Observations of Young Stellar Clusters: From Chandra to Lynx

Part of an unapologetic argument that stellar lifecycles should be a pillar of Lynx Science

Scott Wolk

Big Questions of Relevance to Stellar Astronomy*

- How do rotation and magnetic fields affect stars?
    - How does the dynamo work?
    - How is the corona heated?
- How do stars form?
- How do circumstellar disks evolve, form planetary systems?
- How diverse are planetary systems?
- Do habitable worlds exist on other stars?

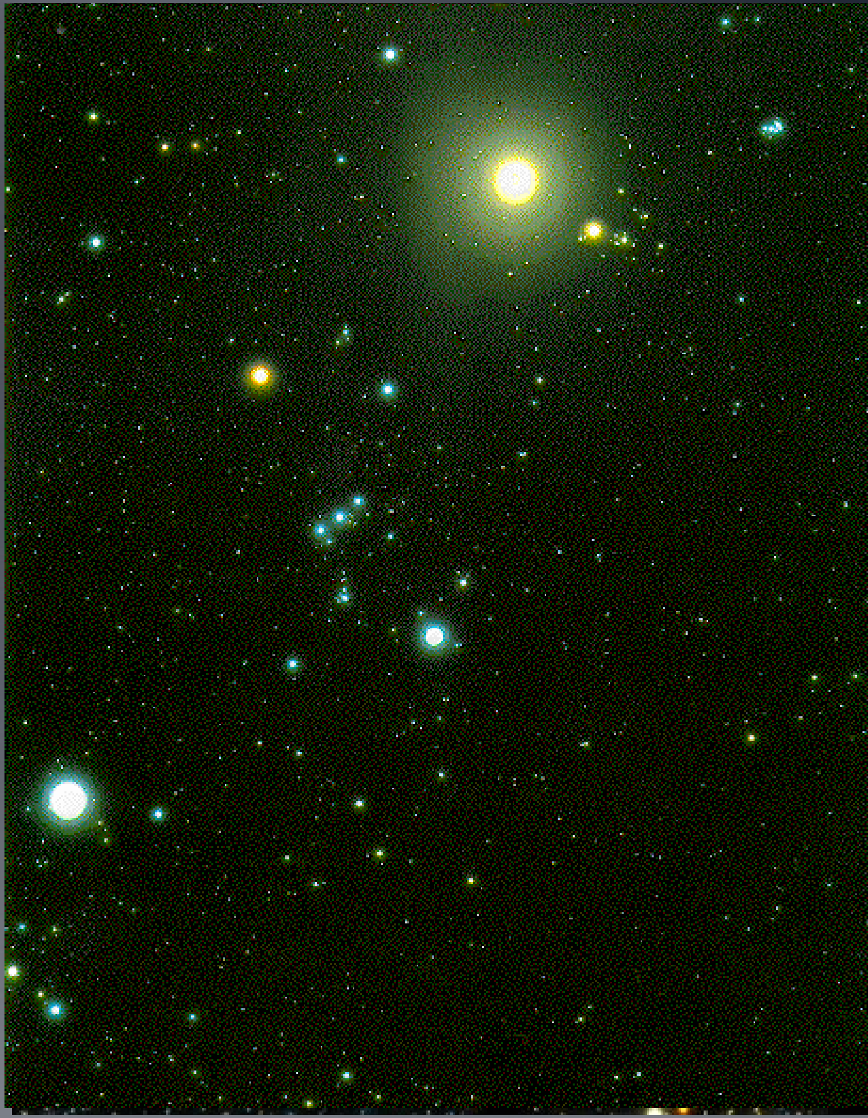
X-rays inform each of these topics, are vital for understanding how stars work and how they interact with their environment

Observations with large collecting area coupled with high spectral, spatial resolution are necessary to make progress in answering these questions

*From R Osten as informed by the Decadal Survey and more recent results

Why Bother Looking at Young Stars in X-rays ?

- Young stars are X-ray bright
  - HMS- High energy wind shocks?
  - LMS- Despite pedestrian 5000K, temperatures they have hot corona.
    - Insight into the interior workings of LMS.
- To identify young stars.
  - After stars lose their disks X-ray surveys are the only way to find young stellar objects
  - This has allowed us to understand the history of star formation in the galaxy.
- Direct observation of material accreting onto very young stars.
- X-rays are probably responsible for rapid heating of protoplanetary disks and can have deleterious effects on young planets



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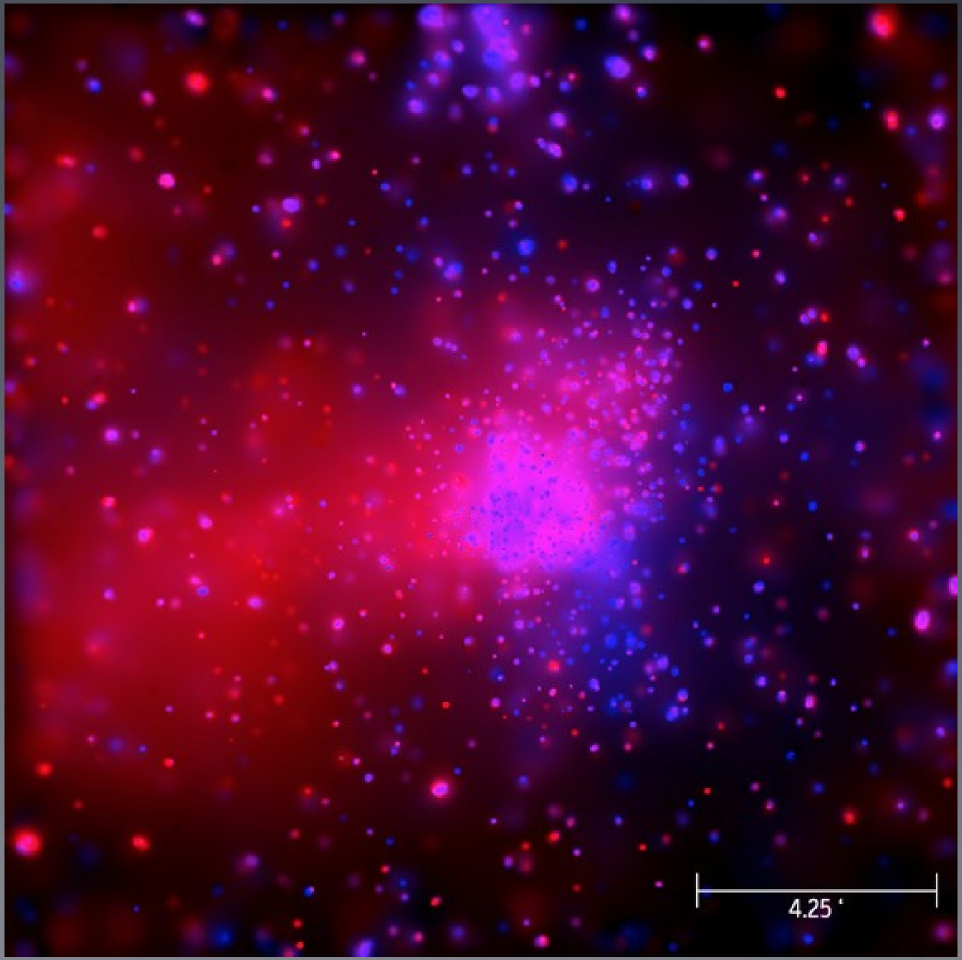
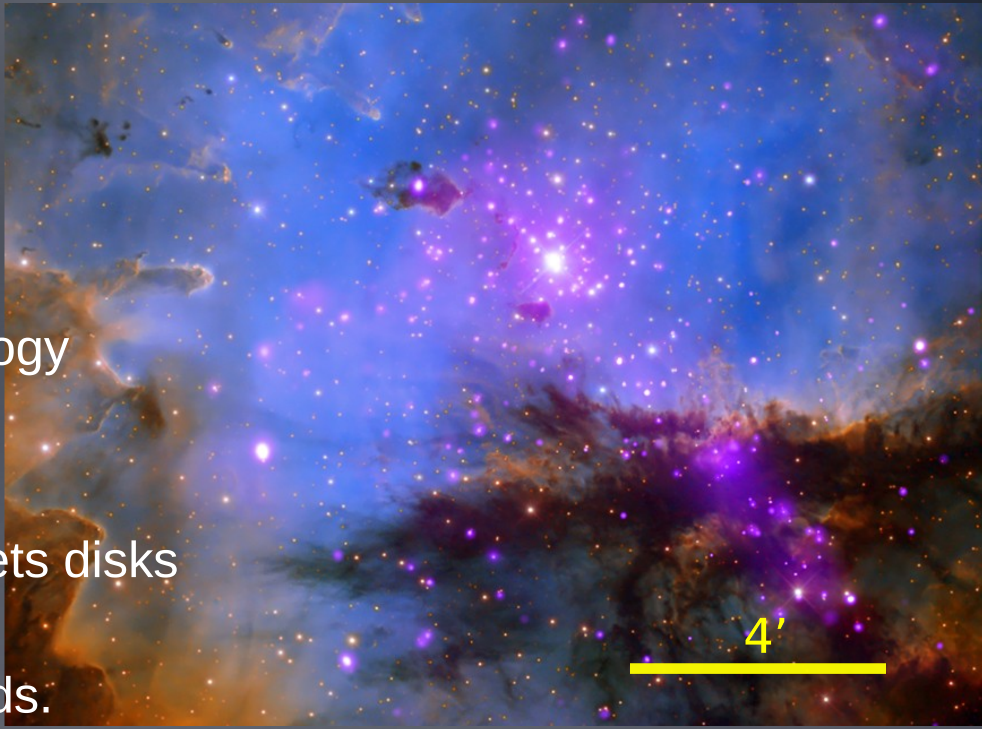
Orion is nice, but

- One age
  - 1-20 Myr (some clusters are up to 100Myr)
- One mass distribution
  - Not a lot of OB stars, especially in Orion A.
  - Binarity seems a function of stellar density
- One set of initial conditions
  - Triggering mechanisms matter to the final elemental abundances and perhaps more.
- One metallicity
- One look angle, M42 has a molecular cloud behind, but there are other arrangements

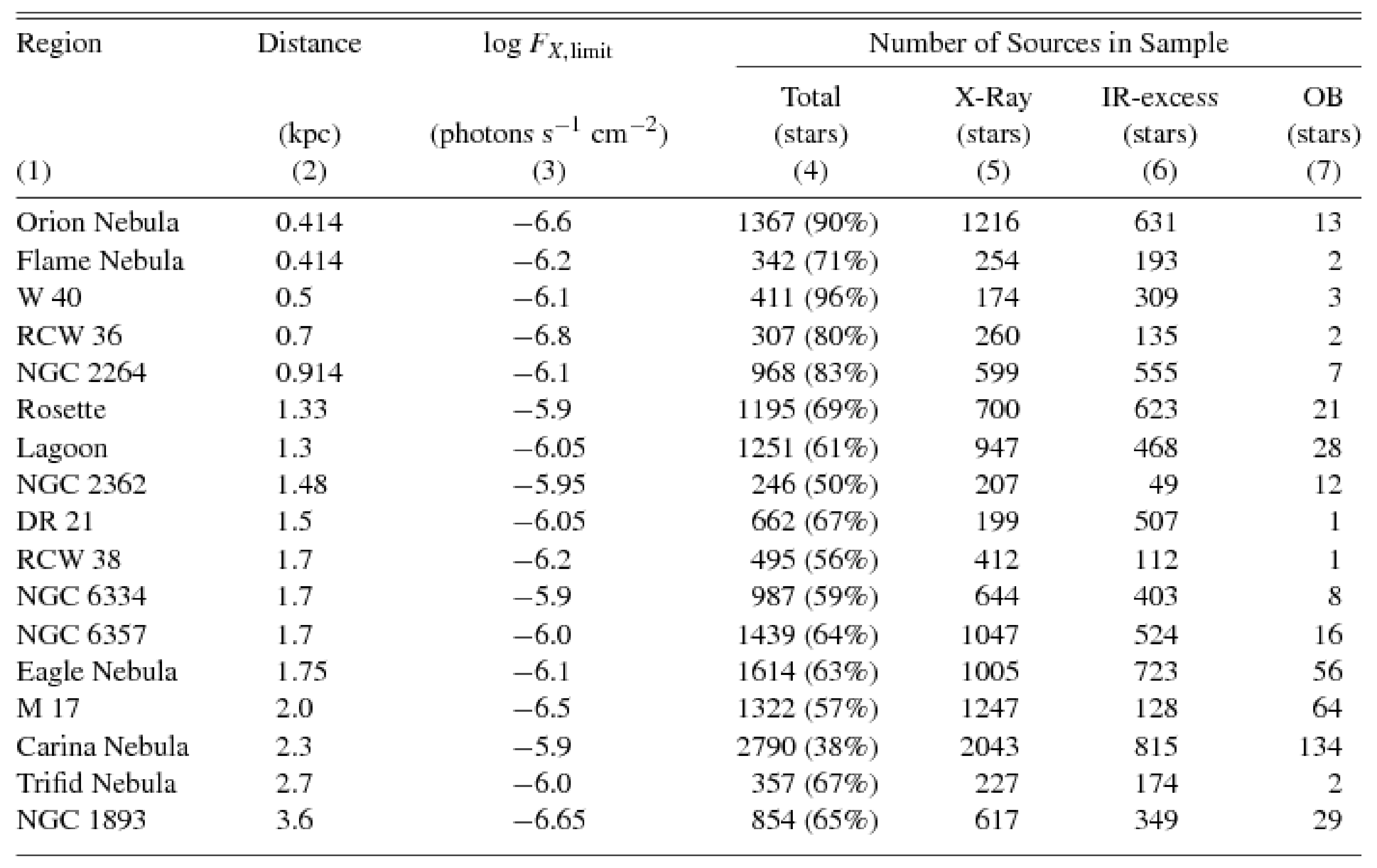


Specific Science goals for Star Formation Regions



- Cluster Census
- Transition disk timescales
- X-ray effects on cluster morphology
- Detecting grain evolution
- X-rays from protostars
- Effect of X-rays on forming planets disks
  - Especially flares.
- Understanding the magnetic fields.
- What are the statistics of radio flaring for young stellar objects?
- Are radio flares correlated with X-ray flares?
- Understanding diffuse emission and feedback.
- What is the relationship between X-rays and radio emission from YSOs?

Massive clusters within ~ 3.5 kpc

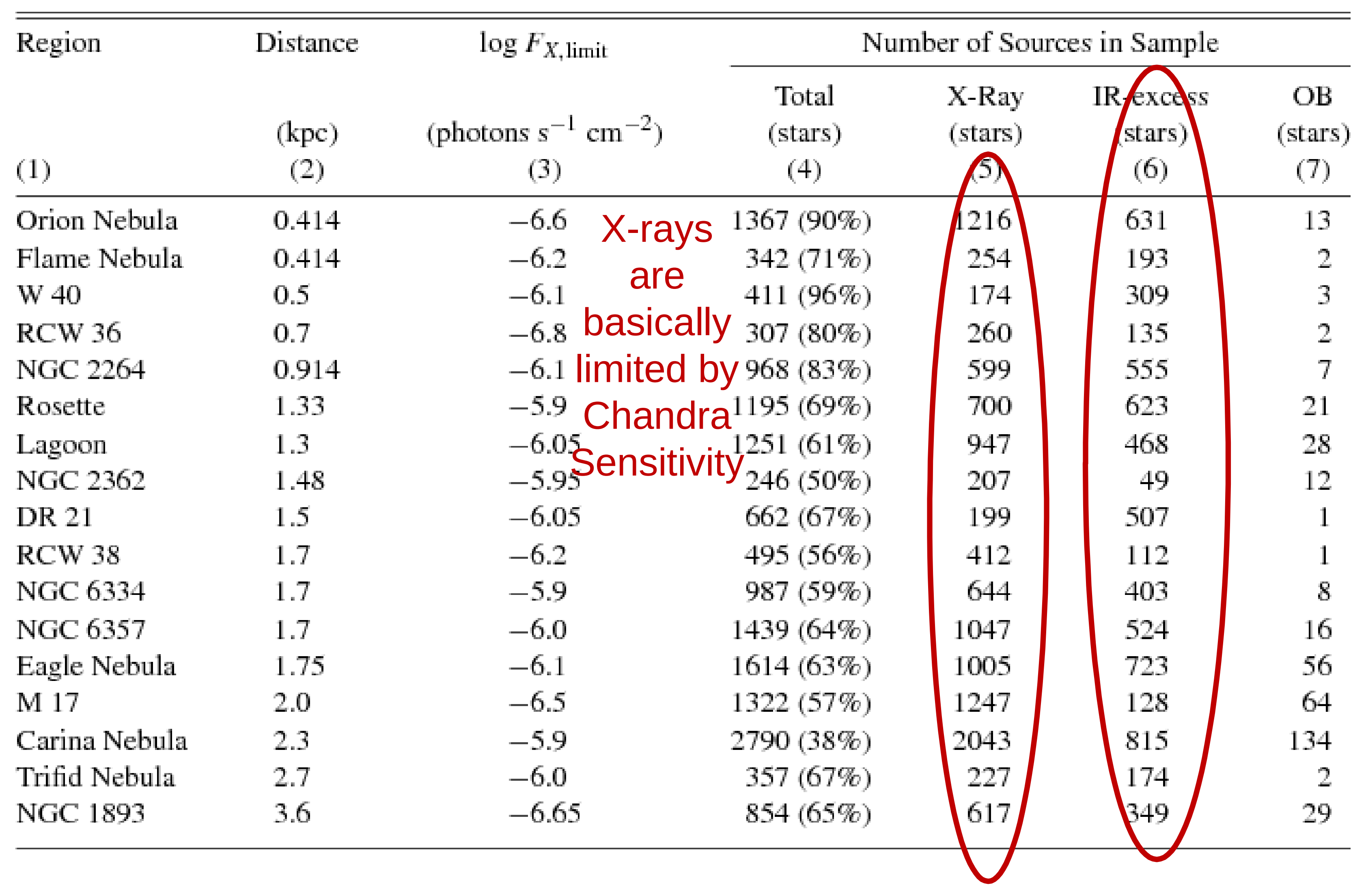


Region (1)	Distance (kpc) (2)	log $F_{X,\mathrm{limit}}$ (photons s^{-1} cm^{-2}) (3)	Number of Sources in Sample Total (stars) (4)	X-Ray (stars) (5)	IR-excess (stars) (6)	OB (stars) (7)
Orion Nebula	0.414	−6.6	1367 (90%)	1216	631	13
Flame Nebula	0.414	−6.2	342 (71%)	254	193	2
W 40	0.5	−6.1	411 (96%)	174	309	3
RCW 36	0.7	−6.8	307 (80%)	260	135	2
NGC 2264	0.914	−6.1	968 (83%)	599	555	7
Rosette	1.33	−5.9	1195 (69%)	700	623	21
Lagoon	1.3	−6.05	1251 (61%)	947	468	28
NGC 2362	1.48	−5.95	246 (50%)	207	49	12
DR 21	1.5	−6.05	662 (67%)	199	507	1
RCW 38	1.7	−6.2	495 (56%)	412	112	1
NGC 6334	1.7	−5.9	987 (59%)	644	403	8
NGC 6357	1.7	−6.0	1439 (64%)	1047	524	16
Eagle Nebula	1.75	−6.1	1614 (63%)	1005	723	56
M 17	2.0	−6.5	1322 (57%)	1247	128	64
Carina Nebula	2.3	−5.9	2790 (38%)	2043	815	134
Trifid Nebula	2.7	−6.0	357 (67%)	227	174	2
NGC 1893	3.6	−6.65	854 (65%)	617	349	29

Kuhn et al. (2014)

Disk Survival timescales

IR sources are only about 50% of the clusters



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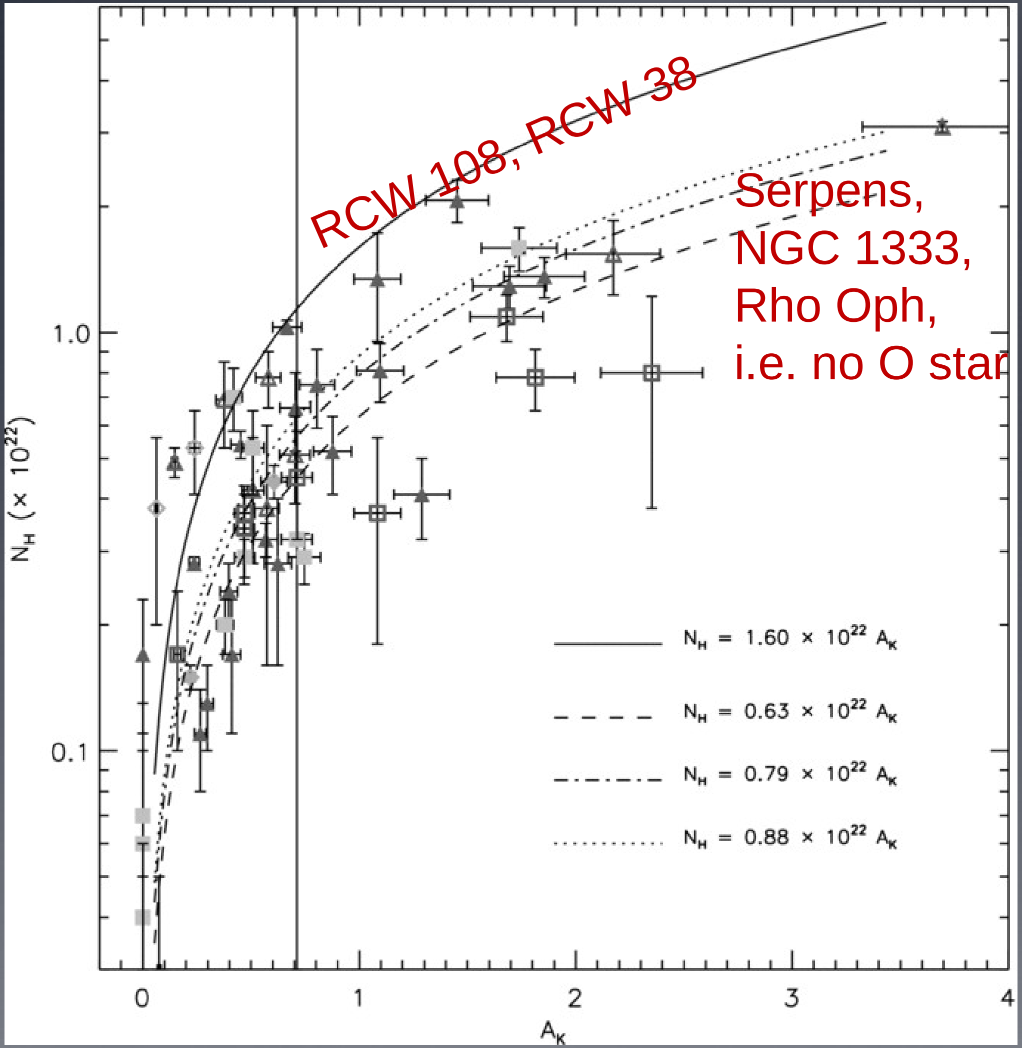
X-rays are basically limited by Chandra Sensitivity

The ratio of disked to diskless stars

Kuhn et al. (2014)

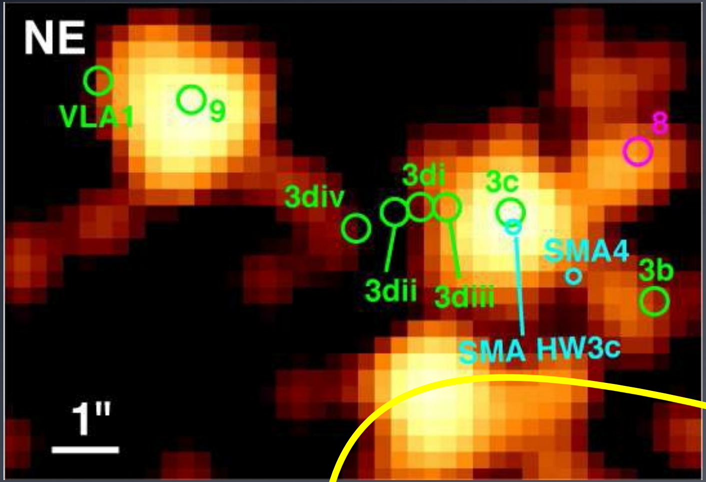
Disk-Grain Evolution



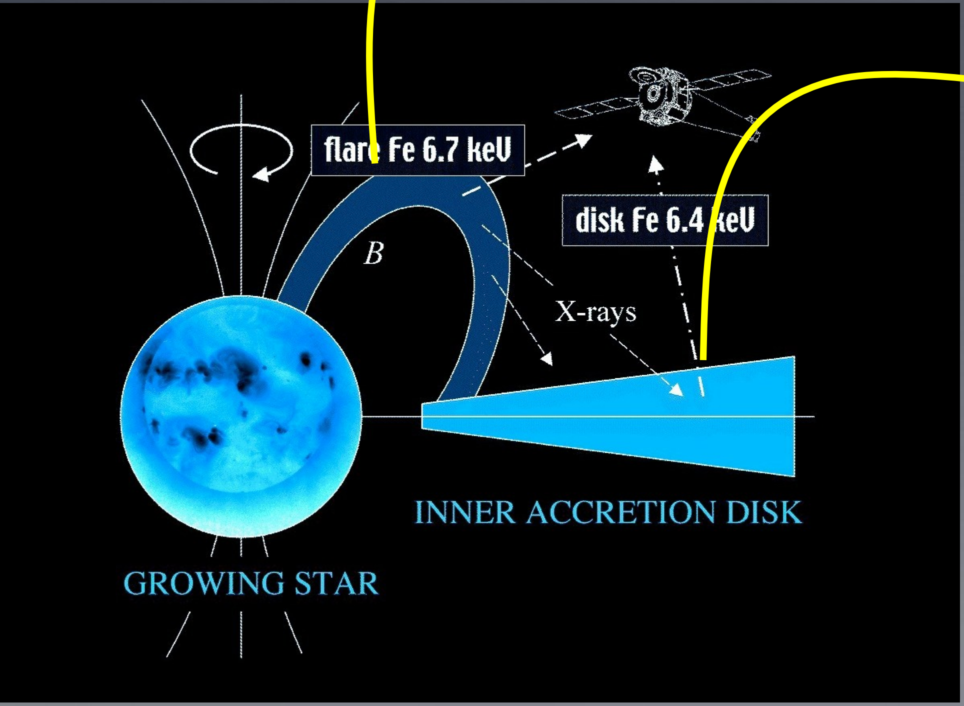
Winston et al. (2009)

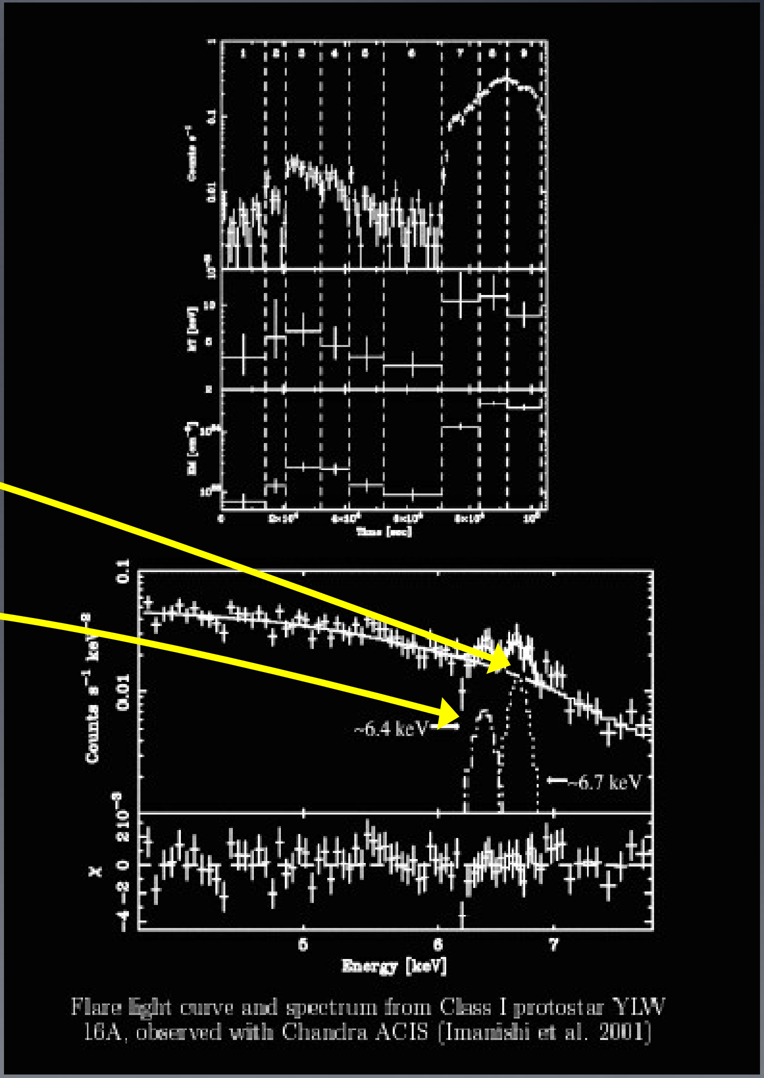
Chandra only has sufficient counts statistics for a few sources and even then the errors are large

Disk irradiation: fluorescence



(Pravdo 2009)
Cep A



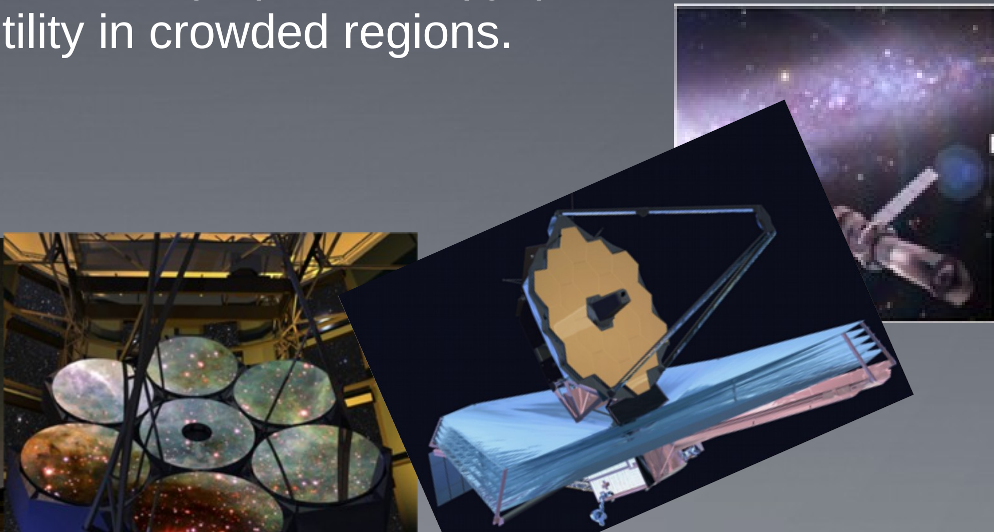


Flare light curve and spectrum from Class I protostar YLW 16A, observed with Chandra ACIS (Imanishi et al. 2001)

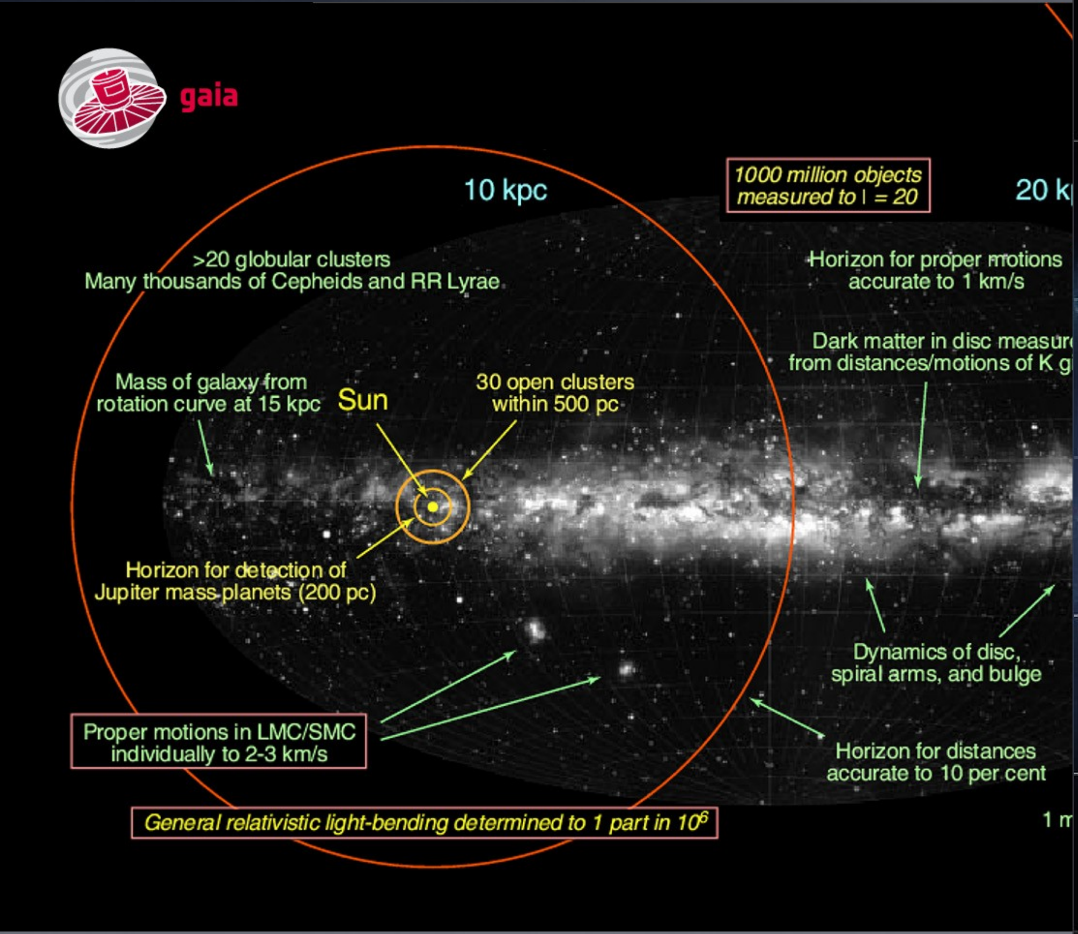
(Imanishi et al. 2001, 2005)

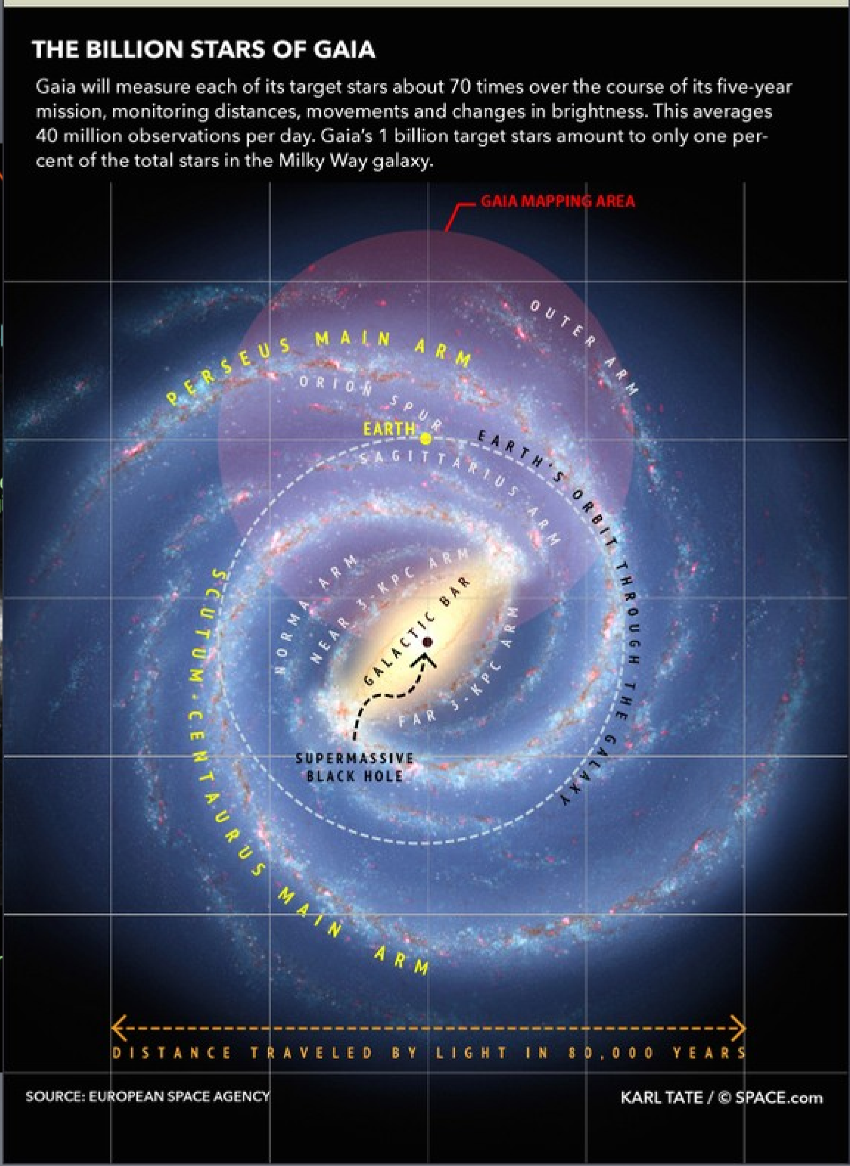
Science Landscape of ~ 2030

- TESS (2018), Plato (2024) – Survey millions of stars to find exoplanets.
- Gaia (2013) – 3D maps of the galaxy to 10 Kpc
- JWST (2018), WFIRST(2025)– Deep IR imaging and spectroscopy. constraints on stellar populations in crowded stellar clusters down to the H-burning limit, properties of starspots in transiting exoplanet systems
- ALMA, VLA SKA (2023+) – Radio telescopes will study chemistry and dynamics of planet-forming disks, non thermal stellar processes
- E-ELT, TMT GMT (2022+) – Ground based optical and NIR telescopes will map surface magnetic fields in a variety of stars
- E-Rosita (2018) – All sky survey will increase the number of known X-ray emitting stars by about 100x.
- Athena (2028) – sensitive R~200-500 X-ray spectroscopy (as far as stars are concerned). PSF limits utility in crowded regions.



Gaia will be great, but





THE BILLION STARS OF GAIA

Gaia will measure each of its target stars about 70 times over the course of its five-year mission, monitoring distances, movements and changes in brightness. This averages 40 million observations per day. Gaia's 1 billion target stars amount to only one percent of the total stars in the Milky Way galaxy.

SOURCE: EUROPEAN SPACE AGENCY

KARL TATE / © SPACE.com

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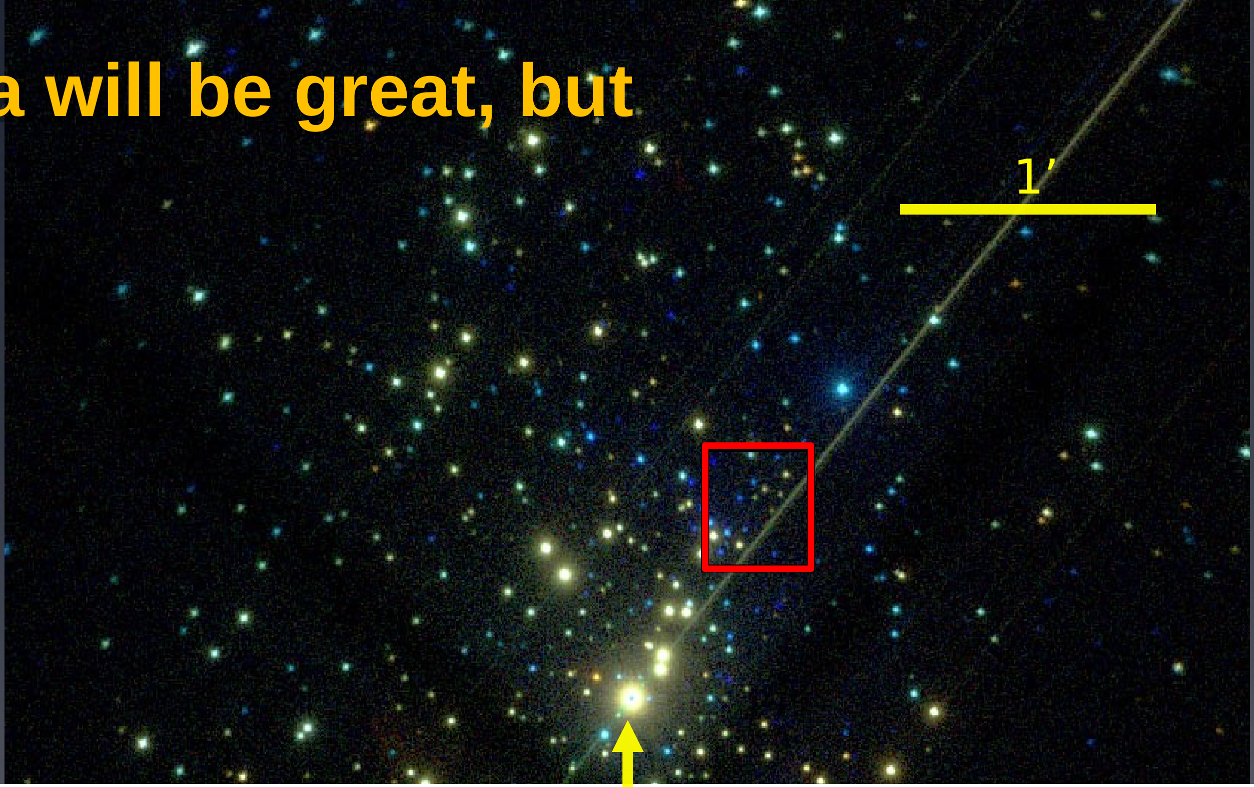
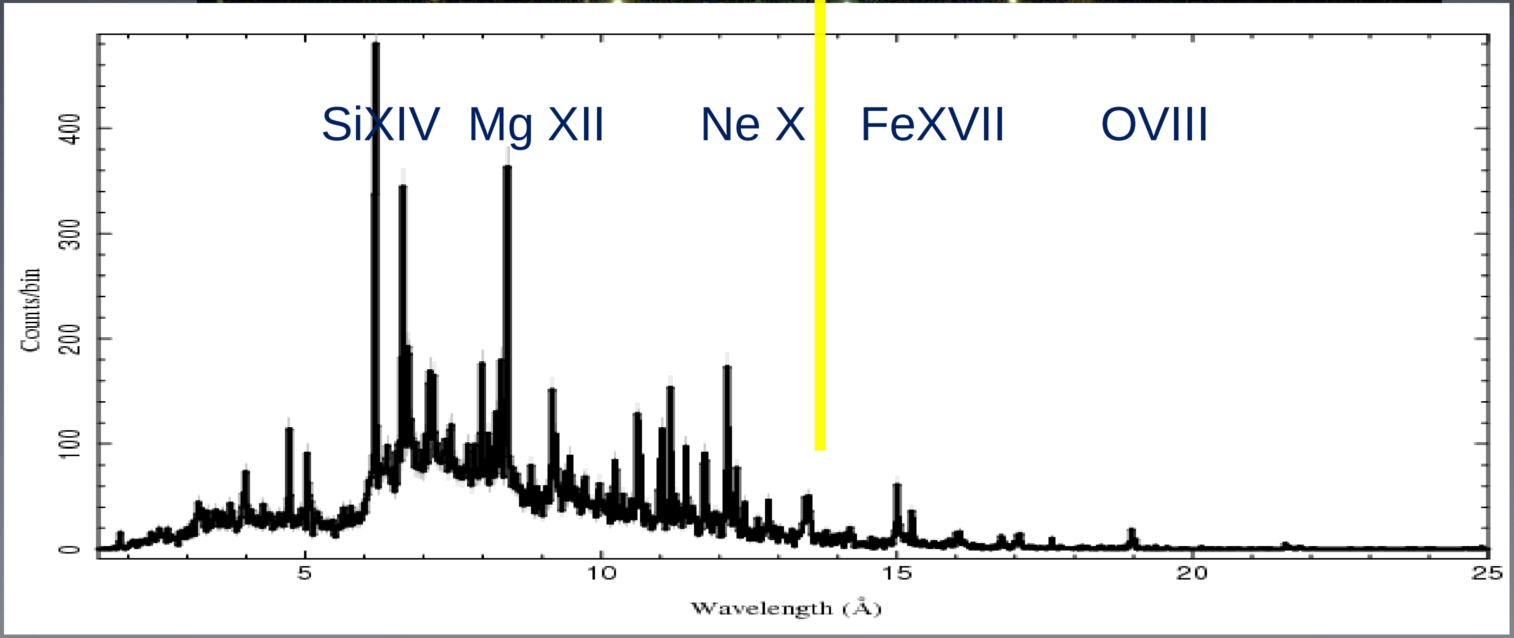




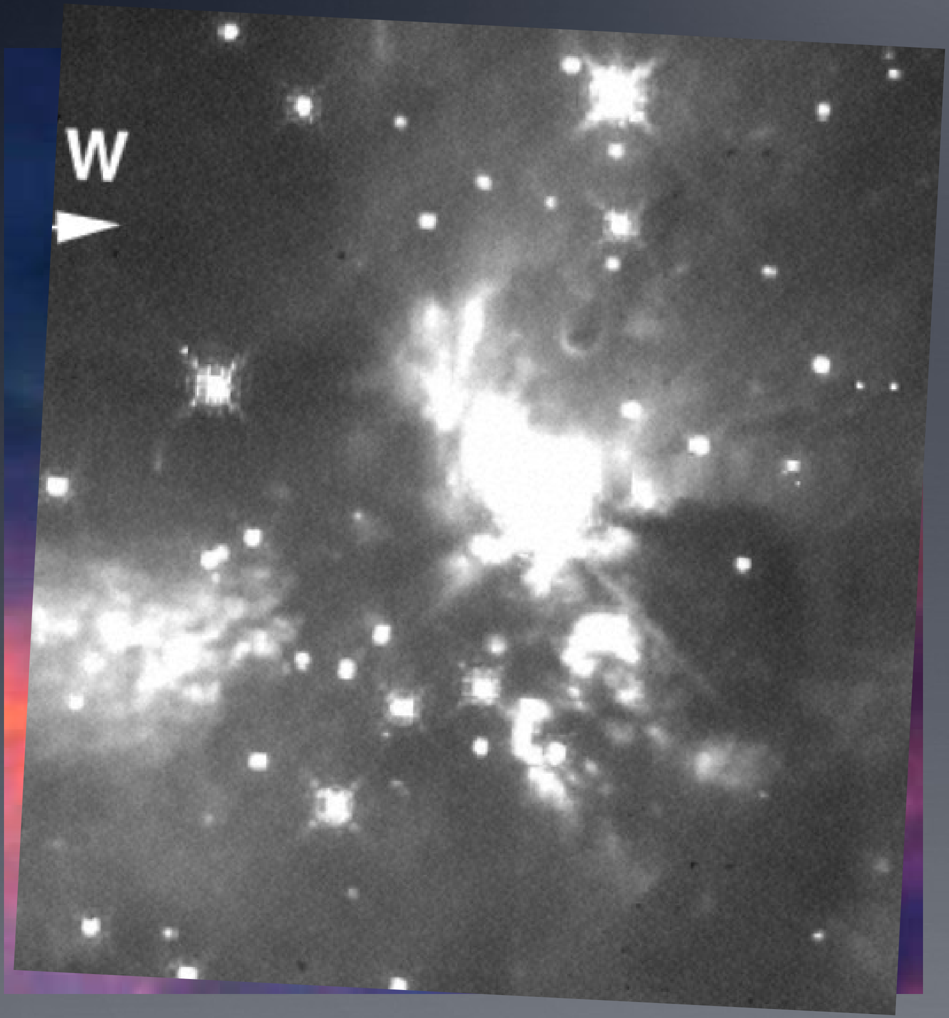
Why are X-rays important/essential in protostars ?

- Feedback irradiation effects on surrounding circumstellar material: ionization, heating, fluorescence
  - Effects on chemistry (=> diagnostics) + heating
- Studied theoretically on disks & jets
  - Provides ionization fraction: $x_e = n_e/n_p \sim 10^{-9} - 10^{-5}$
    - (ISM + LECR => $X_e \approx 10^{-7}$)
  - Effects on cold material: fluorescence (from AGNs)
    - Fe line @ 6.4 keV
- Ionization provides necessary coupling between circumstellar matter and magnetic fields via ambipolar diffusion
- This coupling regulates large-scale accretion vs. ejection in an otherwise neutral environment (e.g., Shu et al., Ferreira et al…)

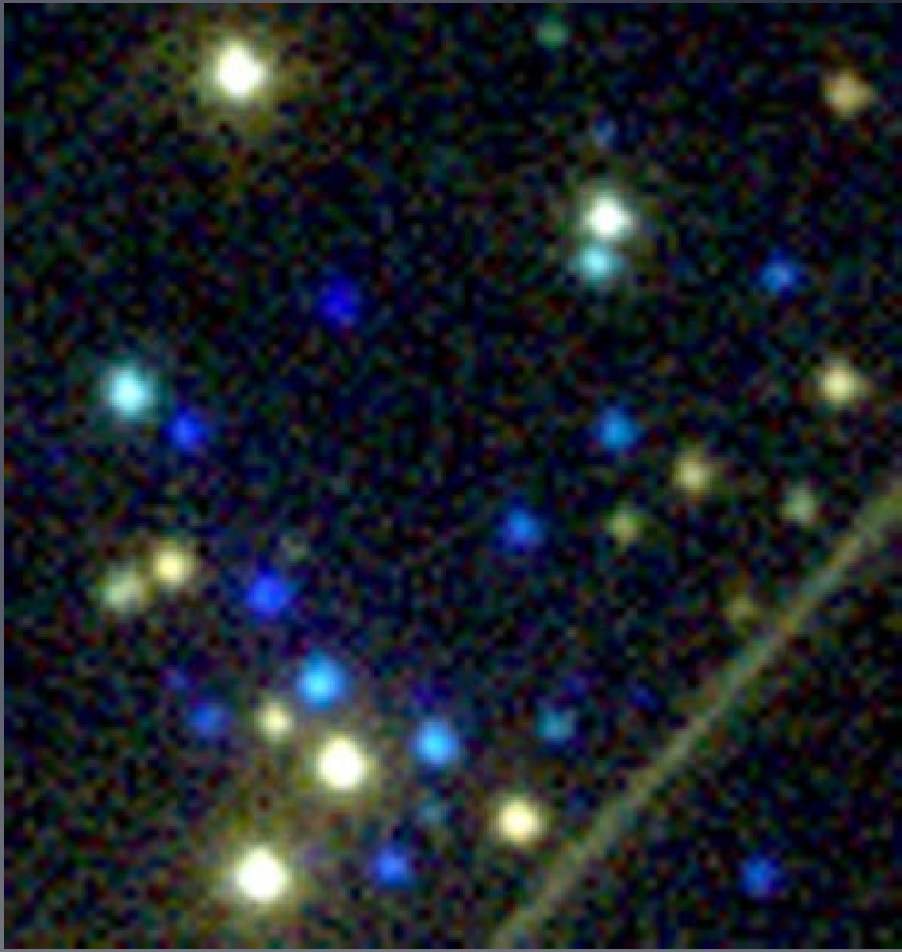
We might know about 10,000 YSOs in X-rays

- We know < 100 protostars,
- they are all faint
- They are all embedded
- They are all close to other X-ray sources

BN/KL Region



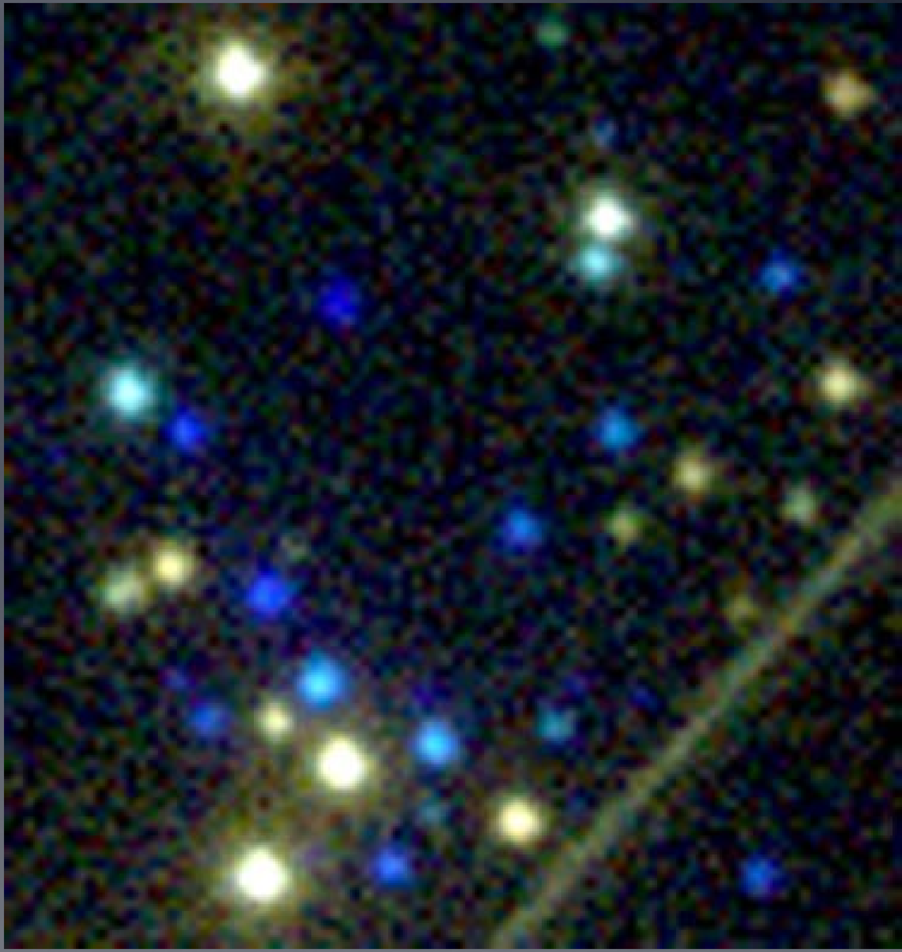
NICMOS 1999



COUP 2005

BN/KL Region

VLT 2005



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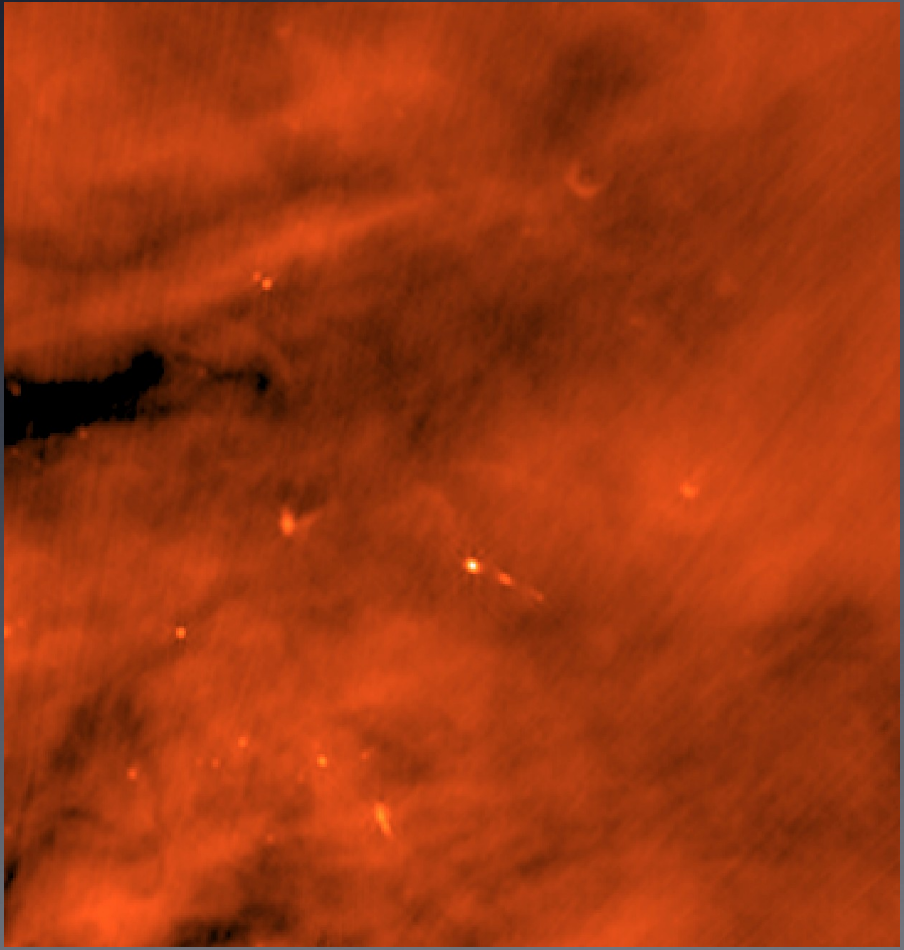
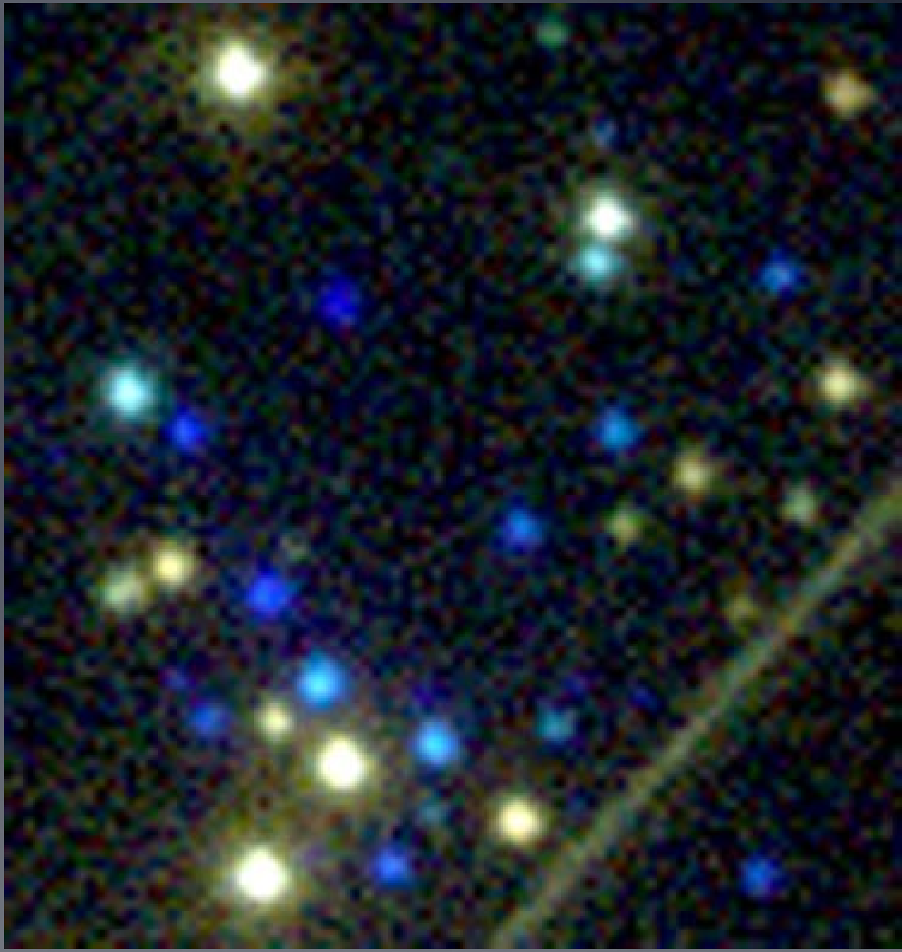


VLA 2016



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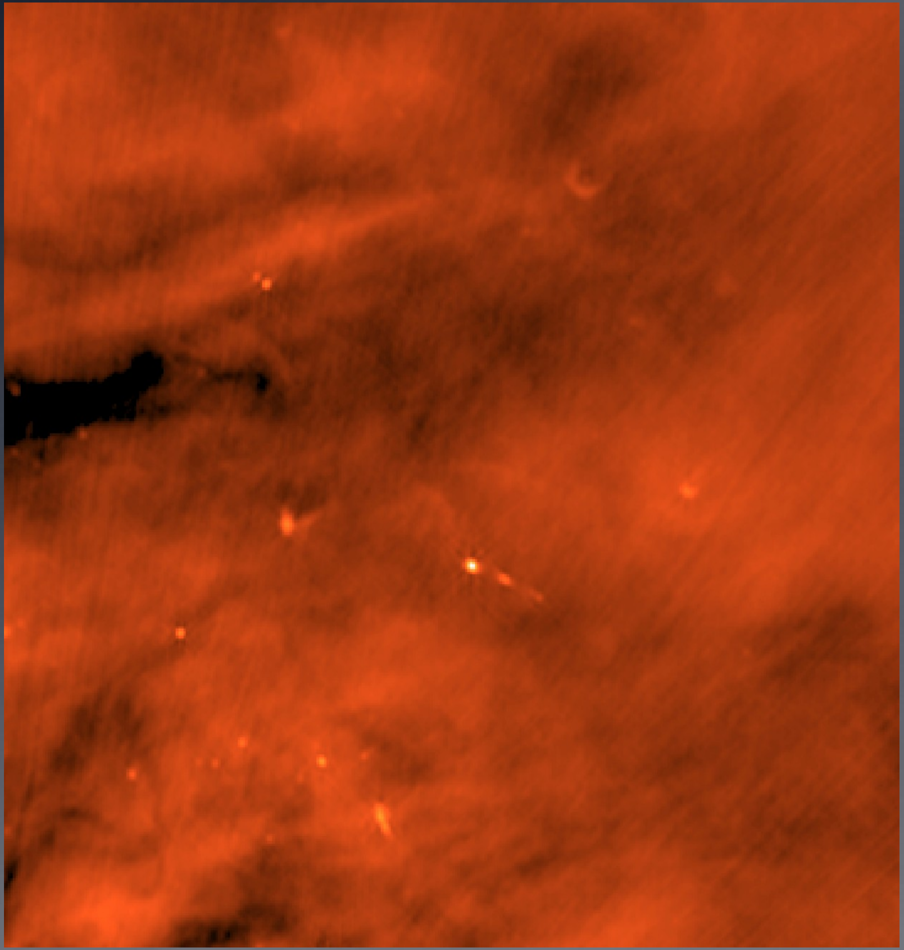

VLA 2016

Athena 2028

Athena will be great, but

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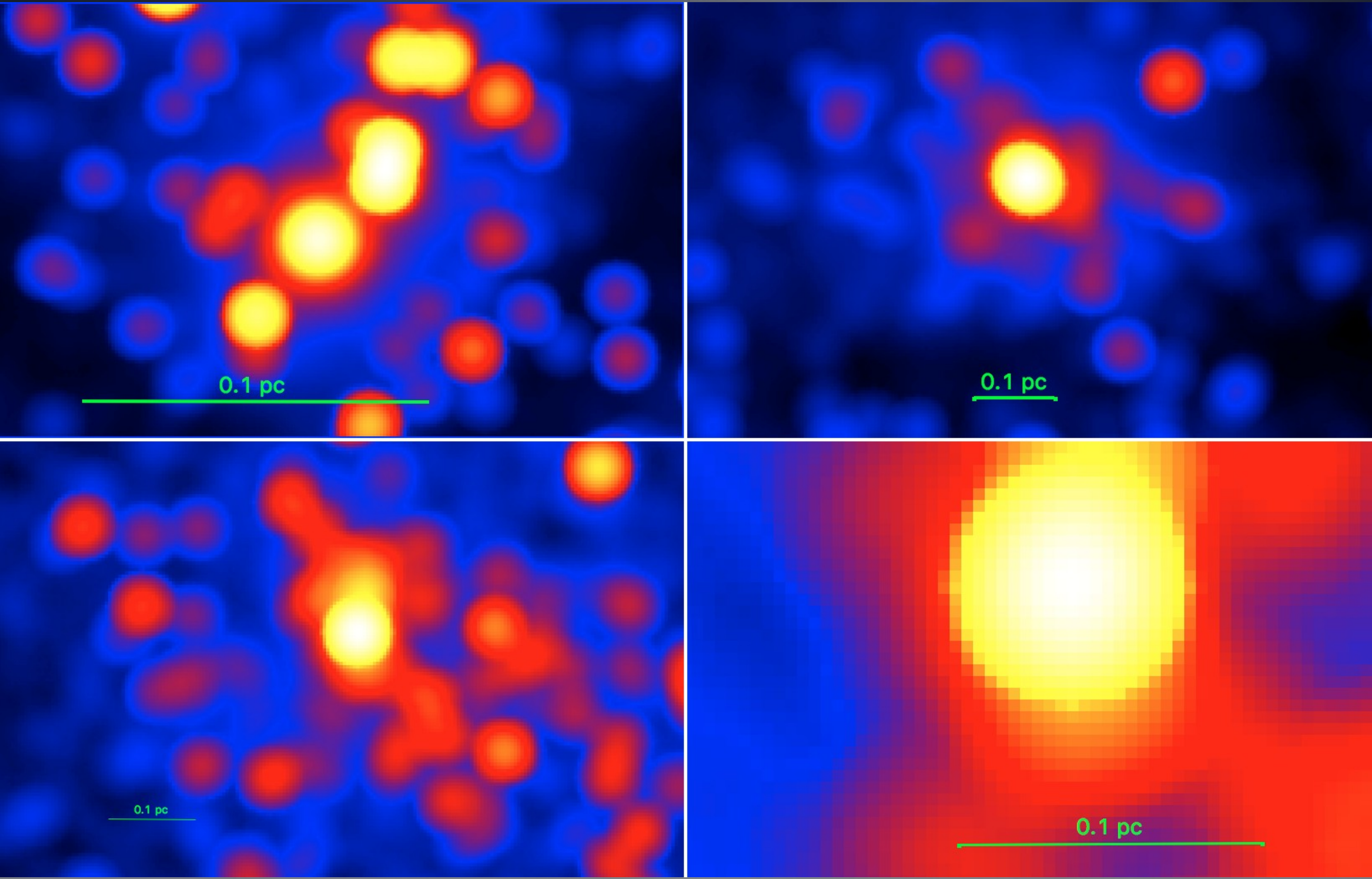
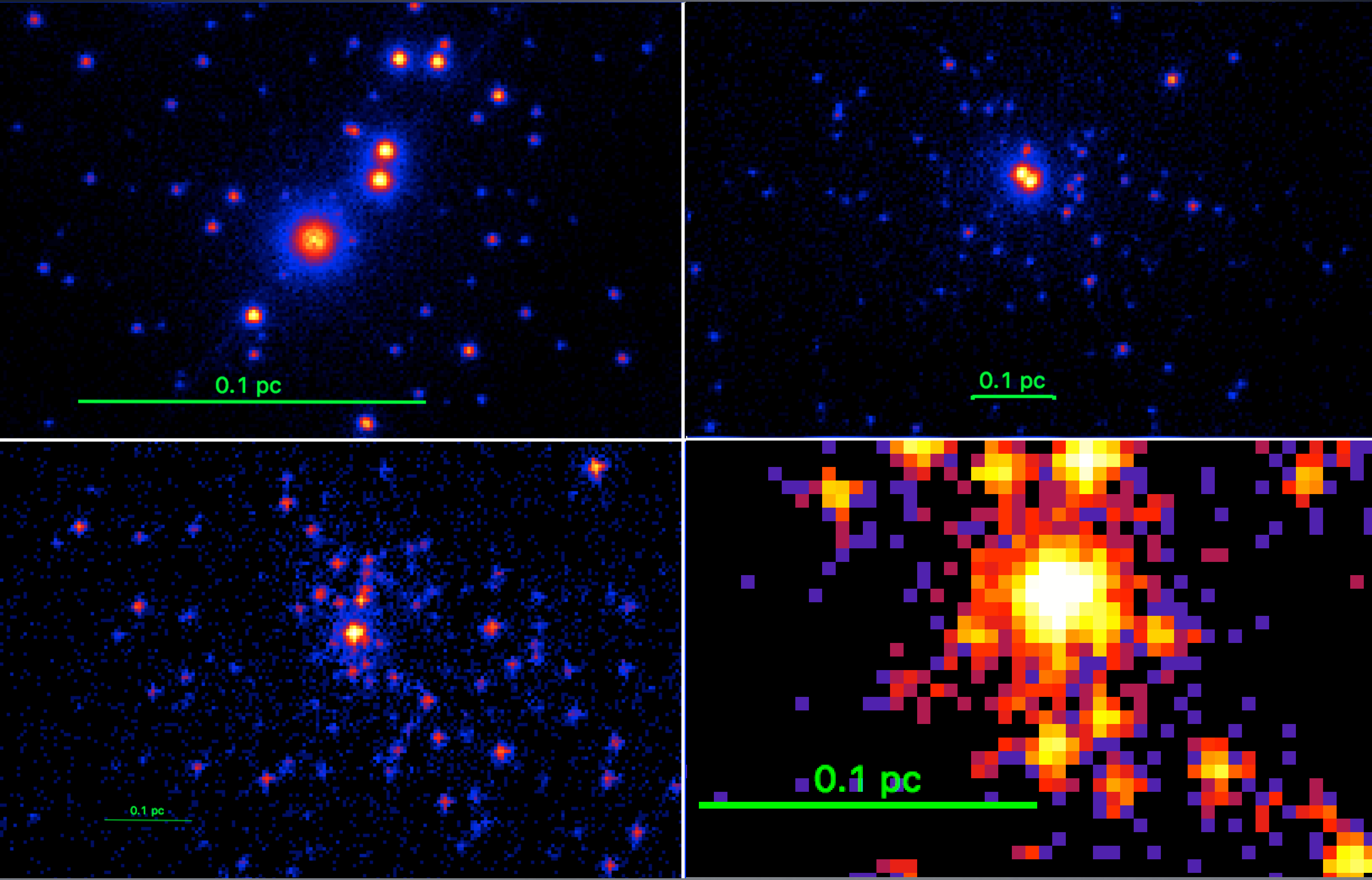
ONC M17



RCW 38

ONC M17



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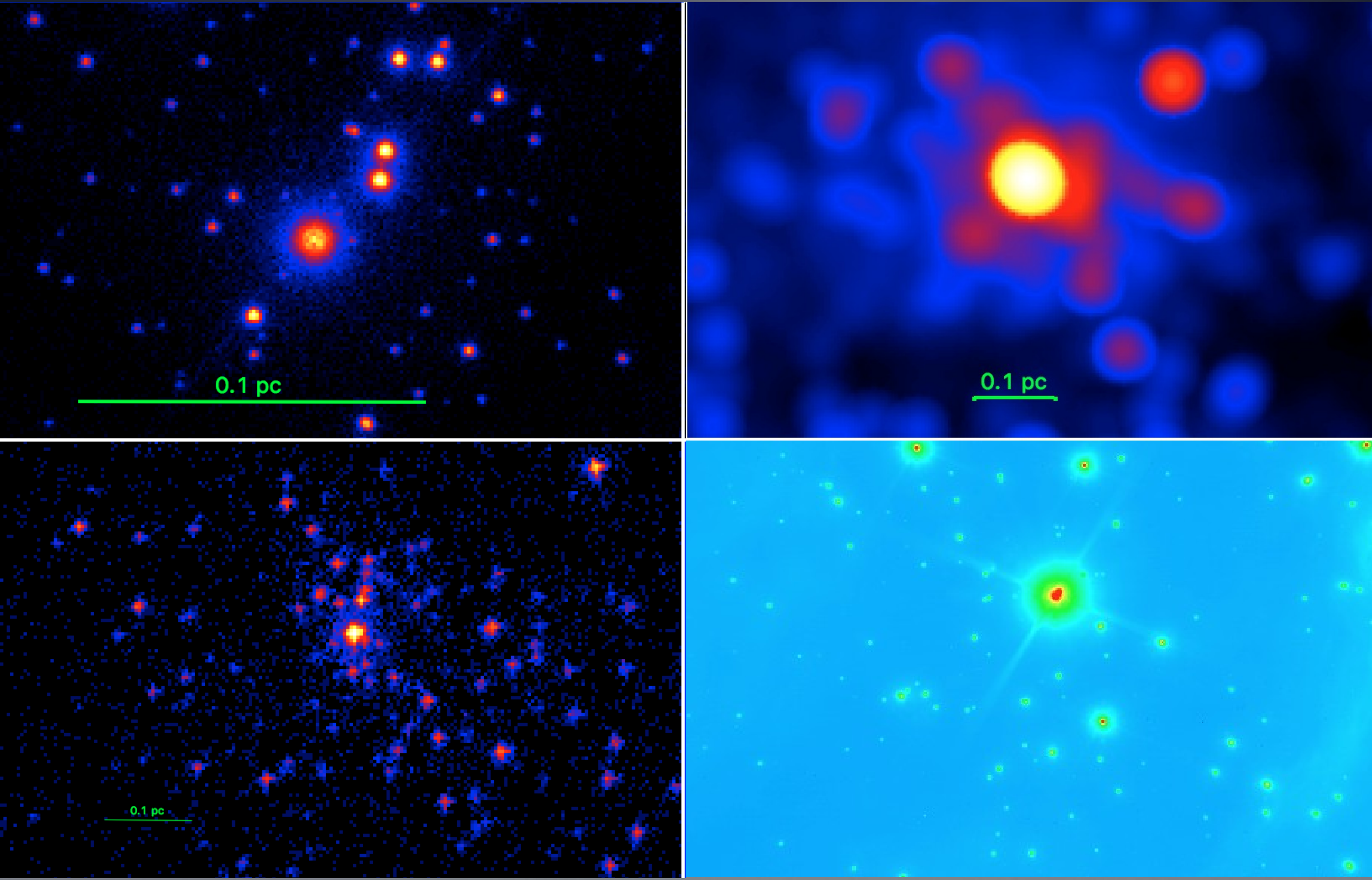
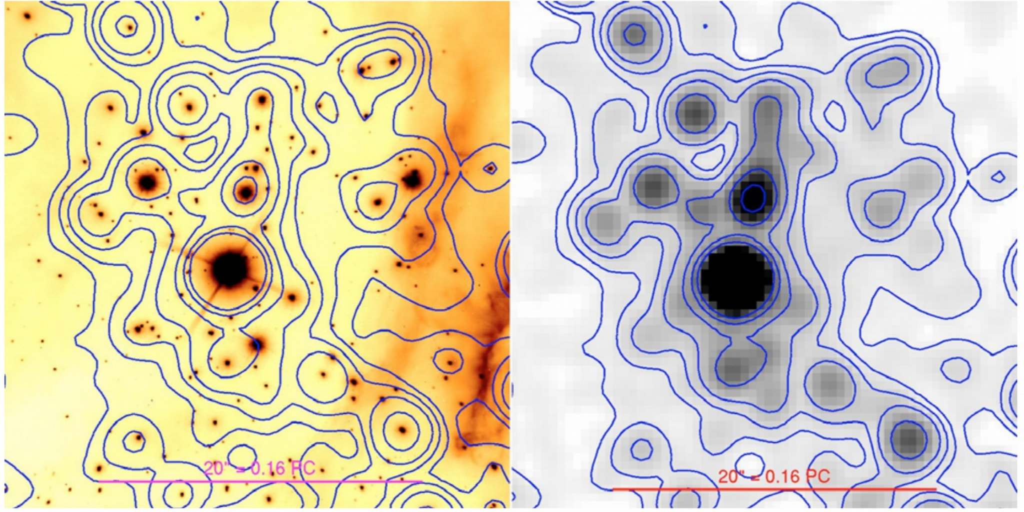


RCW 38

The program: Study Nearby Massive Star Formation Regions

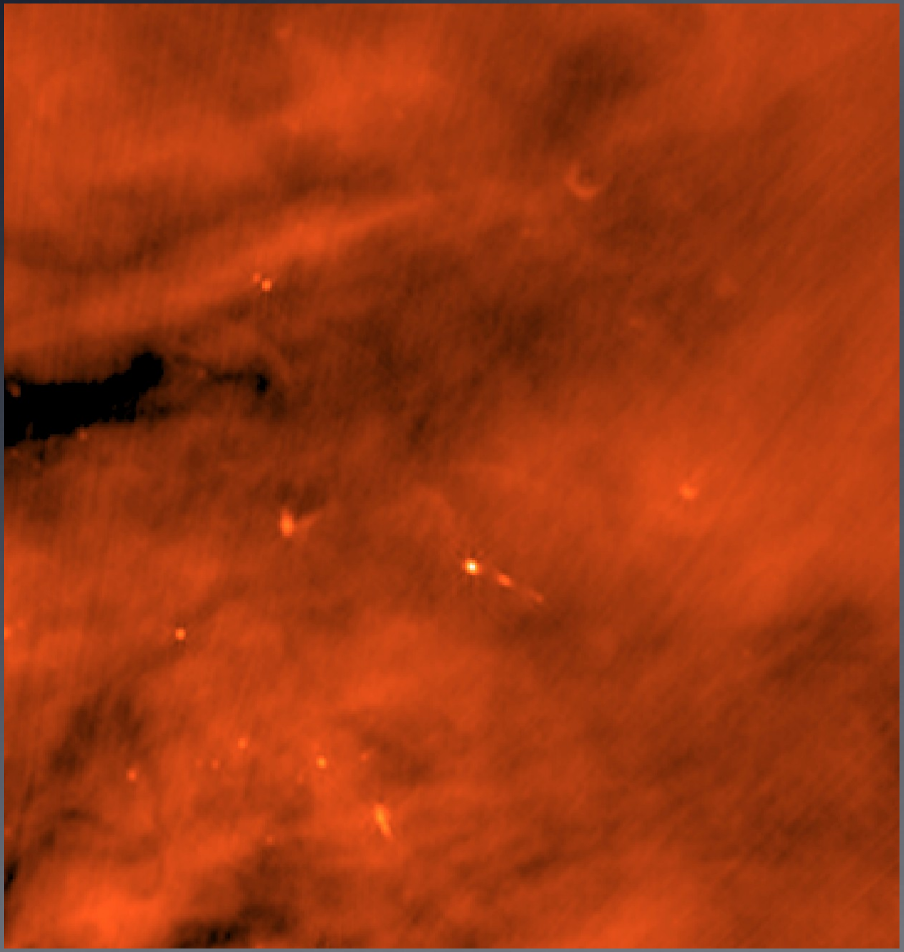
- Goals
  - Cluster Census
  - Transition disk timescales
  - X-ray effects on cluster morphology
  - Detecting grain evolution
  - X-rays from protostars
  - Effect of X-rays on planets and forming disks
    - Especially flares.
    - Understanding the magnetic fields.
  - Understanding diffuse emission and feedback.

- Targets
  - 30 Dor (LMC)
  - ARCHES (~8000pc)
  - NGC 3603 (6900 pc)
  - Carina (2400 pc)
  - NGC 281 (2100 pc)
  - RCW 38 (1700pc)
  - Etc.

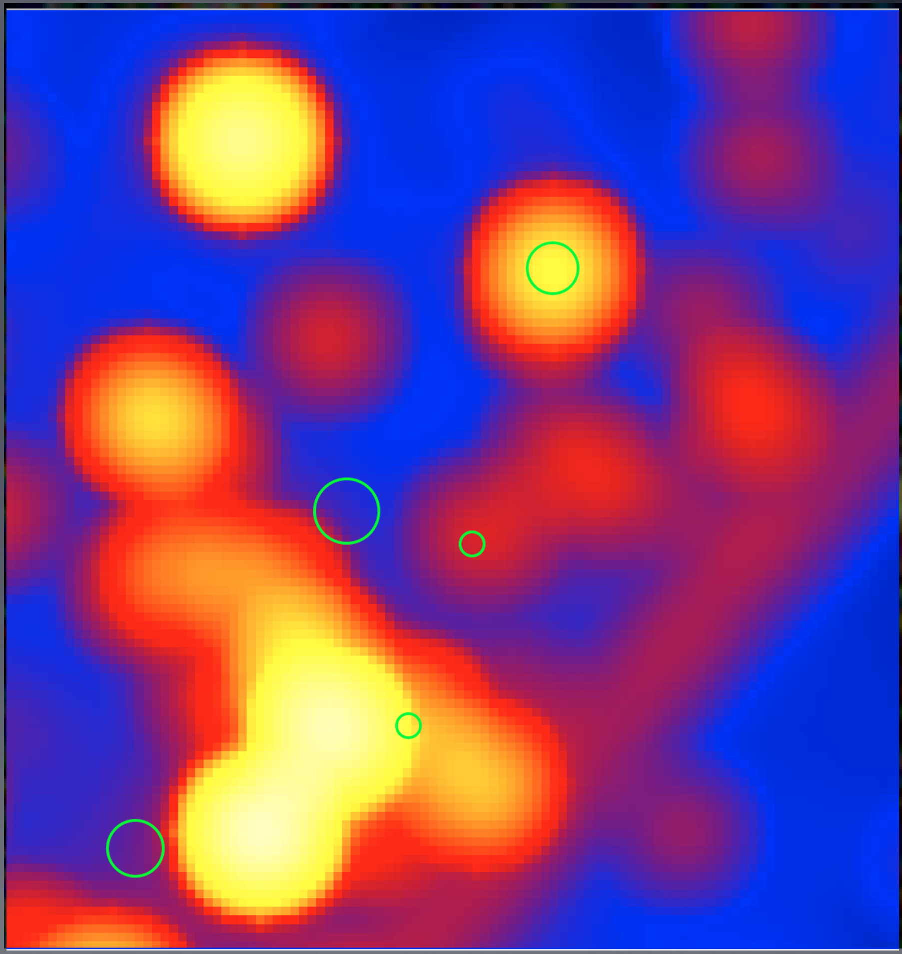


RCW 38
0.1” Left, 0.5” (Chandra) Right

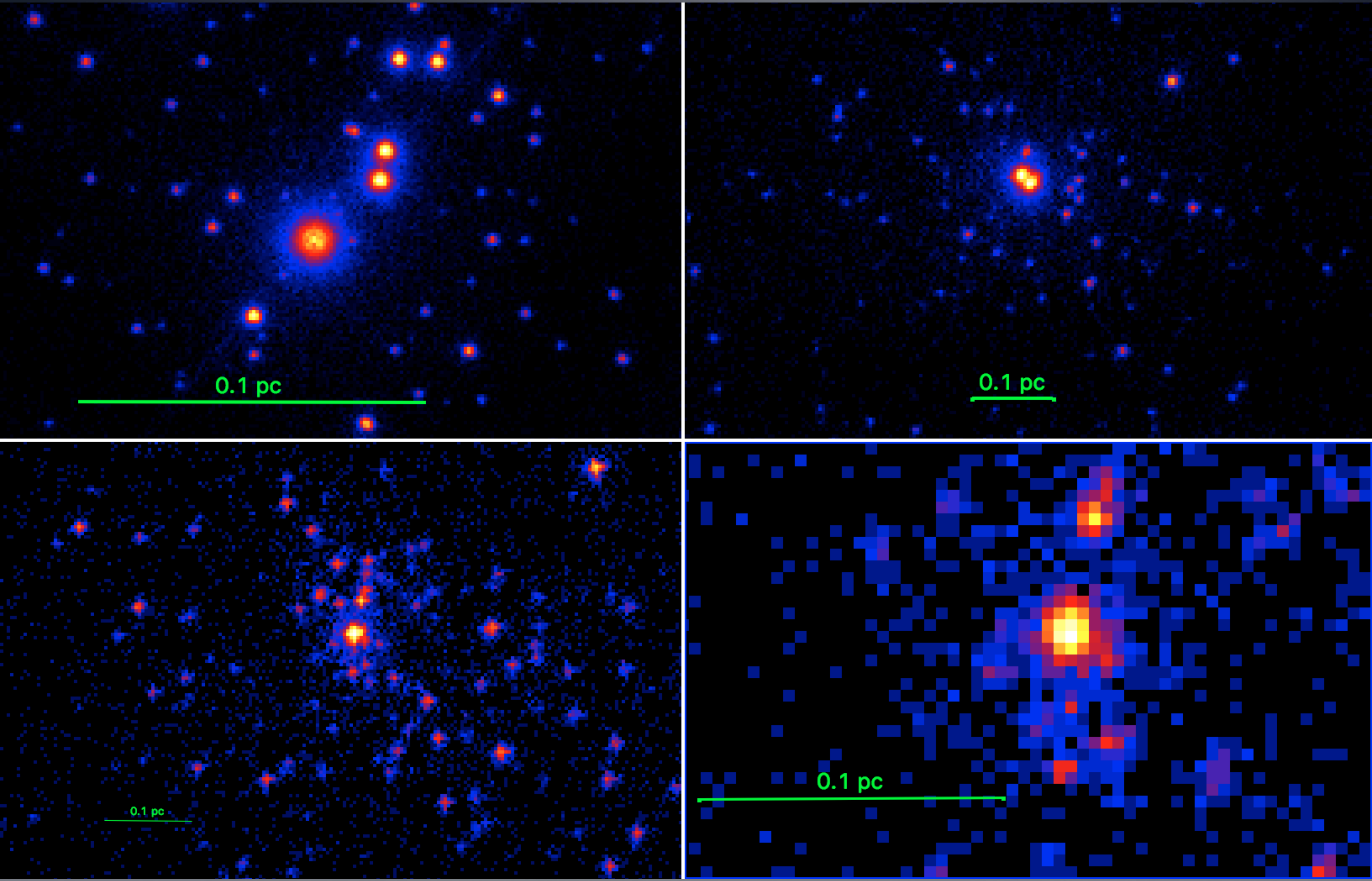
BN/KL Region



VLA 2016



Athena 2028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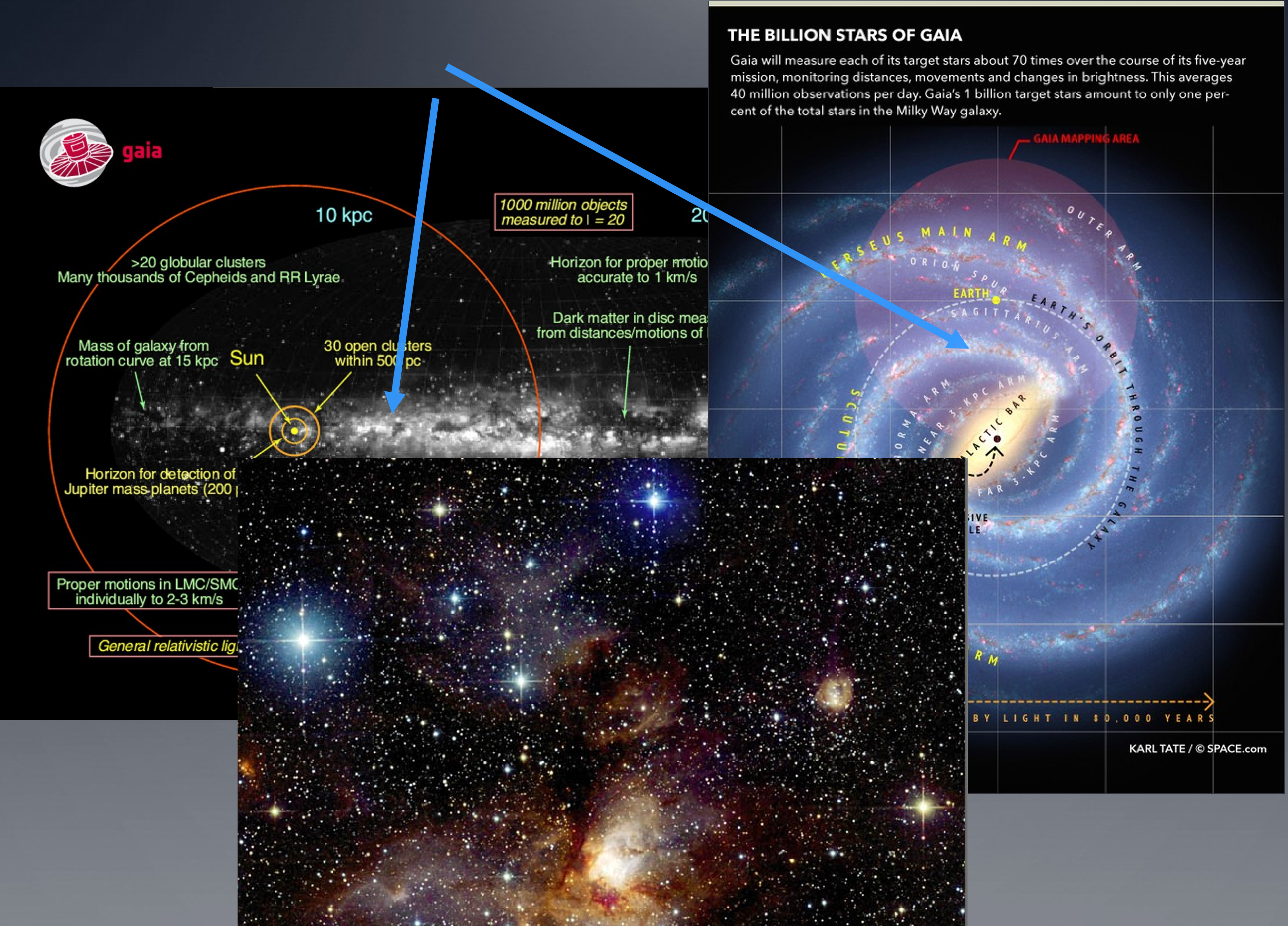

1000 million objects measured to I = 20

>20 globular clusters
Many thousands of Cepheids and RR Lyrae

Horizon for proper motio
accurate to 1 km/s

Mass of galaxy from
rotation curve at 15 kpc

30 open clusters
within 500 pc

Dark matter in disc meas
from distances/motions of

Horizon for detection of
Jupiter mass planets (200

Proper motions in LMC/SMC
individually to 2-3 km/s

General relativistic lig

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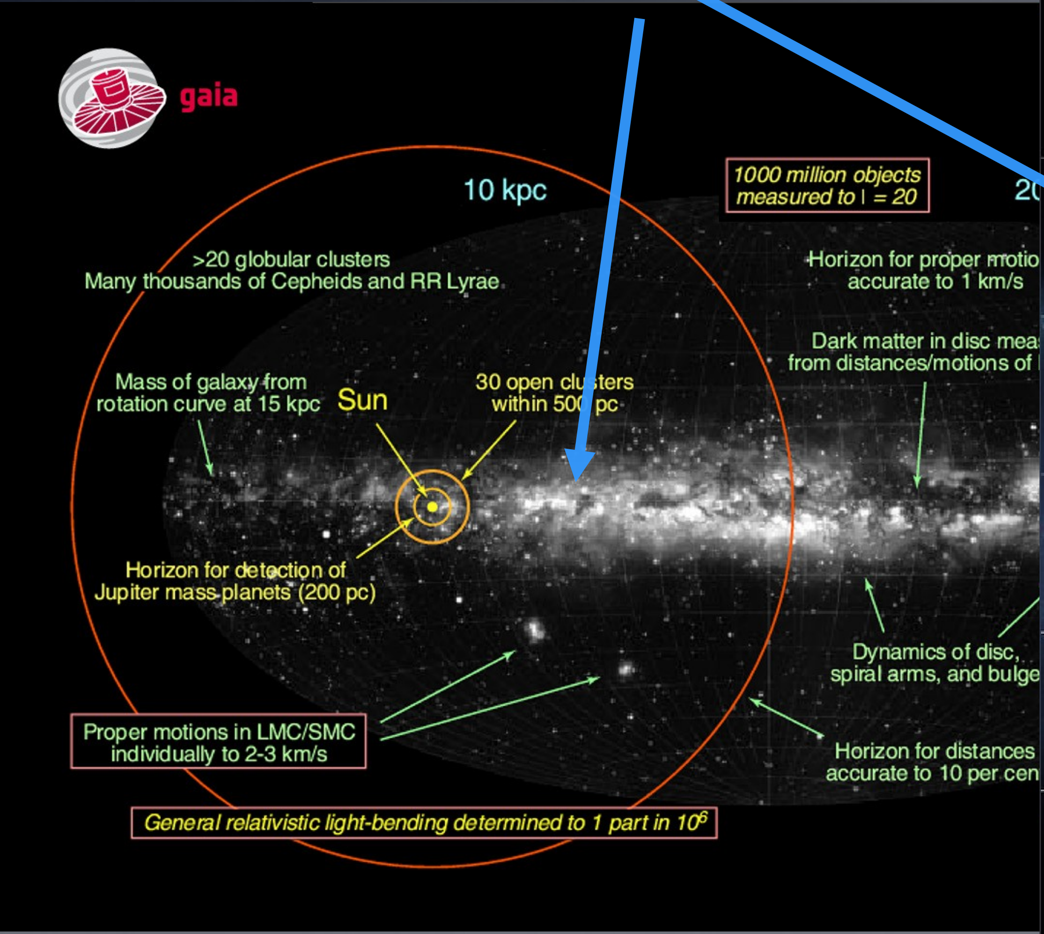
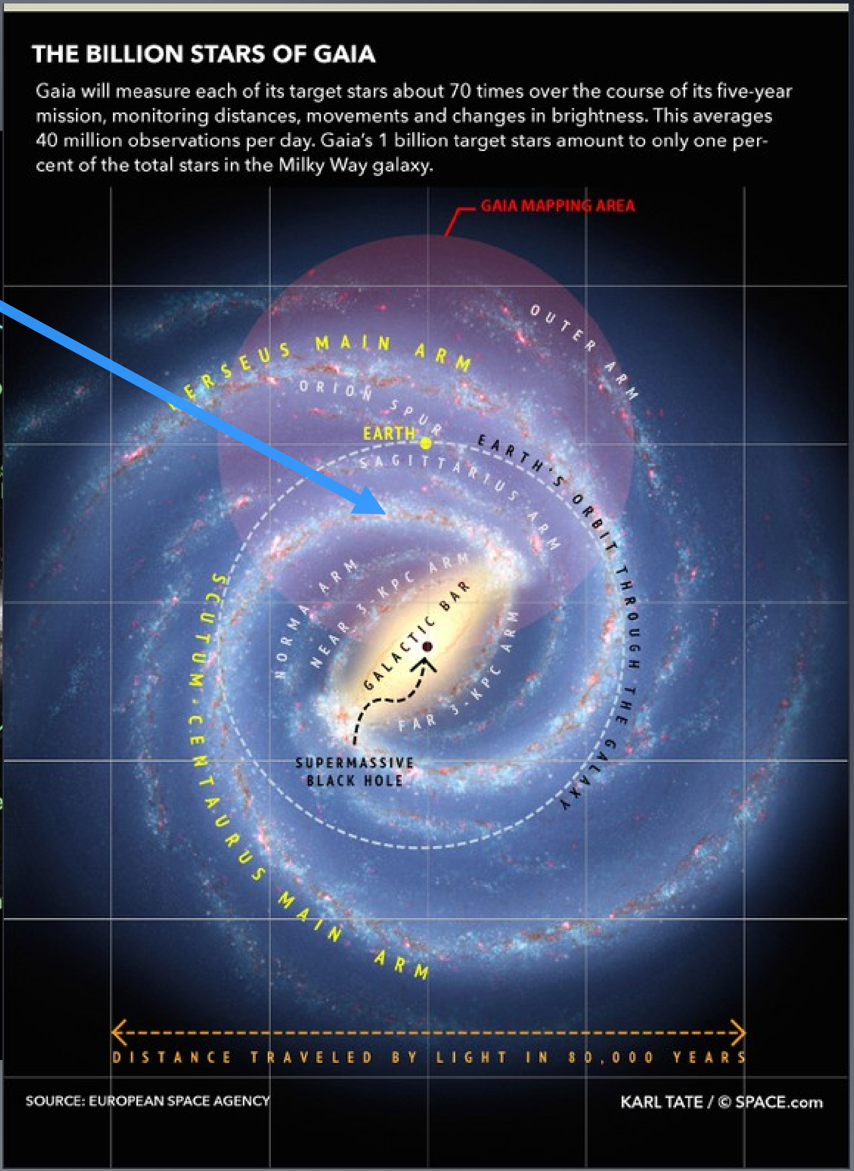
KARL TATE / © SPACE.com





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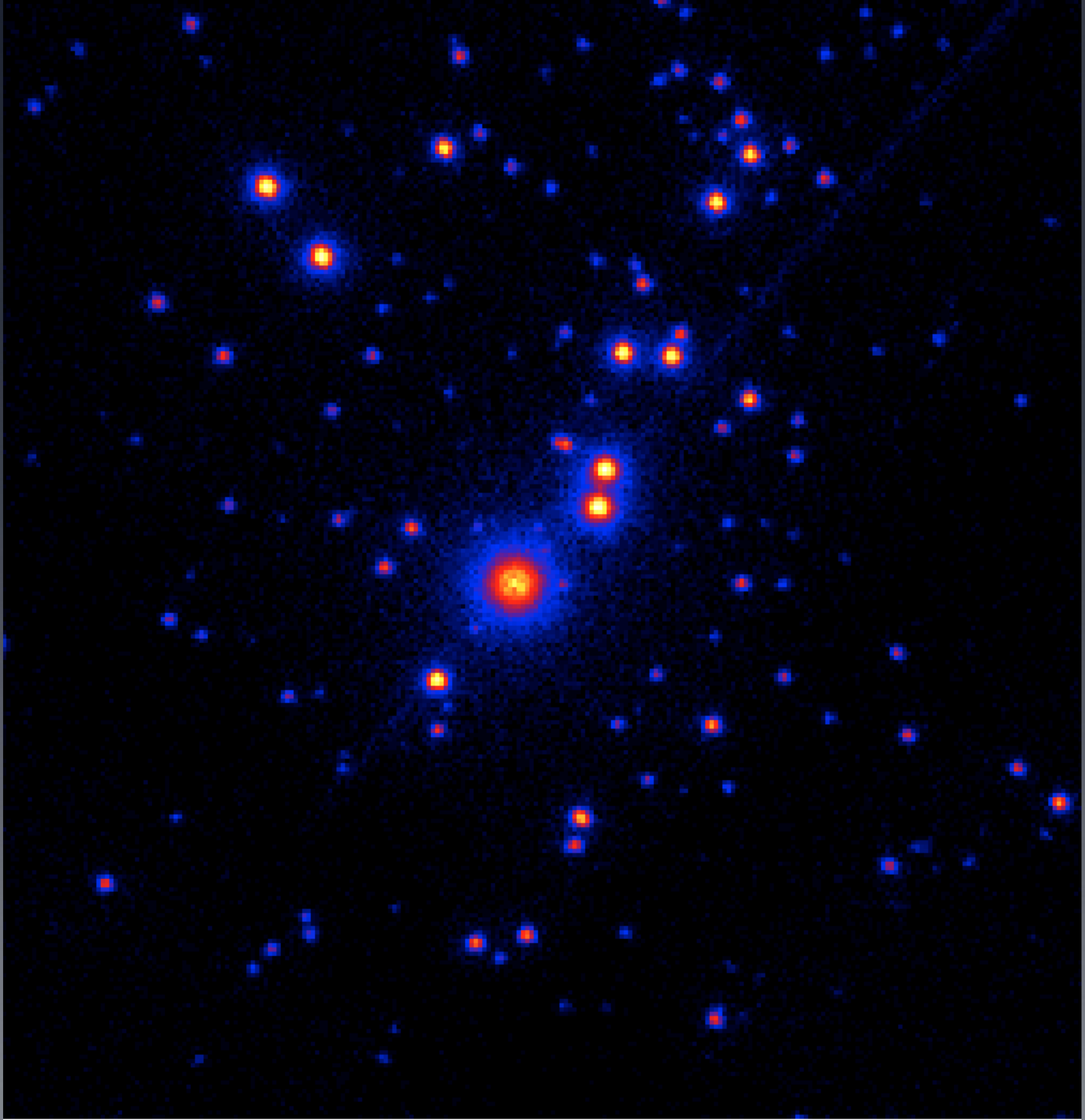
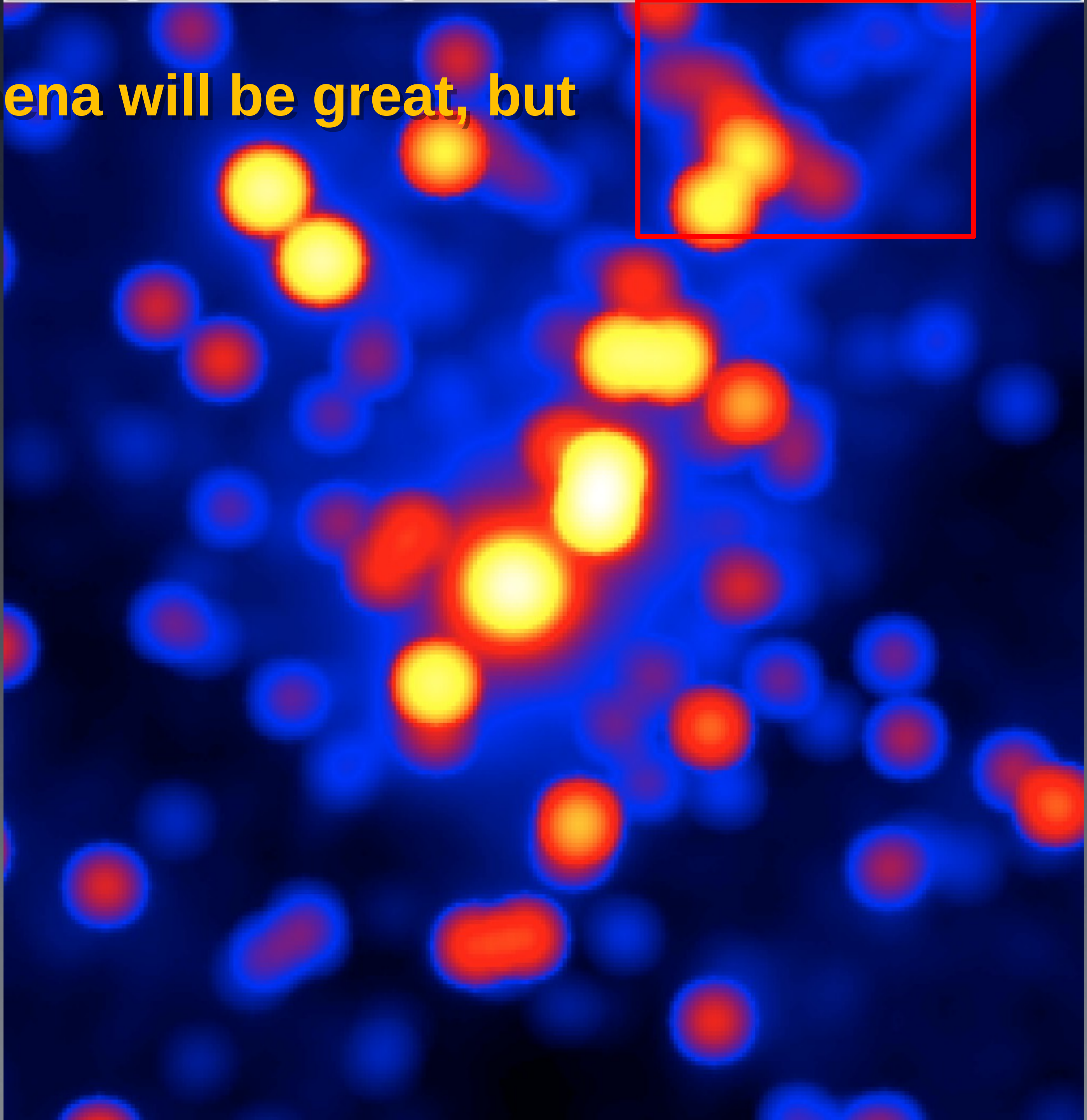
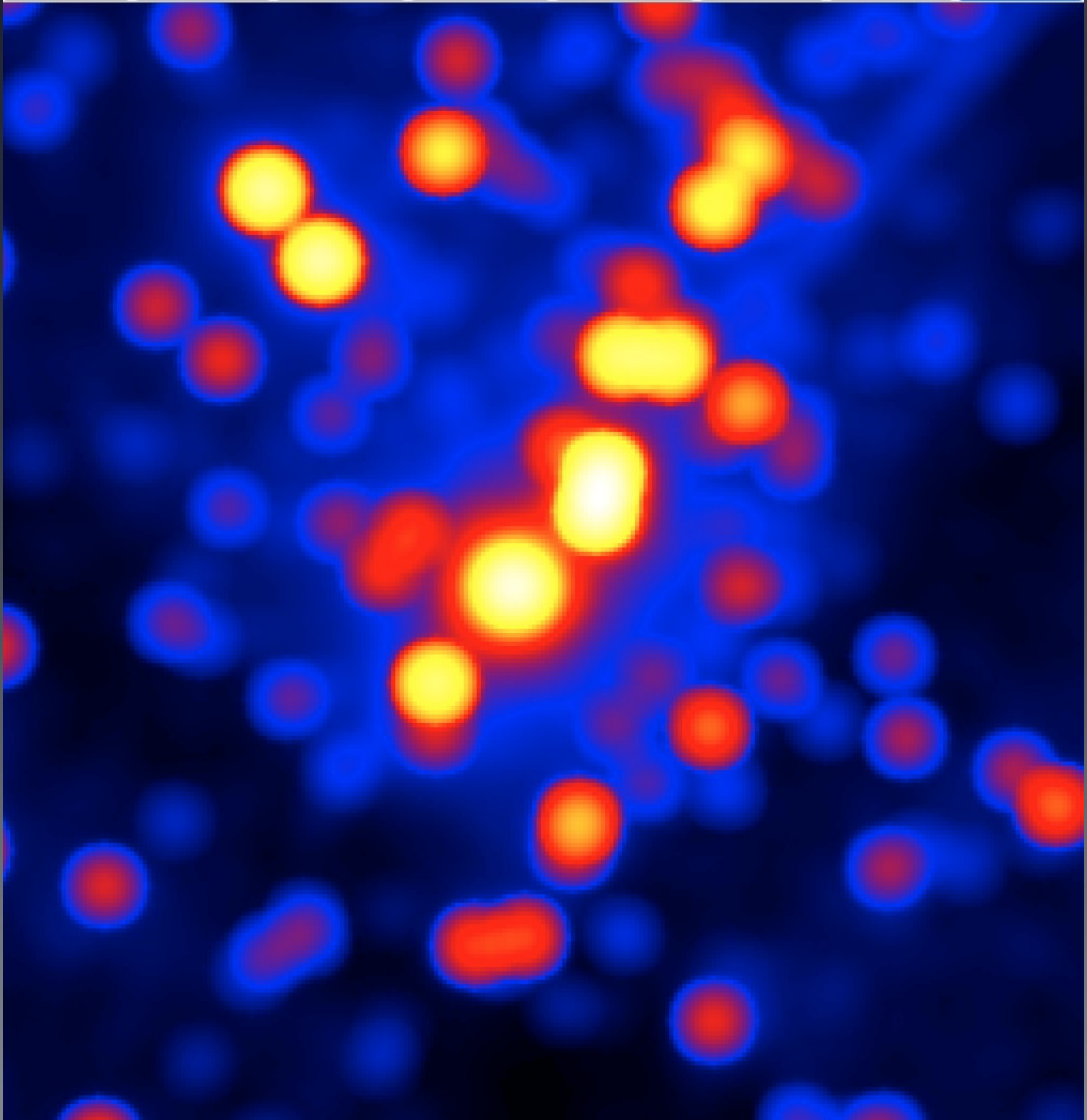
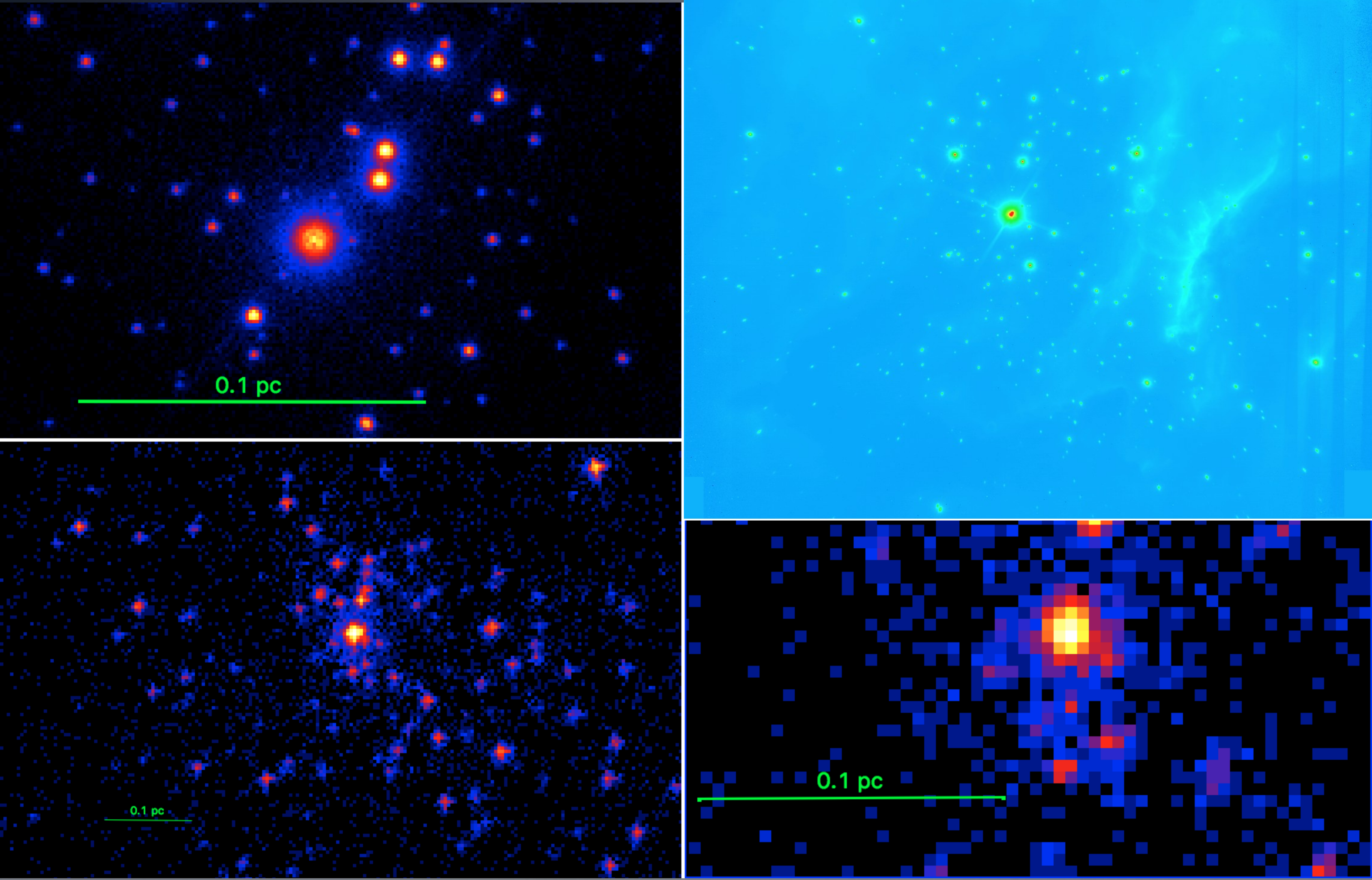


Athena will be great, but



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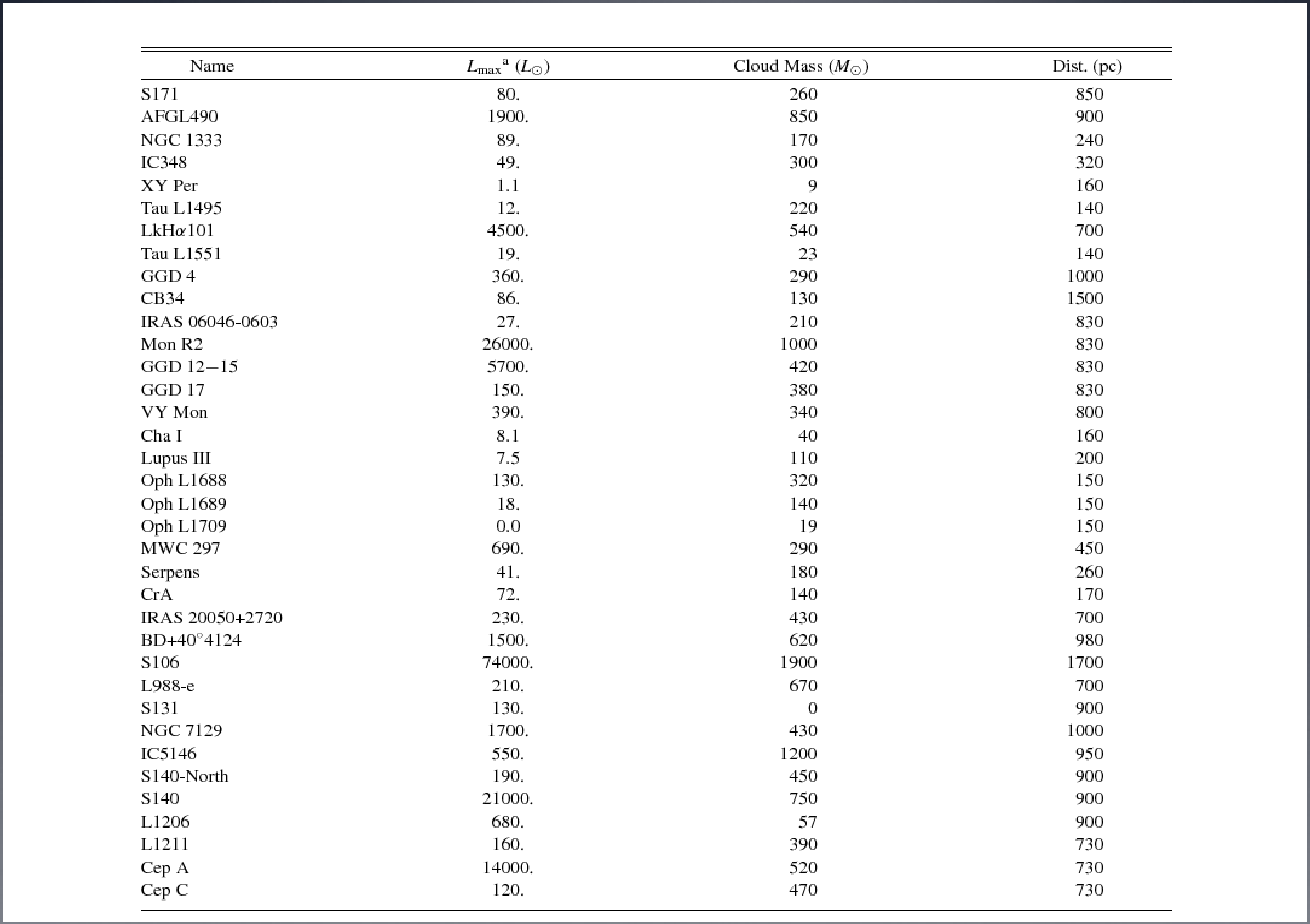
What is the Diffuse Emission?

- Diffuse Emission has now been reported in about half a dozen regions of massive star formation
- An X-ray halo around IRS 2?
  - Diffuse flux is much harder than that of IRS 2.
- Thermal emission?
  - Would need to be hot ~ 10keV electrons.
  - Pressure would be high leading to shocks.
  - No lines seen.
  - Wind driven models of diffuse emission tend have cooler & thermal emission profiles.
- Spectrum dominated by power-law.
  - Synchrotron □ B field to excite electrons
  - Common in SNR but lack of lines implies a shell type SNR, not consistent with the morphology.
  - Energetics
    - L_x~$3x10^{32}$ ergs/sec
    - Assuming Equipartition
      - B~4.9μG
      - $2.2x10^{44}$ ergs in relativistic electrons
      - e^- should decay in 20,000 years (unique among star forming regions)
      - Caused by recent SN? or…
      - Replenished by colliding winds ?
  - Shell supernovae remnants tend to be symmetric

Athena will be great, but

Embedded clusters within ~ 1 kpc

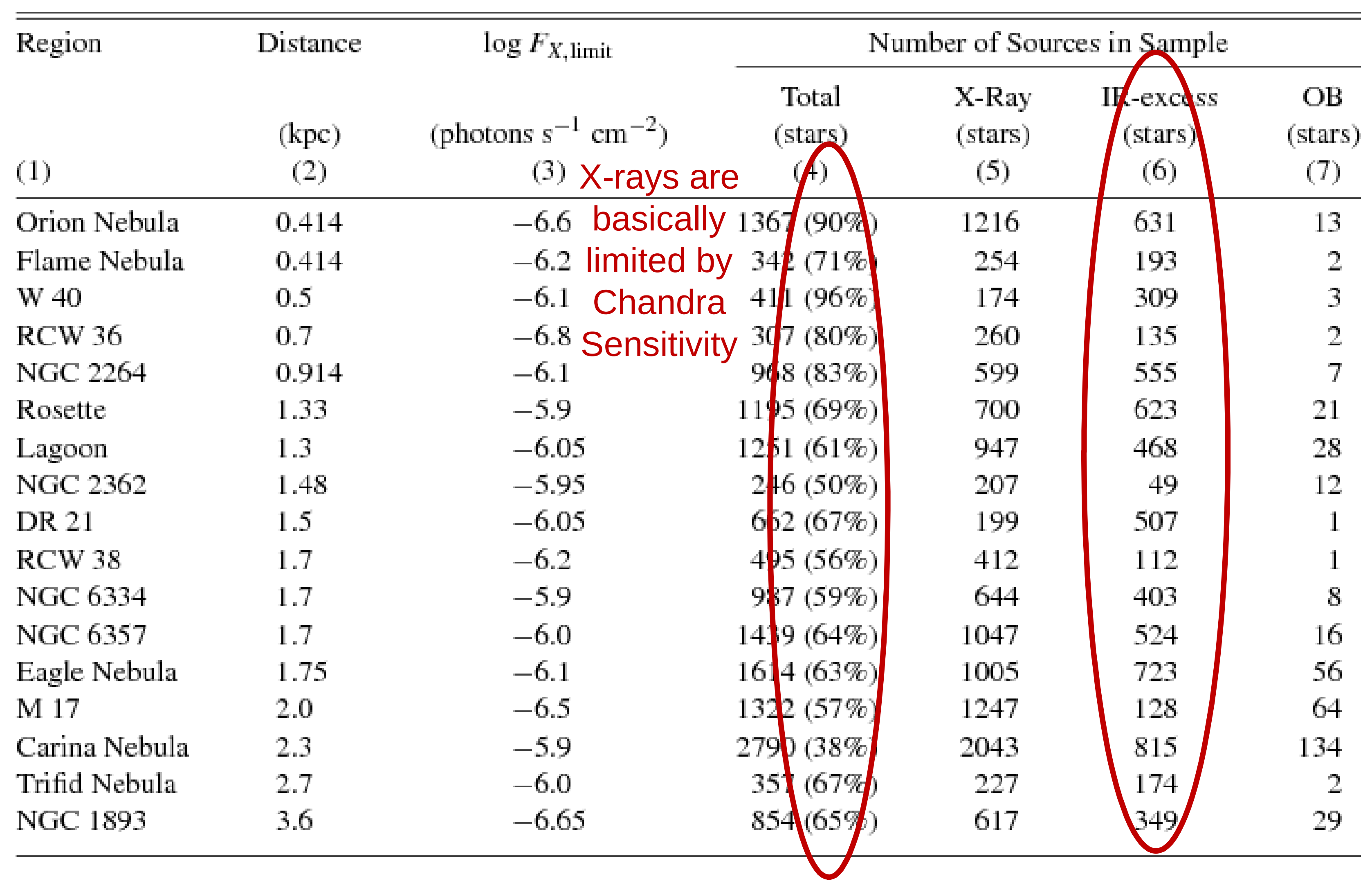


Name	$L_{\max}$[a] ($L_{\odot}$)	Cloud Mass ($M_{\odot}$)	Dist. (pc)
S171	80.	260	850
AFGL490	1900.	850	900
NGC 1333	89.	170	240
IC348	49.	300	320
XY Per	1.1	9	160
Tau L1495	12.	220	140
LkHα101	4500.	540	700
Tau L1551	19.	23	140
GGD 4	360.	290	1000
CB34	86.	130	1500
IRAS 06046-0603	27.	210	830
Mon R2	26000.	1000	830
GGD 12–15	5700.	420	830
GGD 17	150.	380	830
VY Mon	390.	340	800
Cha I	8.1	40	160
Lupus III	7.5	110	200
Oph L1688	130.	320	150
Oph L1689	18.	140	150
Oph L1709	0.0	19	150
MWC 297	690.	290	450
Serpens	41.	180	260
CrA	72.	140	170
IRAS 20050+2720	230.	430	700
BD+40°4124	1500.	620	980
S106	74000.	1900	1700
L988-e	210.	670	700
S131	130.	0	900
NGC 7129	1700.	430	1000
IC5146	550.	1200	950
S140-North	190.	450	900
S140	21000.	750	900
L1206	680.	57	900
L1211	160.	390	730
Cep A	14000.	520	730
Cep C	120.	470	730

Gutermuth et al. (2009)

Census

IR sources are only about 50% of the clusters



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RCW 36	0.7	−6.8	307 (80%)	260	135	2
NGC 2264	0.914	−6.1	968 (83%)	599	555	7
Rosette	1.33	−5.9	1195 (69%)	700	623	21
Lagoon	1.3	−6.05	1251 (61%)	947	468	28
NGC 2362	1.48	−5.95	246 (50%)	207	49	12
DR 21	1.5	−6.05	662 (67%)	199	507	1
RCW 38	1.7	−6.2	495 (56%)	412	112	1
NGC 6334	1.7	−5.9	987 (59%)	644	403	8
NGC 6357	1.7	−6.0	1439 (64%)	1047	524	16
Eagle Nebula	1.75	−6.1	1614 (63%)	1005	723	56
M 17	2.0	−6.5	1322 (57%)	1247	128	64
Carina Nebula	2.3	−5.9	2790 (38%)	2043	815	134
Trifid Nebula	2.7	−6.0	357 (67%)	227	174	2
NGC 1893	3.6	−6.65	854 (65%)	617	349	29

X-rays are basically limited by Chandra Sensitivity

Kuhn et al. (2014)