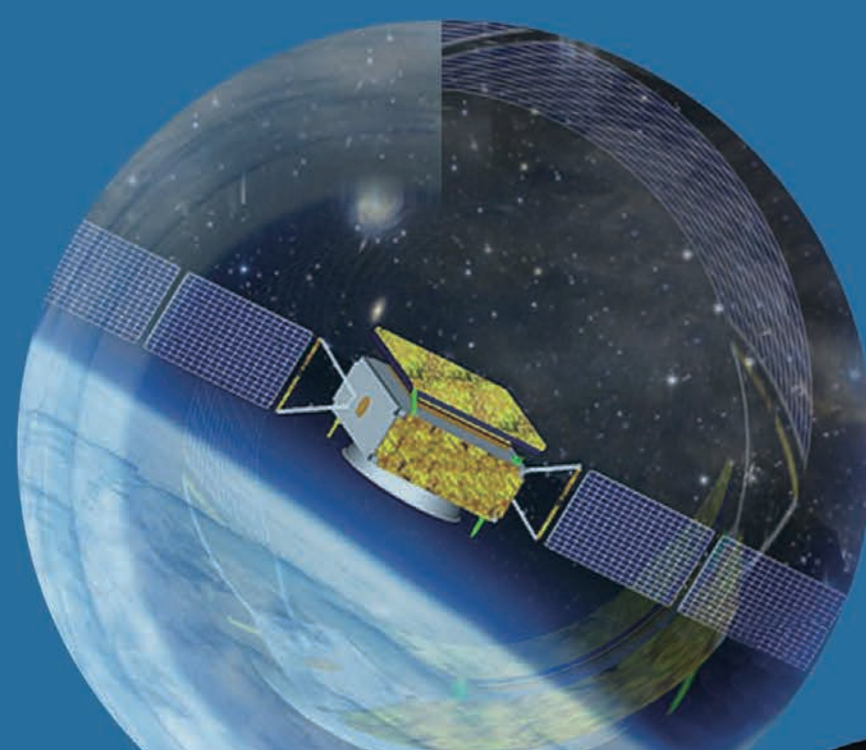
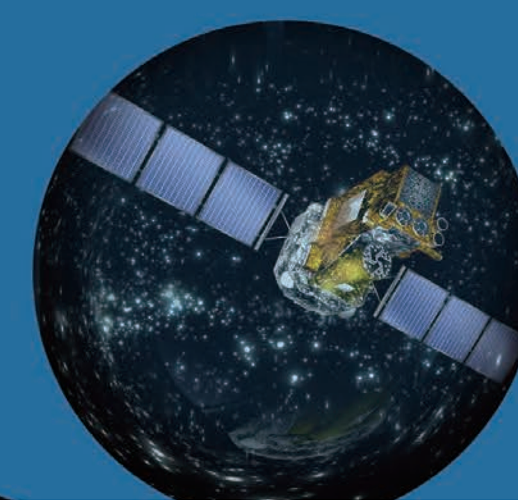
Space Science Mission DATA

How to design a Space Science Mission

October 17 - 26, 2016
Si Racha, Chon Buri, Thailand

www.apsco.int/APSCO_ISSI-BJ_SS/





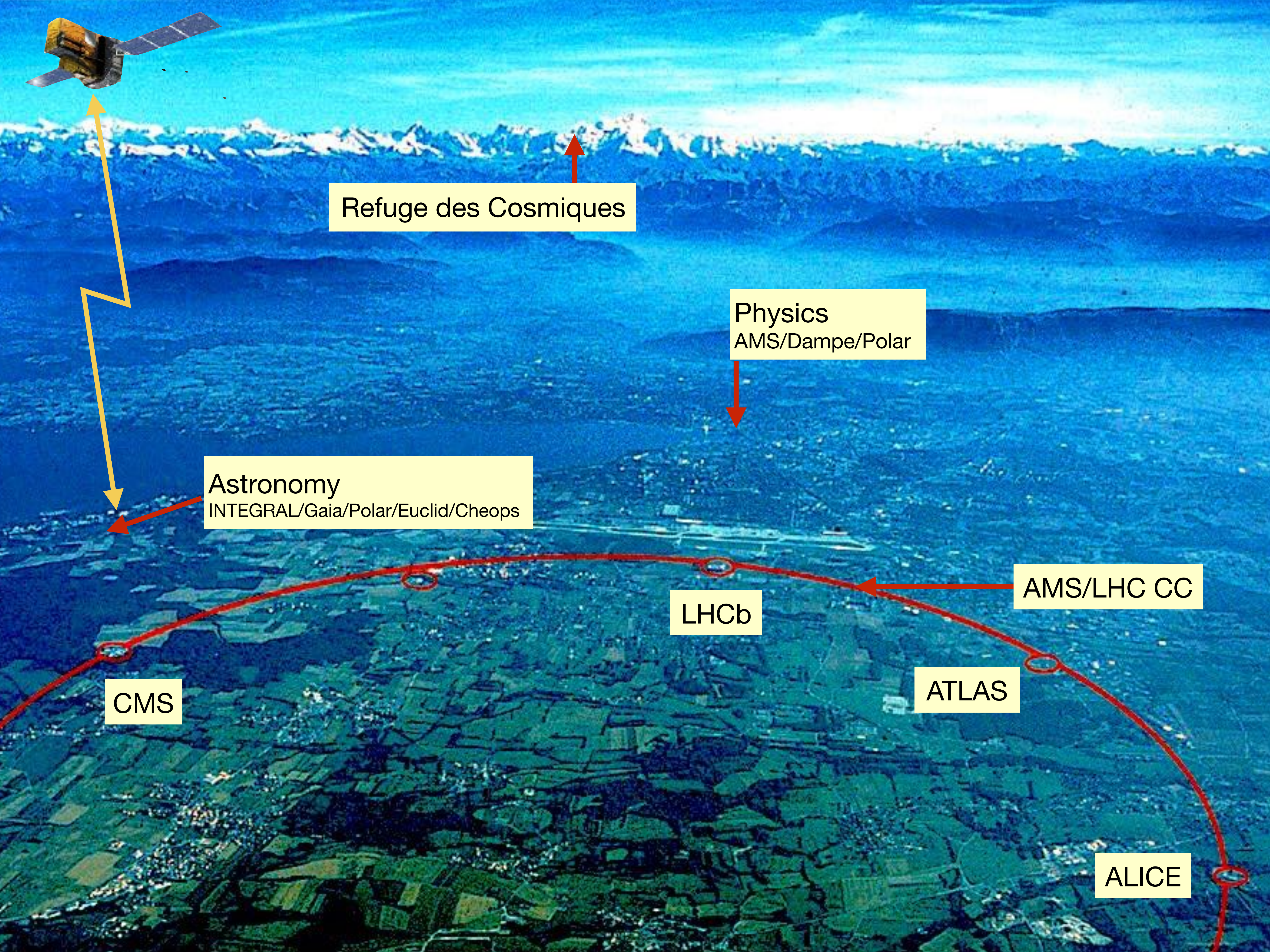
TOPICS

Scientific objectives
Payload design
Orbital constraints
Spacecraft AOCS
Spacecraft design and optimization
Operations ground segment
Scientific management
Project management
Micro-satellite launching and operation
Cubesat mission design and integration
Designing of space science experiment for Space Station

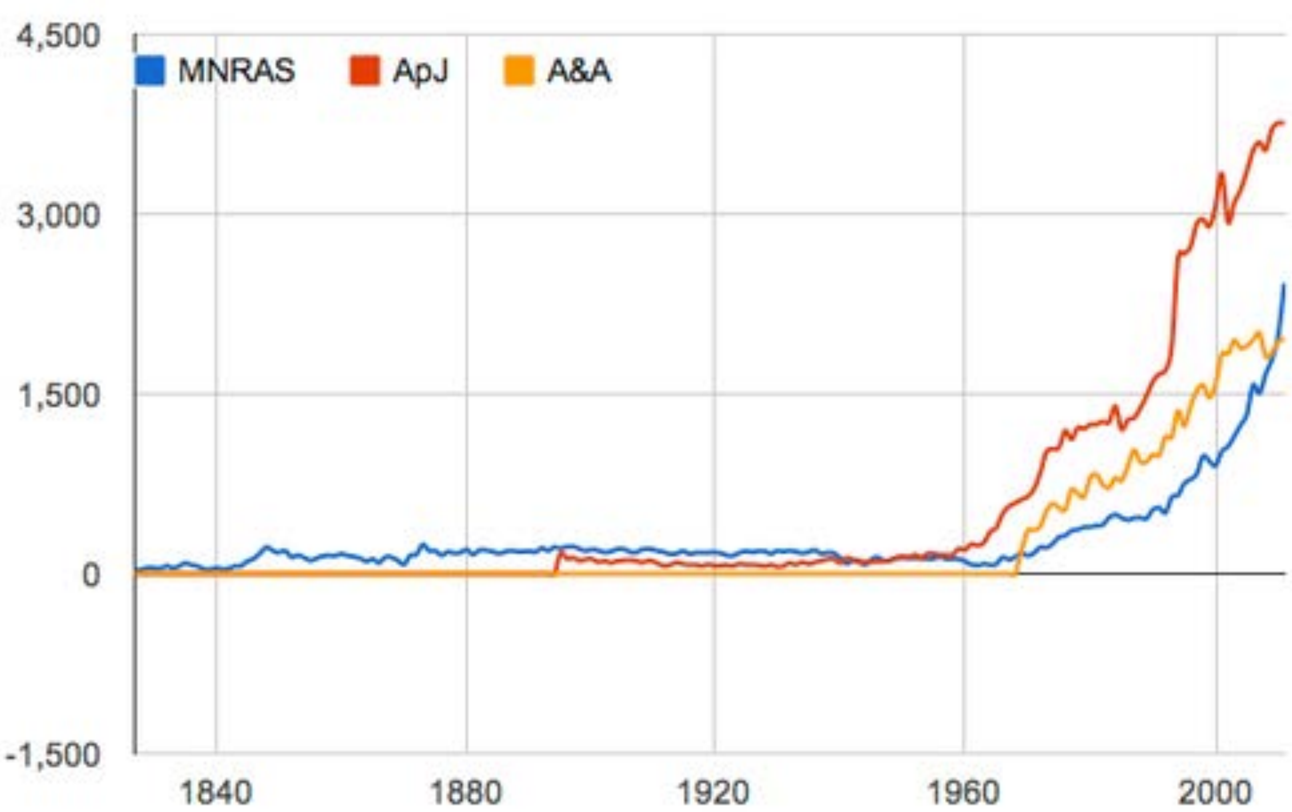
ISDC

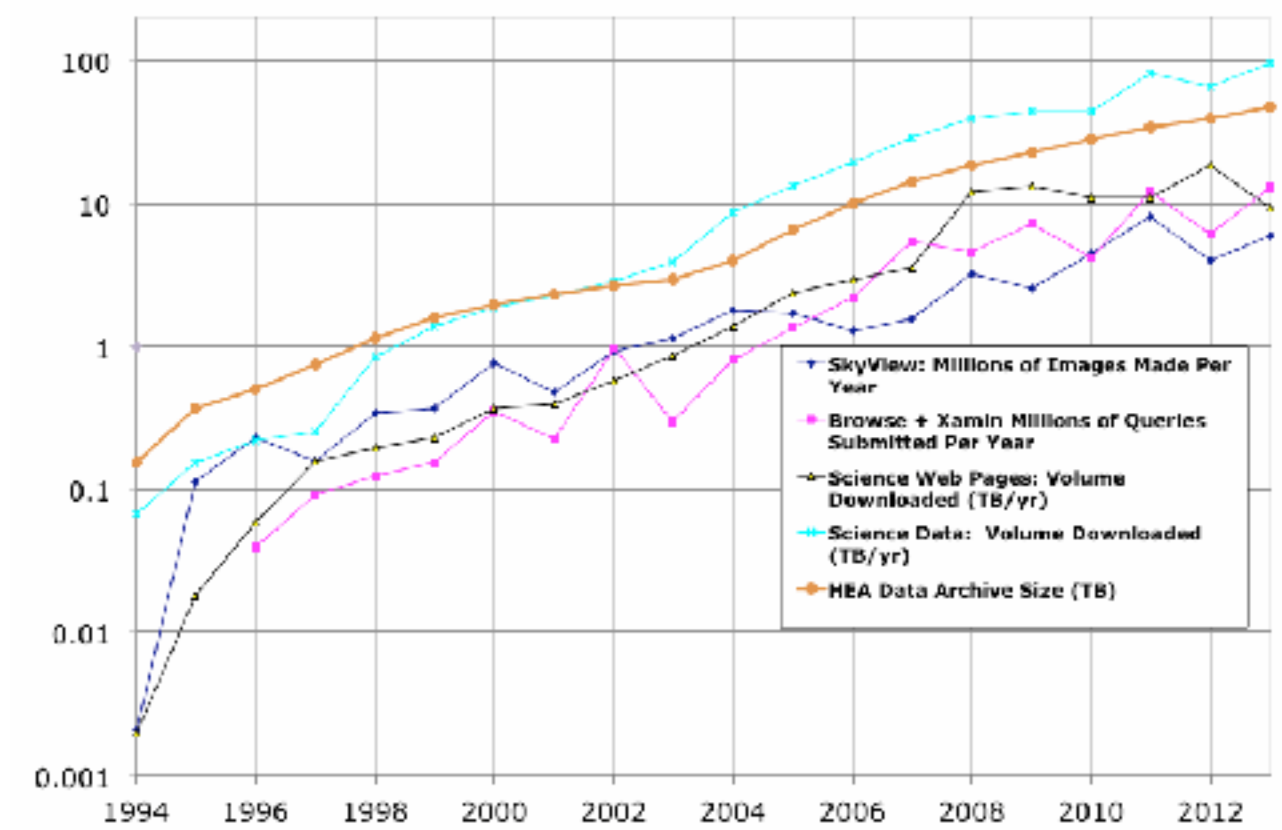
Roland Walter

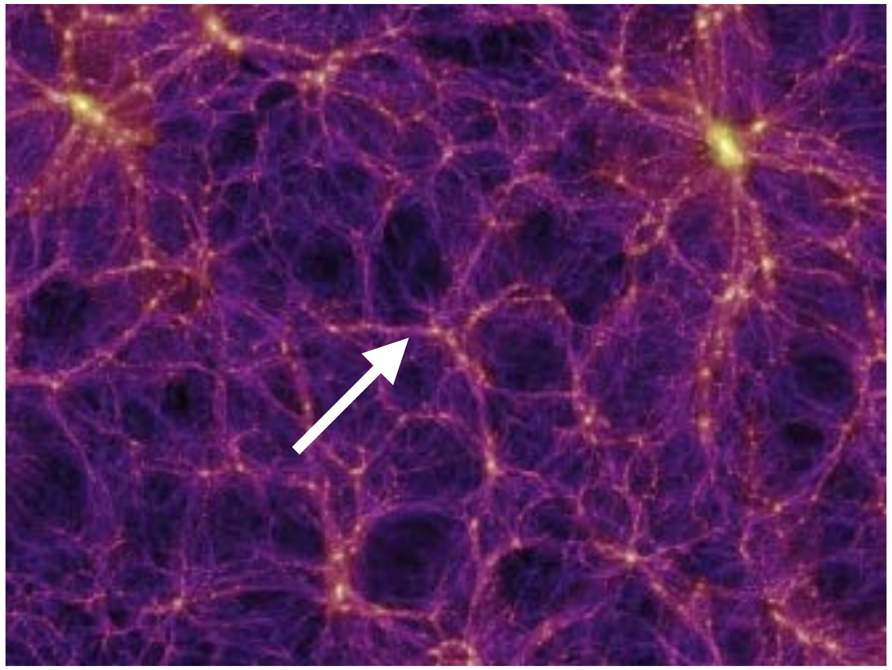
UNIVERSITÉ DE GENÈVE


Refuge des Cosmiques
Physics
AMS/Dampe/Polar
Astronomy
INTEGRAL/Gaia/Polar/Euclid/Cheops
AMS/LHC CC
LHCb
CMS
ATLAS
ALICE

Astronomy vs Space Science vs Data







Space Science Mission DATA

Science and Drivers

Science Mission Elements

Data Handling

Development Management

Data is the Legacy

Light is Emitted by Particles

10^{25} protons @ 200 km/h ~ 10^{12} GeV

Energy	*Cosmic rays*	*Photons*
10^{12} GeV	1 $(10\text{km})^{-2}$ y^{-1}	1 earth^{-1} y^{-1}
10^{3} GeV 	1 m^{-2} min^{-1}	10 m^{-2} y^{-1}
1GeV	10'000 m^{-2} sec^{-1}	1 m^{-2} sec^{-1}

ground

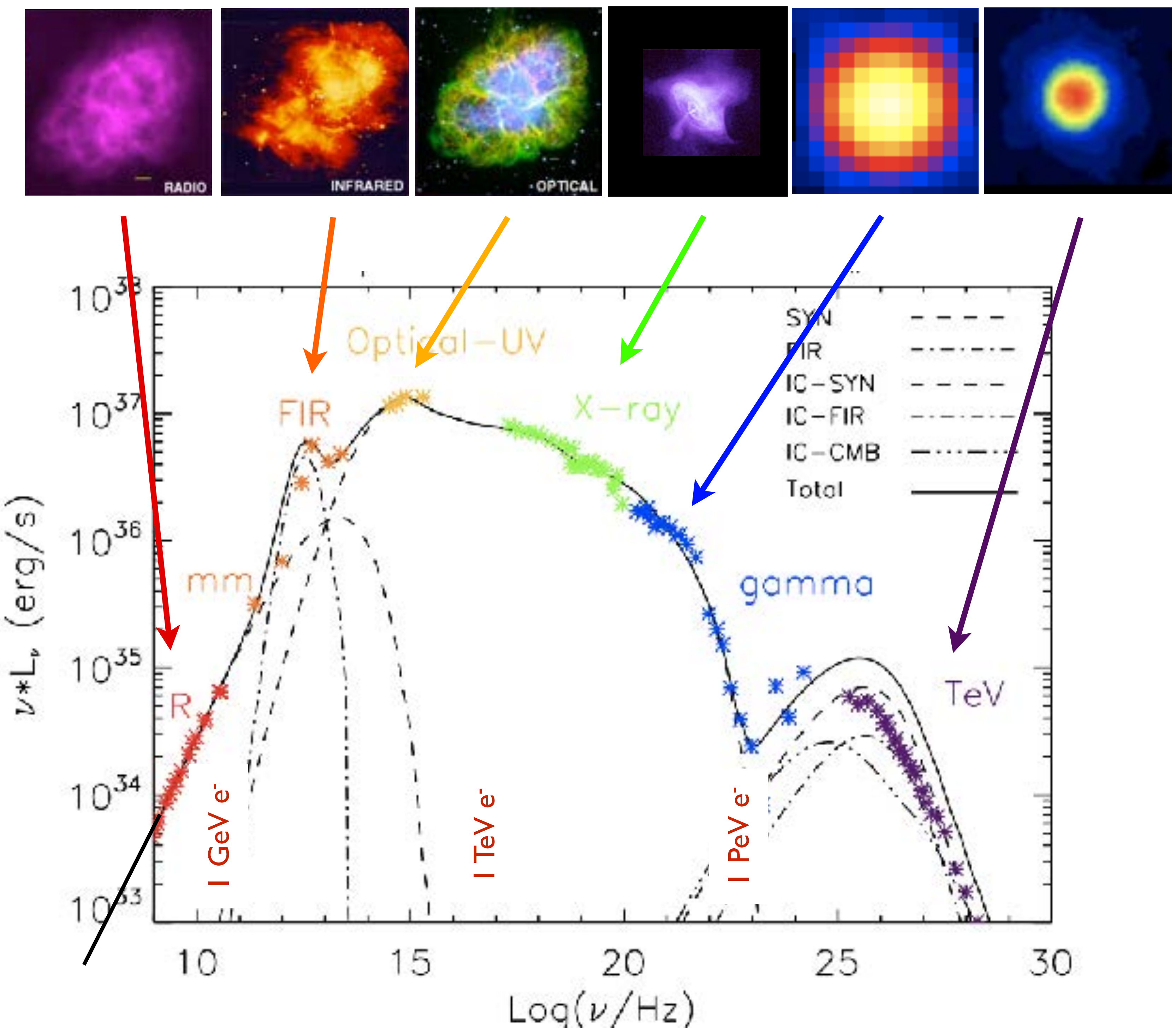
space

- Strong gravitational field
- Strong magnetic field
- Diffuse Shock Acceleration
- Radioactivity/Annihilation

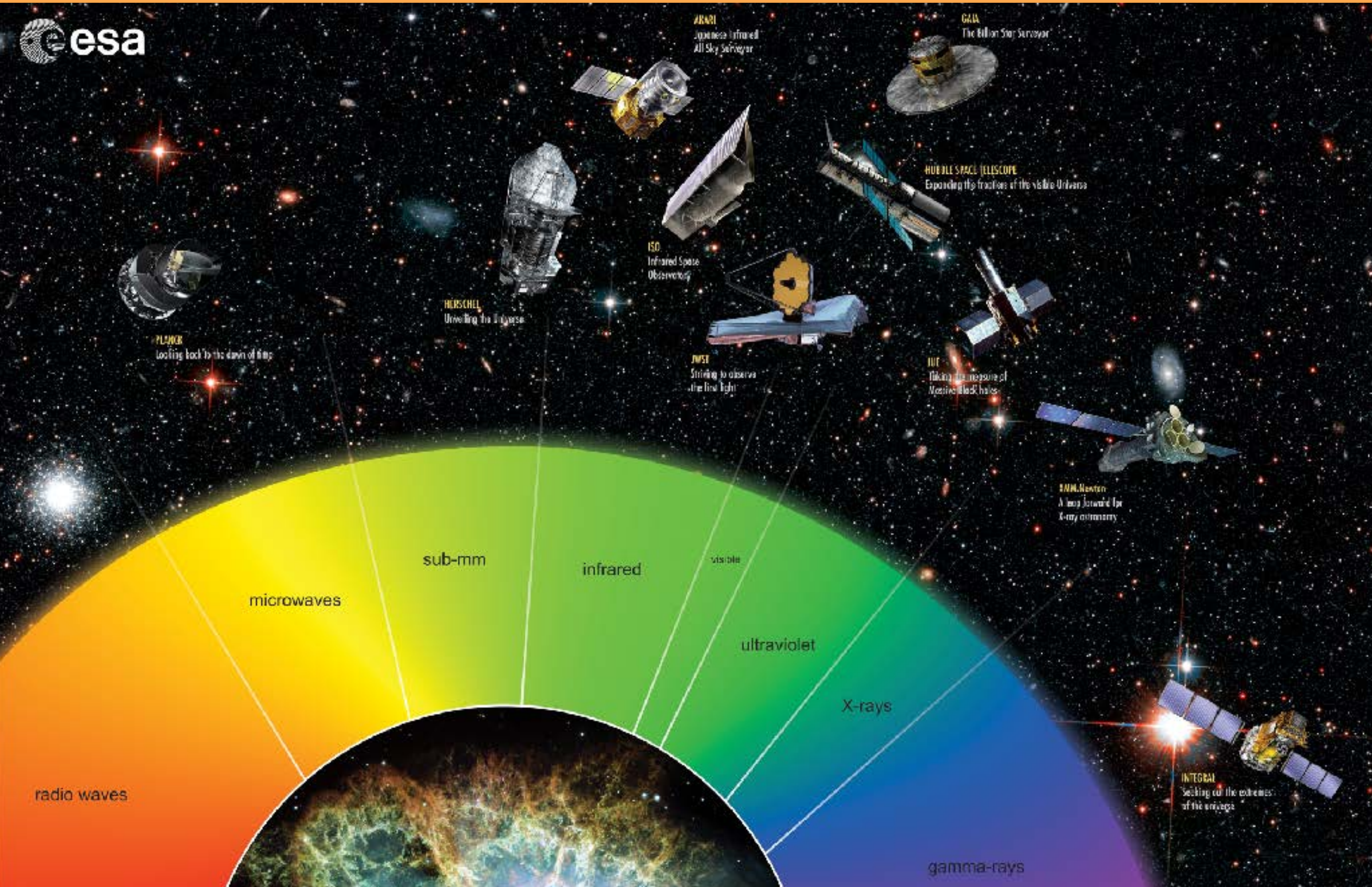
Multi-Wavelength Astronomy

Crab Nebula

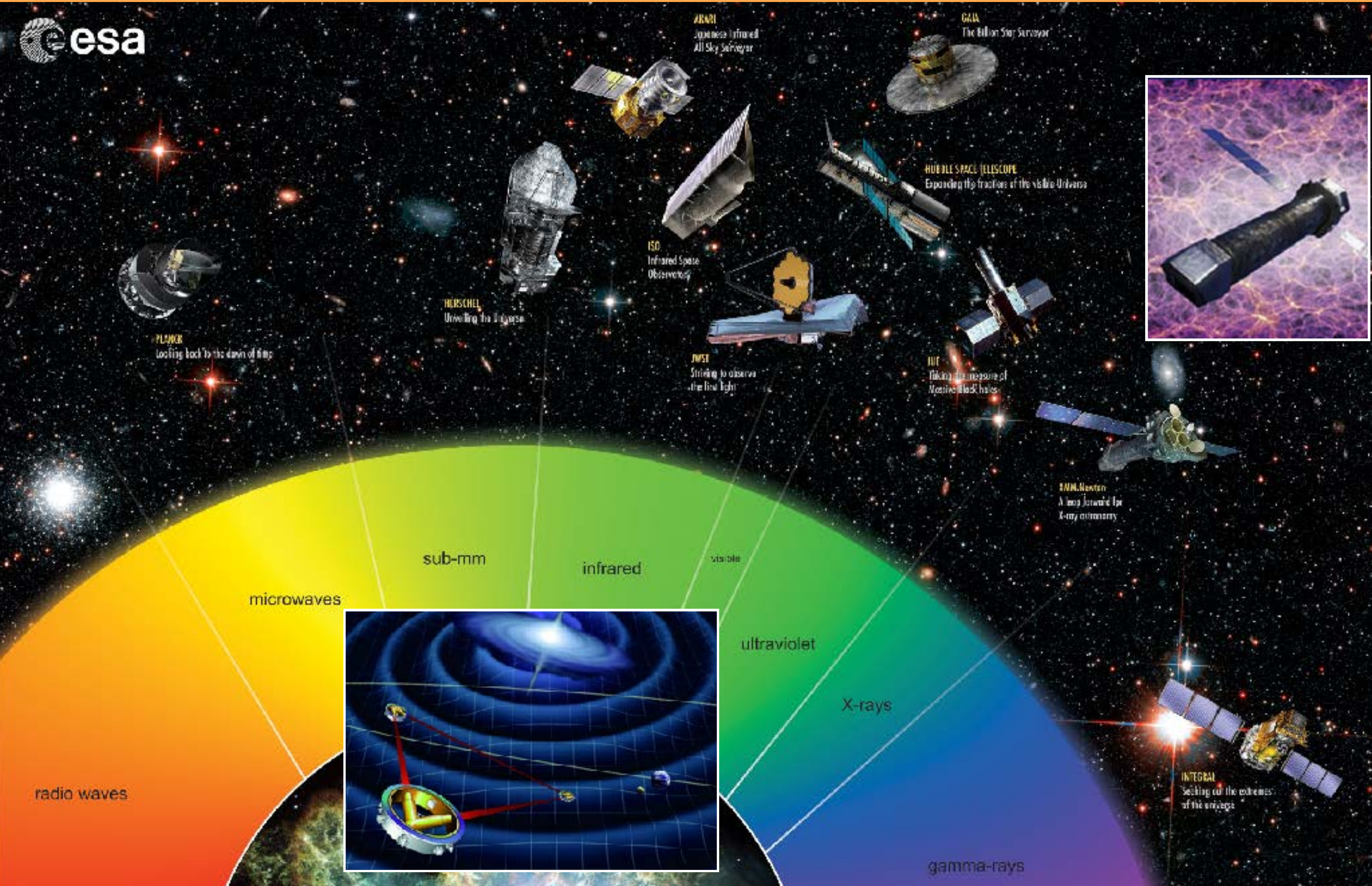
Most energetic (PeV=10^{15} eV) electrons ever detected in the Universe



Space Science Missions
Across the Electromagnetic Spectrum

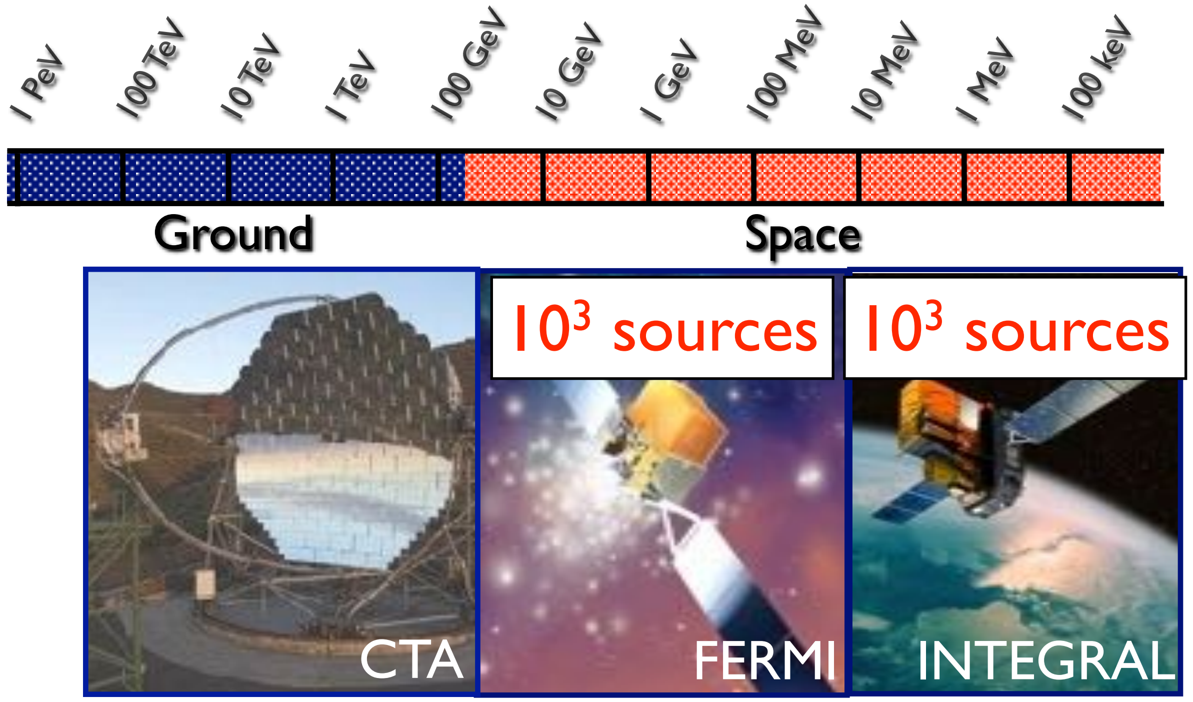


Space Science Missions
Across the Electromagnetic Spectrum

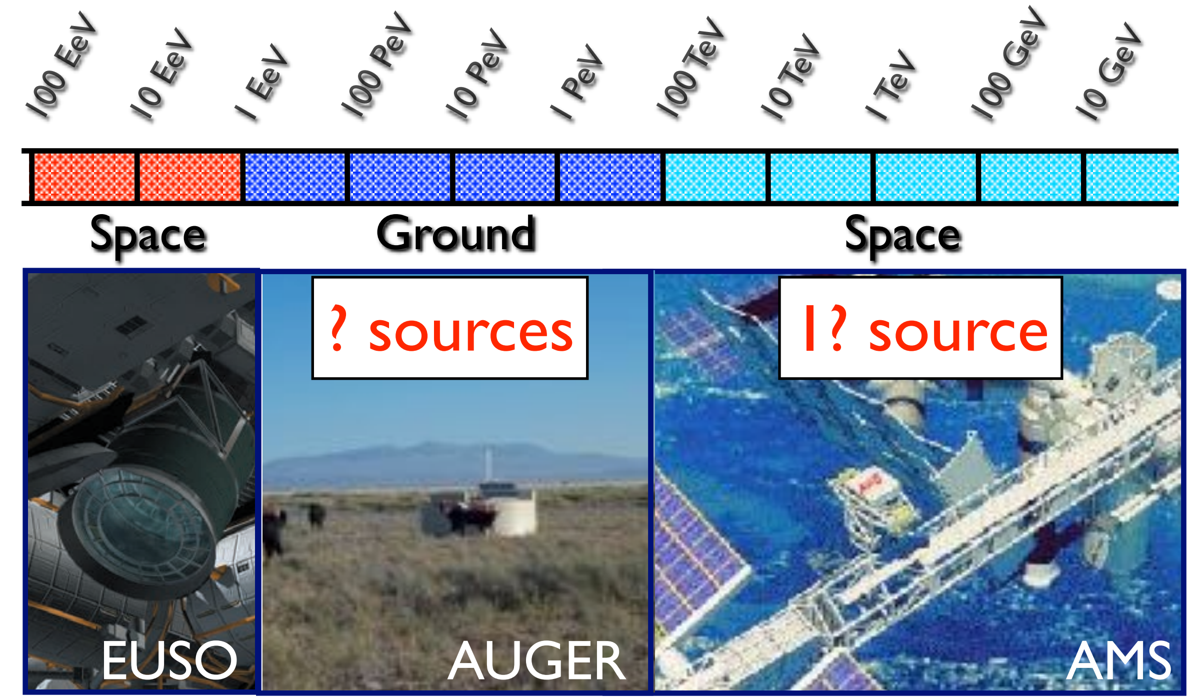


Astrophysics of the 21th Century

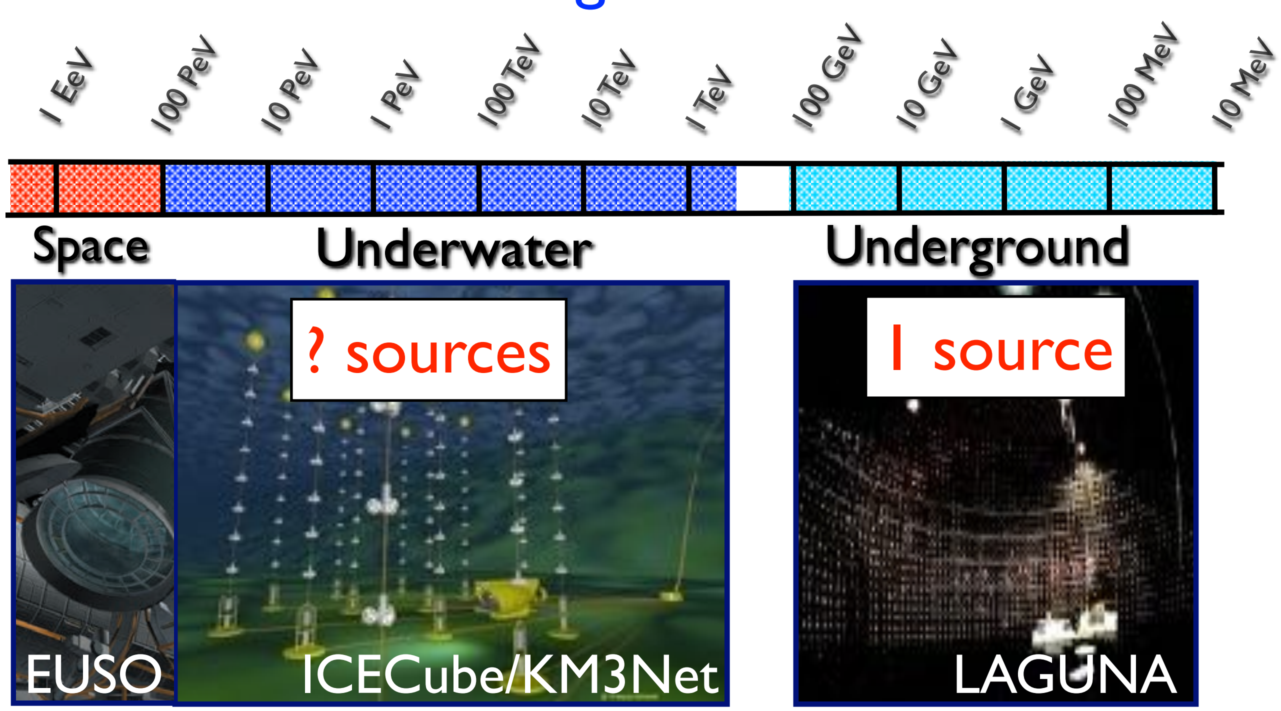
Detecting photons



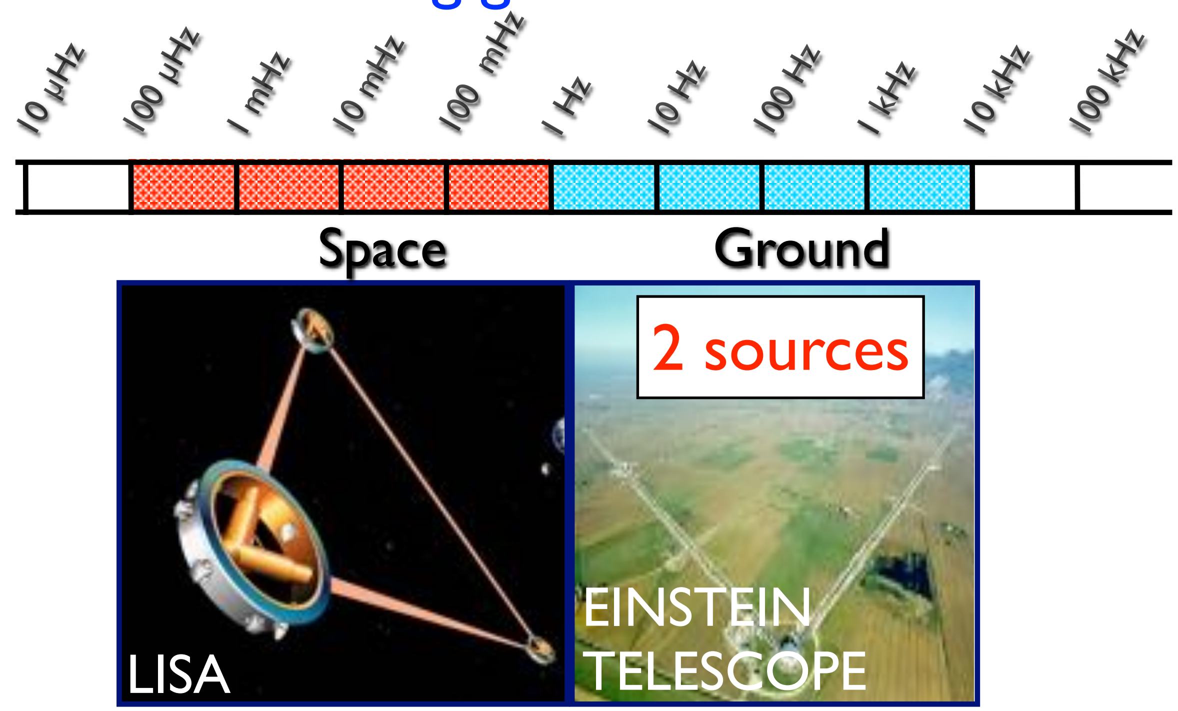
Detecting particles



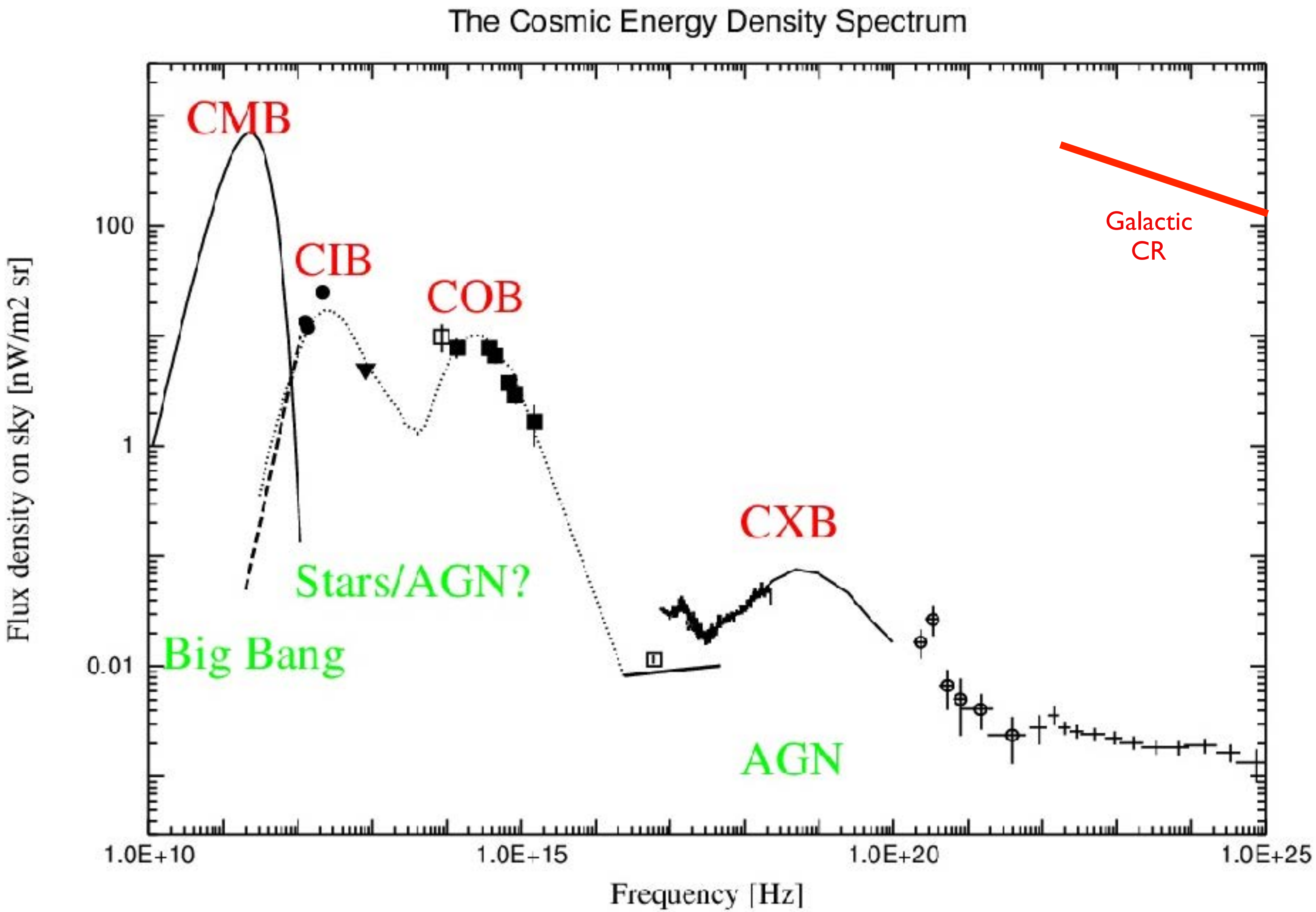
Detecting neutrinos



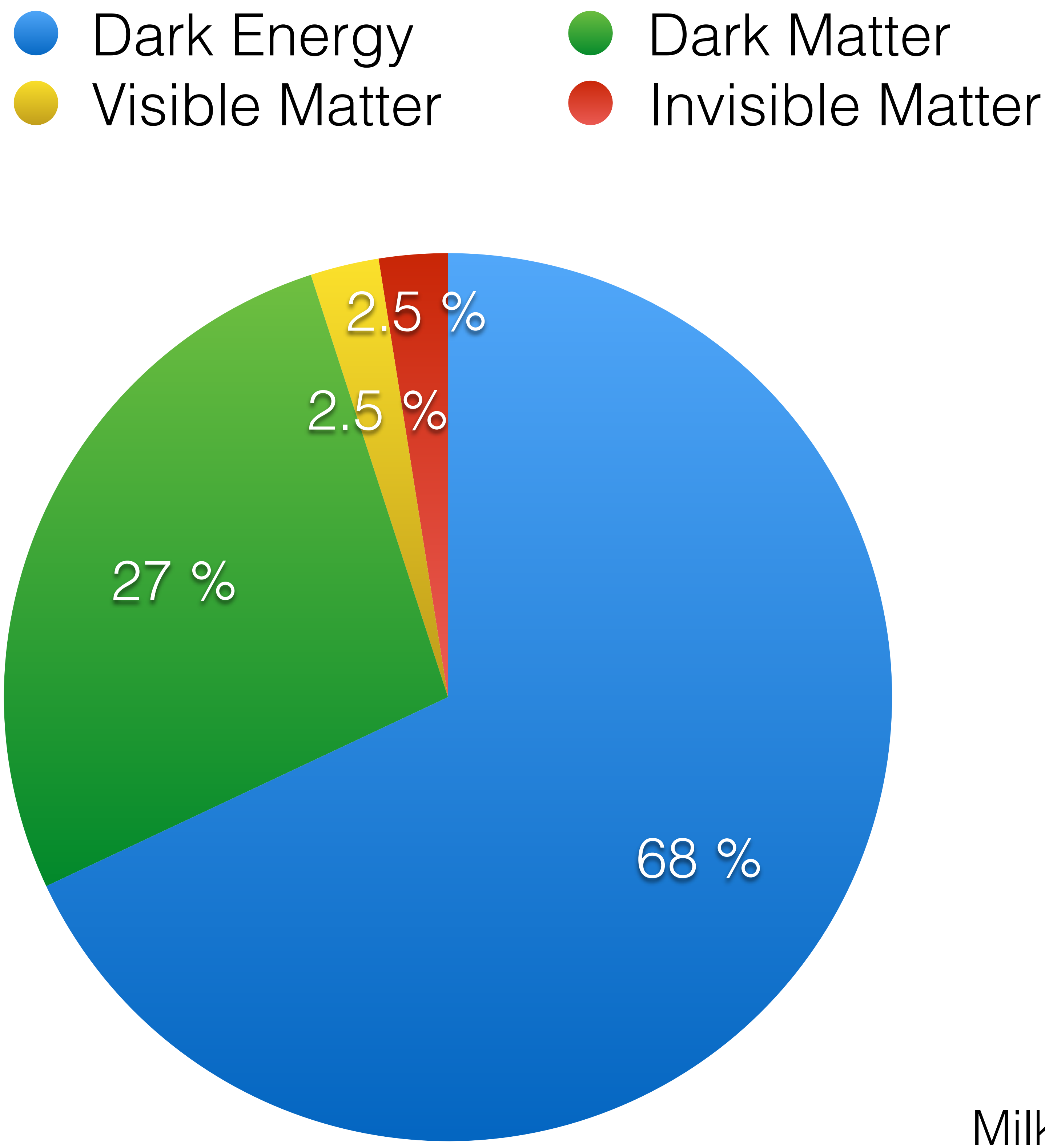
Detecting gravitational waves



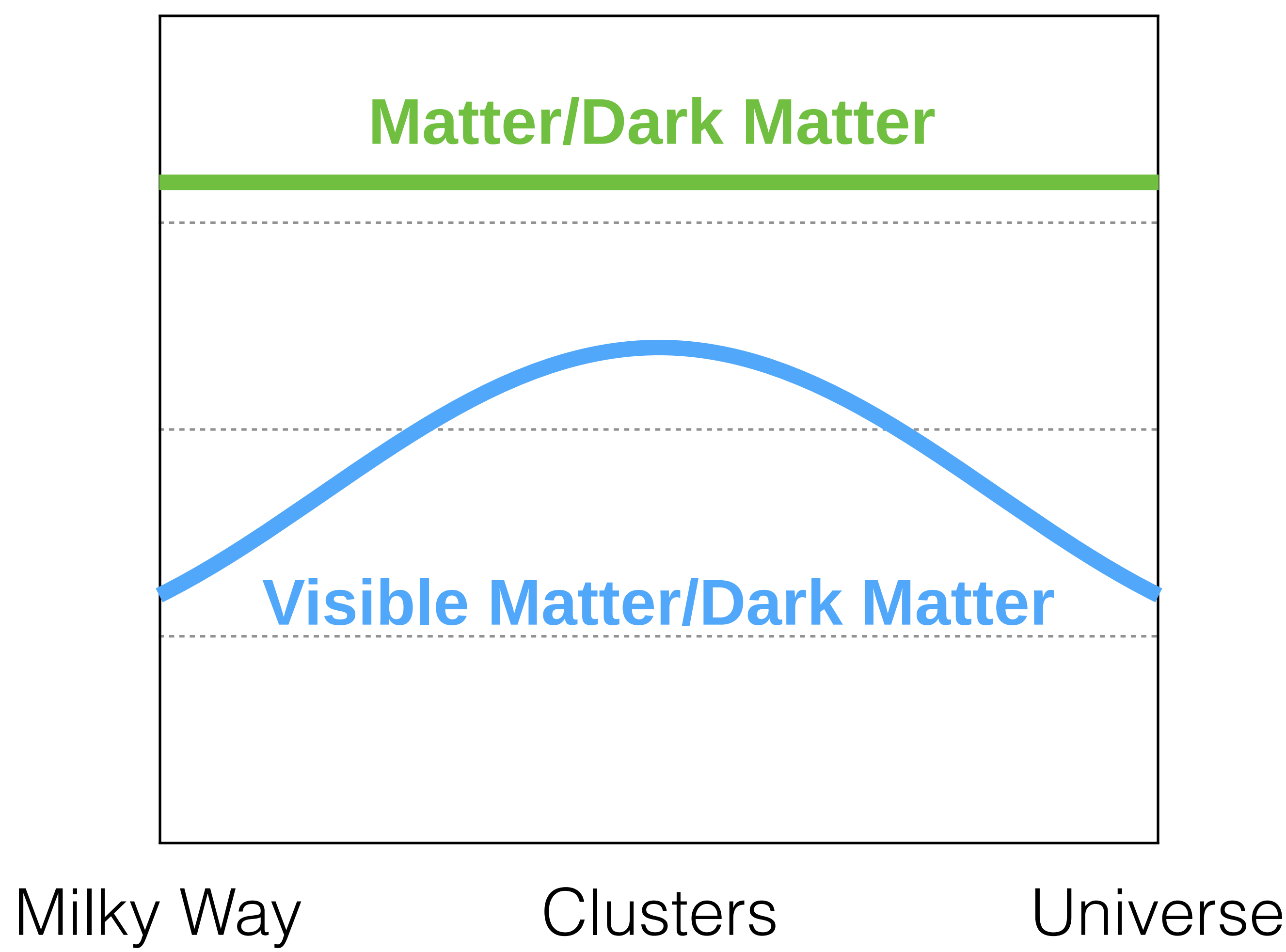
Radiation in the Universe



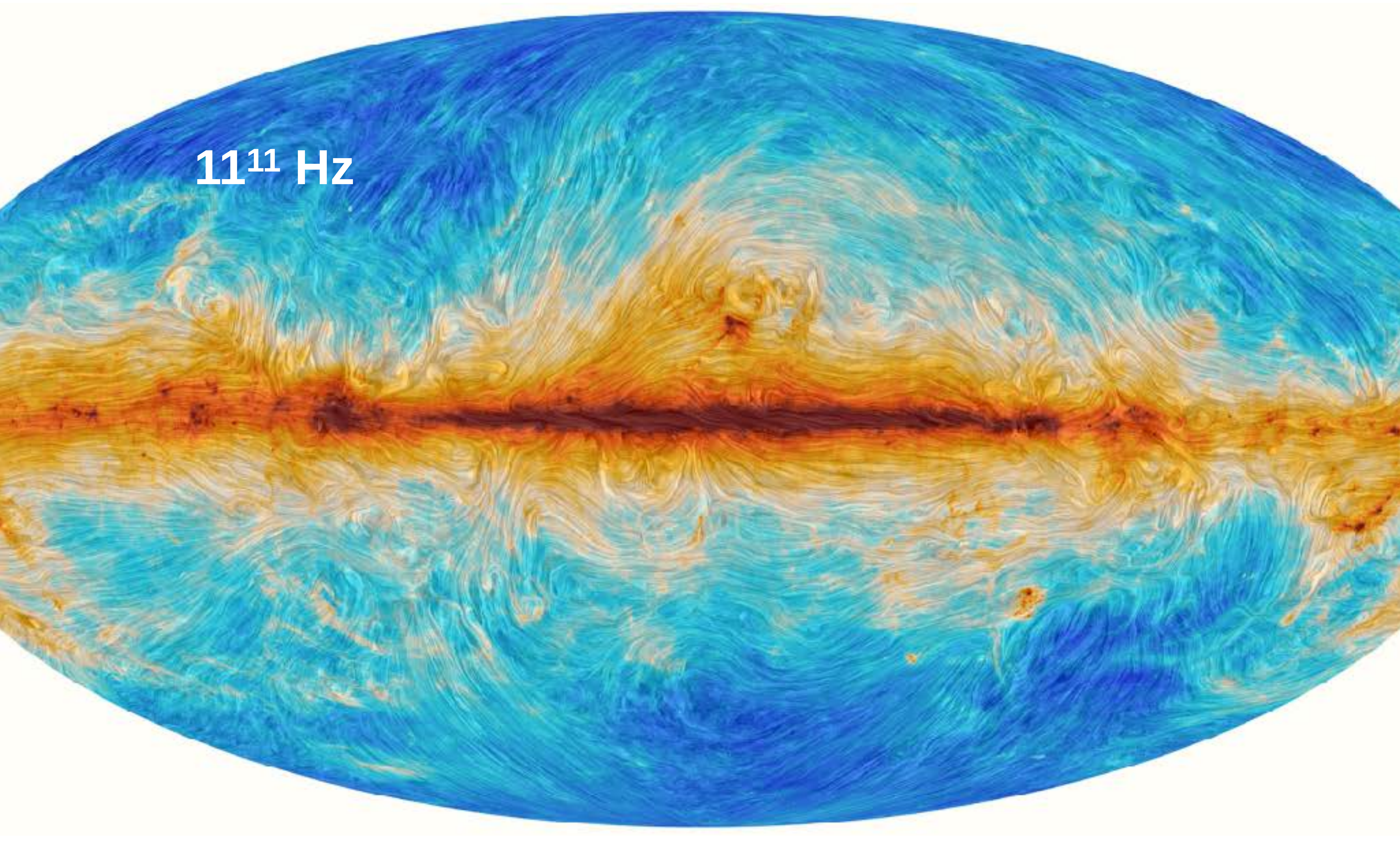
Matter in the Universe



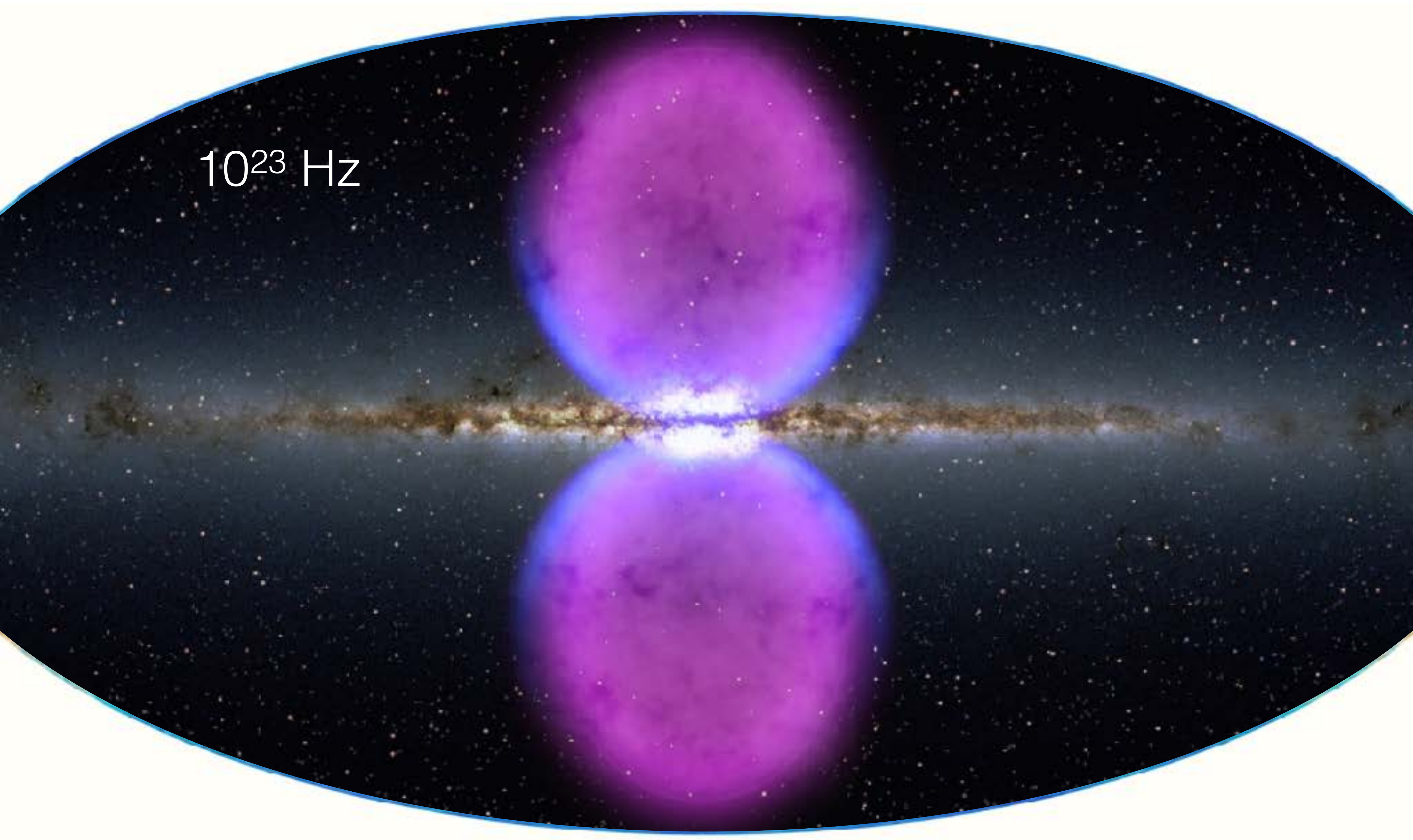
Baryons are missing at all scales



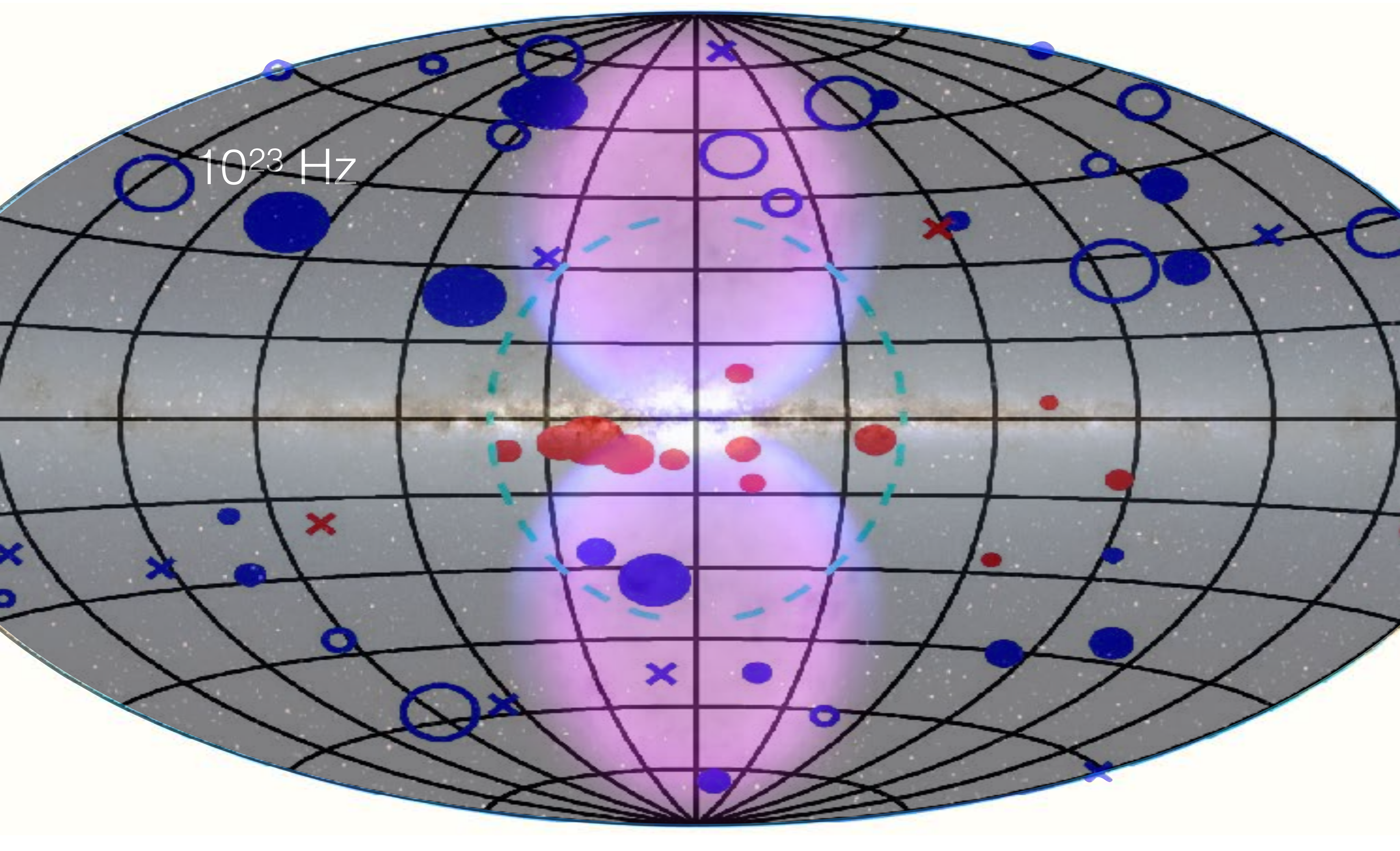
Particle Acceleration and Feedback



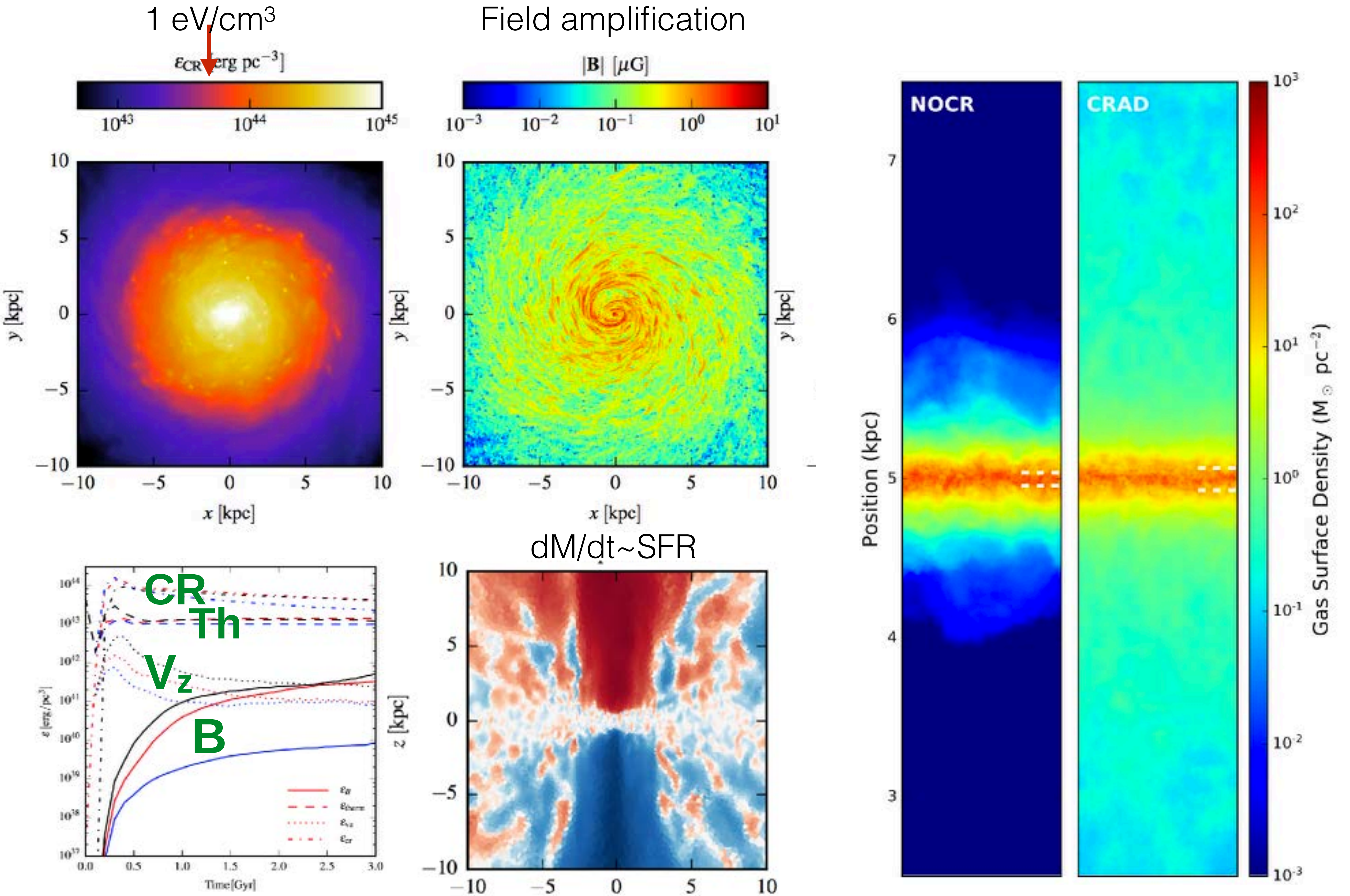
Particle Acceleration and Feedback



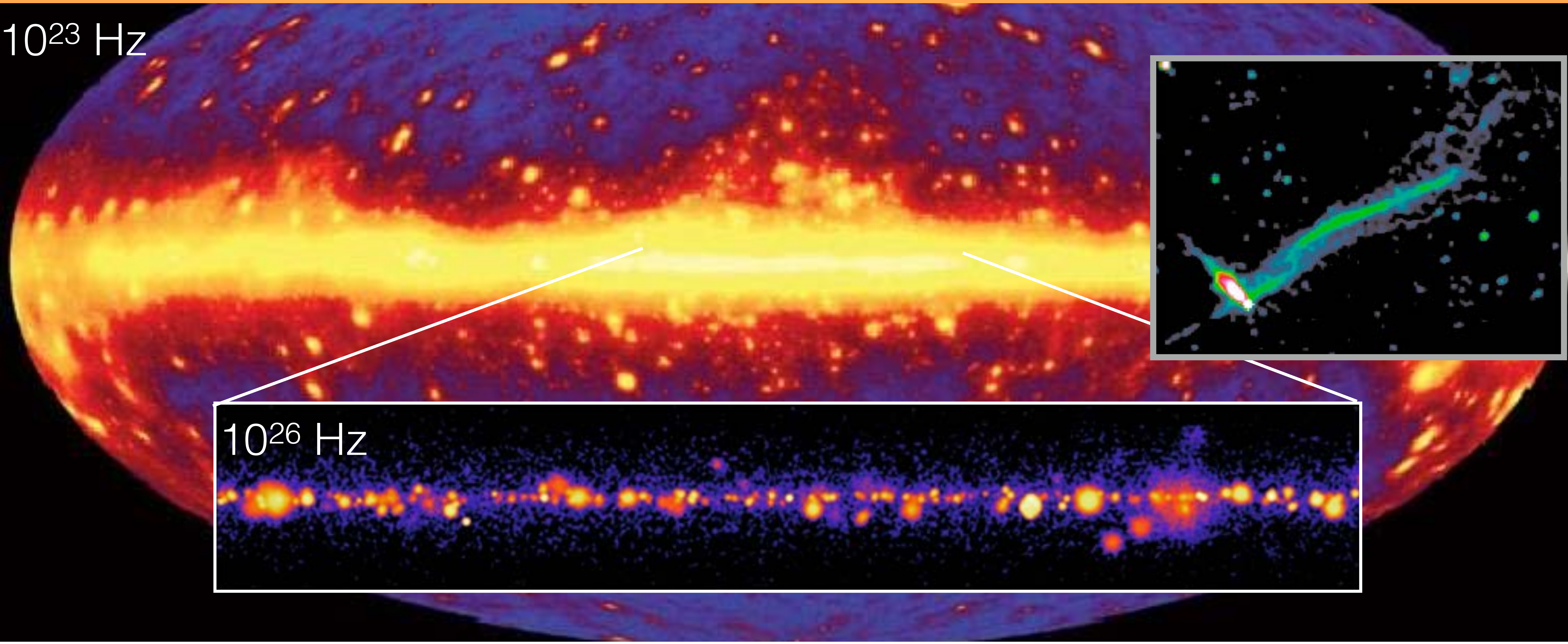
Particle Acceleration and Feedback



Anisotropic CR Diffusion



The Milky Way at Gamma-Rays

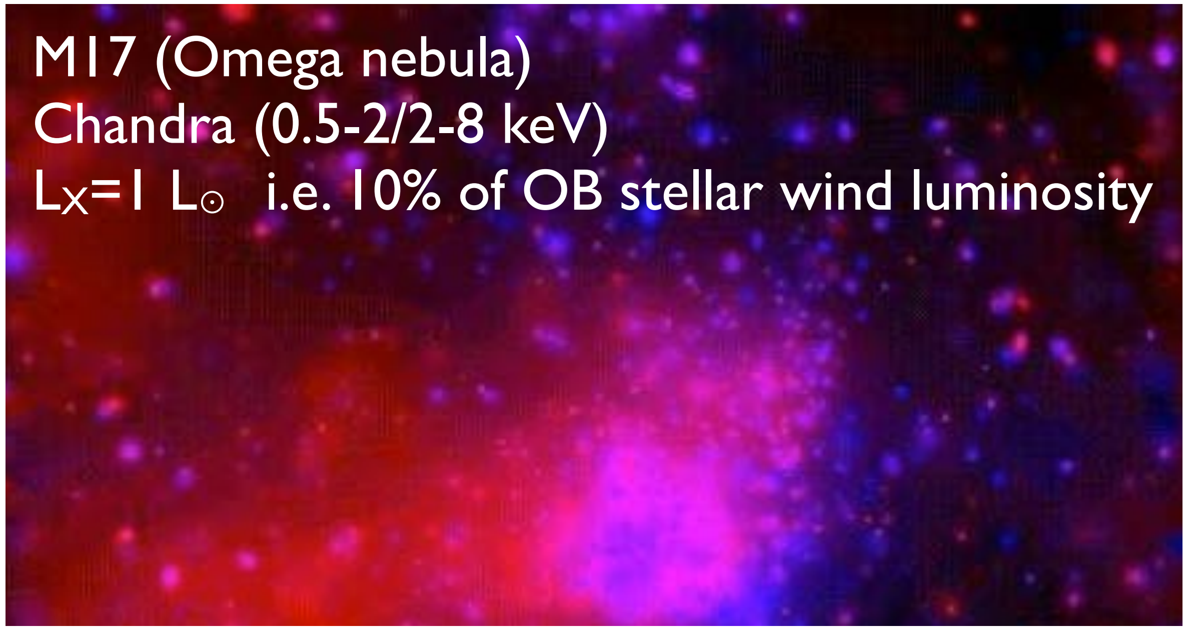


Accelerators:

1 Supernova Remanents

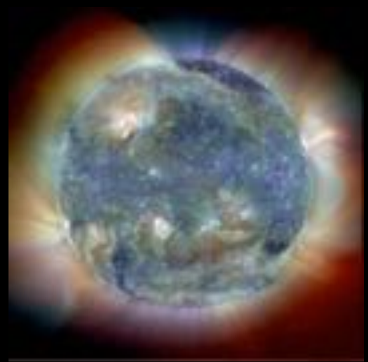
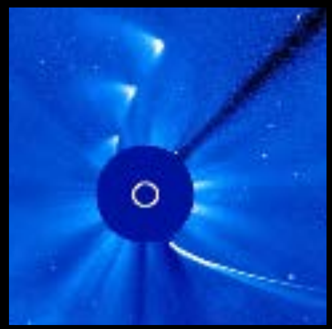
2 Wind collisions in OB regions

3 ....

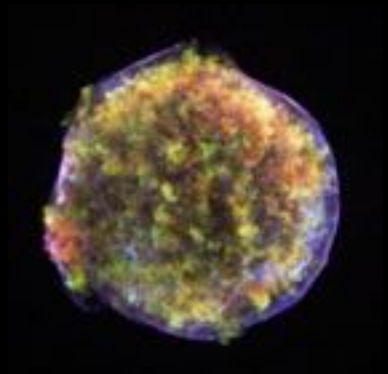


Cosmic Accelerators

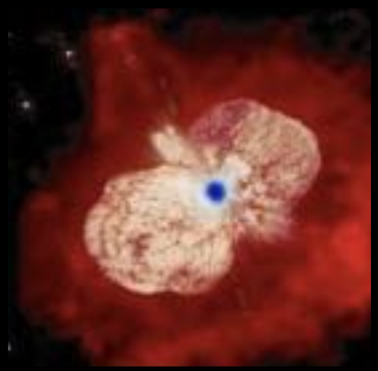
Stars

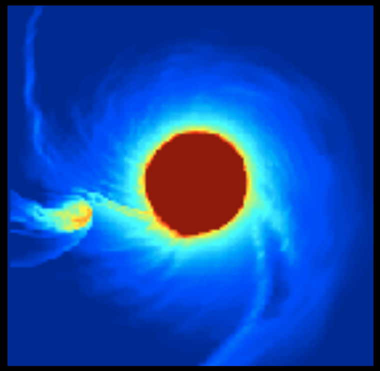
Supernova Remnants

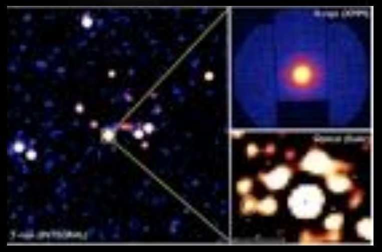


Wind Collisions



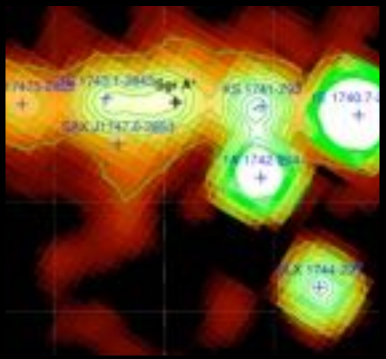

Compact Objects



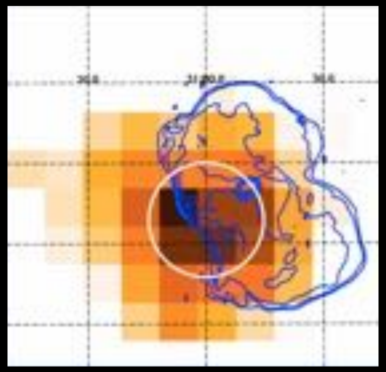


Pulsar Winds

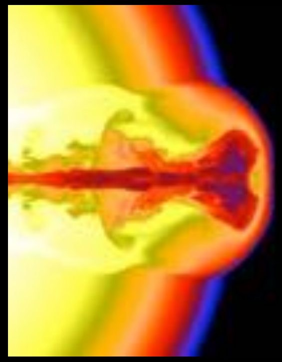

Super-massive Black-Holes



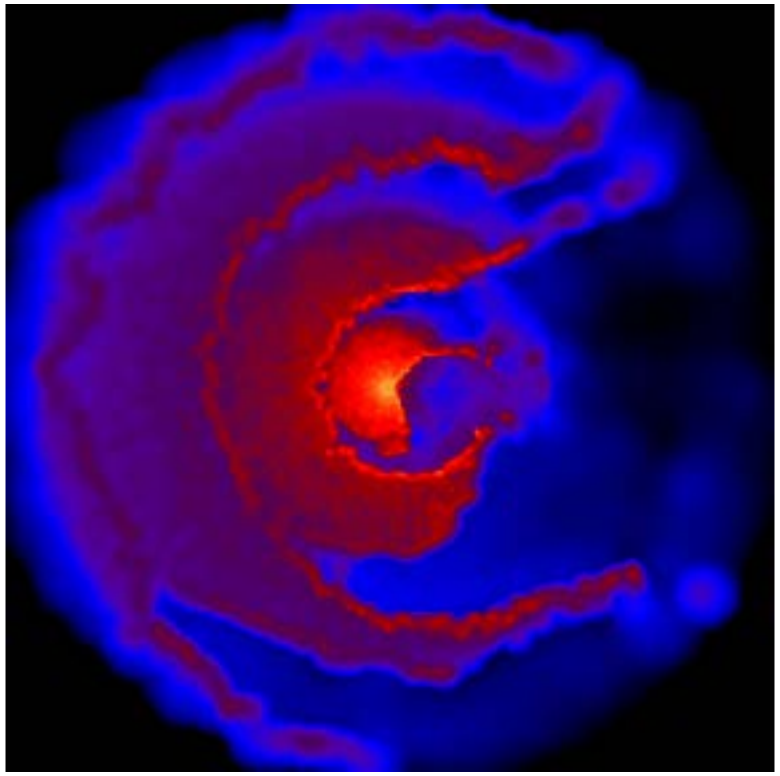

Clusters

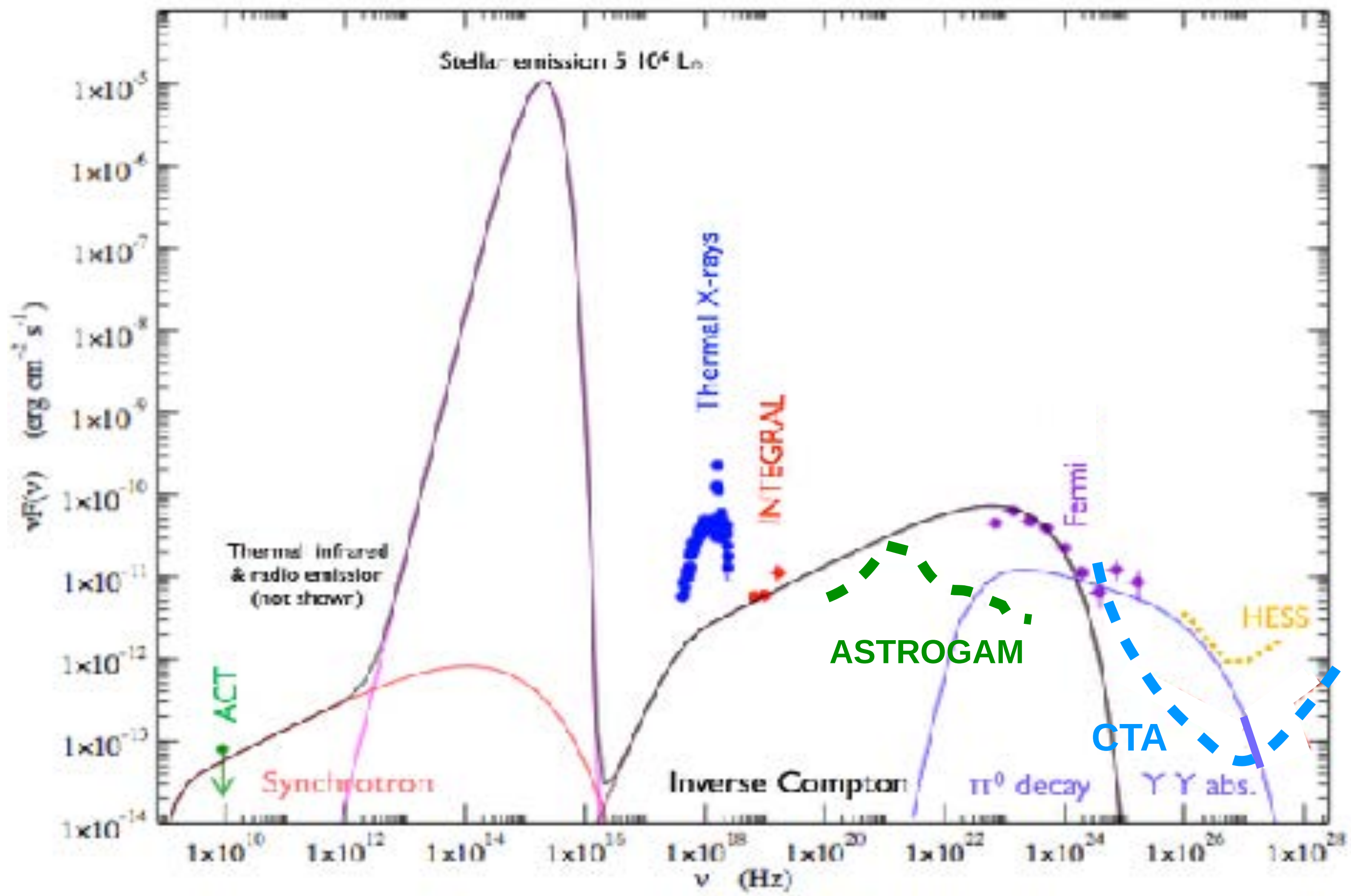


Gamma-Ray Burst

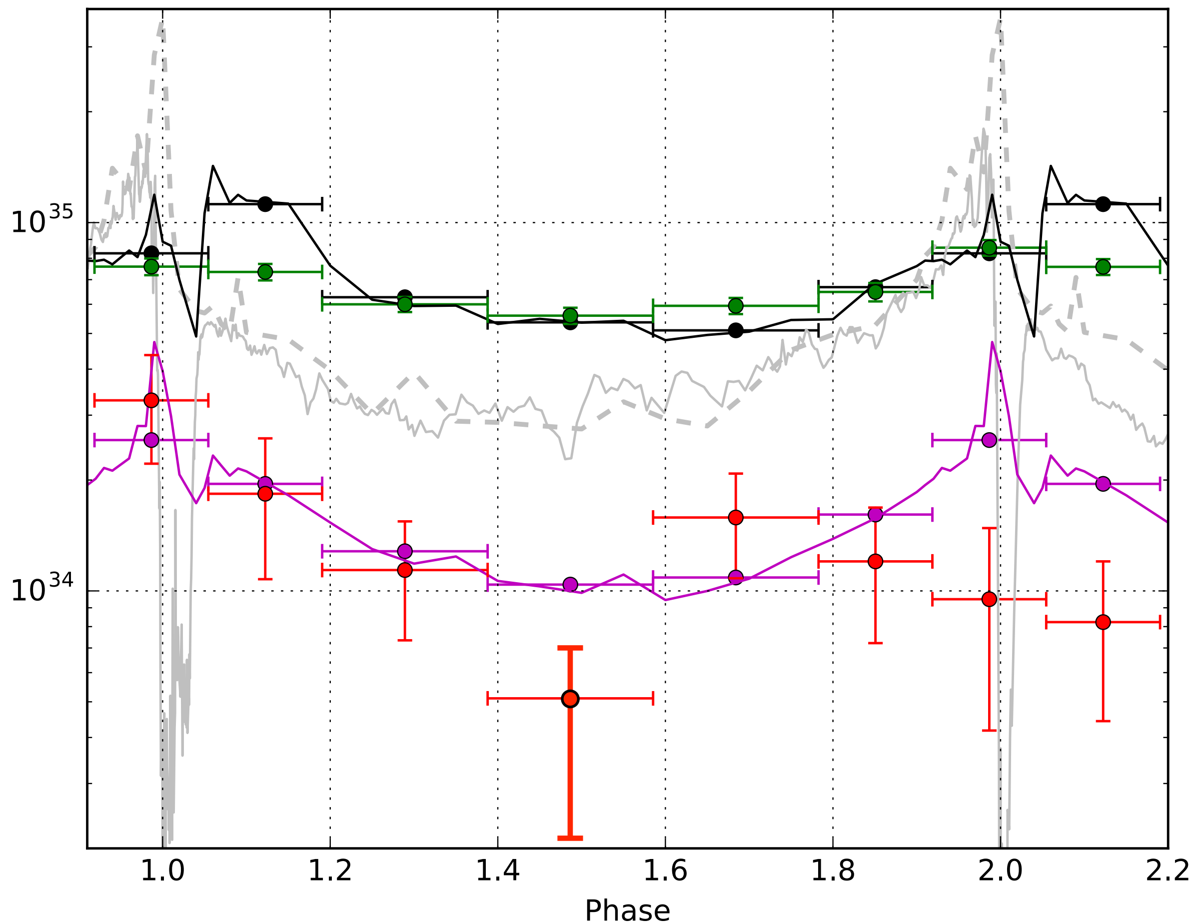


Eta Carinae



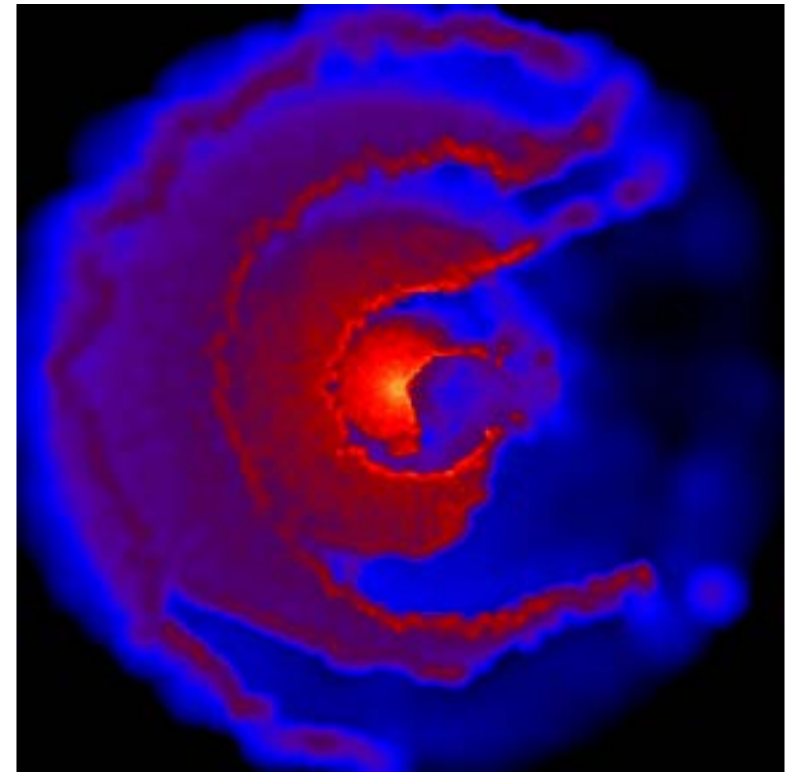


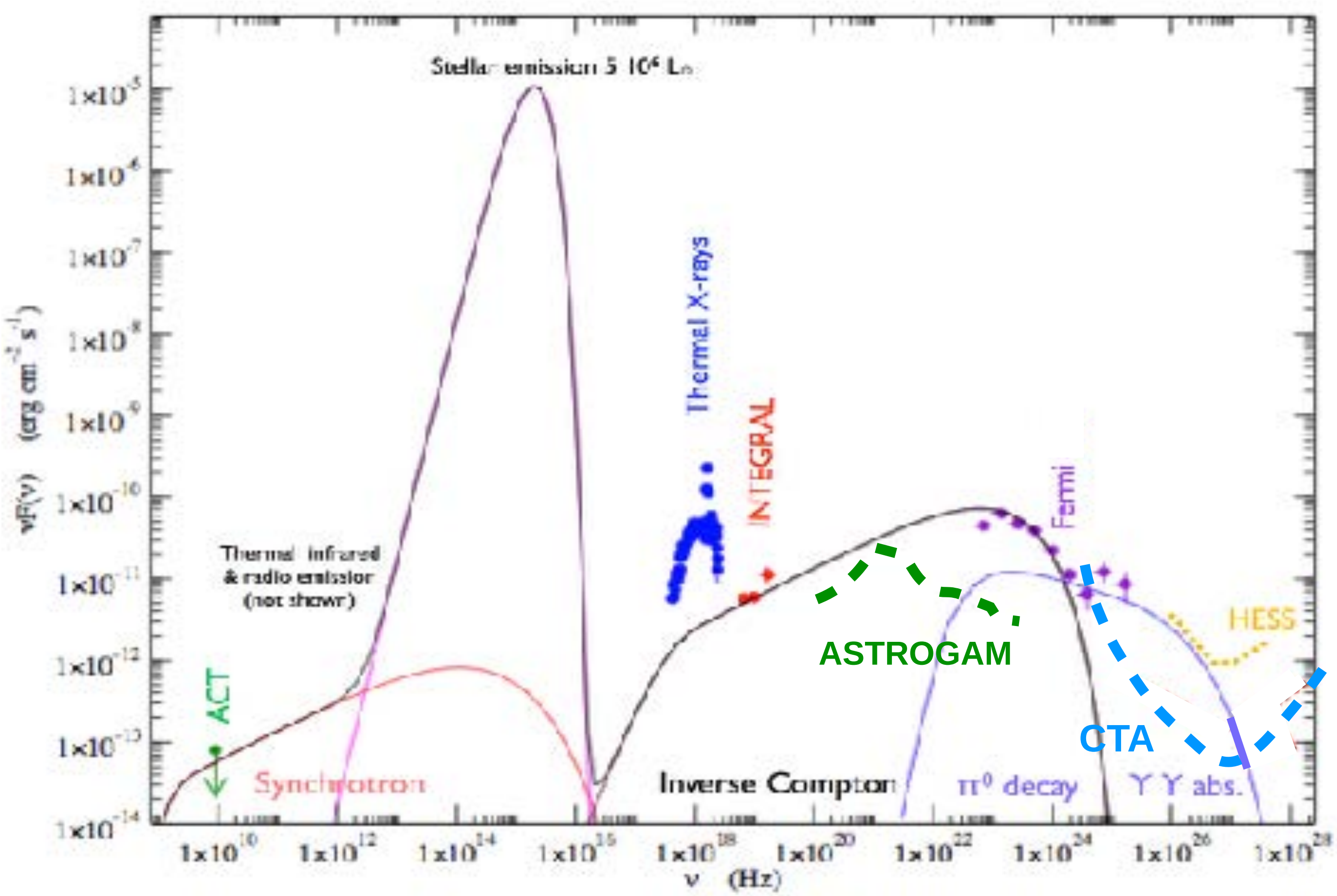
Thermal X-rays
INTEGRAL
Fermi
HESS
ASTROGAM
CTA
ACT
Thermal infrared & radio emission (not shown)
Synchrotron
Inverse Compton
π0 decay
γ γ abs.
ν (Hz)



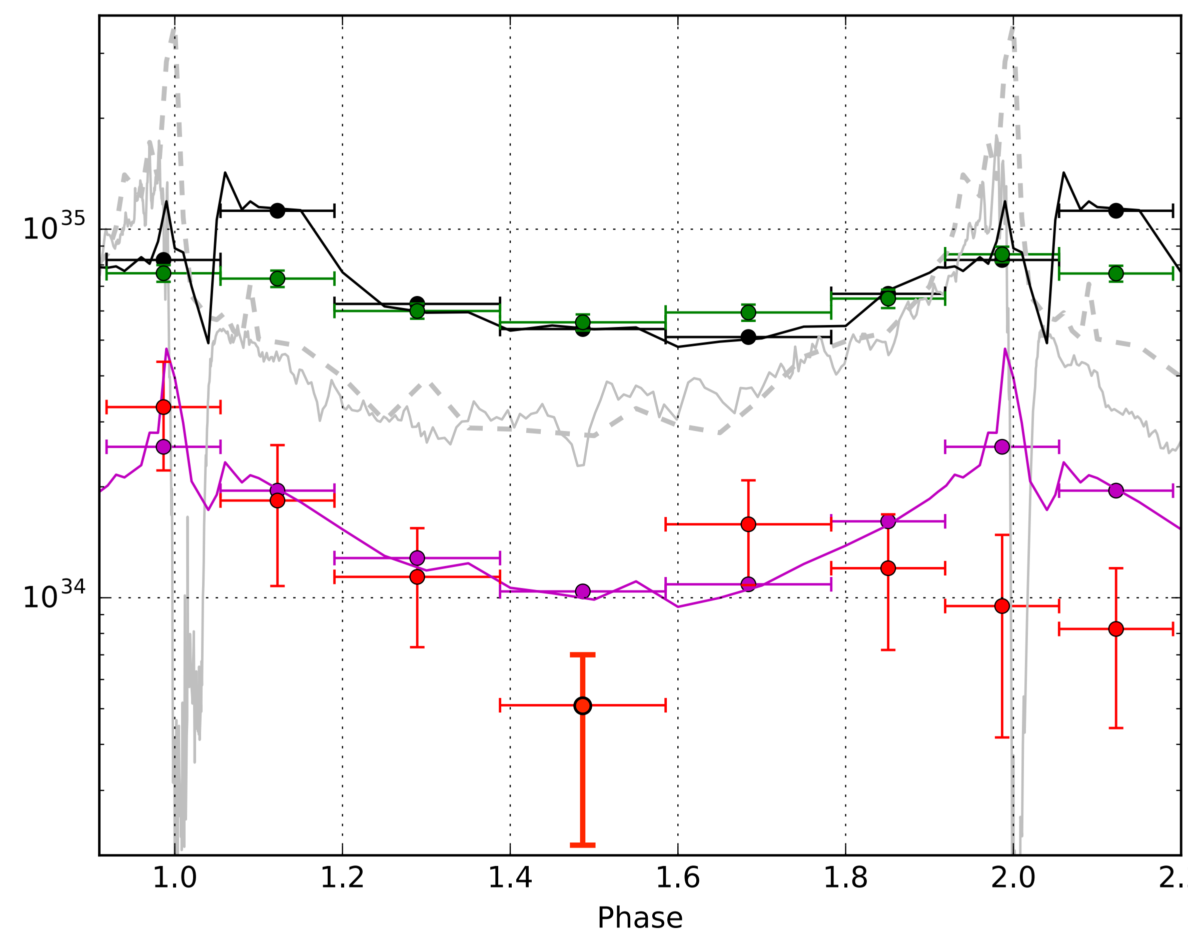
10^{35}
10^{34}
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Phase

Eta Carinae





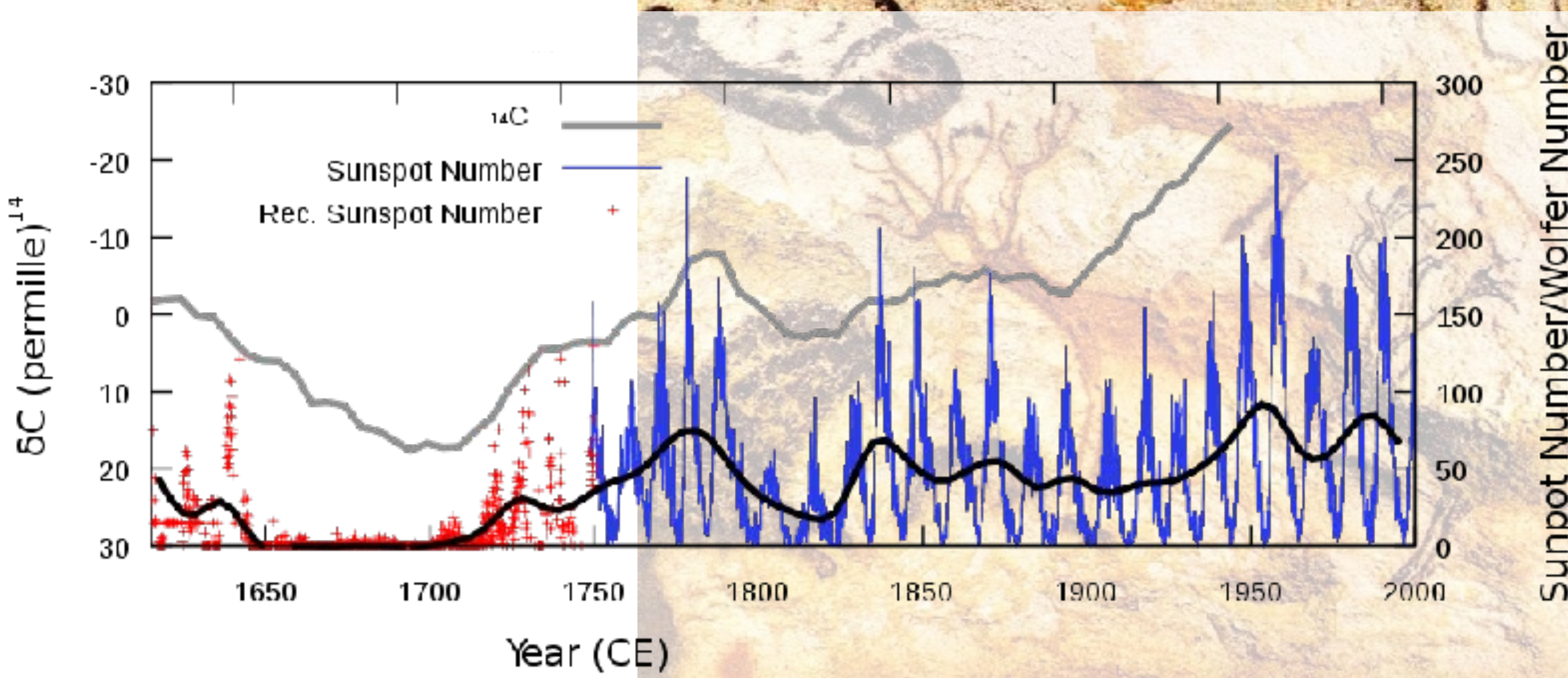
Thermal X-rays
INTEGRAL
Fermi
HESS
ASTROGAM
CTA
ACT
Synchrotron
Inverse Compton
π⁰ decay
γ γ abs.
Thermal infrared
& radio emission
(not shown)
ν (Hz)



10^35
10^34
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Phase

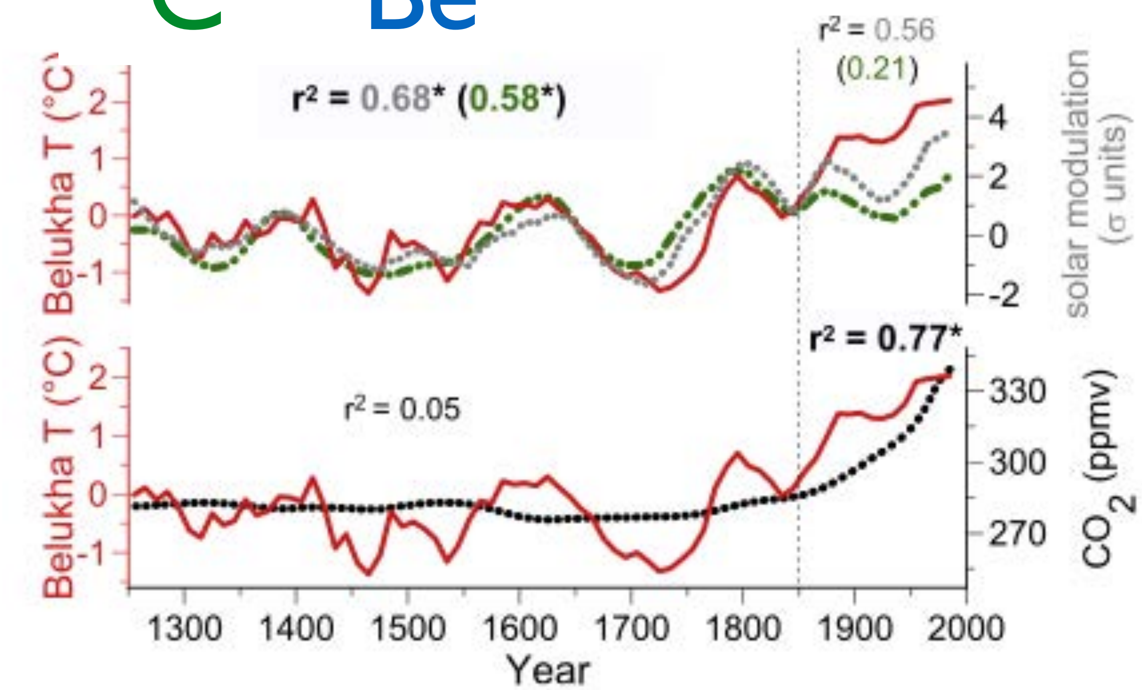
Feedback on Earth: Carbon 14

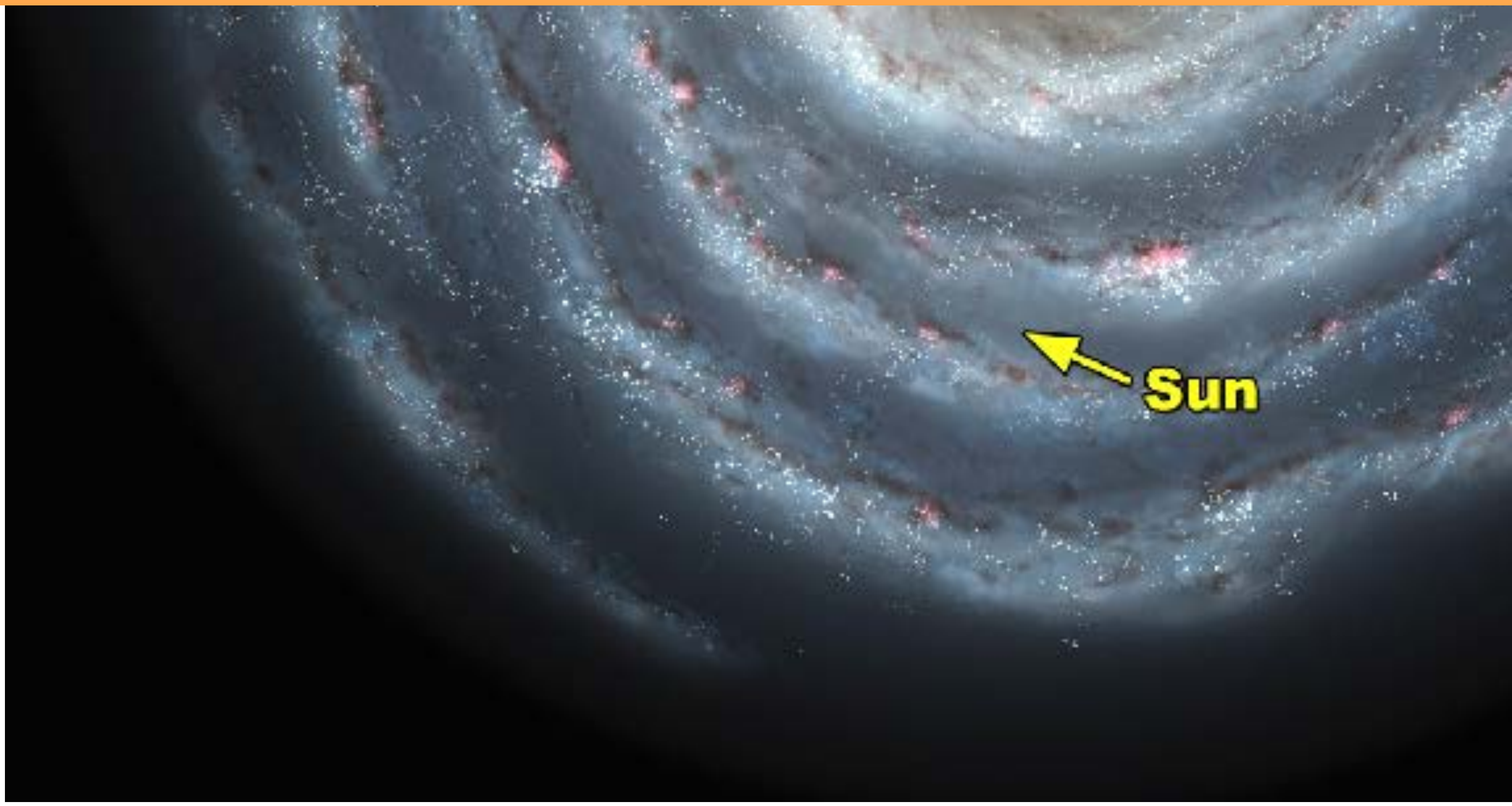
$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}p$$



Feedback on Earth: Climate

^{14}C ^{10}Be





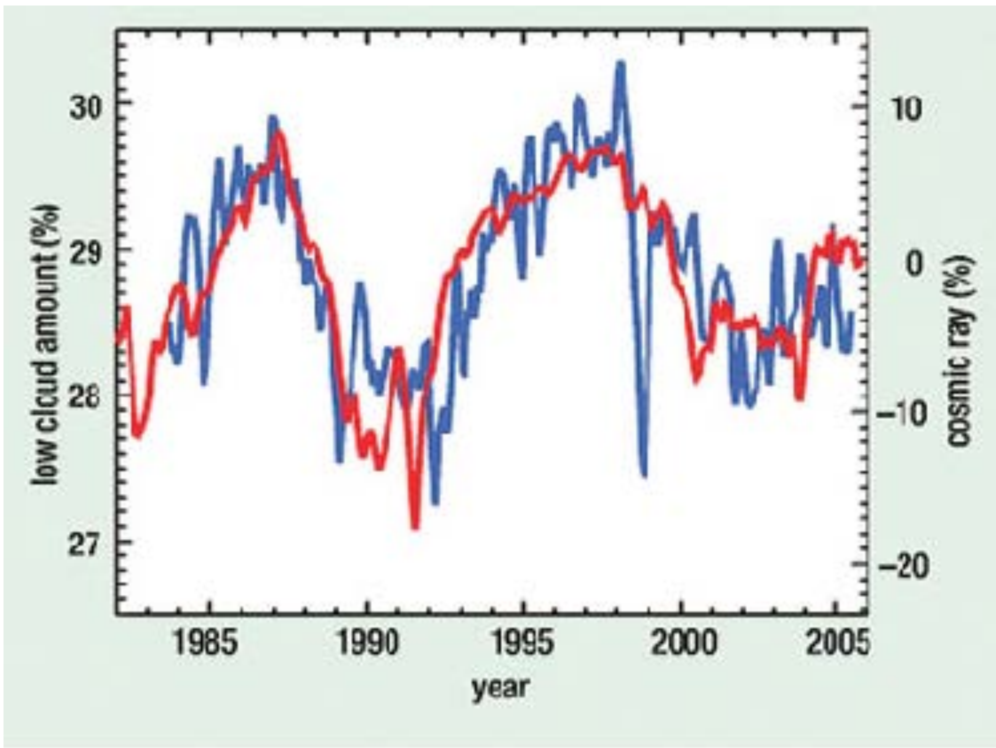


Figure 2. Global variation in cloud amount for clouds below 3.2 kilometers above sea level (blue line) compared to the anomaly in cosmic ray counts at Climax, Colorado (red line).[6]

Atmosphere transparency

Cloud formation

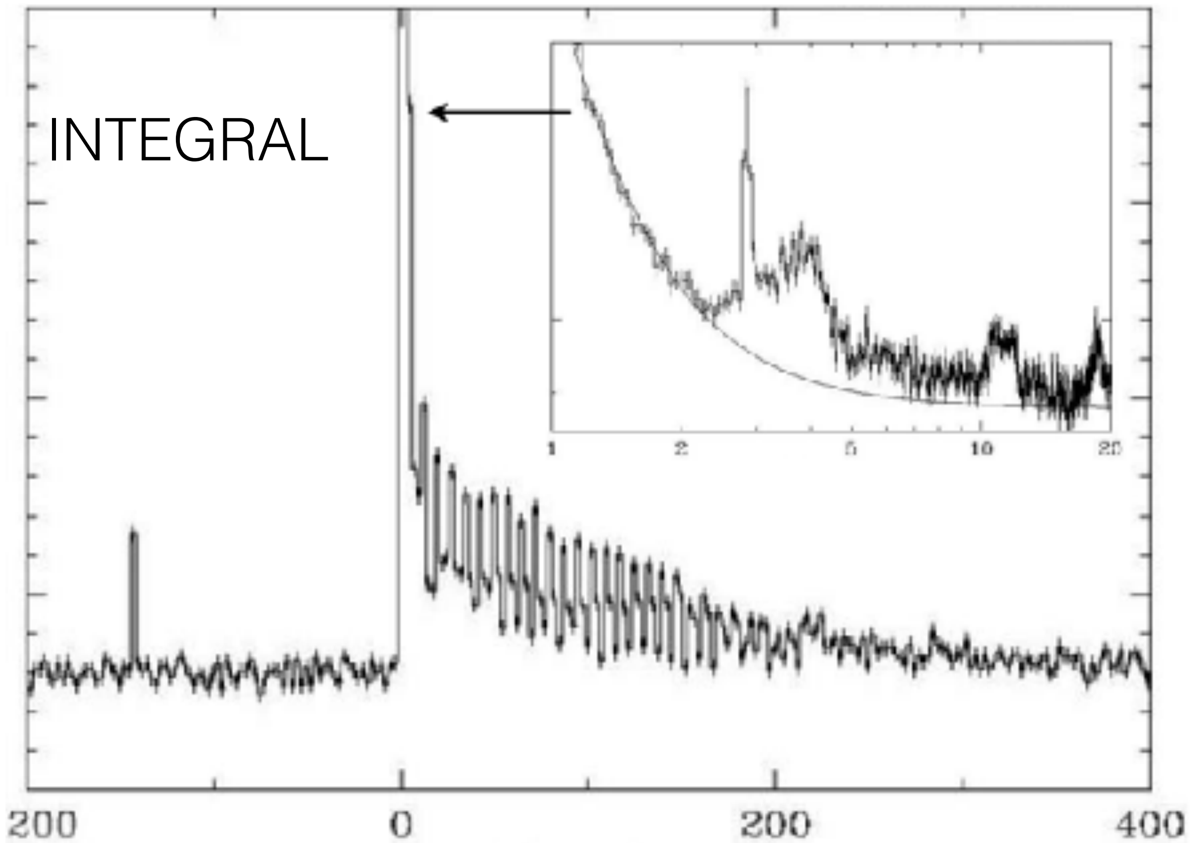
Feedback on Humans: Irradiation

~1Sv/y

Gamma-Ray feedback on Earth

Giant flares from Magnetars

SGR 1806-20 - Dec 24, 2004



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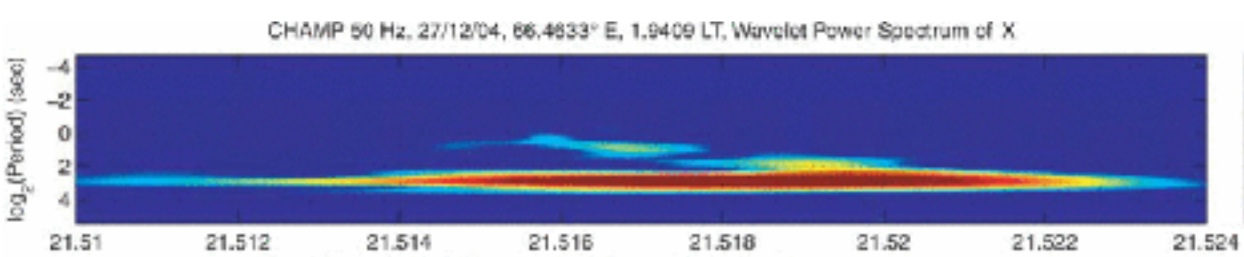
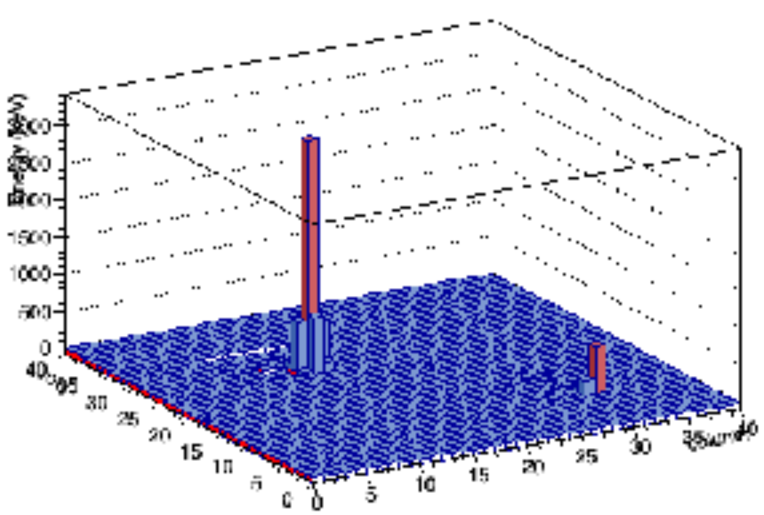


Gamma-Ray Bursts



SCIENCE MISSION ELEMENTS

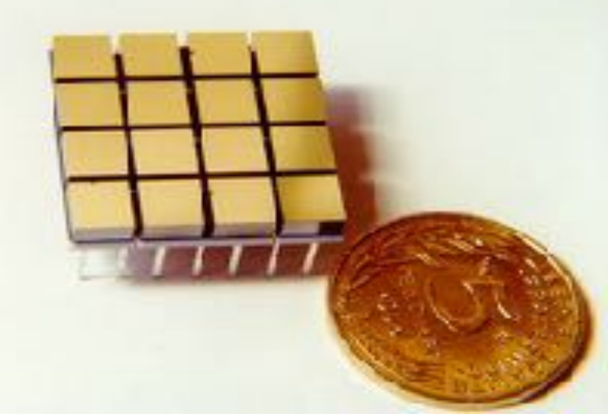
INTEGRAL

Medium mission of the ESA's Horizon 2000 program.
Launched on October 17, 2002.
Hard X-rays & soft gamma-rays.

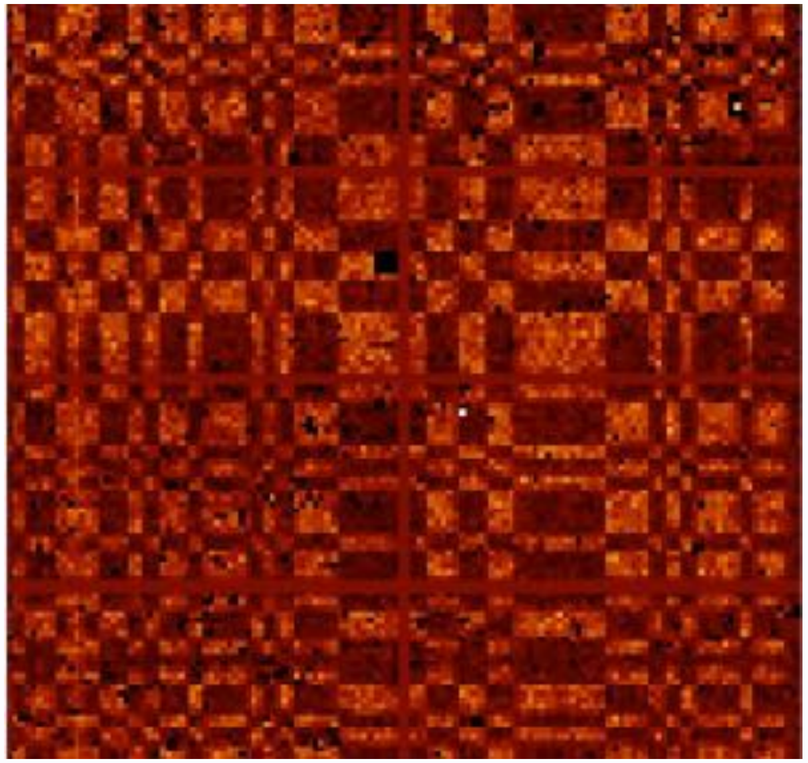
- Best spatial resolution
- Best narrow-line sensitivity
- Large field of view i.e. long effective exposure
- Broad energy range

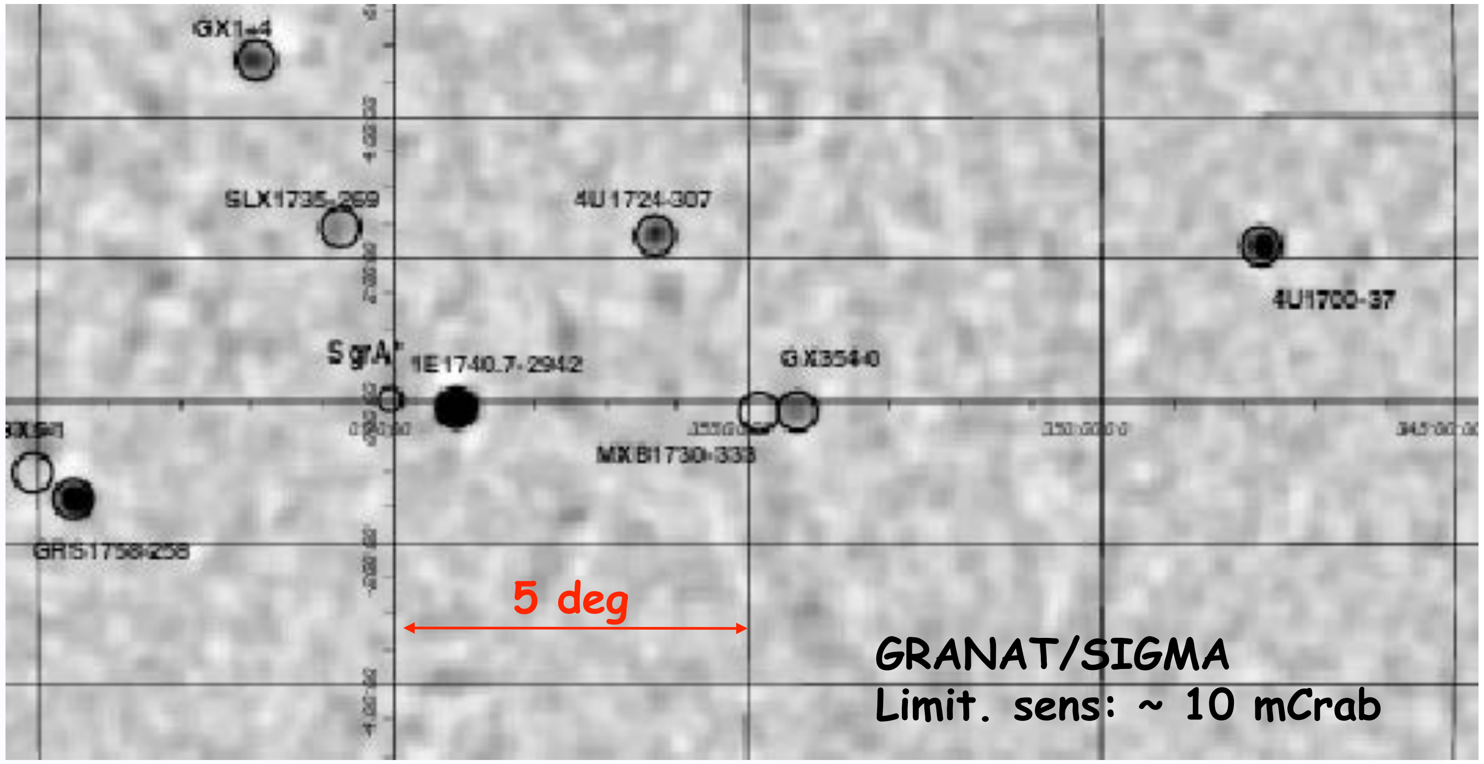
	SPI	IBIS
Energy range	18 keV - 8 MeV	15 keV - 10 MeV
Detector	19 Ge detectors (each 6 × 7 cm), cooled @ 85K	16384 CdTe dets (each 4×4×2 mm), 4096 CsI dets (each 8.55×8.55×30 mm)
Detector area (cm^2)	500	2600 (CdTe), 3000 (CsI)
Spectral resolution (FWHM)	3 keV @ 1.7 MeV	8 keV @ 100 keV
Field of view (fully coded)	16° (corner to corner)	8.3° × 8°
Angular resolution (FWHM)	2.5° (point source)	12'
Source location (radius)	< 1.3° (depending on source strength)	30"@100 keV (50 σ source) 3' @100 keV (5 σ source)
Absolute timing accuracy (3σ)	<200 μs[b]	<100 μs[b]
Mass (kg)	1309	746
Power [max/average] (W)	385/110	240/208

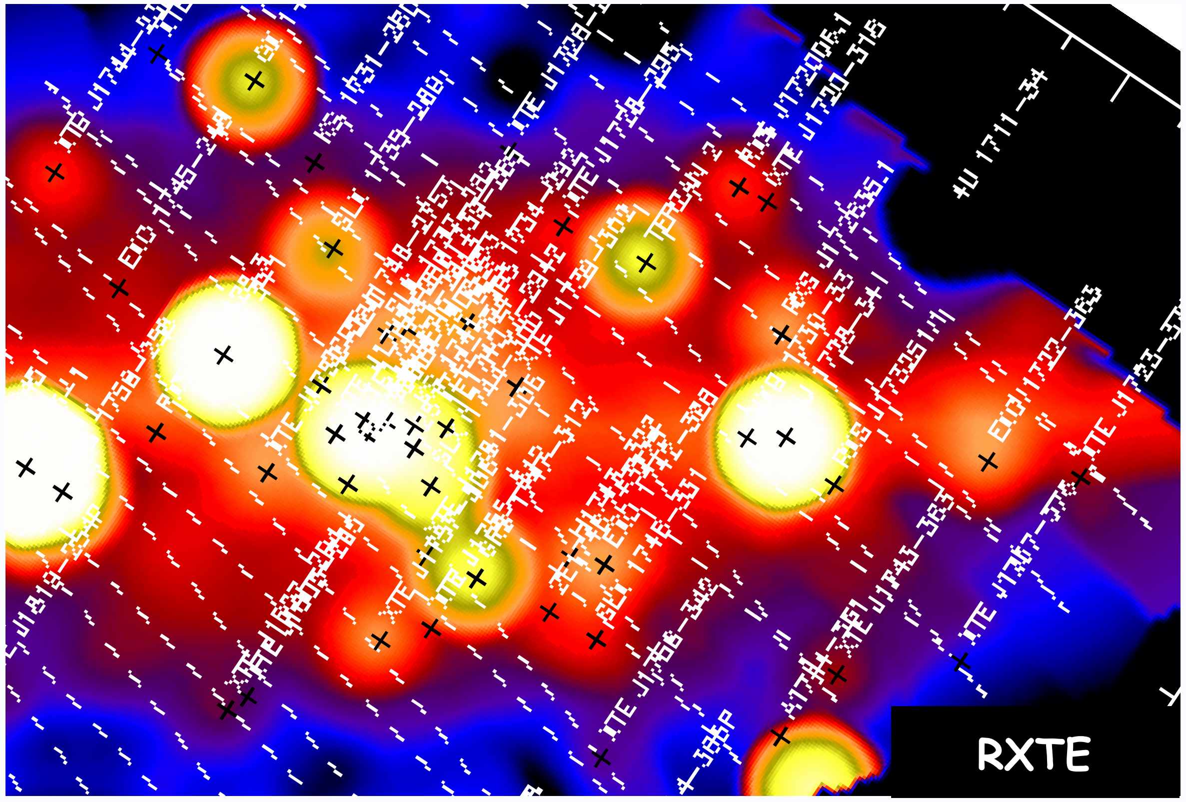
X-ray monitor (JEM-X) 3-35 keV
Optical monitor (OMC) V band

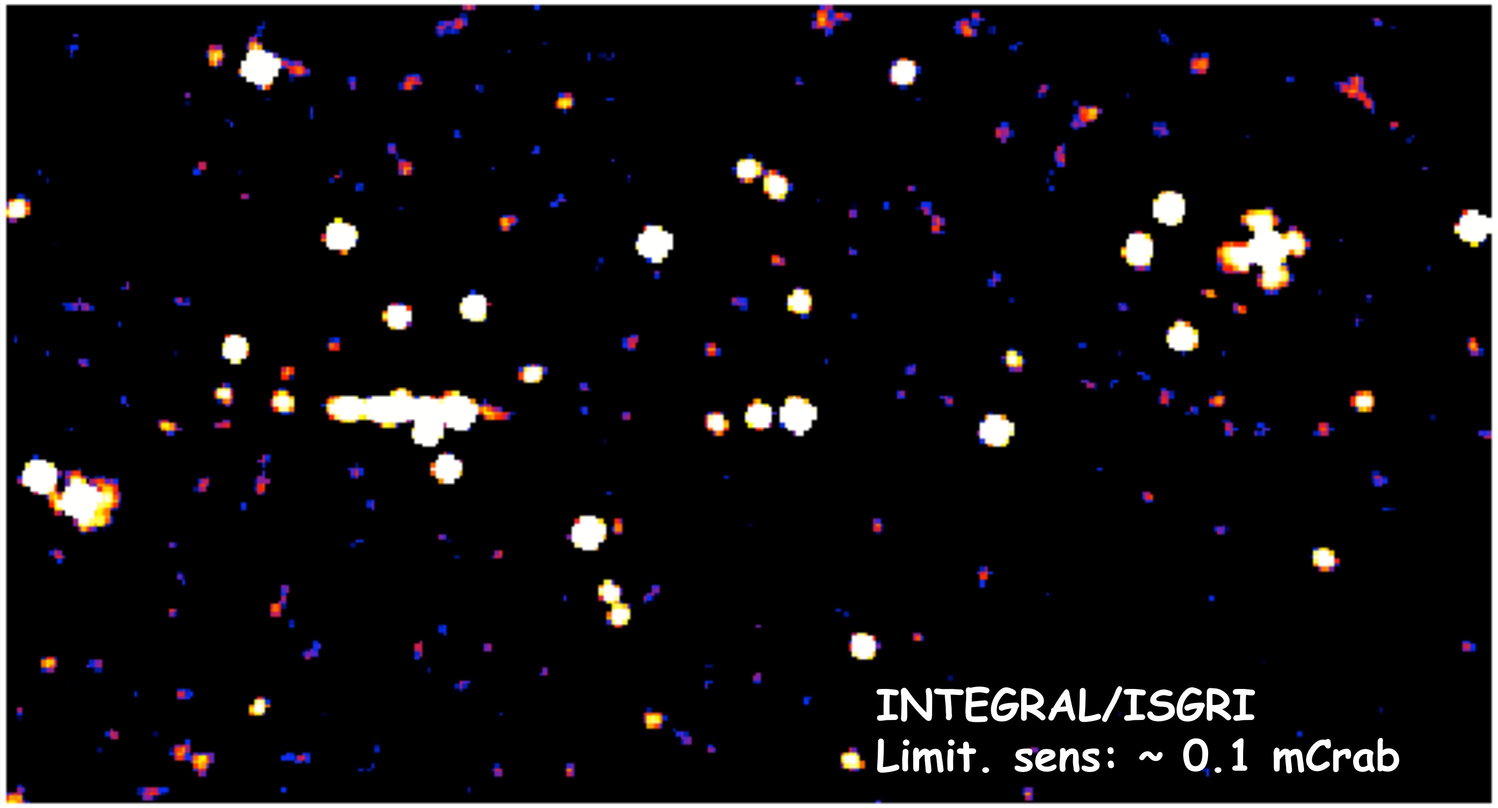


Advances in Imaging

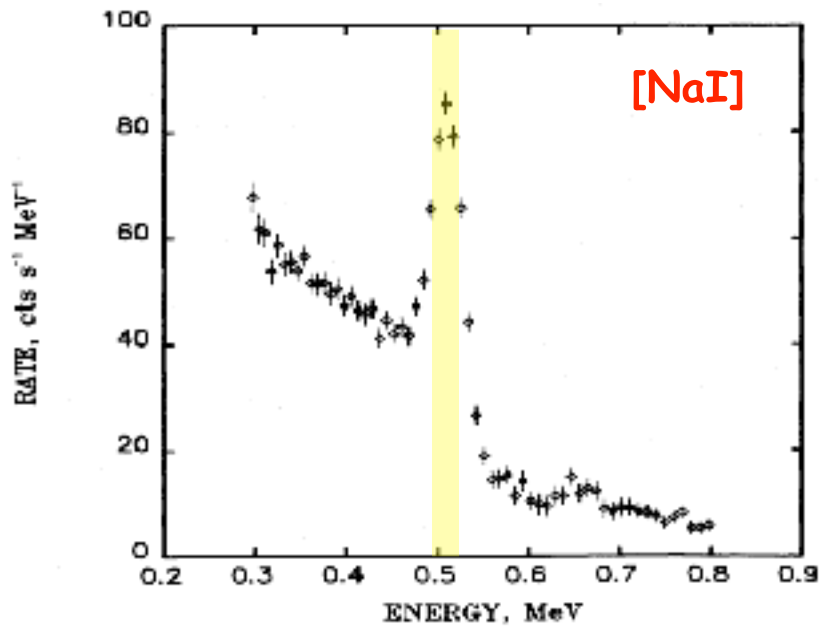




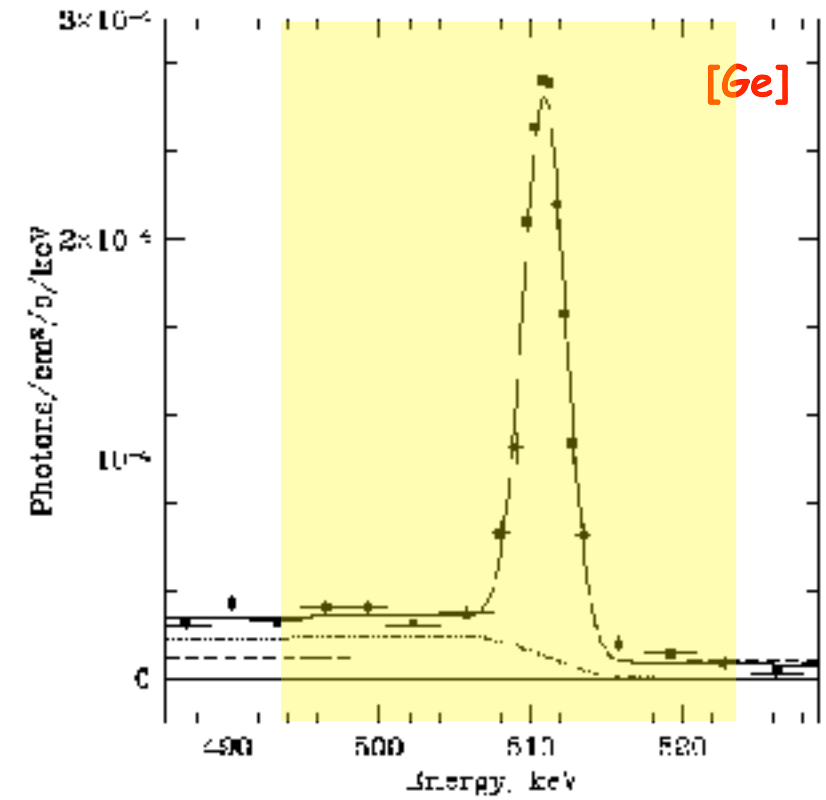


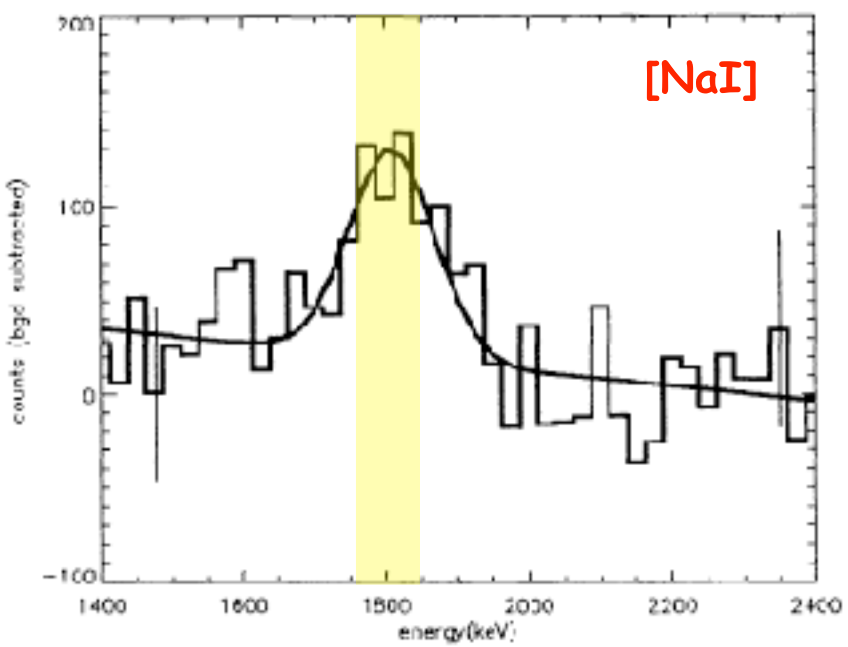


Advances in Spectroscopy

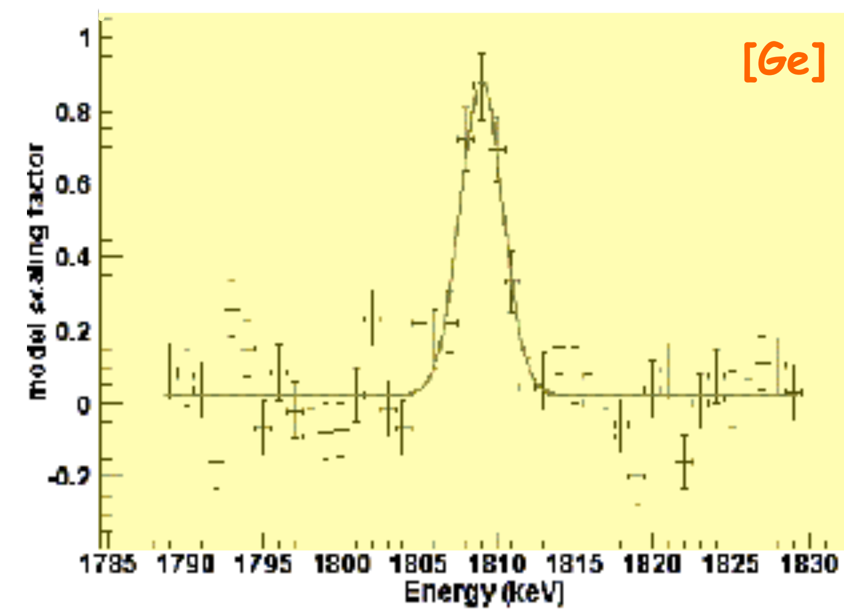


Galactic Bulge
511 keV

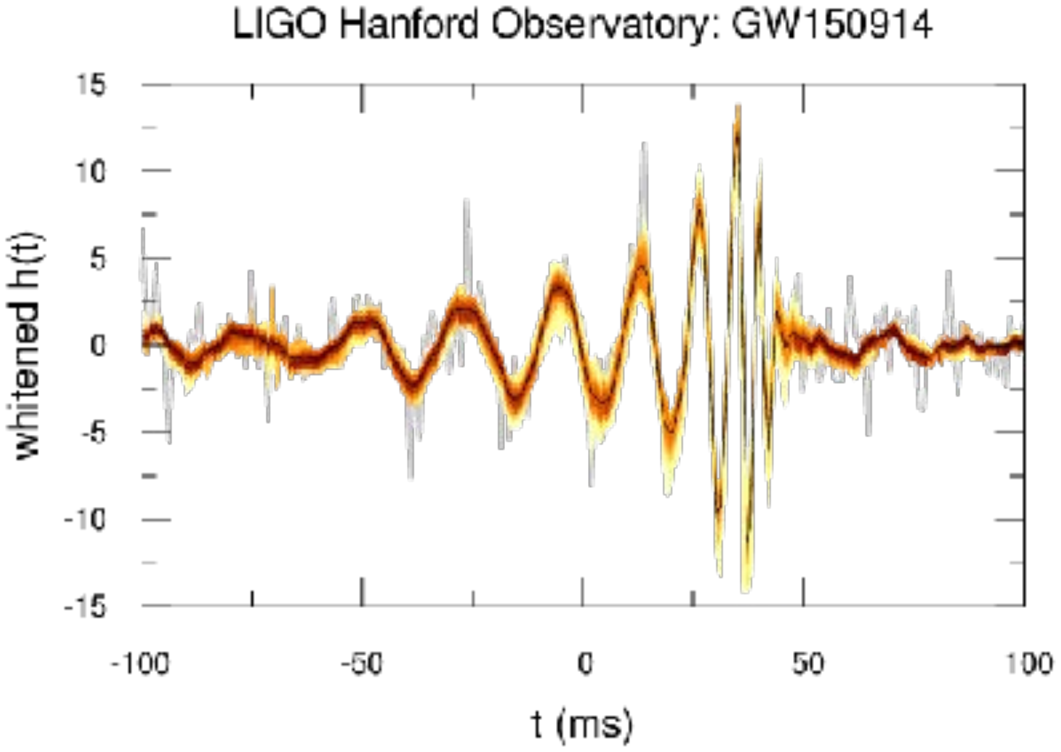


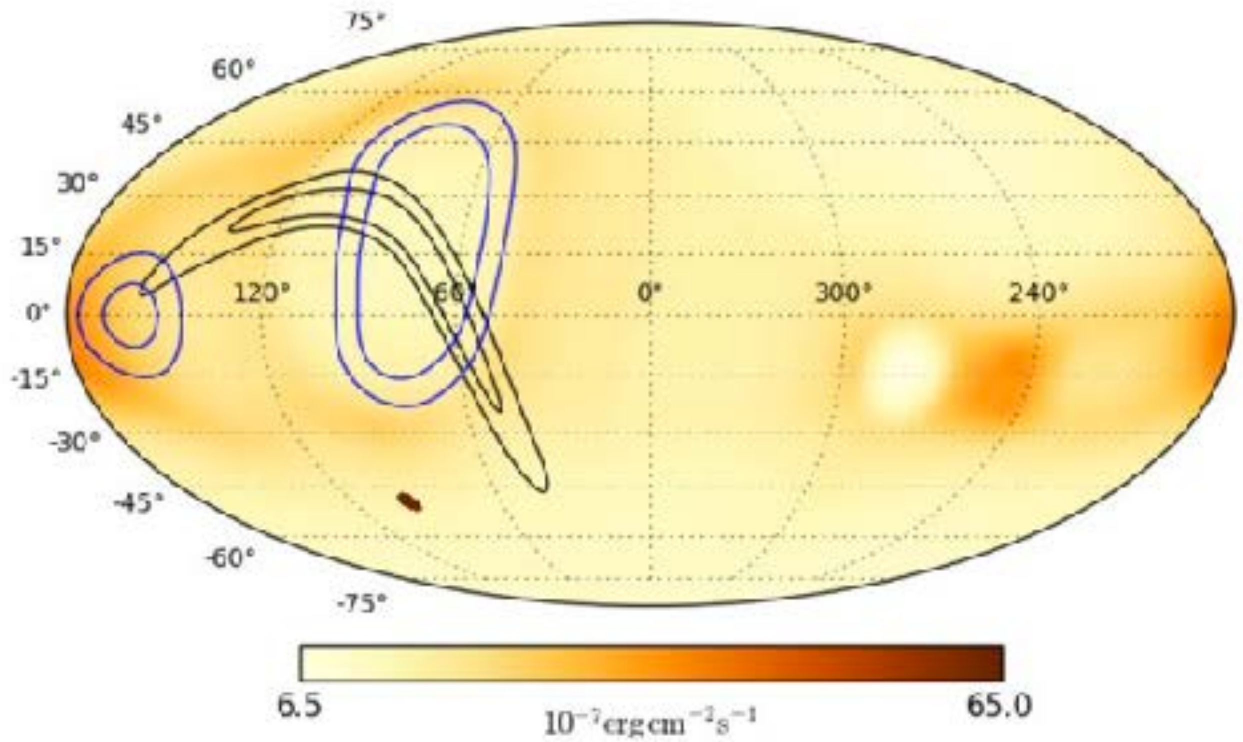


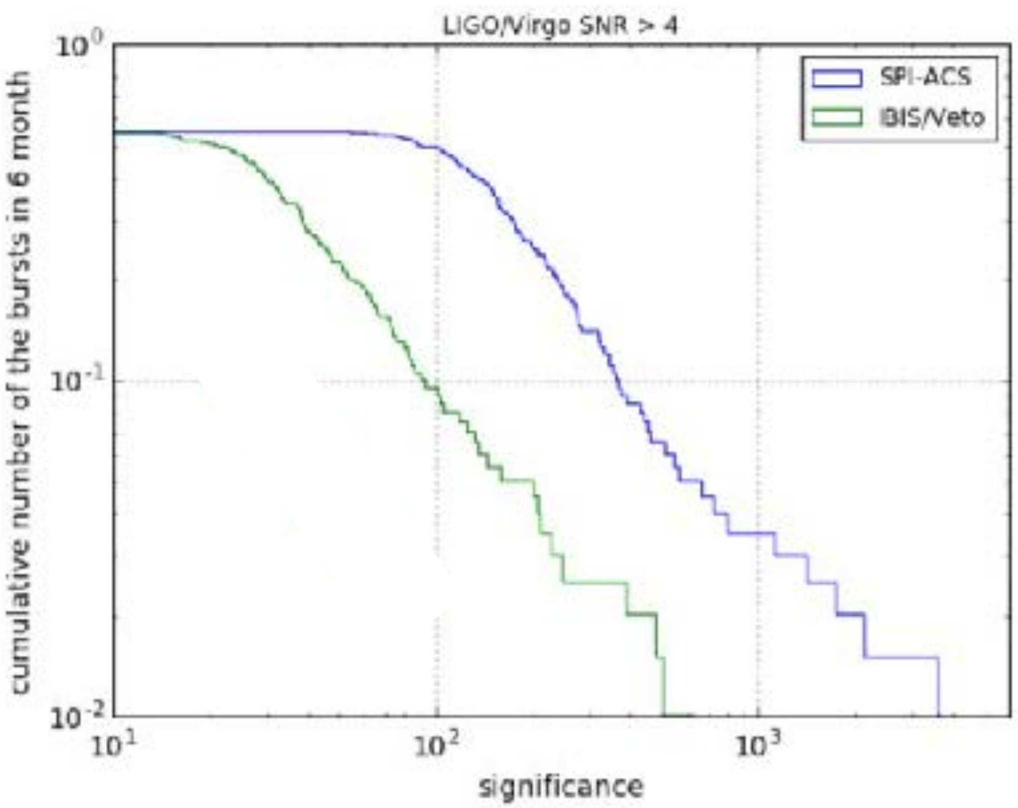
Galactic Plane
1809 keV



Gravitational Wave Counterpart



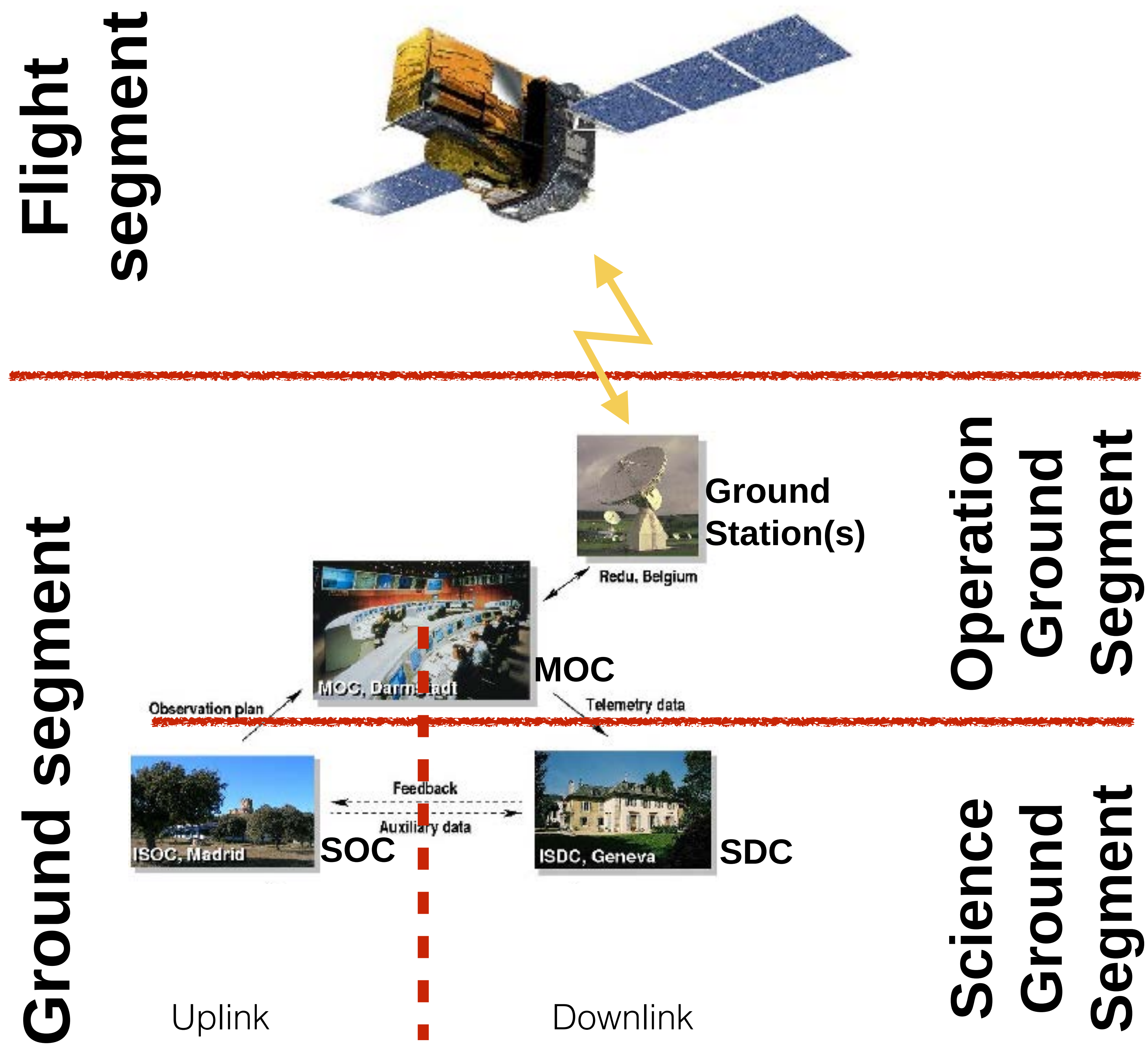




Mission Segments

Launch segment

Program segment



Mission Segments

Launch segment
10-15%

Program segment
10%

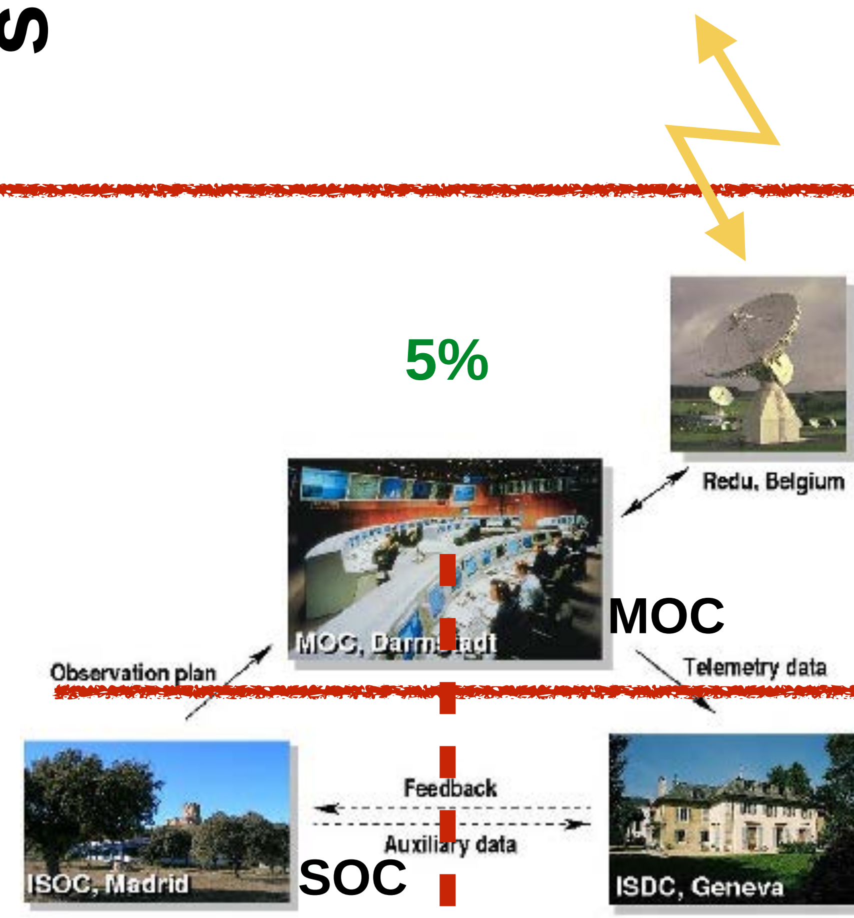
Flight segment

Payload: 30-XX%

Spacecraft: 20%

Contingency: 10%

Ground segment



5% 5%

Uplink Downlink

Operation Ground Segment

Science Ground Segment

(for a few years of operations)

Science Ground Segment

Main tasks:

- Science mission planning and scheduling

  Observation Proposals | Planning Files

- Mission simulations

  Simulators | Oper. Optimisattion

- Science data processing

  Data Products | Alerts

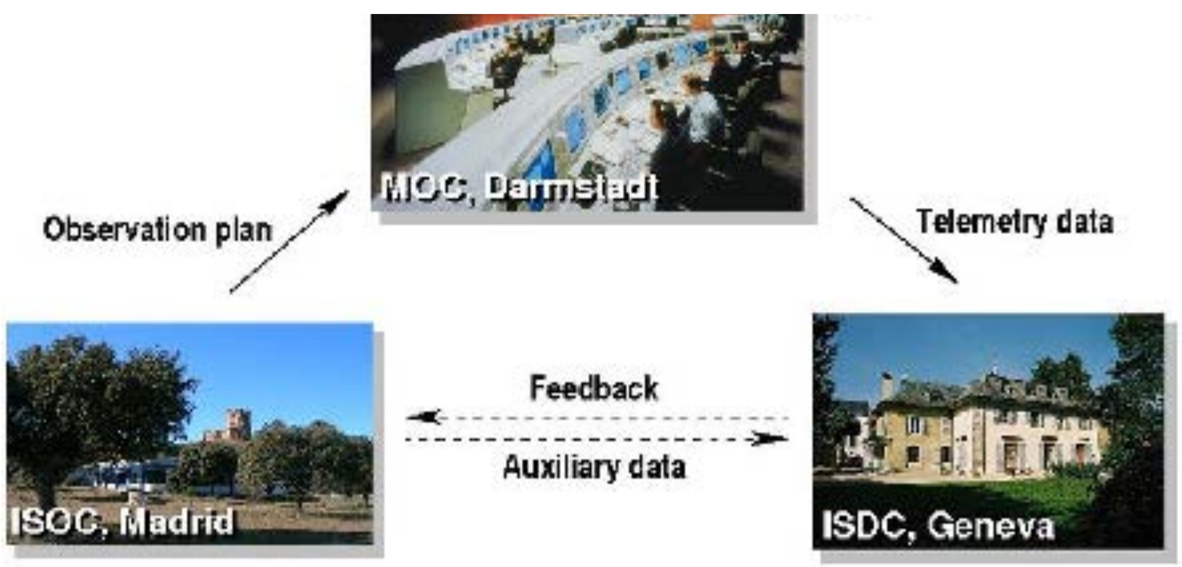
- Mission legacy

  Archive | Data access

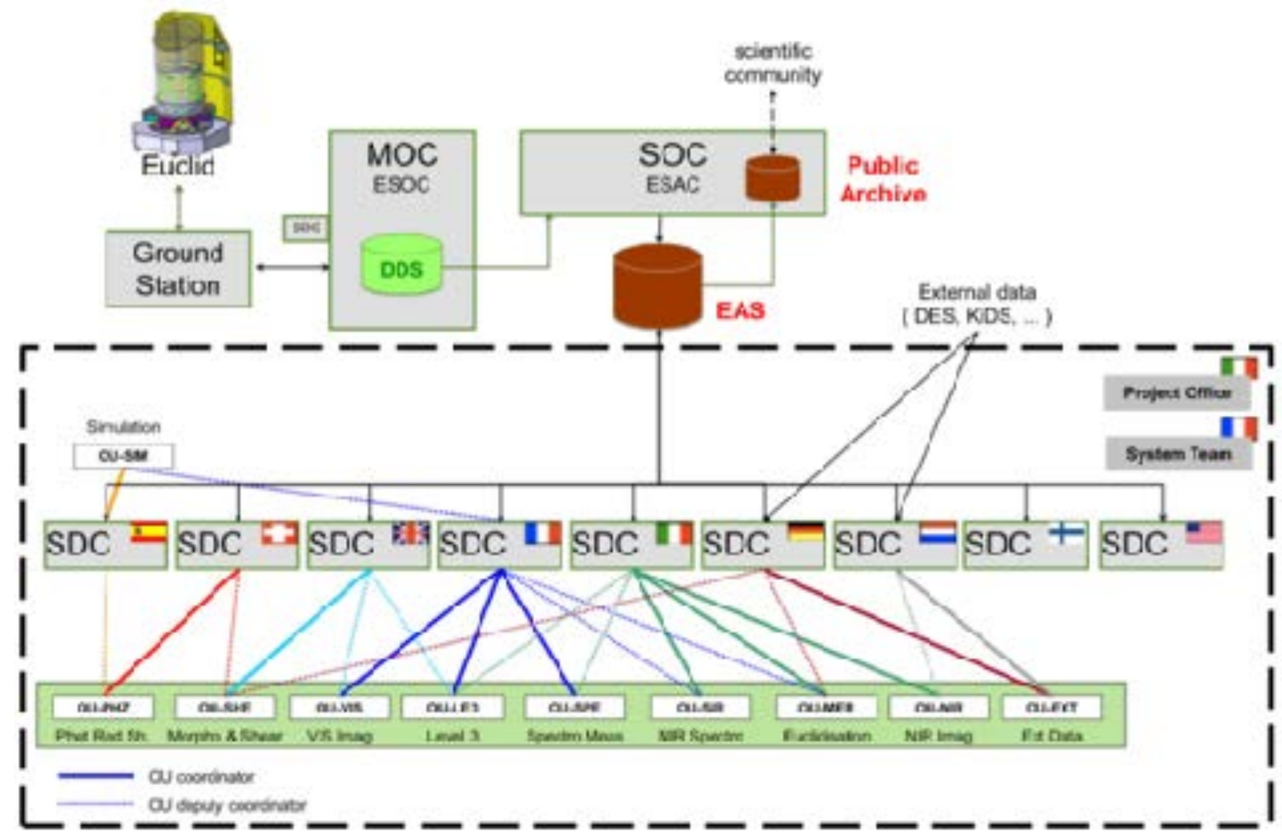
These functions can be located at one or many places

Science Ground Segment

INTEGRAL



Euclid



GAIA

These functions can be located at one or many places

The location of the data will not matter in the future

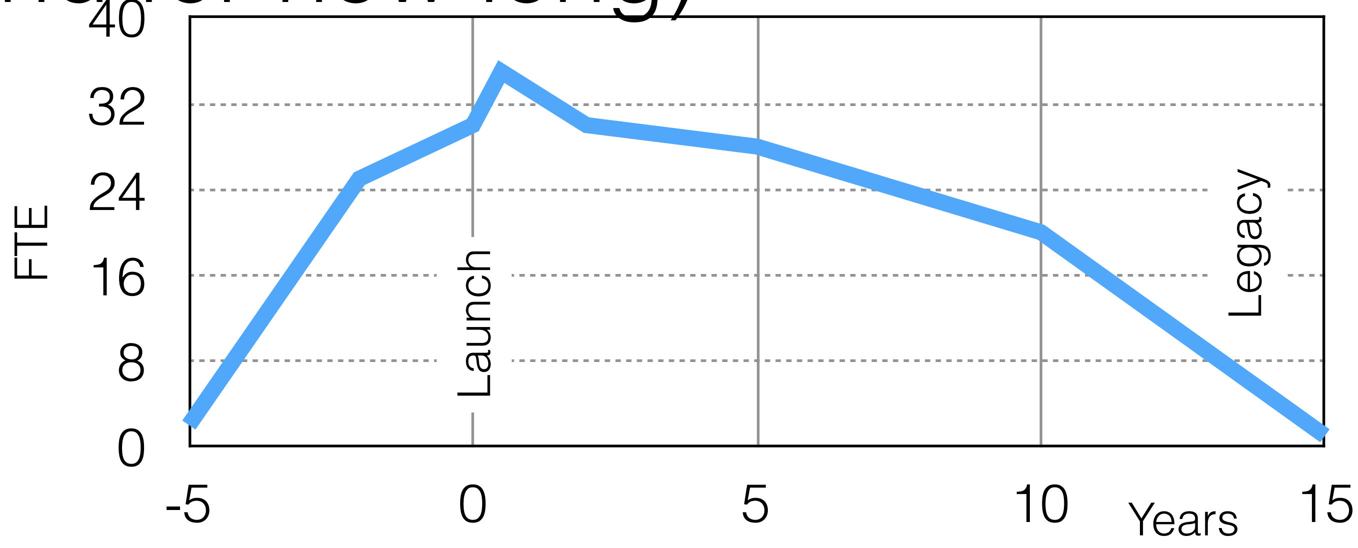
Design Drivers

- Science
  - transient detection
  - number of detected sources/events
  - observatory/PI instrument
  - size/nature of user community
  - evolution of scientific questions
  - scientific parts in the hands of scientists
  - data rights

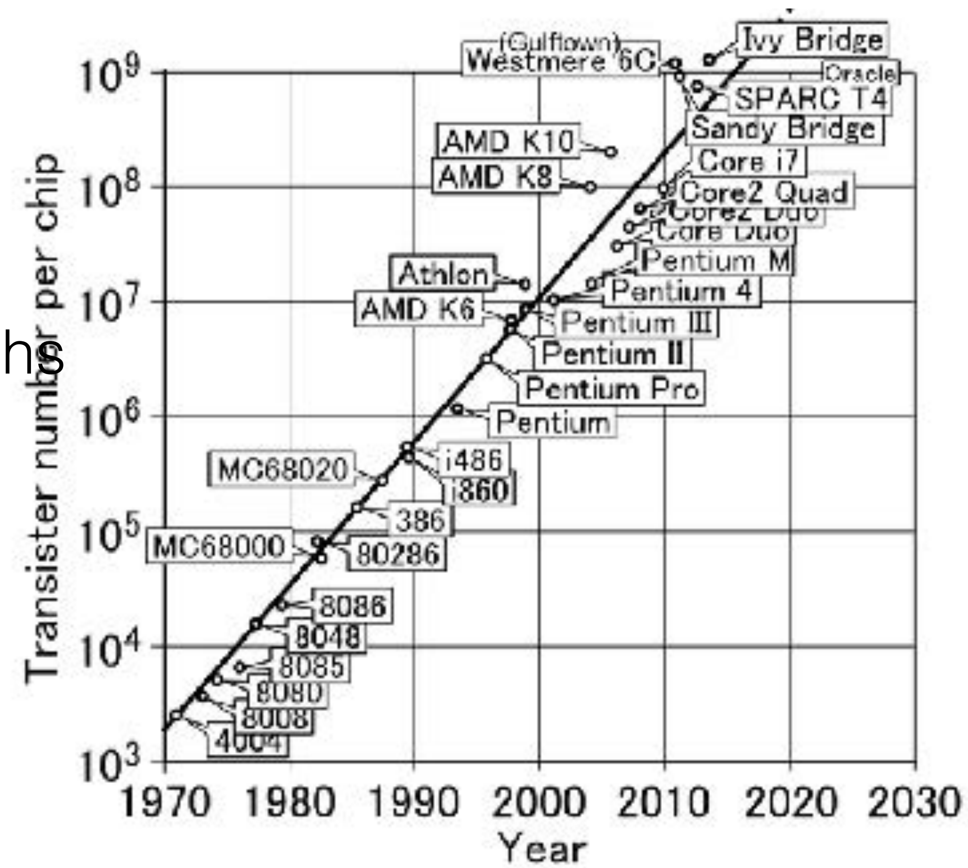
- Legacy
  - data and software maintenance
  - archive scientific value, at different levels
  - possibility to generate new results
  - maintaining/enhancing communities
  - value for education
  - archive fate (is there one ?)

Implementation Drivers

- Ressources (who can pay and for how long)



- Data size and processing power
  - Moore's Law : CPU doubles every 24 months
  - Kryder's Law : Disk size doubles every 12 months
  - Nielsen's Law Network bandwidth doubles every 21 months
  - Disk bandwidth increases by 10% every 12 months



- Unique/multi-sites

  Data could be centralised

Operational Drivers

- Commanding loops
- Handling of critical situations
- Survey, pointing, repointing, orbital period
- Instrument commissioning
- Instrument stability/complex calibration
- Mission duration

Design Principles

- Architecture driven by
  1. science, 2. legacy, 3. implementation, 4. operations
- Asynchronous processes, event driven
- Agreed interfaces rather than complex APIs
- KISS: Keep It Simple, Stupid
- Minimize dependencies between subsystems and components
- Do not reinvent wheels
- Distributing processing is costly
- IT development is not the goal

DATA HANDLING

Science and Drivers

Science Mission Elements

Data Handling

Development Management

Data is the Legacy

Components

- Data formats
- Data acquisition
- Data checks
- Calibration
- Scientific analysis
- Data mining
- Archiving

Data Formats

- Most astronomy mission use FITS
- FITS initially developed for optical astronomy, FITS has conventions for many domains
- FITS is the archival format recognised by the IAU
- Files can include many FITS extensions including headers, tables, N dim images
- Data processing based on files (most observatories) or partially on databases (e.g. survey missions).
- FITS files are good for **long term maintenance** of data and software
- cfitsio (FITS access library) uses template files, which are good for **interface control** and ease data model evolution
- Virtual Observatory files (e.g. XML tables) are also used for high level data

- INTEGRAL:
  1382 FITS data structures
  263 Raw data
  114 Corrected data
  202 Analysis products
  others for calibration and responses

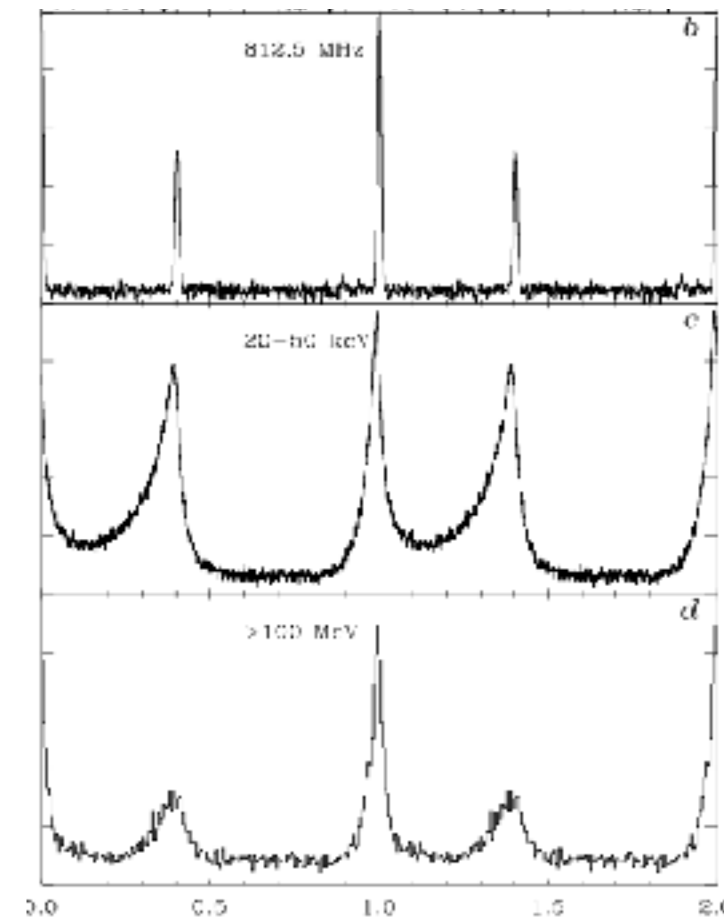
```
################################################################################
#
#DATANAME GENERAL - PACKETS - TELEMETRY DATA
#
#DESCRIPTION
# Contains the FITS wrapped telemetry.
#
#TEMPLATE GNRL-PACK-TLM
#
#CONTENT BINARY TABLE
#
#REMARKS
# The PACK_NUM column can have the values 0, 1, 2 and 3.
# 0 and 2 : normal packets; 1 and 3 : time packets
# 0 and 1 : first position in frame; 2 and 3 : second position in frame
#
#RP tm
#DB No
#V1
#
#CHANGES
# 1.4   : Template creation
# 1.5   : Renamed keyword TSTART (previously MJDSTART)
#       : Renamed keyword TSTOP (previously MJDEND)
#       : Added REVOL keyword
#       : Added time system keywords
# 1.5.1 : Changed format of FRAME_HDR column to 41B
# 1.6   : Time system is now Terrestrial Time (TT)
# 2.1   : Template put under Configuration Control
# 2.3   : Added the following keywords for frame and packet statistics:
#       : FRMTM, FRMIDLE, FRMINVLD, FRMTOTAL, PKTTM, PKTTLCMD, PKTTIME, PKTIDLE,
#       : PKTINVLD and PKTTOTAL (SCREW-00217 and SCREW-00252)
# 7.1   : Added TIMEPIXR keyword (SCREW-01431)
# 9.8.3 : Changed FRAME_SEQ column format from 1V to 1K (SPR-04868)
#
################################################################################
XTENSION   BINTABLE     / Binary table extension
EXTNAME                 GNRL-PACK-TLM     / Extension name
EXTREL                  '9.8.3'           / ISDC release number
BASETYPE   DAL_TABLE    / DAL base type of the data structure
TELESCOP   INTEGRAL     / Telescope or mission name
ORIGIN                  ISDC              / Origin of FITS file
CREATOR                 String            / Program that created this FITS file
CONFIGUR   String               / Software configuration
DATE                    UTC_format / FITS file creation date
MJDREF                  51544.0           / Modified Julian Date of origin
TIMESYS                 TT                / Time frame system
TIMEUNIT   d                    / Time unit
TIMEREF                 LOCAL             / Time reference frame
ERTFIRST   UTC_format / Earth received time of the first packet
ERTLAST                 UTC_format / Earth received time of the last packet
REVOL                   Integer           / Revolution number
TSTART                  Real              / Earth received time of first packet (ISDC-JD)
TSTOP                   Real              / Earth received time of last packet (ISDC-JD)
FRMTM                   Integer           / Number of good telemetry frames
FRMIDLE                 Integer           / Number of idle frames, not stored
FRMINVLD   Integer              / Number of invalid frames, not stored
FRMTOTAL   Integer              / Total number of frames
PKTTM                   Integer           / Number of telemetry packets
PKTTLCMD   Integer              / Number of telecommand packets
PKTTIME                 Integer           / Number of time (STSP) packets
PKTIDLE                 Integer           / Number of idle packets
PKTINVLD   Integer              / Number of invalid packets
PKTTOTAL   Integer              / Total number of packets
TIMEPIXR   0.5                  / Relative position [0,1] of time stamp in bins
           TTYPE#       TIME              / ISDC-JD time
           TFORM#       1D                / Format of column TIME
           TUNIT#       d                 / Unit of column TIME
           TTYPE#       FRAME_SEQ         / Frame sequence number
           TFORM#       1K                / Format of column FRAME_SEQ
           TTYPE#       FRAME_HDR         / Frame header
           TFORM#       41B               / Format of column FRAME_HDR
           TTYPE#       PACK_NUM / Packet number
           TFORM#       1B                / Format of column PACK_NUM
           TTYPE#       CONTENT           / Packet content
           TFORM#       440B              / Format of column CONTENT
```

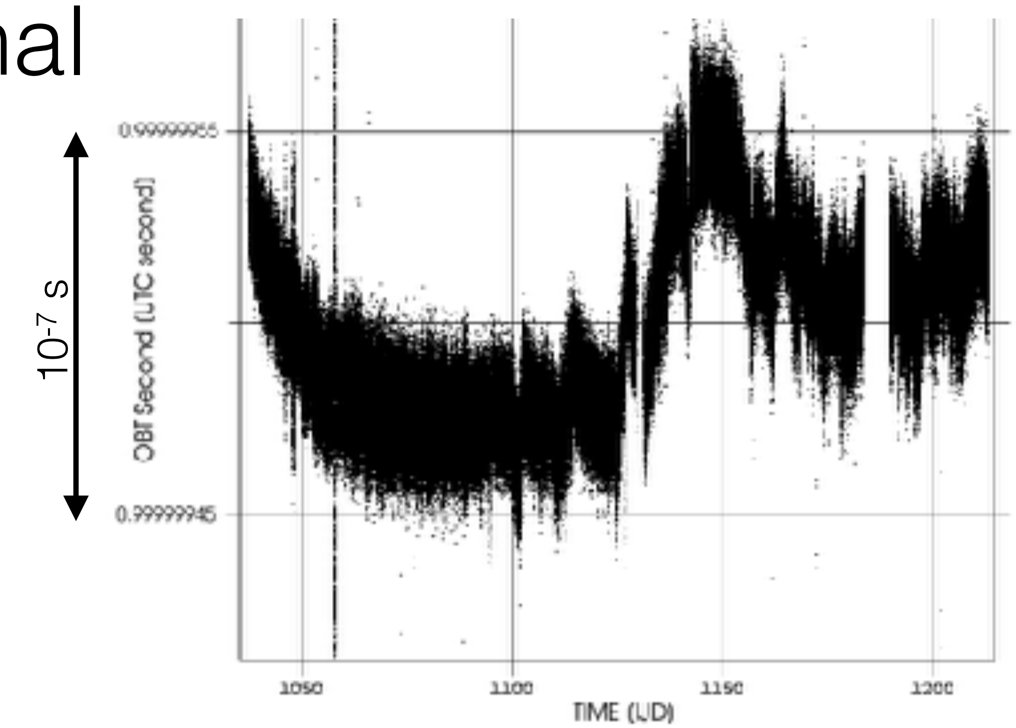
```
################################################################################
#
#DATANAME IBIS-ISGRI - EVENTS - RAW DATA
#
#DESCRIPTION
# Contains the raw photon-by-photon events from the IBIS-ISGRI detector.
#
#TEMPLATE ISGR-EVTS-RAW
#
#CONTENT BINARY TABLE
#
#RP scw
#DB No
#V1
#
#CHANGES
# 1.4   : Template creation
# 2.0   : Added ISDCLEVL keyword
# 2.1.3 : Added SWBOUND keyword
# 2.3   : Changed APID value to 1348_or_1476 (previously 1348)
#       : Template put under Configuration Control
# 3.1   : Removed PLOBTSTR and PLOBTEND keywords (SPR-00570)
# 3.4   : Changed APID value to Integer (SCREW-00412)
#
################################################################################
XTENSION   BINTABLE          / Binary table extension
EXTNAME              ISGR-EVTS-RAW     / Extension name
EXTREL     '3.4'             / ISDC release number
BASETYPE   DAL_TABLE         / Data Access Layer base type
TELESCOP   INTEGRAL          / Telescope or mission name
ORIGIN     ISDC              / Origin of FITS file
INSTRUME   IBIS              / Instrument name
DETNAM     ISGRI             / Name of the detector layer
ISDCLEVL   RAW               / ISDC level of data processing
CREATOR    String            / Program that created this FITS file
CONFIGUR   String            / Software configuration
DATE       UTC_format        / FITS file creation date
ERTFIRST UTC_format     / Earth received time of the first packet
ERTLAST    UTC_format        / Earth received time of the last packet
REVOL      Integer           / Revolution number
SWID       String            / Science Window identifier
SW_TYPE    String            / Type of the Science Window
SWBOUND              String            / Reason for Science Window ending
BCPPID     String            / Broadcast packet pointing ID at ScW start
PREVSWID   String            / Identification of the previous Science Window
PCKSTART   Integer           / Packet time of the start of the Science Window
PCKEND     Integer           / Packet time of the end of the Science Window
APID       Integer           / Application process identifier (1348 or 1476)
SSC_BEG    Integer           / Source sequence count start
SSC_END    Integer           / Source sequence count end
SSC_GAP    Integer           / Number of missing packets
      TTYPE#   DELTA_TIME    / Delta time to previous event
      TFORM#   1B            / Format of column DELTA_TIME
      TTYPE#   RISE_TIME     / Event rise time
      TFORM#   1B            / Format of column RISE_TIME
      TTYPE#   ISGRI_PHA     / Pulse height in the ISGRI layer
      TFORM#   1U            / Format of column ISGRI_PHA
      TTYPE#   ISGRI_Y       / Y location in the ISGRI layer
      TFORM#   1B            / Format of column ISGRI_Y
      TTYPE#   ISGRI_Z       / Z location in the ISGRI layer
      TFORM#   1B            / Format of column ISGRI_Z
```

```
################################################################################
#
#DATANAME IBIS-ISGRI - SKY - IMAGE
#
#DESCRIPTION
# Contains the IBIS-ISGRI sky image obtained for a single Science Window,
# for a given energy band and a given time span.
#
#TEMPLATE ISGR-SKY.-IMA
#
#CONTENT IMAGE
#DATADEF : Image pixel value
#AXDEF 1 : Phi angle (CAR) or X coordinate (TAN)
#AXDEF 2 : Theta angle (CAR) or Y coordinate (TAN)
#
#REMARKS
# This data structure can store either a cartesian (CAR) or a tangential (TAN)
# projection of the celestial sphere. The coordinate system is specific to this
# data structure. The standard keywords defined in this data structure provide
# all information require to compute RA and DEC (or GLON GLAT, or ELON ELAT)
# of any pixel.
#.
# This data structure has been defined according to the standard representations
# of celestial coordinates in FITS proposed by Greisen and Calabretta (AA,
# preprint)
#.
# The IMATYPE keyword can have the following values:
# INTENSITY, VARIANCE, RESIDUAL or SIGNIFICANCE
#.
# The UTC format is YYYY-MM-DDTHH:MM:SS
#
#RP obs/scw
#DB No
#V2
#
#CHANGES
# 2.0.1 : Template creation
# 2.0.2 : Removed the four PC00i00i (i=1,2) keywords
# 2.0.3 : Removed the LONGPOLE and LATPOLE keywords
# 2.1   : Set BUNIT value to count/s/cm**2
# 2.1.1 : Replaced CDELT1,CDELT2 and CROTA2 keywords
#       : by the CD1_1, CD1_2, CD2_1 and CD2_2 keywords
#       : Renamed DATE-END keyword (previously DATE_END)
#       : Temporarily changed BUNIT value from count/s/cm**2 to count/s
#       : Changed possible IMATYPE value from ERROR to VARIANCE
# 2.1.3 : Set the 4 CDi_i (i=1,2) to their default value
# 2.2   : Removed EXPID keyword
#       : Added ONTIME, DEADC and EXPOSURE keywords
#       : Changed HDUVERS value from 1.0 to 3.0
#       : Put back the LONGPOLE and LATPOLE keywords
# 2.3   : Added SWBOUND keyword
# 3.4.2 : Added TFIRST and TLAST keywords
#       : Removed DATE-OBS and DATE-END keywords
# 4.8   : Changed BUNIT value from count/s to String
#       : Changed CD1_1, CD1_2, CD2_1, CD2_2 values to Real (SCREW-00642)
# 4.9   : Template put under Configuration Control
# 6.5   : Changed HDUVERS keyword value to '1.1.0' (SPR-02602)
#
################################################################################
XTENSION IMAGE            / Image extension
BITPIX     -32            / IEEE 32-bit floating point values
NAXIS      2              / Number of data axes
NAXIS1     Integer        / Length of data axis 1
NAXIS2     Integer        / Length of data axis 2
EXTNAME    ISGR-SKY.-IMA  / Extension name
EXTREL     '6.5'          / ISDC release number
BASETYPE DAL_ARRAY        / Data Access Layer base type
TELESCOPINTEGRAL / Telescope or mission name
ORIGIN     ISDC           / Origin of FITS file
INSTRUME IBIS             / Instrument name
DETNAM     ISGRI          / Name of the detector layer
ISDCLEVL  IMA             / ISDC level of data processing
CREATOR    String         / Program that created this FITS file
CONFIGUR   String         / Software configuration
DATE       UTC_format     / FITS file creation date
MJDREF     51544.0        / Modified Julian Date of time origin
TIMESYS    TT             / Time frame system
TIMEUNIT  d               / Time unit
TIMEREF    LOCAL          / Time reference frame
REVOL      Integer        / Revolution number
SWID       String         / Science Window identifier
SW_TYPE    String         / Type of the Science Window
SWBOUND    String         / Reason for Science Window ending
OBTSTART OBT_format       / OBT of the start of the Science Window
OBTEND     OBT_format     / OBT of the end of the Science Window
TSTART     Real           / Start time of the Science Window
TSTOP      Real           / End time of the Science Window
TFIRST     Real           / Time of the first data element
TLAST      Real           / Time of the last data element
TELAPSE    Real           / [s] Total elapsed time of the data
ONTIME     Real           / [s] Sum of good time intervals
DEADC      Real           / Dead-time correction factor
EXPOSURE   Real           / [s] Effective exposure time
BSCALE     1              / Real value=value*BSCALE + BZERO
BZERO      0              / Offset applied to true pixel values
BUNIT      String         / Unit for pixel values
CTYPE1     String         / LONGPROJ where LONG can be RA, GLON, ELON and PROJ can be CAR, TAN or AIT
CRPIX1     Real           / Pixel at reference point
CRVAL1     Real           / LONG at the reference value
CUNIT1     deg            / Physical units of axis 1
CTYPE2     String         / LAT-PROJ where LAT can be DEC, GLAT, ELAT and PROJ can be CAR, TAN or AIT
CRPIX2     Real           / Pixel at reference point
CRVAL2     Real           / LAT at the reference value
CUNIT2     deg            / Physical units of axis 2
CD1_1      Real           / Element (1,1) of coordinate transf. matrix (default 1)
CD1_2      Real           / Element (1,2) of coordinate transf. matrix (default 0)
CD2_1      Real           / Element (2,1) of coordinate transf. matrix (default 0)
CD2_2      Real           / Element (2,2) of coordinate transf. matrix (default 1)
LONGPOLE   180            / Longitude in the native coord. system of the std system's N pole
LATPOLE    0              / Latitude in the native coord. system of the std system's N pole
RADECSYS   FK5            / Stellar reference frame
EQUINOX    2000.0         / Coordinate system equinox
HDUCLASS   OGIP           / Format conforms mostly to OGIP standards
HDUDOC     'ISDC-IBIS ICD' / Document in which the format is defined
HDUVERS    '1.1.0'        / Version of format
HDUCLAS1   IMAGE          / Dataset contains a sky image
CHANTYPE   PI             / Type of detector channels
CHANMIN    Integer        / Lowest channel of the energy range
CHANMAX    Integer        / Highest channel of the energy range
E_MIN      Real           / [keV] Lower energy limit
E_MEAN     Real           / [keV] Mean energy
E_MAX      Real           / [keV] Upper energy limit
IMATYPE    String         / Type of image
```

Data Conventions: e.g. Timing

- On-board (clock) time: kept everywhere with full resolution (1μs), including clock resets. Synchronisation of instruments and spacecraft.
- MJD in terrestrial time (based on atomic clock, no leap second). Bijective translation to on-board time (includes on-board clock synchronisation, thermal effects, propagation time).
- Earth time in UTC





Data Acquisition

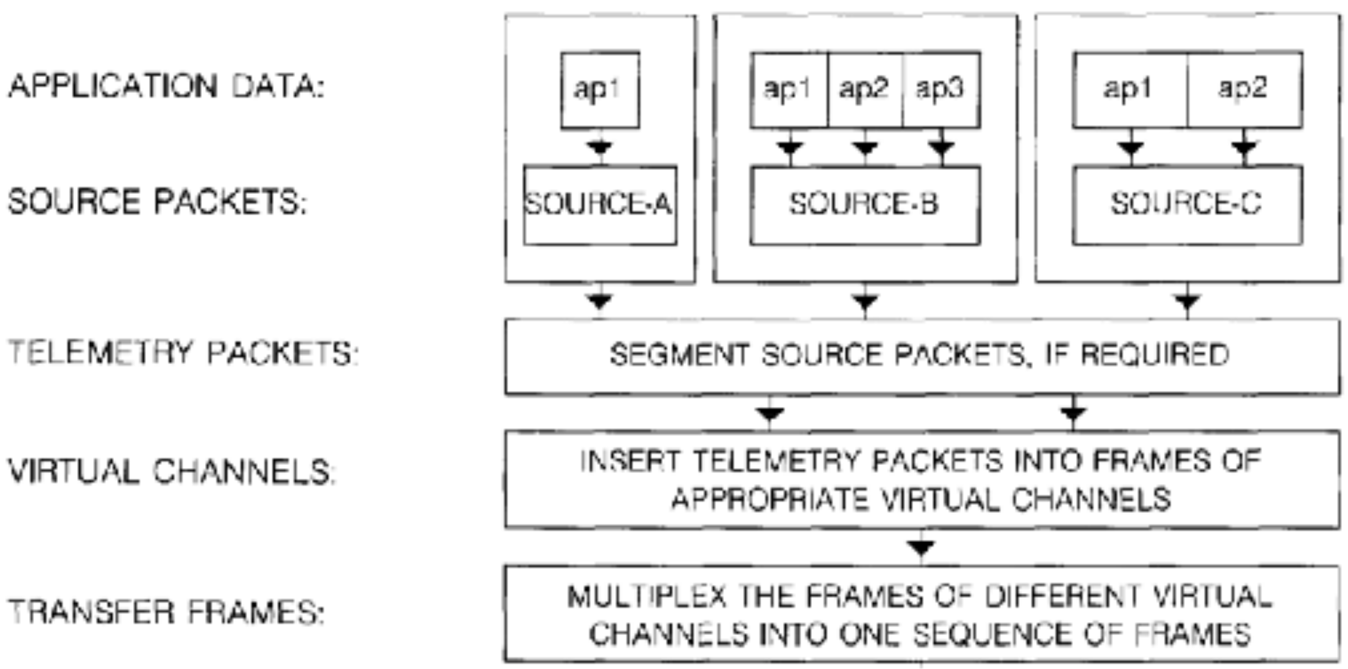
- Spacecraft (or Instrument) Telemetry
  - Packet Telemetry Standard (CCSDS 102.0-B-2 = PSS-04-106)

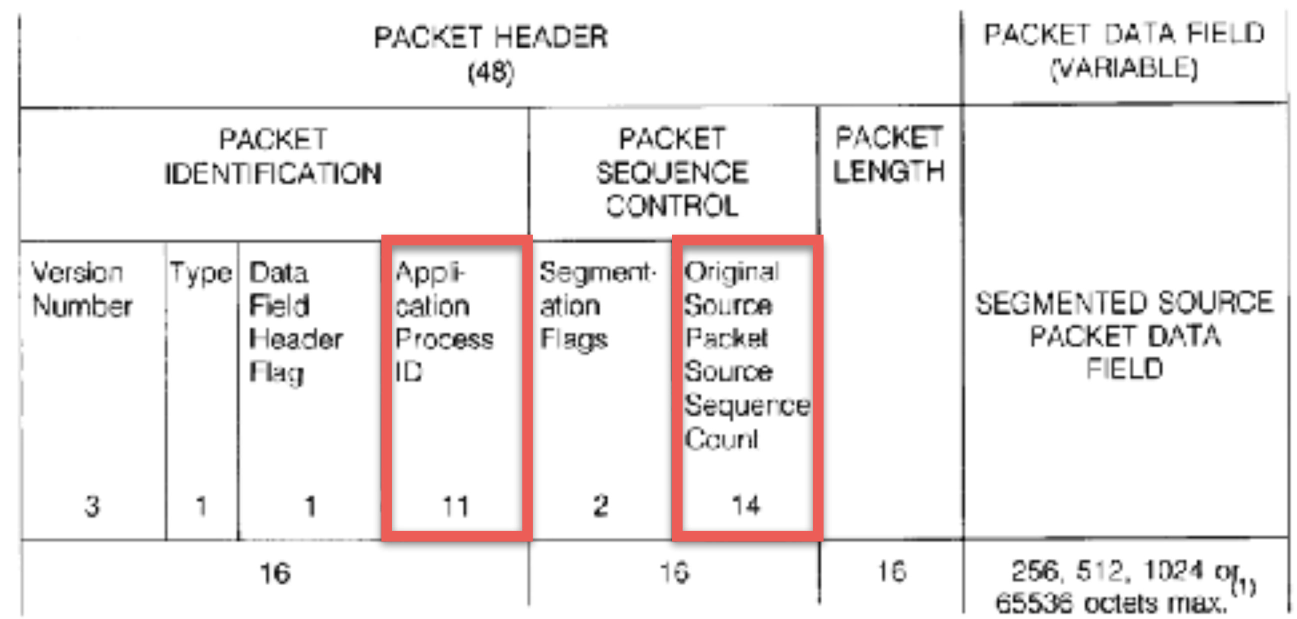
CCSDS=Consultative Committee for Space Data Systems

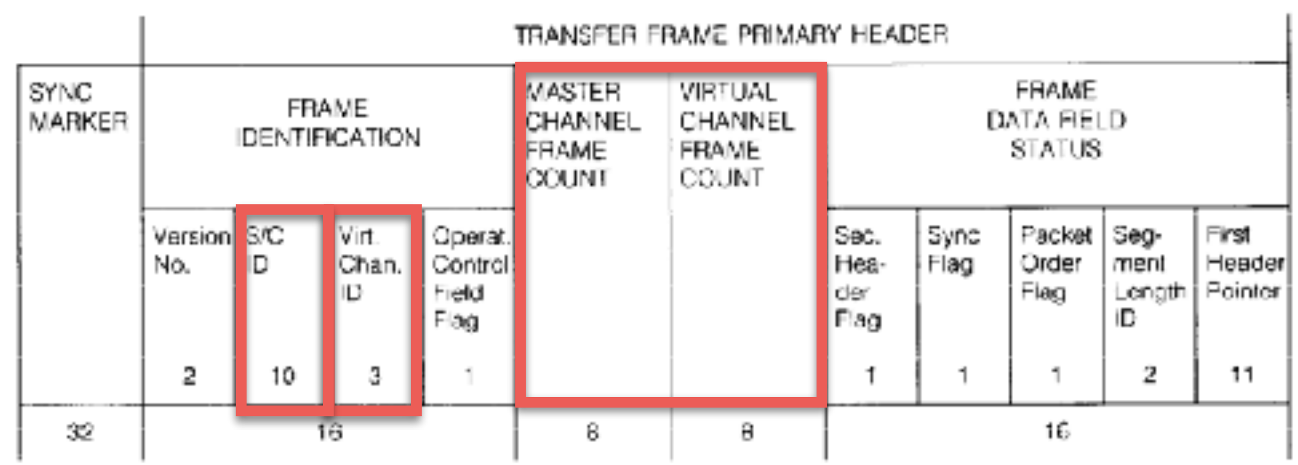
- Auxiliary data
  - Star tracker attitude file (planned/snapshot/historic)
  - Orbit file (planned/historic)
  - Time Correlation
  - Telecommand histories
  - Timeline (planned/historic)

Telemetry Frames and Packets

CCSDS 102.0-B-2





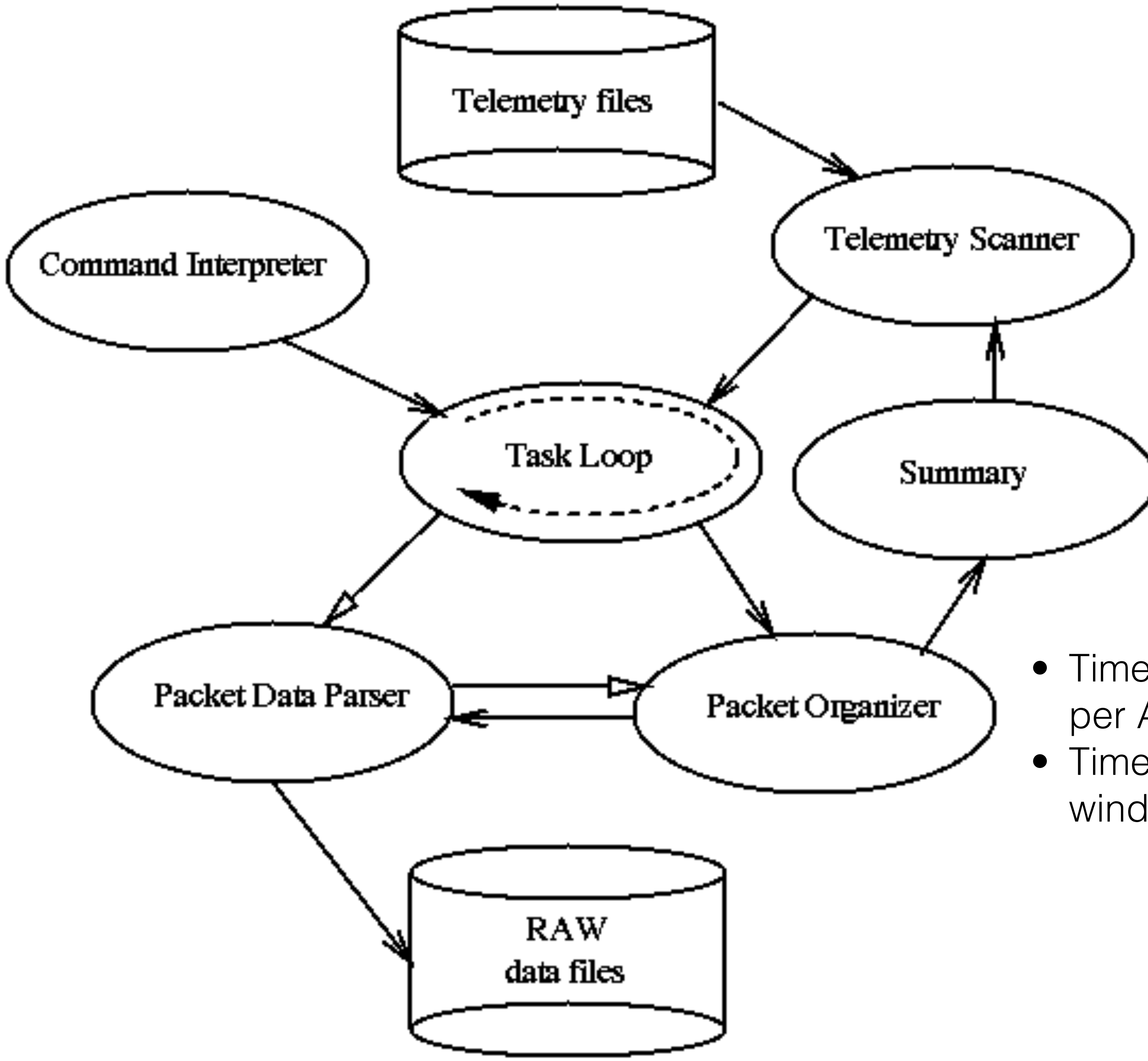


+ Earth Received Time

Need to take care of duplication/out-of-sequence/missing frames

Telemetry Conversion

INTEGRAL: 263 different raw data structures

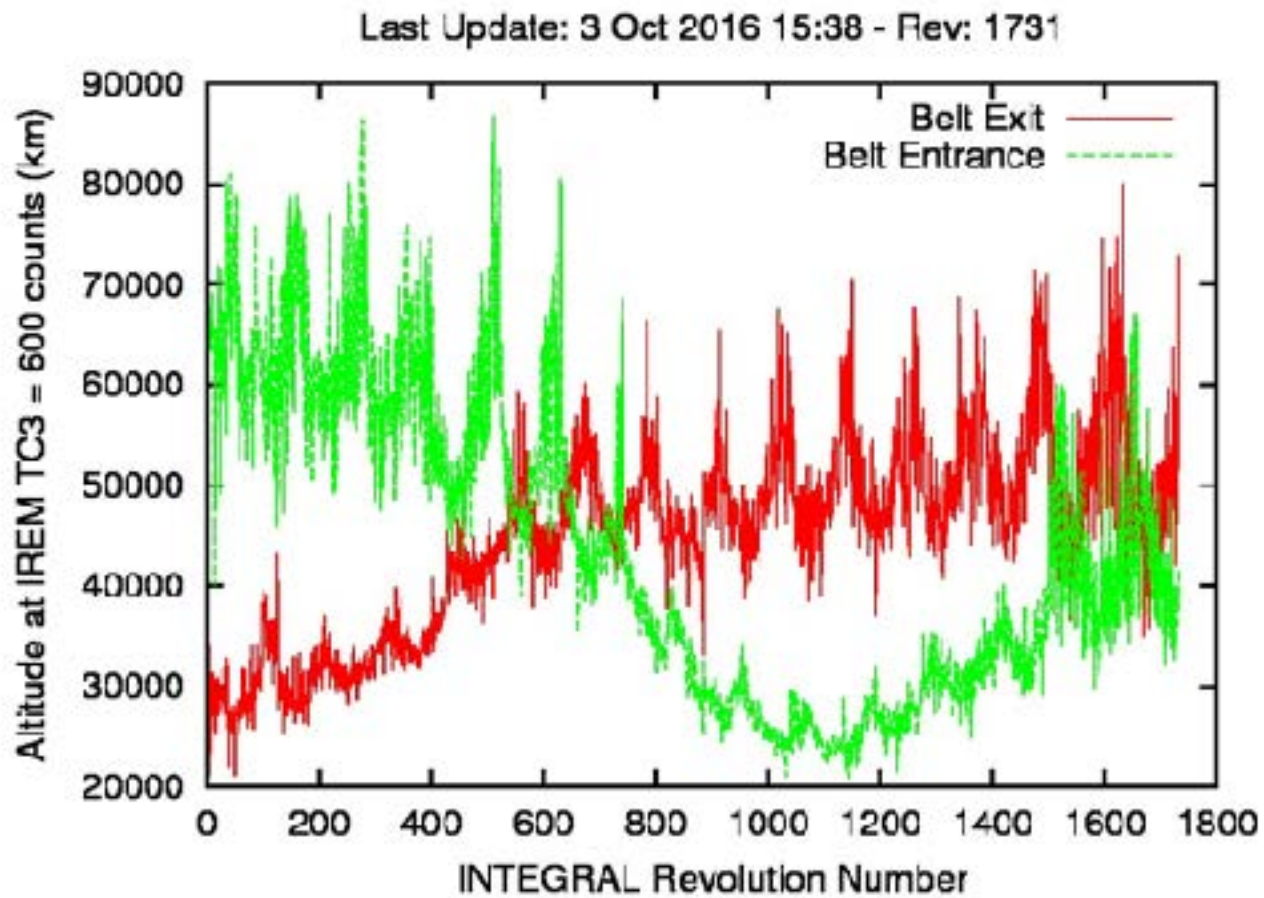


- Code driven parsers
- Database driven parsers

- Time ordered lists of packets per APID (can include "Holes")
- Time ordered list of operational windows

Data Checks

- Check as much as you can !
- Check data acquisition and consistency in real time
- Check instrument health (hk, although a Mission operation center responsibility)
- Check science data quality (not performed by mission operations), especially if related to operations



Calibration and Reduction

- Calibration changes with time and version (two axis)
- Calibration will be done many times and might need to be done by the end-user
- On-the-fly calibration has many advantages:
  - no need to store calibrated and reduced data
  - no need for reprocessing, always the best calibration
  - applying calibration is usually faster than reading data
  and one drawback: the software need to be maintained
- If needed, consider storing only reduced data

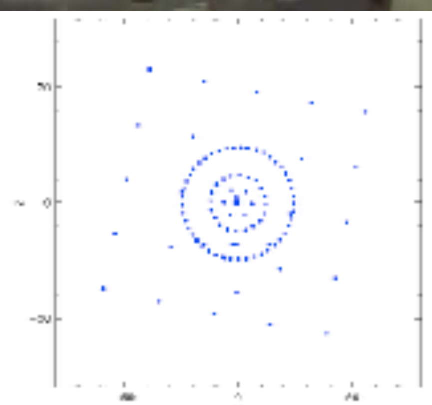
Scientific Analysis

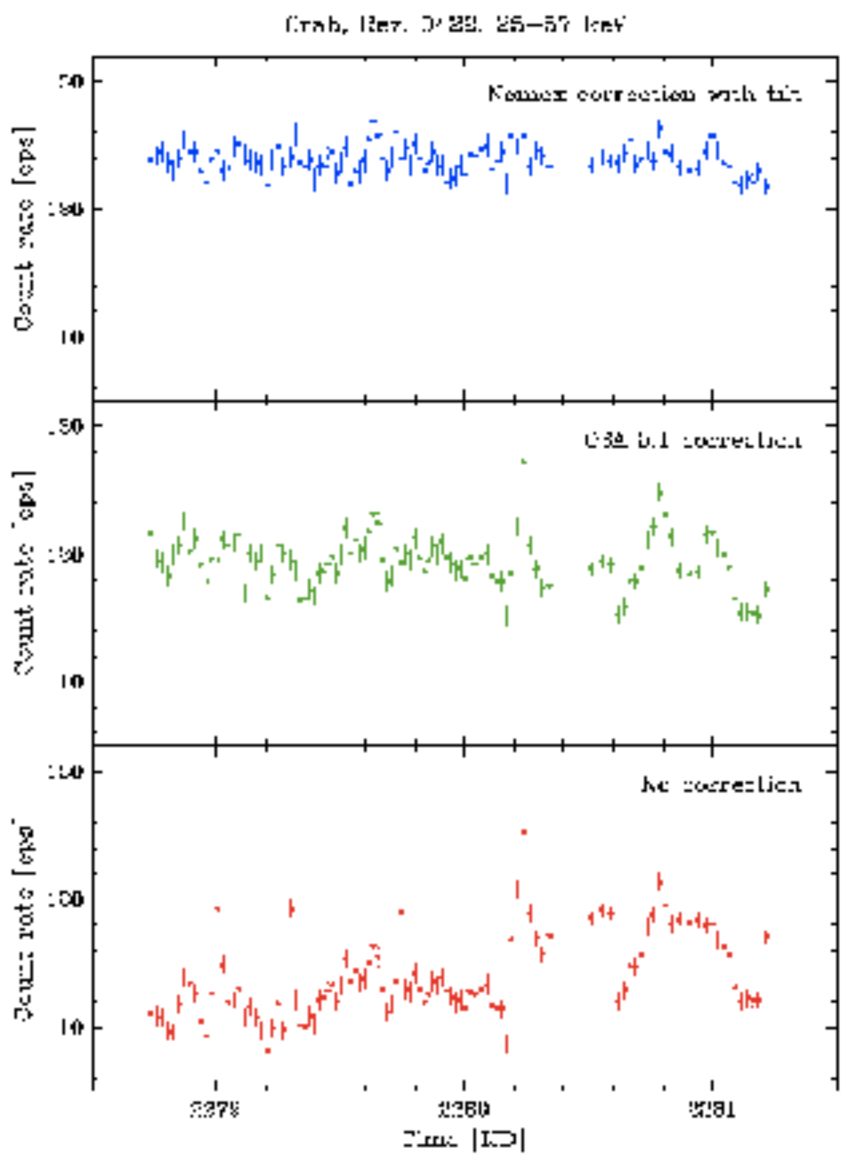
- Quick-look:
  - search exceptional events on-line
  - verify that the data are good enough for the analysis to run
- Standard:
  - based on consolidated TM and historic auxiliary information
  - deliver the best (?) products to the observer
- Off-line:
  - performed by the scientist at home

Hopefully based on exactly the same software

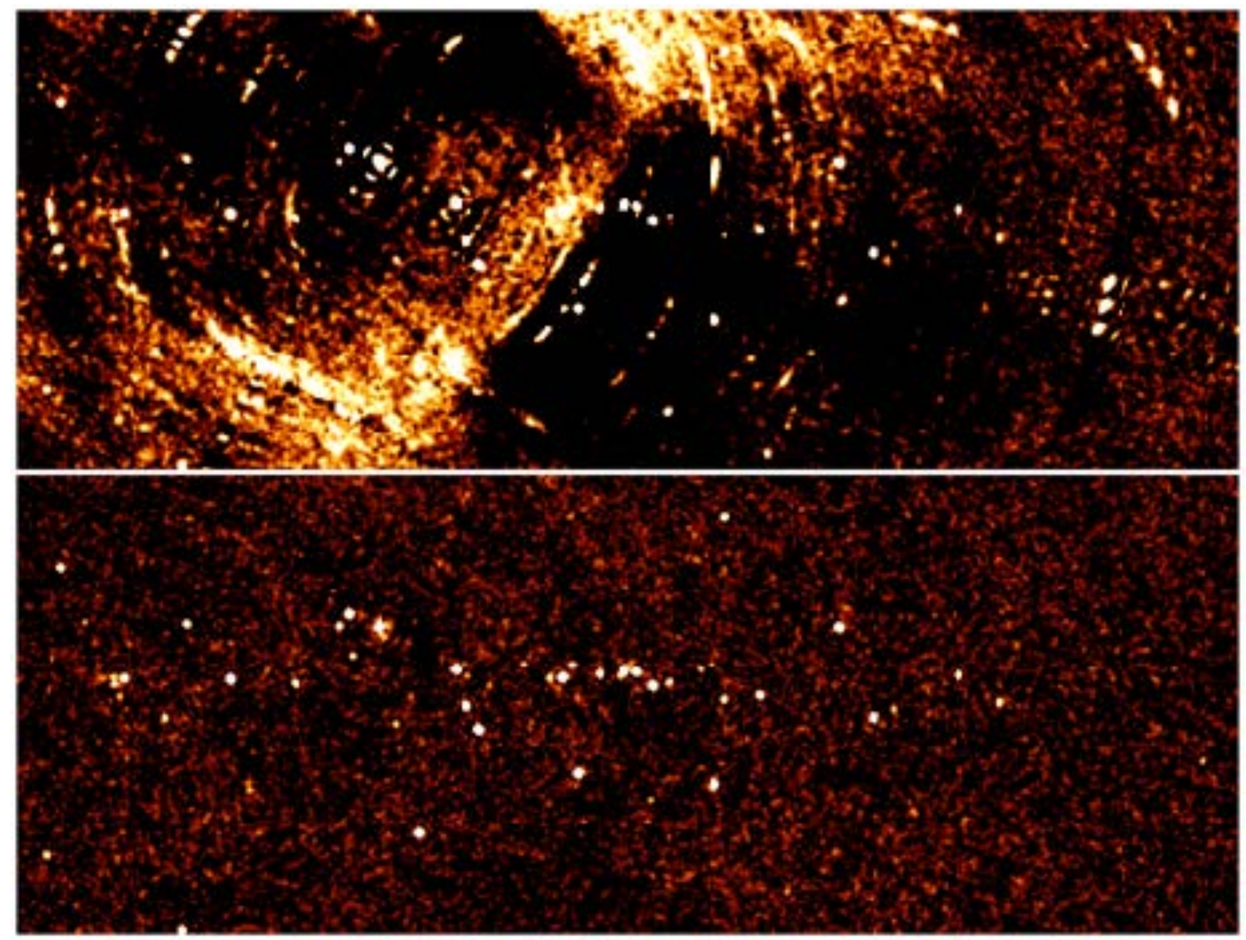
Calibration: an example

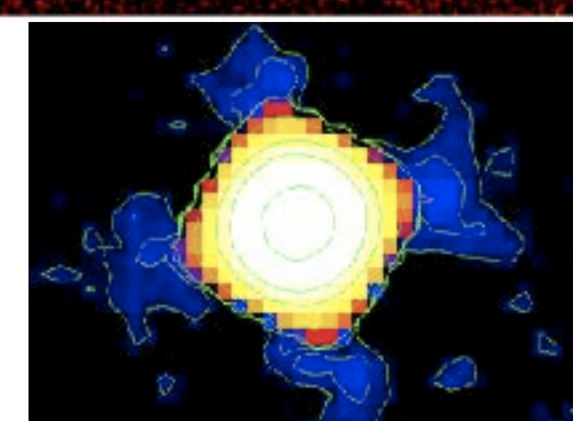
- Detector and mask alignment vs star tracker + thermal deformations
  Current systematics: 14"
- Nomex geometrical model. Current systematics on flux measurement: 1-2%



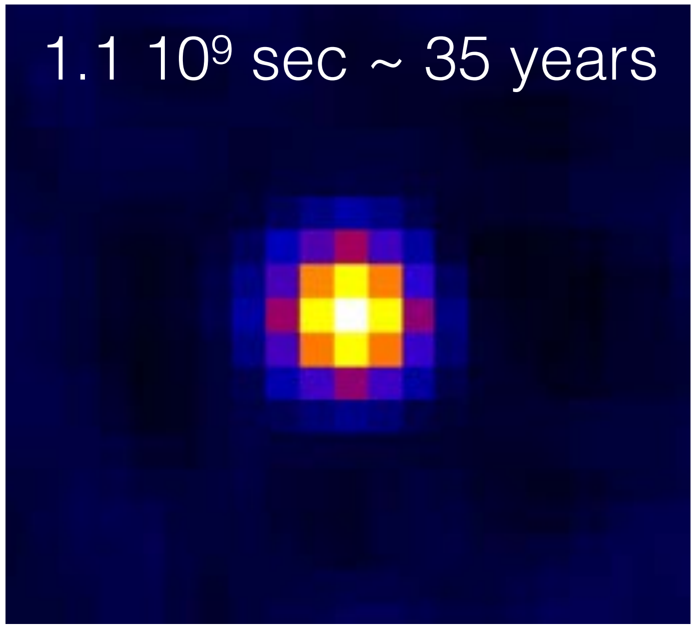


- Image defects related to insufficient instrument modeling. Systematic error on the PSF: 1% limits usable exposure to 2Msec in the vicinity of bright sources



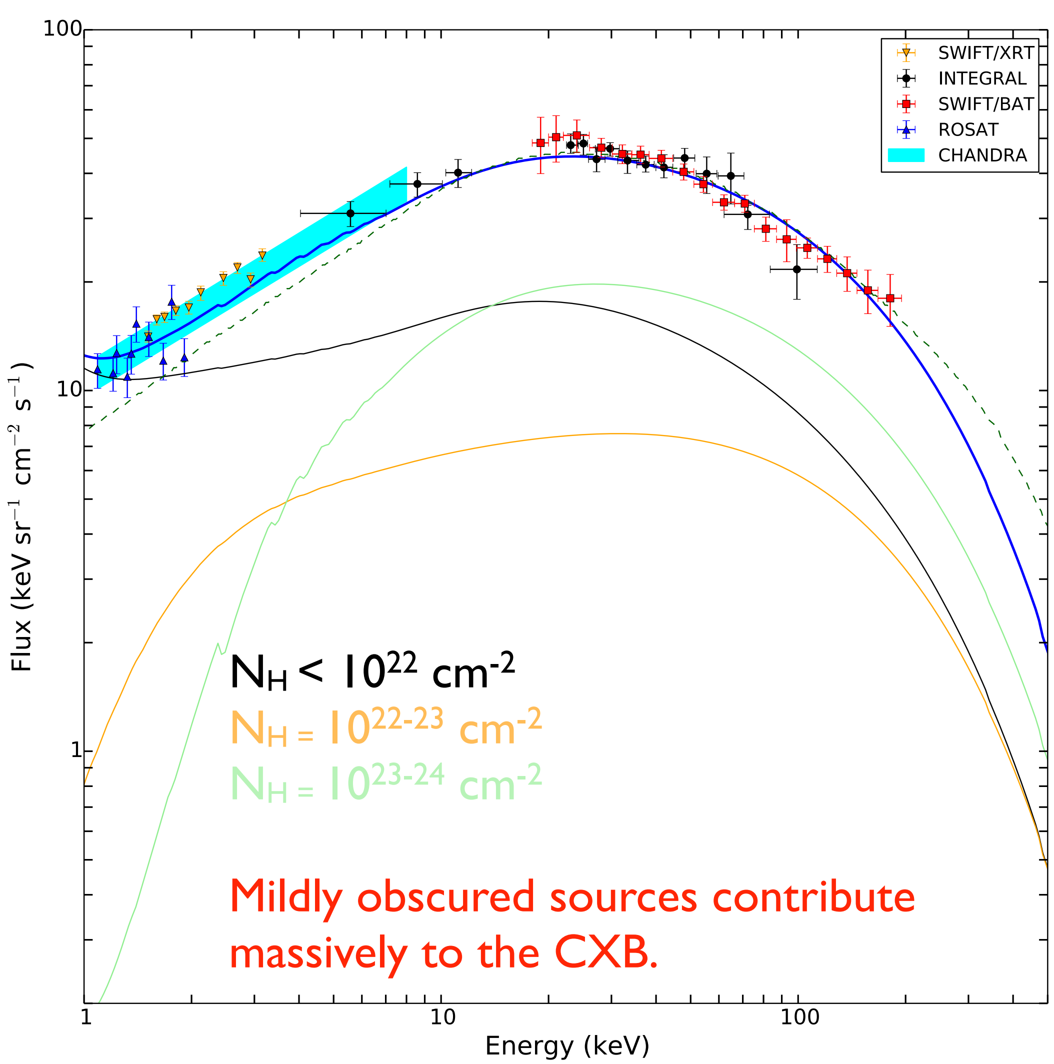


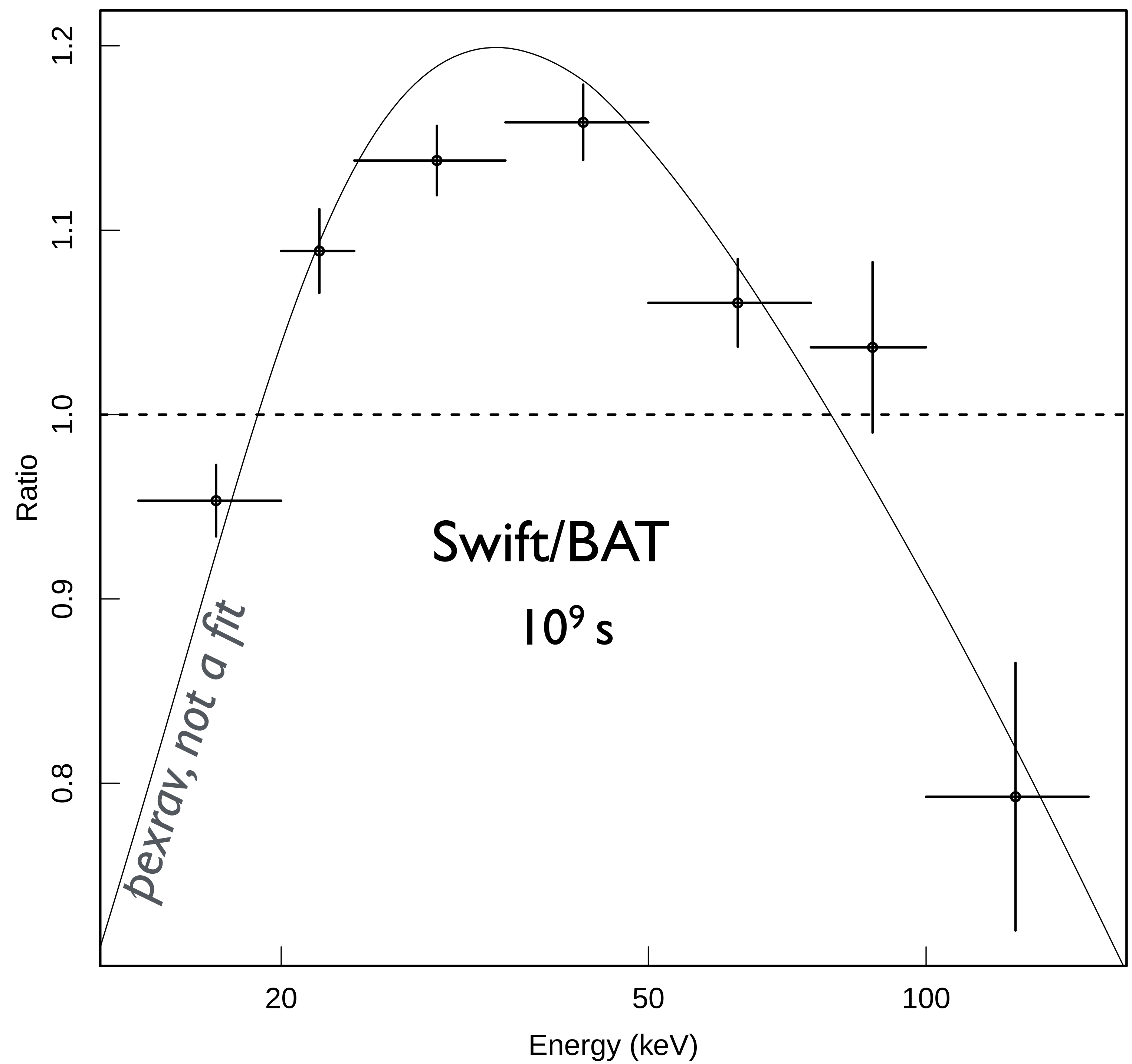
Amazing coded masks



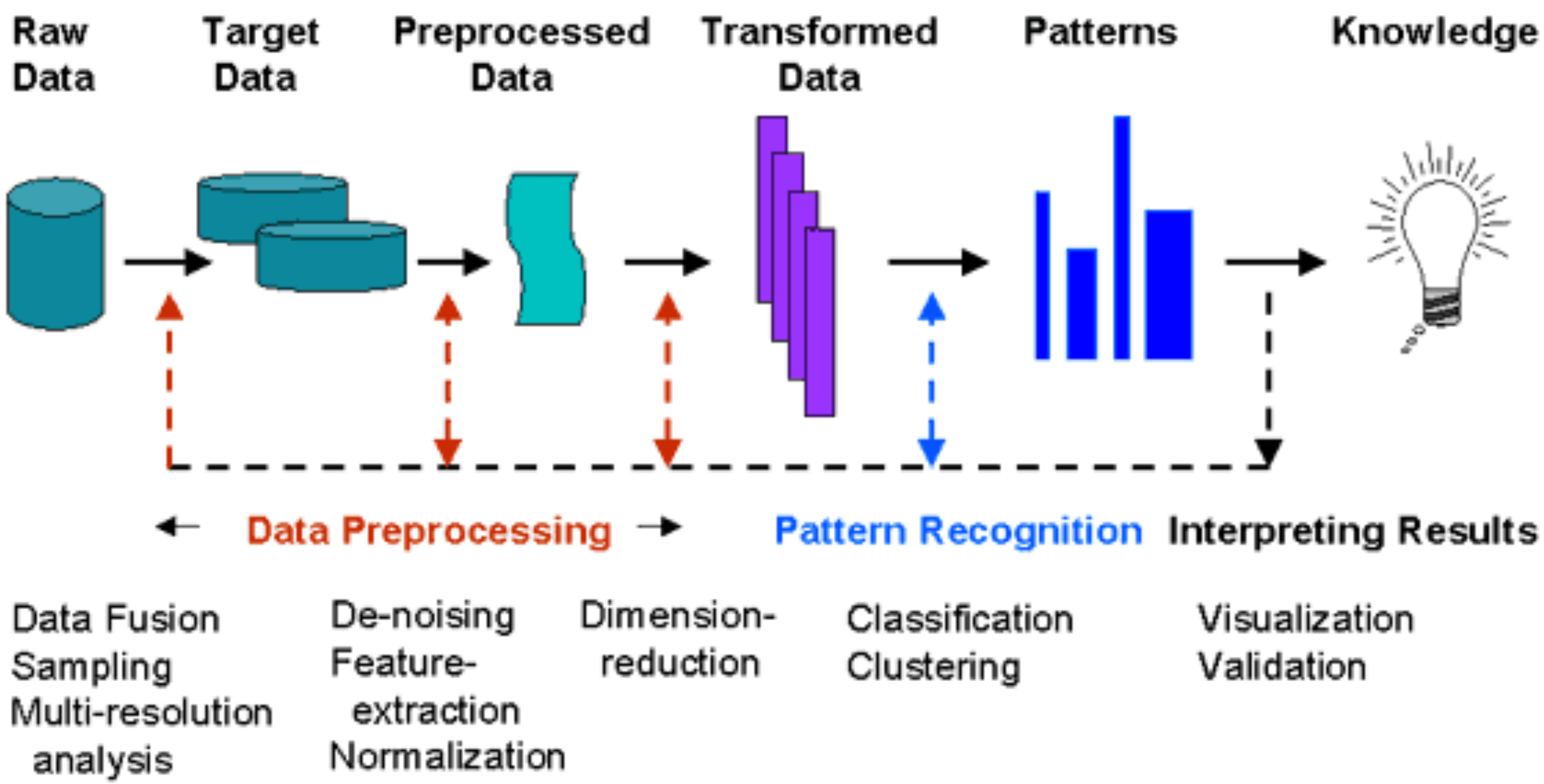
Seyfert 2 : 10^{23-24} cm^{-2} / 10^{22-23} cm^{-2}

(model & calibration independent)





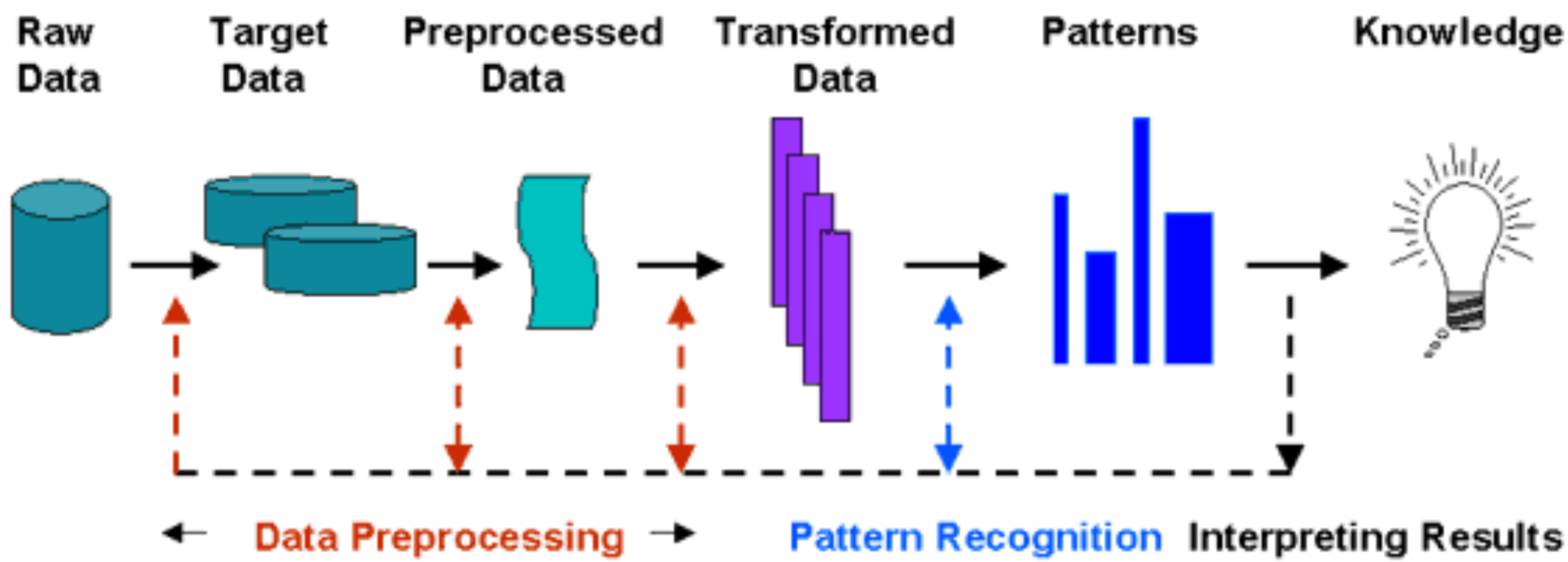
Data Mining

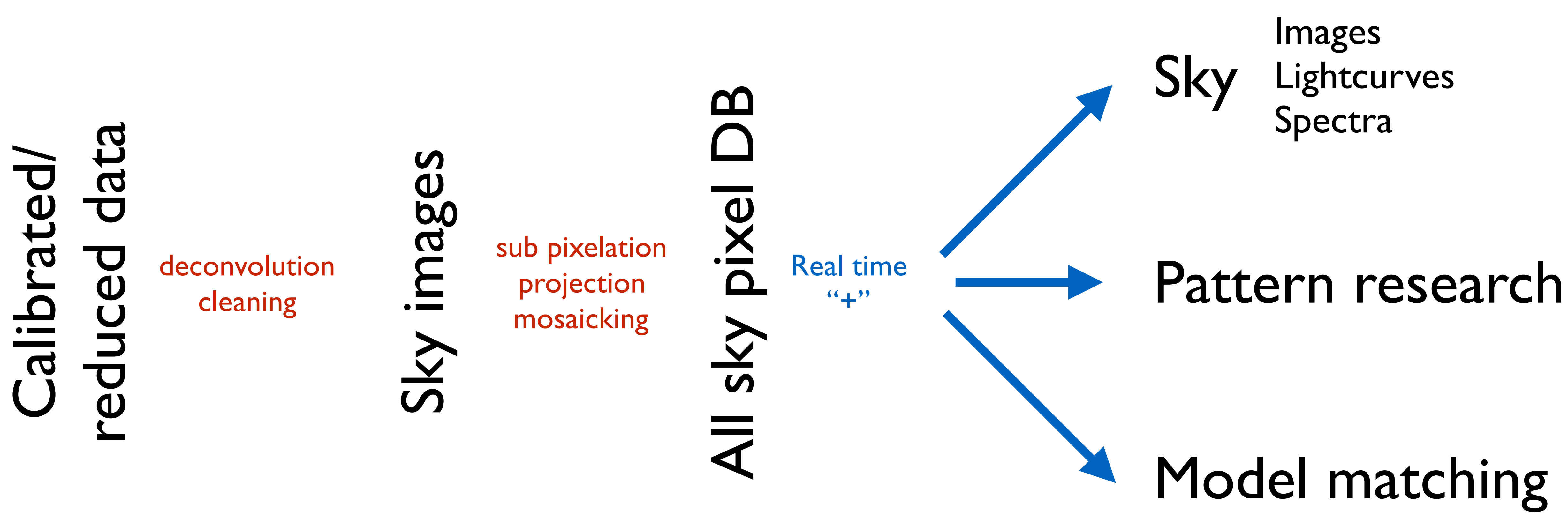


An iterative and interactive process

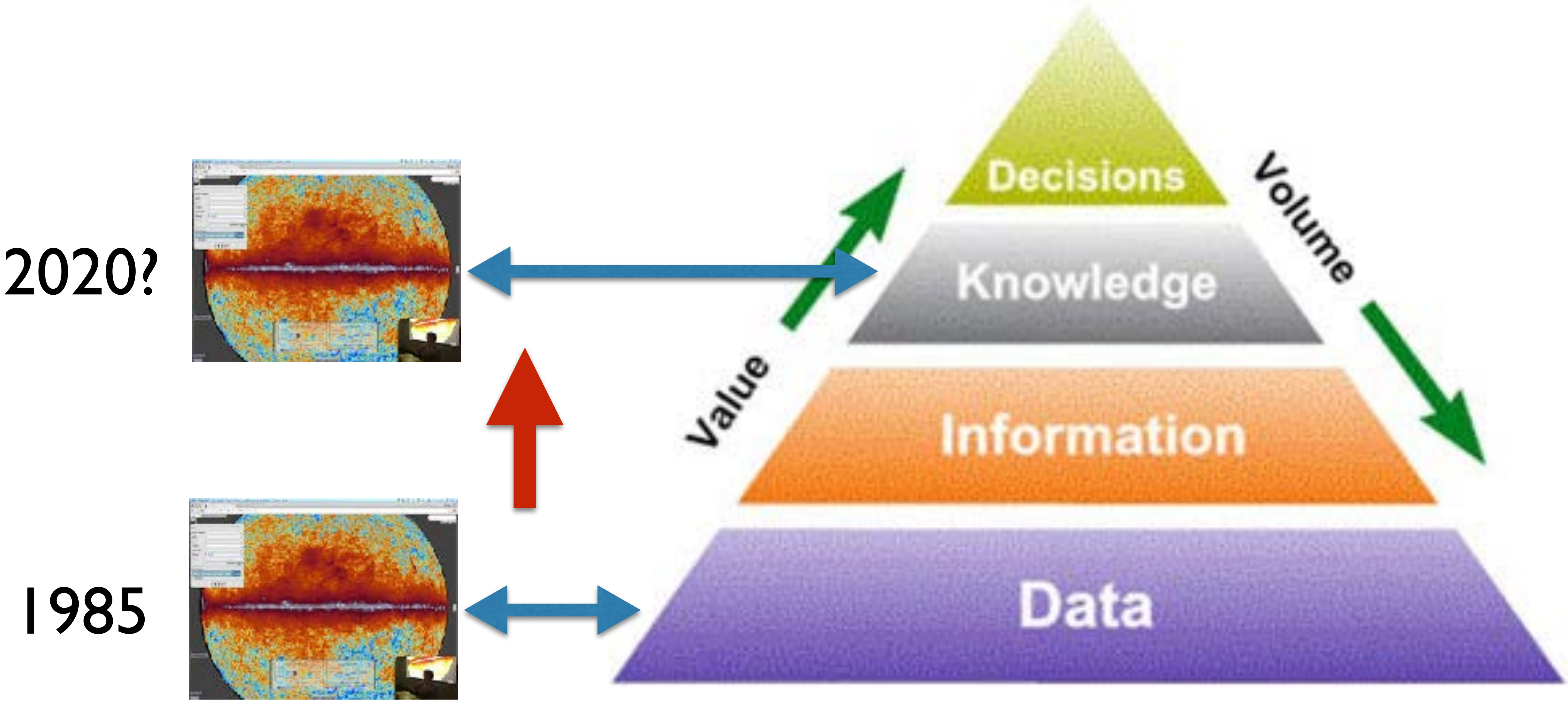
Driven by the needs of science

Data Mining


Raw Data
Target Data
Preprocessed Data
Transformed Data
Patterns
Knowledge
Data Preprocessing
Pattern Recognition
Interpreting Results


Calibrated/ reduced data
deconvolution
cleaning
Sky images
sub pixelation
projection
mosaicking
All sky pixel DB
Real time
"+"
Sky
Images
Lightcurves
Spectra
Pattern research
Model matching

Redesigning Data Management



Requires a merging of archive, pipeline & interpretation

This is a dynamic system, driven by science

Impact on Scientific Operations

Data mining can be used everywhere:

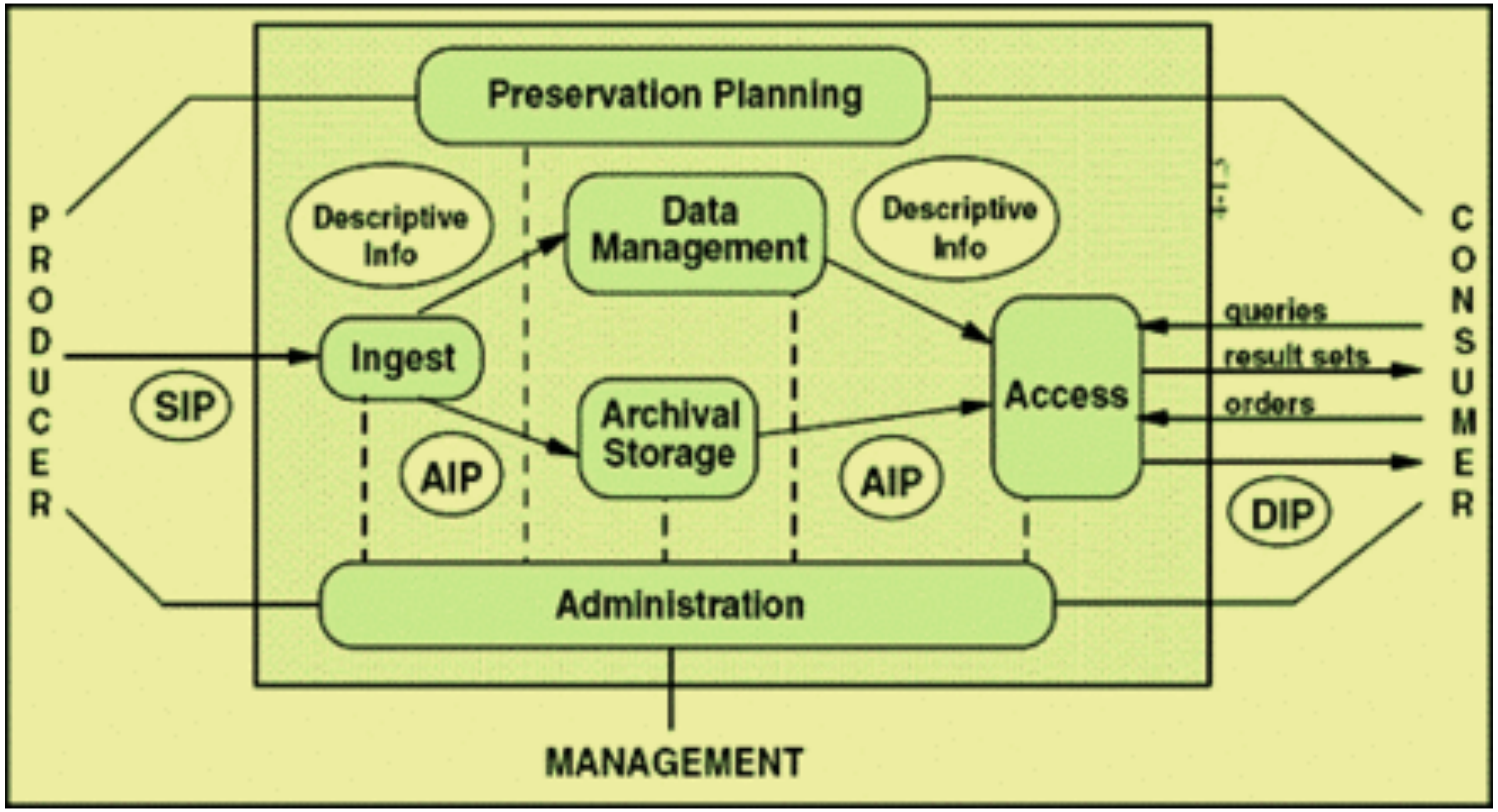
- **Product generation (not “standard analysis” !)**
- **Quick-look analysis** can be performed in real time by observers, instr. teams and the world

Distributed services can be offered/maintained by various partners and can be moved

More flexibility and potentiality does not mean more cost

Open Archival Information System

CCSDS 650.0-B-1 = ISO 14721:2012



- **Ingest**: products verification and metadata extraction
- **Archival Storage**: product storage and maintenance
- **Data Management**: metadata handling and storage
- **Access**: user interface and data retrieval
- **Administration**: manage daily operations (e.g. data rights)
- **Preservation Planning**: long term plans, migration, preservation

DEVELOPMENT MANAGEMENT

Software Engineering Standards

European Cooperation for Space Standardisation ECSS-E-40 / PSS-05 ESA's Board for Software Standardisation and Control

mandatory for all software delivered to ESA

Software Life Cycle
Development Phases
Project Management

The standards seems heavy but can be tailored as a function of

- number of people required to develop, operate and maintain the software;
- number of potential users of the software;
- amount of software that has to be produced;
- criticality of the software, as measured by the consequences of its failure;
- complexity of the software, as measured by the number of interfaces or a similar metric;
- completeness and stability of the user requirements;
- risk values included with the user requirements.

Software is Part of a System

- **Software is frequently part of a larger system.** In this situation a number of activities will already have been performed at 'system level' before the life cycle for any software part of the system can start;
- It is a 'systems engineering' function to define the overall requirements for the system to be built. A **decomposition into subsystems** is performed with resulting subsystem specifications. Once the need for a software item has been established, its life cycle can begin.
- The responsibilities for the production and change control of the **User Requirement Document** should be agreed between 'system' and 'software' project management. The URD should be traceable to the system and/or subsystem documentation.

Software Development Phases

1. **User Requirement phase**
2. **Software Requirement phase**
3. **Architectural Design phase**
4. **Detailed Design Phase**
5. Transfer phase
6. Operation and maintenance phase

The first four phases end with formal reviews, the last two with test reports.

Software Development Phases

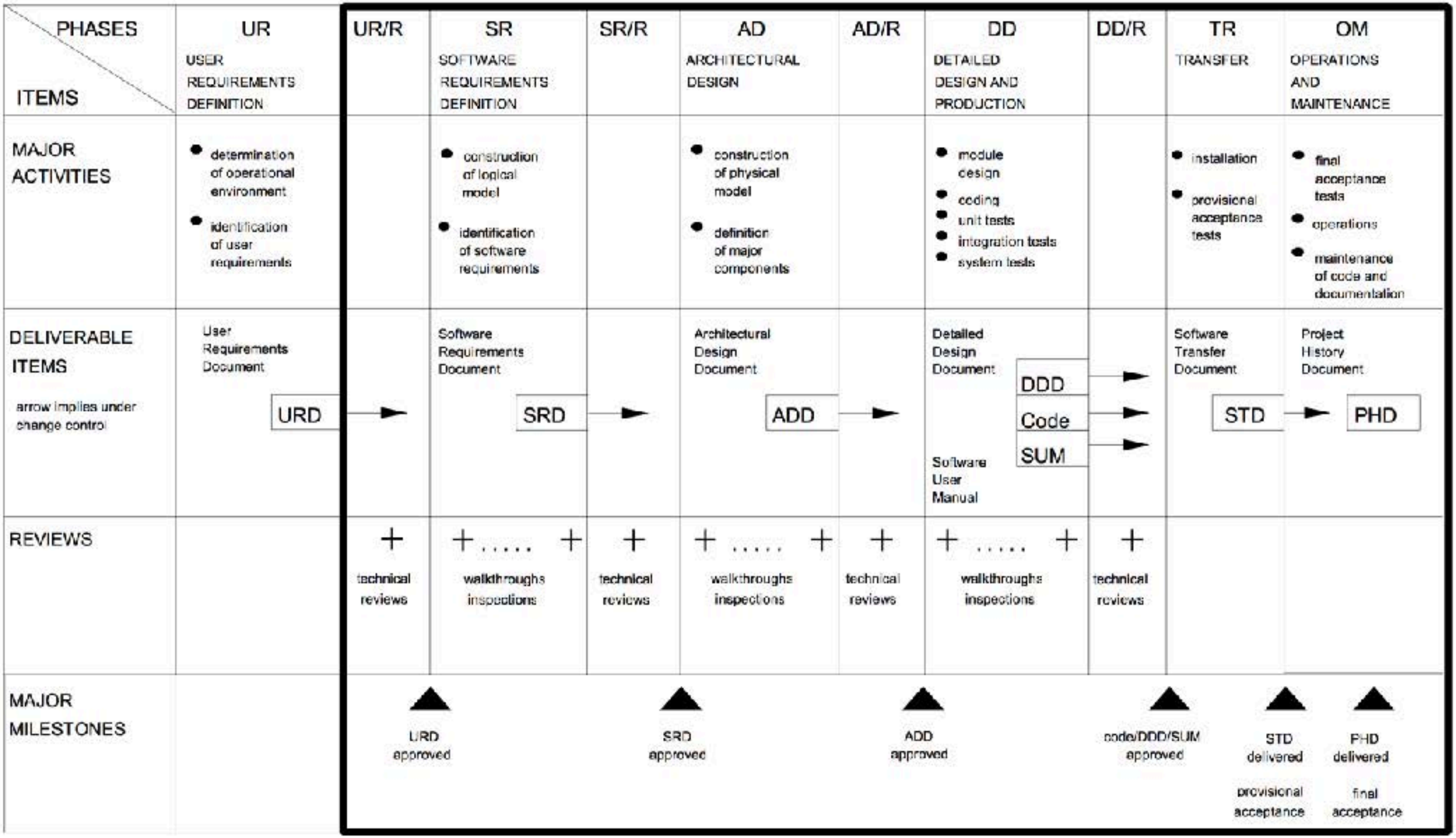
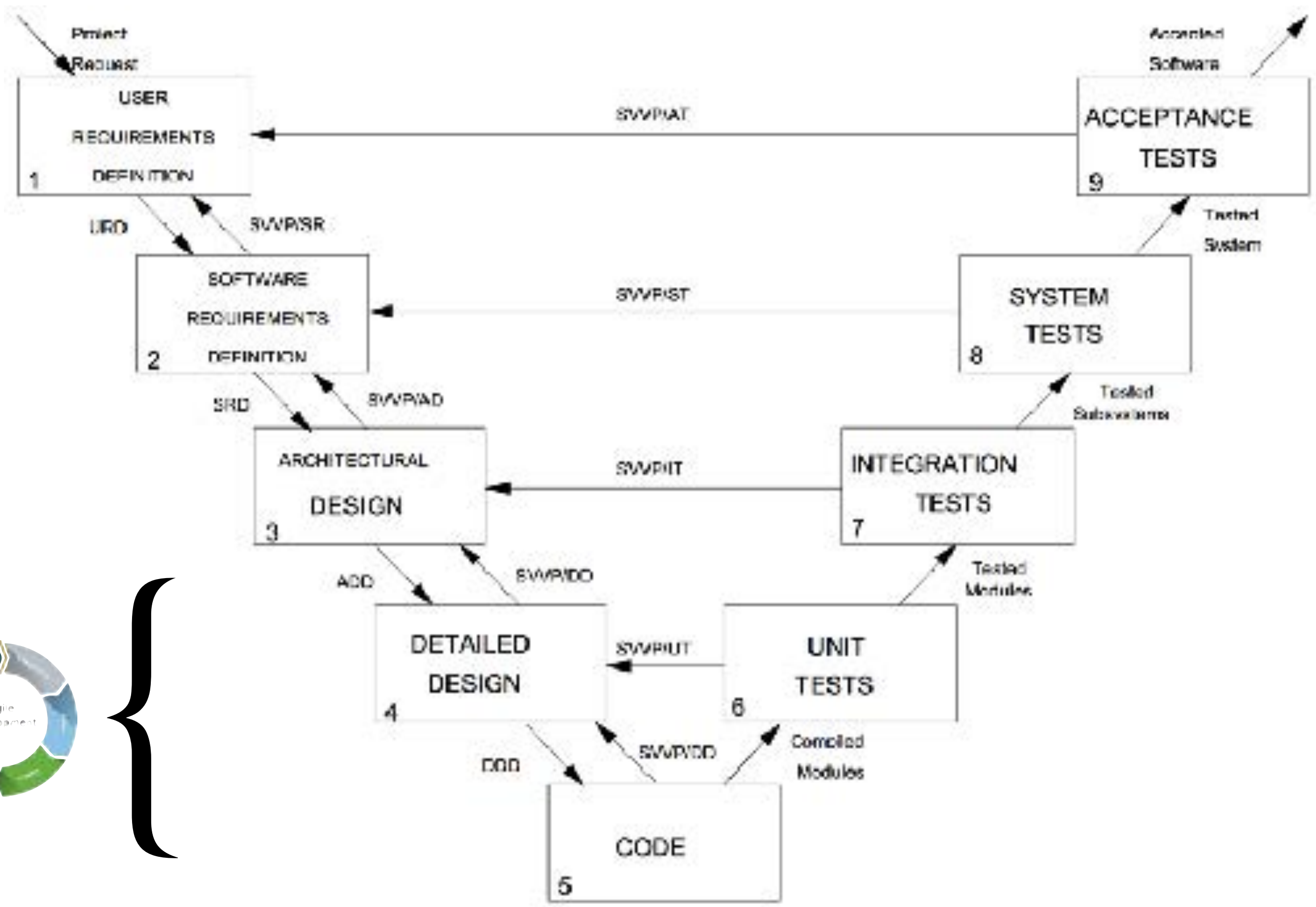
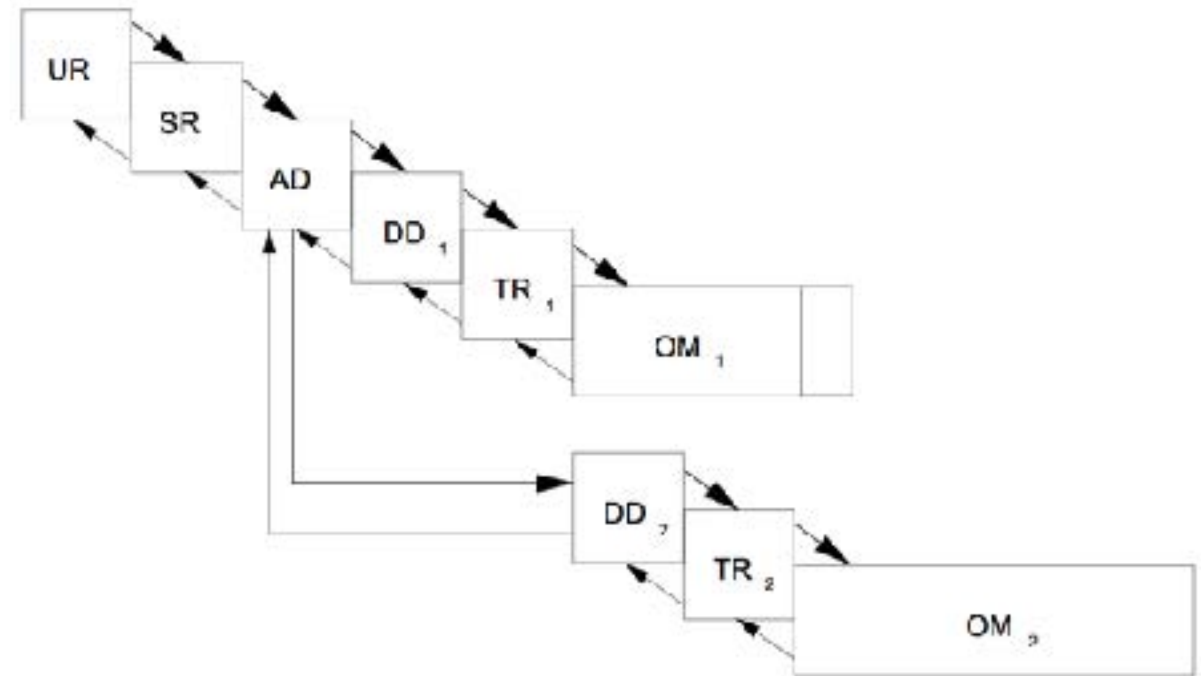


Figure 1.2: The Software Life Cycle Model

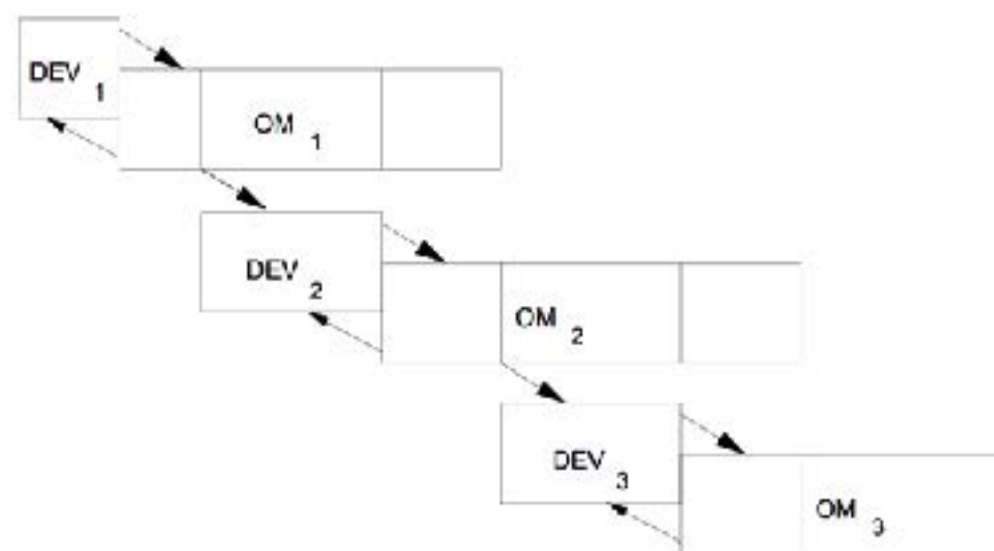
Software Life Cycle



Waterfall or V model

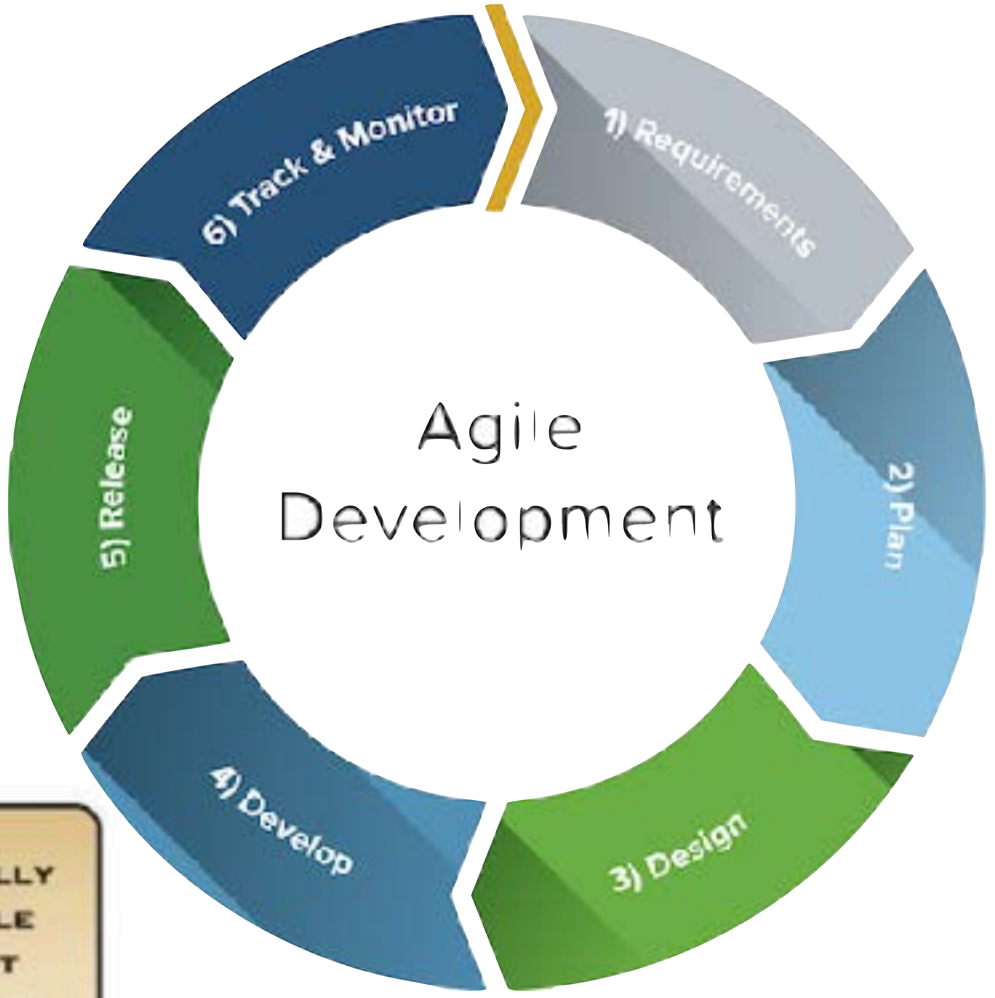


Incremental



Evolutionary or iterative

Software Life Cycle



Agile

when face-to-face interactions are easily established

User Requirement Phase

Problem definition phase:

- UR are the responsibility of the user
- UR should be verifiable
- High level but complete set of UR, keep only fundamentals
- Build a consensus among the users at requirement not implementation level
- Use cases are a way to collect user requirements
- Interfaces (ICD) are considered at user requirements level

Outputs:

- User Requirement Document
- Acceptance Test Plan
- Software Project Management Plan
- Configuration Management Plan
- Verification and Validation Plan
- Quality Assurance Plan

Software Requirement Phase

Problem analysis phase:

- SR are the responsibility of the developper
- SR should be verifiable and complete
- Functional, performance, interface, operational, ressource, security, portability, safety requirements
- Build a consensus between users and developers
- Build a logical model (top-down decomposition)
- Interfaces (ICD) are considered at user requirements level

Outputs:

- Software Requirement Document
- System Test Plan
- Update of Software Project Management Plan (30% cost estimate)
- Update of Configuration Management Plan
- Update of Verification and Validation Plan
- Update of Quality Assurance Plan

Architectural Design Phase

Solution phase:

- AD is the responsibility of the developper
- AD should be verifiable and complete
- Build a physical model and control flow of the system
- Decomposition of the software into components (input, output, function) and data structures.
- Selection of languages, algorithms

Outputs:

- Architectural Design Document
- Integration Test Plan
- Update of Software Project Management Plan (10% cost estimate)
- Update of Configuration Management Plan
- Update of Verification and Validation Plan
- Update of Quality Assurance Plan

Detailed Design Phase

Implementation phase:

- DD is the responsibility of the software engineer
- DD phase is where Agile development is efficient
- Structured programming/pair programming
- Documentation to be produced concurrently
- Unit and integration testing

Outputs:

- Software
- Test data and procedures
- Code Documentation
- User Manual
- Acceptance Test Specification
- Update of Management Plans

Transfer & Operation and Maintenance Phases

Handover phase:

- TR is the responsibility of the software engineer
- Documentation to be produced concurrently
- Acceptance Tests

Outputs:

- Software Transfer Document (software installation)
- Acceptance test report

Practical use phase:

- Acceptance Tests

Outputs:

- Acceptance statement

Management Plans

Software Project Management:

- Project organisation
- Risk analysis
- Technical management
- Planning & budget
- Reporting

Software Verification & Validation:

- Reviews & audits
- Traceability
- Proof & Testing
- Change control

Software Configuration Management:

- Software item identification
- Version management (baseline, releases)
- Configuration management
- Change control

Software Quality Management:

- Management & communication
- Software documentation
- Reviews & audits
- Testing
- Reporting
- Code and media control
- Record collection, minutes
- Training
- Risk

End-to-End Tests

- Every possibility to participate to end-to-end tests should be used. They provides very good confidence that things are working. These tests are rarely complete.

- The schedule of end-to-end tests often vary (the data centre is not a priority at such times), so they are hard to plan

- Partial tests are also available:
  with the MOC, using a spacecraft simulator
  during payload calibration exercices
  during LEOP and spacecraft commissioning

LEOP and Commissioning

- LEOP (Launch and early orbit phase) allows to finalise tests of spacecraft operation and routine data processing. Influence of radiation environment can be probed. Spacecraft performance need to be checked.

- Instrument commissioning mainly target to verify the proper functioning of the instruments. Start as early as possible. It is a very good way to detect and fix problems before the start of scientific operations.

(not so) Routine phase

- Specific instrument calibrations may need a lot of data or observation of sources not visible at launch. Calibration activities are never ending.

- The spacecraft orbit changes. Radiation and thermal environment as well. Misalignment can be an issue.

- Tests need to be repeated each time a new instrument mode is used, a parameter is modified, or a new on-board software is uploaded. This is heavy and should be minimised.

- Instrument and spacecraft may degrade, operations can be even more difficult close to the mission end. Keep expertise !

DATA IS THE LEGACY

DATA IS THE LEGACY

- **Data is the interface between the mission and the scientists**
- **Science is derived from the data**
- **Many science results are derived from the archive, not from individual observations and depend on the availability and usability of the data by the scientific community at large**
- **Scientific papers are still published with 30 years old data**
- **Questions evolve, data remains**

Be serious with the Data…. and use them !