Title: Cosmic ray feedback in galaxies and cool core clusters

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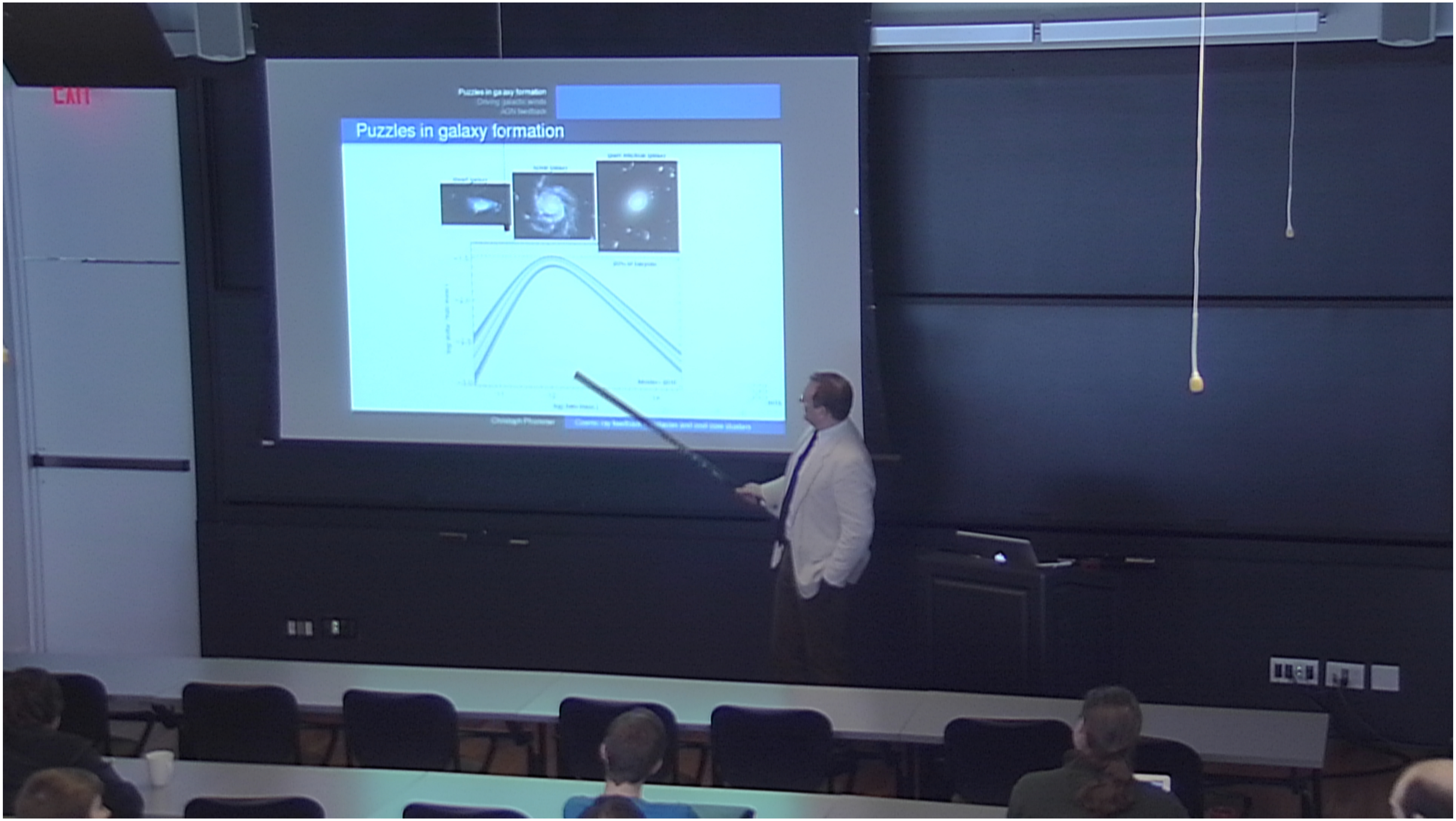
Abstract: <p>Understanding the physics of galaxy formation is arguably among the greatest problems in modern astrophysics. Recent cosmological simulations have demonstrated that "feedback" by star formation, supernovae and active galactic nuclei appears to be critical in obtaining realistic disk galaxies, to slow down star formation to the small observed rates, to move gas and metals out of galaxies into the intergalactic medium, and to balance radiative cooling of the low-entropy gas at the centers of galaxy clusters. However the particular physical processes underlying this "feedback" still remain elusive. In particular, these simulations neglected cosmic rays and magnetic fields, which provide a comparable pressure support in comparison to turbulence in our Galaxy, and are known to couple dynamically and thermally to the gas. Using hydrodynamic simulations of galaxy formation, I will show how cosmic rays are able to drive powerful galactic winds in low-mass galaxies. This reduces the available amount of gas for star formation and implies a shallower slope of the faint-end of the galaxy luminosity function as required by observations. In the second part of the talk I demonstrate that cosmic-ray heating can balance radiative cooling of the low-entropy gas at the centers of galaxy clusters and helps in mitigating the star formation of the brightest cluster galaxies. New data on the low-frequency radio and gamma-ray emission of M87, the closest active galaxy interacting with the cooling cluster plasma, enable us to put forward a comprehensive, physics-based model of feedback by active galactic nuclei.</p>



Puzzles in galaxy formation
Driving galactic winds
AGN feedback

Puzzles in galaxy formation

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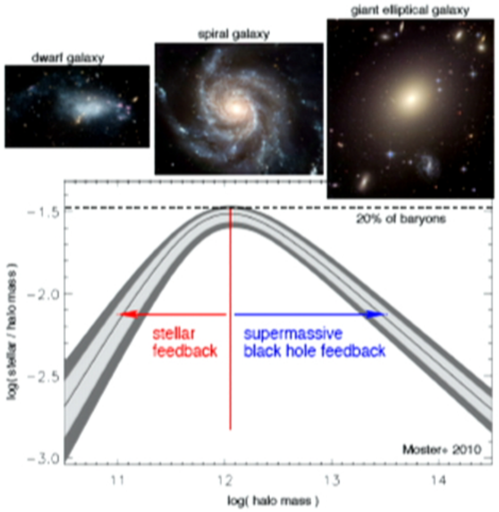
Cosmic ray feedback [illegible] galaxies and cool core clusters

Puzzles in galaxy formation

Bright-end of luminosity function:

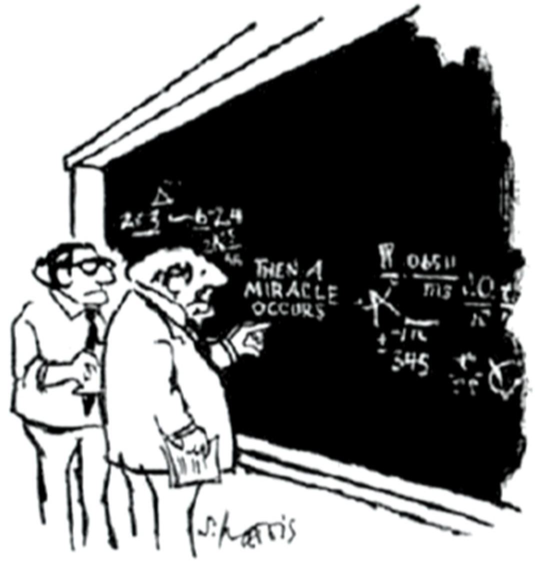
- astrophysical solutions:
  AGN/quasar feedback, . . .



Faint-end of luminosity function:

- dark matter (DM) solutions:
  warm DM, interacting DM, DM from late decays, large annihilation rates, . . .
- astrophysical solutions:
  - preventing gas from falling into DM potential wells:
    increasing entropy by reionization, blazar heating . . .
  - preventing gas from forming stars in galaxies:
    suppress cooling (photoionization, low metallicities), . . .
  - pushing gas out of galaxies:
    supernova/quasar feedback → **galactic winds**

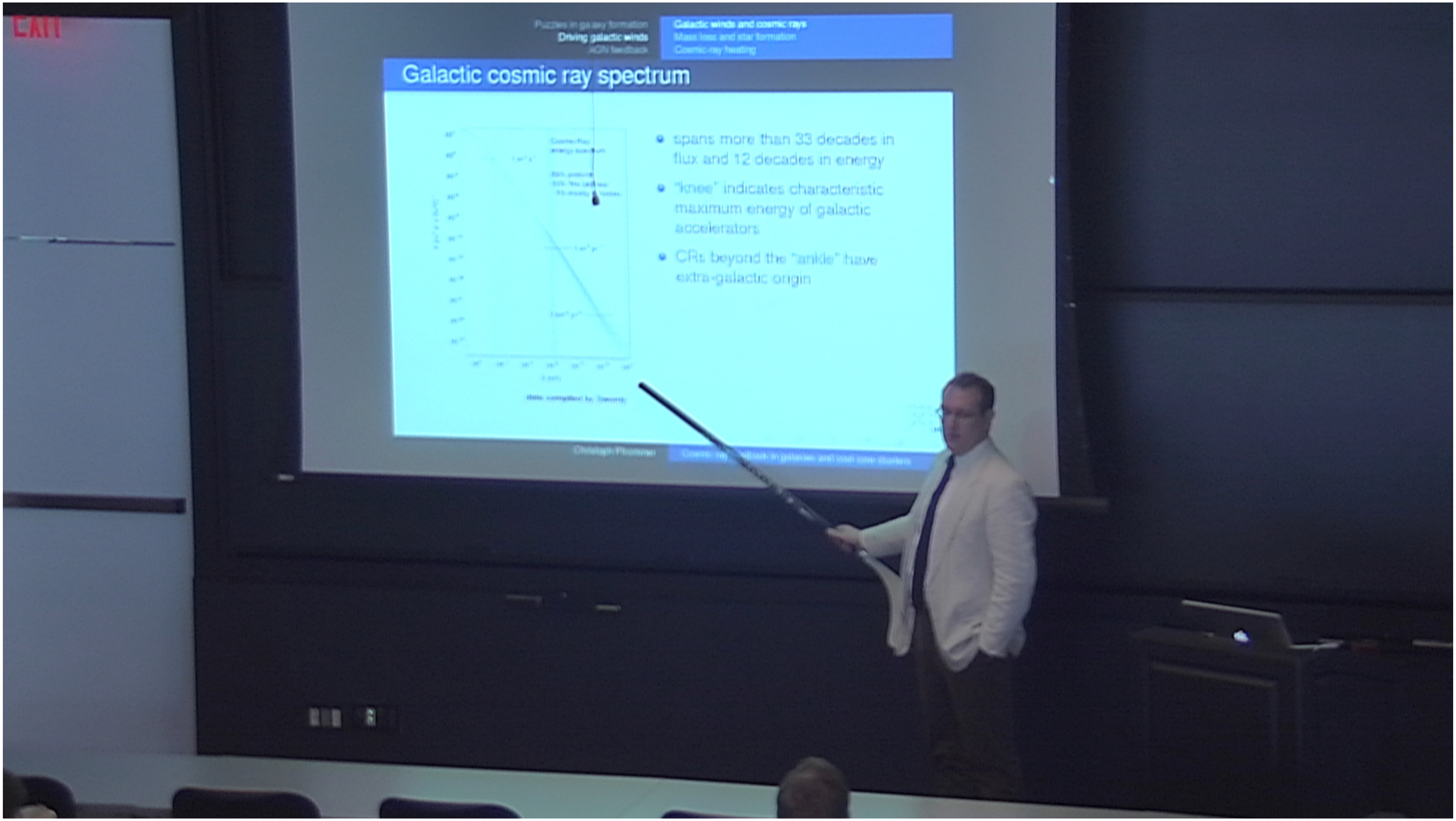
Galactic winds



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

© Sydney Harris

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation → may explain puzzle of low star conversion efficiency in dwarf galaxies



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Galactic winds and cosmic rays
Mass loss and star formation
Cosmic-ray heating

Galactic cosmic ray spectrum

- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin

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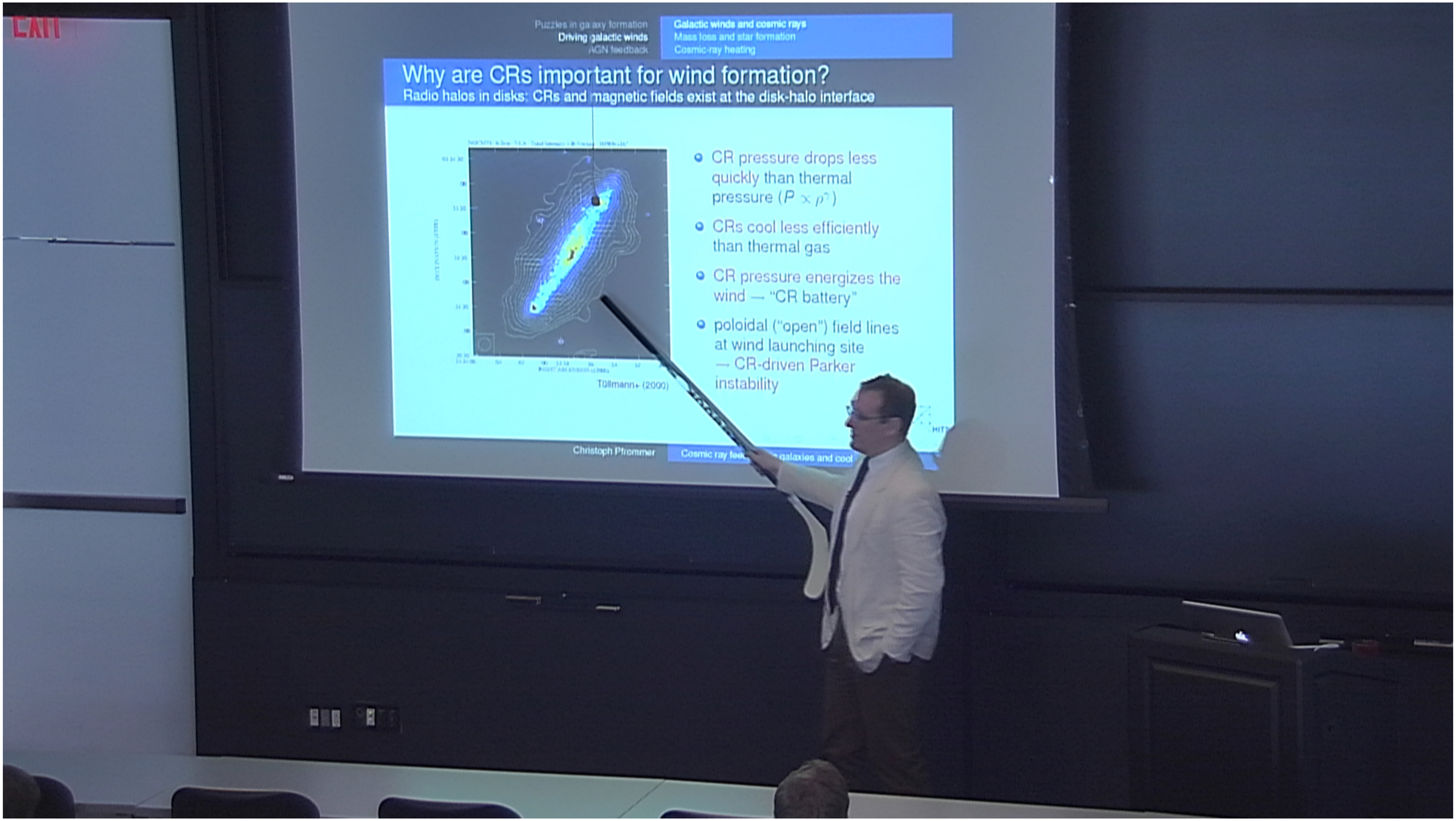

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Why are CRs important for wind formation?

Radio halos in disks: CRs and magnetic fields exist at the disk-halo interface

Tüllmann+ (2000)

- CR pressure drops less quickly than thermal pressure ($P \propto \rho^{\gamma}$)
- CRs cool less efficiently than thermal gas
- CR pressure energizes the wind → "CR battery"
- poloidal ("open") field lines at wind launching site → CR-driven Parker instability

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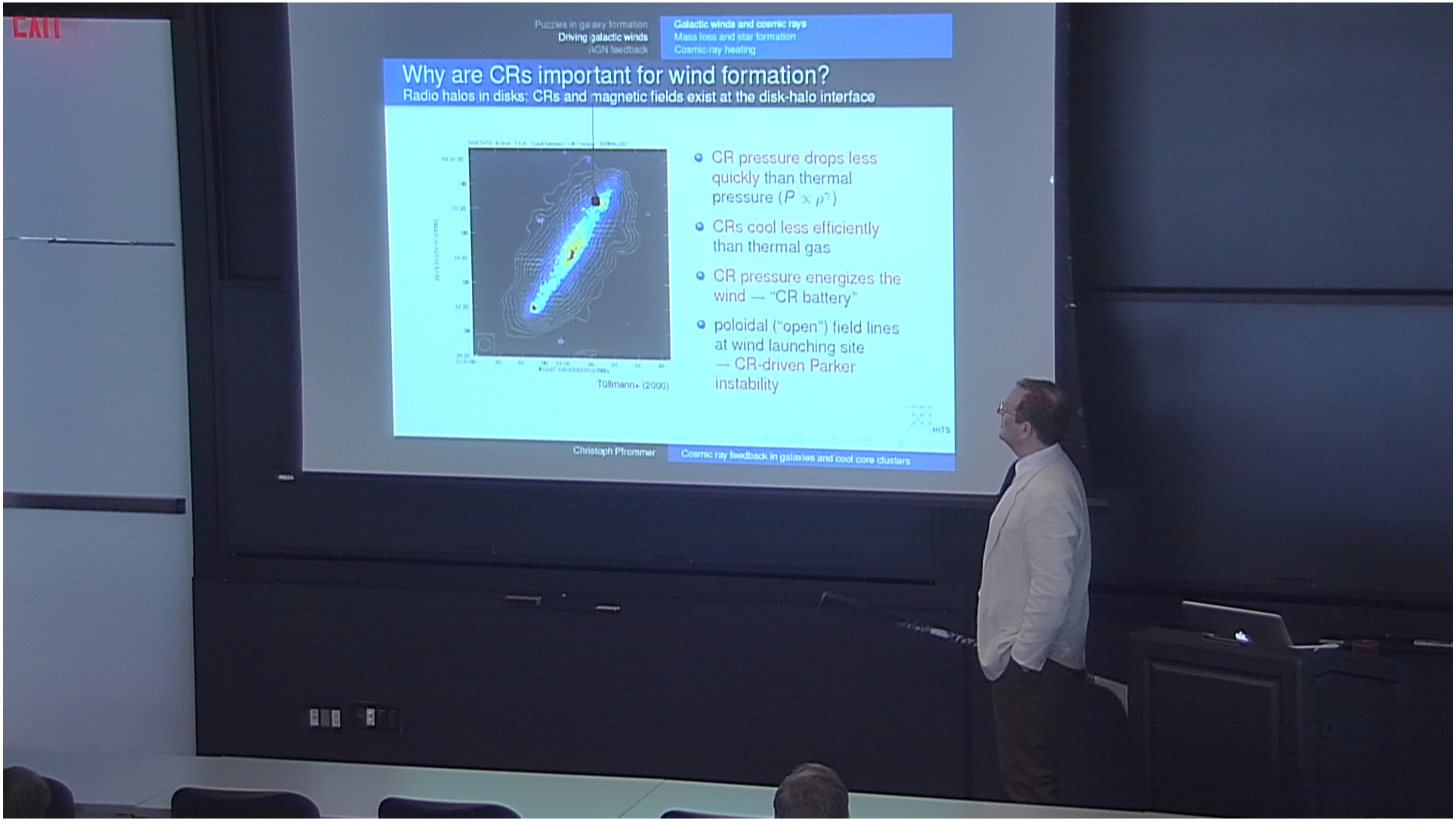
Cosmic ray fee galaxies and cool



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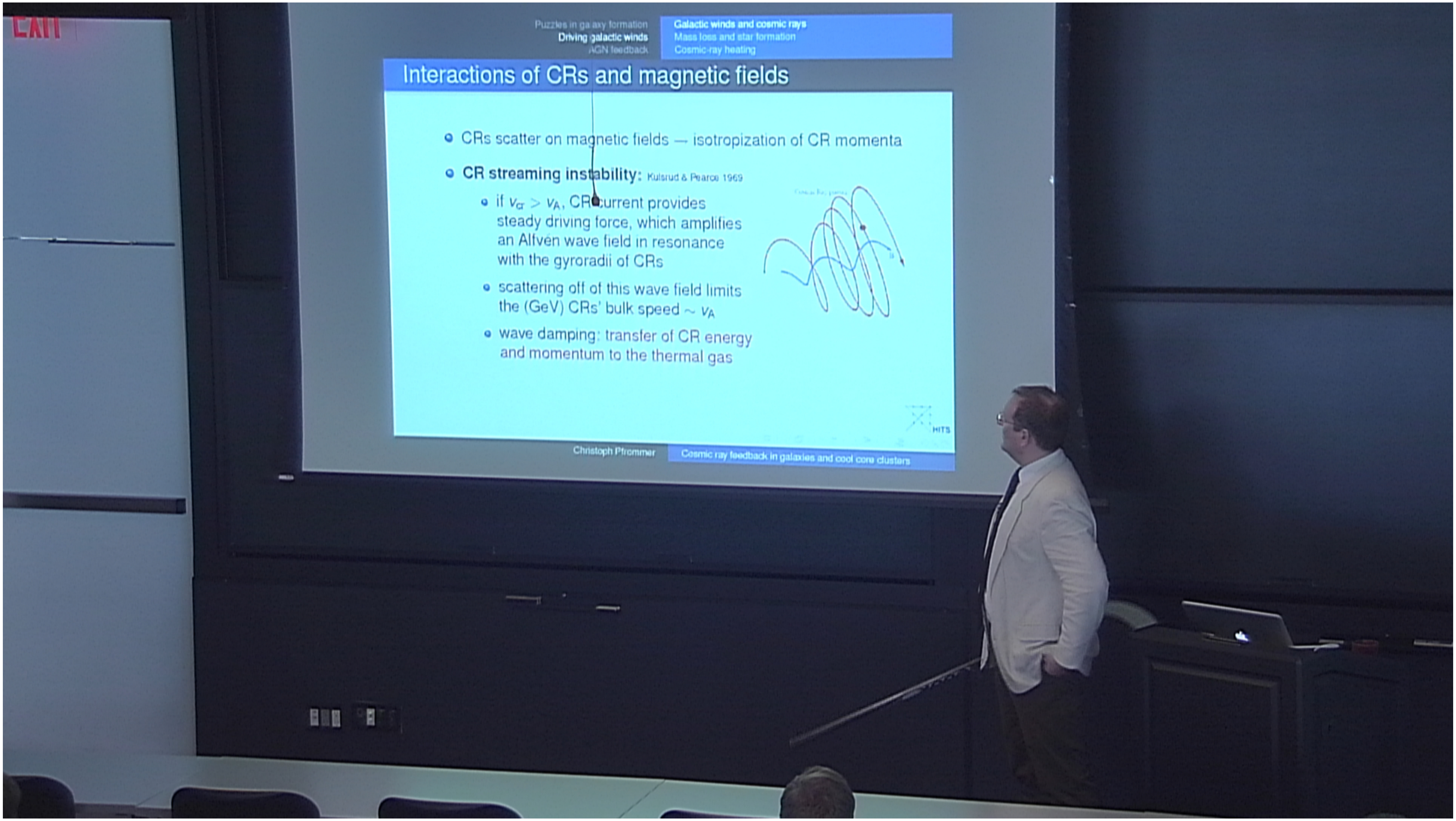
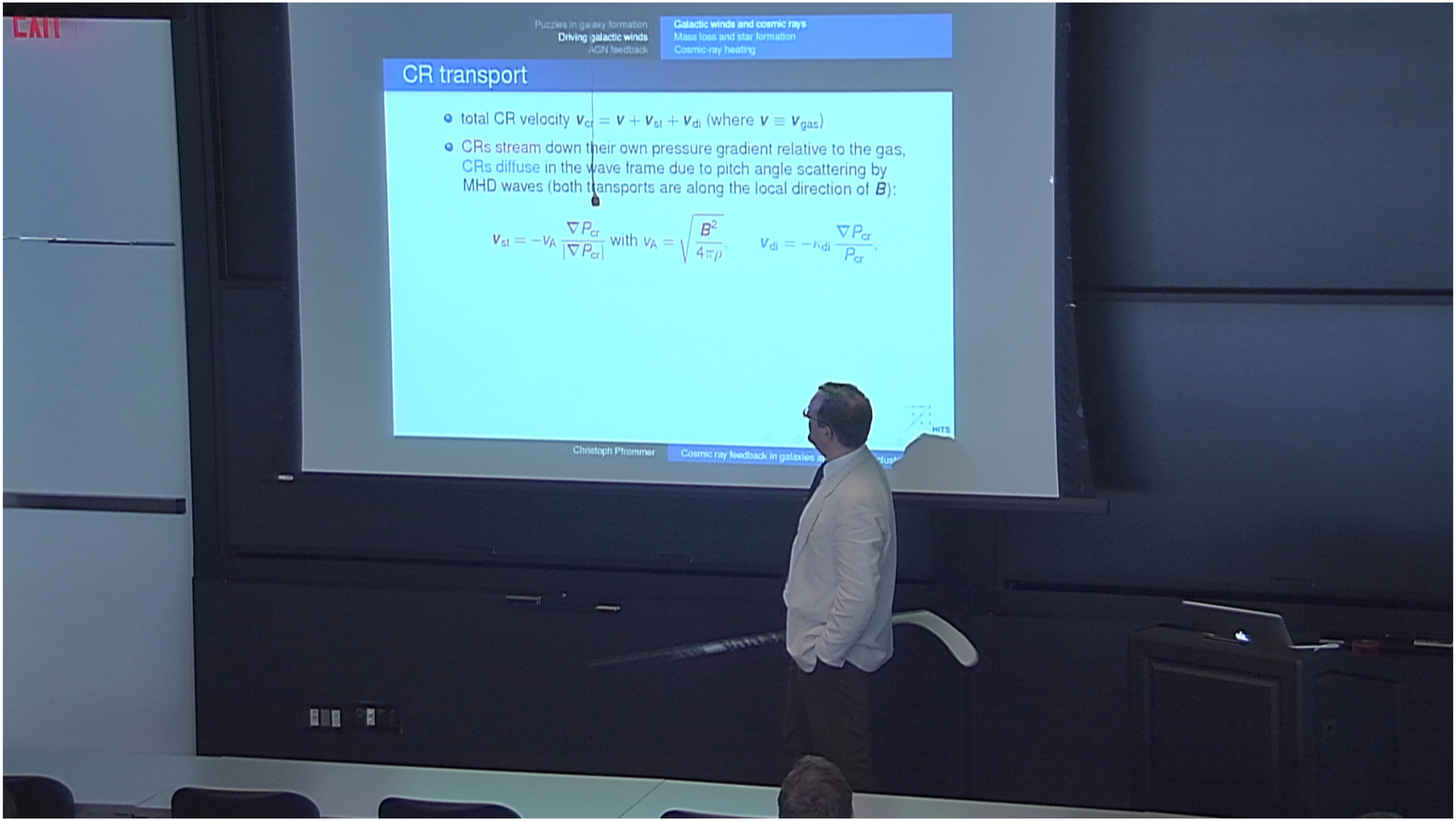


Interactions of CRs and magnetic fields

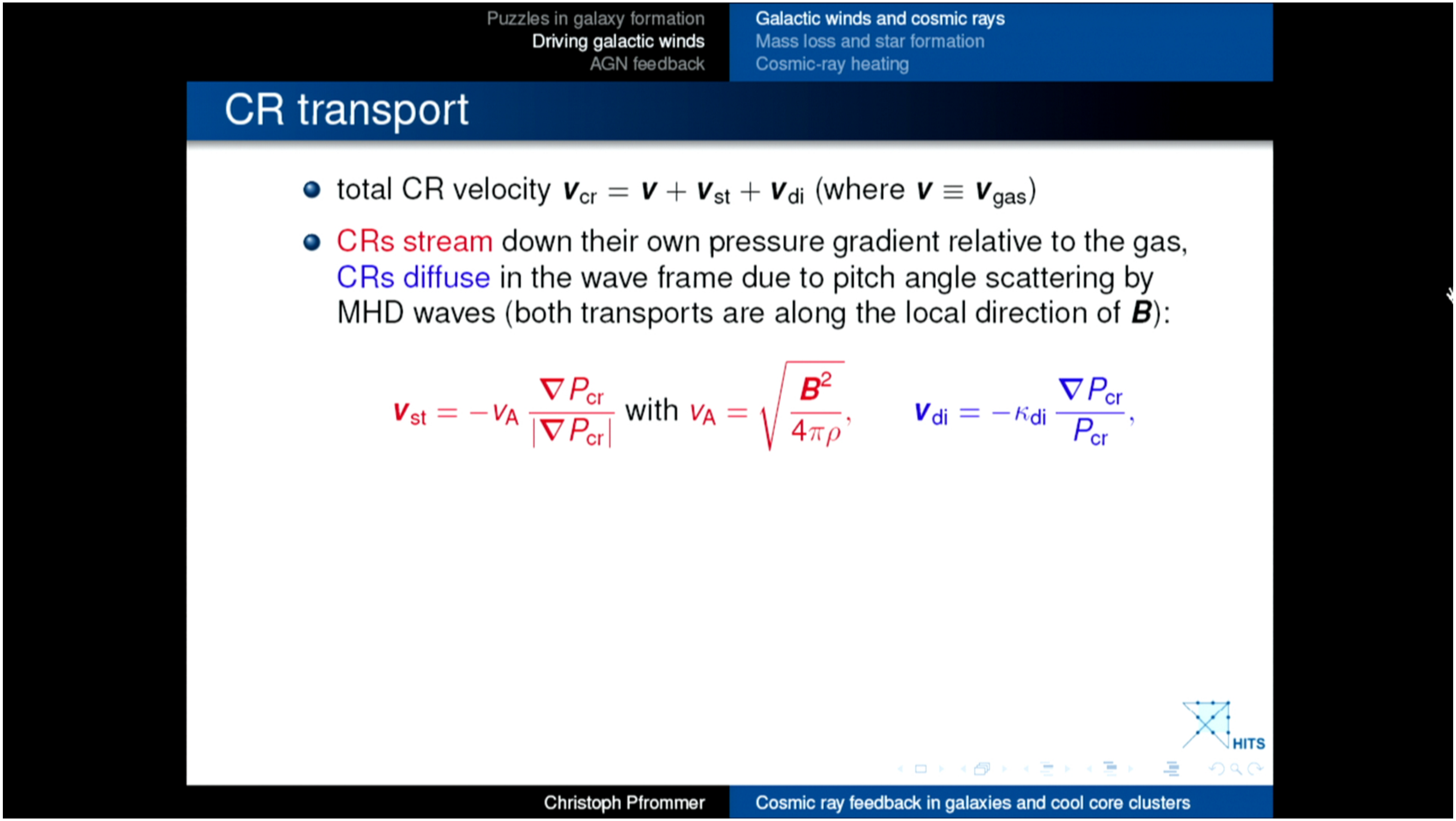
- CRs scatter on magnetic fields — isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\mathrm{cr}} > v_A$, CR current provides steady driving force, which amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_A$
  - wave damping: transfer of CR energy and momentum to the thermal gas



CR transport

- total CR velocity $\mathbf{v}_{\rm cr} = \mathbf{v} + \mathbf{v}_{\rm st} + \mathbf{v}_{\rm di}$ (where $\mathbf{v} \equiv \mathbf{v}_{\rm gas}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\mathbf{B}$):

$$\mathbf{v}_{\rm st} = -v_{\rm A} \frac{\nabla P_{\rm cr}}{|\nabla P_{\rm cr}|} \text{ with } v_{\rm A} = \sqrt{\frac{B^2}{4\pi\rho}}, \qquad \mathbf{v}_{\rm di} = -\kappa_{\rm di} \frac{\nabla P_{\rm cr}}{P_{\rm cr}},$$



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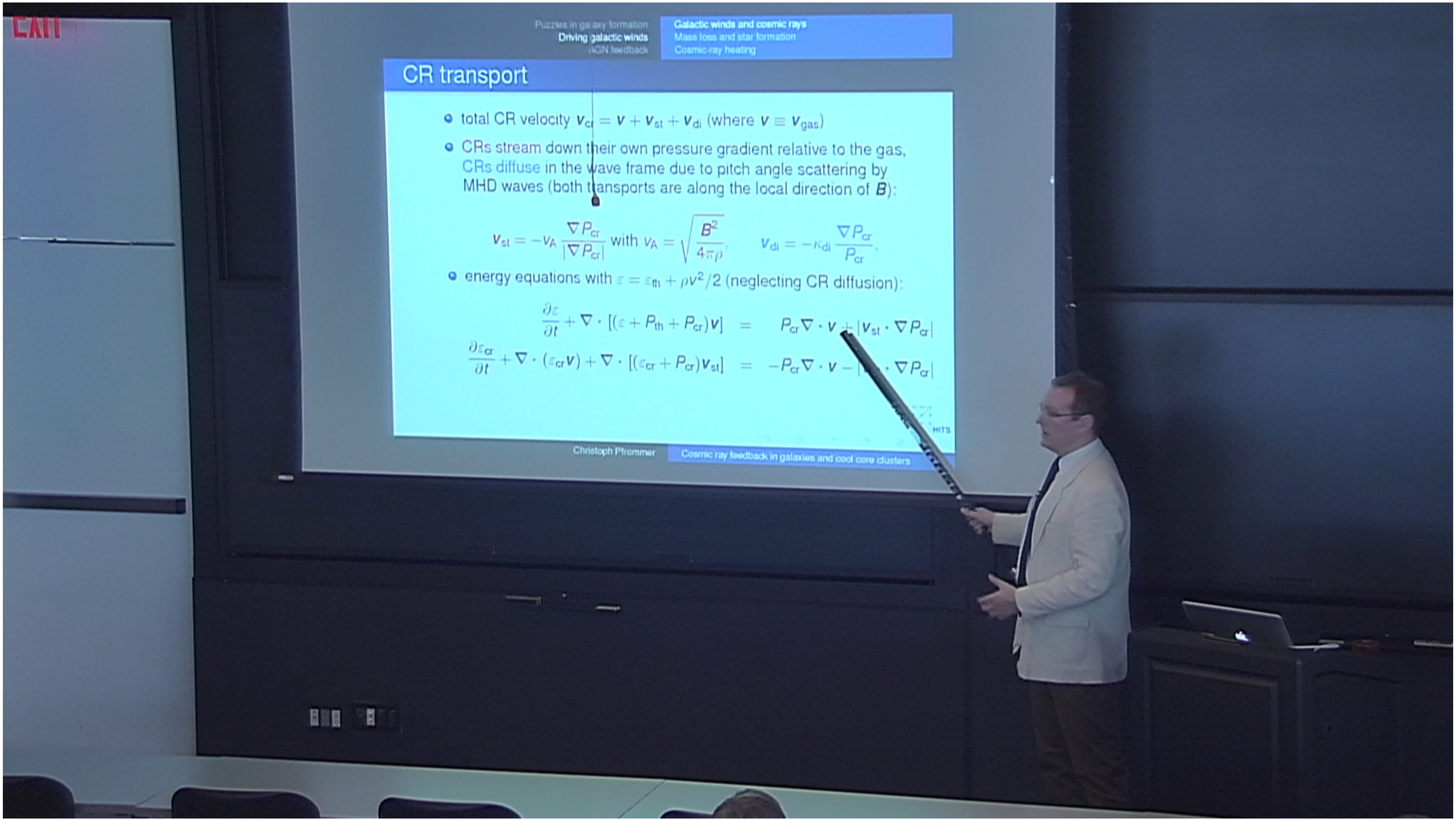

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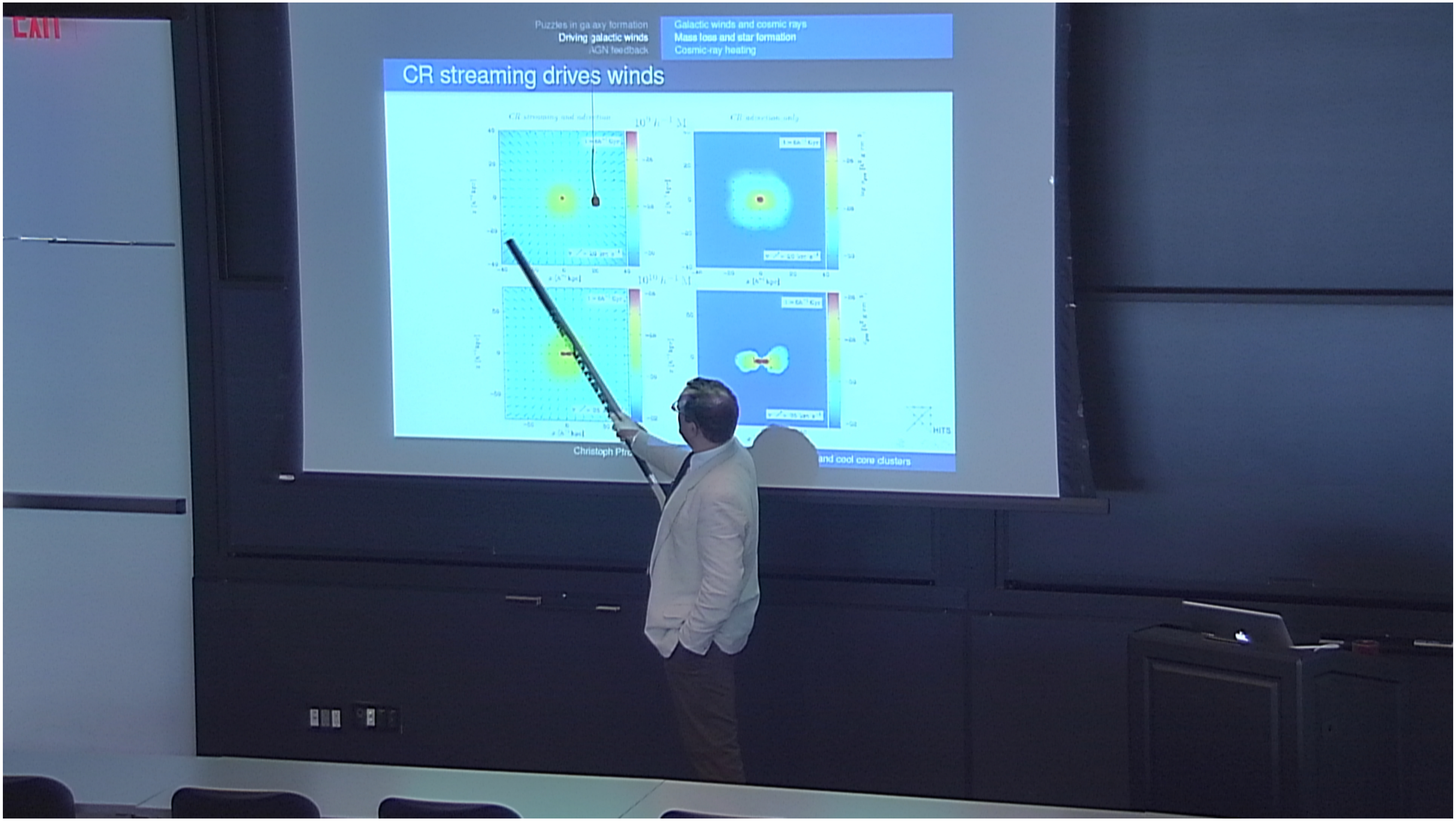
- energy equations with $\varepsilon = \varepsilon_{th} + \rho v^2/2$ (neglecting CR diffusion):

$$\begin{aligned} \frac{\partial \varepsilon}{\partial t} + \nabla \cdot [(\varepsilon + P_{th} + P_{cr})\boldsymbol{v}] &= P_{cr}\nabla \cdot \boldsymbol{v} + |\boldsymbol{v}_{st} \cdot \nabla P_{cr}| \\ \frac{\partial \varepsilon_{cr}}{\partial t} + \nabla \cdot (\varepsilon_{cr}\boldsymbol{v}) + \nabla \cdot [(\varepsilon_{cr} + P_{cr})\boldsymbol{v}_{st}] &= -P_{cr}\nabla \cdot \boldsymbol{v} - |\boldsymbol{v}_{st} \cdot \nabla P_{cr}| \end{aligned}$$



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Cosmic-ray heating

CR streaming drives winds

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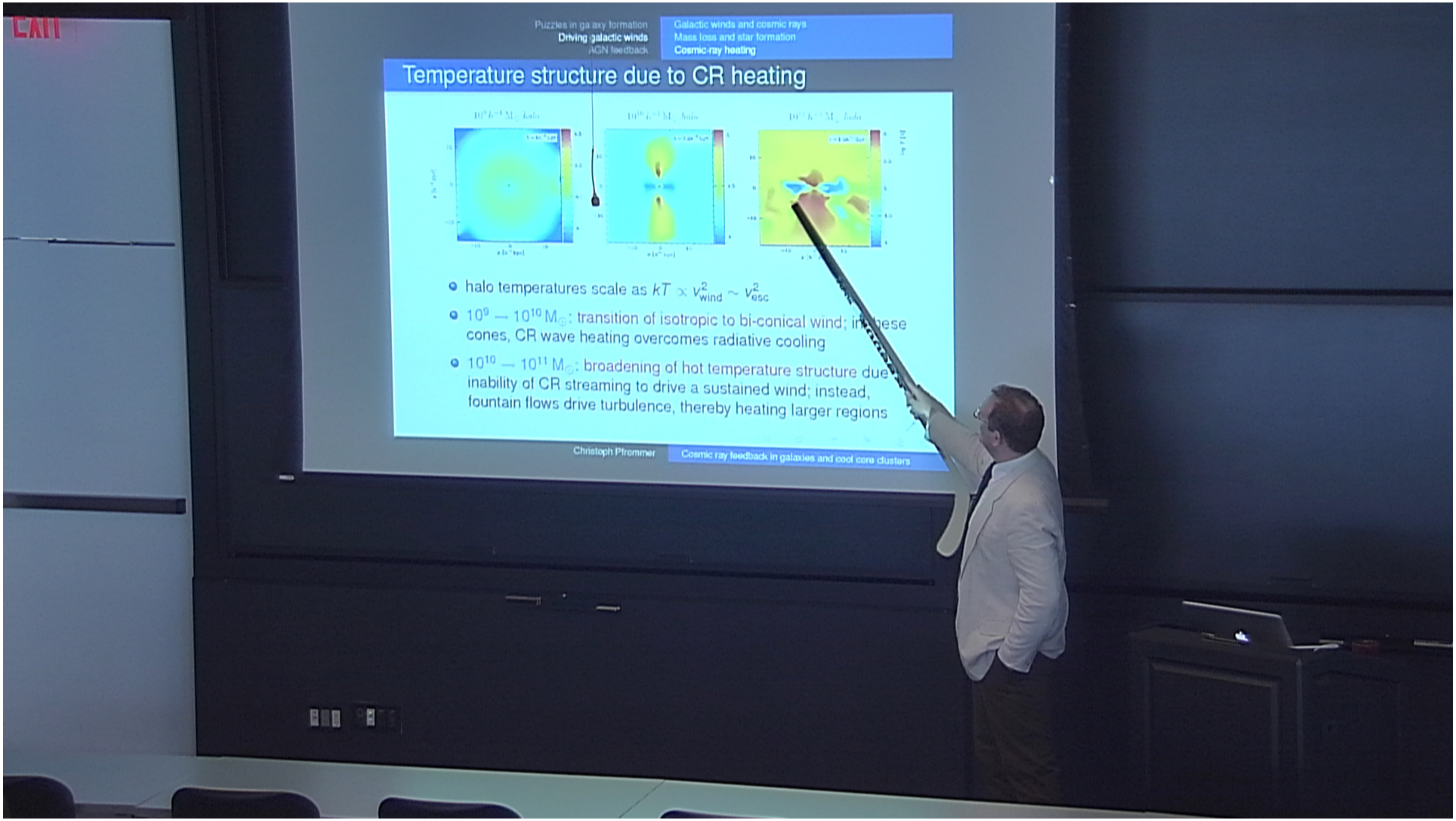
and cool core clusters



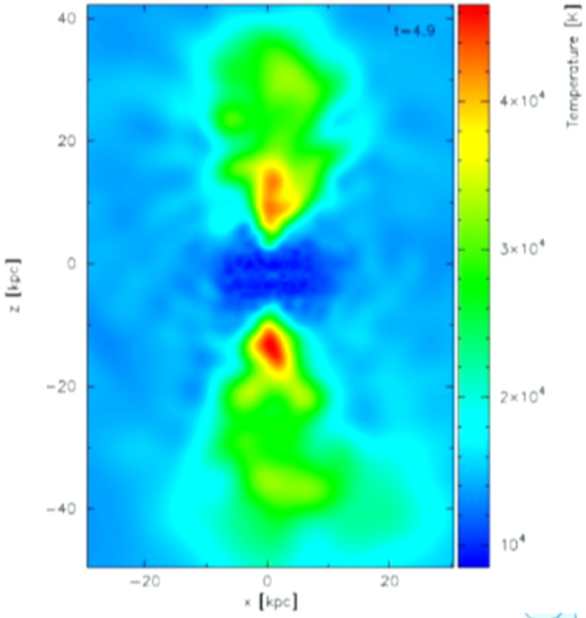
Temperature structure due to CR heating

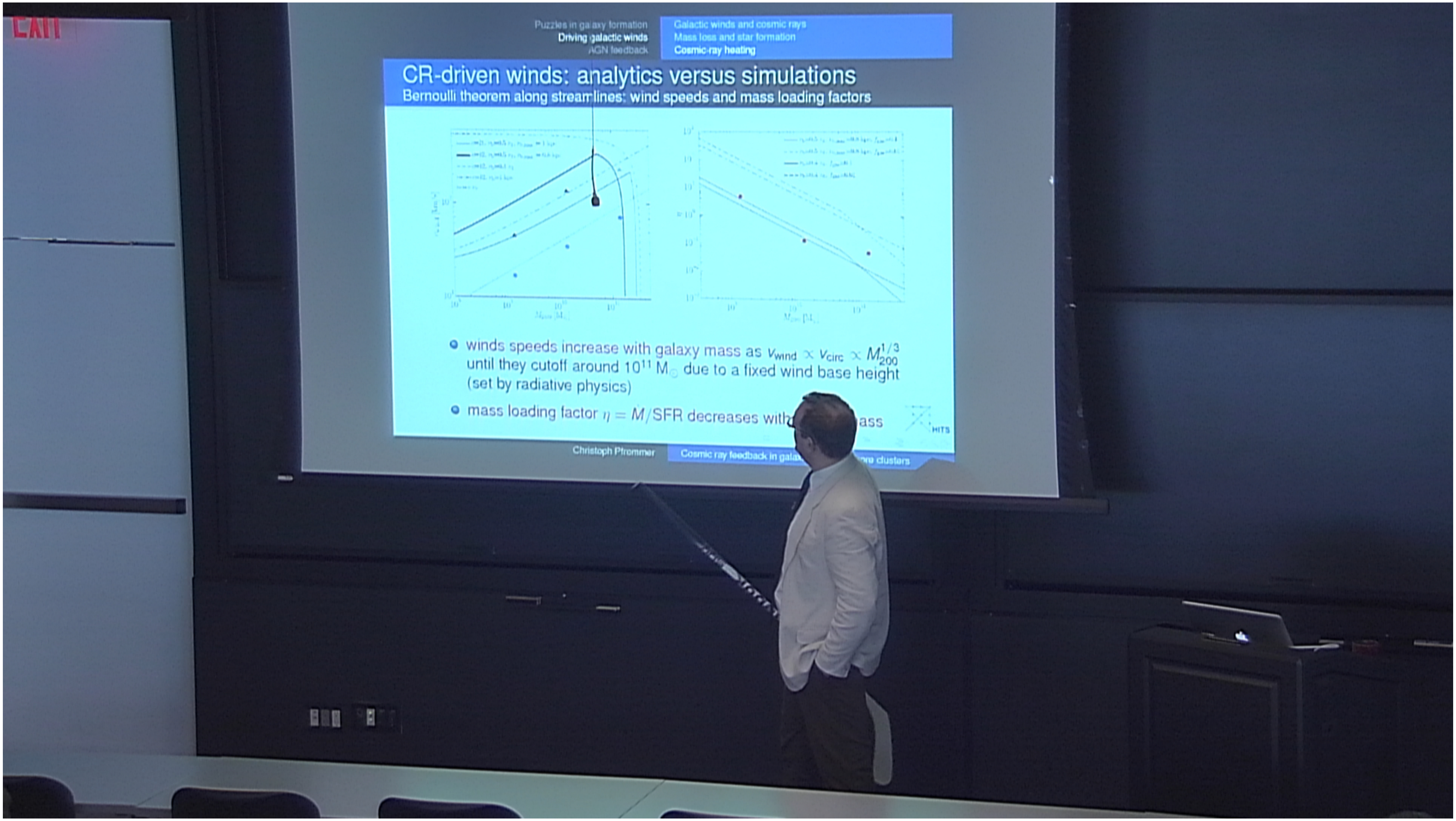
- halo temperatures scale as $kT \propto v_{\mathrm{wind}}^2 \sim v_{\mathrm{esc}}^2$
- $10^9 \rightarrow 10^{10}\,\mathrm{M}_\odot$: transition of isotropic to bi-conical wind; in these cones, CR wave heating overcomes radiative cooling
- $10^{10} \rightarrow 10^{11}\,\mathrm{M}_\odot$: broadening of hot temperature structure due to inability of CR streaming to drive a sustained wind; instead, fountain flows drive turbulence, thereby heating larger regions

Gas temperature: observation vs. simulation

M82 observation

CR streaming ($10^{10}\,M_\odot$)

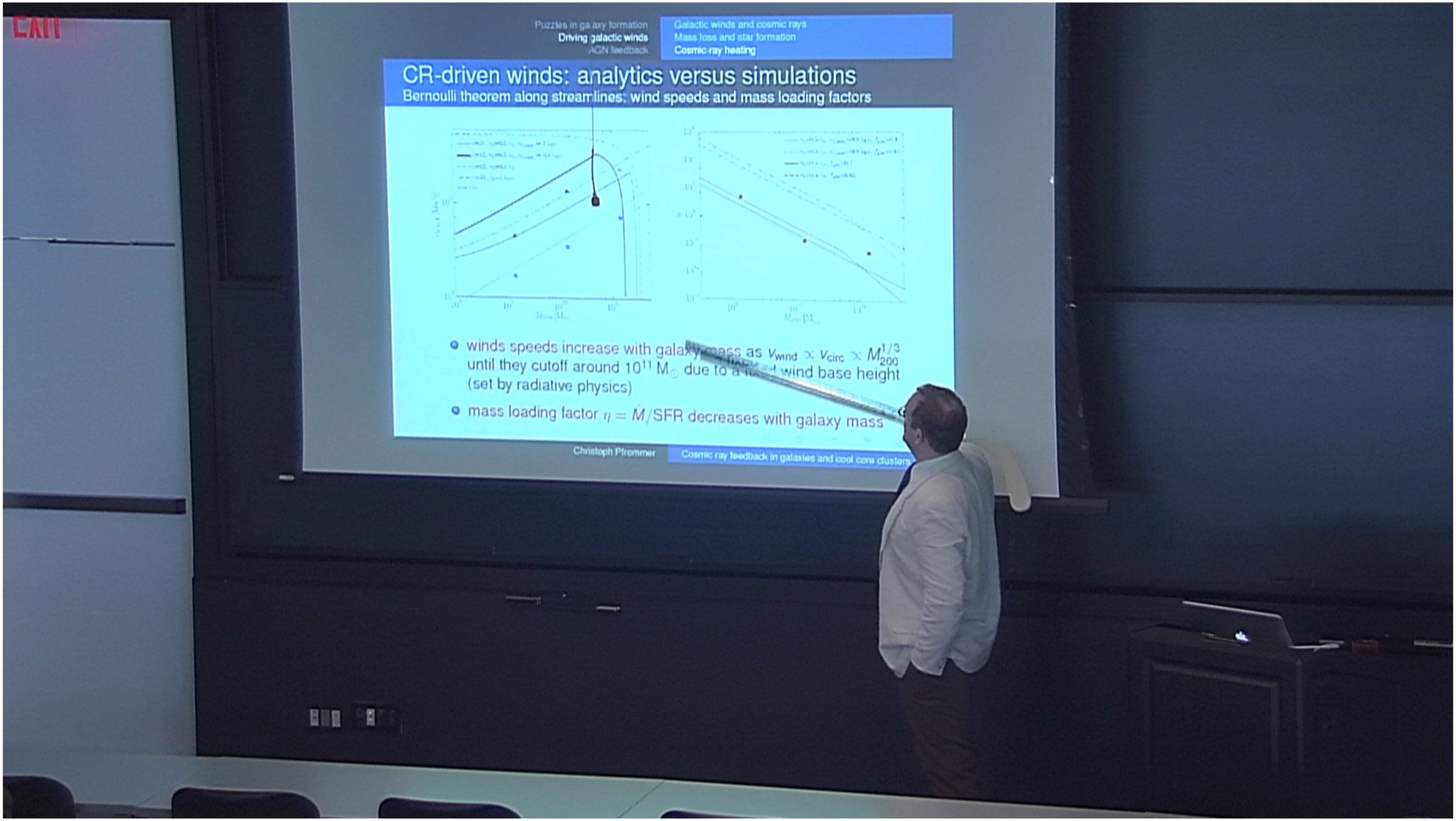




CR-driven winds: analytics versus simulations

Bernoulli theorem along streamlines: wind speeds and mass loading factors

- winds speeds increase with galaxy mass as $v_{\mathrm{wind}} \propto v_{\mathrm{circ}} \propto M_{200}^{1/3}$ until they cutoff around $10^{11}\,\mathrm{M}_\odot$ due to a fixed wind base height (set by radiative physics)
- mass loading factor $\eta = \dot{M}/\mathrm{SFR}$ decreases with [illegible] ass



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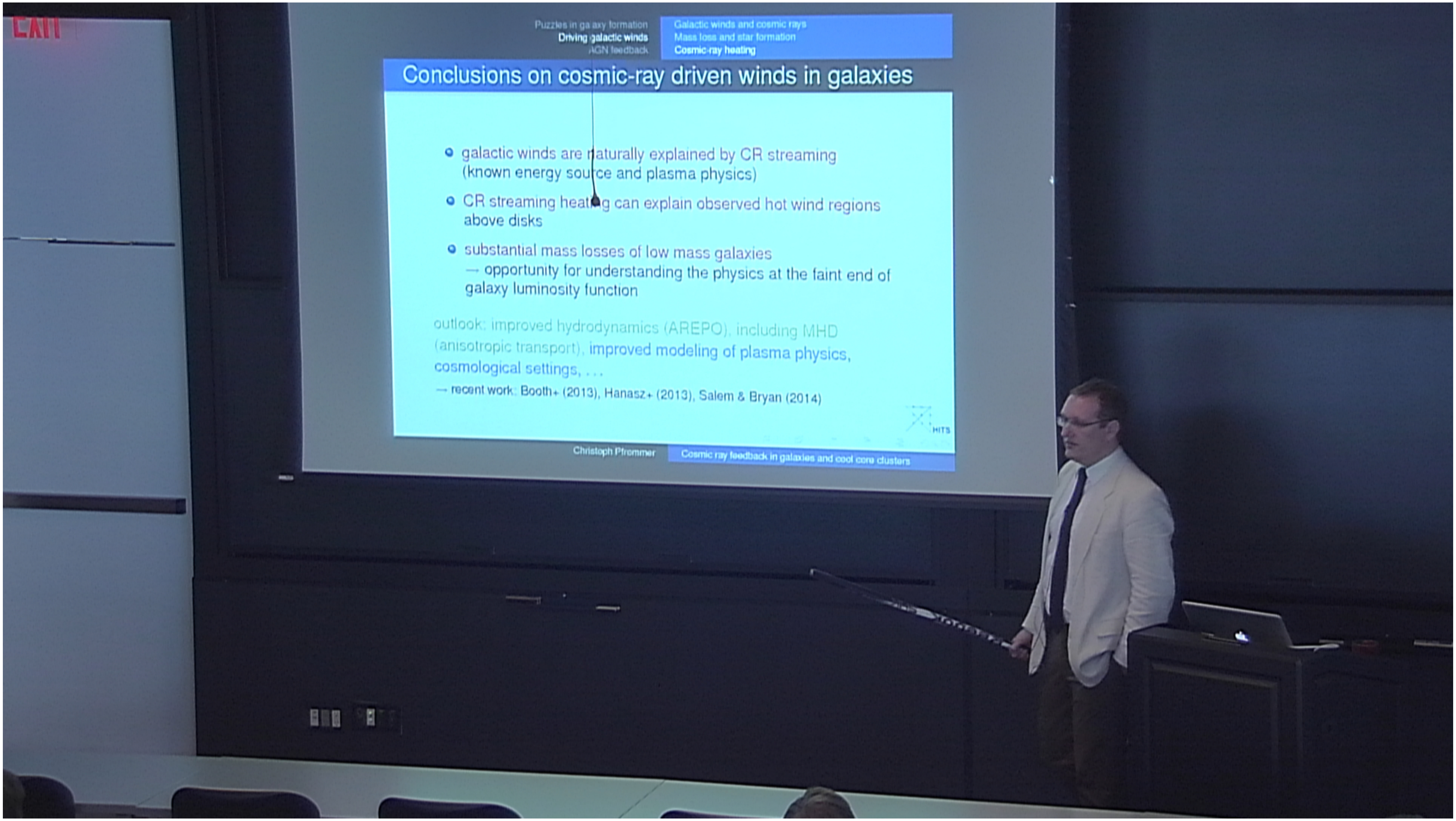


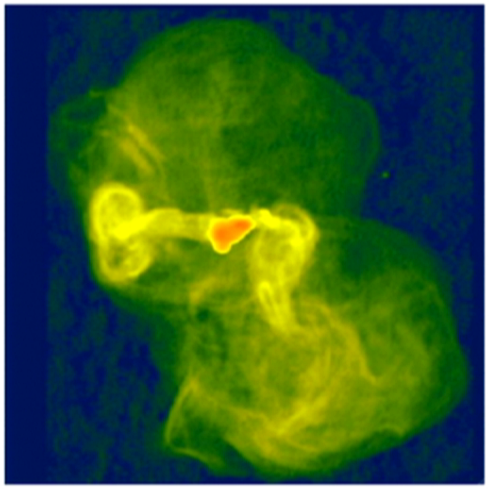
Conclusions on cosmic-ray driven winds in galaxies

- galactic winds are naturally explained by CR streaming (known energy source and plasma physics)
- CR streaming heating can explain observed hot wind regions above disks
- substantial mass losses of low mass galaxies
  → opportunity for understanding the physics at the faint end of galaxy luminosity function

outlook: improved hydrodynamics (AREPO), including MHD (anisotropic transport), improved modeling of plasma physics, cosmological settings, …

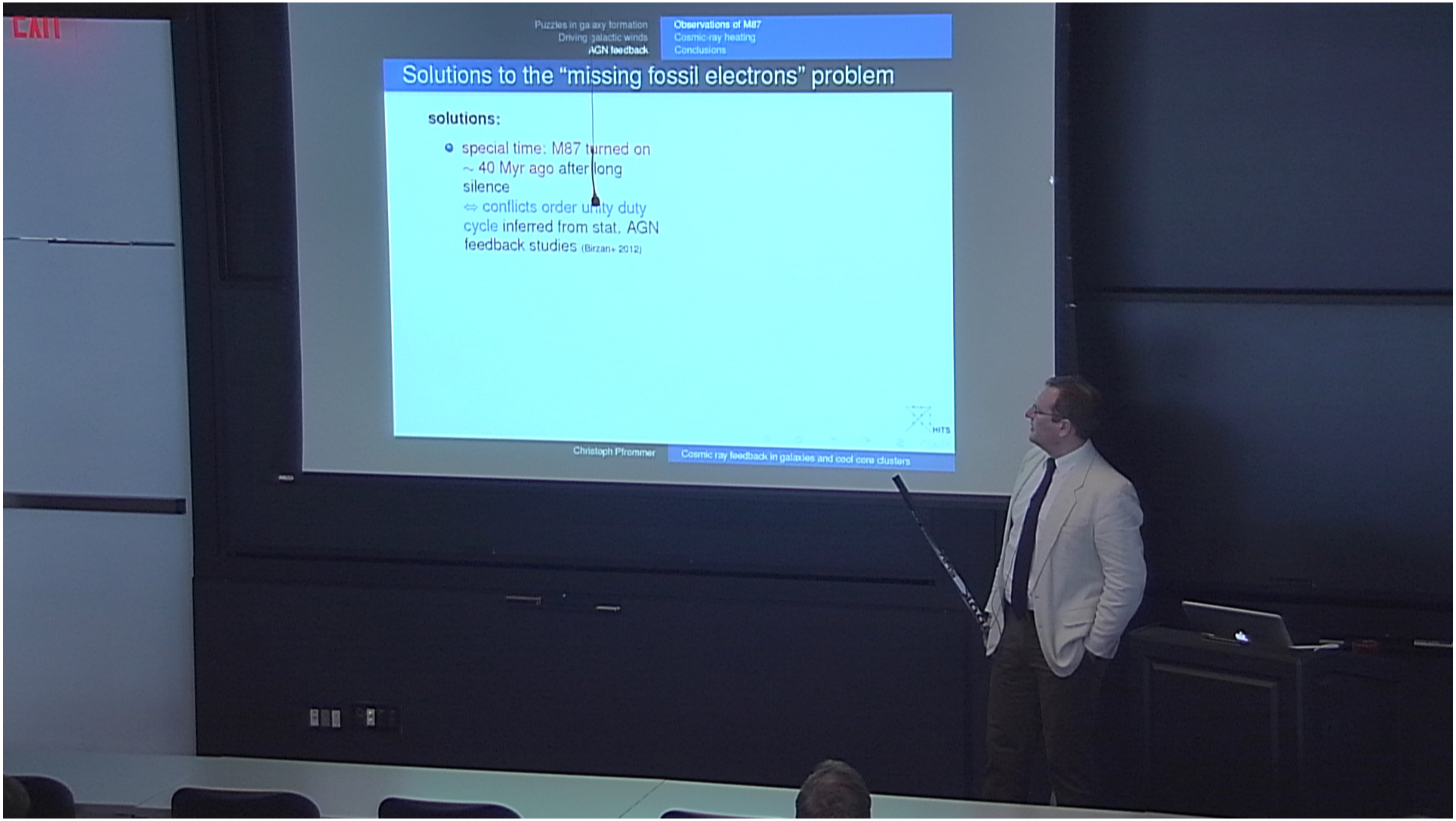
→ recent work: Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014)

Messier 87 at radio wavelengths



$\nu = 1.4$ GHz (Owen+ 2000)

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons → time-integrated AGN feedback!



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Solutions to the "missing fossil electrons" problem

solutions:

- special time: M87 turned on ~ 40 Myr ago after long silence
  ⇔ conflicts order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)

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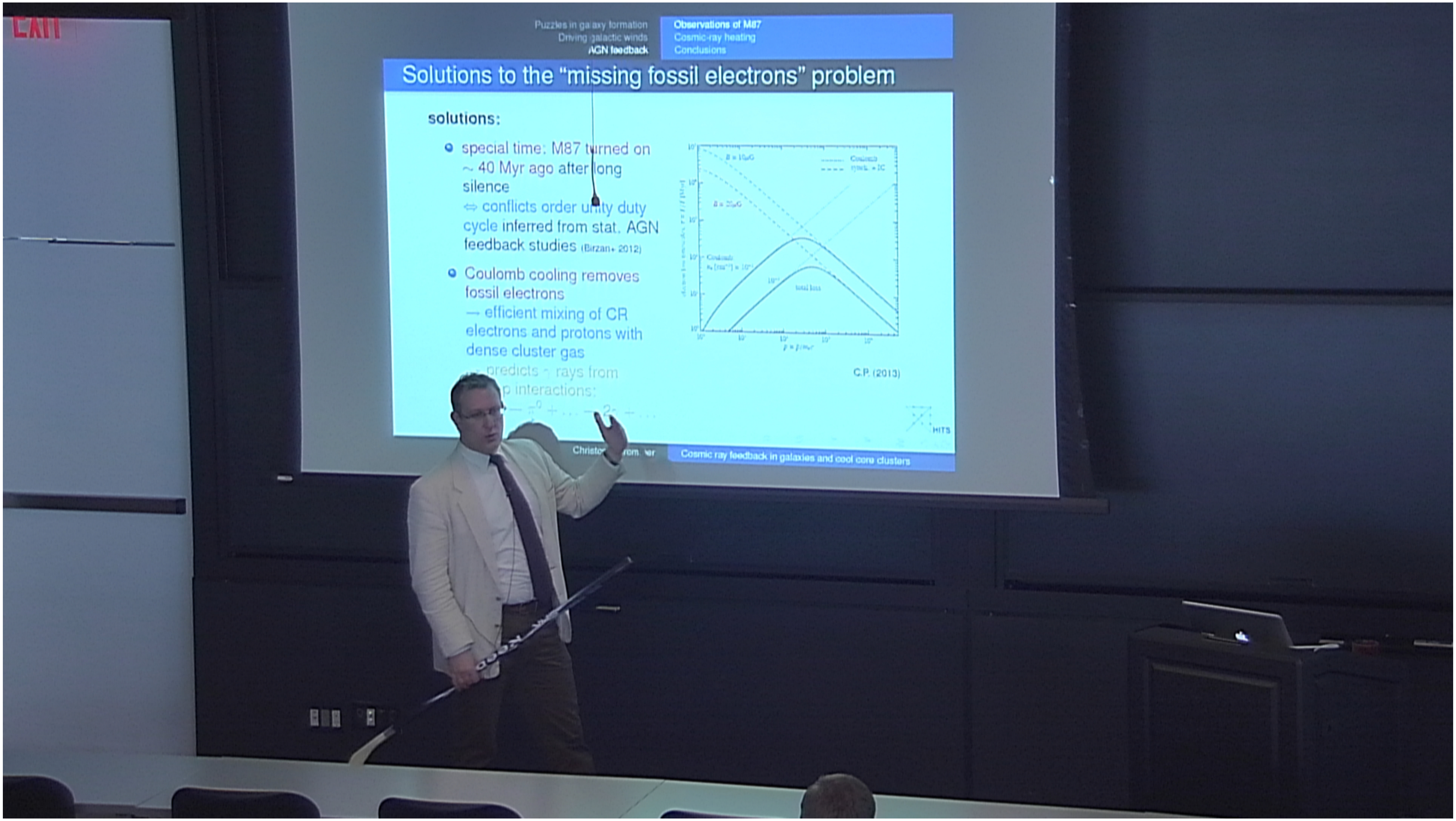
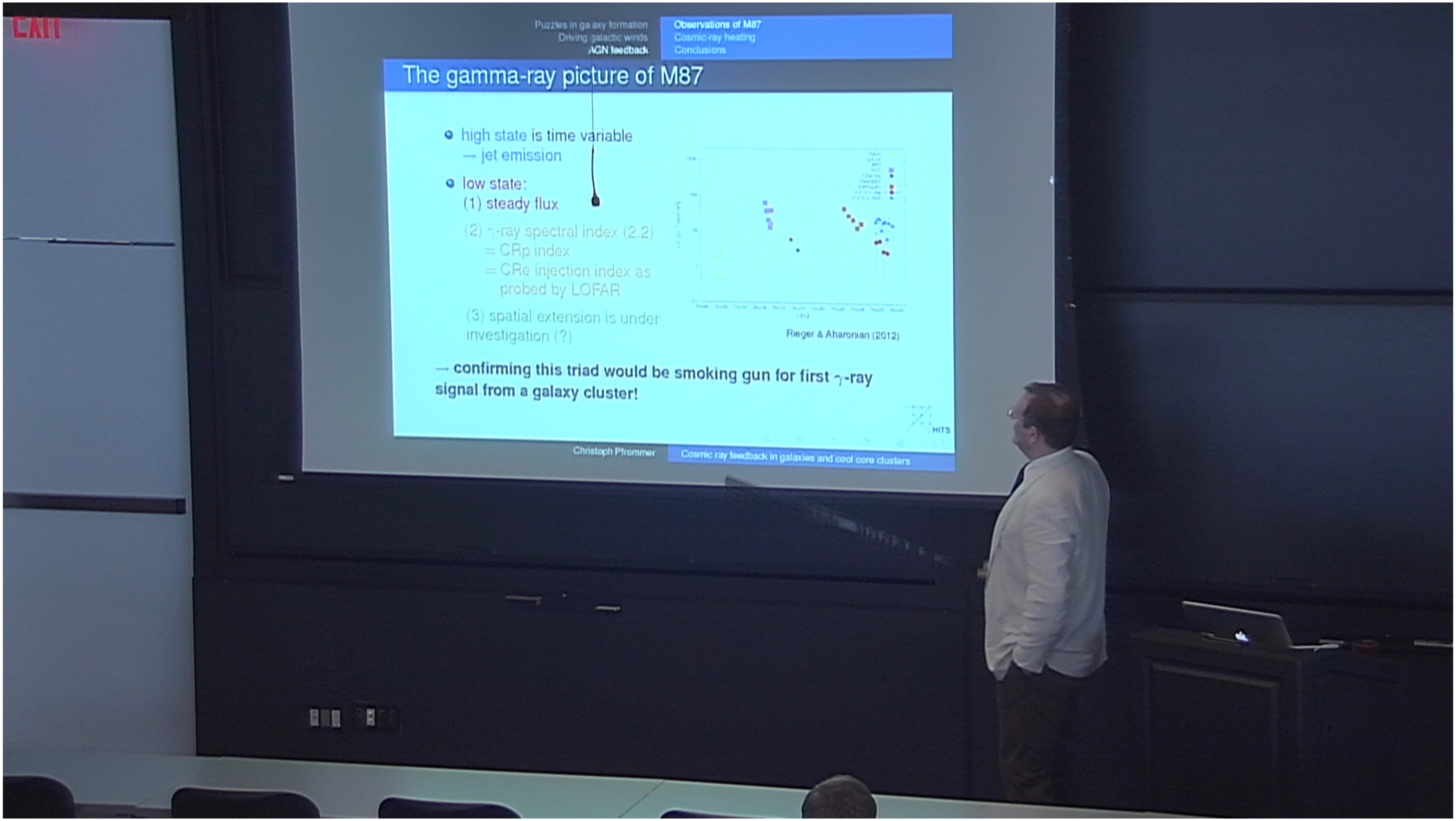


Solutions to the "missing fossil electrons" problem

solutions:

- special time: M87 turned on ~ 40 Myr ago after long silence
  ⇔ conflicts order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)
- Coulomb cooling removes fossil electrons
  → efficient mixing of CR electrons and protons with dense cluster gas
  ⇒ predicts γ rays from p interactions:
  $\pi^0 + \ldots \rightarrow 2\gamma + \ldots$

C.P. (2013)



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The gamma-ray picture of M87

- high state is time variable
  → jet emission
- low state:
  (1) steady flux
  (2) γ-ray spectral index (2.2)
  = CRp index
  = CRe injection index as probed by LOFAR
  (3) spatial extension is under investigation (?)

Rieger & Aharonian (2012)

→ **confirming this triad would be smoking gun for first γ-ray signal from a galaxy cluster!**

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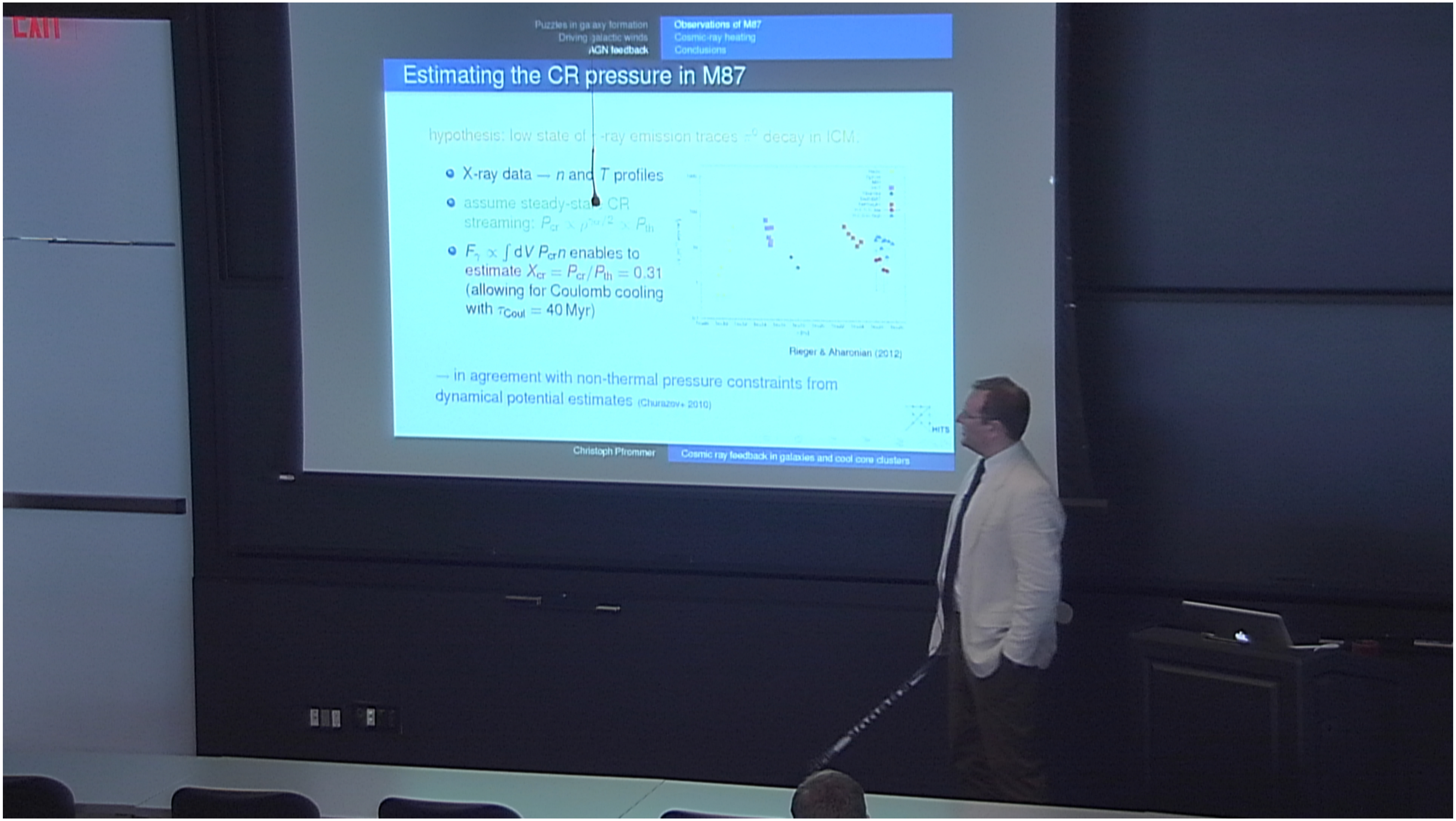

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Estimating the CR pressure in M87

hypothesis: low state of γ-ray emission traces π^0 decay in ICM:

- X-ray data → n and T profiles
- assume steady-state CR streaming: $P_{\rm cr} \propto \rho^{\gamma_{\rm cr}/2} \propto P_{\rm th}$
- $F_\gamma \propto \int \mathrm{d}V\, P_{\rm cr} n$ enables to estimate $X_{\rm cr} = P_{\rm cr}/P_{\rm th} = 0.31$ (allowing for Coulomb cooling with $\tau_{\rm Coul} = 40\,\mathrm{Myr}$)

Rieger & Aharonian (2012)

→ in agreement with non-thermal pressure constraints from dynamical potential estimates (Churazov+ 2010)

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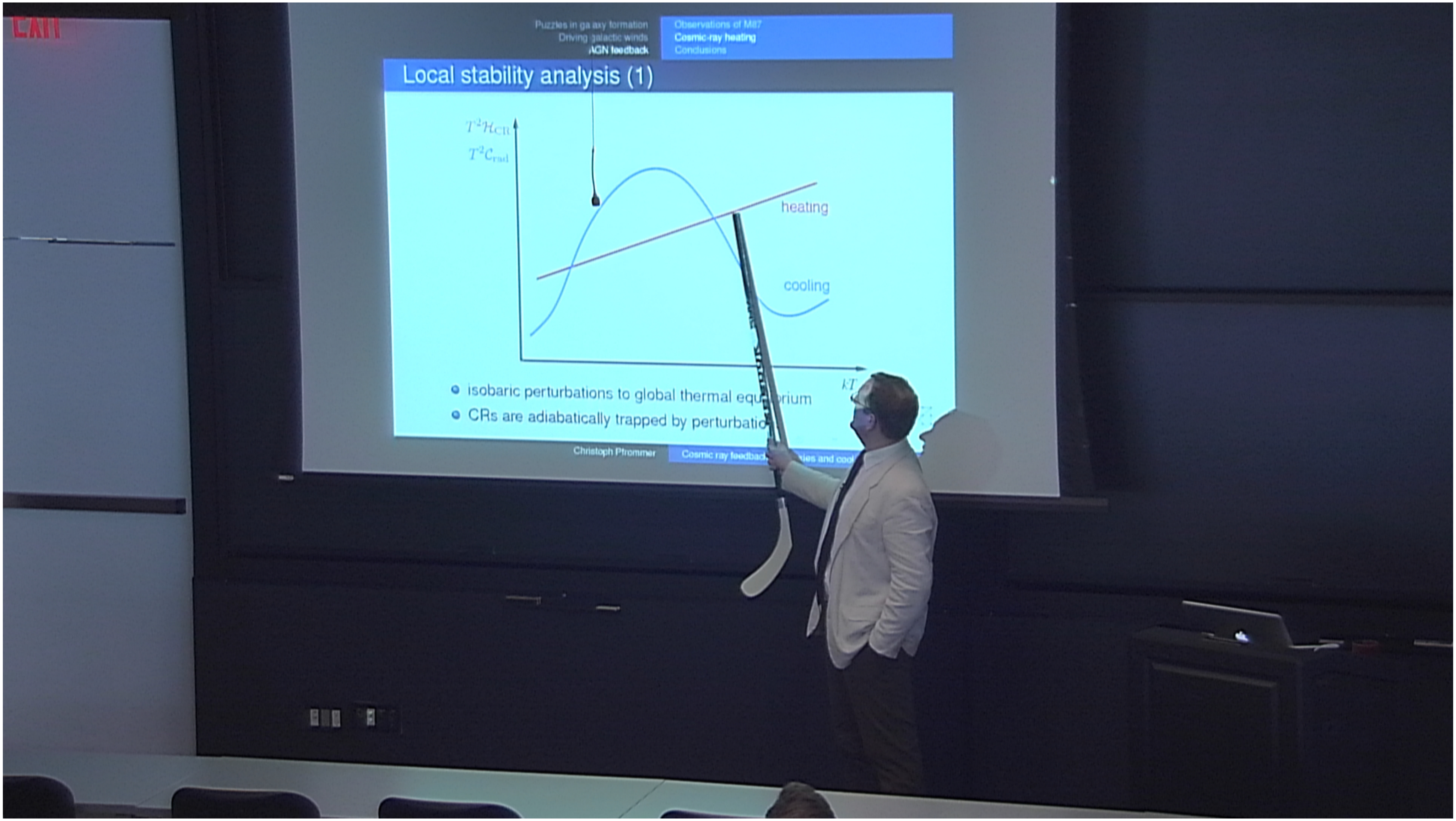

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Local stability analysis (1)

- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbatio

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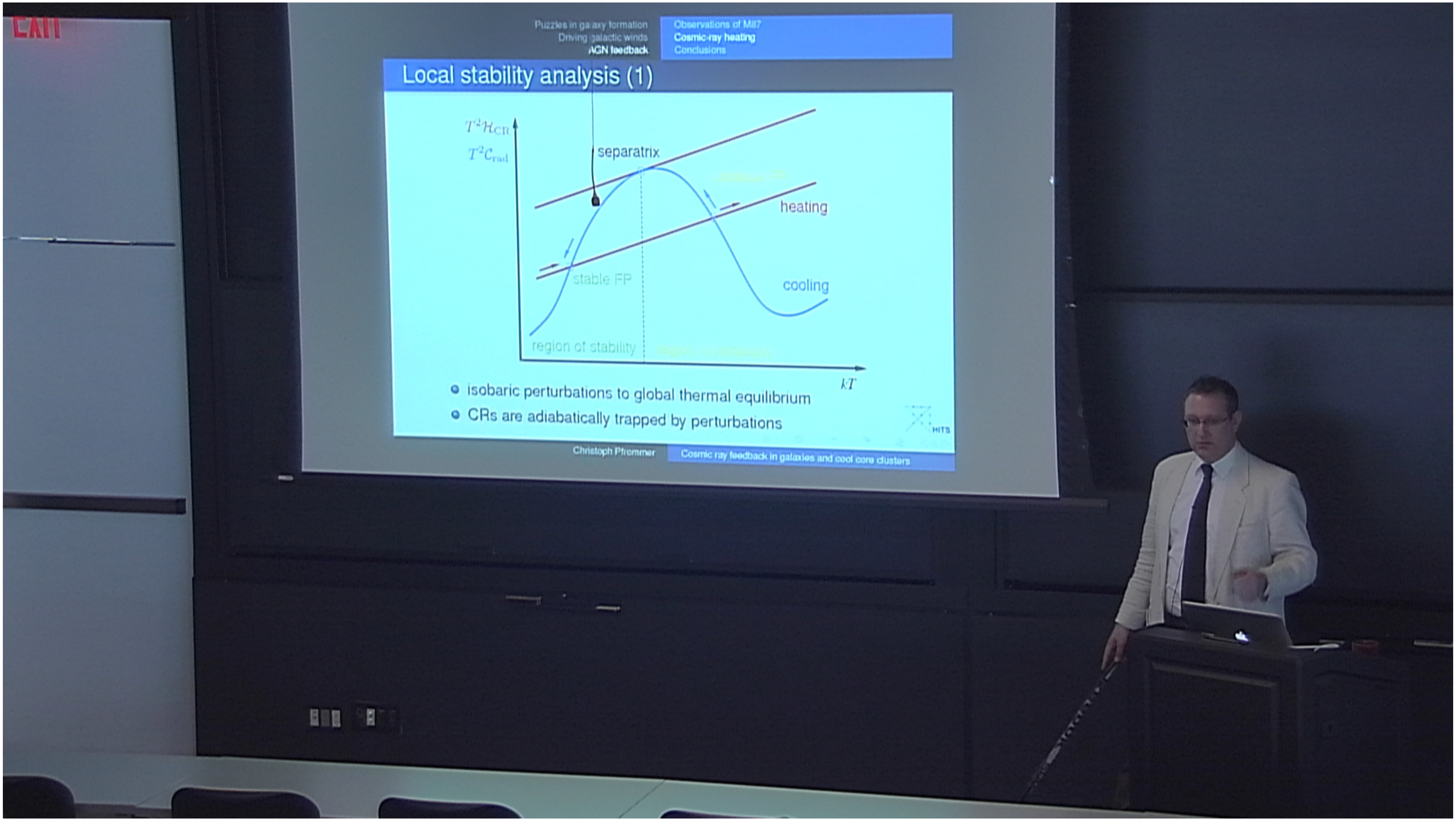
Cosmic ray feedback



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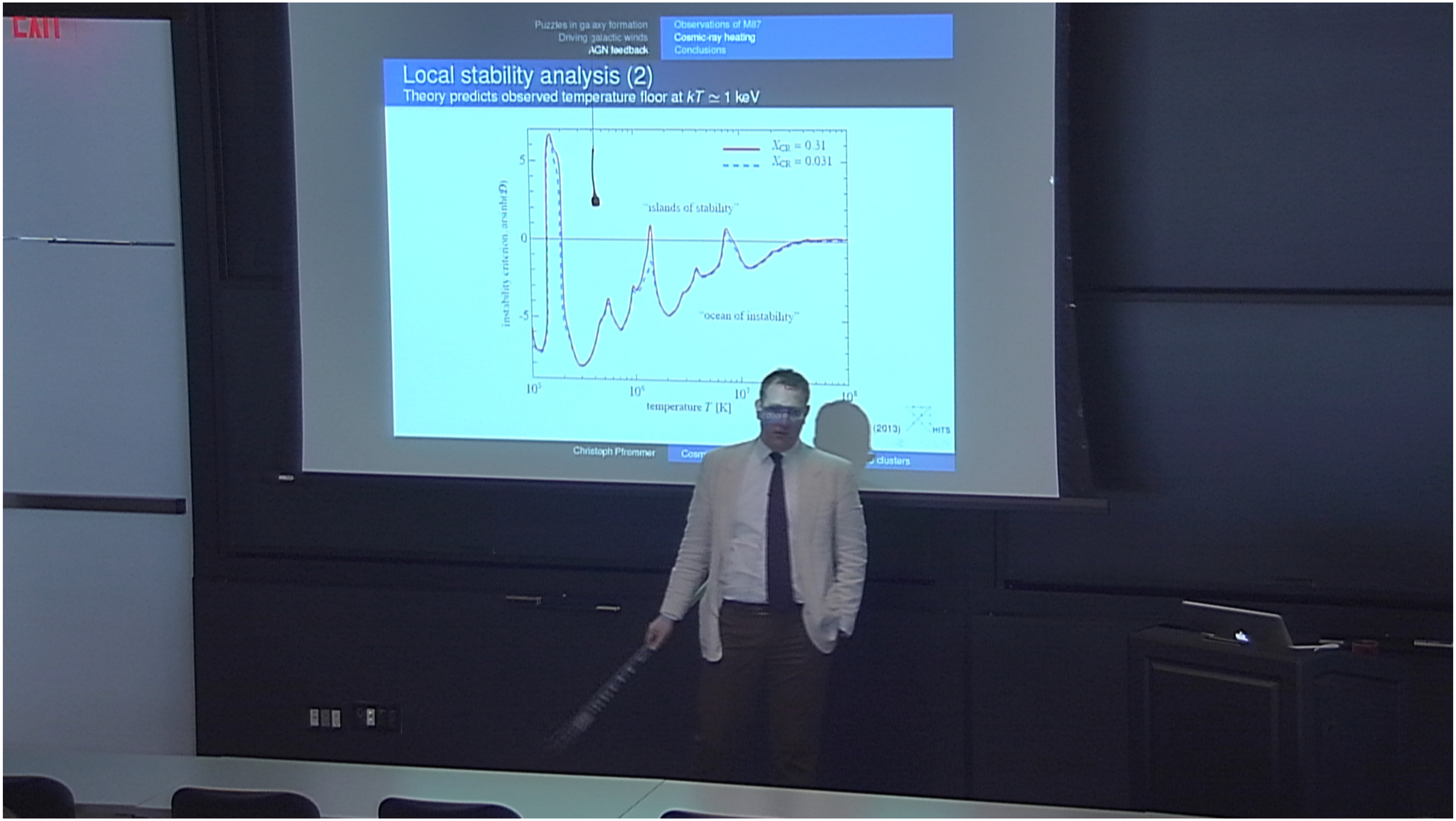

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Local stability analysis (2)

Theory predicts observed temperature floor at $kT \simeq 1$ keV

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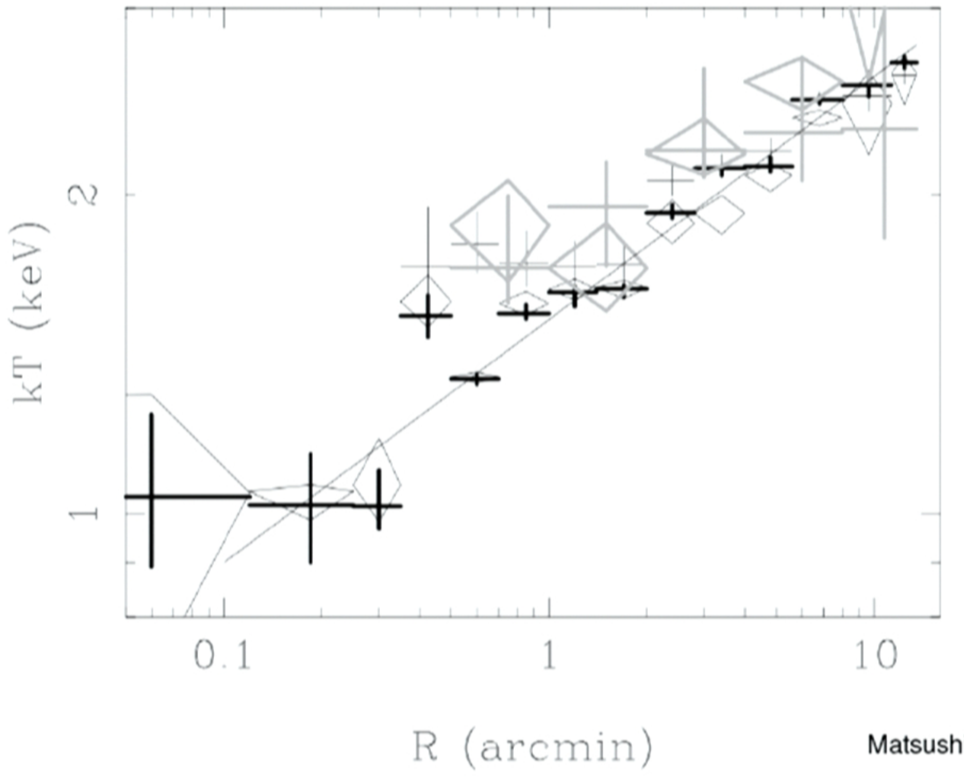
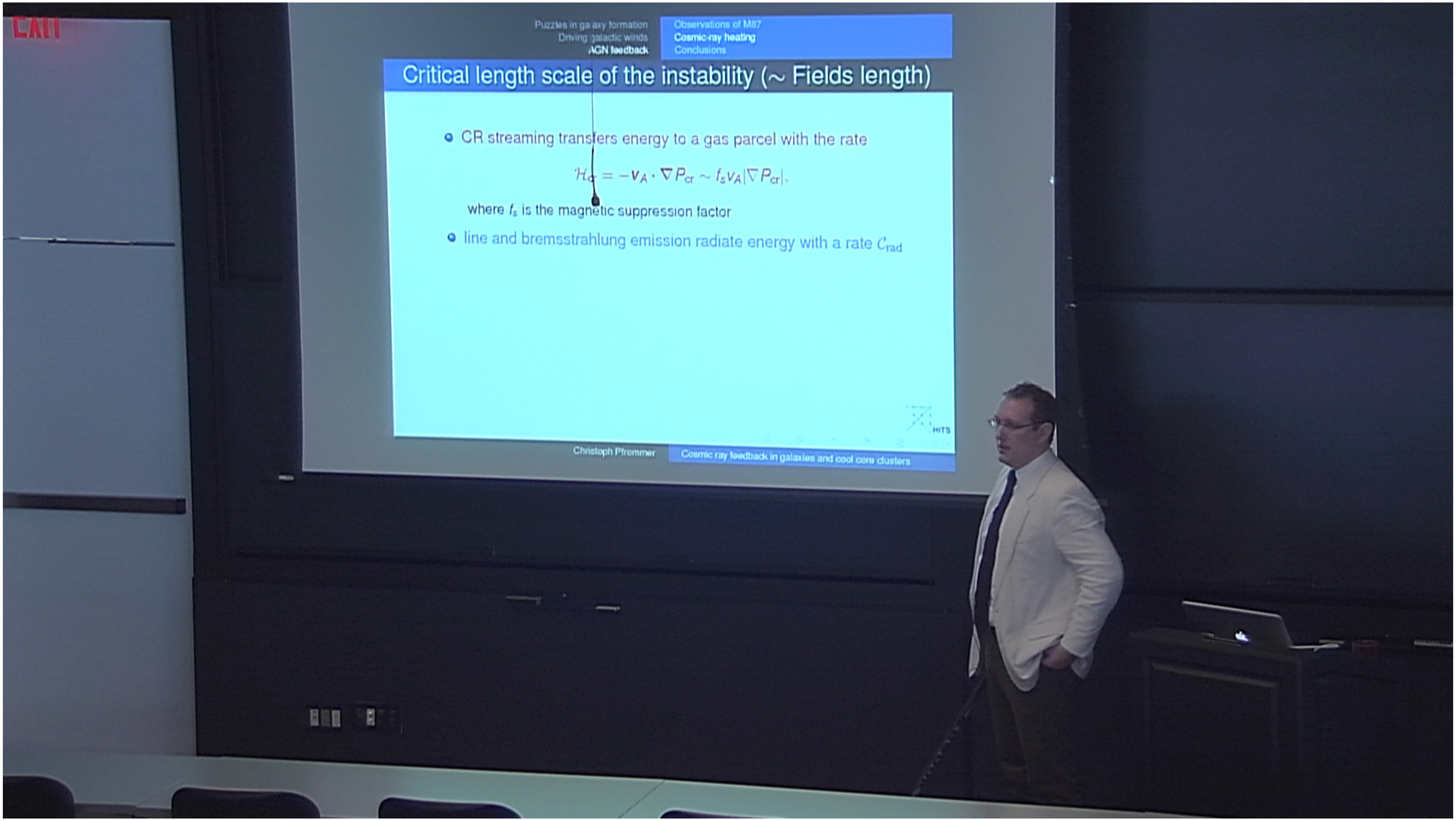
Virgo cluster cooling flow: temperature profile

X-ray observations confirm temperature floor at $kT \simeq 1$ keV



Matsushita+ (2002)



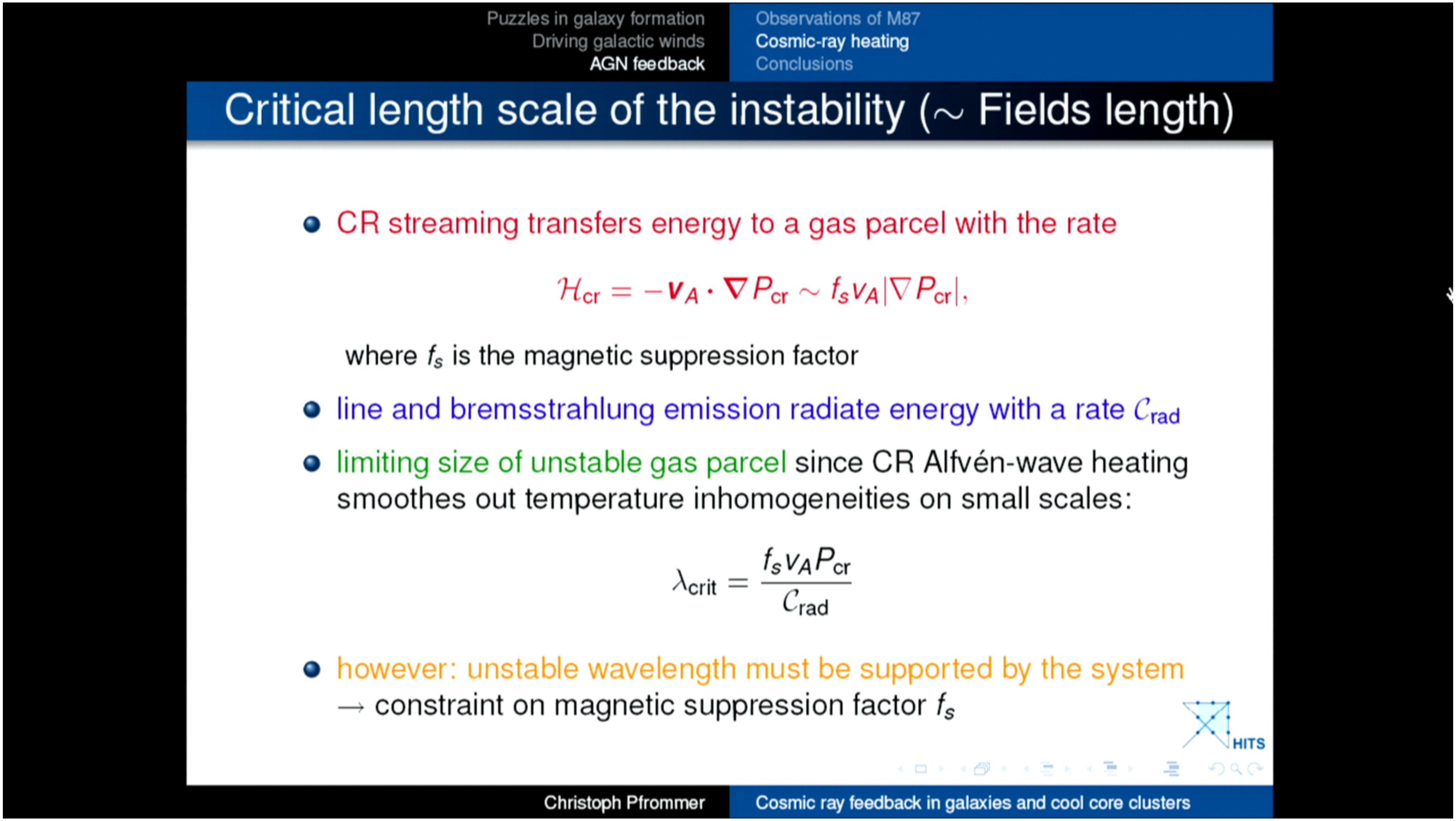
Critical length scale of the instability (∼ Fields length)

- CR streaming transfers energy to a gas parcel with the rate

$$\mathcal{H}_{\mathrm{cr}} = -\boldsymbol{v}_A \cdot \nabla P_{\mathrm{cr}} \sim f_s v_A |\nabla P_{\mathrm{cr}}|,$$

where f_s is the magnetic suppression factor

- line and bremsstrahlung emission radiate energy with a rate $\mathcal{C}_{\mathrm{rad}}$



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- line and bremsstrahlung emission radiate energy with a rate $\mathcal{C}_{\mathrm{rad}}$
- limiting size of unstable gas parcel since CR Alfvén-wave heating smoothes out temperature inhomogeneities on small scales:

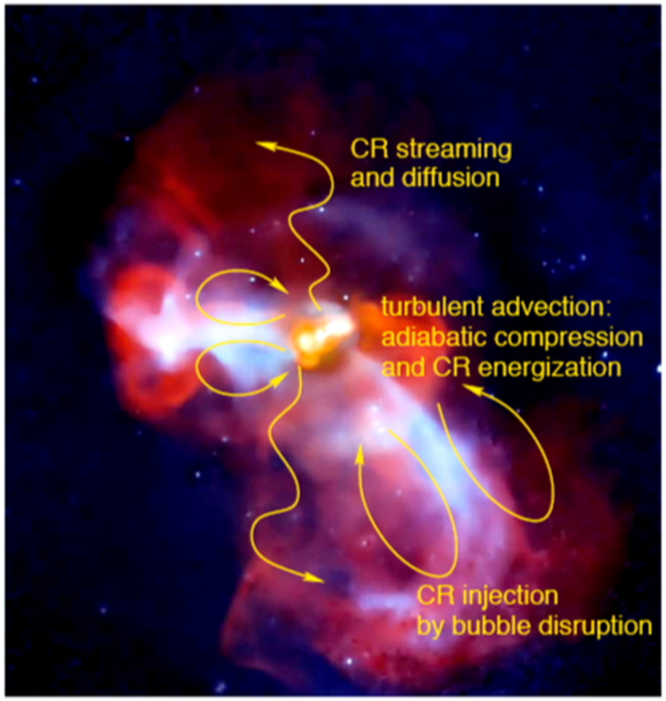
$$\lambda_{\mathrm{crit}} = \frac{f_s v_A P_{\mathrm{cr}}}{\mathcal{C}_{\mathrm{rad}}}$$

- however: unstable wavelength must be supported by the system
$\rightarrow$ constraint on magnetic suppression factor f_s

HITS

Emerging picture of CR feedback by AGNs

(1) during buoyant rise of bubbles: CRs diffuse and stream outward
→ CR Alfvén-wave heating

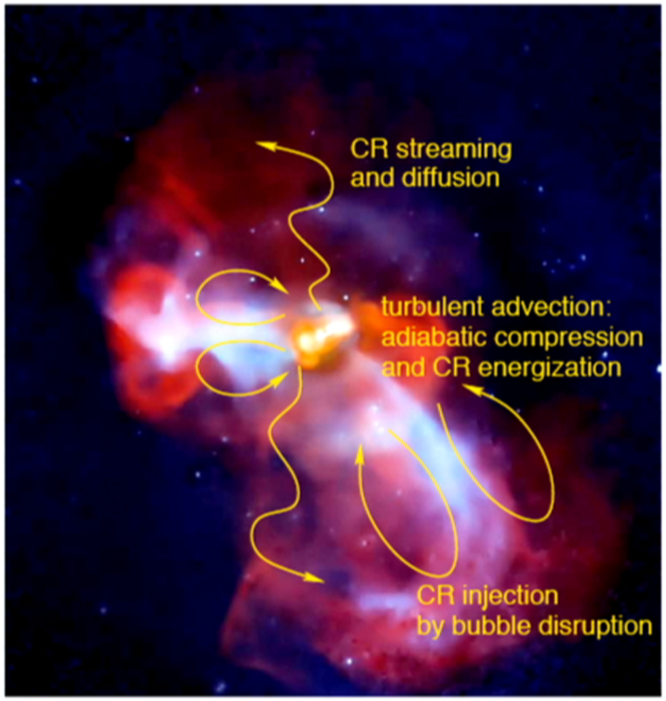


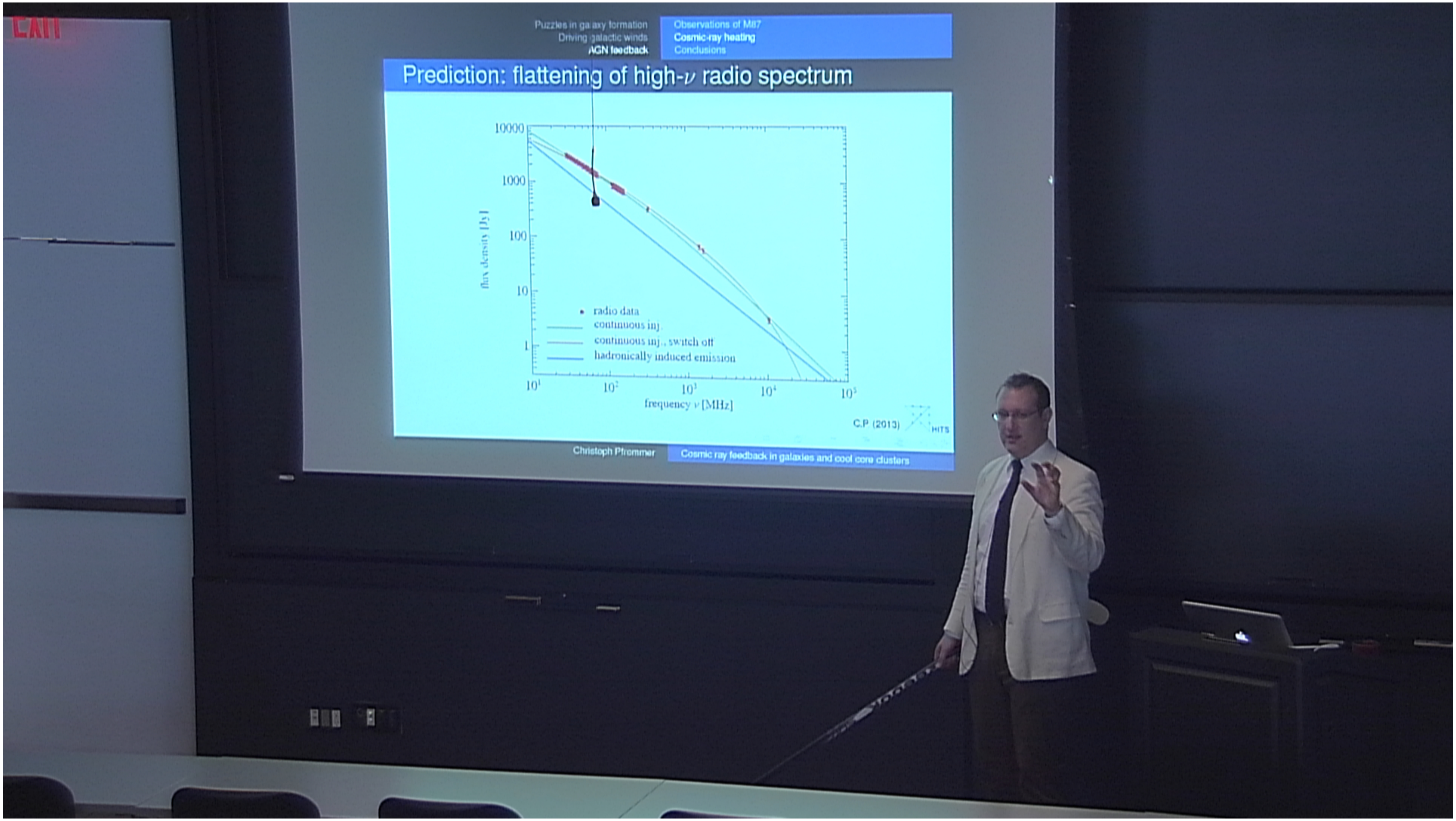
Emerging picture of CR feedback by AGNs

(1) during buoyant rise of bubbles: CRs diffuse and stream outward
→ CR Alfvén-wave heating

(2) if bubbles are disrupted, CRs are injected into the ICM and caught in a turbulent downdraft that is excited by the rising bubbles
→ CR advection with flux-frozen field
→ adiabatic CR compression and energizing: $P_{\mathrm{cr}}/P_{\mathrm{cr},0} = \delta^{4/3} \sim 20$ for compression factor $\delta = 10$

(3) CR escape and outward streaming → CR Alfvén-wave heating





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Prediction: flattening of high-ν radio spectrum

C.P. (2013)

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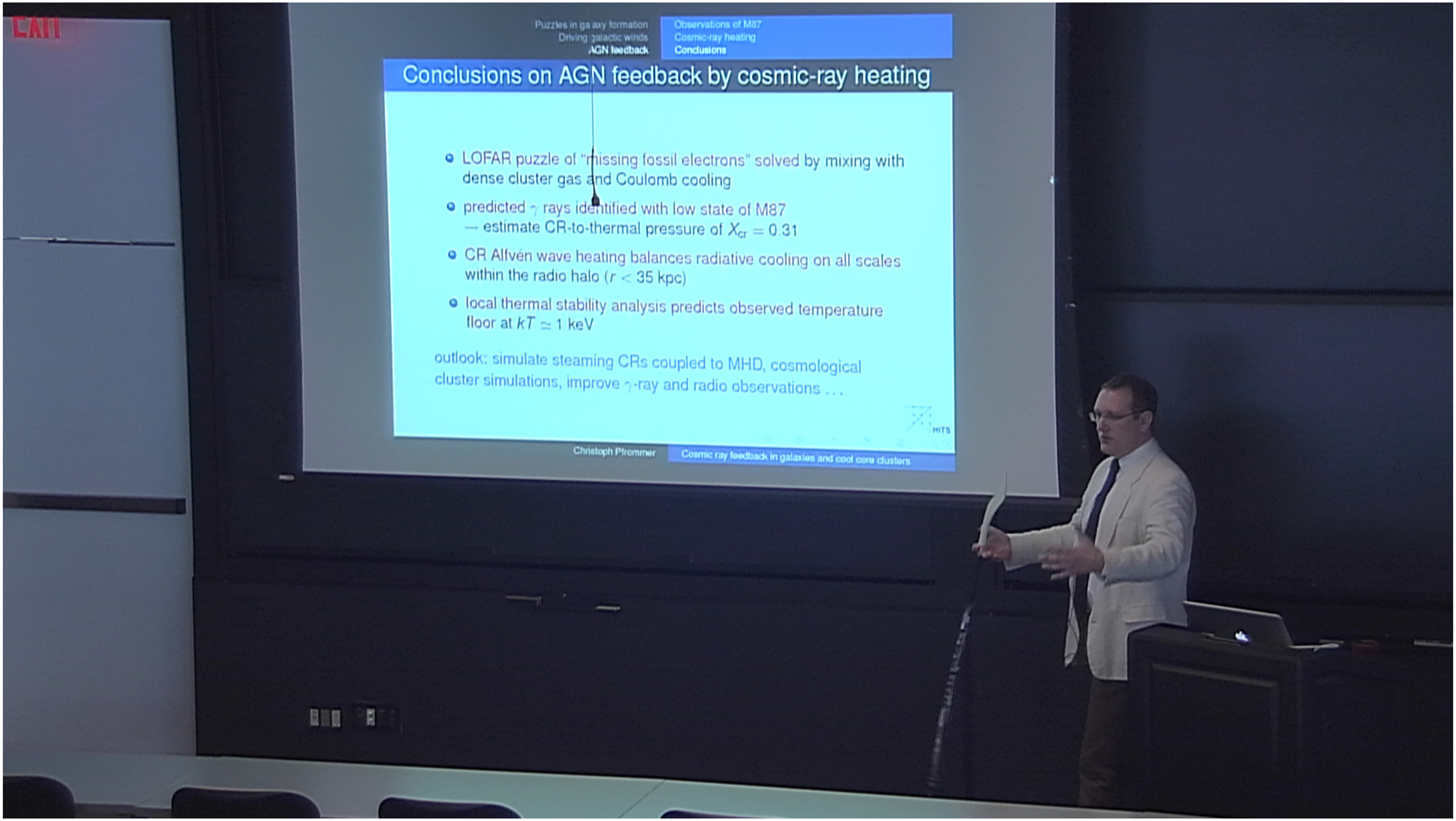

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Conclusions on AGN feedback by cosmic-ray heating

- LOFAR puzzle of "missing fossil electrons" solved by mixing with dense cluster gas and Coulomb cooling
- predicted γ rays identified with low state of M87 → estimate CR-to-thermal pressure of $X_{\mathrm{cr}} = 0.31$
- CR Alfvén wave heating balances radiative cooling on all scales within the radio halo ($r < 35$ kpc)
- local thermal stability analysis predicts observed temperature floor at $kT \simeq 1$ keV

outlook: simulate steaming CRs coupled to MHD, cosmological cluster simulations, improve γ-ray and radio observations ...

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