ADVENTURES OF YOUNG RADIO STARS

Intense radio outbursts, X-ray megaflares, and a novel VLBI search for ensuing coronal mass ejections

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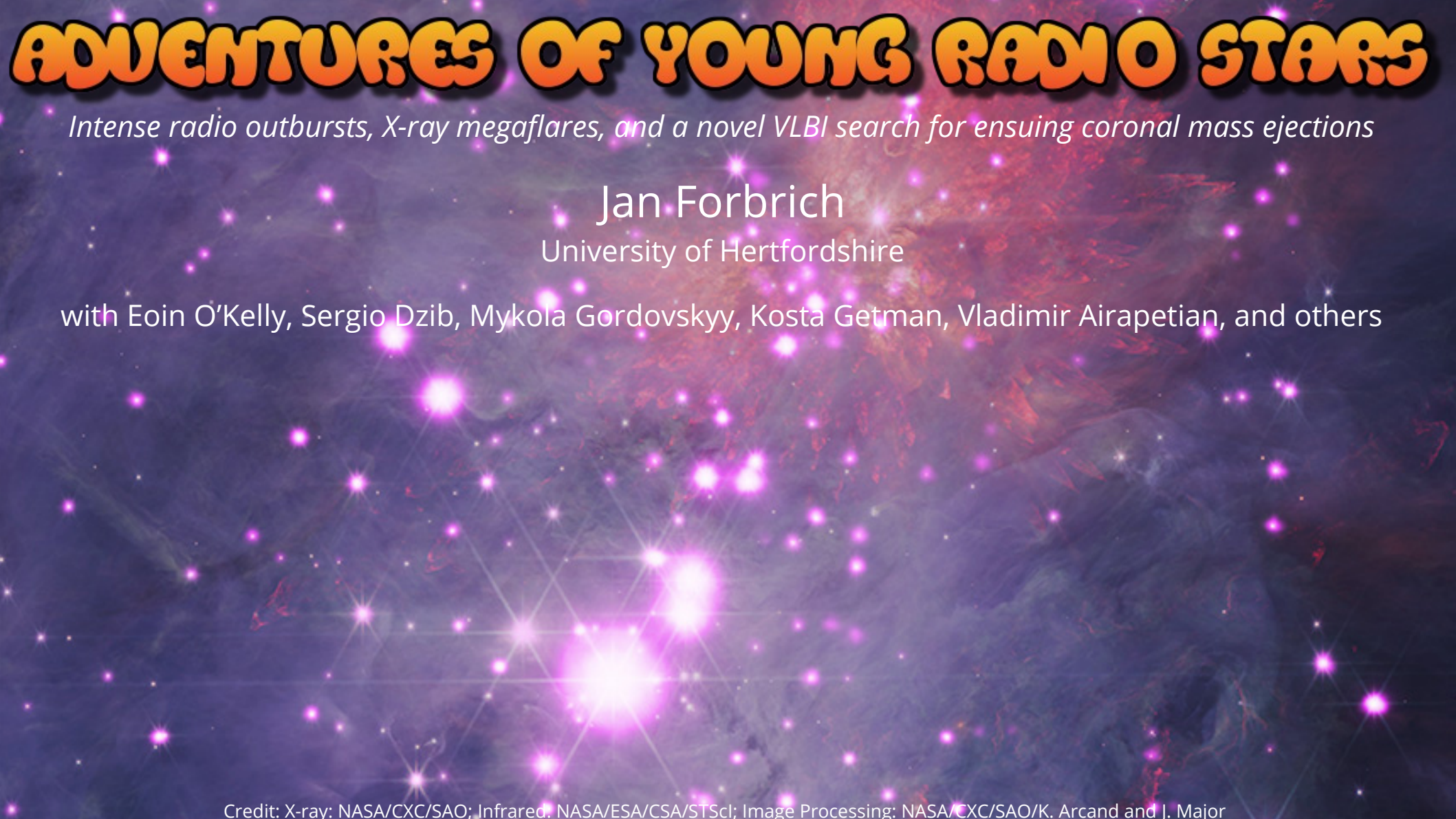


Credit: X-ray: NASA/CXC/SAO; Infrared: NASA/ESA/CSA/STScI; Image Processing: NASA/CXC/SAO/K. Arcand and J. Major

1) Why now?

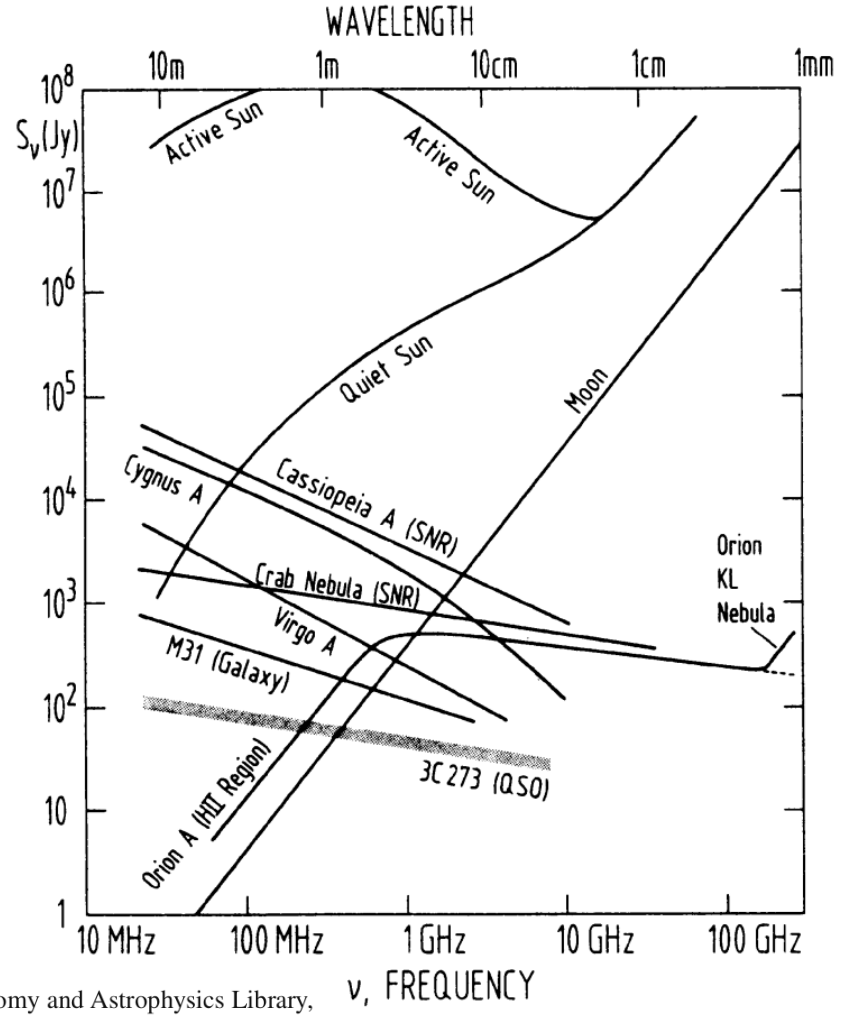
A renaissance of **(stellar) radio astronomy**

New and newly upgraded facilities include

the Karl G. Jansky Very Large Array (**VLA**),
the Very Long Baseline Array (**VLBA**), and
the Atacama Large Millimeter Array (**ALMA**),
and more,

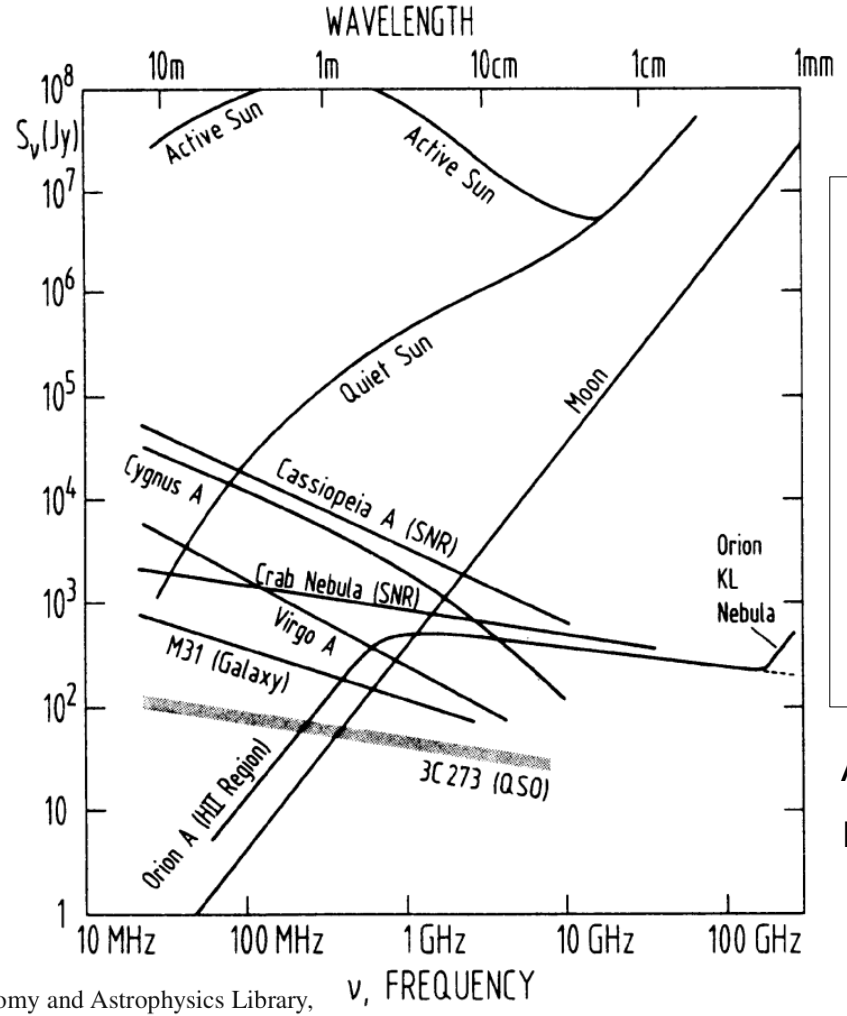
yielding **unprecedented continuum sensitivity** and **wavelength coverage**.

A renaissance of **stellar radio astronomy**



T.L. Wilson et al., *Tools of Radio Astronomy*, 5th ed., Astronomy and Astrophysics Library,
DOI 10.1007/978-3-540-85122-6_10,

A renaissance of **stellar radio astronomy**



Thermal vs non-thermal

- Spectral index
- Polarization
- Rapid variability
- Brightness temperature

$$S_\nu = \frac{2k\nu^2}{c^2} T_\mathrm{b} \Delta\Omega$$

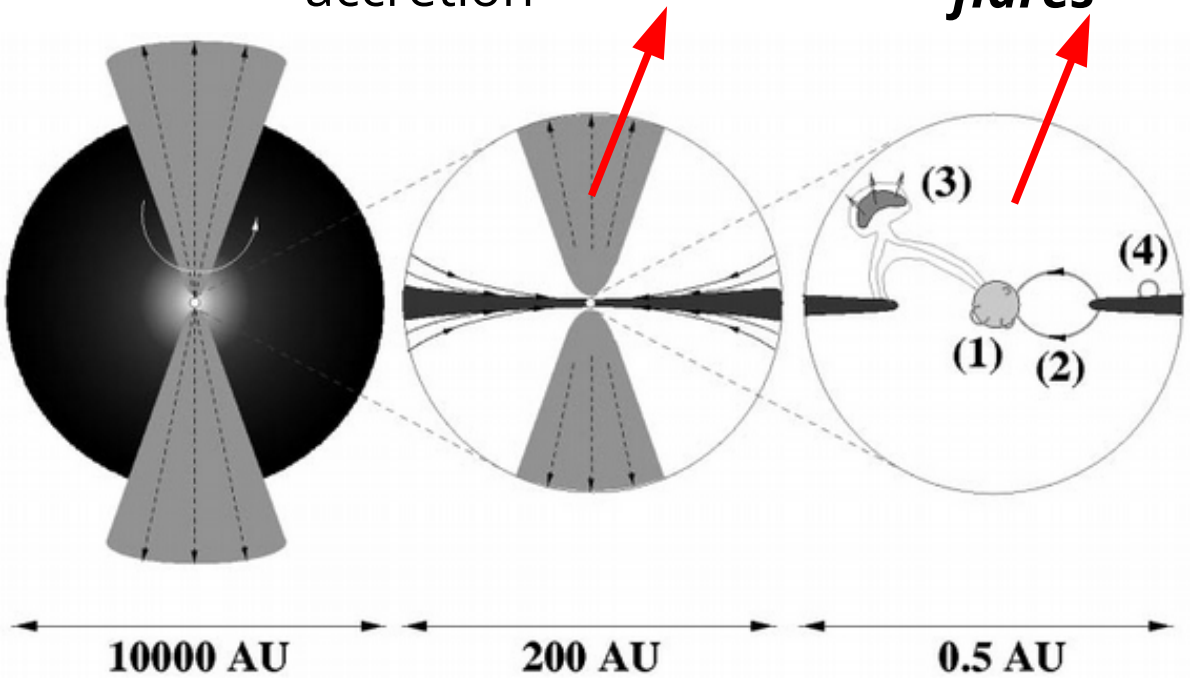
All requiring high S/N, even more so in the time domain

T.L. Wilson et al., *Tools of Radio Astronomy*, 5th ed., Astronomy and Astrophysics Library, DOI 10.1007/978-3-540-85122-6_10,

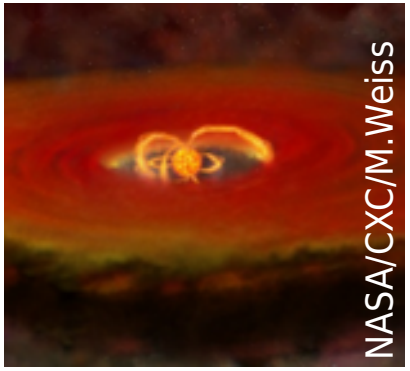
High-energy processes in Young Stellar Objects

Thermal radio emission, could fluctuate with accretion

Thermal X-ray emission, cm & mm nonthermal emission, *flares*

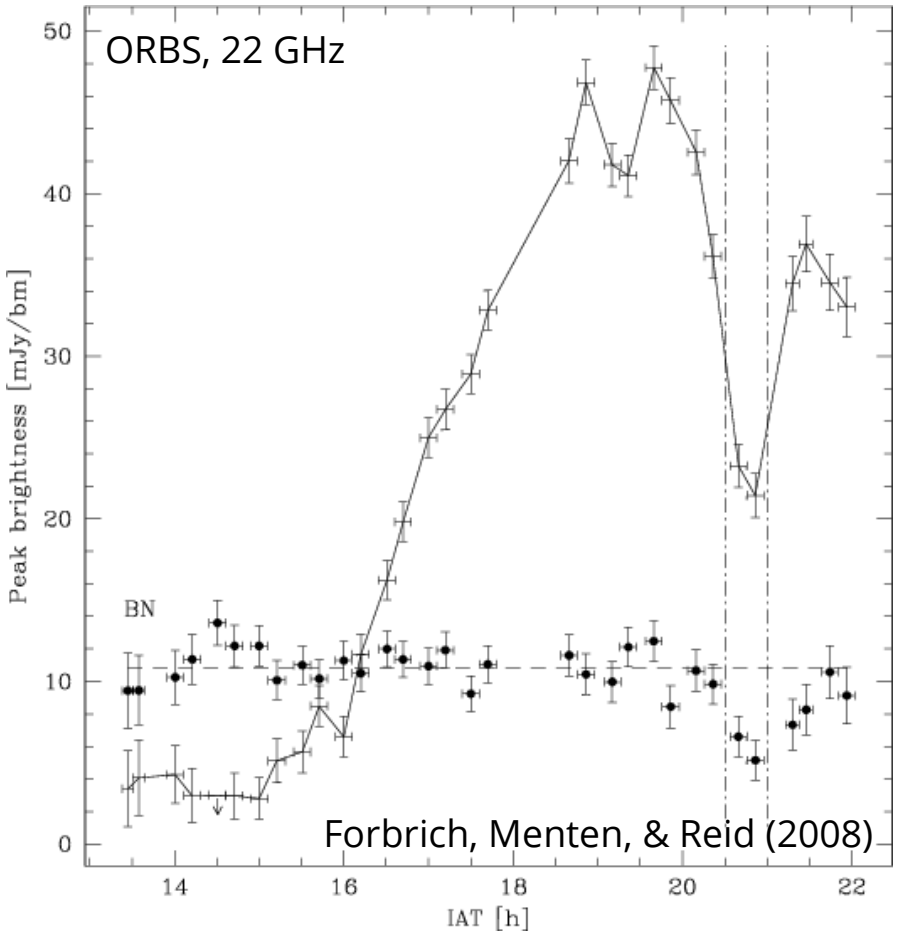


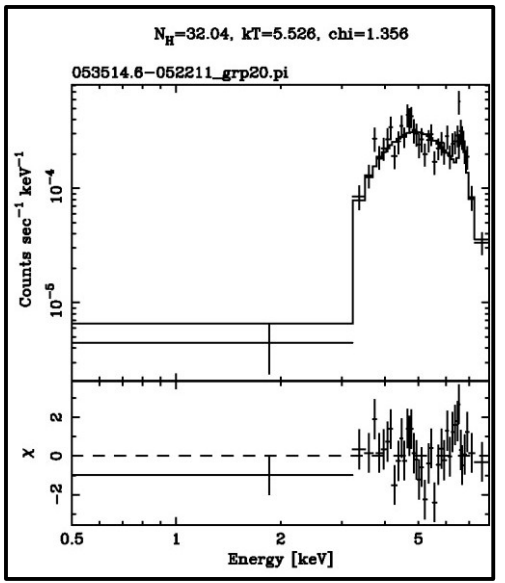
Feigelson & Montmerle (1999)

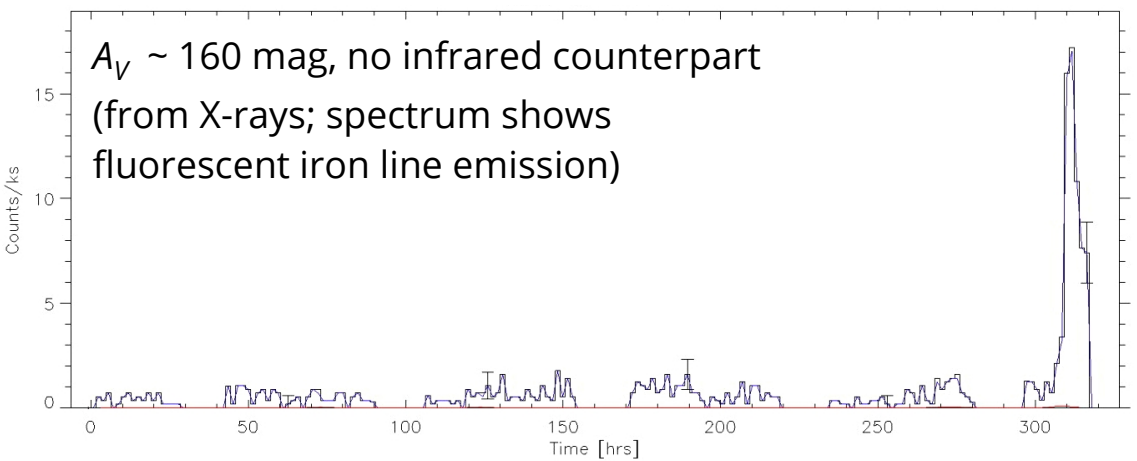


Both X-ray *and* nonthermal radio emission probe the ***innermost vicinities*** of protostars!

YSO radio **superflares**?







Chandra, COUP (Getman et al. 2005)

2) Why Orion?

COMPACT CONTINUUM RADIO SOURCES IN THE ORION NEBULA[1]

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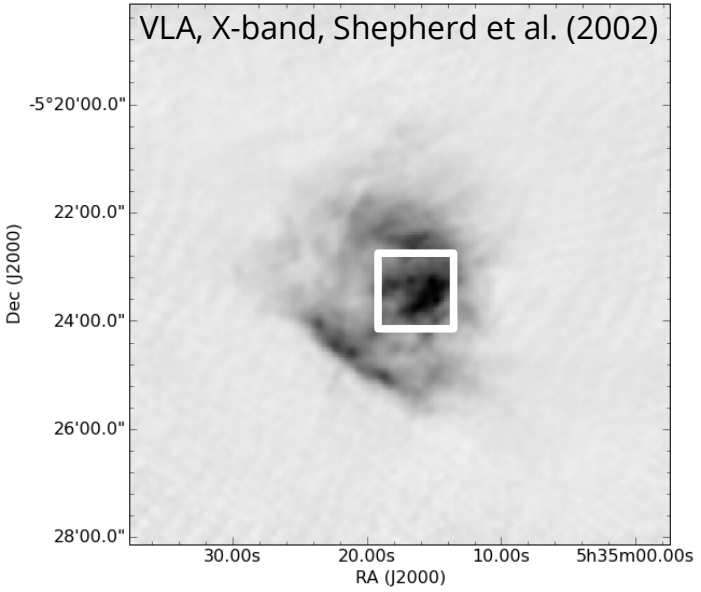
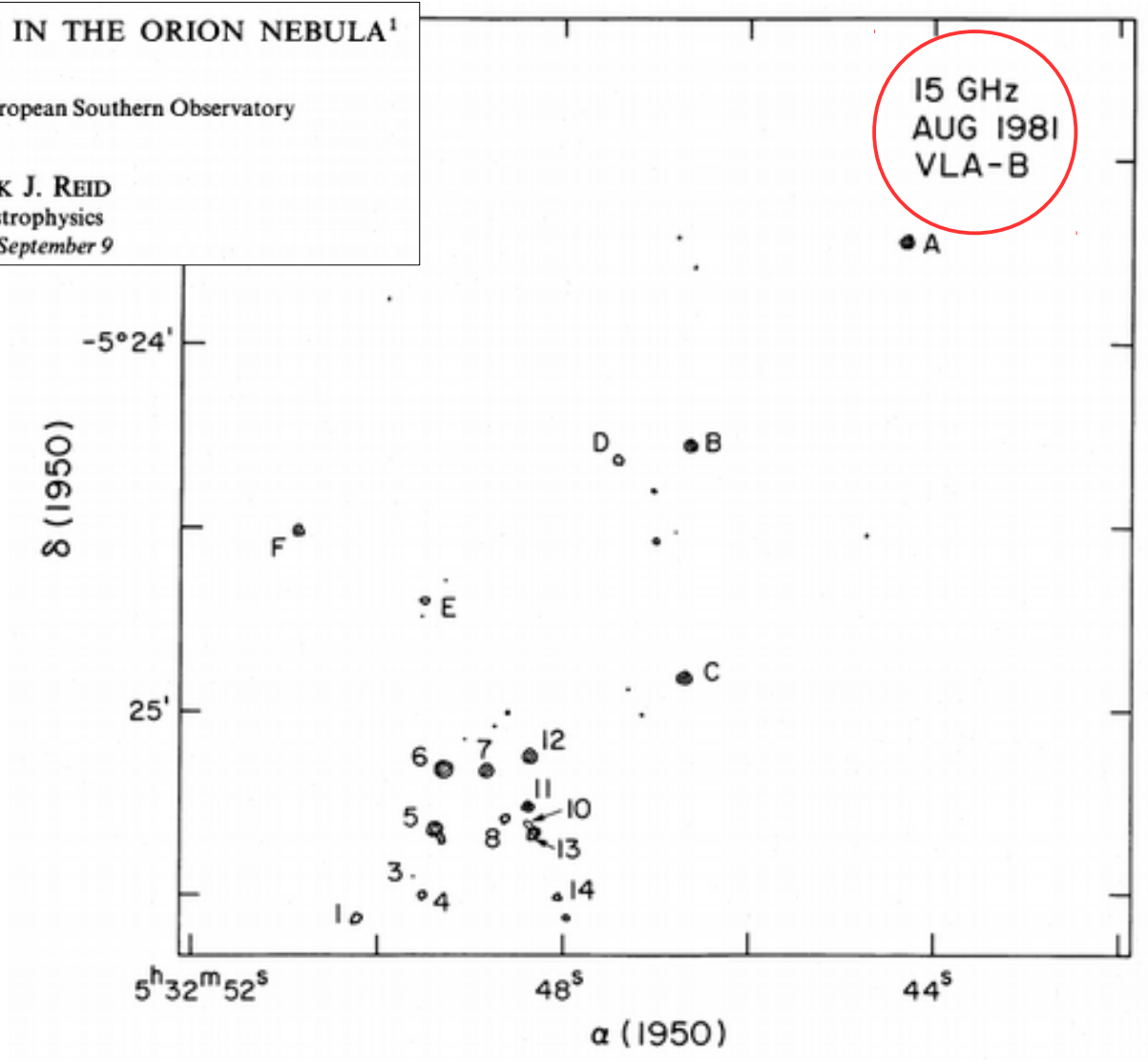
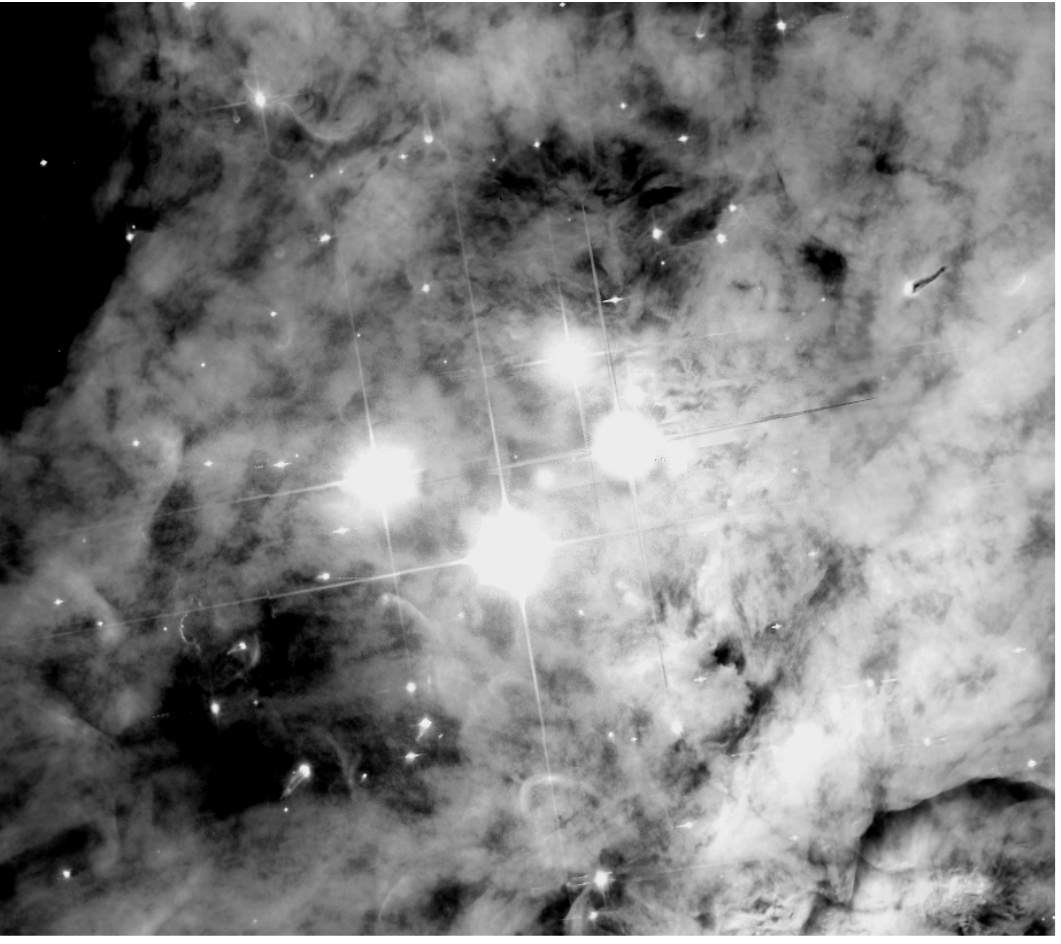
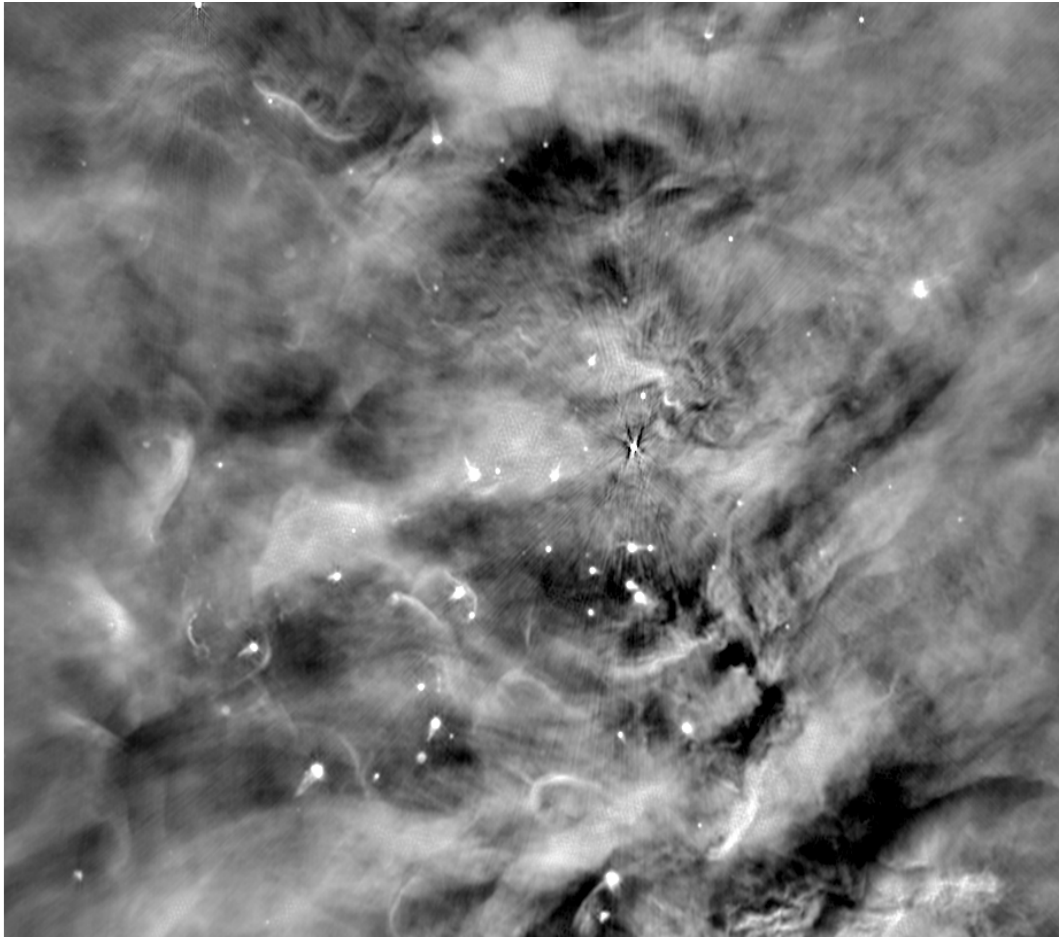
Harvard-Smithsonian Center for Astrophysics
Received 1986 July 7; accepted 1986 September 9





The **proplyds** (and more)





Forbrich et al. (2016, 2017)

The Orion Radio All Stars

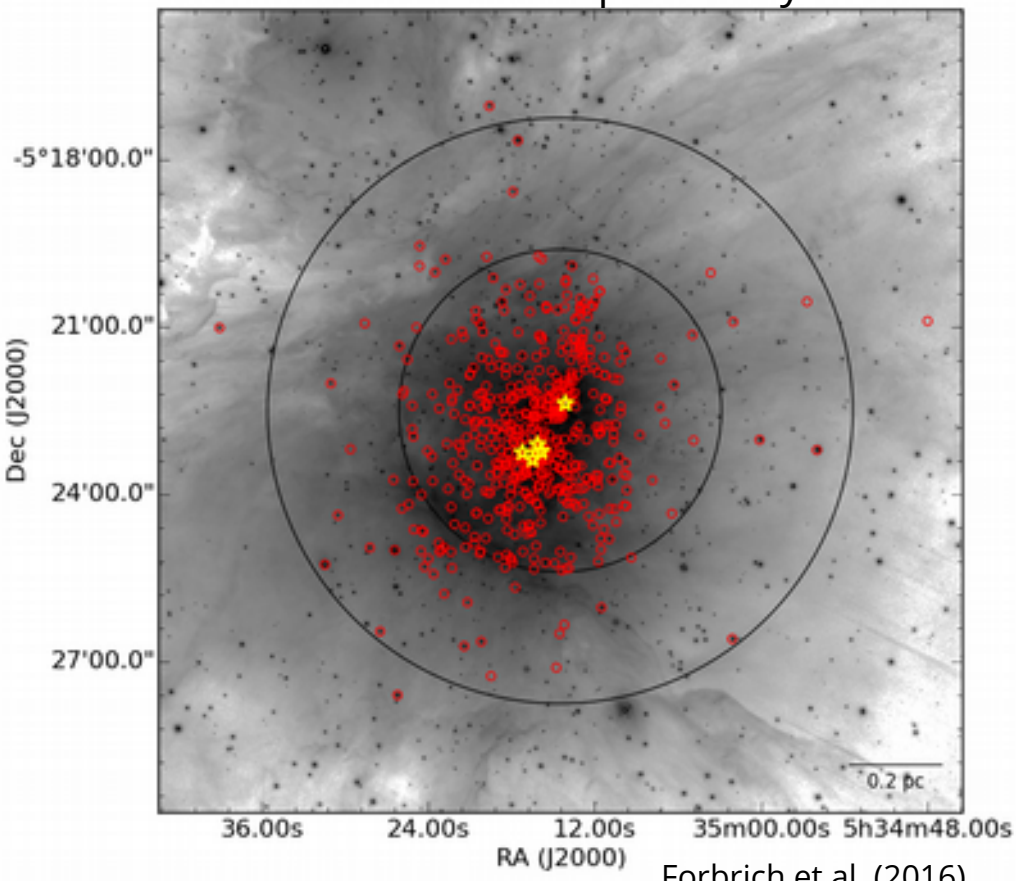
1) 30h of **VLA** C-band data (4–8 GHz) in a single pointing, in A configuration to minimize nebular emission, with simultaneous Chandra observations (Forbrich et al. 2016, 2017)

2) 30h of **VLA** C-band data in adjacent fields, with simultaneous Chandra/NUStAR observations (Vargas-Gonzalez et al. 2021)

3) 10+ epochs of astrometric **VLBA** follow-up of *all 556+ VLA sources* (Forbrich et al. 2021, Dzib et al. 2021, O'Kelly et al. *in prep.*), now *Chandra*+VLBA project (2023-2025)

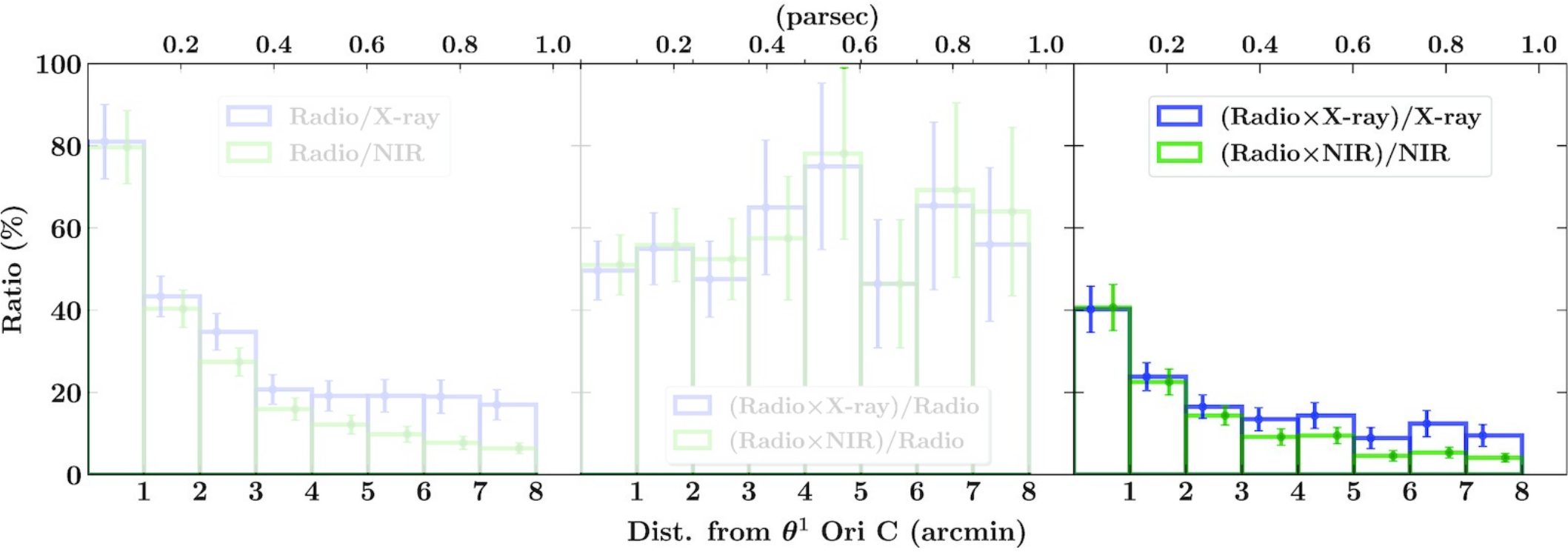
4) ALMA long-baseline snapshots of the center to find synchrotron flares (Vargas-Gonzalez et al. 2023)

7x more sources than previously known!



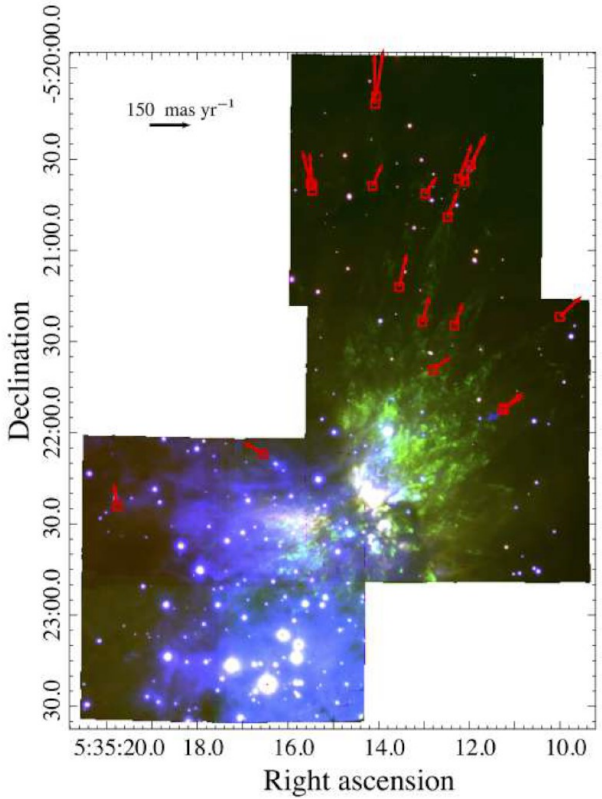
Forbrich et al. (2016)

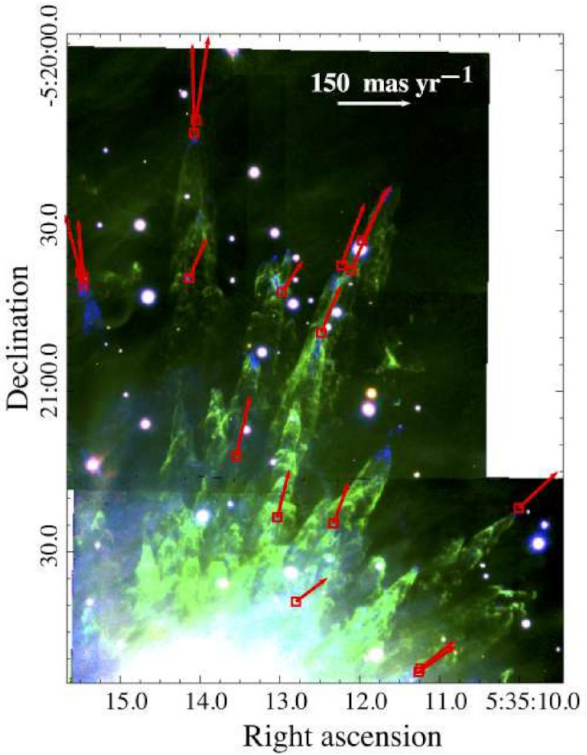
3) Wideband upgrades are enabling a radio (flare) census, catching up with X-ray astronomy

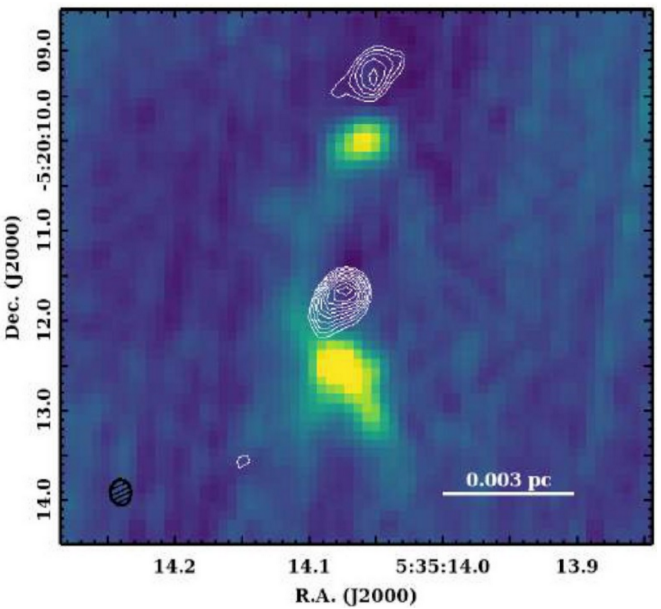


Detection fractions between the three different populations radio/X-ray/NIR as a function of distance to θ^1 Ori C. The left-hand panel shows the fraction of radio sources over the X-ray (blue) and NIR (green) populations. Central panel shows the X-ray (blue) and NIR (green) detection fraction of radio sources. The right-hand panel shows the radio detection fraction of X-ray sources (blue) and NIR sources (green). The 1σ error bars were derived from counting statistics (Poisson errors).

Vargas-González, Forbrich, Dzib, & Bally (2021)

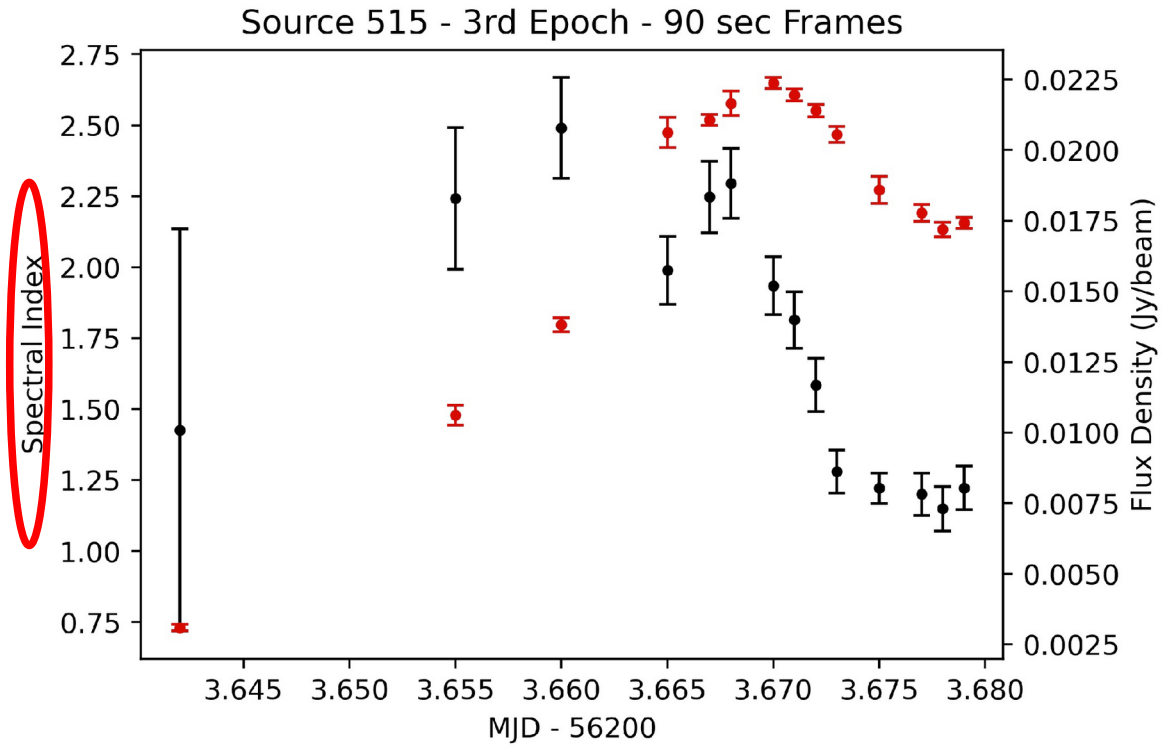


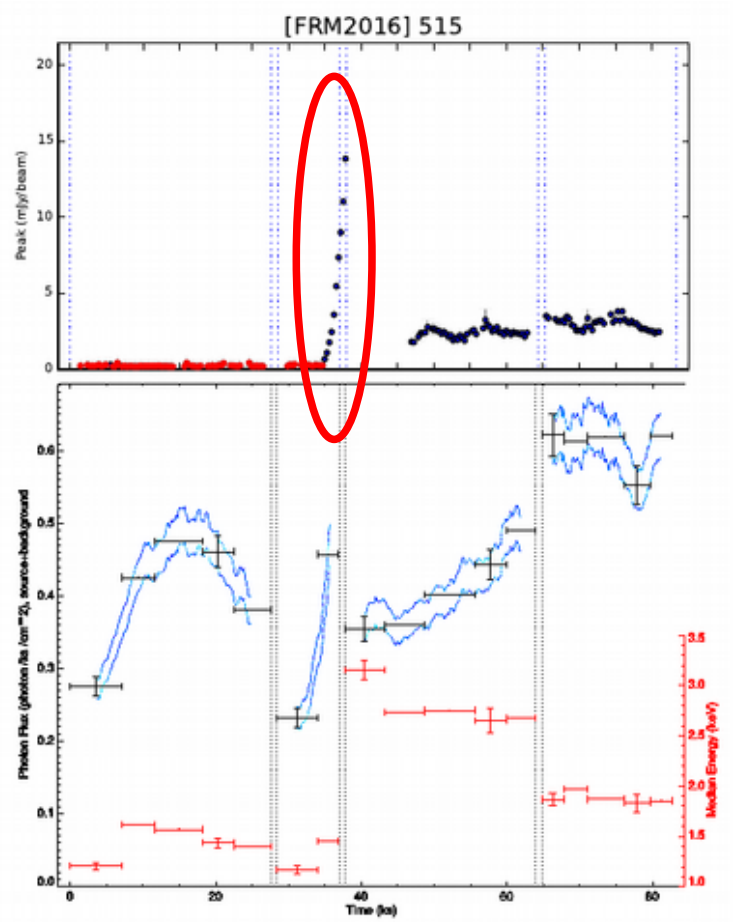




Vargas-González, Forbrich, Dzib, & Bally (2021)

Exploring YSOs in the radio – X-ray **time domain**





Forbrich et al. (2017), O'Kelly et al. *in prep.*

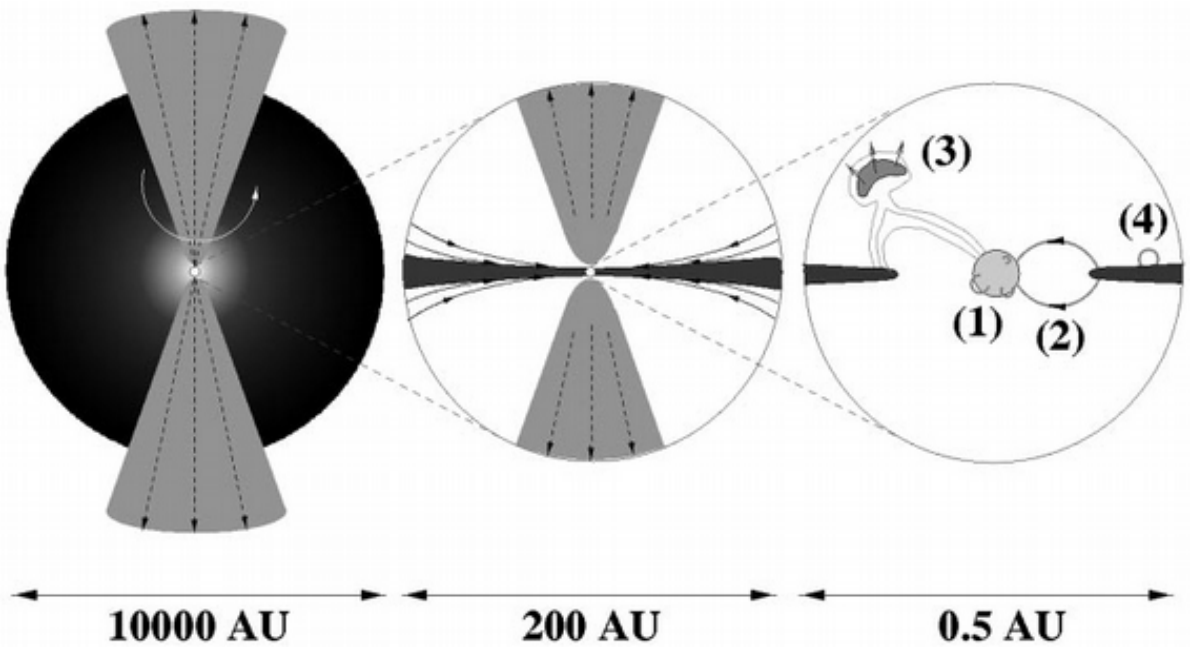
Exploring YSOs in the radio – X-ray time domain: **coming up**

First dynamic 10-40 GHz spectral indices of radio flares from Young Stellar Objects in the Orion Nebula Cluster

ESO/NRAO

4) Wideband and (software) correlator upgrades enable *multi-object* VLBI observations

Spatial scales



Feigelson & Montmerle (1999)

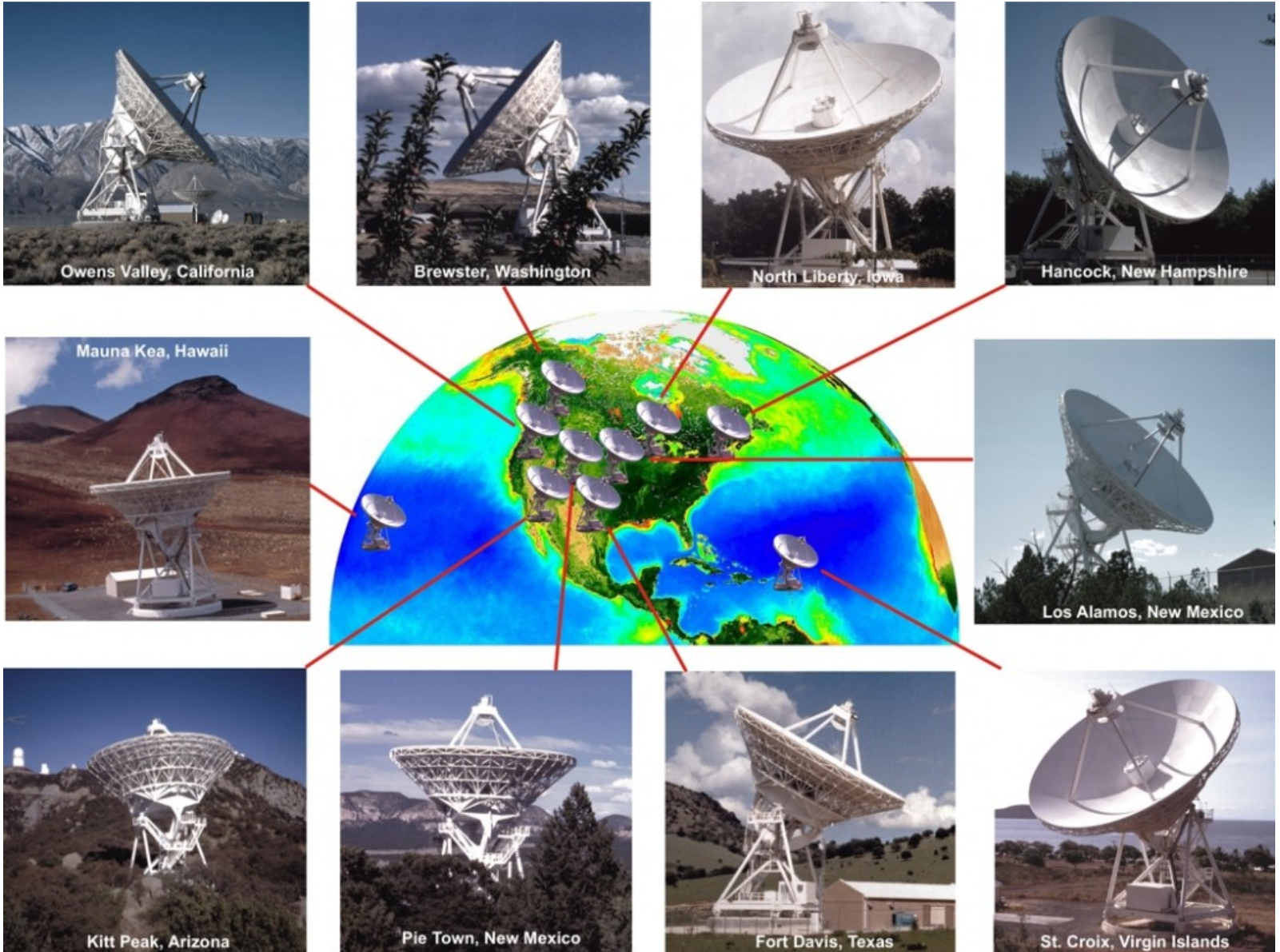
Both X-ray *and* nonthermal radio emission probe the ***innermost vicinities*** of protostars!

Observing at 8 GHz

Beam sizes:
VLA (~0.2”, A config)
VLBA (~1 *mas*)

...in Orion:
VLA ~ 80 AU
VLBA ~ 0.4 AU

...factor of >100!


Owens Valley, California
Brewster, Washington
North Liberty, Iowa
Hancock, New Hampshire
Mauna Kea, Hawaii
Los Alamos, New Mexico
Kitt Peak, Arizona
Pie Town, New Mexico
Fort Davis, Texas
St. Croix, Virgin Islands

Considerations for the **VLBA Orion Radio All-Stars**

- Unbiased VLBI follow-up of all 556 VLA detections in one pointing: **non-thermal census**, 10x deeper (though not as deep as the VLA observations), 100x more sources
- Focus on **absolute proper motions** with annual monitoring: sensitive to motions of 0.1 – 1 km/s, *everything moves!*
- Direct search for **binaries** and companions
- Search for **large magnetic structures**, for the first time in a large sample
- Small overlap with ***Gaia*** (bright nebula and embedded objects) offers an interesting astrometric **cross-check**

VLBA Orion Radio All-Stars: initial results

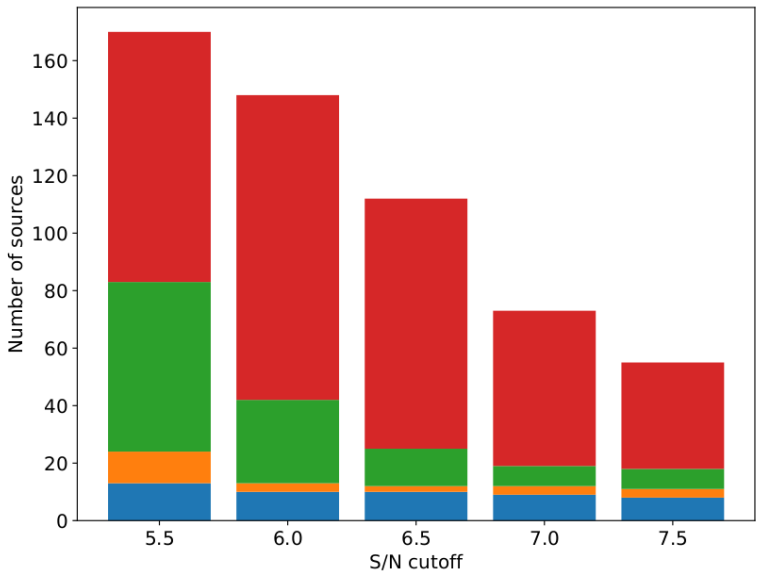
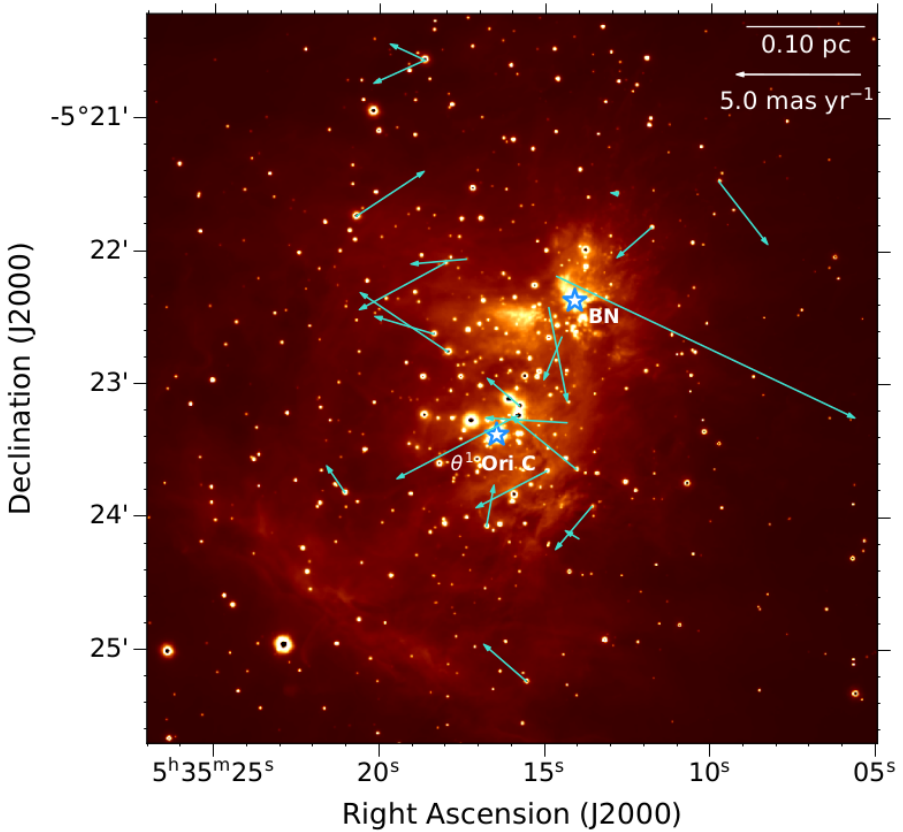
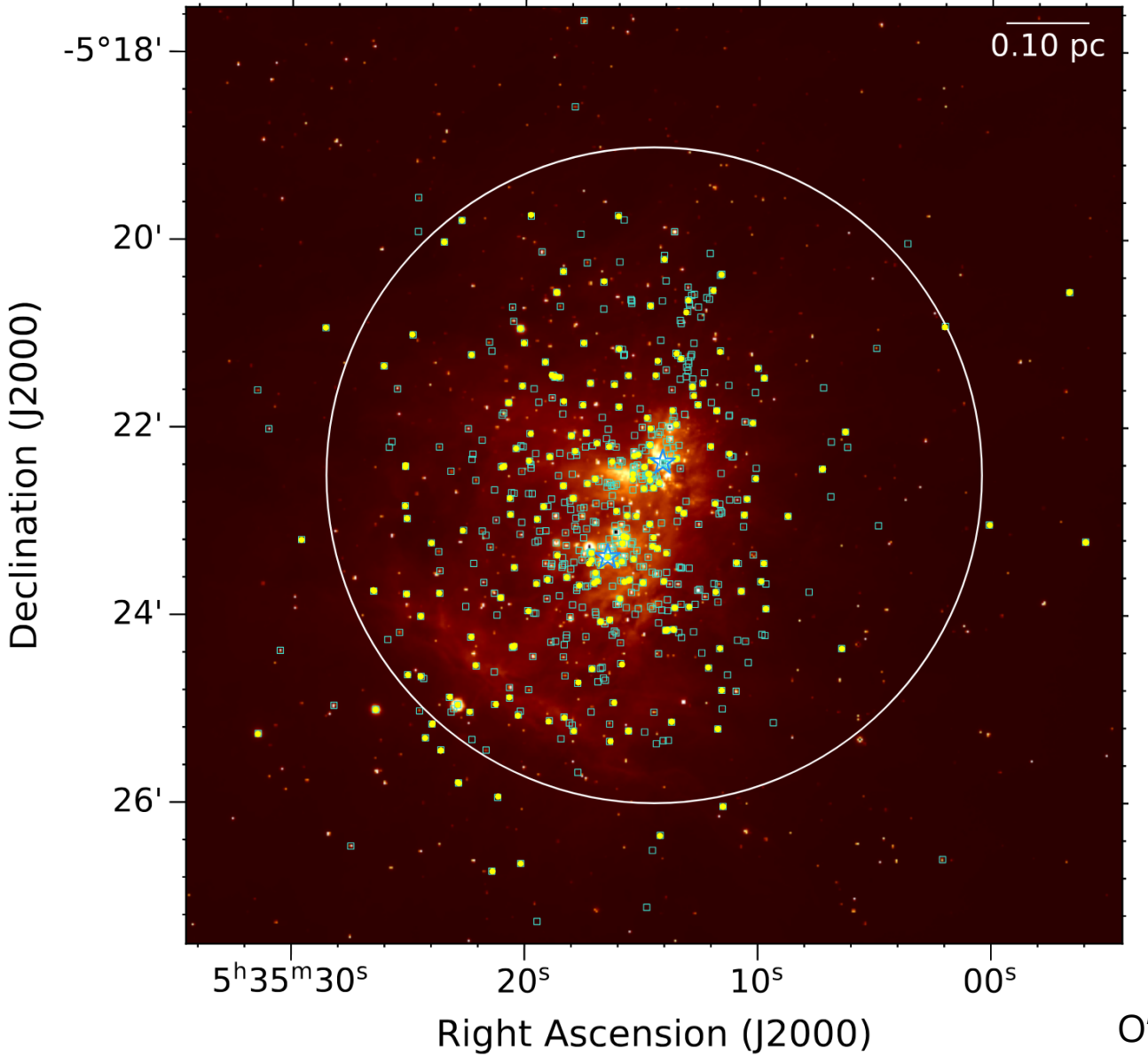


Figure 1. Number of sources detected above a given S/N threshold, color-coded by number of detections among four epochs (red=1, green=2, orange=3, blue=4).

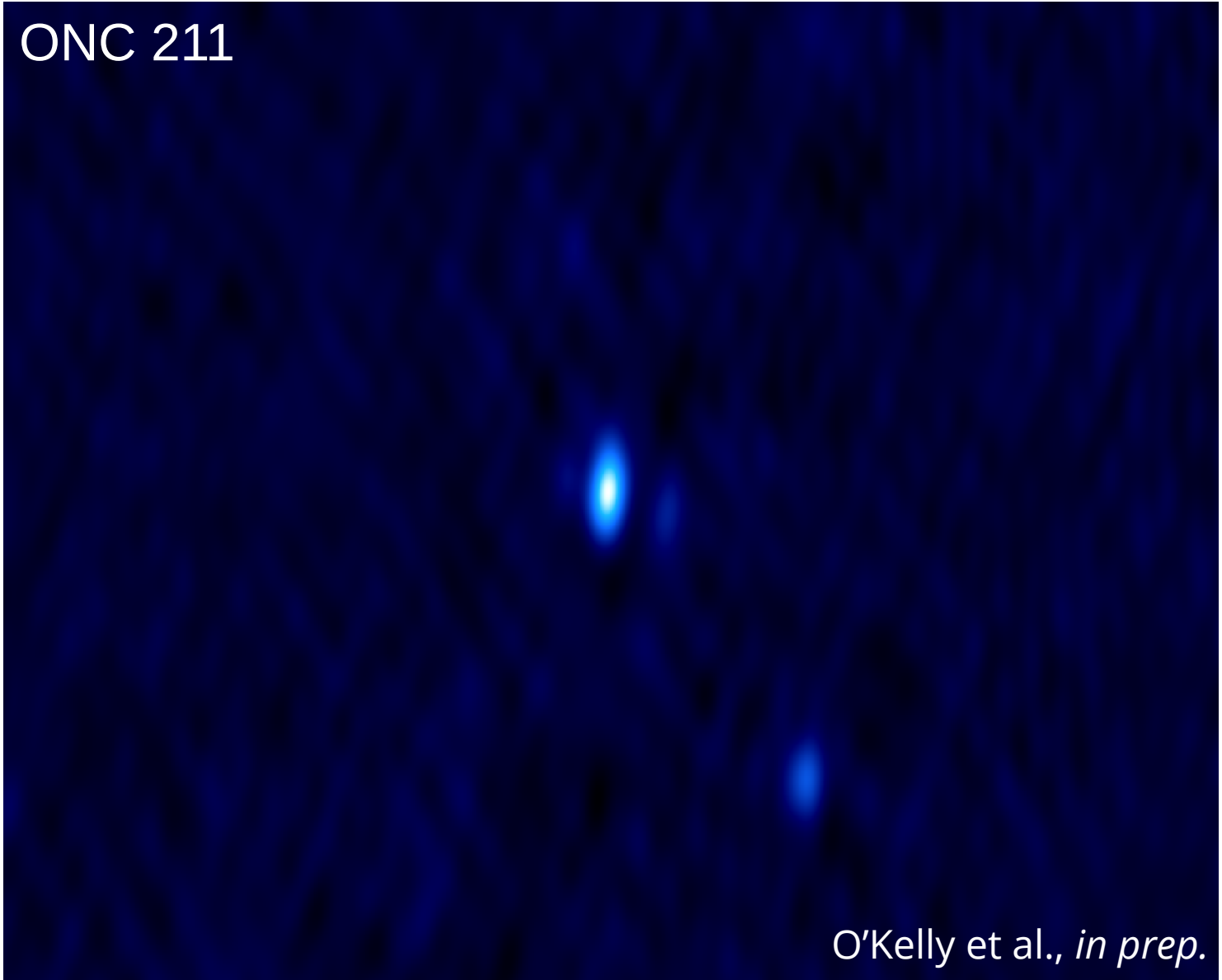


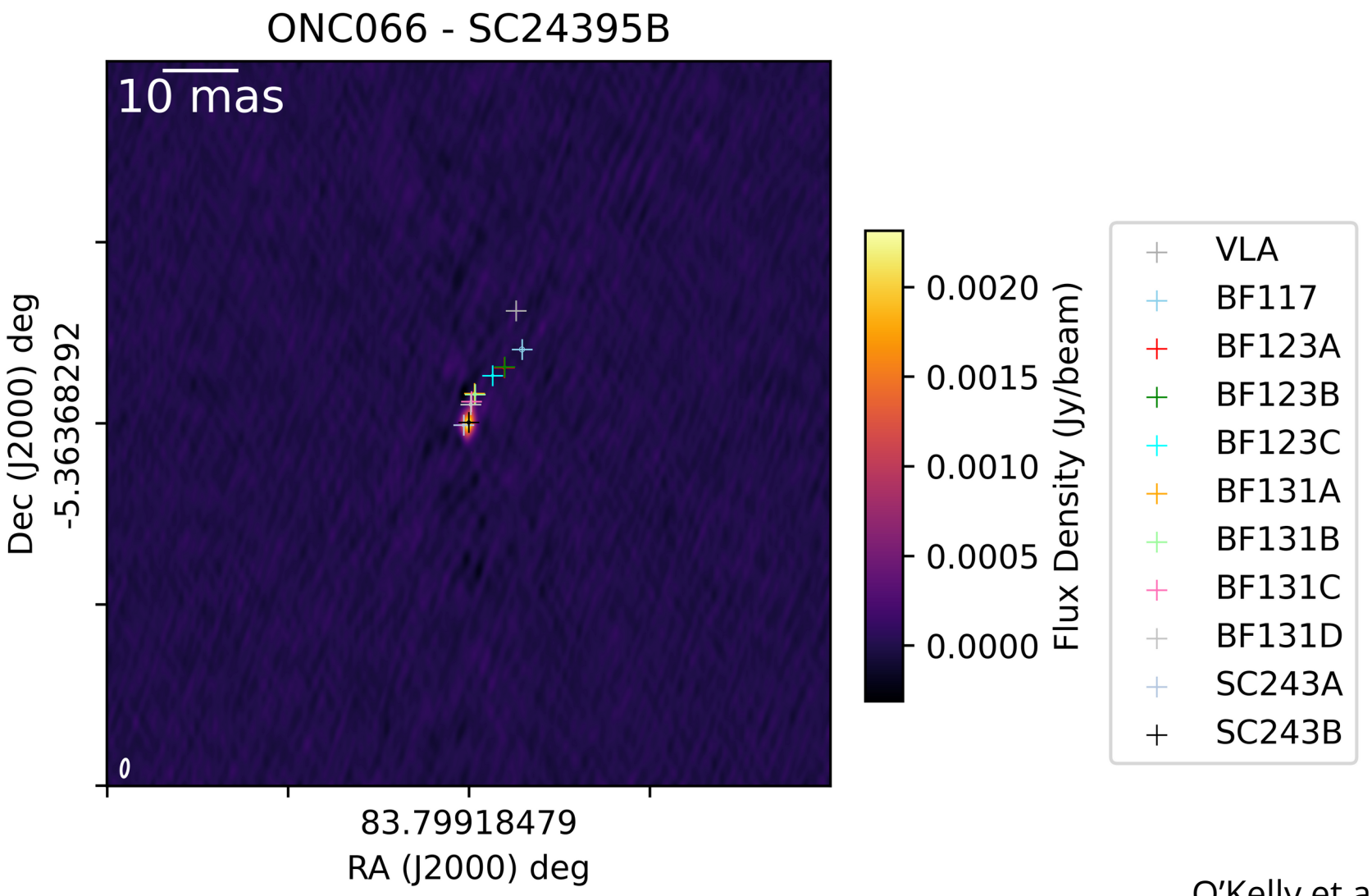
123 nonthermal YSOs detected in inner ONC

Forbrich et al. (2021), Dzib et al. (2021)



O'Kelly et al. (*in prep.*)


ONC 211
O'Kelly et al., *in prep.*

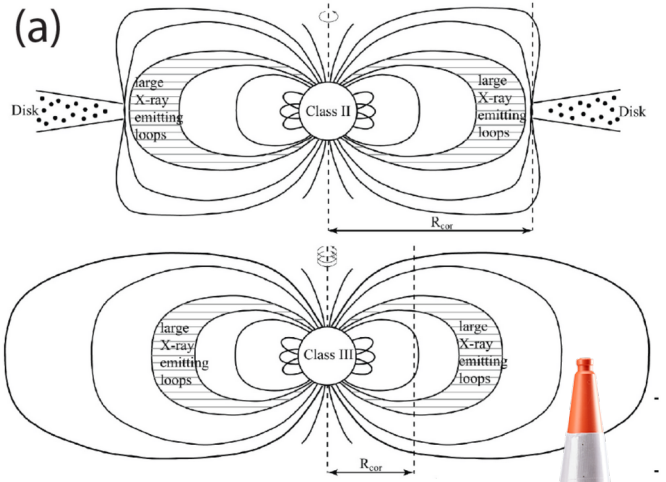


O'Kelly et al. (*in prep.*)

AFTER A MEGA-FLARE: SURFACE MAGNETIC FIELDS, PARTICLE EJECTION AND DISK IONIZATION

A joint *Chandra*-HET-VLBA project

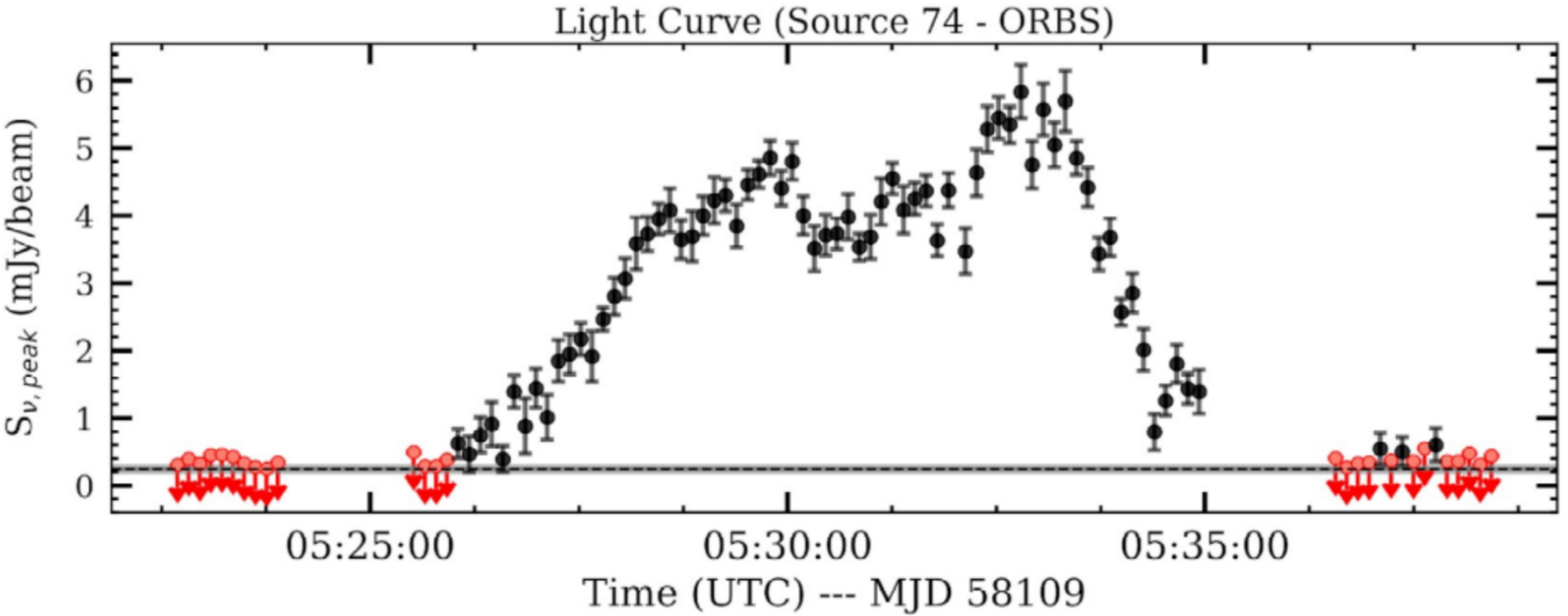
- Targeting the **strongest X-ray flares** in Orion: 36< logEX <38, up to a million times stronger than solar flares
- Searching for **post-flare Coronal Mass Ejections** with the VLBA *after* the *Chandra* observations, with rapid target identification and DiFX software correlation, potentially *resolving* structure → impact on planet atmospheres
- Runs from 2023-2025, *Chandra* PI: Kosta Getman, VLBA: JF



Getman et al. 2018, 2021

5) ALMA is enabling the systematic study of millimeter-wavelength flares

ALMA Orion Radio All-Stars: first results



Vargas-Gonzalez et al. (2023)

Summary on YSOs and prospects

VLA & VLBA **upgrades** and ALMA are providing systematic access to the **time domain** in stellar cm-mm radio astronomy. More to come!

The **Orion Nebula Cluster** provides us with a large sample of highly "radio-active" YSOs – and a wideband imaging testbed.

With high sensitivity and software correlation, the **VLBA** is an ideal tool to study nonthermal YSO emission in Orion, with hundreds of targets in a single primary beam. First results show abundant variability but also pervasive nonthermal emission in this first systematic census.

After simultaneous radio–X-ray studies (VLA-*Chandra*), a novel VLBA–*Chandra* program will allow us to hunt for **CMEs from X-ray megaflares**, impacting exoplanet atmospheres and circumstellar disks.

Transformational science with a (sub-)mm interferometer in the 2040s

Towards a radical upgrade of ALMA

www.euroalma2040.com