Title: Gravitational waves and stalled satellites from massive galaxy mergers at z < 1

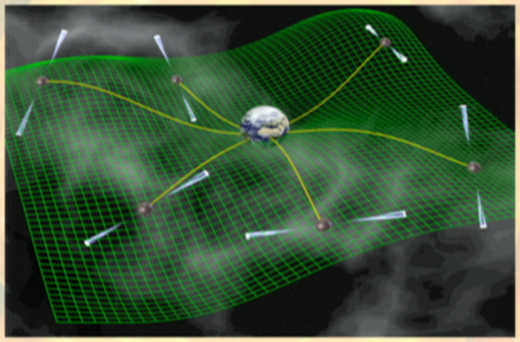
Date: Jul 11, 2013 10:50 AM

URL: http://pirsa.org/13070027

Abstract: Pulsar timing arrays (PTAs), which are currently operating around the world and achieving remarkable sensitivities in the ~1--â€•100 nHz band, will observe supermassive black holes (SMBHs) at redshifts z < ~1. Until now, all estimates of the anticipated signal strength of these sources have relied primarily on simulations to predict the relevant merger rates. I will present results from a completely new approach, which combines observational data and a fully self--â€•consistent numerical evolution of the galaxy mass function. This method, which we will argue is superior to past estimates in several key ways, predicts a merger rate for massive galaxies that is ~10 times larger than that implied by previous calculations. I will explain why previous methods applied to this problem may systematically underestimate this merger rate, and one way in which our method may overestimate the rate, so that our approach has complementary systematic uncertainties in the worst case, and is an overall improvement in the best case. Finally, I will show that the new rate implies a range of possible signal strengths that is already in mild tension with PTA observations, with our model predicting a detection at the 95% confidence level as early as 2016. This could make PTAs the first instruments to directly detect gravitational waves, and will provide unprecedented information about the dynamics of merging galaxies, and merging bulges and supermassive black holes within those galaxies.

Gravitational waves from massive galaxy mergers at z < 1

Based on STM, J. P. Ostriker, and F. Pretorius, arXiv:1211.5377 [astro-ph.CO]



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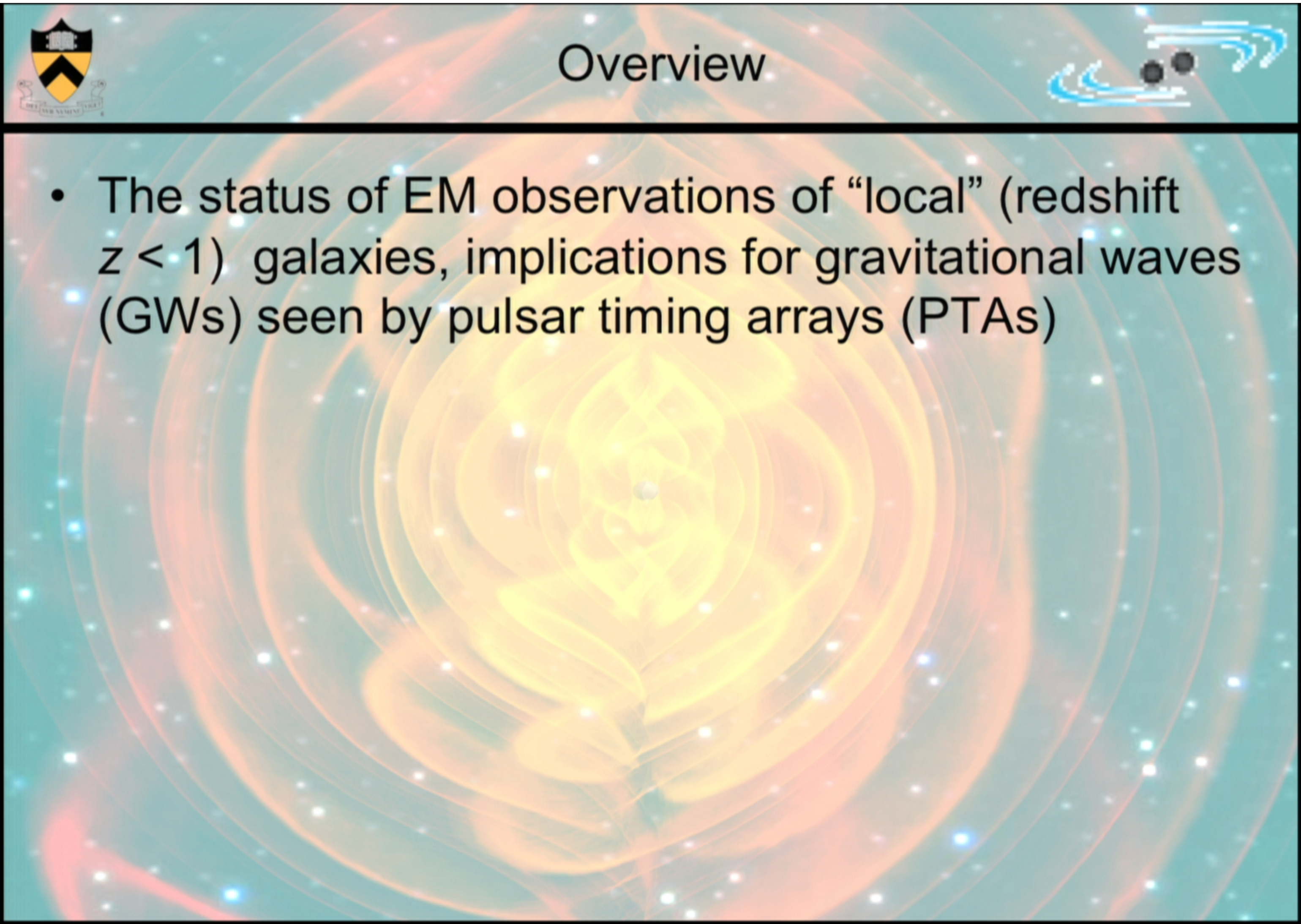
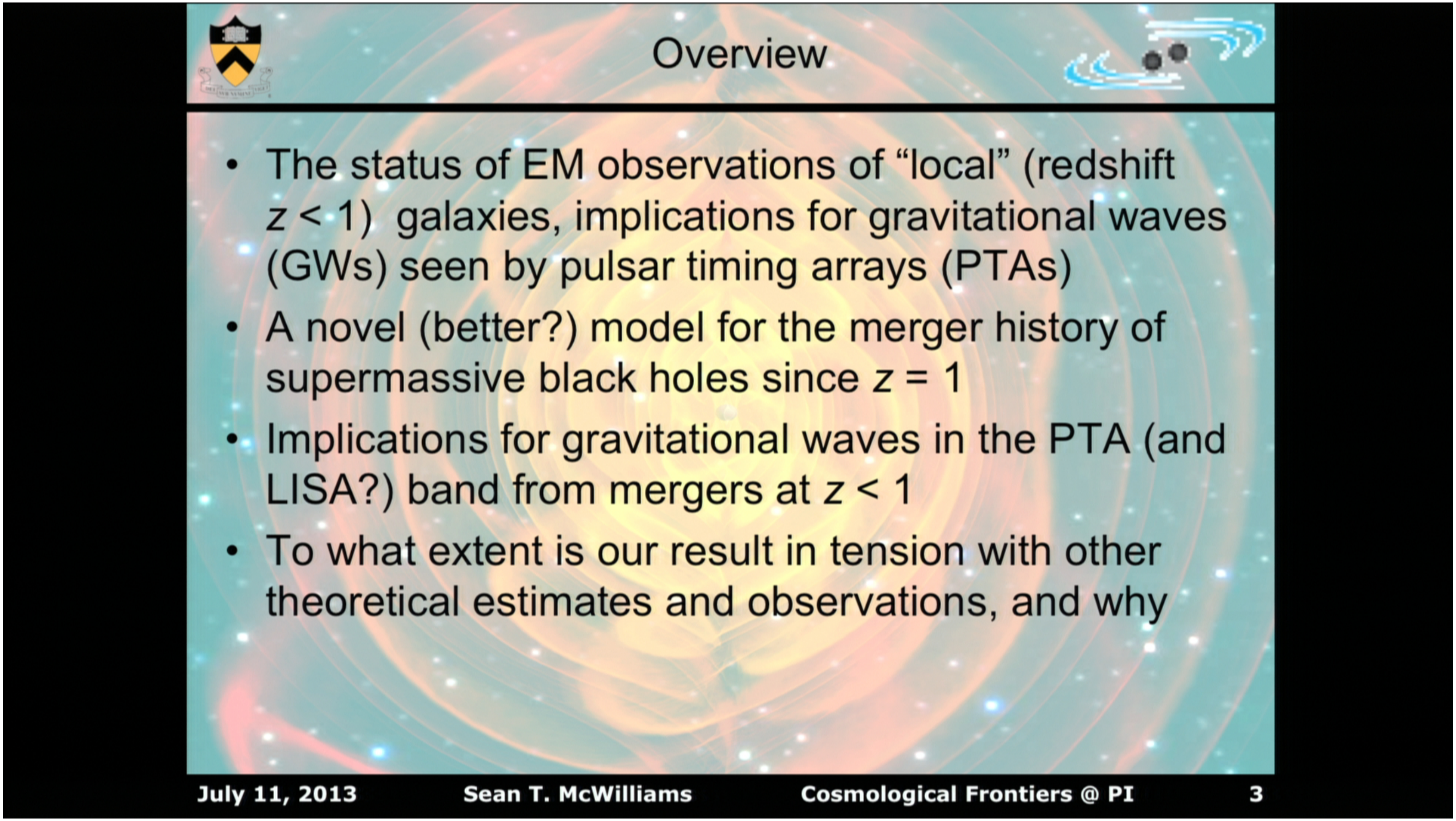
Cosmological Frontiers in Fundamental Physics
Perimeter Institute
July 11, 2013



Overview

- The status of EM observations of “local” (redshift $z < 1$) galaxies, implications for gravitational waves (GWs) seen by pulsar timing arrays (PTAs)



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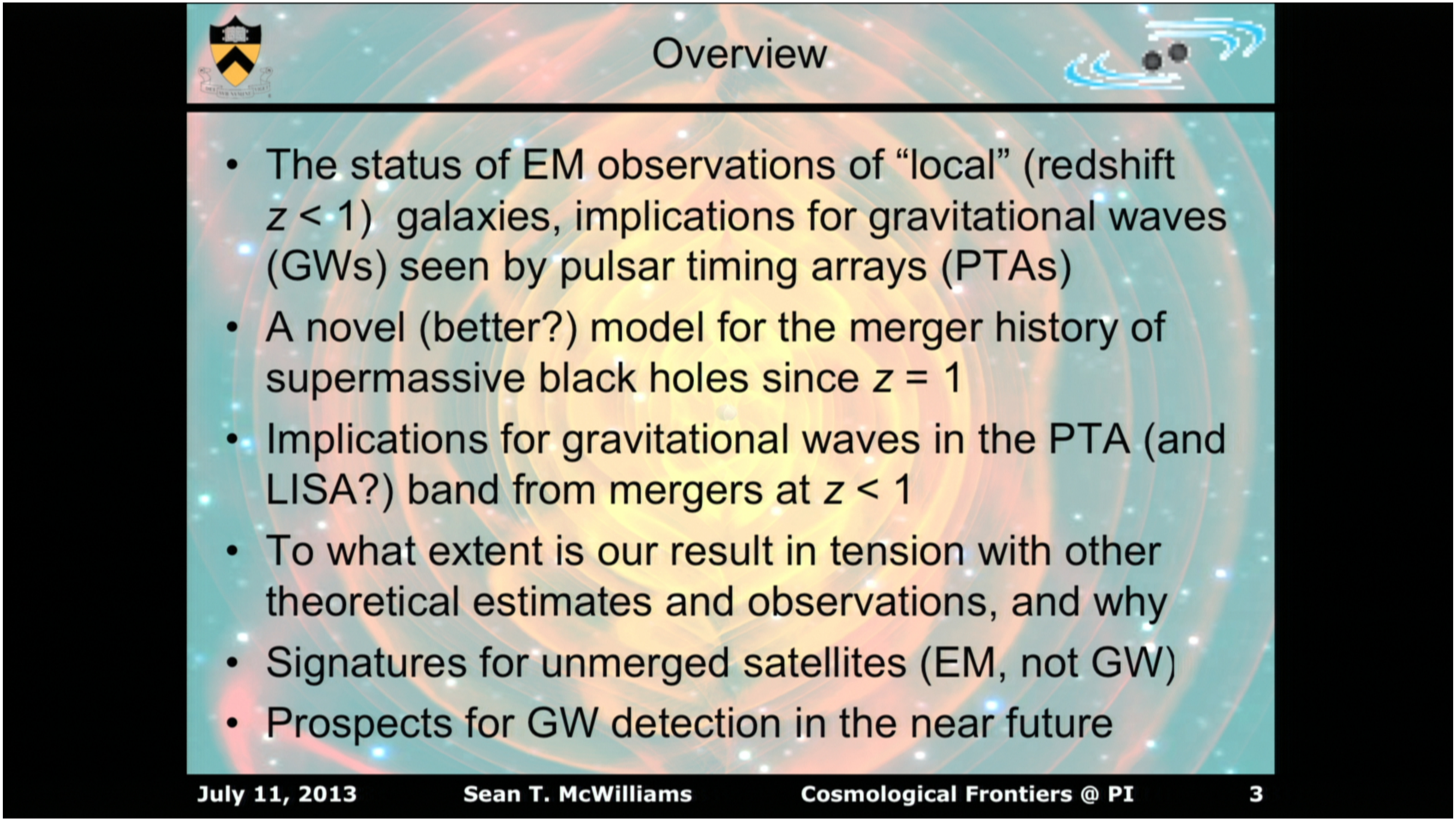
- A novel (better?) model for the merger history of supermassive black holes since $z = 1$
- Implications for gravitational waves in the PTA (and LISA?) band from mergers at $z < 1$
- To what extent is our result in tension with other theoretical estimates and observations, and why



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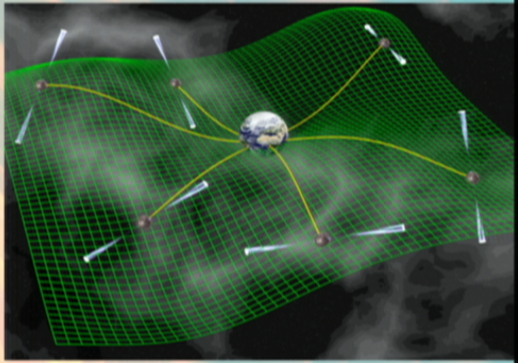
- Signatures for unmerged satellites (EM, not GW)
- Prospects for GW detection in the near future

MBHBs with PTAs

- Current PTAs time ~20 pulsars, search for correlated changes in pulse arrival times due to GWs



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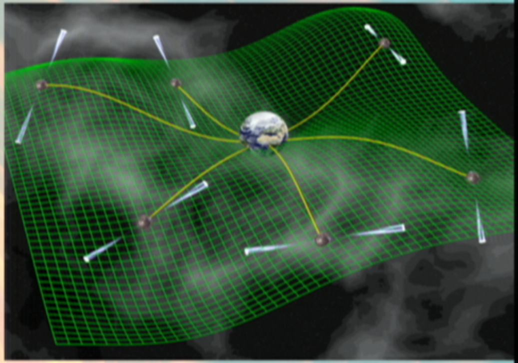

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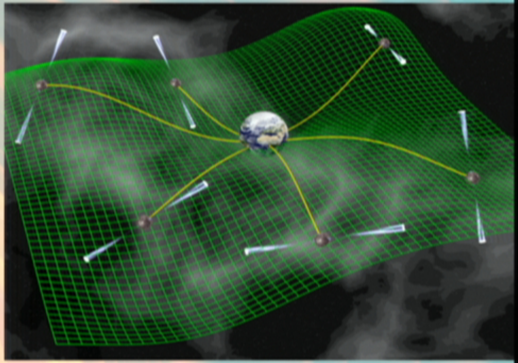
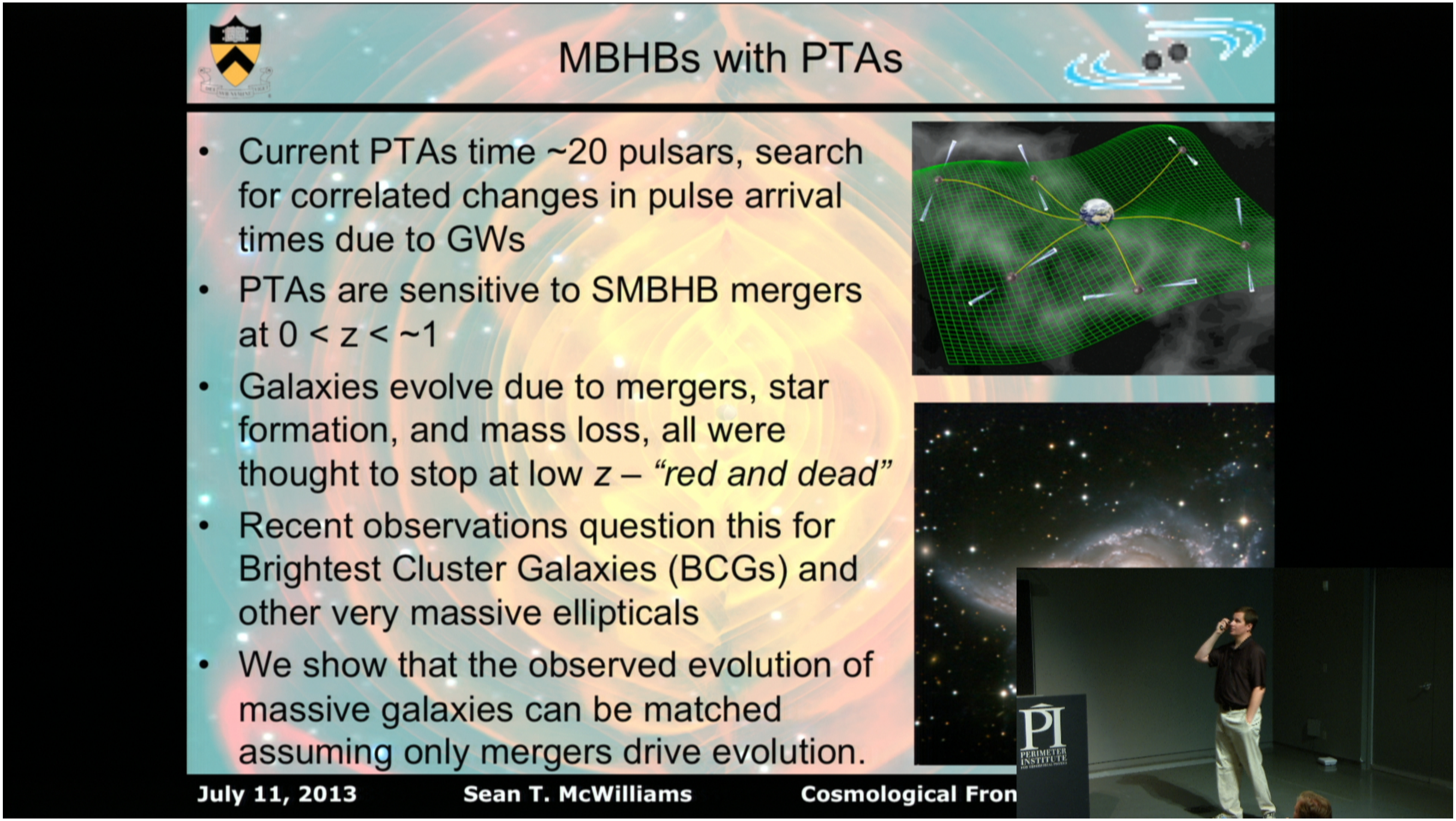
- Recent observations question this for Brightest Cluster Galaxies (BCGs) and other very massive ellipticals





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- Recent observations question this for Brightest Cluster Galaxies (BCGs) and other very massive ellipticals
- We show that the observed evolution of massive galaxies can be matched assuming only mergers drive evolution.

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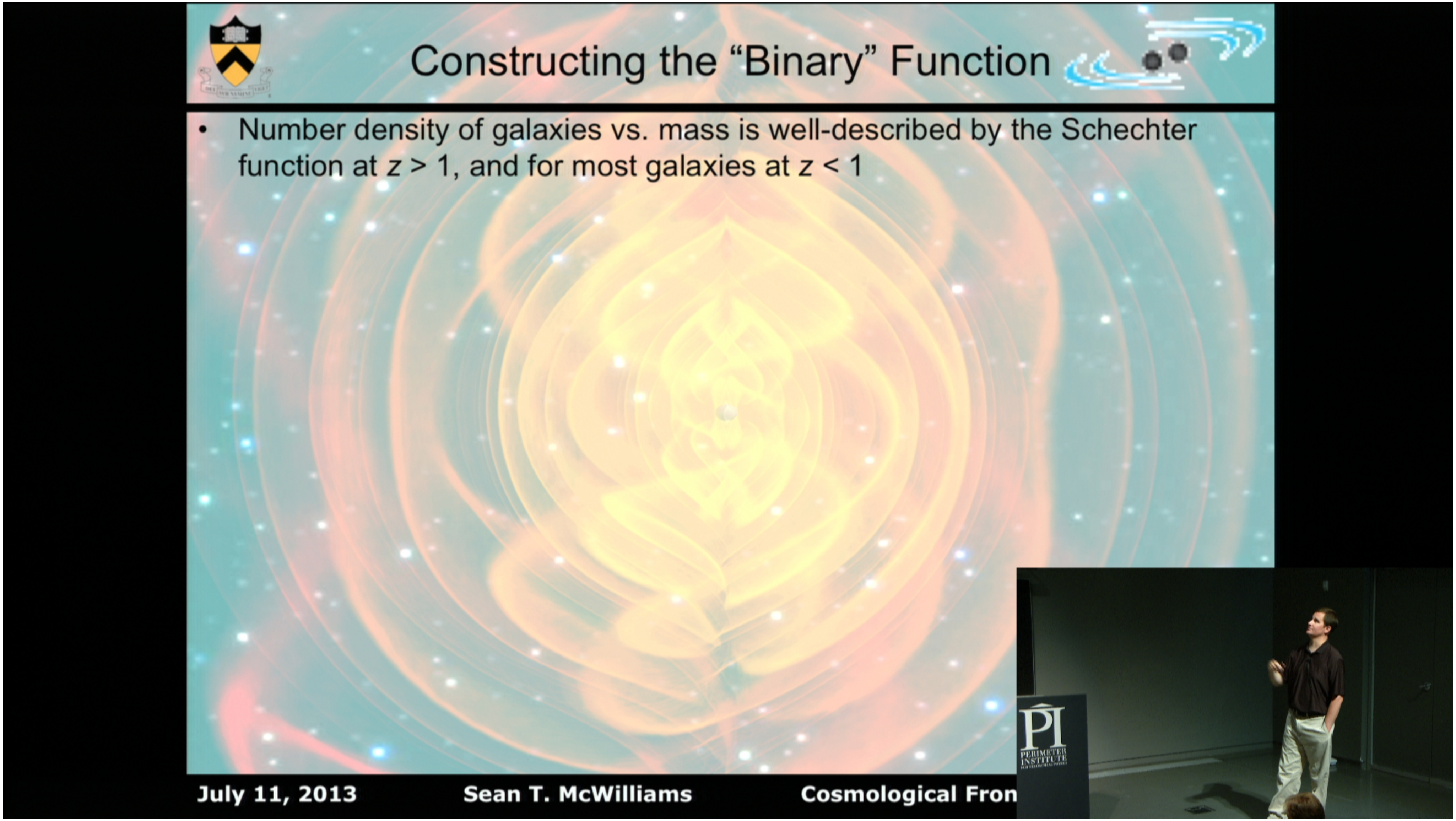

Constructing the “Binary” Function

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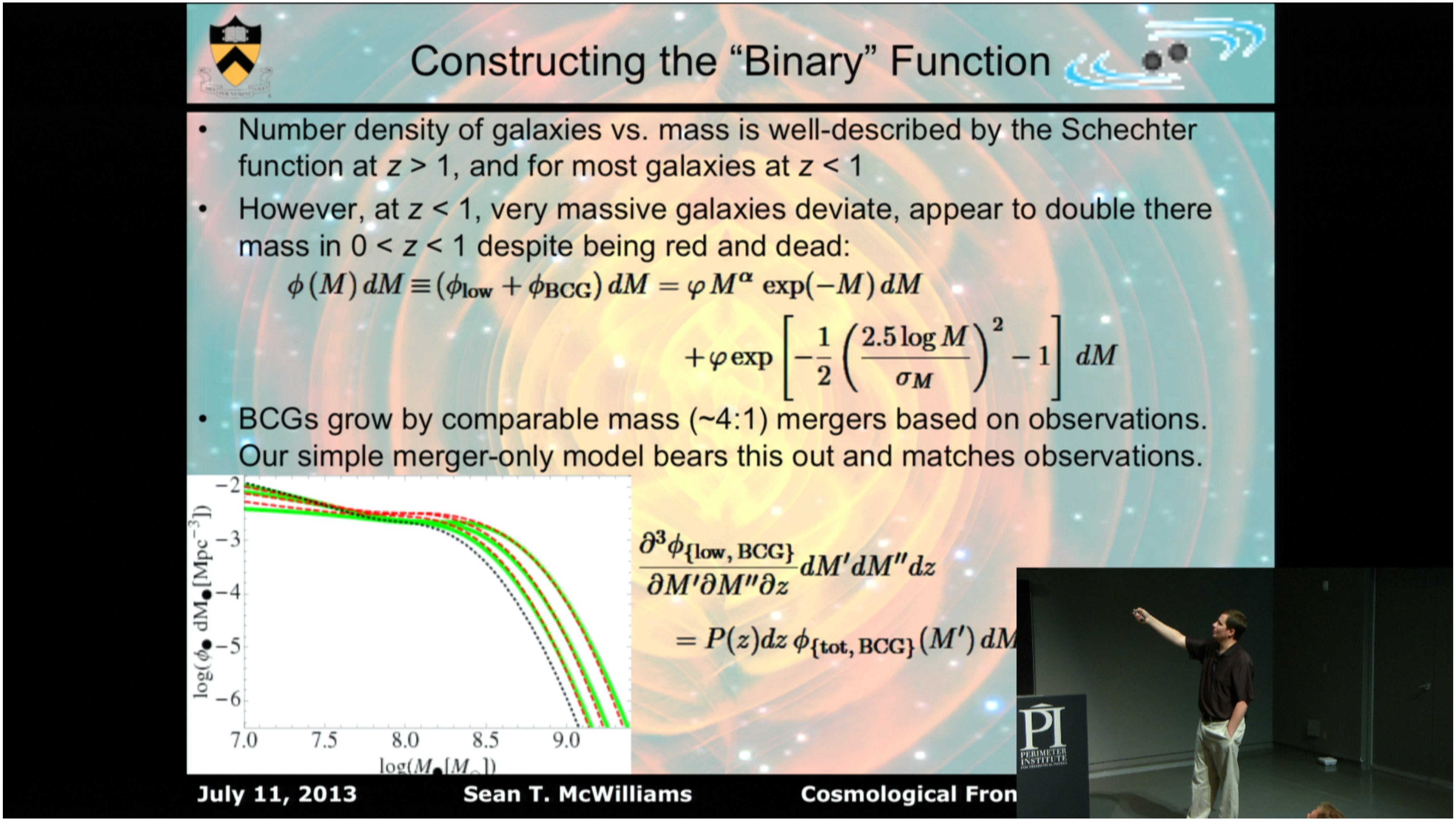

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$$\phi(M)\,dM \equiv (\phi_{\rm low} + \phi_{\rm BCG})\,dM = \varphi\, M^{\alpha}\,\exp(-M)\,dM + \varphi\exp\left[-\frac{1}{2}\left(\frac{2.5\log M}{\sigma_M}\right)^{2} - 1\right] dM$$

- BCGs grow by comparable mass (~4:1) mergers based on observations. Our simple merger-only model bears this out and matches observations.

$$\frac{\partial^3\phi_{\{\rm low,\,BCG\}}}{\partial M'\partial M''\partial z}\,dM'dM''dz = P(z)dz\,\phi_{\{\rm tot,\,BCG\}}(M')\,dM$$

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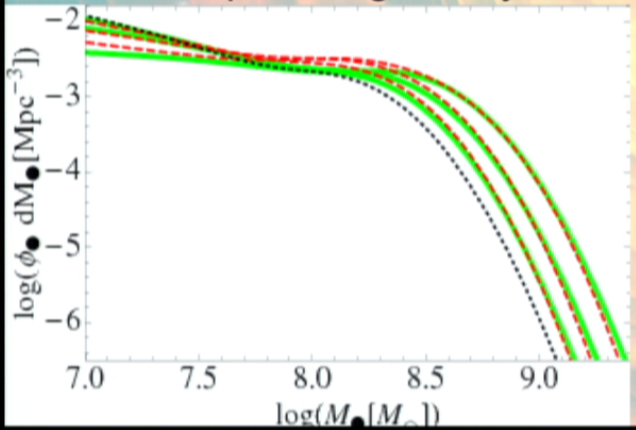
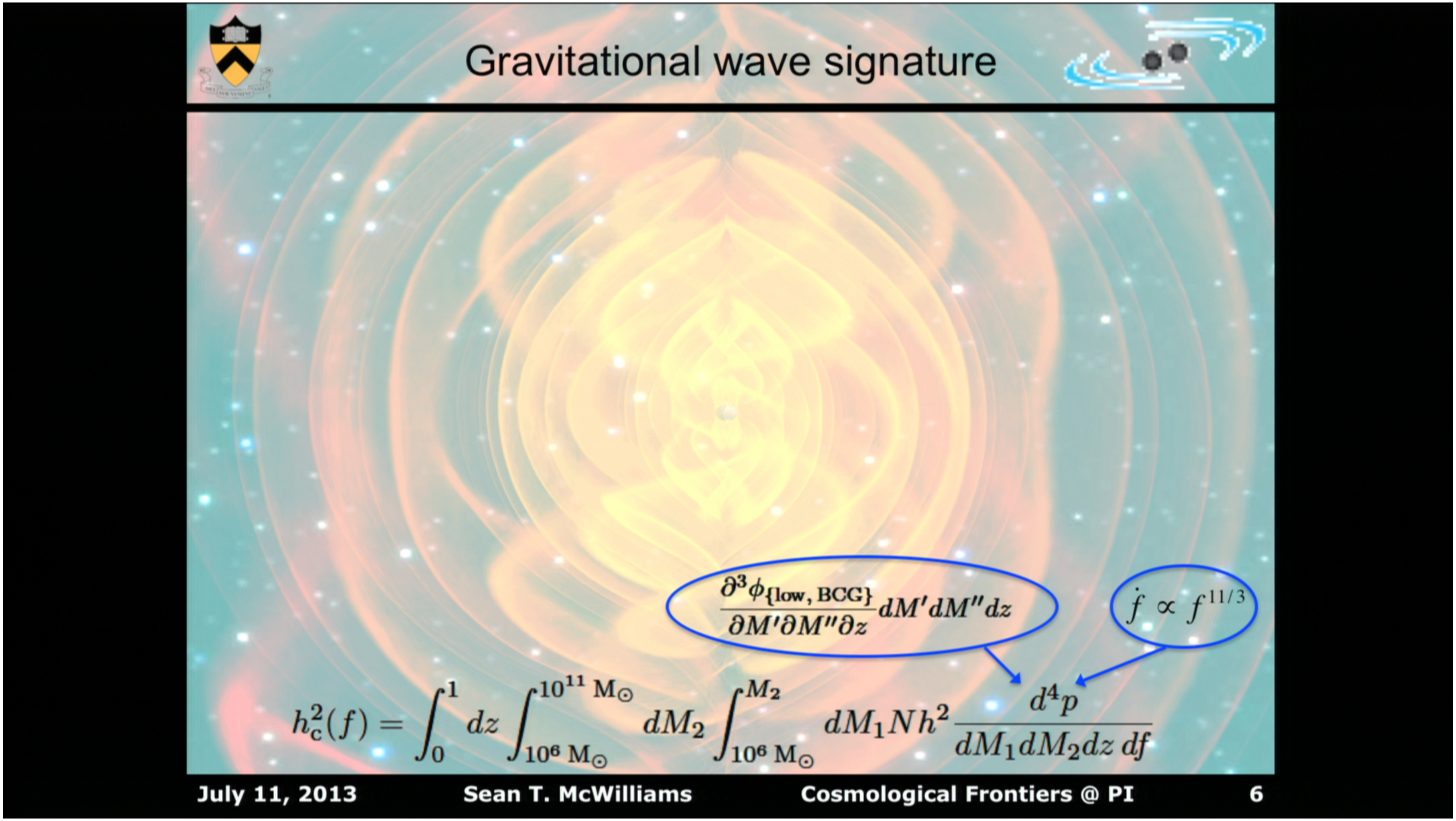


$$\frac{\partial^3 \phi_{\{\rm low,\,BCG\}}}{\partial M' \partial M'' \partial z}\, dM'\, dM''\, dz = P(z)\,dz\, \phi_{\{\rm tot,\,BCG\}}(M')\, dM'\, \phi_{\{\rm tot,\,low\}}(M'')\, dM''$$

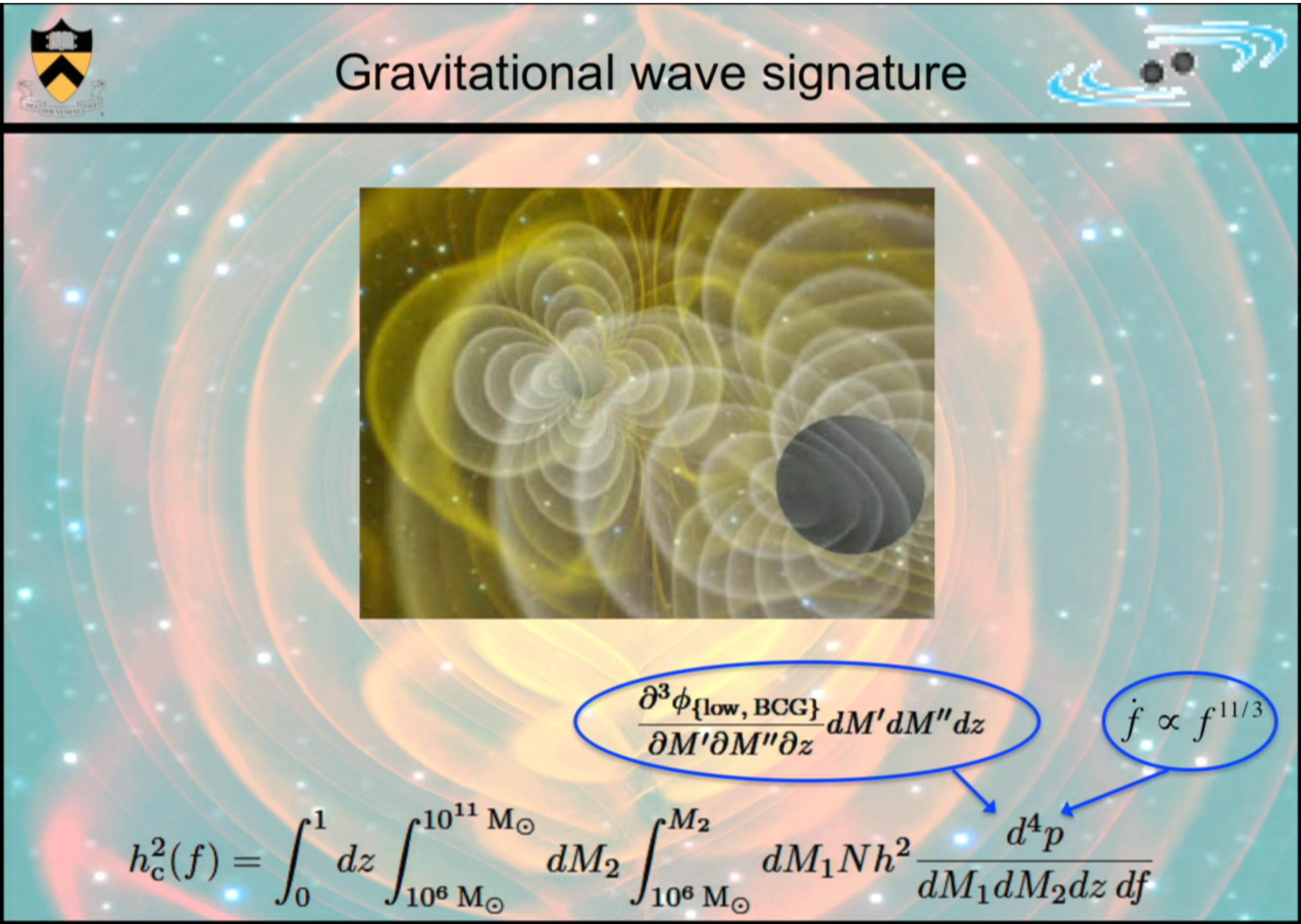


Gravitational wave signature

$$\frac{\partial^3 \phi_{\{\mathrm{low},\,\mathrm{BCG}\}}}{\partial M' \partial M'' \partial z} dM' dM'' dz$$

$$\dot{f} \propto f^{11/3}$$

$$h_c^2(f) = \int_0^1 dz \int_{10^6\,\mathrm{M}_\odot}^{10^{11}\,\mathrm{M}_\odot} dM_2 \int_{10^6\,\mathrm{M}_\odot}^{M_2} dM_1 N h^2 \frac{d^4 p}{dM_1 dM_2 dz\, df}$$



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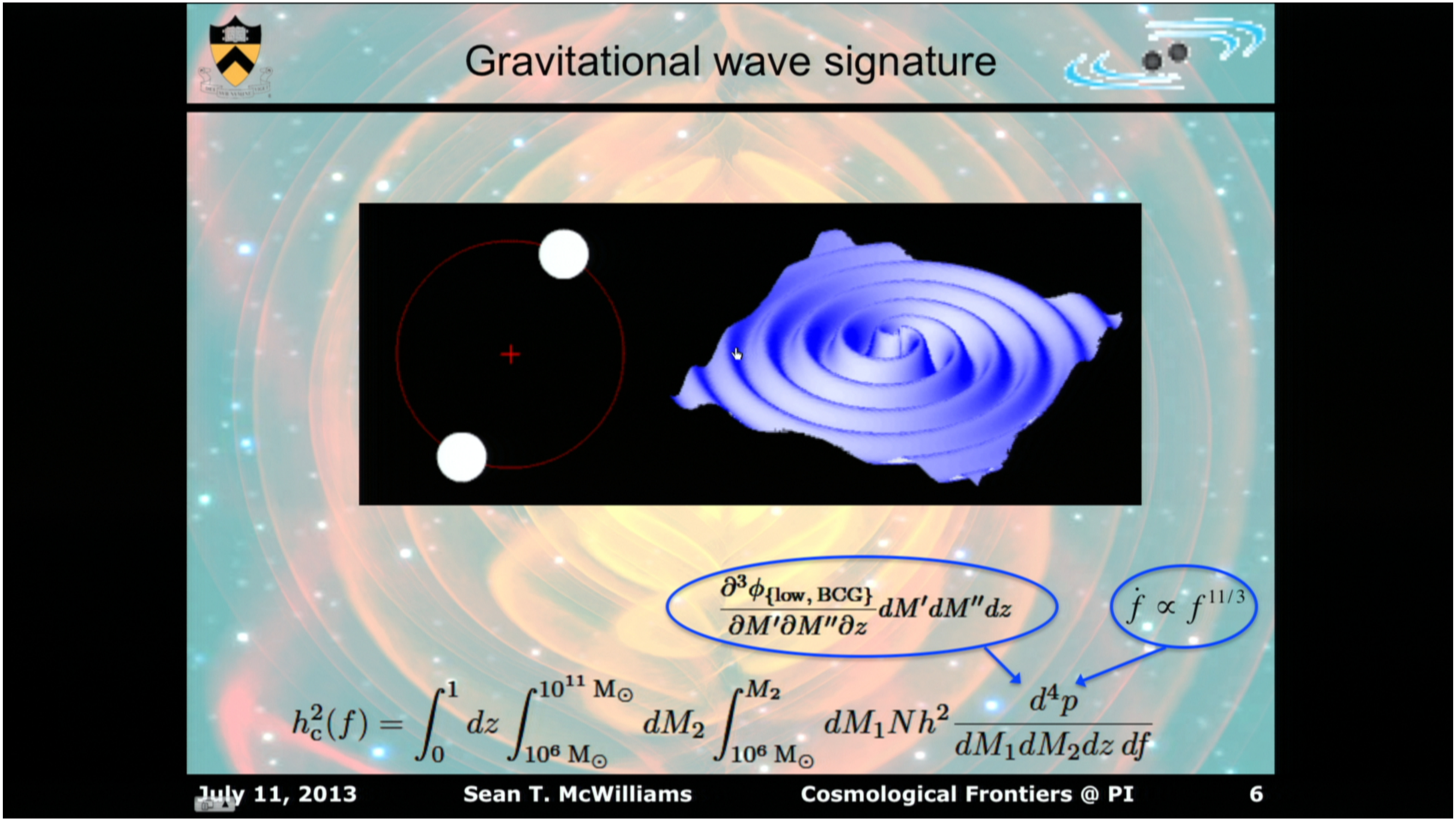

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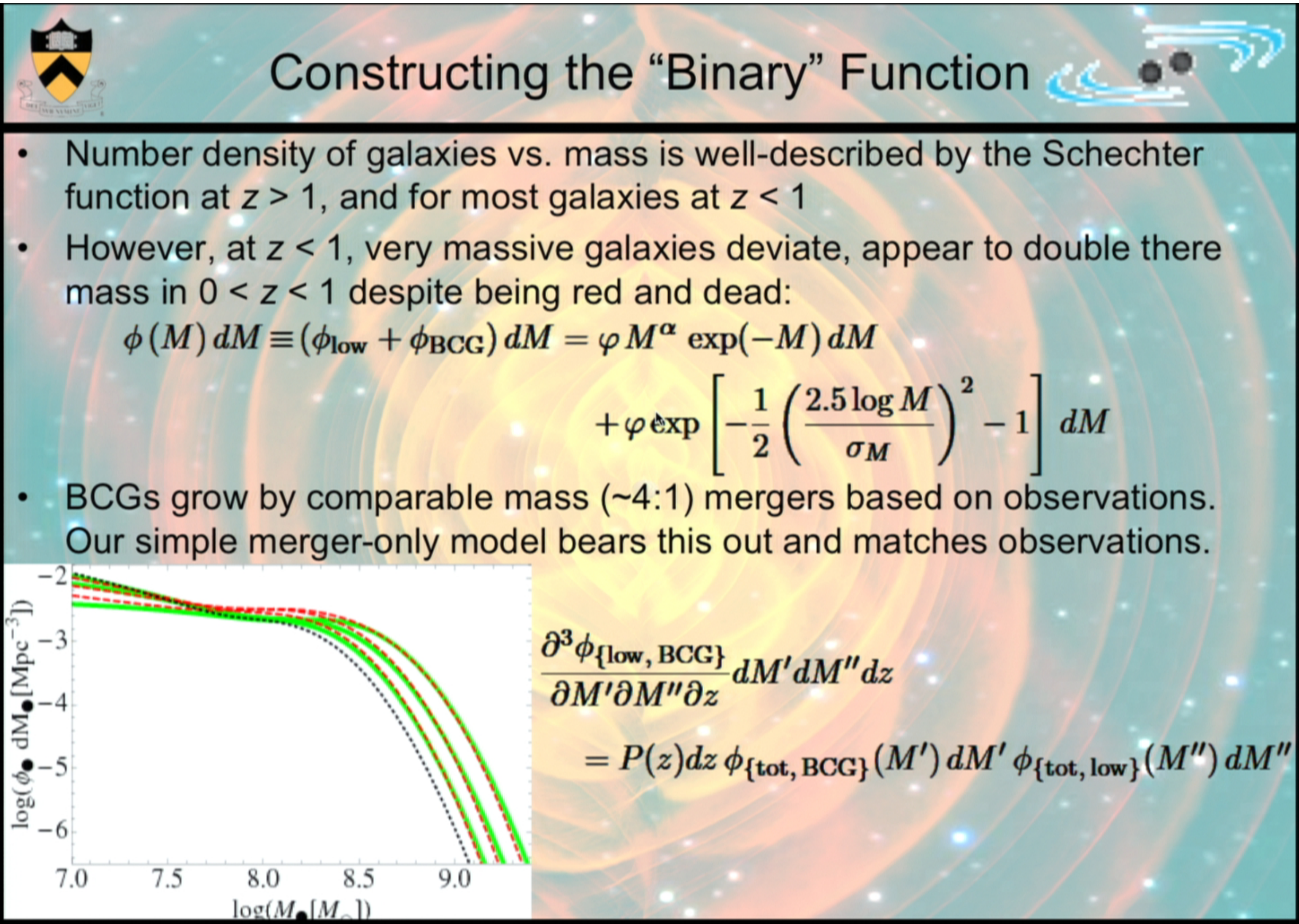

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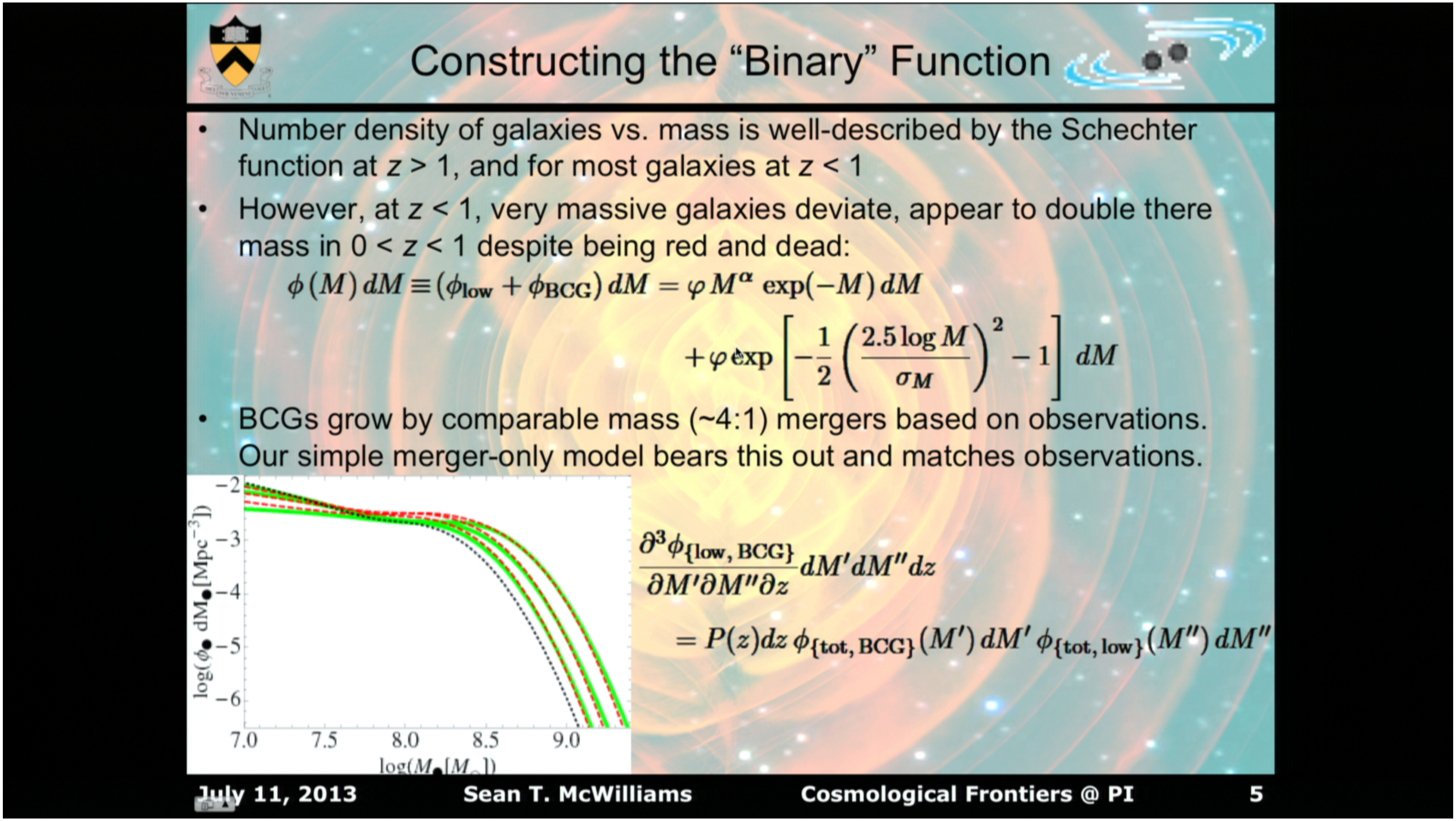

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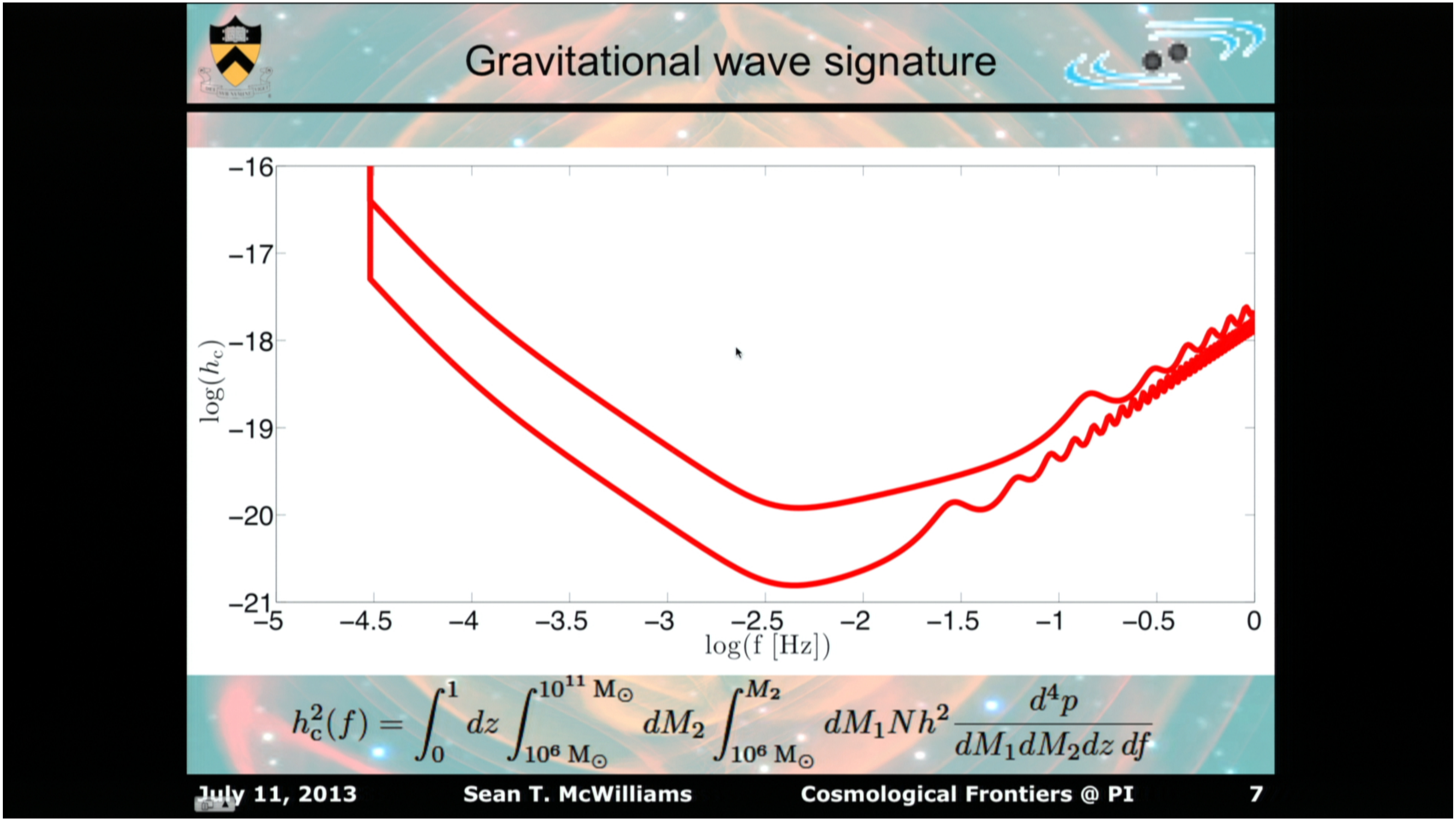

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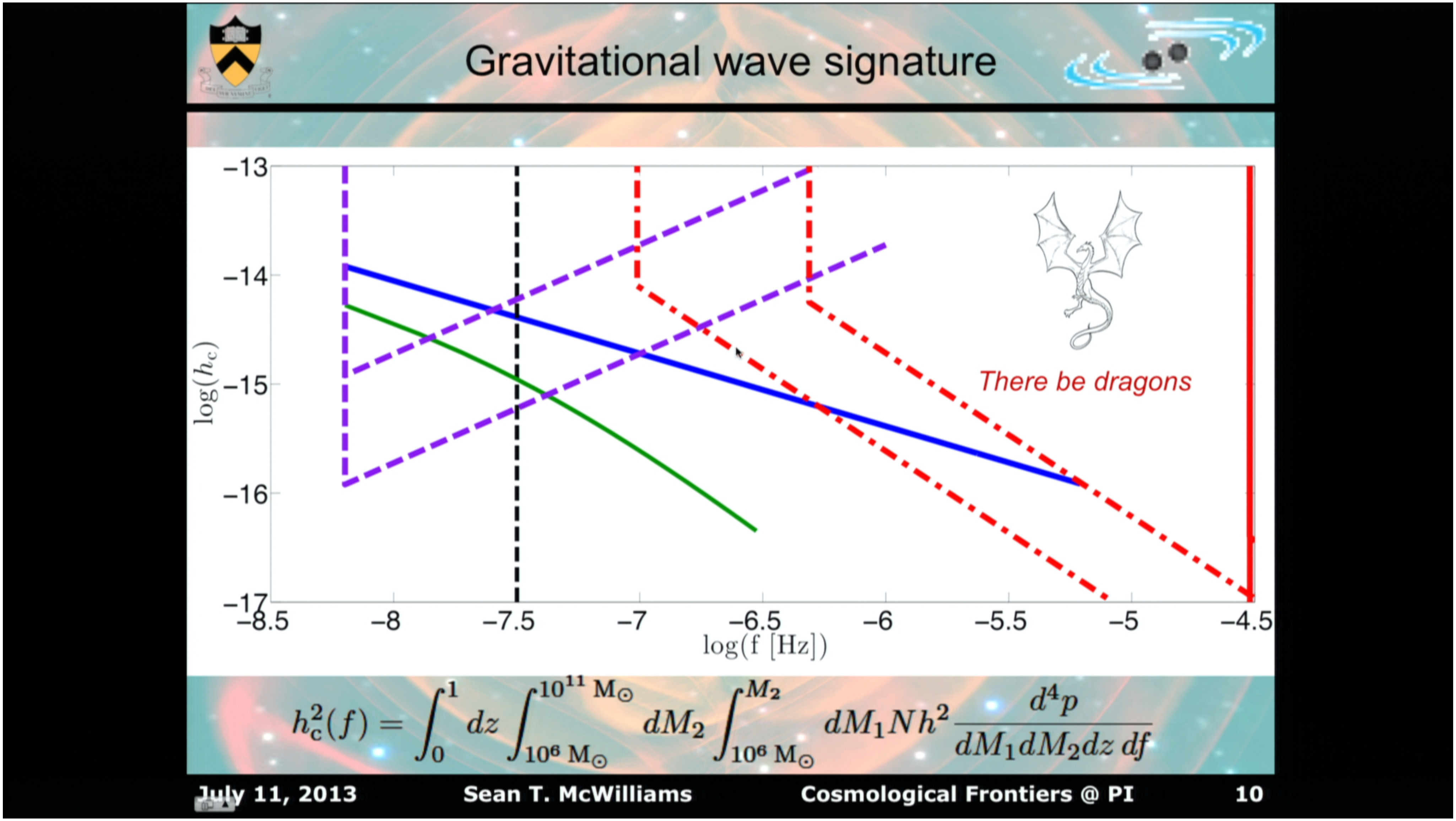

Gravitational wave signature

There be dragons

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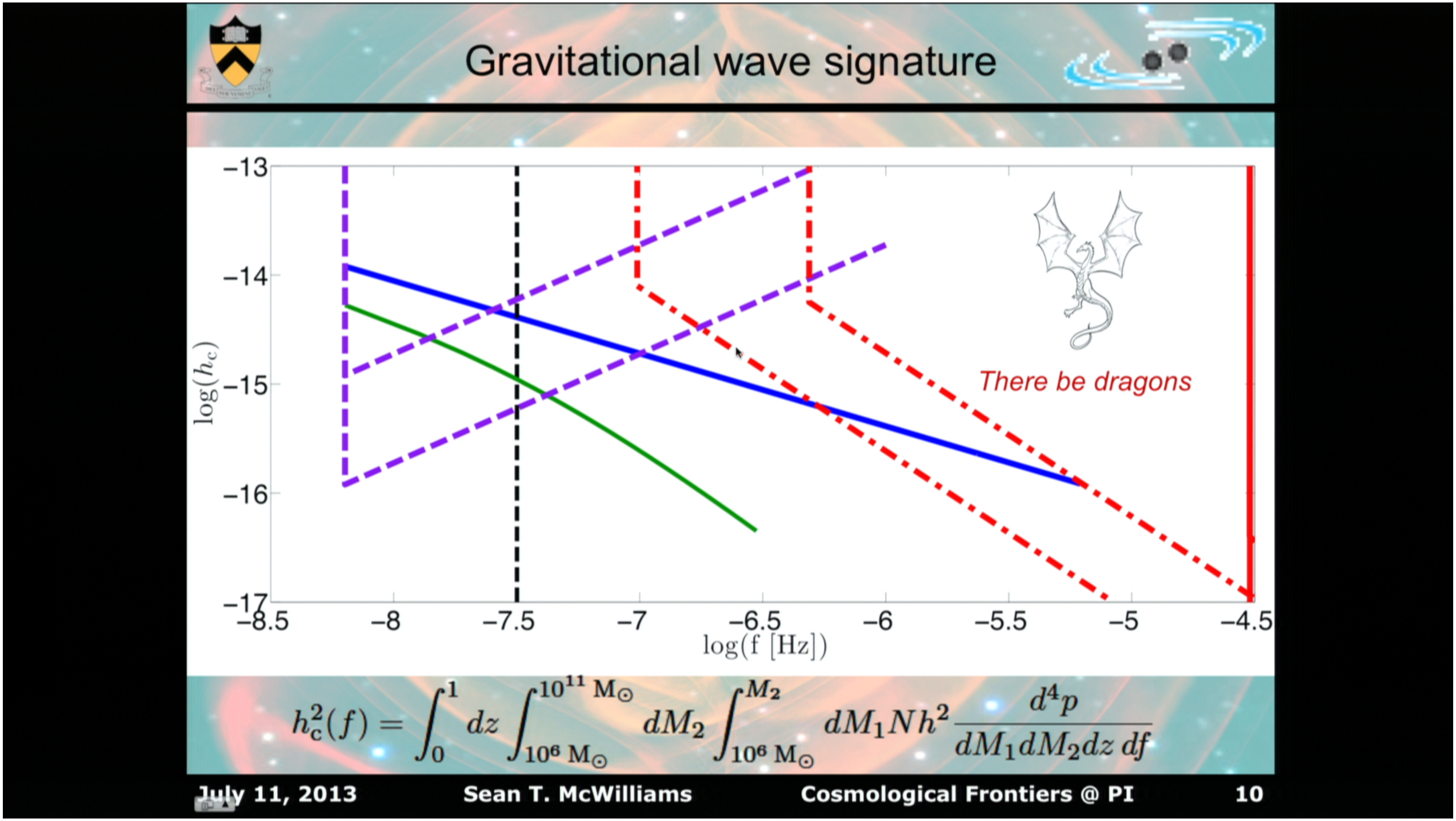

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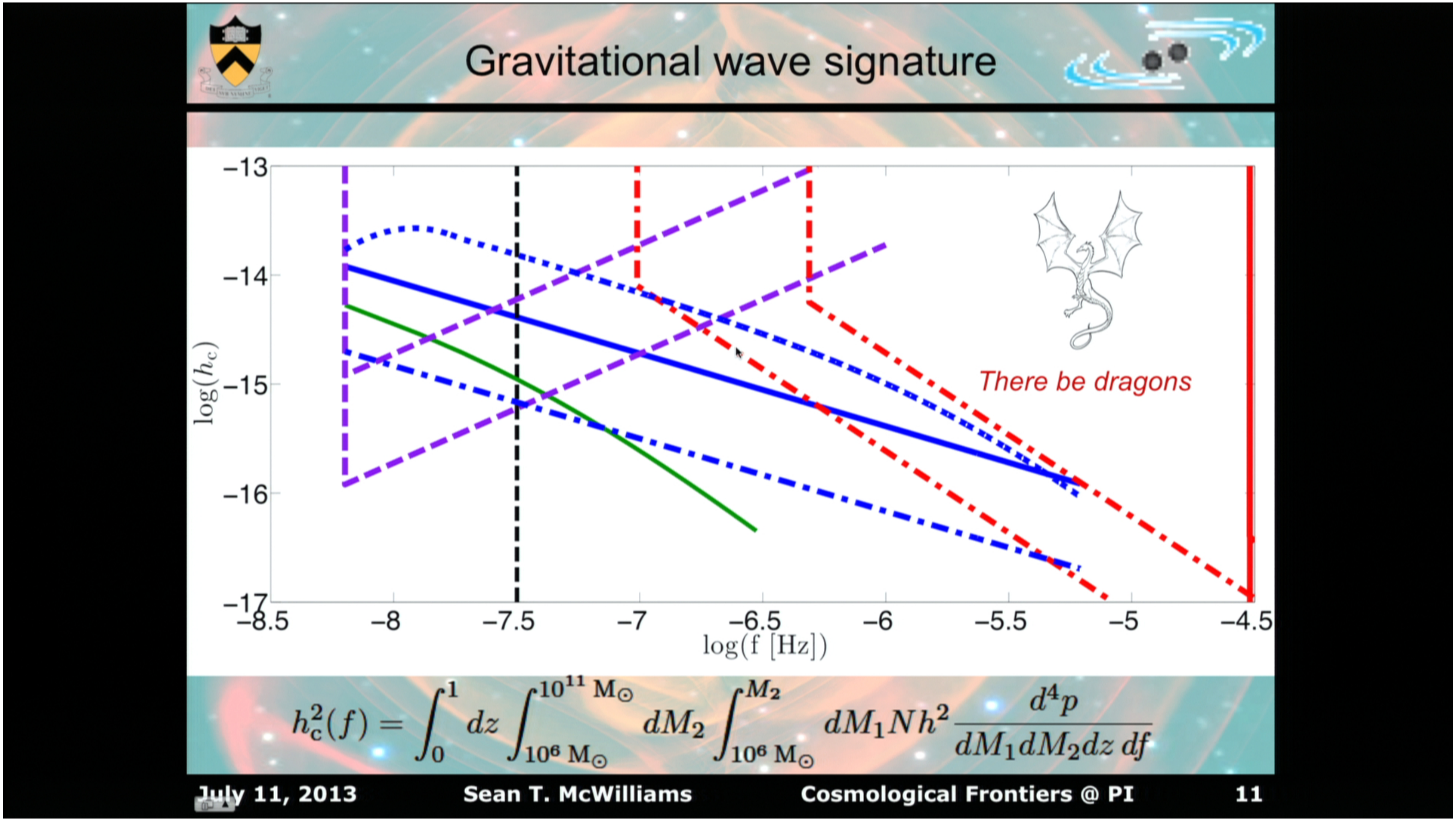

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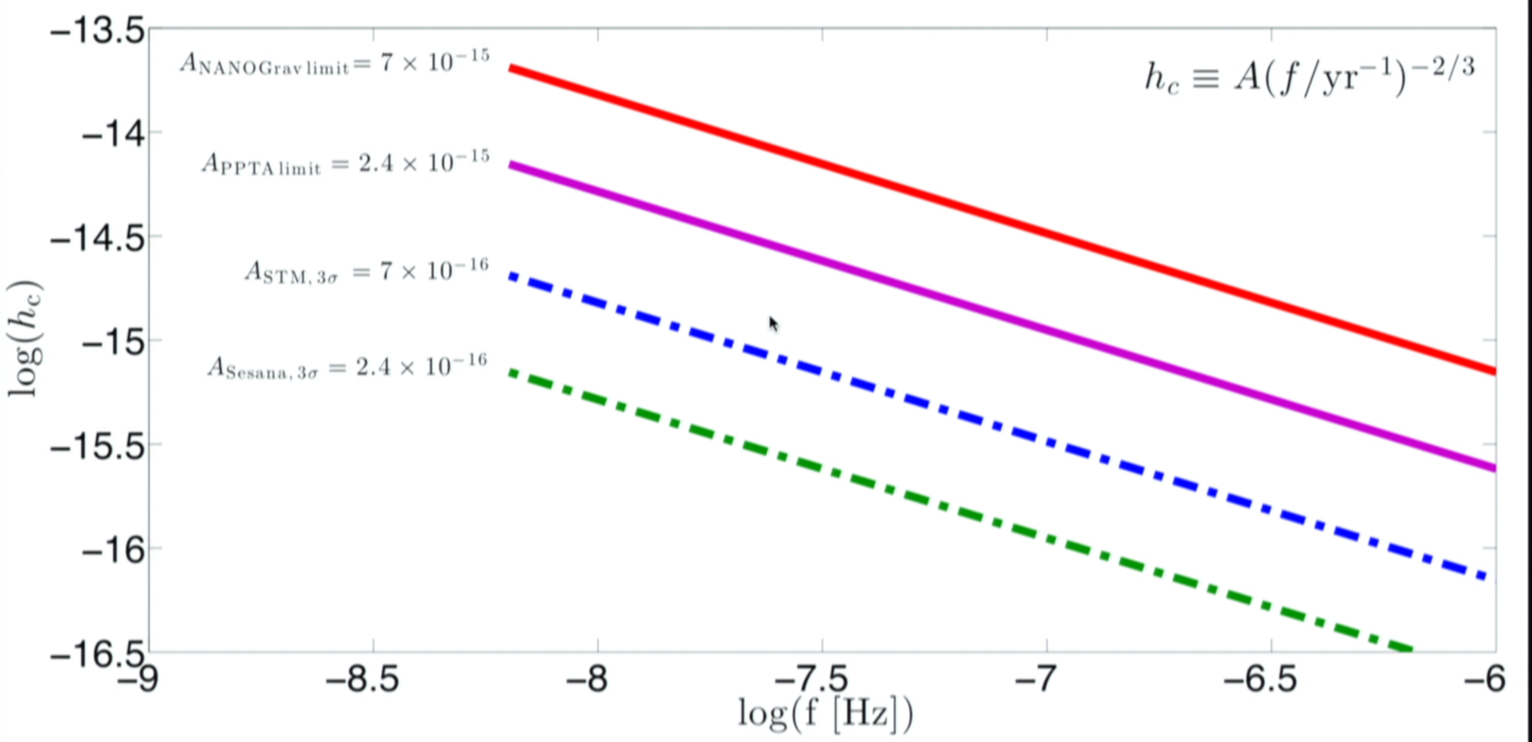
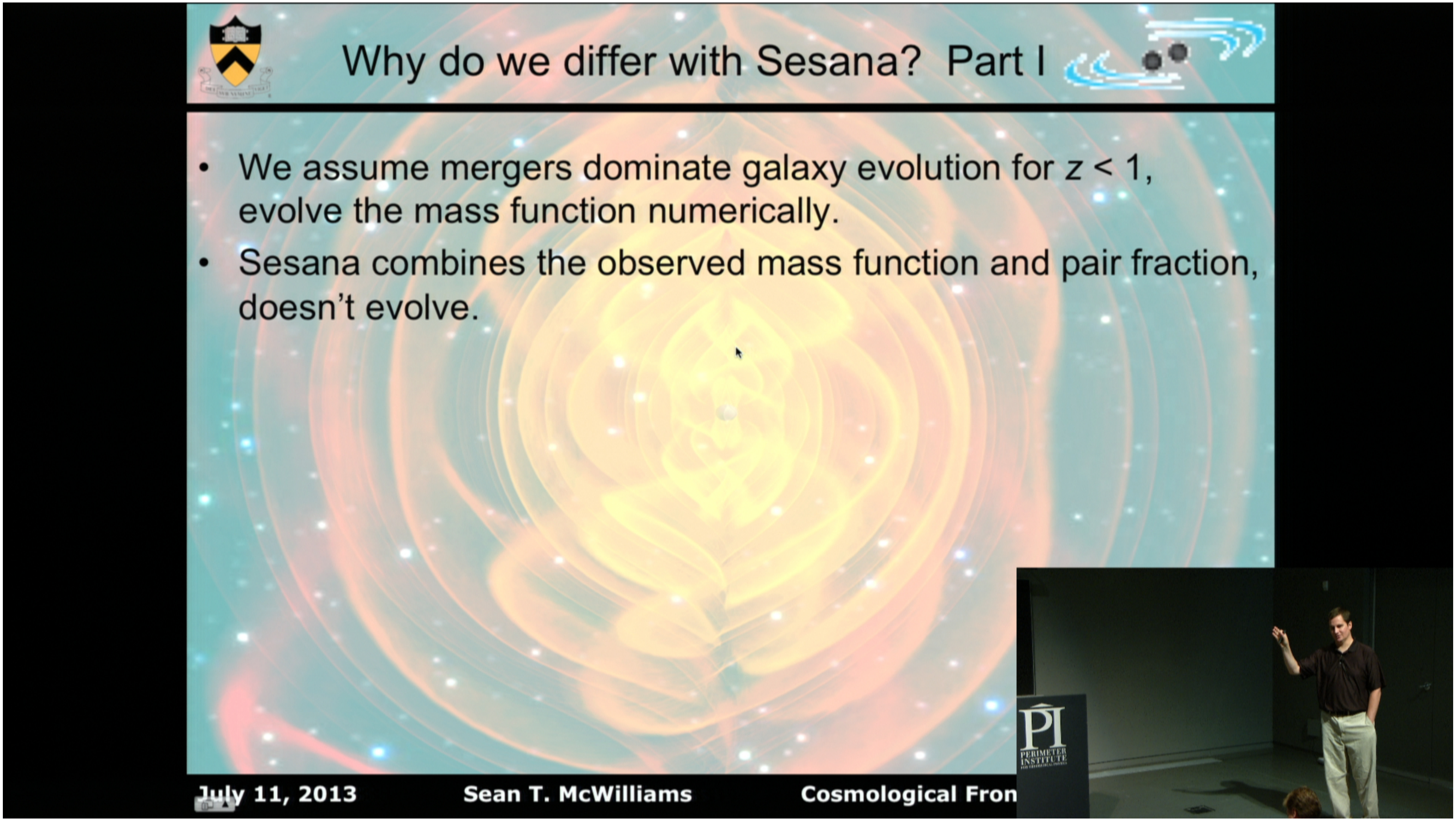
Theoretical estimates vs. observations



“STM”: STM, Ostriker, and Pretorius, http://arxiv.org/abs/1211.5377
“Sesana”: Sesana, http://arxiv.org/abs/1211.5375
“PPTA”: Talk at Aspen by Ryan Shannon, no paper yet



Why do we differ with Sesana? Part I

- We assume mergers dominate galaxy evolution for $z < 1$, evolve the mass function numerically.
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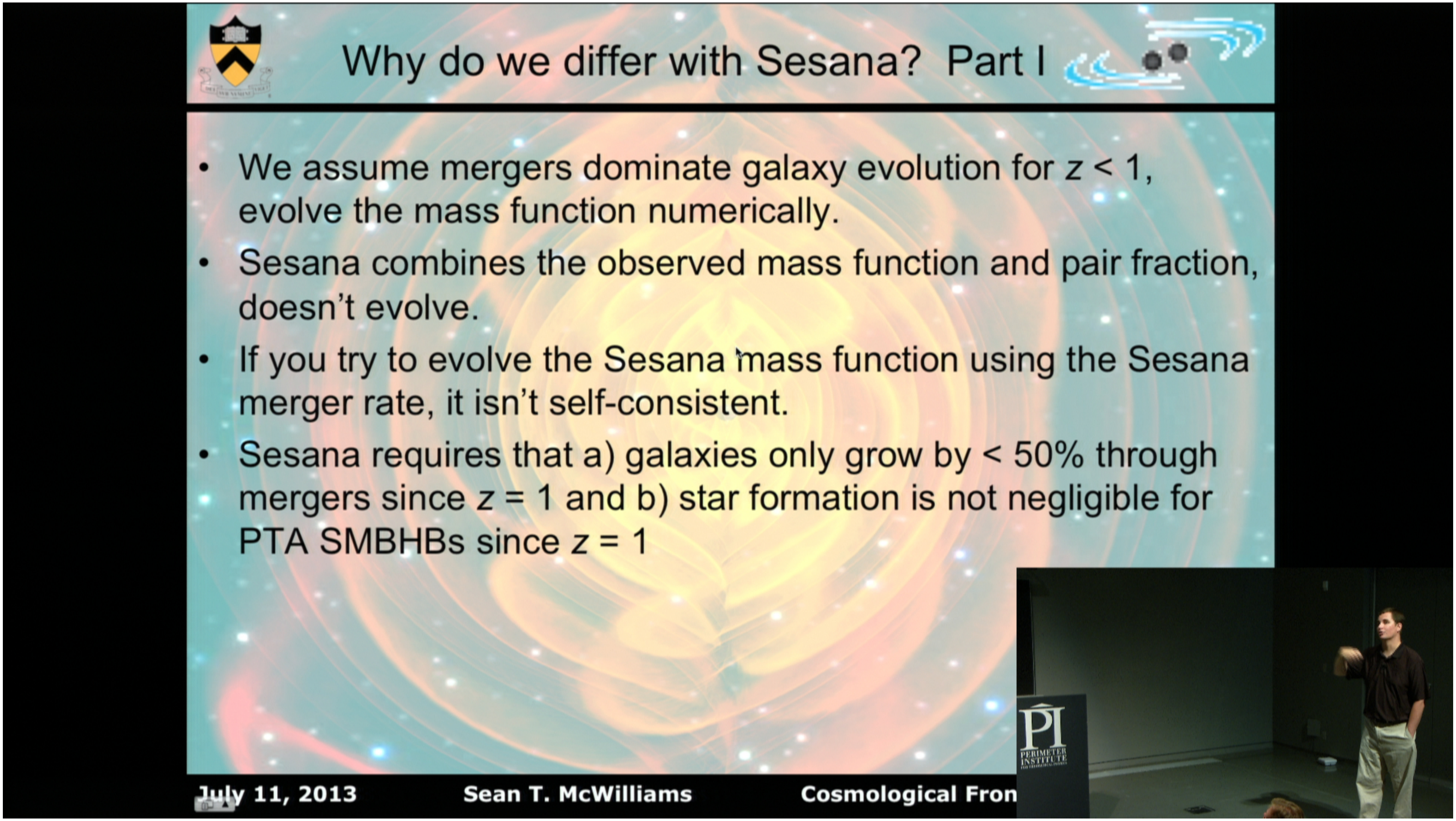

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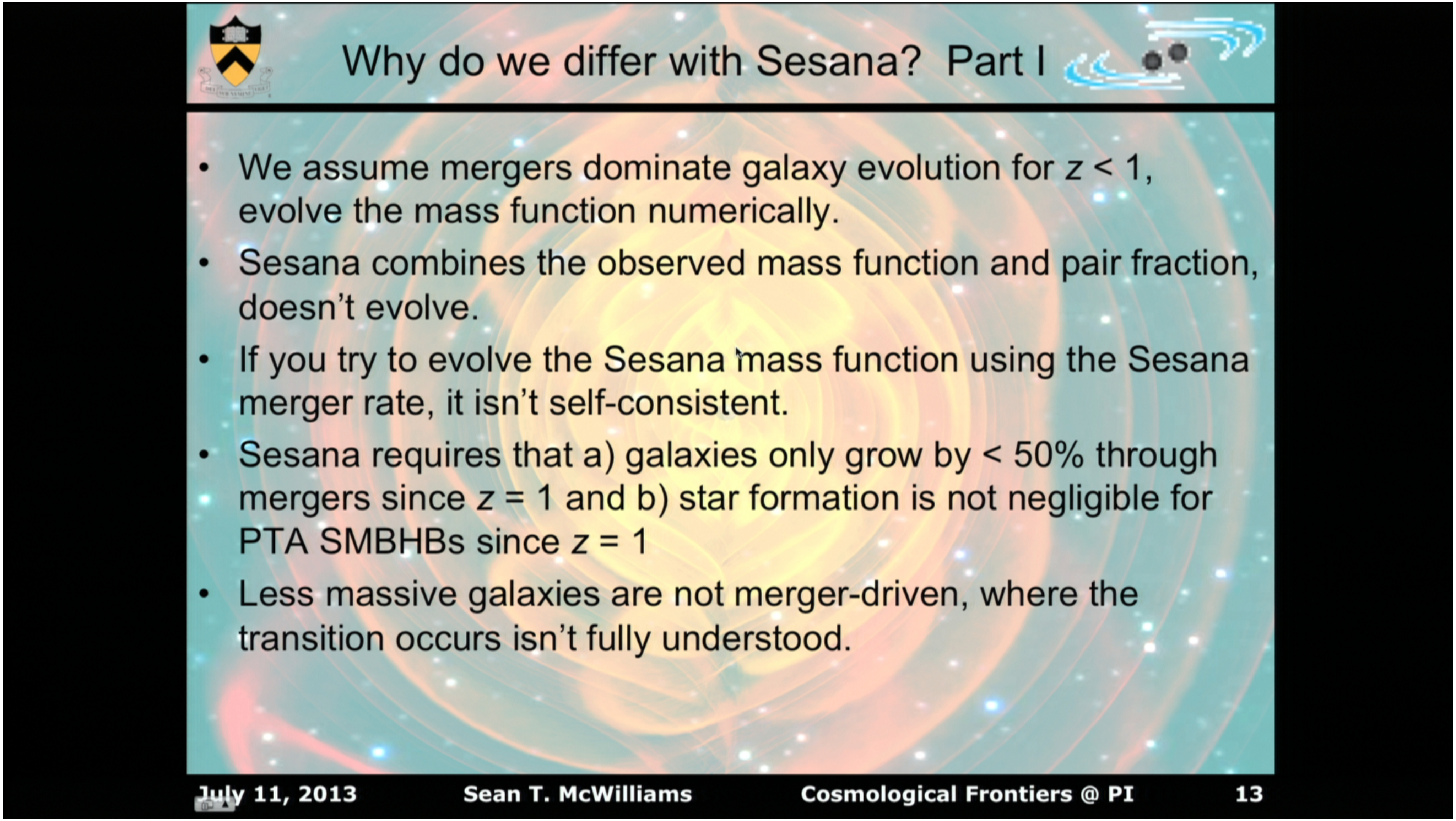

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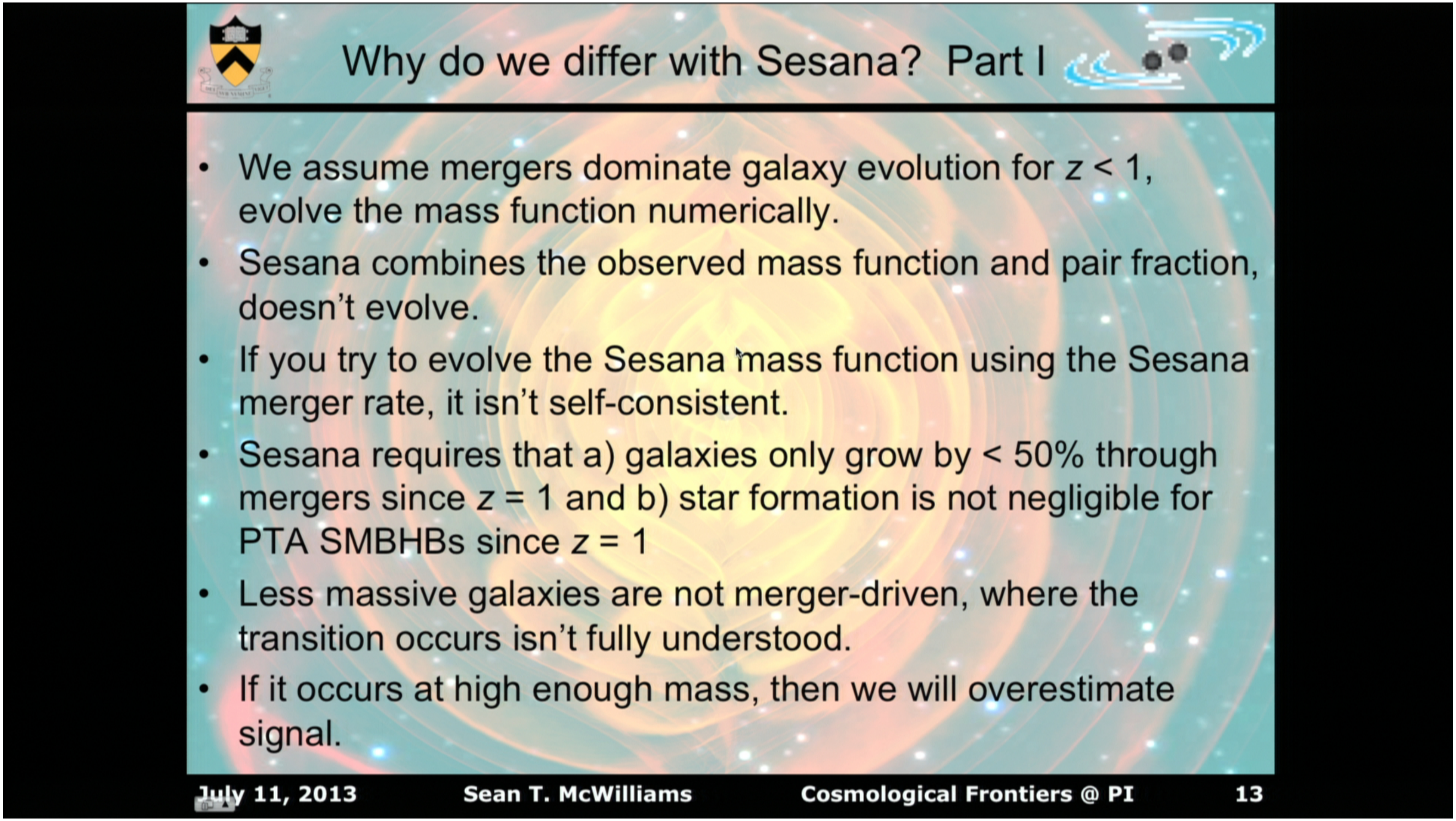

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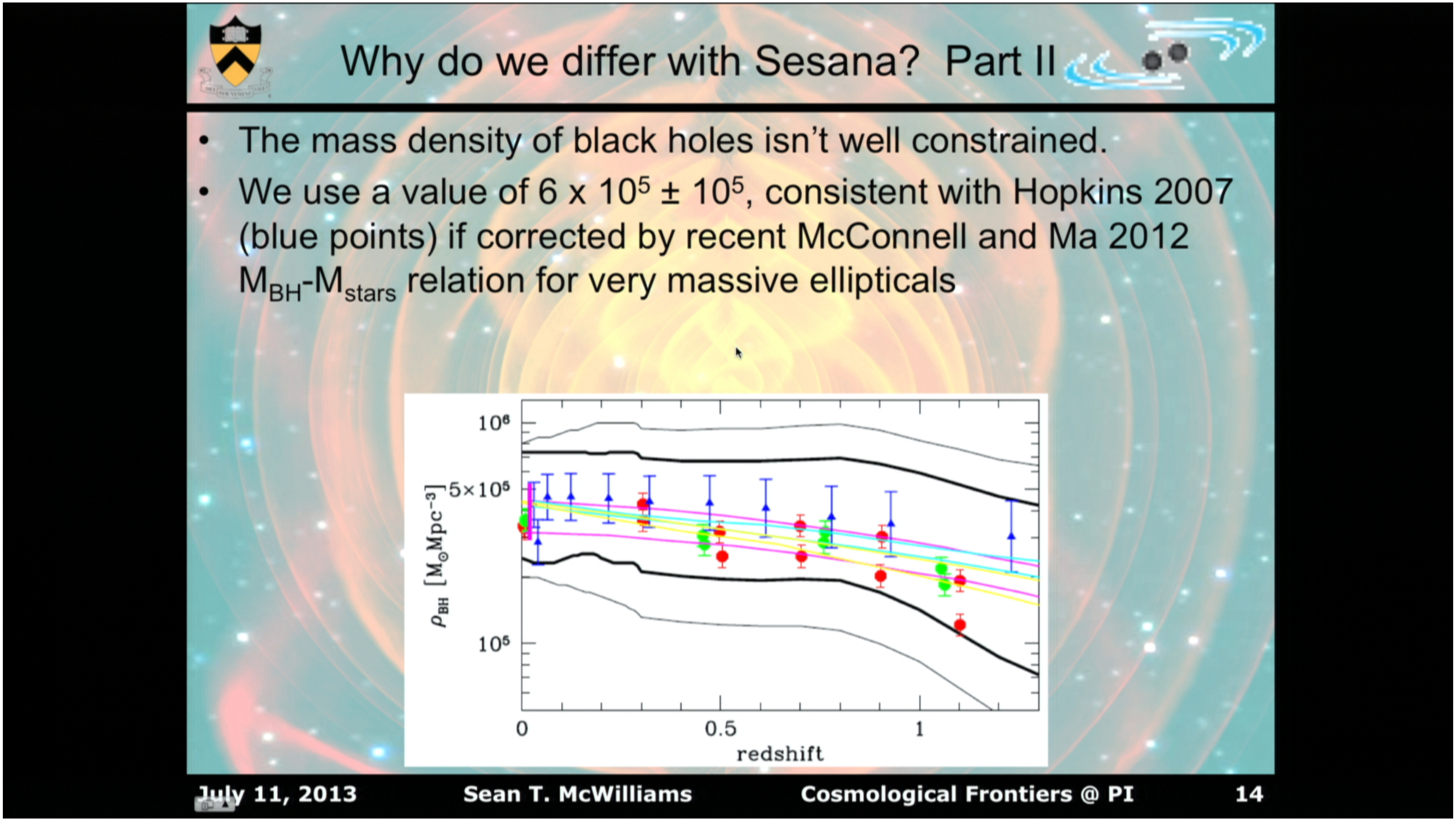
- If it occurs at high enough mass, then we will overestimate signal.



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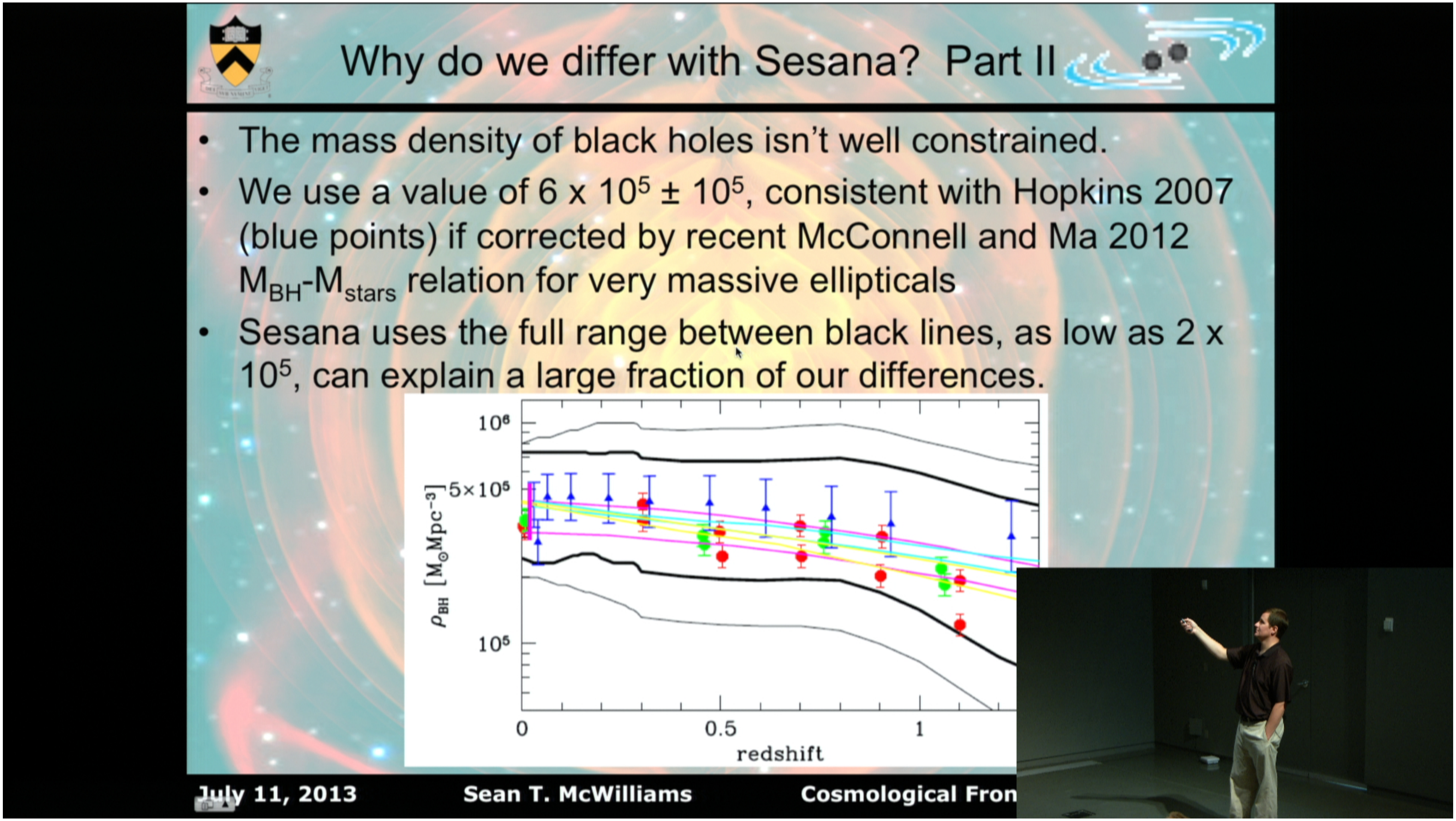

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- Sesana uses the full range between black lines, as low as 2×10^5, can explain a large fraction of our differences.

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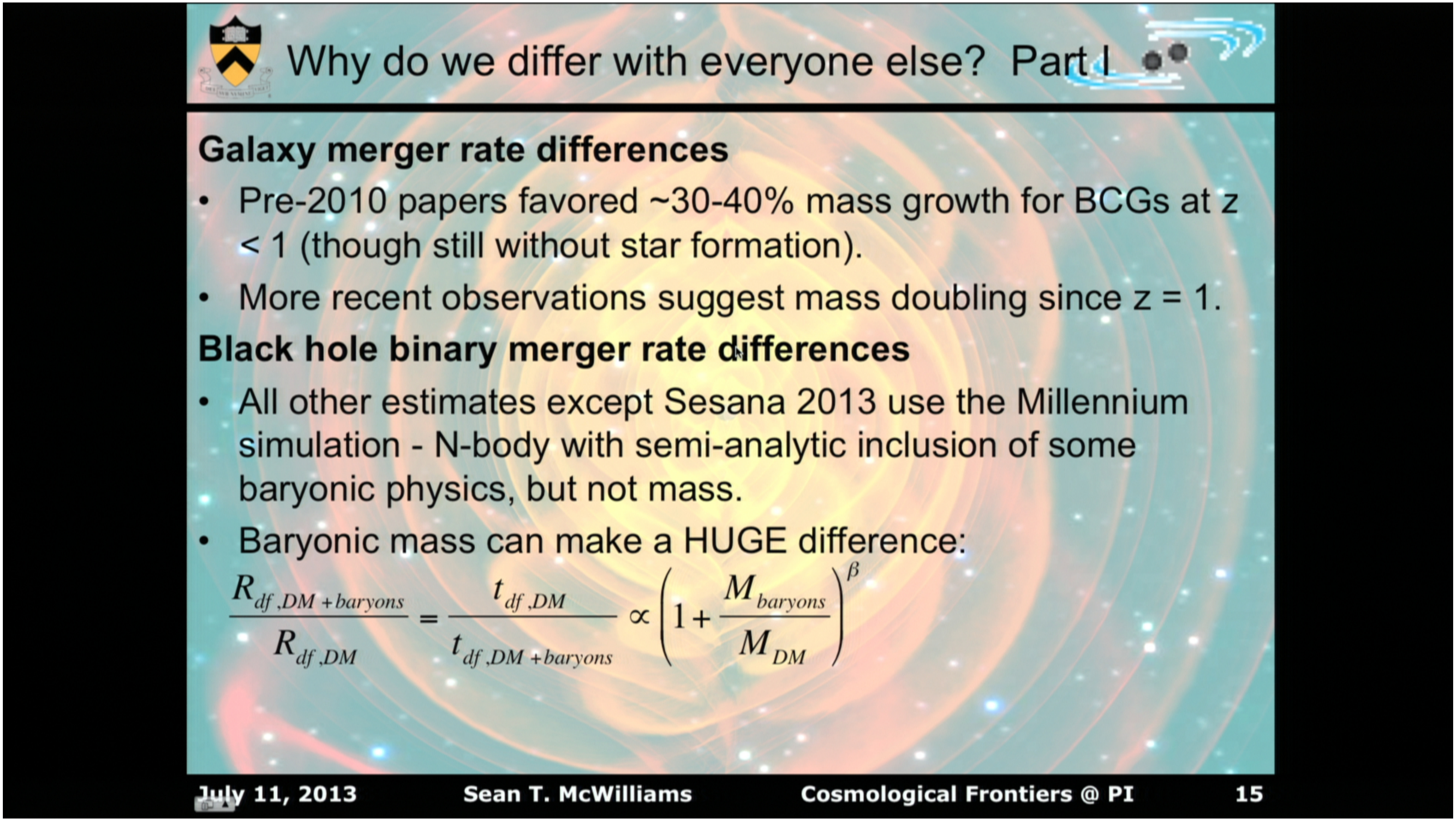

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Galaxy merger rate differences

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- More recent observations suggest mass doubling since $z = 1$.

Black hole binary merger rate differences

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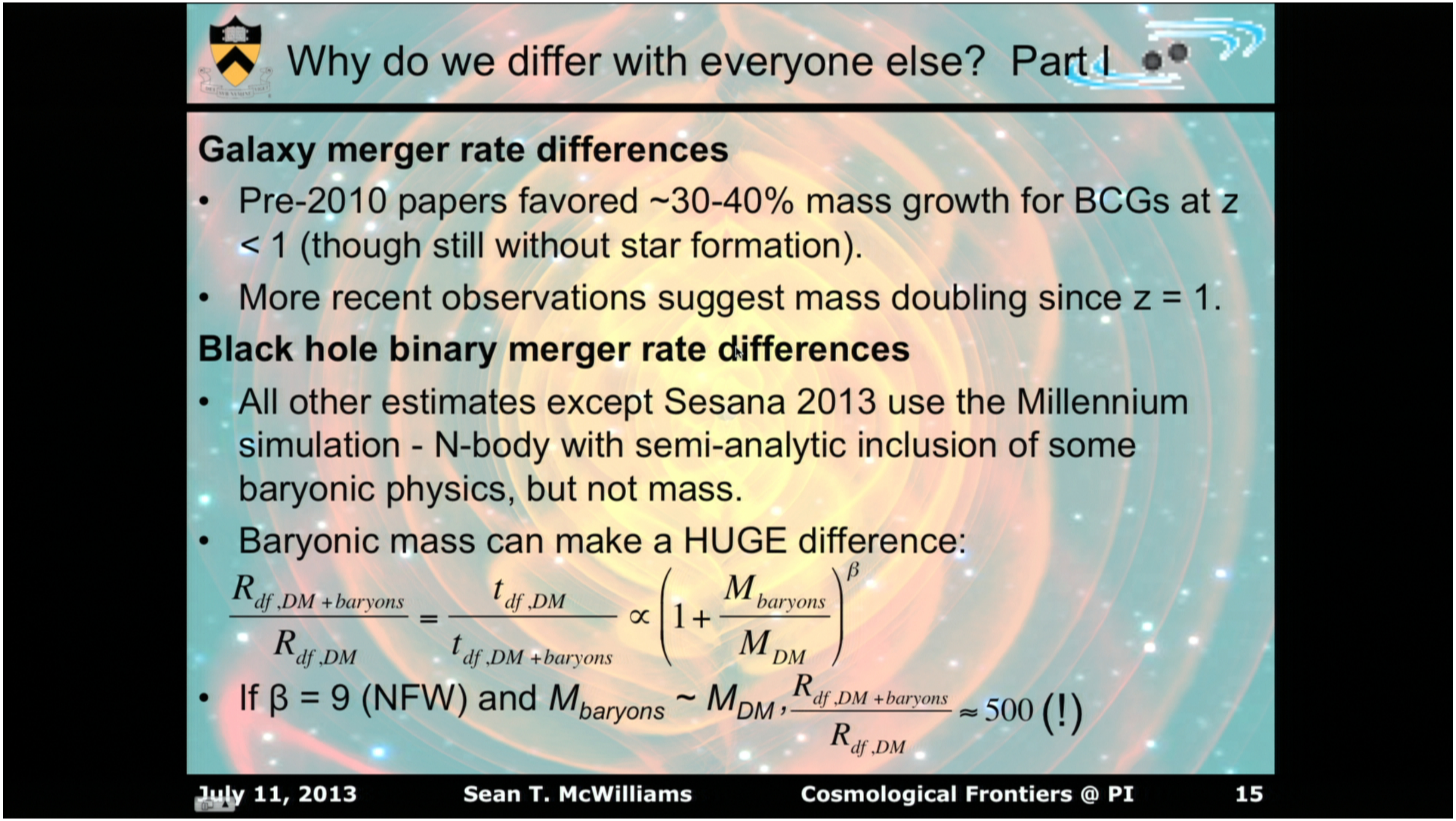
- Baryonic mass can make a HUGE difference:

$$\frac{R_{df,DM+baryons}}{R_{df,DM}} = \frac{t_{df,DM}}{t_{df,DM+baryons}} \propto \left(1+\frac{M_{baryons}}{M_{DM}}\right)^{\beta}$$



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- If $\beta = 9$ (NFW) and $M_{baryons} \sim M_{DM}$, $\frac{R_{df,DM+baryons}}{R_{df,DM}} \approx 500$ (!)

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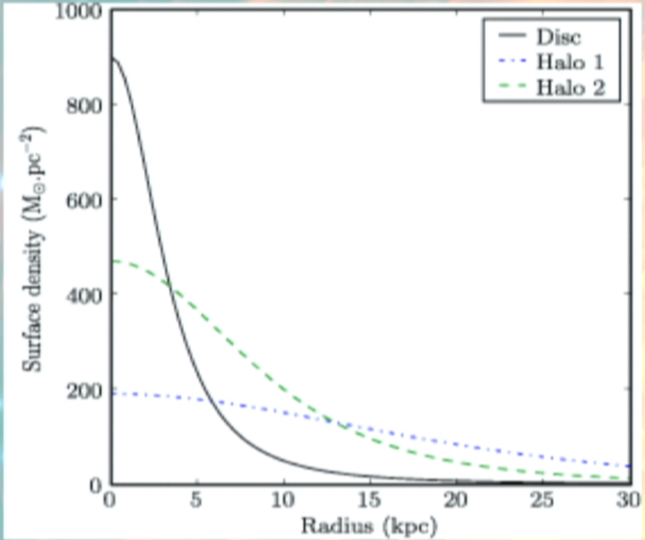

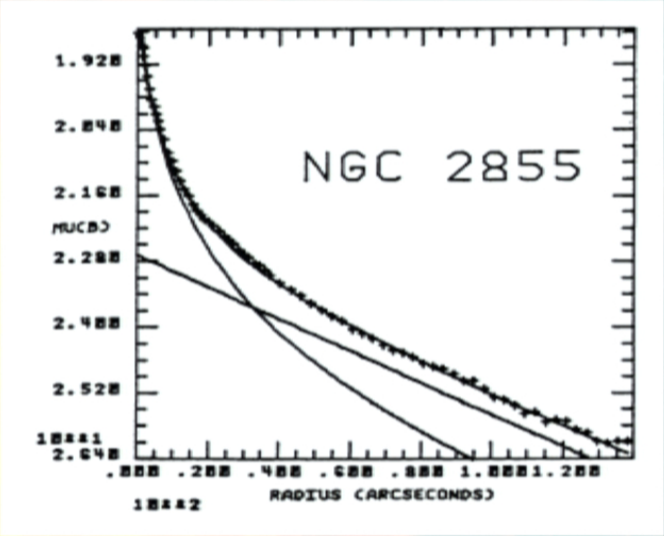

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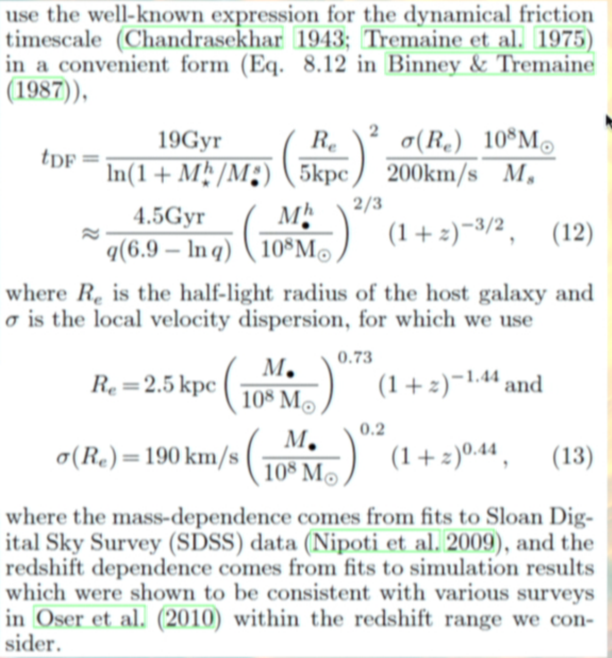
Why do we differ with everyone else? Part II

- Baryons can make a difference, but our whole prescription for dynamical friction is different.
- Past estimates used a mass-independent $t_{df.}$

STM, Ostriker, and Pretorius, http://arxiv.org/abs/1211.5377



use the well-known expression for the dynamical friction timescale (Chandrasekhar 1943; Tremaine et al. 1975) in a convenient form (Eq. 8.12 in Binney & Tremaine (1987)),

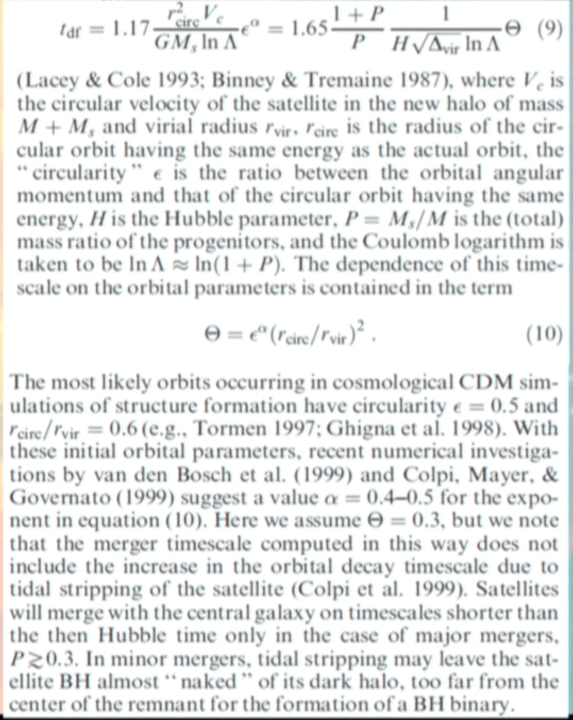
$$t_{\rm DF} = \frac{19{\rm Gyr}}{\ln(1+M^h_\star/M^s_\bullet)}\left(\frac{R_e}{5{\rm kpc}}\right)^2 \frac{\sigma(R_e)}{200{\rm km/s}}\frac{10^8{\rm M}_\odot}{M_s}$$
$$\approx \frac{4.5{\rm Gyr}}{q(6.9-\ln q)}\left(\frac{M^h_\bullet}{10^8{\rm M}_\odot}\right)^{2/3}(1+z)^{-3/2}, \quad (12)$$

where R_e is the half-light radius of the host galaxy and σ is the local velocity dispersion, for which we use

$$R_e = 2.5\,{\rm kpc}\left(\frac{M_\bullet}{10^8\,{\rm M}_\odot}\right)^{0.73}(1+z)^{-1.44}\ \text{and}$$
$$\sigma(R_e) = 190\,{\rm km/s}\left(\frac{M_\bullet}{10^8\,{\rm M}_\odot}\right)^{0.2}(1+z)^{0.44}, \quad (13)$$

where the mass-dependence comes from fits to Sloan Digital Sky Survey (SDSS) data (Nipoti et al. 2009), and the redshift dependence comes from fits to simulation results which were shown to be consistent with various surveys in Oser et al. (2010) within the redshift range we consider.

Volonteri, Haardt, and Madau, ApJ 582 559 (2003)

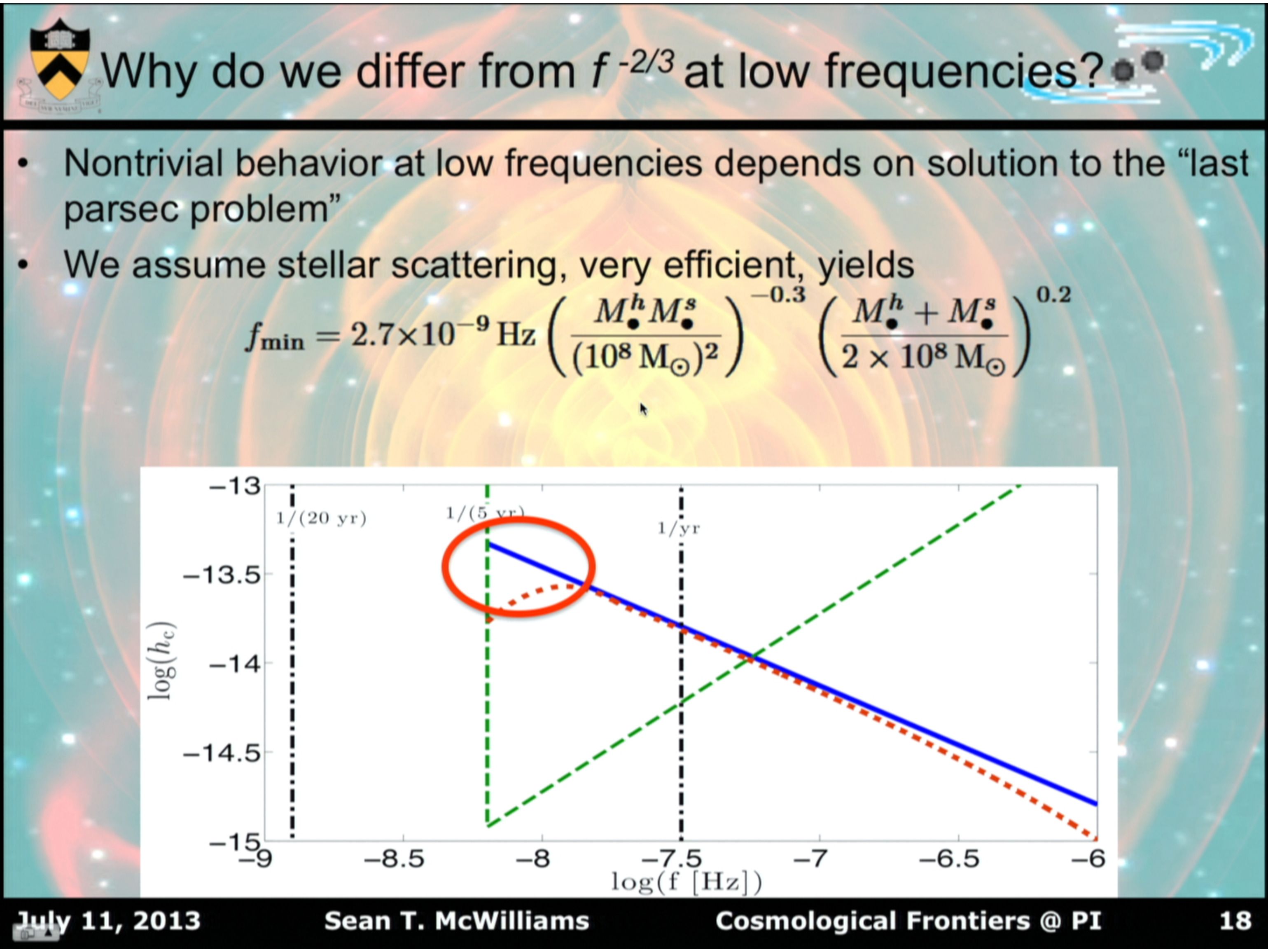


$$t_{\rm df} = 1.17\frac{r^2_{\rm circ}V_c}{GM_s\ln\Lambda}\epsilon^\alpha = 1.65\frac{1+P}{P}\frac{1}{H\sqrt{\Delta_{\rm vir}}\ln\Lambda}\Theta \quad (9)$$

(Lacey & Cole 1993; Binney & Tremaine 1987), where V_c is the circular velocity of the satellite in the new halo of mass $M + M_s$ and virial radius $r_{\rm vir}$, $r_{\rm circ}$ is the radius of the circular orbit having the same energy as the actual orbit, the "circularity" ϵ is the ratio between the orbital angular momentum and that of the circular orbit having the same energy, H is the Hubble parameter, $P = M_s/M$ is the (total) mass ratio of the progenitors, and the Coulomb logarithm is taken to be $\ln\Lambda \approx \ln(1+P)$. The dependence of this timescale on the orbital parameters is contained in the term

$$\Theta = \epsilon^\alpha(r_{\rm circ}/r_{\rm vir})^2\,. \quad (10)$$

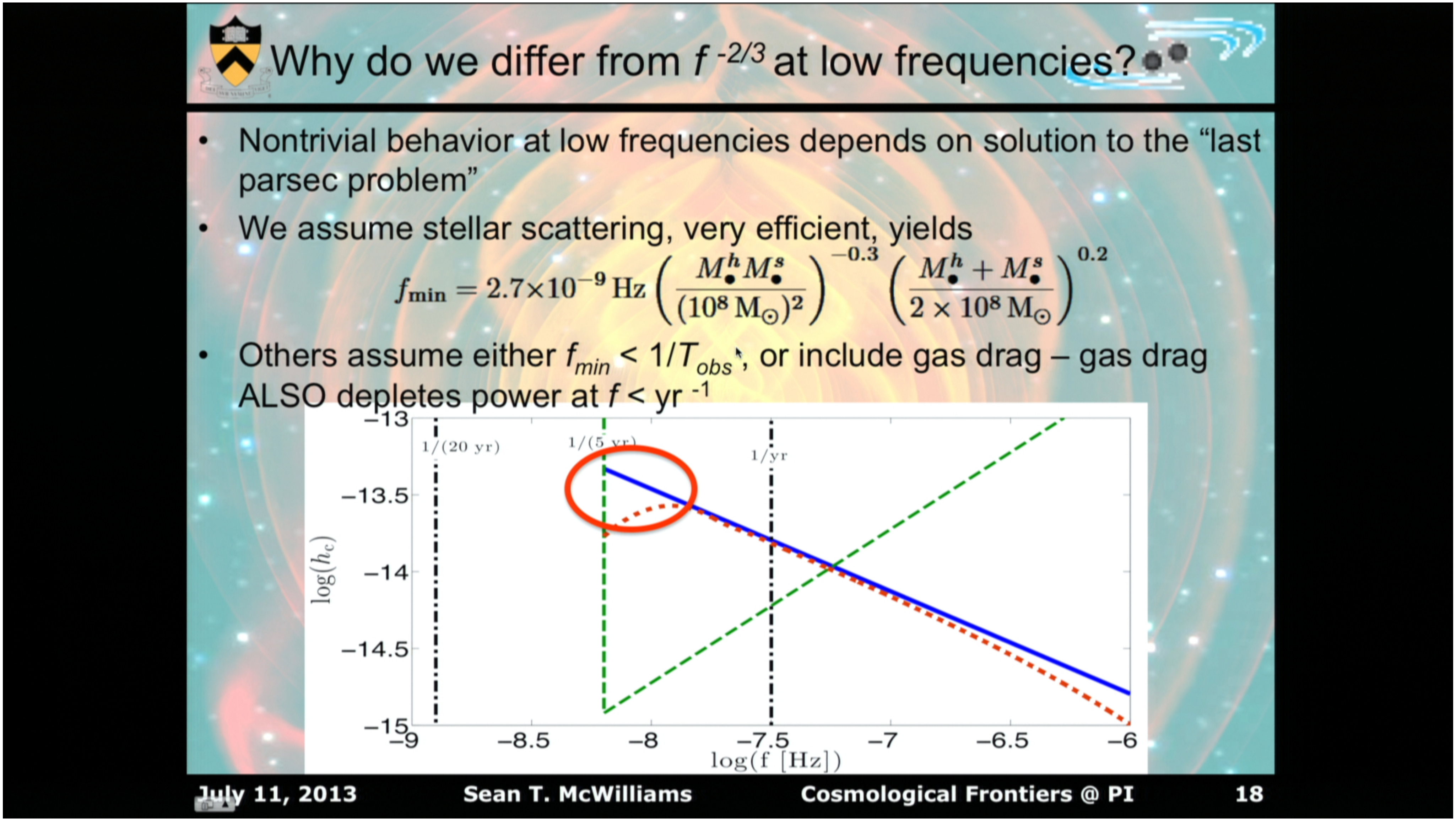
The most likely orbits occurring in cosmological CDM simulations of structure formation have circularity $\epsilon = 0.5$ and $r_{\rm circ}/r_{\rm vir} = 0.6$ (e.g., Tormen 1997; Ghigna et al. 1998). With these initial orbital parameters, recent numerical investigations by van den Bosch et al. (1999) and Colpi, Mayer, & Governato (1999) suggest a value $\alpha = 0.4$–0.5 for the exponent in equation (10). Here we assume $\Theta = 0.3$, but we note that the merger timescale computed in this way does not include the increase in the orbital decay timescale due to tidal stripping of the satellite (Colpi et al. 1999). Satellites will merge with the central galaxy on timescales shorter than the then Hubble time only in the case of major mergers, $P \gtrsim 0.3$. In minor mergers, tidal stripping may leave the satellite BH almost "naked" of its dark halo, too far from the center of the remnant for the formation of a BH binary.



Why do we differ from $f^{-2/3}$ at low frequencies?

- Nontrivial behavior at low frequencies depends on solution to the "last parsec problem"
- We assume stellar scattering, very efficient, yields

$$f_{\rm min} = 2.7\times10^{-9}\,{\rm Hz}\left(\frac{M_\bullet^h M_\bullet^s}{(10^8\,{\rm M}_\odot)^2}\right)^{-0.3}\left(\frac{M_\bullet^h + M_\bullet^s}{2\times10^8\,{\rm M}_\odot}\right)^{0.2}$$



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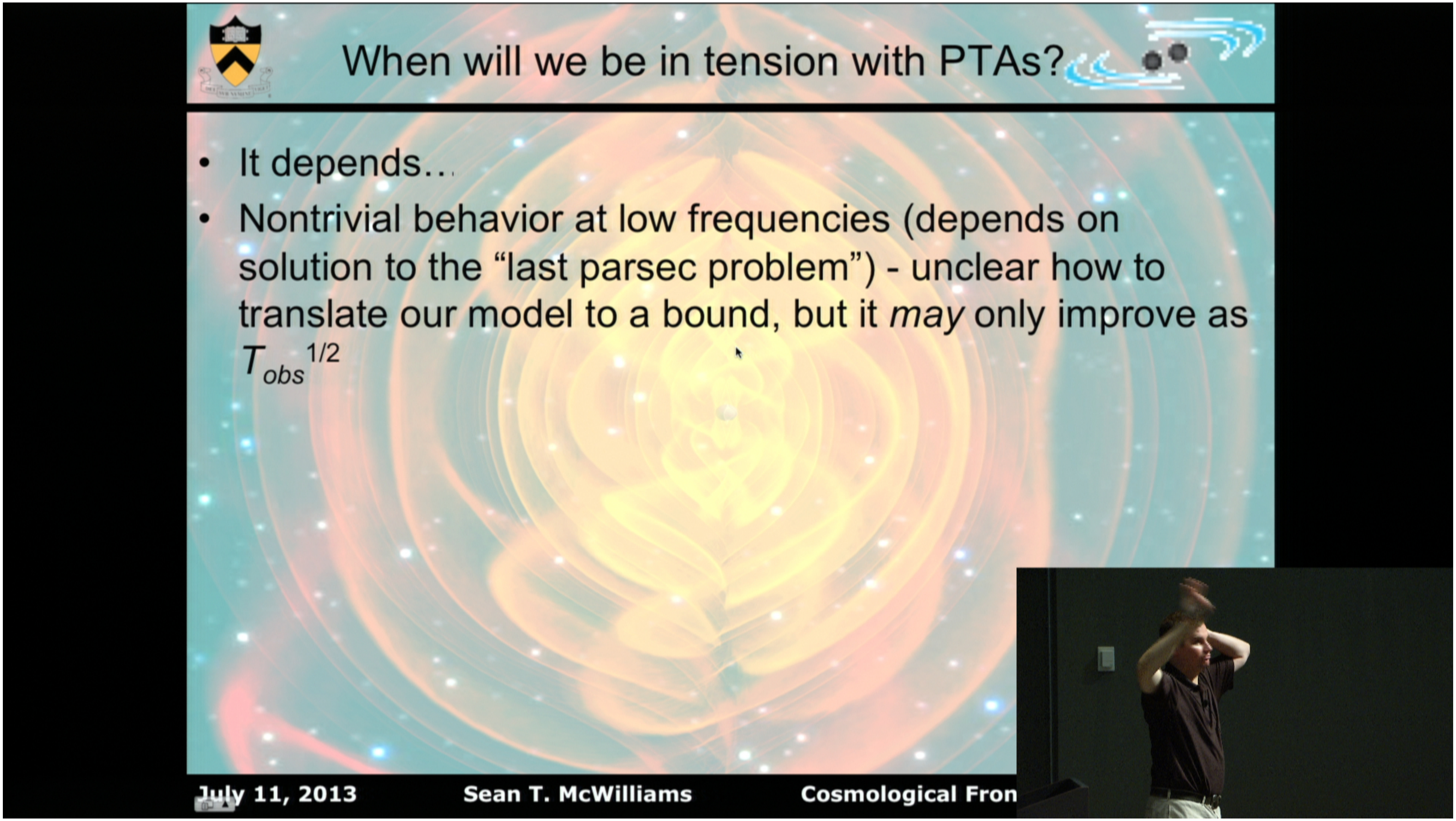
- Others assume either $f_{min} < 1/T_{obs}$, or include gas drag – gas drag ALSO depletes power at $f < \mathrm{yr}^{-1}$



When will we be in tension with PTAs?

- It depends…
- Nontrivial behavior at low frequencies (depends on solution to the “last parsec problem”) - unclear how to translate our model to a bound, but it *may* only improve as $T_{obs}^{1/2}$

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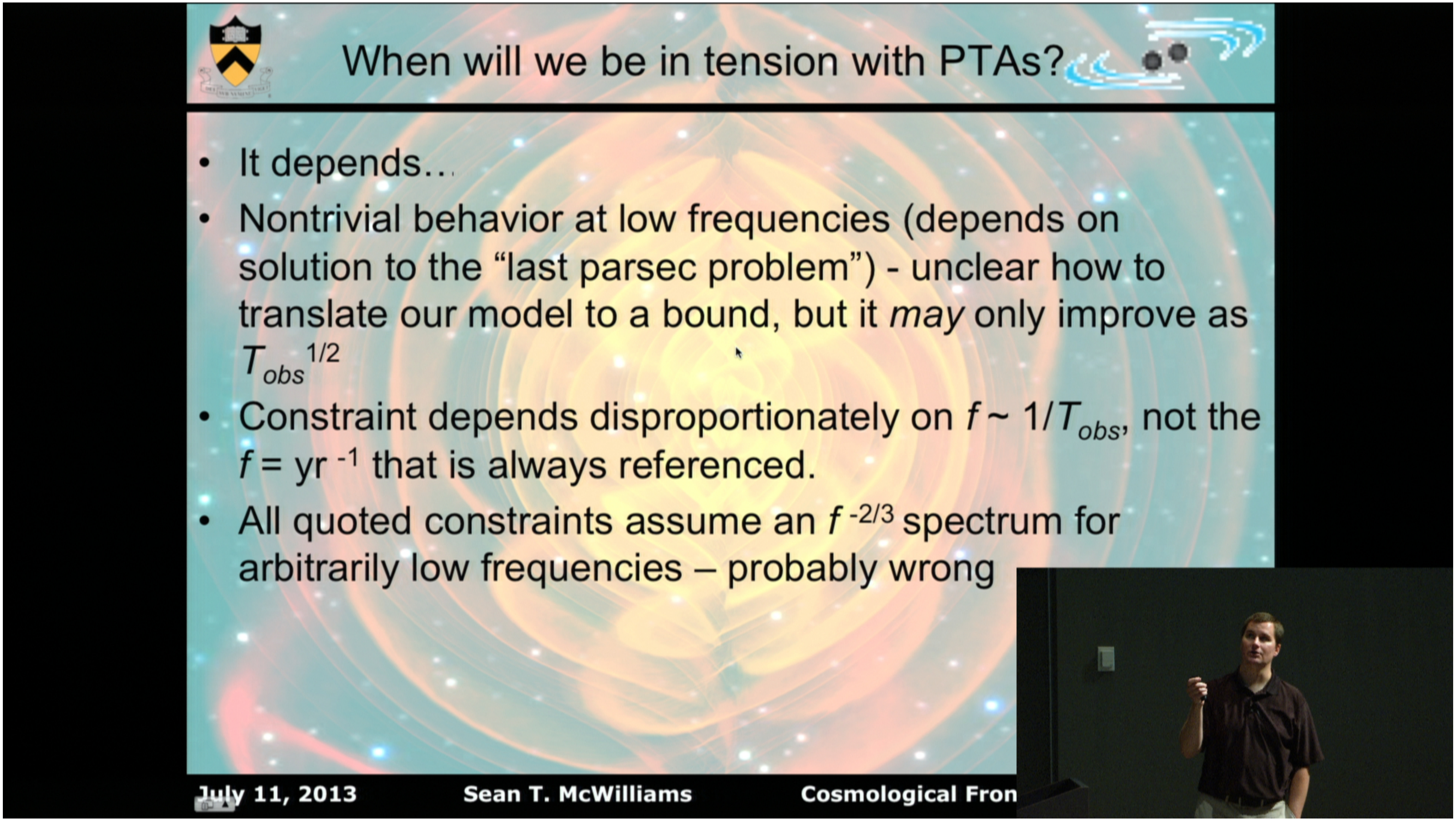

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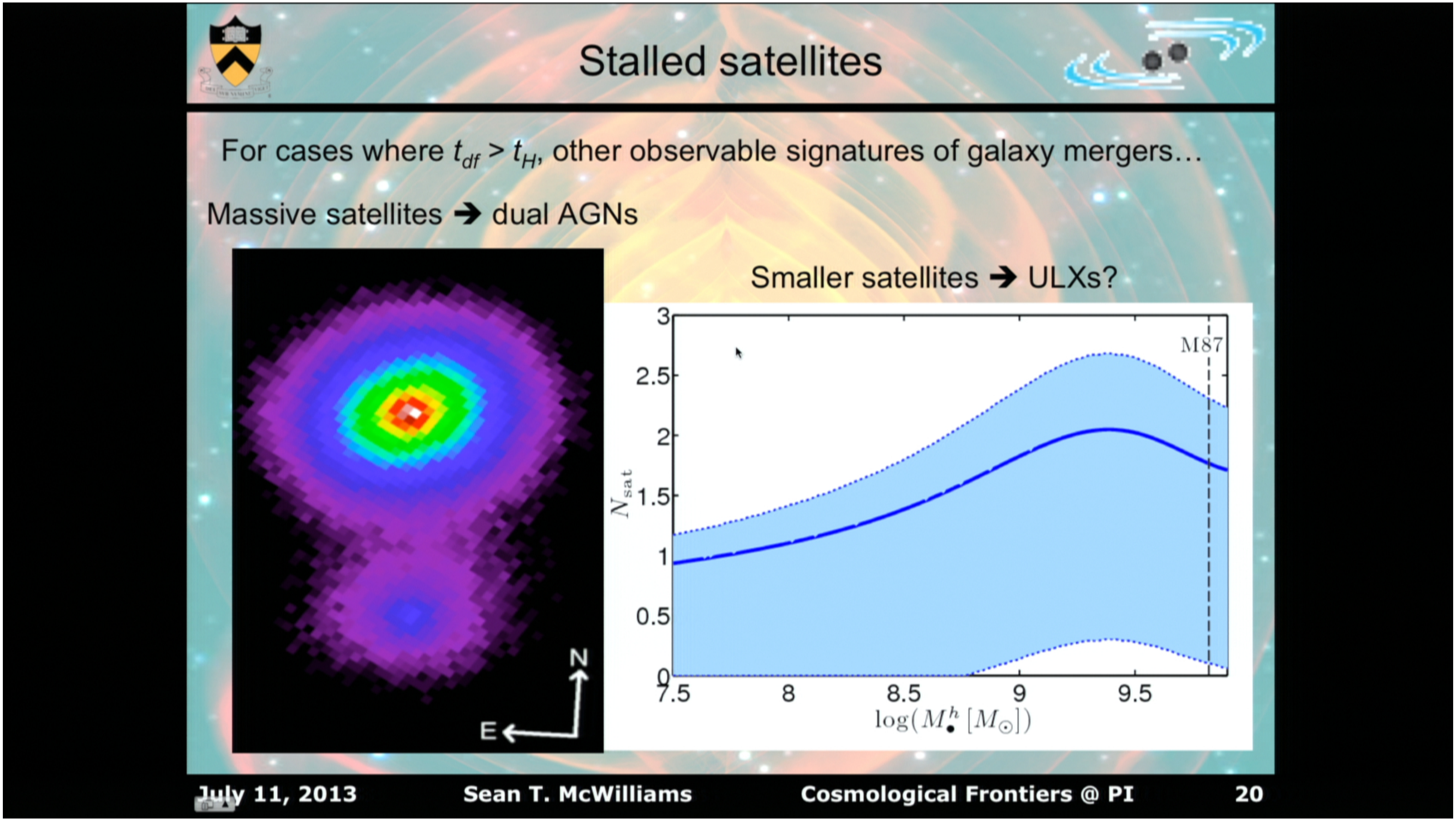
- All quoted constraints assume an $f^{-2/3}$ spectrum for arbitrarily low frequencies – probably wrong
- Technical point: the most recent, as-yet-unpublished constraint from Parkes PTA is ~3x tighter than any other, BUT it assumes the data is noise-dominated



Stalled satellites

For cases where $t_{df} > t_H$, other observable signatures of galaxy mergers…

Massive satellites ➔ dual AGNs

Smaller satellites ➔ ULXs?

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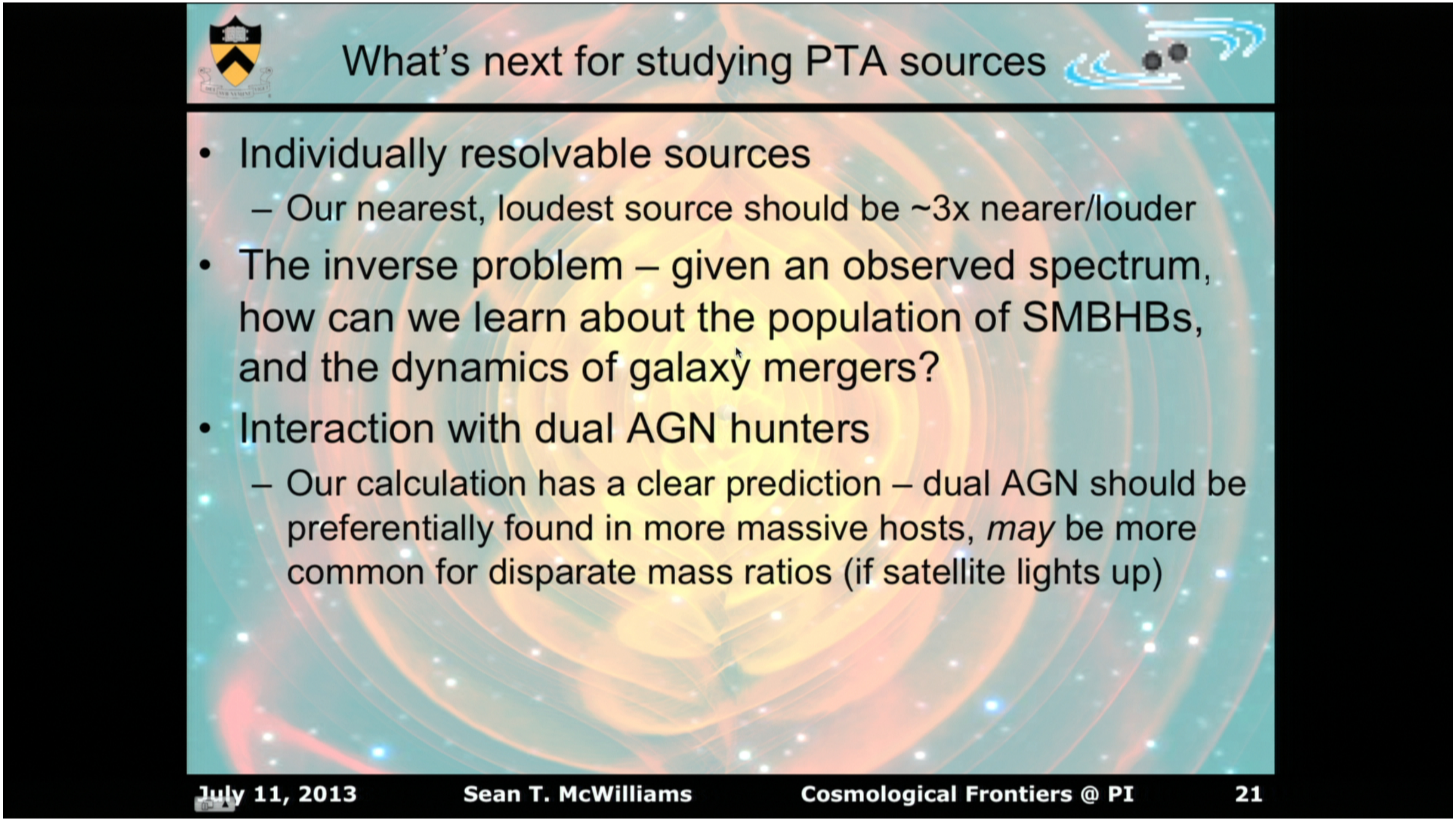
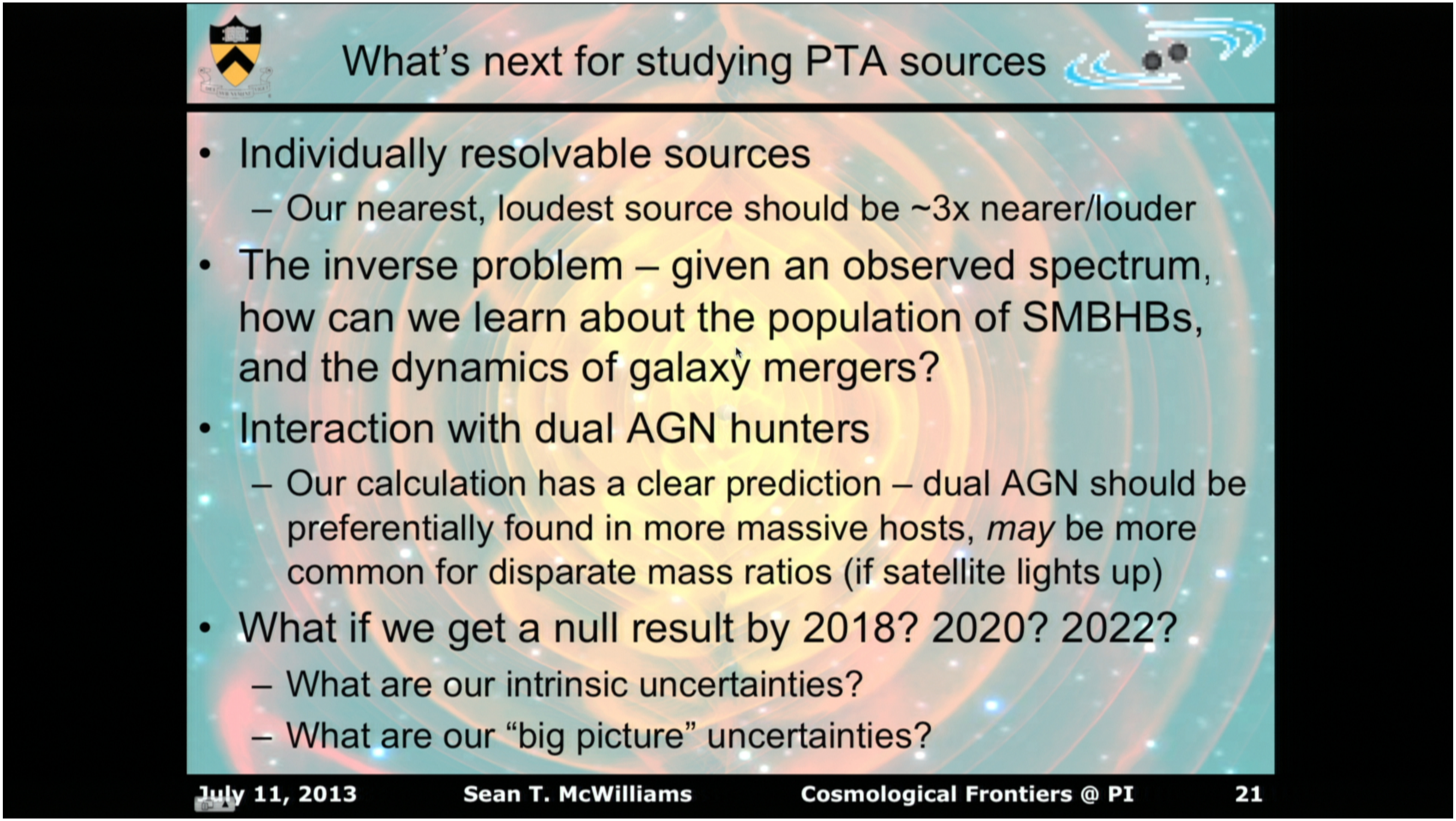


What’s next for studying PTA sources

- Individually resolvable sources
  - Our nearest, loudest source should be ~3x nearer/louder
- The inverse problem – given an observed spectrum, how can we learn about the population of SMBHBs, and the dynamics of galaxy mergers?
- Interaction with dual AGN hunters
  - Our calculation has a clear prediction – dual AGN should be preferentially found in more massive hosts, *may* be more common for disparate mass ratios (if satellite lights up)



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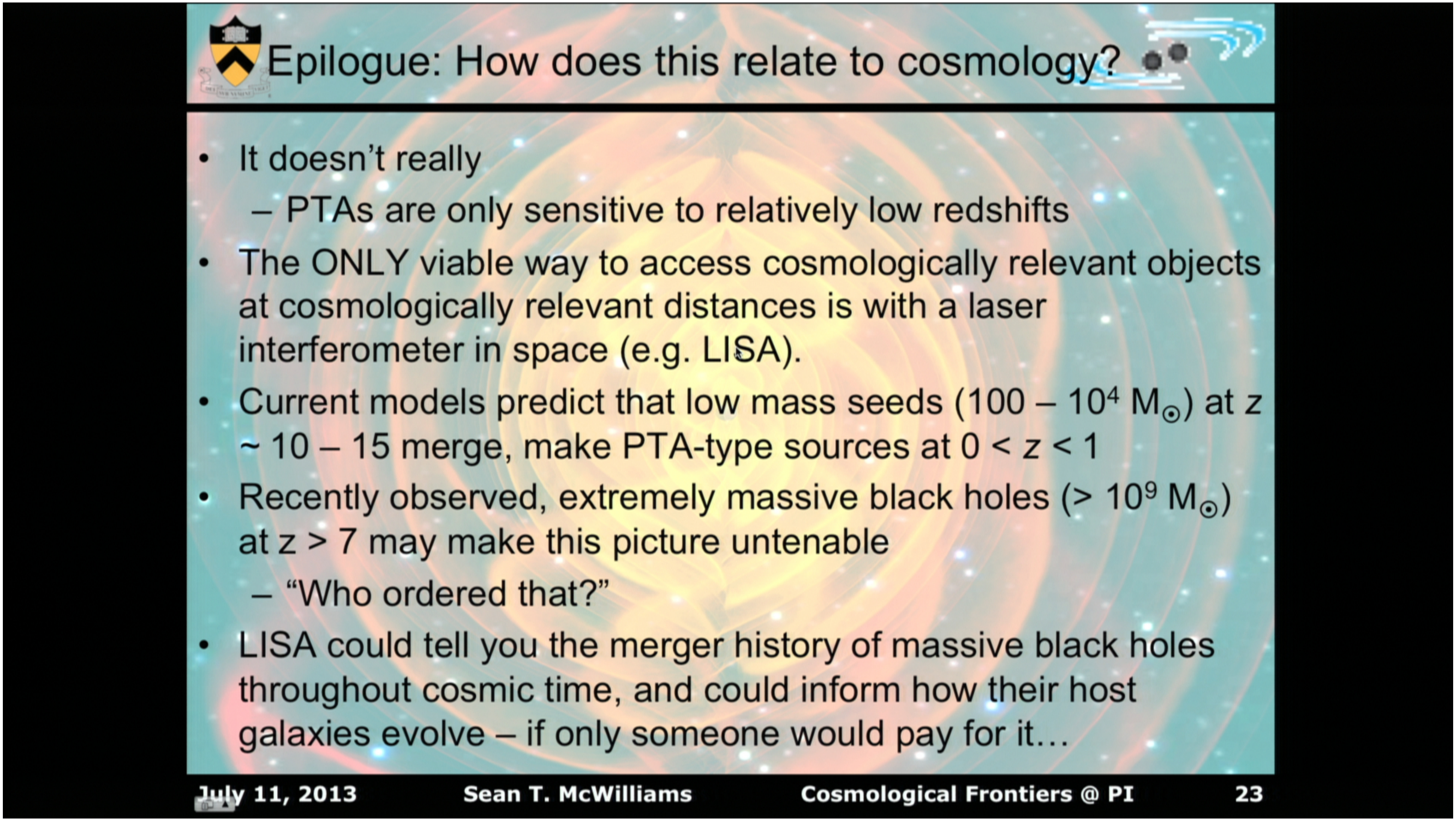
- Interaction with dual AGN hunters
  - Our calculation has a clear prediction – dual AGN should be preferentially found in more massive hosts, *may* be more common for disparate mass ratios (if satellite lights up)
- What if we get a null result by 2018? 2020? 2022?
  - What are our intrinsic uncertainties?
  - What are our “big picture” uncertainties?

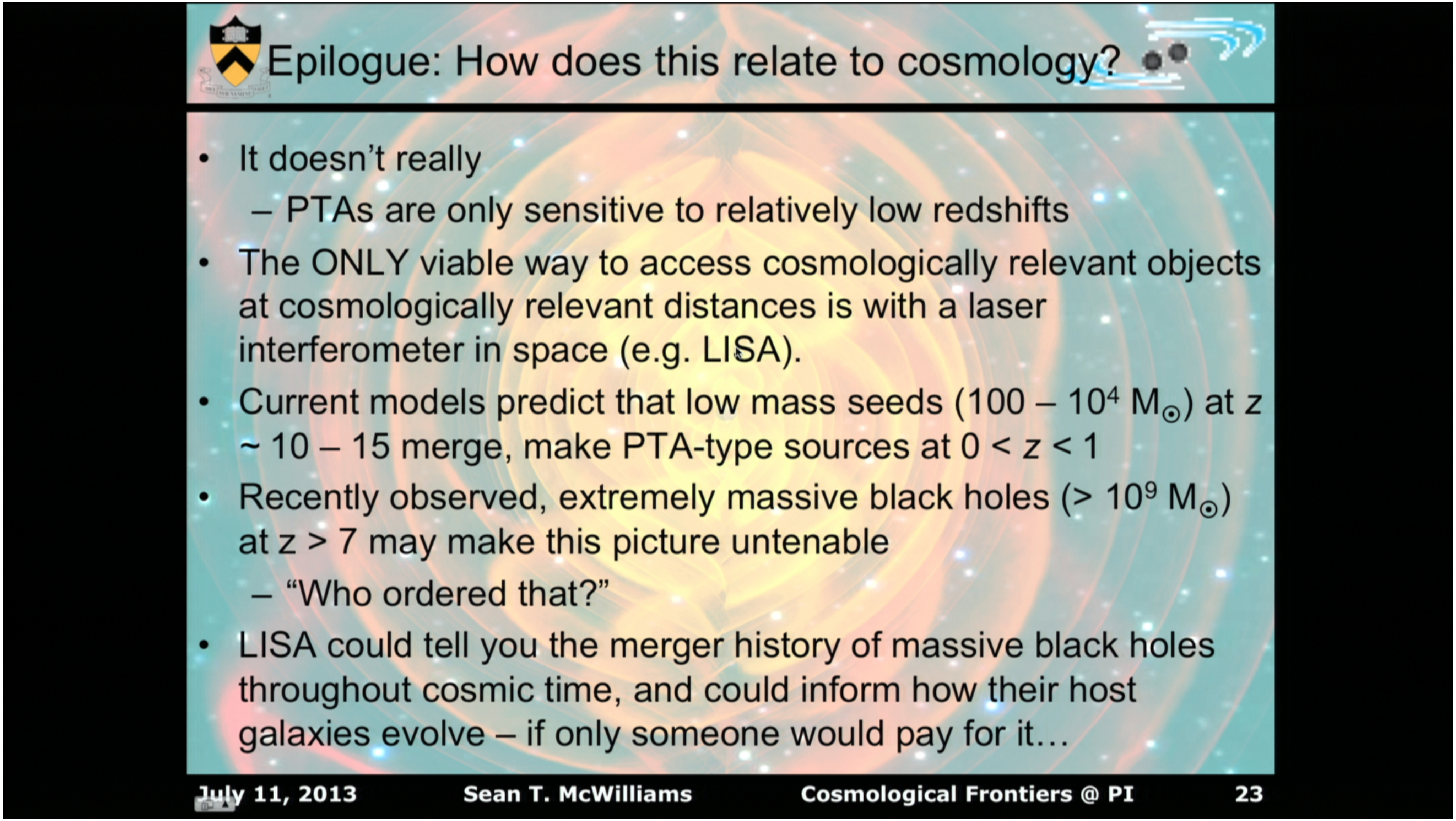
Conclusions

- We've developed a new approach to predict the PTA stochastic GW signal, differ with others by ~3x in our 3-sigma lower bound.
- The easy factor – different mass density of BHs can cause as much as 3x in the merger rate in a fixed volume, ~1.7 in signal. If too inefficiently, we get a null result, we need nature to strike a balance.
- The hard factor – our model seems to imply a 3x larger merger rate at fixed mass density, another ~1.7 in signal.
- This second factor is a result of our novel treatment of dynamical friction, and the mass range dominating the signal.
- NB: Our model will be in tension with observational constraints as early as 2016 **iff nature picks a realization with little/no dip at low frequencies** – otherwise, sensitivity improves as $T_{obs}^{1/2}$, not $T_{obs}^{13/6}$.
- The key point of a potential low frequency dip depends on the approach to the last parsec problem – if it's solved too efficiently, signal is removed at low frequency. If too inefficiently, we get a null result, we need nature to strike a balance.



Epilogue: How does this relate to cosmology?

- It doesn't really
  - PTAs are only sensitive to relatively low redshifts
- The ONLY viable way to access cosmologically relevant objects at cosmologically relevant distances is with a laser interferometer in space (e.g. LISA).
- Current models predict that low mass seeds ($100 – 10^4\ M_\odot$) at $z \sim 10 – 15$ merge, make PTA-type sources at $0 < z < 1$
- Recently observed, extremely massive black holes ($> 10^9\ M_\odot$) at $z > 7$ may make this picture untenable
  - "Who ordered that?"
- LISA could tell you the merger history of massive black holes throughout cosmic time, and could inform how their host galaxies evolve – if only someone would pay for it…



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