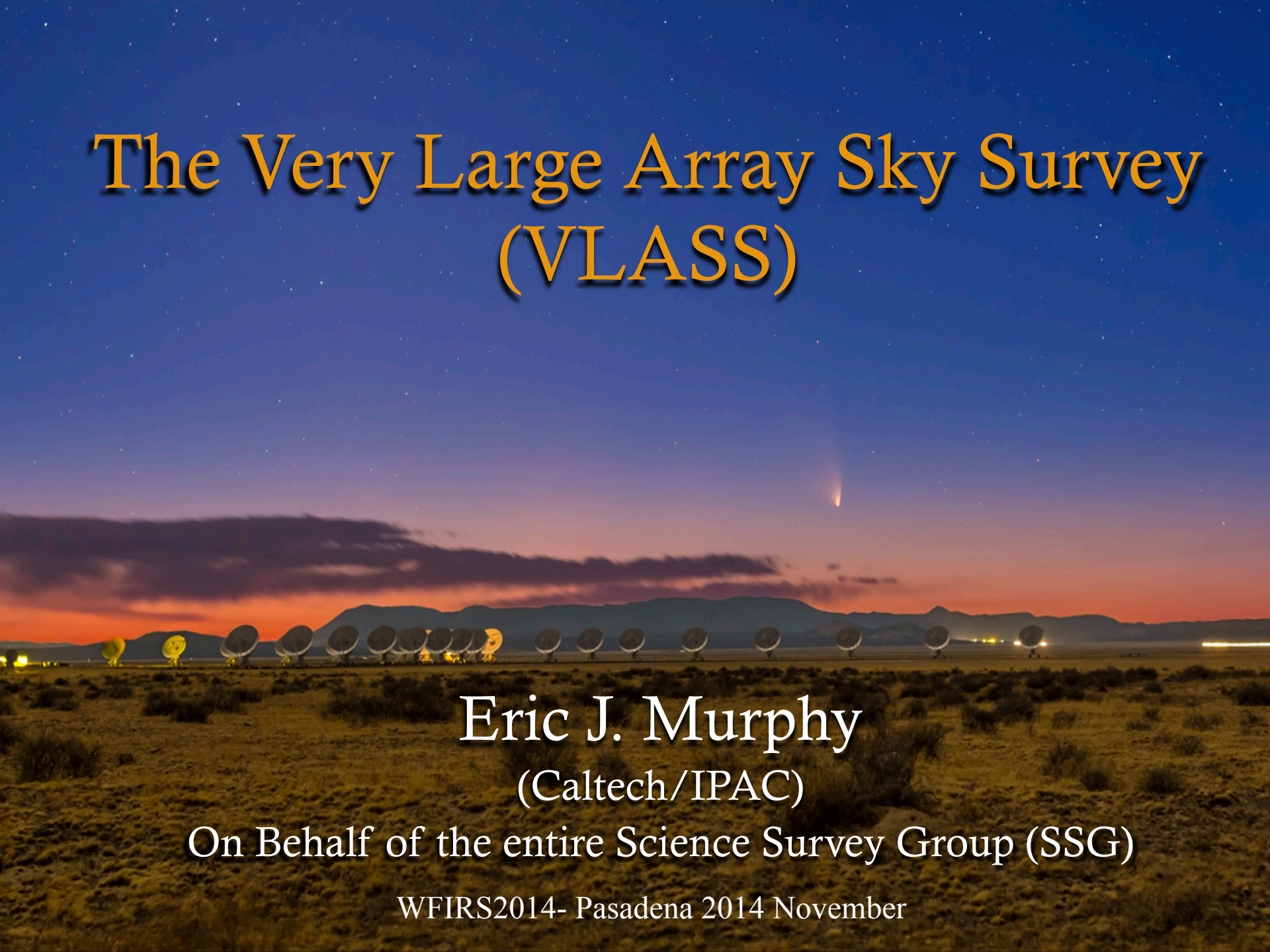
The Very Large Array Sky Survey (VLASS)

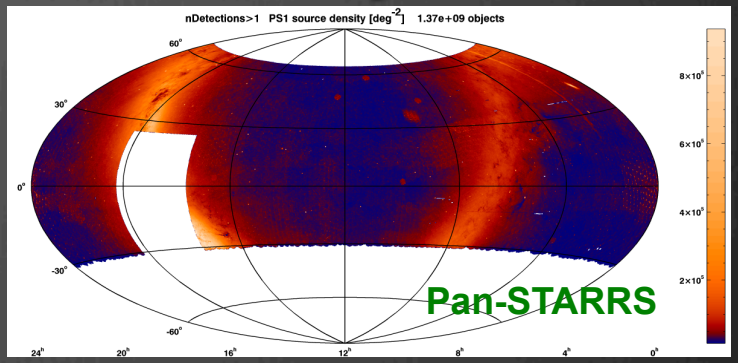


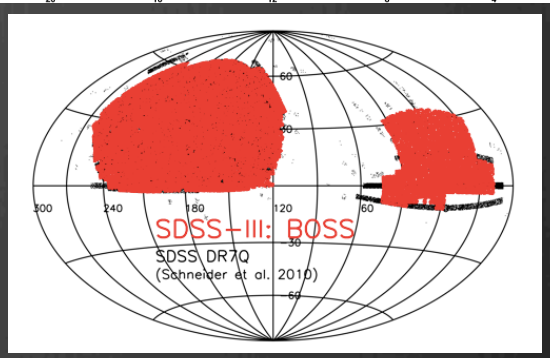
Eric J. Murphy
(Caltech/IPAC)
On Behalf of the entire Science Survey Group (SSG)

WFIRS2014- Pasadena 2014 November

Surveys and the VLA/Why Now?

- Science based on surveys comprise a steadily increasing fraction of publications from the VLA
- 20 years since NVSS and FIRST!





- ***New capabilities on the VLA***
  - OTF mosaics, wide fractional bandwidths for increased continuum sensitivity, instantaneous spectral index determination, polarization
- ***New survey instruments being specifically designed for all-sky coverage***
  - need radio counterpart *with comparable or better resolution*
- ***New scientific opportunities***
  - especially in time domain, need to start now to build time series

The VLA Sky Survey (VLASS) initiative

- In July 2013 NRAO announced that it would consider a new radio sky survey using the Karl G. Jansky VLA
- Website : https://science.nrao.edu/science/surveys/vlass
- Science and survey definition led by the community
- Open *international* participation, public data and products
- NRAO role is to facilitate survey definition, implement survey if approved, deliver basic data products, support community with higher level data products
- White Papers solicited on aspects and science goals for the survey:
  - 22 papers submitted; ~200 authors
- Scientific Organizing Committee convened
  - Review White Papers and set up workshop at Jan. 2014 AAS meeting
  - Define structure of Science Survey Group (SSG)

VLASS Science Planning Workshop

- Held 5 Jan 2014 just before AAS 223 meeting National Harbor
- Agenda and Talks posted online
- https://science.nrao.edu/science/surveys/vlass/vlass-science-planning-workshop
- Around 50 attendees
- Morning talks
- Afternoon discussion

Active discussion! No convergence but areas for debate are apparent.

Key science cases: highlights from the White Papers

- Medium/Deep Fields for Galaxy Evolution & Cosmology
  - AGN and Clusters of Galaxies, Feedback
  - Star-forming Galaxies
  - Weak Lensing

Cosmology & AGN: Brown et al., Mao et al., Spoalor et al.,

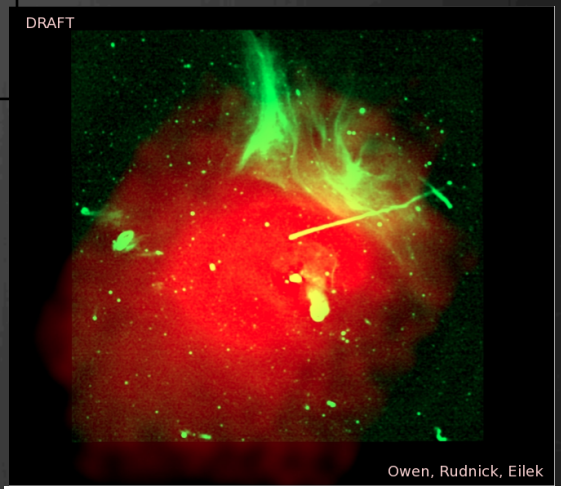
Clusters & Polarization: Clarke et al., Edge et al., Mao et al.
Cosmic Deep Fields: Hales et al,, Jarvis et al., Richards et al., Wang et al.

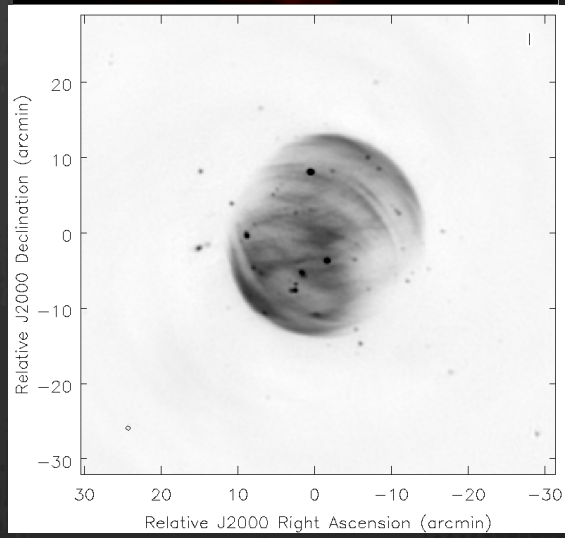
- Large Area Survey for Transients & Faraday Tomography
  - Full Polarimetry for B-field Studies
  - EM Counterparts to GW events (LIGO/VIRGO)
  - Radio Bursts on timescales from 1ms to >1 year

Transients: Chatterjee et al., Hallinan et al., Kamble et al., Law et al., Wilson et al.

- Galactic Plane and Center
  - Atomic and Molecular Lines from 0.2-50 GHz
  - Stars and Stellar Systems

Galactica: Bastian et al., Bhatnagar et al., Sjouwerman et al., Mills et al.





Science Survey Group (SSG)

- Co-Chairs: Eric Murphy (IPAC) & Stefi Baum (RIT, U. Manitoba)
- Working Group Co-Chairs:
  - Programmatic: Jim Condon (NRAO), Rick White (STScI)
  - Extragalactic: Gordon Richards (Drexel), Jackie Hodge (NRAO)
  - Galactic*: Rachel Osten (STScI), Joe Lazio (JPL)
  - Transients: Gregg Hallinan (Caltech), Ashley Zauderer (CfA)
  - Technical: Casey Law (UC Berkeley), Steve Myers (NRAO)
  - Outreach: Susana Deustua (STScI), Nicole Gugliucci (SIUE/CosmoQuest)
- At-Large Councilors:
  - Niel Brandt (Penn State), Jim Cordes (Cornell), Mark Dickinson (NOAO), Tracey Clarke (NRL), Sui Ann Mao (MPIA), Michael Strauss (Princeton)

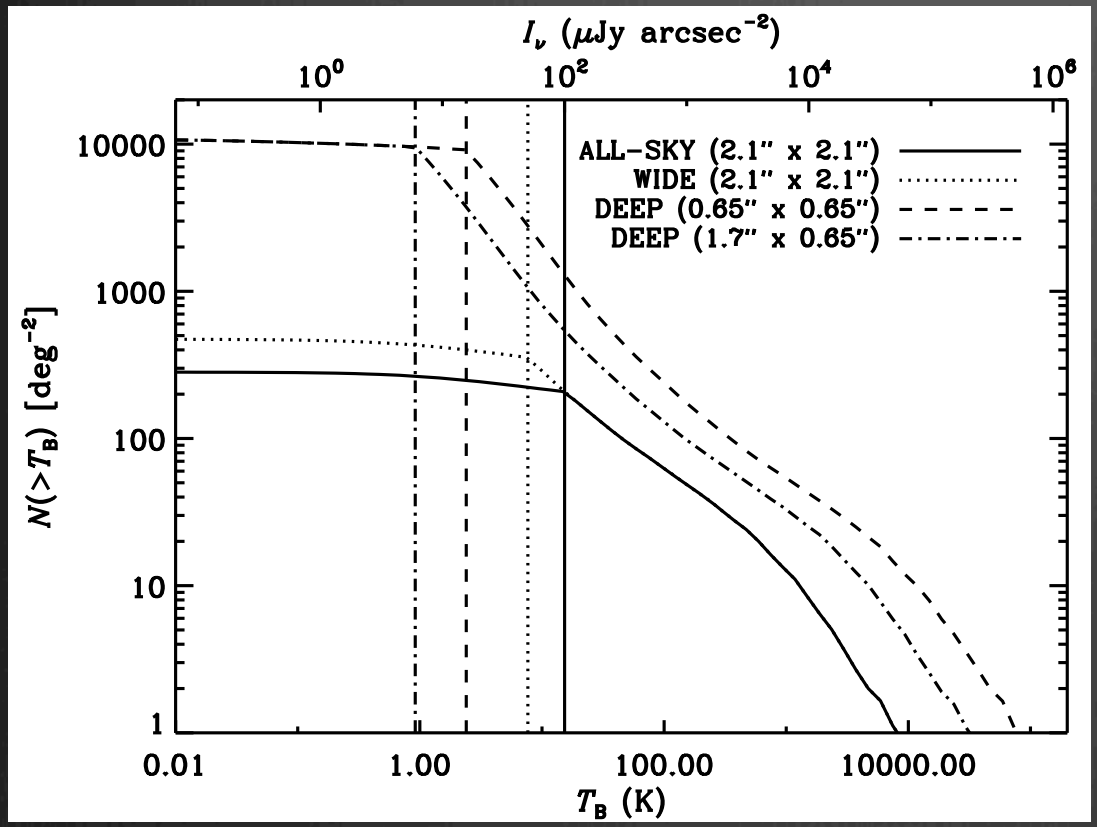
* Ex-Galactic Co-Chair: Cornelia Lang (U Iowa)

VLASS: Survey Definition

- Comprehensive, Multi-tiered Approach
  - Enables wide ranging studies (multi-wavelength, statistical, time domain)
- All in S-Band (2 – 4 GHz), B/BnA/A-configurations
  - Full Polarization – Improved RM Synthesis Imaging
  - Less stringent dynamic range requirements
  - High Angular Resolution Imaging (0.65" – 2.1")
- SKA 1.4 GHz Pathfinder Surveys Considered
  - Complements: ASKAP/EMU, APERTIF/WODAN, MeerKAT/MIGHTEE
  - ***Resolution/Depth of Deep Tier not matched until SKA1-MID >>2020!***
- ~9000 hr investment over ~5yr (~25% impact on PI time)

Tier	Area (deg^2)	Resolution ('')	Rms (μJy/bm)	Time (hr)	Epochs
All-Sky	33,885 (δ > -40°)	2.1	100	1904	1
Wide	10,000 (SDSS-III/DESI)	2.1	50	2824	4
Galactic	3160 (plane/bulge: $\|b\|$ < 5°/14°)	0.76	50	840	4
Deep	10 (COSMOS/ECDFS/EN-1)	0.65	1.5	3391	4

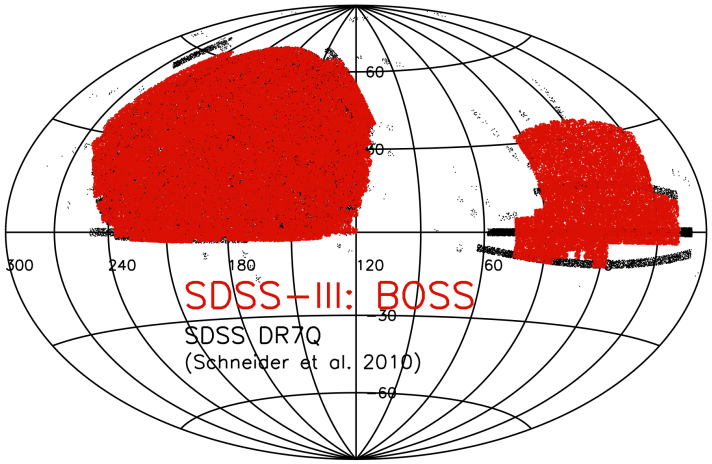
Expected Extragalactic Source Statistics



Tier	Density (deg^{-2})	Total Detections
All-Sky	205	7,000,000
Wide	350	3,500,00
Deep	9200	92,000

Based on S^3 (Wilman et al. 2008)

SDSS-III Footprint, which is the proposed area for the Wide tier. DESI will further target this full area and HSC will target key parts of it.



VLASS Headline Science Themes

- Hidden Explosions:

  Unbiased Measurements of Energetic Events.

- Faraday Tomography of the Magnetic Sky:

  Charting the Emergence of Large-Scale Magnetic Fields in Galaxies

- Imaging Galaxies Through Time and Space:

  Following the Ecology of Galaxies, Star Formation, and their Black Hole Engines.

- Peering Through Our Dust Galaxy:

  Finding and Studying the Tracers of Stellar and Chemical Evolution.

- Radio Sources as Cosmological Probes:

  Tracing the Underlying Dark Matter Density Field.

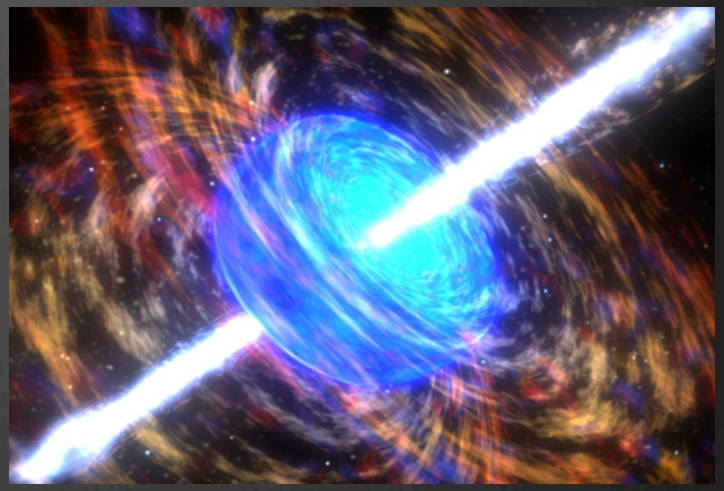
- Missing Physics:

  Enabling the Incorporation of Radio Astrophysics in Multi-Wavelength Astronomy.

Time Domain Science
VLASS: Un-obscured view of cosmic explosive events

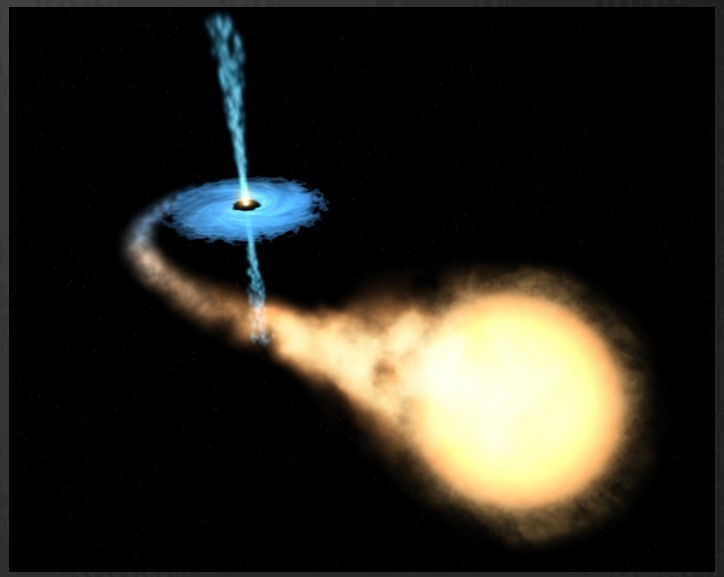
- **<u>Explosive Galactic and Extragalactic populations</u>**

- Interaction of ejecta with the ISM
- Typically synchrotron emission
- Variable on timescales of days – years
- *Typically discovered at optical/high-energy*
- *Followed up at radio wavelengths*



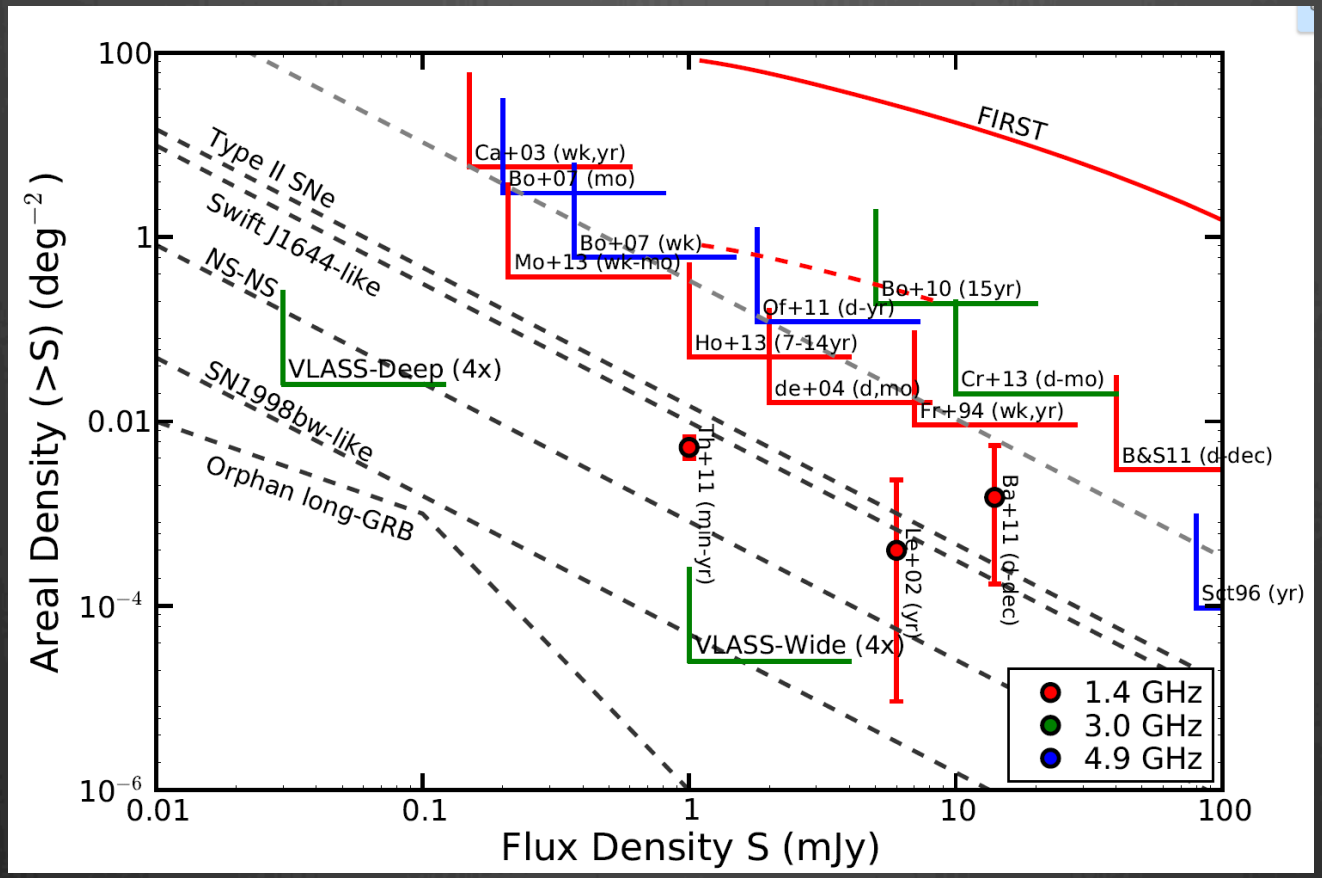
Examples:

- AGN and Microquasar jets
- Supernovae & GRBs afterglows
- Black hole tidal disruption events (TDEs)
- Giant flares from magnetars



- ***VLASS will see an entirely new population, invisible in other wavebands***

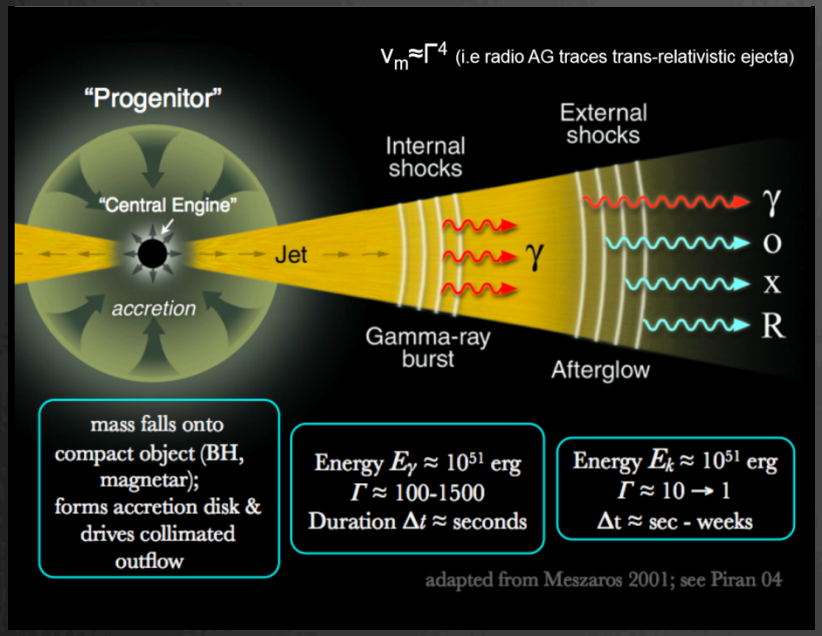
- *Will measure true rate and energetics (calorimetry)*
  - Obscured supernovae in dusty environments
  - GRB orphan afterglows
  - Binary neutron star mergers



- ***VLASS will be the first synoptic radio survey to detect large samples of explosive transients***

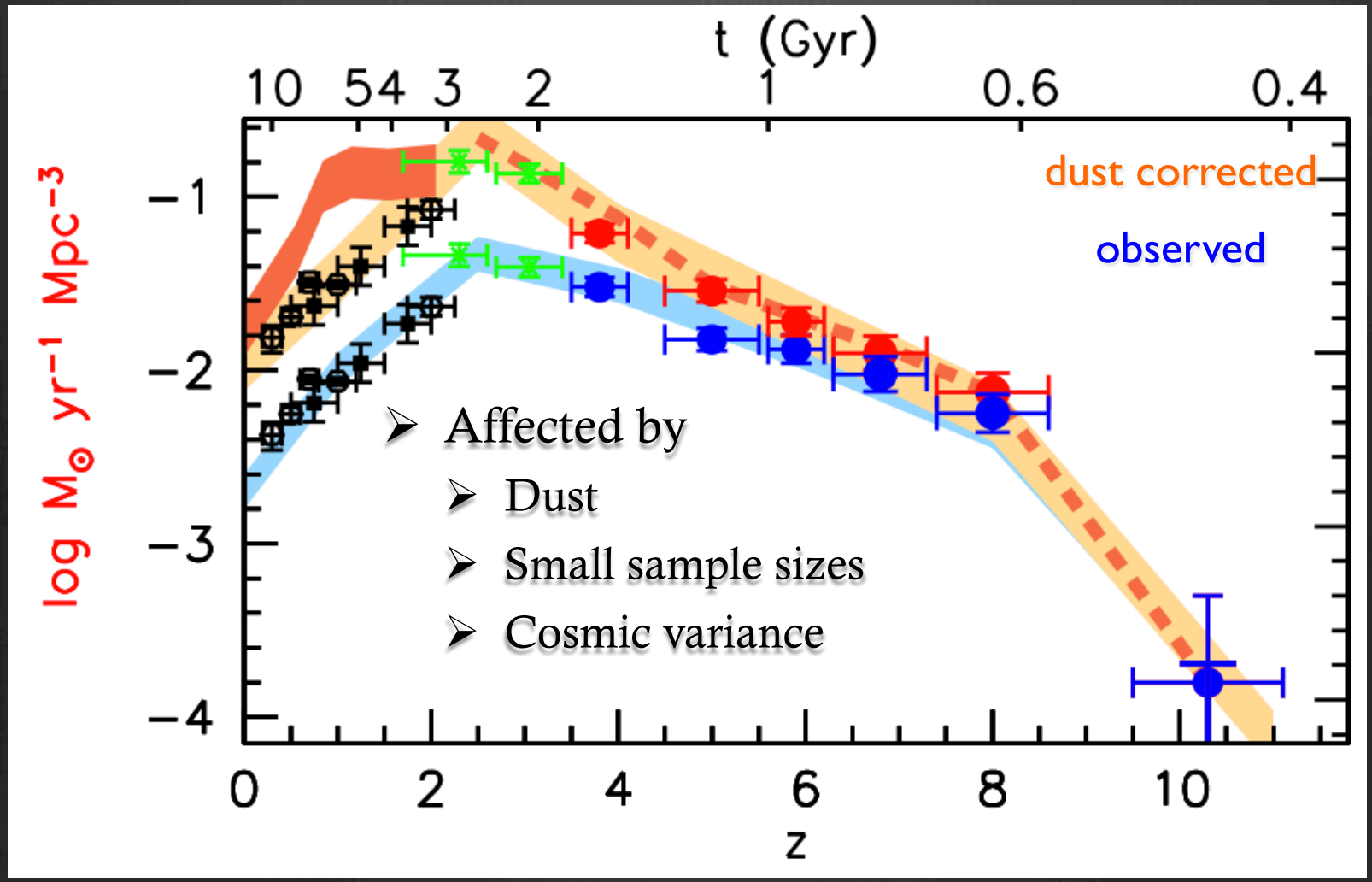
- Slow evolution timescale – VLASS epochs spaced to maximize detection rate
- Choice of frequency and resolution key advantage relative to SKA pathfinders
- Faster evolution timescale at S band relative to L band –
  - e.g. supernovae typically reach peak brightness in < 1 yr at 3 GHz; ~ few yrs at 1.4 GHz
- Resolution of ~3” key to localizing events w/in galaxies
  - e.g. distinguishing GRBs/SNe/BNS-mergers from AGN activity

Highlight: BNS-mergers in the Gravitational Wave Era



- Advanced LIGO (aLIGO) and Advanced Virgo (AdV) commence in 2015
- Binary neutron star (BNS) coalescence the most likely source detected
- Associated γ -ray burst is highly beamed - true rate poorly constrained
- Radio afterglows are isotropic – detectable with the VLA (Nakar & Piran 2011)
- ***VLASS will provide an unbiased measure of the BNS-merger rate***

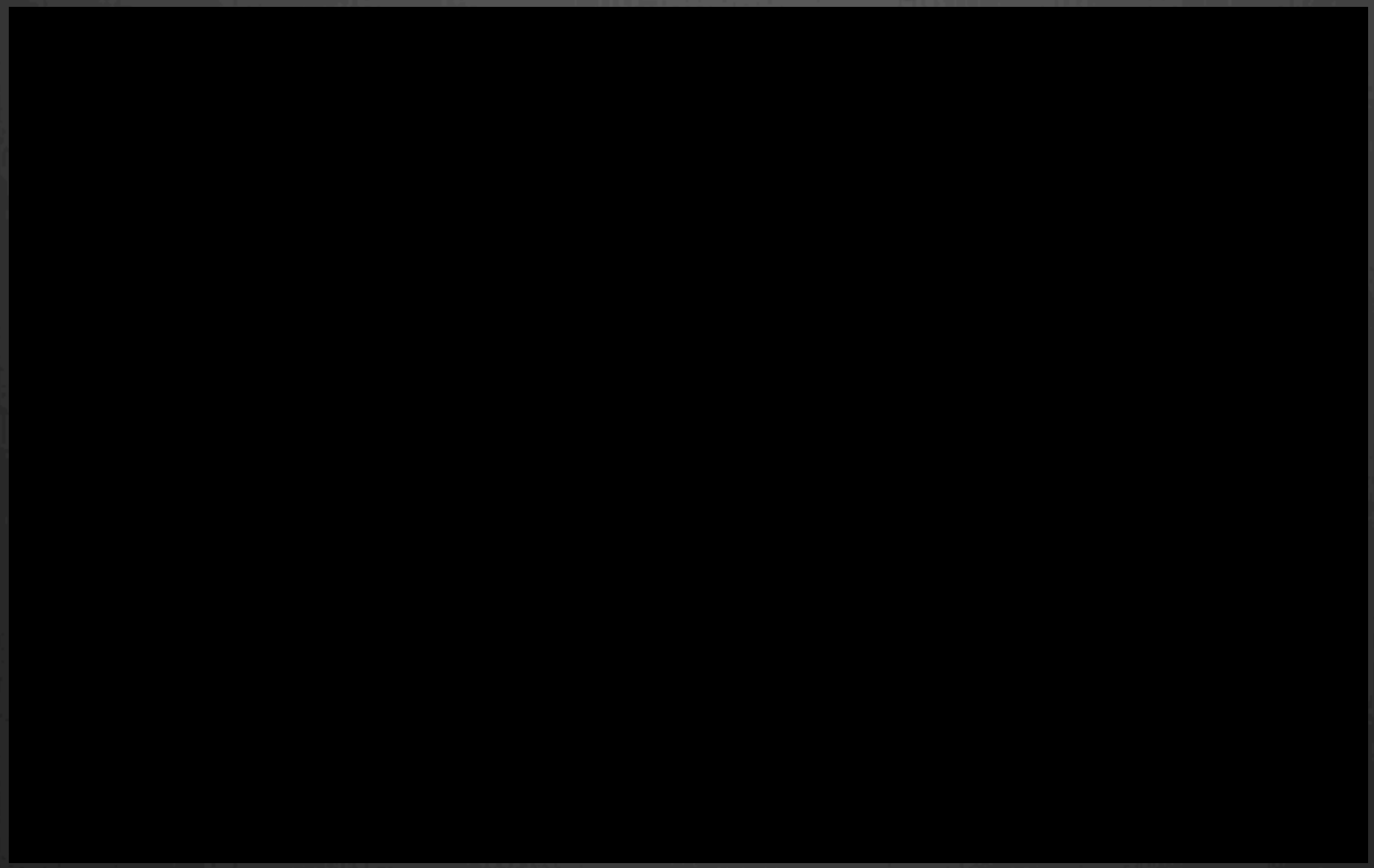
Extragalactic Science
The star-formation history of the Universe
Age of the Universe (Gyr)



Star formation rate density

Bouwens+12

Extragalactic Science
The star-formation history of the Universe

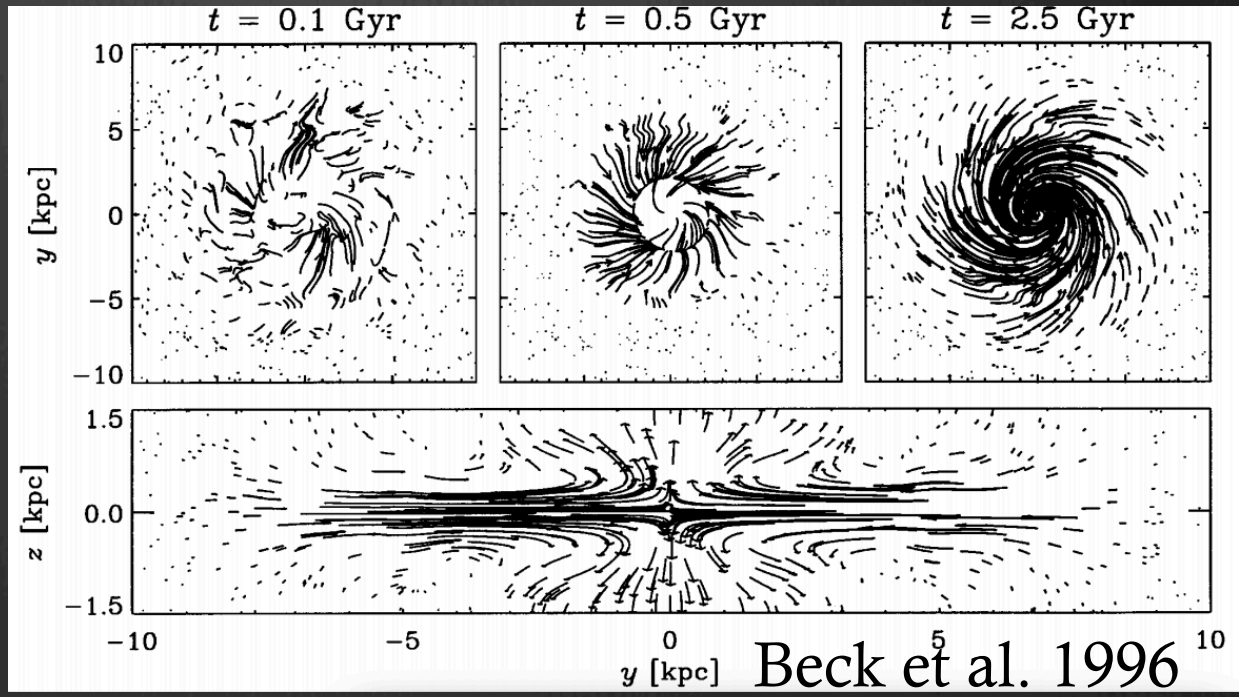


- **As sensitive to obscured star as the deepest *Herschel* data**
  - ***Covering 100x the area***
  - ***More sensitive beyond z > 2***

Emergence of Magnetic Fields

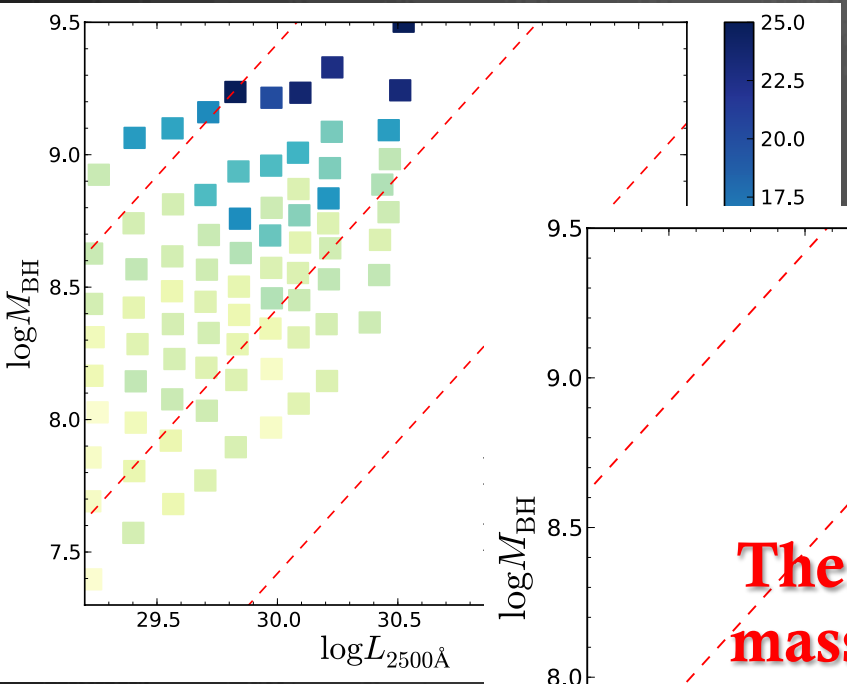
- Combined with baseline sample of nearby ($z \leq 0.5$) galaxies from WIDE, addresses:
  - Environmental dependence (Lewis et al. 2002)
  - Dependence on host galaxy mass (Peng et al. 2010, 2012)
  - Growth of galactic-scale magnetic fields (e.g., Zweibel & Heiles 1997)

- Using the statistics of synchrotron polarization of unresolved galaxies (e.g., Stil et al. 2009)
- To avoid depolarization, wide-band spectro-polarimetry at 2-4GHz is ideal

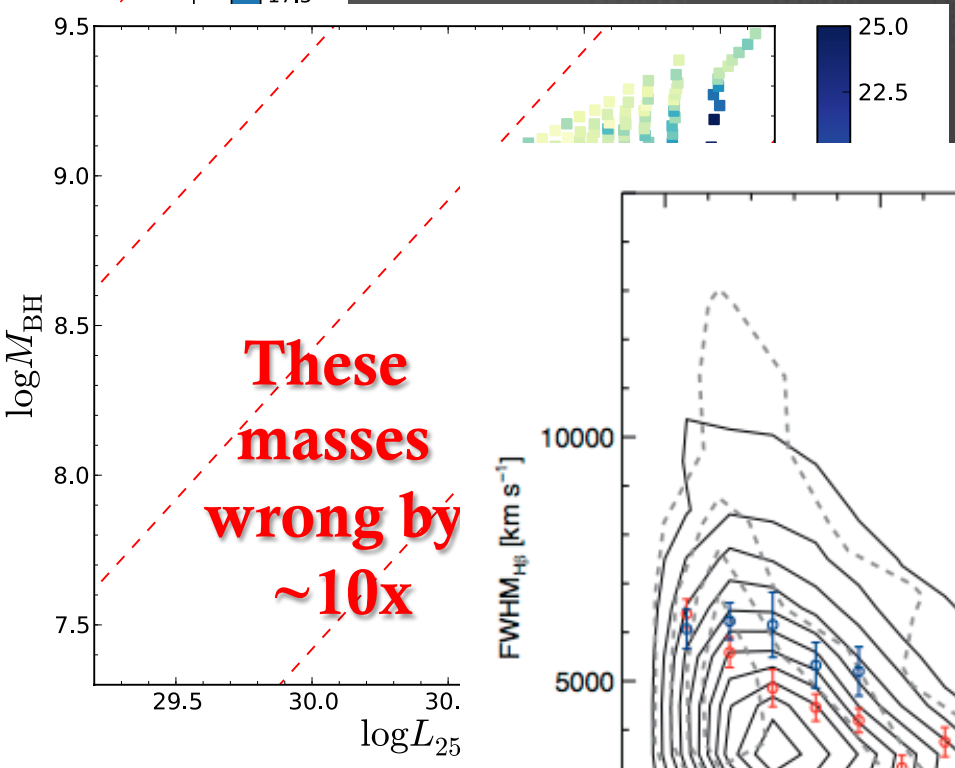


Beck et al. 1996

Insight on BH masses from radio

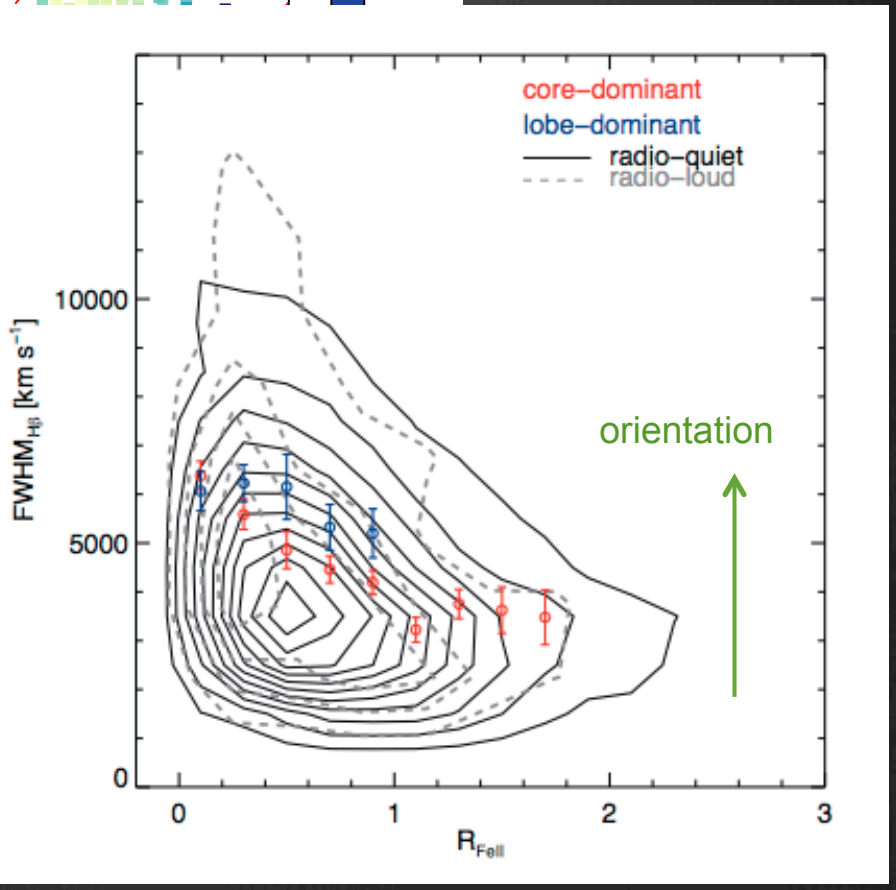


Radio data reveal an error in distant BH mass estimates



Shen & Ho 2014

These masses wrong by ~10x



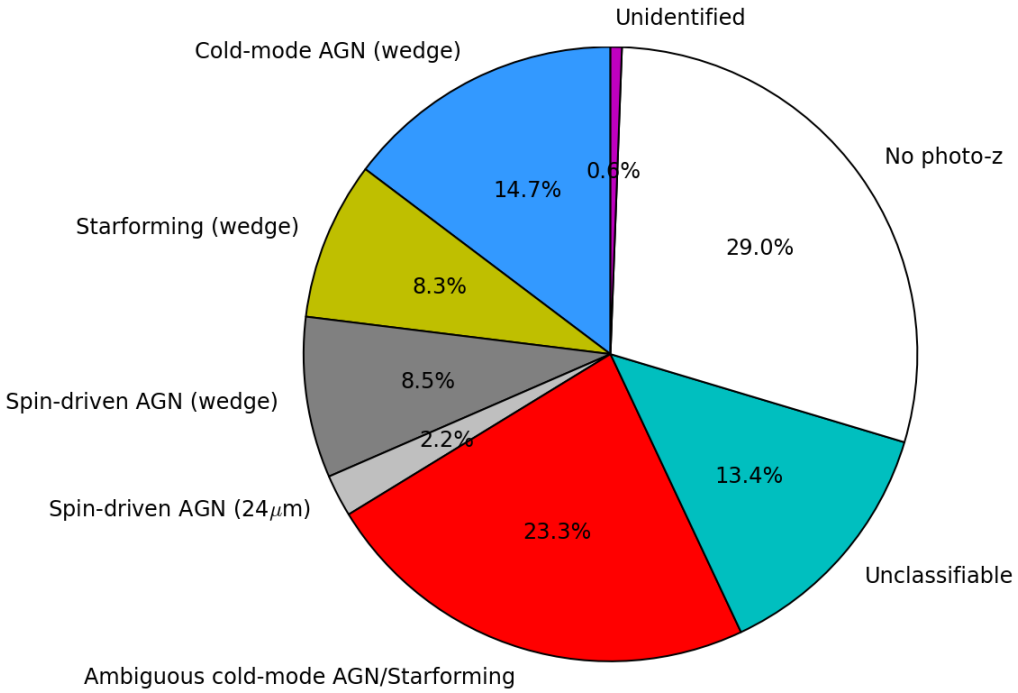
Nearby RL quasars are high L/L_{Edd}

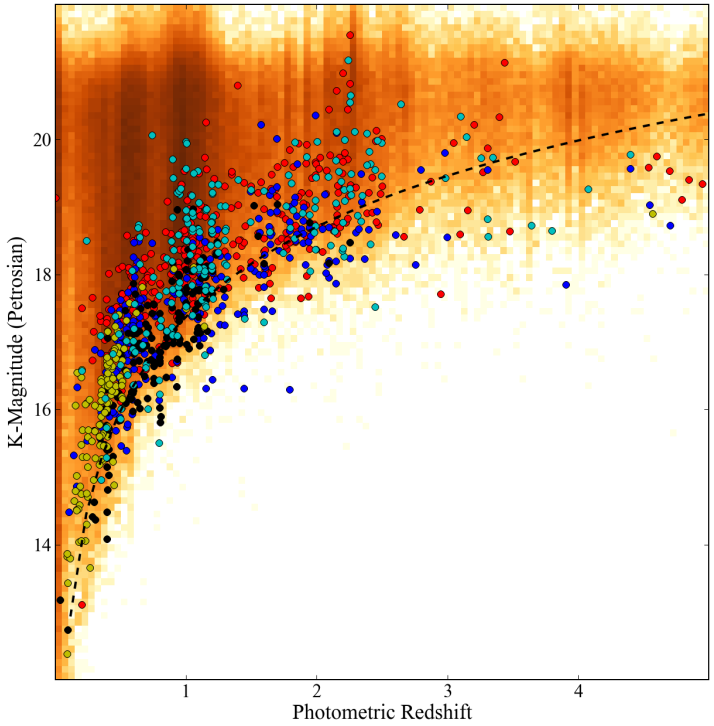
Kratzer & Richards 2014

Low-z BH masses should be more accurate, but Shen & Ho 2014 argue that FWHM of Hbeta may have an orientation dependence. Only radio data (e.g., α) can fully test this.

Faint radio survey follow-up with SERVS

(Luchsinger et al. 2014 submitted)





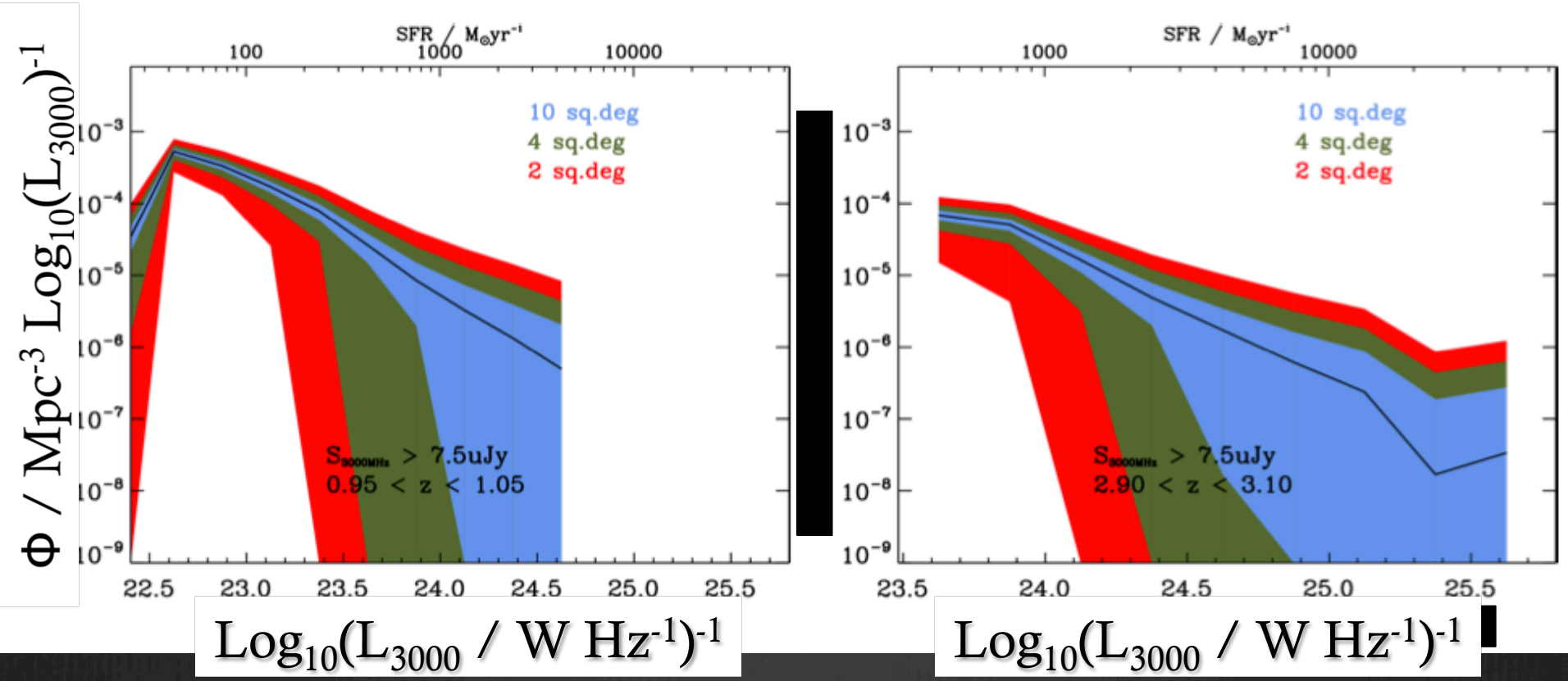
>99% of ~50μJy radio sources identified in SERVS (AB~22.7 at [3.6]), ~50% classifiable. Star-forming galaxies to z~0.7

Radio source hosts are the brightest galaxies at a given redshift (orange background is overall galaxy distribution).

VLASS DEEP will be 4x deeper and cover 20x the area.

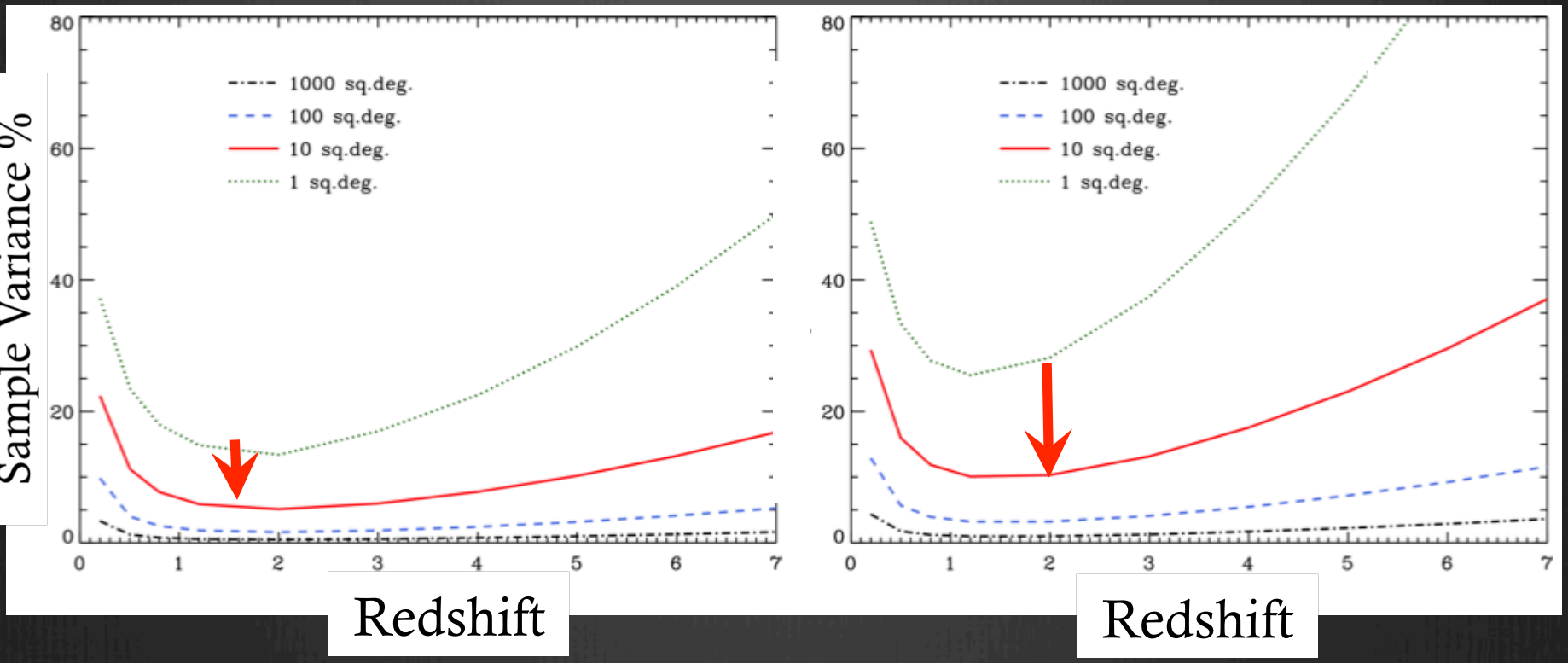
VLASS Luminosity Functions

(SF galaxies - based on Wilman et al. 2008, 2010)



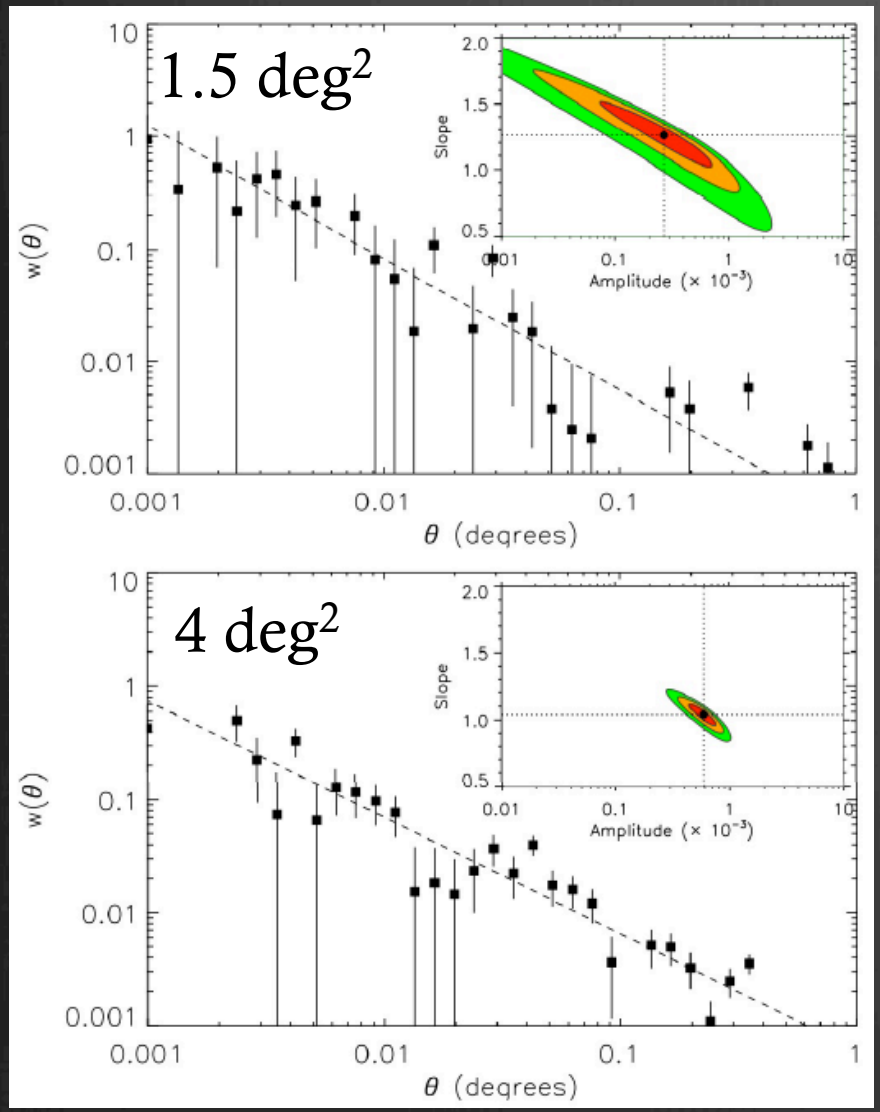
→Order of Magnitude increase in sample size will improve the constraints significantly over COSMOS

Cosmic Variance



→Area of 10deg^2 significantly reduces sample variance due to large scale structure

Clustering & Large Scale Structure

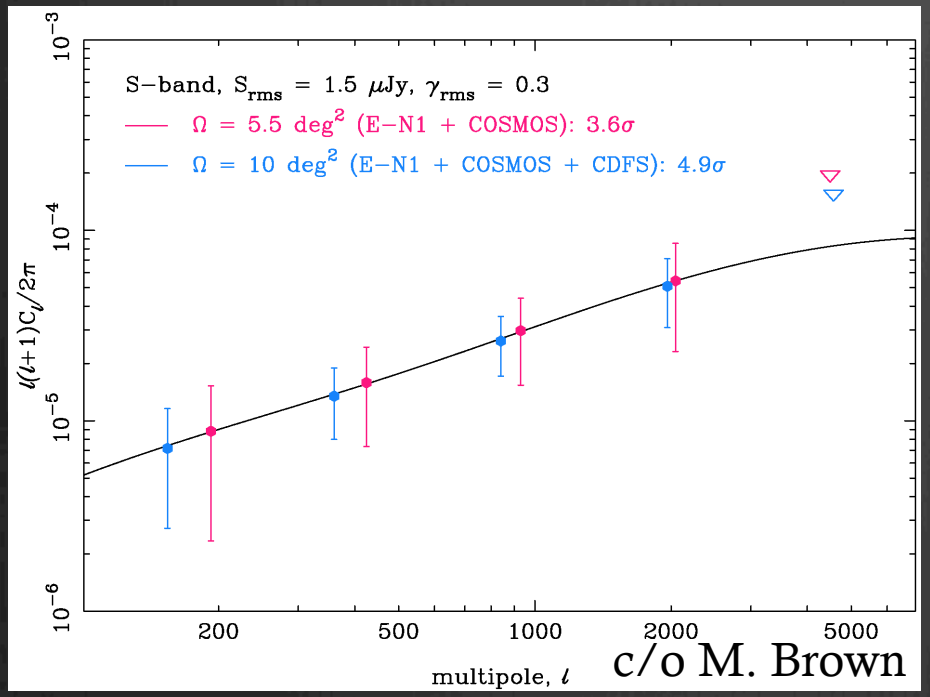


Lindsay et al. (2014)

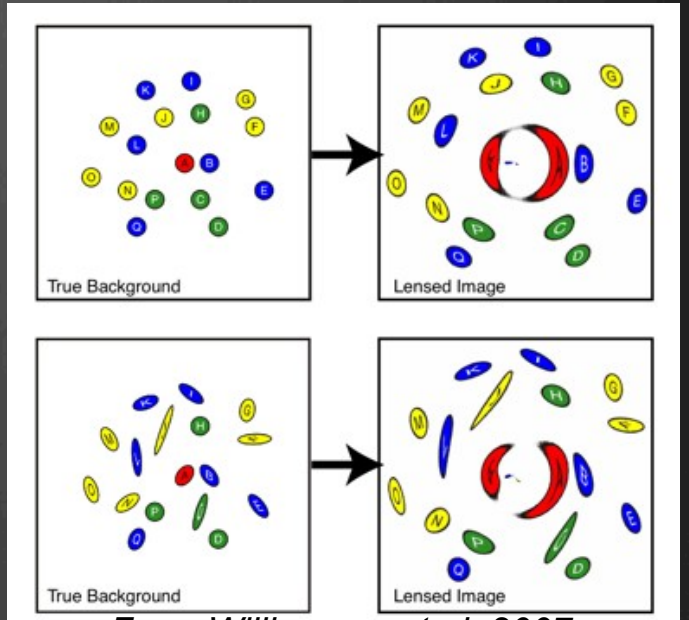
- Bias -- How well do radio sources trace the underlying dark matter density field?
- Measurements of 2-pt correlation function
  - Information on bias at z>1 -- redshift distribution peaks 1<z<2
- Move from non-linear to linear regime:
  - linear dimension of ~2 deg (i.e., 2 of the VLASS DEEP fields)
  - the two-halo term in halo-occupation distribution models begins to be sampled at 2-3 Mpc scales.
- Additional information can be obtained by cross-correlating with optical/NIR data.

Cosmic Lab: Radio Weak Lensing

- High enough source density of galaxies for weak lensing studies -- Key science goal of SKA.
  - Probe higher *z* than optical lensing surveys.
  - Different systematics than optical (know the beam)
  - direct measurement of shapes in *uv* plane
  - Polarization can help identify intrinsic position angles



- Forecasted constrains on cosmic shear power spectrum with VLASS-DEEP
  - first deep radio data set that can obtain a statistically significant weak-lensing signal.



From Williamson et al. 2007

Core of mass profile produces strong lensing arcs (Einstein radius)

Tangential shear (stretch) in outer weakly lensed regions

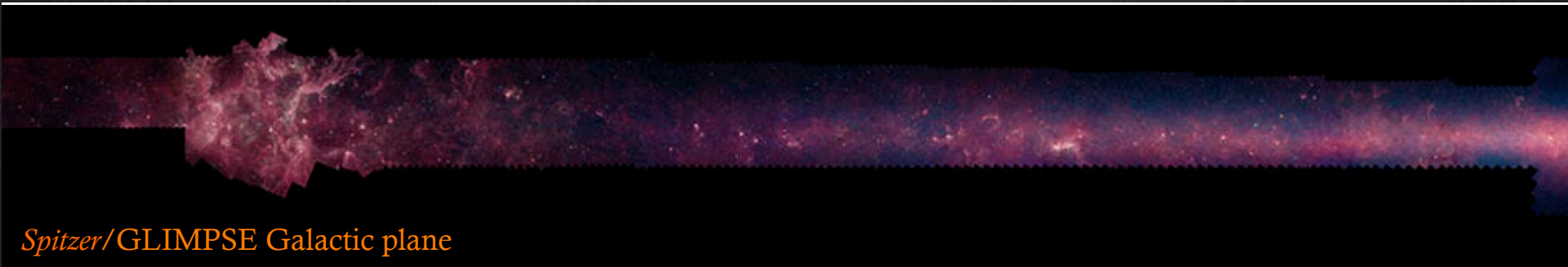
Look for presence of coherent shear signal above (random?) intrinsic shapes

VLASS Galactic Science

Powerful combination:
VLASS = Sensitivity + angular resolution + wavelength

- identify compact objects and discrete sources where energetic phenomena are occurring
- obscuration and absorption effects are not problematic

VLASS Galactic plane
Coming soon!



Spitzer/GLIMPSE Galactic plane

Exotic Extremes

Neutron stars are fantastic laboratories

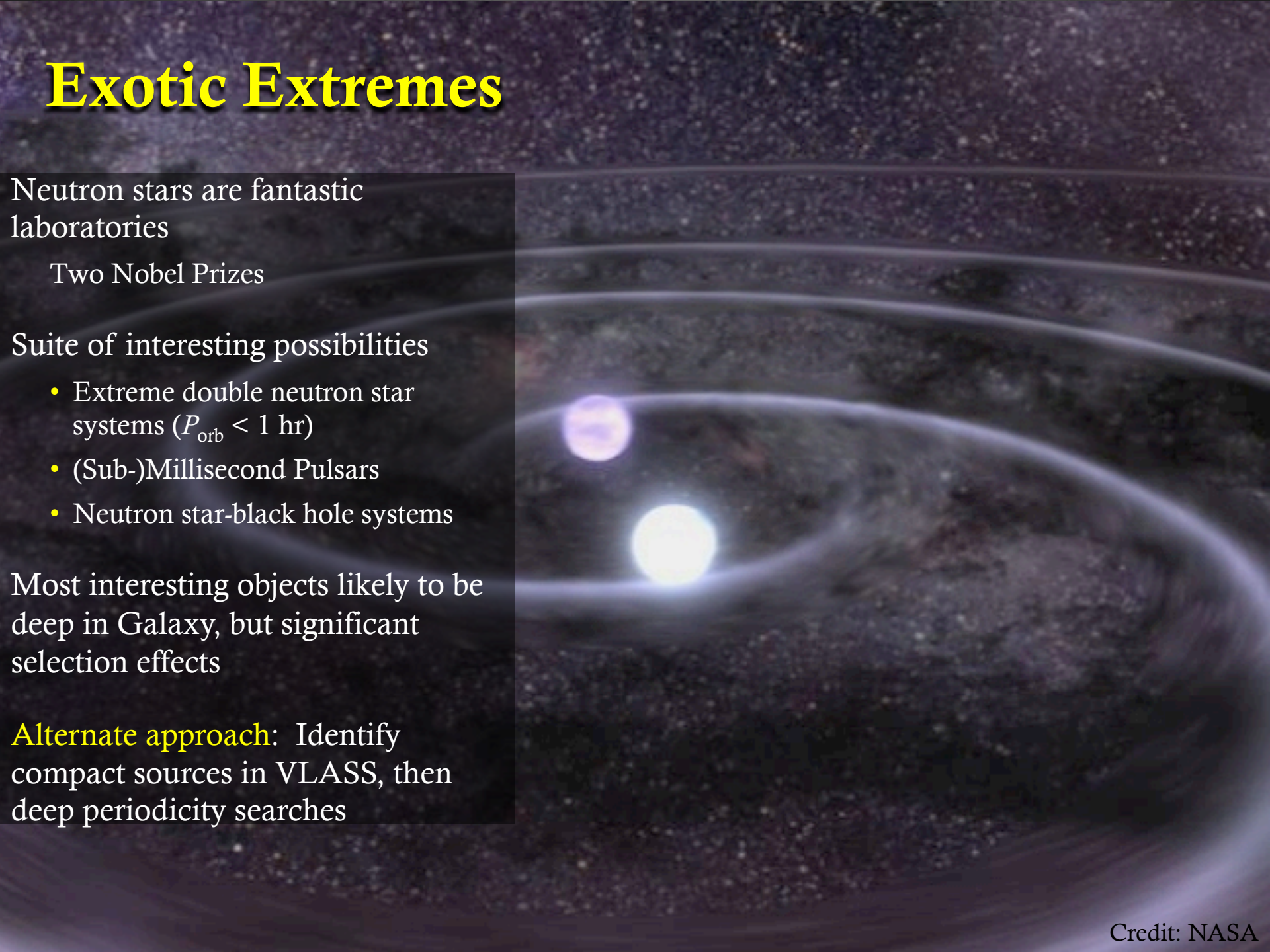
Two Nobel Prizes

Suite of interesting possibilities

- Extreme double neutron star systems (P_{orb} < 1 hr)
- (Sub-)Millisecond Pulsars
- Neutron star-black hole systems

Most interesting objects likely to be deep in Galaxy, but significant selection effects

Alternate approach: Identify compact sources in VLASS, then deep periodicity searches

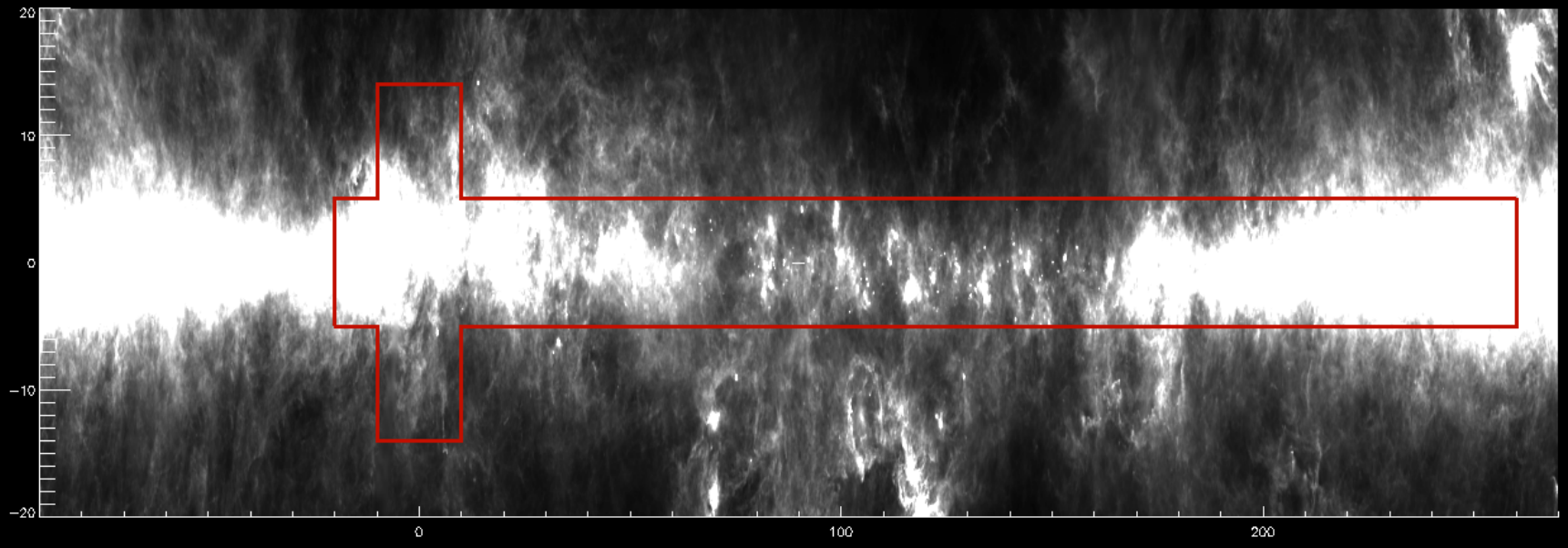


Credit: NASA

Activity on Dwarf Stars

- Radio emission provides key insights to particle acceleration, magnetic activity
  - Compare and contrast with our Sun!
  - *important for habitability
- Complements forthcoming eROSITA and LSST surveys
- Scaling luminosity distribution of currently known active stars, VLASS will detect
  - ultracool dwarfs ~ 10–20 pc
  - active dwarf stars ~ 30 pc
  - active binaries <~ 2 kpc

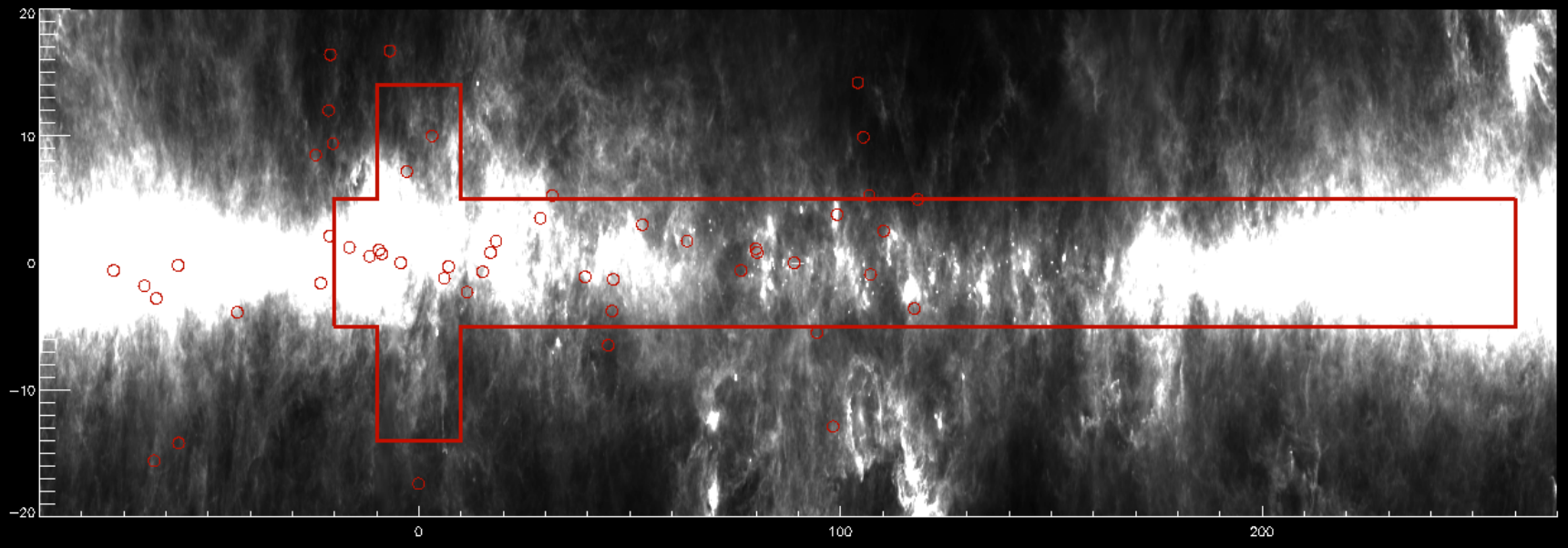
VLASS Galactic Science



IRAS 100 micron intensity map; Schlegel et al. (1998)

VLASS Galactic coverage

VLASS Galactic Science

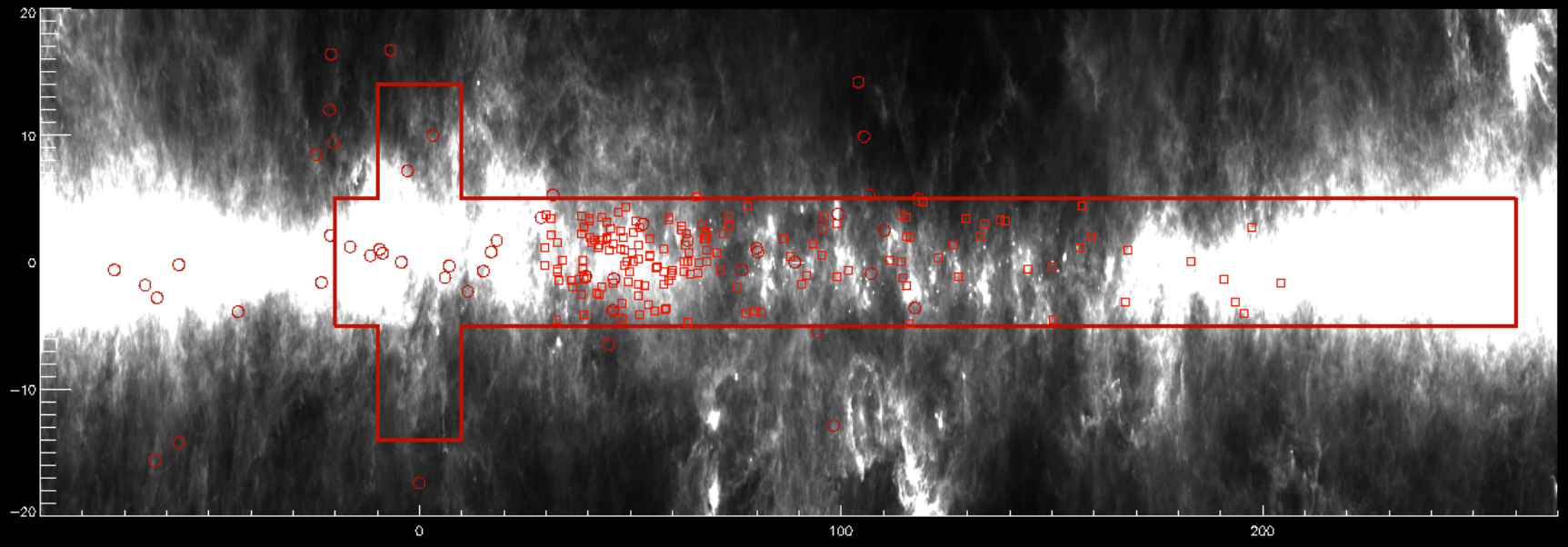


IRAS 100 micron intensity map; Schlegel et al. (1998)

VLASS Galactic coverage

Star Forming Regions

VLASS Galactic Science



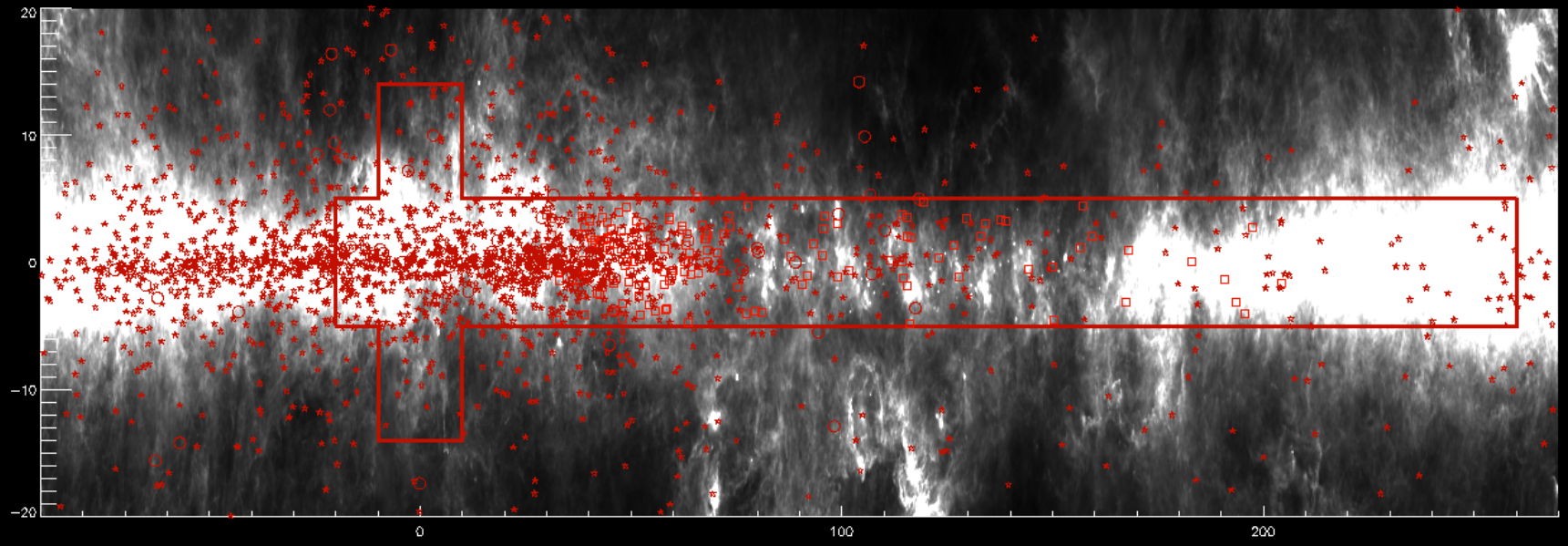
IRAS 100 micron intensity map; Schlegel et al. (1998)

VLASS Galactic coverage

Star Forming Regions

Known Planetary Nebulae (Sabin et al. 2014)

VLASS Galactic Science



IRAS 100 micron intensity map; Schlegel et al. (1998)

VLASS Galactic coverage

Star Forming Regions

Known Planetary Nebulae (Sabin et al. 2014)

Known Pulsars (ATNF pulsar catalog)

VLASS Basic Data Products

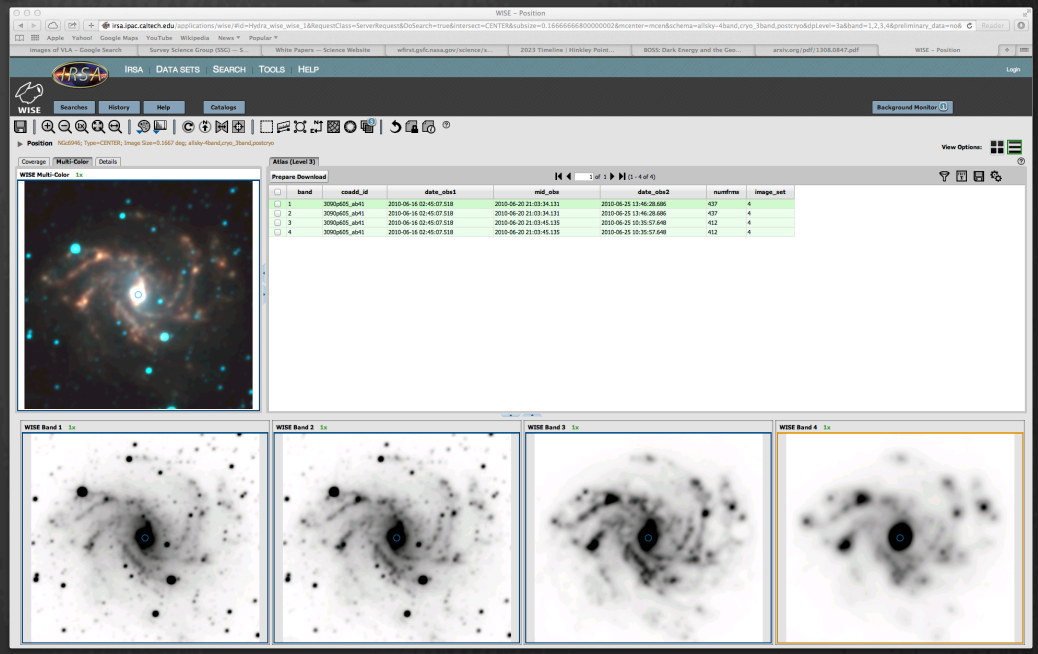
Data Product	Components	Production Time Scale
Raw Visibility Data	standard VLA data	Immediate
Calibrated Data	Final Calibration Tables Pipeline Control Script Flagging Commands QA Reports & Plots *Calibration Sky Models*	1 Week after Observation
Quick-Look Images	Stokes IV Images Stokes IV Noise Images	48 hr
Single-Epoch Images	Stokes IQUV images: Calibrated beam-corrected and rms noise Spectral Index and uncertainty images for Stokes I (generated using Multi-Frequency Synthesis)	2 mon. for Tiers 1 & 2 6 mon. for Tier 3
Single-Epoch Basic Object Catalog	Position, and uncertainty (centroid of Stokes I emission) Peak Brightness in Stokes IQUV and uncertainty Flux Density in Stokes IQUV and uncertainty Spectral Index at Peak Brightness (Stokes I) and uncertainty Integrated Spectral Index (Stokes I) and uncertainty	With Single-Epoch Images
VLASS Images	Calibrated beam-corrected Stokes IQUV images rms noise images for the Stokes IQUV images Spectral Index and uncertainty images for Stokes I	Within 6 mon. for Tiers 1 & 2 Within 1 yr for Tier 3
VLASS Catalog	Position, and uncertainty (centroid of Stokes I emission) Peak Brightness in Stokes IQUV and uncertainty Flux Density in Stokes IQUV and uncertainty Spectral Index at Peak Brightness (Stokes I) and uncertainty Integrated Spectral Index (Stokes I) and uncertainty	With VLASS Images

Enhanced Data Products/Services

Requires a community led effort!

- Transient Object Catalogs & Alerts
- Rotation Measure Images and Catalogs
- Light Curves (IQU)
- Multi-Wavelength Catalogs for VLASS sources
- A VLASS Archive with Image and Catalog Service

  - e.g., as currently available by **IPAC/IRSA** allowing for VLASS data to be integrated with Spitzer/Planck/WISE/Euclid/etc…



VLASS Schedule

Date	Activity
2013 September	Call for White Papers
2014 January	VLASS Planning Workshop
2014 February	SSG convened
2014 March – June	SSG finalizes science definition
2014 October 15	Proposal submitted for internal review
2014 Oct. 15 – Nov. 15	NRAO Internal Review
2015 January 1	Final proposal posted for community comment
2015 February 15	Community commenting closed (for Community Review)
2015 March 4 – 6	External Community Review (Socorro)
2016 Spring –	VLASS observations commence*

https://science.nrao.edu/science/surveys/vlass/timeline-structure

*Pending outcome of review process

VLASS: Take away message

A new era of wide-area high-resolution radio synoptic surveys is about to begin!

- A modern multi-tier multi-use public legacy survey
  - Support broad community & enable wide range of science and discovery
  - Hidden explosions, Faraday Tomography, Galaxies & AGN Everywhere
- Building on the past, looking towards the future
  - Snapshots of our Universe unique in time & space!
  - A springboard into the LSST and SKA science era
  - A substantial real world test-bed for SKA science and processing
- Look us up online: https://science.nrao.edu/science/surveys/vlass
  - Follow links to Survey Proposal and the Technical Implementation Plan
  - Leave comments and suggestions on the Science Forum

Why do surveys?

- Surveys can be efficient use of telescope time and have a far-reaching impact!

The FIRST image server (third.ucllnl.org) provides JPEG or FITS cutouts extracted from the FIRST survey at user-specified positions.

Currently the cutout server delivers on average more than 12,000 image cutouts every day.

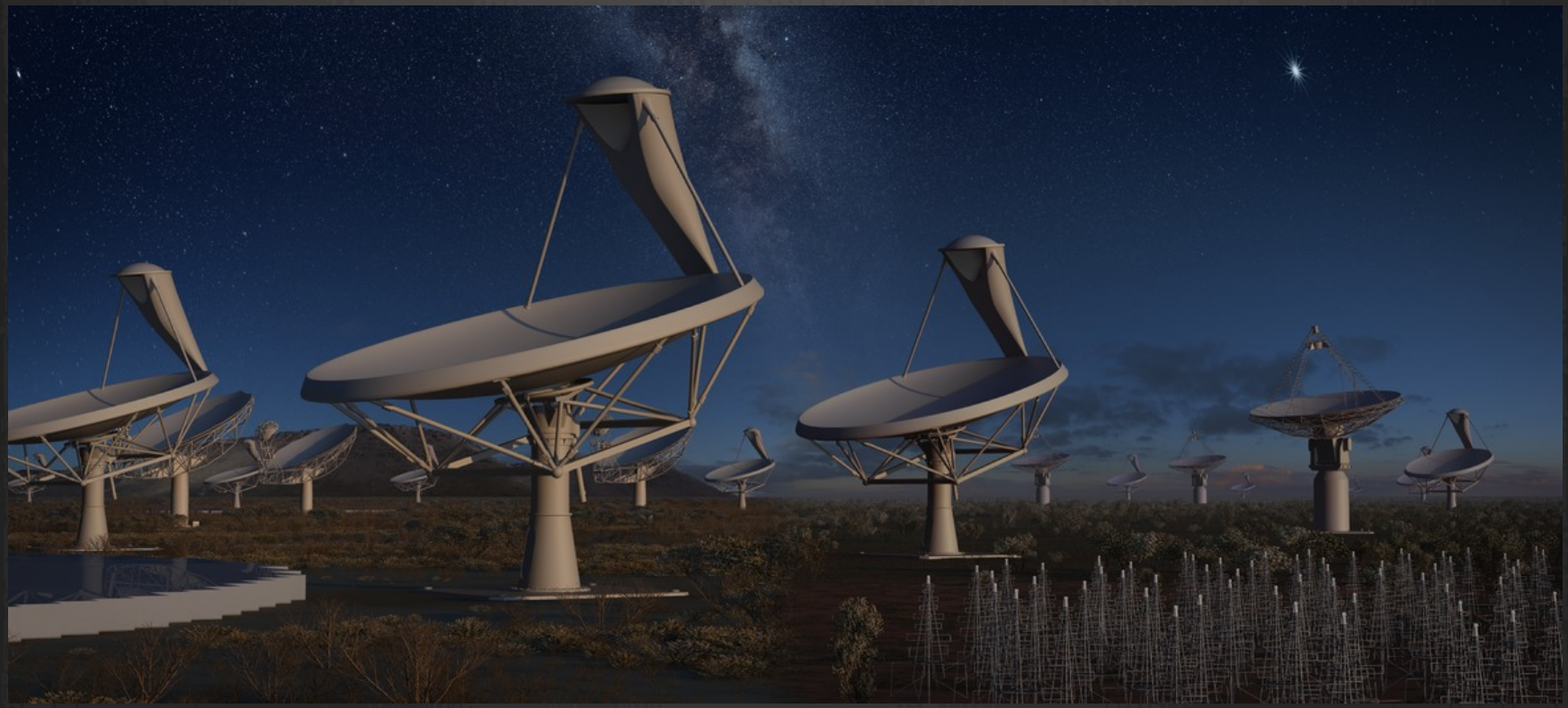
Each image served is equivalent to a three-minute VLA observation; thus, our image server issues the equivalent of a 3-minute VLA observation every 7 seconds!

Every week the FIRST cutout server distributes snapshots with a total exposure time equal to the entire 4000 hours invested in the FIRST survey.

White – VLASS workshop Jan 2014

An SKA Pathfinder Now!

- Jansky VLA science operations began March 2010
  - A laboratory on the sky
  - Study potential dynamic range issues
  - Data rates and pipeline processing tools



Artist's impression of the SKA dishes operating at nighttime. Credit: SKA Organisation

Time Domain Science

A new era of wide-area high-resolution radio synoptic surveys!

Unobscured view of cosmic explosive events

- Detection of dual Neutron Star merger event, characterization of rates (for GW)
- Determination of the Tidal Disruption Event (TDE) rate
- Determination of the rate of obscured supernovae in local Universe
- Exotic Neutron Stars (Chatterjee white paper) and new Galactic Center radio transients
- Determination of the rate of other Radio Transients and Variables (Galactic & EG)
- ***Key capability:*** large area and high resolution (locate event within optical galaxy)
- High quality high resolution all-sky and wide area radio maps and catalogs as basis ("Epoch Zero") for future radio transient surveys and follow-up of multi-wavelength transient events (Gravity Waves, LSST, etc.)