Rates of Stellar Tidal Disruption: Theory vs Observation

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10/28/15 EINSTEIN SYMPOSIUM

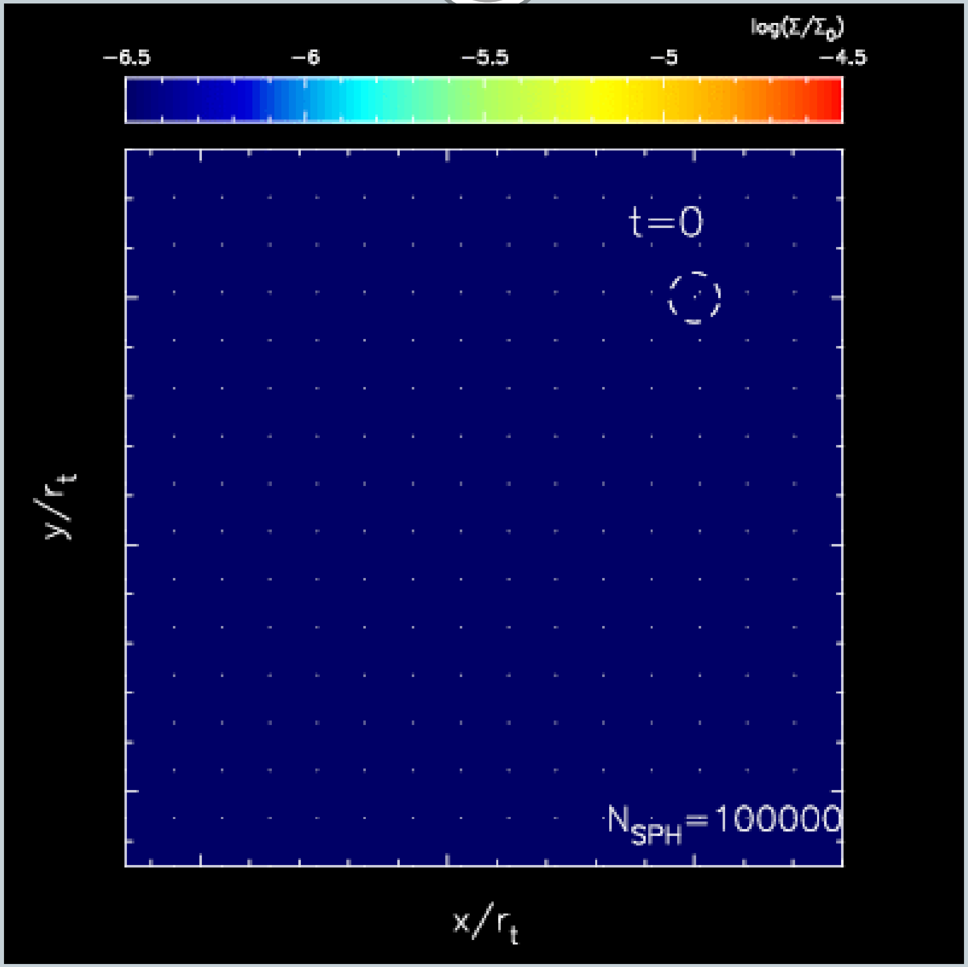
WITH BRIAN METZGER

Outline

- Missing flare problem
  - Theoretical two-body relaxation rate calculation
  - Large discrepancy between theory ($>10^{-4}$/yr) & observation ($\sim10^{-5}$/yr)
- Resolution?
  - Selection effects
  - Exotic dynamics
  - Emission mechanisms

(Wikimedia Commons)

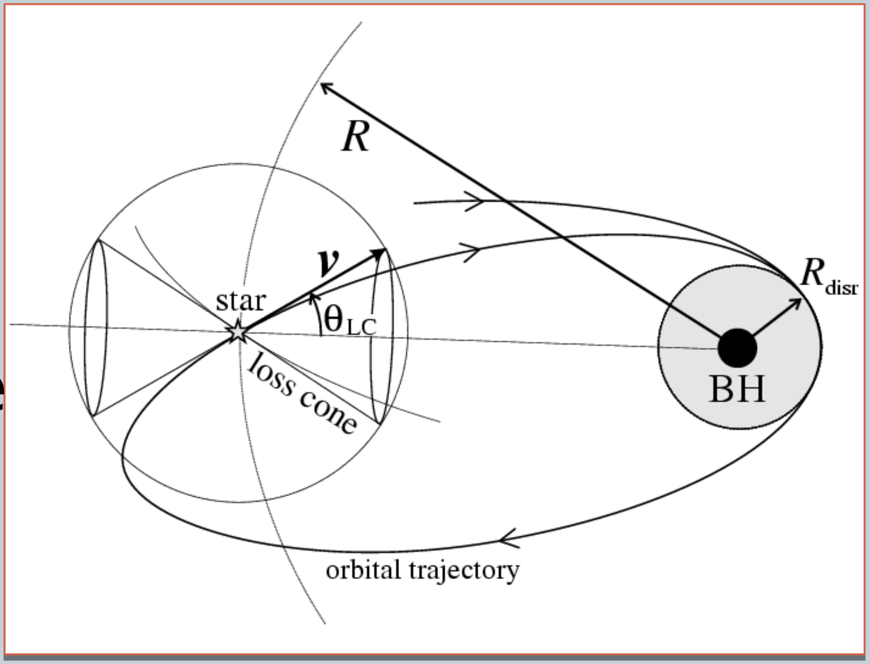
Tidal Disruption: Spinning SMBH



(Hayasaki, **Stone** & Loeb 2015)

Tidal Disruption Rates

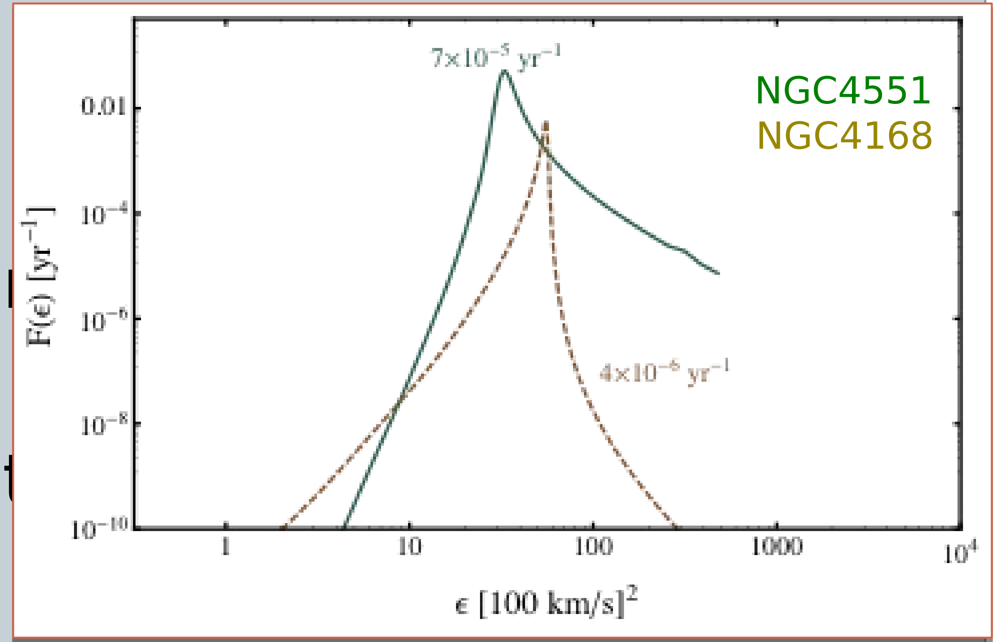
- Loss cone (two body scattering): $J<J_{LC}=(GM_{BH}R_t)^{1/2}$
  - Loss cone replenished via two-body relaxation
- Alternative relaxational mechanisms increase rate
- Motivations
  - Tension between theory (10^{-4} yr^{-1}) and observation (10^{-5} yr^{-1})
  - Probe of low mass SMBH demographics?



(Freitag & Benz 02)

Two Body Scattering Rates

- Our approach: take Nuker galaxy sample, apply Wang & Merritt 04
- Deproject I(R)
  - Calculate ρ(r), f(ε)
- Orbit-average diffusion coefficients μ(ε)
- Calculate flux, F(ε), into loss cone
- Integrate over stellar PDMF, vary I(R), relax other assumptions…



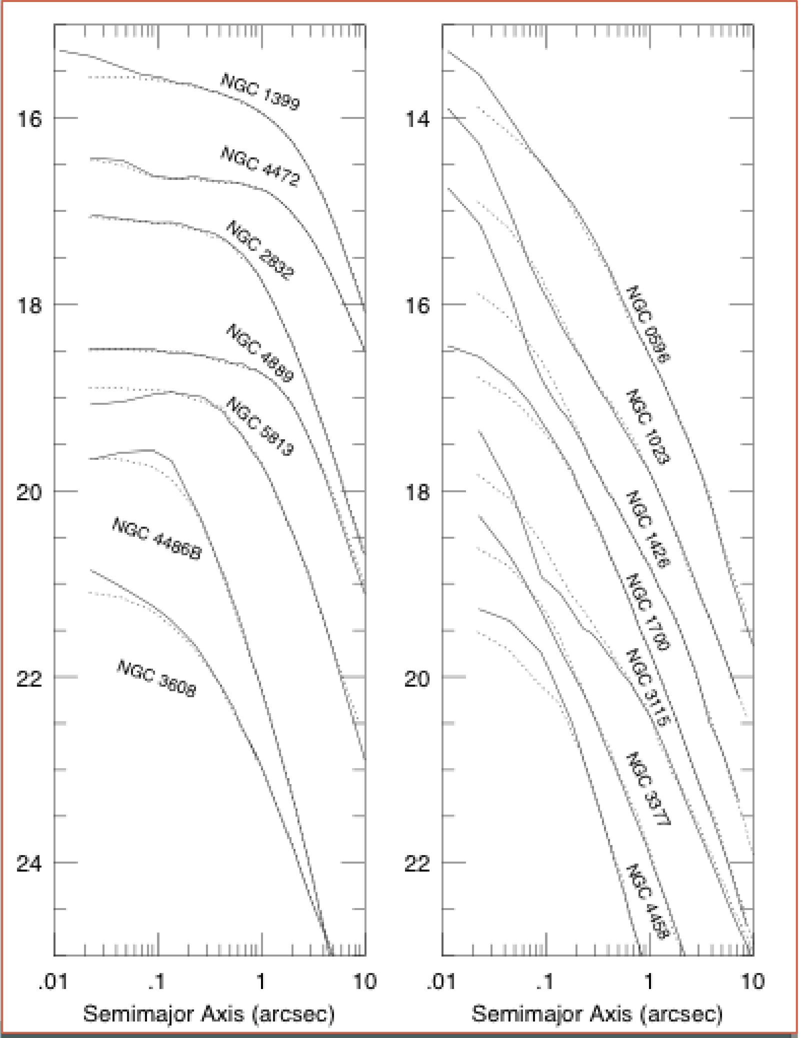
(**Stone** & Metzger 15)

Galaxy Sample

- "Nuker" galaxy sample (Lauer+05, Lauer+07)
- High resolution HST imaging
  - Fit to parametrized profile:

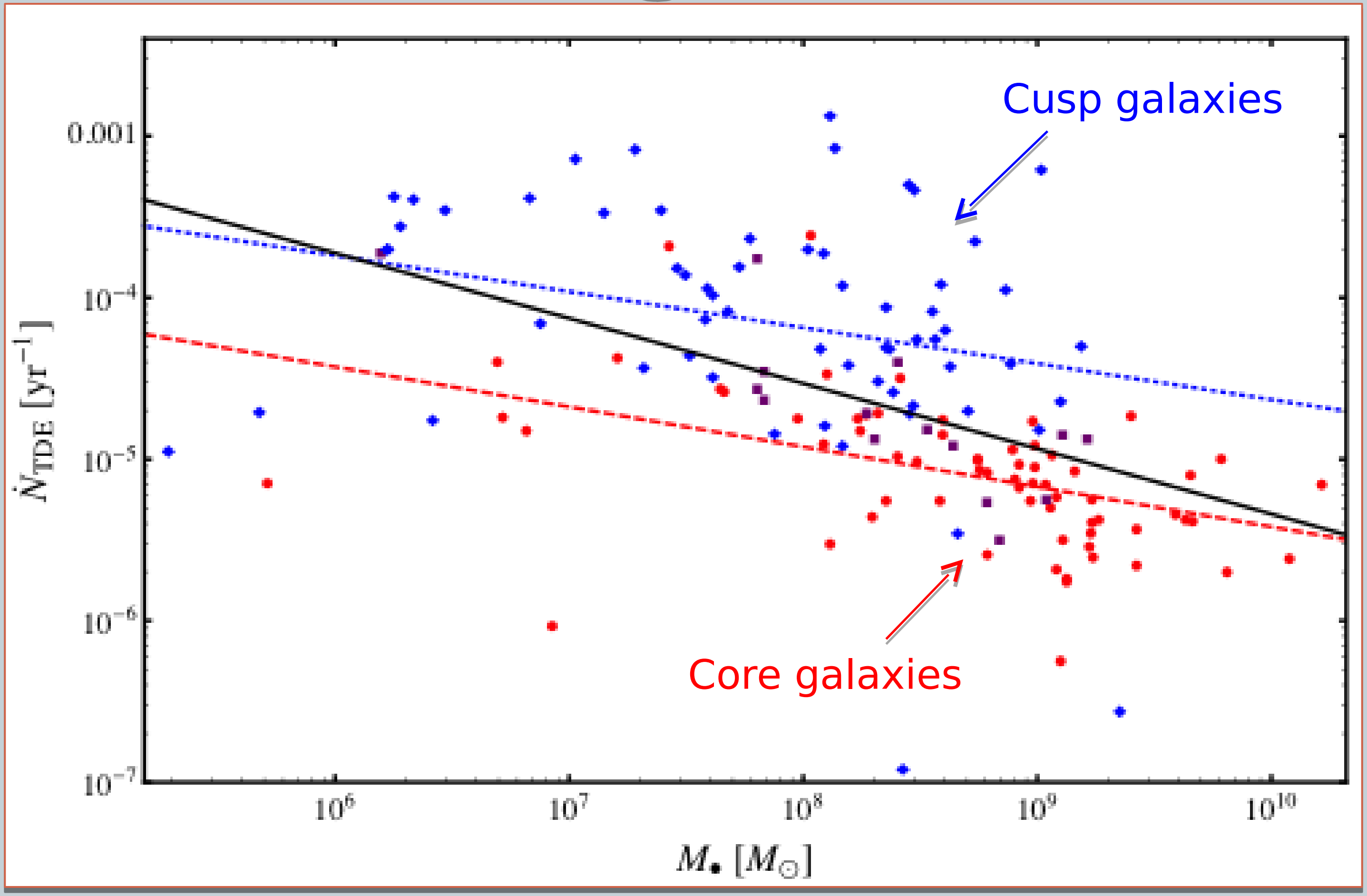
$$I(R) = 2^{(\beta-\gamma)/\alpha} I_b \left(\frac{R_b}{R}\right)^{\gamma} \left(1 + \left(\frac{R}{R_b}\right)^{\alpha}\right)^{(\gamma-\beta)/\alpha}$$

- Black hole masses calculated from M_{BH}-σ
- 144 galaxies after rejections (<40 in past works)



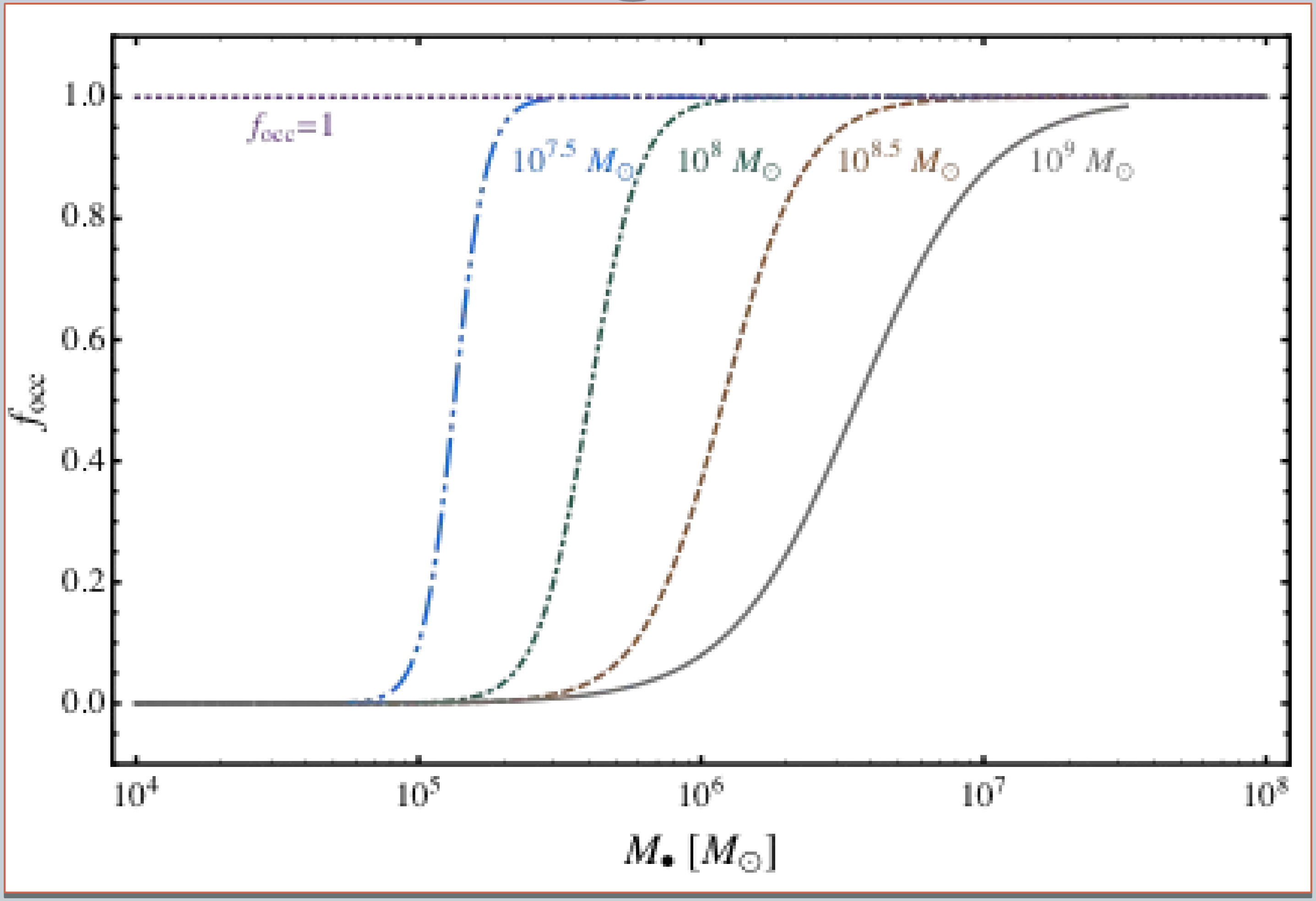
(Lauer+05)

TDE Rates



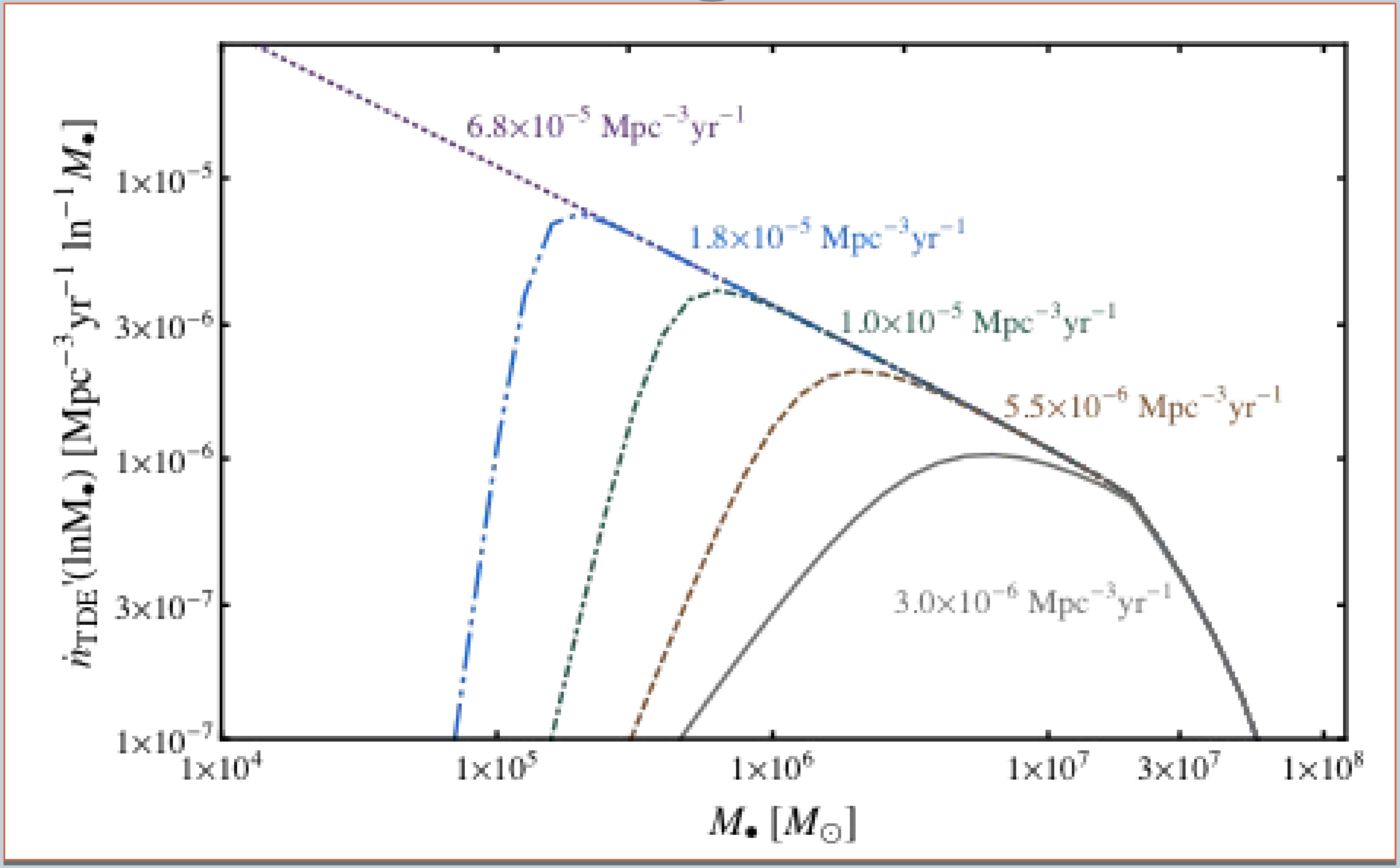
(**Stone** & Metzger 15)

Occupation Fractions



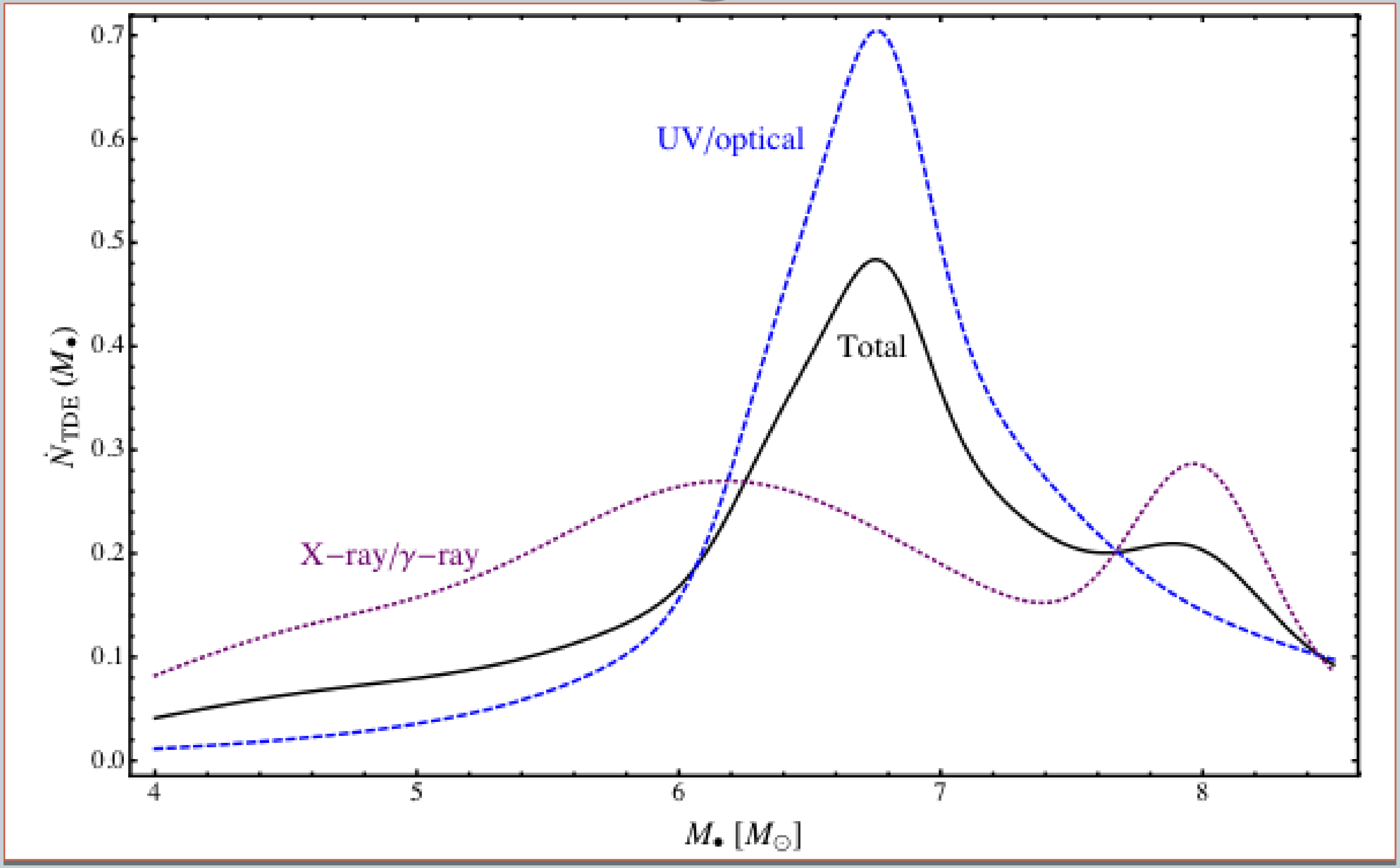
(**Stone** & Metzger 15)

Intrinsic TDE Rates



(**Stone** & Metzger 15)

Observed SMBH Masses



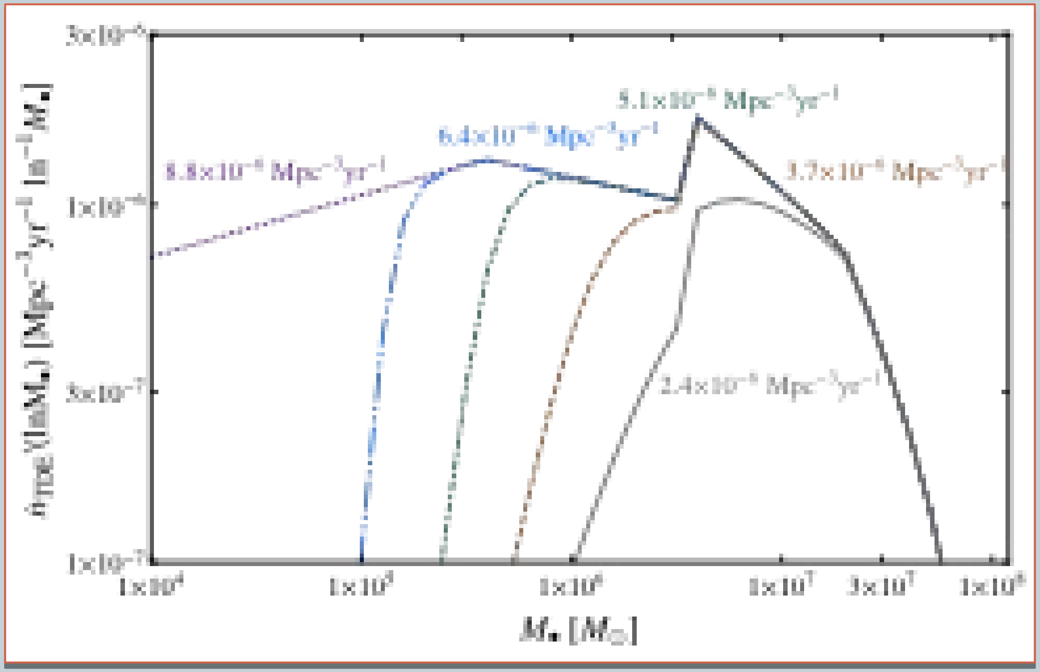
(**Stone** & Metzger 15)

Rates Discrepancy

- Persistent! Our calculation is conservative:
  - 2-body relaxation only
  - Neglect enhanced diffusion from remnants
  - Spherical symmetry
- Possible ways out:
  - *Not* occupation fraction
  - *Probably not* dust obscuration
  - *Maybe* selection effects – but see van Velzen & Farrar 14
  - Strong and tangential velocity anisotropies? Aka SMBH binaries? (Lezhnin & Vasiliev 15)
  - Bimodality in optical emission?

Circularization-Limited Emission?

- Prompt circularization may require relativistic R_p
- Extreme R_p cutoff required to remove rate tension
  - Shown below: $R_p/R_g<12$ cut



(**Stone** & Metzger 15)

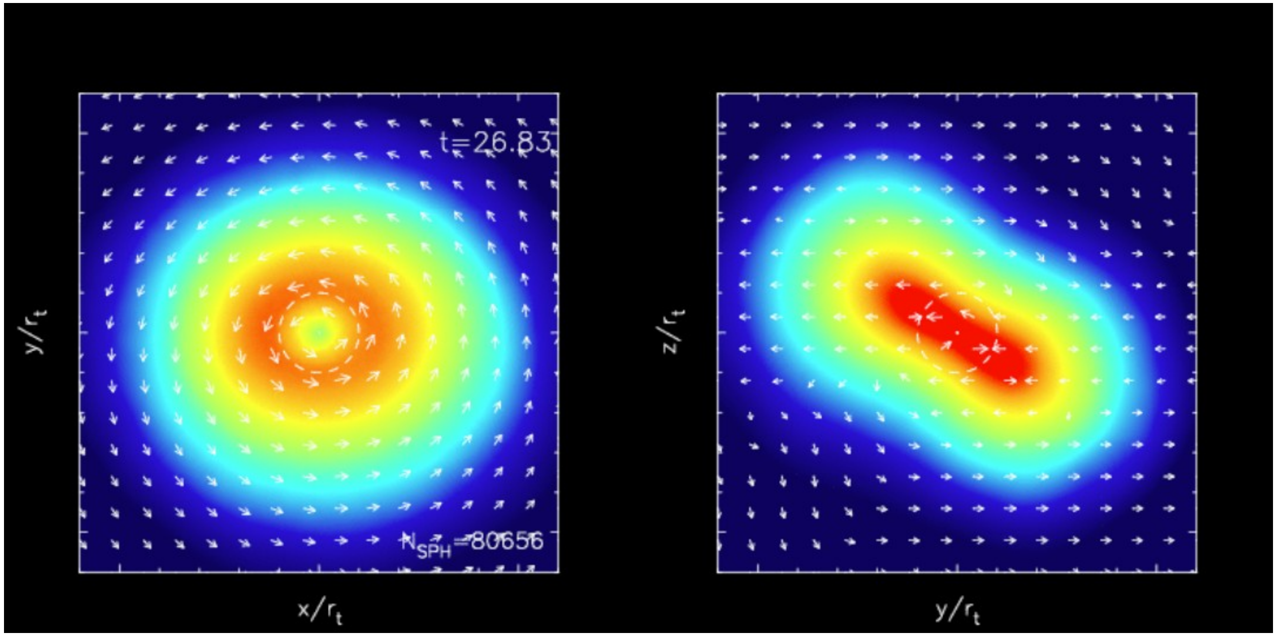
Conclusions

- Discrepancy between theory and observation?
  - Persistent! Even for 2-body scattering
  - Gets worse with realistic IMF, alternate galaxy parametrizations, alternate relaxational mechanisms…
- Several possible resolutions
  - Bimodal emission appears most promising
  - Severe circularization requirements on R_p possible explanation
- Intrinsic TDE rates sensitive to SMBH occupation fraction, observable rates may not be

Questions?

Tidal Disruption of Stars

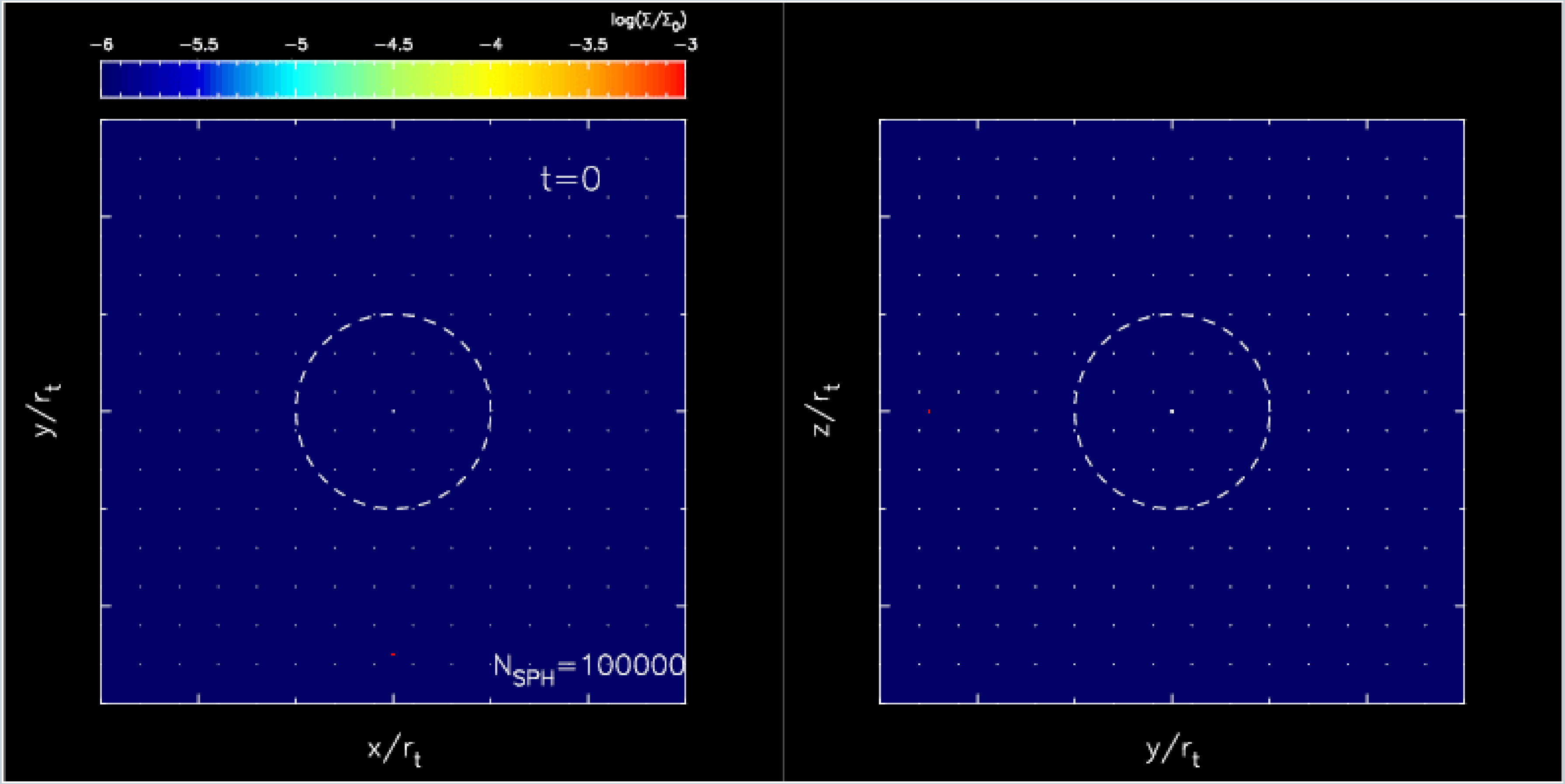
- Disruption when $R_p < R_t = R_*(M_{BH}/M_*)^{1/3}$
- Laboratory for accretion/jet astrophysics
  - Super-Eddington flows
  - Jet launching mechanisms



(Hayasaki, **Stone**, & Loeb 15)

- Unique probe of quiescent galactic nuclei
  - M_{BH} [a_{BH}?] from *lightcurve, SED*; stellar dynamics from *rates*

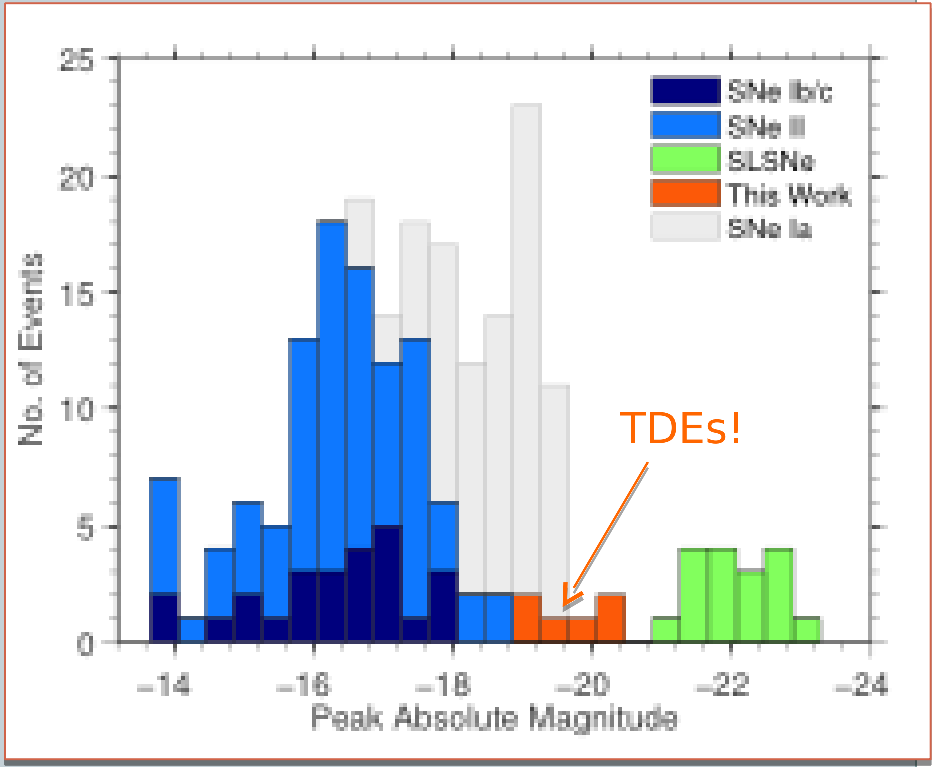
Kerr Circularization



(Hayasaki, **Stone** & Loeb 2015)

Observational Summary

- ~20 strong candidates
  - First found in X-ray
  - Then UV/optical (PTF, Pan-STARRS)
  - ~10^{-5}/galaxy/yr
- Recent surprises:
  - Relativistic jets! (Bloom+11, Zauderer+11)
  - Hydrogen-free spectra? (Gezari+12)
  - ~20% in E+A (Arcavi+ 14)
- Upcoming time domain surveys expected to see ~10s-1000s/yr
  - LSST particularly promising (Strubbe & Quataert 09)



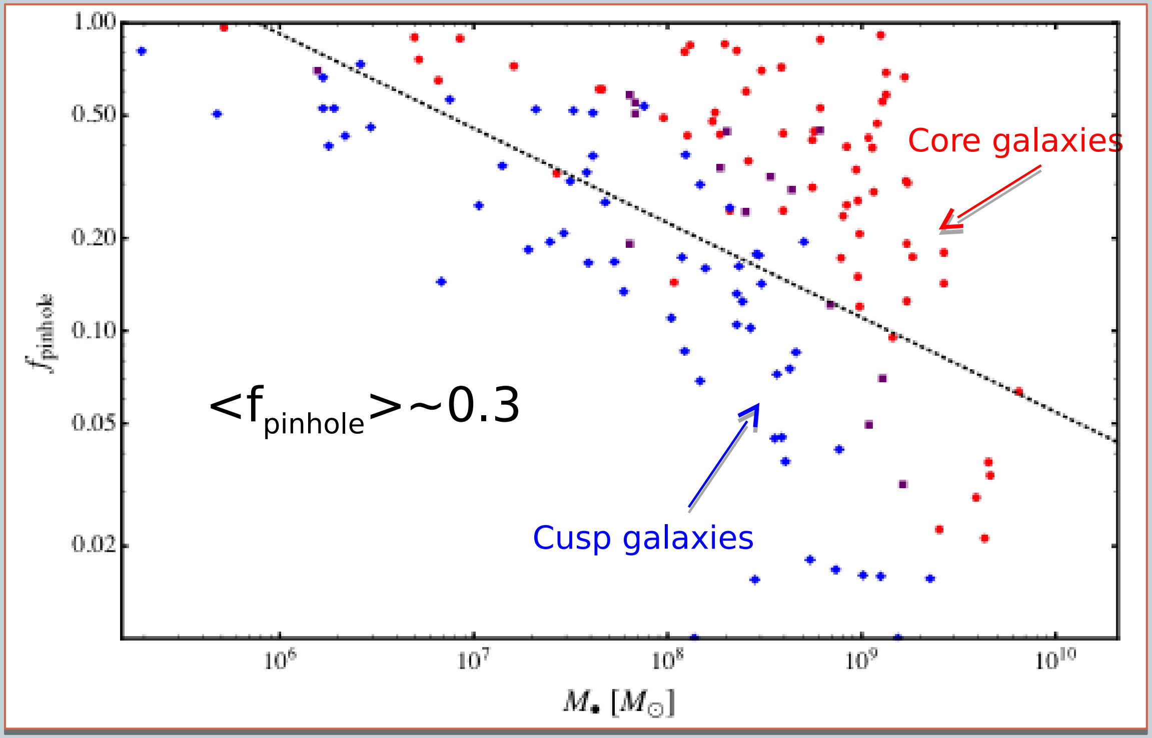
(Arcavi+ 14)

Uncertainties in 2-Body Calculations

- Choice of I(R) parametrization
  - Nuker, Sersic, core-Sersic all similar in results
- Scaling relations
  - Unimportant
- Symmetry assumptions
  - Sphericity conservative
  - Isotropy mixed – radial bias ups rates, tangential decreases
- Stellar mass function
  - Functional form (Kroupa vs Salpeter) unimportant
  - Smallest stars dominate rate, heaviest diffusion coefficients
  - Stellar remnants *important*

Pinhole Fraction

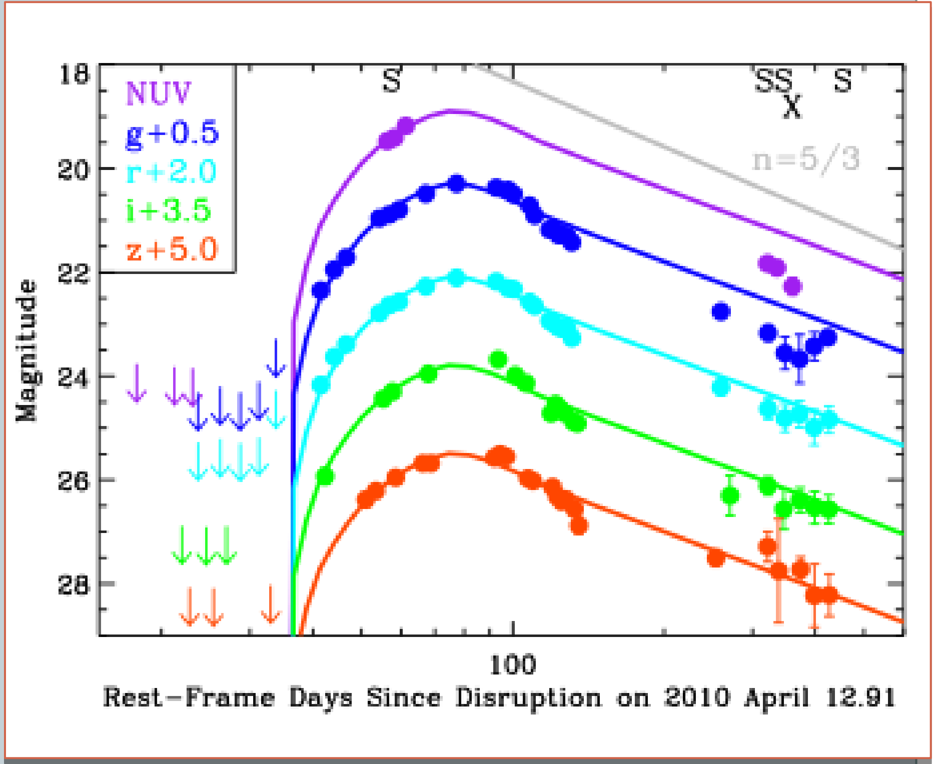
- Two regimes of tidal disruption
- Identified by $q(\varepsilon)=(\Delta J/J_{LC})^2$
  - $J_{LC}=(GM_{BH}R_t)^{1/2}$
- Diffusive regime: $q<1$, $\beta=R_t/R_p=1$
- Pinhole regime: $q>1$, $N(\beta) \propto \beta^{-1}$
  - Only ~50% partial disruptions



(**Stone** & Metzger 14)

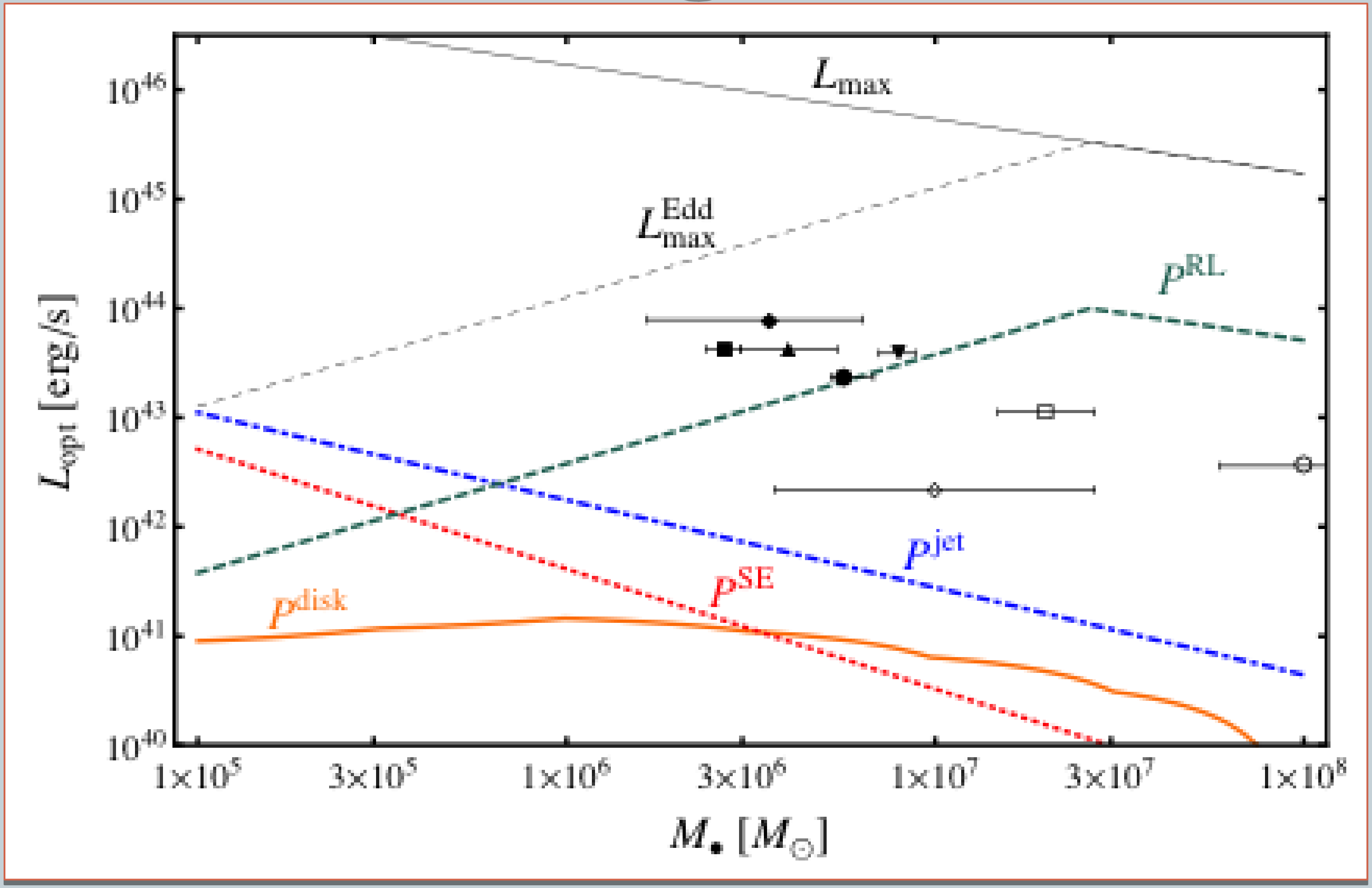
Optical Emission from TDEs

- Highly uncertain, many proposed mechanisms
  - Reprocessing layer (e.g. Loeb & Ulmer 97, ZEBRA, Guillochon+14)
  - Outflows (fade too fast, $t^{-95/36}$, but see Metzger & Stone 15)
  - Accretion disk (too dim, fade too slow, $t^{-5/12}$)
  - Relativistic jet (nonthermal spectrum, radio nondetections)
- Our paper: agnostic



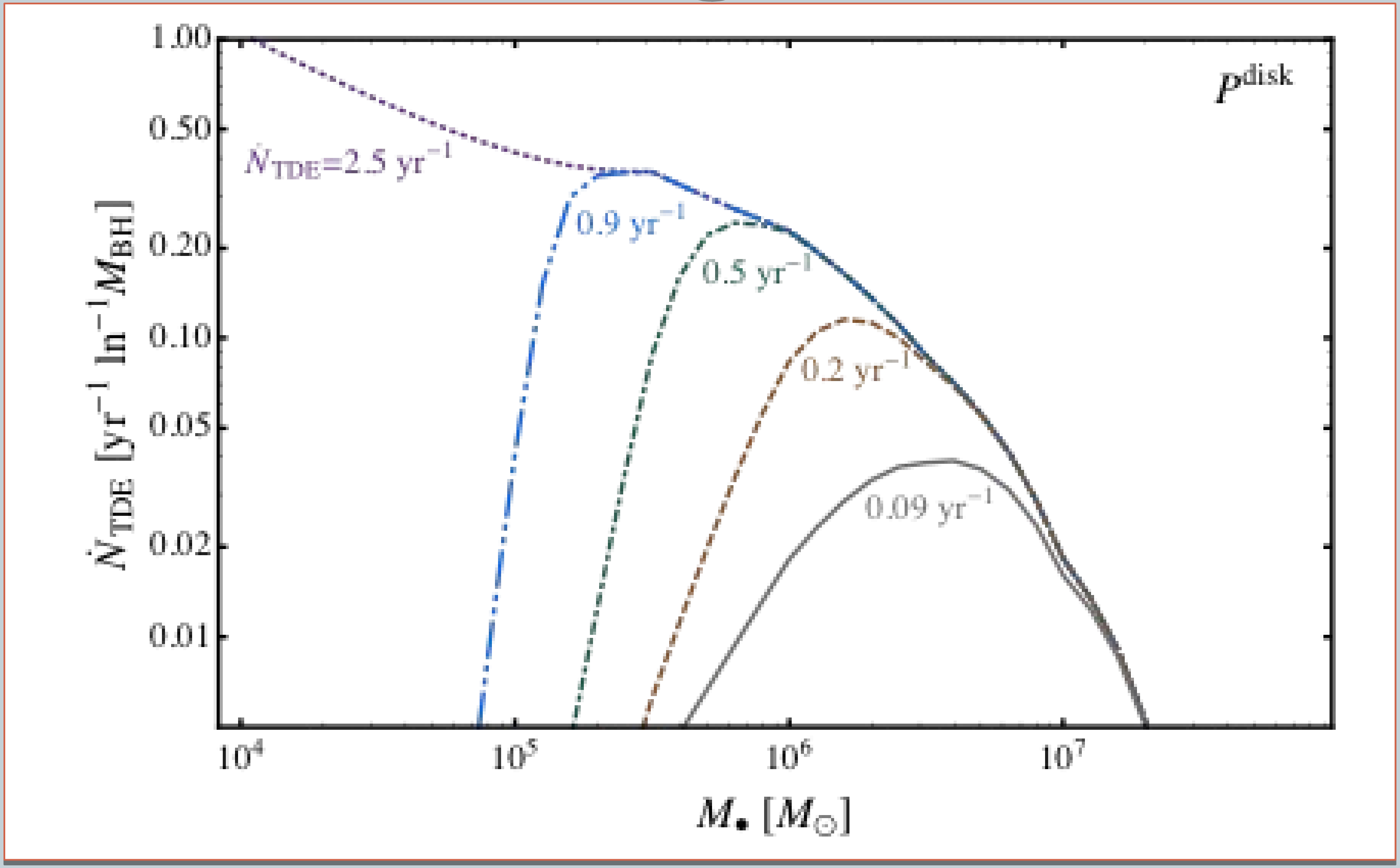
(Gezari+ 12)

Peak Luminosities



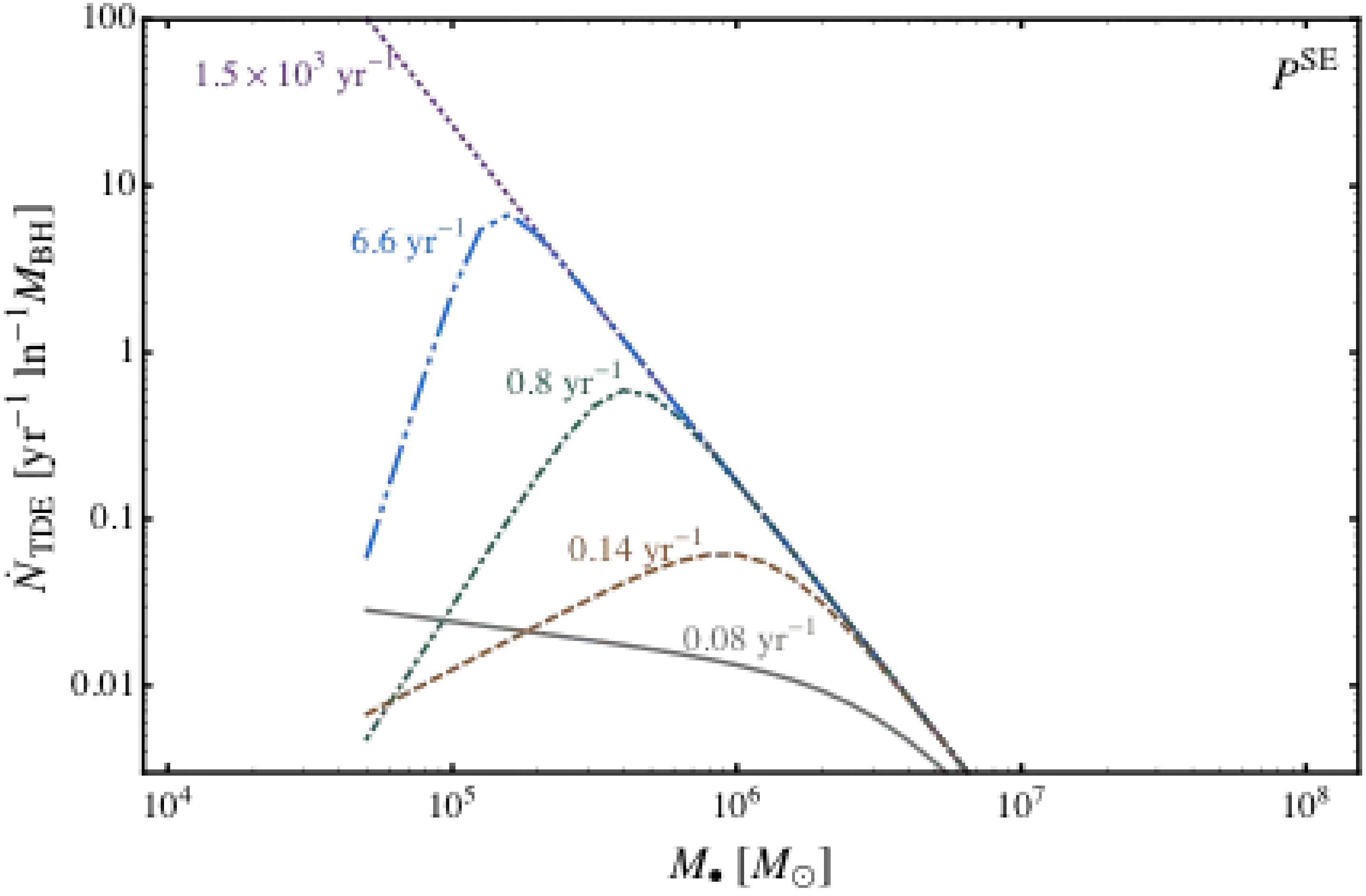
(**Stone** & Metzger 14)

Detectable TDE Rates (Disk)



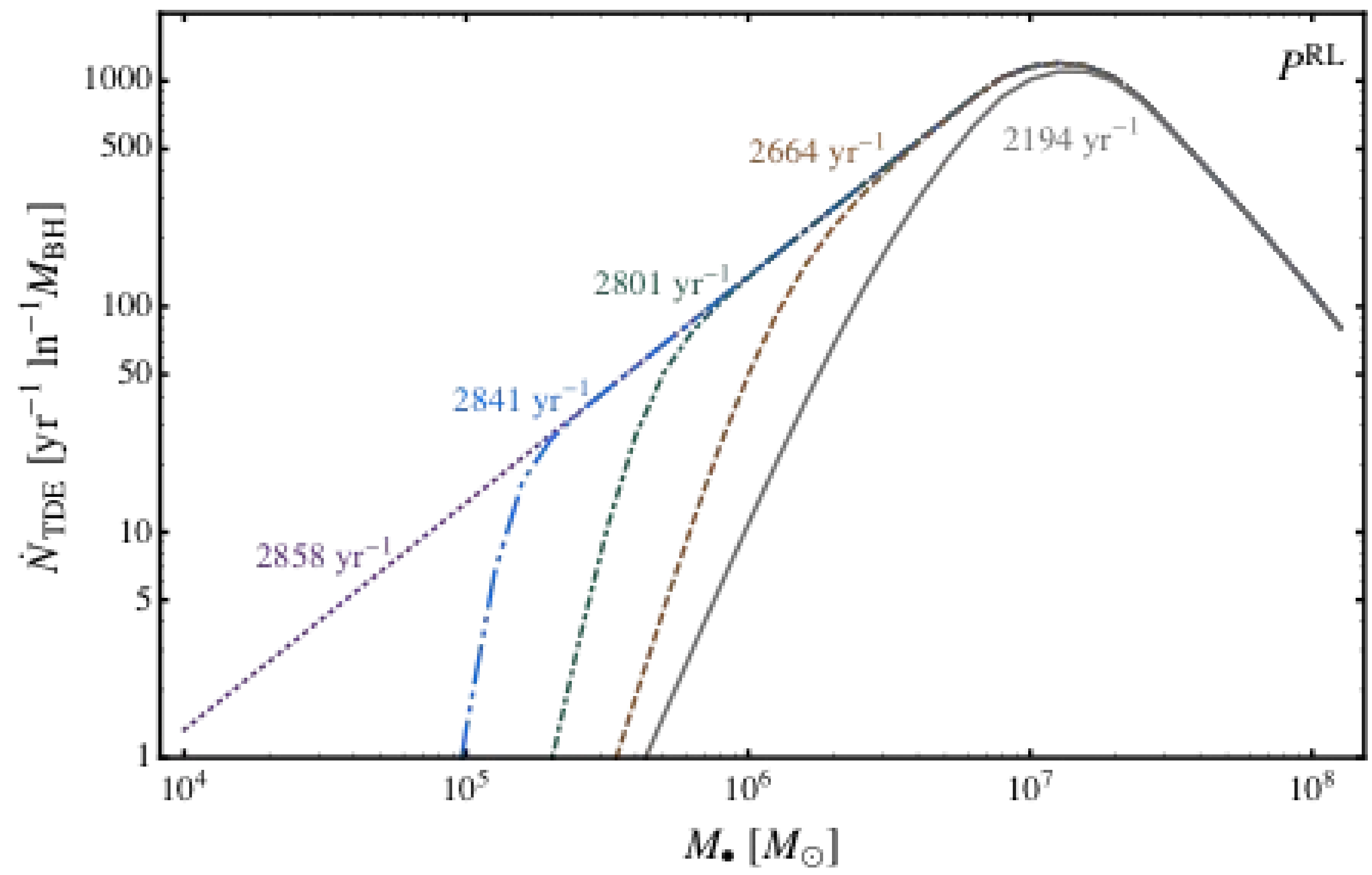
(**Stone** & Metzger 14)

Detectable TDE Rates (Outflow)



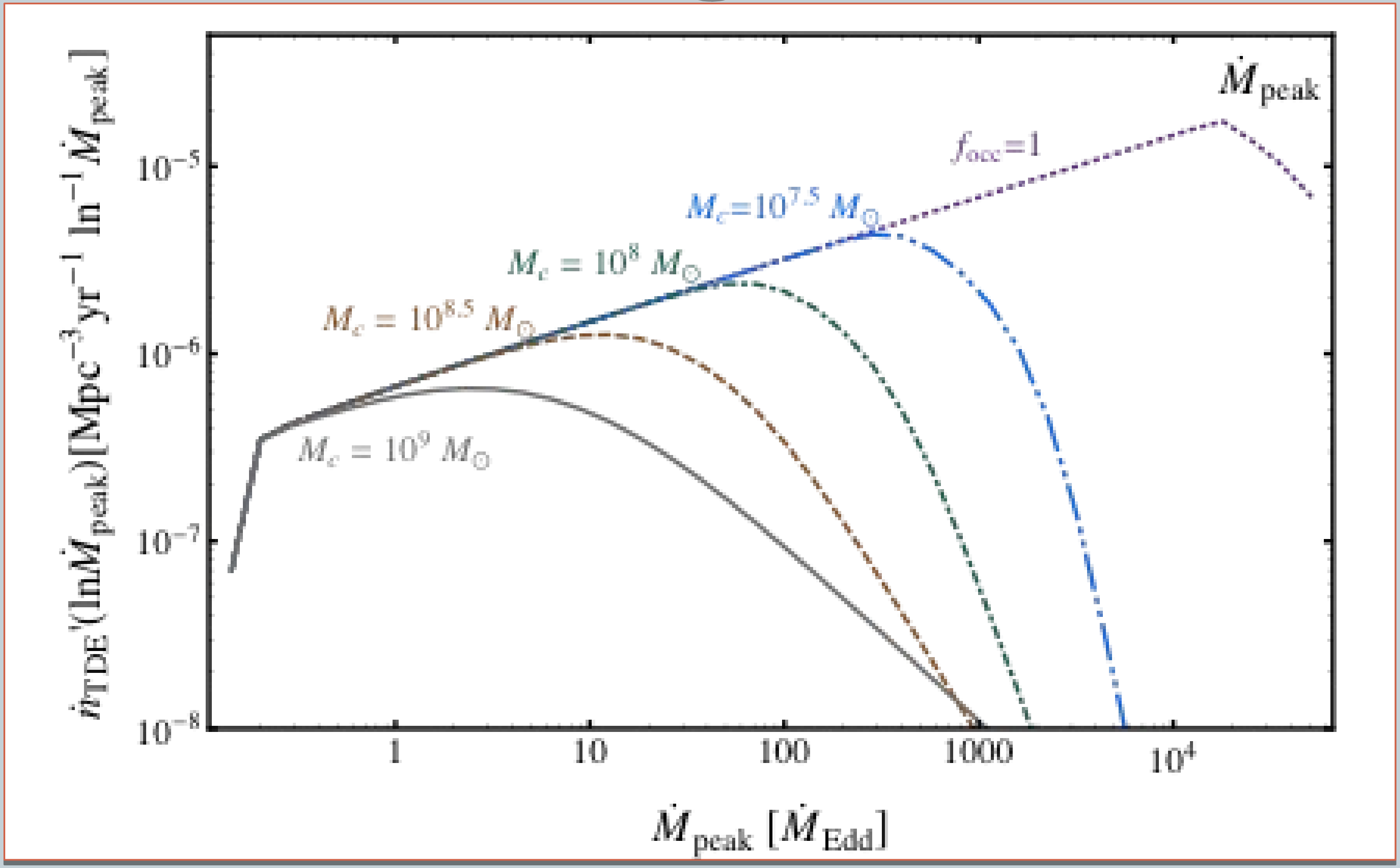
(**Stone** & Metzger 14)

Detectable TDE Rates (Reprocessing Layer)



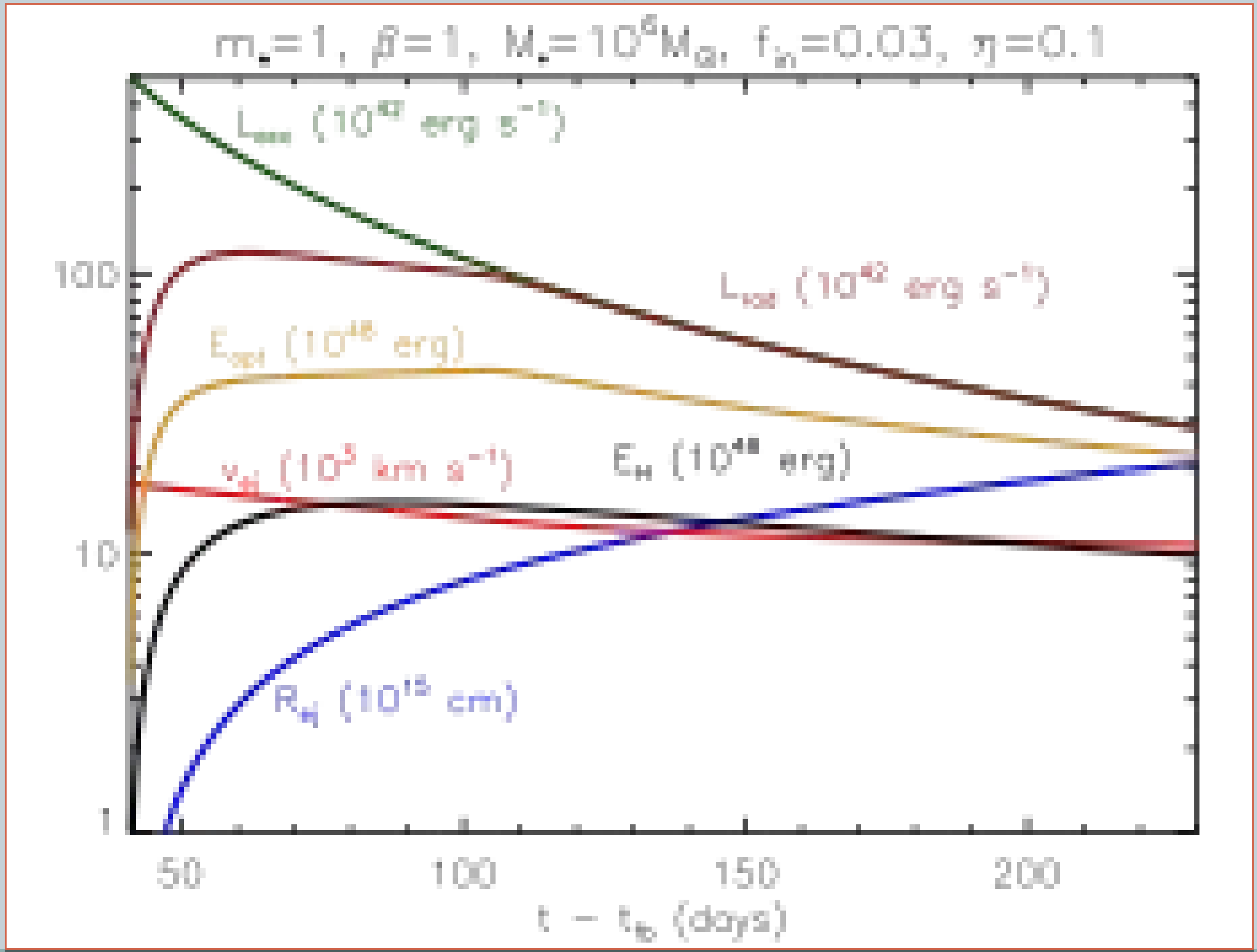
(**Stone** & Metzger 14)

Intrinsic Fallback Rates



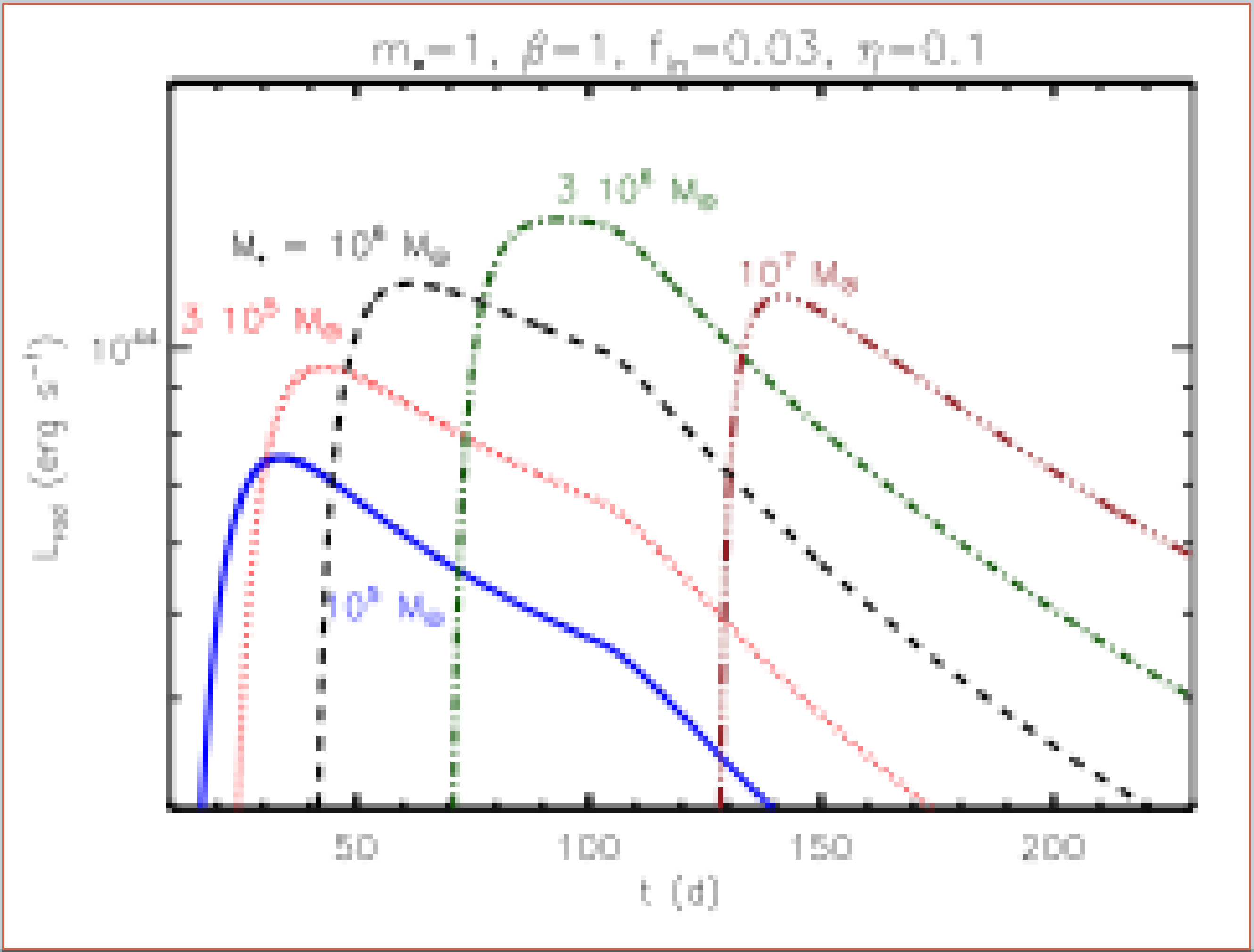
(**Stone** & Metzger 14)

Outflow Evolution



(Metzger & **Stone** 15)

Lightcurves: β=1



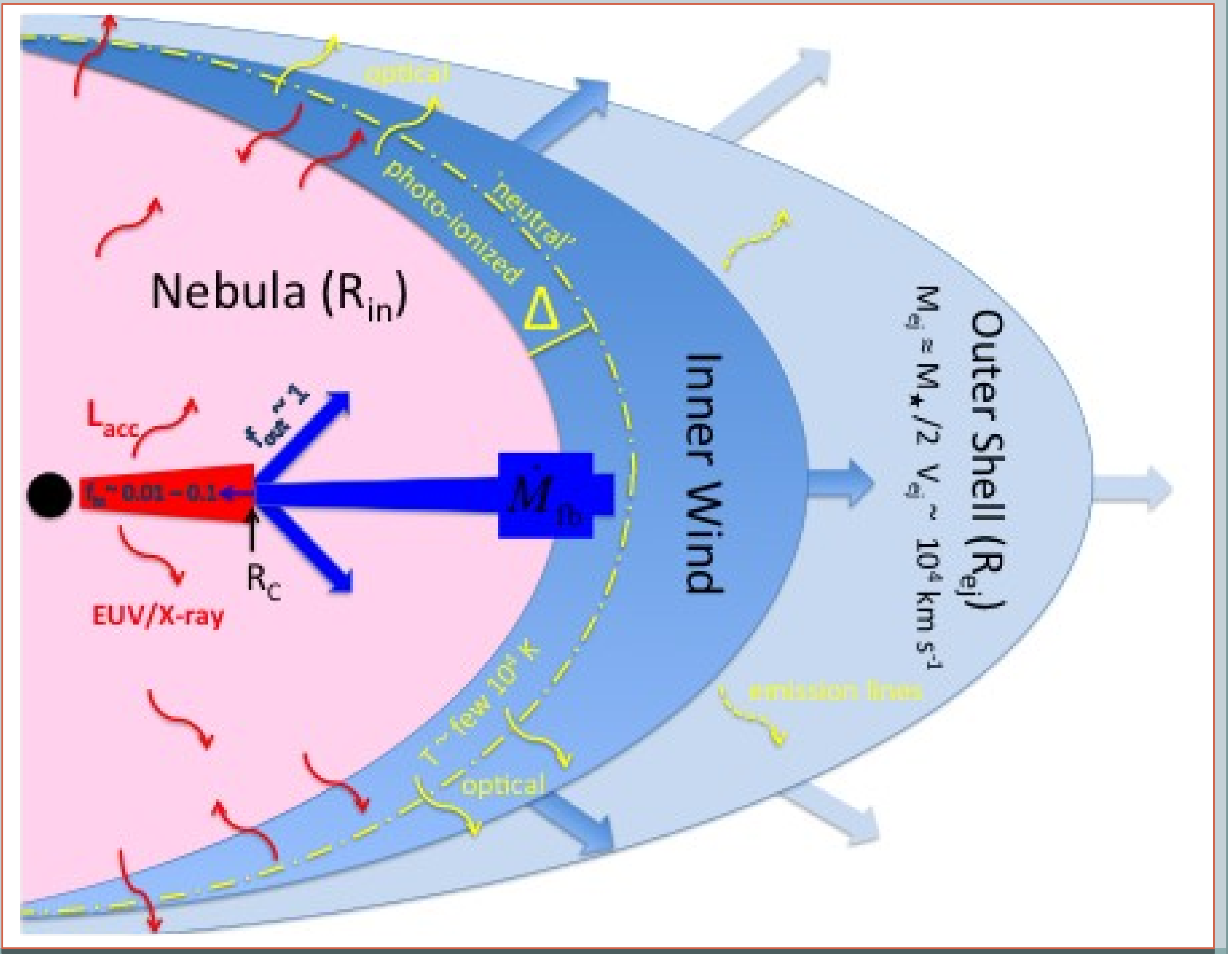
(Metzger & **Stone** 15)

What's Going on in the Optical?

- Spreading disk far too dim to explain observations
- Super-Eddington mechanisms extremely sensitive to f_{Occ}
  - Optical synchrotron constrains jet launching fraction
- Reprocessing layer model ad hoc, closest to observations
  - Detected rate tension unless reprocessing fraction low: kill two birds with one stone?
  - Circularization efficiency?
- Current MBH sample inhomogeneous, but nonetheless:
  - May rule out super-Eddington optical mechanisms

Our Model: Outflows++

- Mass-loaded
  - f_{in} << 1
  - Debris very weakly bound
- Slow
  - V_{ej}~10^{3-4} km/s
- Opaque
  - Bound-free > electron scattering



(Metzger & **Stone** 15)

Model Predictions

- Optical lightcurve predictions
  - Adiabatic losses minor, except for small SMBHs
  - Details dependent on outflow properties
- Late-time optical disappearance; X-ray breakout
  - Probable direction dependence (AS-14LI?)
  - Optically selected flares: late-time followup
  - X-ray selected flares: need better cadence