UNIVERSITY OF CAMBRIDGE

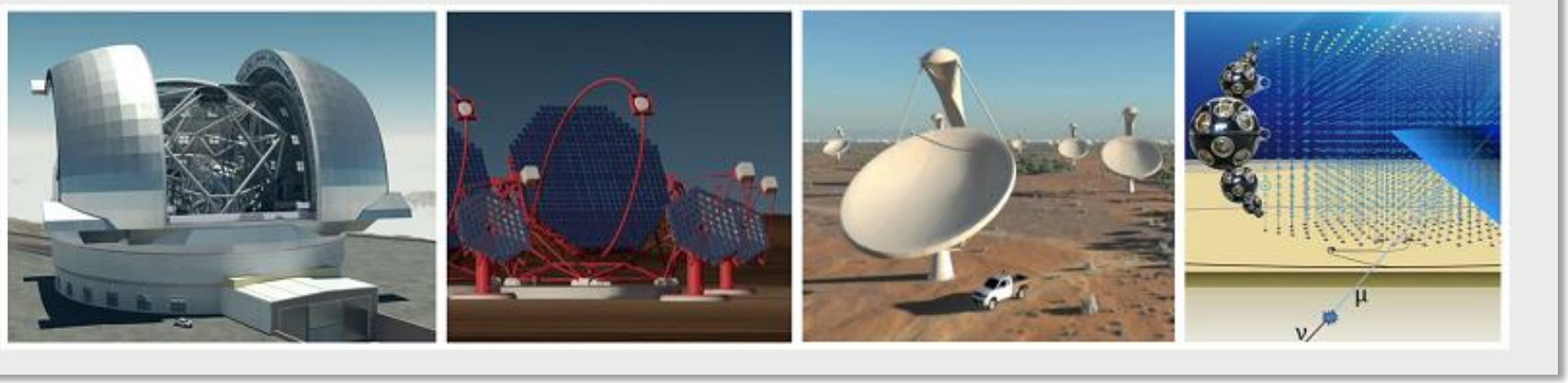
ASTERICS
&
Work Flows within the SRC

Paul Alexander

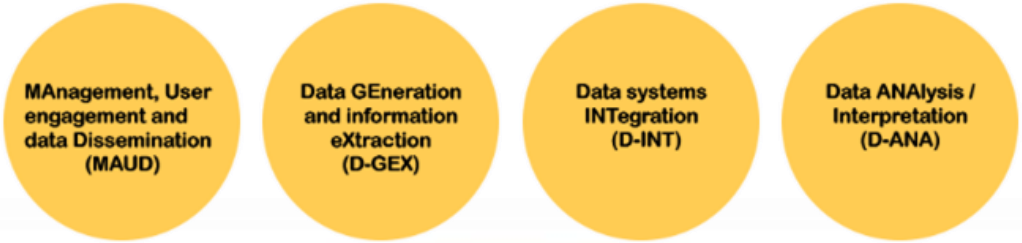
ASTERICS

ASTERICS:

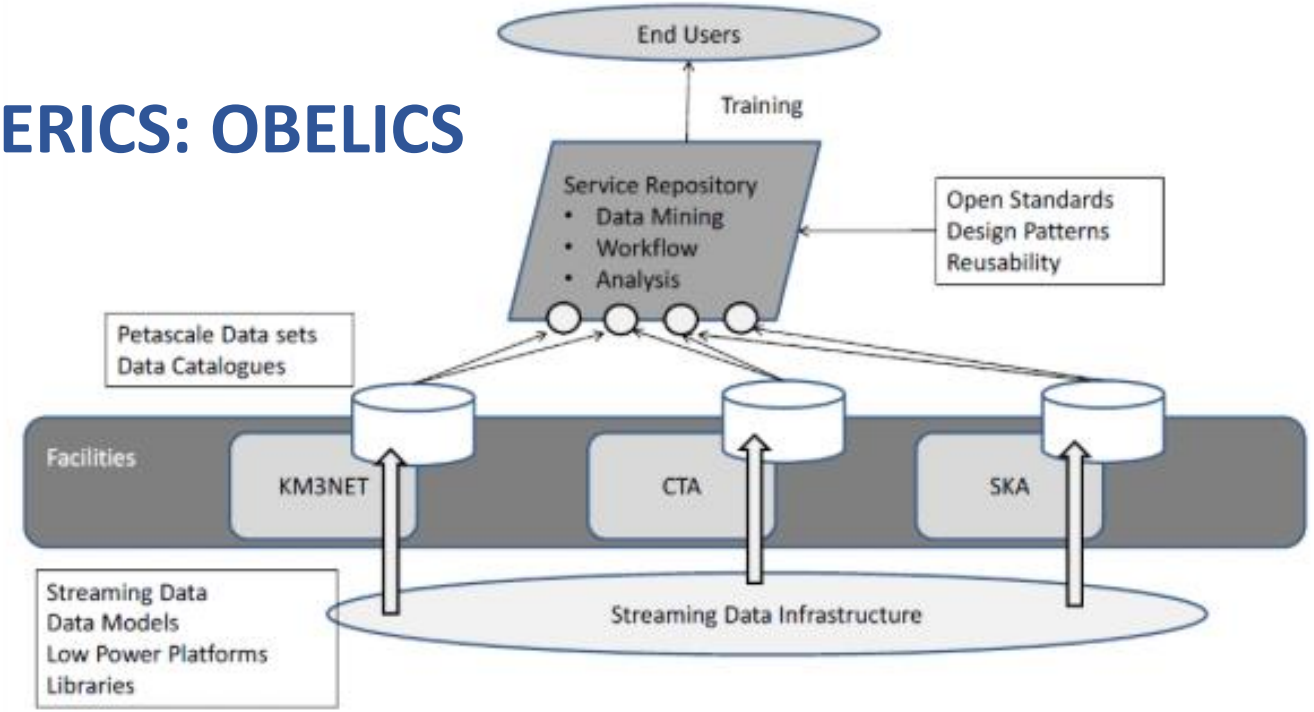
Support and accelerate the implementation of the ESFRI telescopes, to enhance their performance beyond the current state-of-the-art, and to see them interoperate as an integrated, multi-wavelength and multi-messenger facility



E-ELT | CTA | SKA | KM3NET

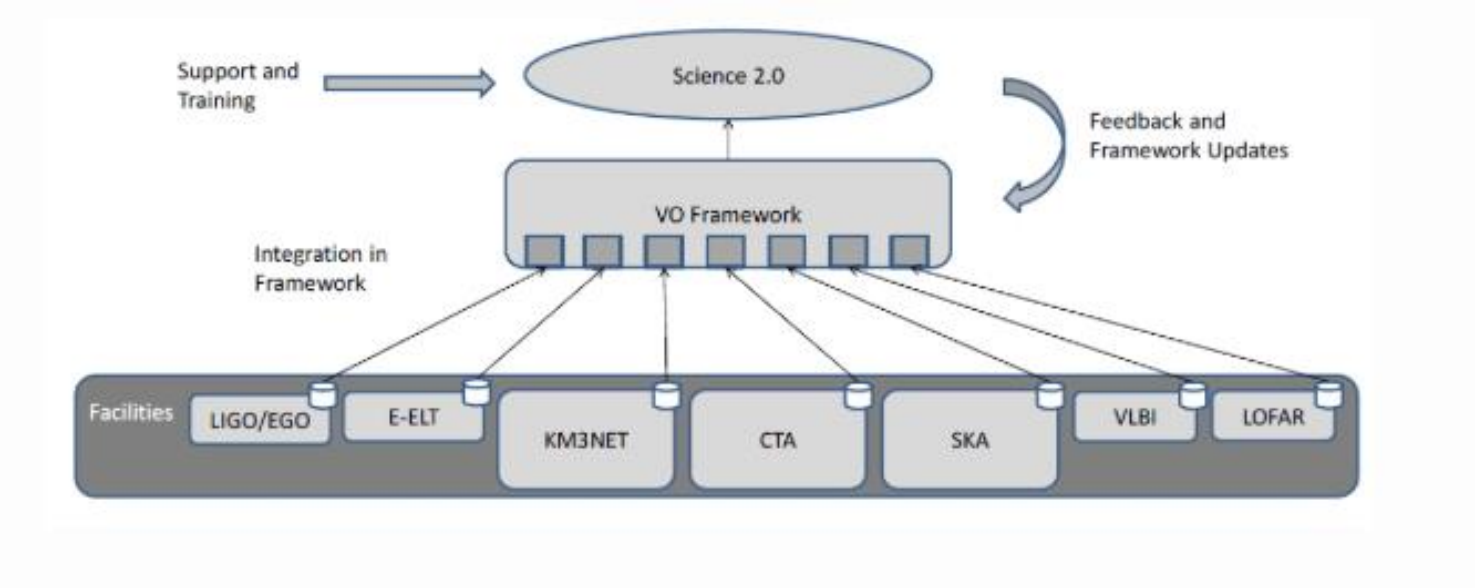


ASTERICS: OBELICS



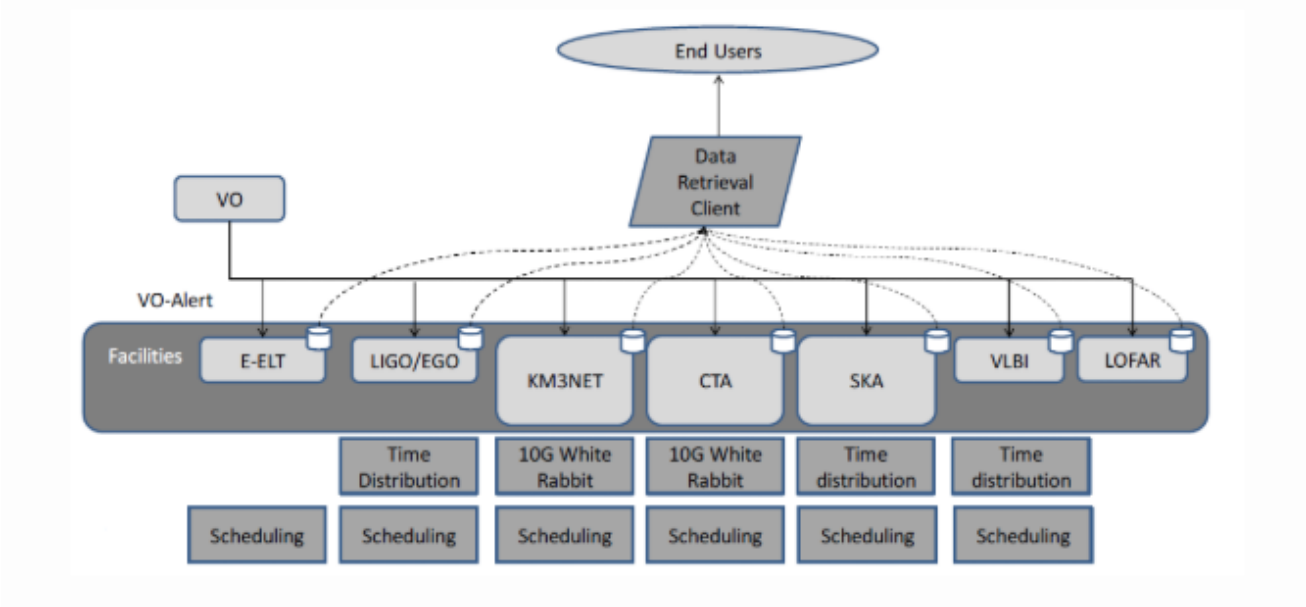
- Maximise software re-use and co-development of technology for Petascale data
- Adapt and optimise extremely large database systems to fulfil the requirements of the ASTERICS ESFRI projects.
- Study and demonstrate data integration across ASTERICS ESFRI and pathfinder projects using data mining tools and statistical analysis techniques on Petascale data sets.

ASTERICS: DADI



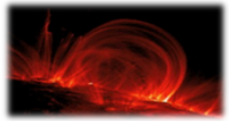
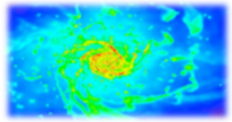
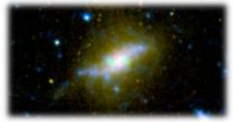
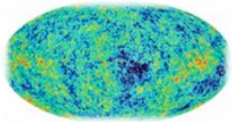
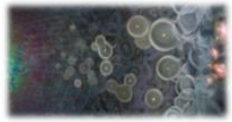
- Adapt the VO framework and tools to the ESFRI project needs, and make sure European astronomers remain lead actors in the IVOA, influencing it in the interest of the European infrastructures and the European scientific community

ASTERICS: CLEOPATRA

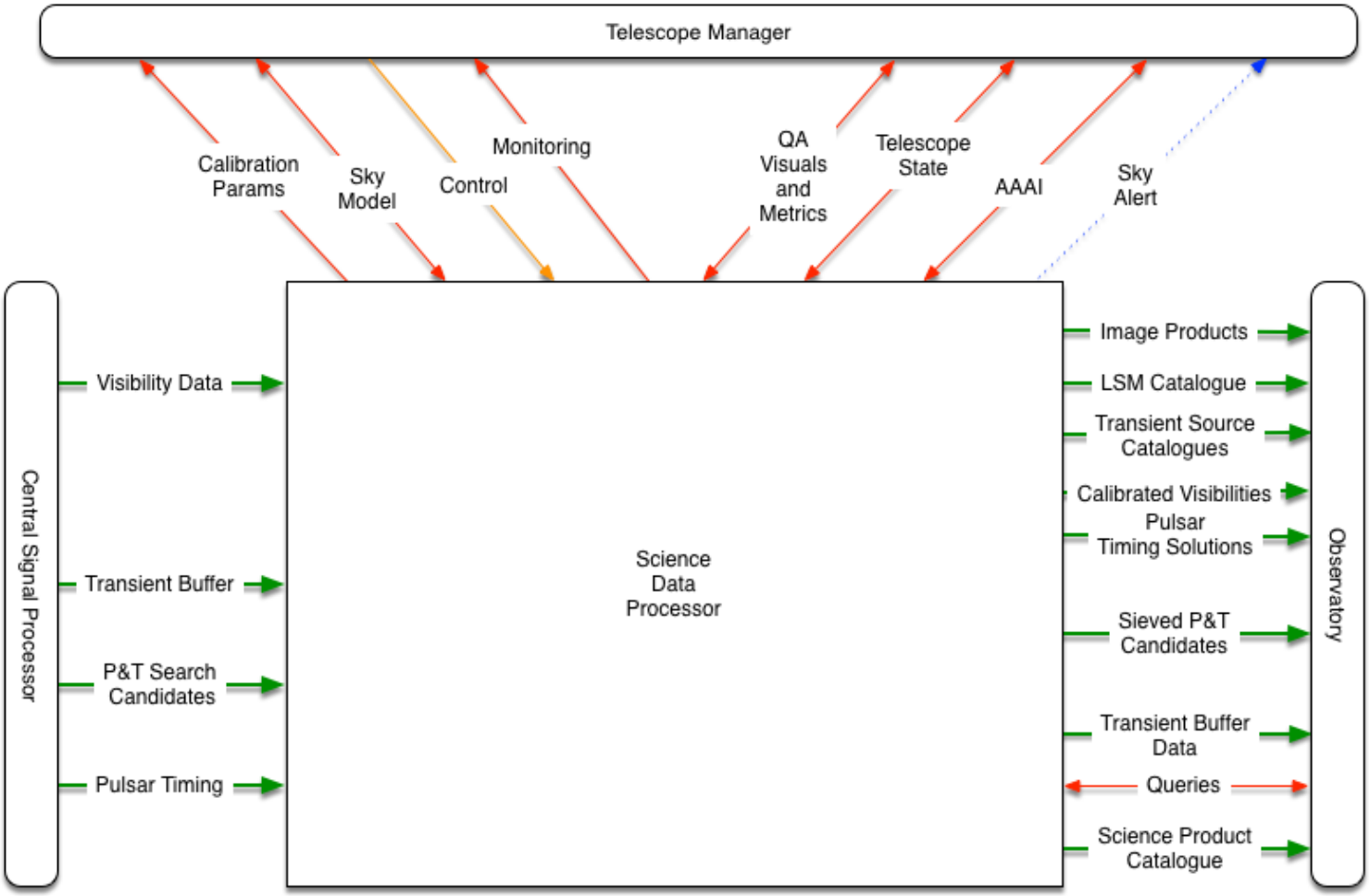


- Develop technology for the enabling of long-haul and many-element time and frequency distribution over fibre connections.
- Develop methods for relaying alerts, which will signal transient event detections between the facilities and enable joint observing programmes, including scientific strategies and methods for joint observing.
- Foster the development of advanced scheduling algorithms, using AI approaches for optimal usage of the ESFRI facilities. CLEOPATRA's tasks reflect a consistent set of enhancements of the facilities based on developments in connectivity and data transport.

Data Products: From Science Case

	SKA1	SKA2	
The Cradle of Life & Astrobiology	Proto-planetary disks; imaging inside the snow/ice line (@ < 100pc), Searches for amino acids.	Proto-planetary disks; sub-AU imaging (@ < 150 pc), Studies of amino acids.	
	Targeted SETI: airport radar 10^4 nearby stars.	Ultra-sensitive SETI: airport radar 10^5 nearby star, TV ~10 stars.	
Strong-field Tests of Gravity with Pulsars and Black Holes	1st detection of nHz-stochastic gravitational wave background.	Gravitational wave astronomy of discrete sources: constraining galaxy evolution, cosmological GWs and cosmic strings.	
	Discover and use NS-NS and PSR-BH binaries to provide the best tests of gravity theories and General Relativity.	Find all ~40,000 visible pulsars in the Galaxy, use the most relativistic systems to test cosmic censorship and the no-hair theorem.	
The Origin and Evolution of Cosmic Magnetism	The role of magnetism from sub-galactic to Cosmic Web scales, the RM-grid @ 300/deg2.	The origin and amplification of cosmic magnetic fields, the RM-grid @ 5000/deg2.	
	Faraday tomography of extended sources, 100pc resolution at 14Mpc, 1 kpc @ z ≈ 0.04.	Faraday tomography of extended sources, 100pc resolution at 50Mpc, 1 kpc @ z ≈ 0.13.	
Galaxy Evolution probed by Neutral Hydrogen	Gas properties of 10^7 galaxies, <z> ≈ 0.3, evolution to z ≈ 1, BAO complement to Euclid.	Gas properties of 10^9 galaxies, <z> ≈ 1, evolution to z ≈ 5, world-class precision cosmology.	
	Detailed interstellar medium of nearby galaxies (3 Mpc) at 50pc resolution, diffuse IGM down to N_H < 10^17 at 1 kpc.	Detailed interstellar medium of nearby galaxies (10 Mpc) at 50pc resolution, diffuse IGM down to N_H < 10^17 at 1 kpc.	
The Transient Radio Sky	Use fast radio bursts to uncover the missing "normal" matter in the universe.	Fast radio bursts as unique probes of fundamental cosmological parameters and intergalactic magnetic fields.	
	Study feedback from the most energetic cosmic explosions and the disruption of stars by super-massive black holes.	Exploring the unknown: new exotic astrophysical phenomena in discovery phase space.	
Galaxy Evolution probed in the Radio Continuum	Star formation rates (10 M_Sun/yr to z ~ 4).	Star formation rates (10 M_Sun/yr to z ~ 10).	
	Resolved star formation astrophysics (sub-kpc active regions at z ~ 1).	Resolved star formation astrophysics (sub-kpc active regions at z ~ 6).	
Cosmology & Dark Energy	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: competitive to Euclid.	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: redefines state-of-art.	
	Primordial non-Gaussianity and the matter dipole: 2x Euclid.	Primordial non-Gaussianity and the matter dipole: 10x Euclid.	
Cosmic Dawn and the Epoch of Reionization	Direct imaging of EoR structures (z = 6 - 12).	Direct imaging of Cosmic Dawn structures (z = 12 - 30).	
	Power spectra of Cosmic Dawn down to arcmin scales, possible imaging at 10 arcmin.	First glimpse of the Dark Ages (z > 30).	

Scope of the SKA Science Data Processor (SDP)



SKA Data Products

Table 1: SDP Data Products

Data Product	Description **(For each product a QA and Processing Log will also be maintained)**
Image Products 1: Image Cubes	1. Imaging data for Continuum, as cleaned restored Taylor term images (n.b. no image products for Slow Transients detection have been specified – maps are made, searched and discarded) 2. Residual image (i.e. residuals after applying CLEAN) in continuum 3. Clean component image (or a table, which could be smaller). 4. Spectral line cube after continuum subtracted 5. Residual spectral line image (i.e. residuals after clean applied) 6. Representative Point Spread Function for observations (cutout, small in size compared to the field of view (FOV))
Image Products 2: UV-grids	1. Calibrated visibilities, gridded at the spatial and frequency resolution required by the experiment. One grid per facet (so this grid is the FFT of the dirty map of each facet). c.f. ECP150007 [AD02] 2. Accumulated Weights for each uv cell in each grid (without additional weighting applied).
Calibrated Visibilities	Calibrated visibility data (for example for EoR experiments) and direction-dependent calibration information, with time and frequency averaging performed as requested to reduce the data volume.
LSM Catalogue	Catalogue of a subset of the Global Sky Model (GSM) containing the sources relevant for the scheduling block being processed. These are the sources in the FOV, as well as, potentially, strong sources outside of the current FOV. Initially, the LSM is filled from the GSM; during the data processing the sources found in the images are added to the LSM.
Transient Source Catalogue	Time-ordered catalogue of candidate transient objects pertaining to each detection alert from the real-time, so-called, Fast Imaging.
Pulsar Timing Solutions	For each of the observed pulsars the output data from the pulsar timing section will include the original input data as well as averaged versions of these data products (either averaged in polarisation, frequency or time) in PSRFITs format. The arrival time of the pulse. The residuals from the current best-fit model for the pulsar. An updated model of the arrival times.
Transient Buffer Data	Voltage data passed through from the CSP when the transient buffer is triggered.
Sieved Pulsar and Transient Candidates	A data cube which will be folded and dedispersed at the best Dispersion Measure (DM), period and period derivative determined from the search. A single ranked list of non-imaging transient candidates from each scheduling block. For those transients deemed of sufficient interest, the associated "filterbank" data will also be archived. A set of diagnostics/heuristics that will include metadata associated with the scheduling block and observation. If a sufficiently interesting pulsar is discovered this will generate an alert as well as being recorded in a Log. (While we have a requirement to report single pulse events, it is not clear whether we have to provide alerts for anything other than single pulses. This is being referred to the Telescope Teams.)
Science Alerts Catalogue	Catalogue of Science Alerts produced and communicated by the SDP. The alerts themselves are IVOA alerts; this catalogue provides a searchable and retrievable record of past alerts.
Science Product Catalogue	A database relating to all Science Products processed by the SDP. It includes associated scientific metadata that can be queried and searched and includes all information so that the result of a query can lead to the delivery of data.

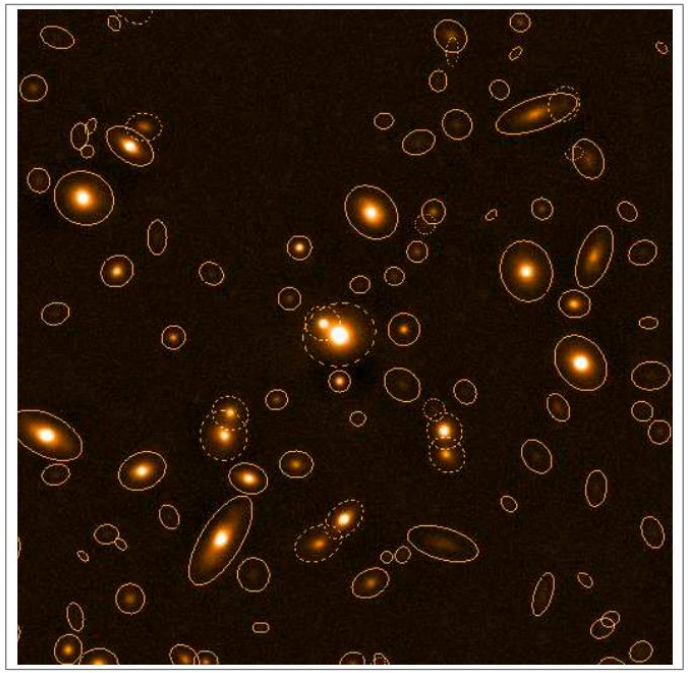
Image-based types of Analysis

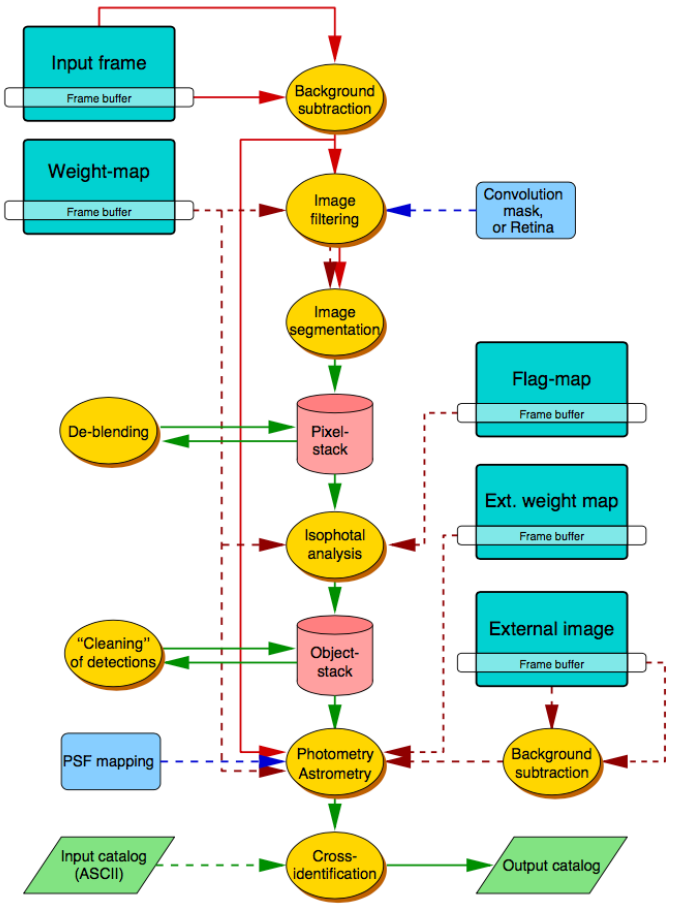
- **General Image Processing**
  - Visualisation
  - Noise estimation
  - Basic image operations, weighted averaging
  - Filtering and masking
  - Deconvolution and smoothing
  - Standard image-based feature detection and extraction
- **Specialised Image Processing**
  - Source Detection in noisy data
  - Faraday and rotation-measure imaging
- **Feature detection Classification**
  - Model fitting (simple or statistically robust)
  - Representation in a new basis (wavelets, compressed sensing, …)
  - Direct machine learning classification in image space
  - High-dimensional classification prior to scientific statistical analysis
    - E.g. based on image features + spectral features + polarization features

Multi-dimensional image data
size up to 50k x 50k x 64 k

Spatial
Spectral / velocity
Polarization

Source detection and feature extraction



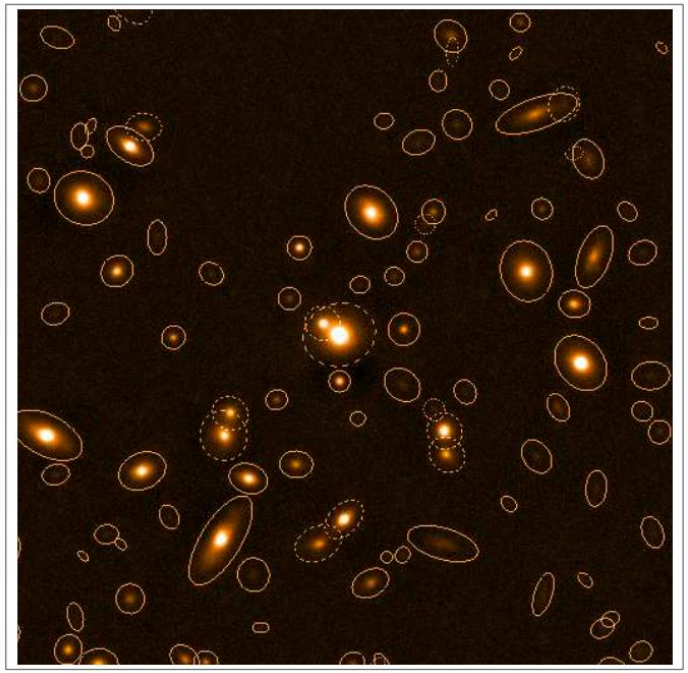


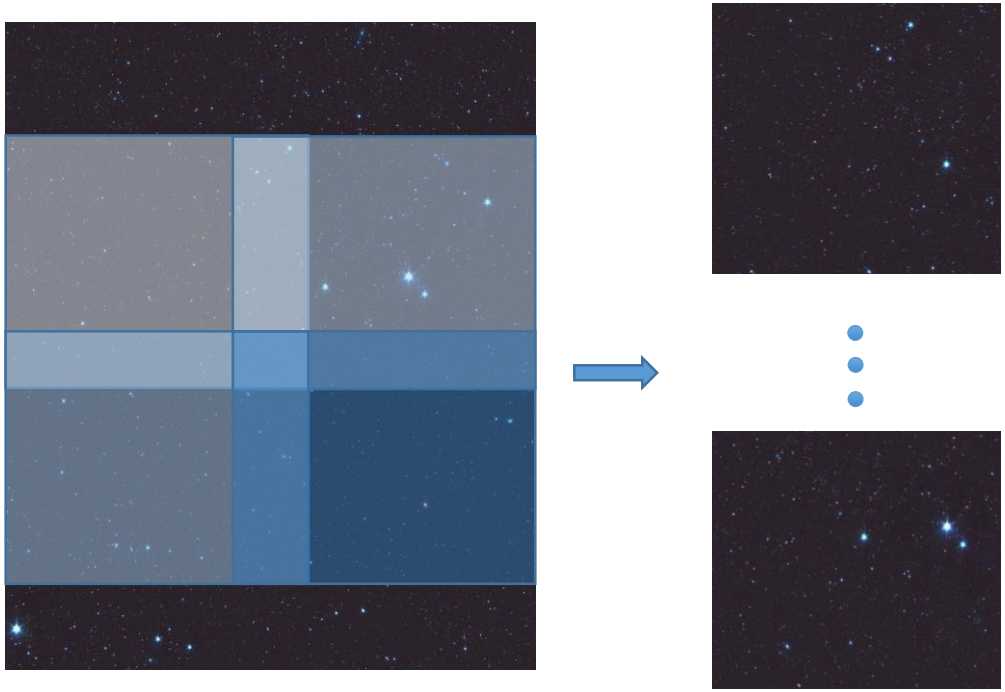
Sextractor very widely used algorithm

Key aspects of algorithm

- Filtering
- Noise measurement
- Segmentation
- Object identification
- Classification

Source detection and feature extraction





Sextractor very widely used algorithm

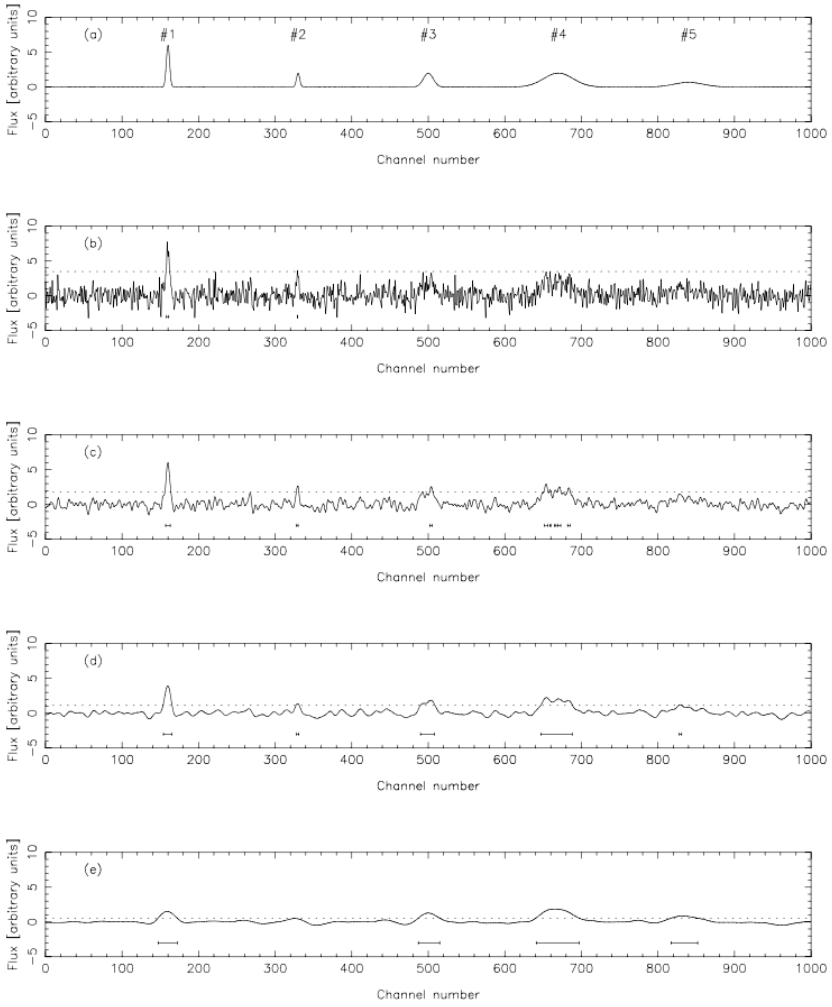
Key aspects of algorithm

- Filtering
- Noise measurement
- Segmentation
- Object identification
- Classification

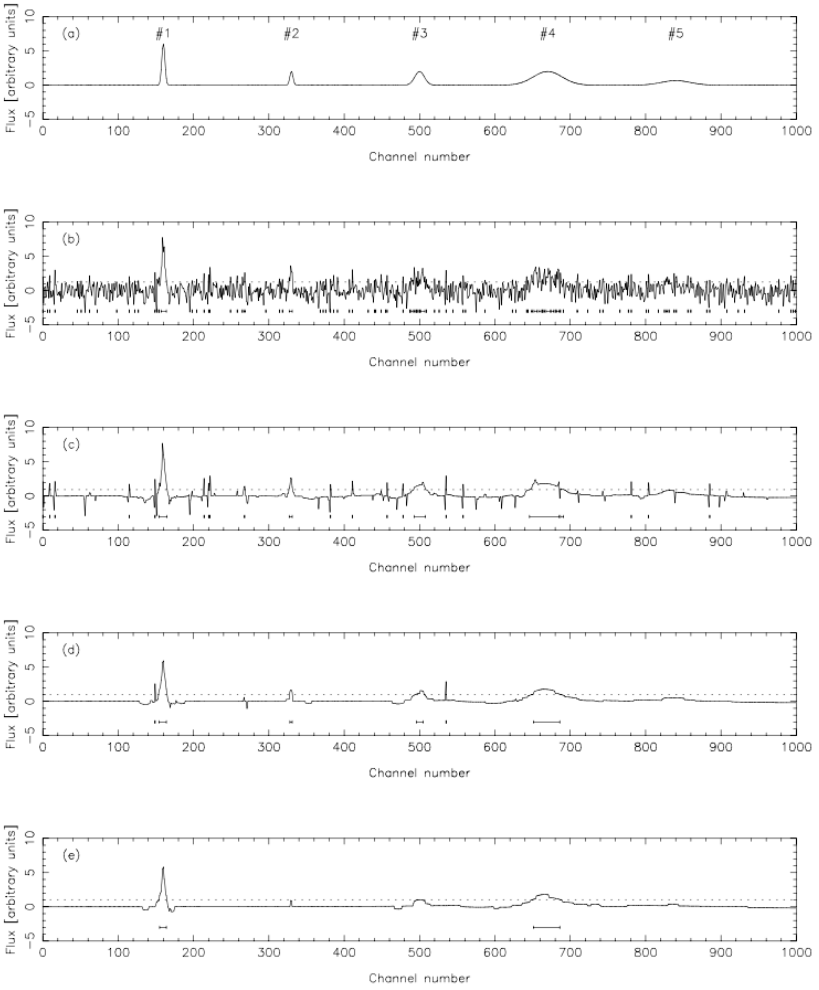
Embarrassingly parallel

- Distribute with simple guard region
- Simple extension to multi dimensions

Extension to multi-scale: Duchamp



Multi-scale smoothing



Wavelet representation

Full Bayesian Source Finding

likelihood

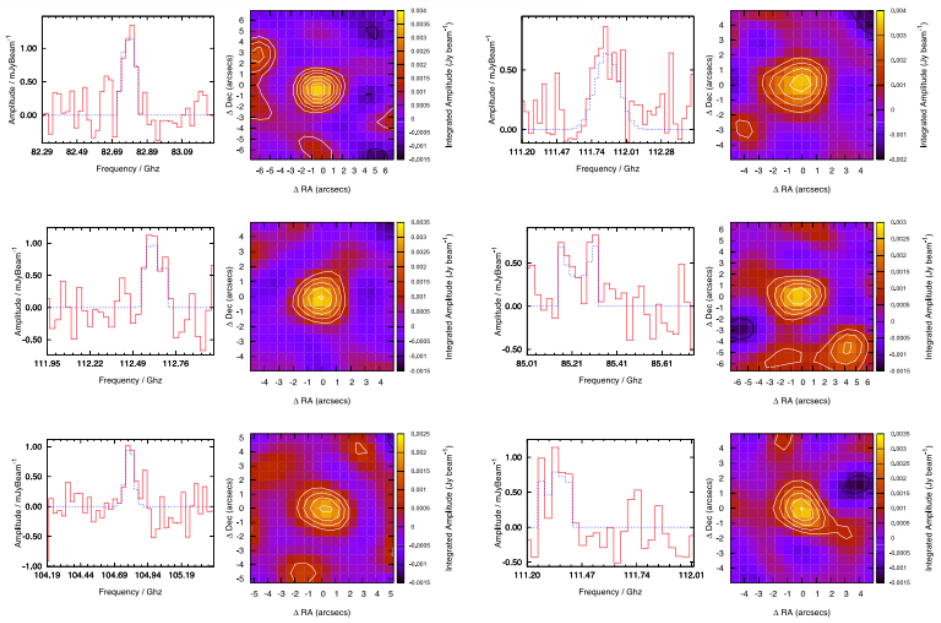
prior

$$\Pr(\Theta \mid D, \mathcal{H}) = \frac{\Pr(D \mid \Theta, \mathcal{H})\Pr(\Theta \mid \mathcal{H})}{\Pr(D \mid \mathcal{H})}$$

posterior

Bayesian evidence

$$\Pr(d|\Theta) \propto \Pr(\Theta) \prod_{i=1}^{N_{\text{chan}}} \exp\left[\frac{1}{2}(A_i - s(v_i))^2)/\sigma_i^2\right]$$



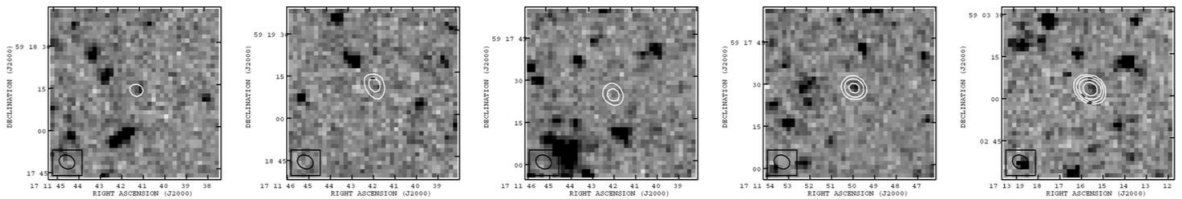
Finding galaxies in Alma fields

Full Bayesian analysis

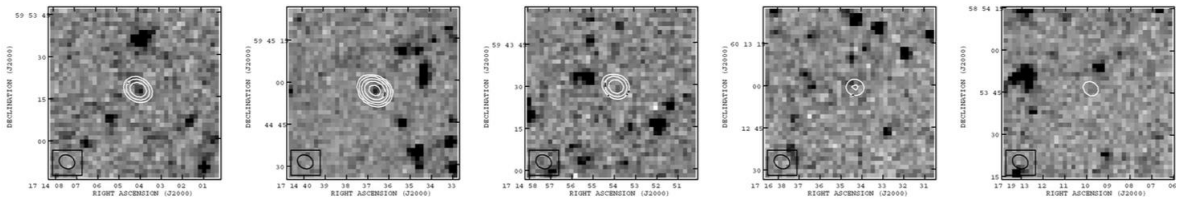
- Model for the source simple or complex
- Compare evidence – is there evidence of 1, 2, … N sources
- Quantifies detectability
- Can get very computationally challenging
- Image-space parallel
- Visibility space very computationally expensive

Building source detection as part of deconvolution step using Bayesian / MEM approach

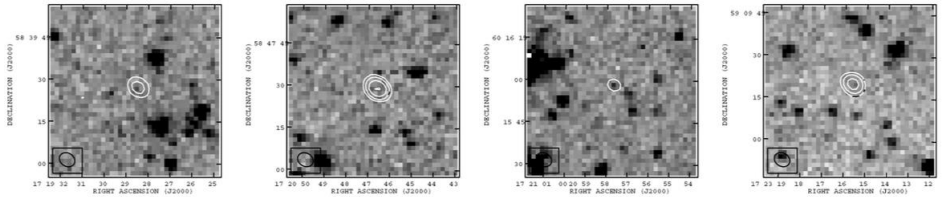
Comparison between wavebands



(a) J171141.3+591813 (b) J171141.8+591910 (c) J171141.9+591726 (d) J171149.8+591727 (e) J171315.5+590302



(f) J171404.0+595317 (g) J171436.6+594456 (h) J171453.8+594329 (i) J171634.2+601258 (j) J171909.8+585346

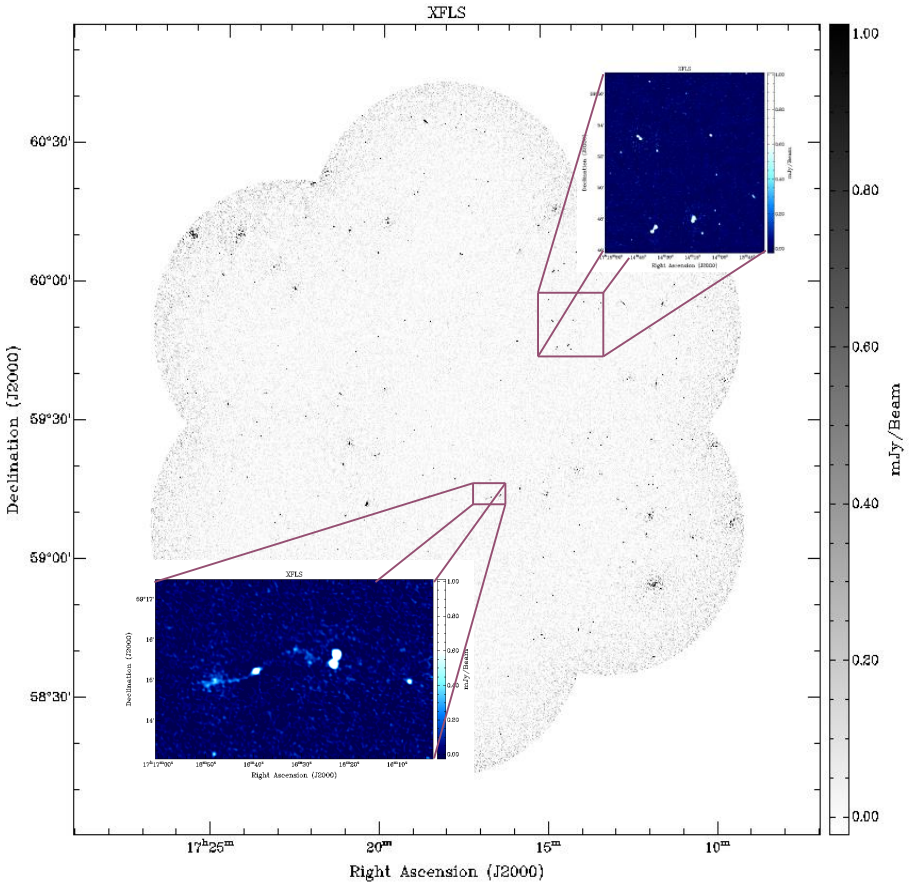


(k) J171928.4+583927 (l) J172046.5+584729 (m) J172057.6+601558 (n) J172315.5+590919

Currently source detection in both and compare lists (catalogues)

ASTERICS task is to develop joint Bayesian analysis

Comparison between wavebands: Stacking



Stacking is simply adding image and/or spectral data referenced to give better sensitivity

- E.g. emission detected in one waveband for a class of object and not in another
- Use positions from detected band for referencing

Comparison between wavebands: Stacking

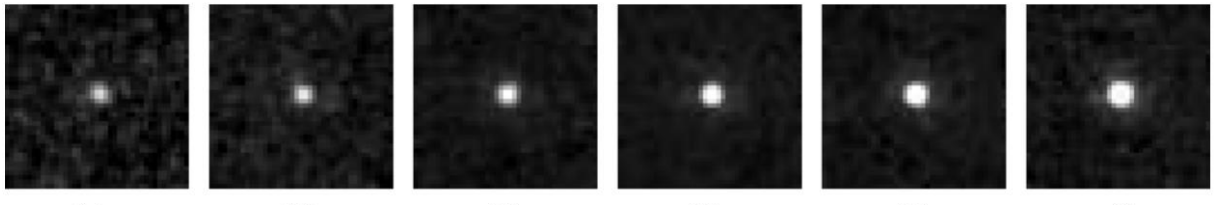


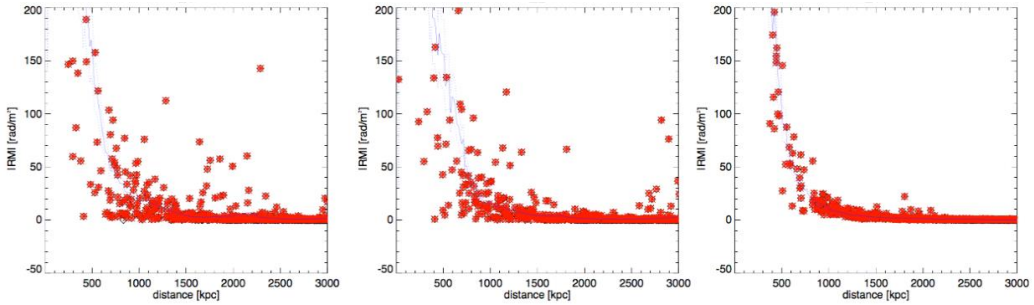
Figure 2. Median stacked 1.4-GHz radio images for the faintest six flux density bins. All images have a size of 61.5 × 61.5 arcsec^2 (41 × 41 pixel). The 24-μm flux density range of sources used to create the stacked image are given below each sub-image, with further details in Table 2. The grey-scale ranges between −2 and 20 μJy beam^{-1}. (a) 150–201 μJy. (b) 201–268 μJy. (c) 268–359 μJy. (d) 359–479 μJy. (e) 479–641 μJy. (f) 641–857 μJy.

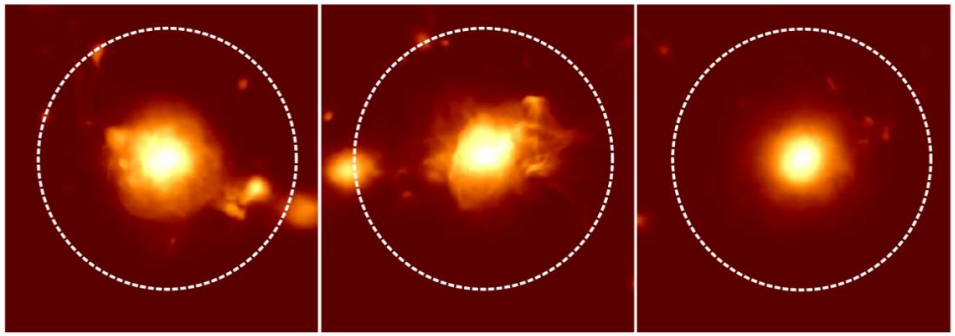
ASTERICS task is to develop
Bayesian approach
Extension of joint analysis

Stacking is simply adding image and/or spectral data referenced to give better sensitivity

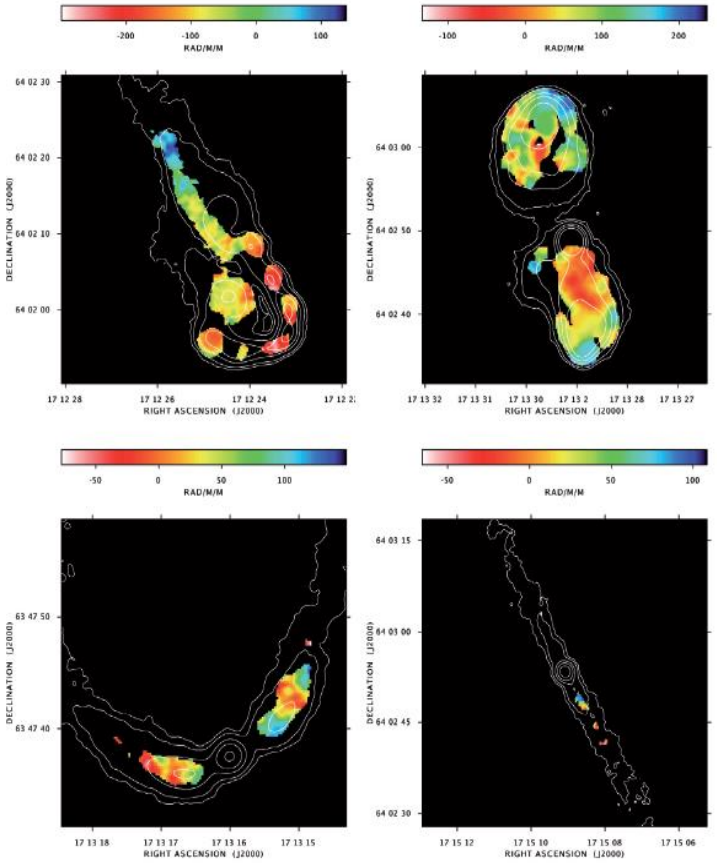
- E.g. emission detected in one waveband for a class of object and not in another
- Use positions from detected band for referencing

Rotation Measure Synthesis





Vazzaet al. 2010



Govoni et al. 2006

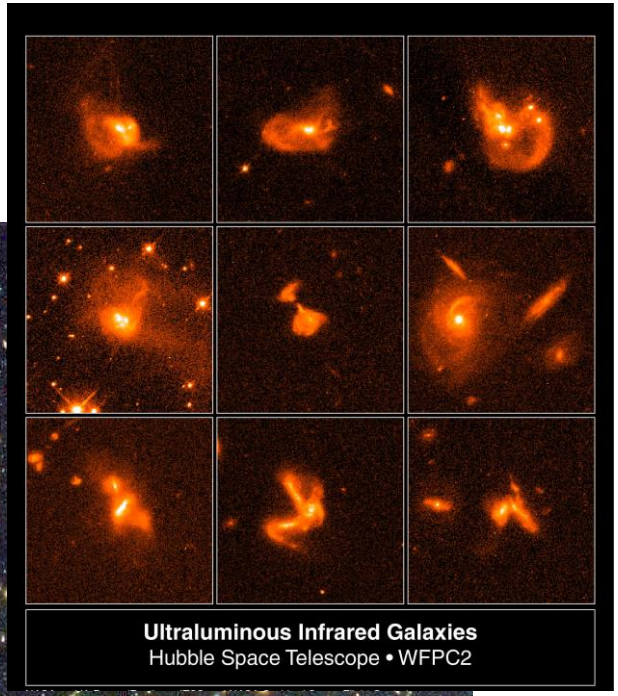
- Use RM Grid to probe evolution of field in clusters
- RM Synthesis gives much more information

$$\tilde{P}(\lambda^2) = W(\lambda^2) \int_{-\infty}^{+\infty} F(\phi) e^{2i\phi\lambda^2} d\phi$$

This can be inverted (note the addition of λ_0^2):

$$\tilde{F}(\phi) = K \int_{-\infty}^{+\infty} \tilde{P}(\lambda^2) e^{-2i\phi(\lambda^2-\lambda_0^2)} d\lambda^2 = F(\phi) * R(\phi) \neq F(\phi)$$

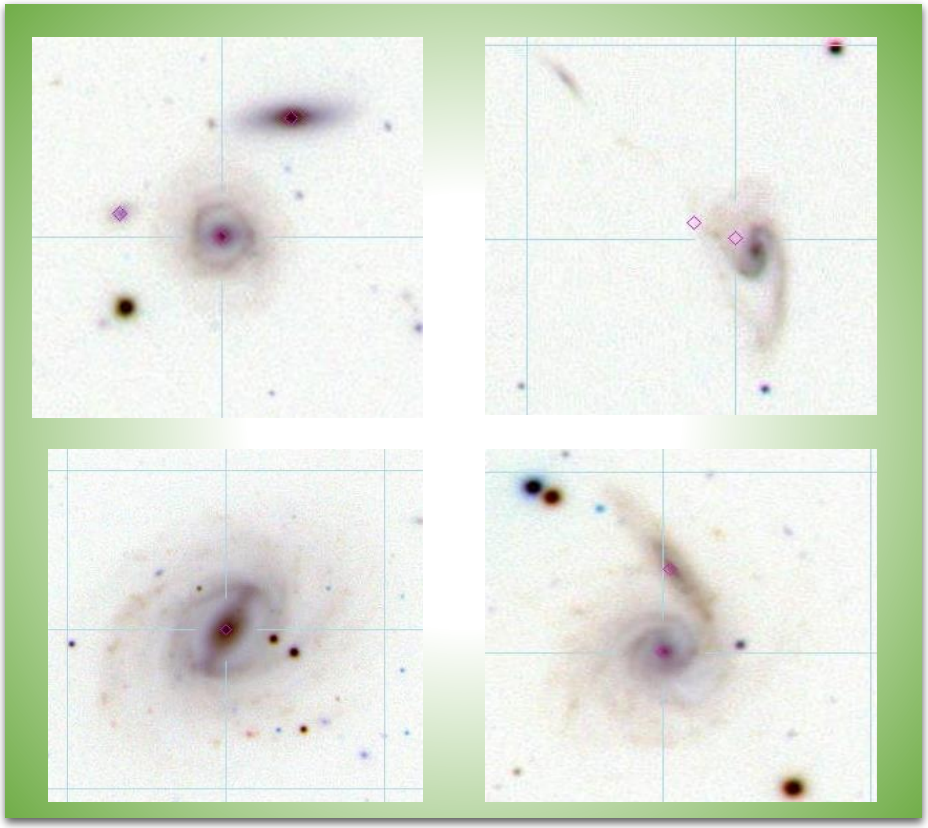
Feature extraction and classification: galaxy types

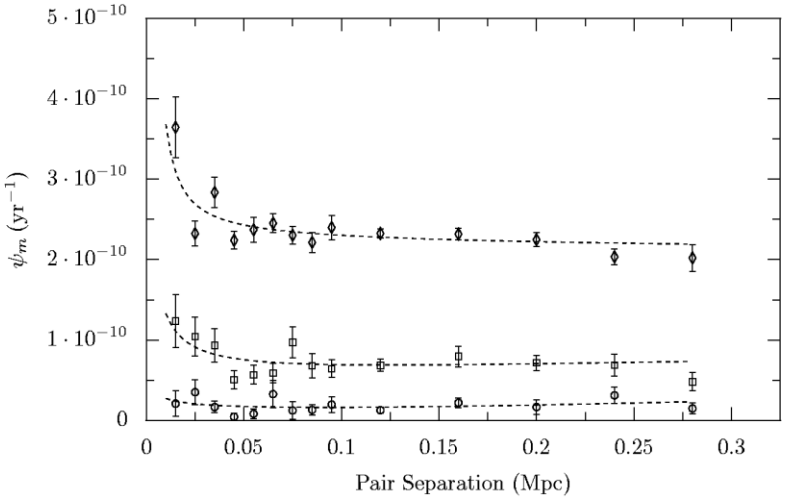


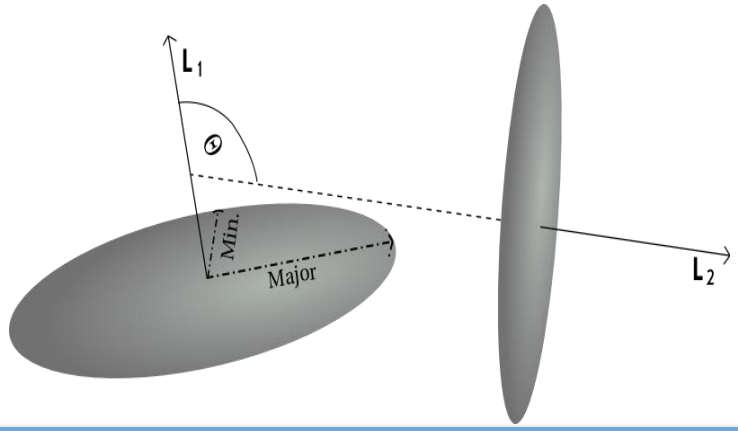
- Representation in a basis
- Machine learning
  - Deep neural nets
  - Gaussian processes

Demanding use case is weak lensing
- Determine systematic background image distortion around a foreground gravitating mass

Feature extraction and classification: dynamics





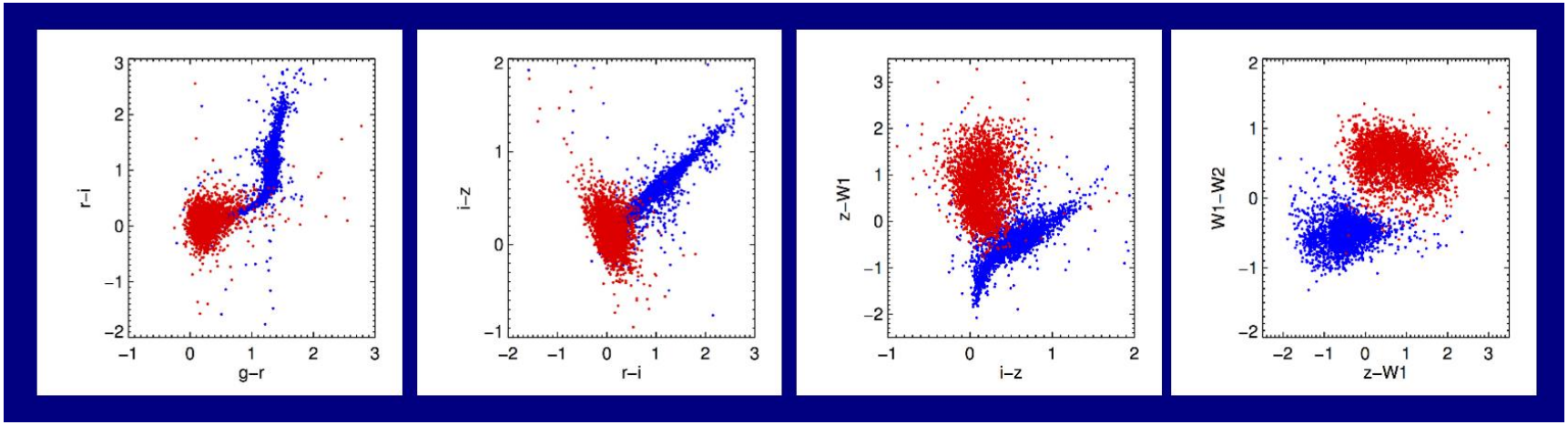


Identify in image-velocity space physically close pairs

- Estimate dynamics from imaging
- Measure Star formation from spectroscopy or multi-waveband images

Star formation increased by spin-aligned interactions

Classification based on features



- Simple problems tackled via PCA
- Machine learning preferred approach
- Gaussian processes particularly suited to this sort of classification

Deep learning is potentially very computationally intensive

- Likely to be a major activity to extract science once initial analysis is done

Visibility-based types of Analysis

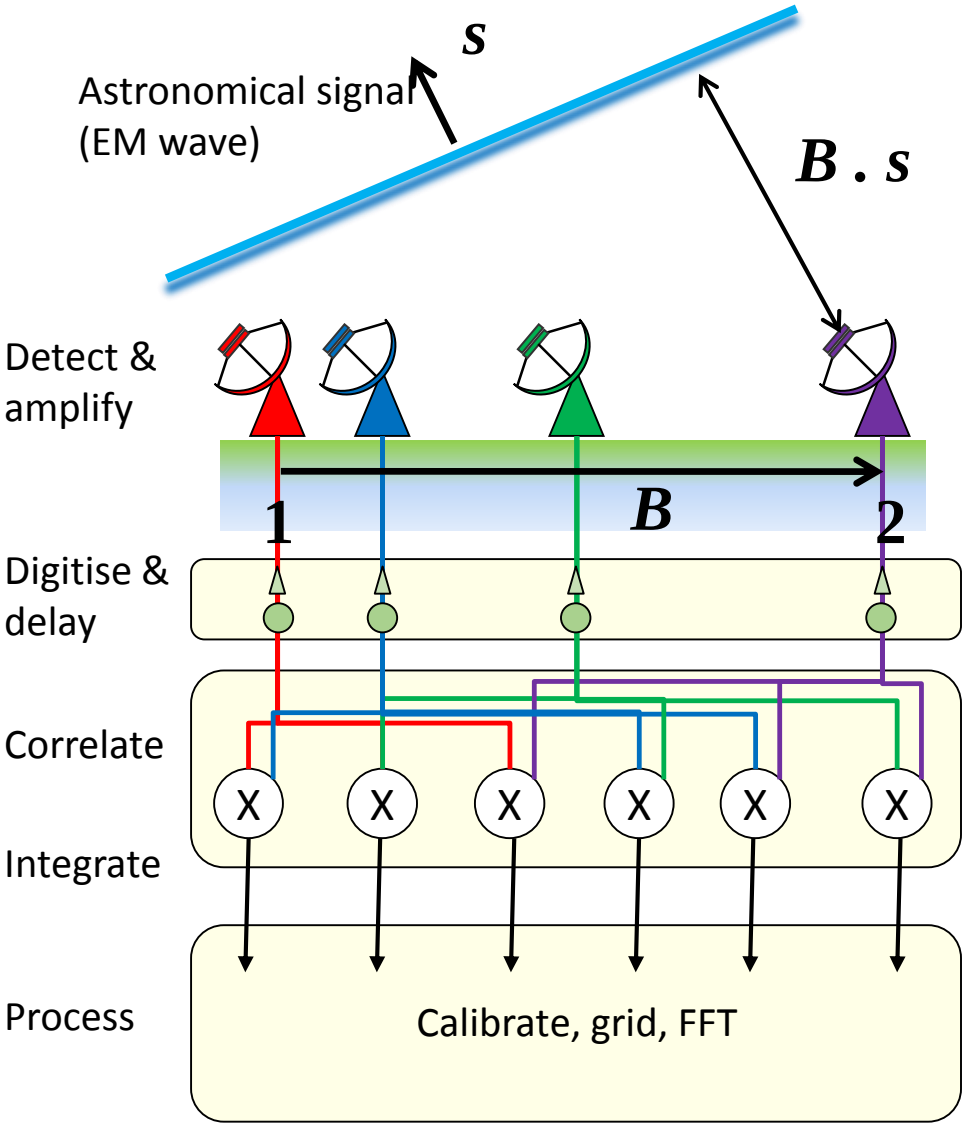
- **Imaging**
  - Re-imaging from “visibility data” similar to SDP processing
  - Re-imaging from gridded “visibility data”

Re-imaging needed in most demanding cases and learning about instrument

- **Power-spectral estimation and model comparison**
  - Estimate information direct in the visibility space
  - Model fitting
  - Bayesian analysis

Extremely compute intensive

Imaging



- Visibility:

$$V(\boldsymbol{B}) = E_1 E_2^* = I(\boldsymbol{s}) \exp(i \omega \boldsymbol{B}.\boldsymbol{s}/c)$$

- Resolution determined by maximum baseline

$$\theta_{max} \sim \lambda / B_{max}$$

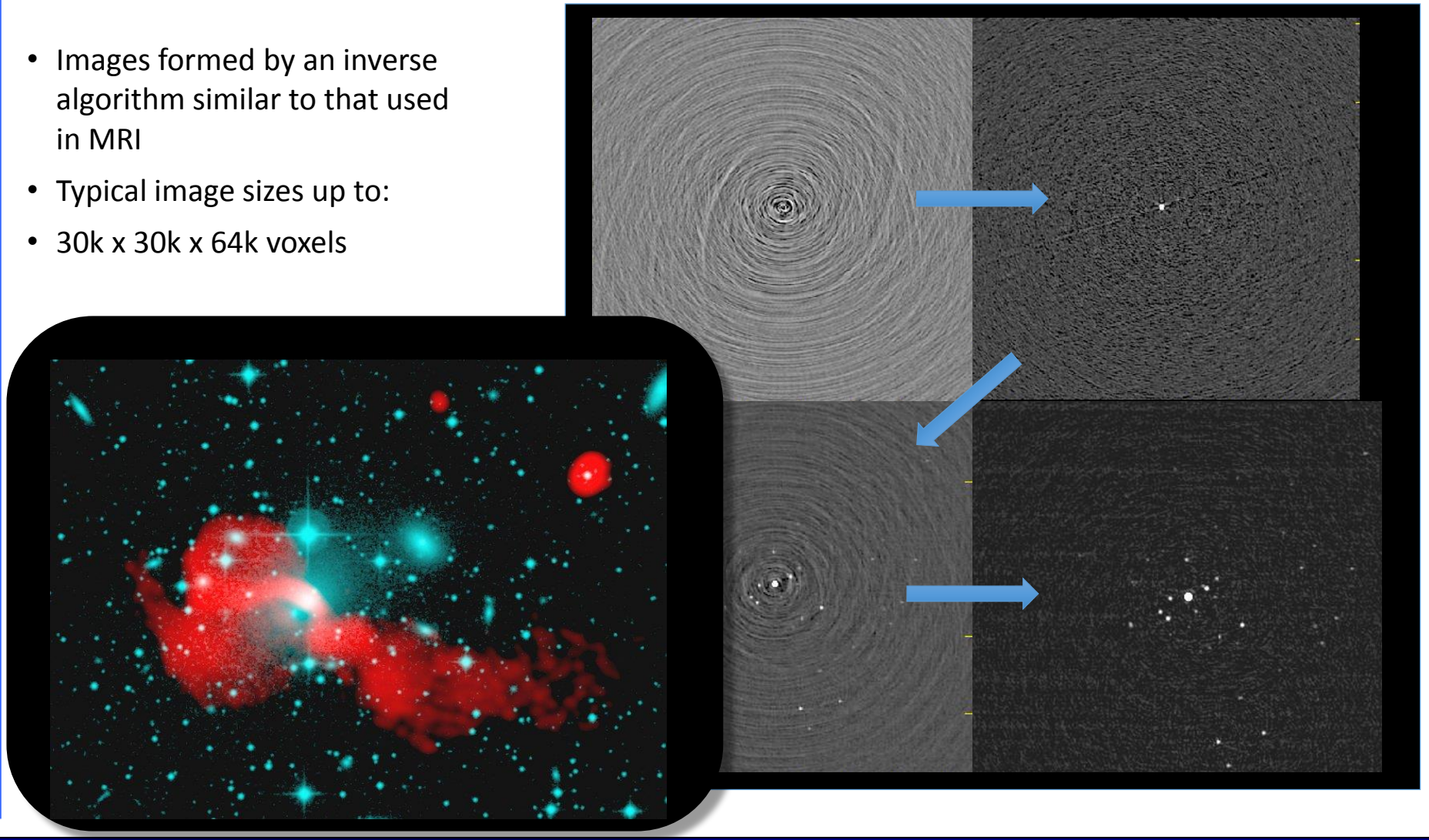
- Field of View (FoV) determined by the size of each dish

$$\theta_{dish} \sim \lambda / D$$

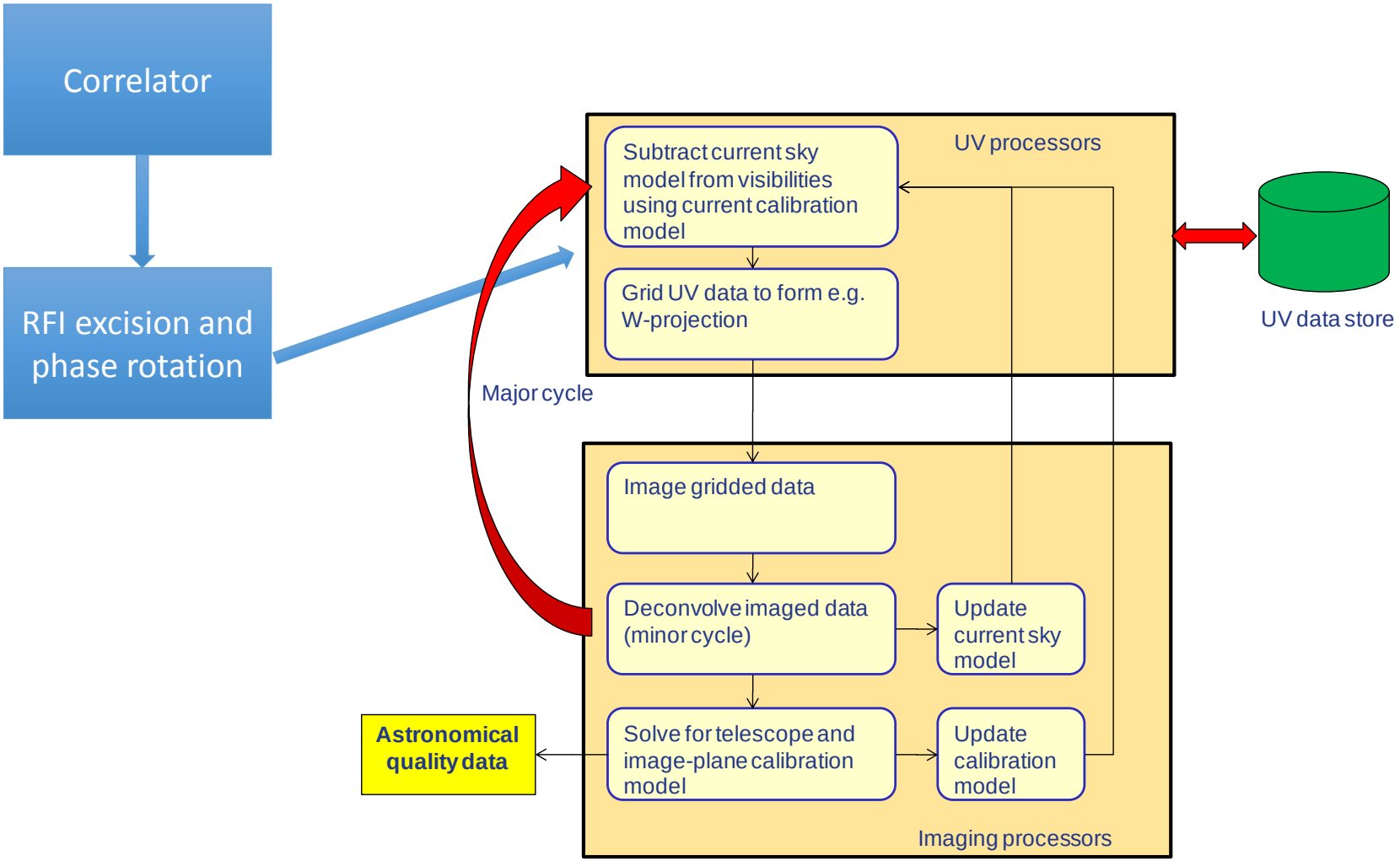
SKY Image

Imaging

- Images formed by an inverse algorithm similar to that used in MRI
- Typical image sizes up to:
- 30k x 30k x 64k voxels



Imaging Workflow



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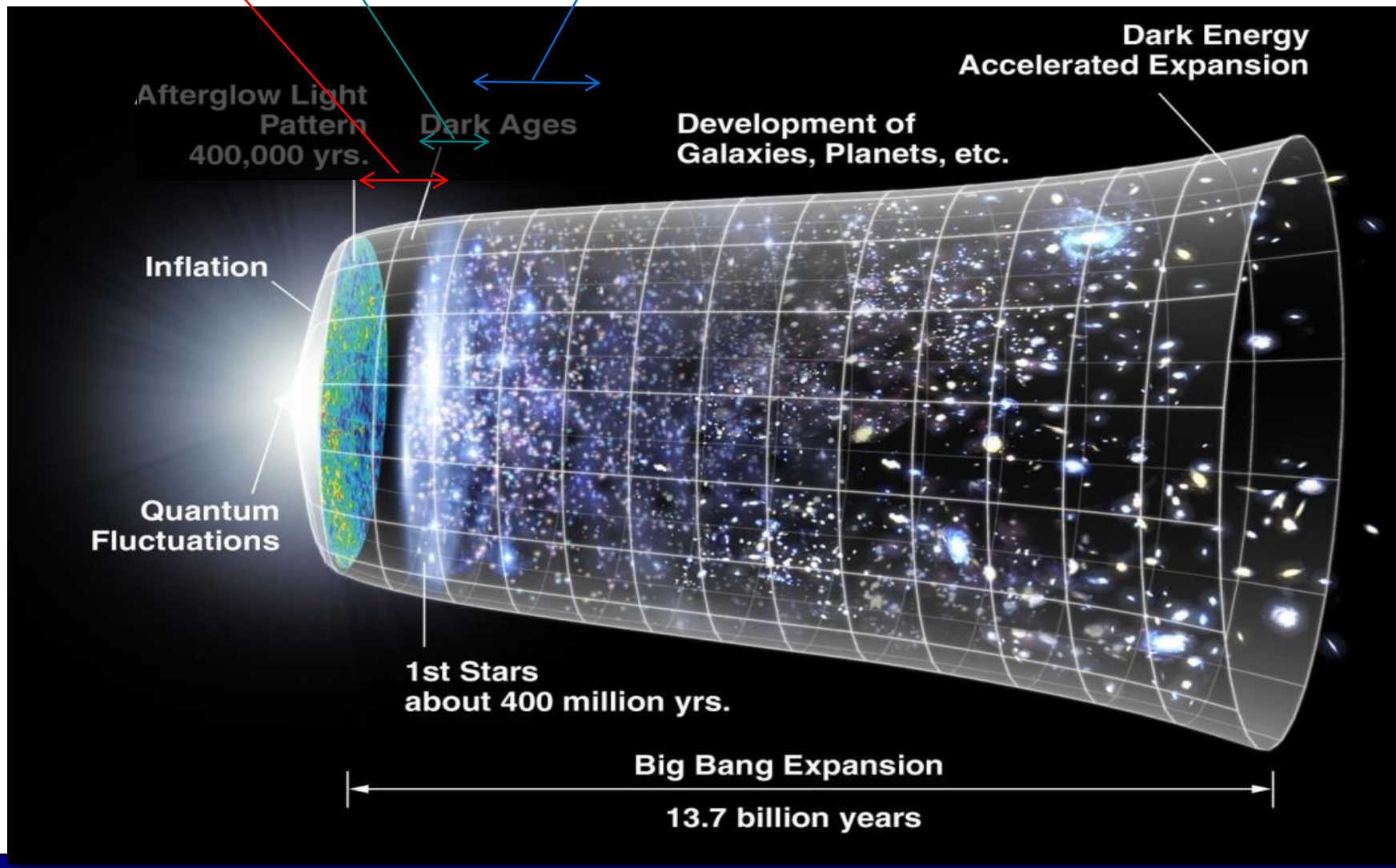

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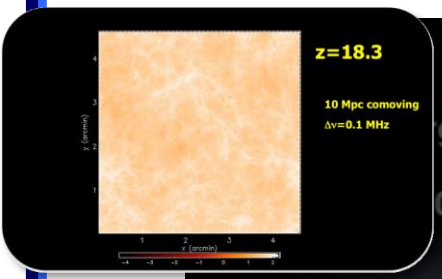
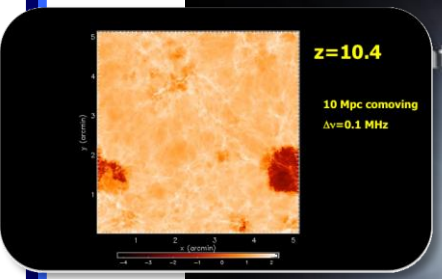
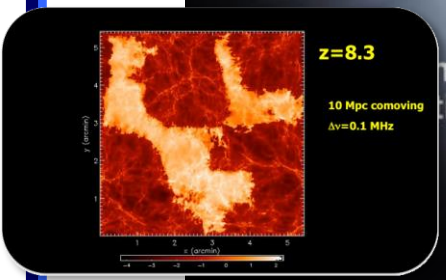
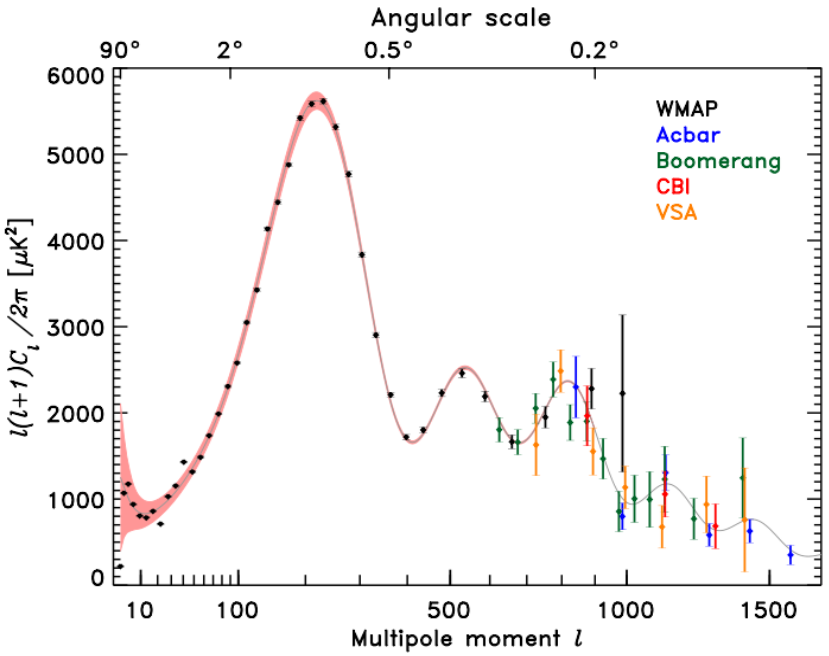
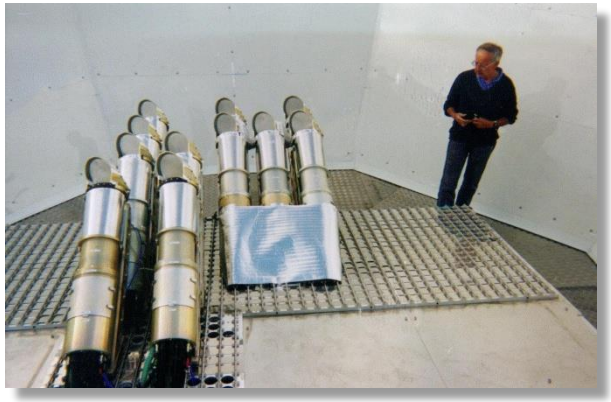






glow Light Pattern
00,000 yrs.
Dark Ages
tion
ntum
tions
Development of Galaxies, Planets, etc.
Dark Energy Accelerated Expansion
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years





VSA experiment

Measurements of CMB power-spectrum have established era of "precision cosmology"

Universe has a flat geometry

$\Omega = 1$

Matter contribution

$\Omega_m \sim 0.25$

Normal (baryonic) matter

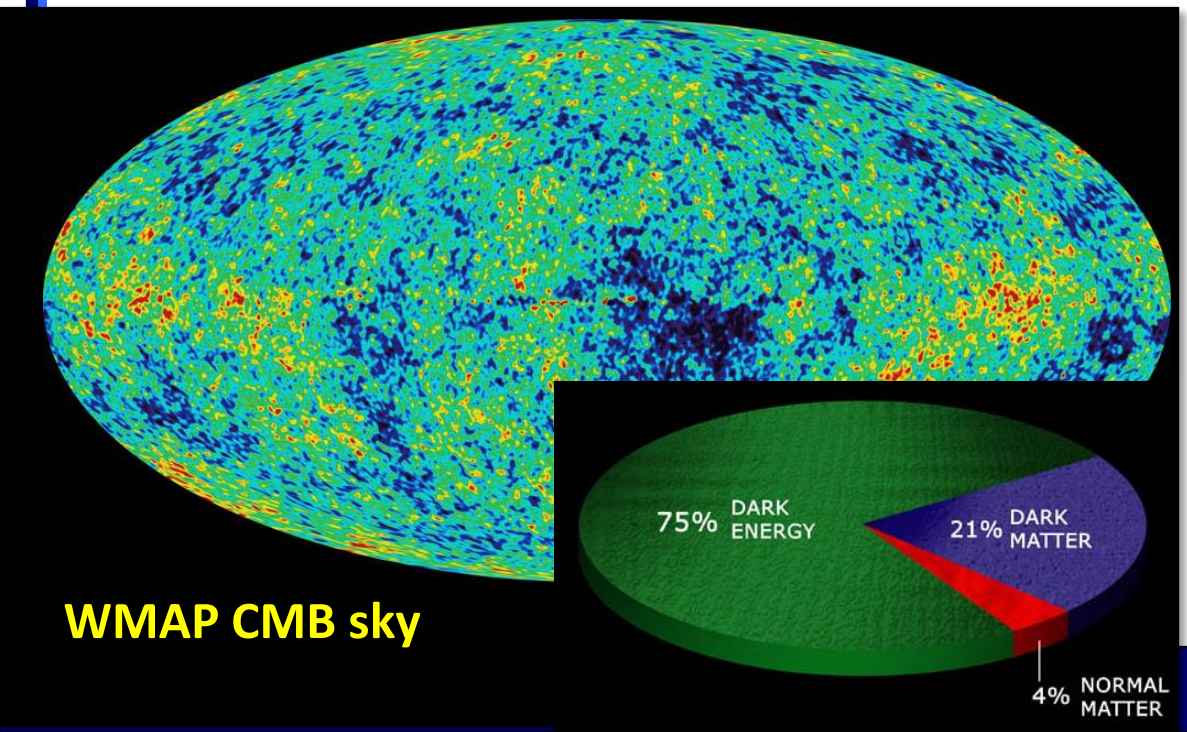
$\Omega_B \sim 0.04$

Cold Dark Matter (CDM)

$\Omega_m \sim 0.21$

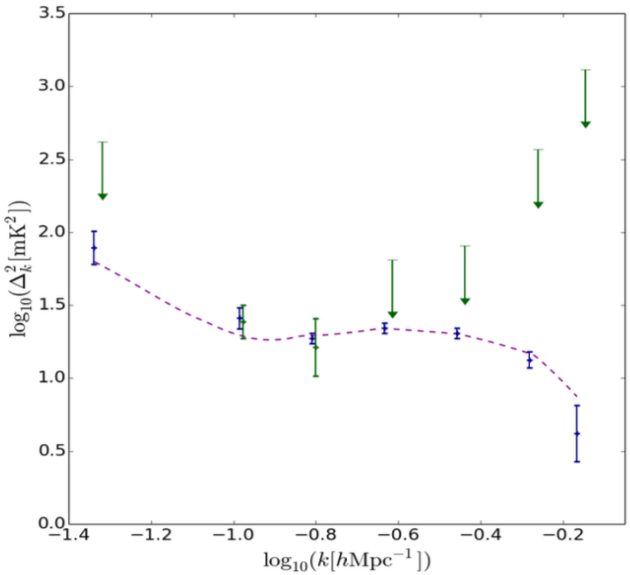
Dark energy

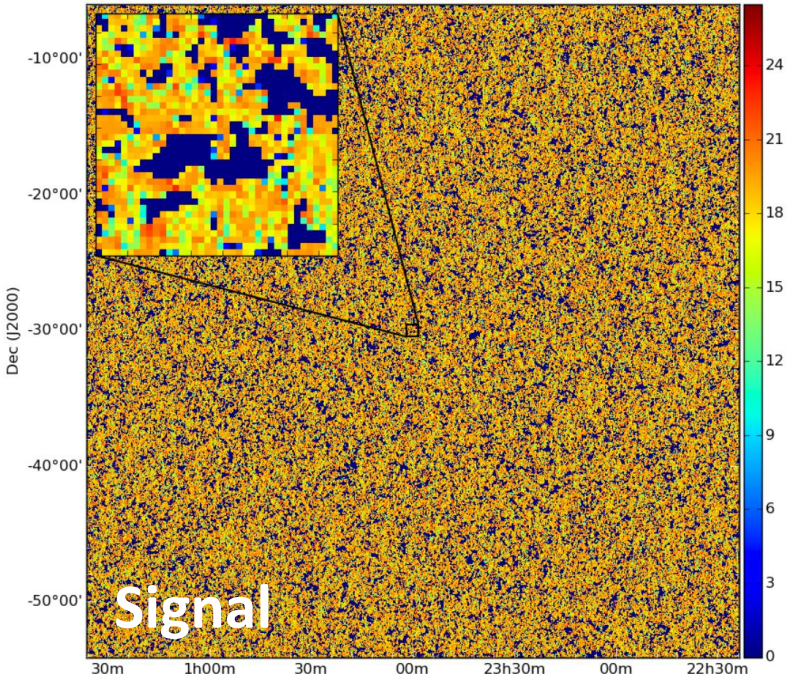
$\Omega_\Lambda \sim 0.75$

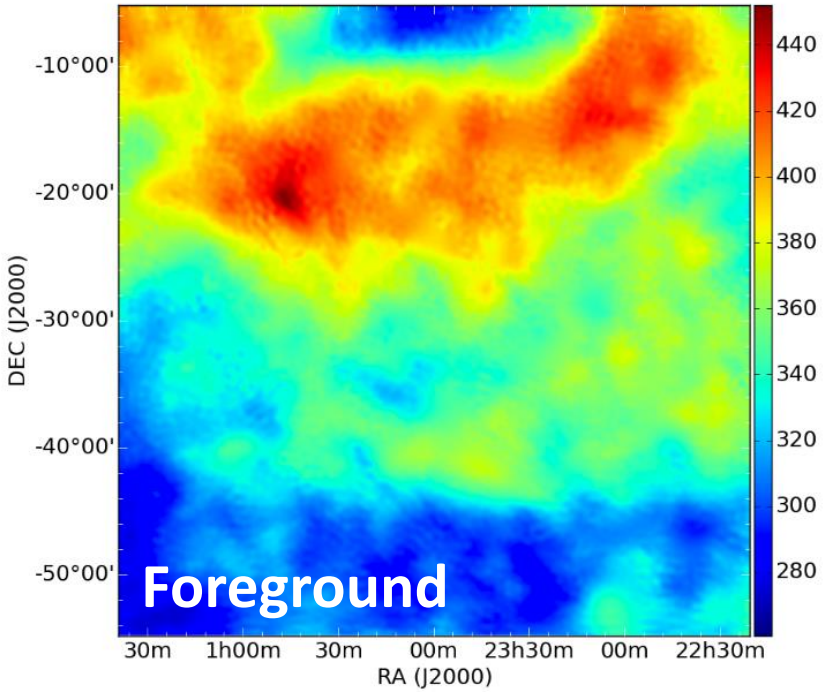


WMAP CMB sky

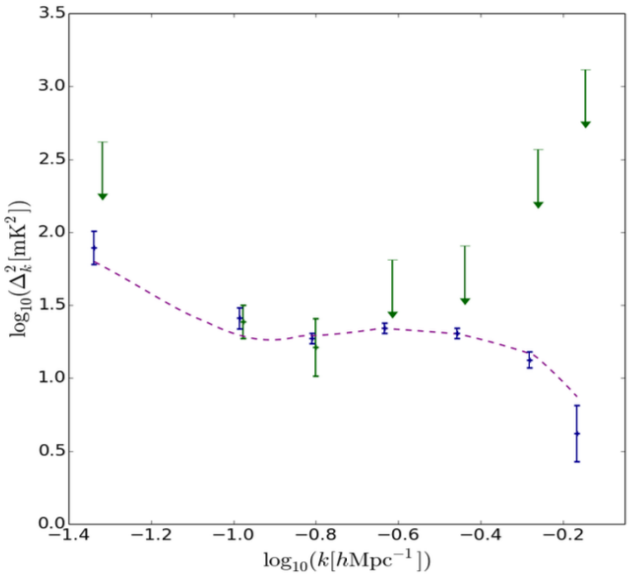
HERA SKA Precursor

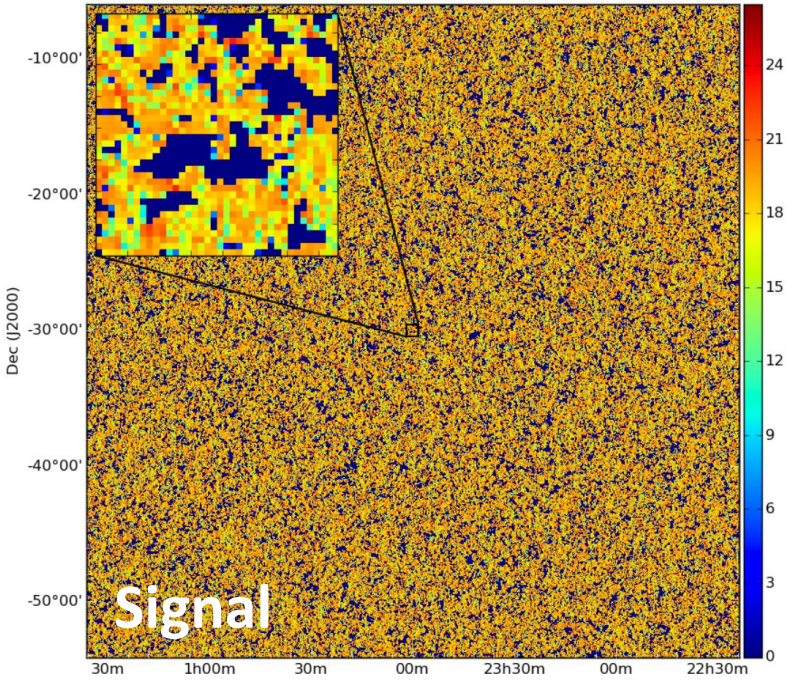






HERA SKA Precursor



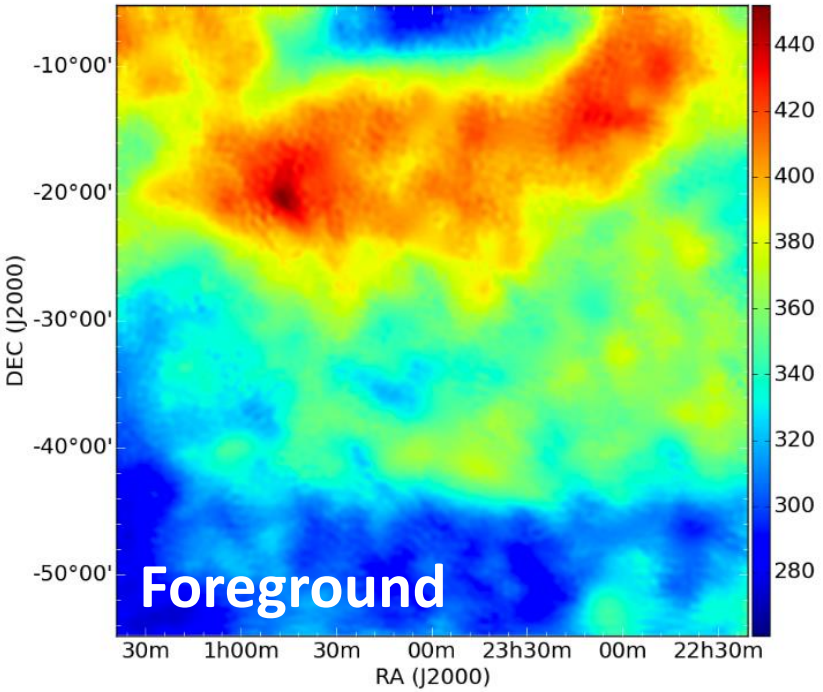


Work from visibility data

- Improve calibration via imaging-like workflow
- Solve for time varying phase screen
- Remove foreground emission

Direct Bayesian estimation of the power spectrum

- Model is a spherically symmetric
- Marginalise over residual foreground



Science analysis and data mining

- **Science Analysis**
  - Visualisation
  - Standard data analytics
  - Model fitting including model generation

Total SKA Archive can grow at 300 Pbytes / yr

- **Data mining**
  - Data-base like analytics on SKA and other data
  - Importing data from multiple sources
  - Context based searches
    - Users will expect to be able to do the same searches as they see on Google / Facebook
    - Find me all images including extended spiral larger than 100 arcsec …

Even “Standard” analysis now challenging

Could be very challenging

Experiment definition

- **Science Simulation**
  - Simulation of science target space

How much simulation will need to be done at SRC?

- **Experimental simulation**
  - Simulate experimental response
  - Simulate analysis procedure
    - E.g. co-adding (averaging) many separate observations on a field → does the experiment need to average in image or UV-space?

Experimental simulation requires running a data generator plus the SDP environment as run at the observatory

$$\langle \mathbf{V}_{p,q} \rangle = \sum_s \mathbf{K}_{p,s}\mathbf{E}_{p,s}\mathbf{G}_{p,s}\mathbf{P}_{p,s}\langle \mathbf{B}_s \rangle \mathbf{P}^H_{q,s}\mathbf{G}^H_{q,s}\mathbf{E}^H_{q,s}\mathbf{K}^H_{q,s}$$

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Possible SKA1 Continuum Survey Strategy

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Deep / Multi-tier

- Star formation & BH accretion history
- Role of AGN feedback over cosmic Time
- Evolution of FIR-Radio correlation
- Role of environment

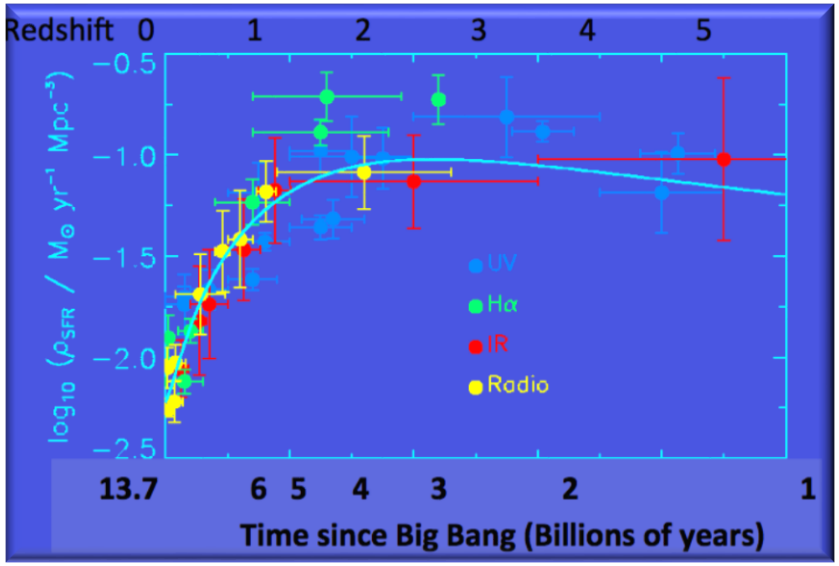
Wide / All Sky

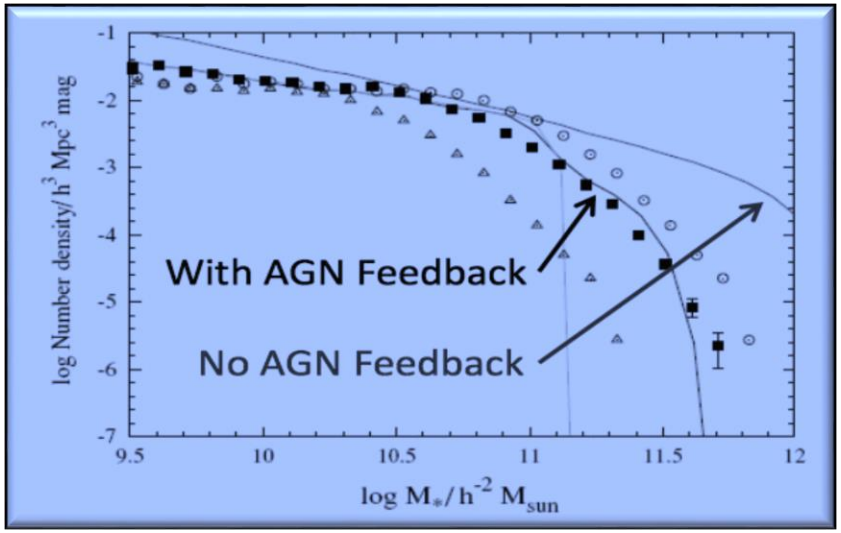
- First galaxies, BHs & protoclusters
- Galaxy clusters, cosmic web
- RL AGN physics/lifecycle
- RQ/RL AGN dichotomy
- ISM and SF physics in nearby galaxies
- Origin of FIR-Radio correlation
- Strong lensing

Science Drivers	Freq.	Tier	Rms (full BW)	Area	Res.	Science/ Commensality
SFHU Non-thermal (gal/AGN co-evol.)	~1 GHz Band 1/2	Ultra Deep	50 nJy	1 deg2	~0.5"	AGN/gal co-evol.
		Deep	200 nJy	10-30 deg2	~0.5"	AGN/gal co-evol. **High-z Magnetism** HI deep field (B1)
		Wide	1 uJy	1000 deg2	~0.5"	Weak/Strong Lensing
SFHU Thermal (gal/AGN co-evol.)	~10 GHz Band 5	Ultra Deep	40 nJy	0.008 deg2	~0.1"	AGN/gal co-evol.
		Deep	300 nJy	1 deg2	~0.1"	AGN/gal co-evol.
Legacy Strong Lensing (rare populations)	~1 GHz Band 2	All-sky	4 uJy	31000 deg2	~2" 0.5"	**Magnetism** Cosmology tests Transients (beam forming) HI surveys Our Galaxy
Clusters (RL AGNs)	~120 MHz	All-sky	20 uJy (confusion)	31000 deg2	8"	**EoR**

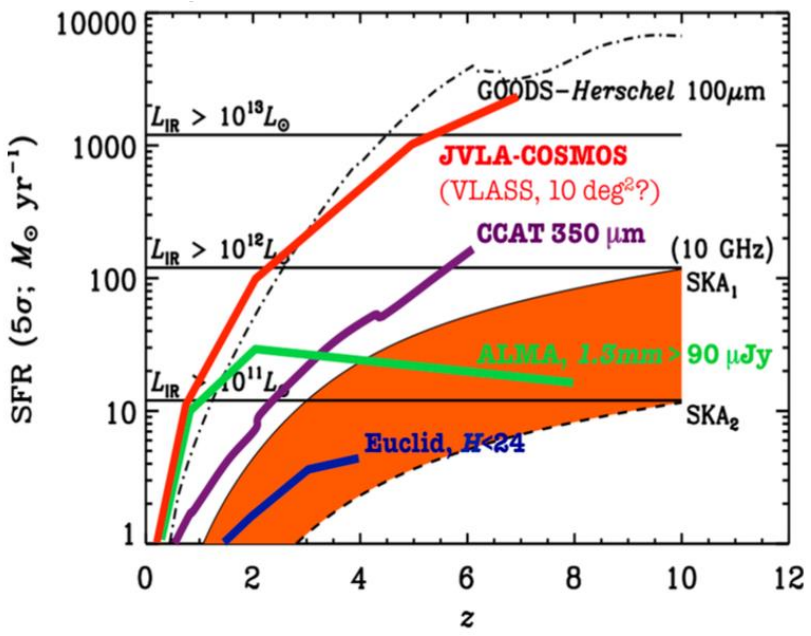
Galaxy Evolution: Star formation and feedback

Hopkins et al. 2004



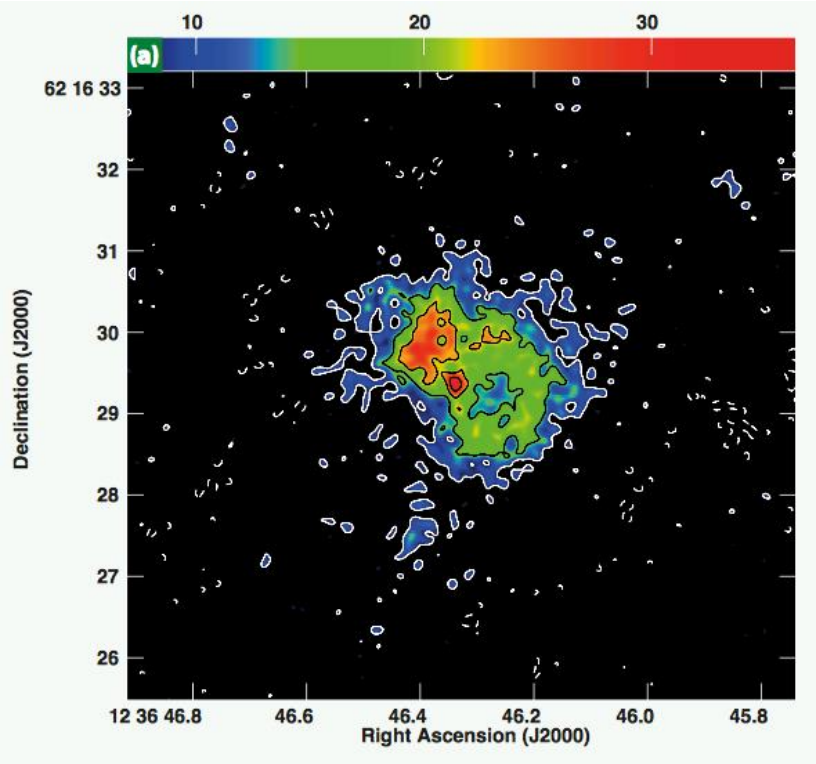


Murphy, Sargent et al 2015

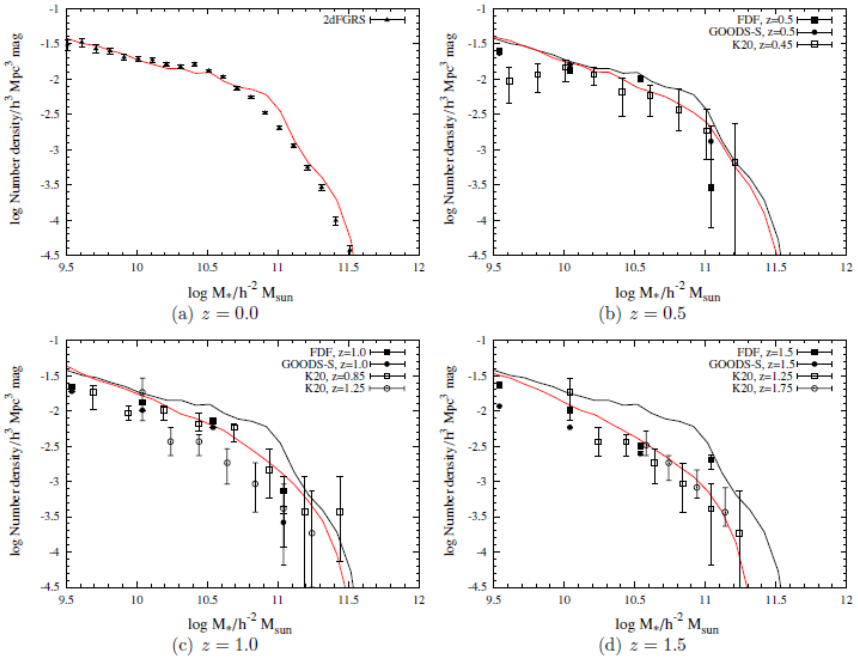


- Radio continuum excellent tracer of SF in SKA era
- AGN Feedback radio essential

Galaxy Evolution: Star formation and feedback

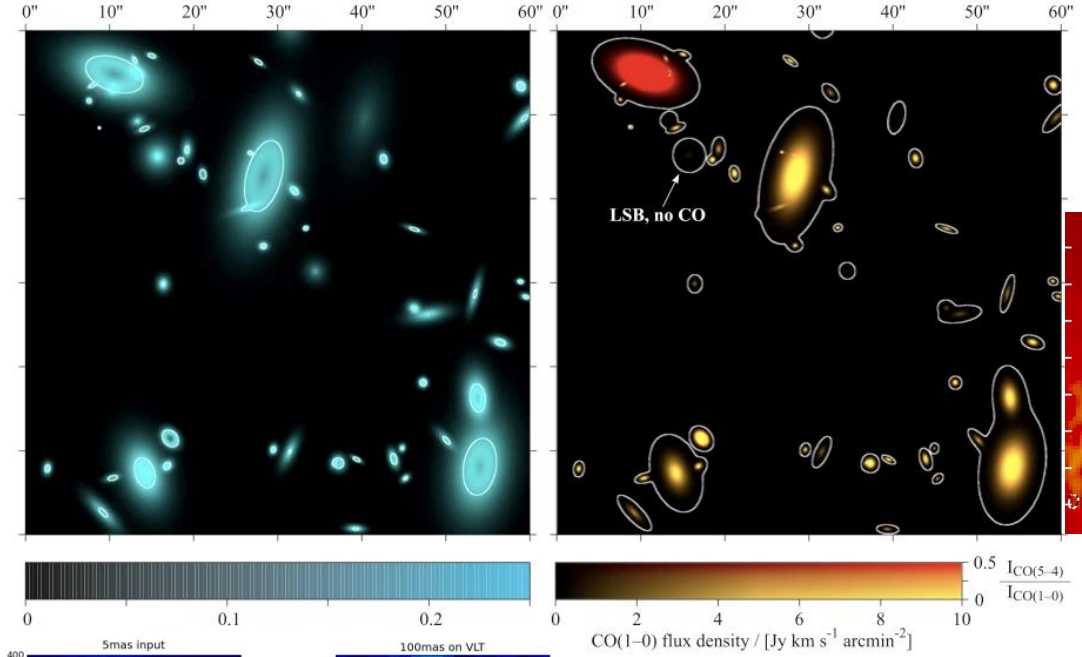


One source from e-MERGE showing embedded AGN and ring of star formation across massive spheroidal

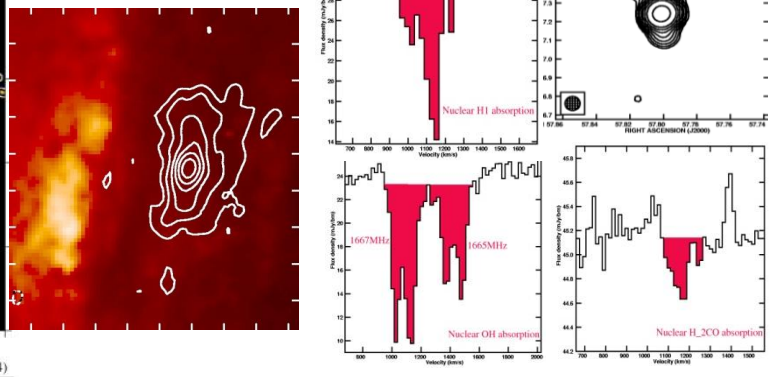


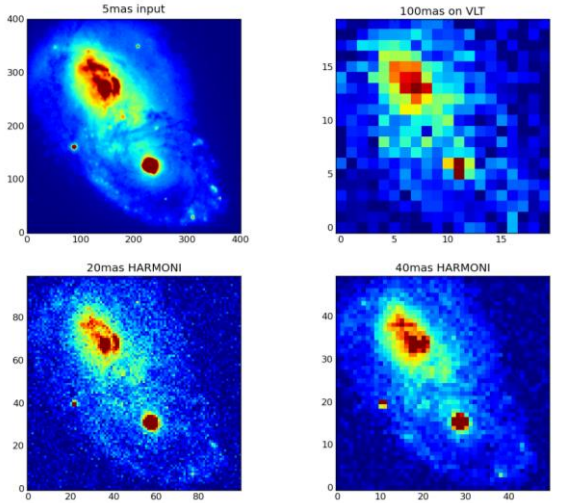
- e-MERLIN demonstrated the power of resolving AGN and star-forming contributions
- e-MERLIN follow up of brighter galaxies to probe detailed star-formation / AGN interactions and feedback
- Large fraction of wide-field sample will be accessible to e-MERLIN

Galaxy Evolution: SKA / ALMA / E-ELT /e-MERLIN synergy



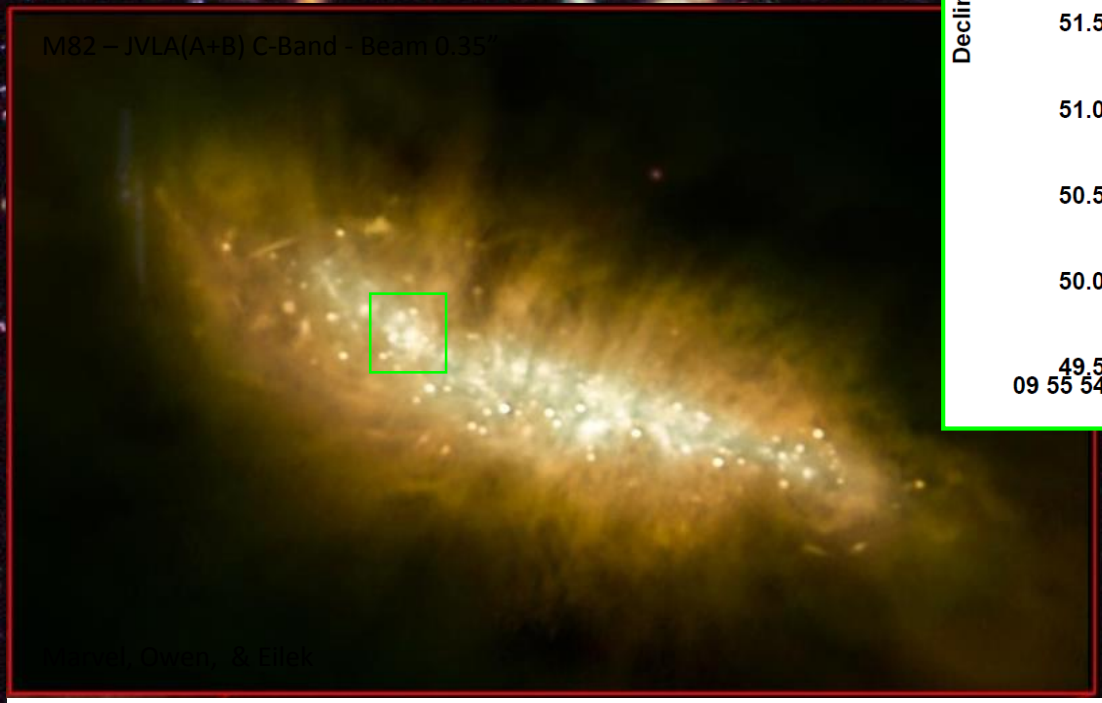
NGC3079 HI, OH and H_2CO absorption (Beswick et al)

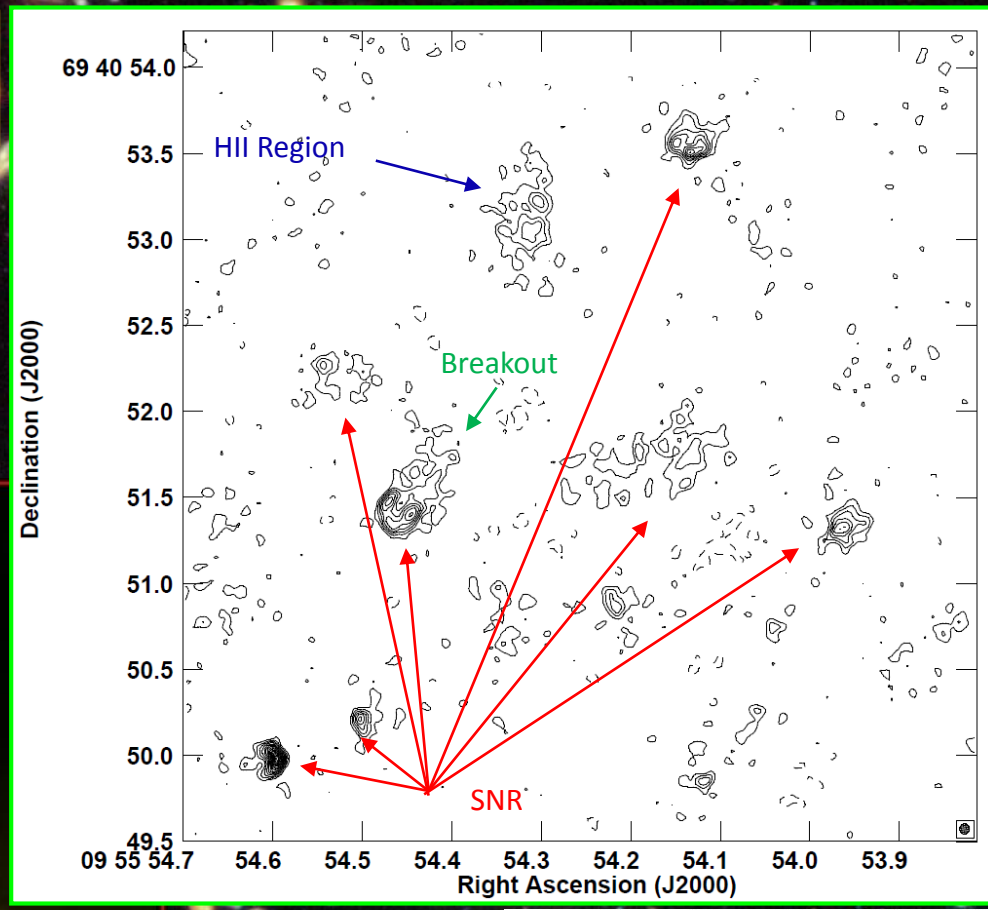


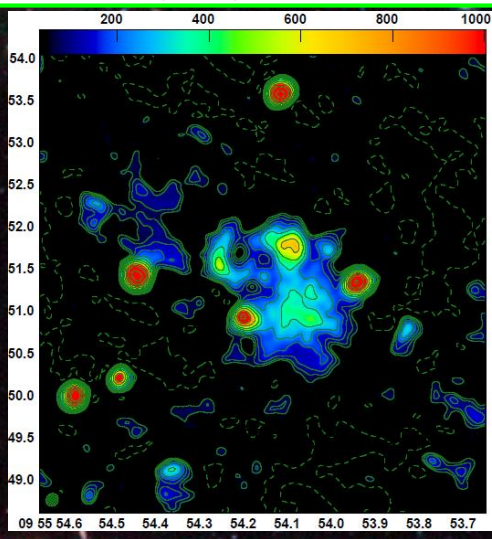


- ALMA, SKA and e-MERLIN are natural IFUs at different scales and transitions
- E-ELT IFU maps, e.g. Halpha
- Continuum imaging e-MERLIN + VLBI

Tom Muxlow/Rob Beswick: Star-formation
Across Cosmic Time: M82





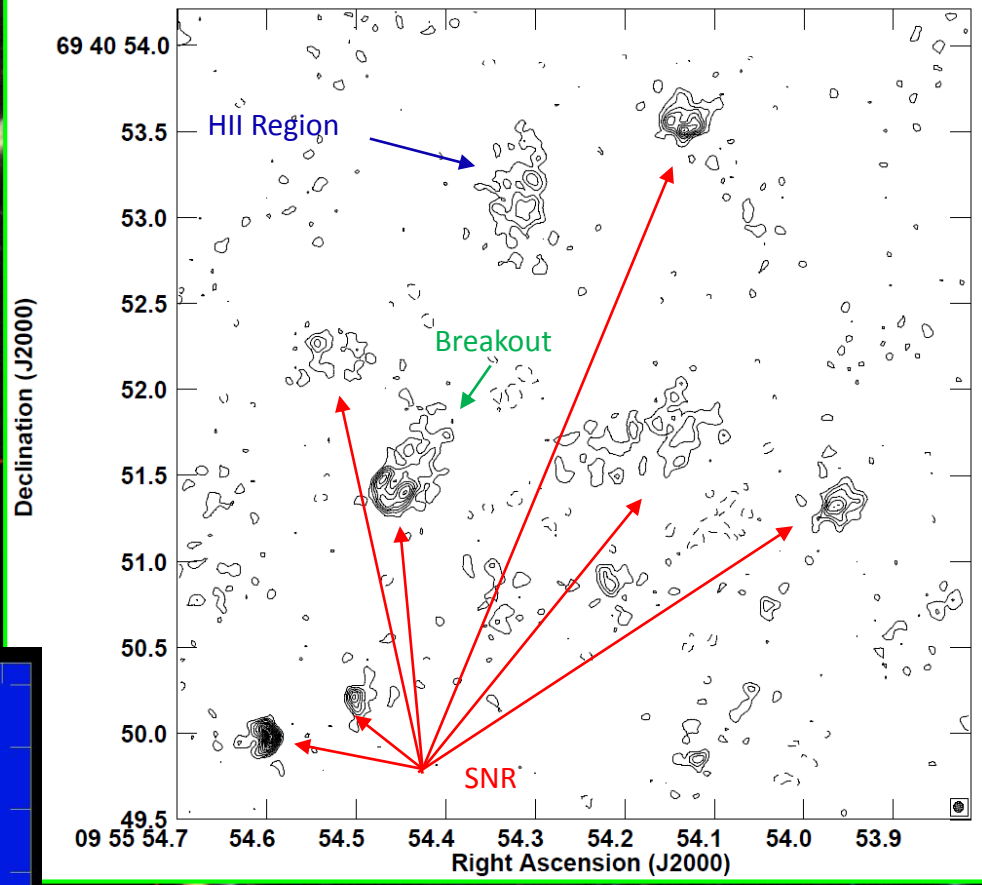


Calibrate star-formation rate derivation on nearby galaxies like M82

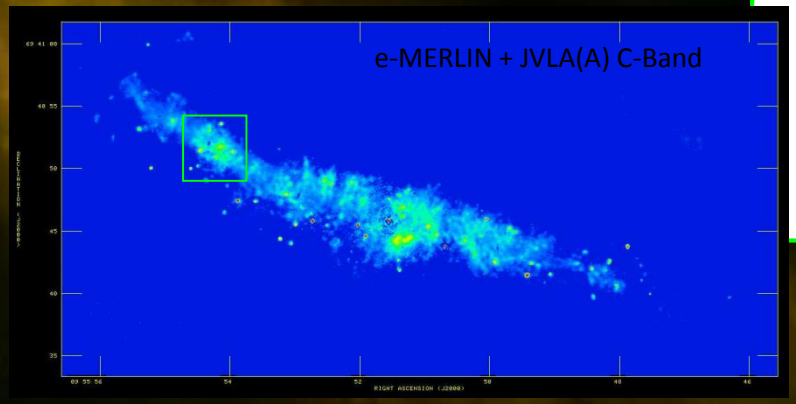
Separate AGN / S-F (& SNR from HII) by sensitive high resolution imaging at C- & L-Band

Extend to distant galaxies 1000 times further away and 1 million times fainter

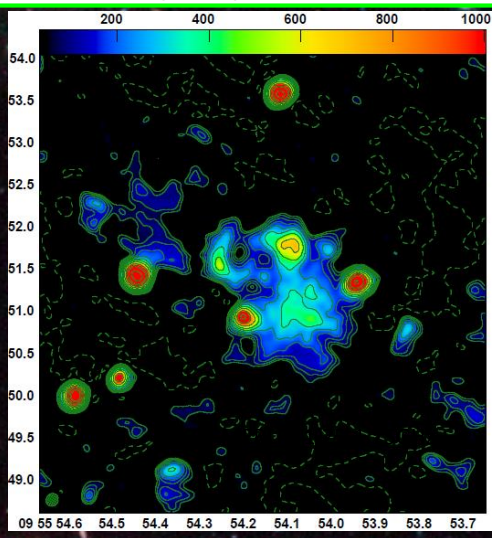
Tom Muxlow/Rob Beswick: Star-formation
Across Cosmic Time: M82



M82 – JVLA(A+B) C-Band - Beam 0.35"



Marvel, Owen, & Ellek



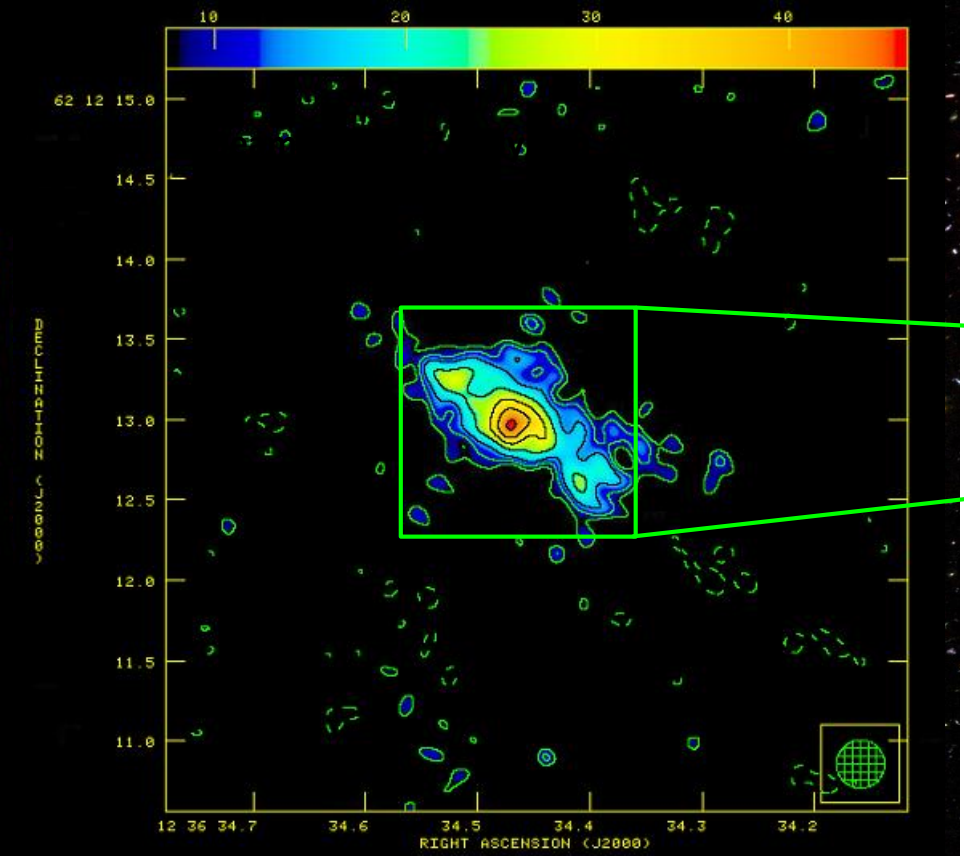
Calibrate star-formation rate derivation on nearby galaxies like M82

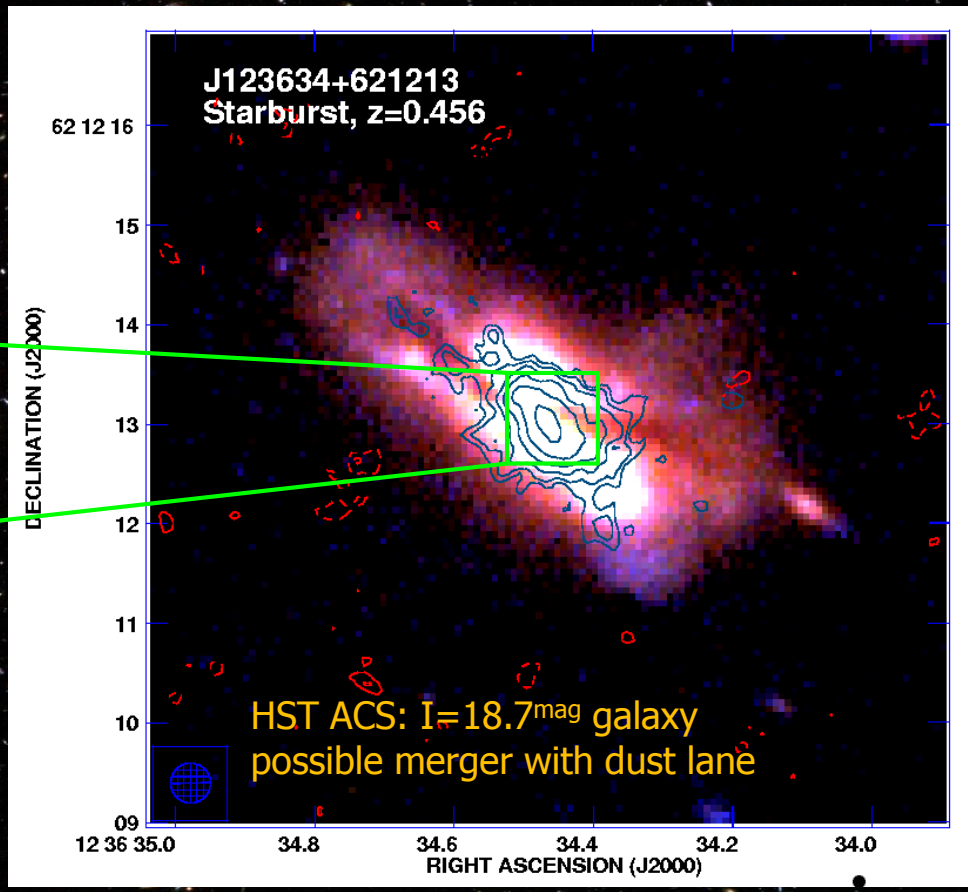
Separate AGN / S-F (& SNR from HII) by sensitive high resolution imaging at C- & L-Band

Extend to distant galaxies 1000 times further away and 1 million times fainter

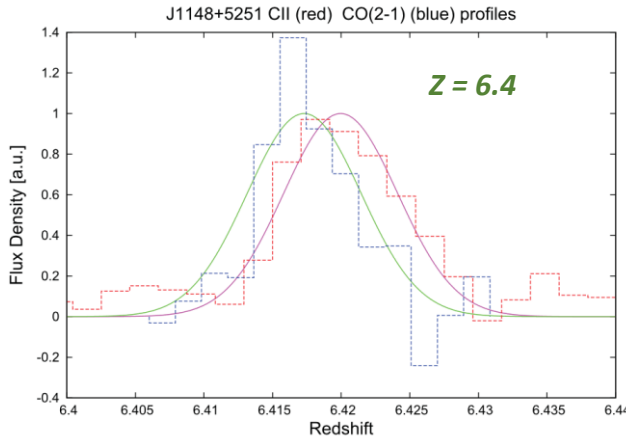
Star-formation Across Cosmic Time: *e*-MERGE Tier 1

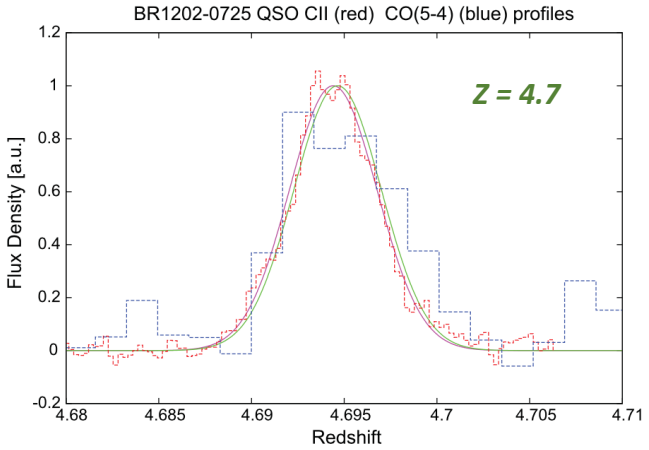
J123634+621213:



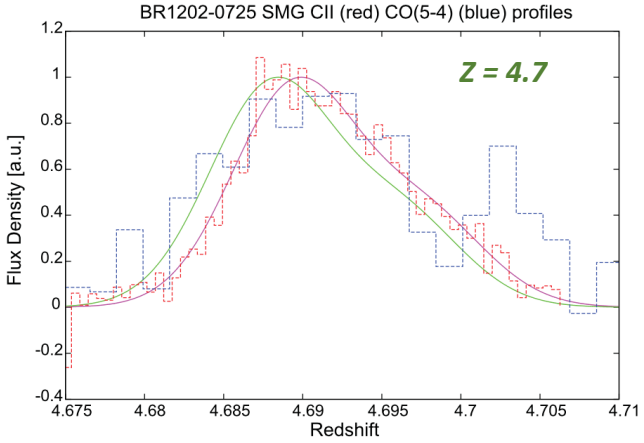


Cosmology: Variation of fundamental constants?





$$F = \frac{\alpha^2}{m_p/m_e}$$



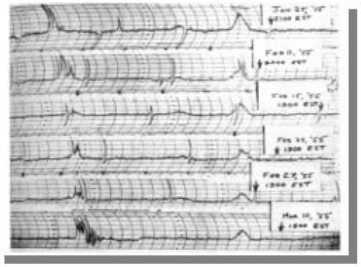
$$\frac{\Delta F}{F} = -3.3 \pm 2.3 \times 10^{-4} \text{ (12.9 Gyr)}$$

Lentati et al 2013

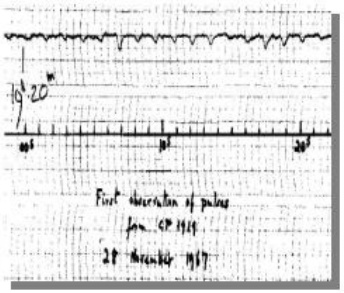
DF/F = -3.3

- Observe different types of transitions (e.g. electronic vs rotational) in galaxies at range of z
- Use differences in inferred redshits of the lines to look for evidence of variation in fundamental constants
- Problem
  - Are we tracing same gas in the two transitions?
  - Do we observe astrophysics or physics?
- Here resolution of e-MERLIN very helpful
  - HI / OH
  - More transitions

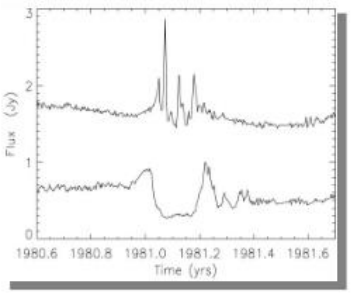
Transient Universe



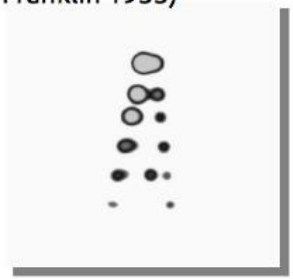
Radio Bursts from Jupiter (Burke & Franklin 1955)



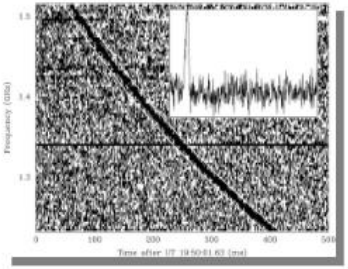
Pulsars (Hewish et al. 1968)



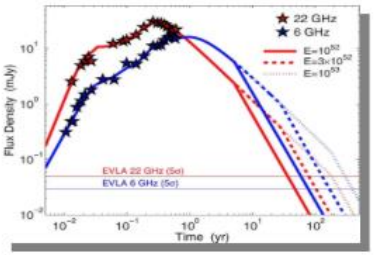
Extreme scattering events (Fiedler et al. 1987)



A superluminal source in our galaxy (Mirabel & Rodriguez 1994)



Fast radio bursts Lorimer et al. (2007)



A relativistic jet from a tidal disruption event (Zauderer et al. 2011)

- Traditional area of big impact e-MERLIN science
- SKA1 Discovery +
  - Power of responsive observing
  - Resolution
  - Link to EVN

Transient Universe

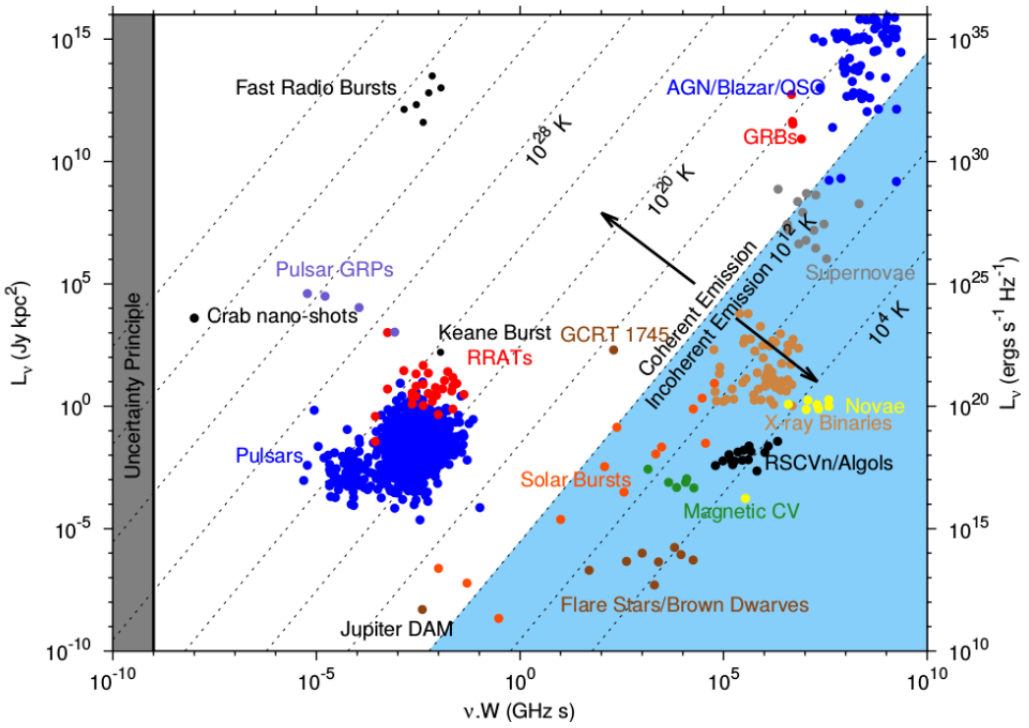
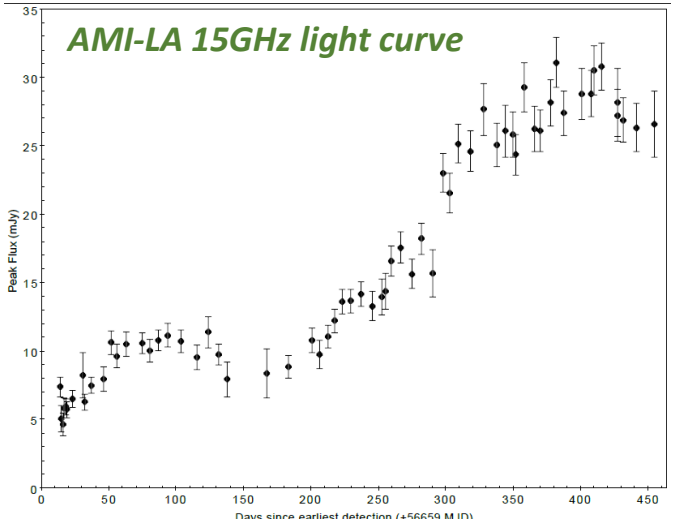


Figure 4: Transients parameter space expanded to include coherent sources. From Pietka, Fender & Keane (2015), following a long line of similar plots (e.g. Cordes, Lazio & McLaughlin 2004).

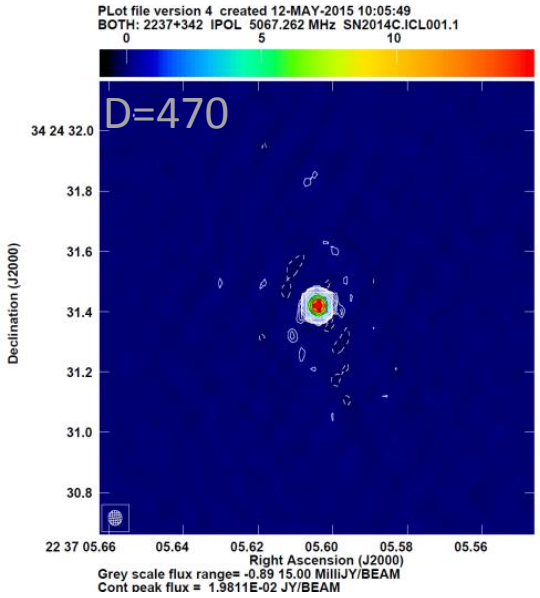
- Traditional area of big impact e-MERLIN science
- SKA1 Discovery +
  - Power of responsive observing
  - Resolution
  - Link to EVN

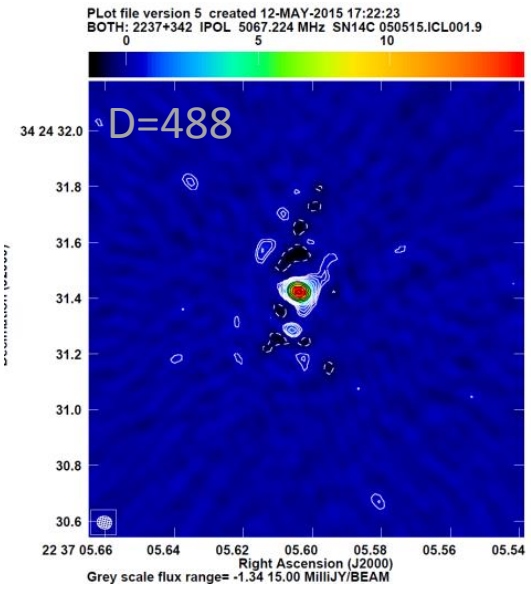
Transient Universe: SN2014C

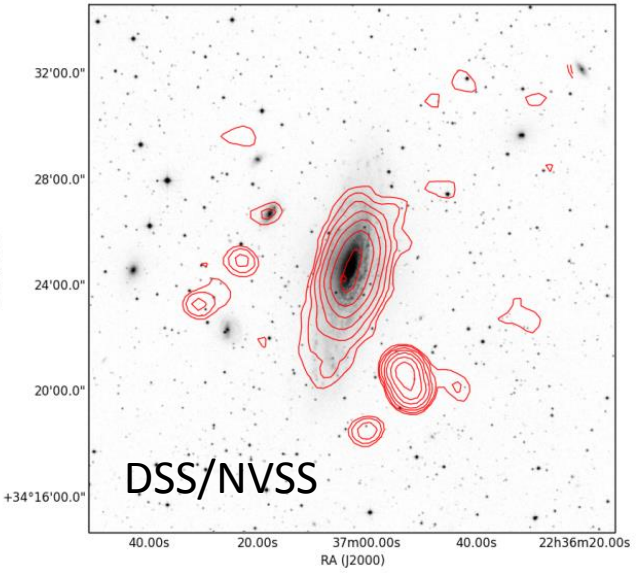


SN2014C (Lick discovery)

- D=15.1Mpc in NGC7731
- Unusual double peak
- Indicative of shell interaction with dense CSM
- Possibly radio bright SN1b
- *Now trigger VLBI follow-up pending*
- e-MERLIN resolution vital to remove confusion



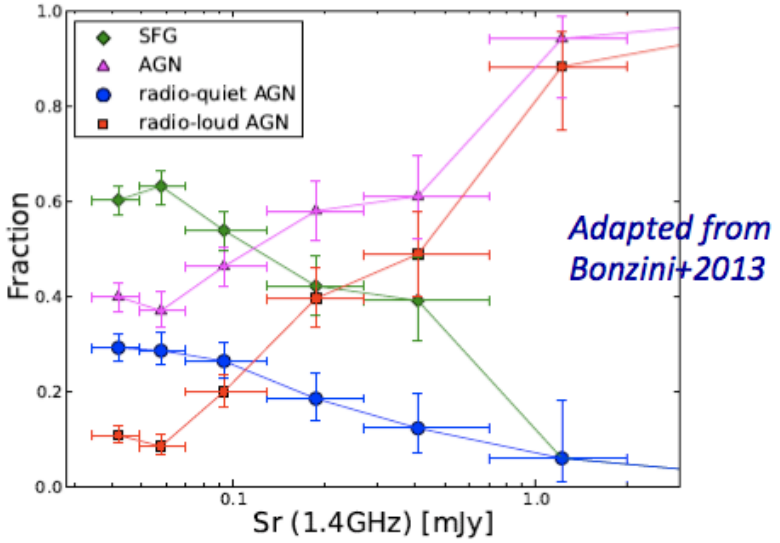




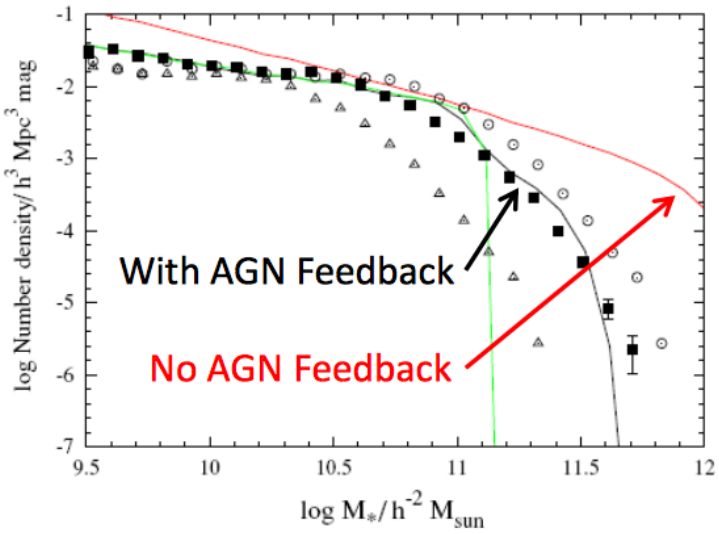
Anderson, Fender et al

AGN Physics

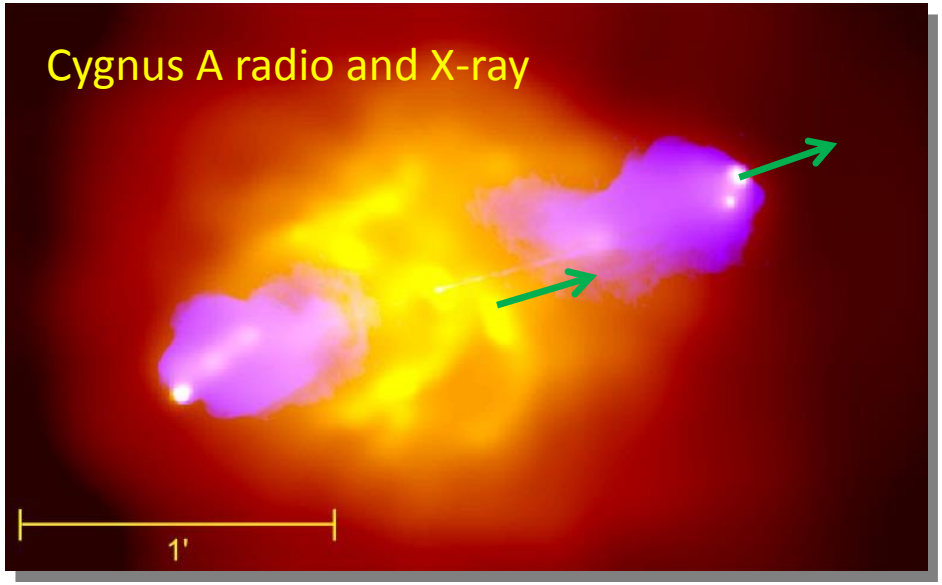
- Physics of RL AGN physics/lifecycle
- Physics of RQ/RL AGN dichotomy
- How do RL / RQ AGN provide feedback
- Jet Physics: origin and propagation

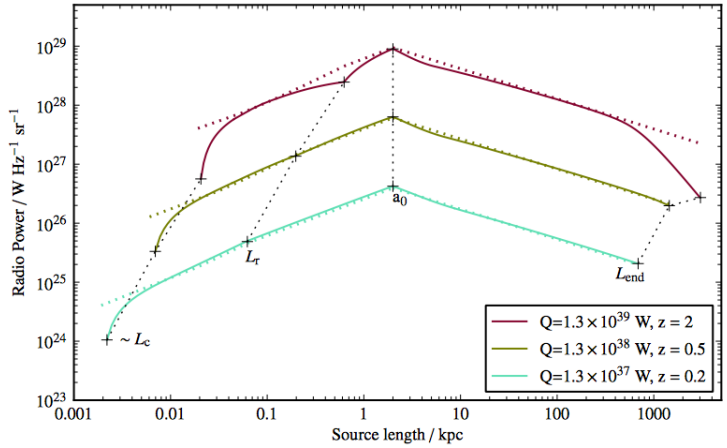


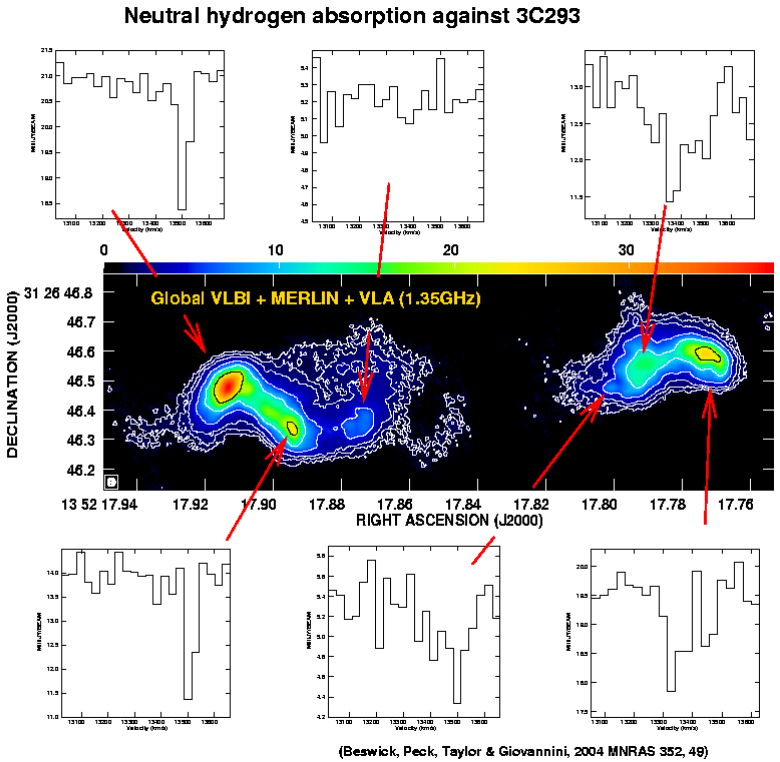
- Radio Astronomy and AGN Physics !!
- Much progress but still many unsolved problems
- Interesting in own right as well as importance in overall galaxy evolution
- AGN physics is interesting



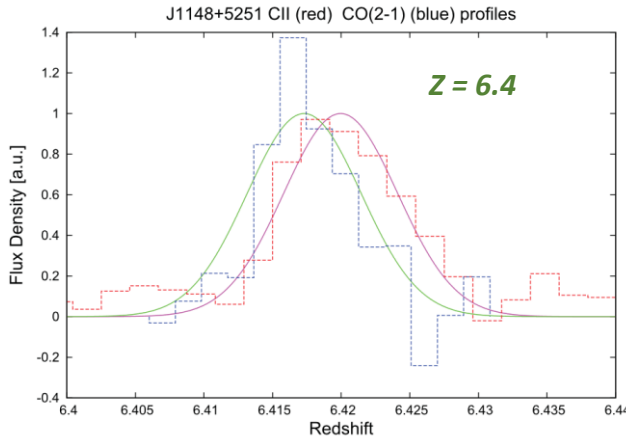
AGN Physics

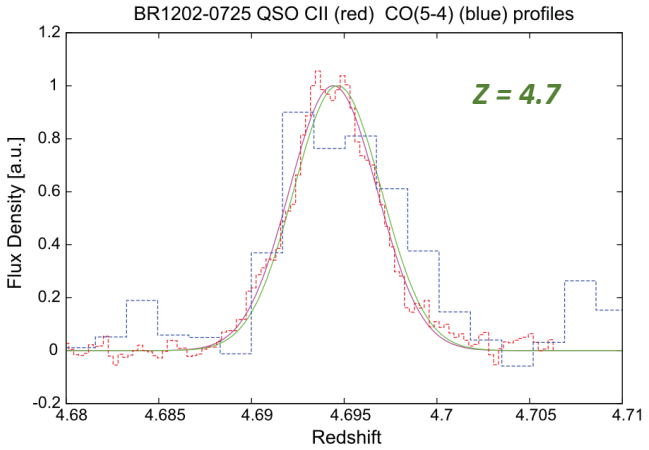

Cygnus A radio and X-ray
1'


Radio Power / W Hz^{-1} sr^{-1}
Source length / kpc
a_0
L_r
L_{end}
$\sim L_c$
Q=1.3×10^{39} W, z = 2
Q=1.3×10^{38} W, z = 0.5
Q=1.3×10^{37} W, z = 0.2

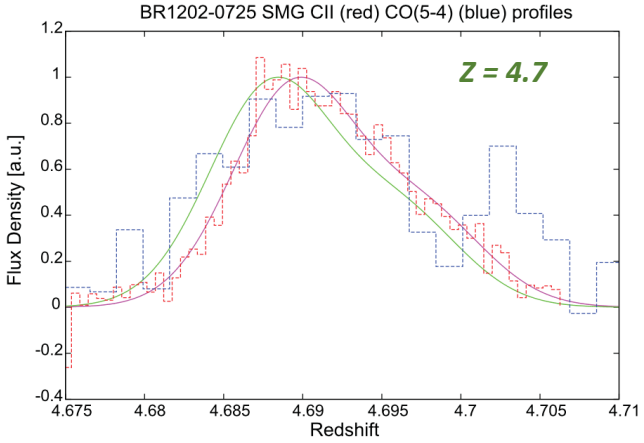

Neutral hydrogen absorption against 3C293
Global VLBI + MERLIN + VLA (1.35GHz)
DECLINATION (J2000)
RIGHT ASCENSION (J2000)
(Beswick, Peck, Taylor & Giovannini, 2004 MNRAS 352, 49)

Cosmology: Variation of fundamental constants?





$$F = \frac{\alpha^2}{m_p/m_e}$$



$$\frac{\Delta F}{F} = -3.3 \pm 2.3 \times 10^{-4} \text{ (12.9 Gyr)}$$

Lentati et al 2013

DF/F = -3.3

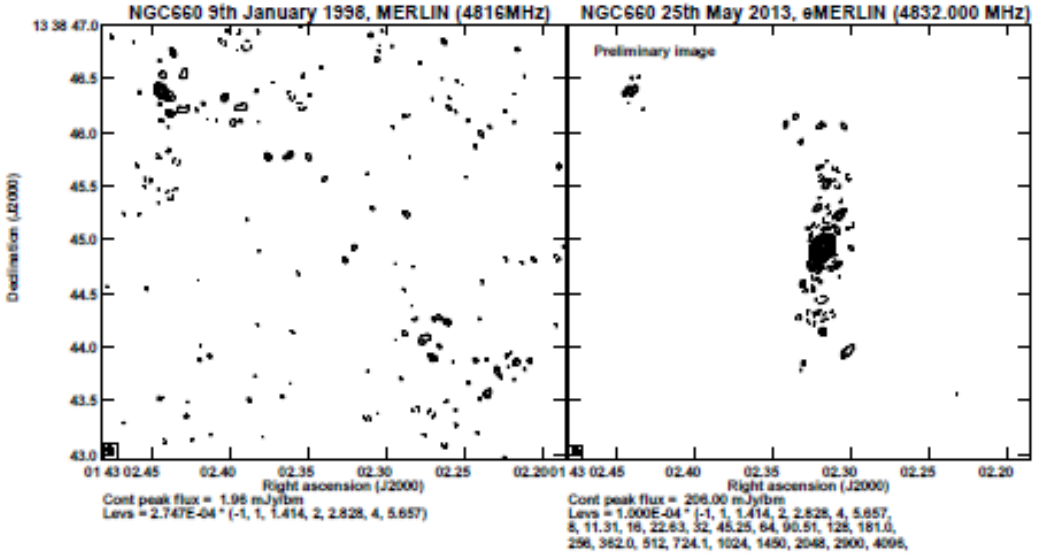
- Observe different types of transitions (e.g. electronic vs rotational) in galaxies at range of z
- Use differences in inferred redshits of the lines to look for evidence of variation in fundamental constants
- Problem
  - Are we tracing same gas in the two transitions?
  - Do we observe astrophysics or physics?
- Here resolution of e-MERLIN very helpful
  - HI / OH
  - More transitions

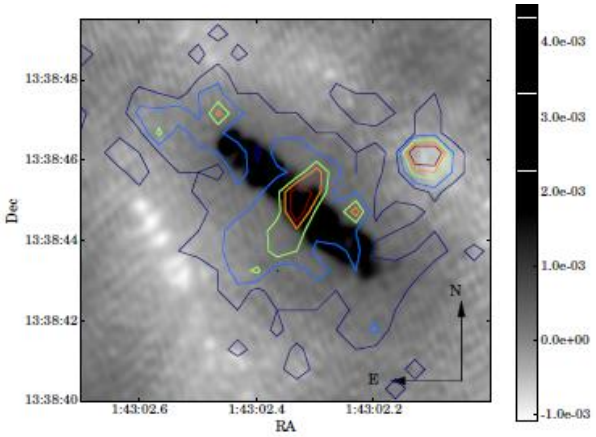
A new period of activity in NGC660

Witnessing the **(re-)birth** of an AGN

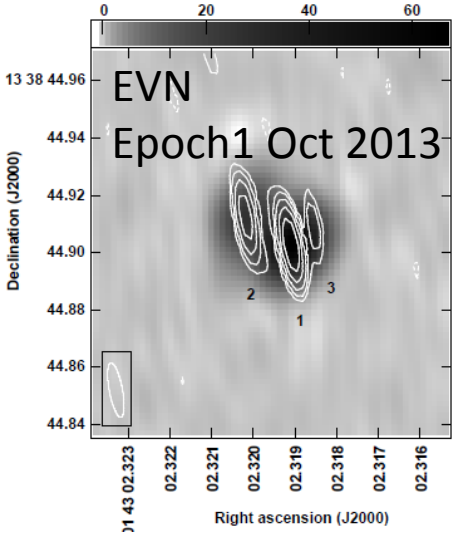
Joint eMERLIN/EVN/WSRT study of spectral lines and continuum

- New source discovered in Arecibo monitoring (2008-2010)
- Nuclear continuum source peaked at ~0.5Jy – now in steady decline





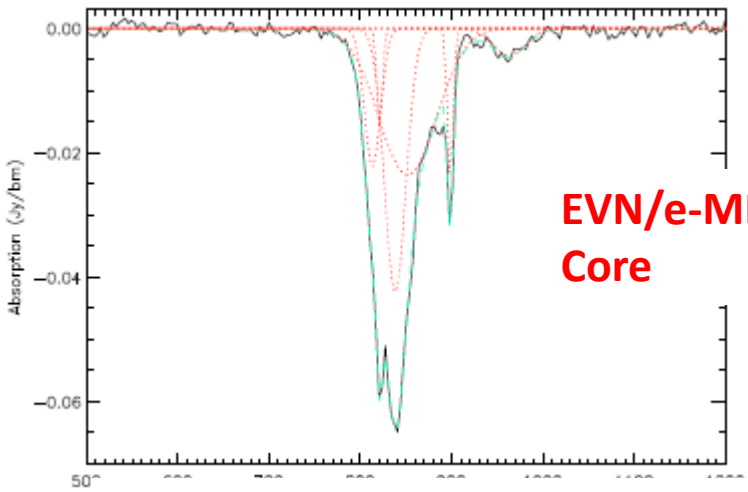
Pre-outburst MERLIN L-band and post outburst X-ray (Chandra)



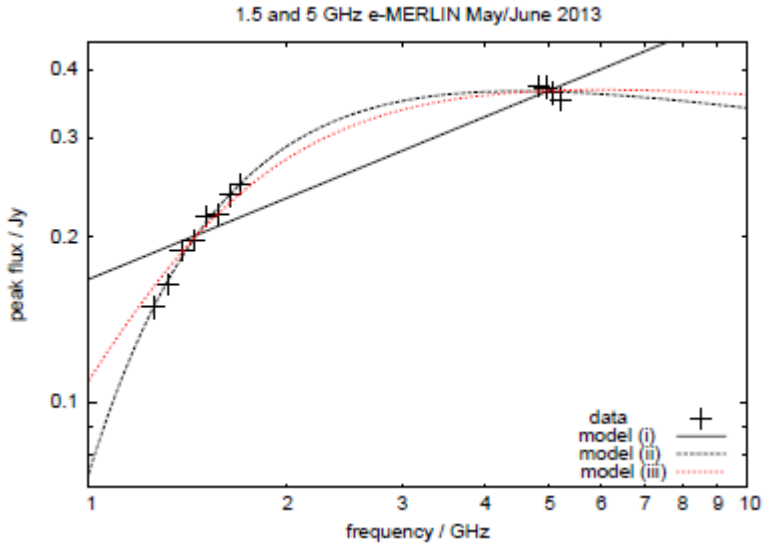
Nuclear source & Gas?

- Outburst provide chance of high-res/sen line observations of neutral molecular ISM
- Wide-band continuum SED

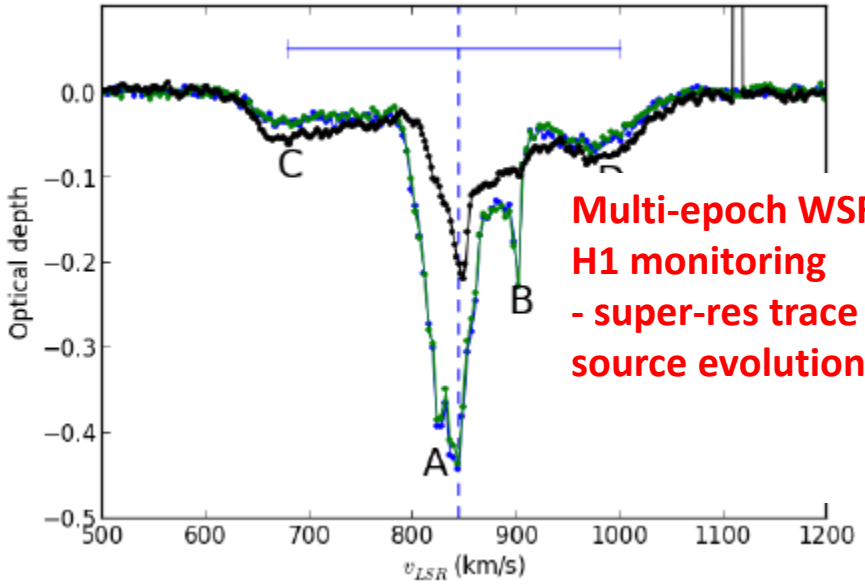
- New GPS source



EVN/e-MERLIN H1 against Core



Argo et al MNRAS in press



Multi-epoch WSRT H1 monitoring
- super-res trace of source evolution

van Bemmel in prep

UNIVERSITY OF CAMBRIDGE