Our scientific debt to ***David Band***…
A brief survey of a remarkable career

Josh Grindlay
Harvard

Overview of David's science

- Thesis, and my first contacts with David
- From SS433 jets (and new insights) to the cores of AGN
- From explorations of optically thick, spherical, SSC models
- To expanding sources in jets…
- To the most remarkable jets of all: GRBs!
- Constraining GRB models, and how to observe them
- To help define *EXIST*
- And his legacy to GLAST/Fermi…

David’s Thesis…

NON-THERMAL RADIATION MECHANISMS AND PROCESSES

IN SS 433 AND ACTIVE GALACTIC NUCLEI

A thesis presented
by

David Louis Band

to
The Department of Physics
in partial fullfilment of the requirements
for the degree of

Doctor of Philosophy

in the subject of

Physics

Harvard University
Cambridge, Massachusetts

August, 1985

and Thesis Abstract (skim….)

Abstract

Studies of the jet emitting compact binary system SS 433 and the non-thermal synchrotron-self-Compton scattering process reveal features of the interaction of compact objects with their environments.

The *Einstein* MPC X-ray observations of SS 433 are best fit by a non-thermal power law spectrum where both the intensity and (energy) spectral index varied on a timescale of hours to days. Flares characterized by an intensity increase and a hardening of the spectral index are attributed (within the context of the slaved disk model) to accretion surges that occur at certain orbital phases in a binary with a Roche-lobe filling primary whose spin axis is misaligned with the orbital axis.

The synchrotron-self-Compton methodology in spherical geometries is refined, emphasizing both geometrical and spectral factors for both homogeneous and inhomogeneous sources. Electron and photon energy distribution cutoffs, as well as the high energy Klein-Nishina scattering cross-section, are considered in the spectral calculation. Physically reasonable variations on the standard model create observable breaks, spectral index changes, and peaks in the observed spectrum.

The spectra from radio quiet active galactic nuclei (such as Seyfert 1 galaxies and radio quiet quasars) can result from a non-thermal model with a "broken" power law electron distribution where synchrotron losses cause the distribution to steepen. The canonical source has a turnover at about 10^{12} Hz, and a broken synchrotron power law with a far infrared (energy) spectral index of $\alpha \sim .7$ and a near infrared spectral index $\alpha \sim 1.2$. The scattered spectrum with $\alpha \sim .7$ intersects the steeper synchrotron spectrum in the soft X-ray band. Observable radio emission originates in extended sources and jets outside of the core. Re-acceleration is required throughout the source. The flat hard X-ray spectra from Seyferts requires the scattering of optical and ultraviolet thermal photons.

Finally, the model of expanding sources (perhaps embedded in jets) is extended to included both continuous electron injection and inverse Compton X-ray production. Application of this methodology to SS 433 suggests that the radio flares require additional electron injection into the expanding sources in the jets, while the X-ray emission cannot originate in these expanding sources. Analogous to the sources within radio quiet quasars, a self-consistent non-thermal source within the binary can satisfy observational constraints.

David probed the "first ULX" source: SS433

- His model (following Avni et al and others) for "slaved disk" accretion and "Roche-lobe squeeze" explained the X-ray flaring (2X per orbit)
- His model (Band and Grindlay 1984) provided early evidence, still among the most convincing, that SS433 contains a stellar mass black hole (~8Msun)
- His work constrained the jet emission models and predicted the strong Fe line emission seen later with Ginga and then mapped with Chandra from the inner jets…

And went on to spherical, thick SSC sources

- SS433 was the warmup for bigger black holes: AGN, but radio quiet ones
- What happens when a central (spherical) source is “thick” to its own synchrotron (and then scattered, synchrotron-self-Compton) radiation? Band and Grindlay (1985) (i.e. *David…*) provided the first insights
- His formalism for spherical geometries (like “spherical cows”) was the starting point for more complex models that could be applied to expanding bubbles in non-spherical geometries – Jets.
- His formalism showed his physical insight and *mathematical acuity*, which served him throughout his career

Applications to AGN

- David's 1986 paper on SSC models for radio quiet AGN provided new insights into the emission cores of Seyfert I galaxies and then recent *IRAS* to *Einstein* (IR – X-ray) spectra – e.g. Mkn509 below

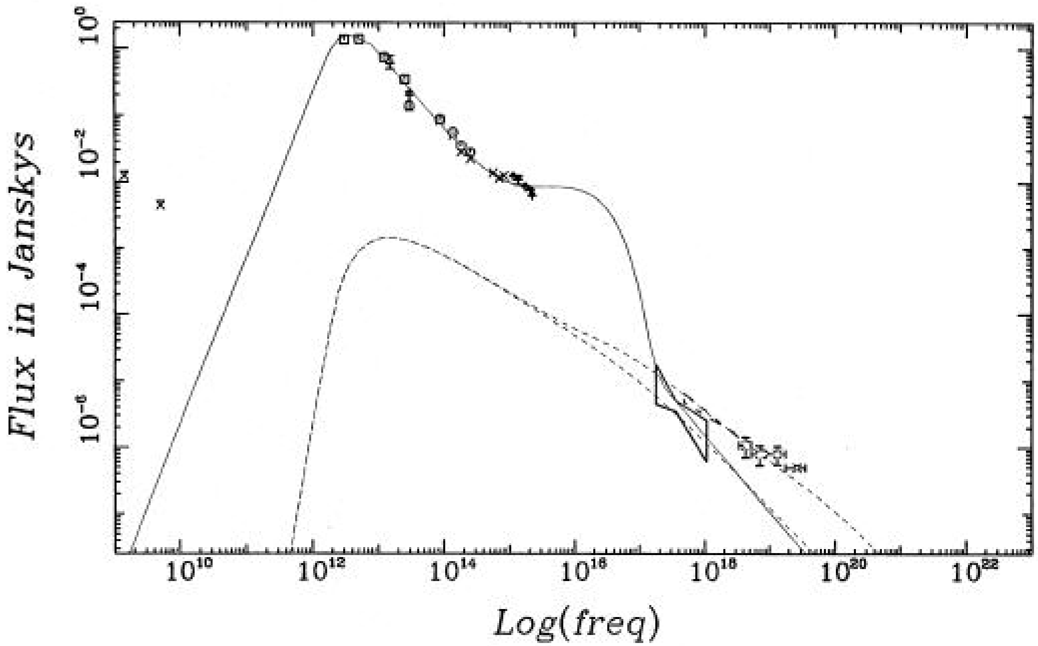


FIG. 3a

And on to expanding sources in Jets…and back to SS433

- The SS433 flares due to injection of expanding blobs into the jet:

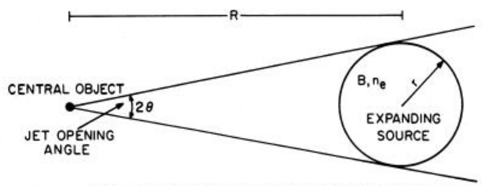


FIG. 1.—Sketch of the geometry assumed in the model. Note that in sources with two-sided jets there may be two expanding sources.

- And resulting SSC spectra:

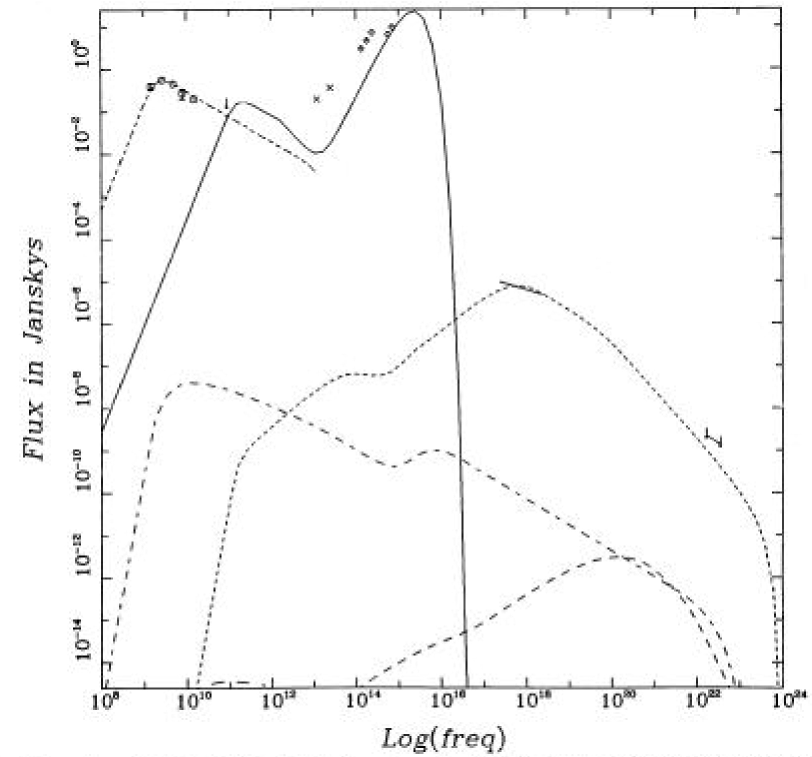
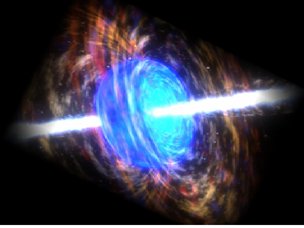
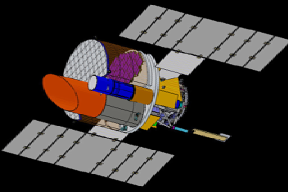


FIG. 3.—Model and observations of SS 433 on 1979 October 5.21. The model consists of a blackbody source in the center of the binary system ($L = 2.6 \times 10^{39}$ ergs s^{-1}, $T = 4 \times 10^4$ K) surrounded by a compact nonthermal source (*solid infrared through ultraviolet curve*) and expanding source in the approaching jet (*dash-dot-dot radio curve*) at a distance of 2.13×10^{15} cm from the central object. The once-scattered spectrum from the expanding source (*dot-dash curve*) is significantly below the scattered spectrum from the central source (*small dashed curve*), and is exceeded at high frequencies by the twice-scattered spectrum from the central source (*large dashes*). Radio observations are from SGJG, while 90 GHz upper limit is from Landau, Epstein, and Rather (1980). *IRAS* 12 and 25 μm observations were provided by Gillett (1985, private communication). The near-infrared and optical observations from Giles *et al.* (1980) were dereddened assuming $A_V \approx 7.5$. The *Einstein* 1–10 keV observations are from GB84, and the *COS B* 70–150 MeV upper limits were provided by Bignami (1981, private communication). The radio, infrared, optical, and X-ray observations are all from 1979 5 October. Parameters of the central source are $B = 65.1$ G, $r = 5.66 \times 10^{11}$ cm, $dn = 4.21 \times 10^7 \gamma^{-2.2} d\gamma$ cm^{-3} for $10 \leq \gamma \leq 100$, and $dn = 4.21 \times 10^6 \gamma^{-3.2} d\gamma$ cm^{-3} for $100 \leq \gamma \leq 10^4$. Parameters of the expanding source are $dn = 4.72 \times 10^2 \gamma^{-2.2} d\gamma$ cm^{-3} for $1 \leq \gamma \leq 2600$, $B = 0.697$ G, and $r = 7.10 \times 10^{13}$ cm. Emissions from the expanding jet source are blueshifted by the relativistic factor $D = 1/(1 + z) = 1.109$.

Launched David into the Jet world of GRBs…

- V/Vmax tests…
- Flash photoionization….
- Limits on those “Ginga lines” (that were never confirmed)….
- And GRB-mission sensitivity calculations leading to EXIST





EXIST

Surveying Black Holes from the Early Universe to Local Galaxies

David was a key member
of the ***EXIST Team***

Survey and ***Identification*** (with redshifts) of Black Holes on all scales:
High-z GRBs, obscured/dormant AGN & the Transient Universe

To use the earliest (stellar mass) BHs as Cosmic Probes of the Early Universe and study BHs over space & time

Under Decadal Survey Review (Astro2010) as a joint US-Italy mission

What is *EXIST?*

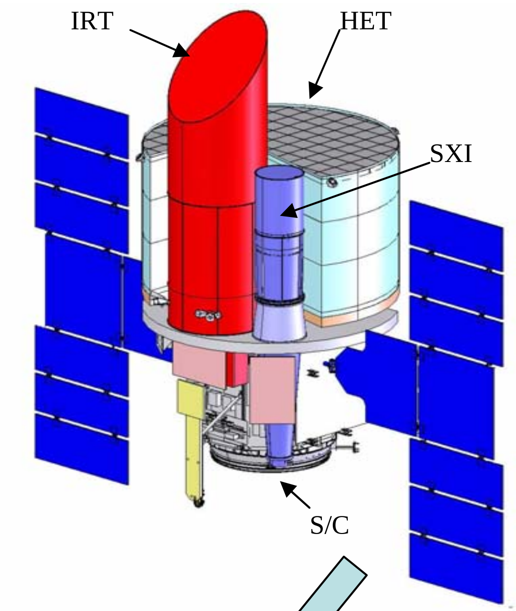
- A *Medium Class Mission* (~$800M) to conduct the most sensitive full-sky survey for ***Black Holes*** on all scales (stellar to supermassive)

- A leading candidate to be the ***Black Hole Finder Probe (BHFP)*** as one of the 3 *Einstein Probe* missions (hopefully in c. 2017, next after JDEM)

- A mission completing a study for the ***Astrophysics Strategic Mission Concept (ASMC)*** *Study* program, in preparation for review by the *Astronomy/Astrophysics Decadal Survey (Astro2010)*

- A wide-field (90^o) **hard X-ray (5-600 keV) imaging** (2 arcmin resolution) telescope surveying/monitoring full sky every 3h *plus* a 1.1m **optical-IR telescope** and contributed (Italy) **soft X-ray imaging (0.1-10keV) telescope** to obtain identifications, redshifts and diagnostics of black holes, transients & extreme objects for followup study by **Fermi, IXO, JWST, LSST and LISA**

A Hard X-ray, full-sky, deep imaging Survey and IR/X-ray followup is required for the Black Hole Finder Probe to *EXIST*



HET at ~zenith ***scans*** at orbital rate & ***points*** **IRT**/**XRT**/**HET** to GRBs within ~100s

HET: CZT detector arrays + mask: 5-600 keV **$4.5m^2$ tiled CZT**, **coded mask** images 90^o diam. FoV, 2' resol. & <20" positions; BGO rear shield (0.2-2MeV)

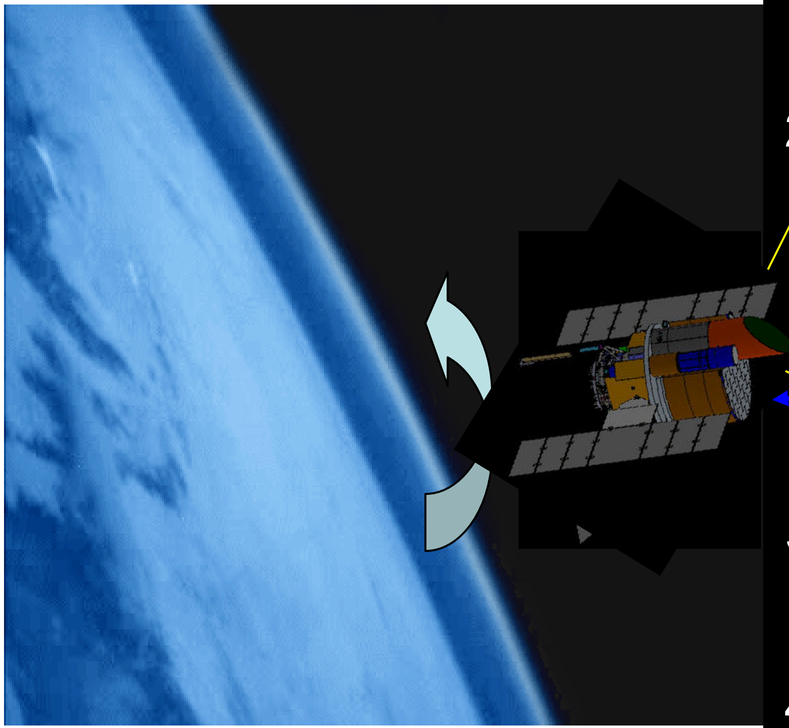
IRT: 1.1m; cooled (-30C) (dichroic: 0.3-0.9μm (HyViSI) and 0.9–2.3 μm (NIRSPEC)

SXI: 0.6m; Italy/ASI contributes upgrade of *Swift/XRT: **S**oft **X**-ray **I**mager* (0.1-10keV (CCD))

The *proposed (to Astro2010)* ***EXIST*** mission:

- ***2y full sky survey:*** ±20deg *Zenith-pointed* **scanning**, 2sr FoV, *full-sky ea. 3h*.
- ***3y followup IDs:*** **IRT/XRT/HET** **pointings** for IDs, redshifts, spectra & timing

How does ***EXIST*** operate?



1. Zenith (+/-~30°) **scan** of 90° FoV of HET at orbital rate to cover ~half-sky each orbit

2. Imaging in 90° FoV detects Gamma-ray burst (GRB) -- or variable AGN or transient

3. ***EXIST*** slews S/C onto GRB for IRT imaging ID and spectrum (optical + IR) for redshift

4. Pointing for 1-2 orbits to measure structure in distant Universe; HET measures spectrum & variability of target *and* continues Survey

5. Resume scan (years 1 & 2) or new target

Hard X-ray Sky

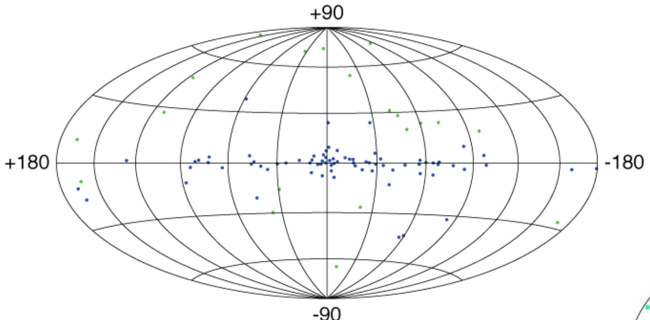
- **Hard X-ray (10-600 keV) sky not yet surveyed to ROSAT sensitivity. *EXIST* would be ~10X more sensitive than *Swift* or *INTEGRAL* and cover full sky**

- ***EXIST* will detect ≥4 x 10^4 sources, ≤15″ positions, 5-600 keV spectra**

- ***EXIST* would provide unique temporal survey: *full sky imaging every 2 orbits***

2000 Hard X-ray Sky

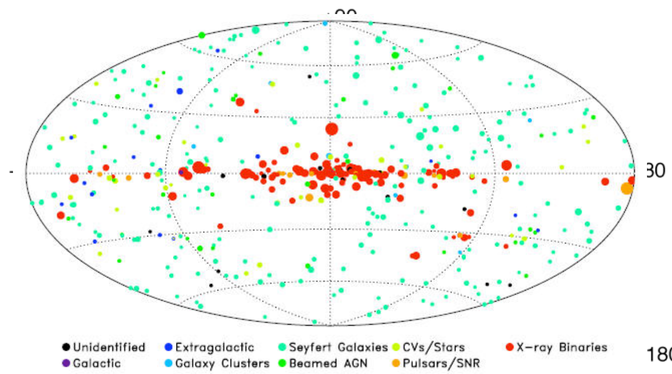
HEAO-1, BeppoSAX



~100 sources

2010 Hard X-ray Sky

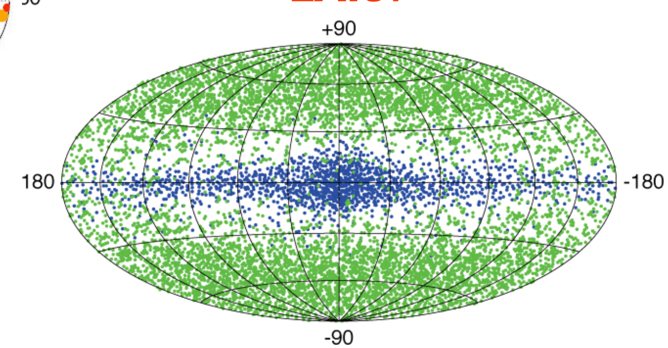
Swift (& INTEGRAL)



~600 sources

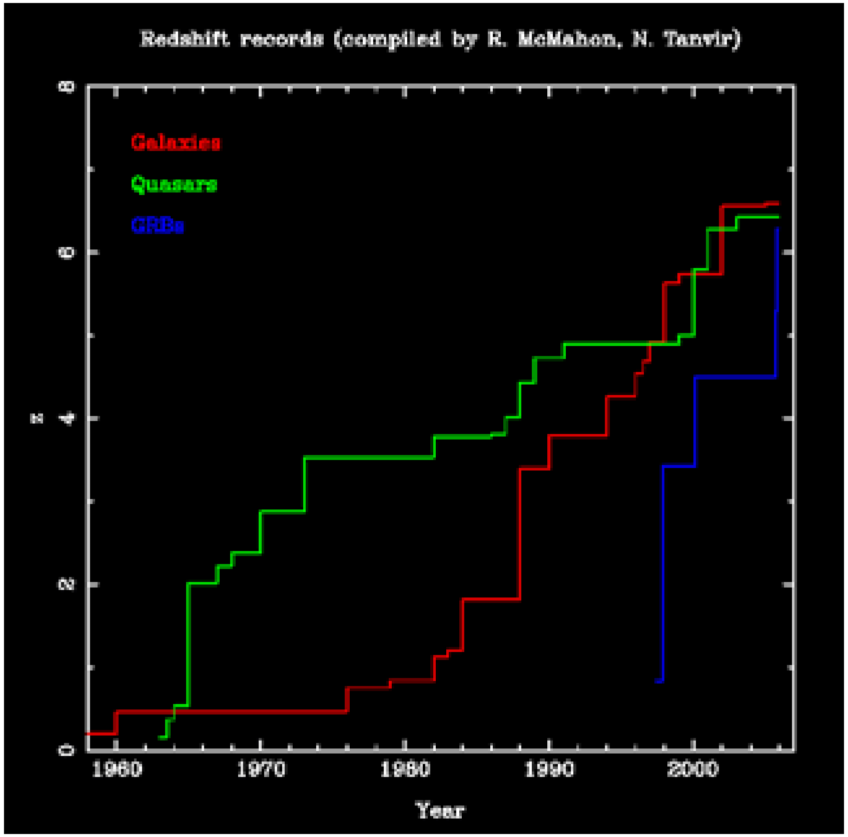
2017(?) Hard X-ray Sky

EXIST



~40,000 sources

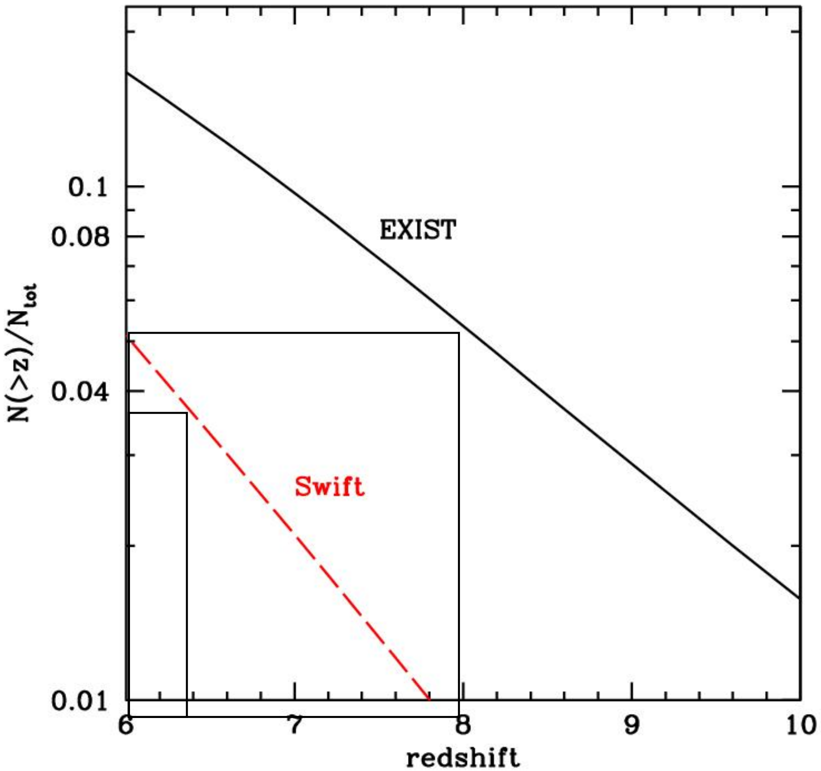
GRBs must *preceed* QSOs: highest-z stellar Probes



***Outdated* record redshift vs. time: GRBs clearly outpace AGN for most effective high-z probes!**

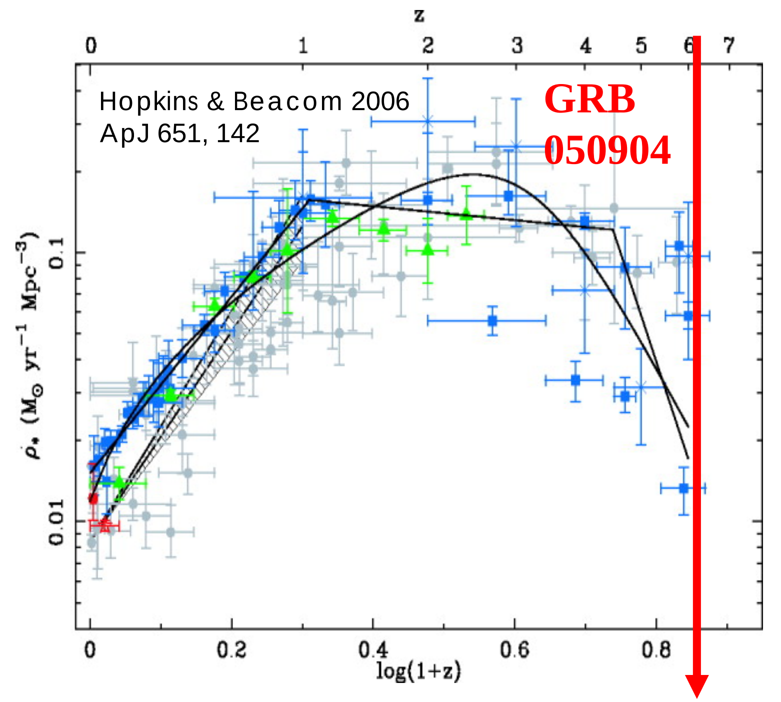
- *Swift* GRBs at z = 6.3, 6.7 and recent record GRB090423 at z = 8.2! *GRBs **are detectable** out to at least z ~8-10 and early Pop II & possibly even PopIII?*
- *Swift logN-logS* for optically **Dark Bursts** suggests high z? (Dai 2008)
- Broader energy band, higher sensitivity & FoV needed for large sample at z ≥ 8-10
- IR from space needed for z ≥7 since Ly-dropout then in NIR & spectra less sensitive from ground
- GRBs provide "back-light" for IR spectroscopy of host ISM & IGM gas. *Measure galactic structure (vs. z) back to epoch of re-ionization (EOR)*

P1: *EXIST* GRBs *probe stellar universe to z ≥ 10*



Predicted *fractional* GRB rates *above* z vs. z for *EXIST* vs. Swift/BAT based on Salvaterra (2009). *EXIST will detect ~600 GRBs/y and thus ~90/y at Z > 6 and thus ~0.055 x 600 = <u>33 at z >8 per year</u>!*

Swift detects ~100 GRBs/y and now ~450 GRBs. It Should detect ~0.04 x 450 = 18 at z >6 and has now detected 3, suggesting most are missed.

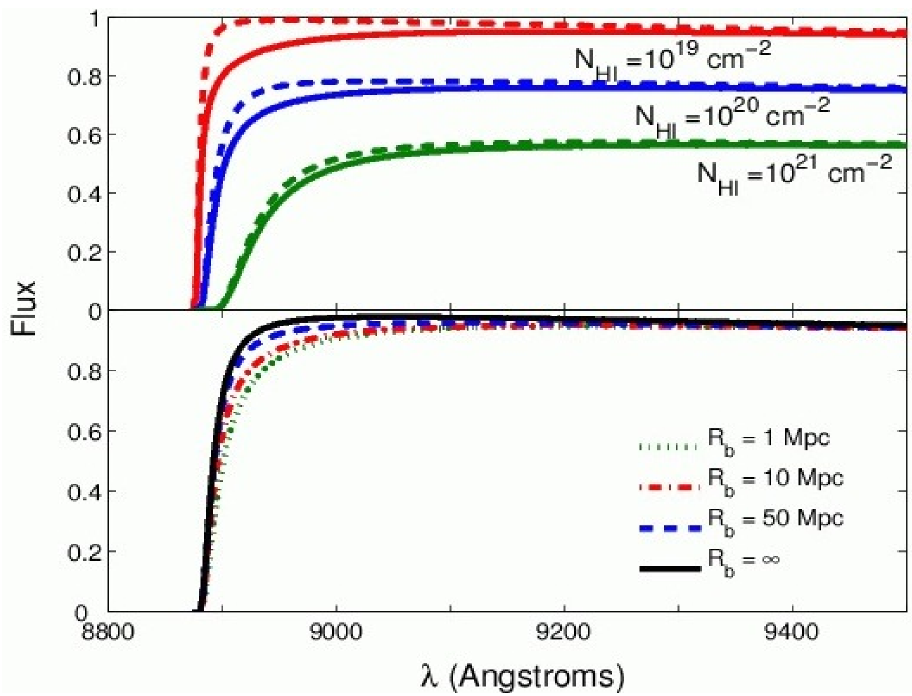


***EXIST* GRBs vs. z will probe the star formation rate (SFR) vs. z at highest redshifts, and constrain/measure Pop III.**

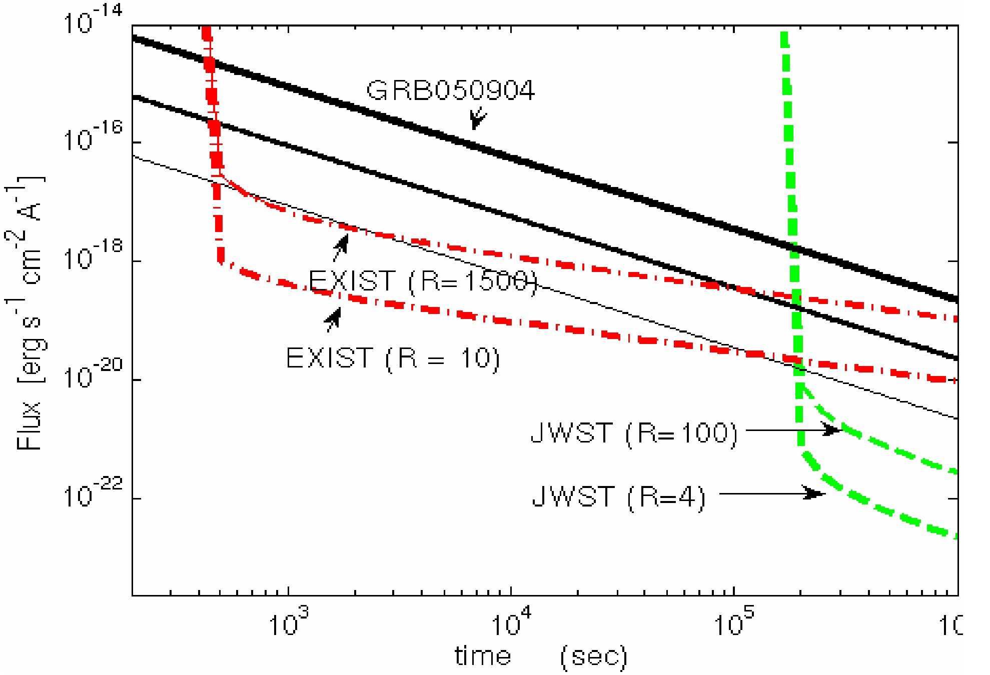
***EXIST will* probe:**

EXIST IRT spectra (R = 30) in 300-1000s: AB(H) ~23-24

2 VIS + 2 IR bands enable GRB redshifts out to z ~20(!)



Sensitivity of Ly-break *shape* to local IGM & EOR



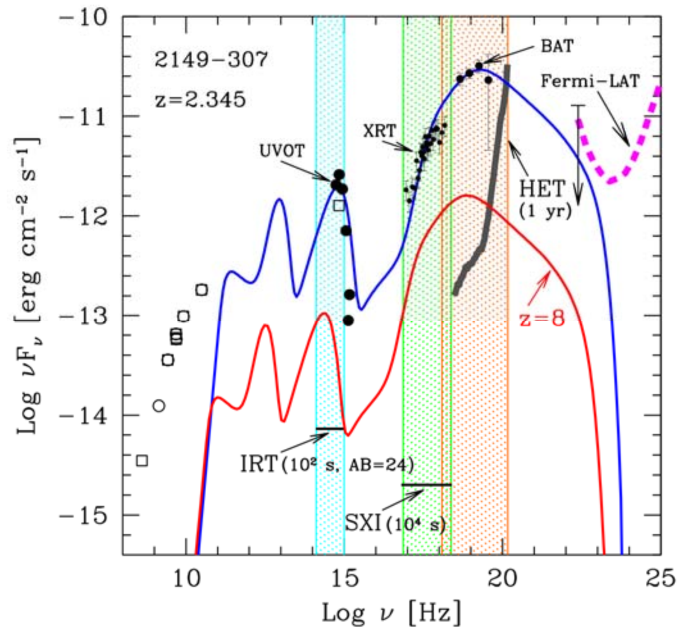
IRT vs. JWST for GRBs 1X, 0.1X and 0.01X flux of GRB050904.

- **IRT spectra (R ~3000) for AB(H) ~18-20 in 2000sec exp. *simultaneously* for optical (0.3-0.9μm) and IR (0.9-2.1 μm): Ly profiles for EOR studies of high-z IGM**

- **Simulations: *>75% of EXIST GRBs would have z measured* ; >450 GRBs/yr with measured z. Thus N(z>8) ~25/y and N(z>10) ~7/y for 5y mission total N(z>10) ~35!**

EXIST could extend Blazar surveys to z >4-8

- Blazars are the AGN analog of GRBs: persistent, extreme-beamed and exceptionally luminous and variable
- Understanding their formation and evolution requires deep full sky samples with sensitivity to rapid variability
- ***EXIST*** could detect the Blazar 2129-307 detected by Swift/BAT, XRT, UVOT (see Fig.) out to z ~8. *This would constrain epoch of formation of first SMBHs!*
- Sensitivity for detection and variability study with ***EXIST***/HET exceeds Fermi/LAT



IRT and SXI sensitivities allow short observations during HET survey or pointings. IRT measures redshifts directly for Blazar survey

David will be remembered….

- As a great scientist

- As a conscientious Team player

- As an exceptional analytic thinker

- And as a wonderful Colleague

I will always miss him….