Linking Galaxy Evolution Parameters and Pulsar Timing Array Observations

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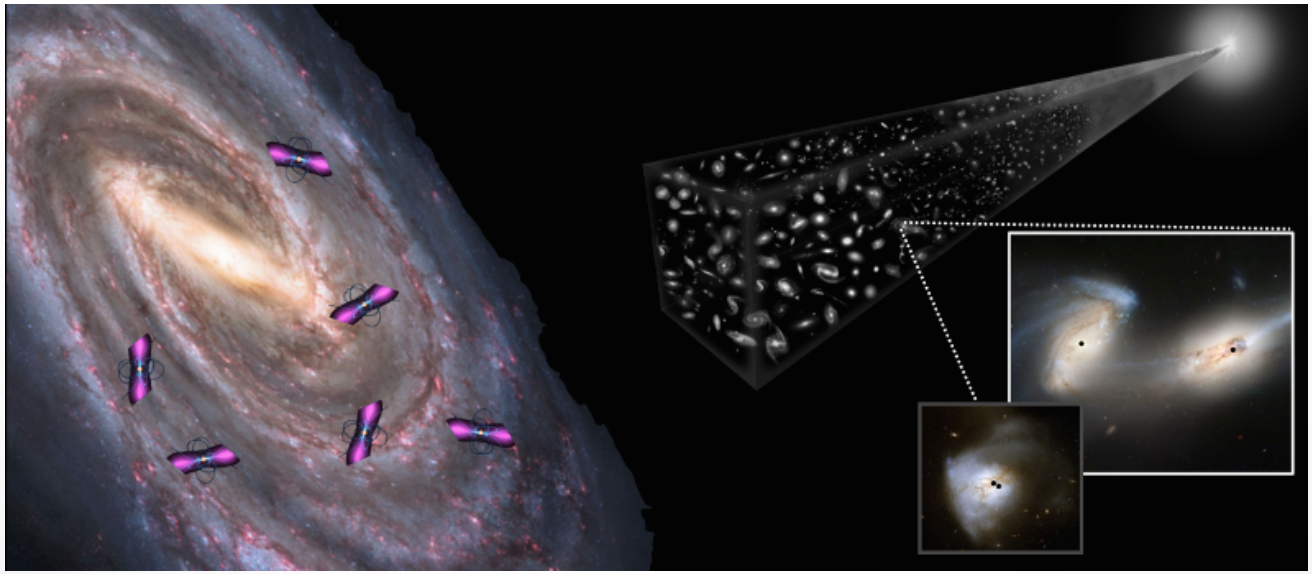
GR 21 – New York, NY

Model for GW Background

- Background is Built Up From Quadrature Sum Of Binaries:
  - Analytic Expression gives rise to simple Power Law, assuming circular binaries with gravitational radiation dominating orbital evolution.

$$h_c^2(f_r) = \int\int\int \frac{d^4N}{dz\ dM\ dq\ d(\ln f_r)} h_s^2\ dz\ dM\ dq = A_{yr}^2 \left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-4/3}$$



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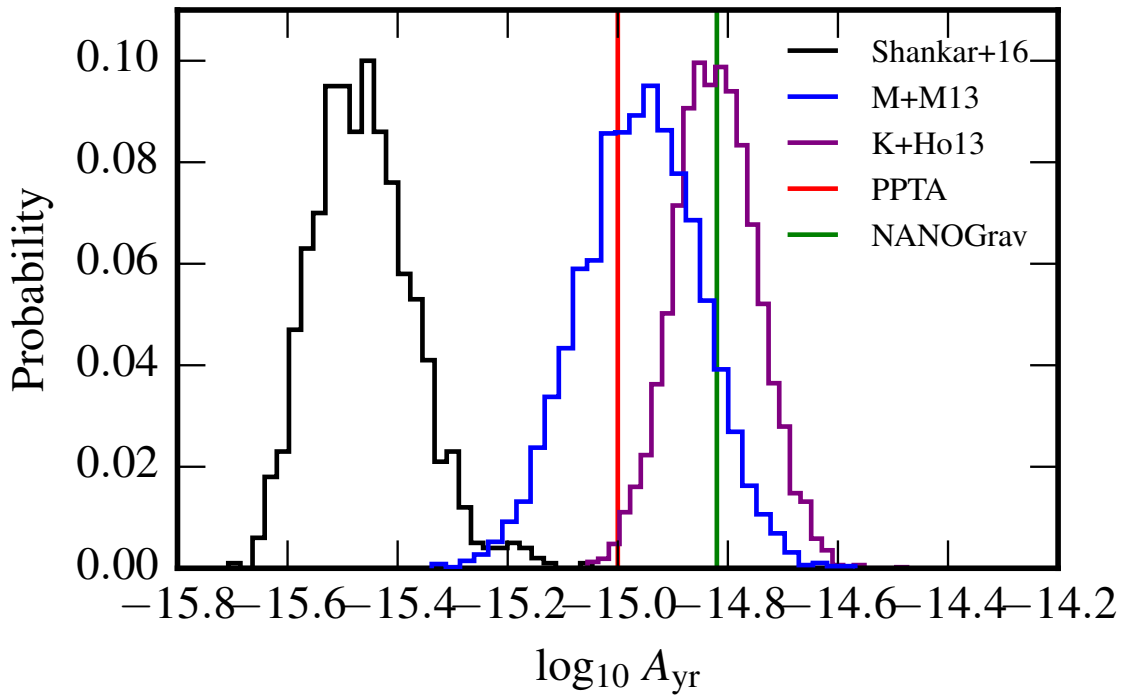
- Cannot Observe Black Hole Merger Rate
  - Use Galaxy Merger Rate Density As Proxy
  - Populate Galaxies With Co-Evolving Black Holes

$$\log M_\bullet = \alpha + \beta \log\left(\frac{M_{bulge}}{10^{11}\ M_\odot}\right), \epsilon$$

Model for GW Background:

Predictions For Strain Amplitude

$$A^2_{yr} = \int\int\int dz\, dM\, dq \left[\frac{dn_G}{dz\, dM\, dq}\right]_{*\to\bullet} \frac{dV_c}{dz}\frac{dz}{dt}\left(\frac{dt}{d\,(\ln f)}h^2\right)\Bigg|_{f=yr^{-1}}$$



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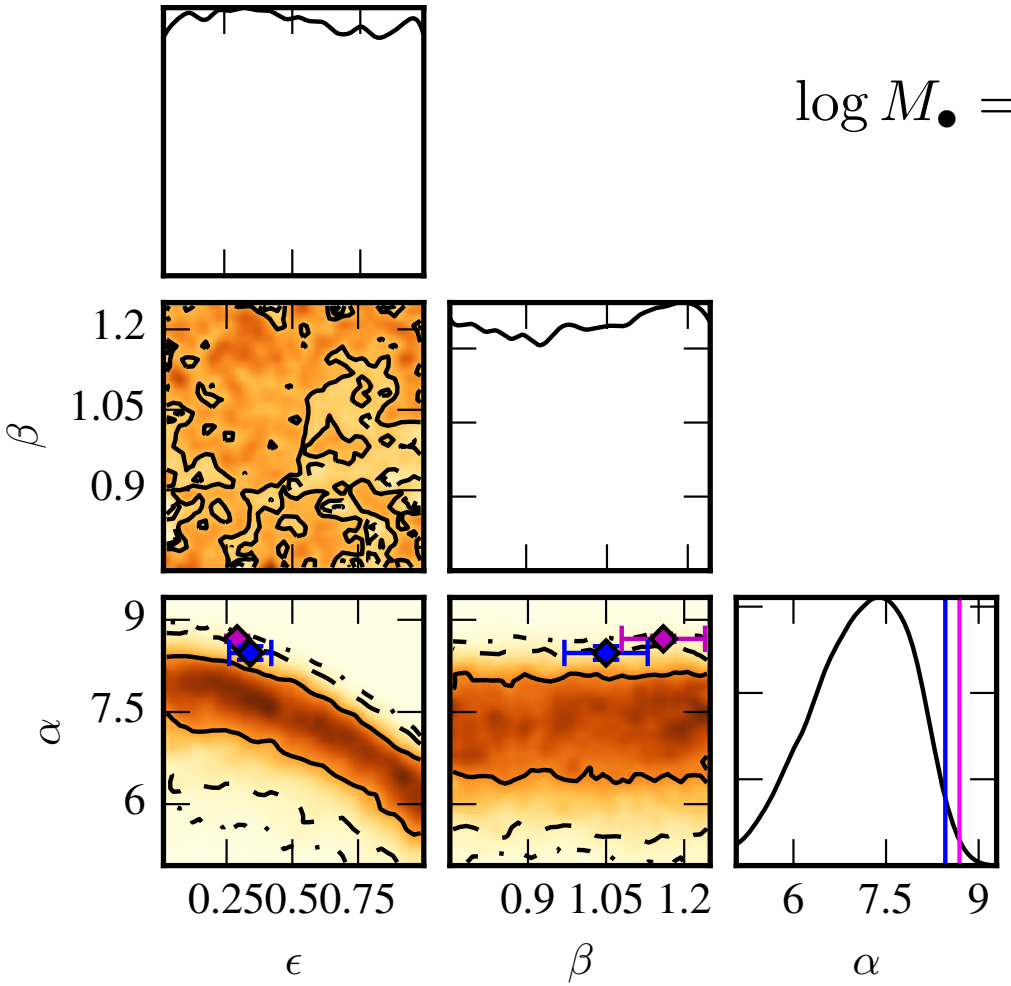
- Model Gives Prediction on A_{yr}
- Parameter Of Greatest Impact is Black Hole – Host Galaxy Relation
  - Sets Mean Value of A_{yr} distribution

Translating GWB Limits and Astrophysical Parameters:

Using PTA Upper Limits Directly



$$\log M_{\bullet} = \alpha + \beta \log \left(\frac{M_{bulge}}{10^{11}\, M_{\odot}} \right), \epsilon$$

- Change in β has negligible contribution to A_{yr}
- α is largest factor, with α - ϵ space having biggest impact on predictions

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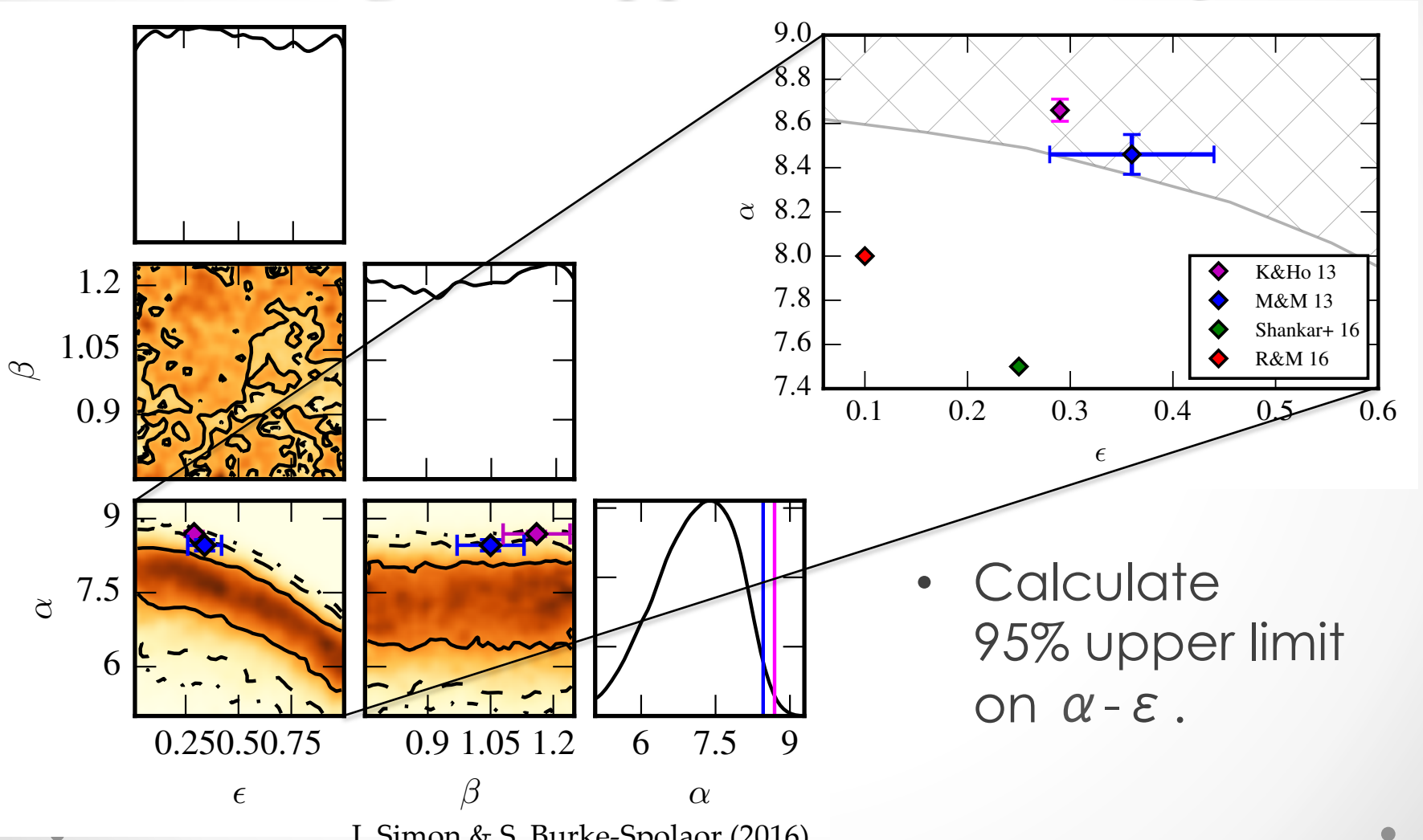

- Calculate 95% upper limit on α - ϵ .

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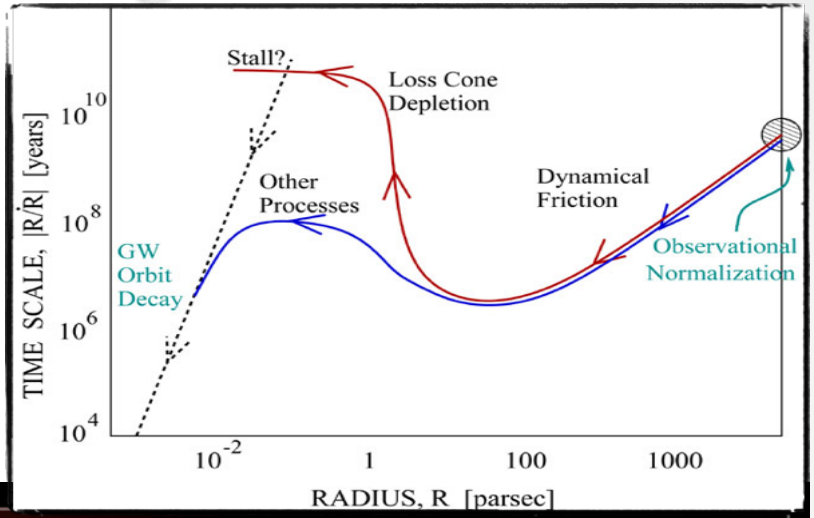
Translating GWB Limits and Astrophysical Parameters:

Binary Stalling

- Basic Model Assumption:
  Galaxy Merger occurs at same cosmological time as binary SMBH enters PTA band
- Relax Assumption:
  Introduce variable, T_{stall}, to allow time offset



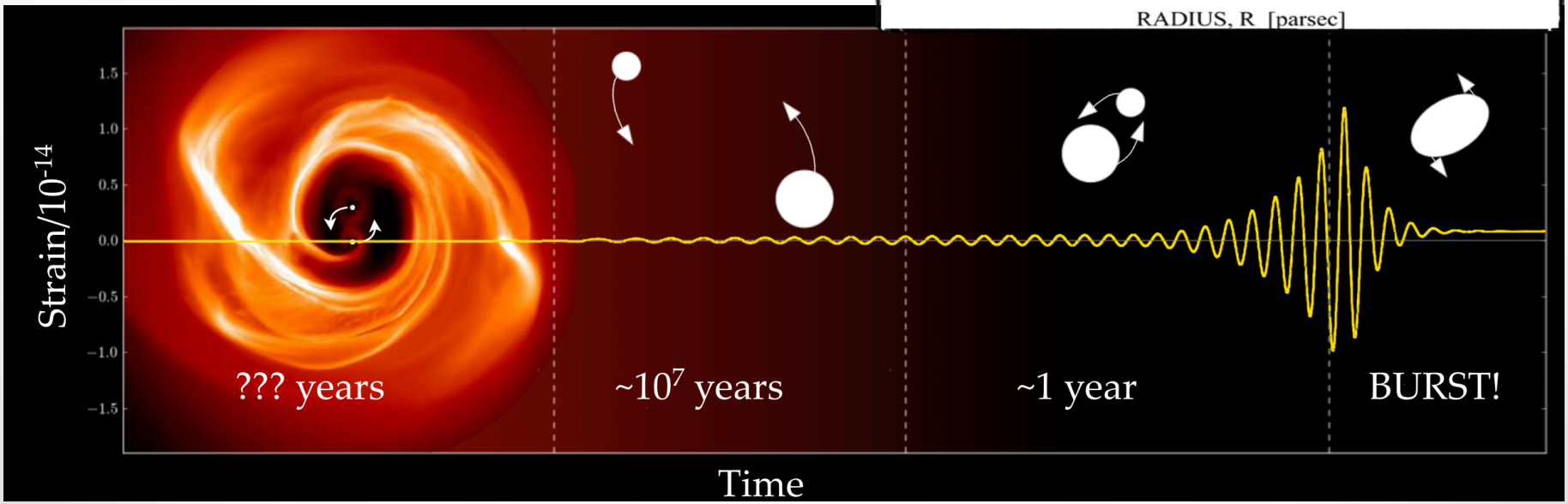
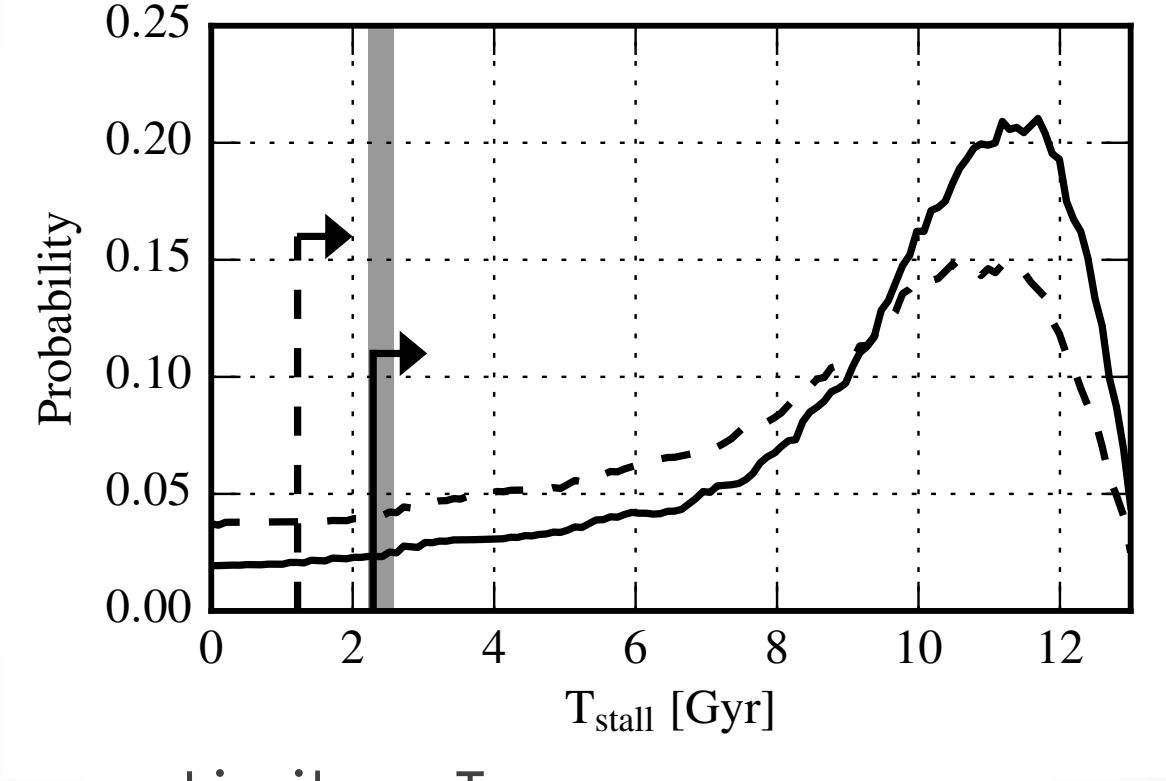


Image Credit: J. Cordes, D. Madison, S. Burke-Spolaor

Translating GWB Limits and Astrophysical Parameters:

Binary Stalling



- 95% Lower Limit on T_{stall}:
  - 2.3 Gyr with Kormendy&Ho 2013 [solid curve]
  - 1.2 Gyr with McConnel&Ma 2013 [dashed curve]

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Model for GW Background: Can We Improve M_{BH} Accuracy?

- Current SAM Models - Galaxy Stellar Mass Functions
  - Observed GSMF is split by morphology
  - Assume some fraction of mass is in bulge, again split by morphology
  - Calculate M_{BH} from M_{bulge}

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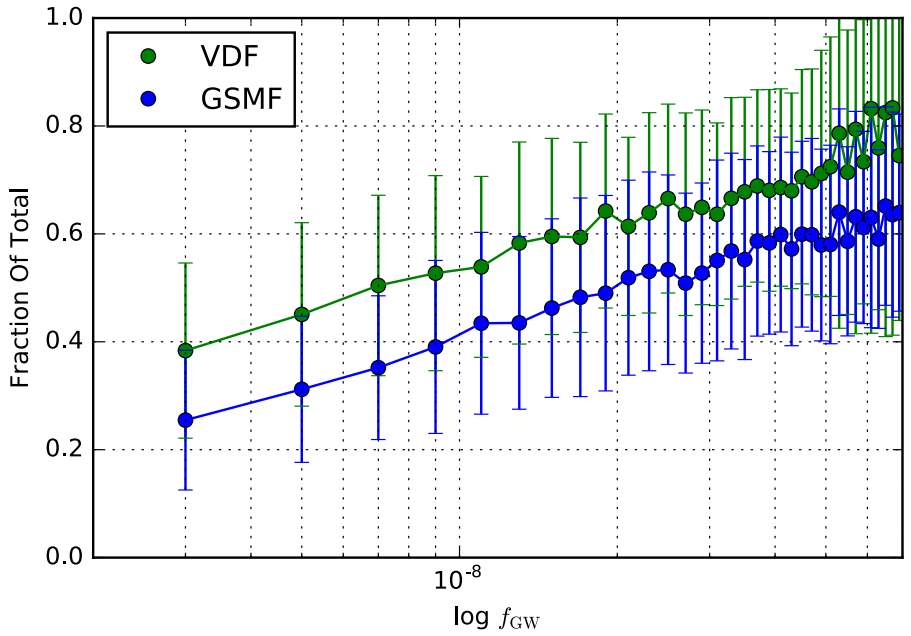
- Many Studies show σ to be better tuned to M_{BH} Can we use that?

- Velocity Dispersion Function [e.g. Bezanson+12]
  - No intermediate step to get from M_{galaxy} to M_{BH}
  - Less Intrinsic Scatter in $M_{BH} - \sigma$ relation than in M_{BH} - M_{Bulge}

Model for GW Background: Use Velocity Dispersion Function

- Overall Level of GWB is the same, but underlying distribution of binary SMBHs is different.



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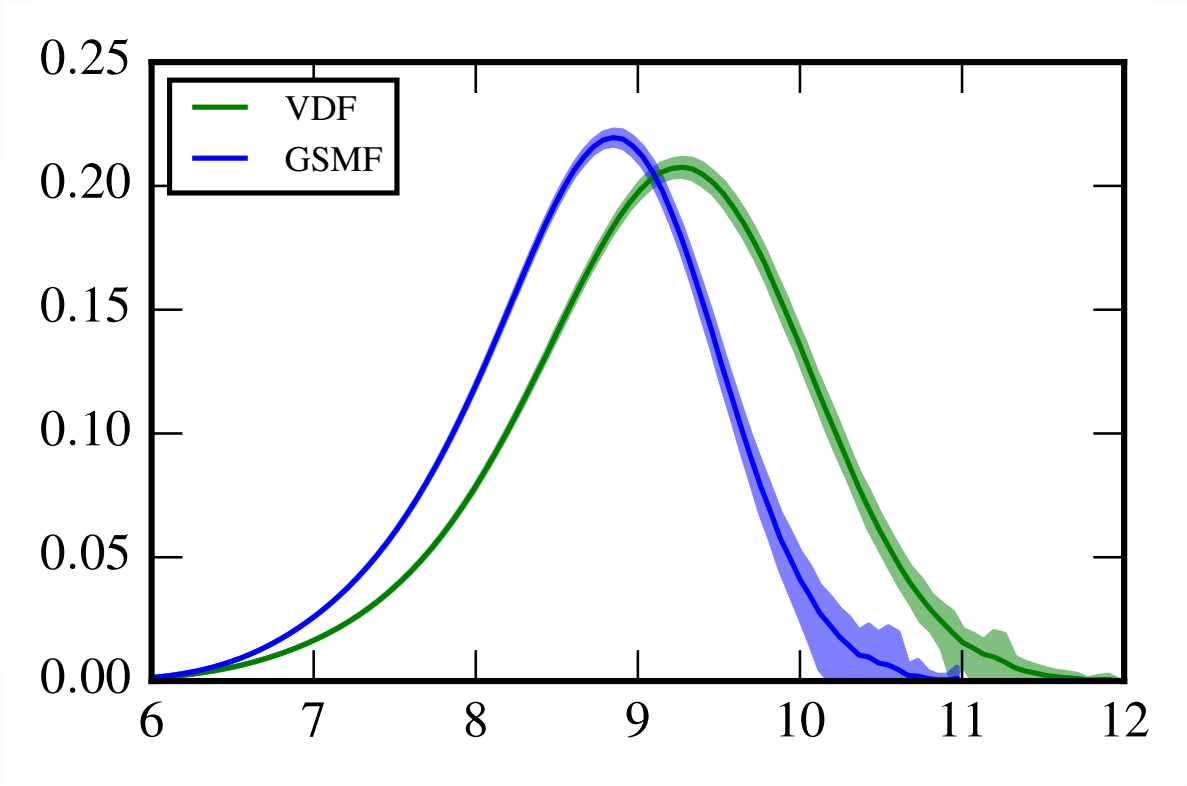
- VDF gives rise to larger single sources at lower frequencies
- Implications for individually resolvable sources and anisotropy

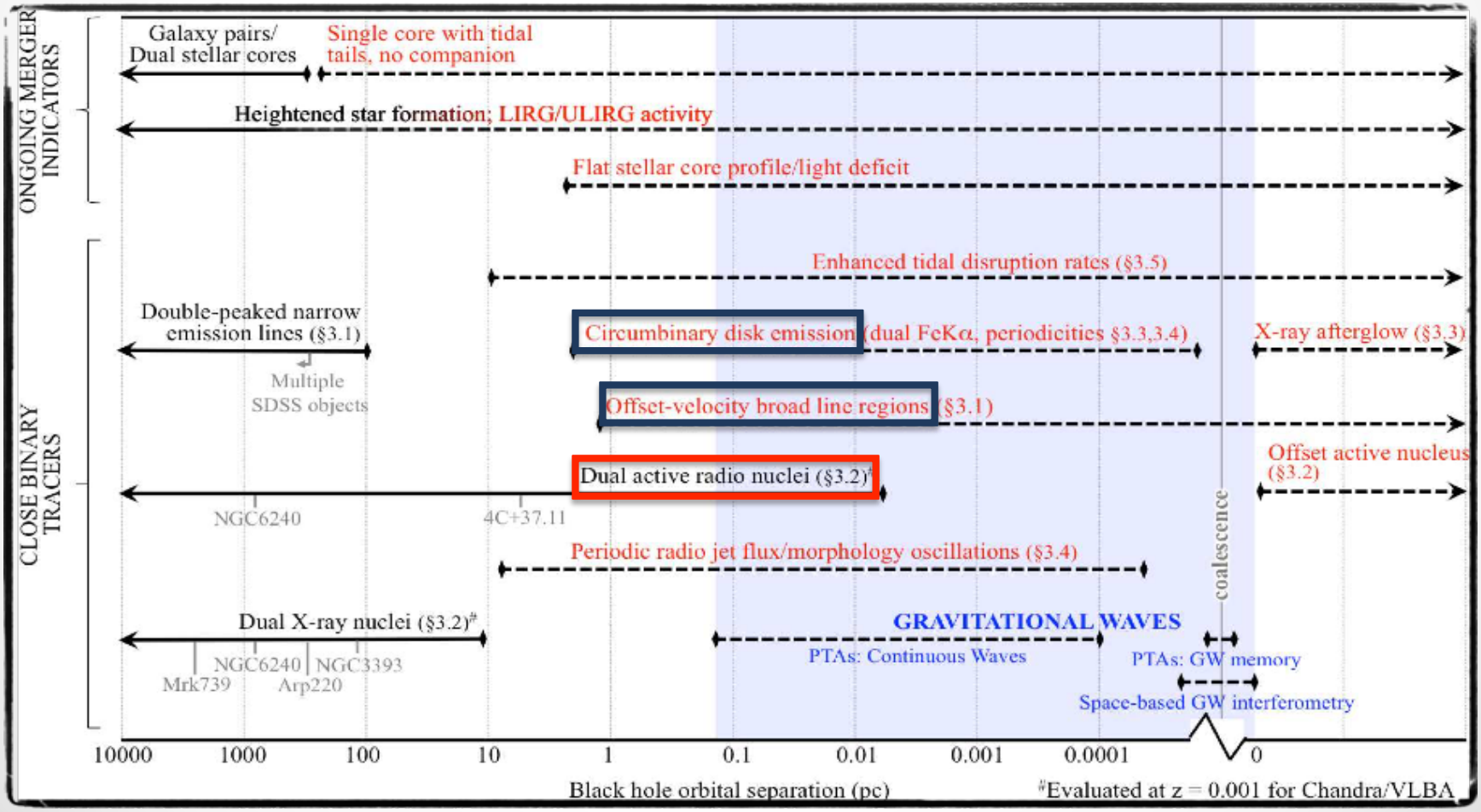
Summary

- PTA Upper Limits are currently informing Astrophysics discussions through out the community!
- PTA Limits can be used to directly inform individual parameters
  - Be Careful not to over interpret, as effects of many parameters are degenerate
- Uncertainties in BH-Host Galaxy Relation have a Major Impact on GWB models for PTAs
  - Different approaches to calculating M_{BH} give rise to various population demographics in the background


0.25
0.20
0.15
0.10
0.05
0.00
6
7
8
9
10
11
12
VDF
GSMF

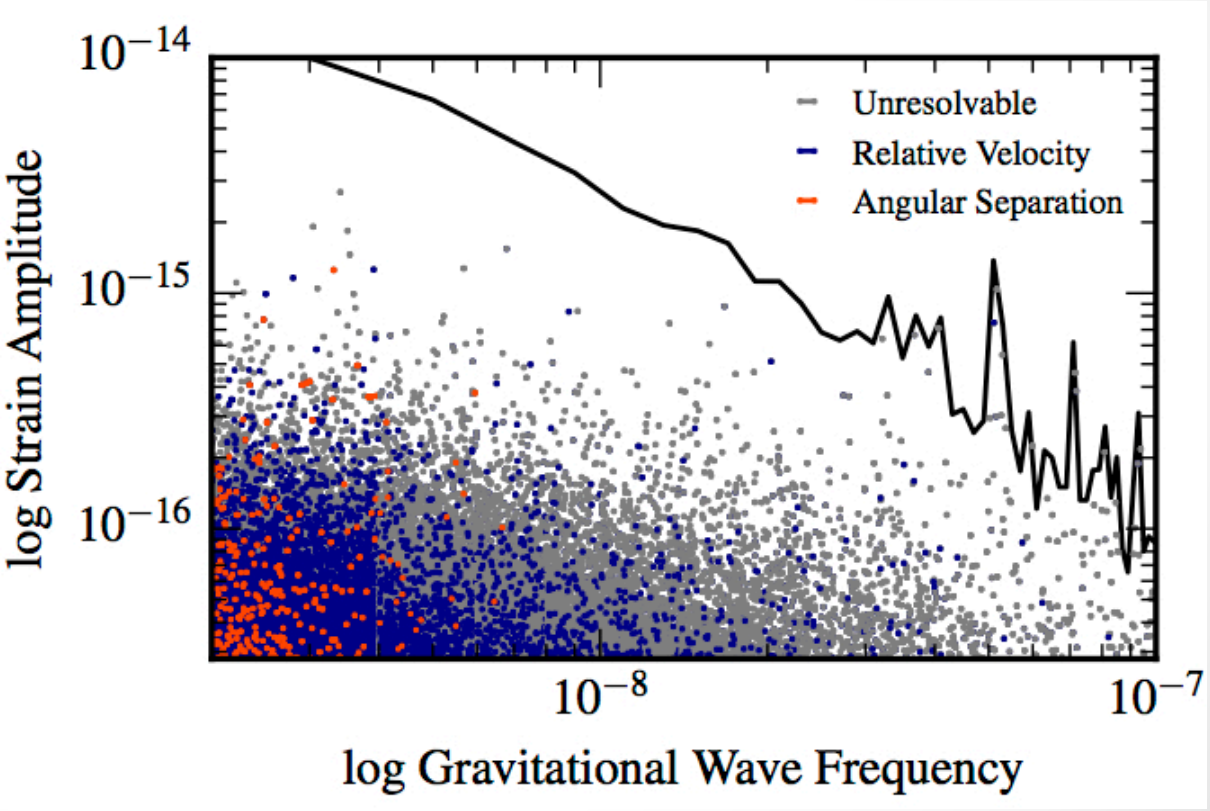
How Can We Learn More About Binary SMBH Environments?

- Use Expected Electromagnetic Signatures



Observing Individual Sources

- Dual AGN: Observable primarily at lower frequencies, when binary is entering PTA frequency band
- Individually resolvable source in both EM and GW is not likely



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