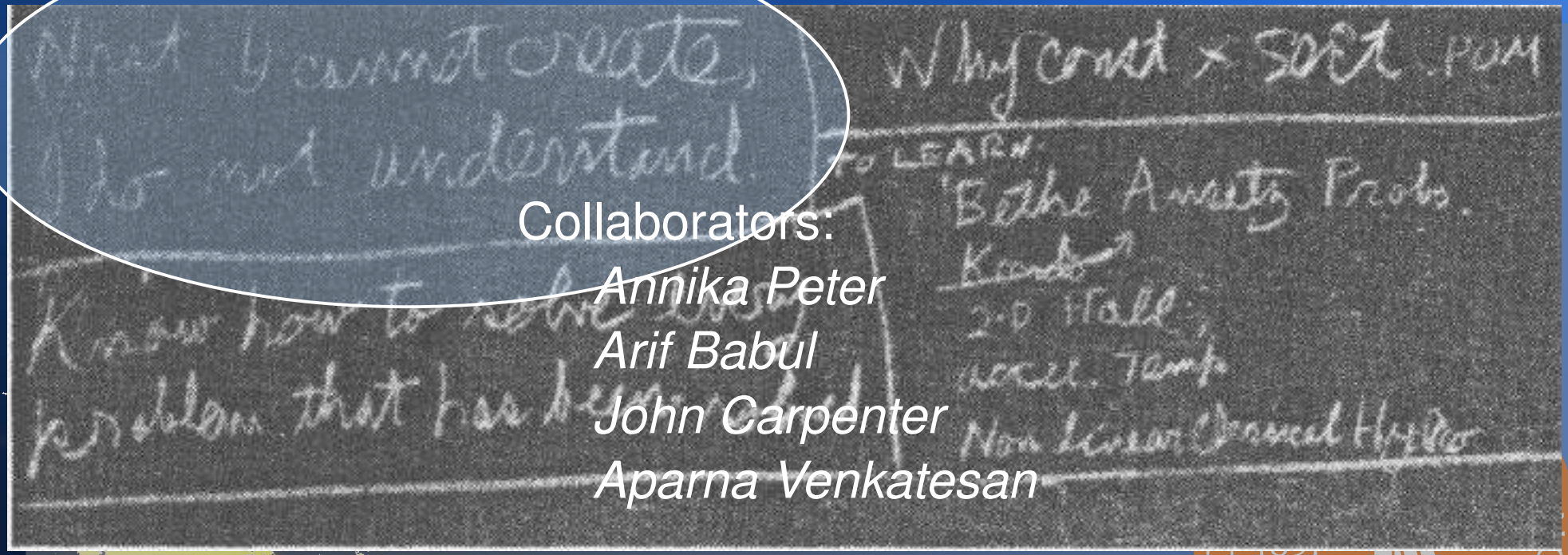
“What I cannot create, I do not understand”
A galaxy builder's toolkit

Andrew Benson, Caltech

KITP Mar 31, 2011



Collaborators:

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Arif Babul

John Carpenter

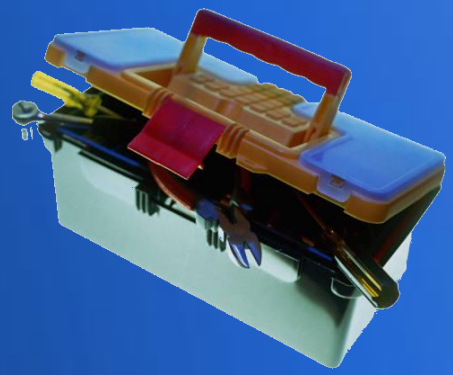
Aparna Venkatesan

Motivation

- How do galaxies form and evolve?
  - What physical processes are at work?
- A well established “standard model” exists
  - Is it correct?
  - Where does it fail?
  - Does it describe all known phenomena?
- Need a coherent framework for calculating expectations

Galacticus v0.9.0

- A Galaxy Formation Toolkit
  - Modular
  - Comprehensive
  - Well documented
  - Open Source
  - Aims to include current best understandings and calibrations



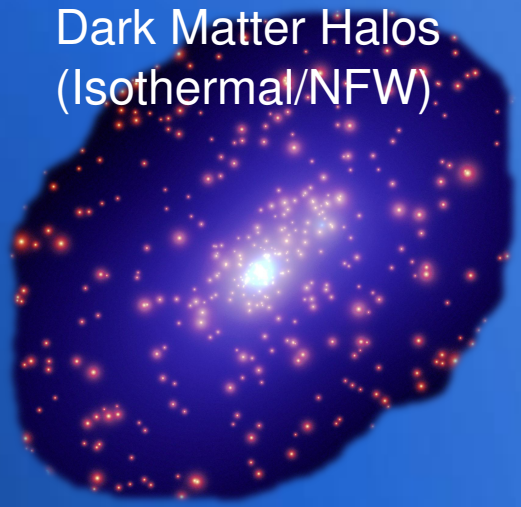
Design Features

- Extensible
  - Physical components
  - Functions
- Parallelized
  - OpenMP
  - MPI (soon...)
- Robust
  - Growing suite of test cases

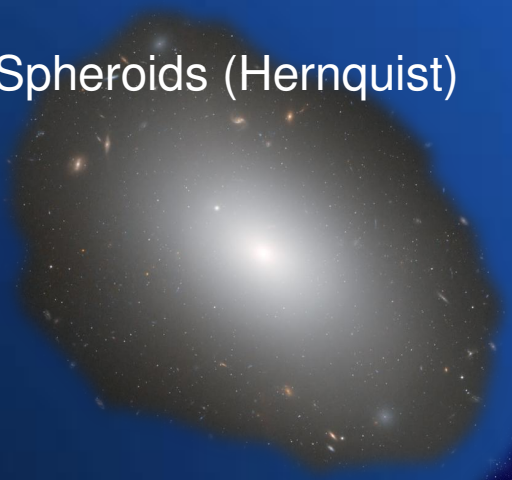
Galaxy Components

Disks (Exponential)

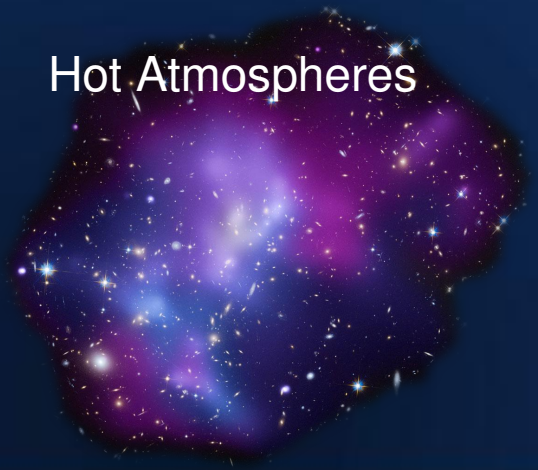
Dark Matter Halos
(Isothermal/NFW)



Spheroids (Hernquist)



Hot Atmospheres



Black Holes

Physics

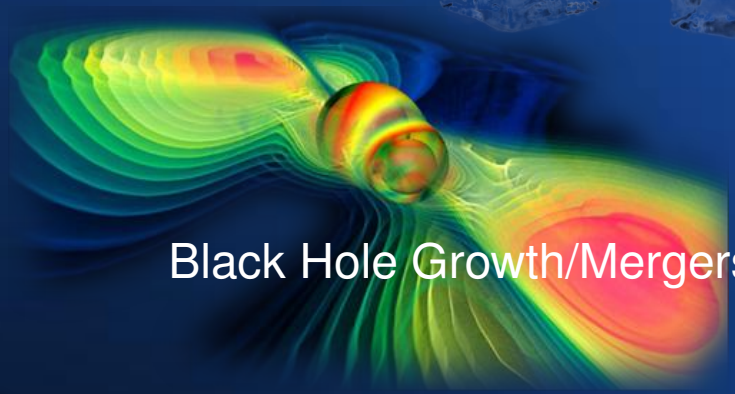
DM Structure Formation

Gas Cooling

Dynamical Friction/Merging

AGN Feedback

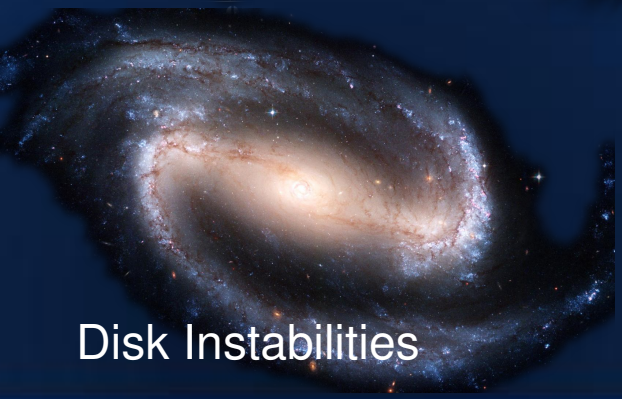
Disk Formation



Black Hole Growth/Mergers

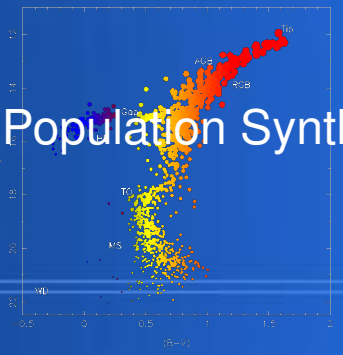
Dust

SNe Feedback



Disk Instabilities

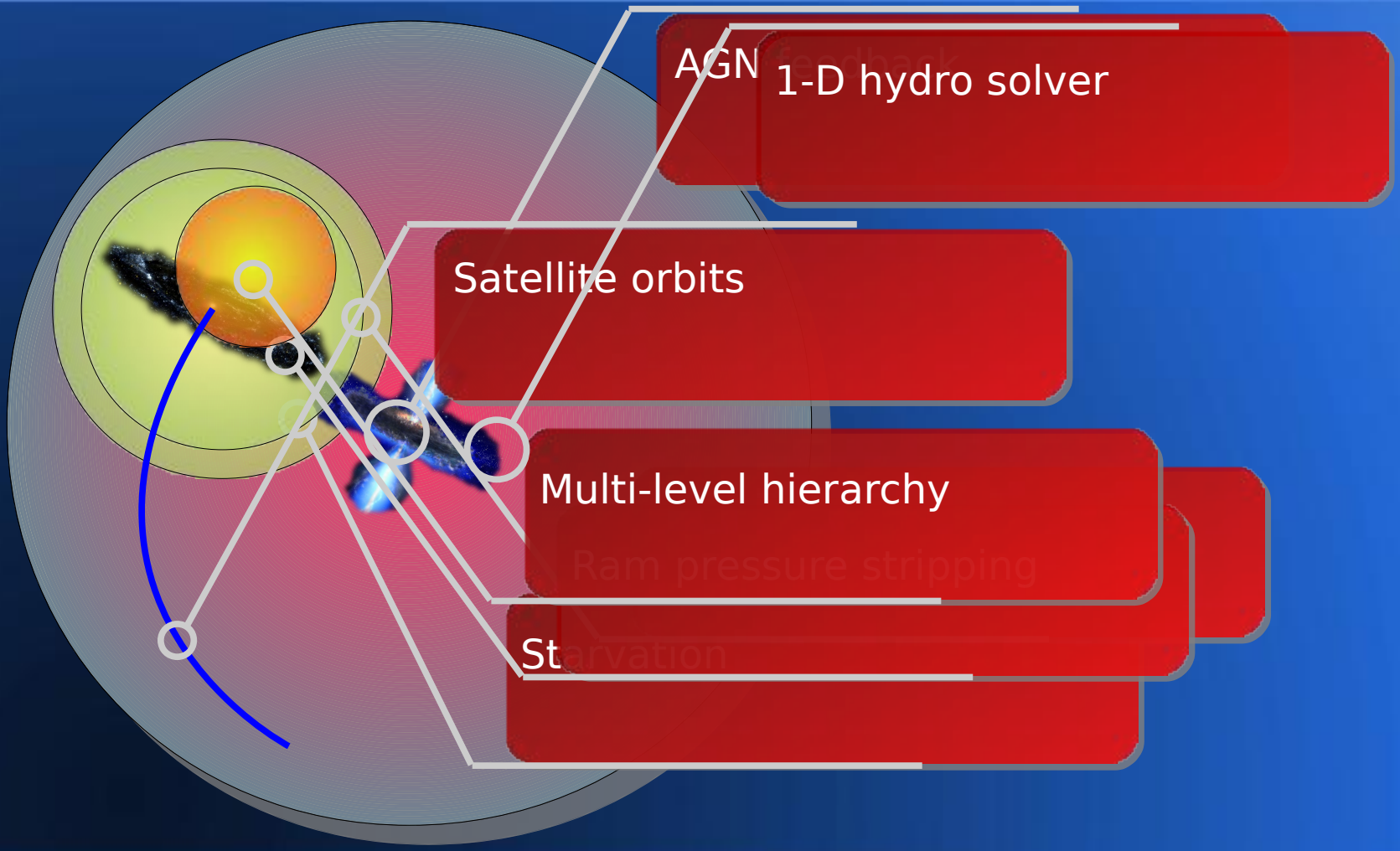
Sizes/Adiabatic Contraction



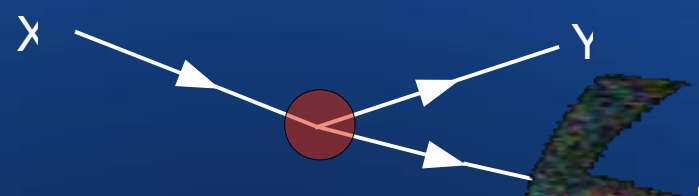
Stellar Population Synthesis

GALACTICUS Usage

Cluster Physics



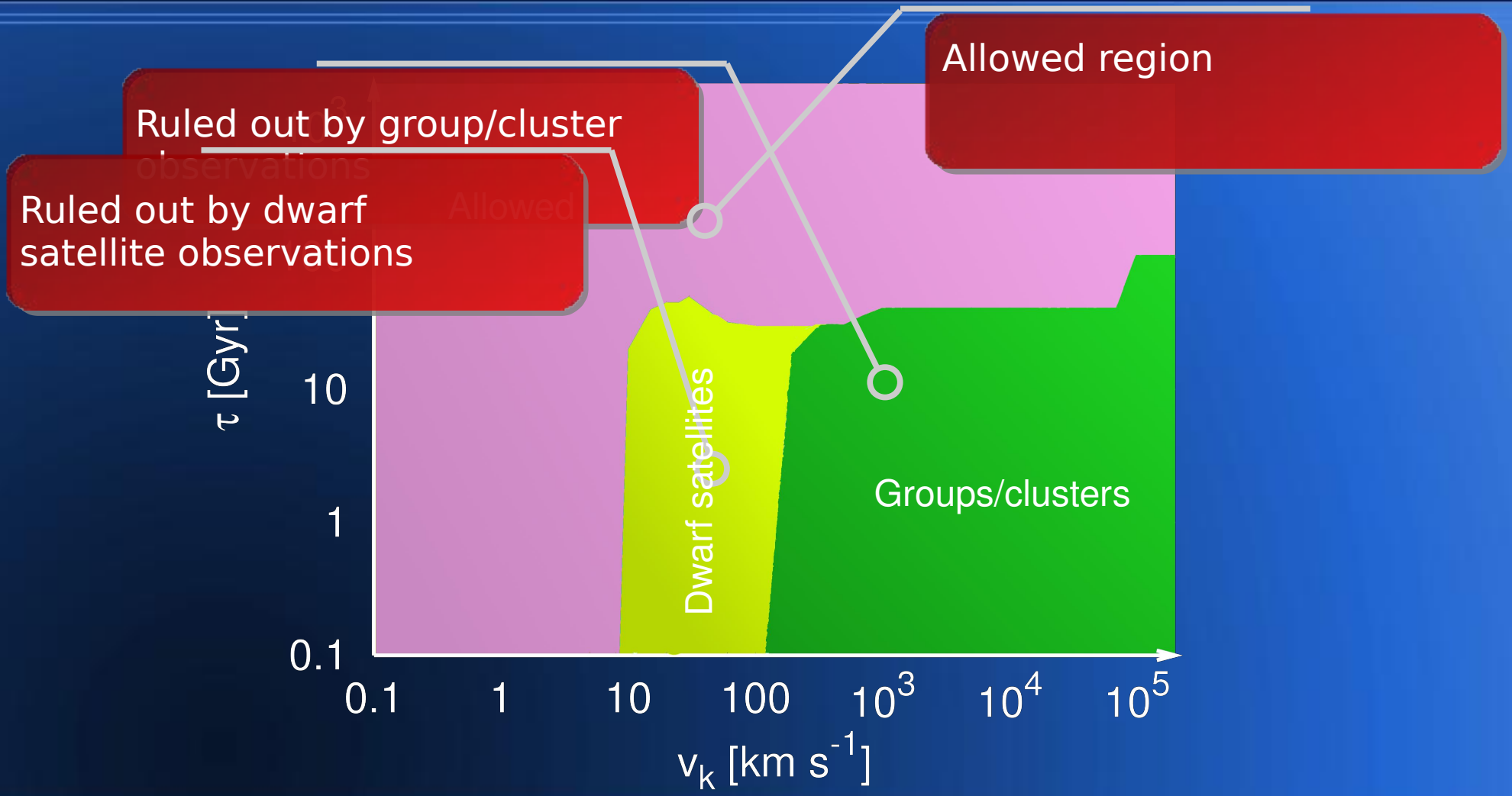
Decaying Dark Matter



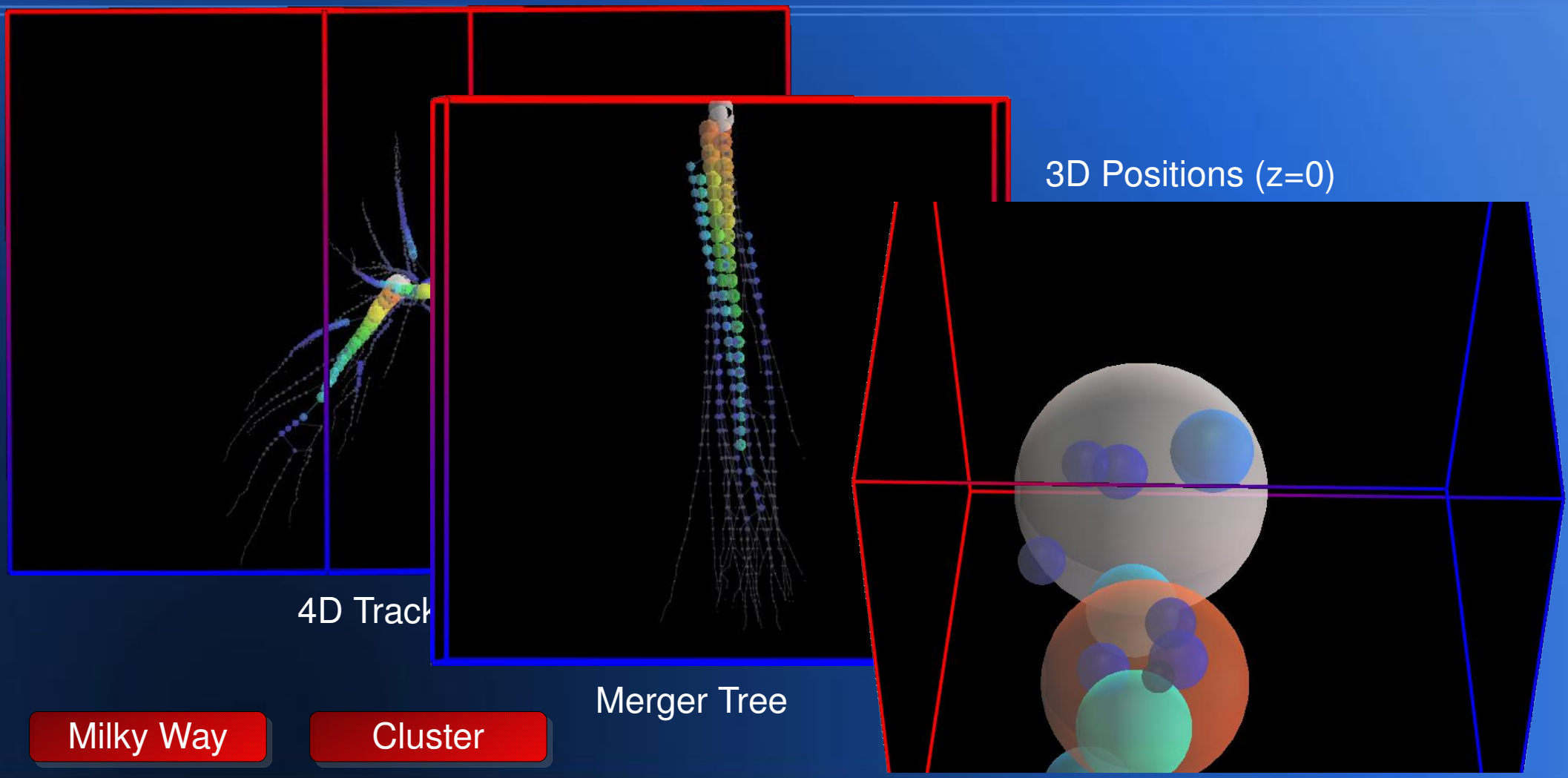
- $M_Y \sim M_X/2$
- $\varepsilon \ll 1$
- $v_k > 5 \times 10^6 M_\odot$ within 300pc gets non-relativistic kick (v_k)
- Decay time is τ

Peter & AJB (2010; PRD; 82, 3521)

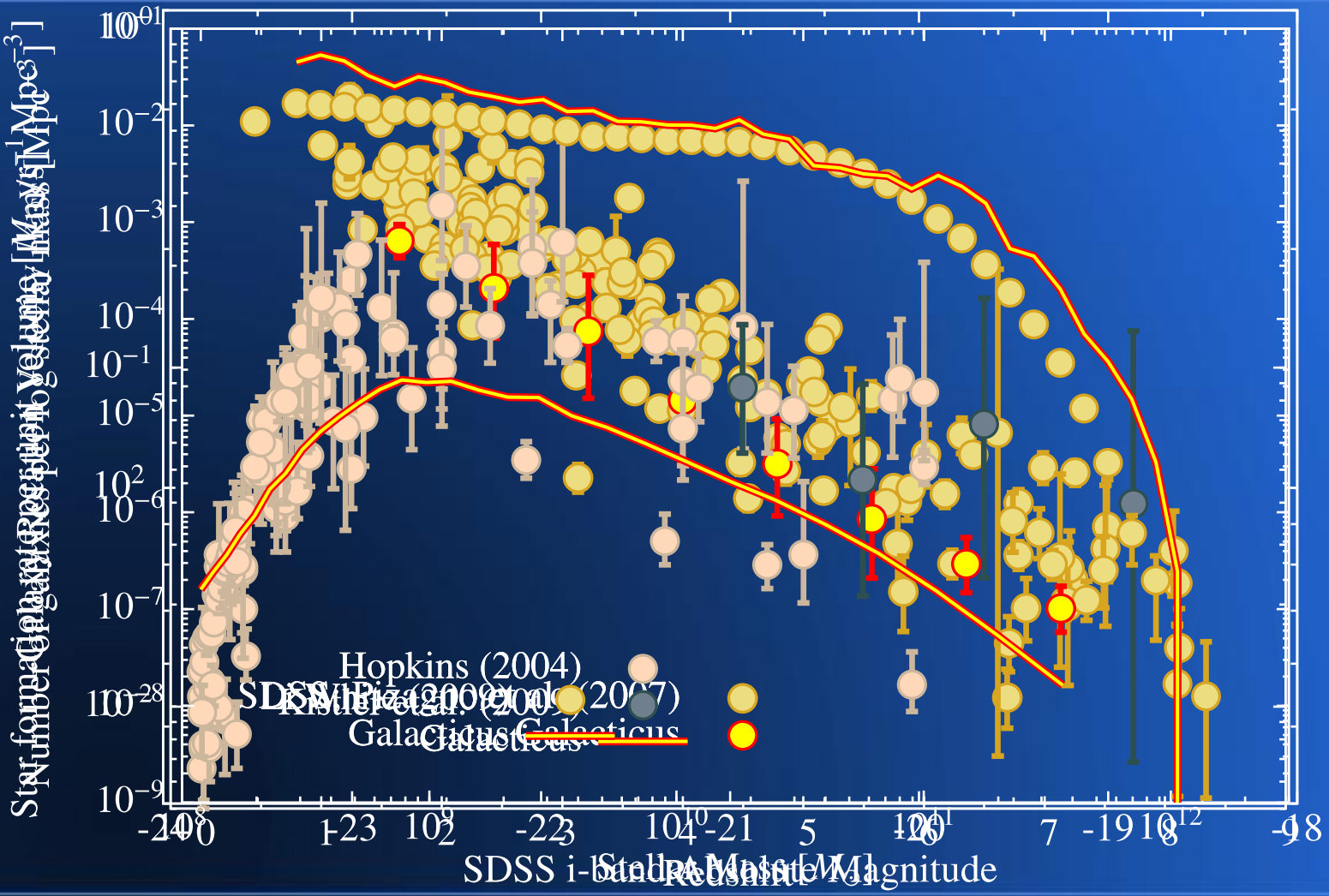
Decaying Dark Matter: Constraints



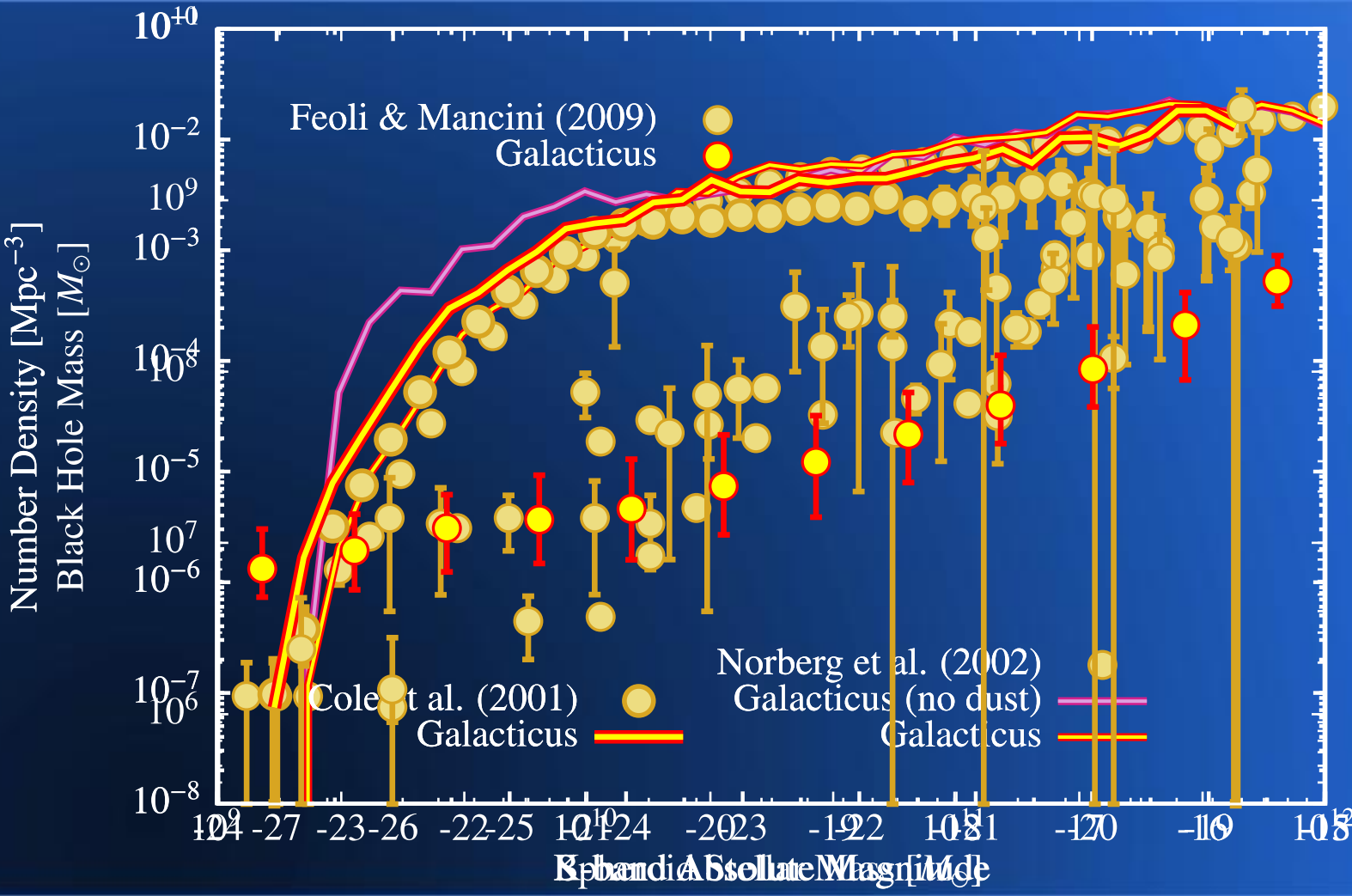
Tree Evolution



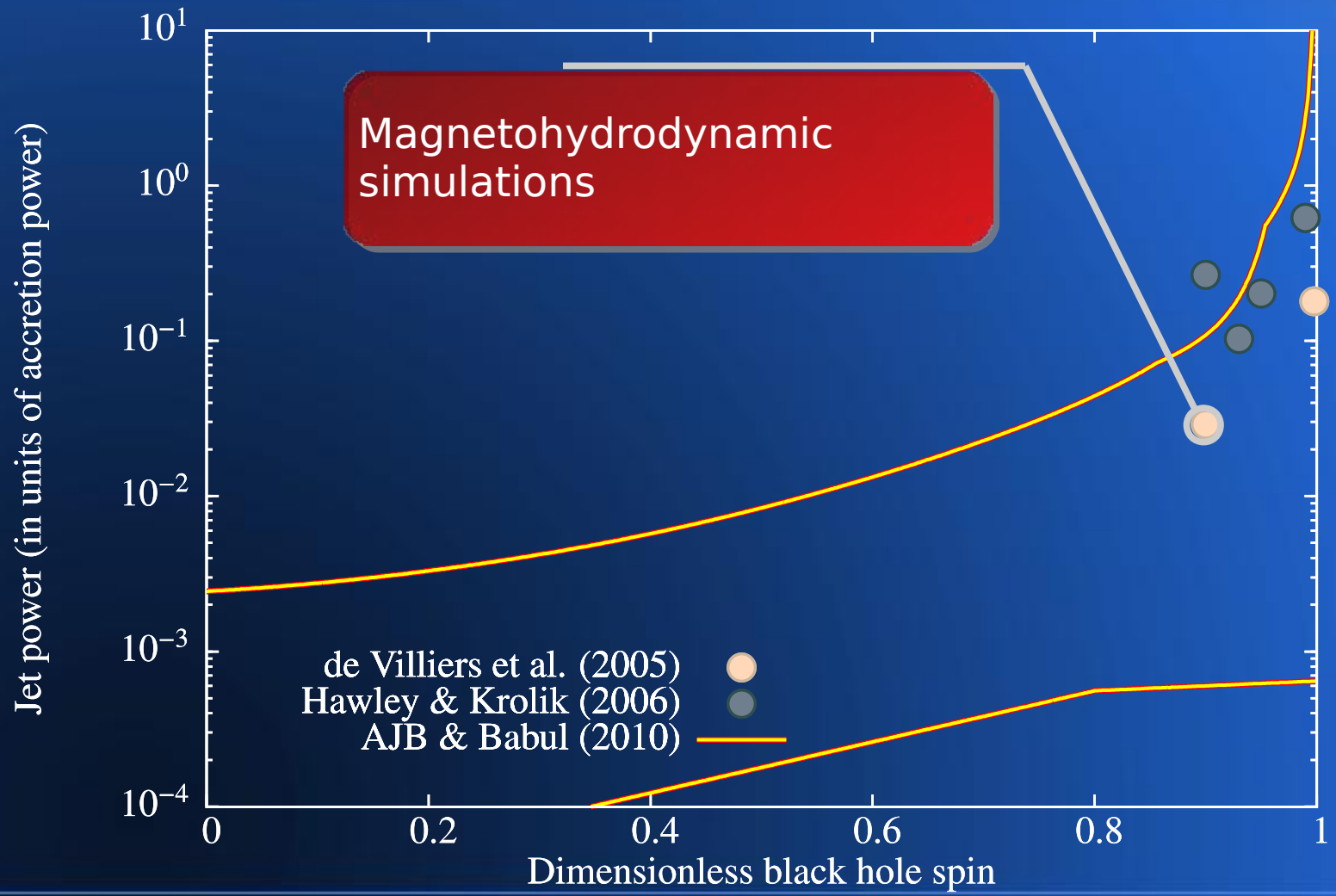
Standard Diagnostics



Additional Diagnostics



Black Hole Jets



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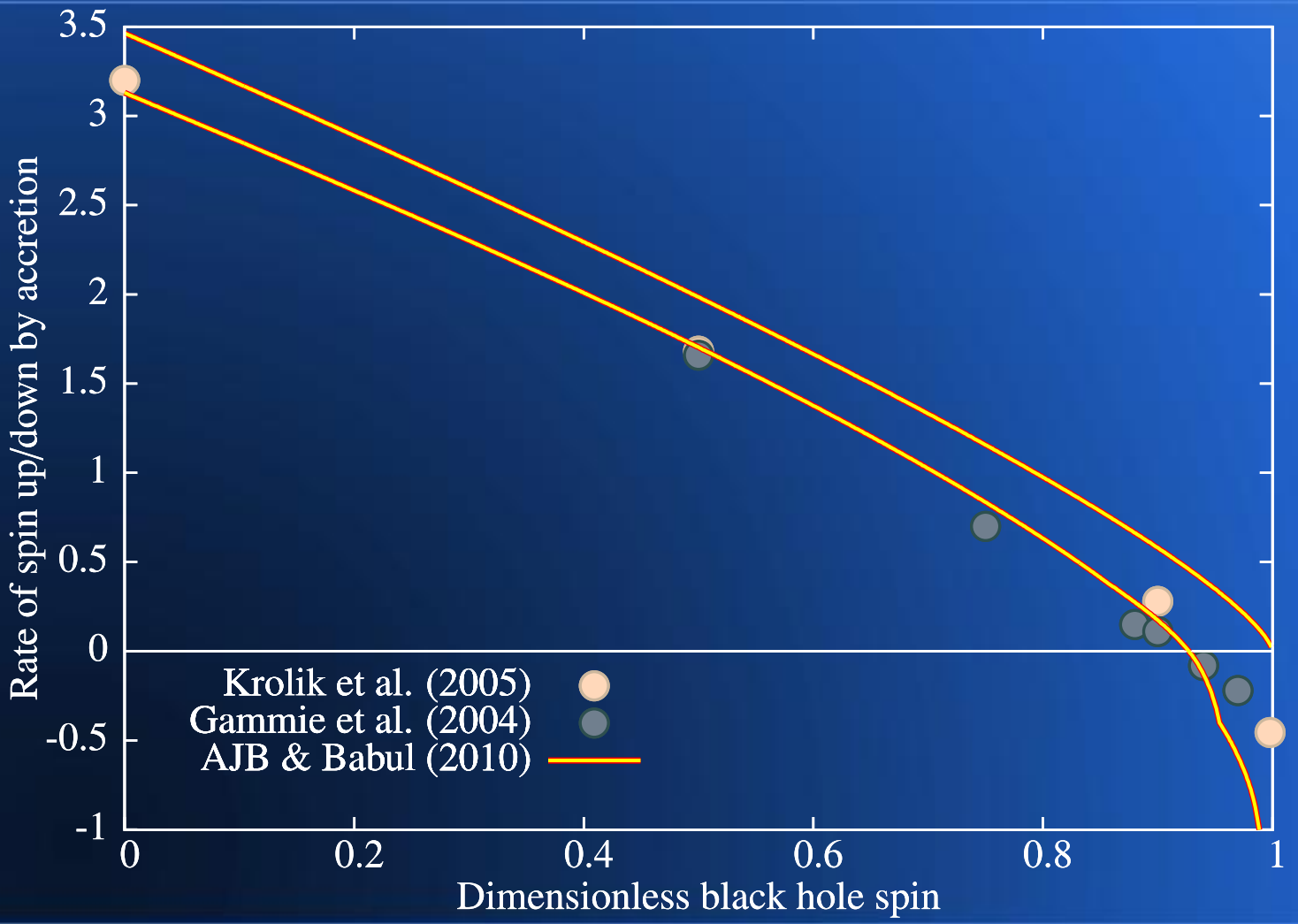
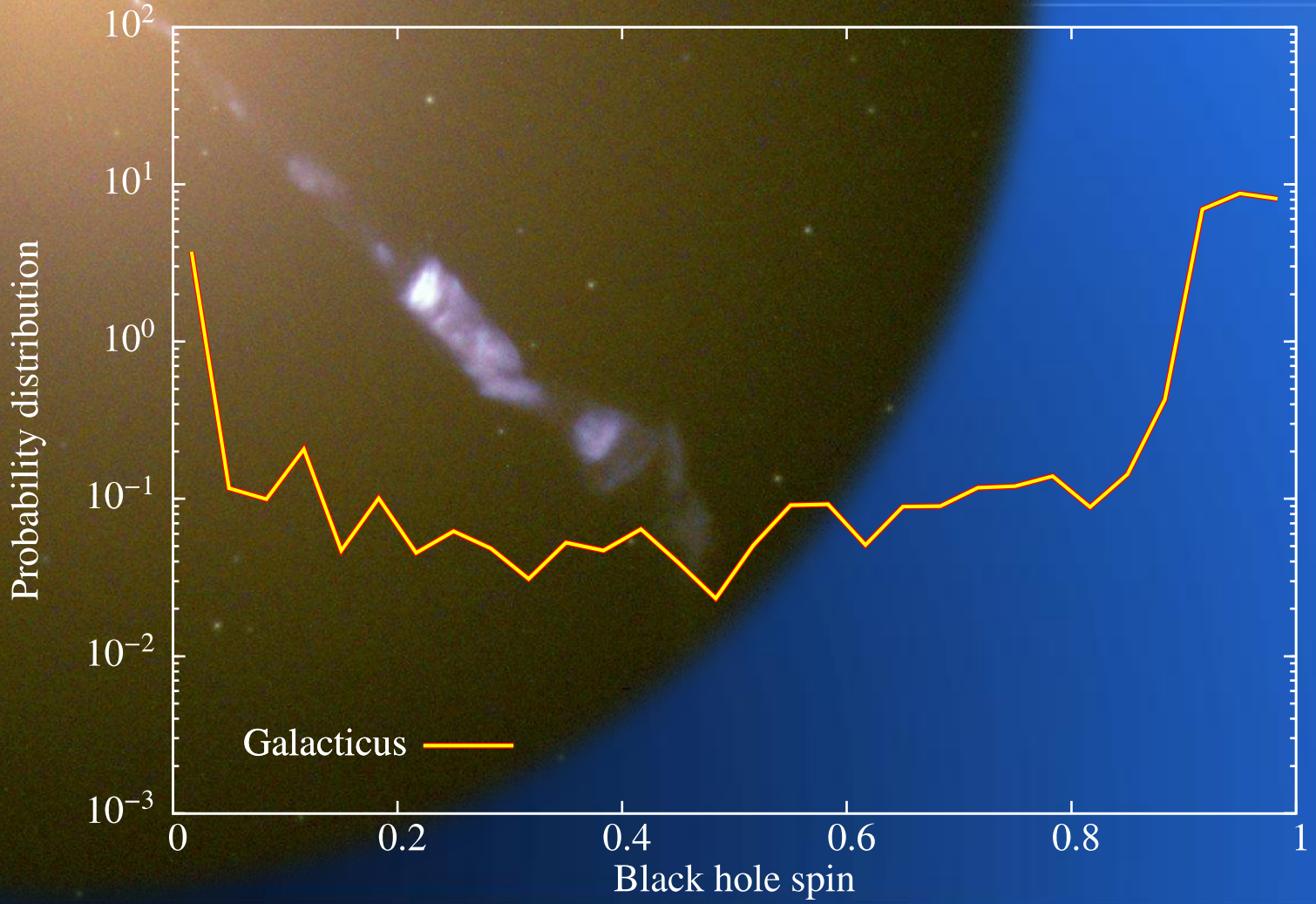
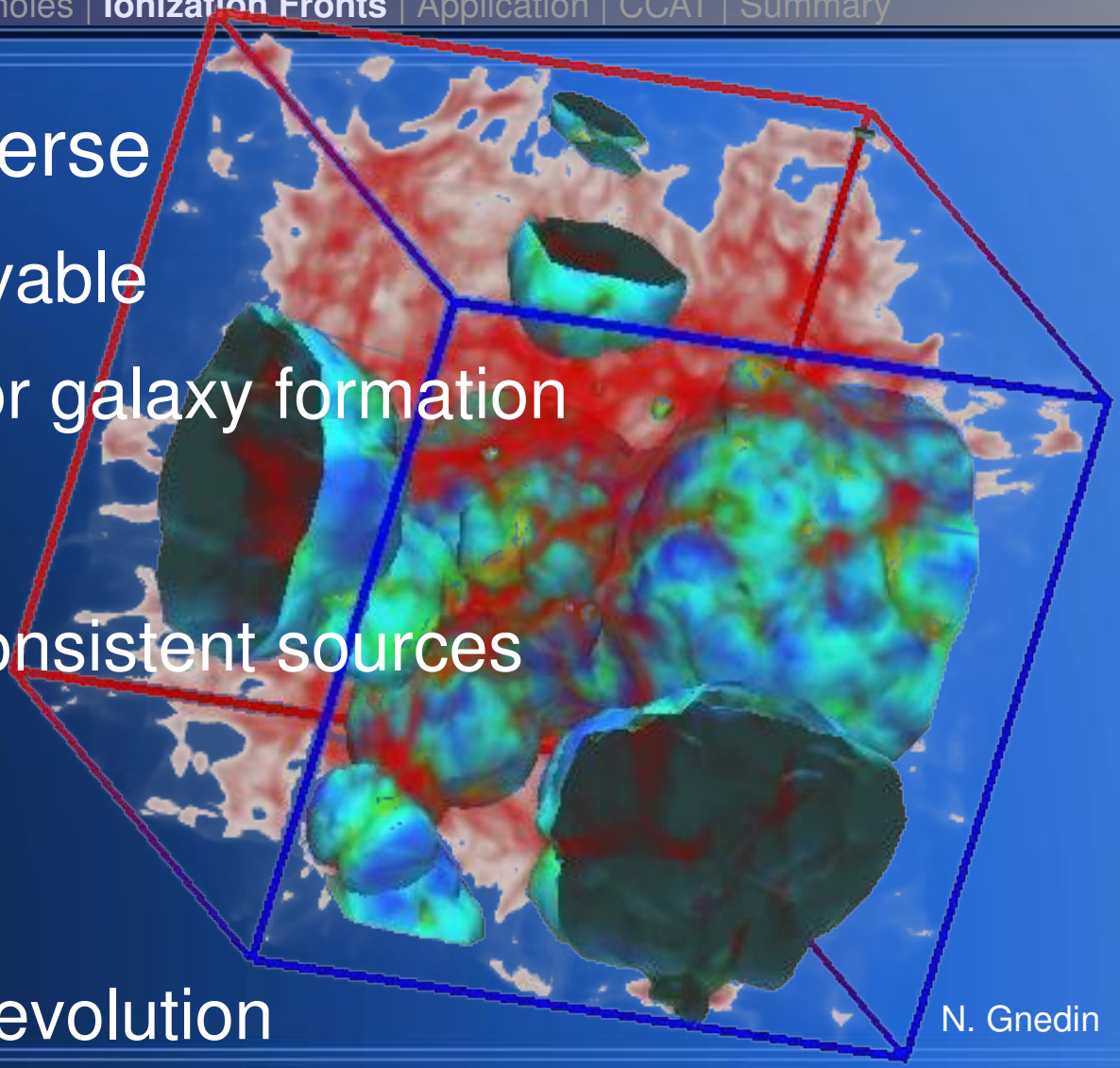


Black Hole Spin Distribution



Cosmological Ionization Fronts

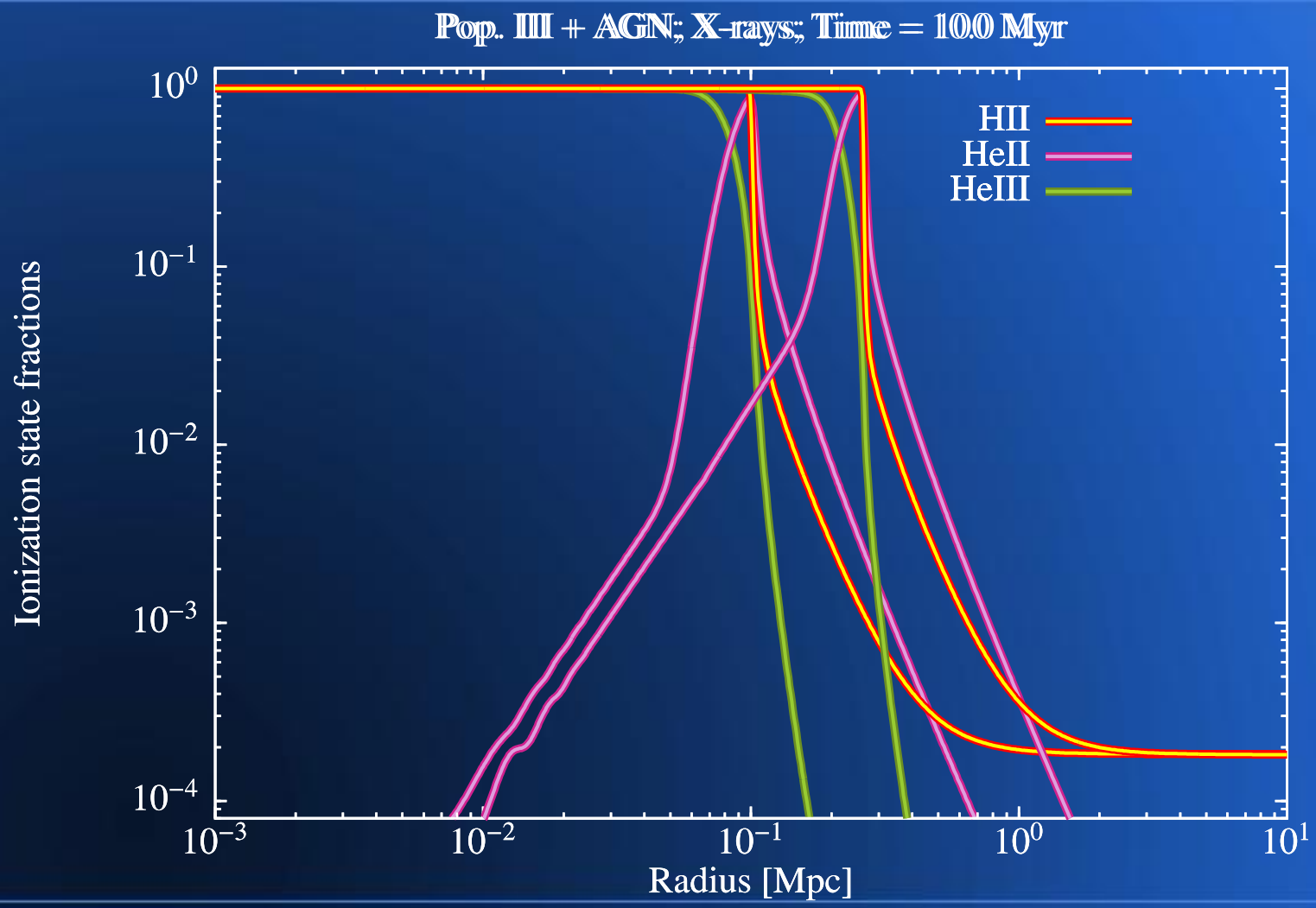
- Reionization of Universe
  - Potentially observable
  - Consequences for galaxy formation
- Simulate
  - Realistic + self-consistent sources
- Physics
  - X-rays
  - Time-dependent evolution



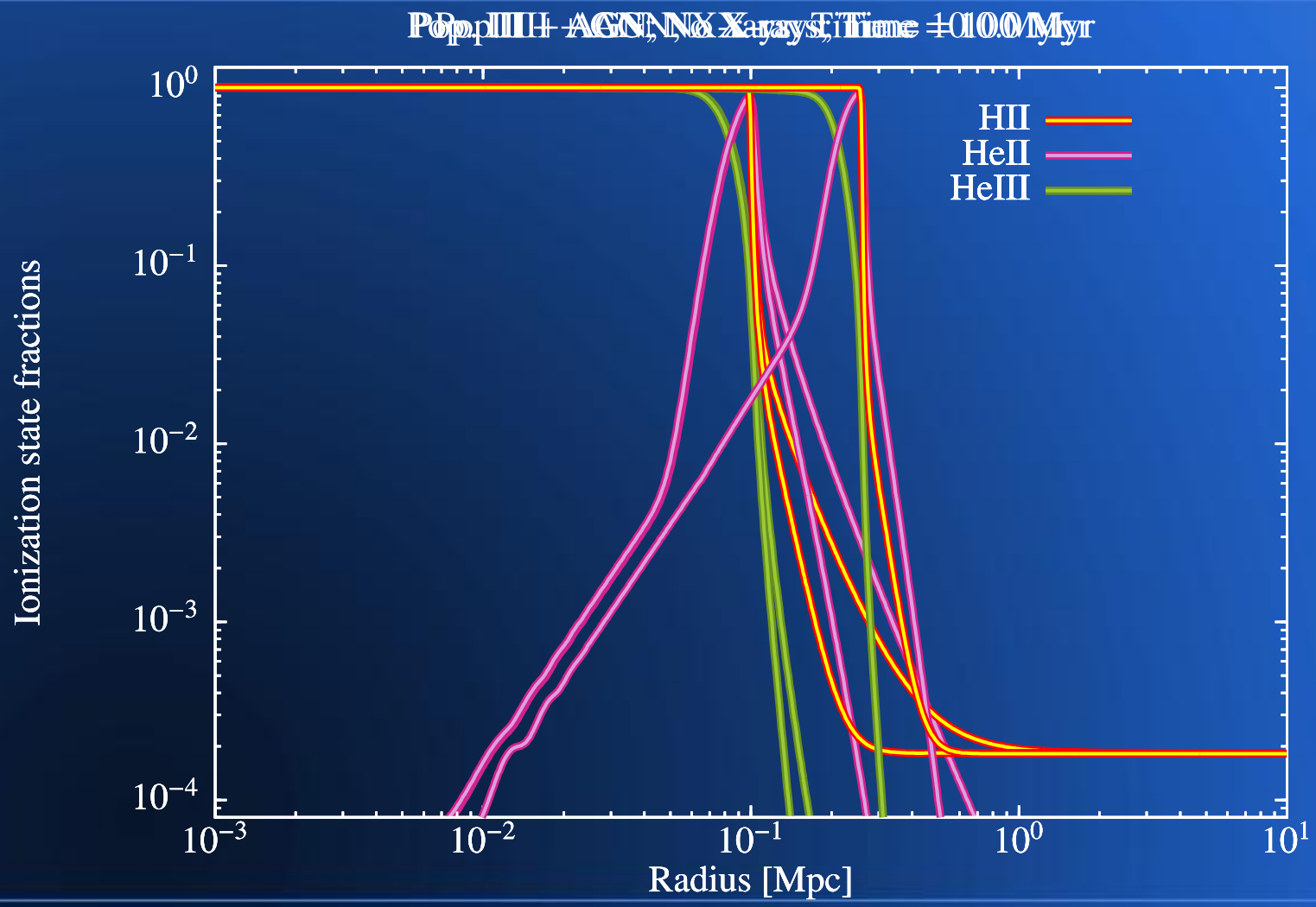
Venkatesan & AJB (2003)

N. Gnedin

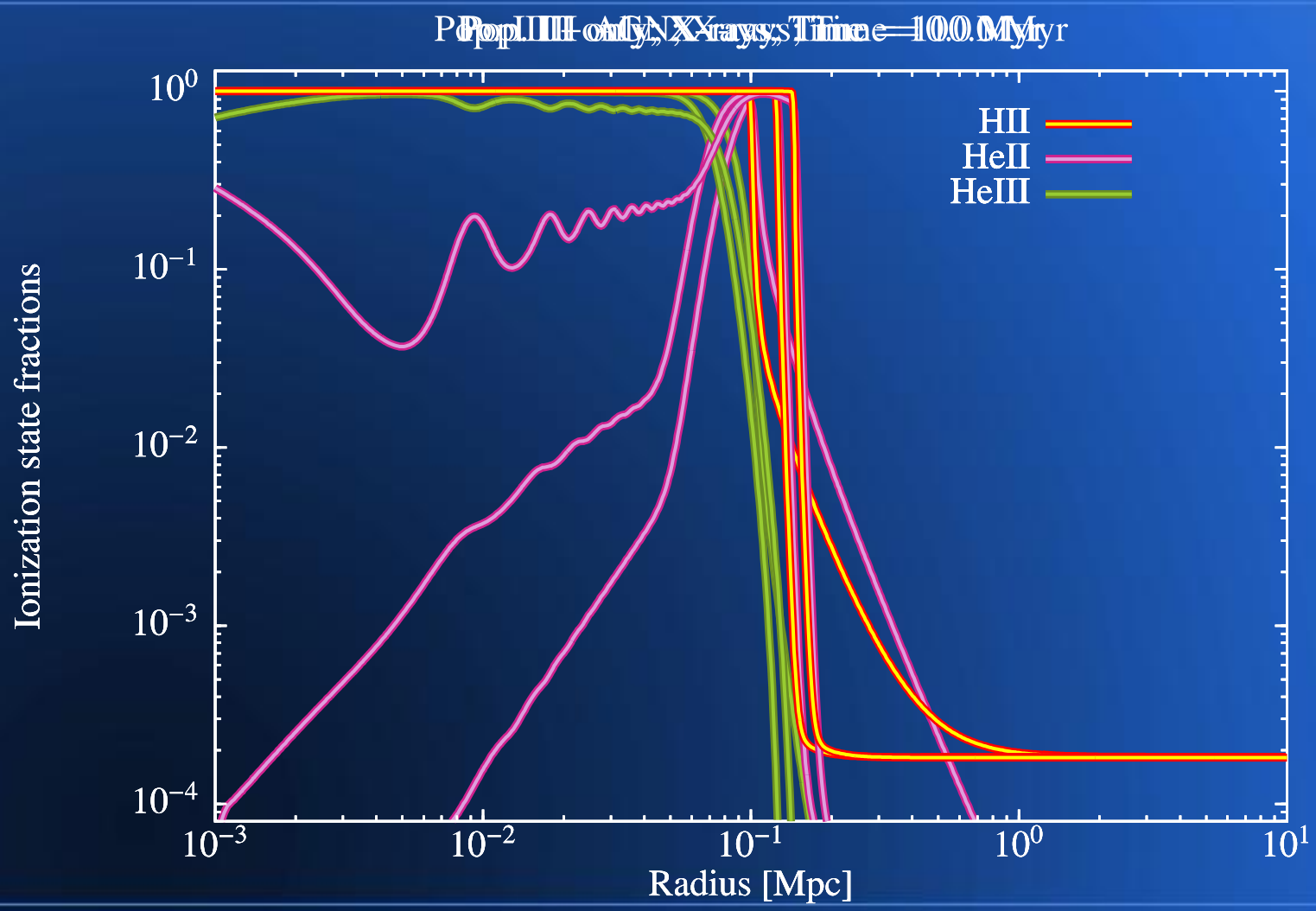
Cosmological Ionization Fronts



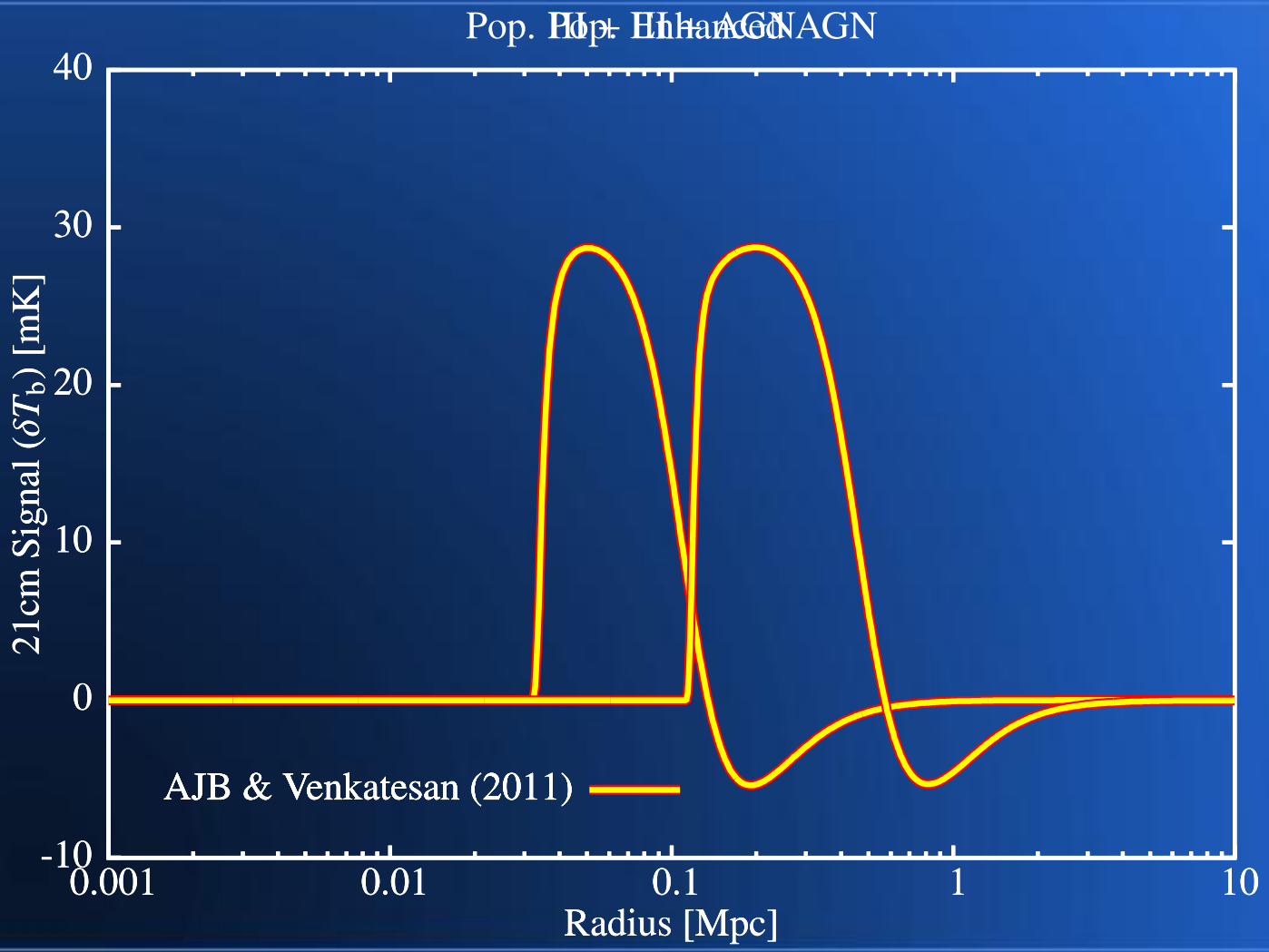
Cosmological Ionization Fronts



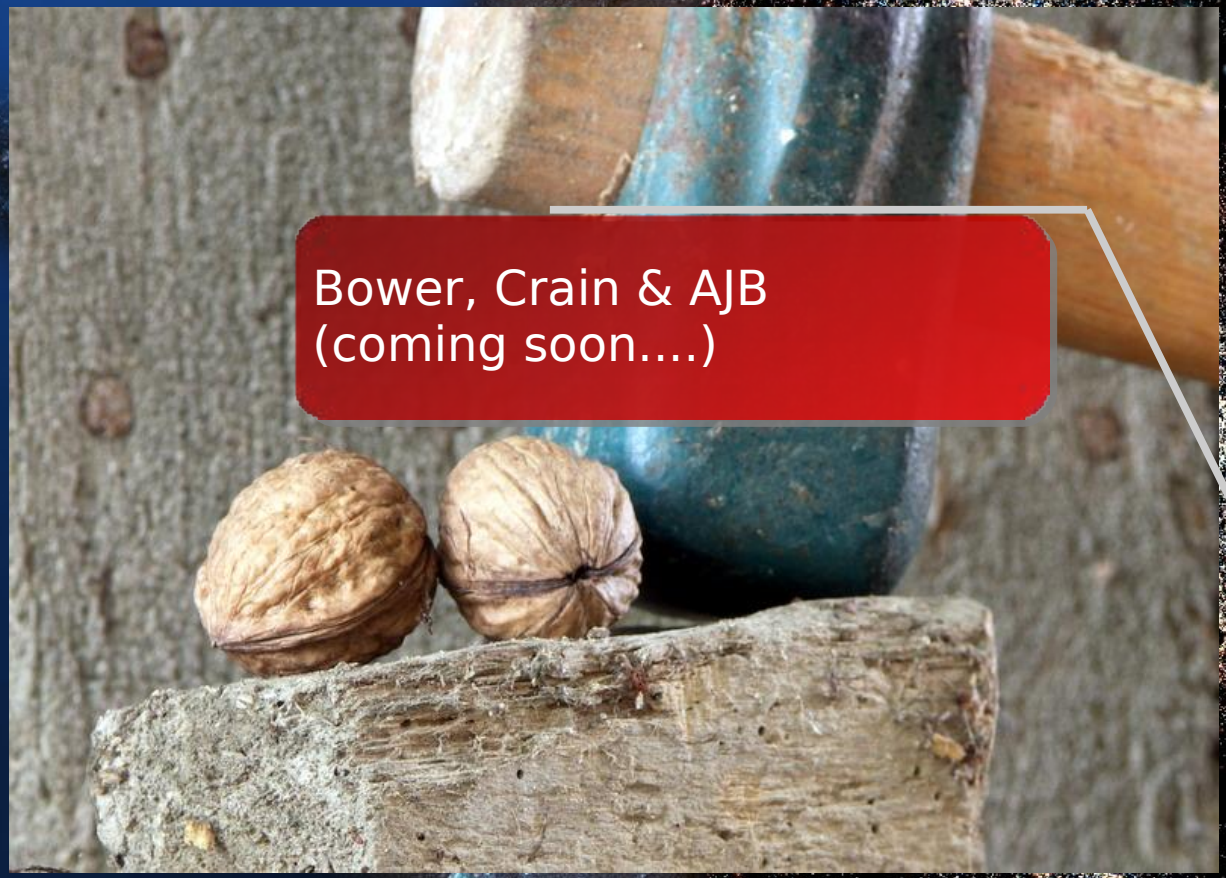
Cosmological Ionization Fronts



21cm Cosmology Signal



Using the Right Tool



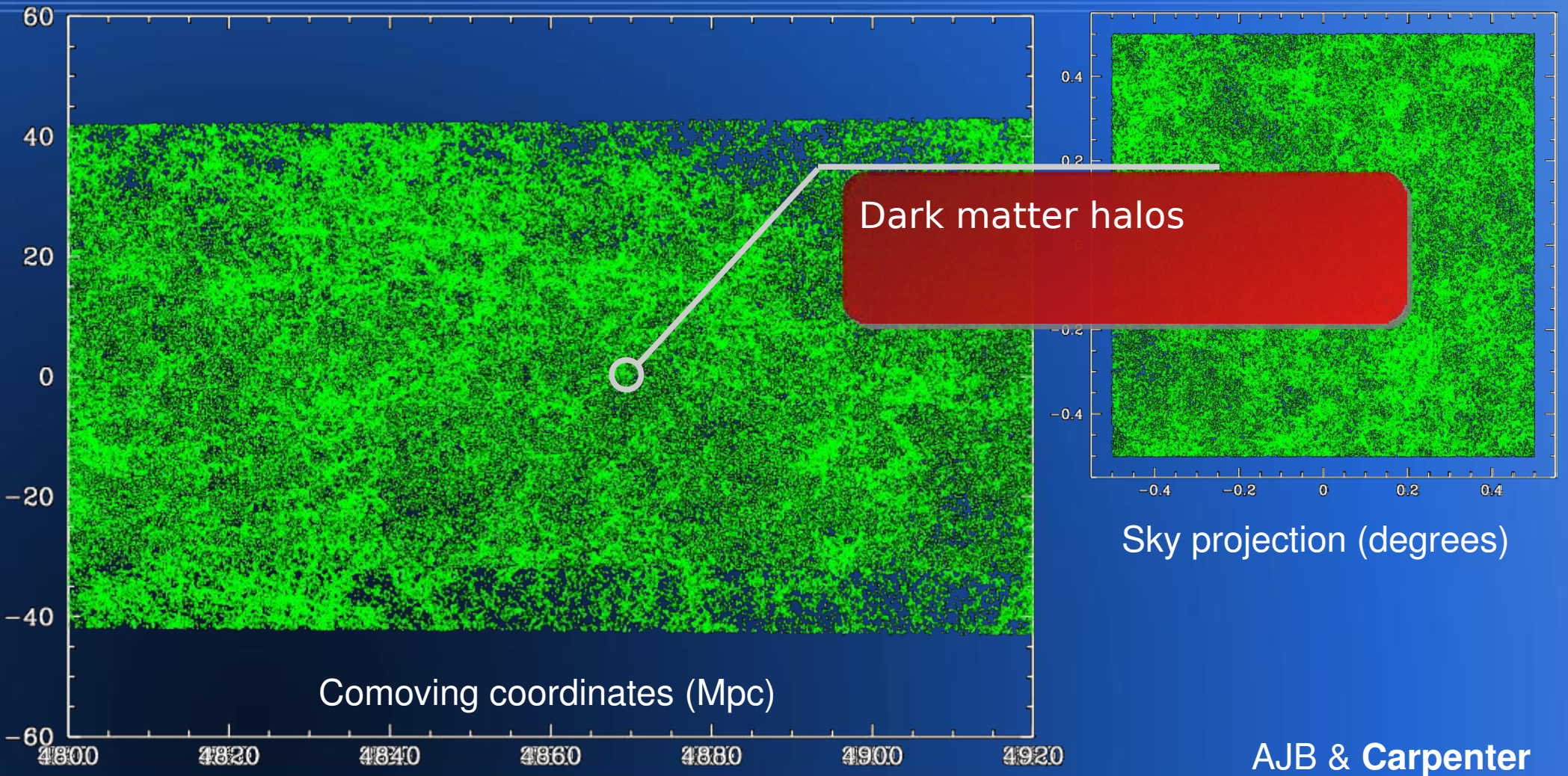
- Select the right tool
- Understand limitations
- Test robustness
- Statistical comparisons show excellent agreement

- 25 m sub-mm telescope
- Up to 1 square degree field of view
- 200μm to 3mm wavelength range

Caltech-Cornell Atacama Telescope

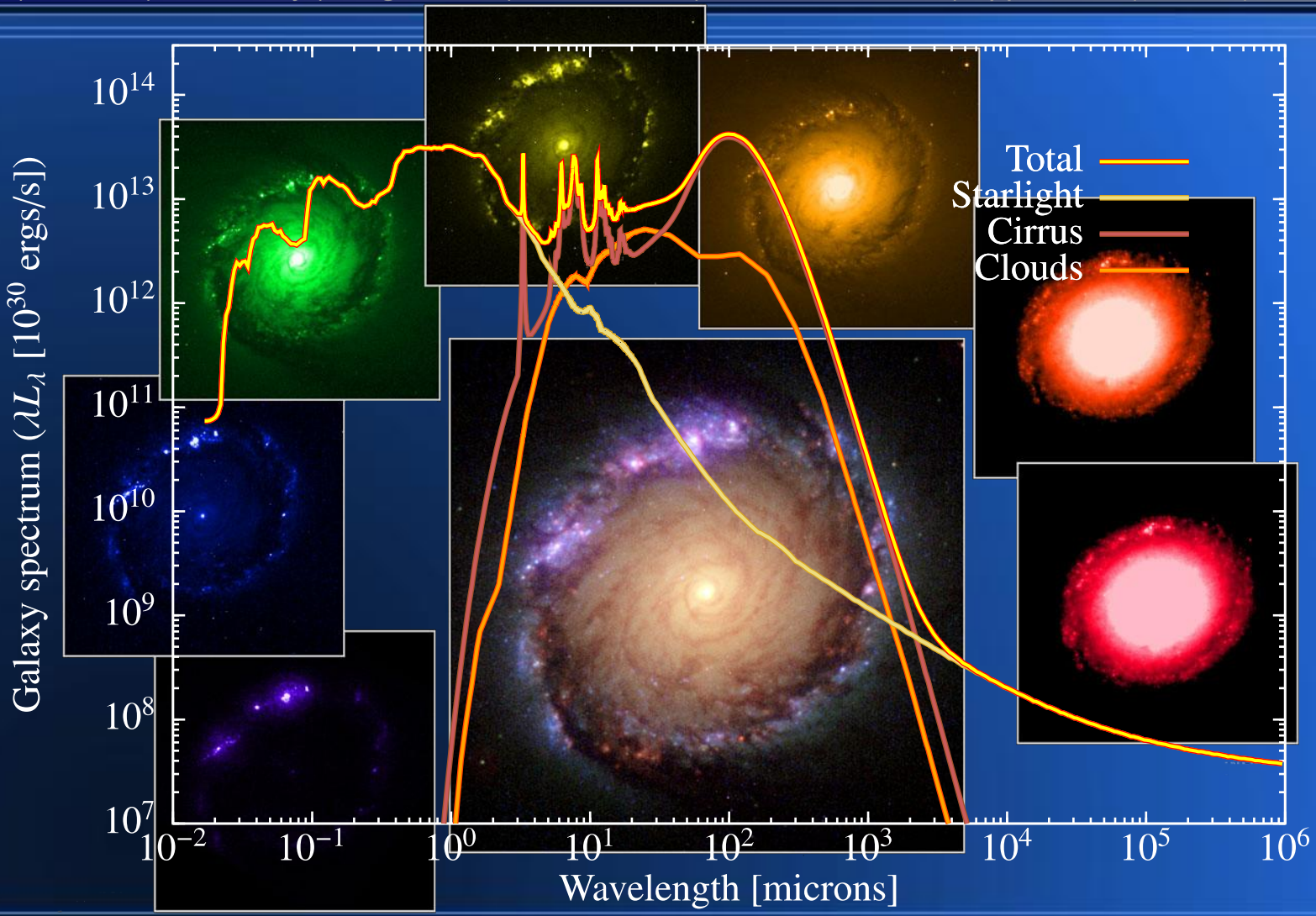
http://www.submm.org

CCAT Virtual Universes

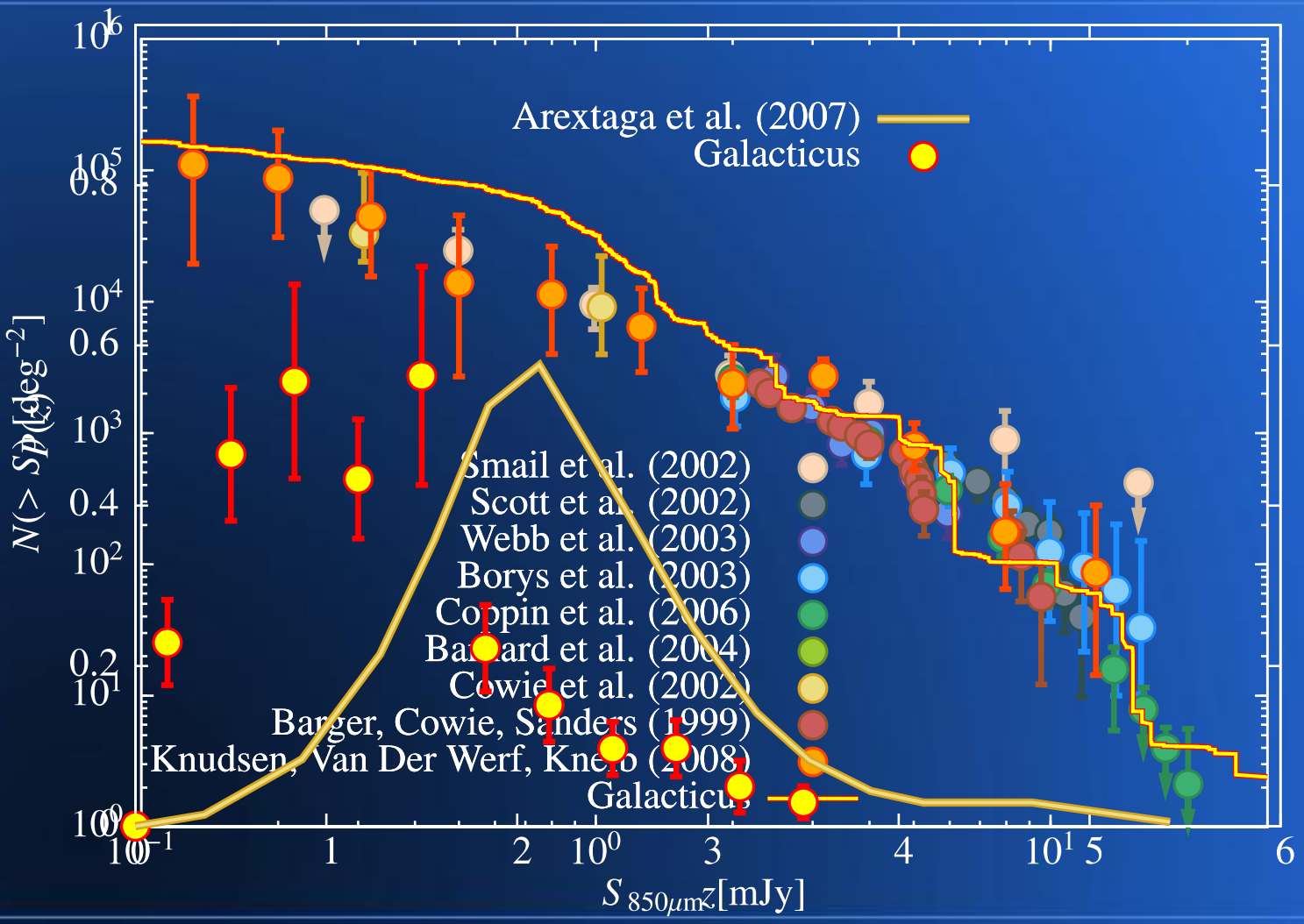


AJB & **Carpenter**

Example SED


Galaxy spectrum (λL_λ [10^{30} ergs/s])
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Wavelength [microns]
Total
Starlight
Cirrus
Clouds

Sub-mm Galaxy Properties



Galacticus v0.9.0

sites.google.com/site/galacticusmodel

www.ctcp.caltech.edu/galacticus/download.htm

feeds.launchpad.net/~abenson/galacticus/v0.9.0/branch.atom

GalacticusModel

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launchpad.net/galacticus

aws.amazon.com/amis/4142

sites.google.com/site/galacticusmodel/home/documentation

Summary

- Galaxy formation is complex
  - Standard model exists
  - Need to test it
- Coherent framework is necessary
- Next steps
  - Incorporation into Bolshoi/Multidark
  - Couple directly to N-body codes
  - Add/improve physics
  - Test, test, test.....!