# 25 years in the life of SN 1987A


## Revealing the highest resolution X-ray structure with **Chandra and Jolideco**

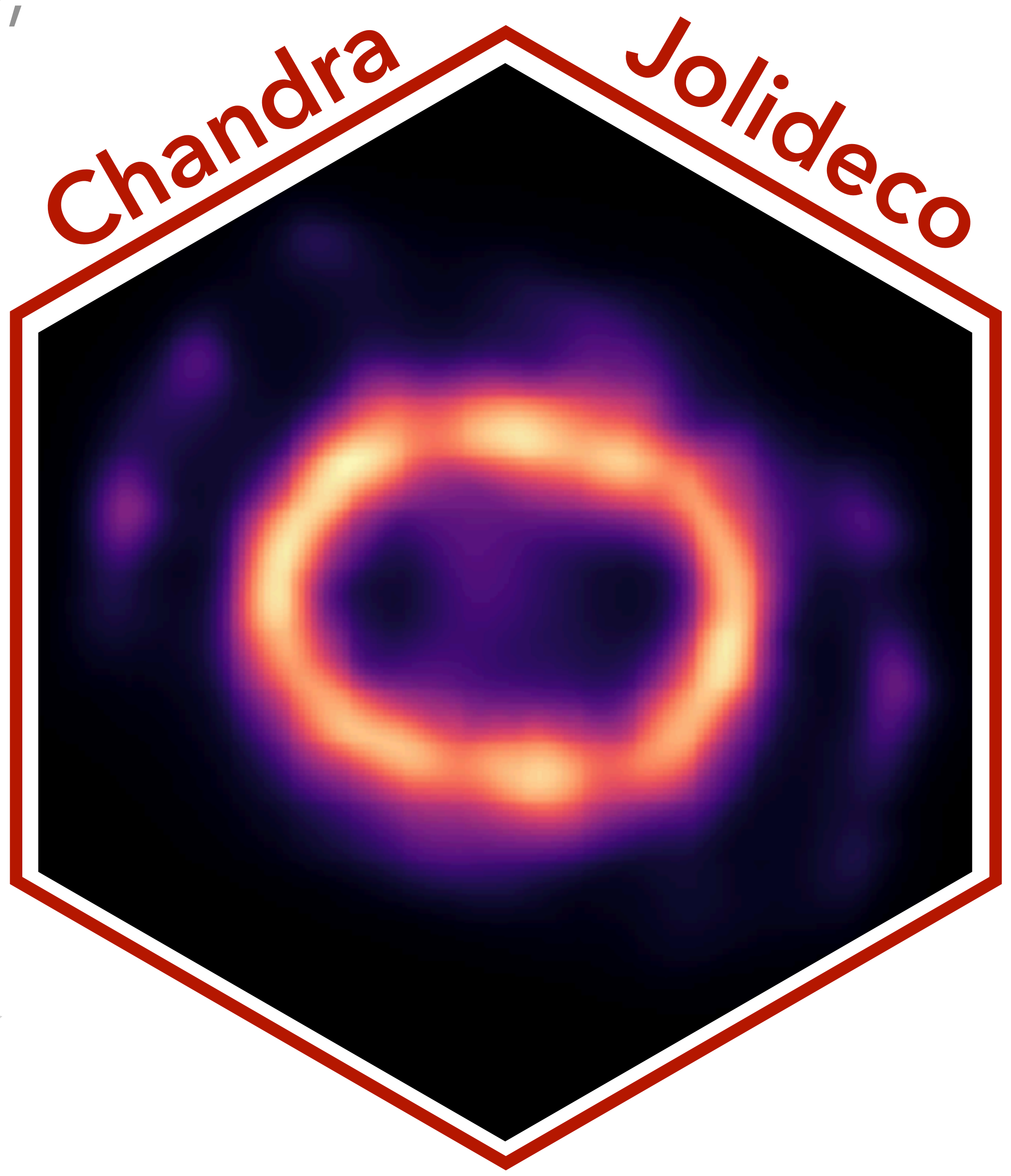
**Axel Donath**, A.Siemiginowska, V.Kashap,
D. Burke and D. van Dyk

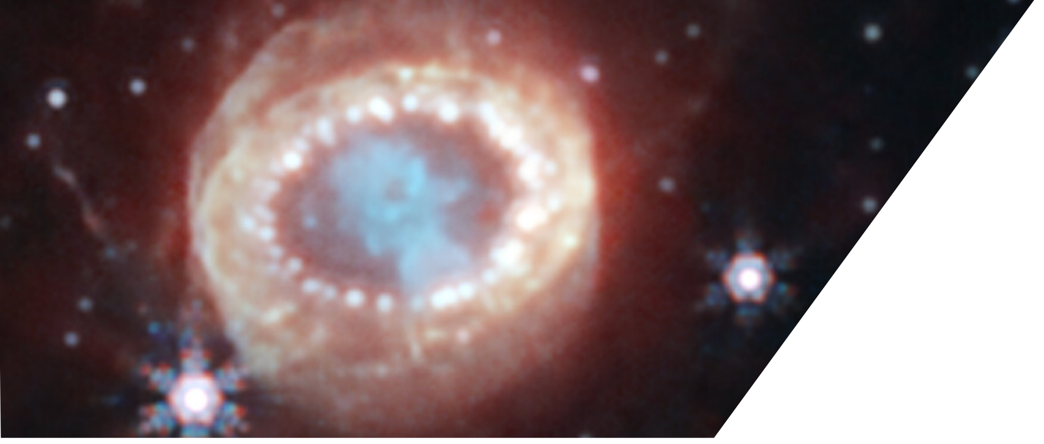
"25 Years of Science with Chandra"
Symposium, Boston, Dec 4th, 2025

$$\mathscr{L}(\mathbf{d}\,|\,\lambda) = \prod_i^N \frac{\lambda_i^{d_i} e^{-d_i}}{d_i!}$$

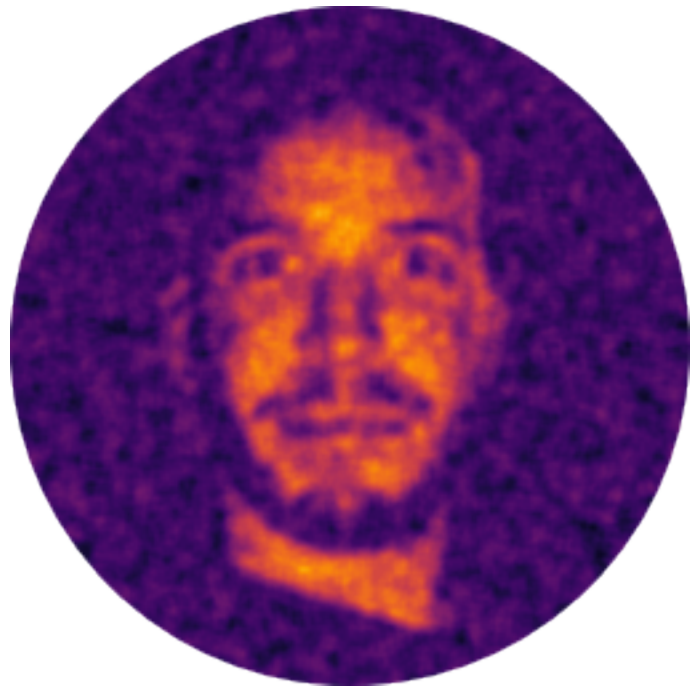
$$\lambda = \mathbf{x} \circledast \mathrm{PSF}$$

$$\lambda_i = \sum_k \left(e_i \cdot (x_i + b_i)\right) p_{i-k}$$

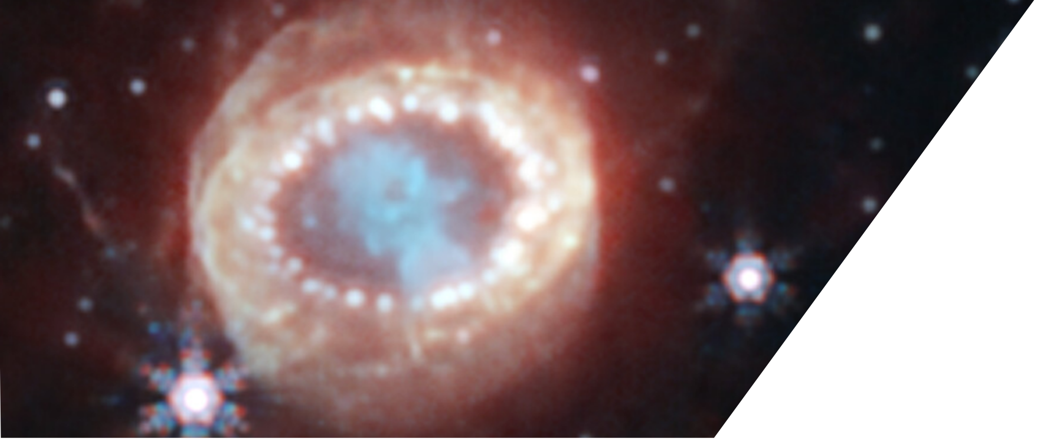




# About me

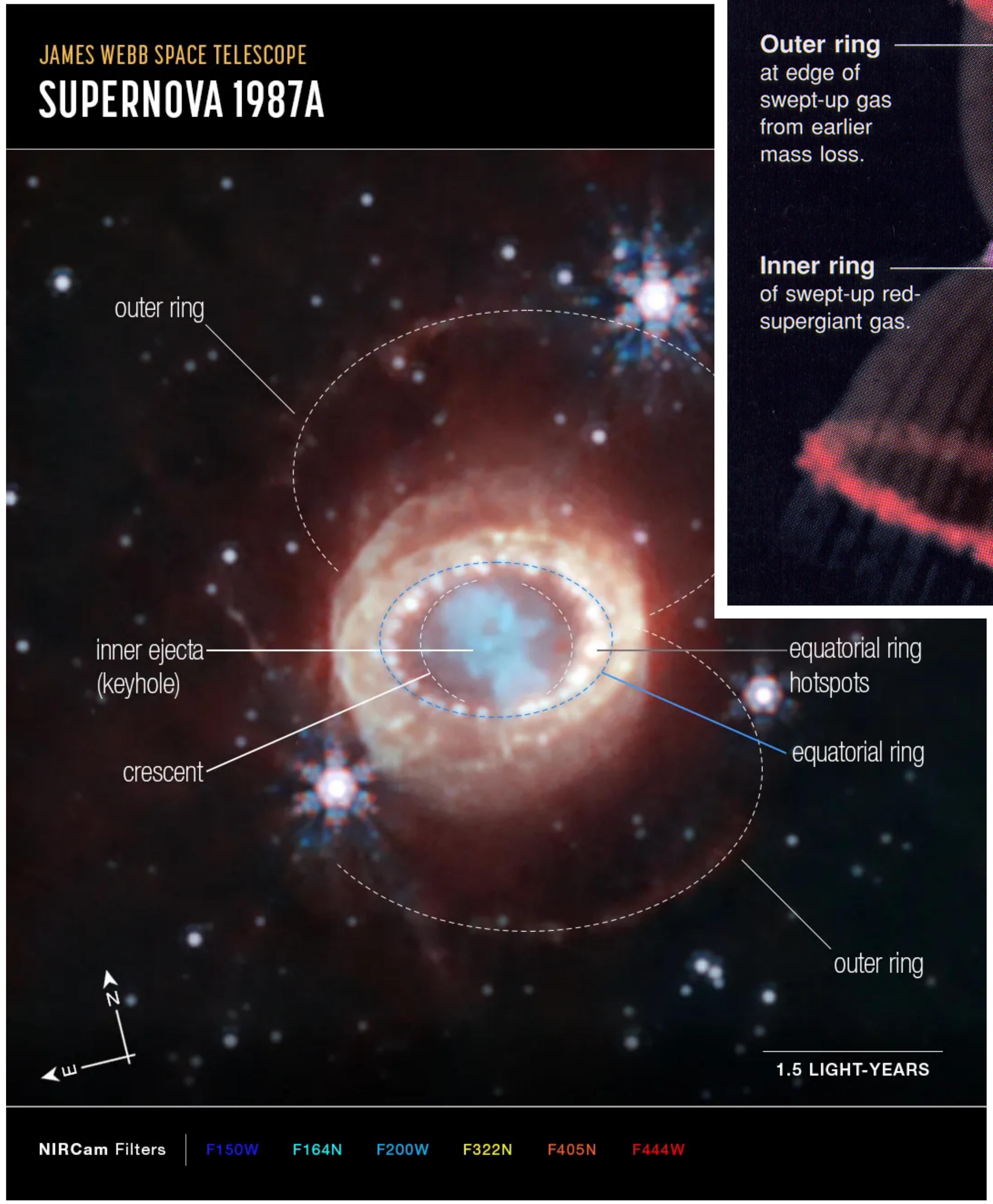


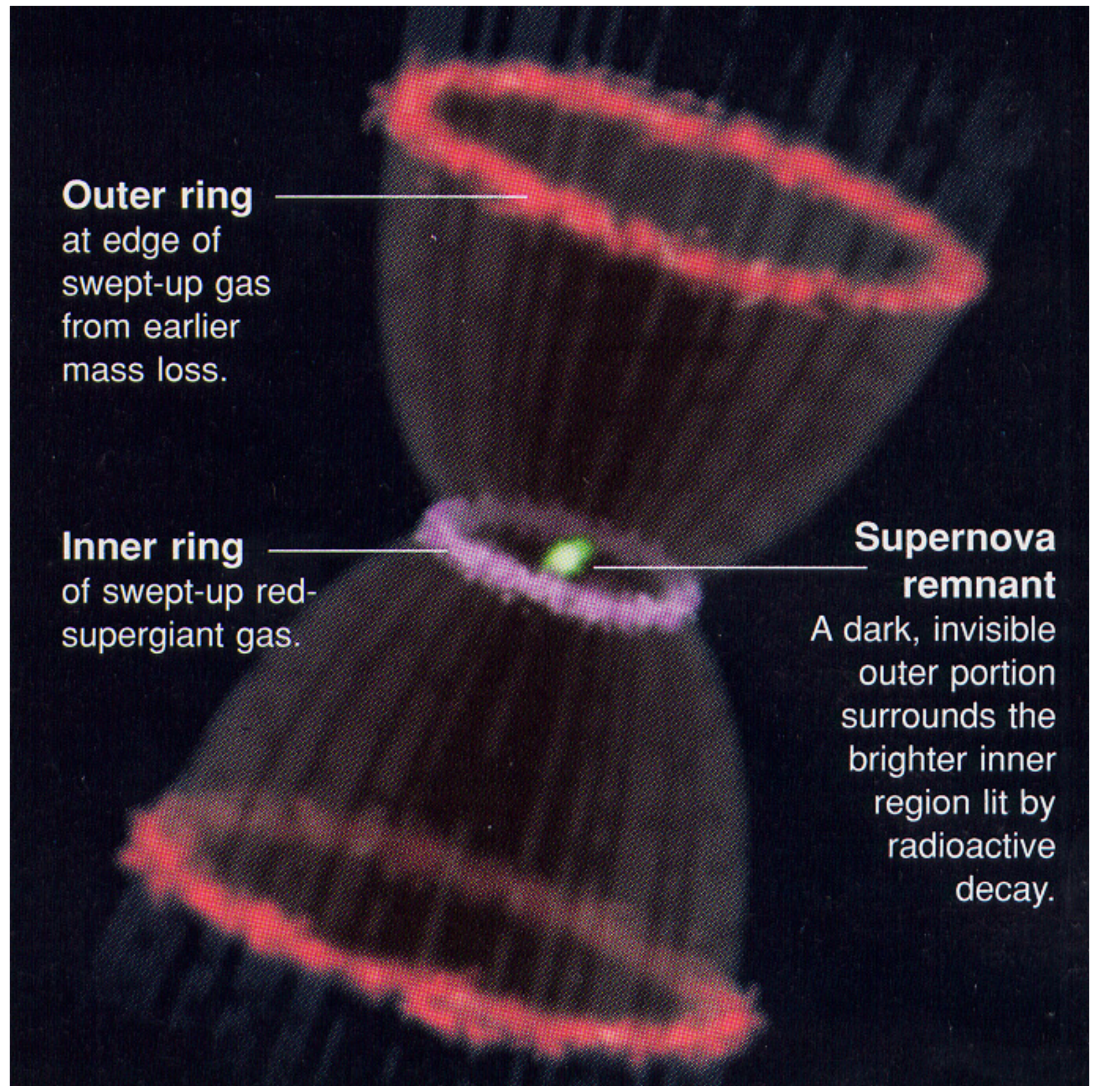
- Postdoctoral Researcher in the CHASC astrostatistics group: https://hea-www.harvard.edu/astrostat/ at the Center for Astrophysics (CfA)
- I work on new analysis methods for low-counts X-ray and gamma-ray data and apply them to selected science cases
- Before I joined CfA,I mostly worked in TeV gamma-rays and the H.E.S.S. Galactic Plane Survey
- Interest open source software development, follow me on GitHub: https://github.com/adonath
- Find more about my work on: axeldonath.com
- **Disclaimer:** I am not an expert on the object SN 1987A, neither on the physics behind! My motivation is from the "data science" and statistics perspective! But I am more than happy to talk to all the experts in the audience!



# SN 1987A overview

- Located in the LMC, distance of 51.4kp, exploded Feb 23rd,  1987
- The most **important science target to study supernova "aftermath**" and evolution of early supernova remnants
    - Evidence for hard non-thermal X-ray emission from the central region by Gerco et al. (2021) (early PWN)
    - JWST also found evidence for a neutron star, by detecting ionized argon from the central region. Neutron star illumination gas.
- Known spatial features:
    - **Inner ejecta "keyhole":** dense clumpy gas and dust ejected by the SN
    - **Equatorial ring (ER):** ejected from the progenitor star earlier
    - **Outer ring:** ejected from the progenitor star earlier
- **Blast wave passed through and is now leaving the ER**. Shock wave from the SN explosion passed through the surrounding material and "lights it up"



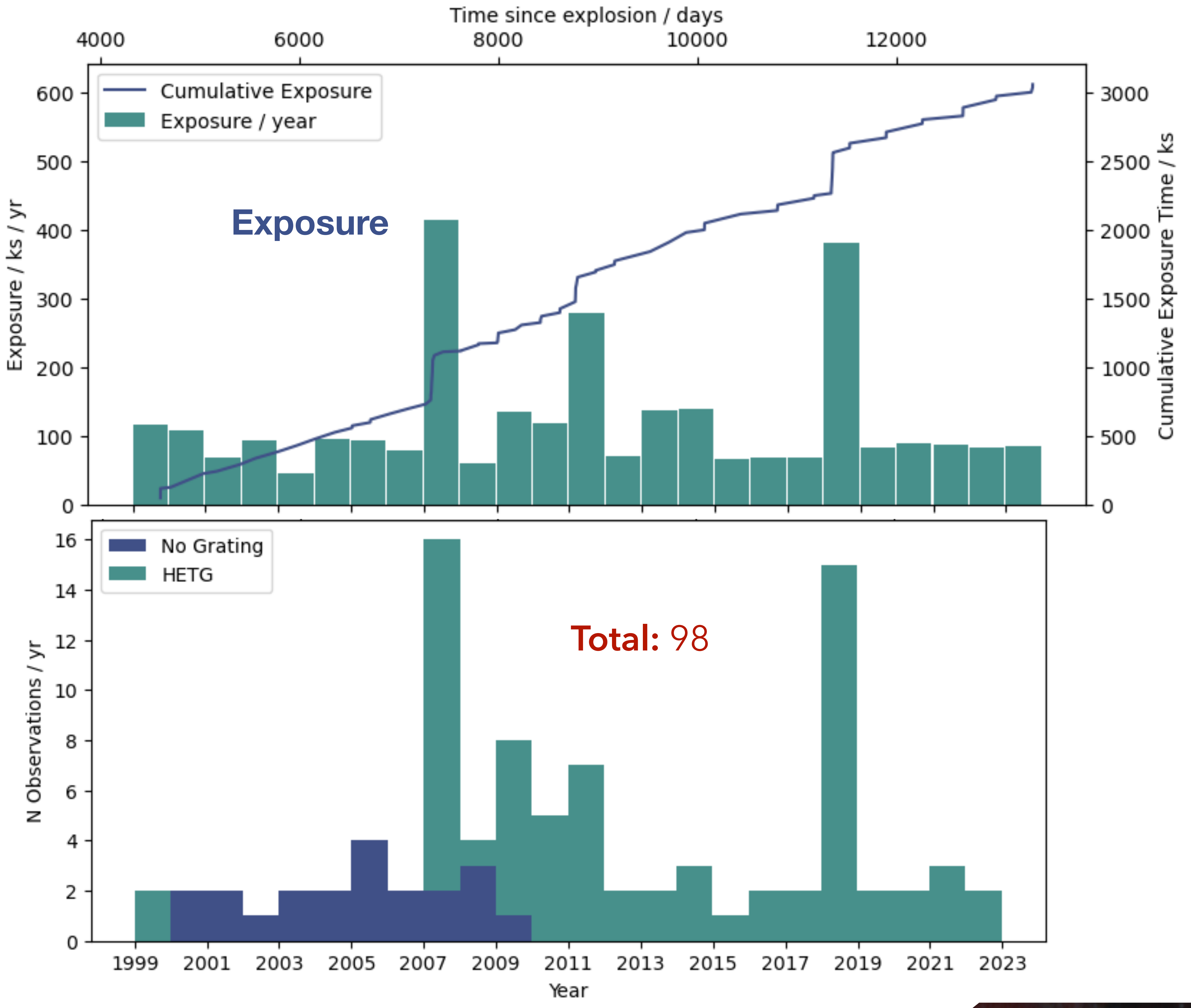




"hourglass shape" geometry

Deep JWST/NIRCam imaging of Supernova 1987A: https://doi.org/10.1093/mnras/stae1032

# Chandra observations overview

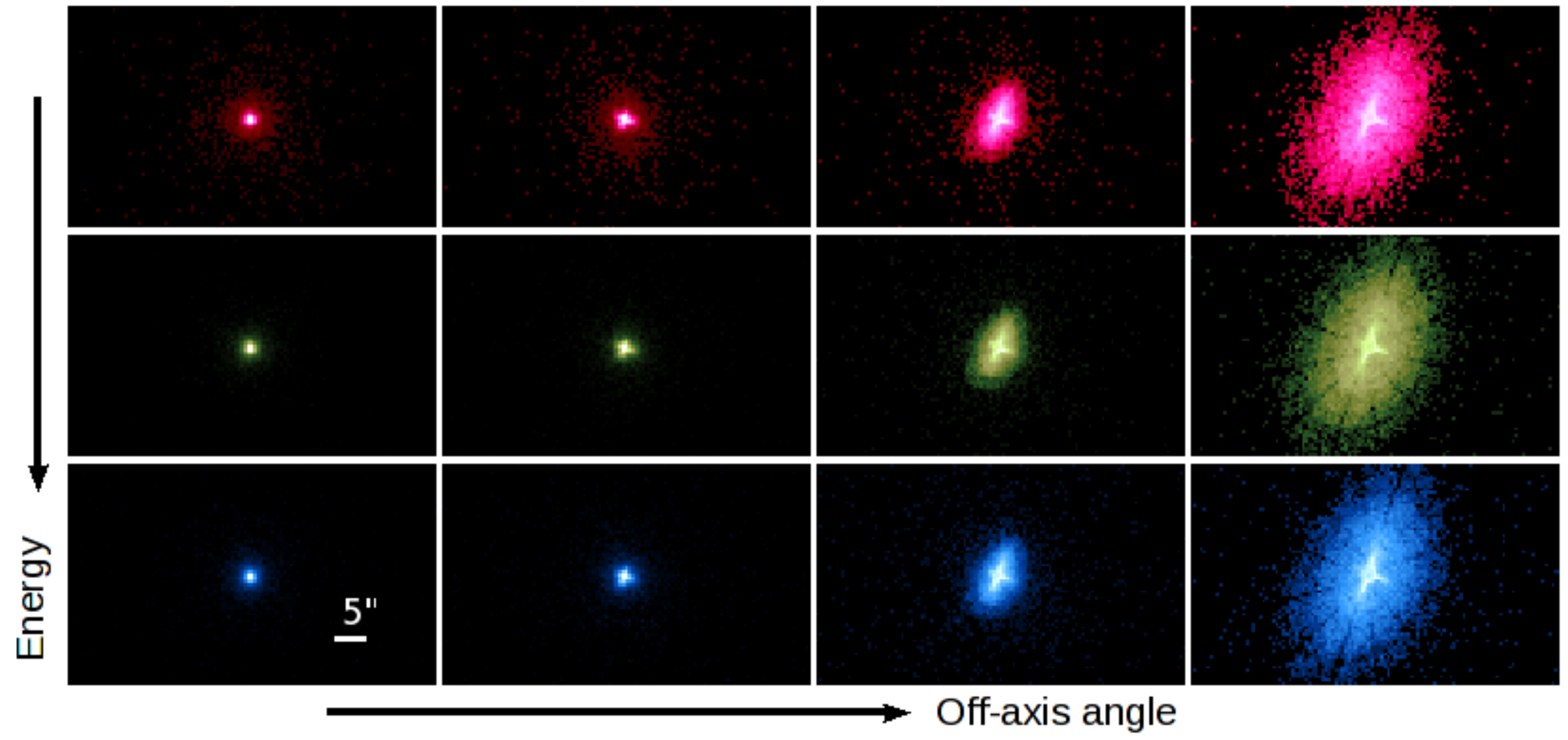
- SN1987A has been **continuously monitored by Chandra,** with at least 1 observation per year, often more
- Different configurations, but **mostly HETG and no grating**
- Selection for this analysis:
  - All observations with offset < 1.0 arcsec, to reduce PSF systematics / weirdness
  - ACIS and combined HETG and non-grating observations
  - Full energy range from 0.5 - 7 keV
- 98 observations with **3000 ks total exposure time**
- On **average ~100 ks / year** on SN 1987A
- Two **large observation campaigns in 2007 and 2018**



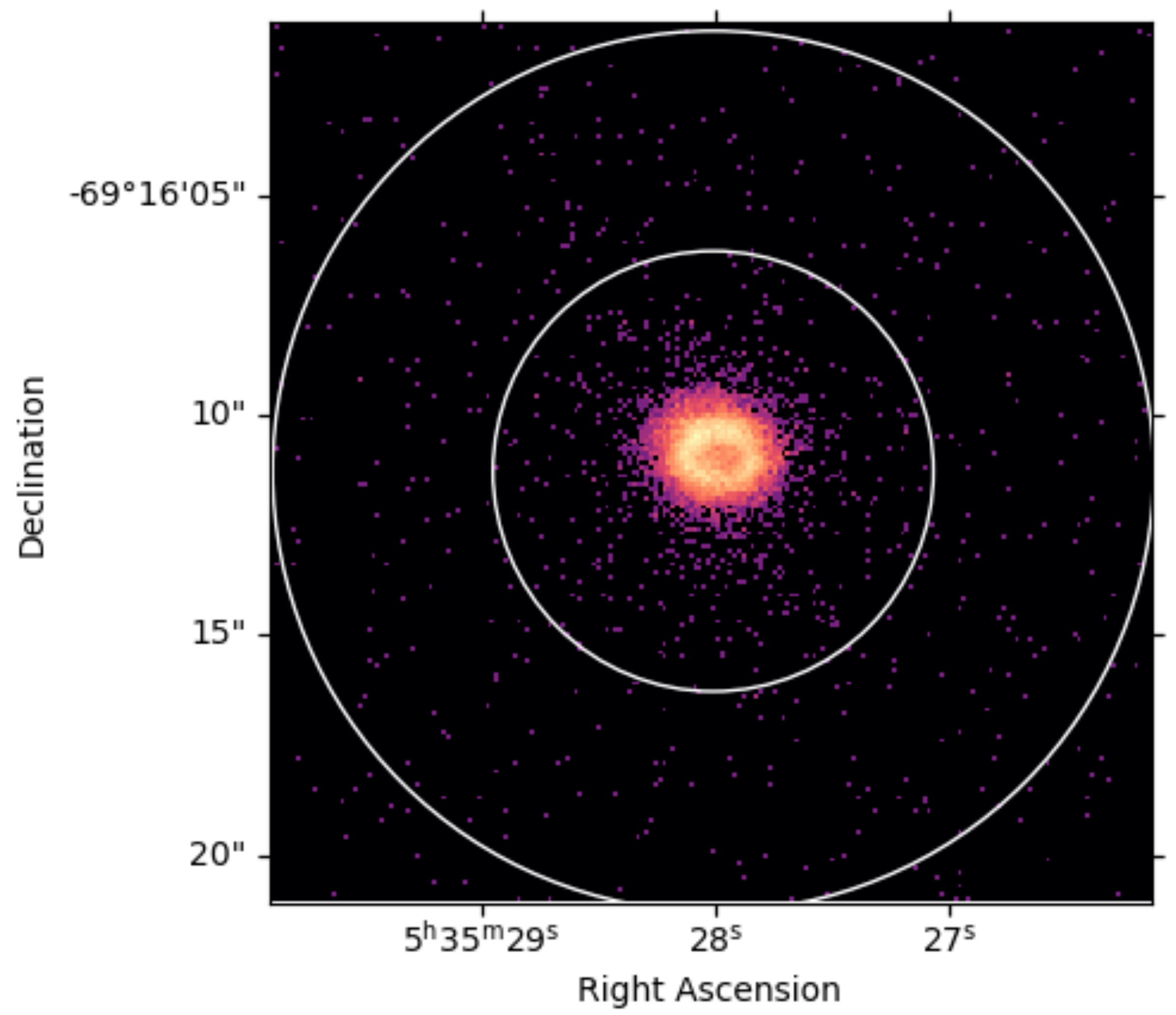
# Data reduction and PSF simulation

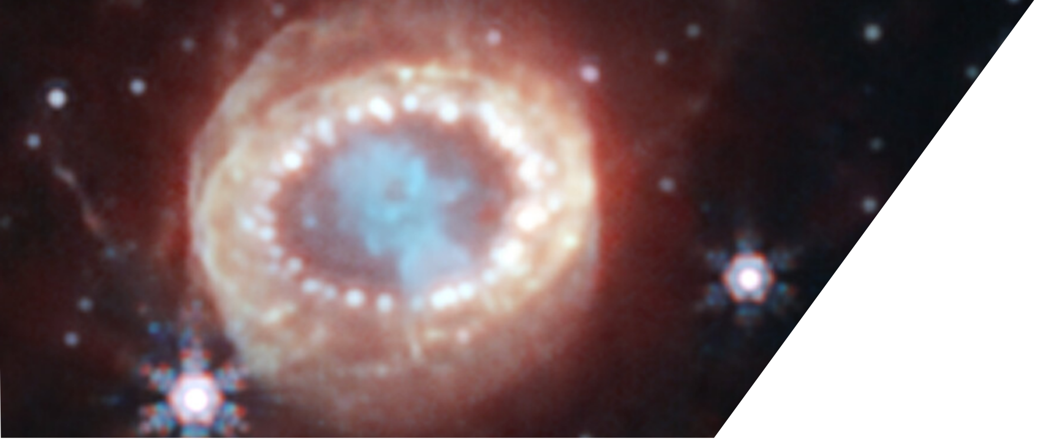
- Run ciao 4.16 for each of the 98 observations, to produce **counts and exposure images**
- **Spectral fit using a two component shock model,** following Frank et al. (2016)
- Simulations of the points spread function (PSF) using Marx and the best fit spectral model. For HETG observations only the 0th order was considered
- Uniform **background extracted from an annulus** with inner radius of 5 arcsec and outer radius of 10 arcsec
- Data reduction chain bundled into **scalable and reproducible "Snakemake" workflow,** available at: https://github.com/adonath/snakemake-workflow-chandra/

**Chandra PSF**



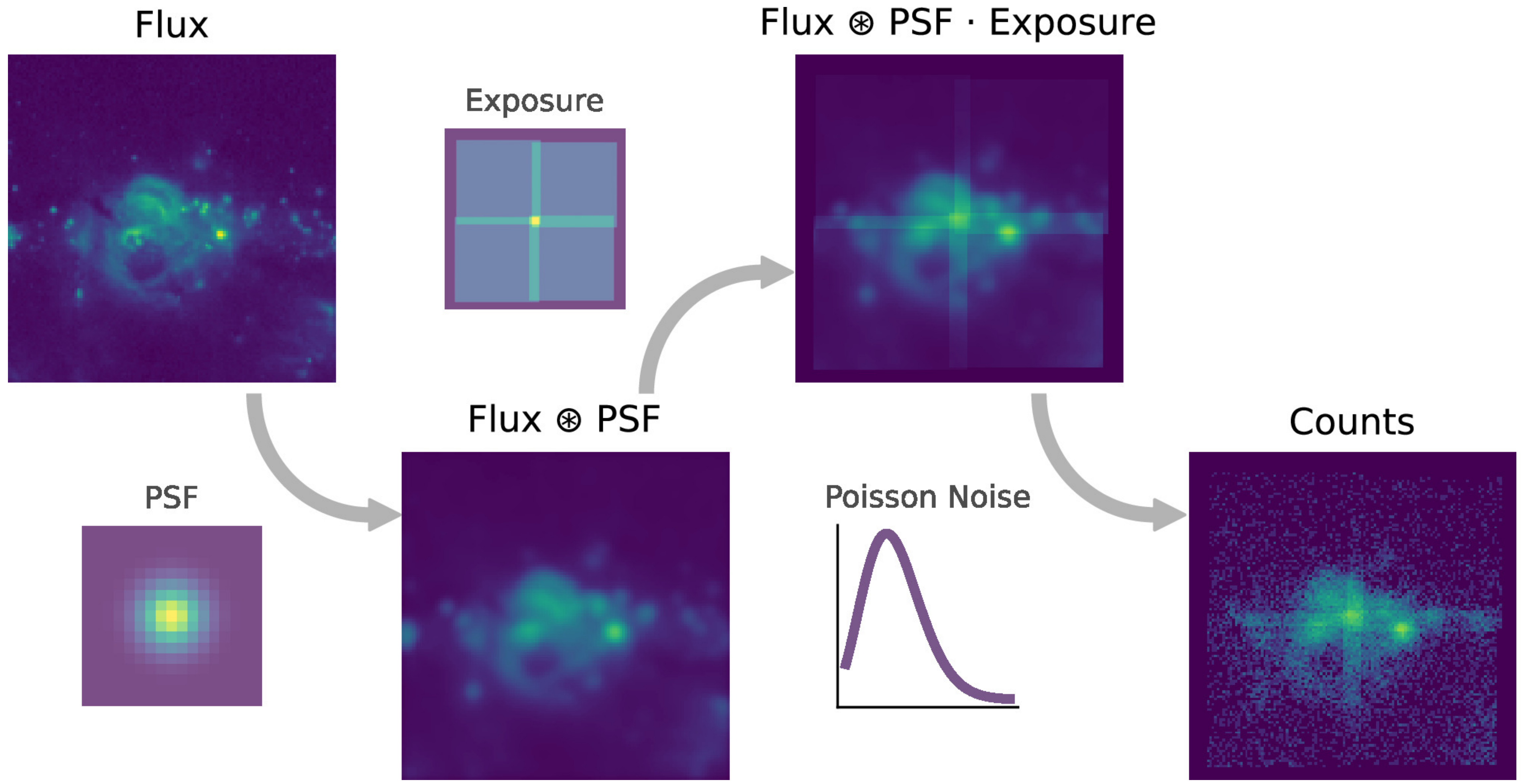

https://cxc.cfa.harvard.edu/ciao/PSFs/

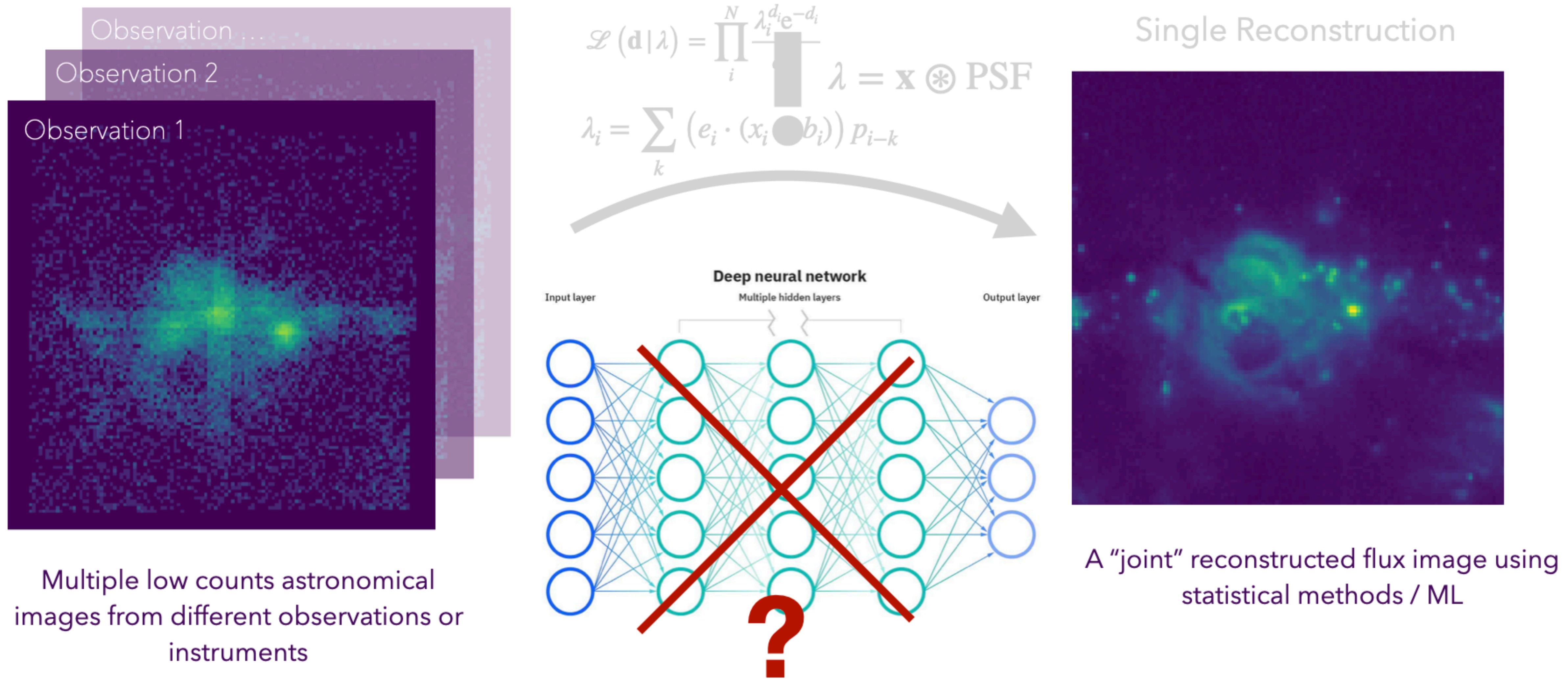




# "Jolideco" method motivation

- **Image deconvolution is not "black magic"**, but by using the information on the shape of the PSF one can approximately solve an ill-posed inverse problem!
- Image deconvolution on X-ray images has been used many times in literature, mostly **"Richardson-Lucy", however the method has problems**:
    - unclear when to stop iteration, no uncertainties
    - does not take exposure and background into account
- LIRA method developed in the CHASC group ~20 years ago: https://github.com/astrostat/pylira
- **"Joint Deconvolution of Astronomical Images in the Presence of Poisson Noise" (Jolideco):** new method inspired by image reconstruction from the Event Horizon Telescope: https://doi.org/10.3847/1538-3881/ad6b98




Multiple low counts astronomical images from different observations or instruments

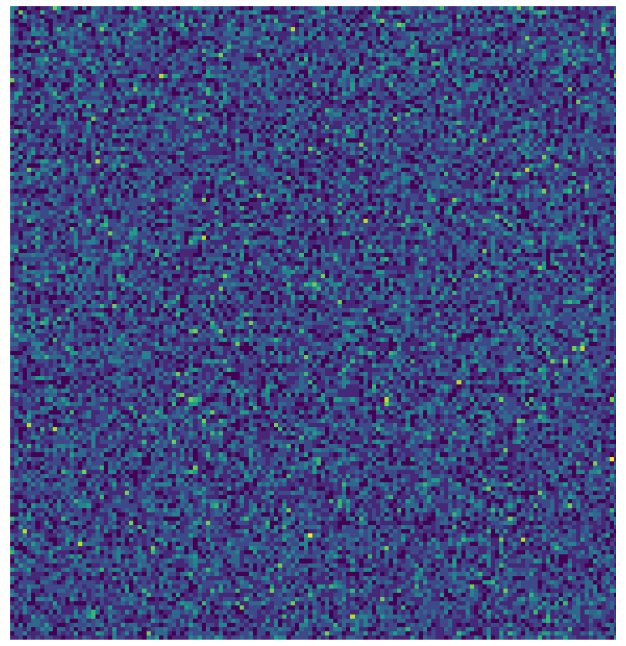
A "joint" reconstructed flux image using statistical methods / ML

# Jolideco method details

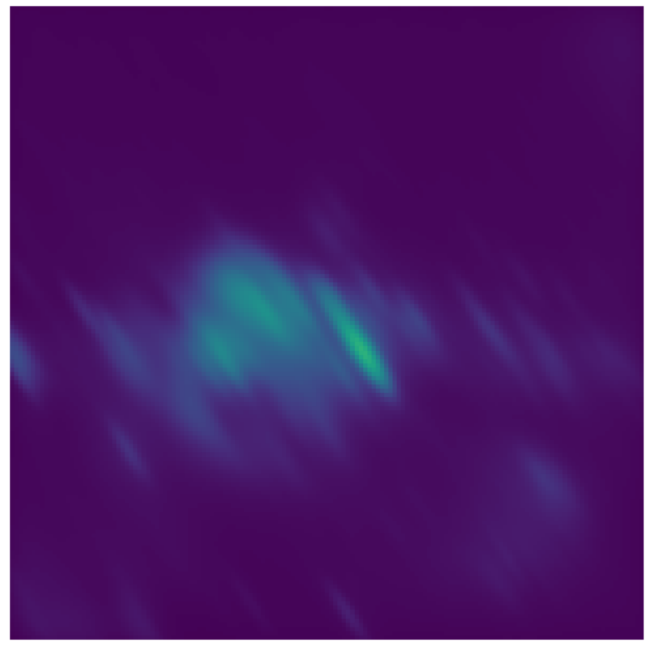
$$\mathcal{L}\left(\mathbf{x}\,|\,\mathbf{D}\right) = \sum_{j=1}^{J} \mathcal{C}\left(\mathbf{D}_j\,|\,\mathbf{x}\right) - \mathcal{P}(\mathbf{x})$$

Log-Posterior Log-Likelihood **Log-Prior**

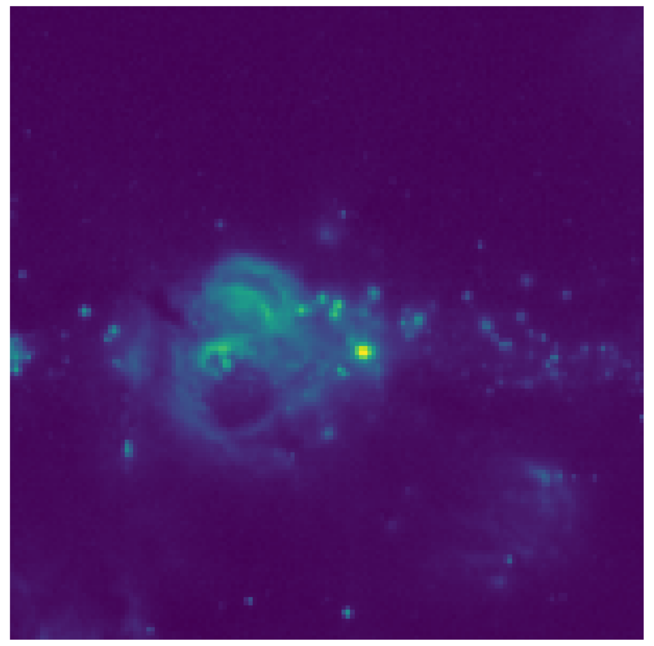
Represents our prior knowledge…



An unlikely image



A more likely image



A likely image

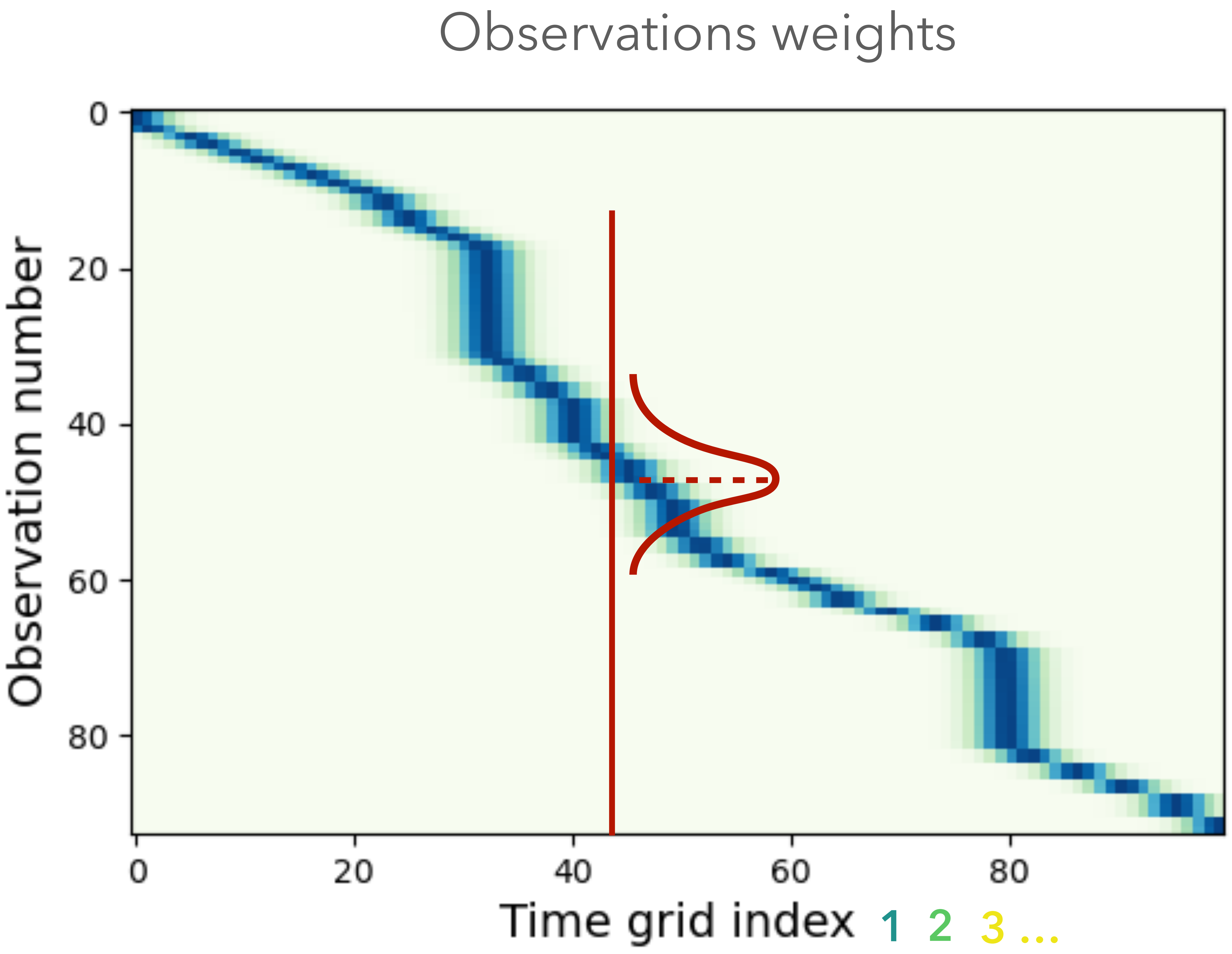
- For the **log-likelihood we use a "hand crafted" forward model**, that includes all our knowledge on PSF, exposure, Poisson statistics etc.
- Sum goes over multiple observations, which can be from different epochs, however for each epoch the flux assumed to be constant
- To break the "ill-posedness" of the problem we introduce a **learned image prior**
- Given that that the PSF is "local" we are only interested in the correlation between neighboring pixels, **a patch based image prior is sufficient**, parametrized by a Gaussian Mixture Model
- Than Maximum A Posteriori estimation is used to create the best fit model for the flux x

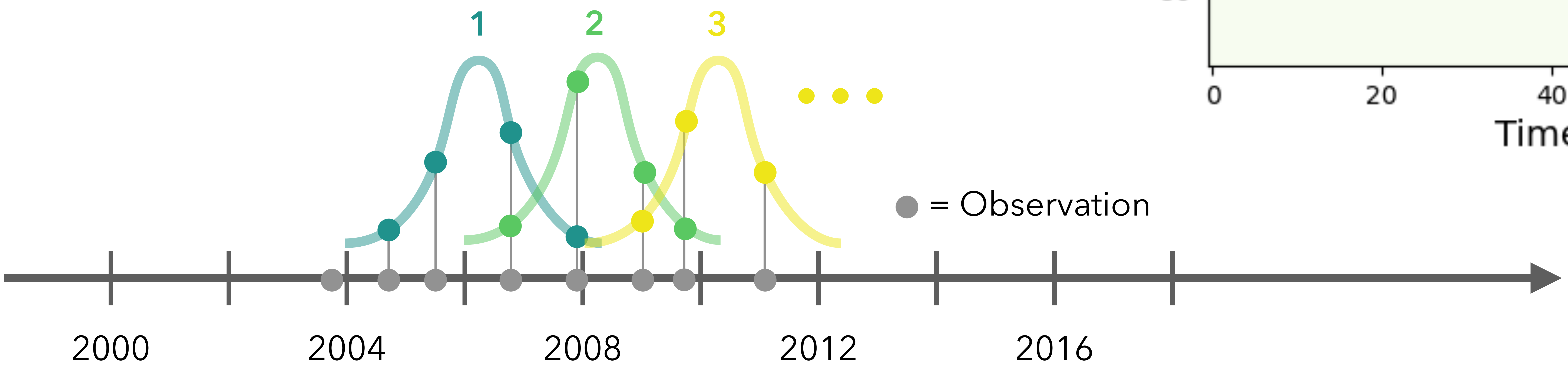
# Jolideco for time reconstruction

- **Weighted joint reconstruction of observations grouped by time**. Where observation are assigned a likelihood weight based on the distance from the grid point using a Gaussian shape

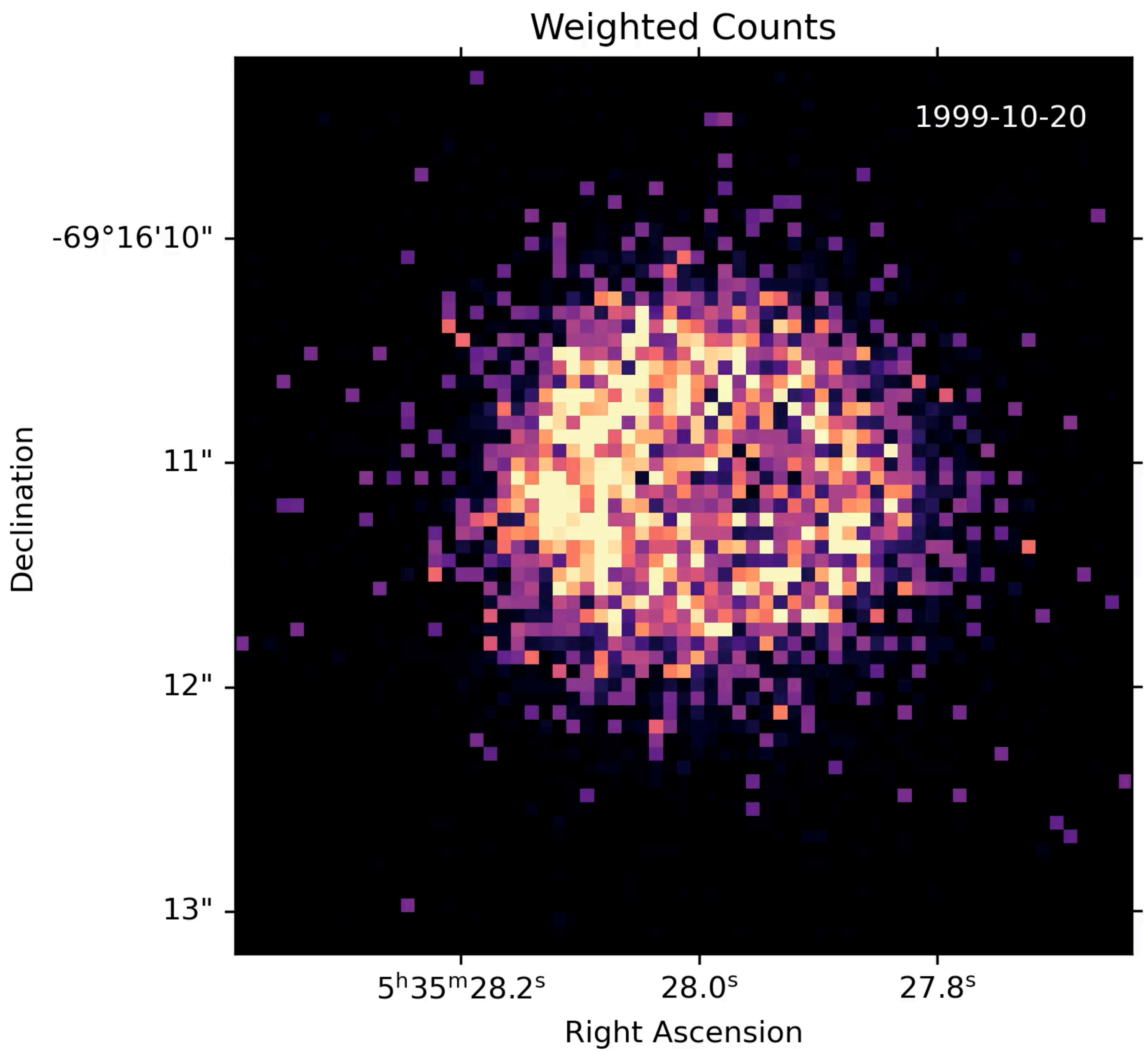
- This allows for **reconstruction ("interpolation") of images at arbitrary times on a regular grid.** Similar to a Gaussian smoothing along the time axis, however combining likelihoods is non-linear!

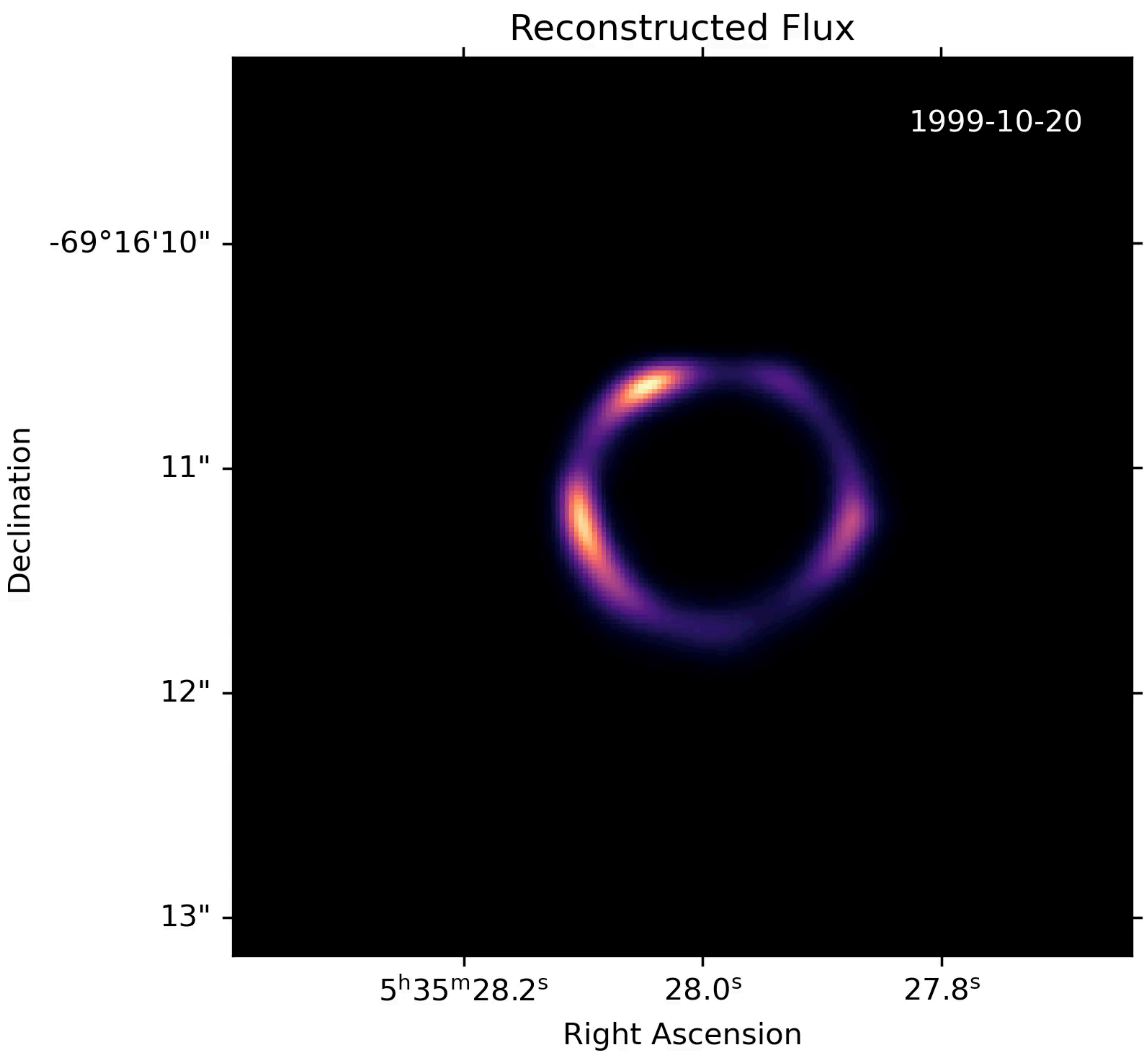
- **However:** exposure is taken into account, so high exposure observations might dominate individual time bins

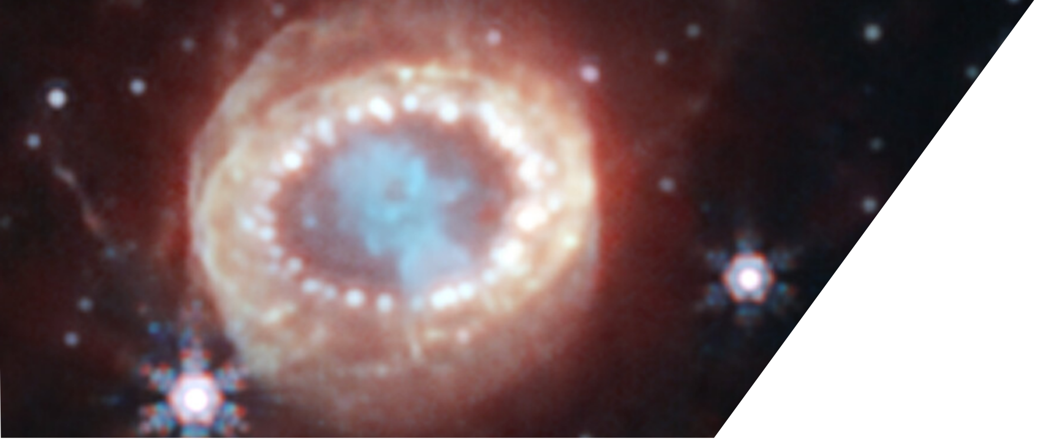


# Animation of 25 Years of SN1987A





# Remarks on the animation

- **Astrometry is very challenging**, however Jolideco does relative astrometry "on the fly": it allows for an observation specific shift, which is optimized along with the image reconstruction. However absolute astrometry might be off. This can **lead to the "drift" in absolute position** seen in the animation…

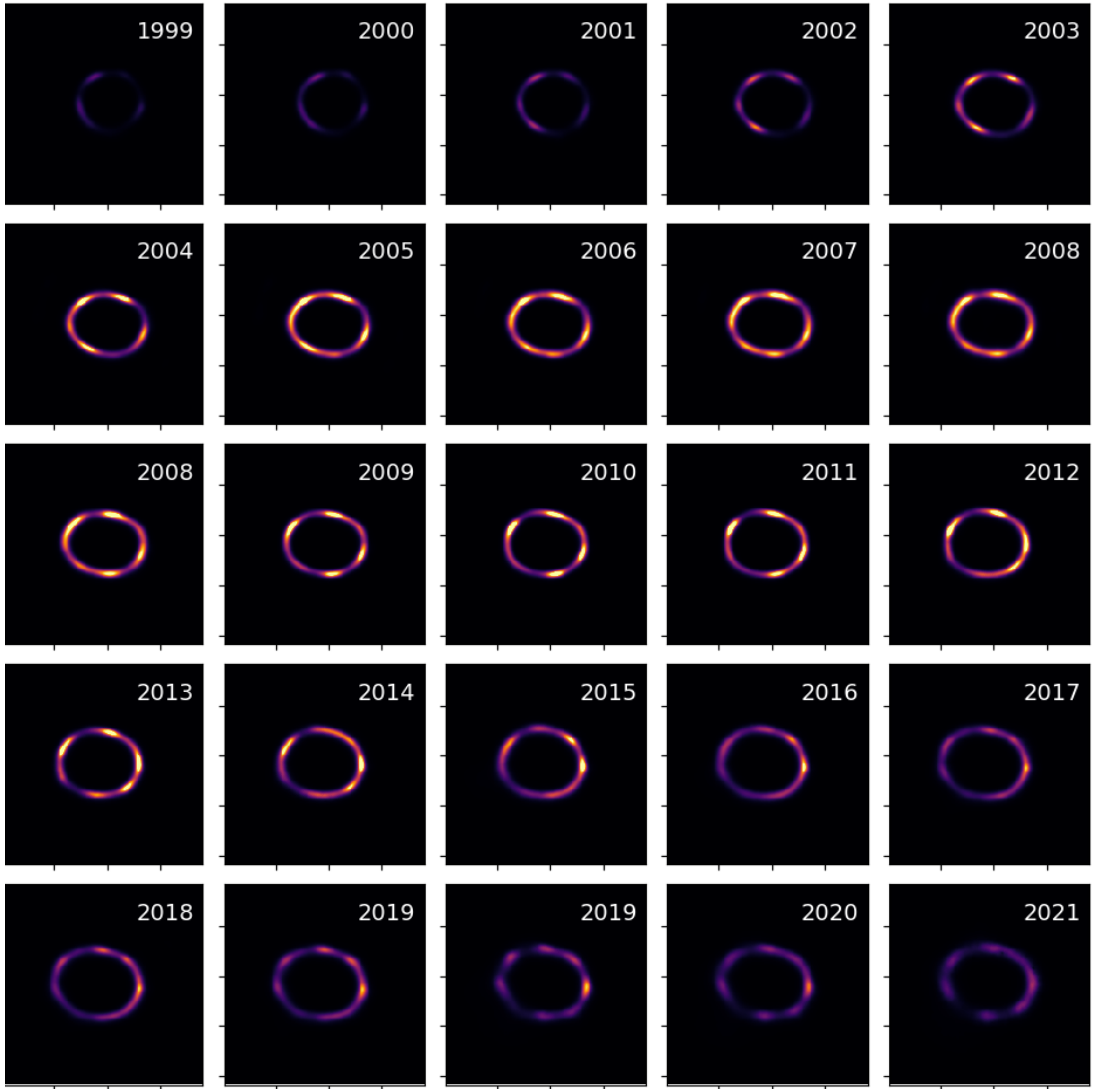
- Bright **features seem rather positionally stable over time**, they might be real. Seen previously as "four lobes" (Racusin et al. (2009)). But a dedicated analysis is needed!

- Reversal in the East-West asymmetry clearly visible (Frank et al. (2016))

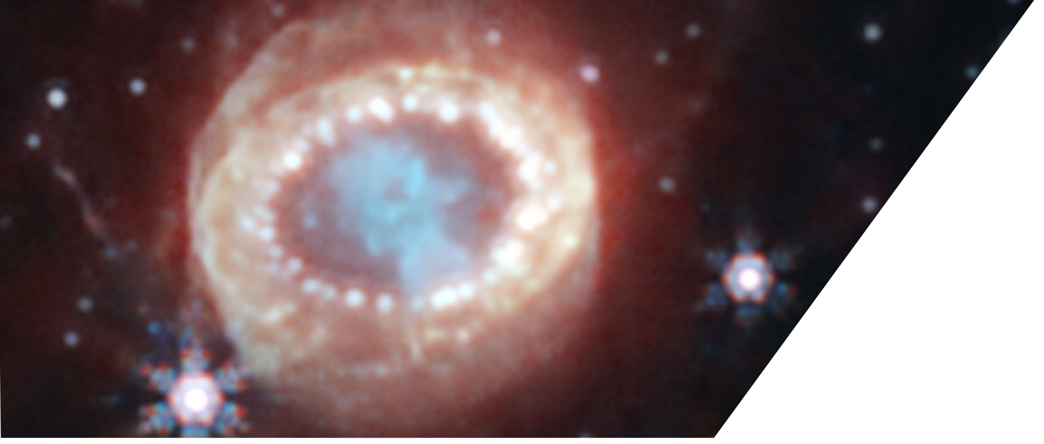
- For the animation images have been re-normalized to equal brightness. The **image on the right shows absolute brightness.** Brightening and dimming clearly visible!

- Please also note the effects of the image scaling:  linear - sqrt - log

- Reconstruction in later time bins is difficult, because of lower exposure and dimmer source




Linear



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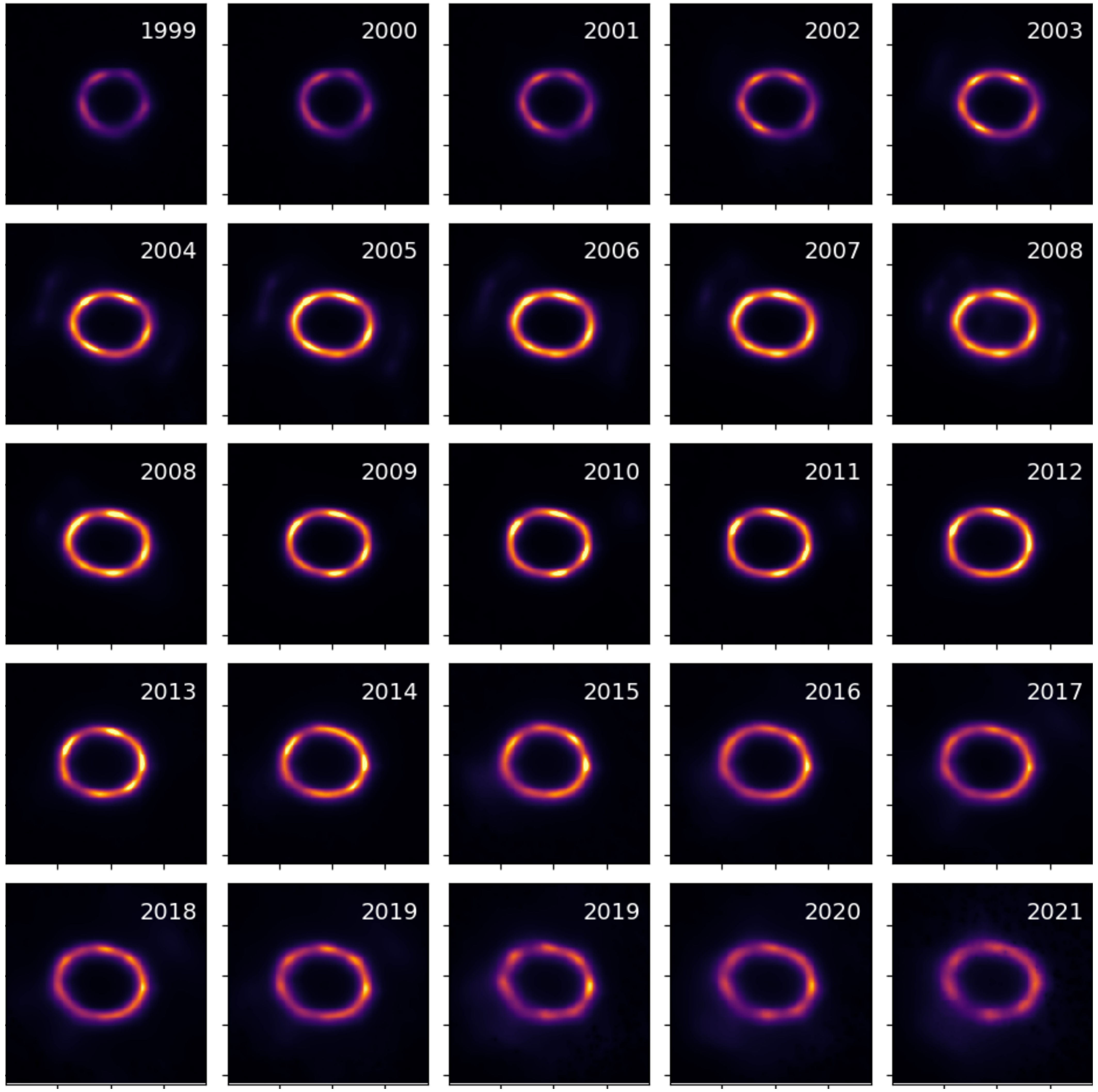

Sqrt

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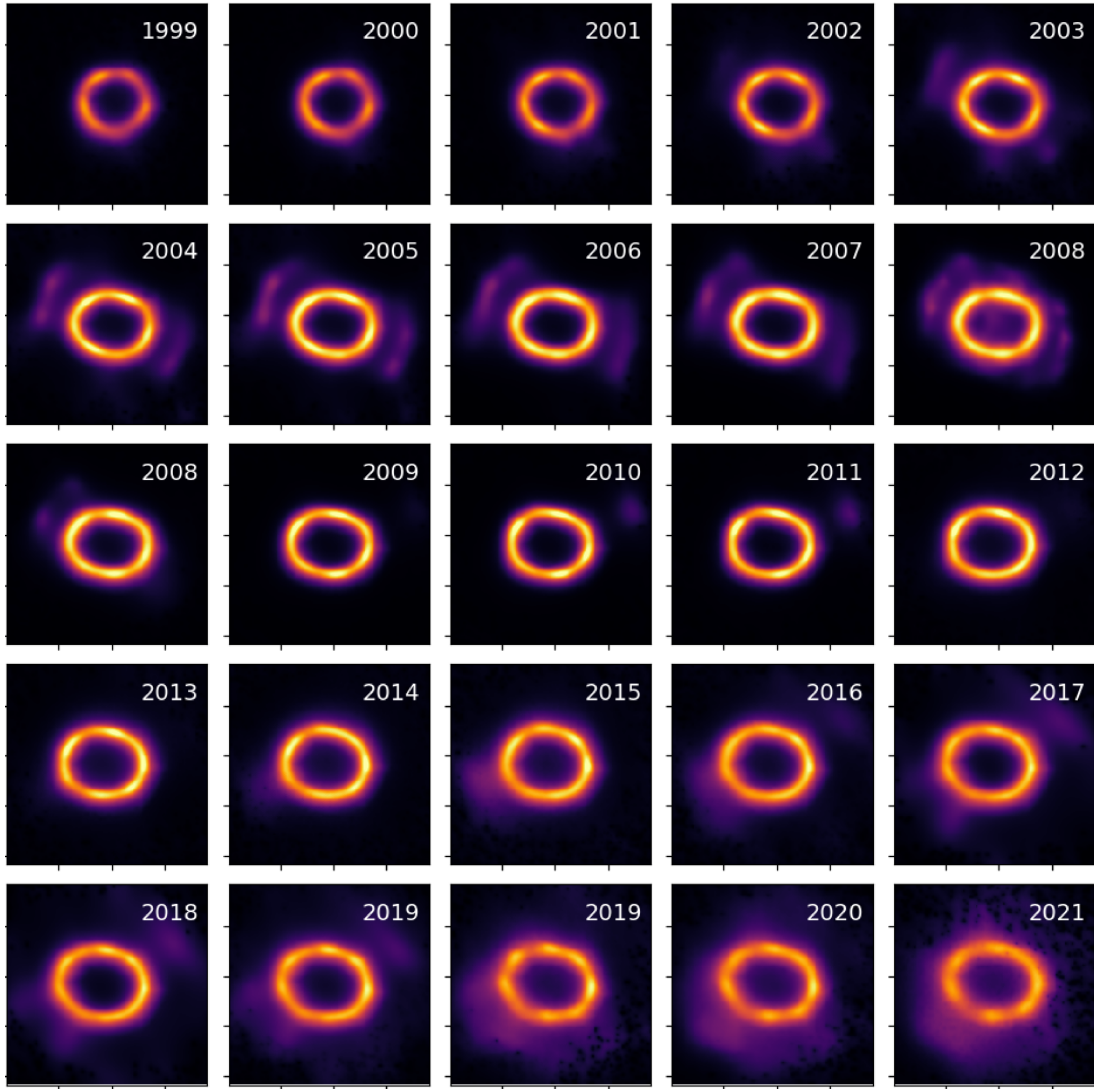
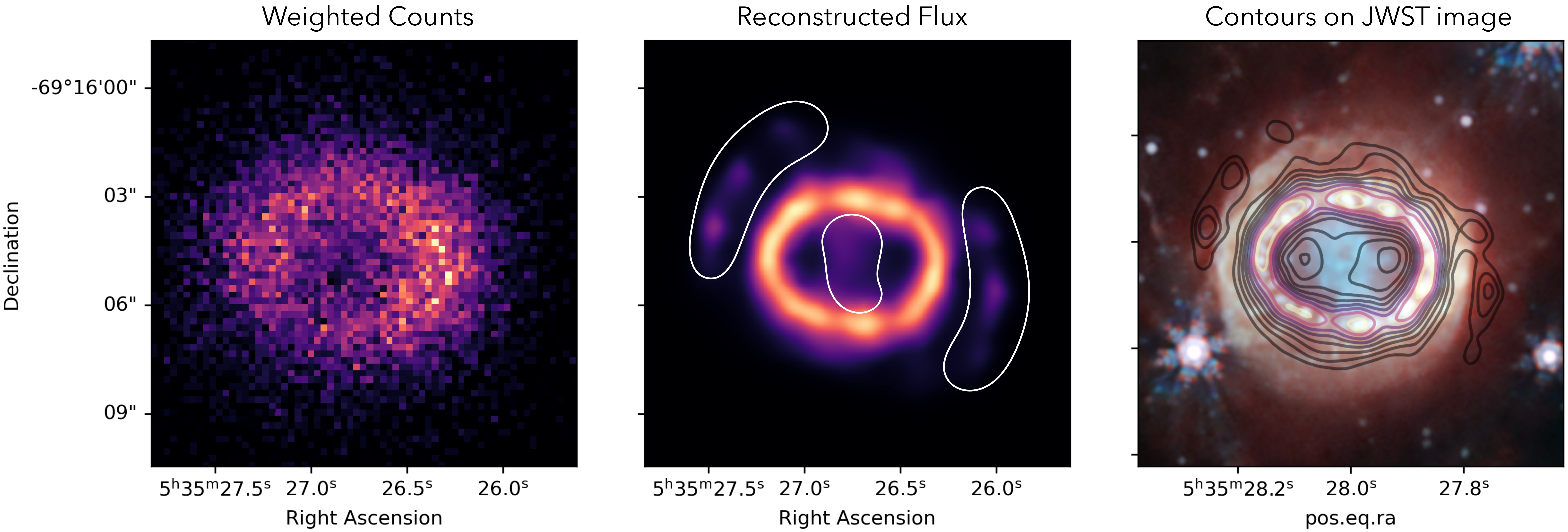



Log

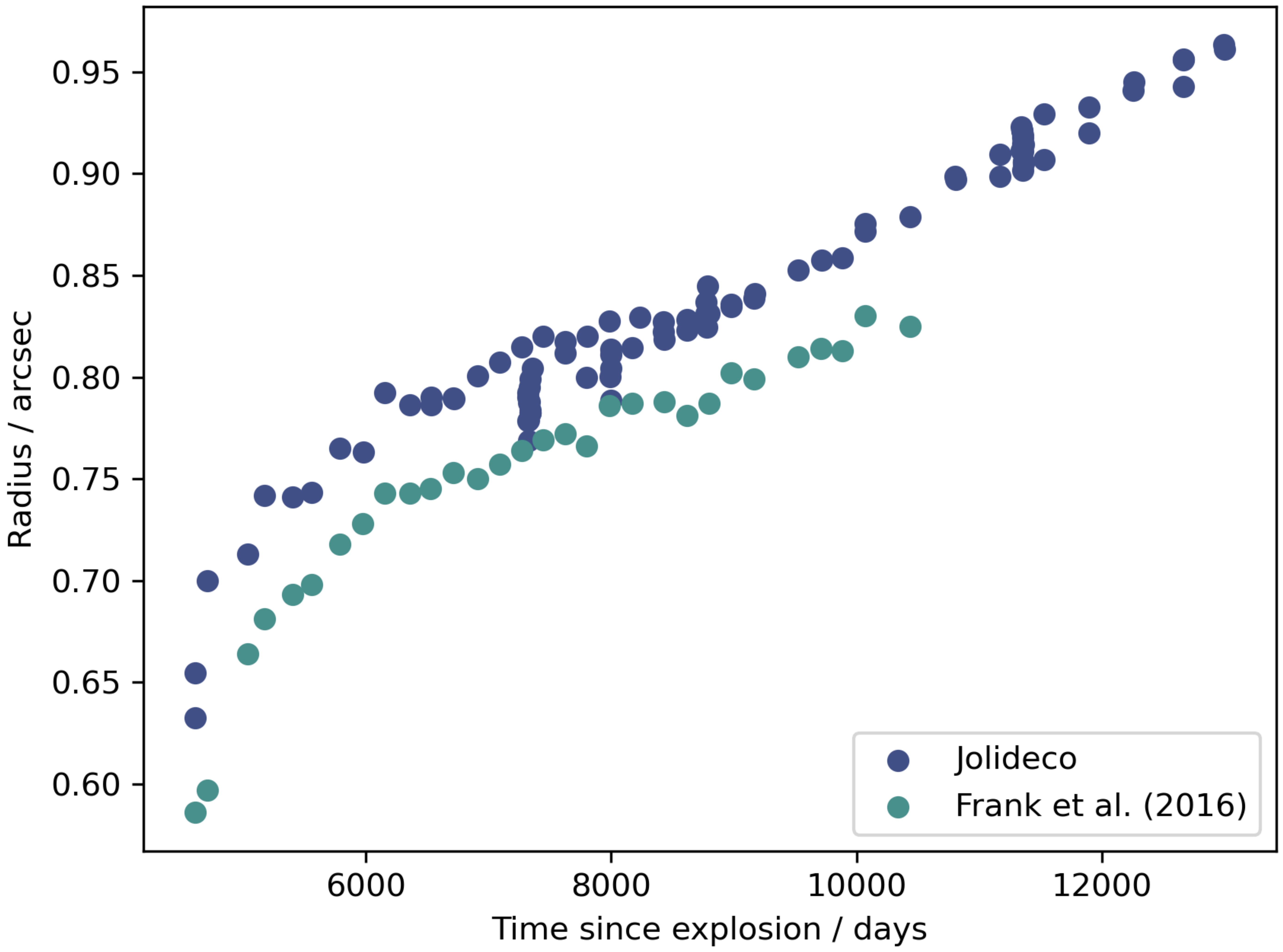
# New X-ray features?

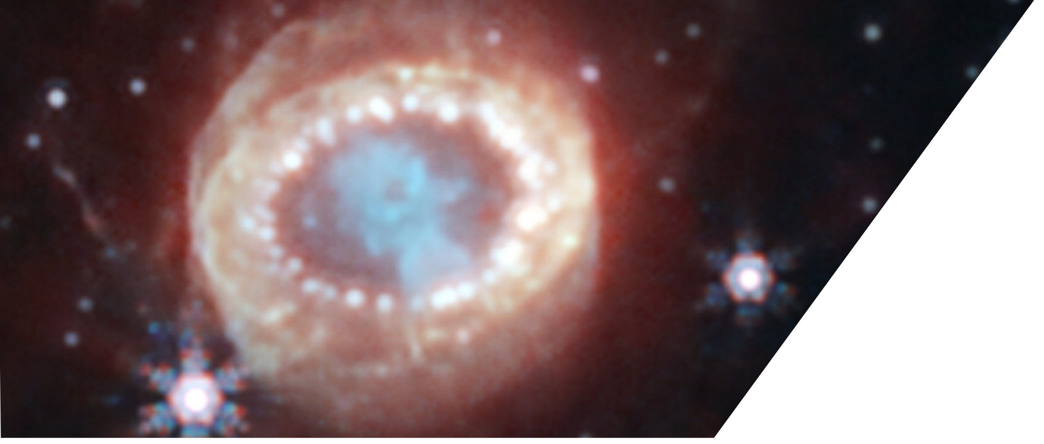



- Weak artifacts popped up in time bins around idx=36, which combines a **series of ~30 observations from 2004 - 2008** with high exposure (~30% of the total exposure). Note there is a ~**15 year time gap between the Chandra and the JWST image**.
- Are those real? I don't know 100%...however, the chance of reconstructing features that align with existing features in the JWST image by chance is really small. Again a **dedicated analysis is needed,** especially investigating PSF systematics!
- Low emission features contain ~5% of the total flux in the image

# Extension over time

- One **Jolideco reconstruction per observation**, then fit a "smooth" elliptical annulus to the deconvolved images. Radius given as the mean between the inner and outer radius of the annulus
- Frank et al. (2016) fitted on Richardson-Lucy deconvolved images and included four asymmetric Gaussian "lobes"
- Absolute deviation not yet understood, but the **time evolution agrees well with the previous analysis** by Frank et al. (2016). But they also found energy dependence of the radius!
- Plausible evolution after ~10.000 days





# Conclusion & outlook

- There are still surprises hidden in Chandra archival data!
- Result are very preliminary, but the **Jolideco reconstruction finds good agreement with previous analyses on general morphological features**, such as extension and reversal of the East-West symmetry
- We find **hints for new X-ray features by** combining high exposure observations between 2004 - 2008 into a single reconstruction
- **Lots of future work:** extraction of the light curve, incorporating PSF systematics into Jolideco, dedicated analysis of “hot spots”, study differences in spectral bands, …
- **Experts on SN1987A please come and talk to me!**
- Checkout interesting statistical methods developed by CHASC on our GitHub: https://github.com/astrostat and https://github.com/jolideco