Exploration of dark matter sub-halos by using *N*-body simulations

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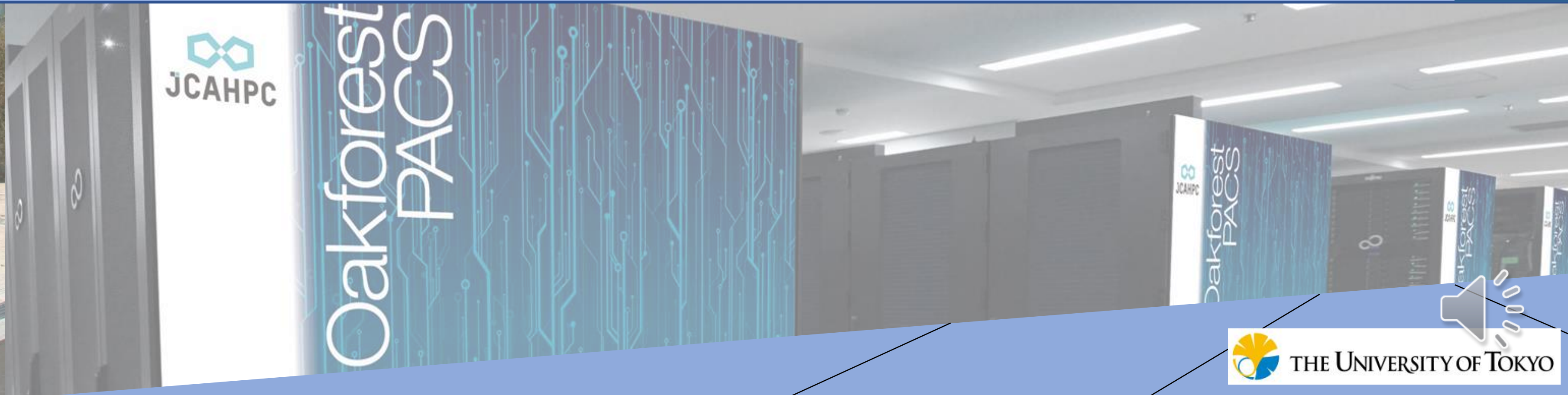
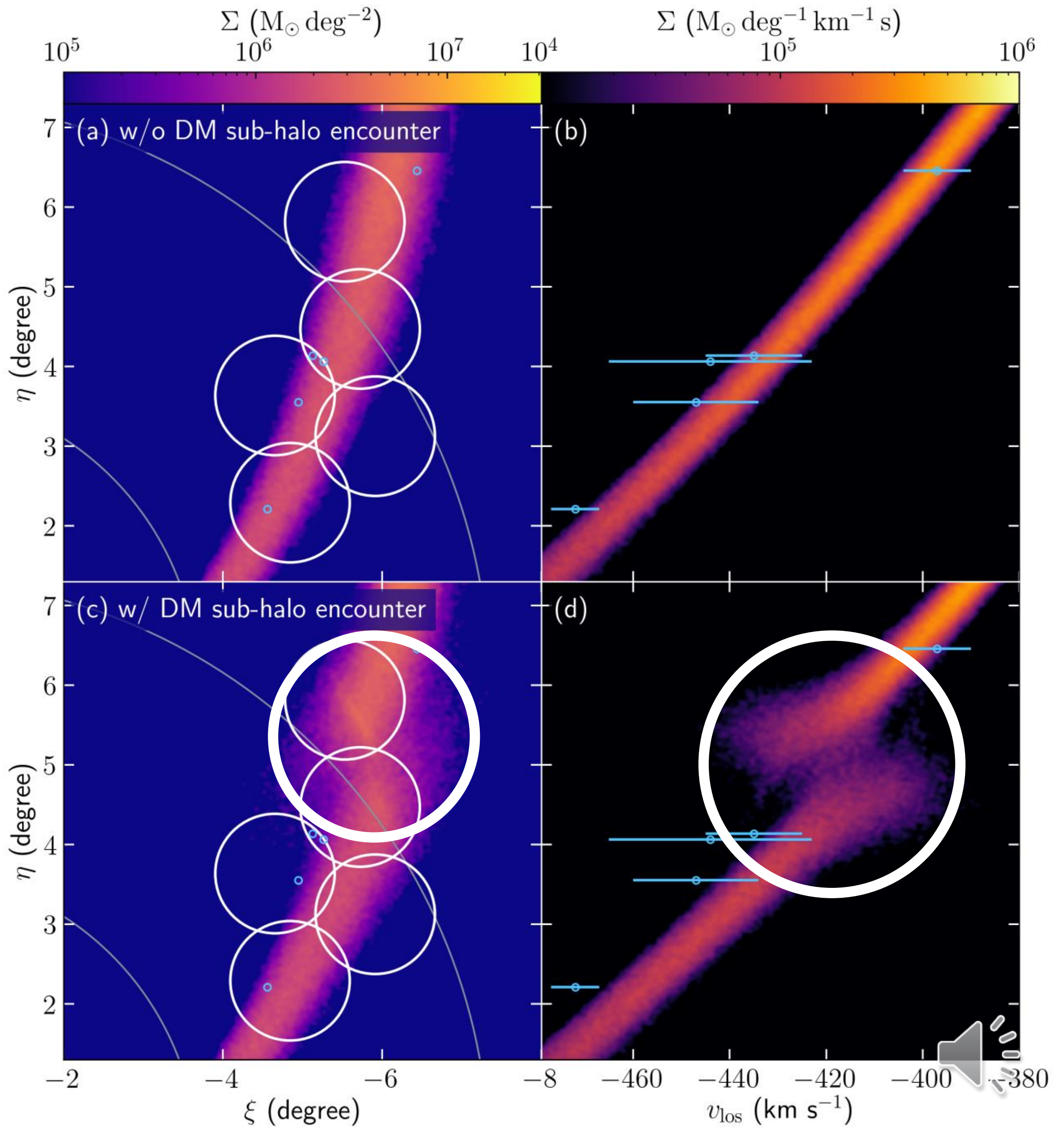


Missing satellite problem

- Observation (e.g. McConnachie 2012): number of satellite galaxies around the Milky Way-sized galaxy is $\mathcal{O}(10)$
  - ~40 satellites around the Milky Way (~60 including candidates)
  - ~30 satellites around the Andromeda galaxy (M31)
- Theory (e.g. Ishiyama et al. 2009): cosmological N-body simulations predict that the Milky Way-sized galaxies host $\mathcal{O}(100)$ dark matter (DM) sub-halos
- Missing satellite problem (Moore et al. 1999): order-of-magnitude disagreement about the number of satellites between the observation and the theory
- Contradiction: comparison between the number of the observed satellites and that of "invisible" DM sub-halos
  - Hypothesis: ~10% of DM sub-halos succeeded to form stars
  - Challenge: observational estimation of DM sub-halo counts

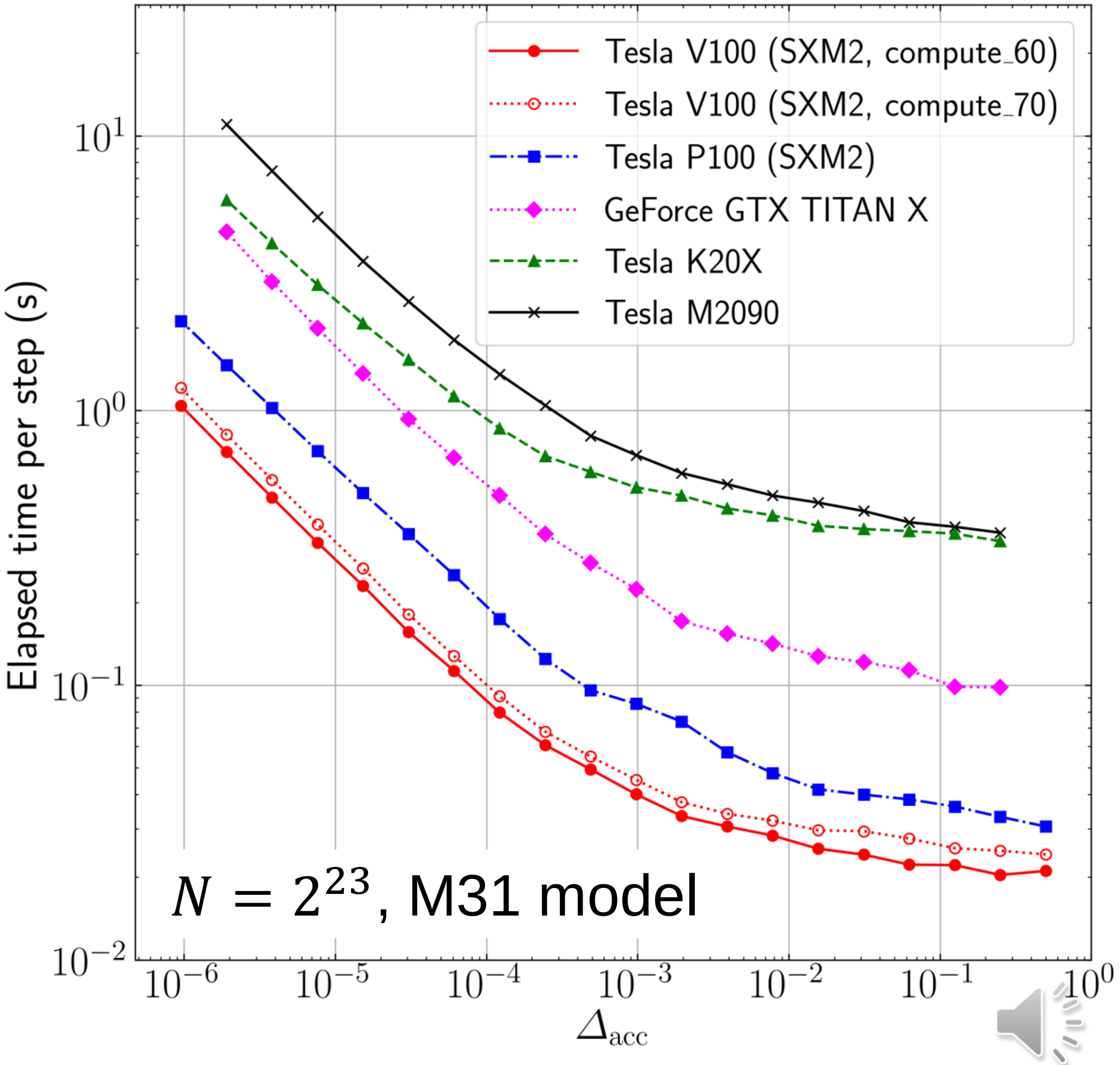
How to detect DM sub-halos

- Close encounter of a DM sub-halo perturb the shape of stellar streams (Carlberg 2012)
- We can estimate the number of DM sub-halos based on the number of remnants of the close encounter (gap) in the stellar stream
    - North-Western (NW) stream in the M31 halo is a suitable object for this study



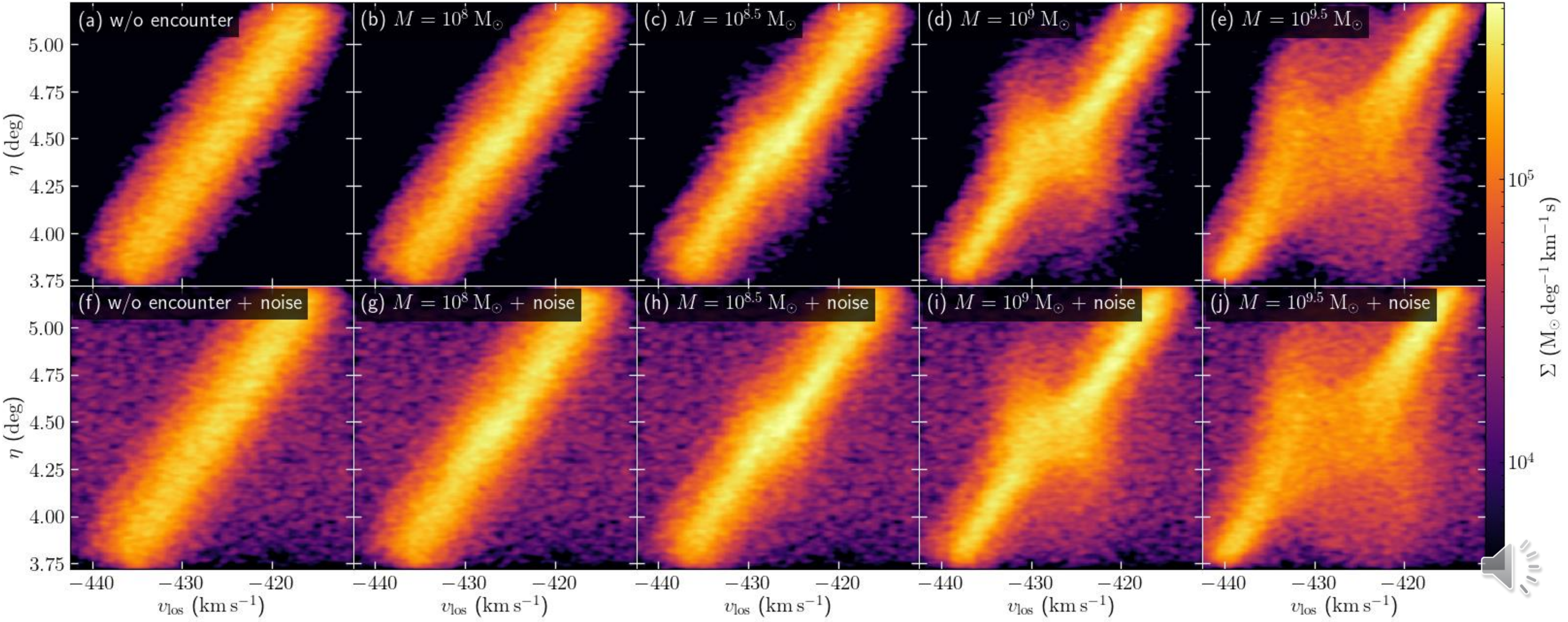
Configuration of *N*-body simulations

- Progenitor of the NW stream
  - Plummer sphere ($M = 5 \times 10^7 M_\odot, N = 2^{20}$), where $M_\odot = 2.0 \times 10^{33}\mathrm{g}$ is the solar mass
- DM sub-halo (test particle)
  - $M = 10^7, 10^{7.5}, 10^8, 10^{8.5}, 10^9, 10^{9.5} M_\odot$
  - Collide with the NW stream in a circular orbit
- System (GPU supercomputers)
  - Reedbush-L (Tesla P100) @ ITC, UTokyo
  - TSUBAME3.0 (Tesla P100) @ GSIC, TITech
  - Cygnus (Tesla V100) @ CCS, UTsukuba
- Software
  - MAGI (YM & Umemura 2018)
  - GOTHIC (YM & Umemura 2017, YM 2019)
    - Gravitational octree code optimized for GPU



Mock observation by using Subaru/PFS (S/N = 3)

- PFS: Prime Focus Spectrograph on the Subaru telescope
- Gap detection is feasible if the width of the stream ($\sim 10\ \mathrm{km\ s^{-1}}$) is resolved!!



Conclusion

- Counting the number of DM sub-halos is essential to solve the missing satellite problem
  - We are focusing on the NW stream in the M31 halo
- Results of numerical simulations
  - Signature of a collision between the NW stream and a DM sub-halo whose mass is $\gtrsim 10^9 M_\odot$ is visible in the phase space
  - Even S/N = 3 observations will detect the gap
- Subaru/PFS can observe the line-of-sight velocity of 2400 objects in ~ $1.25\ \mathrm{deg}^2$
  - Very suitable for observations in the phase space
  - Promising facility to excavate fossil records of DM sub-halo encounters
- Future work: construction of relation between the number of DM sub-halos and that of the observed gaps in stellar streams

Thank you for watching