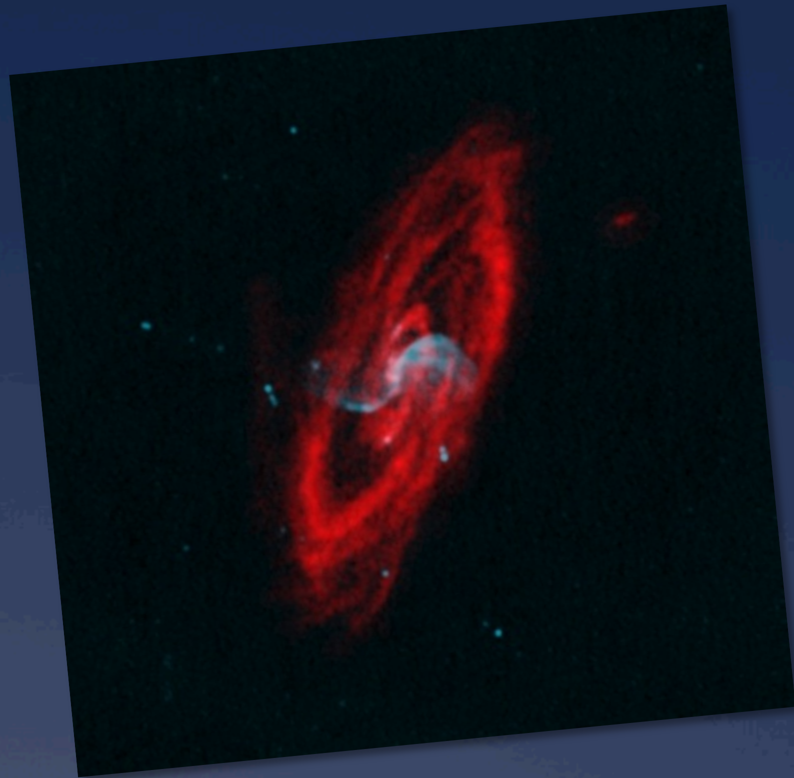


Carole Mundell

THE ROYAL SOCIETY

Astrophysics Research Institute
Liverpool John Moores University

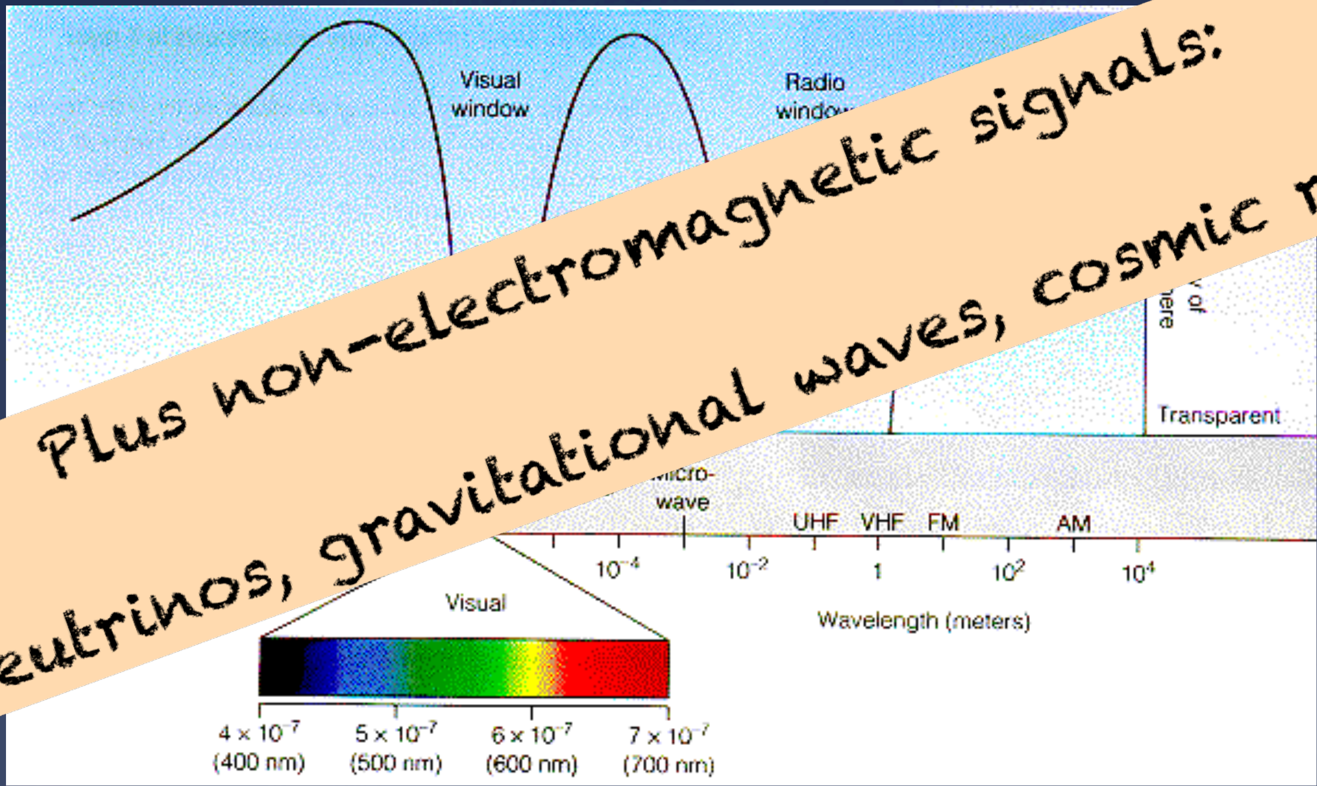
The Dynamic and Explosive Universe

Liverpool, Oct 2013

Black-hole Driven Accretion

* Accretion and jet production
* Stellar mass black holes
  * Gamma Ray Bursts
  * Magnetic fields
* Supermassive black holes
  * Host galaxy – inflow and outflow
  * Flares and activity timescales
* Tidal disruption events – a missing link?

Electromagnetic Spectrum

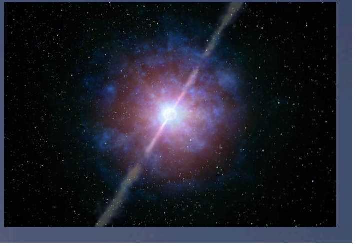


Plus non-electromagnetic signals:
Neutrinos, gravitational waves, cosmic rays

- Black-hole driven systems emit radiation across the electromagnetic spectrum

Localisation and Response

* Identification and localisation
* Trigger and response
* Classification and distance
* Multi-messenger follow-up
* Gamma ray bursts as case study…

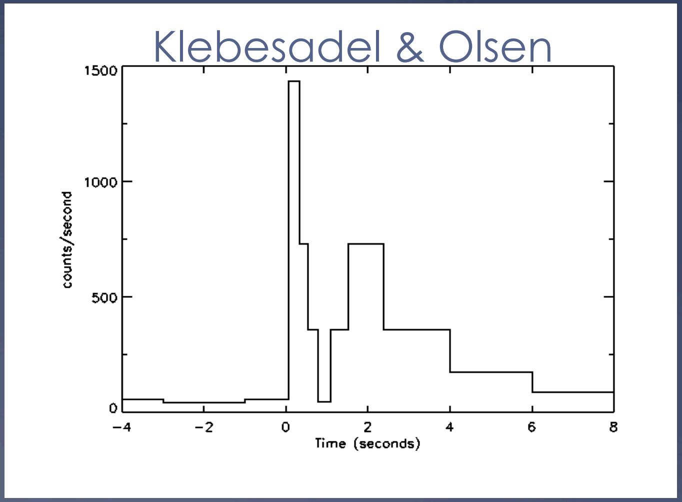


Scientific Motivation

- Extreme physics
  - Strong gravity
  - High Lorentz factors
  - Large magnetic fields
  - Fundamental physics
- Jet physics/emission mechanisms
- Most distant objects in the Universe
- Rapid timescales – real-time observing!

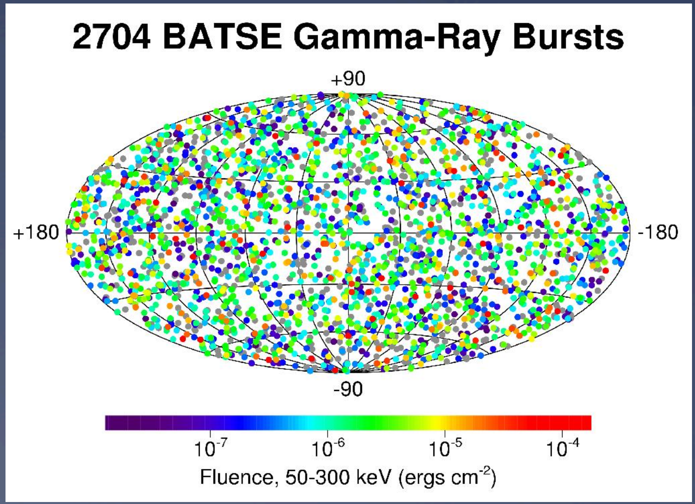
A Brief History of GRBs…

- Discovered by military satellites in 1960s
- Reported in 1973 but remained mysterious - unlike quasars/active galaxies and pulsars
- BATSE on CGRO provided first statistically-useful sample

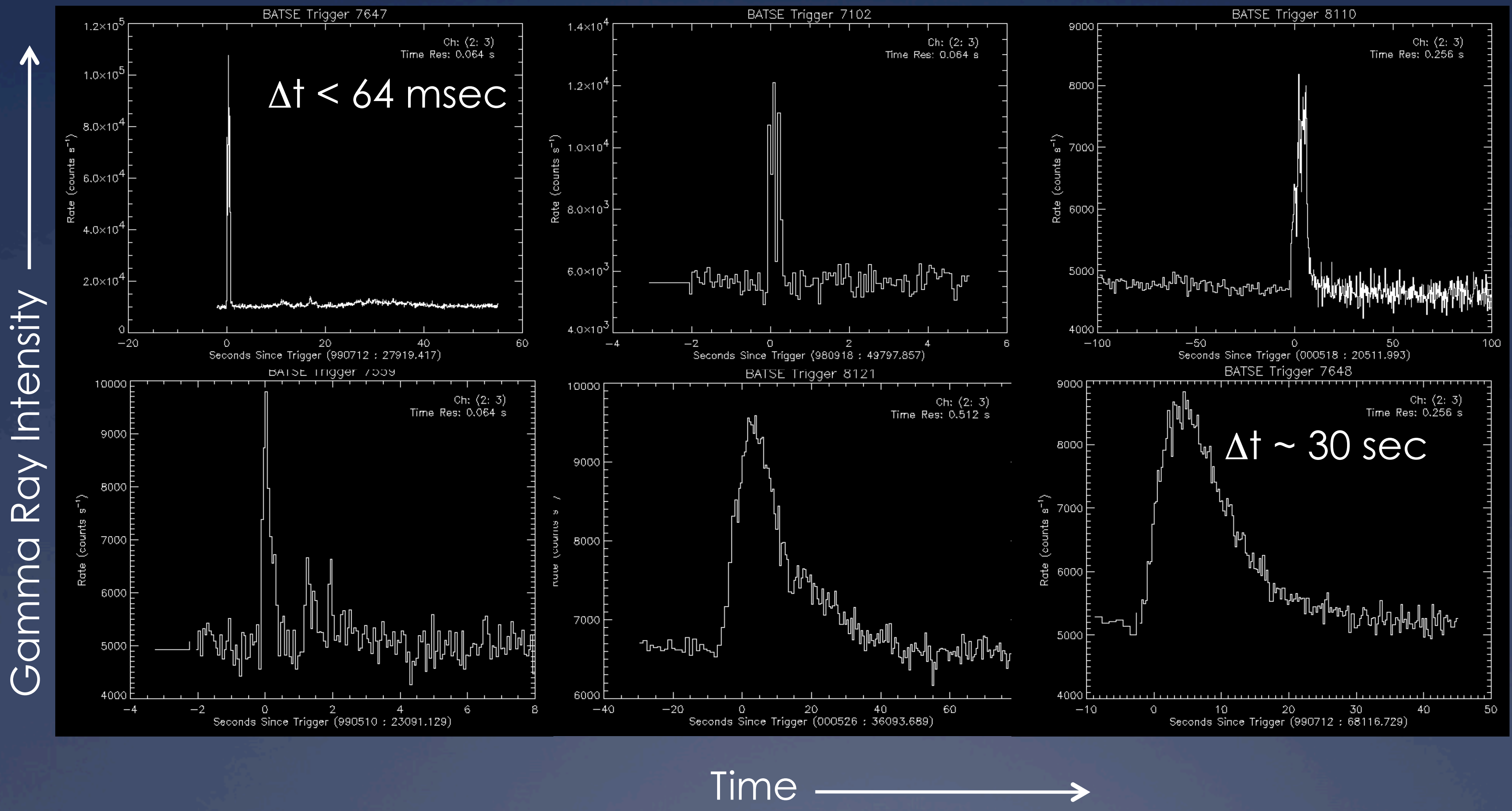


Where and when…

- Discovered by military satellites in 1960s
- Reported in 1973 but remained mysterious - unlike quasars/active galaxies and pulsars
- BATSE on CGRO provided first statistically-useful sample
- Sky distribution uniform
- Distance unknown
- Variety of γ-ray profiles

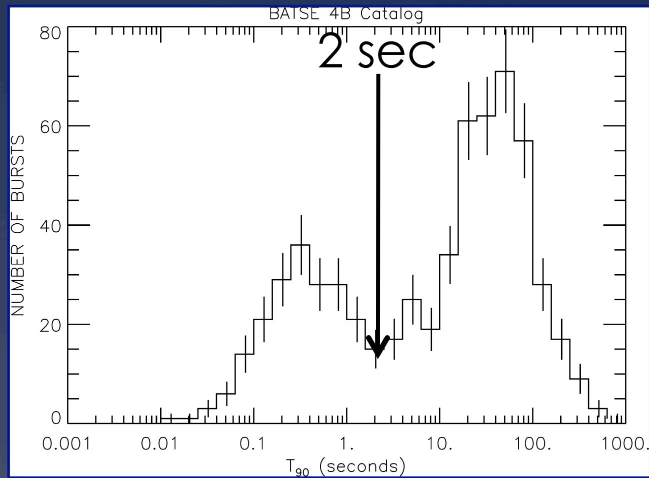


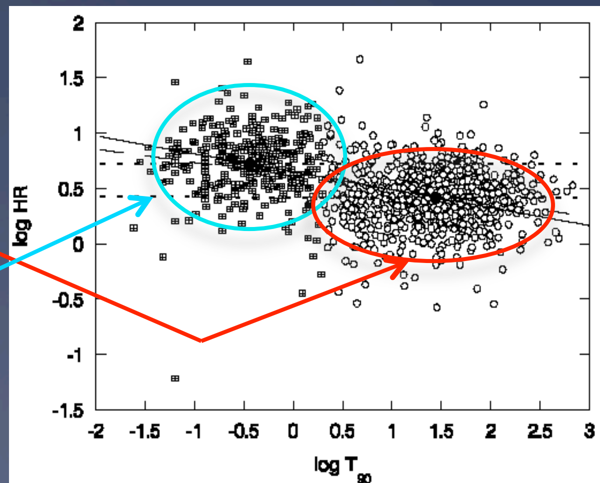
BATSE Light Curves



Long and Short GRBs

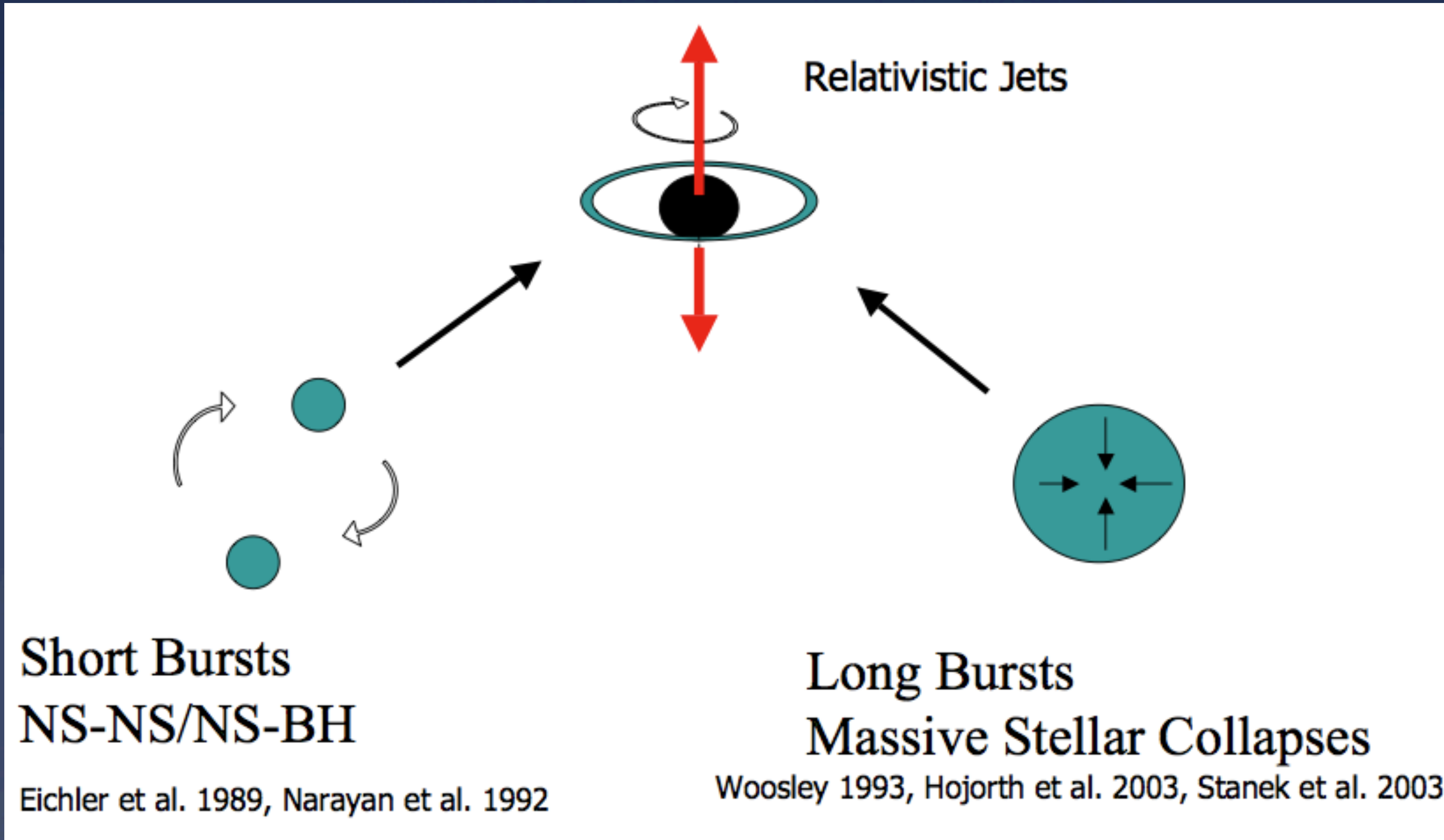
- Synchrotron spectrum
- Power law can extend to GeV
- Bimodal distribution of durations;
  - Two broad peaks at ~0.3 & ~40 s (minimum @ ~ 2s)
  - Hardness Ratio (HR32): fluence ratio in (100-300 keV)/(50-100 keV) bands
- Two categories: 'long, soft' and 'short, hard' bursts





(Kouveliotou et al. 1993)

GRB Progenitors



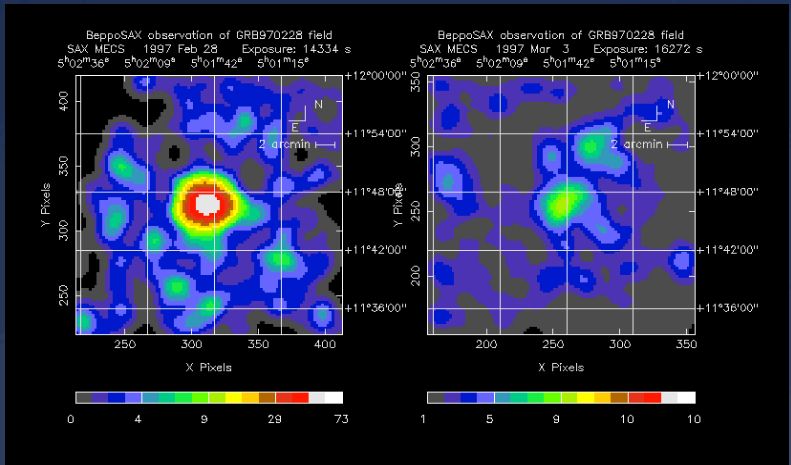
Kobayashi 2010

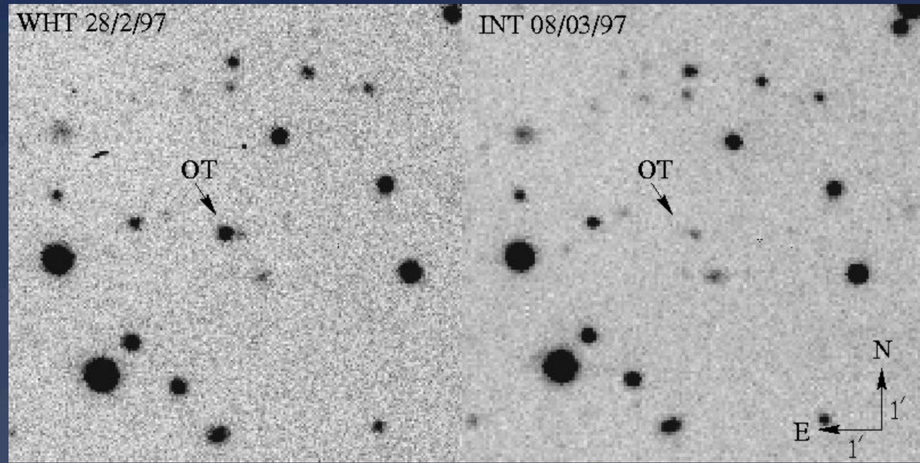
The Great Debate - 1995

- Lamb-Paczynski debate
- Washington 1995

- Distance scale to GRBs unknown - likened to uncertainty over distance to ‘spiral nebulae’ - likened to Shapley-Curtis debate of 1920
- Galactic origin seemed likely !
- Better localisations needed to resolve debate

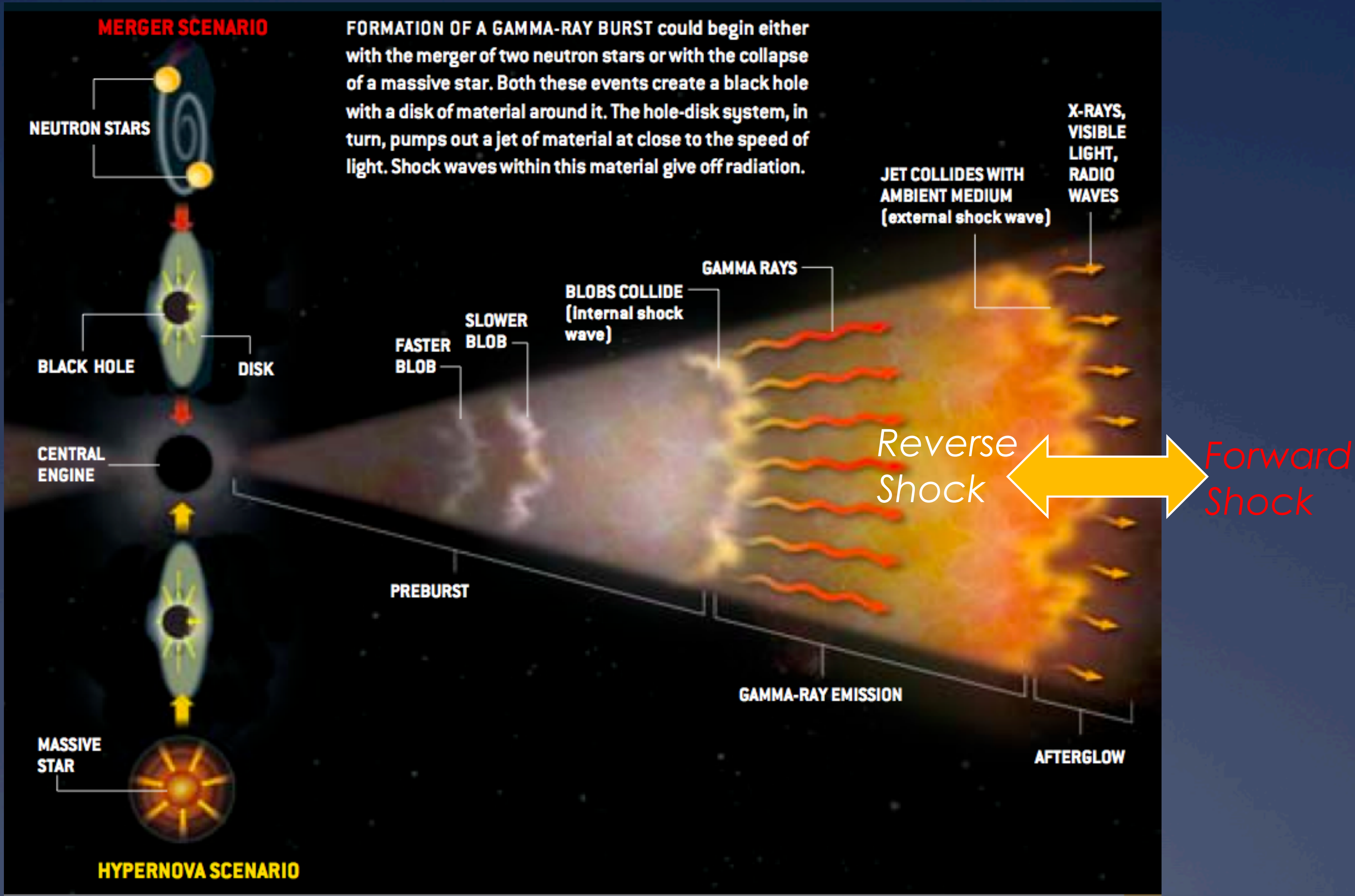
The First GRB Afterglow



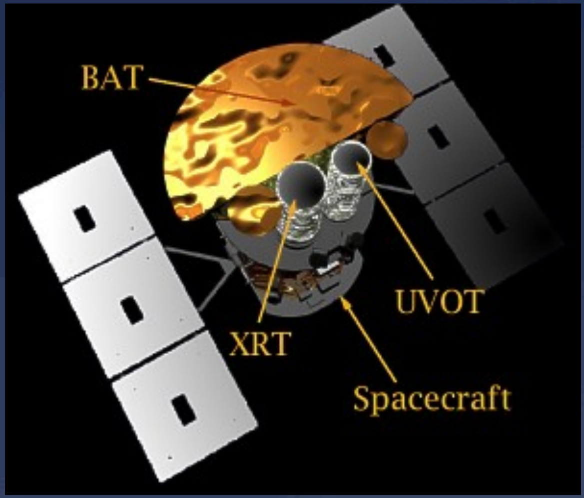


- BeppoSAX NFI localised GRB 970228 (Costa et al.); Z ~0.695 (Djorgovski et al.)
- Optical counterpart discovered (Groot et al. 1997)
- Opened door for redshift measurements (GRB 970507 z ~ 0.835 Metzger et al. 1997) and light curve observations
- *'Rapid' in 1997* ***~10 hours*** *- Rapid now = 100 sec*

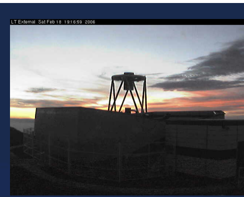
GRB Fireball Model



2004 - Era of Rapid Followup



* Dedicated GRB satellite: SWIFT
  * Burst Alert Telescope (BAT): 15-150 keV
  * X Ray Telescope (XRT): 0.3-10 keV
  * Ultraviolet Optical Telescope (UVOT): 150-650 nm
* Real-time GRB sky map at: **http://grb.sonoma.edu/**

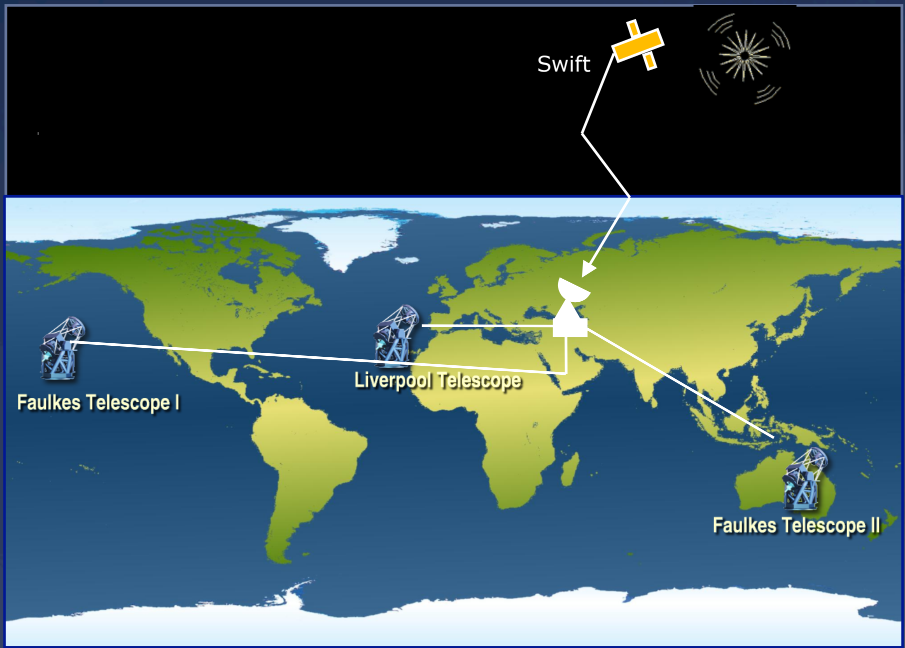


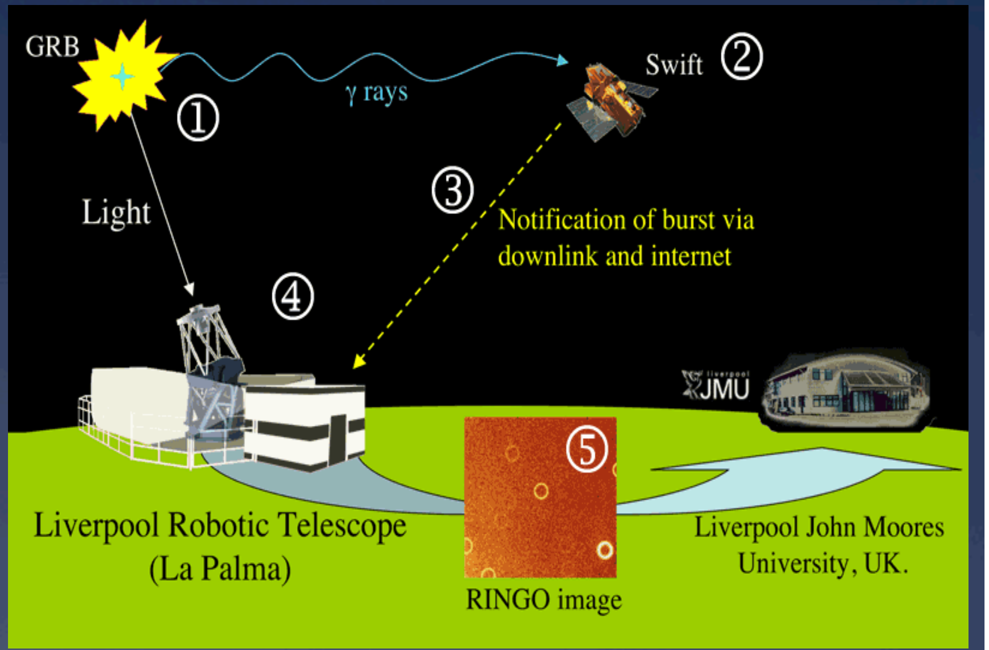
Liverpool Telescope

- Primary mirror diameter 2m
- Rapid slew rate > 2°/sec
- Fully open enclosure
- Nine instrument ports selected by deployable, rotating mirror in the A&G Box within 30 s
- Robotic autonomous operation with intelligent automated scheduler
- General user facility - *not dedicated GRB telescope*

Timescales 10 msec to 10 years!

GRB Robotic Followup

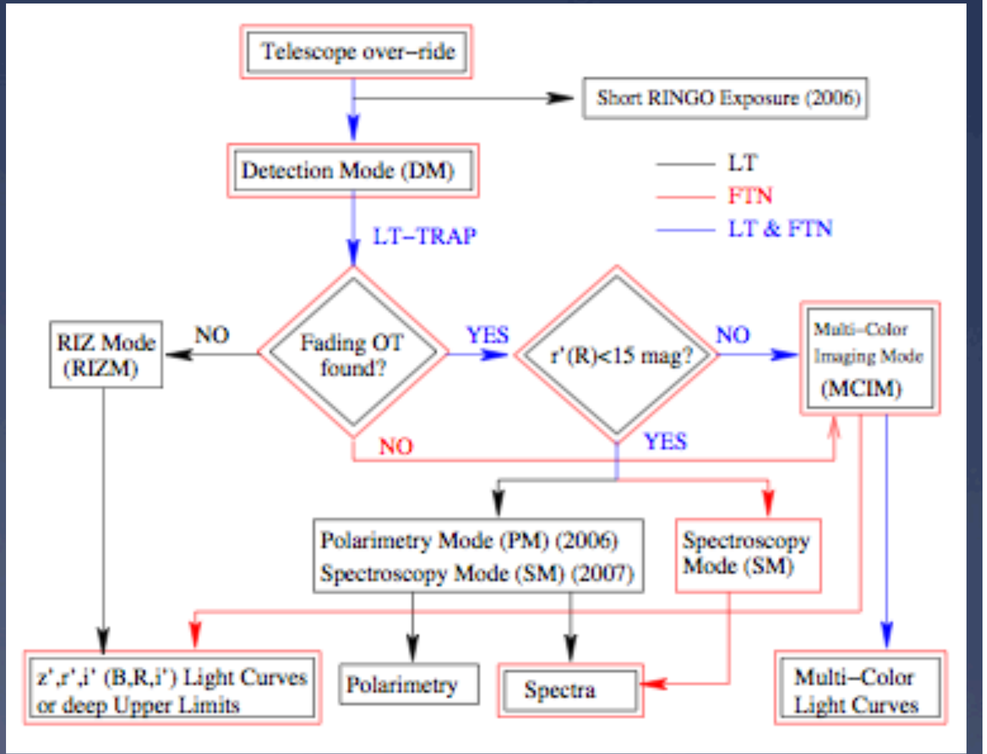




- Immediate automatic response (over-ride), data analysis & interpretation strategy
- No human intervention from receipt of alert ➜ observations ➜ automatic object ID ➜ choice and execution of subsequent observations

LT-TRAP ('Transient Rapid Analysis Pipeline')

- Sophisticated I.D. & decision making algorithm
- Over-ride mode starts on alert arrival
- Detection mode starts (n x 10s in r')
  - Astrometric fit, object extraction, cross-correlation with catalogues
  - Optical candidate?
  - Repeat for each image
  - Variability test (α>1)
  - Optical candidate I.D.?
  - Reports (16-bit) confidence level
- Detection threshold R~22 mag
- ***Auto-ID*** to R~19 mag in ~20s
- Subsequent strategy optimised and executed *automatically*
- Public email circular issued

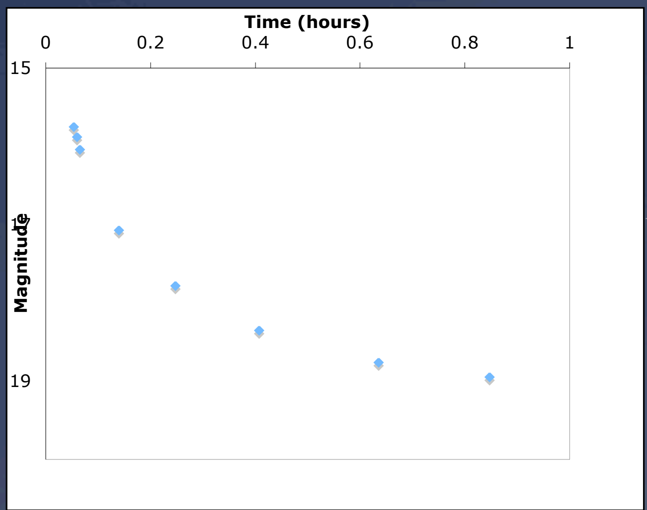


Guidorzi et al. 2006, PASP ,118, 288

And it works ...

```
Date: Sun, 1 May 2005 22:16:30 -0400
From: Bacodine <vxw@capella.gsfc.nasa.gov>
To: ag@astro.livjm.ac.uk, grb@astro.livjm.ac.uk
Subject: GCN/INTEGRAL_POSITION

TITLE:          GCN/INTEGRAL NOTICE
NOTICE_DATE:    Mon 02 May 05 02:14:36 UT
NOTICE_TYPE:    INTEGRAL Wakeup
TRIGGER_NUM:    2484,    Sub_Num: 0
GRB_RA:         202.4403d {+13h 29m 46s} (J2000),
                202.4982d {+13h 29m 60s} (current),
                201.8971d {+13h 27m 35s} (1950)
GRB_DEC:        +42.6722d {+42d 40' 20"} (J2000),
                +42.6448d {+42d 38' 41"} (current),
                +42.9301d {+42d 55' 48"} (1950)
```

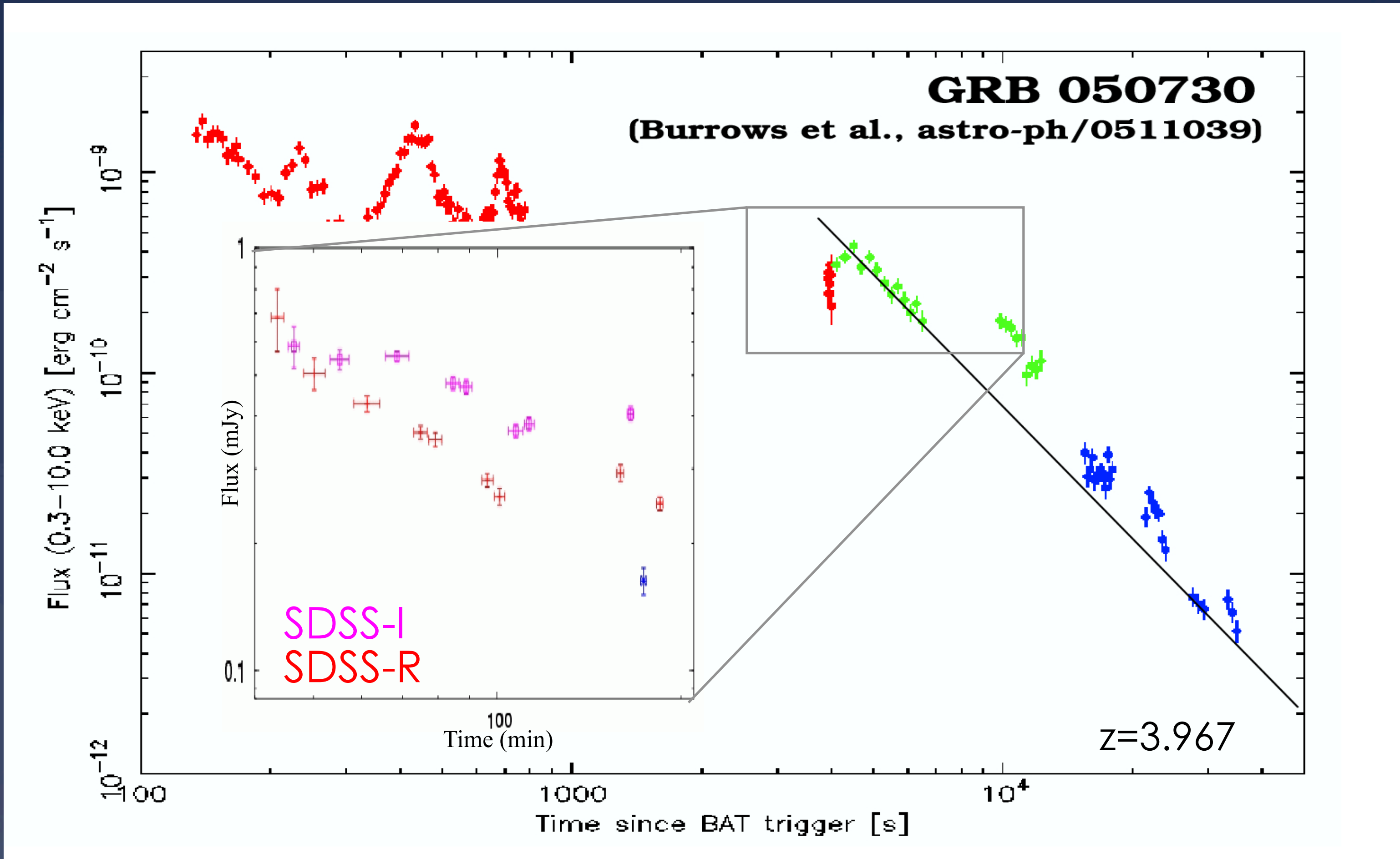
```
Date: Mon, 2 May 2005 03:18:40 +0100
From: Engineer account <eng@astro.livjm.ac.uk>
To: ag@astro.livjm.ac.uk, am@astro.livjm.ac.uk, cgm@astro.livjm.ac.uk,
     cjm@astro.livjm.ac.uk, crg@astro.livjm.ac.uk, grb@astro.livjm.ac.uk,
     grbgroup@star.herts.ac.uk, grbgroup@star.le.ac.uk, ias@astro.livjm.ac.uk,
     ltops@astro.livjm.ac.uk, mfb@astro.livjm.ac.uk, mjb@astro.livjm.ac.uk,
     rjs@astro.livjm.ac.uk
Subject: GRB Alert : LT : OT CANDIDATE

I have completed detection mode.
The best optical transient I could find has a position of 13:29:46.25 ,
+42:40:27.50 (J2000).
Thats at (approximate) pixel position (760.260010,567.530029) on the detection
mode images.
It has a magnitude of 15.575000 (vs USNOB1) and counts 13166.900391.
The astrometric fit has a residual of 0.160000 arc-seconds.
The confidence level is 1.000000.
I am confident that I have found an genuine OT.
I am now changing to lt_ot_imaging mode.
```



Guidorzi et al. 2006

- LT began observing <u>3.1 min</u> after GRB onset.
- *Automatic I.D.* within 1 minute (**r'~15.8** & rapid fa
- Multi-colour imaging sequence **auto-triggered**
- Earliest-ever *multi-colour* light curve of afterglow.

Early-Time Light Curves



Optical/X-ray flares; energy injection and long-lived central engines a surprise (Monfardini+06, ApJ, 648, 1125; Melandri+09, MNRAS, 395, 1941)

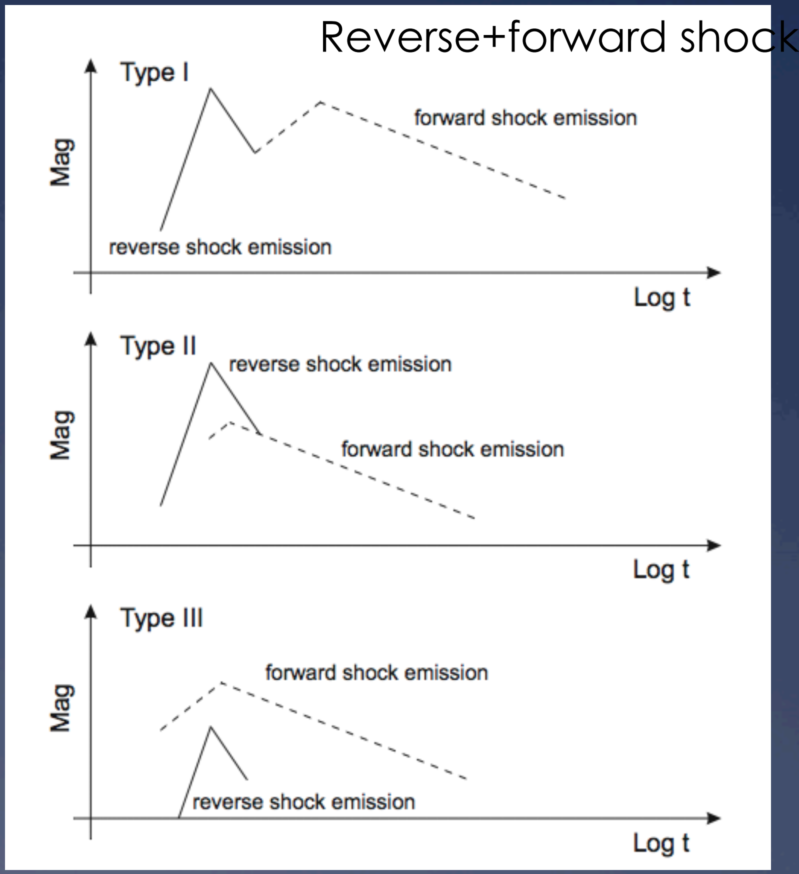
Fireball Magnetization

* Origin of magnetic fields unknown
  * Energy transfer physics still unknown
* Standard (internal shock) synchrotron model
  * Baryon-dominated jet creates tangled B-field in shock layer
  * Inefficient conversion of bulk:radiated energy
* Alternative: Poynting flow
  * Large-scale ordered magnetic fields in flow
  * Powerful acceleration and collimation

Fireball Magnetization

Indirect Probe

- Light curve shapes
- Compare strengths of reverse and forward shock emission
- Estimate magnetization fraction



Gomboc+09, AIPC, 1133, 145
Harrison & Kobayashi 2013 ApJ, 772, 101

Magnetic Field Structure

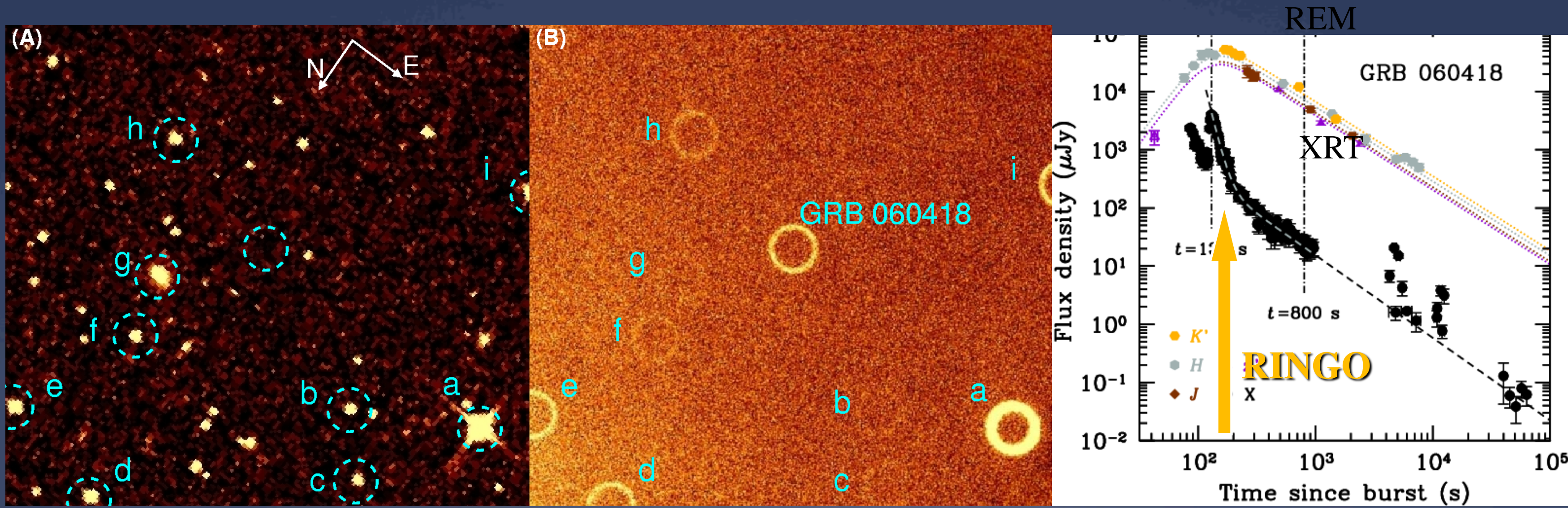
Direct probe:

* Measure degree of polarization
* Synchrotron emission ➜ intrinsically polarized
* Magnetic field structure and scale length
* *Early-time* optical polarization powerful

RINGO polarimeters on the Liverpool Telescope...

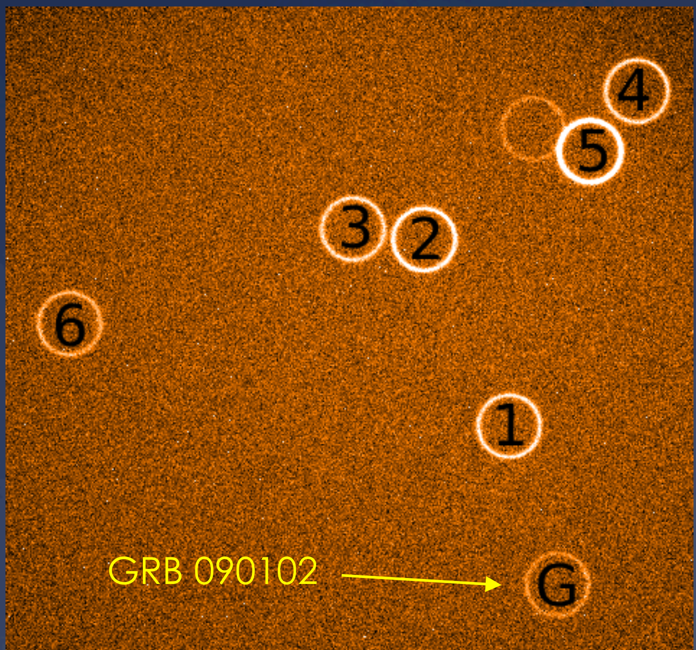
GRB 060418

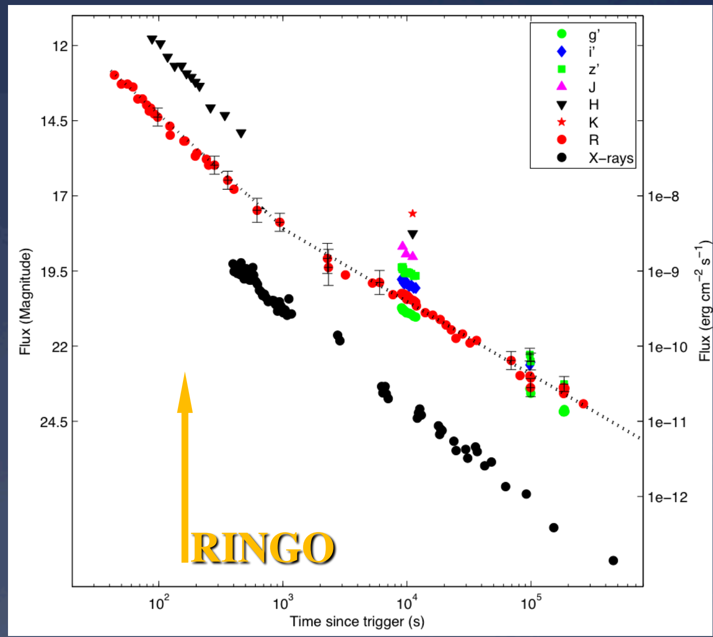
- RINGO polarimetry of GRB 060418 at ***t* = 203 sec**
  - Measurement coincided with deceleration of fireball
    - (Γ_0~400; R_{dec}~ 10^{17}) cm
  - Strongly-constrained upper-limit: **P<8%**
  - Equal contribution from forward and reverse shocks



Steele et al. 2006, SPIE, 6269 ,179; Mundell et al. 2007, Science, 315, 1822

GRB 090102

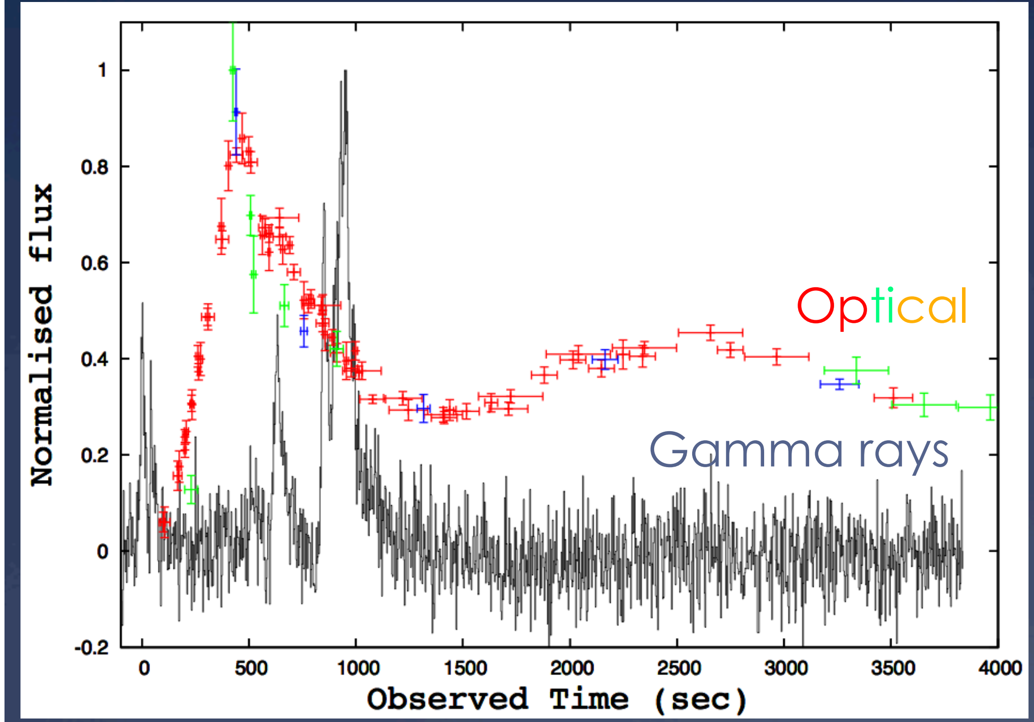




- 60-s RINGO exposure began ***t = 160 s*** post-burst
- Stars in field provide additional calibration
- First detection of early time GRB afterglow polarisation
  P=10.2±1.3%

Steele+09 Nature, 462, 767

Temporal Evolution?



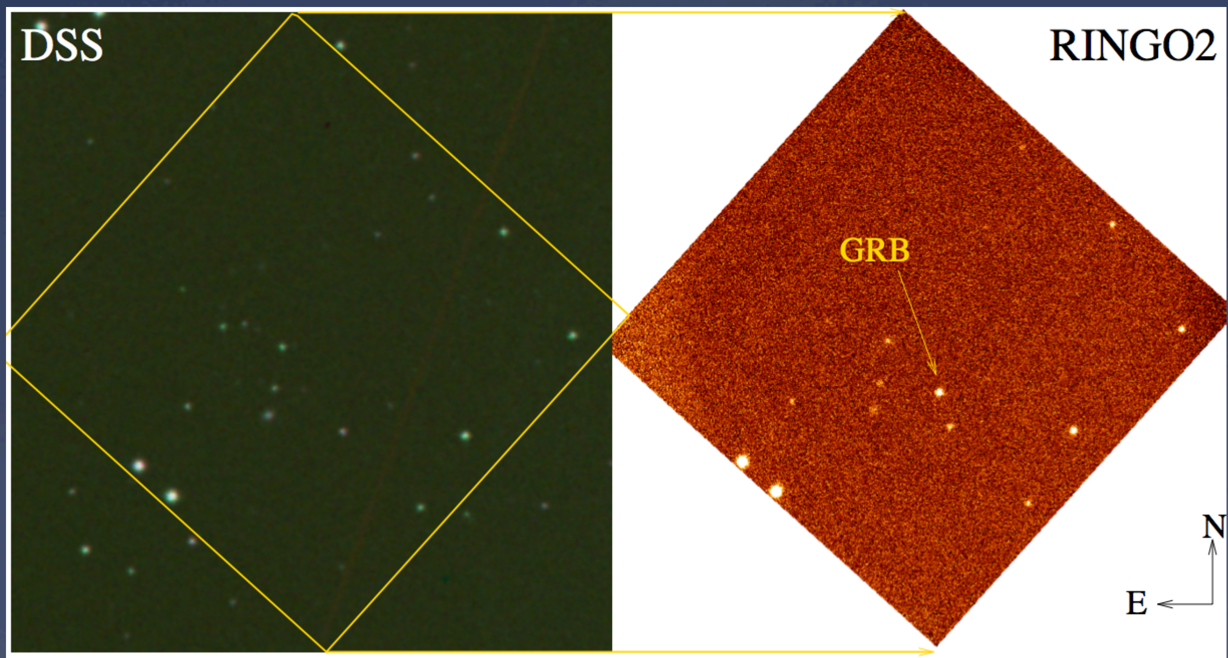
Ultra-long GRB 091024
z=1.092
t_{gamma} ~1200 sec !

Virgili et al. 2013, ApJ, in press

* Complex light curves
* Polarised flares?
* Recycled RINGO into RINGO2…
* *Time-resolved* polarimetry

RINGO2 Imaging Polarimetry

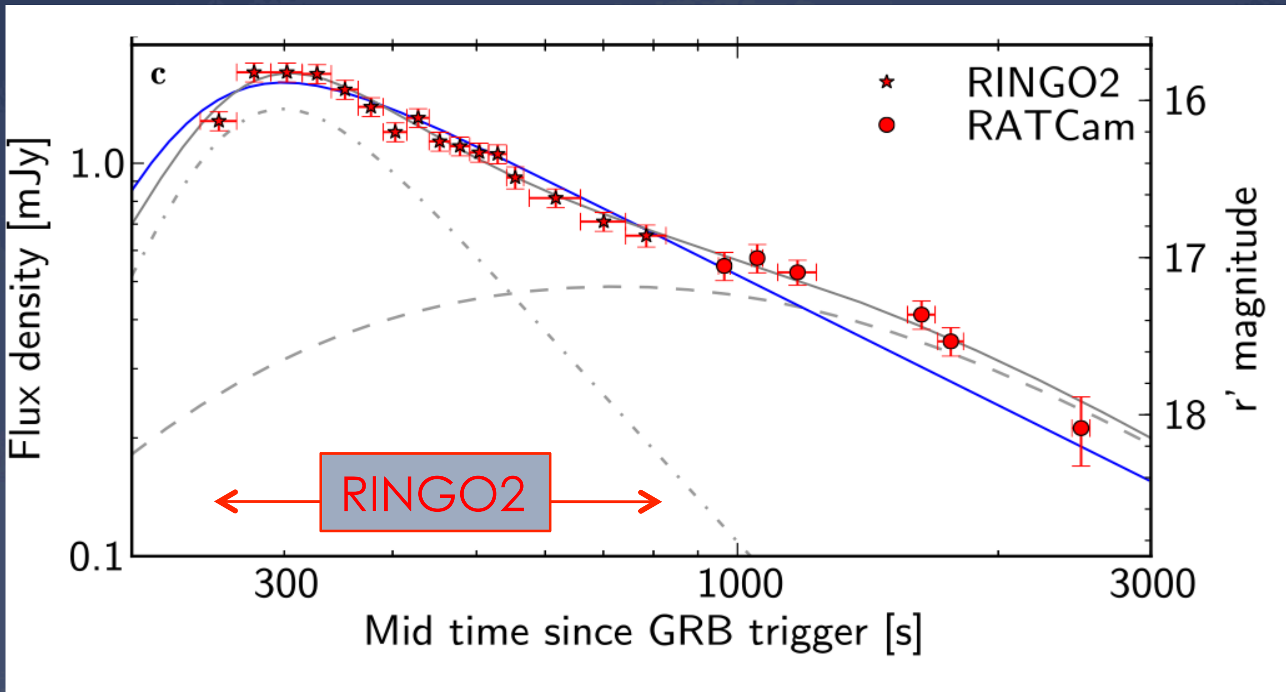
* Swift GRB; immediate followup with LT/ RINGO2
* Bright optical counterpart found by LT



Mundell+13, Nature

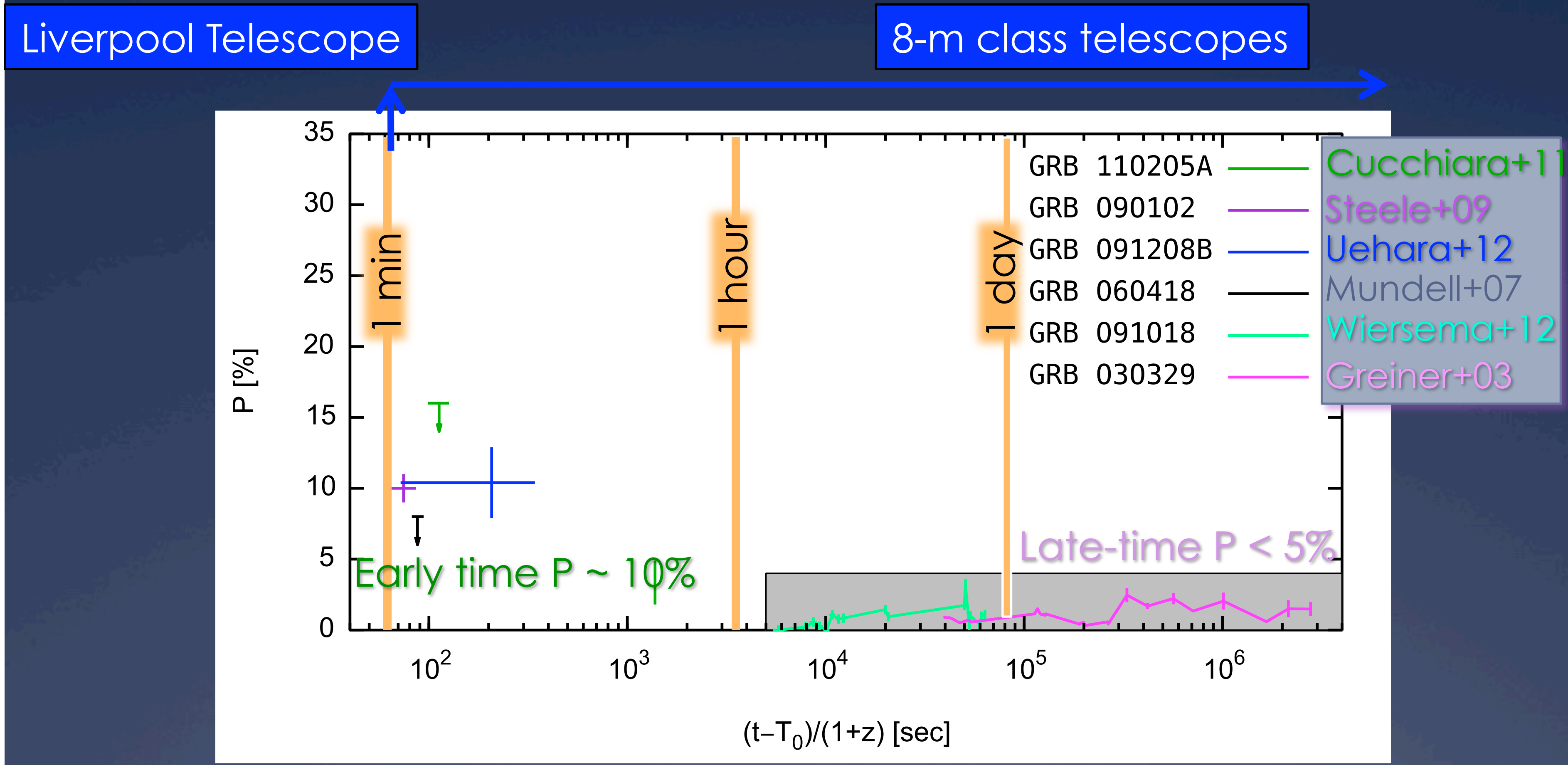
RINGO2 Imaging Polarimetry

* Swift GRB; immediate followup with LT/ RINGO2
  - Bright optical counterpart found by LT
  - Well-sampled light curve and polarization

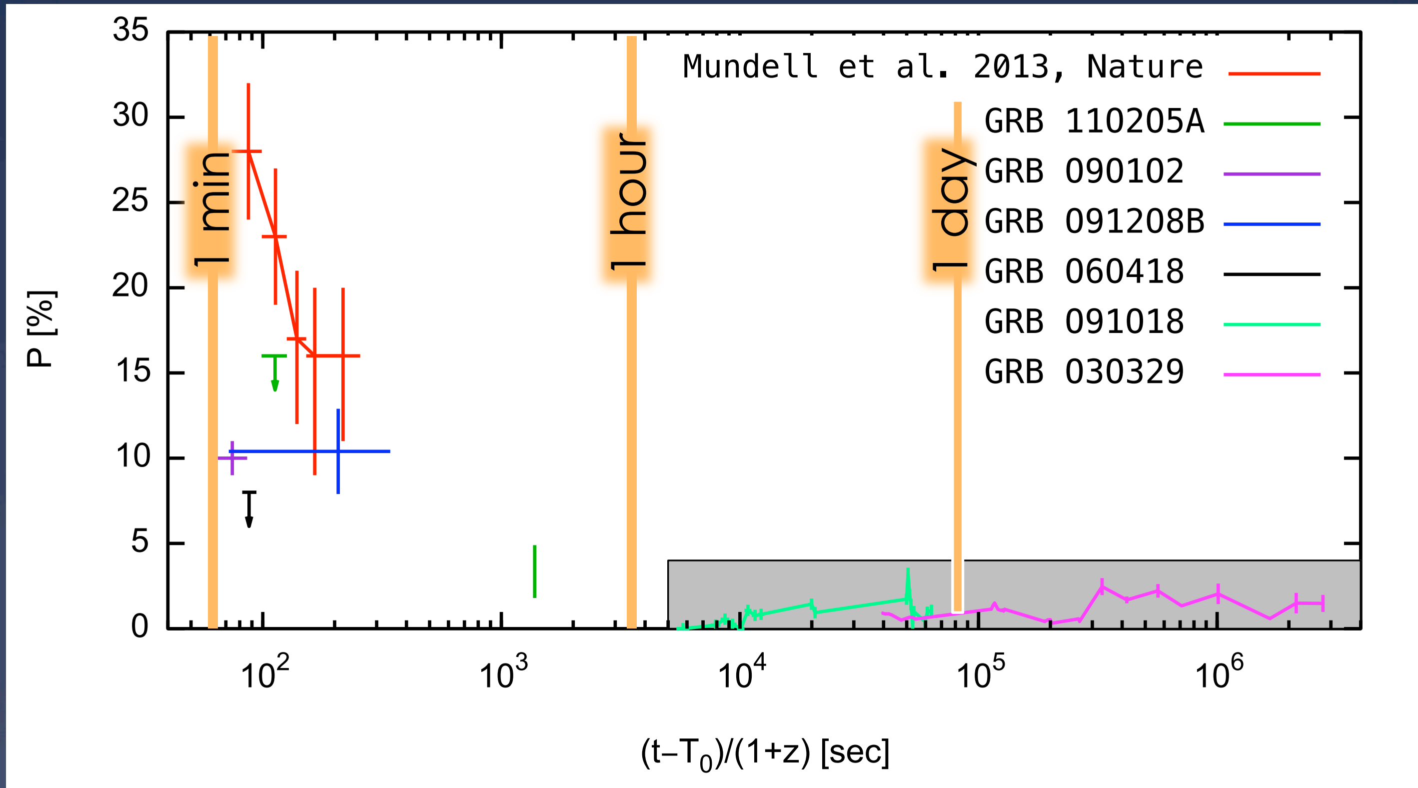


Mundell+13, Nature

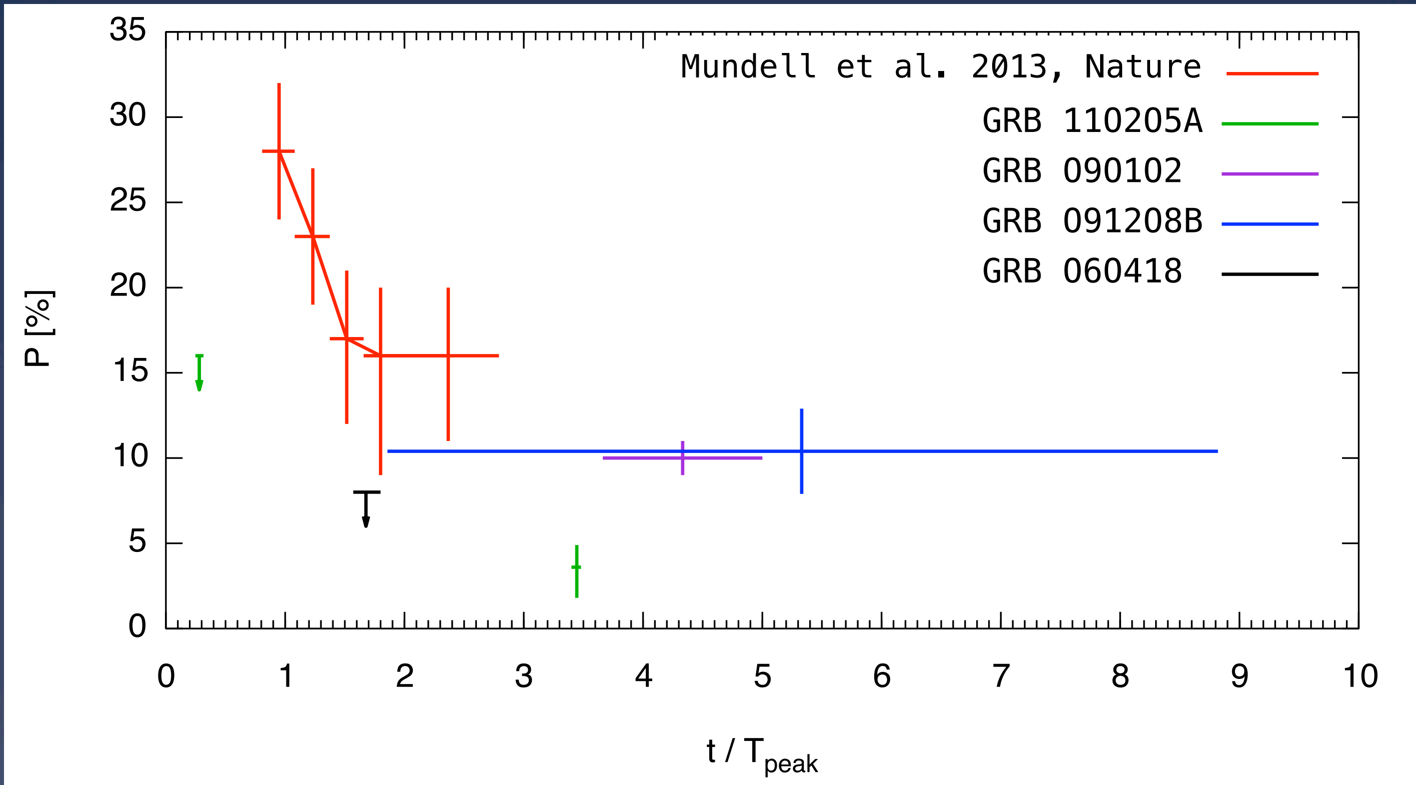
Previous measurements



High polarization



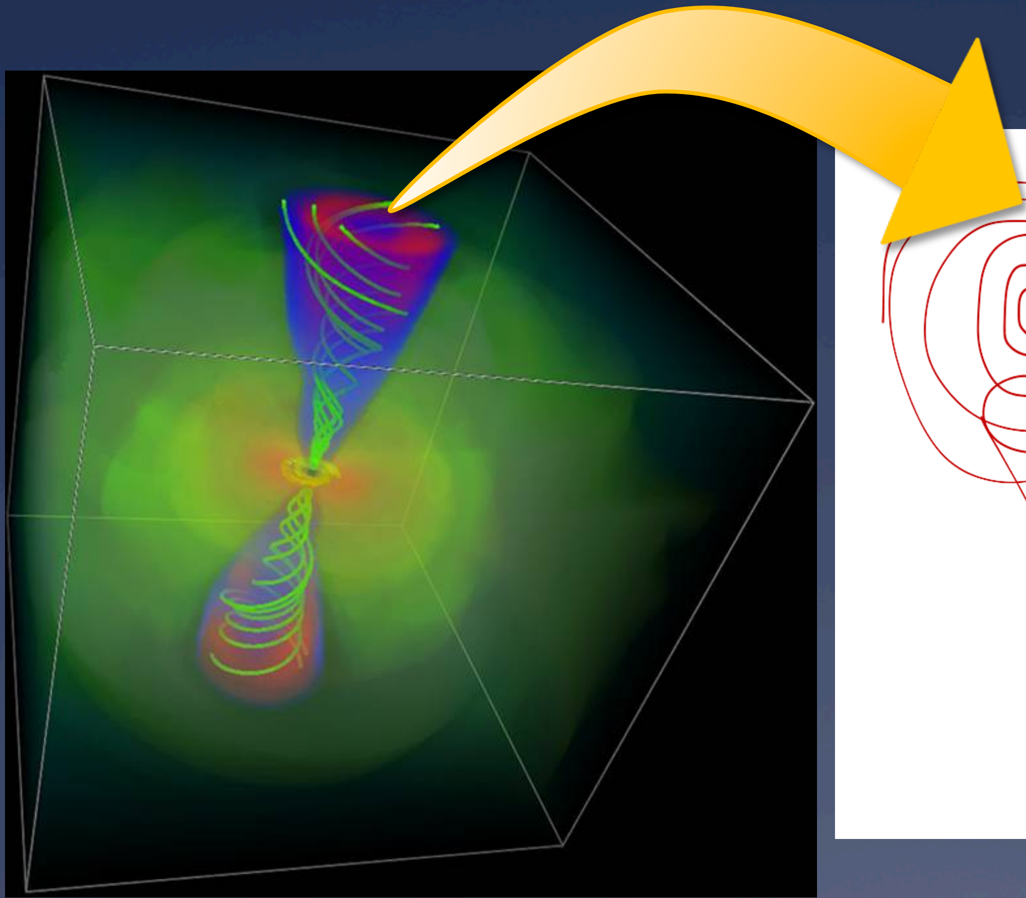
Birth of a jet

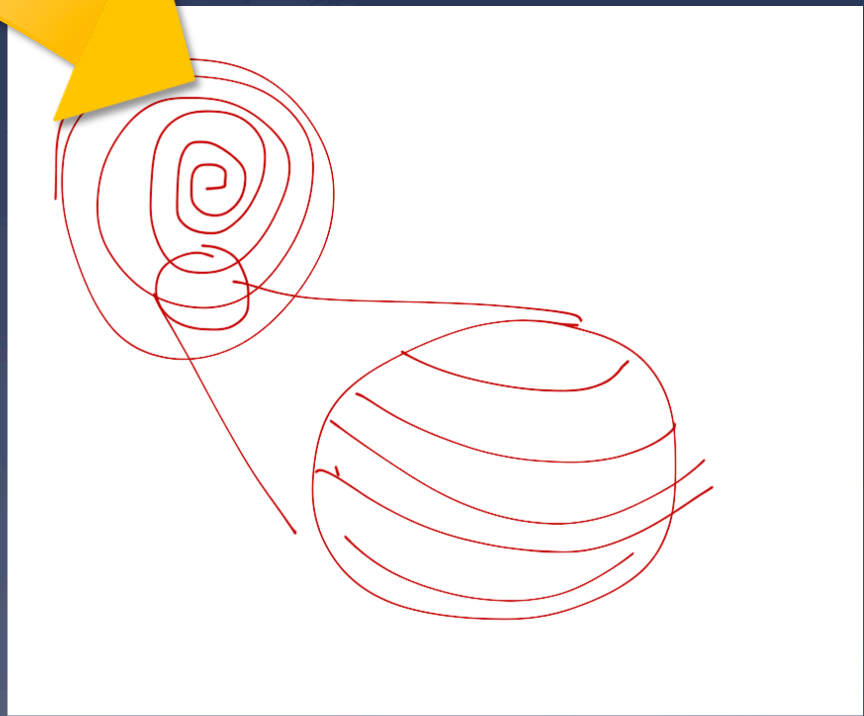


Highest measured optical polarization

Long-lived, large-scale ordered magnetic fields

Ordered Magnetic Fields

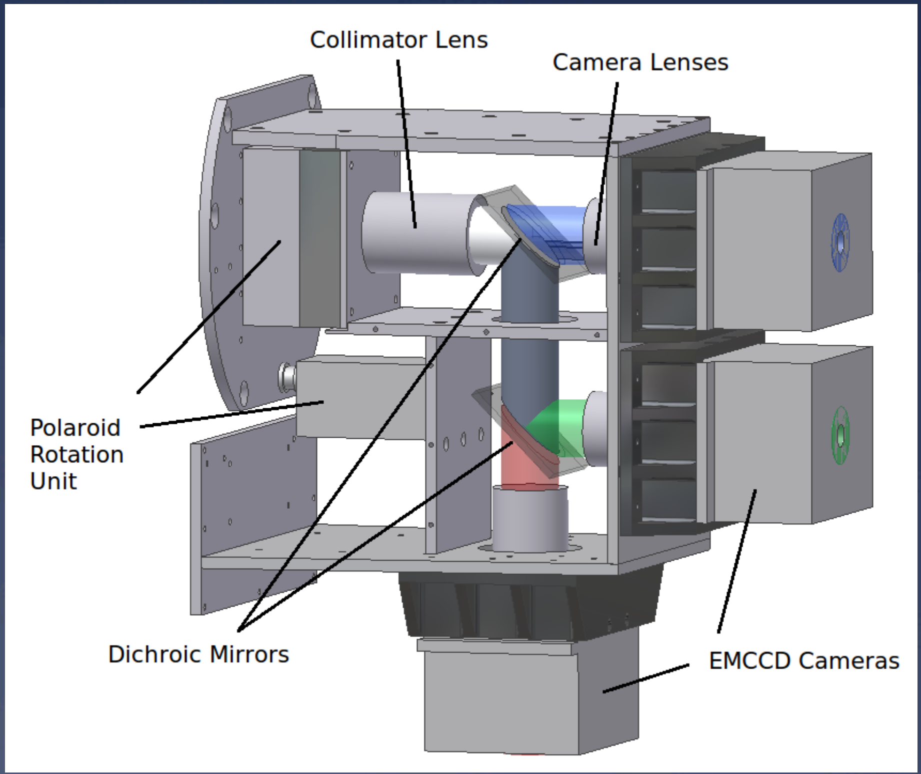




$\sim 1/\Gamma$

RINGO3 (March 2013)

- Simultaneous 3-camera polarimeter
- 3500-10000 A (BV,R,I)
- 1 sec time resolution
- Polarisation purity 1% at 17 mag in 20s
- All GRBs from ~t_0+100s



Arnold+2012

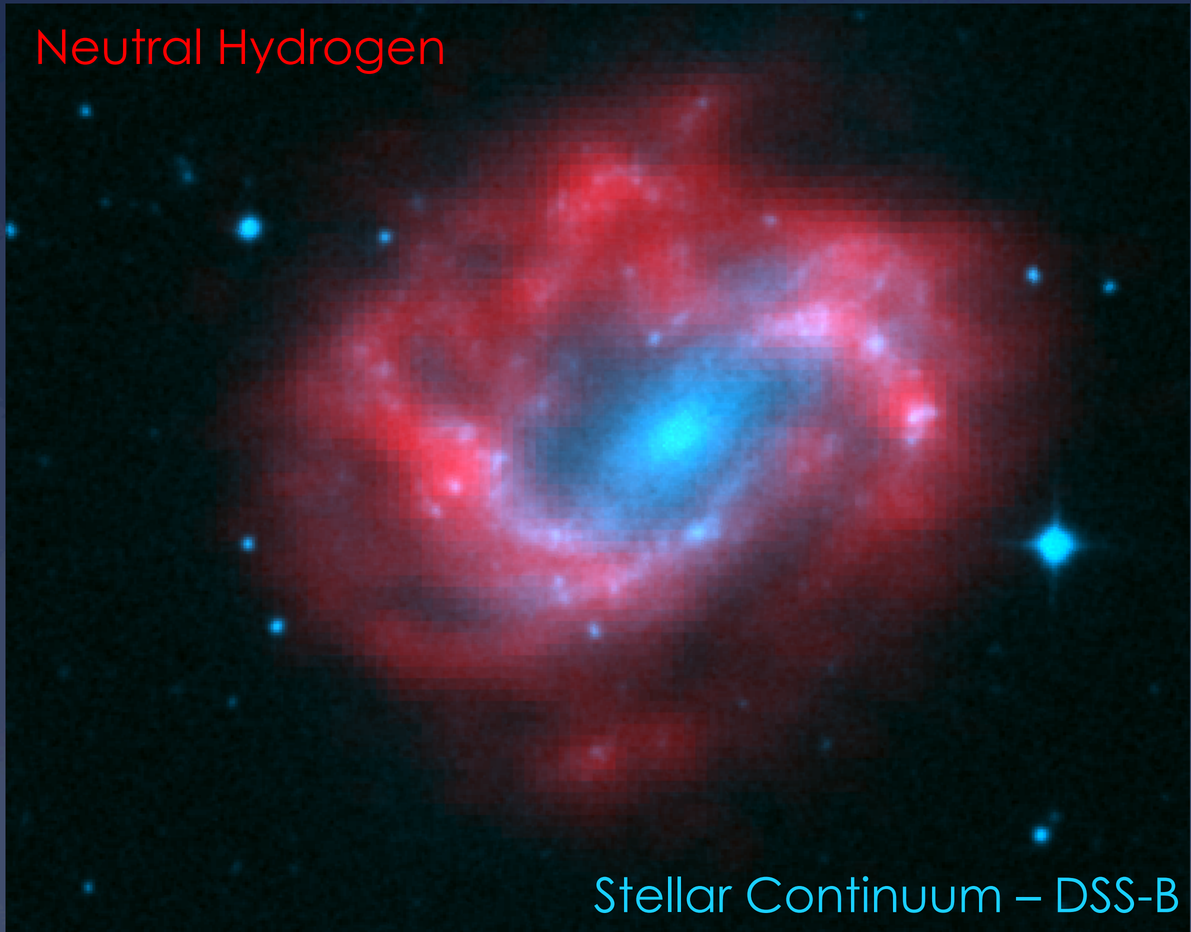
On sky now for GRBs and blazars.

Seyfert Galaxies

* Spiral galaxies with bright, non-stellar nuclei (Seyfert, 1943)
* Closest & most common type of AGN
* Jets of radio-emitting plasma – black-hole exhaust material
* Local laboratories for galaxy formation/evolution studies
* Study host galaxy and AGN in more detail

Active Galaxies

NGC 4051



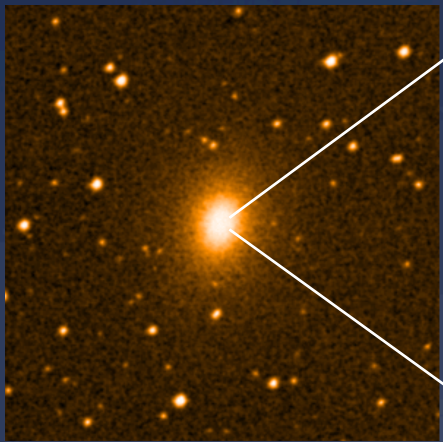
Seyfert Galaxies

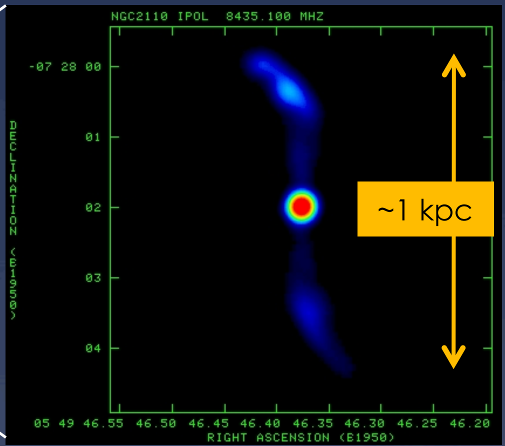
- Spiral galaxies with bright, non-stellar nuclei (Seyfert, 1943)
- Closest & most common type of AGN
- Jets of radio-emitting plasma – black-hole exhaust material!
- Local laboratories for galaxy formation/evolution studies
- Study host galaxy and AGN in more detail

Seyfert Galaxies

Optical

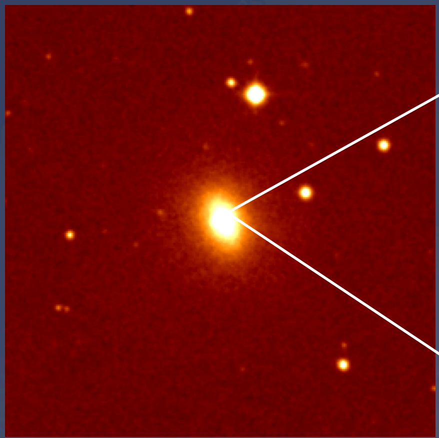
Radio

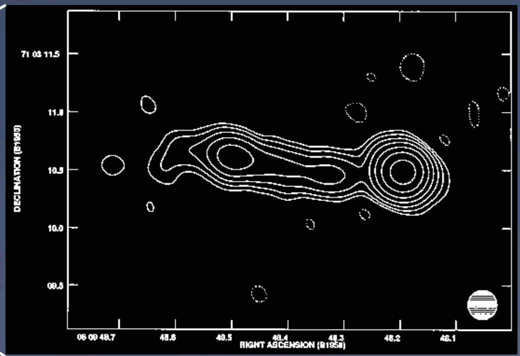




NGC 2110

Mundell, Ferruit, Nagar, Wilson, 2009, ApJ, 703, 802





Mrk 3

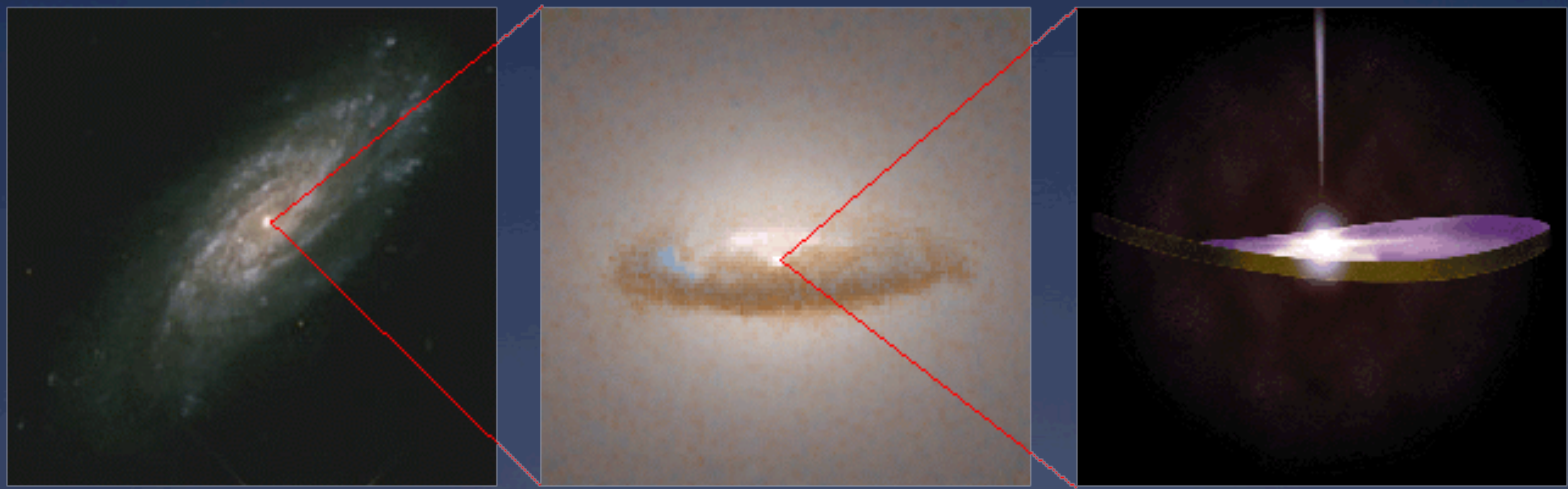
Kukula et al., 1993, MNRAS, 264, 893

Sites of UHECRs?

Seyfert Galaxies

* Spiral galaxies with bright, non-stellar nuclei (Seyfert, 1943)
* Closest & most common type of AGN
* Jets of radio-emitting plasma – black-hole exhaust material!
* Local laboratories for galaxy formation/evolution studies
* Host galaxy and AGN in more detail

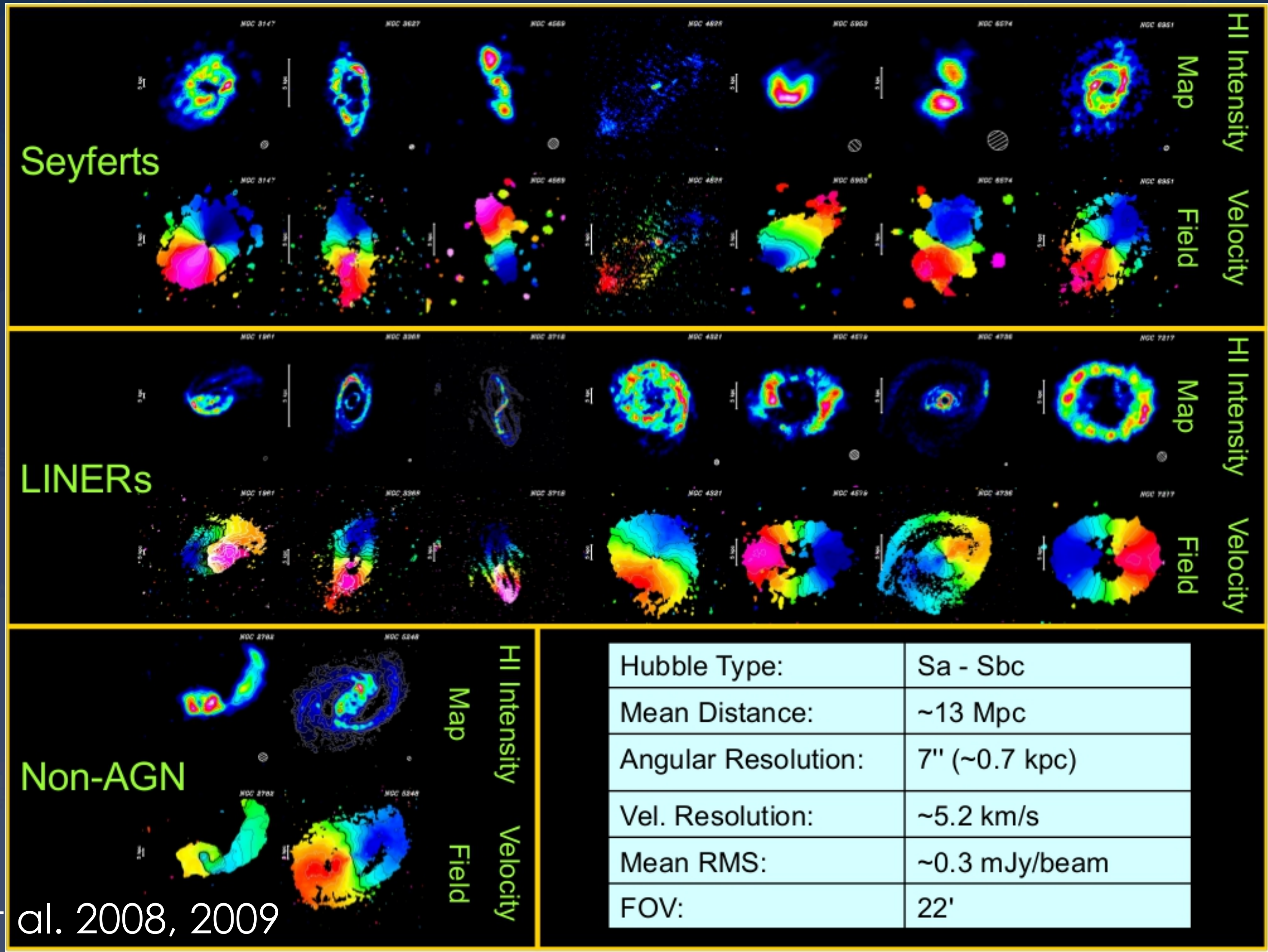
Spatial scale perspective….



- Host galaxy
  - 10 - 100 kpc
- Obscuring torus
  - 1 - 100 pc
- Accretion disk
  - 10 - 100 AU

- (10^8 M_M black hole ⇨ R_S ~ 10^{-5} pc ~ 2 AU)

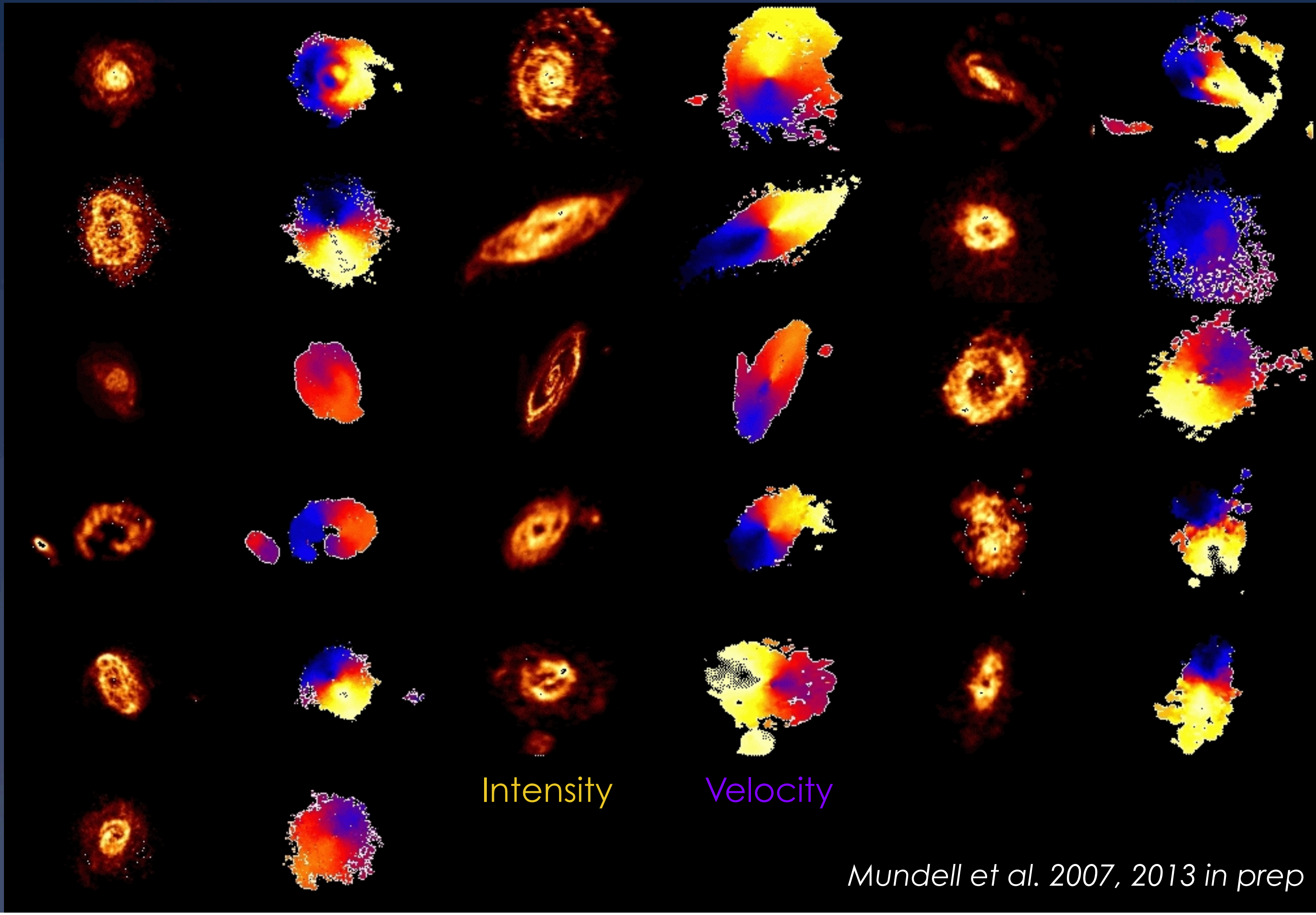
Active vs Inactive Dynamics



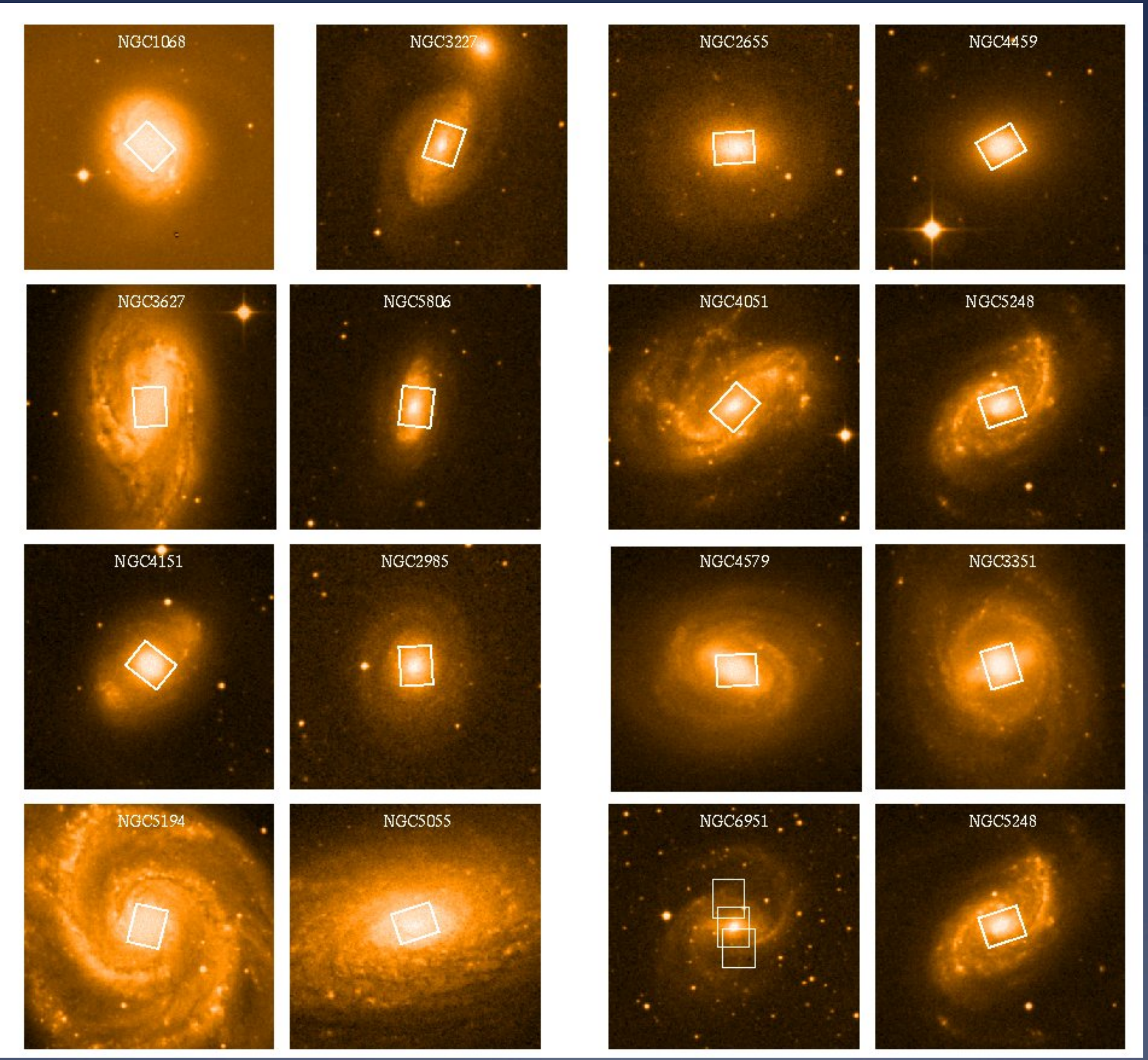
Hubble Type:	Sa - Sbc
Mean Distance:	~13 Mpc
Angular Resolution:	7'' (~0.7 kpc)
Vel. Resolution:	~5.2 km/s
Mean RMS:	~0.3 mJy/beam
FOV:	22'

Haan et al. 2008, 2009

Active vs Inactive Dynamics



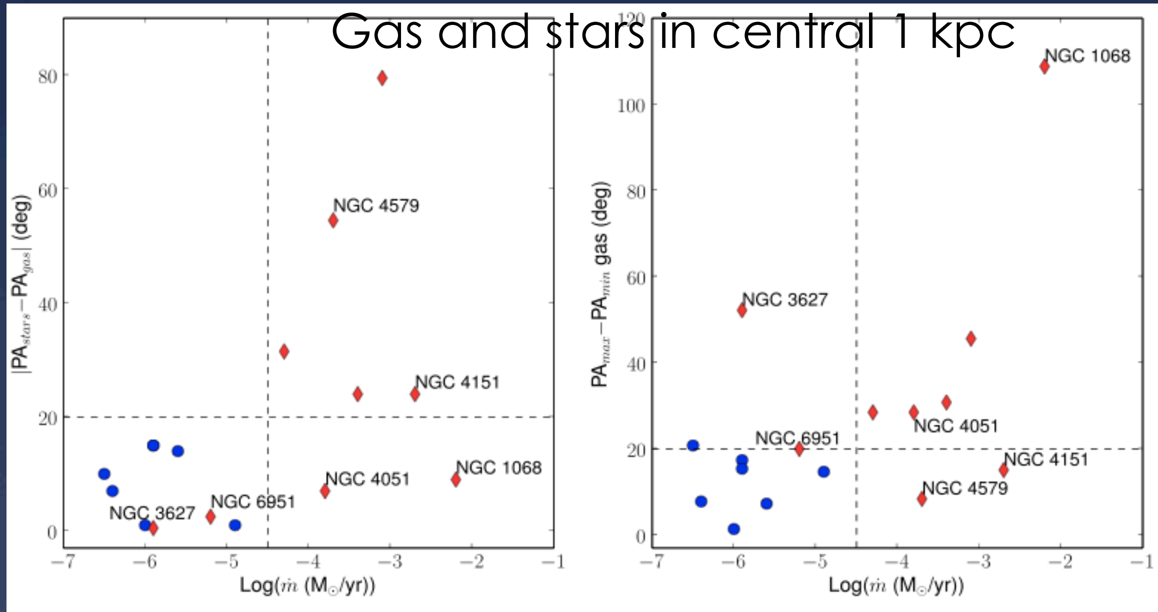
Active vs Inactive Dynamics



Active vs Quiescent Kinematics

Gas and stars in central 1 kpc

Disturbance



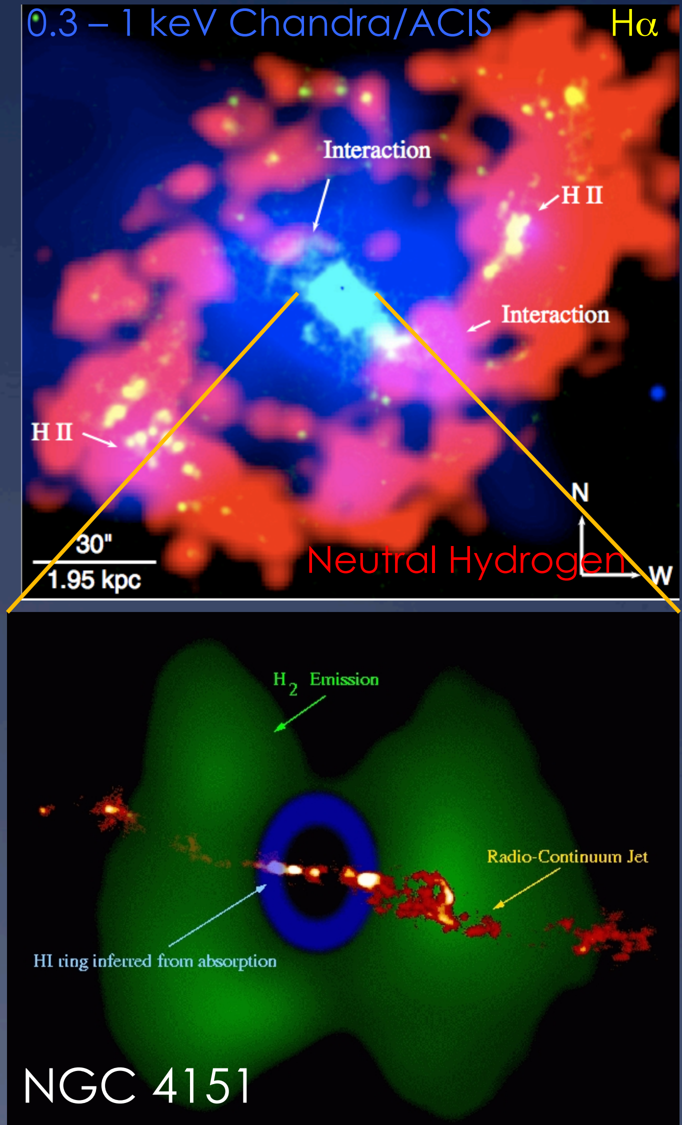
Accretion Rate

- Active (♦) and (●) inactive pairs
- First evidence that black-hole accretion rate correlates with host disturbance

(Dumas, Mundell, Emsellem, Nagar 2007, MNRAS, 379, 1249)

Feedback & AGN Duty Cycles

- Chandra soft X-ray emission to R = 2 kpc, L(0.5-2keV)~10^{39} erg/s (Wang et al. 2010)
- Recent AGN:host interaction
  - Mechanical energy deposited < 10^5 years or
  - *Eddington-limited high luminosity < 2.5 x 10^4 yrs*
- Live systems c.f. Milky Way
- Short timescale – outbursts > 1% AGN lifetime



Wang et al. 2010; Mundell et al. 2003

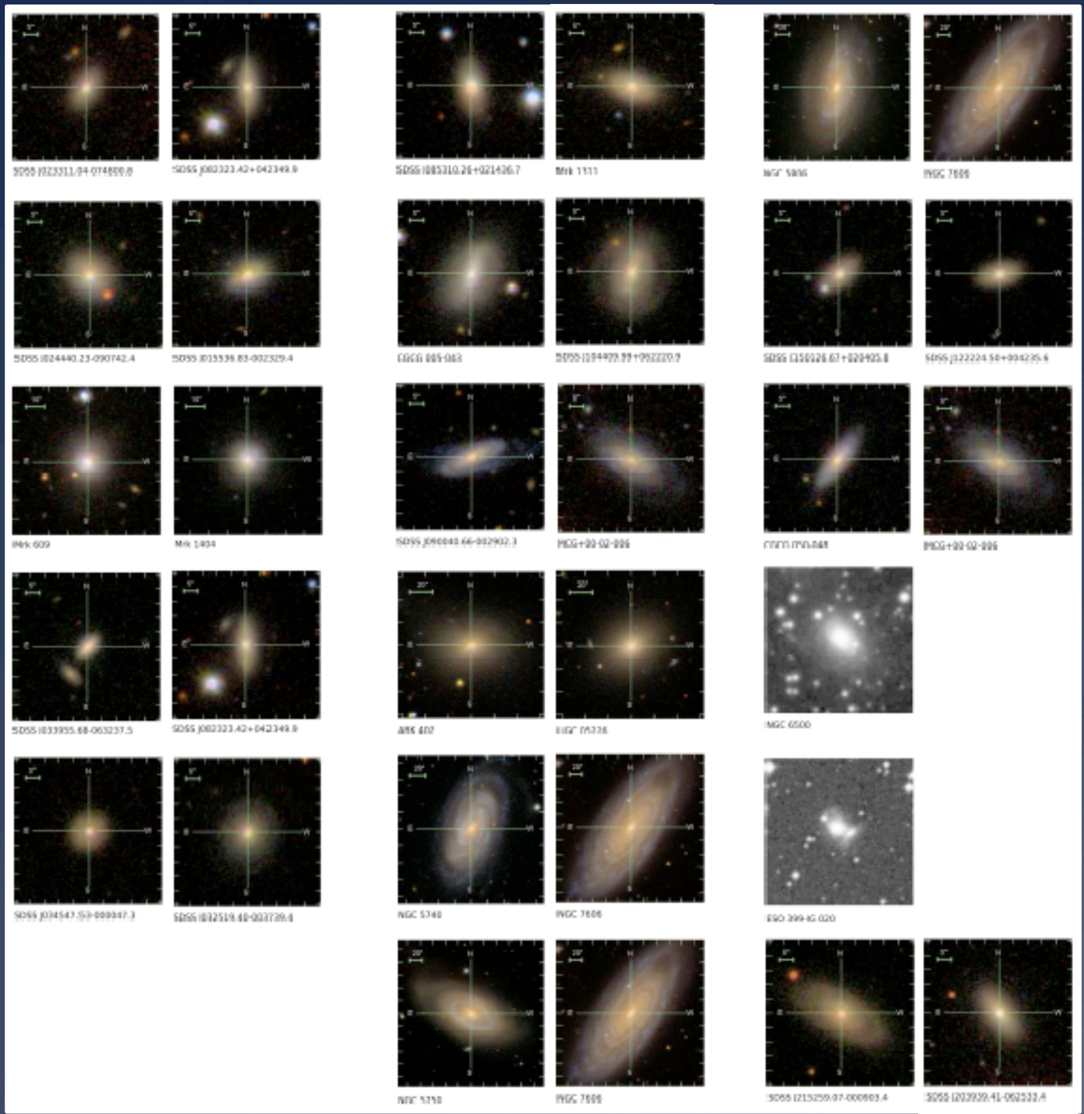
‘Live’ Galaxies

- Rich supply of molecular, ionised and neutral gas on a wide range of scales
- Newly accreted cold gas
- Host disturbance and accretion rate correlation
- Rapid evolution – dynamical and feedback
- AGN duty cycles may be shorter than thought
  - ~10,000 years rather than 10^7 years!
- ‘Live’ systems:
  - Milky Way Fermi bubbles
  - Earth-mass gas cloud shredded to produce flare now!

Summary

- Sky is highly variable if we look
- Black holes as extreme physics probes
- BH-accretion disk – relativistic jets ubiquitous
- Activity from stellar and supermassive black holes observable on human timescales!
- Next step – where and when to look?
  - Counterparts to high energy neutrino sources
  - Counterparts to gravitational wave sources
- Dark matter, dark energy and new physics?

More distant galaxies



Matched pairs with active and inactive black holes

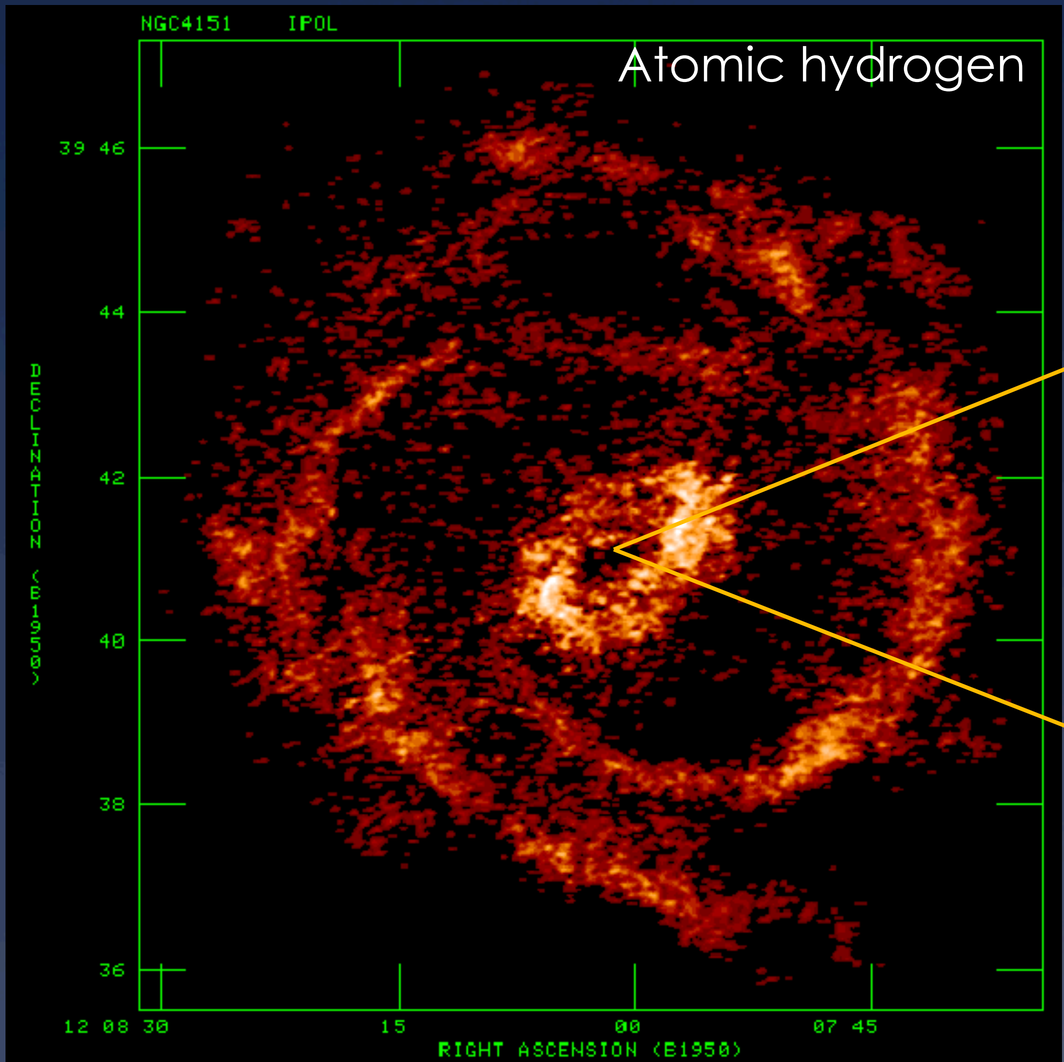
Fast gas outflows from actives
New stars in actives

Inactives – gas poor

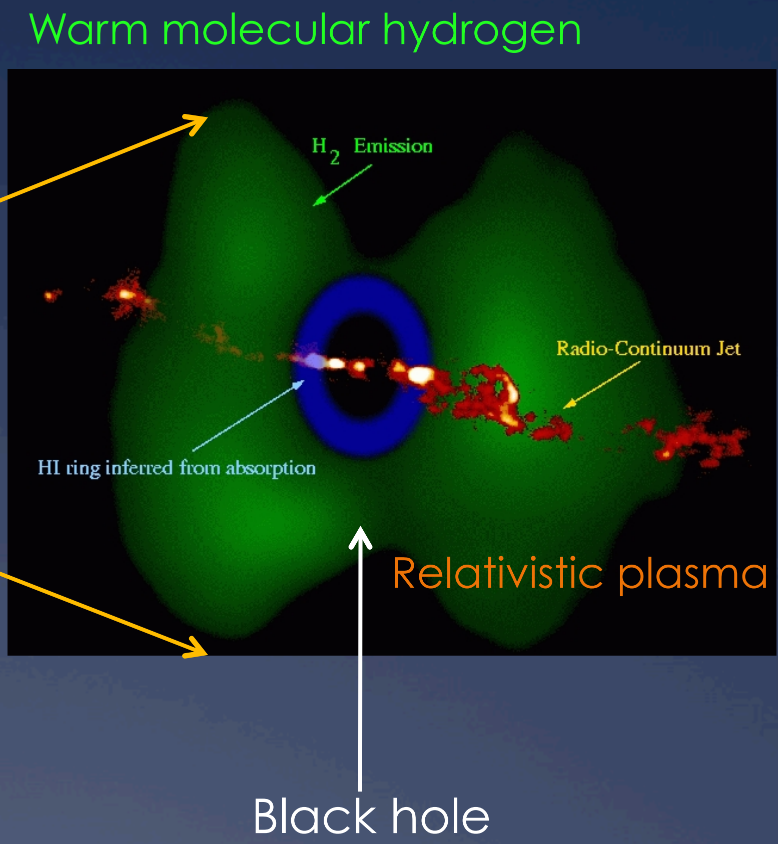
How to trigger black hole?

Disrupt nuclear stars?

Westoby et al. 2012



Mundell et al. 1995



Mundell et al. 2003

The origin of VHE γ-ray flares?