IceCube
South Pole Neutrino Observatory

Technische Universität München

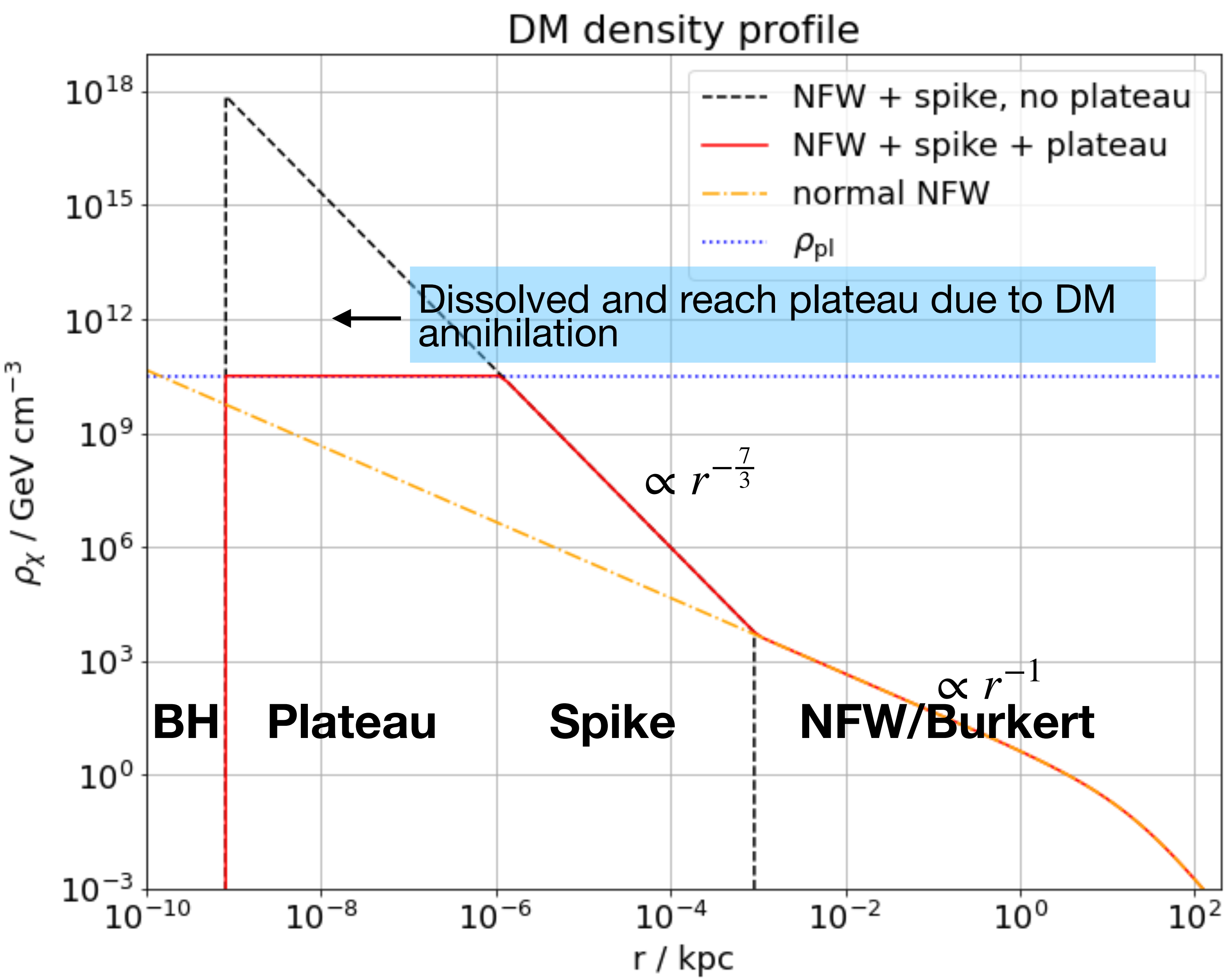
SFB 1258 Neutrinos Dark Matter Messengers

Search for DM annihilation from extra-galactic point sources with IceCube

Ruohan Li
Technical University of Munich

Neutrino from DM halo spike

Dark Matter Annihilation at the Galactic Center, Gondolo&Silk Phys. Rev. Lett. 83, 1719, 1999



J-factor for extra-galactic object:

$$J = 4\pi \int_{R_{schwarz}}^{R_{200}} \rho^2(r)dr$$

Integral over DM profile with parameters$\rho(\rho_0, r_s)$.

J integral for difference profiles (MW):

- spike + plateau: 1.01e23
- normal NFW: 2.02e22

MW example: Spike + Plateau/NFW $\approx$ 49; NFW/Burkert $\approx$ 31

DM annihilation Neutrino Spectra

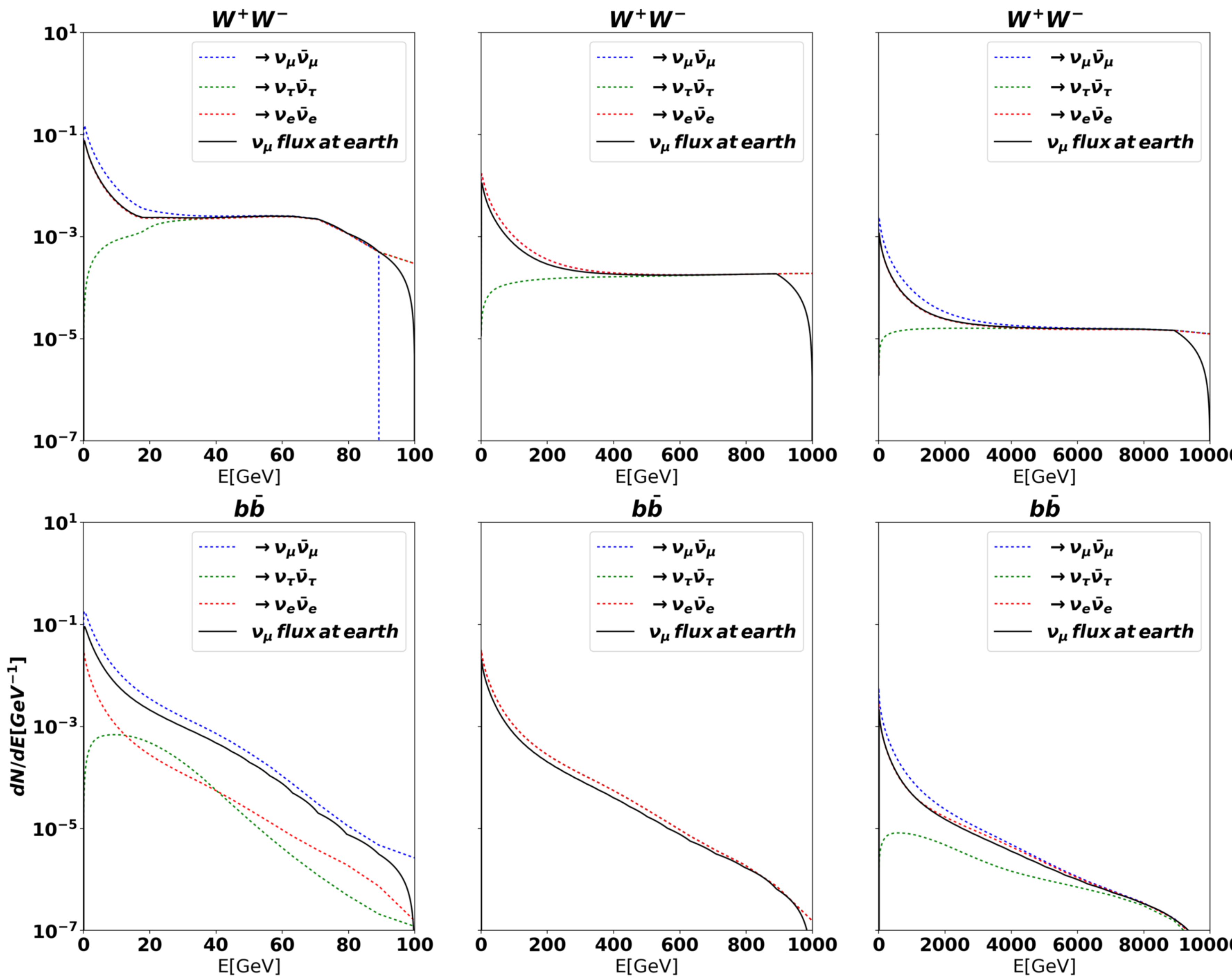
Estimated muon neutrino flux from a galaxy:

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{\kappa m_\chi^2}\frac{1}{3}\frac{dN_\nu}{dE_\nu}J(\Omega)$$

Input: Catalogs | Simulation | IceCube data

Output: To constraint

- W^+W^-/b^+b^- (softest/ hardest)channel
- Spectra at Earth modified due to the oscillation during propagation



Selection of Extragalactic Sources

Many different catalogues providing black hole mass, with criterion:

- Northern sky (dec > $-5°$)
- z<0.33 (redshift of TXS 0506+056)
- $10^6 M_\odot <= M_{BH} <= 10^{10} M_\odot$

M_{BH} measured by different methods: by photometry(larger error)/velocity dispersion (smaller error)with basic infos (name, M_{BH}, error, redshift):

	Object	log M_{BH} (M_{sun})	RA (hh:mm:ss.s)	Dec (dd:mm:ss)	z	Alternate Names
▶	Mrk335	7.230 ($^{+0.042}/_{-0.044}$)	00:06:19.5	+20:12:10	0.02579	PG0003+199
▶	Mrk1501	8.067 ($^{+0.119}/_{-0.165}$)	00:10:31.0	+10:58:30	0.08934	Mrk9007 PG0007+106
▶	PG0026+129	8.487 ($^{+0.096}/_{-0.119}$)	00:29:13.6	+13:16:03	0.14200	
▶	PG0052+251	8.462 ($^{+0.083}/_{-0.094}$)	00:54:52.1	+25:25:38	0.15445	

Many DM profile physical properties are related to each other, mathematical derivation see *Halo concentrations in the standard LCDM cosmology, Francisco Prada et.al., MNRAS, Volume 423,Issue 4, July 2012.*

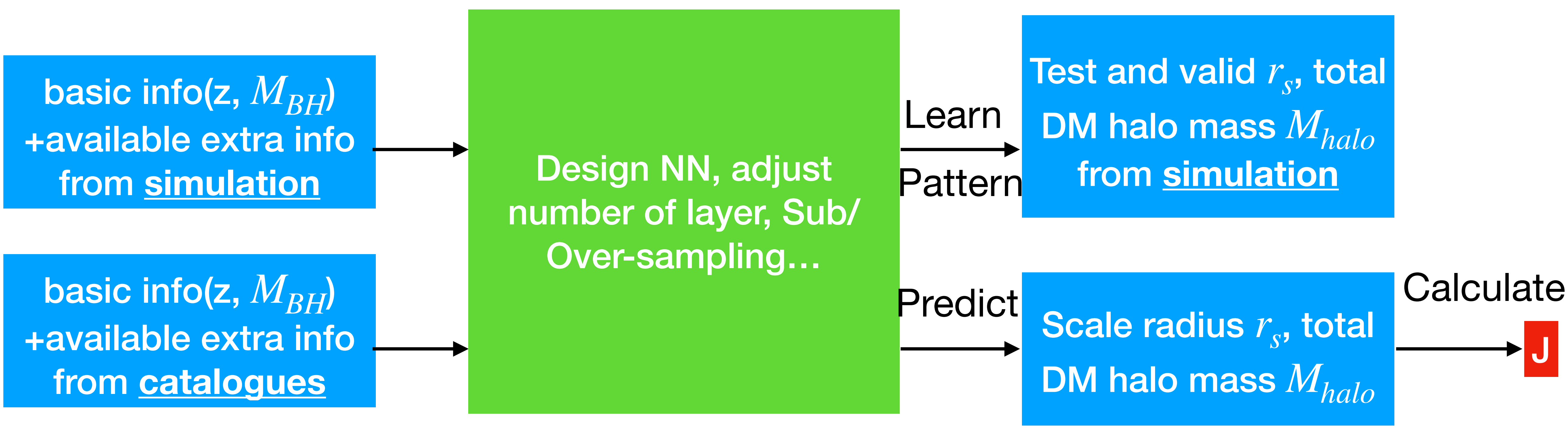
DM Halo Estimation via Machine Learning

$$M_{halo,total} = \int \rho(r, r_s) dr^3 \rightarrow \rho_r$$

known r_s(scale radius), known total mass of DM halo → know profile and J

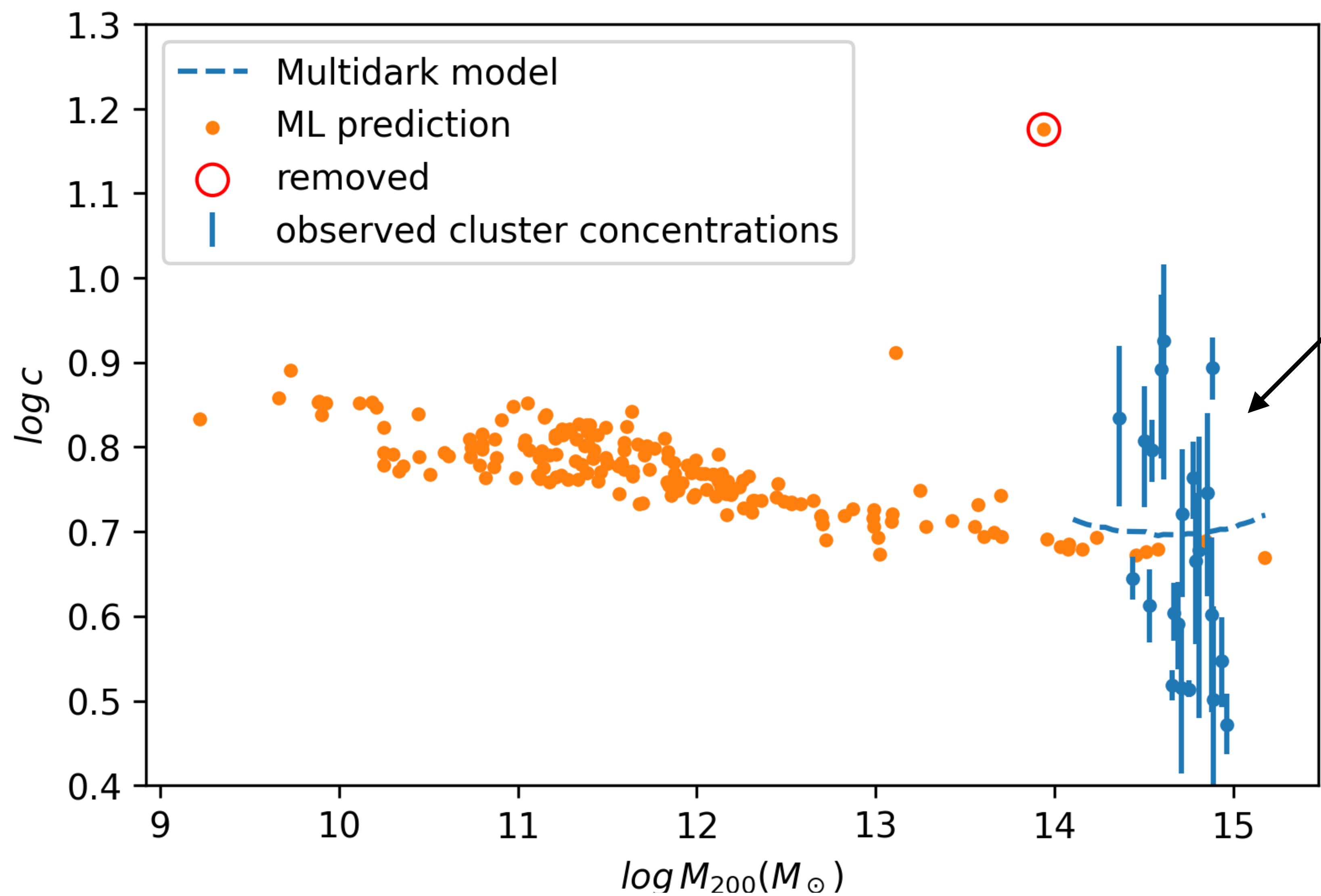
Can not use analytical solution because of unknown parameters?
Use Machine learning!

From www.cosmosim.org/, Dataset: *MultiDark*. After the *same selection as for sources*, there are still 10 millions simulated galaxies to train.



Prediction has **10%-30% uncertainty**(details in backup) mainly from measurement uncertainty of M_{BH}.

Compare machine learning method with MultiDark simulation



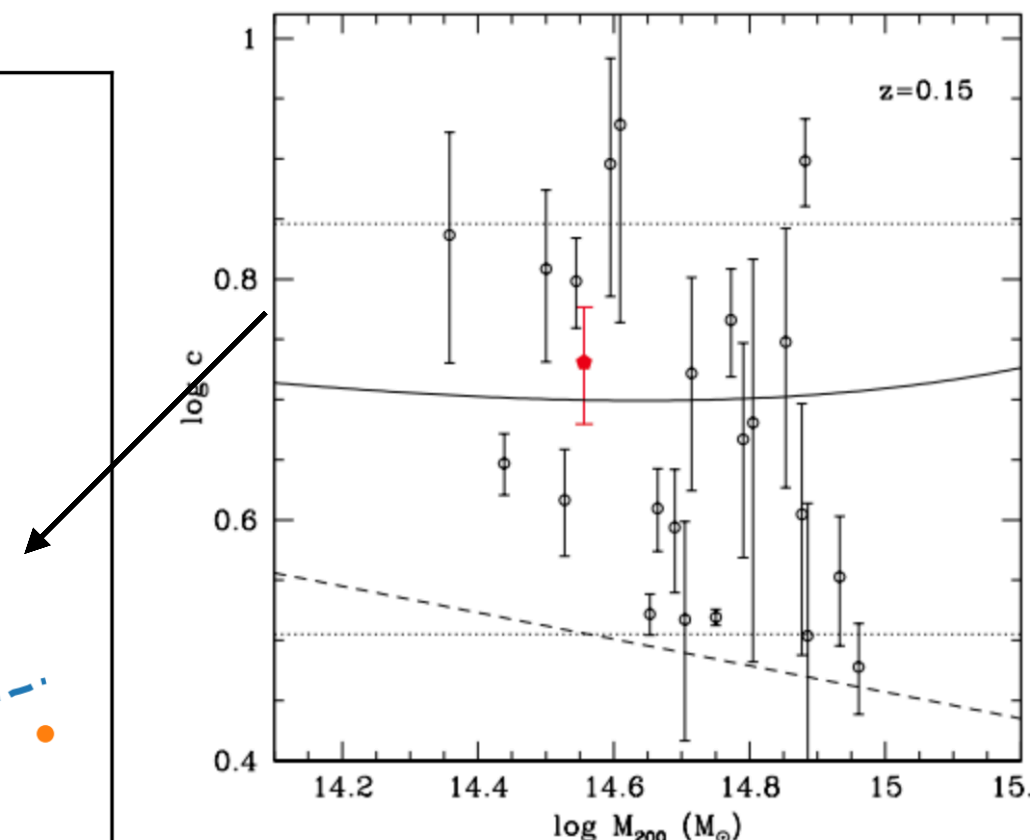


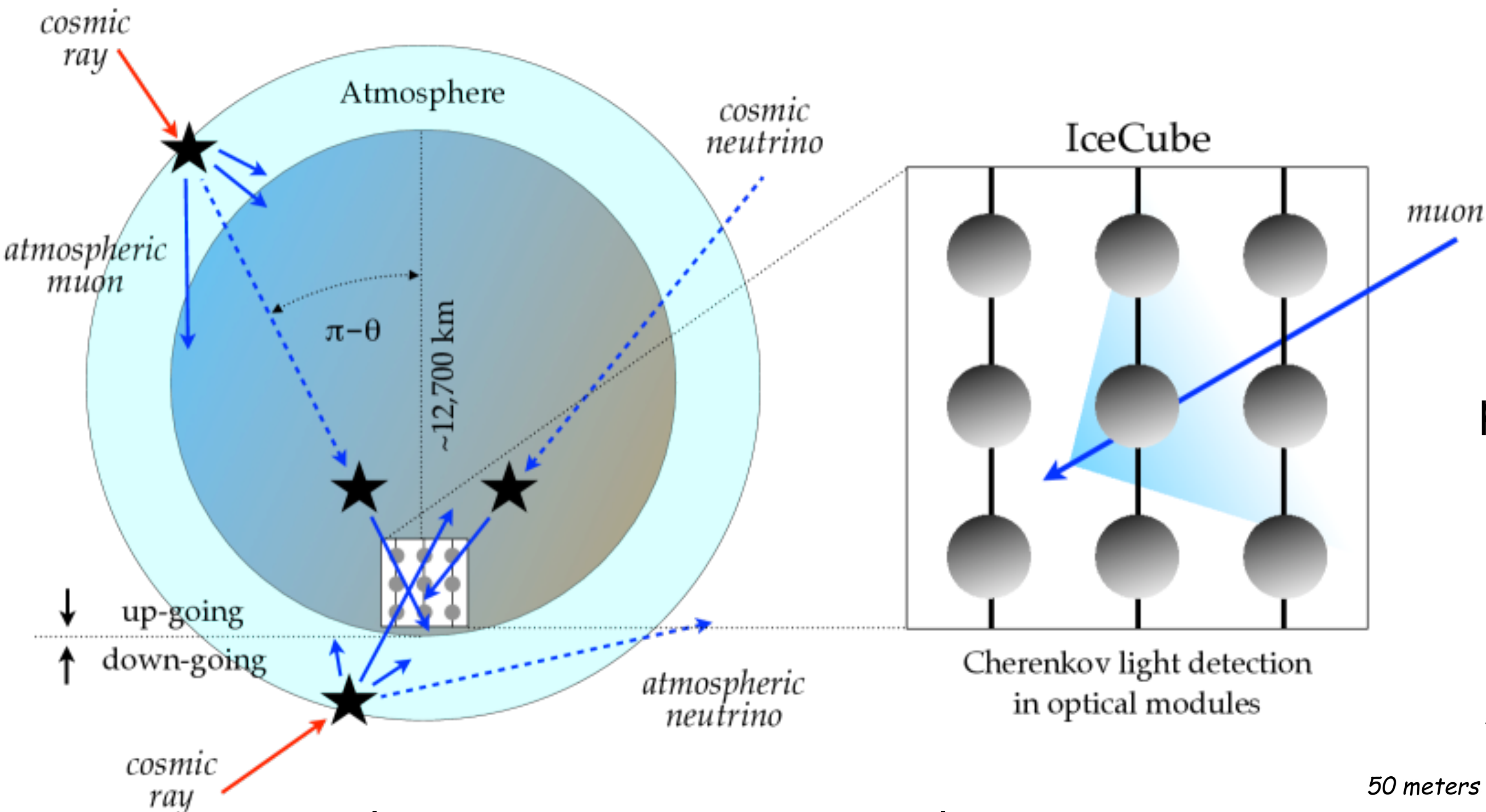
Figure 13. from Halo concentrations in the standard LCDM cosmology, Francisco Prada et.al., MNRAS, Volume 423,Issue 4, July 2012.

	log $(M/M_\odot)$	Halo concentration log(c)	$\rho_s\ [\frac{GeV}{cm^3}]$	r_s[kpc]	J $[\frac{GeV^2}{cm^5}]$
Milky Way	12.1	1.11	0.87	18.62	2.51e22
Andromeda	11.9	1.25	0.21	22.04	2.09e22

Conclusion:

- Most of prediction corresponds simulation
- Blazar has large uncertainty on M_{bh} measurement

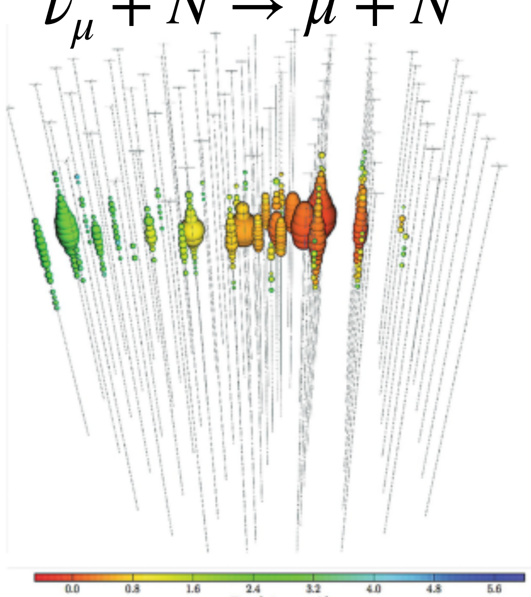
IceCube Neutrino Observatory



Neutrinos interacts with ice and creates charged particle tracks/cascades and later detect by **Cherenkov light**

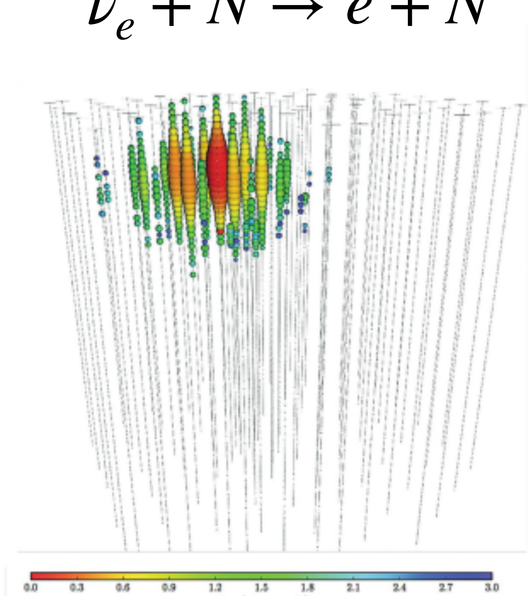
track

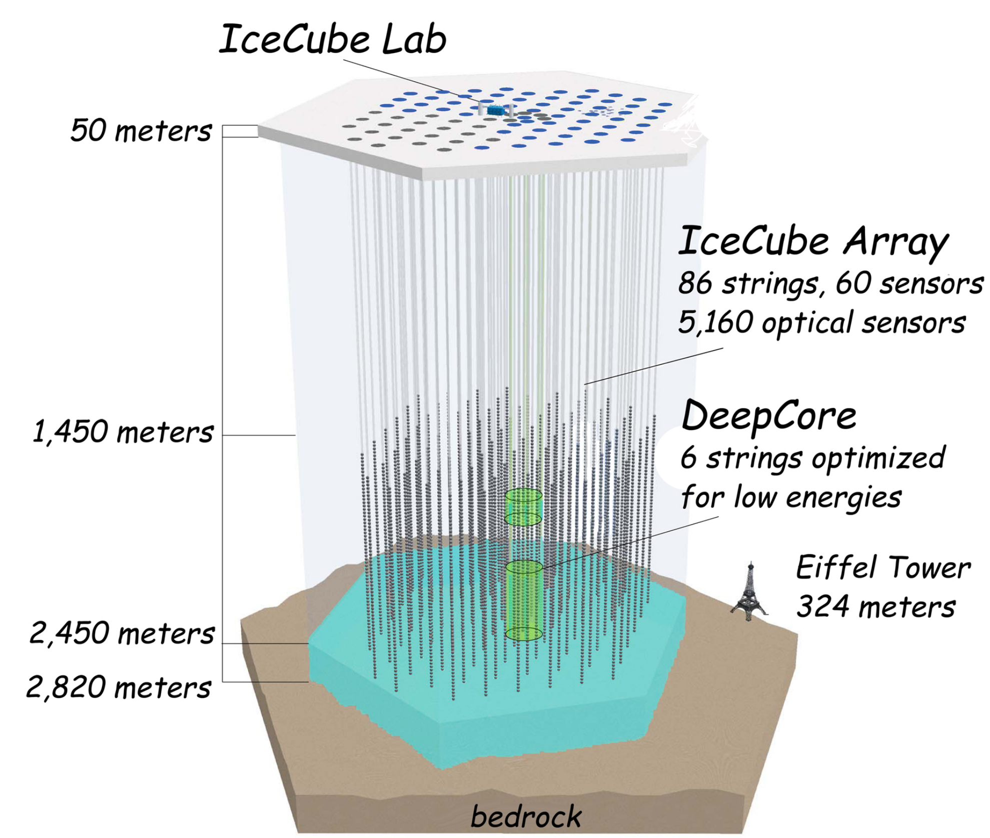
$$\nu_\mu + N \rightarrow \mu + N$$



cascade

$$\nu_e + N \rightarrow e + N$$





Analysis Plan

Scene	Power-law	DM annihilaion
Weights	$V_{infall}^2/d^2 = GM_{BH}/30R_s/d^2 \propto \sqrt{M_{BH}}$	$J/d^2 \propto \Phi$
Spectrum	floating gamma	Channel: W^+W^-/b^+b^- and decay into $\nu_\mu\bar{\nu}_\mu$ DM mass: 100GeV/1TeV/10TeV

- **Stacking & Catalog** search + binomial test as comparison

- Consider W^+W^-/b^+b^-(softest/hardest) channels

- Power law weighting motivated by BH infall velocity conversion into kinematic energy : Sub-GeV Gamma Rays from Nearby Seyfert Galaxies and Implications for Coronal Neutrino Emission Kohta Murase et al 2024 ApJL 961 L34

Cross Catalogues Check

- This analysis:

DM weight	PL weight
NGC4151	NGC4395
3C390.3	NGC4151
3C273	NGC4258
4C74.26	NGC5273
NGC4258	NGC5033
3C382	NGC4138
PG1426+0	NGC4051
NGC4388	NGC5506
NGC4138	NGC4180
NGC3227	NGC4388

- Previous analyses:

Object Name	• IceCube Extended Improved PS Analysis	FermiLAT and IceCube
NGC4151	both	no
3C390.3	DM	no
3C382	DM	no
NGC4388	both	no
NGC3227	DM	no
NGC5506	PL	no

- See Wednesday plenary: Active Galactic Nuclei as Counterparts of IceCube Neutrinos, Elisa Resconi

- Mostly gamma ray obscured source like NGC1068
- Mostly AGNs, several non-active galaxies in total 49 sources

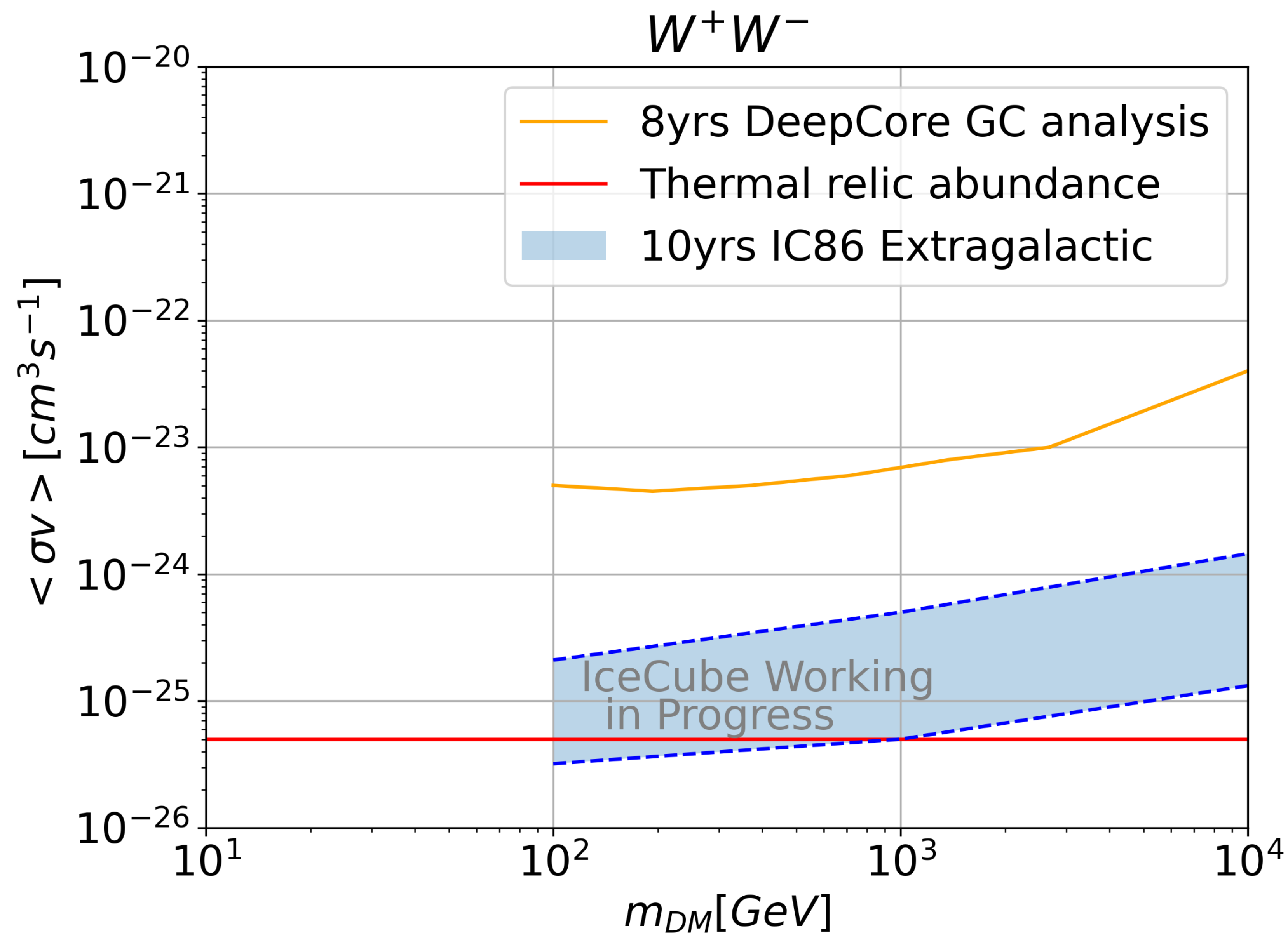
Performance Check with MC

- Power law:

Best fit gamma	2.58
Sensitivity [event number (flux) $\mathbf{GeV}^{-1}\mathbf{cm}^{2}\mathbf{s}^{-1}$]	10.7 (9.13e-16)
3-sigma discovery potential	16.8 (1.43e-15)
5-sigma discovery potential	25.4 (2.16e-15)

(Estimated with 5%-95% of dataset energy range. Normalisation reference at 1TeV)

- DM annihilation:



(Including systematics from cusp-core profile. DOM efficiency and ML systematics to be include)

Summary & Outlook

- Super massive black hole at galaxy centre, especially the accretion disk surrounding the black hole, could be the origin of extragalactic multi-messenger emission.
- To estimate the neutrino flux from extragalactic supermassive black hole, we developed a machine learning method to predict DM halo parameter based on M_{BH}.
- Stacking and catalog search will be done with IceCube data, covering possible DM annihilation mass range.

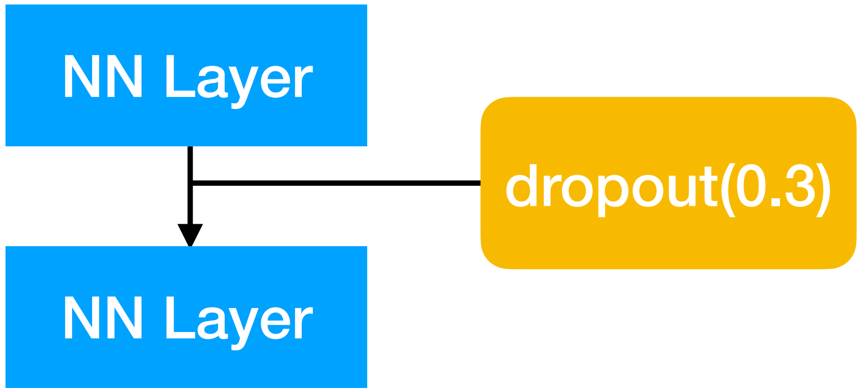
- We hope this analysis could not only improve on the cross section constrain by stacking many sources, but also reveal the link between supermassive black hole and neutrino production by comparing the significance between binomial test and stacking test.
- Providing the potential candidates for future searches.

Thank you for your attention!

Any questions or comments are welcomed

Back Up Slides

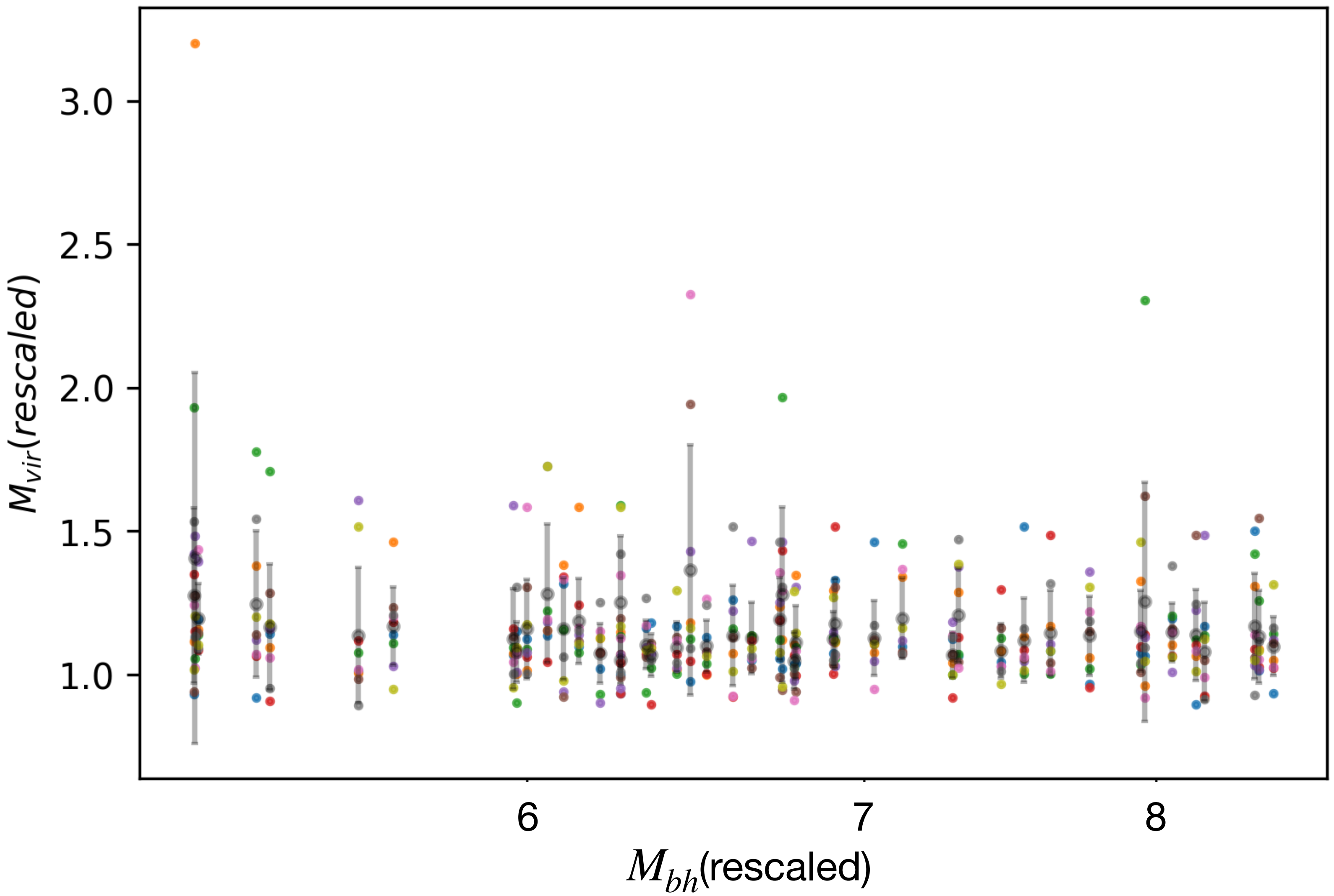
Estimate the Error of Machine Learning



- M_{bh} has uncertainty 10-30%

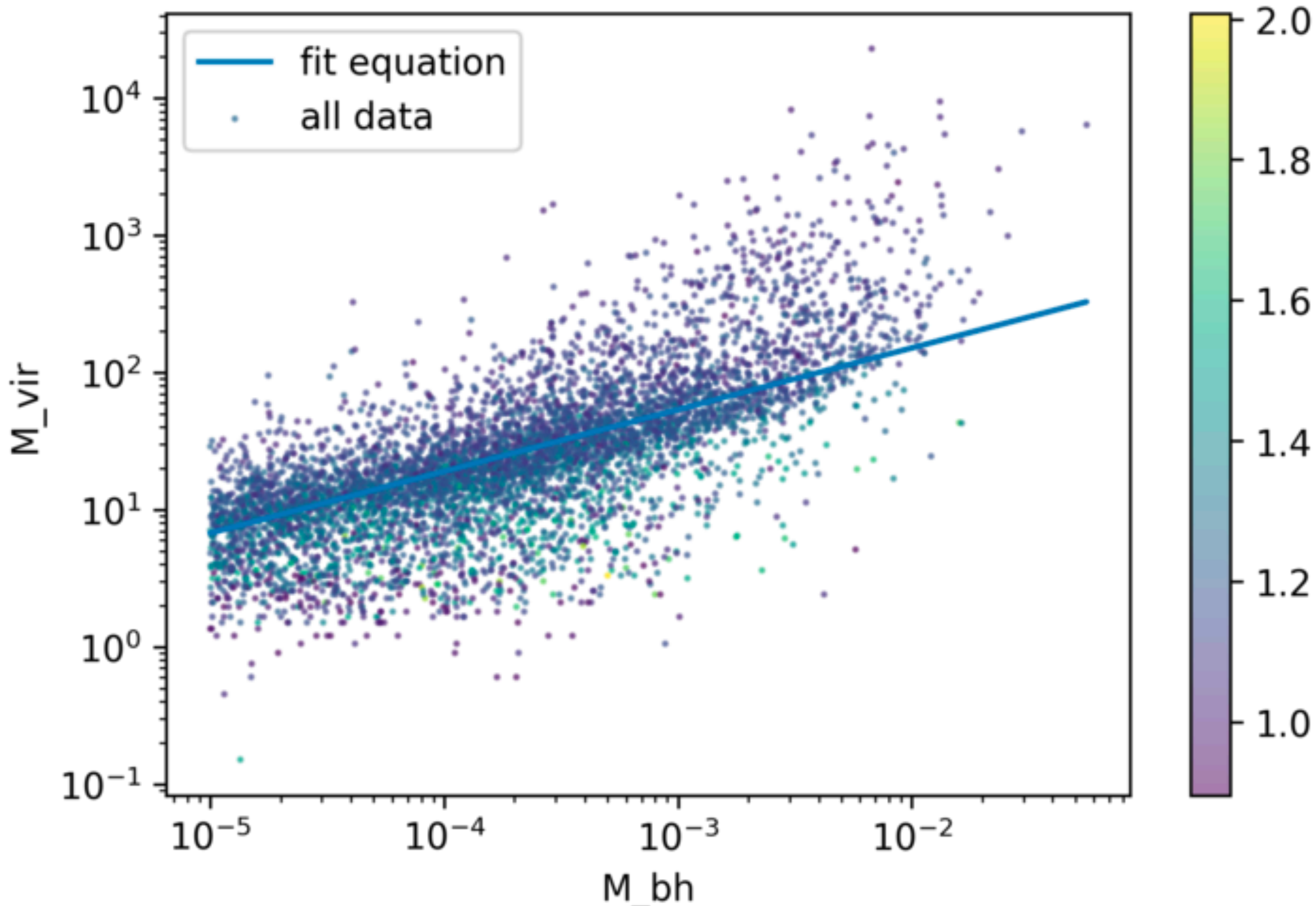
(Imaging NN-algorithm is a function with parameter uncertainty $f(M_{bh}) = A^{+a}_{-a}M_{bh} + B^{+b}_{-b}M^2_{bh} + C^{+c}_{-c}M^3_{bh}\ldots)$

- NN prediction uncertainty: add random dropout layers between original NN-layers. As dropout value/position changing, the outputs change accordingly -> **the range of uncertainty**.



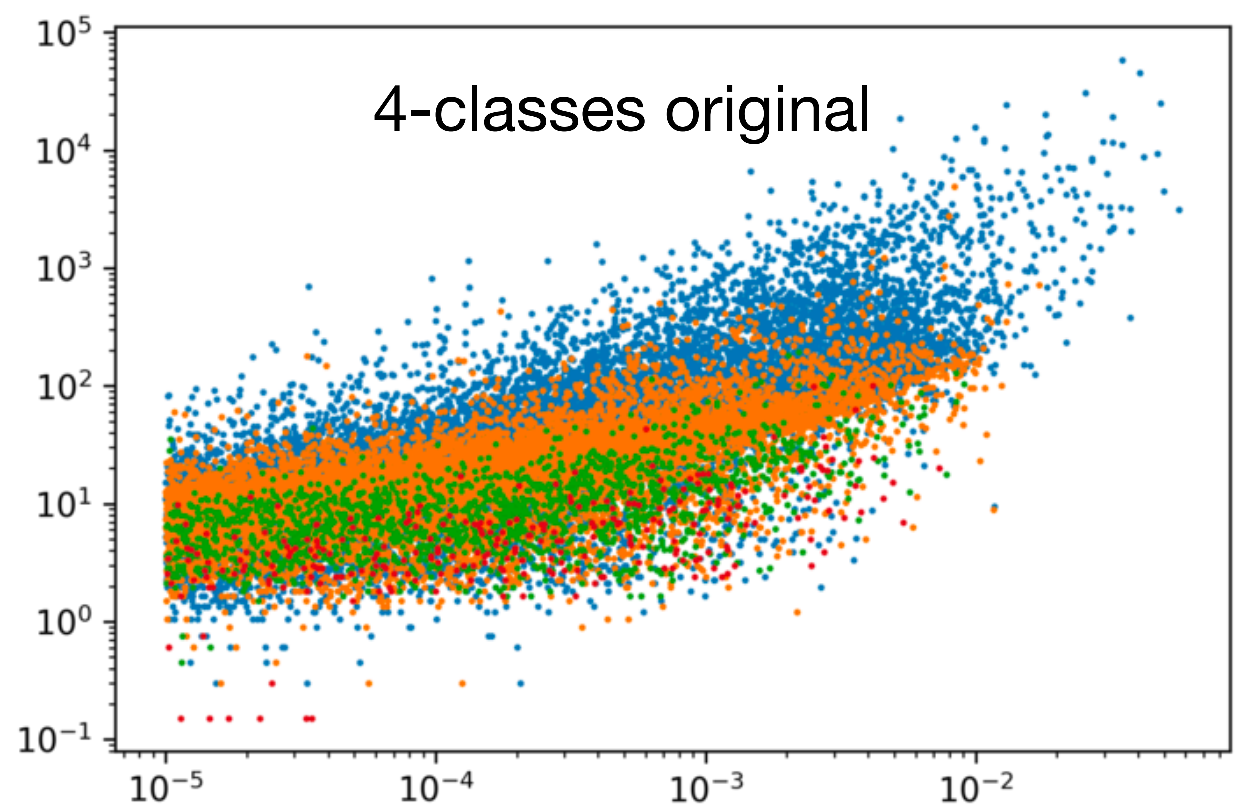
- Grey bar: standard deviation of coloured points at same x-input (each bar corresponds to an input value M_{bh})

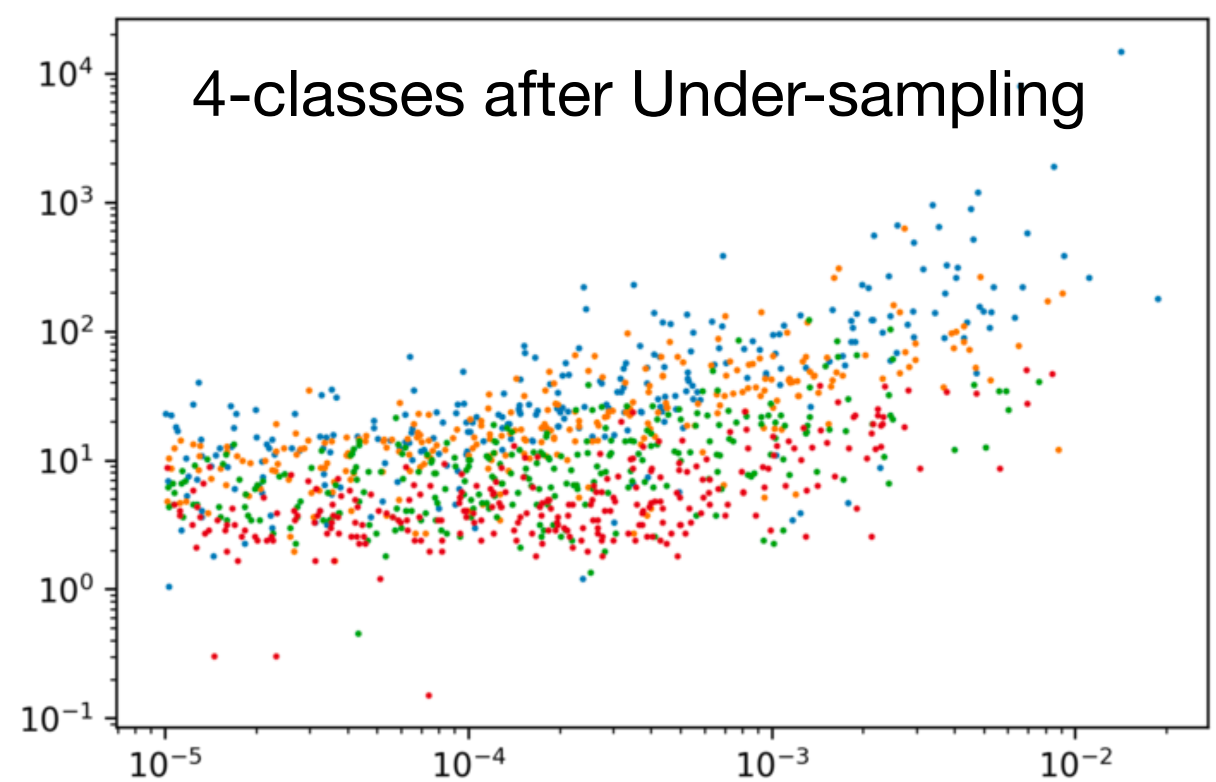
- Coloured points: each point correspond to a set of random dropout layers with $M_{bh} \pm \Delta M_{bh}$ as input.



Deal with imbalanced dataset:

1. Classify them
2. Then under-sample each class





Getting Burkert profile from NFW profile?

- Call back: Scale radius r_s and total DM halo mass M_{halo} are predict.
- Use Milky Way $M_{halo} \approx 10^{12} M_{\odot}$ as example: most recent measurement:

$r_{s,NFW} = 16.1^{+17.0}_{-7.8}$, $r_{s,Burkert} = 9.26^{+5.6}_{-4.2}$ -> $r_{s,NFW}/r_{s,Burkert} \approx$ 1 - 3

- To keep mass integral M_{halo} same -> $M = \frac{4}{3}\pi \int_{R_{schwarz}}^{R_{vir}} \rho(r) r^3 dr$ -> $\rho_{s,Burkert}(R) \approx 6^{+6}_{-2}\, \rho_{s,NFW}(R)$

Match the measurement $\rho_{s,NFW} = 1.40^{+2.90}_{-0.93}$, $\rho_{s,Burkert} = 4.13^{+6.2}_{-1.6}$

Conclusion: if the galaxy has Milky Way similar scale, its NFW/Burkert conversion should use similar parameters

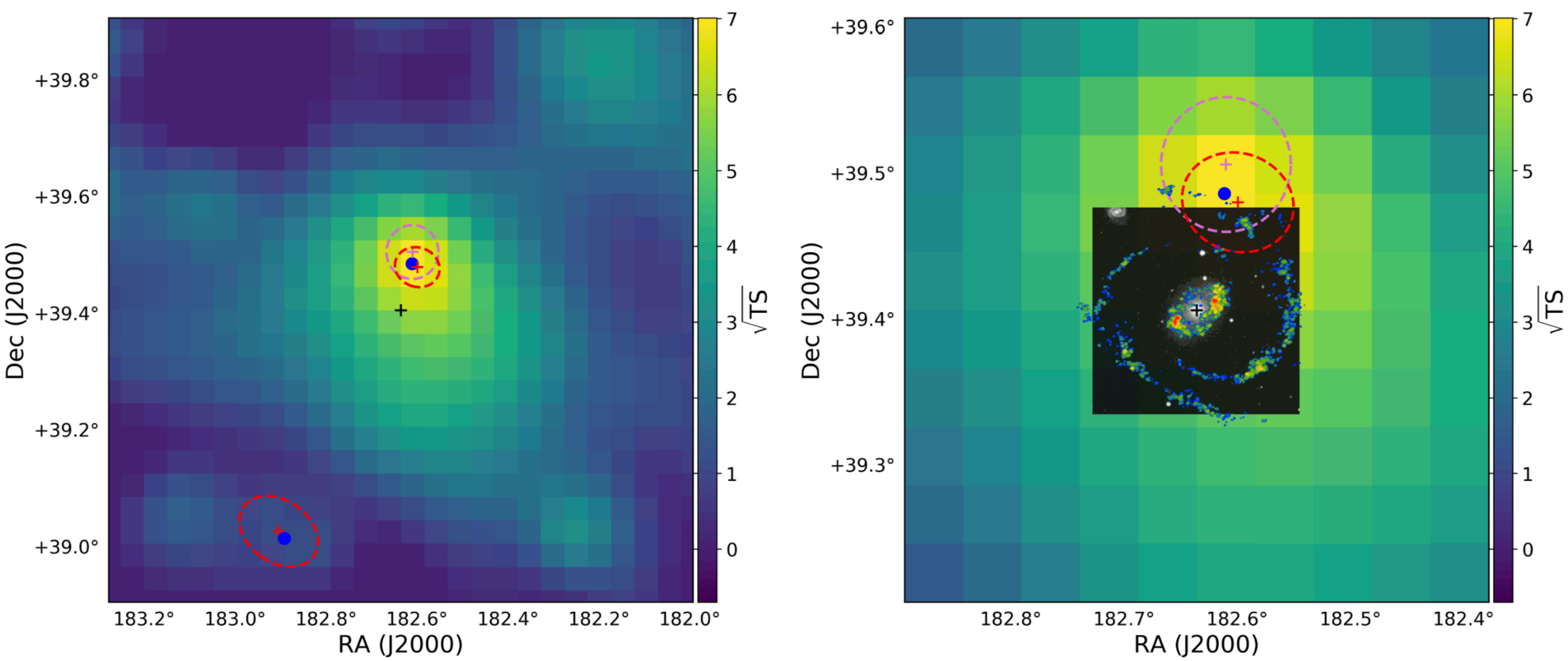
- Beside Milky Way, we only have nearby dwarf galaxies ~ $M_{halo} \approx 10^{8-10} M_{\odot}$ as references. Use interpolate value for intermedia mass.

Compare to NGC4151 Fermi-LAT measurement

The reason why *Fermi-LAT/IceCube did not see the same candidates* probably is:

4FGL catalog has a selection of 0.05GeV-1TeV Gamma-ray
IceCube 10yrs PS search 1.selected >1GeV based on 4FGL catalog and weighted the sources by integrated Gamma-ray flux 2.then selected 5% top weighted.

One special case is NGC4151(which included in my candidates list but not in Fermi-LAT):
it has two near by BL Lacs. Fermi determines the most gamma-ray comes from BL Lac instead of the galaxy self. The galaxy itself is very probably gamma-ray obscured. So that, in 4FGL catalog NGC4151 is not a Fermi-LAT point source but the two near by BL Lacs are.



blue points: BL Lacs
black cross: NGC4151

Cross-check of the flux and events number for DM case

Theory prediction -> Flux -> Event number expectation

Galaxies in the catalogue has mostly the values:

Intrinsic J-factor: $10^{39/40/41}$GeV^{2}cm^{-5}
Distance to earth:~ kpc to Mpc
$J(\frac{d_{bh\_vincinity}}{d_{earth}})^2$:$10^{21/22/23}$GeV^{2}cm^{-5}
Sum of individual J: $1.15 \cdot 10^{24}$GeV^{2}cm^{-5}

Sum of flux: $8.74 \cdot 10^{-14}$GeV^{-1}cm^{-2}s^{-1}
Individual Flux:$10^{-16/15/14}$GeV^{-1}cm^{-2}s^{-1}

Correspond the sum of event number: ~100
Individual event number: 1-2

Software frame Sensitivity(Event number)->Flux

DM Stacking sensitivity: 10.5
($8.73 \cdot 10^{-14}$GeV^{-1}cm^{-2}s^{-1})

DM catalogues search sensitivity:6 to 8
($4.99 \cdot 10^{-14}$GeV^{-1}cm^{-2}s^{-1}to
$6.65 \cdot 10^{-14}$GeV^{-1}cm^{-2}s^{-1})

Parameters used:
- $\langle \sigma v \rangle = 5.71 \cdot 10^{-25}$cm^{3}s^{-1}
- $m_\chi = 1\, TeV$
- $\frac{dN}{dE} = 1 \cdot 10^{-3}$ at 1TeV