ADVENTURES OF YOUNG RADIO STARS

Intense radio outbursts, X-ray megaflares, and a VLBI search for ensuing CMEs

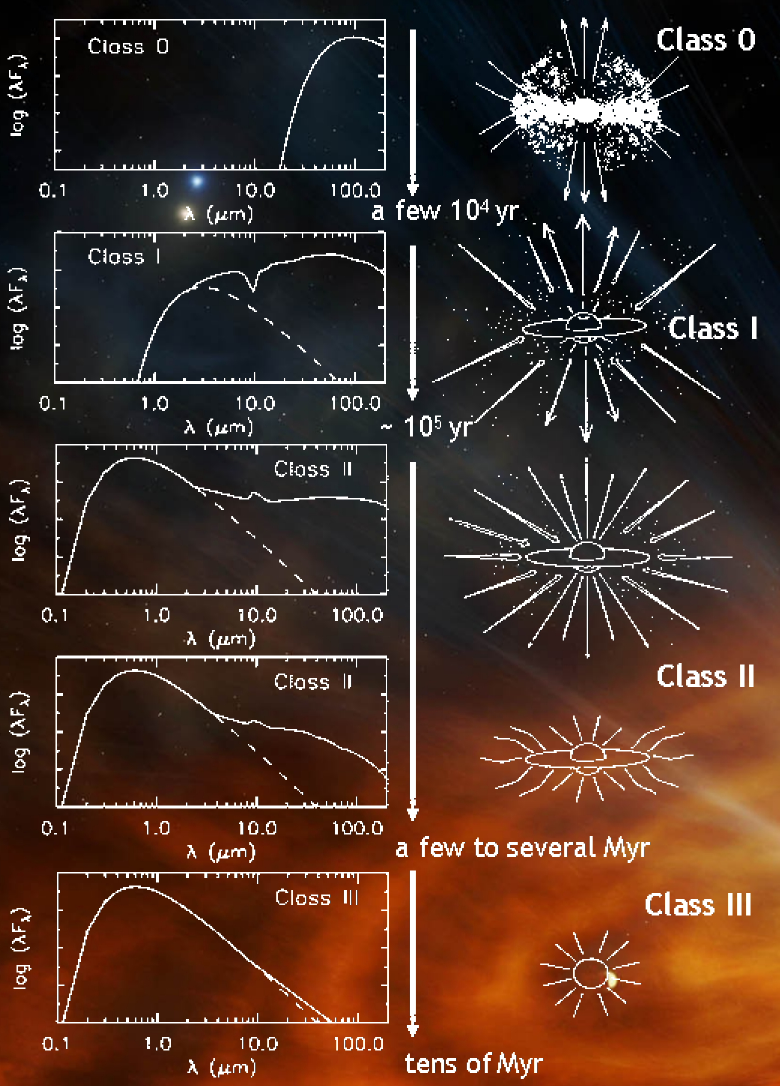
Jan Forbrich

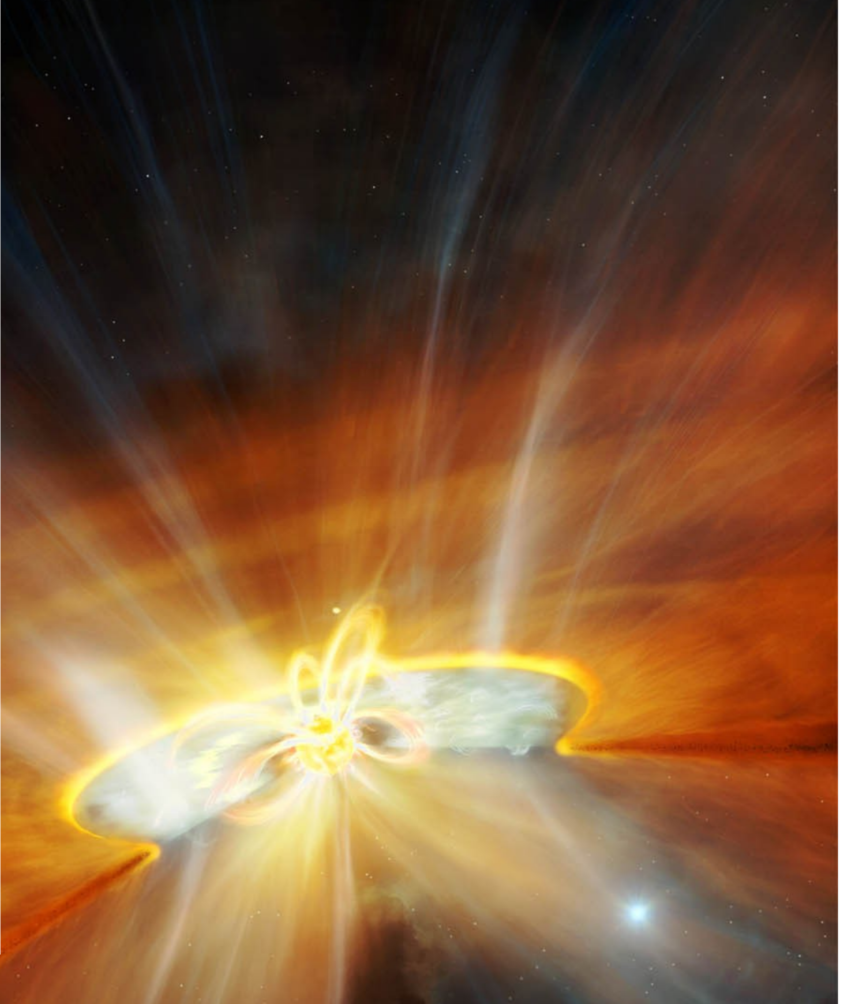
with Sergio Dzib, Eoin O'Kelly, Kosta Getman, Vladimir Airapetian,
and others

University of Hertfordshire UH

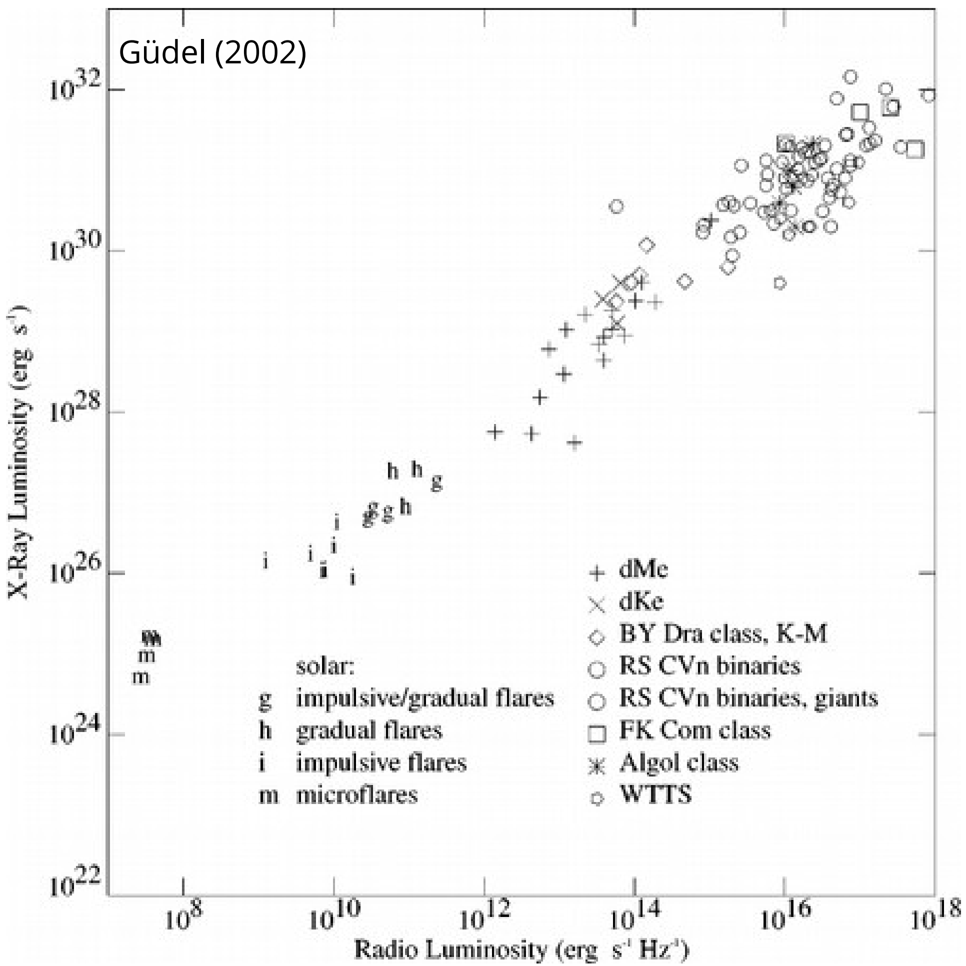
1 Young Stellar Objects are among the most luminous radio *and* X-ray stars

Young Stellar Objects





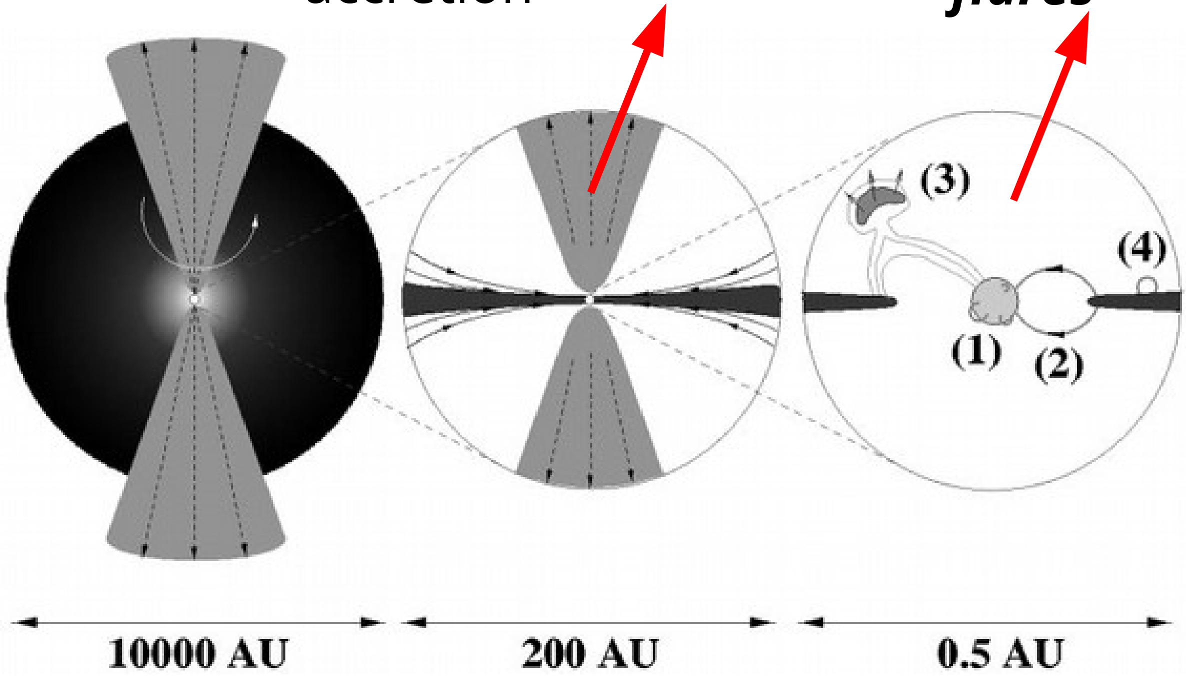
The **radio-X-ray connection**



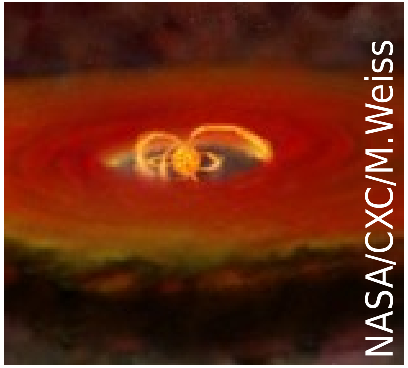
High-energy processes in Young Stellar Objects

Thermal radio emission, could fluctuate with accretion

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

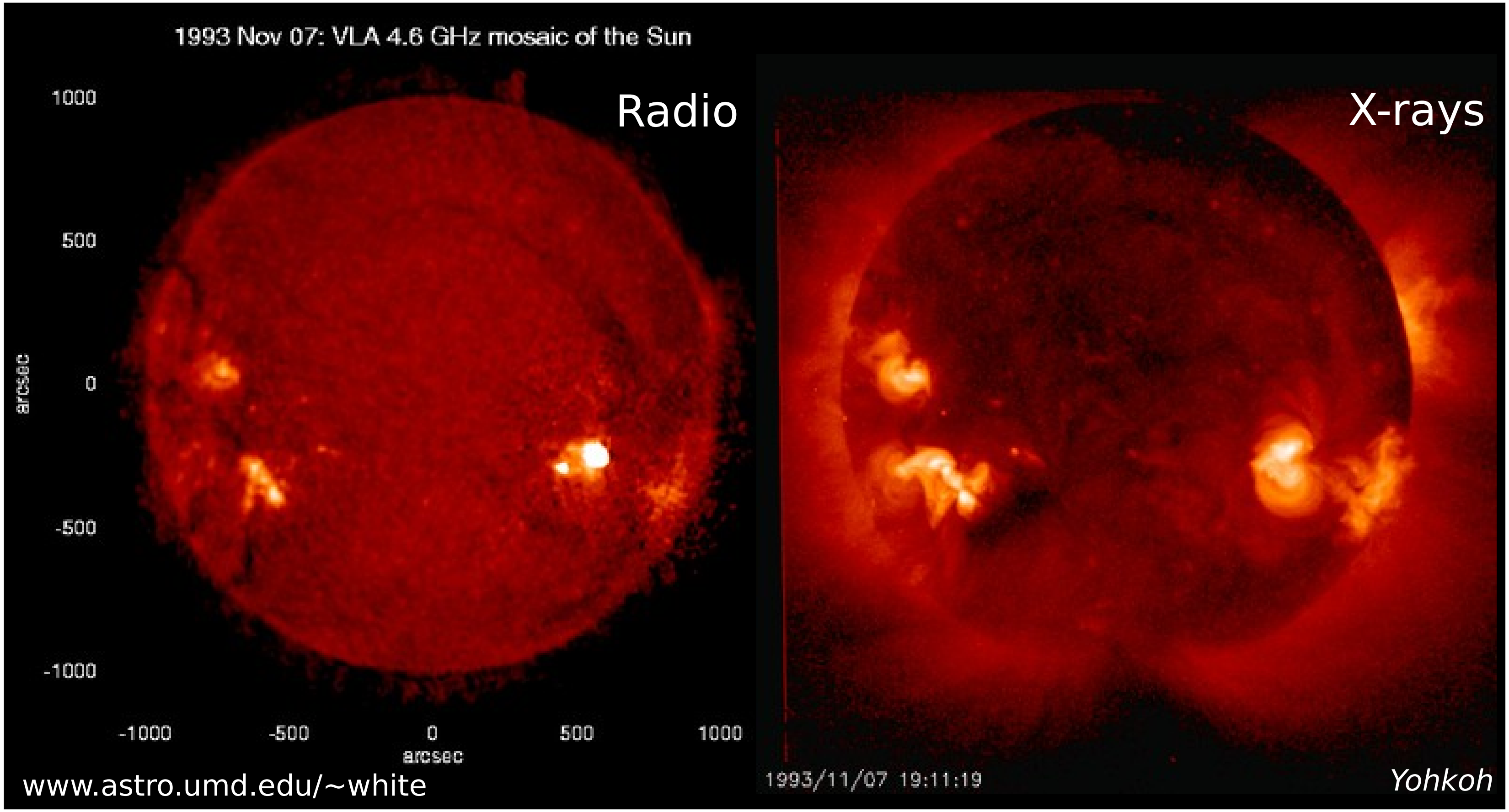


Feigelson & Montmerle (1999)



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

The **solar paradigm**



Radio and X-ray emission constrain the **full sequence** of magnetic energy release, particle acceleration, energy transformation, and heating.

2 Young Stellar Objects show intense X-ray *and* radio flares

The Orion Radio All Stars

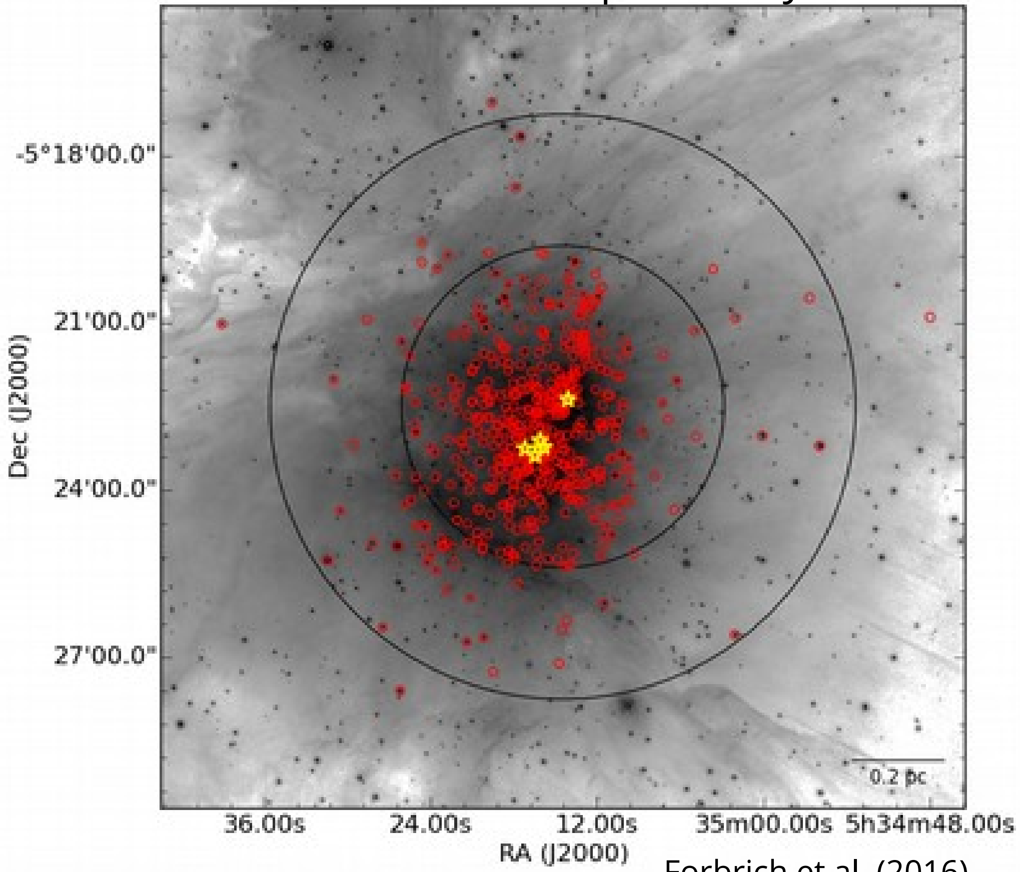
1) 30h of **VLA** C-band data (4–8 GHz) in a single pointing, in A configuration to minimize nebular emission, with simultaneous Chandra observations (Forbrich et al. 2016, 2017)

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), now *Chandra*+VLBA project (2023+)

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

7x more sources than previously known!

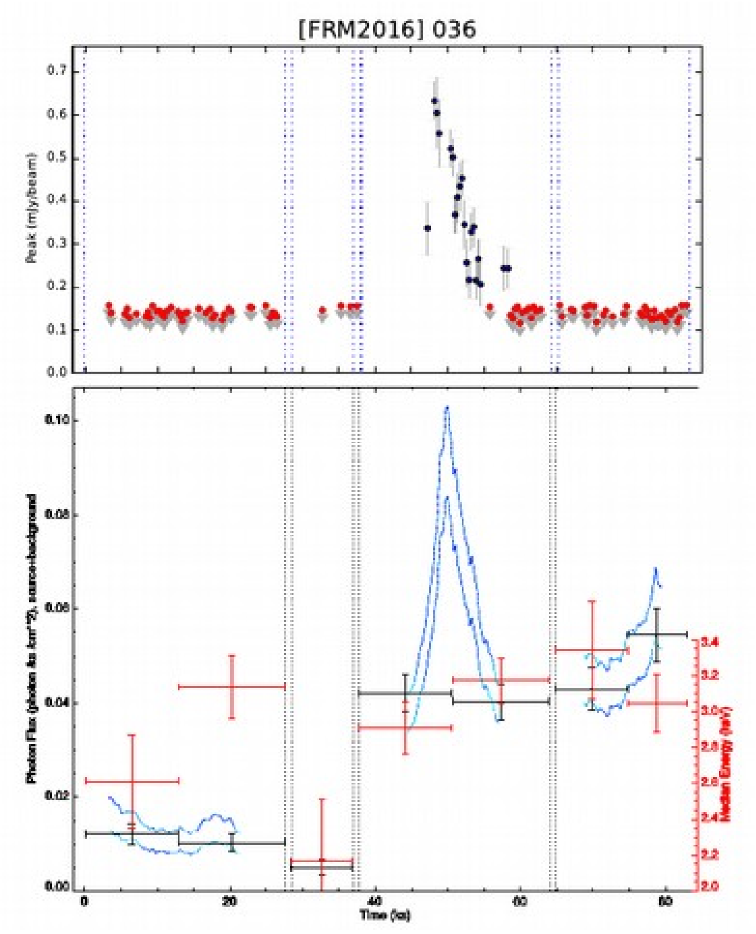


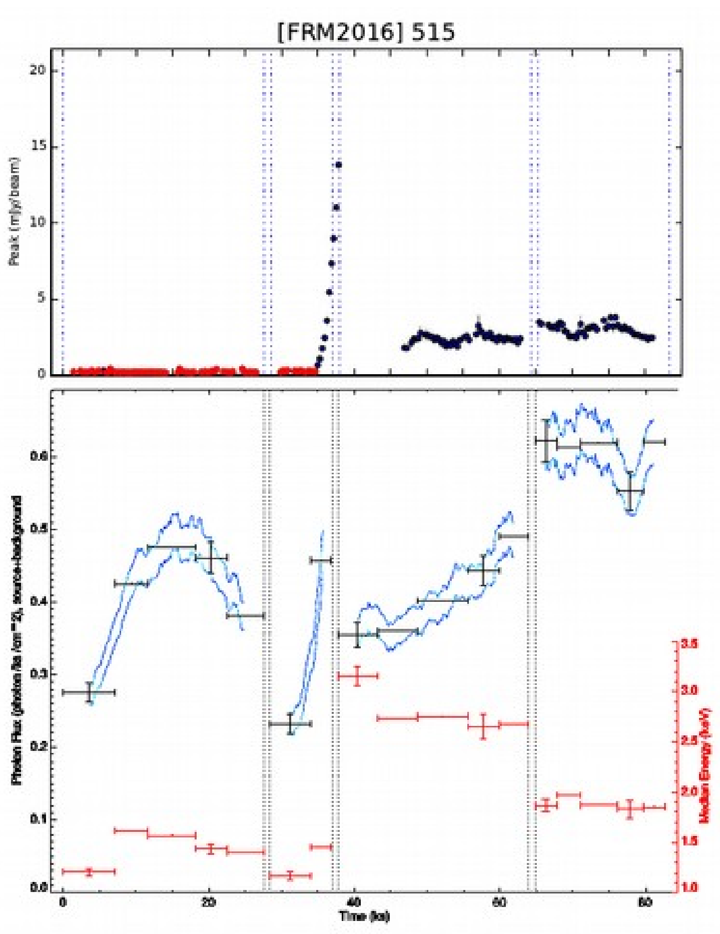
Forbrich et al. (2016)

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

cm radio

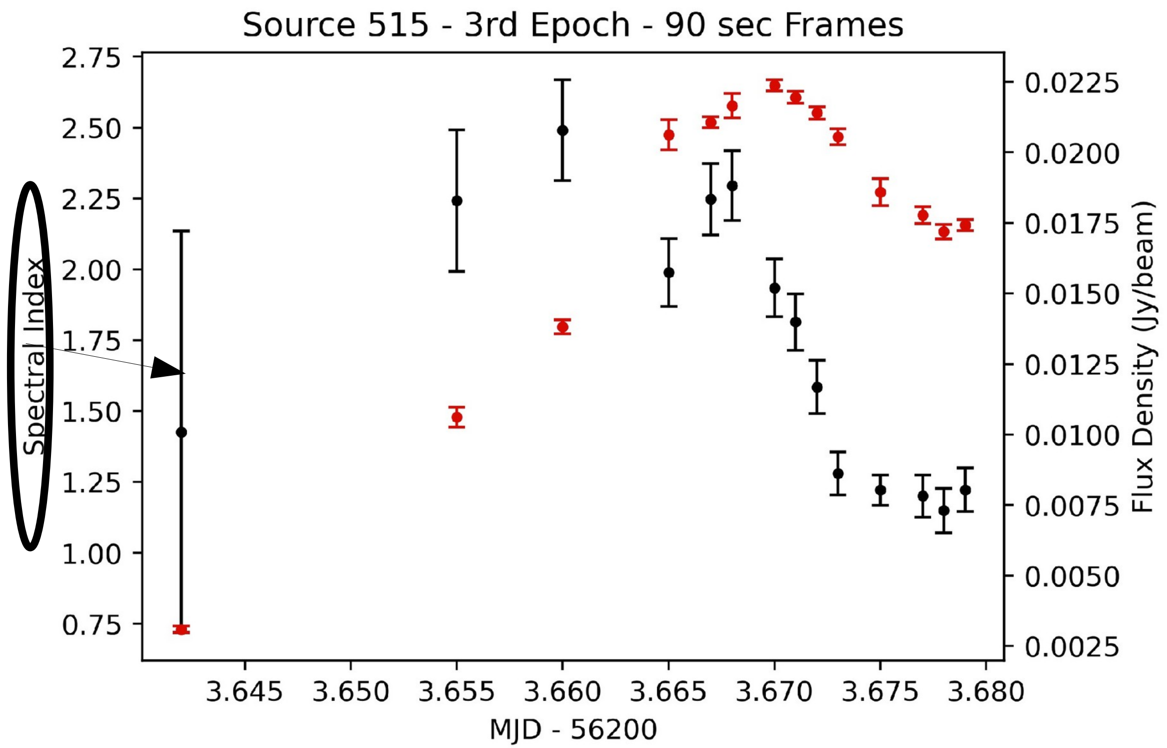
X-rays

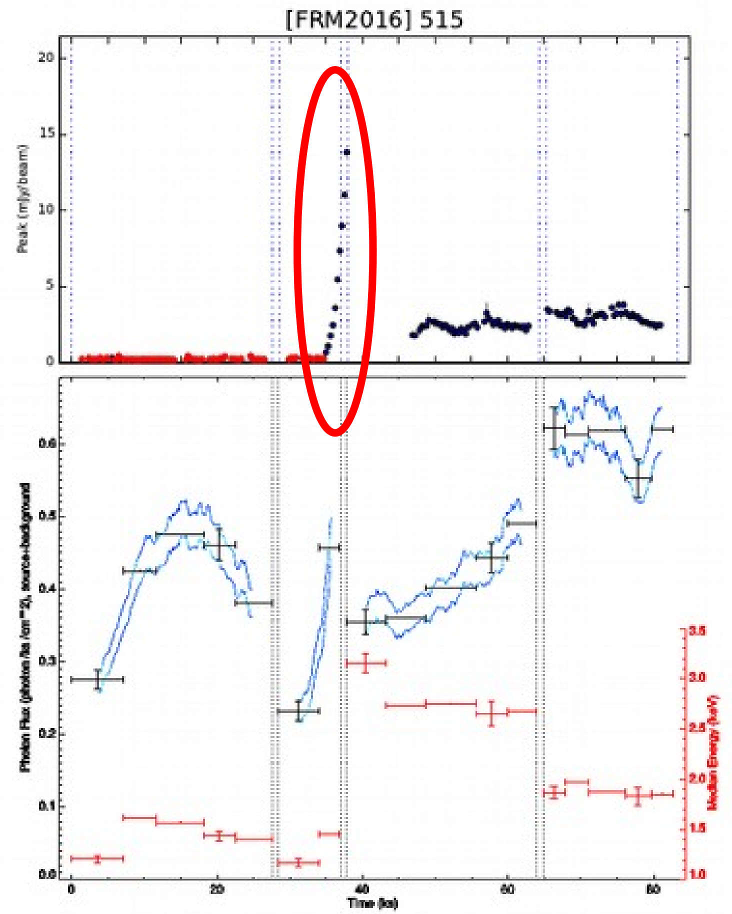




Forbrich et al. (2017)

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





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

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

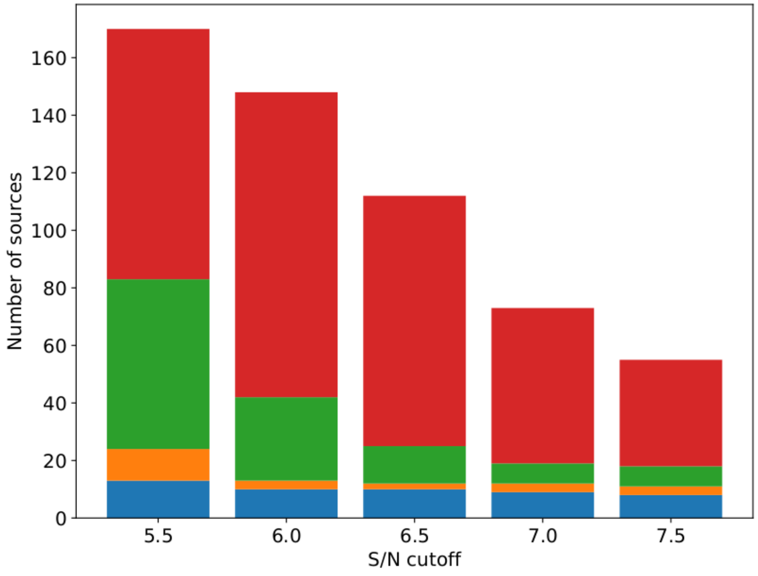
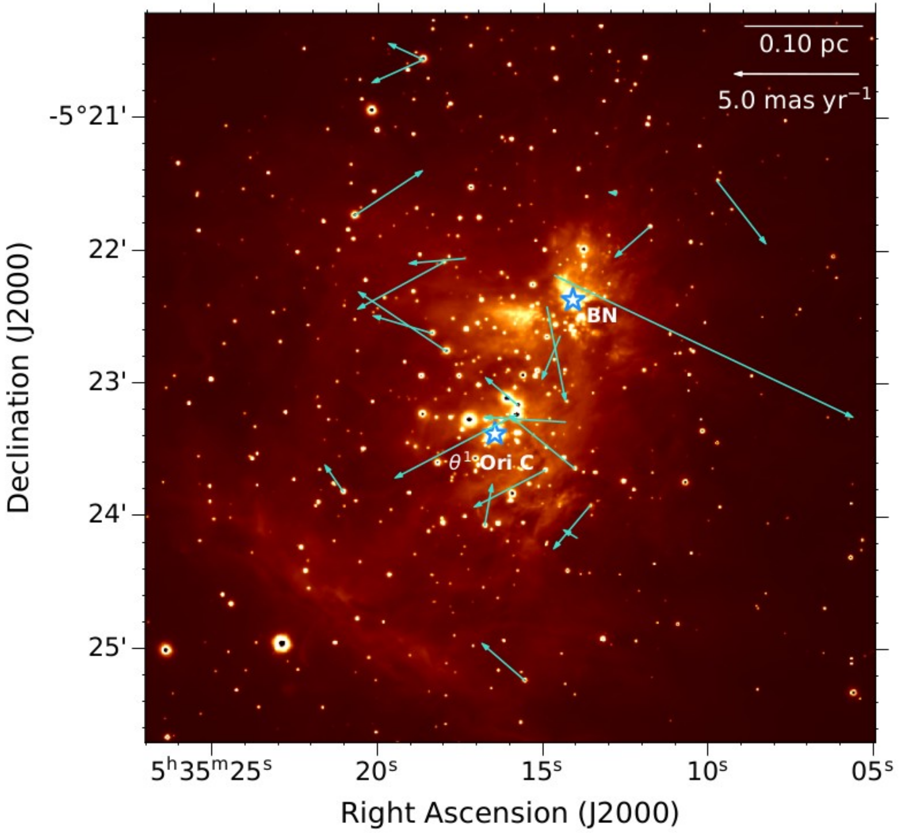


Figure 1. Number of sources detected above a given S/N threshold, color-coded by number of detections among four epochs (red=1, green=2, orange=3, blue=4).

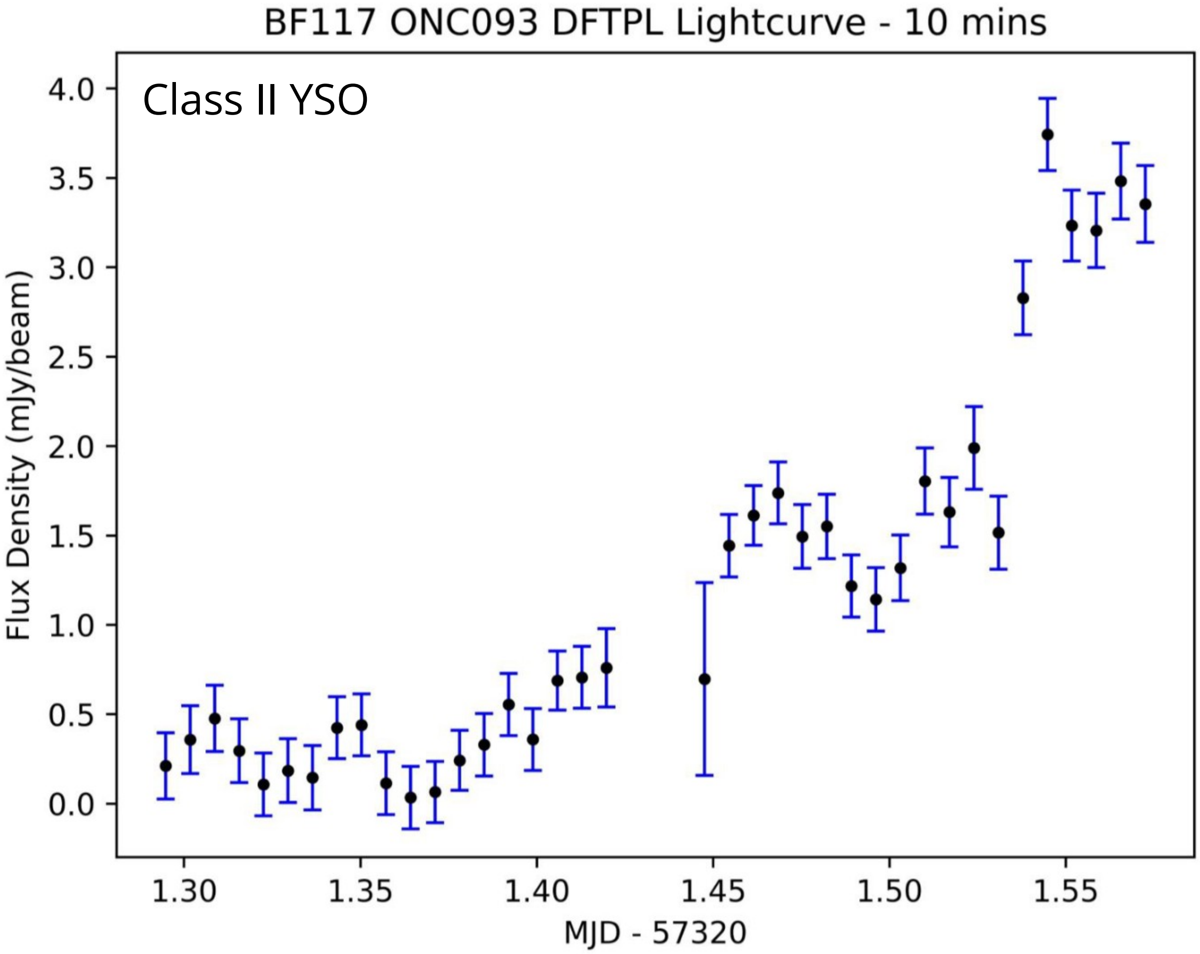


123 nonthermal YSOs detected in inner ONC

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

VLBA Orion Radio All-Stars: time domain analysis

Enabled by DiFX software correlation and DFT of visibilities at detection position.



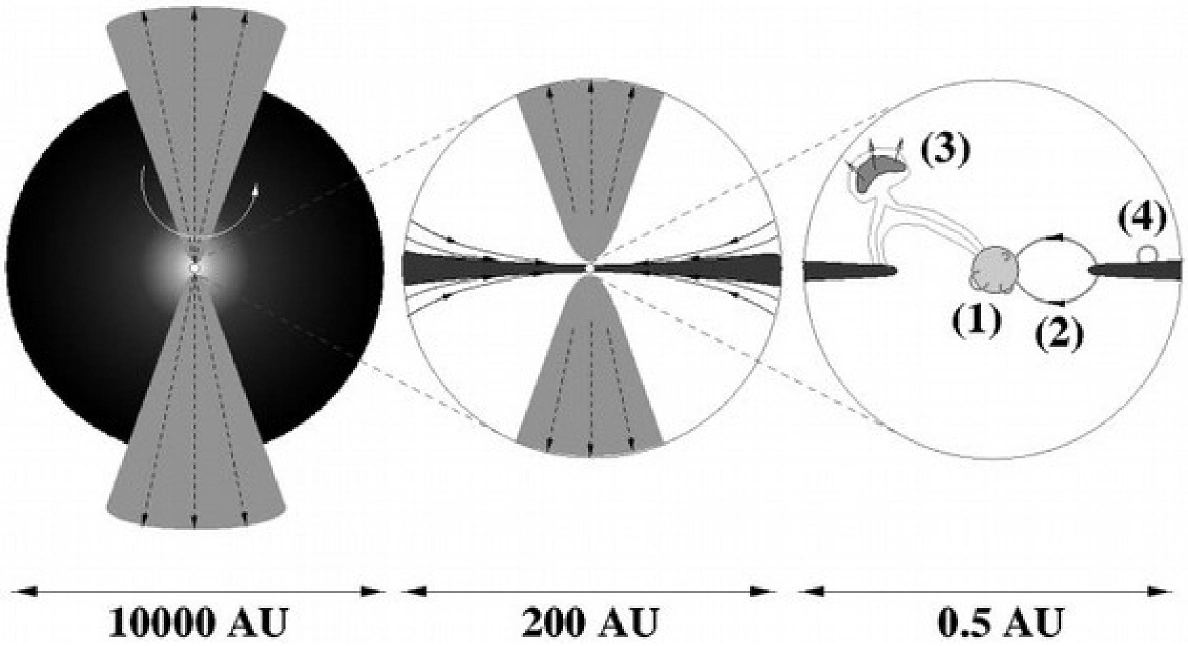
O'Kelly et al. *in prep.*

3 Ensuing Coronal Mass Ejections could have a major impact on disks and planet formation…

…but how can we look for them?

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!

Known unknowns

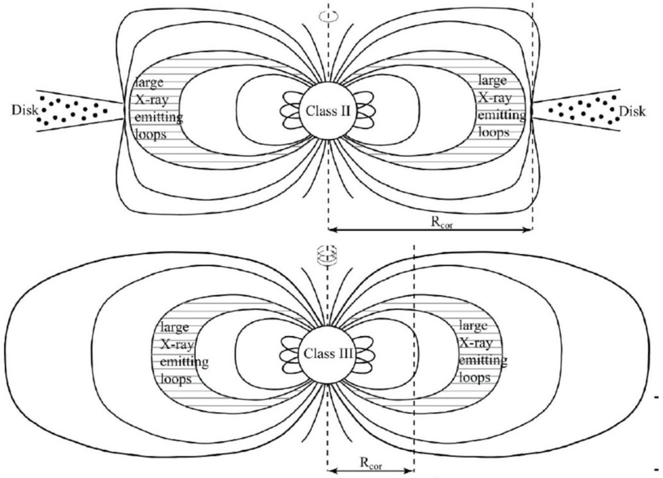
0. Occurrence of X-ray megaflares (reasonably well constrained)
1. Fraction of megaflares generating CMEs.
2. Viewing angle
3. Plasma density
4. Emission frequency
5. Timescale after flare: spectral evolution, distance from YSO

Needs >1 source...

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

A joint *Chandra*-HET-VLBA-ALMA 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
- Correlating X-ray megaflares with **HPF NIR Zeeman polarimetry** for accurate surface magnetic fields.
- **ALMA** follow-up to also look for subsequent **disk ionization**
- First data in Dec 2024, *Chandra* PI: Kosta Getman, VLBA: JF, ALMA: Abby Waggoner
- Meshes well with our existing VLBA monitoring.



Getman et al. 2018, 2021

Getman et al. (2008, 2021) Hayashi et al. (1996) Lynch et al. (2019)

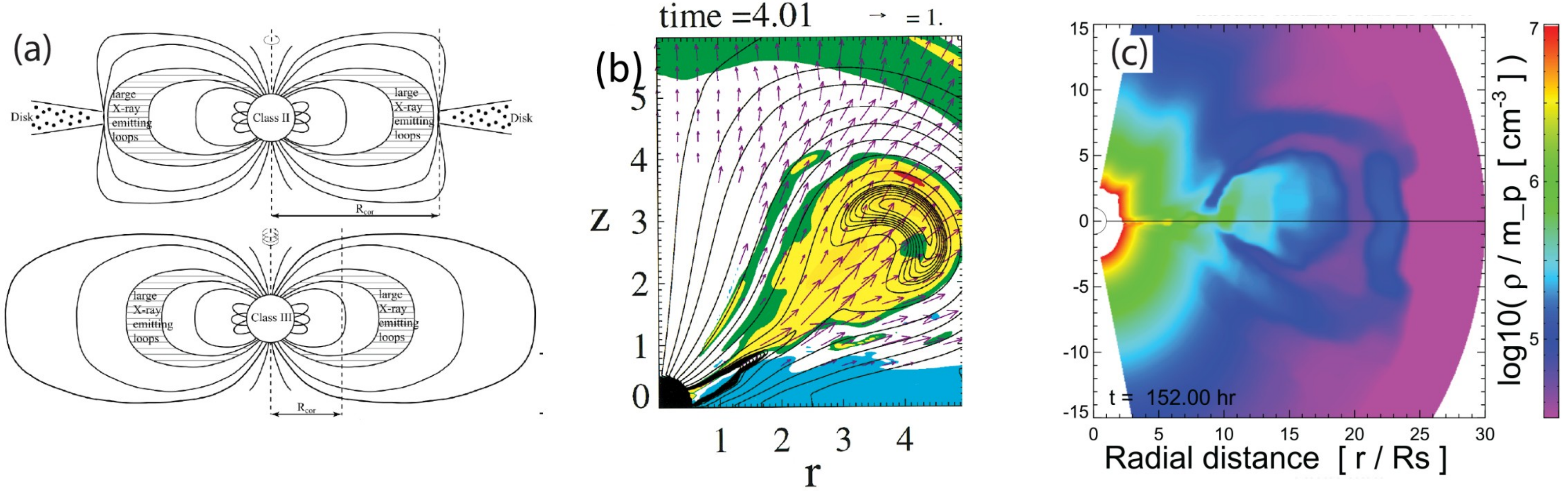
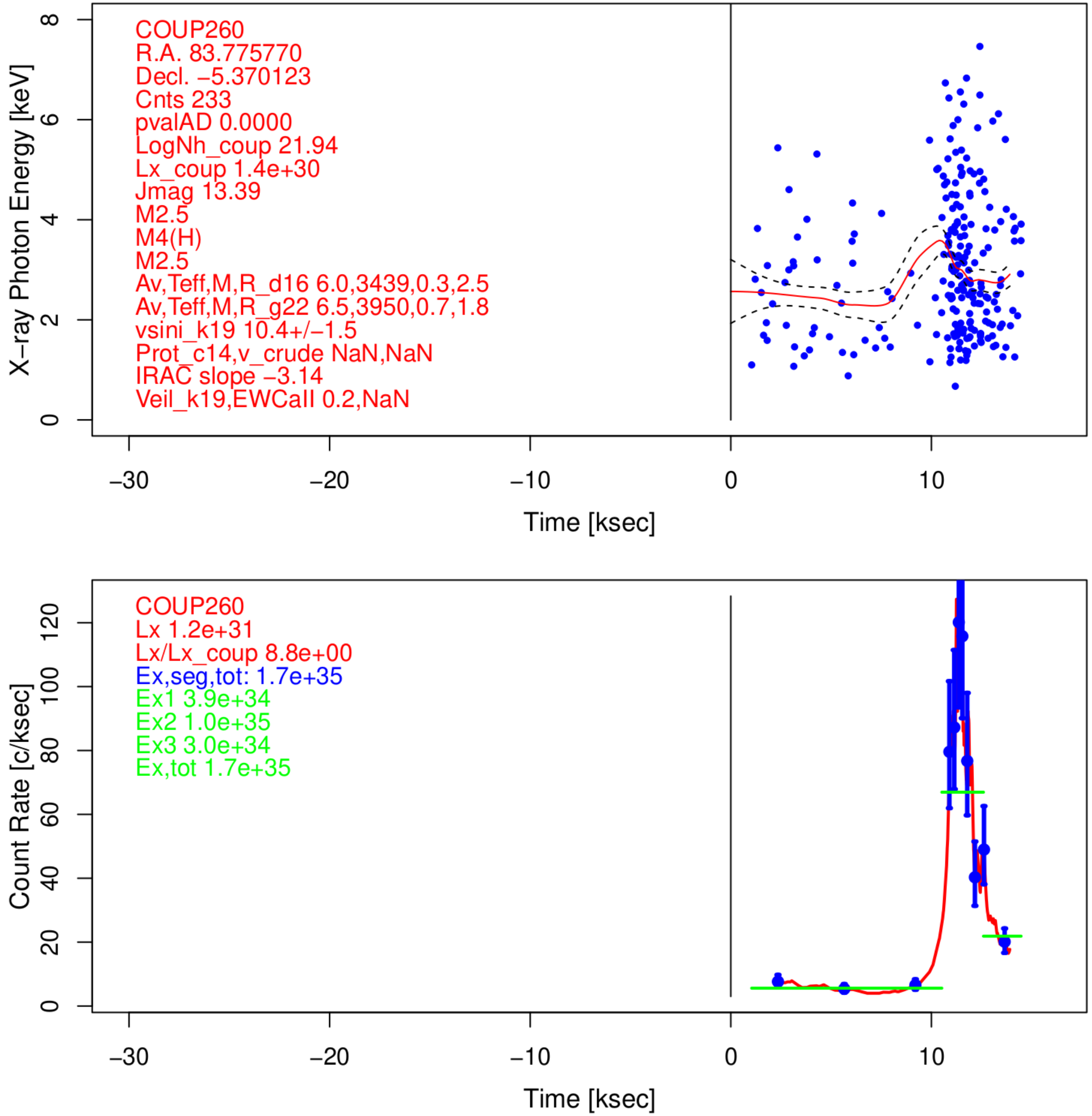


Figure 3: (a) Magnetosphere structure inferred from PMS X-ray mega-flare modeling with and without a confining disk [12;13]. (b) MHD calculation of a CME emerging from a PMS magnetosphere with a disk [35]. (c) MHD calculation of a CME emerging from an active star without a disk (6 days after eruption with velocities up to 1000 km/s) [20].

CME emission associated with Orion mega-flares would be detected as a rise and fall of radio flux over days after the X-ray mega-flares in emission spatially resolved and displaced from the star on scales ≥ 1 AU.



Getman et al. (*in prep.*)

Running total of obvious CME detections
(plus nonthermal census)

But lots of parameter space in 20 TB of correlated data... from epoch 1... with a lot more to come!

Summary 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 multi-phase center VLBI 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), an ongoing VLBA–*Chandra* program is allowing us to hunt for **CMEs from X-ray megaflares**, impacting exoplanet atmospheres and circumstellar disks.