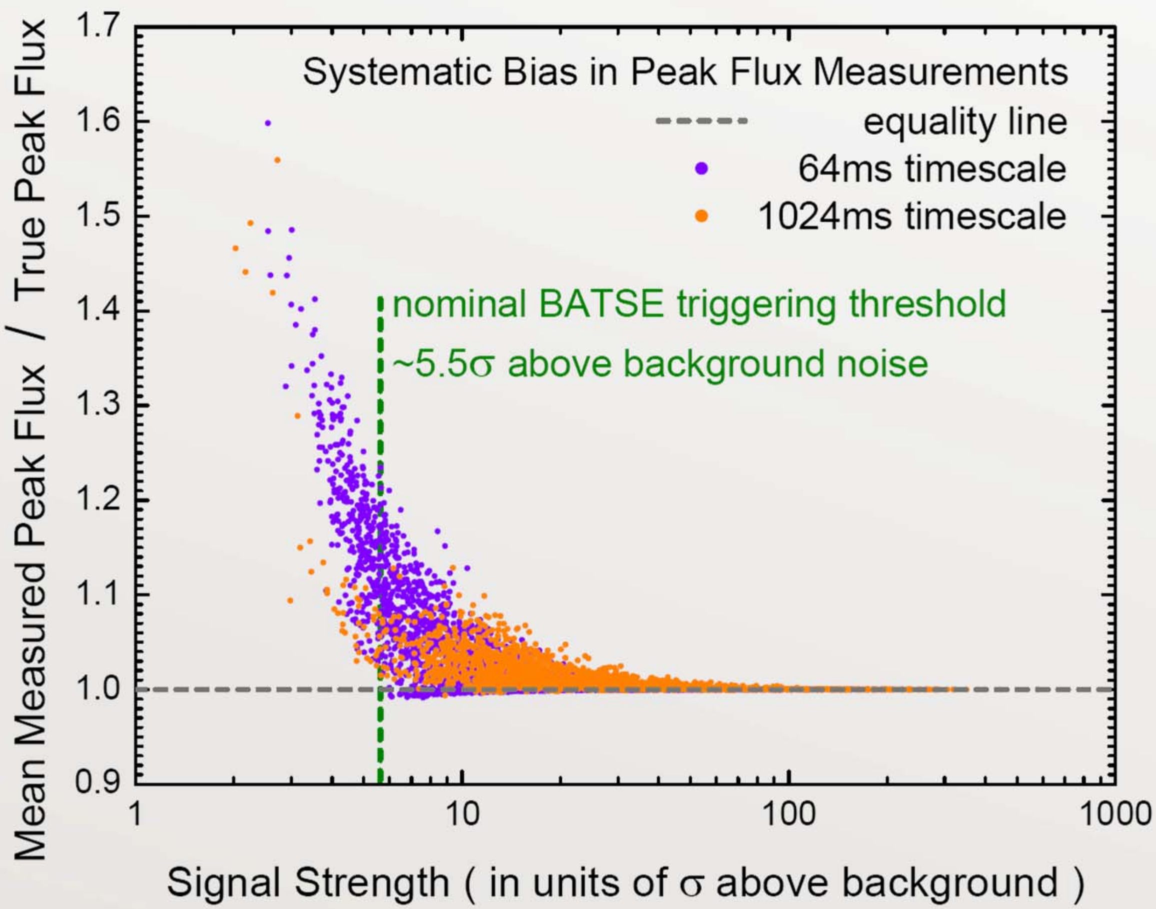
$$\eta\left(\boldsymbol{\theta}\,|\mu_{\mathrm{thresh}}, \sigma_{\mathrm{thresh}}\right) = \frac{1}{2} + \frac{1}{2} \times \mathrm{erf}\left(\frac{\log\left(P_{\mathrm{eff}}(L_{iso}, E_{p,z}, T_{90,z}, z) - \mu_{\mathrm{thresh}}\right)}{\sqrt{2}\sigma_{\mathrm{thresh}}}\right)$$



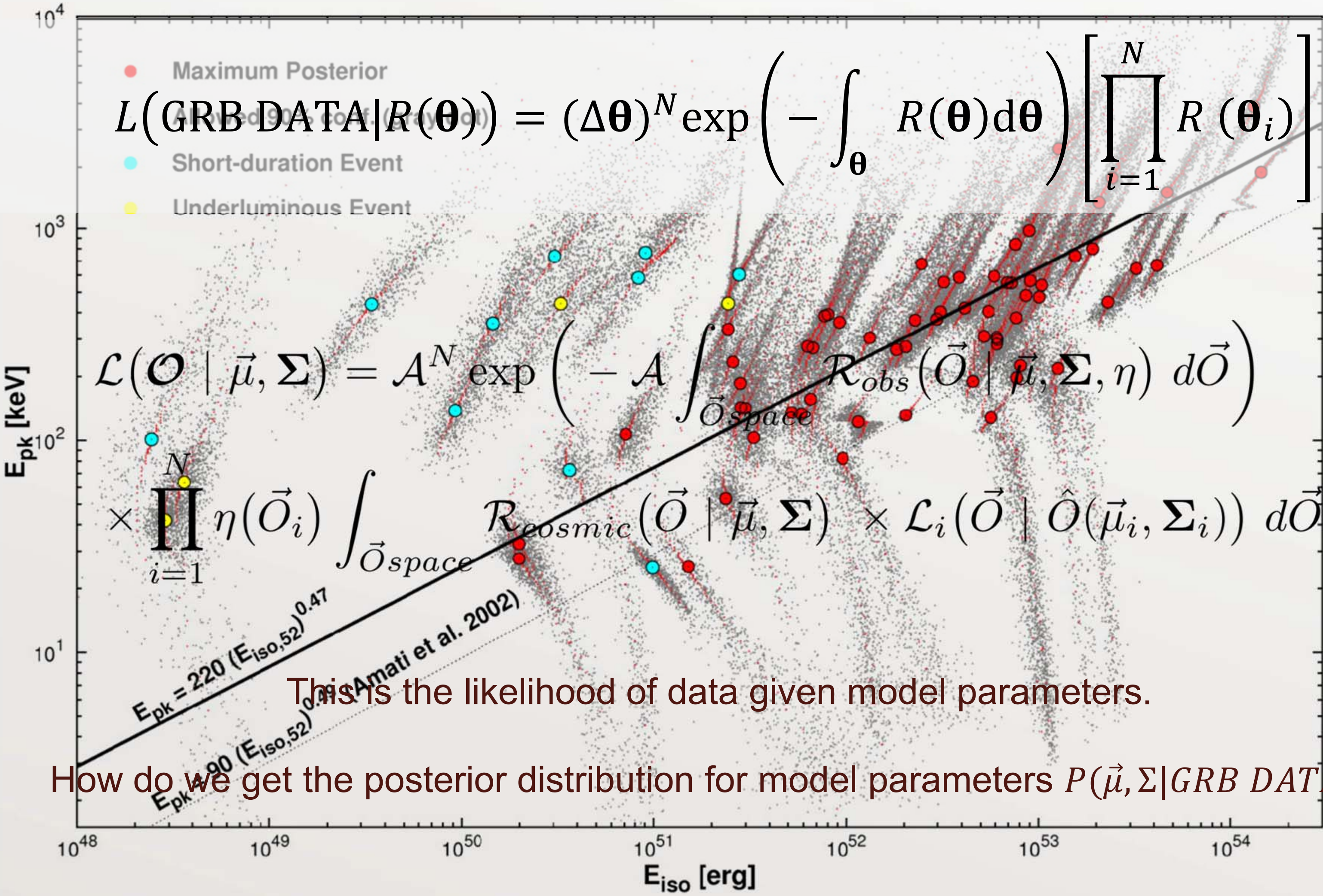


Bayesian Multilevel modeling automatically corrects for systematic biases in data

$$P(S_{true}|S_{obs}) \propto P(S_{obs}|S_{true}) \times P(S_{true})$$



Observational data uncertainties are very important and must be taken into account



$$L\big(\text{GRB DATA}|R(\boldsymbol{\theta})\big) = (\Delta\boldsymbol{\theta})^N \exp\left(-\int_{\boldsymbol{\theta}} R(\boldsymbol{\theta})\mathrm{d}\boldsymbol{\theta}\right)\left[\prod_{i=1}^{N} R\,(\boldsymbol{\theta}_i)\right]$$

$$\mathcal{L}(\mathcal{O}\mid\vec{\mu},\boldsymbol{\Sigma}) = \mathcal{A}^N \exp\left(-\mathcal{A}\int_{\vec{O}_{space}} \mathcal{R}_{obs}(\vec{O}\mid\vec{\mu},\boldsymbol{\Sigma},\eta)\; d\vec{O}\right)$$

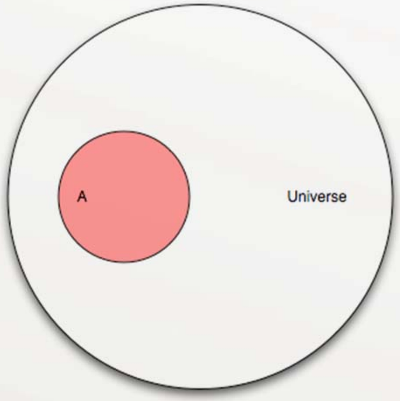
$$\times \prod_{i=1}^{N} \eta(\vec{O}_i)\int_{\vec{O}_{space}} \mathcal{R}_{cosmic}(\vec{O}\mid\vec{\mu},\boldsymbol{\Sigma})\;\times\mathcal{L}_i(\vec{O}\mid\hat{O}(\vec{\mu}_i,\boldsymbol{\Sigma}_i))\; d\vec{O}$$

This is the likelihood of data given model parameters.

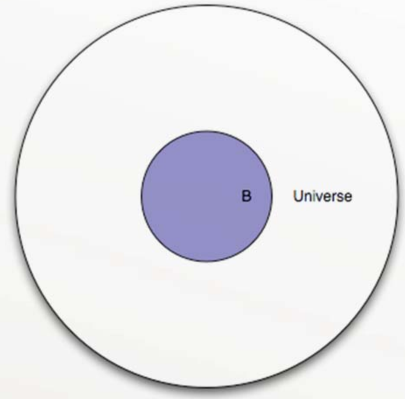
How do we get the posterior distribution for model parameters $P(\vec{\mu},\Sigma|GRB\ DATA)$?

Bayes theorem

$$P(A) = \frac{A}{U}$$

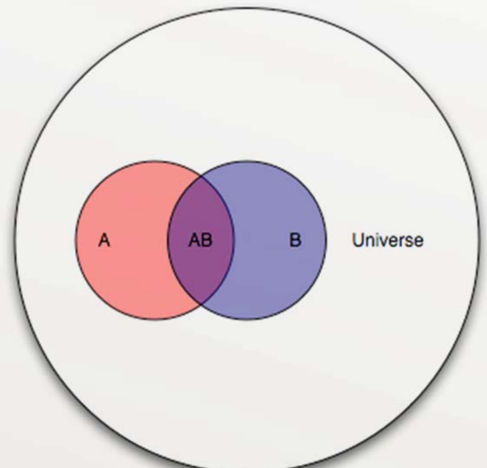


$$P(B) = \frac{B}{U}$$



$$P(A|B) = \frac{AB}{B} = \frac{\frac{AB}{U}}{\frac{B}{U}} = \frac{P(AB)}{P(B)}$$

$$P(AB) = \frac{AB}{U}$$



$$P(B|A) = \frac{AB}{A} = \frac{\frac{AB}{U}}{\frac{A}{U}} = \frac{P(AB)}{P(A)}$$

$$\boxed{P(A|B) = \frac{P(A)P(B|A)}{P(B)}}$$

The posterior probability density of model parameters can be obtained from Bayes rule

$$\boxed{P(A|B) = \frac{P(A)P(B|A)}{P(B)}}$$

$$\mathcal{L}(\boldsymbol{\mathcal{O}} \mid \vec{\mu}, \boldsymbol{\Sigma}) = \mathcal{A}^N \exp\left(- \mathcal{A} \int_{\vec{O}space} \mathcal{R}_{obs}(\vec{O} \mid \vec{\mu}, \boldsymbol{\Sigma}, \eta)\ d\vec{O} \right)$$

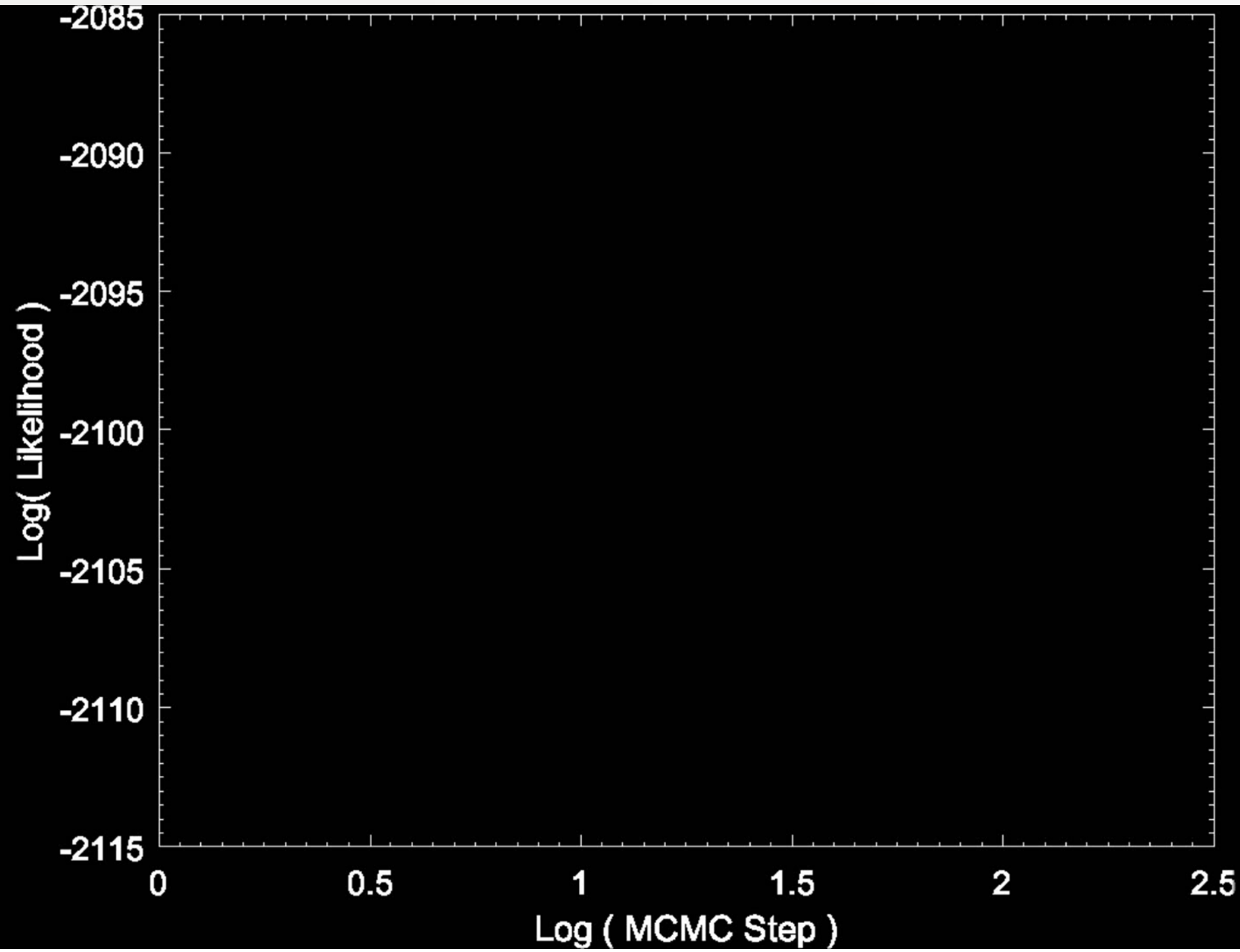
$$\times \prod_{i=1}^{N} \int_{\vec{O}space} \eta(\vec{\mu}_i, \boldsymbol{\Sigma}_i) \mathcal{R}_{cosmic}(\vec{O} \mid \vec{\mu}, \boldsymbol{\Sigma})\ \times \mathcal{L}_i(\vec{O} \mid \hat{O}(\vec{\mu}_i, \boldsymbol{\Sigma}_i))\ d\vec{O}$$

$$\underbrace{\mathcal{P}(\vec{\mu}, \boldsymbol{\Sigma}|\boldsymbol{\mathcal{O}})}_{P(A|B)} \propto \underbrace{\mathcal{P}(\vec{\mu}, \boldsymbol{\Sigma})}_{P(A)} \times \underbrace{\mathcal{L}(\boldsymbol{\mathcal{O}}|\vec{\mu}, \boldsymbol{\Sigma})}_{P(B|A)}$$

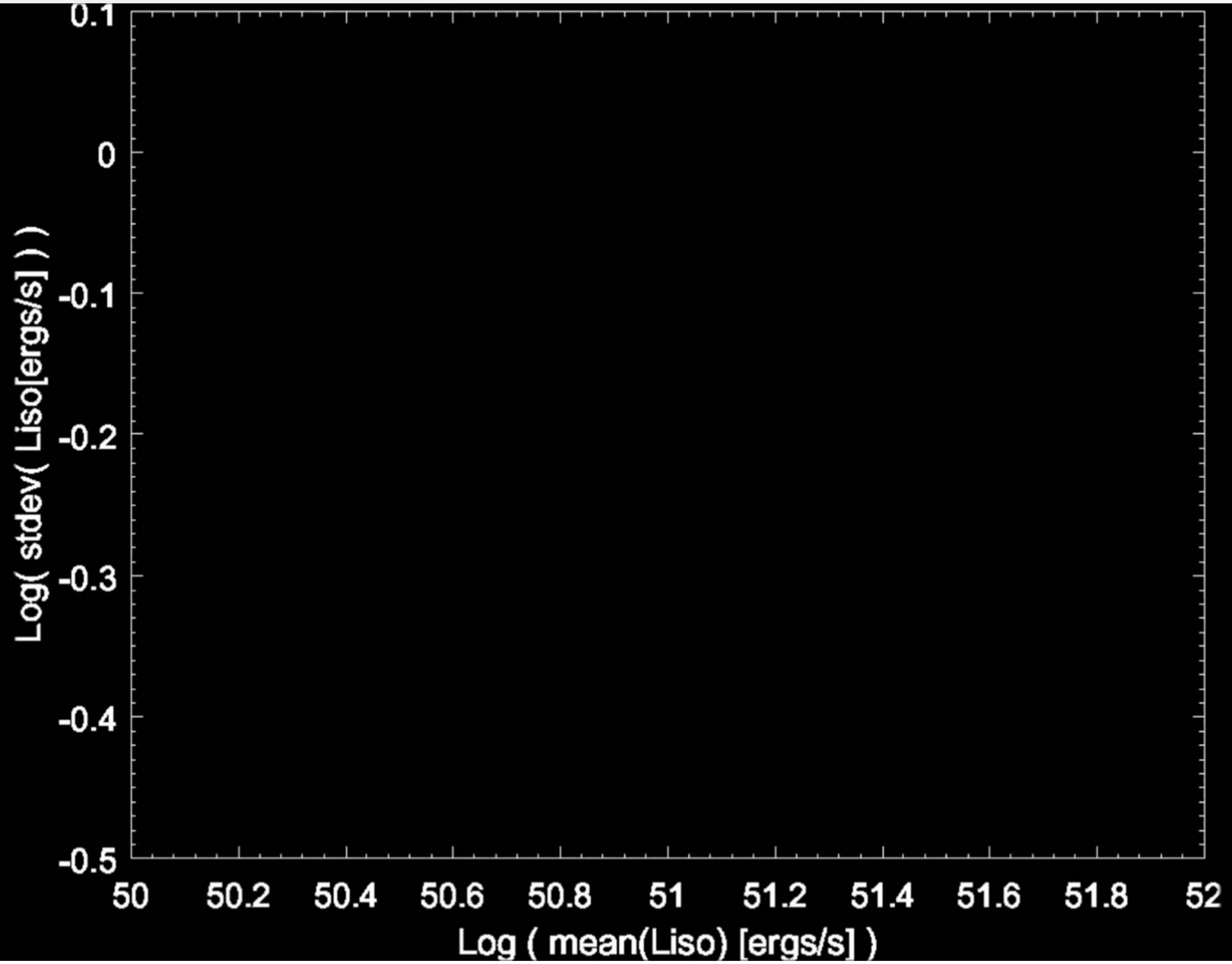
The 16-D parameter posterior density is sampled via an Adaptive Metropolis-Hastings Markov Chain Monte Carlo algorithm

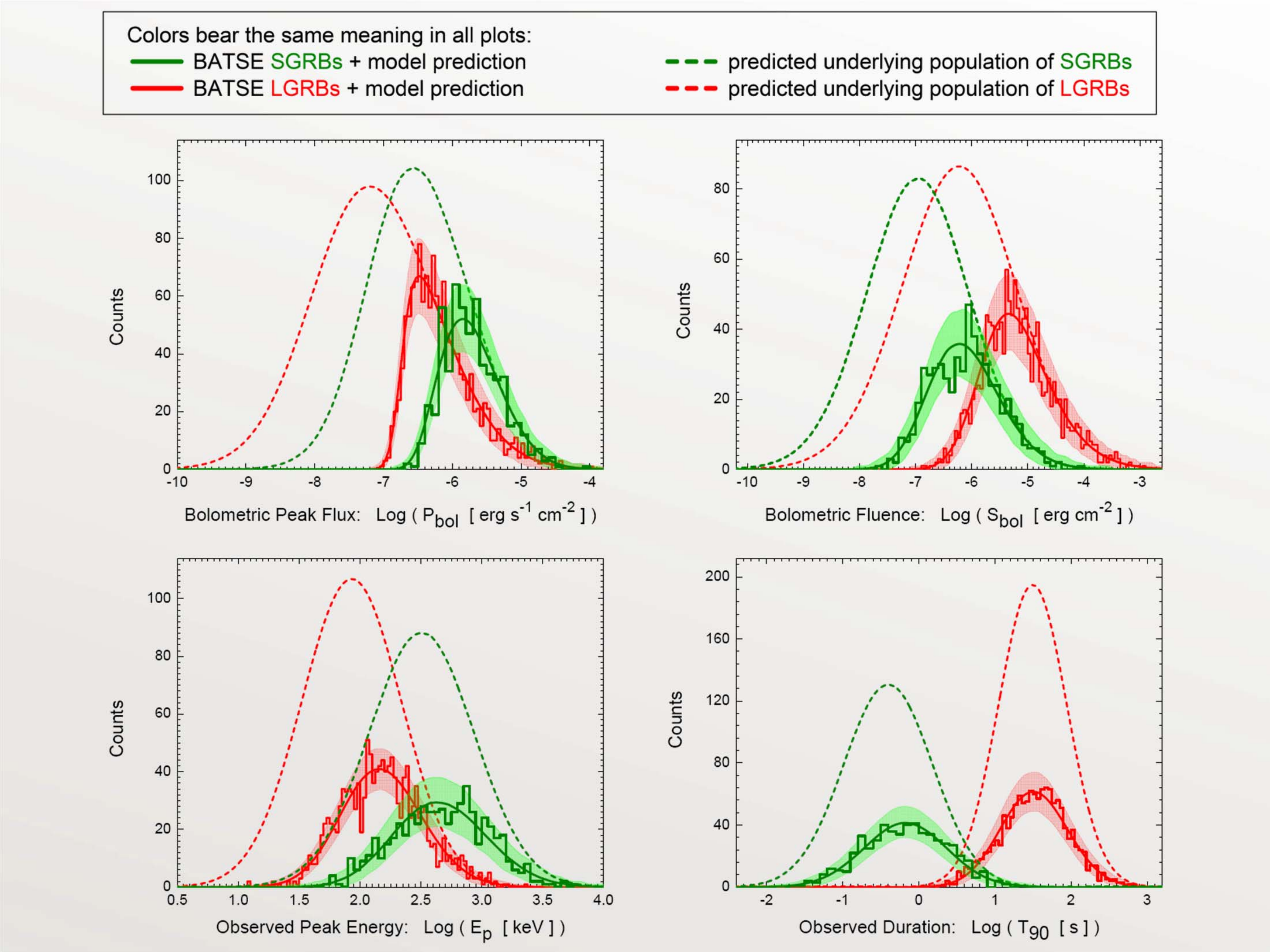
https://github.com/shahmoradi/grb_world

The posterior probability density of model parameters can be obtained from Bayes rule

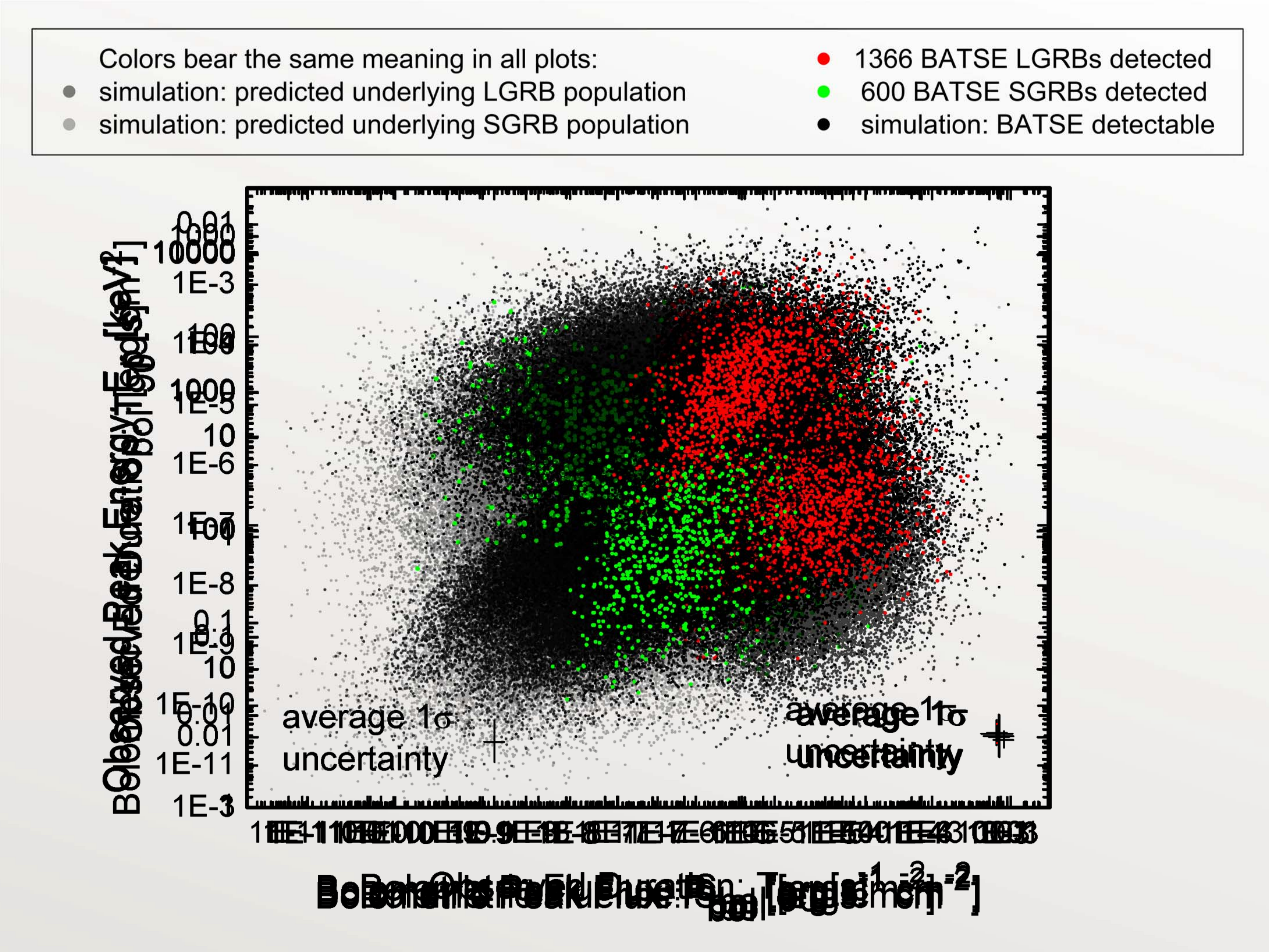


The posterior probability density of model parameters can be obtained from Bayes rule



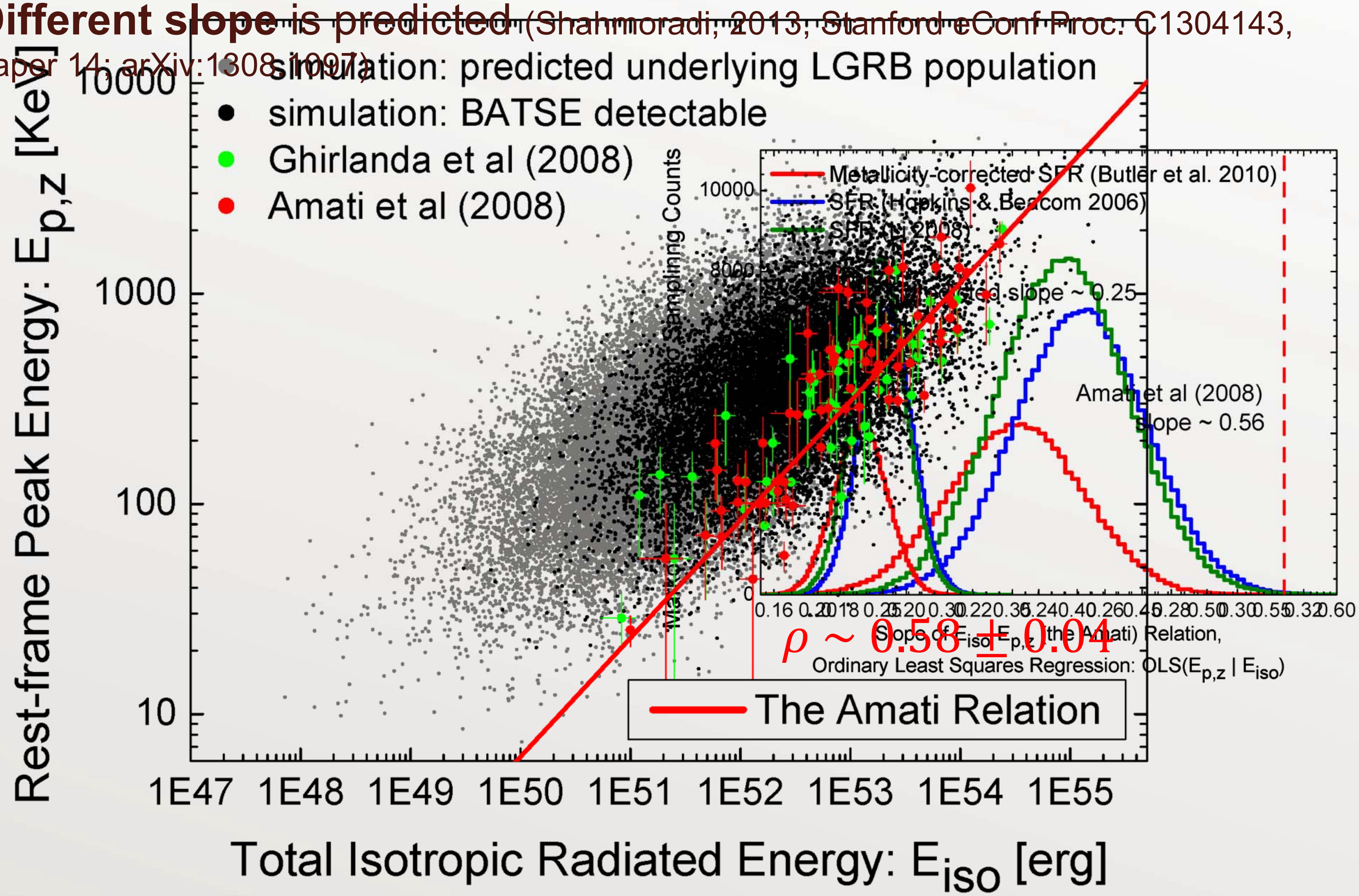


Colors bear the same meaning in all plots:
BATSE SGRBs + model prediction
BATSE LGRBs + model prediction
predicted underlying population of SGRBs
predicted underlying population of LGRBs
Counts
Bolometric Peak Flux: Log (P_{bol} [erg s^{-1} cm^{-2}])
Bolometric Fluence: Log (S_{bol} [erg cm^{-2}])
Observed Peak Energy: Log (E_p [keV])
Observed Duration: Log (T_{90} [s])

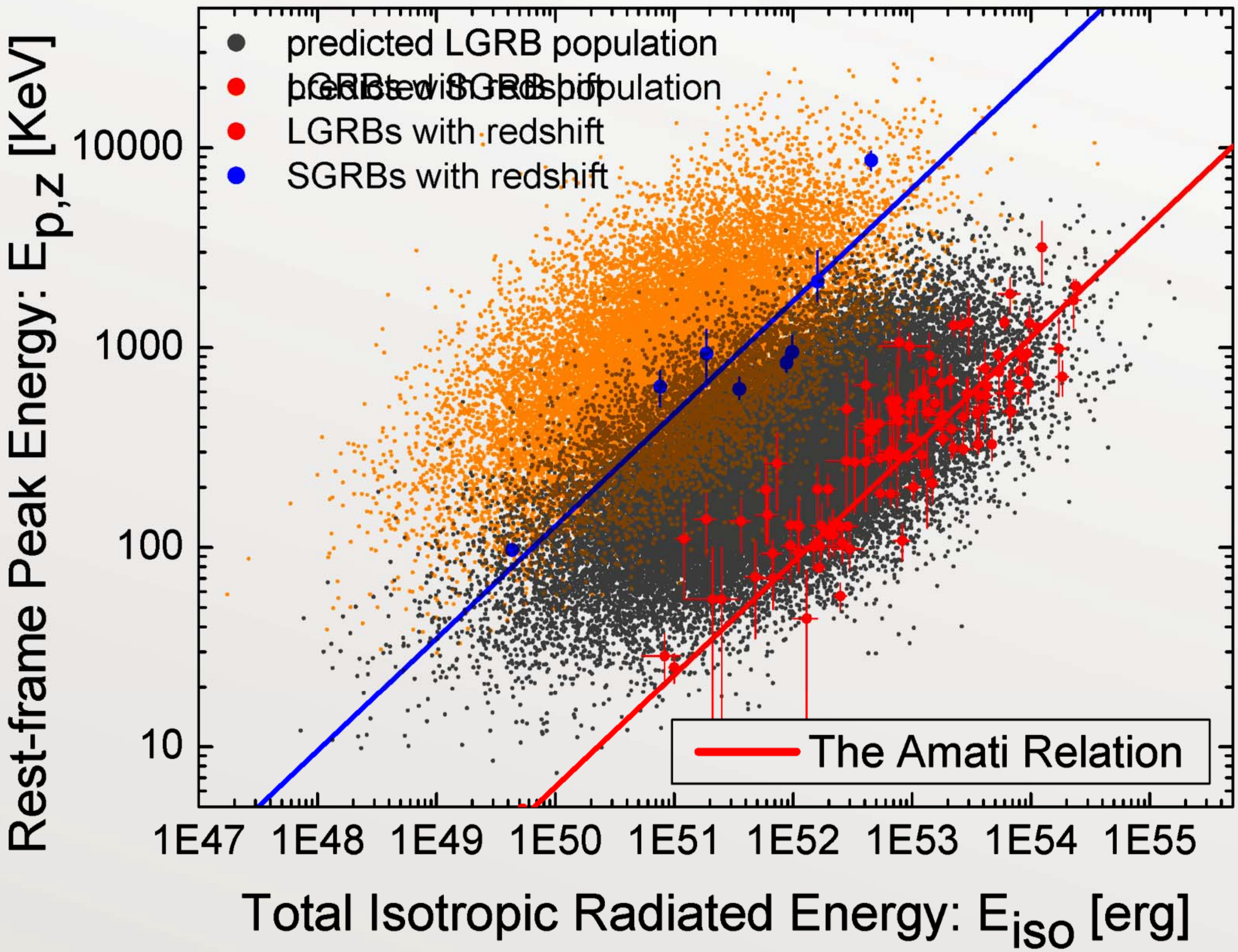

Colors bear the same meaning in all plots:
simulation: predicted underlying LGRB population
simulation: predicted underlying SGRB population
1366 BATSE LGRBs detected
600 BATSE SGRBs detected
simulation: BATSE detectable
average 1σ uncertainty
1E-3
1E-6
1E-8
1E-9
1E-11

The Amati relation

- **Larger dispersion** is predicted (Shahmoradi, 2013, ApJ, 766, 111)
- **Different slope is predicted** (Shahmoradi, 2013, Stanford eConf Proc. C1304143, paper 14; arXiv:1308.1097)



Short and long GRBs exhibit similar prompt correlations



Summary for GRB astronomers

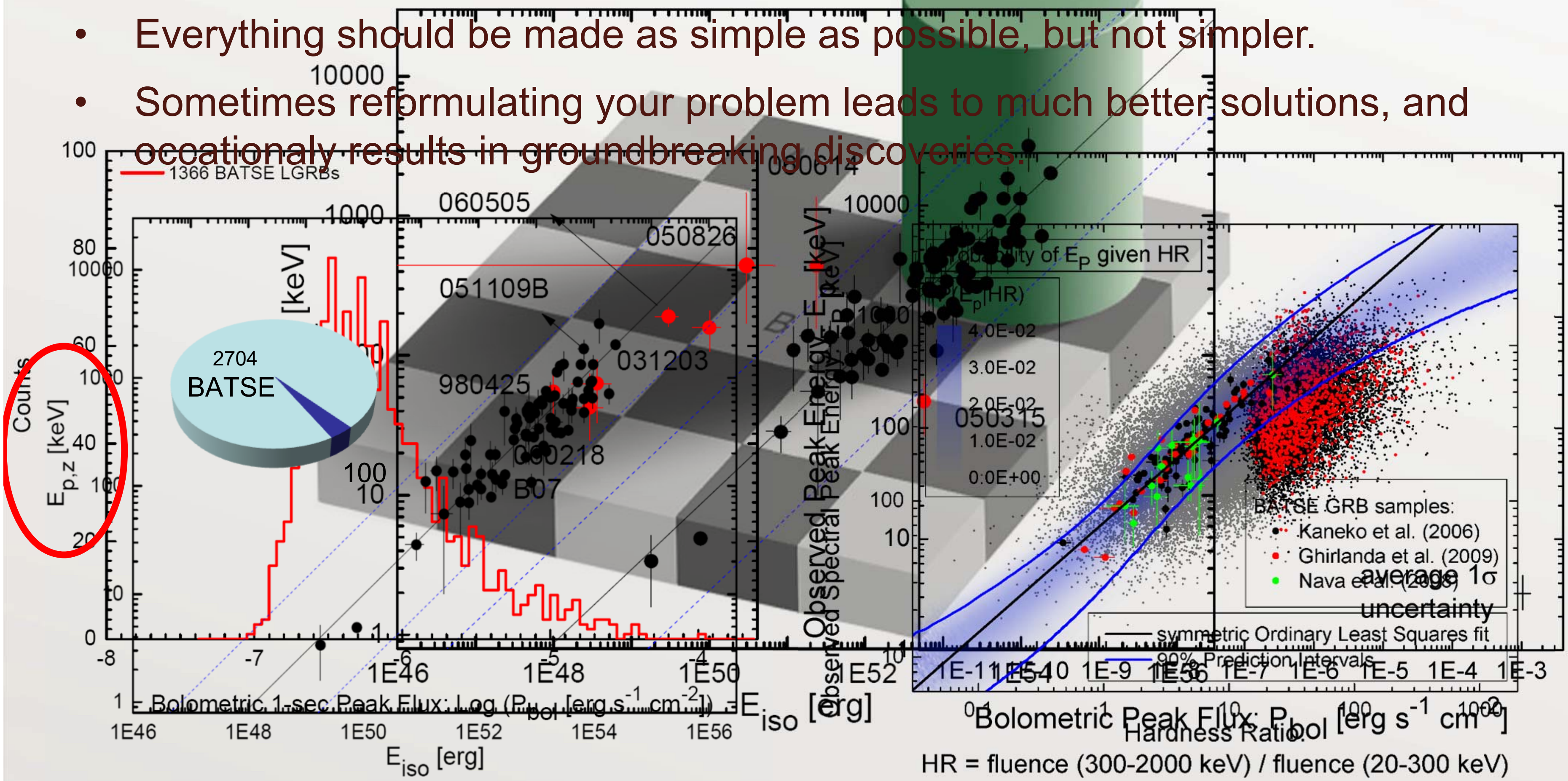
- Multivariate log-normal distribution provides good fit to BATSE short and long GRB prompt emission data *(peak luminosity, isotropic emission, intrinsic peak energy, intrinsic duration).*
- The Amati (E_{iso}-$E_{P,z}$) relation is confirmed, but with significantly **higher dispersion** and **shallower slope** of the regression line (0.25 vs. 0.55).
- Short GRBs exhibit very similar prompt emission correlations to long GRBs prompt correlations.
- BATSE Long GRBs data favor, though do not necessitate, a cosmic rate tracing metallicity evolution consistent with a cutoff $Z/Z_{\odot} \sim 0.2$–0.5, assuming no luminosity–redshift evolution.
- The proposed method provides the most accurate, as of today, method of GRB classification based on prompt emission data.

Further results on GRB energetics & correlations

- Shahmoradi, 2013, ApJ, **766**, 111
- Shahmoradi, 2013, Stanford eConf Proc. C1304143, paper 14; arXiv:1308.1097
- Shahmoradi & Nemiroff, 2010, MNRAS, **407**, 2075–2090
- Shahmoradi & Nemiroff, 2011, MNRAS, **411**, 1843–1856
- Shahmoradi & Nemiroff, 2009, AIP Conf Proc, **1133**, 425

Summary: Lessons learned for everyday life (scientific & non-scientific)

- Never underestimate human cognitive biases in scientific research and life in general
- If you obtain new data in your research that does not match your prior belief, do not discard it as bad-quality data.
- Everything should be made as simple as possible, but not simpler.
- Sometimes reformulating your problem leads to much better solutions, and occationaly results in groundbreaking discoveries.



What if there are better models of GRB rate than multivariate log-normal?

$$P(M_k|D) = \frac{P(D|M_k)P(M_k)}{\sum_k P(D|M_k)\,P(M_k)}$$

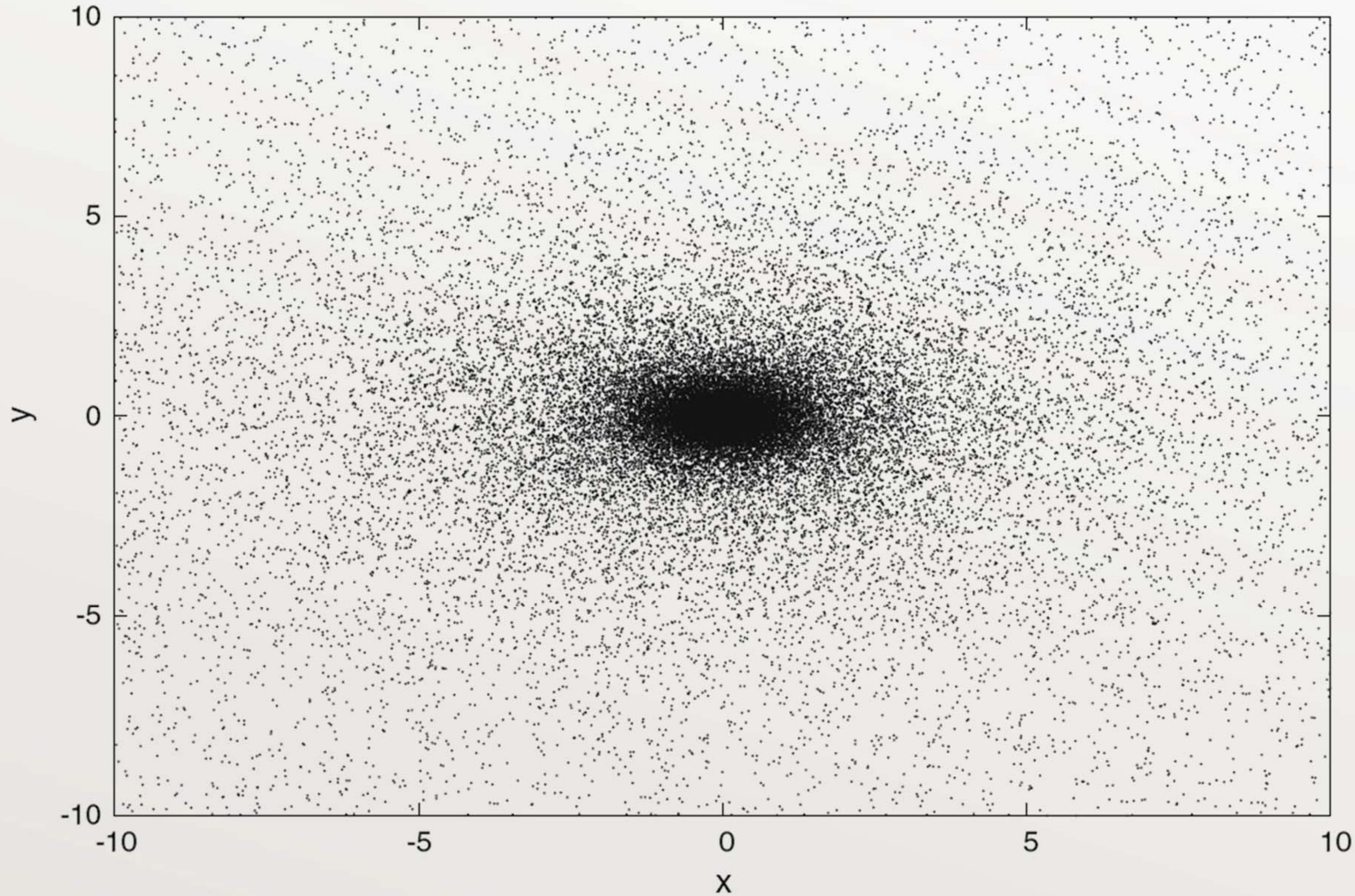
Marginal likelihood (evidence)

$$P(D|M_k) = \int P(D|\boldsymbol{\theta}, M_k)P(\boldsymbol{\theta}|\mathrm{M_k})\mathrm{d}\boldsymbol{\theta}$$

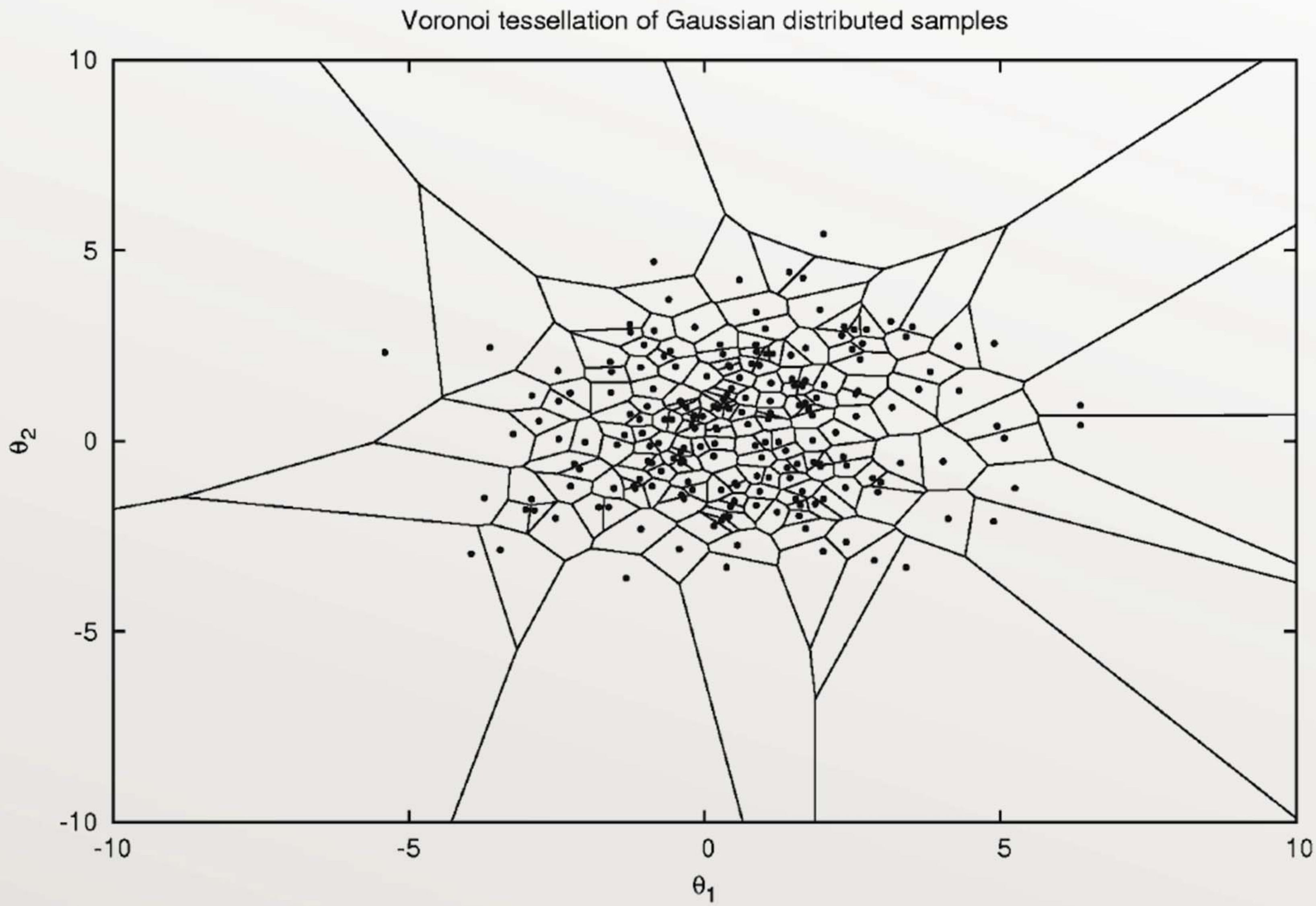
$$\frac{P(M_1|D)}{P(M_2|D)} = \frac{P(D|M_1)}{P(D|M_2)} \times \frac{P(M_1)}{P(M_2)}$$

Bayes factor

How to calculate evidence?



How to calculate evidence?



How do astronomers measure the expansion rate of the universe?

Recipe for measuring the expansion rate of the universe:

1. Assume a cosmological model.

2. Find a celestial object that has a known fixed luminosity (a **standard candle**) and measure its distance according to,

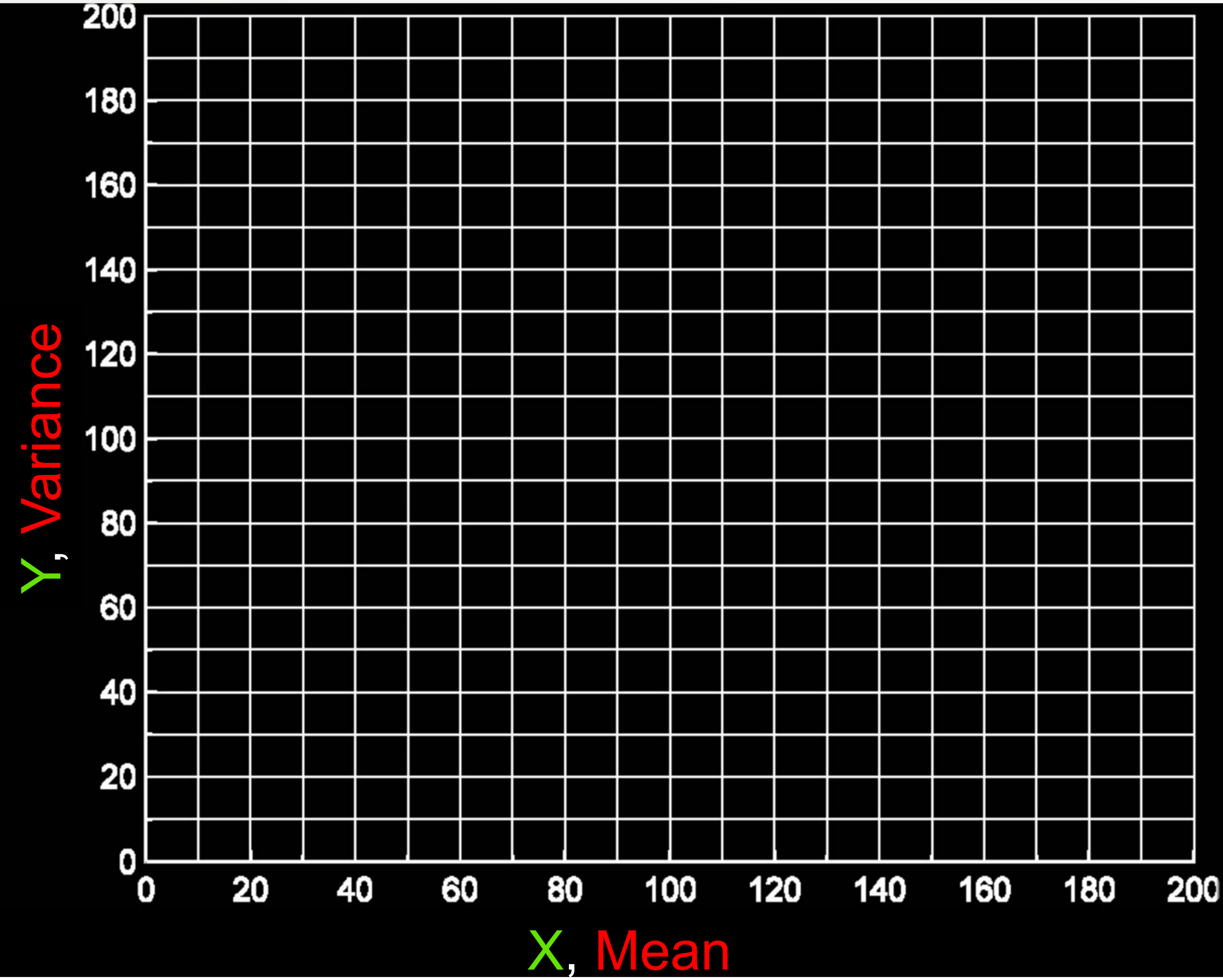
$$D_{L,obs} = \sqrt{\frac{1}{4\pi}\frac{Intrinsic\ brightness}{observed\ brightness}}$$

3. Somehow magically measure the redshift (z) of the standard candle. Then calculate,

$$D_{L,theory} = \frac{c}{H_0}(1+z)\int_0^z \frac{dz'}{\sqrt{(1+z')^3\Omega_M(z') + \Omega_\Lambda(z')}}$$

4. Now compare $D_{L,obs}$ with $D_{L,theory}$.

Hallmark of Poisson Stochastic Process: Equal mean and variance of sample



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  volume={451},
  number={1},
  pages={126--143},
  year={2015},
  publisher={Oxford University Press}
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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={Detection Threshold Effects on GRBs as a Cosmological Standard Candle},
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  volume={411},
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  pages={1843--1856},
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  title={A Multivariate Fit Luminosity Function and World Model for Long Gamma-Ray Bursts},
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  title={Classification and Energetics of Cosmological Gamma-Ray Bursts},
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