Search for neutrinos from AGN using a data-driven source selection

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Sebastian Schindler
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Neutrinos from Active Galactic Nuclei

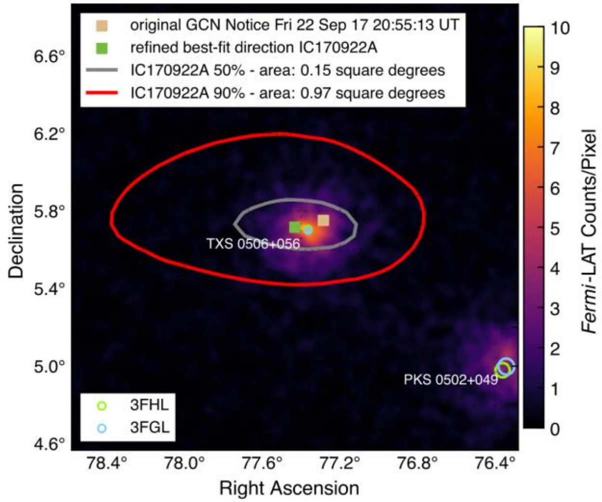
TXS 0506+056

significance: ~ 3 σ

type: ***Blazar***

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†



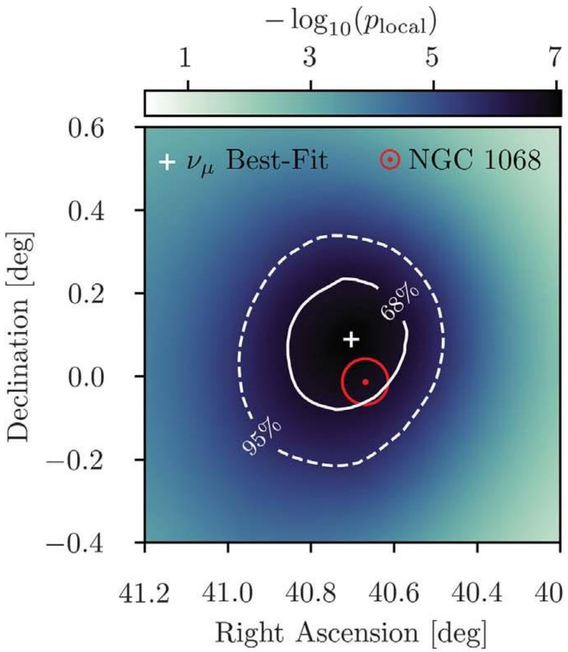
NGC 1068

significance: 4.2 σ

type: ***Seyfert 2 galaxy***

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†



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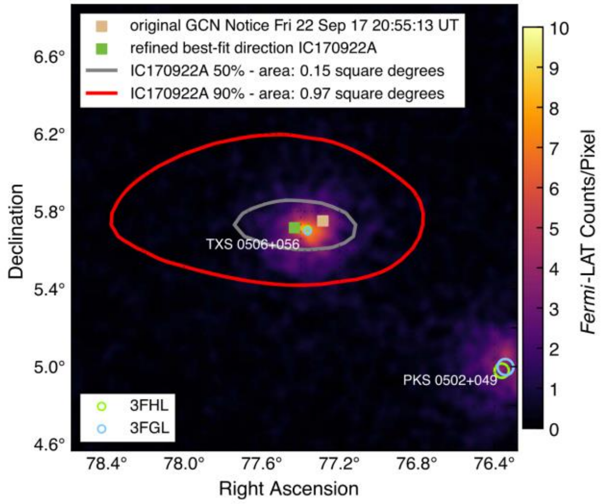

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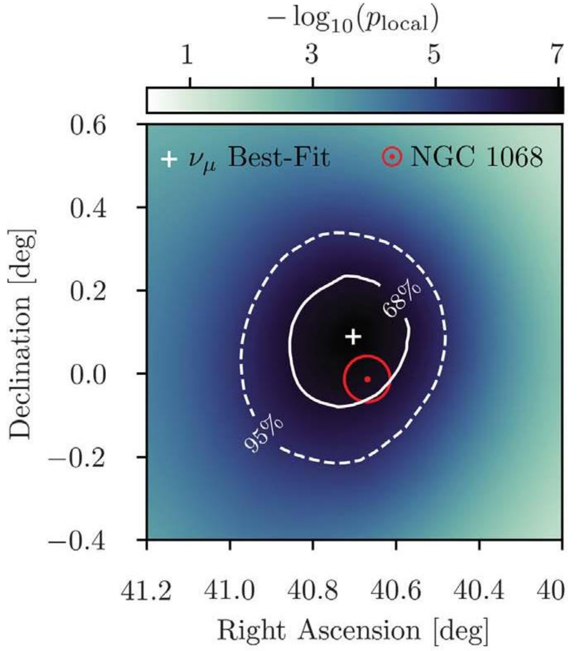

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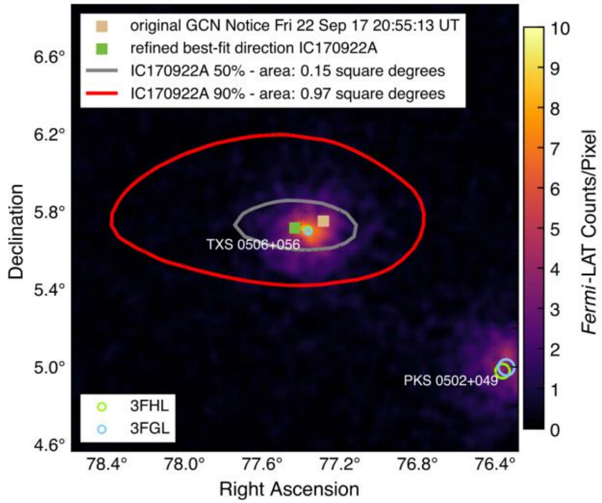

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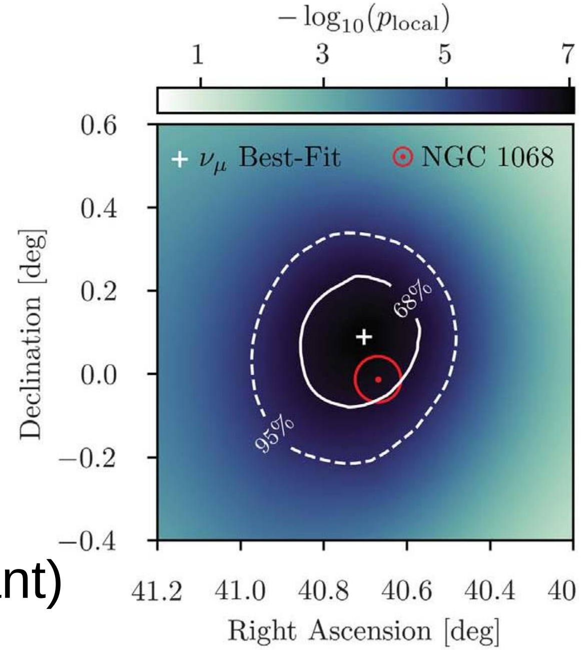
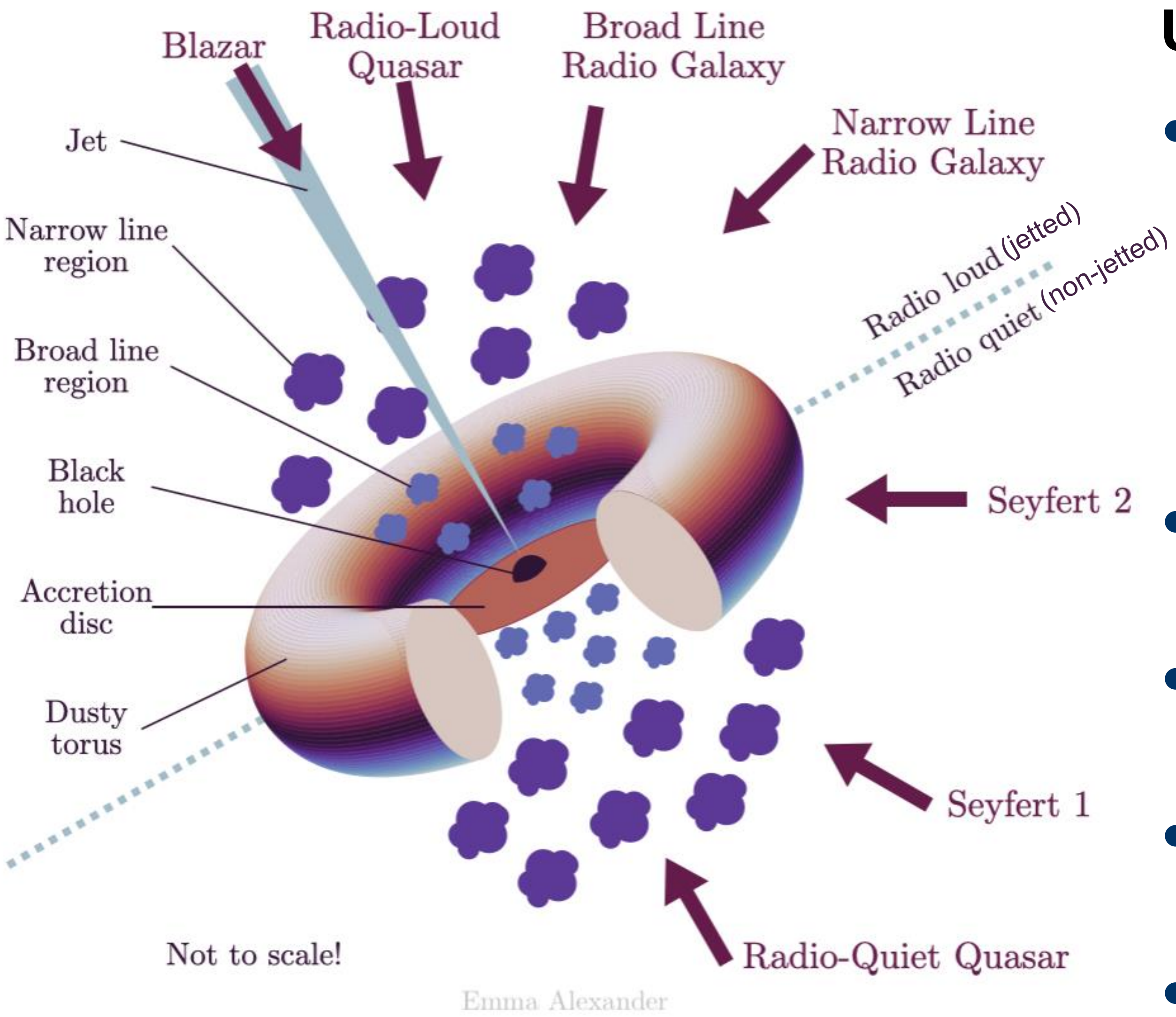


but which subset?

→ so… stacking search with AGN ???

(stack signal from (not-too-large) number of sources to become significant)

Classification of AGN as a problem



Unified Model of AGN (Urry, Padovani 1995)

- many observationally diverse extragalactic objects
  - e.g. small/large radio flux
  - spectral lines large/small or broad/narrow
  - variability in time yes/no etc. pp. …
- explained as one type of object, appearing differently due to orientation to observer
- Type 1 *vs* Type 2 = **black hole** in center is obscured *vs* unobscured by a **dusty torus**
- **sub-classification** remains quite historical
  → not necessarily optimal for neutrino search!
- **neutrino emission** via several processes

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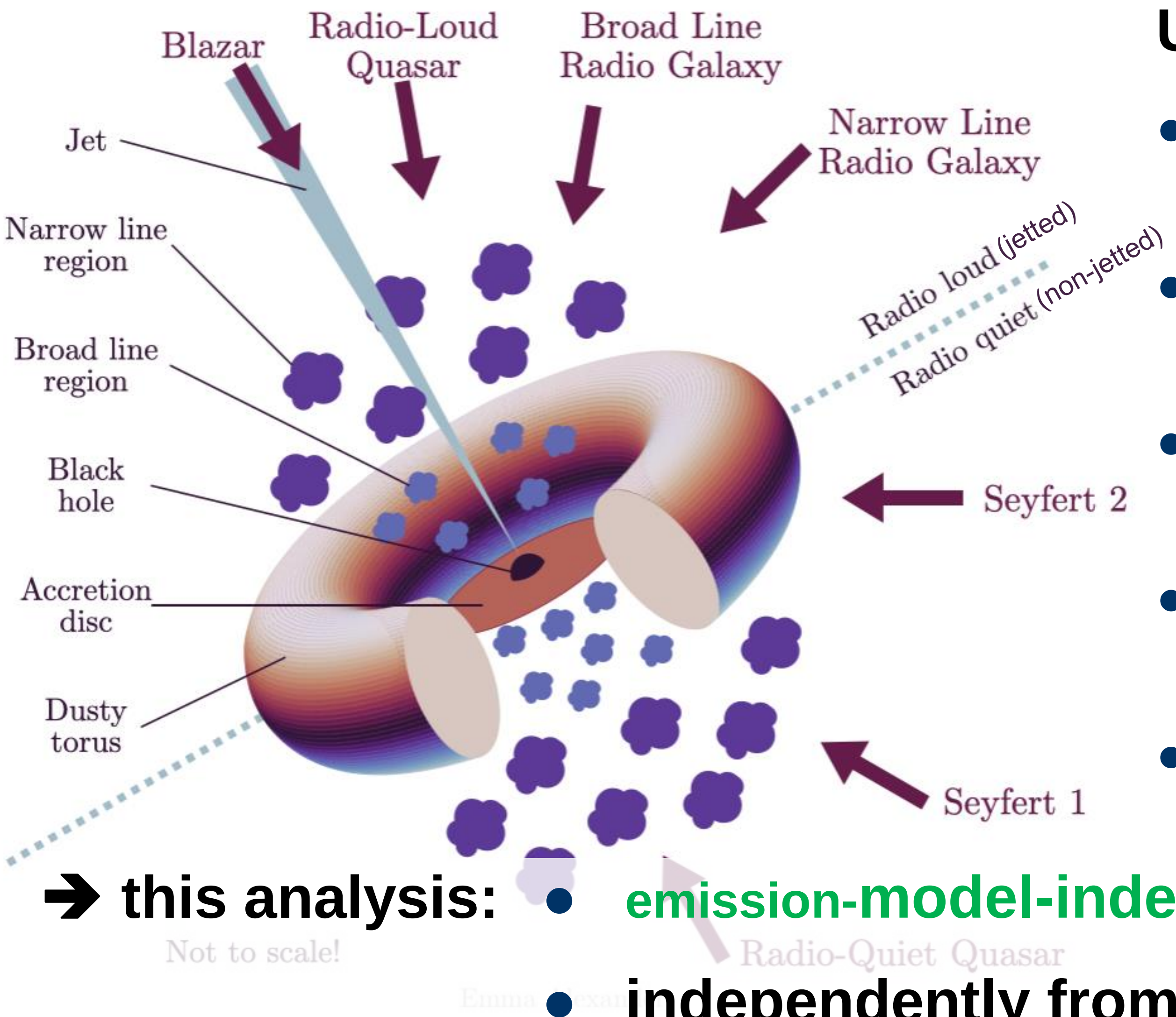

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➔ **this analysis:**
- **emission-model-independent search**
- **independently from existing AGN classification scheme**

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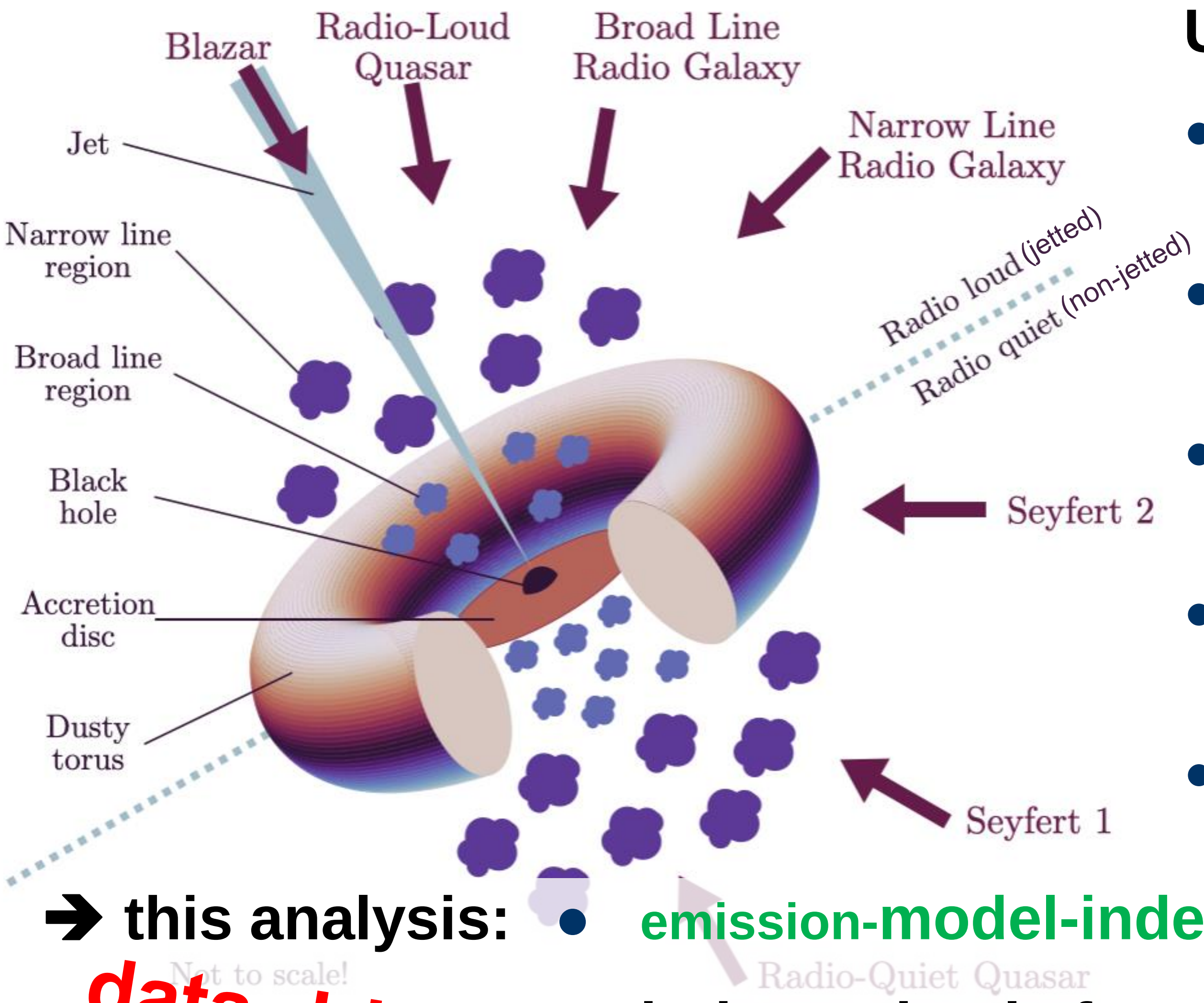

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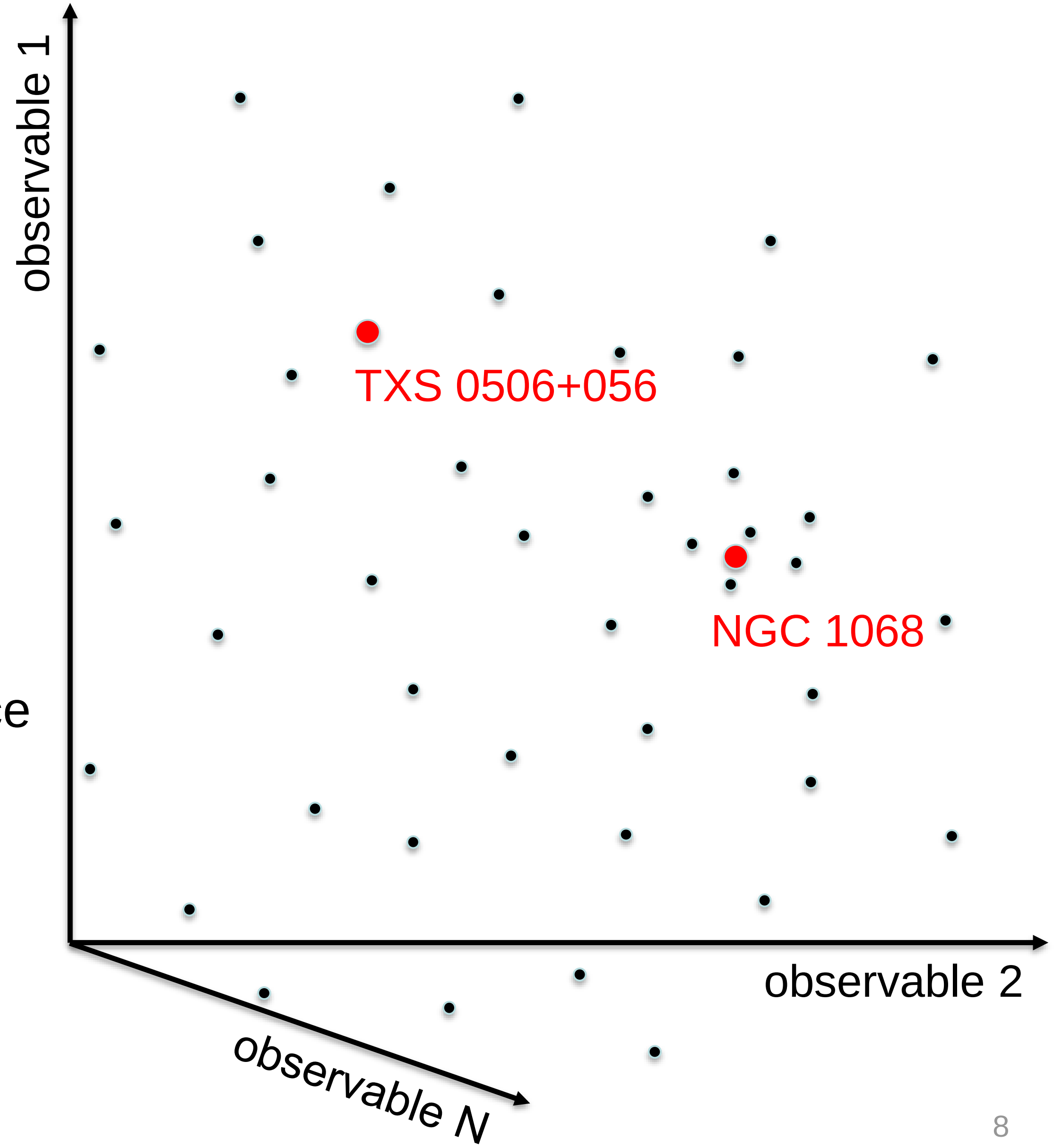
- **emission-model-independent search**
- **independently from existing AGN classification scheme**

data-driven!

Phase space of AGN observables

- **many different observable quantities** from AGN:
  - flux in some waveband: radio, x-ray, γ-ray etc.
  - strength, broadness, shape etc.
    of spectral line X, Y, Z etc.
  - polarization etc.
- **each observable is a continuum** (axis in space)
  → many observables span a high-dimensional space
- **populate space** with many observed AGN
  → probably not homogenously distributed



Phase space of AGN observables

distance in phase space

↕

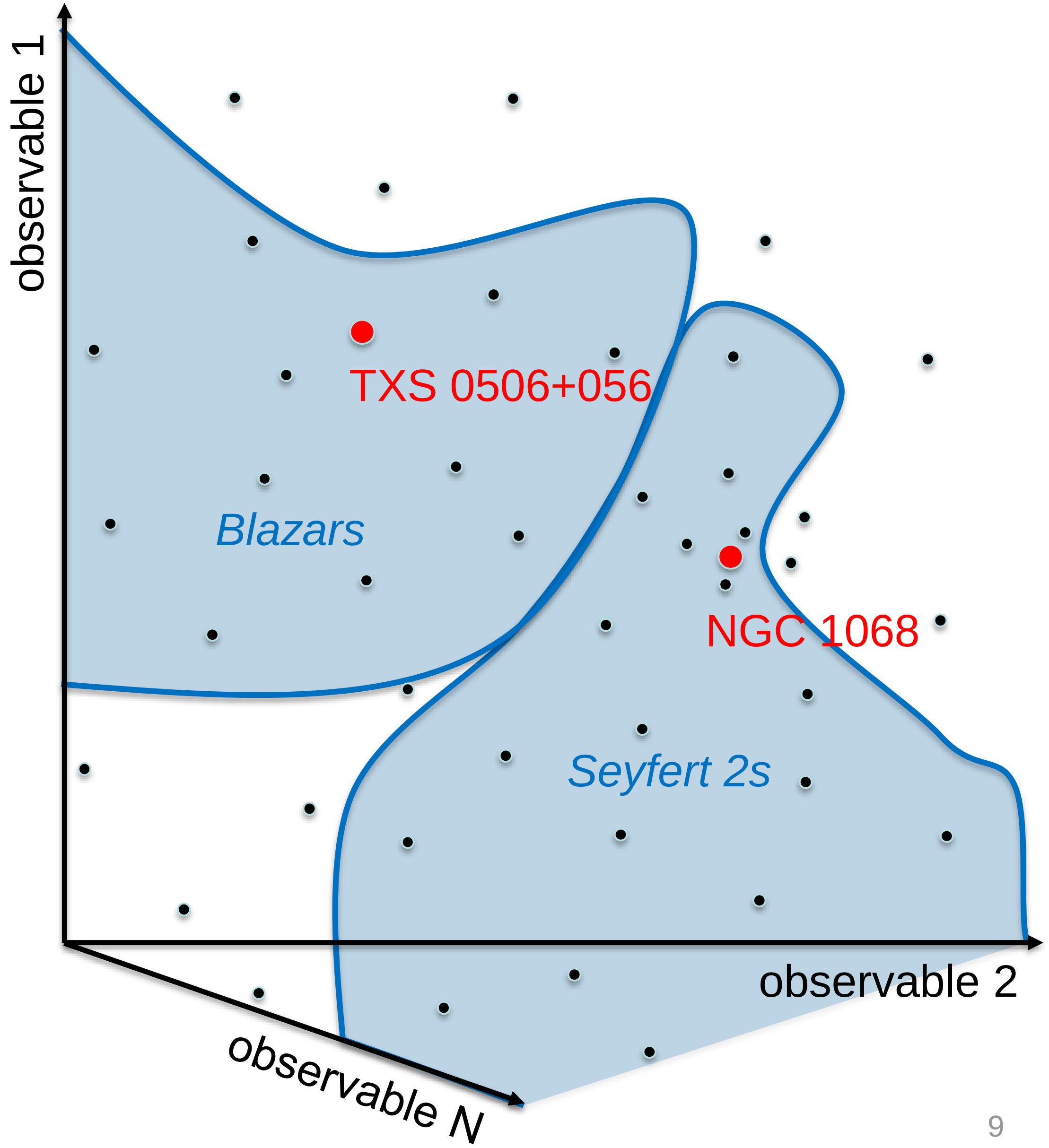
measure for similarity of AGN

clusterings / distinguishable groups

↕

common features,

indication for sub-classes?



Phase space of AGN observables

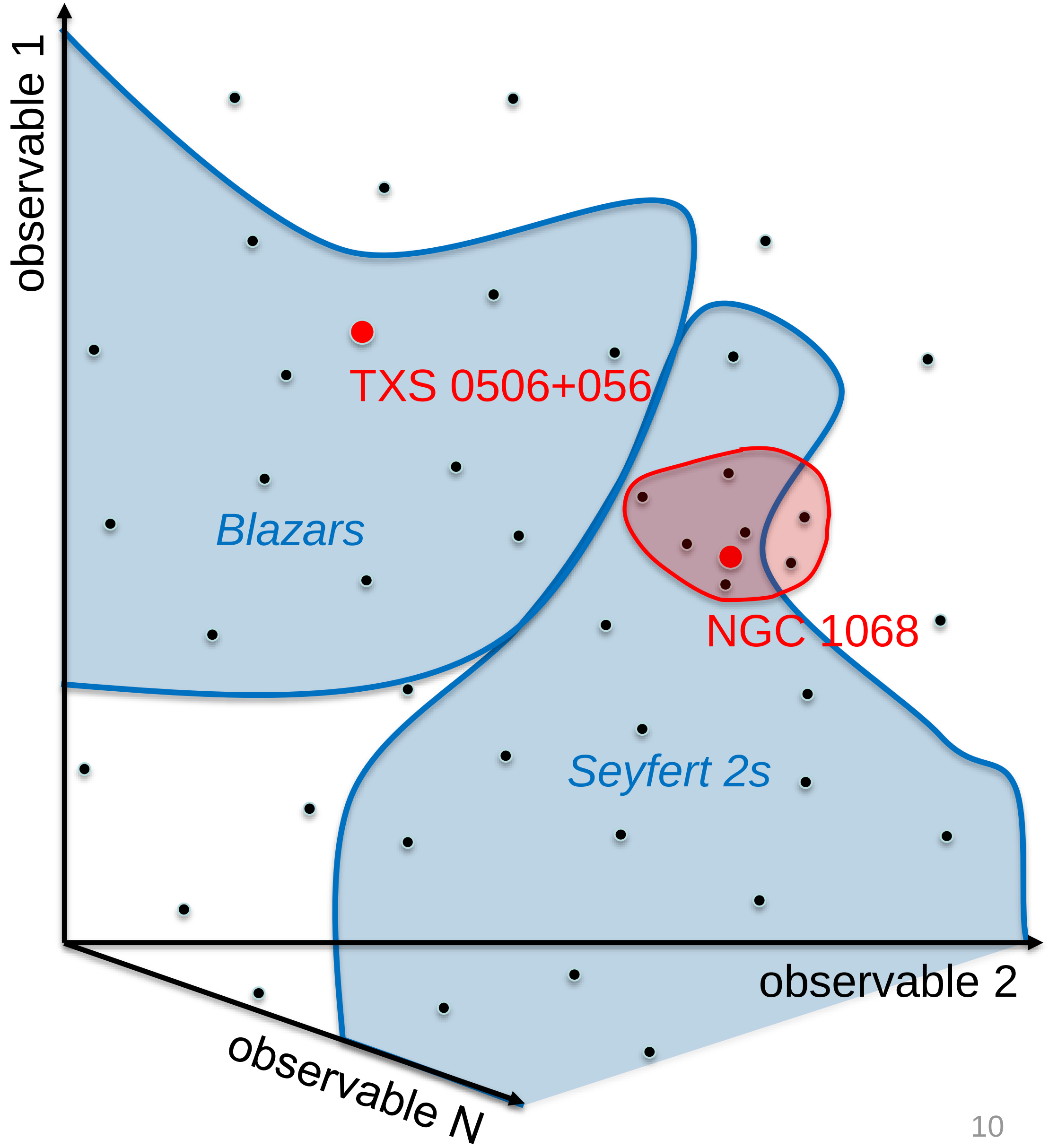
- use **interesting clusters of AGN** as source list for stacking search
- interesting clusters?

  e.g. inclusion of **existing candidate** in cluster

  → "which smallest cluster includes NGC 1068?"

→ stack sources that are **intrinsically similar to existing candidates**

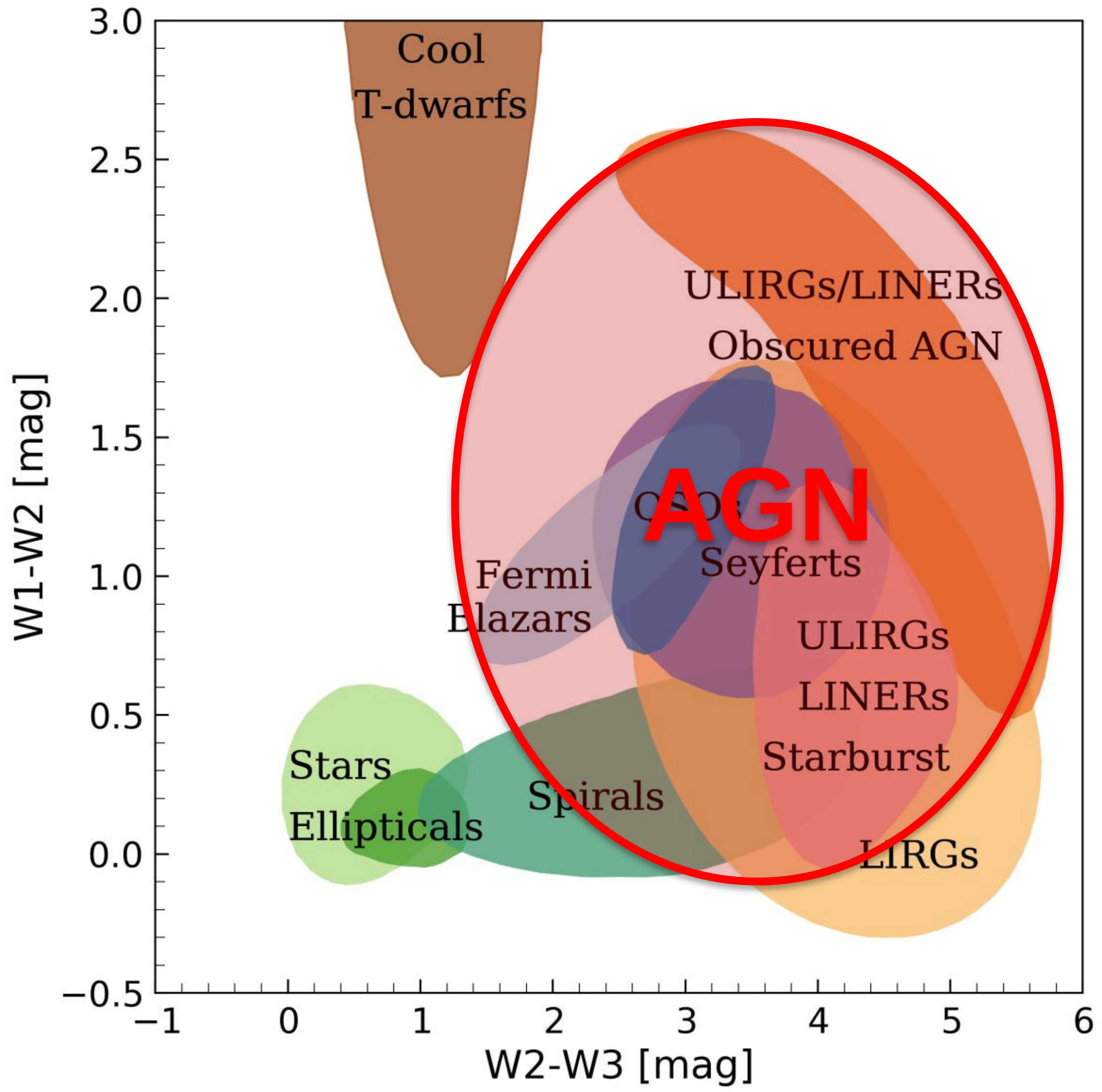
(e.g. TXS 0506+056 & NGC 1068)



IR color-color diagrams

AllWISE: magnitude in 4 infrared bands (W1, …, W4)

- differences of bands („colors“) = slope of spectrum
- color-color diagrams: shown to have good discrimination power between classes of objects
  Nikutta et al. https://doi.org/10.1093/mnras/stu1087
- e.g. selection of AGN possible with cuts in this 2D space



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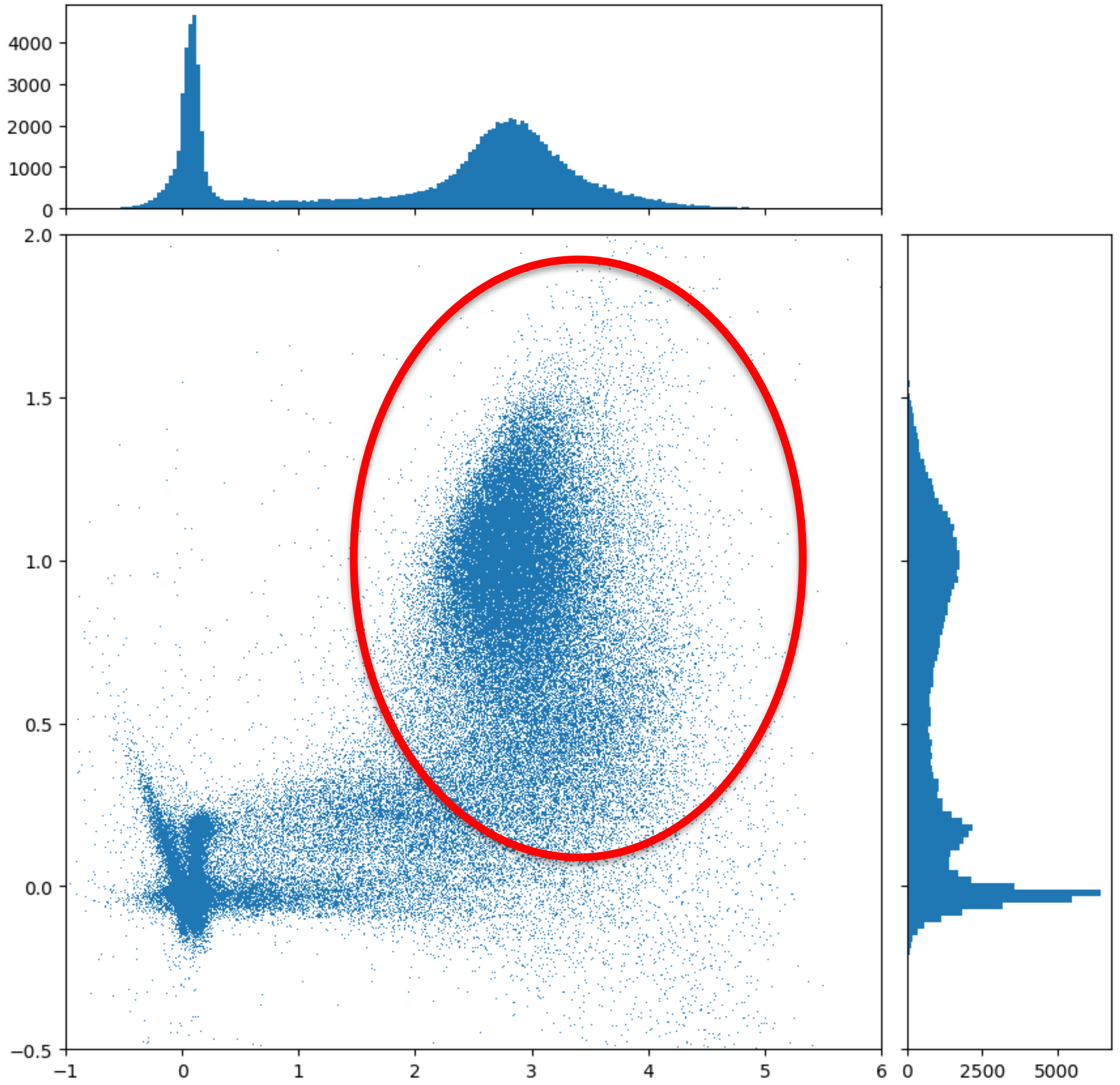
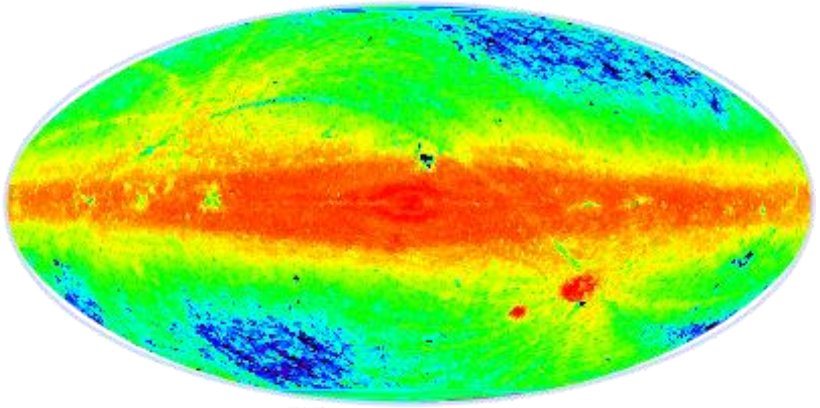
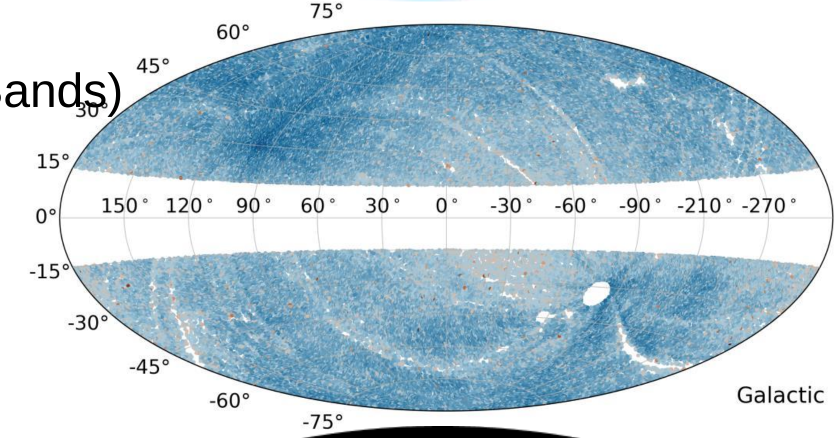


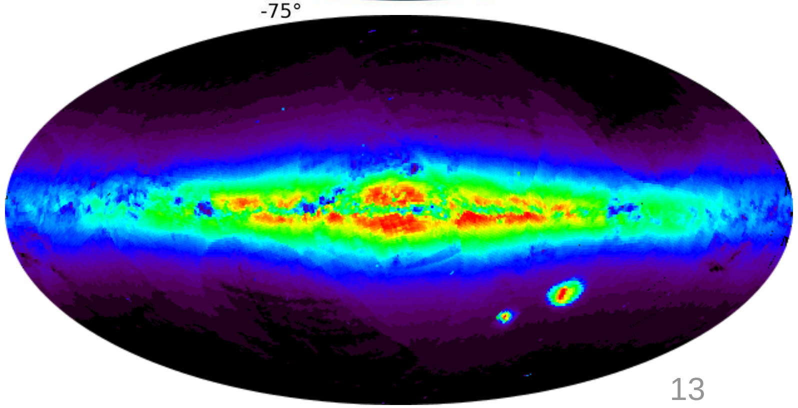
Dataset

add more observables:

- infrared: **AllWISE** (*Wide-field Infrared Survey Explorer*, 2010, 4 bands at a few μm)
- x-ray: **2RXS** (*ROSAT All-sky Survey*, 1990, 0.1 – 2.4 keV)
  + XMMSL2 (*XMM-Newton Slew 2 Survey*, 2017, 0.2 – 12 keV)
- optical: **Gaia** + **SDSS** (*Sloan Digital Sky Survey*, mean flux + u g r i z Bands)







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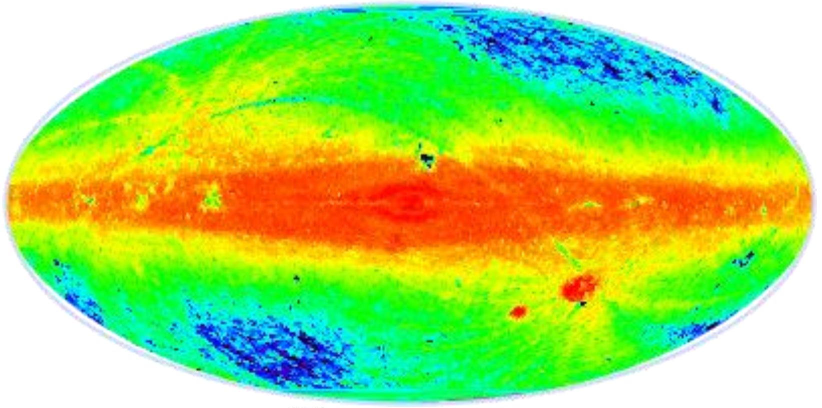

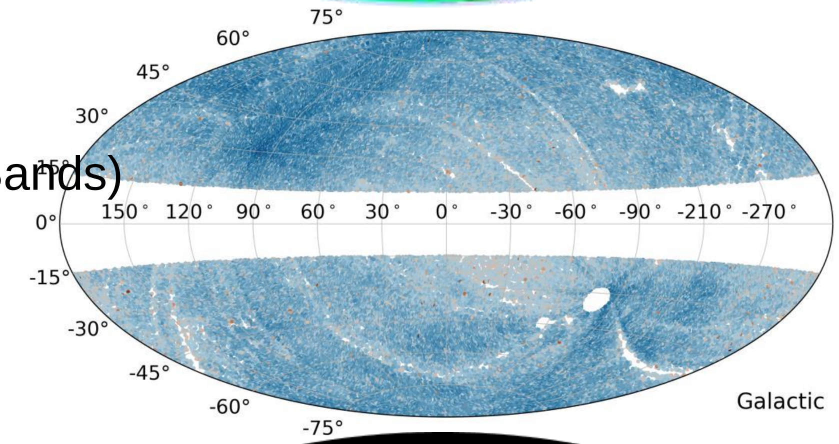

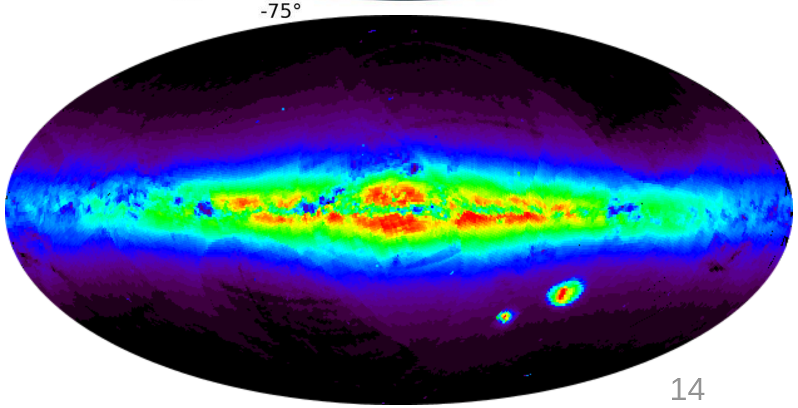

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  correlated catalog of 2RXS and AllWISE by Salvato et al. 2017
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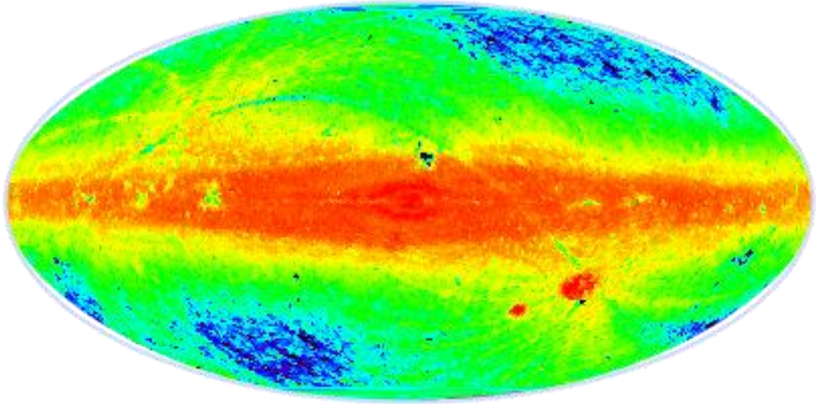

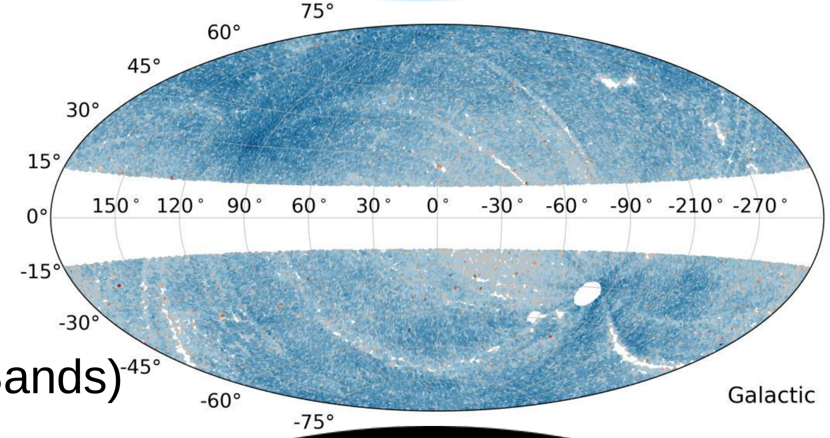

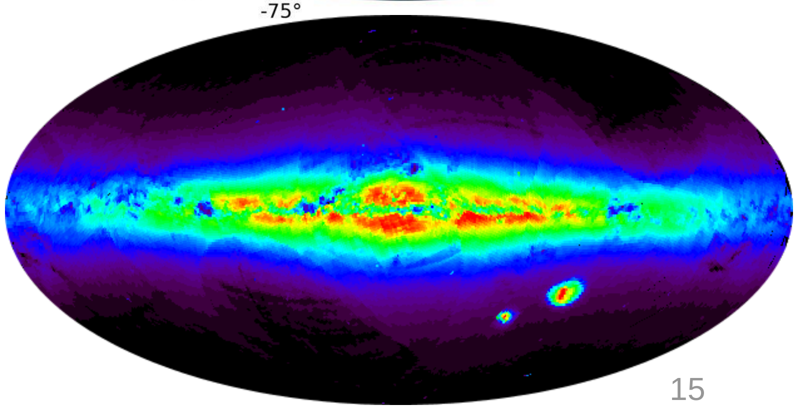

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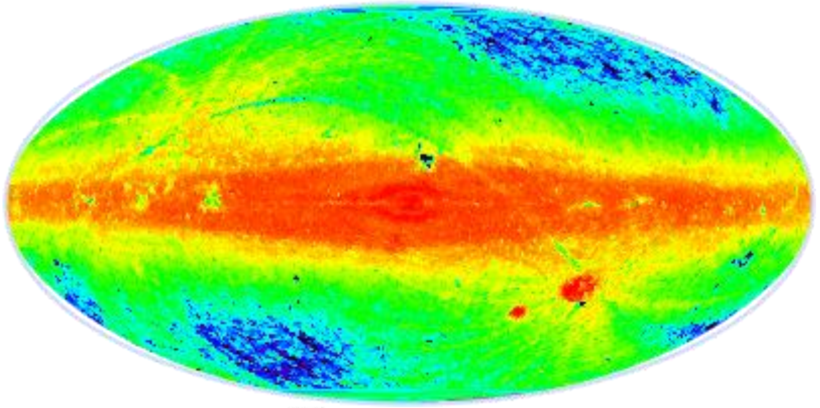
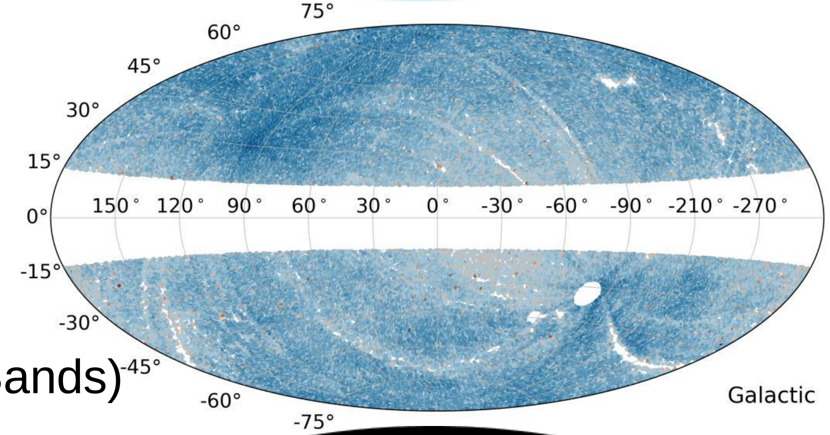
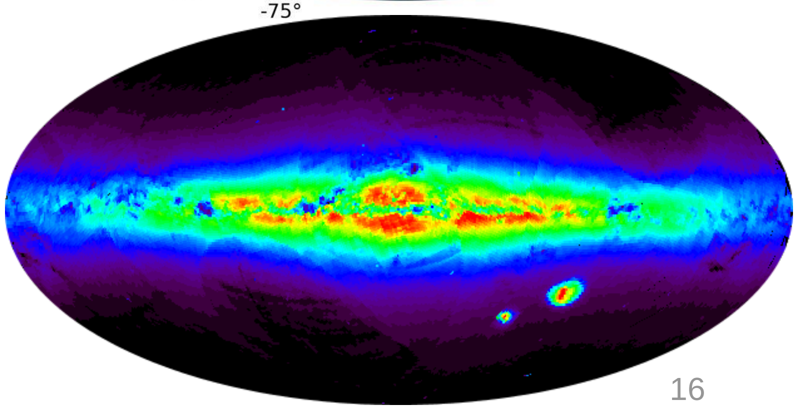




→ photometric data: 18 observables

- 4 infrared bands
- x-ray flux
- optical mean flux + 5 optical bands
- + 7 differences of fluxes (e.g. W1-W2, u-g)

combined catalogs from Mechbal et al. (pre-print)
arXiv:2303.18076



18-dim. AGN data

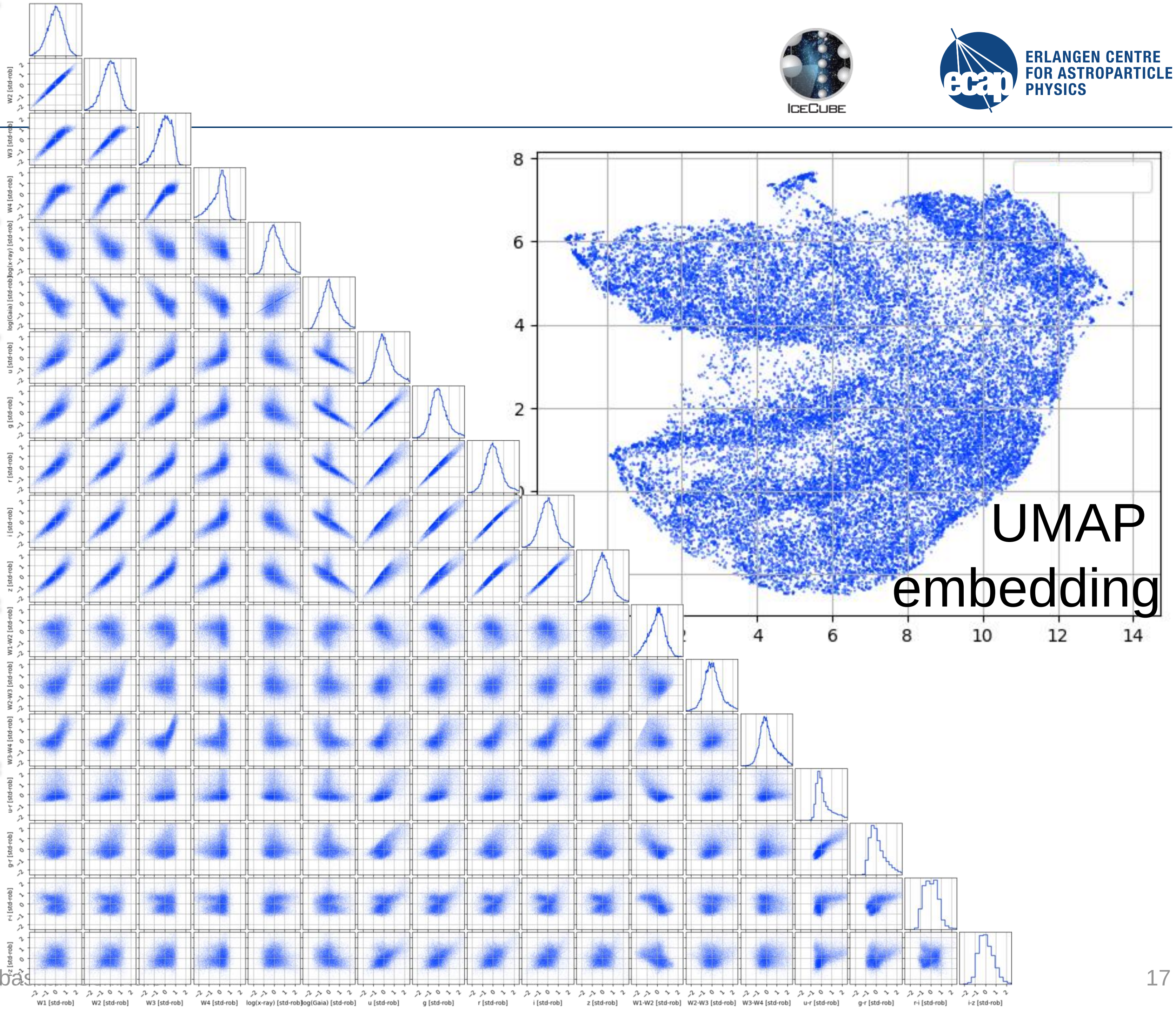
infrared (W1, …, W4)

log(x-ray)
log(optical mean)

optical bands (u, g, r, i, z)

infrared differences

optical differences

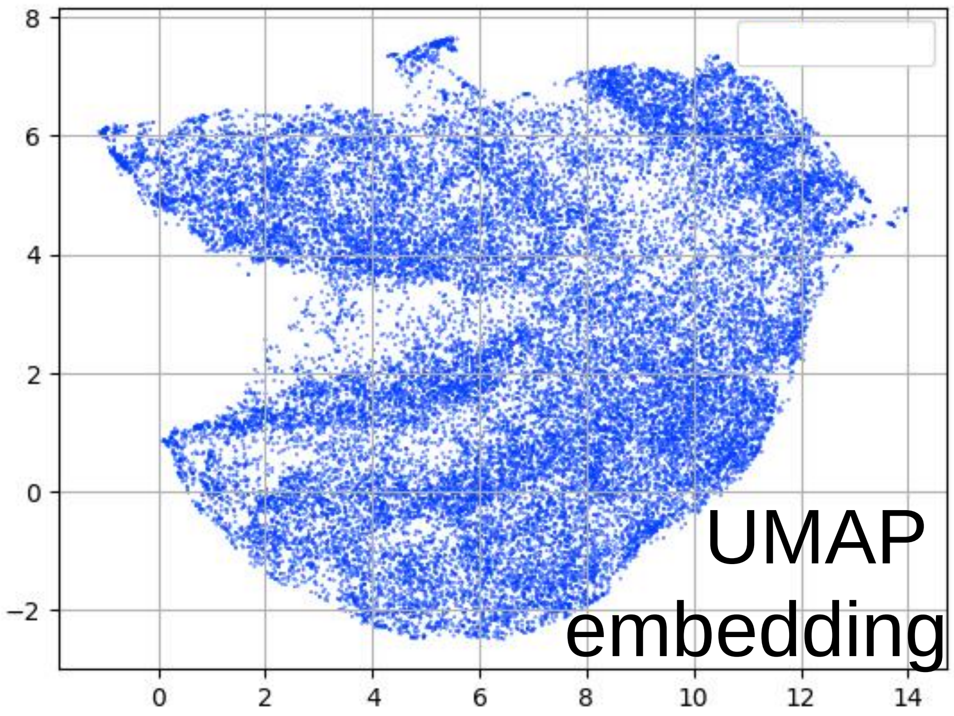


18-dim. AGN data

- rather homogeneous, connected distribution in most observables
  → no to-the-eye obvious distinguishable classes

- but high-dimensional = cannot see all hidden details even in corner plot
  illustrative example:
  sphere inside a spherical shell
  → 2D projections cannot depict problem entirely

- UMAP embedding:
  - difficult to interpret, however:
  - some structure: lower & upper part, upper-right part? → investigate!

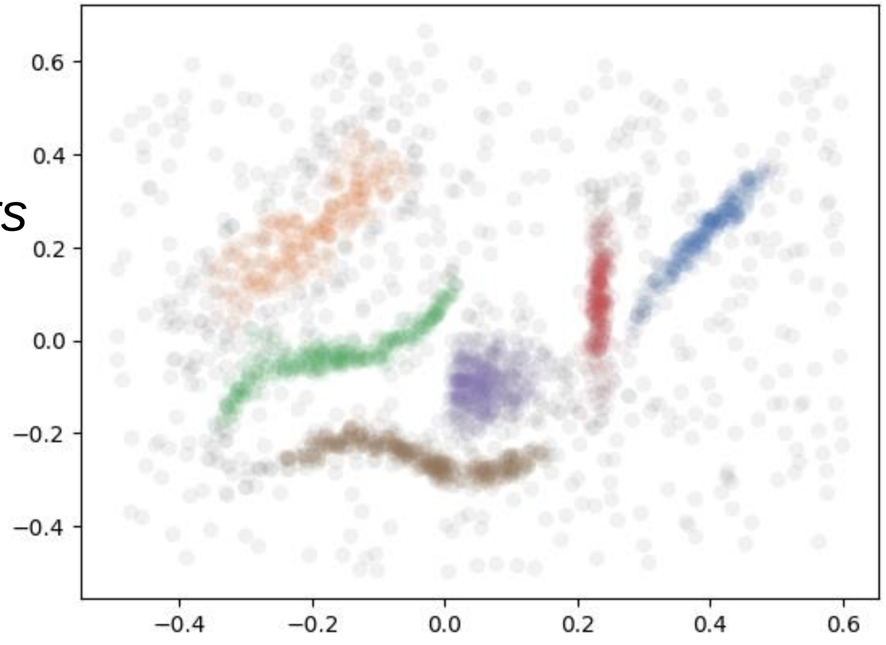


Cluster algorithm

HDBSCAN: state-of-the-art algorithm for searching for clusters in arbitrary data

(*Hierarchical Density-Based Spatial Clustering of Applications with Noise*
Campello, Moulavi, Sander https://doi.org/10.1007/978-3-642-37456-2_14)

- high dimensionality of data possible
- explorative: no required knowledge of number of clusters, arbitrary cluster shape
  → *but tends to produce some small additional clusters that seem like noise*
- fast (few seconds for 30k points in 18 dimensions)
- two main parameters to tune
  → *but not very easy to interpret these hyperparameters*
- has notion of unclustered data
  → *but often just leaves points around a central cluster unclustered, which is not that helpful*



Clustering applied

(one particular choice of hyperparameters)

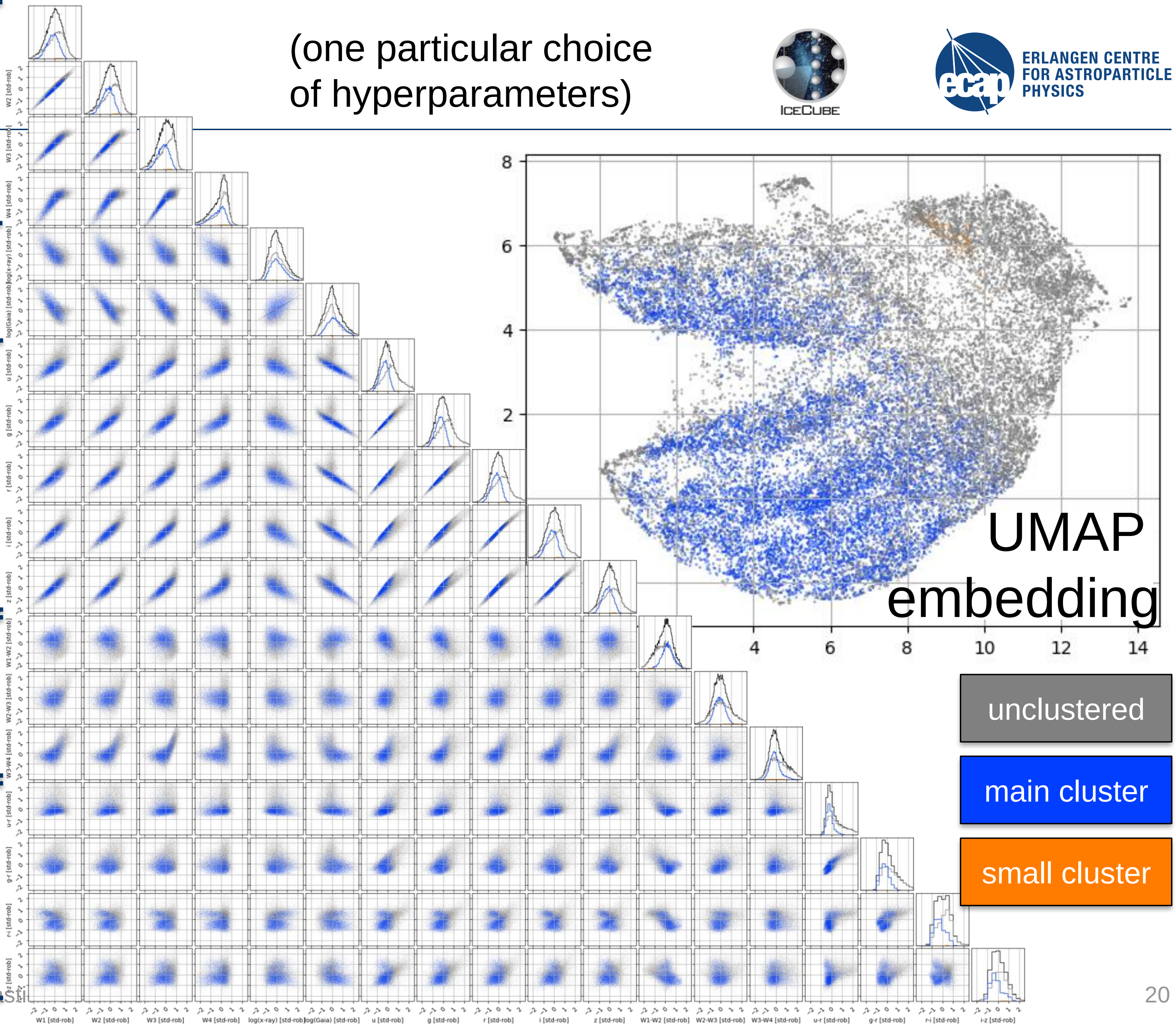
infrared (W1, …, W4)

log(x-ray)
log(optical mean)

optical bands (u, g, r, i, z)

infrared differences

optical differences



unclustered

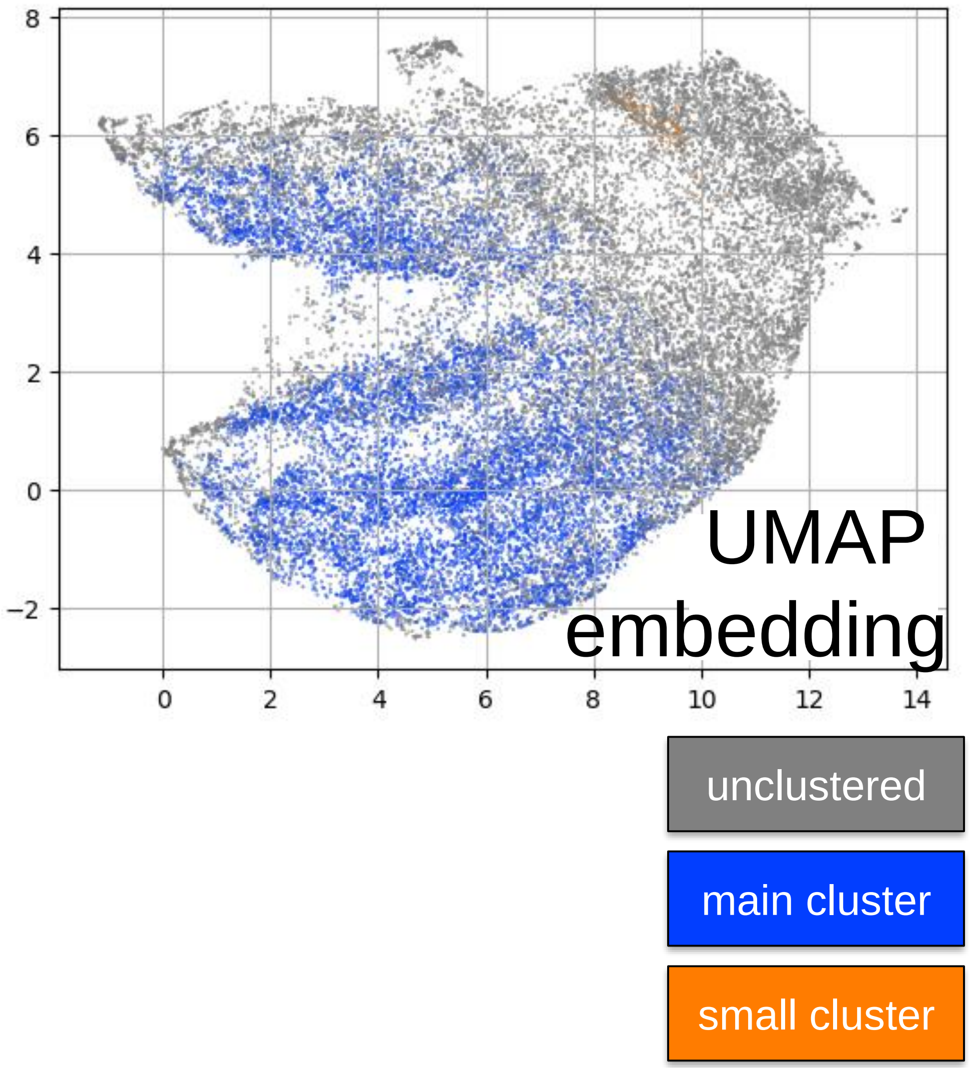
main cluster

small cluster

Clustering applied

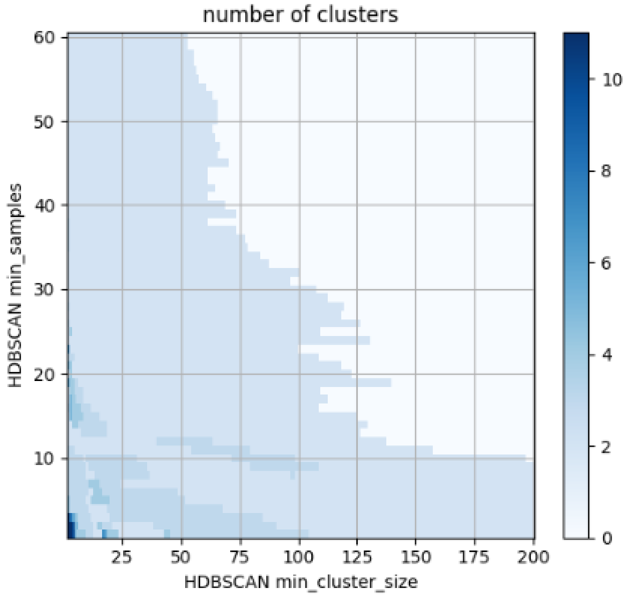
(one particular choice of hyperparameters)

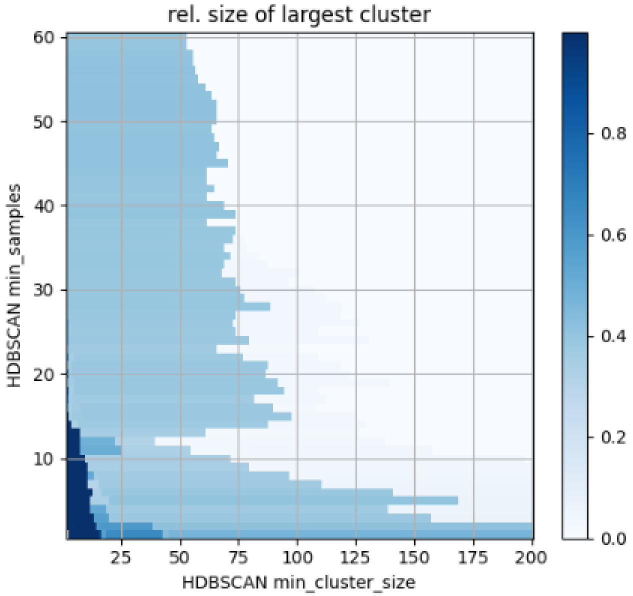
- one continuous, regularly shaped main cluster in most dense area
- many points around it remain unclustered (few micro clusters)
- hyperparameter choice does not change much
- UMAP embedding: clustering does not follow the visible structure…

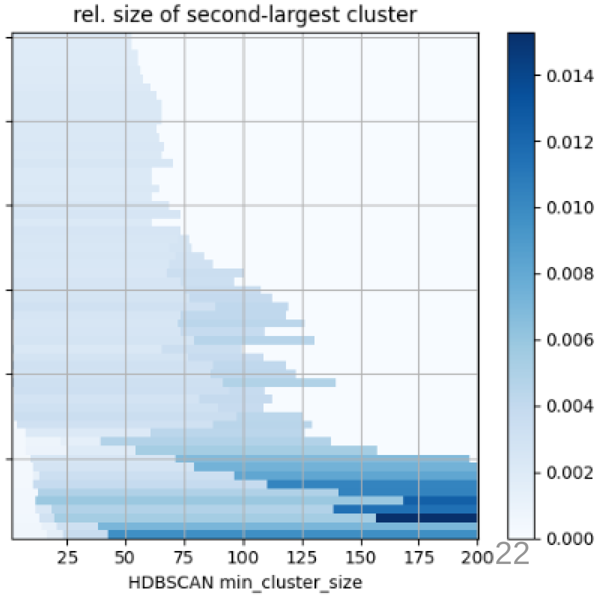


Hyperparameter scan

- hyperparameter choice for cluster algorithm is not obvious
  → scan hyperparameter space (i.e. run HDBSCAN for all combinations)
- look at summary quantities
  - number of clusters found
  - relative size of largest & second-largest cluster (fraction of points in this cluster)
- what choice is sensible?
  → introduce artificial clusters to test hyperparameter choice
  - introduce obvious clusters into the data
  - only hyperparameters that can identify those should be used







What to make of this?

naïve and hopeful idea does not really work:

- not that much structure in the phase space
- algorithm does not seem to find interesting non-obvious clusters

→ fault of HDBSCAN? use different cluster algorithm?

other Ansatz:

- compile list of interesting sources and mark them in the phase space
- (should not be a problem with blindness, as no neutrino data yet involved)

→ can we see something around the sources by eye?

fall-back option:

- use all sources in a pre-defined radius around very interesting sources (like NGC 1068)
- maybe radius such that ~ 100 sources are contained

Summary

Summary

- look for source list for stacking search based on similarity to known candidate sources
- high-dimensional dataset: about 30k AGN in 18 observables
- search for structures/clusters using HDBSCAN and UMAP
- not successfull currently → possibly pursue different Ansatz

Different idea

- instead of many different observables, use wealth of data in **optical only**
- optical spectra: treat each bin as one dimension (~ 1000 dimensions)
- apply UMAP (or other dimensionality reduction), then search for clusters again

Thank you for your attention

Questions?

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Backup

Analysis plan

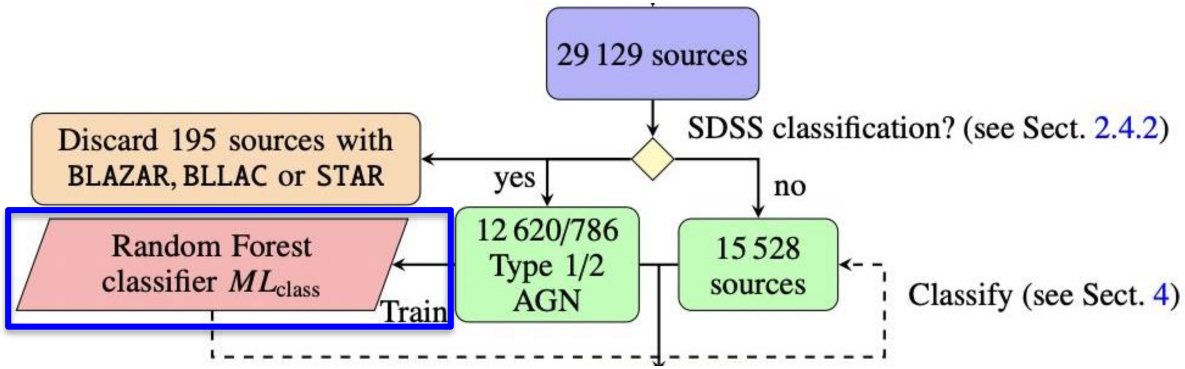
1. **build extensive catalog** of AGN with many different observables
   a) decide on observables to use (flux in certain waveband, spectral lines etc.)
   b) combine astronomical catalogs
   c) populate phase space
2. **cluster search** in observable space to select AGN closest to candidates
   a) run cluster search algorithm
   b) select interesting clusters based on location of candidate sources
3. perform **stacking analysis** with AGN within selected clusters

Testing with a supervised-learning classifier

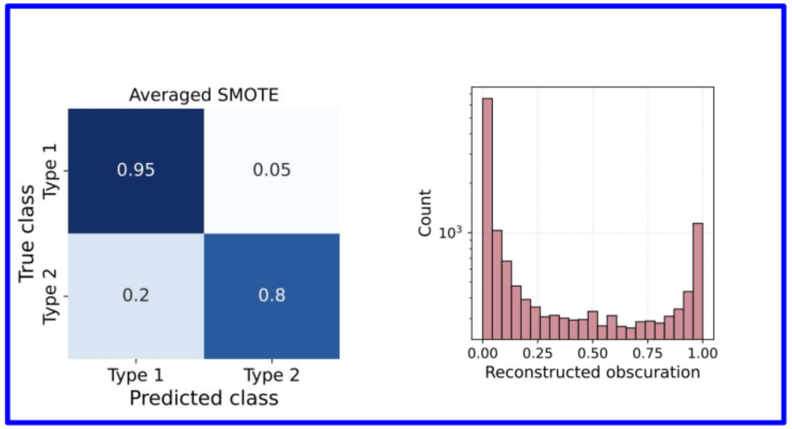
- can classify AGN as…
  - Type 1: unobscured disk, broad lines
  - Type 2: obscured disk, narrow lines
- Mechbal et al. pre-print arXiv:2303.18076:

  classification exists for ~ ½ of AGNs in dataset
  (from SDSS catalog by visual inspection)

  → **train machine-learning classifier**
  - photometric data of AGNs as input
  - supervised learning with labels from existing classification
  - apply to other ½ of AGNs



Classification task



→ also possible with **unsupervised clustering?**

- classification problem is binary (Type 1 or 2)
- … so there should be two clusters in the data

Classifier (Mechbal et al.)

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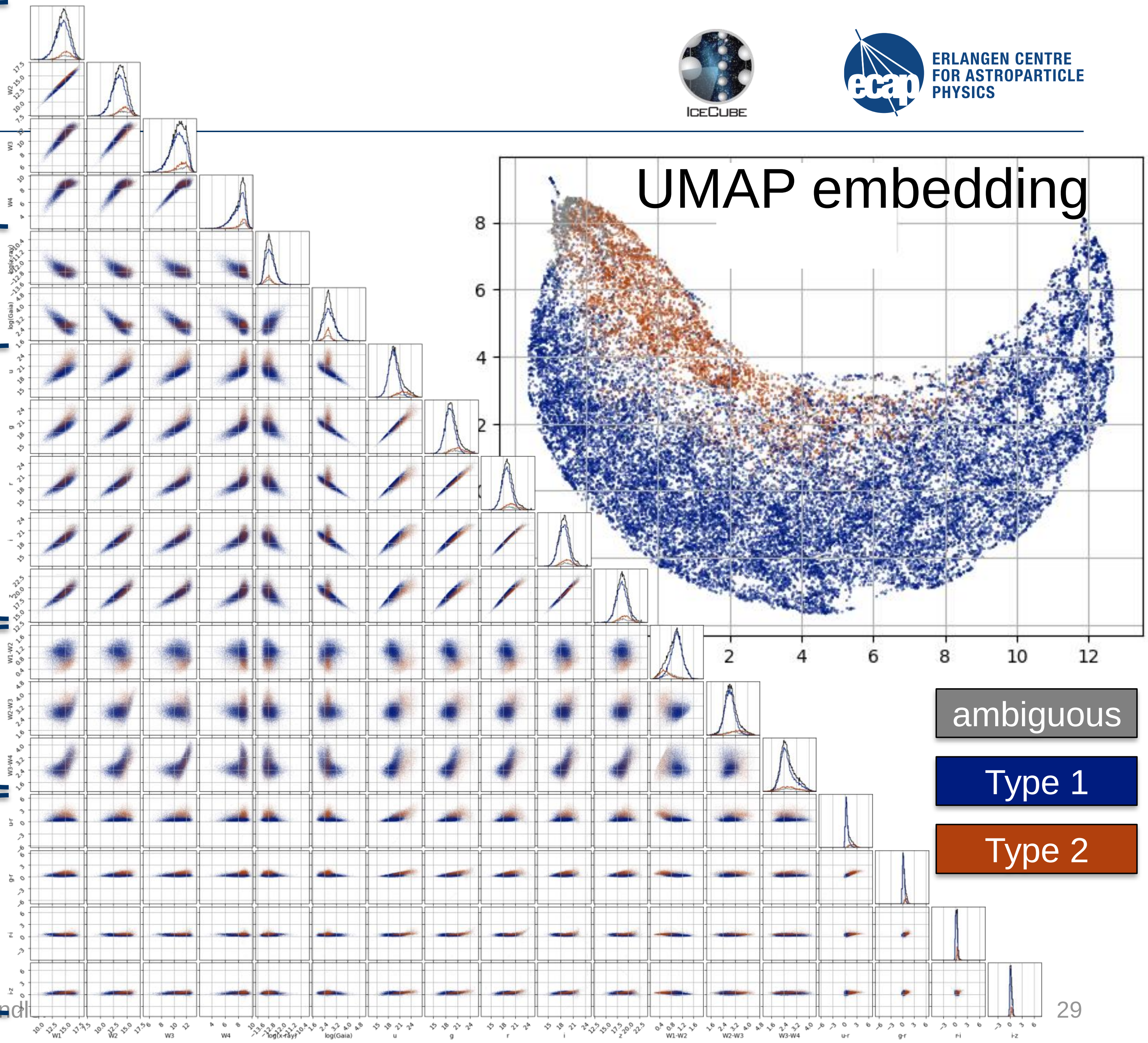
log(x-ray)

log(optical mean)

optical bands (u, g, r, i, z)

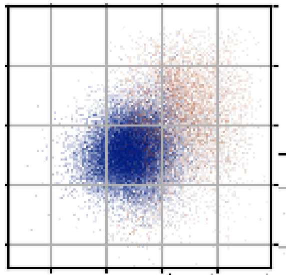
infrared differences

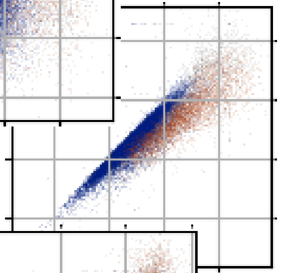
optical differences



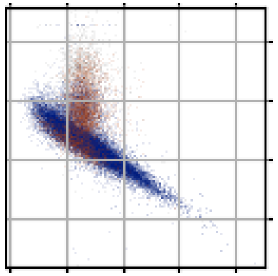
Classifier (Mechbal et al.)

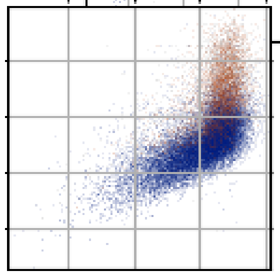
- separation between Type 1 / 2 somewhat similar to clusterin
  - Type 1 more in dense center area
  - Type 2 more at the fringes
  - also the case in UMAP





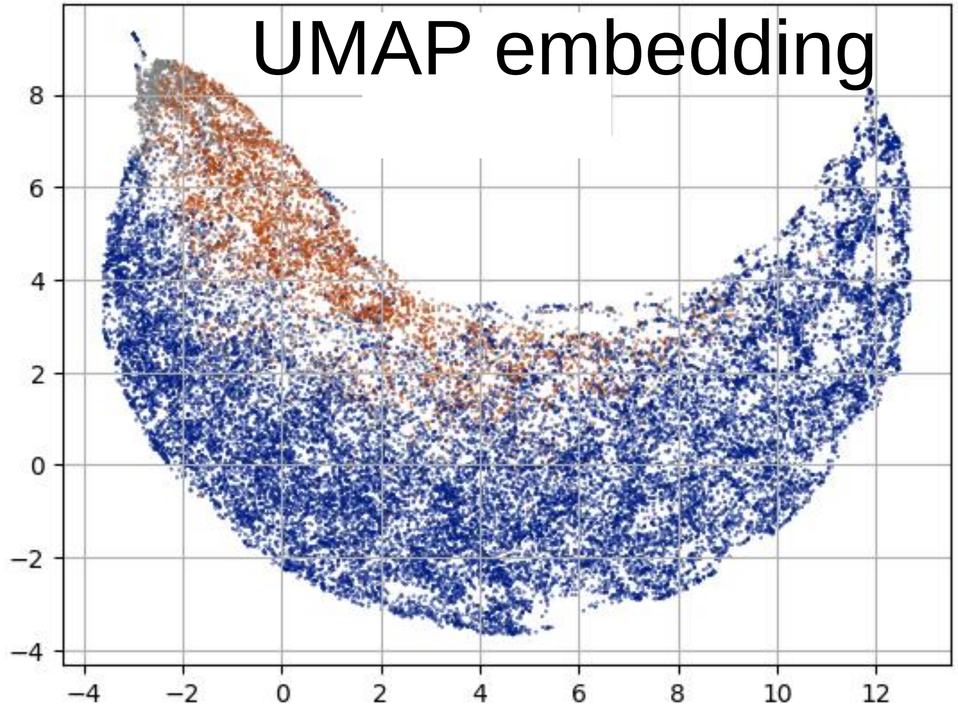
- some smaller features can be mapped to Type 1 / 2





→ for **comparison with clustering**, associate…

- unclustered with Type 2
- main cluster with Type 1



ambiguous

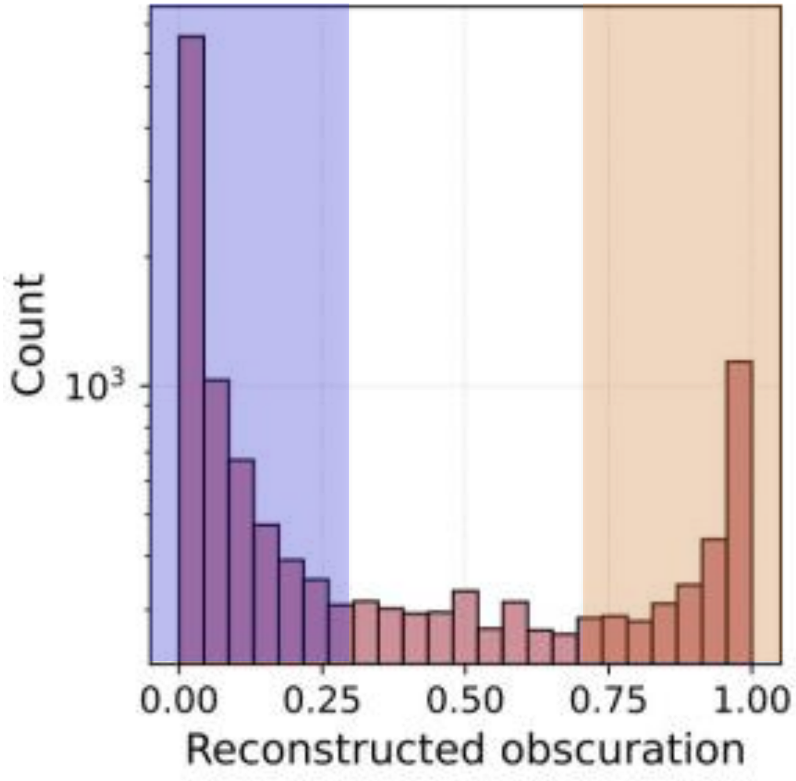
Type 1

Type 2

Classifier (Mechbal et al.)

obscuration score μ

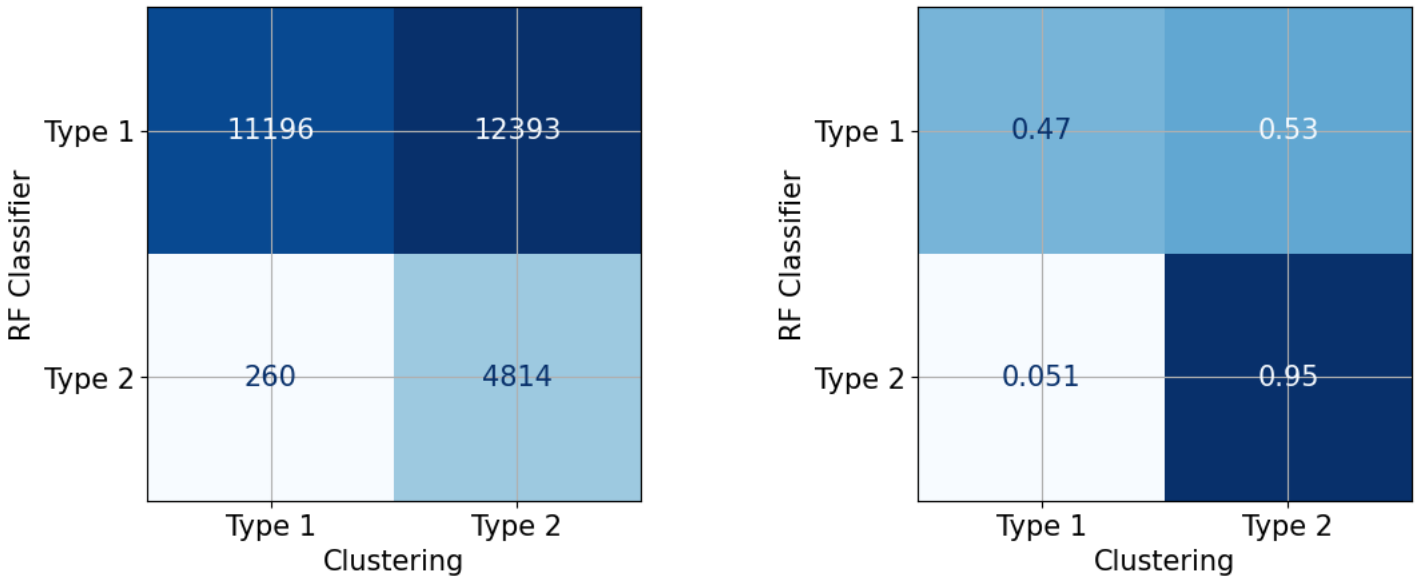
- $\mu < 0.3$ → Type 1
- $\mu > 0.7$ → Type 2
- $0.3 < \mu < 0.7$ → ambiguous type



Performance of clustering

current work in progress:

compare cluster result (prediction) to classifier (as truth):



→ clusterer…

- finds most Type 2 (95 %)
- but is just guessing for Type 1 (47 %)

however:
Type 1 more numerous!