

ブラックホールと 高エネルギー宇宙

Black Holes and High Energy Universe

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HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION



25 Sep 2015

BH & HE Universe by Kunihito IOKA

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2

特集「発展し続ける一般相対論」

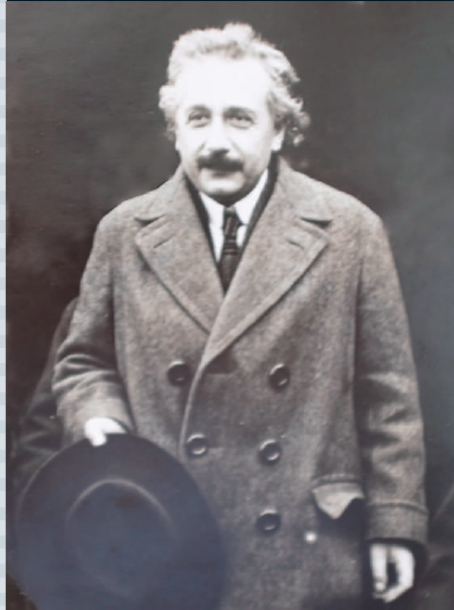
代議員選挙(信任投票)

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**General
Relativity**



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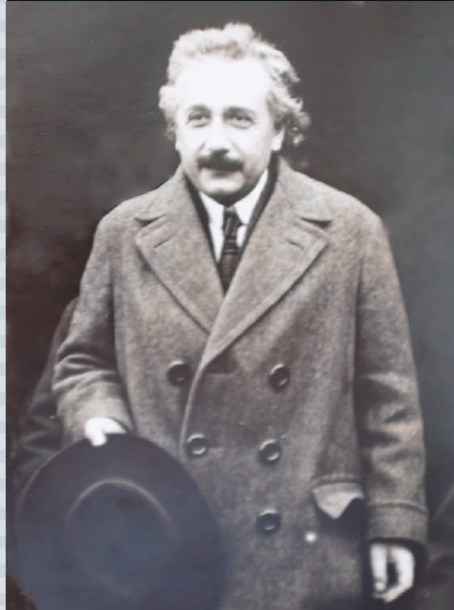
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**General
Relativity**



Book

KEK物理学シリーズ

3

宇宙物理学



高エネルギー加速器研究機構 [監修]

[著]

小玉英雄
井岡邦仁
郡 和範

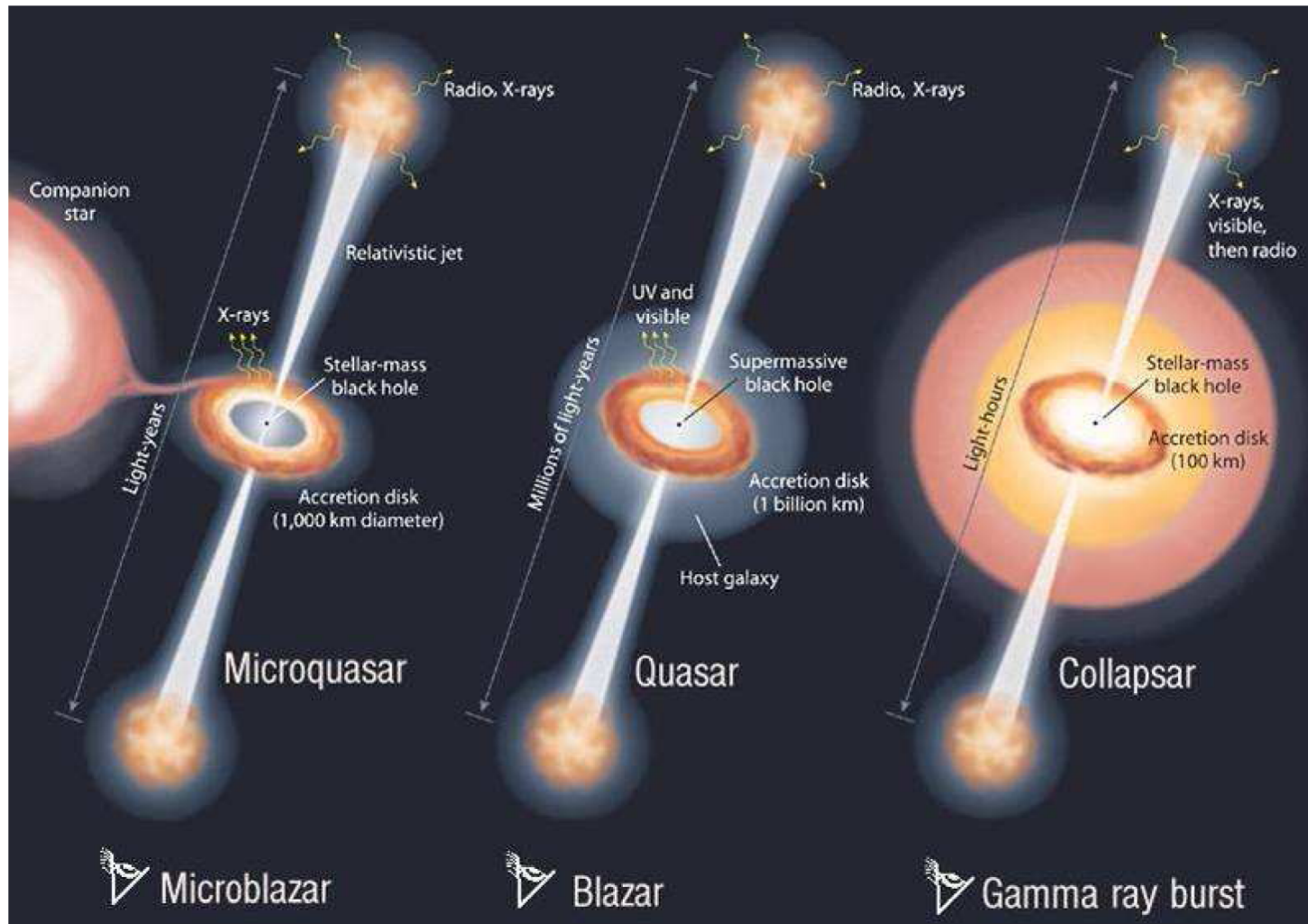
共立出版

- KEK素粒子原子核研究所に創設された宇宙物理学理論グループの現在のメンバーが総力を結集して書いた宇宙物理学の教科書。
- 素粒子宇宙論、高エネルギー天体物理、宇宙線の全般についてその基礎から最前線の研究までカバーする。
- 1章: 宇宙の姿
- 2章: 星の構造・進化
- 3章: 超新星爆発とガンマ線バースト
- 4章: 中性子星、ブラックホール
- 5章: 高エネルギー宇宙線・ γ ・ ν や重力波
- 6章: 宇宙マイクロ波背景放射(CMB)
- 7章: 宇宙初期における元素合成
- 8章: ダークマター、バリオン数生成
- 9章: インフレーション

100 Years Ago

- We did not know the concept of BH
- We did not know that BHs are observed as brightest sources in the universe
- We did not know that BHs are observed as highest energy sources in the universe

Observed BHs

 $\sim 10 M_{\odot}$ $\sim 10^6 - 10^9 M_{\odot}$ $\sim 10 M_{\odot}$ 

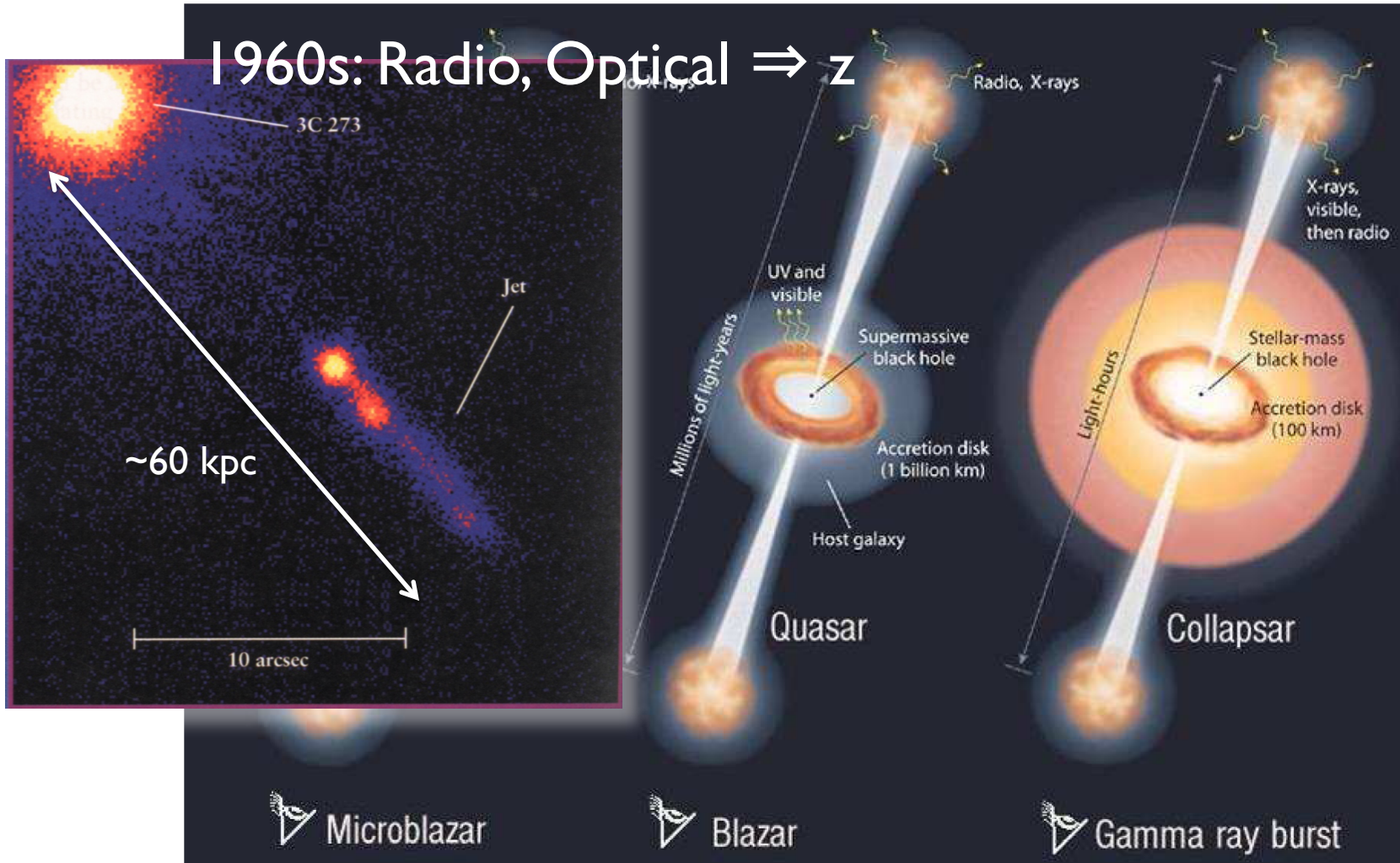
Observed BHs

$\sim 10 M_{\odot}$

$\sim 10^6 - 10^9 M_{\odot}$

$\sim 10 M_{\odot}$

1960s: Radio, Optical $\Rightarrow z$

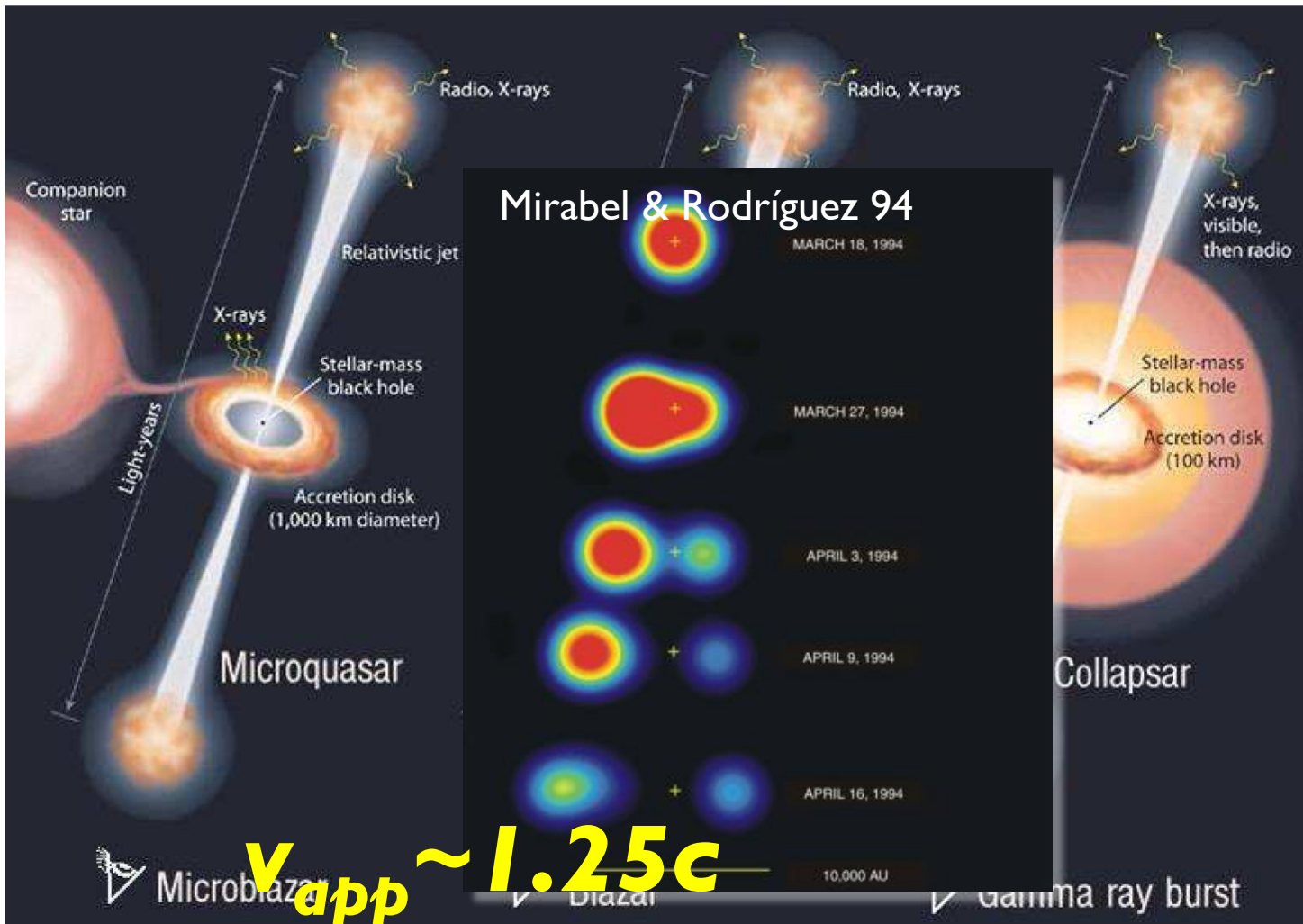


Observed BHs

$\sim 10 M_{\odot}$

$\sim 10^6 - 10 M_{\odot}$

$\sim 10 M_{\odot}$

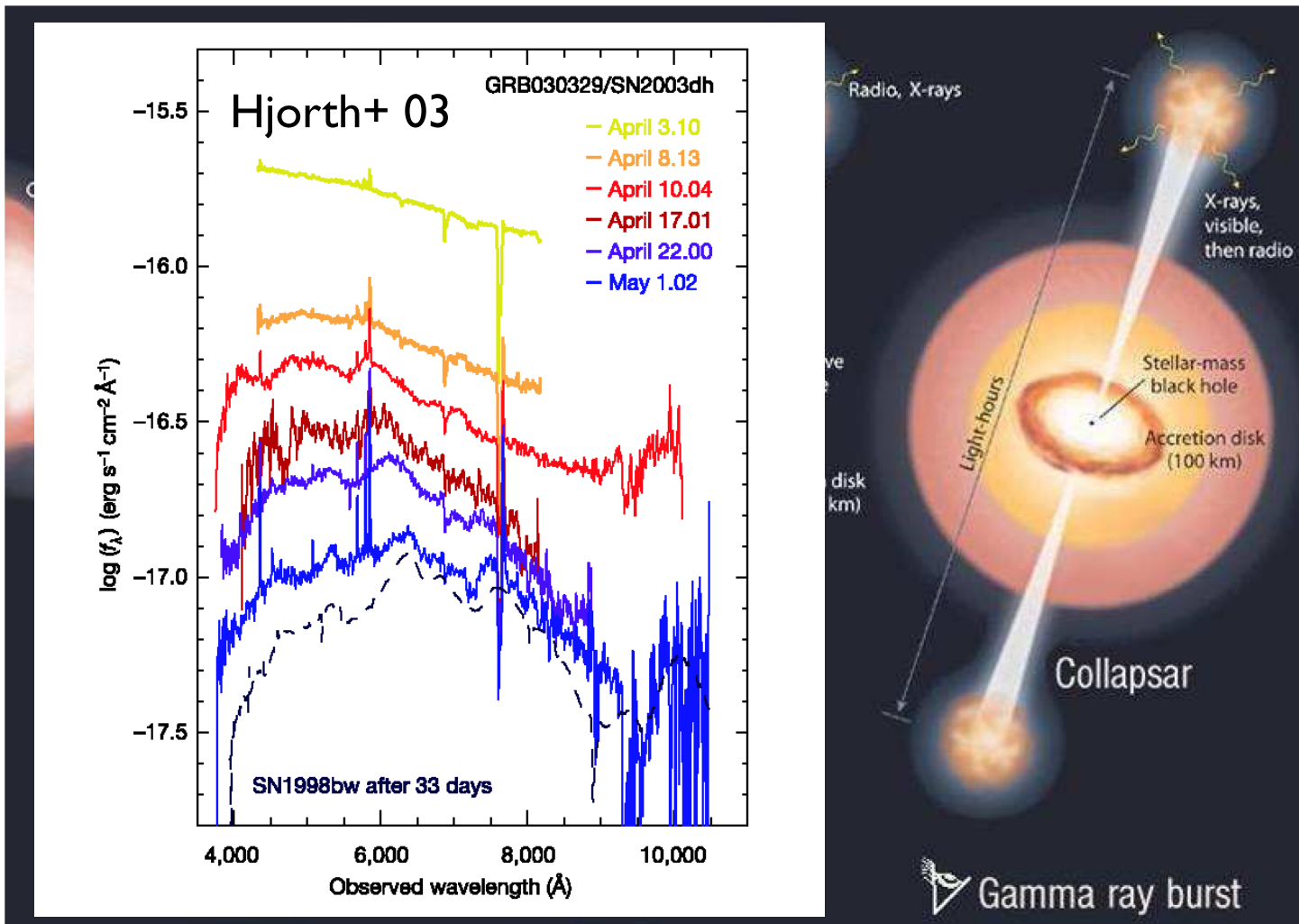


Observed BHs

$\sim 10 M_{\odot}$

$\sim 10^6 - 10 M_{\odot}$

$\sim 10 M_{\odot}$



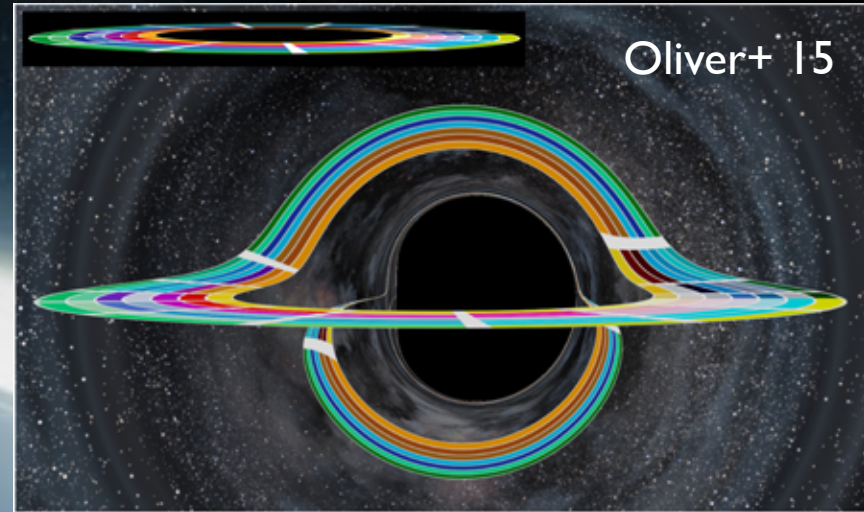
100 Years from Now

100 Years from Now

- We will find a nearby worm hole
- We will travel into a BH
- We will understand extra dim,
time travel, quantum gravity, etc.



INTERSTELLAR



INTERSTELLAR

~20? Years from Now

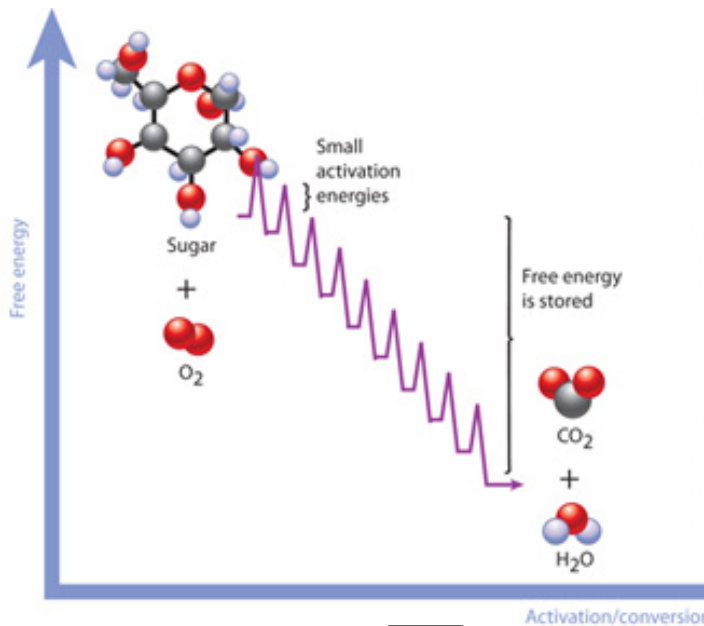
- **We will fully understand energy flows from BHs?**
- **We will make a complete census of BHs?**
- **We will witness multidisciplinary revolutions?**

~20? Years from Now

- We will fully understand energy flows from BHs?
- We will make a complete census of BHs?
- We will witness multidisciplinary revolutions?

BH = Efficient Engine

Chemical reaction

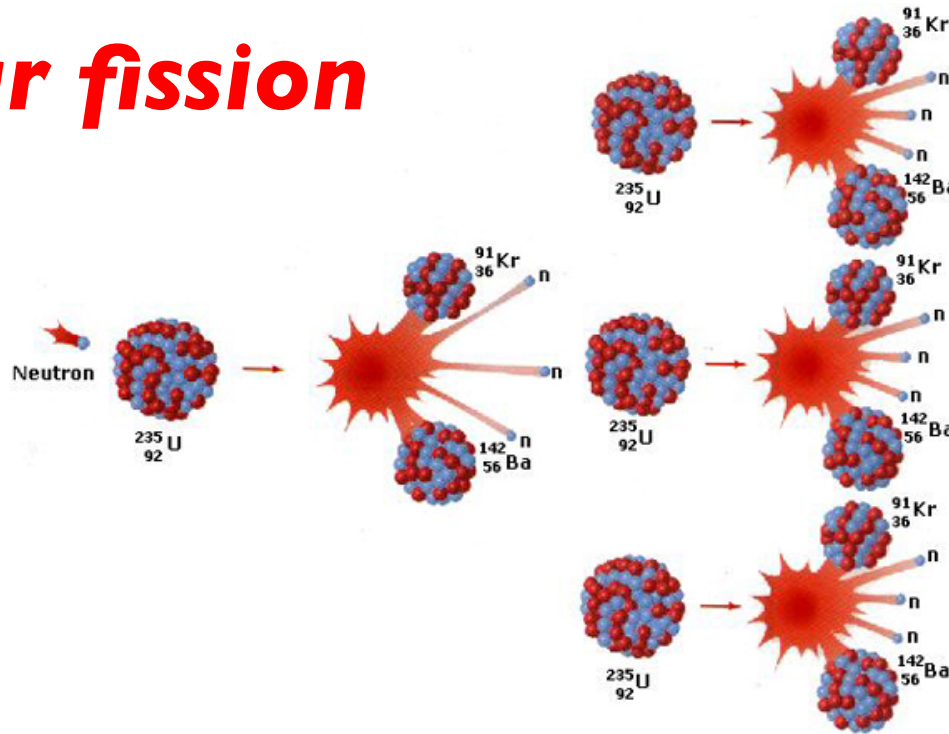


1 kcal
 = 4.2 kJ
 = 2.6e22 eV
 ~ eV per molecule

$$\eta = \frac{E}{mc^2} \sim \frac{\text{eV}}{10 \text{ GeV}} \sim 10^{-10}$$

BH = Efficient Engine

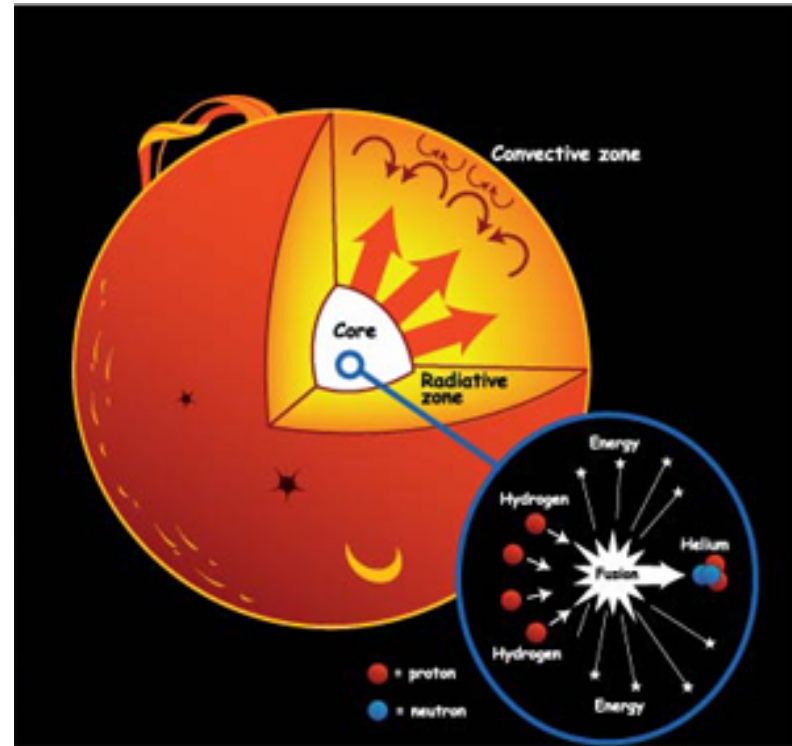
Nuclear fission



$$\eta = \frac{E}{mc^2} \sim \frac{0.2 \text{ GeV}}{235 \times 0.94 \text{ GeV}} \sim 9 \times 10^{-4}$$

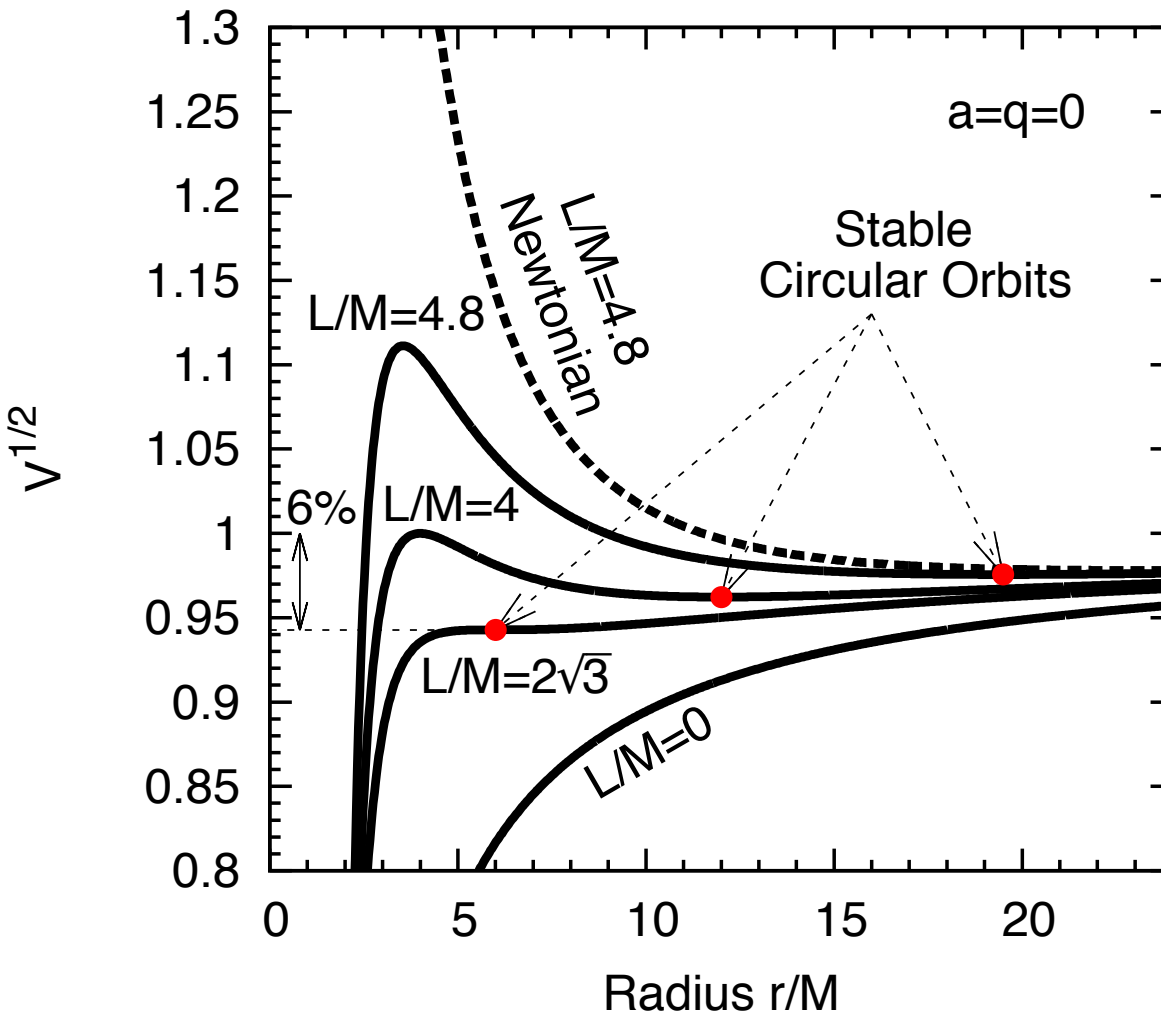
BH = Efficient Engine

Nuclear fusion



$$\eta = \frac{E}{mc^2} \sim 9 \times 10^{-3} \times 0.1 \sim 9 \times 10^{-4}$$

BH = Efficient Engine



Gravitational energy

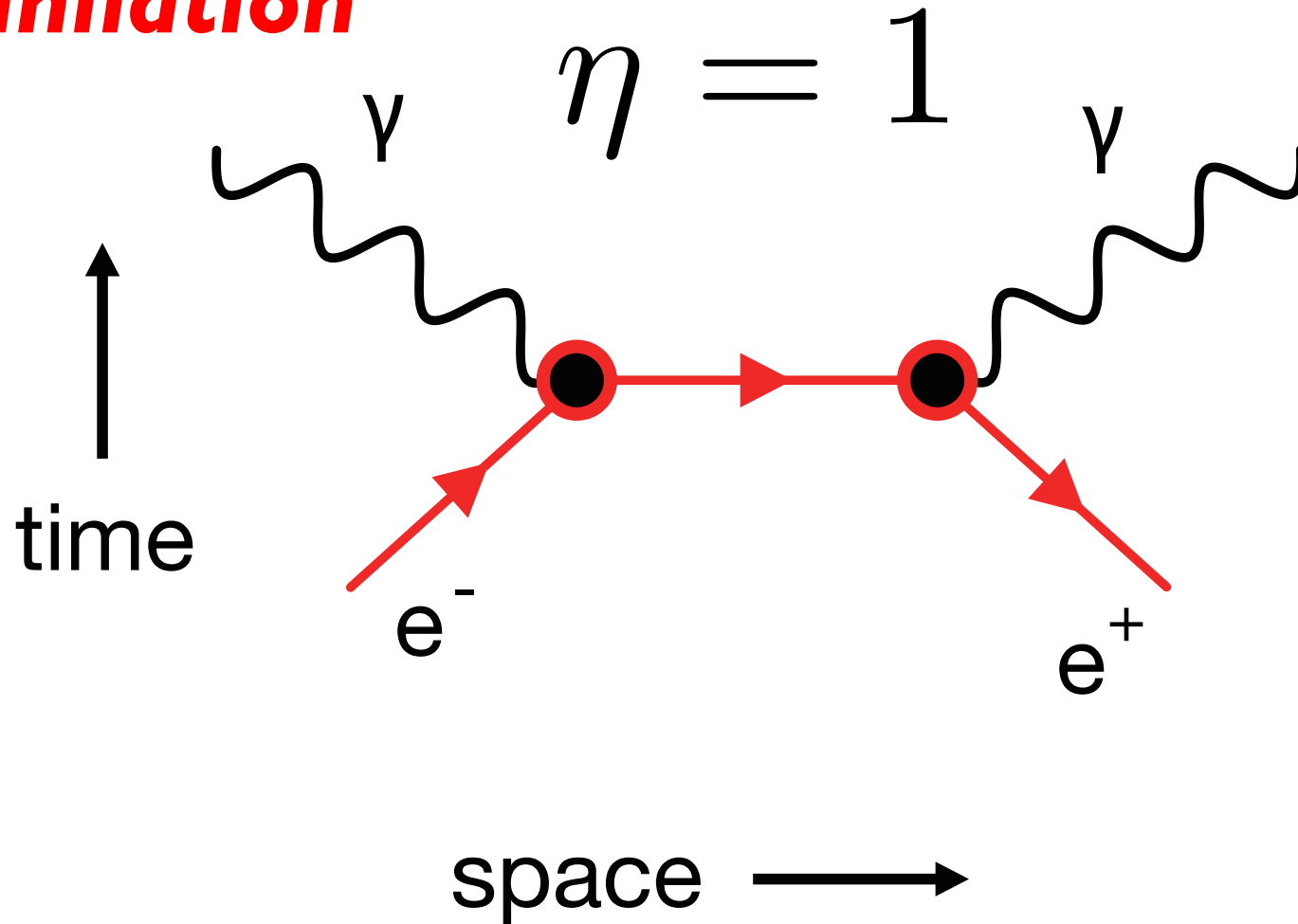
$$\eta \sim \frac{GMm/2R}{mc^2}$$

$$\sim \frac{R_g}{2R}$$

$$\sim 0.1 - 0.3$$

BH = Efficient Engine

Annihilation



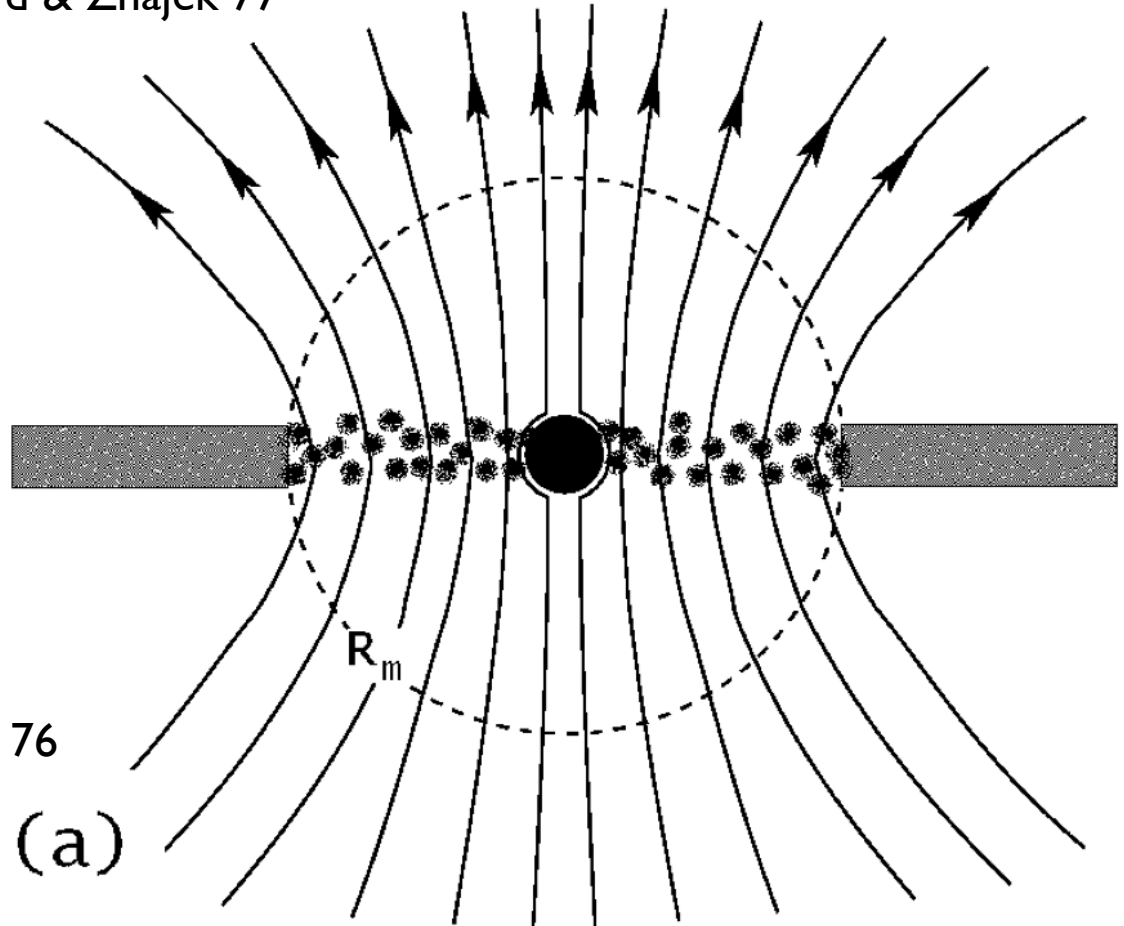
BH = Efficient Engine

BH spin Blandford & Znajek 77

$$\eta > 1$$

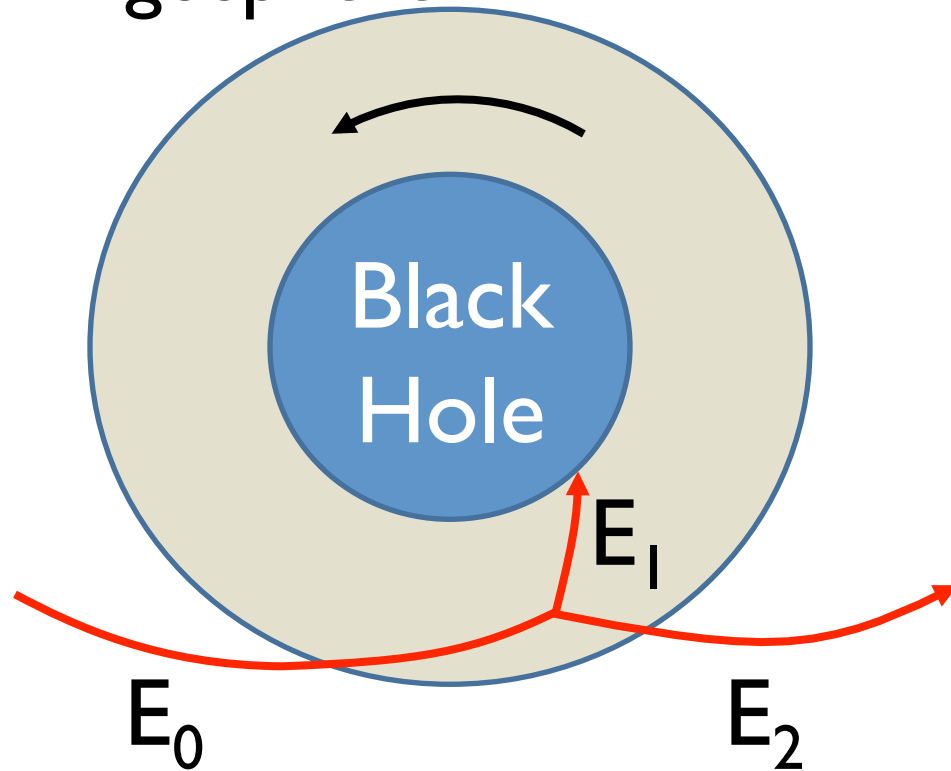
is possible since
B extract energy
stored in BH spin
($\eta_{\text{total}} < 1$)

Bisnovatyi-Kogan & Ruzmaikin 74, 76
Narayan & Abramowicz 03
Igumenshchev, Narayan 02
Igumenshchev+ 03



Penrose Process

Ergosphere



$E_1 < 0$ is possible

since $g_{tt} < 0$

in Ergosphere

$$E_0 = E_1 + E_2$$

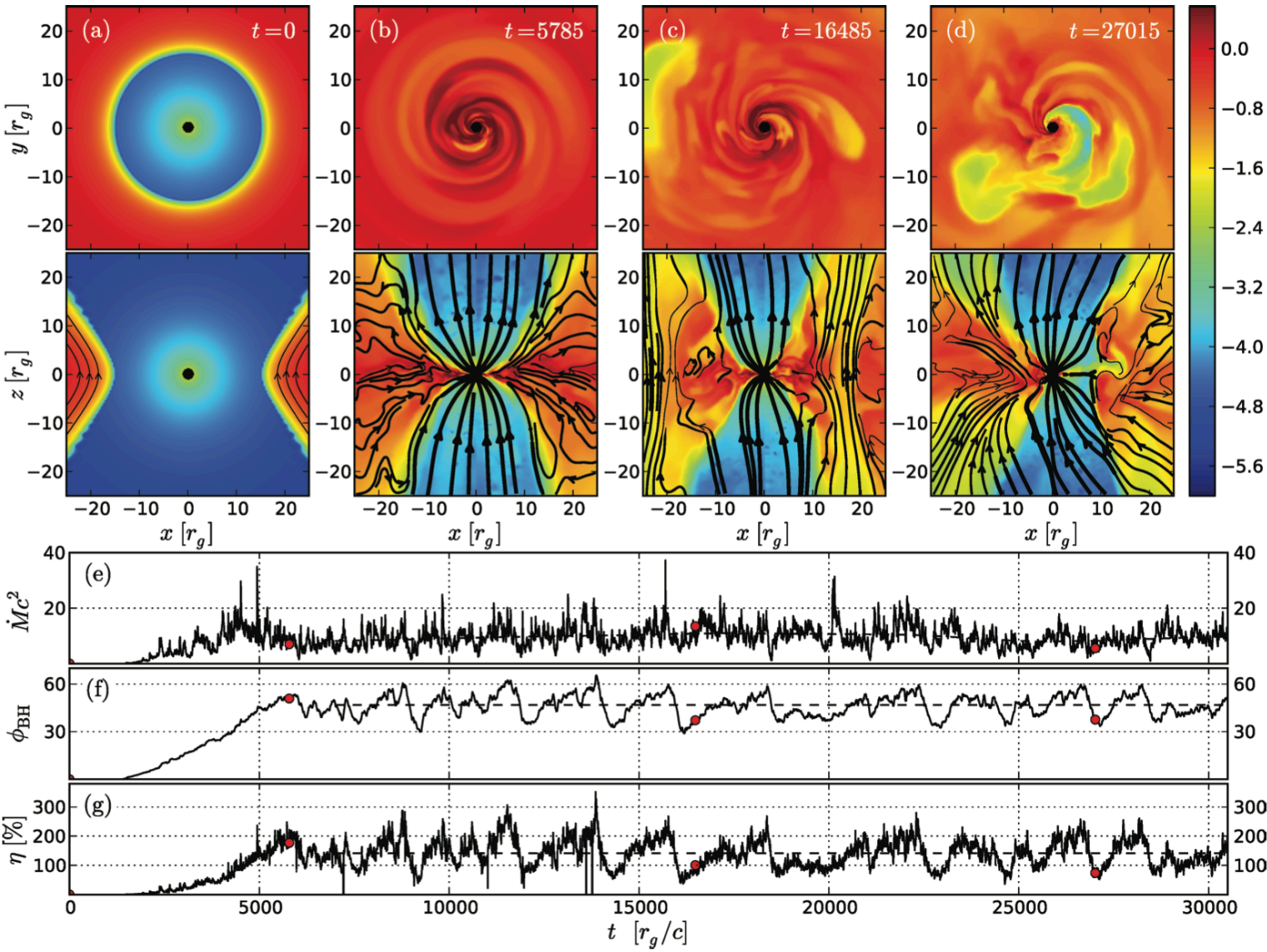
$$\Rightarrow E_2 > E_0$$

Penrose 69; Blandford & Znajek 77

We can extract energy from BH!!

Max $\sim 29\% Mc^2$ (if $a=M$)

GR MHD Simulation



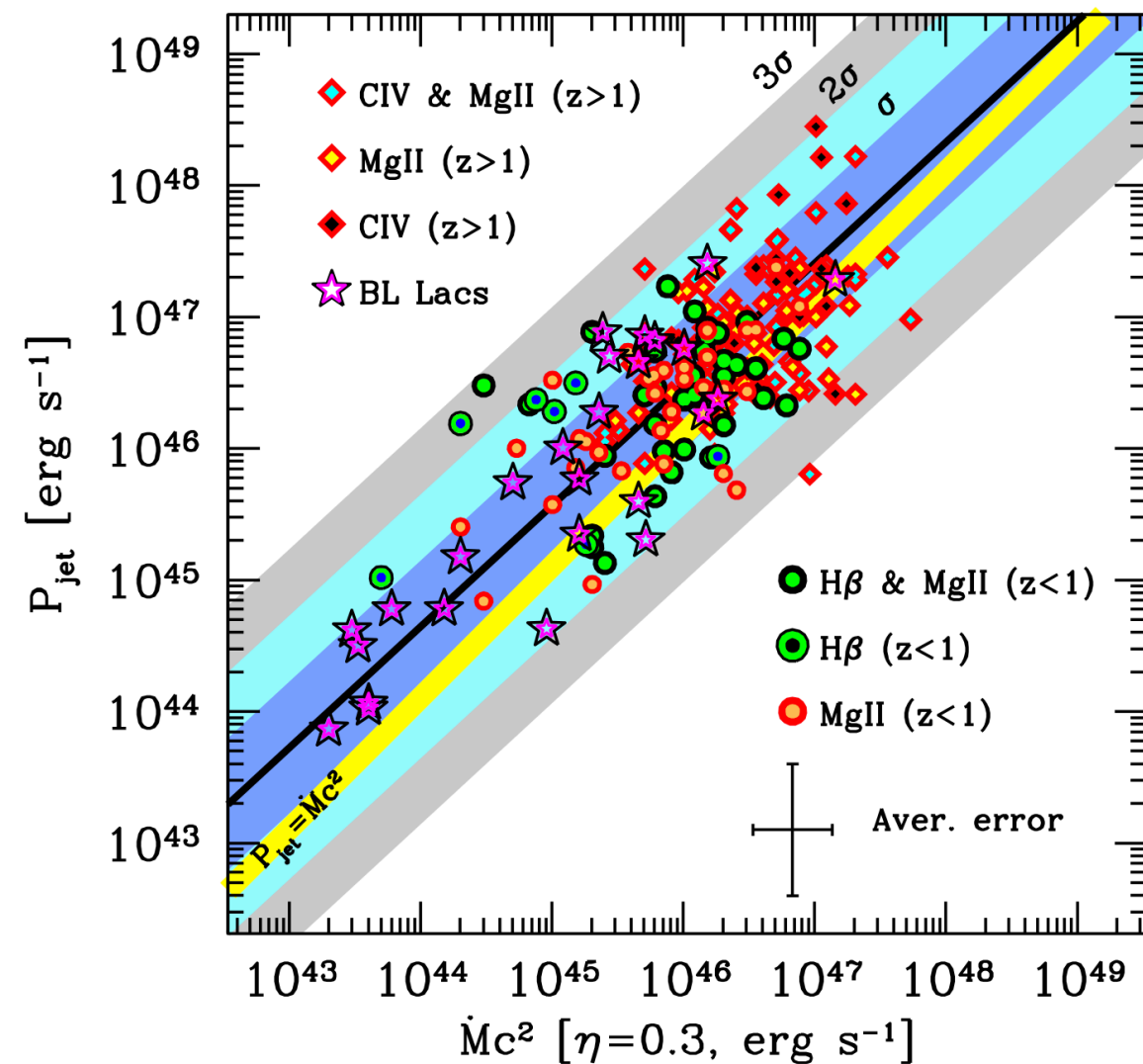
Face-on view

Edge-on view

Tchekovskoy,
Narayan &
McKinney I I

$\eta > 100\%$

Observations of Efficiency



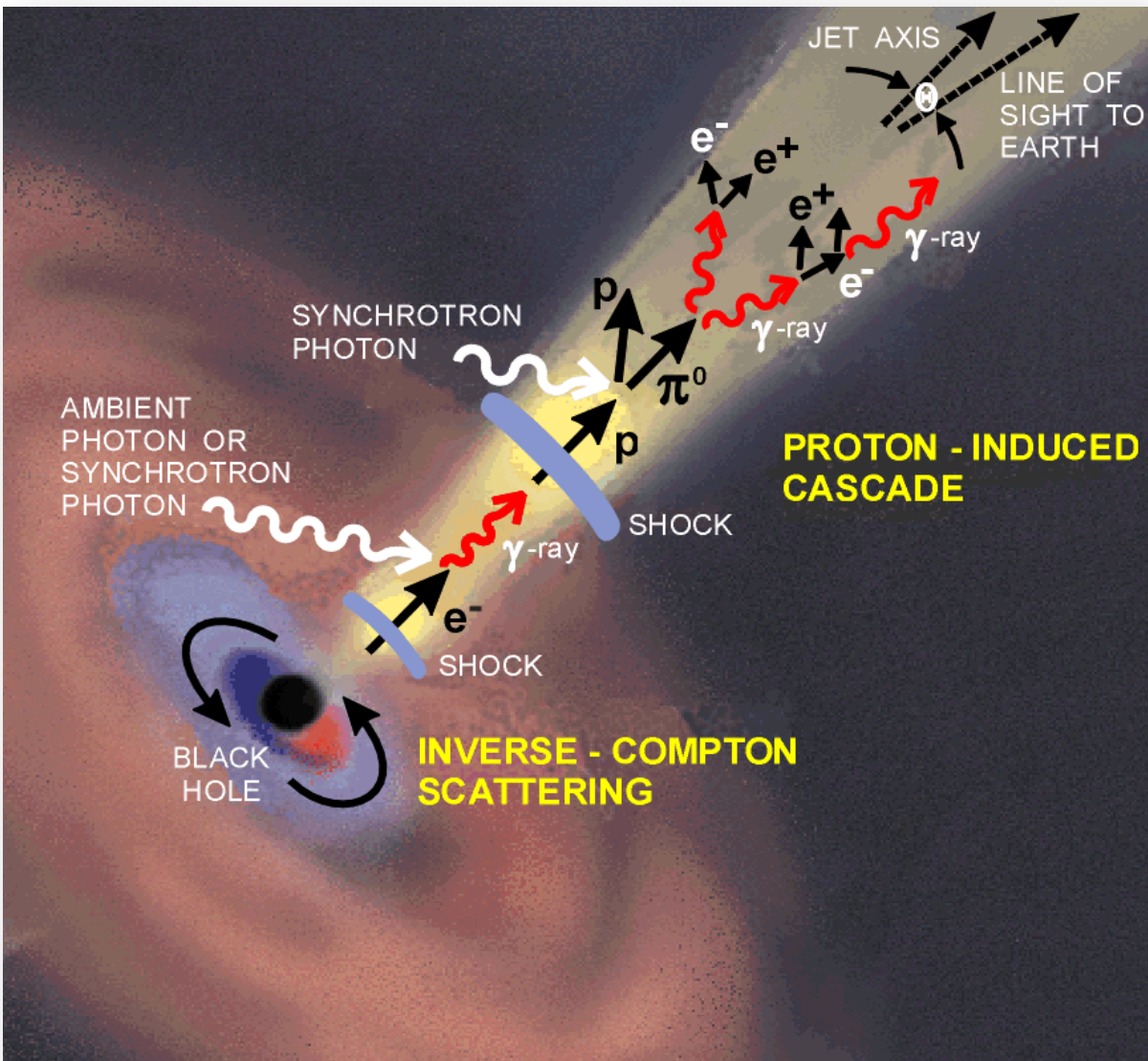
$$P_{\text{jet}} > \dot{M}_{\text{dot}} c^2$$

if one proton
per electron,
i.e., no pairs

Broad emission line $\Rightarrow \dot{M}_{\text{dot}}$
 γ -ray observation $\Rightarrow P_{\text{jet}}$
 LAT + Multi-wavelength data
 191 FSRQ, 26 BL Lacs

Ghisellini+ 14

Composition is Unknown



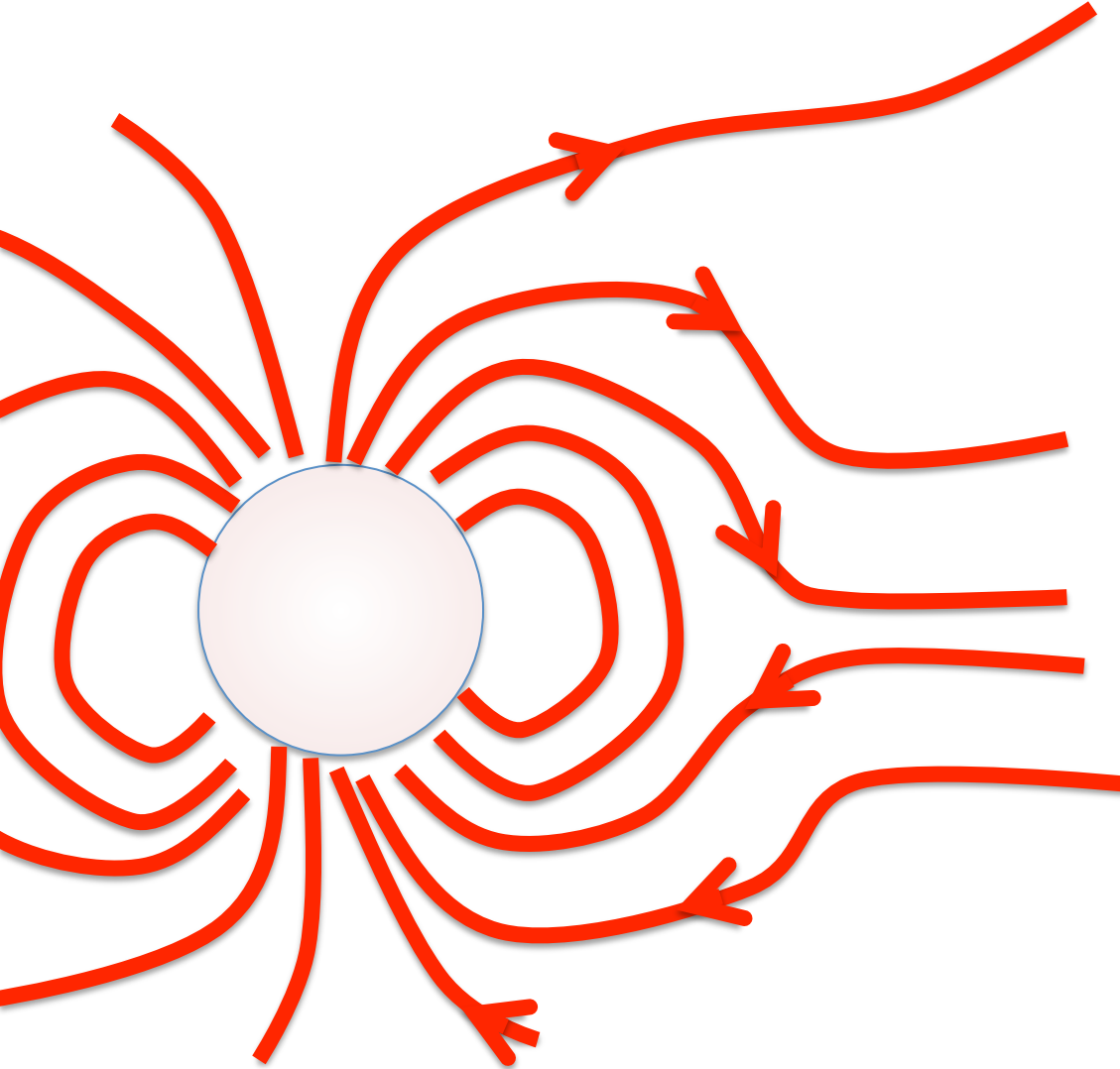
B , $e^\pm$, p , Fe ?
Lorentz factor?
Dissipation?
 p acceleration?

Jet? Disk wind?



has a jet has no jet

Reconnection

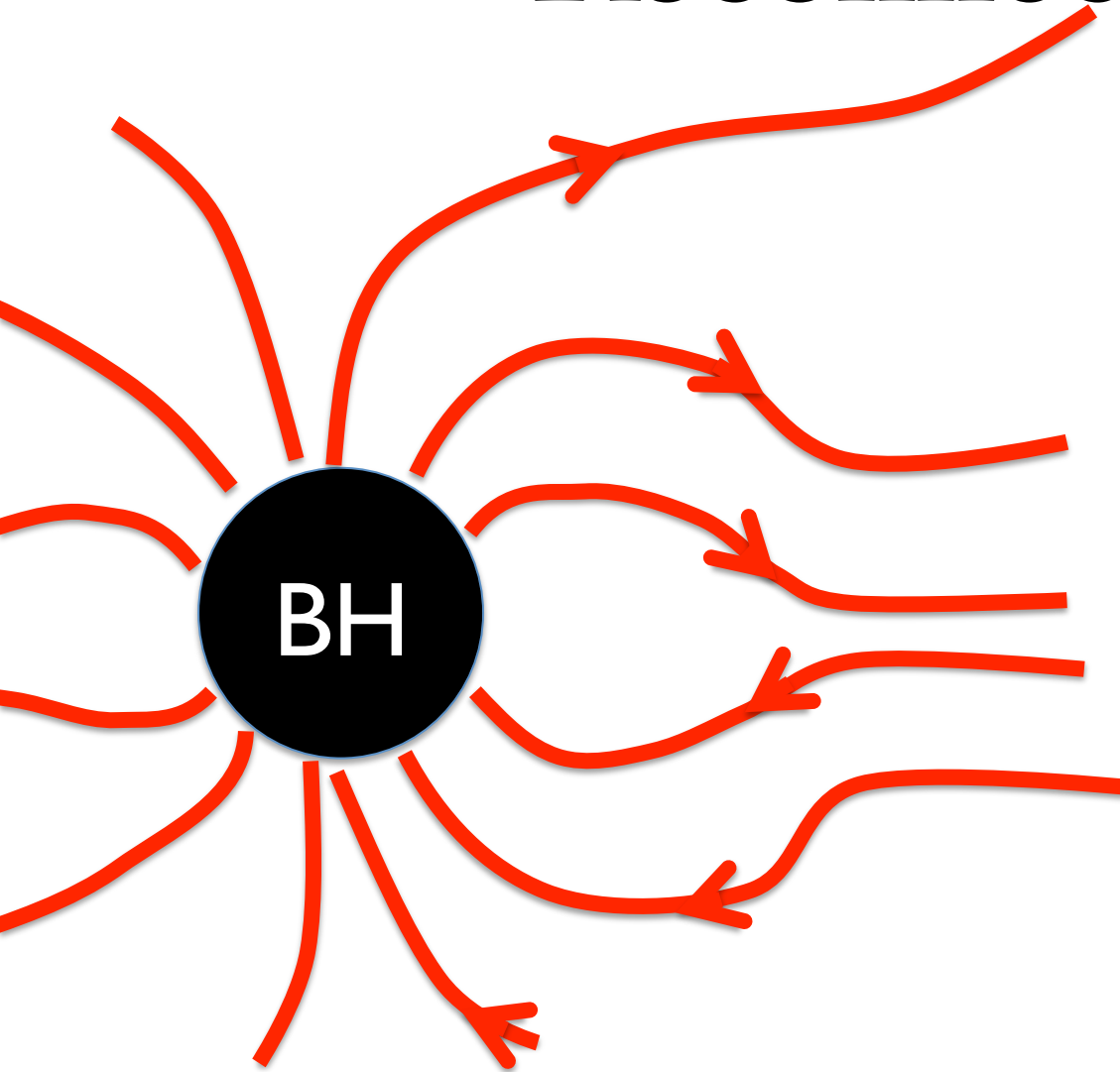


$BH + B \Rightarrow$

Electric field

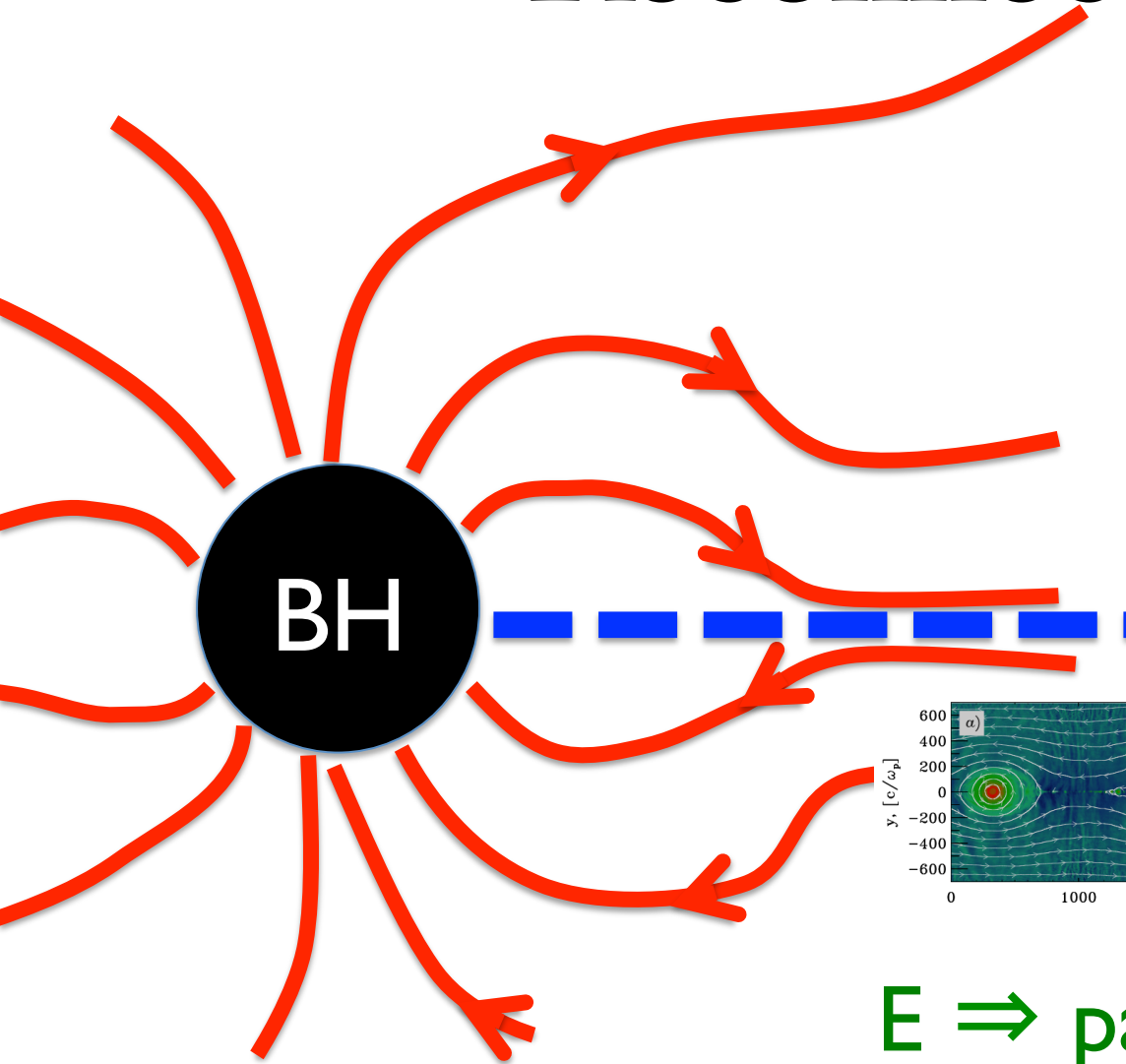
MHD is not good

Reconnection



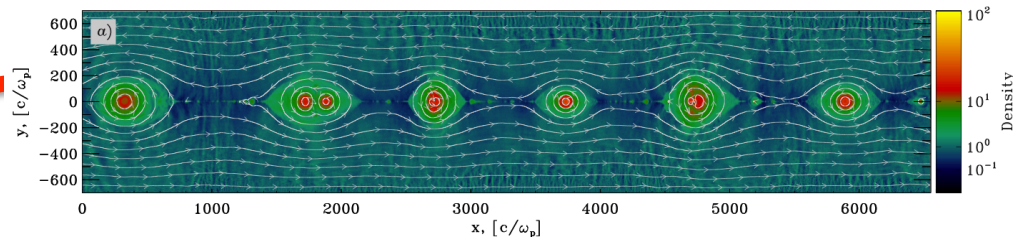
$BH + B \Rightarrow$
Electric field
MHD is not good

Reconnection



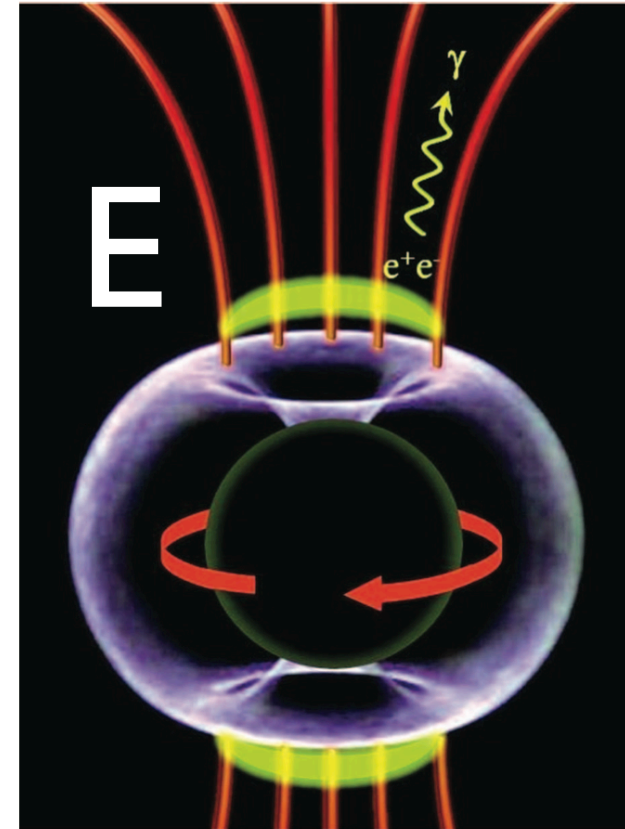
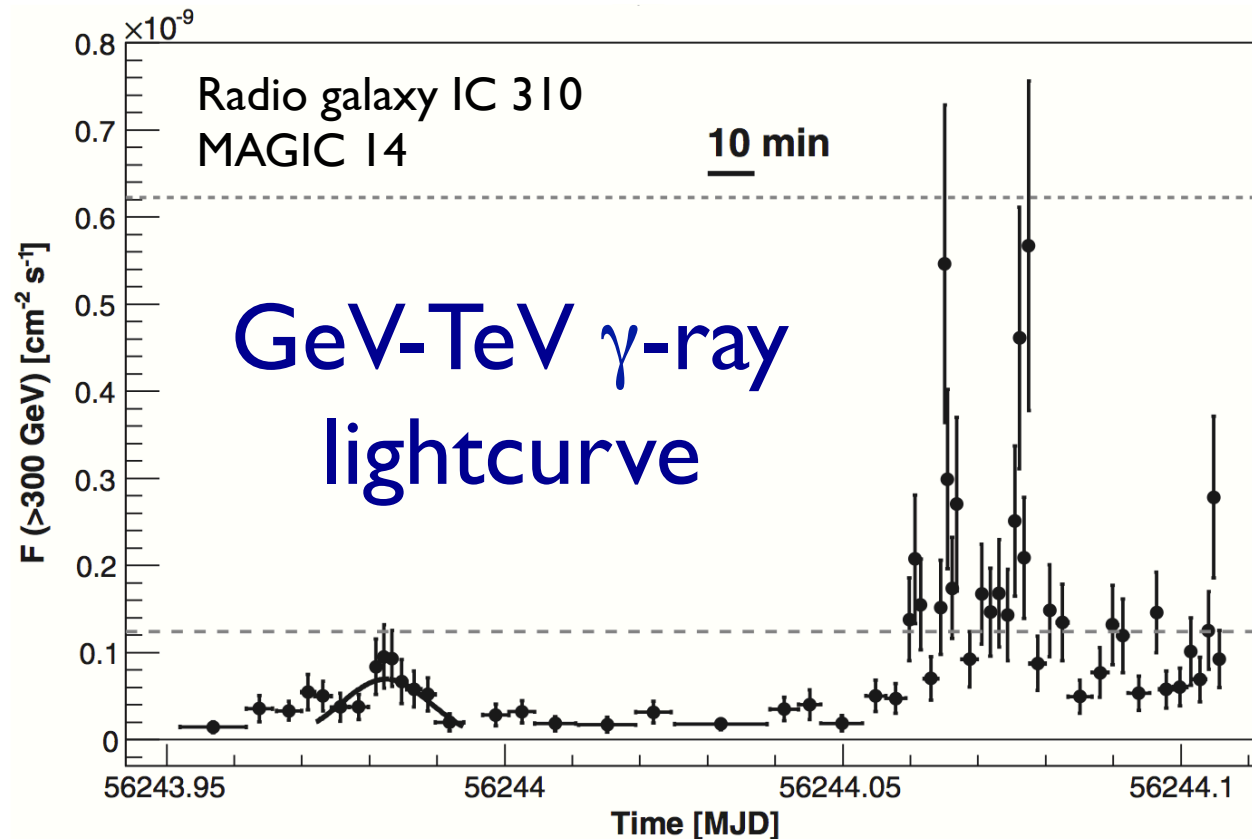
$BH + B \Rightarrow$
Electric field
MHD is not good

Current sheet



$E \Rightarrow$ particle acceleration

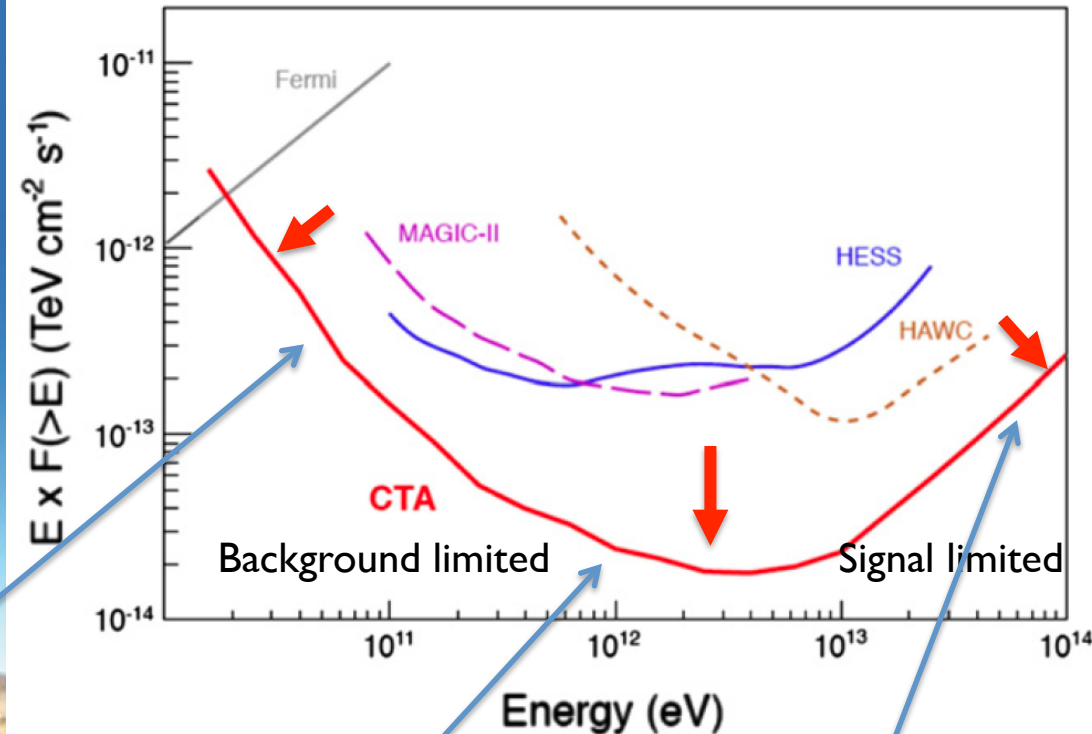
γ -Ray Variability



$\Delta t \sim 4.8 \text{ min} \sim 20\% r_g \text{ (Sub-horizon)}/c?$

CTA

- $\sim 20\text{ GeV} - 100\text{ TeV}$
- $\times 10$ Sensitivity
- $\Delta\theta \sim 1 - 2$ min
- $\text{FOV} \sim 5 - 10$ deg
- ~ 20 s slew (LST)
- $\sim 2016 -$
- $\sim 150\text{€}$



AGN
Pulsar
GRB

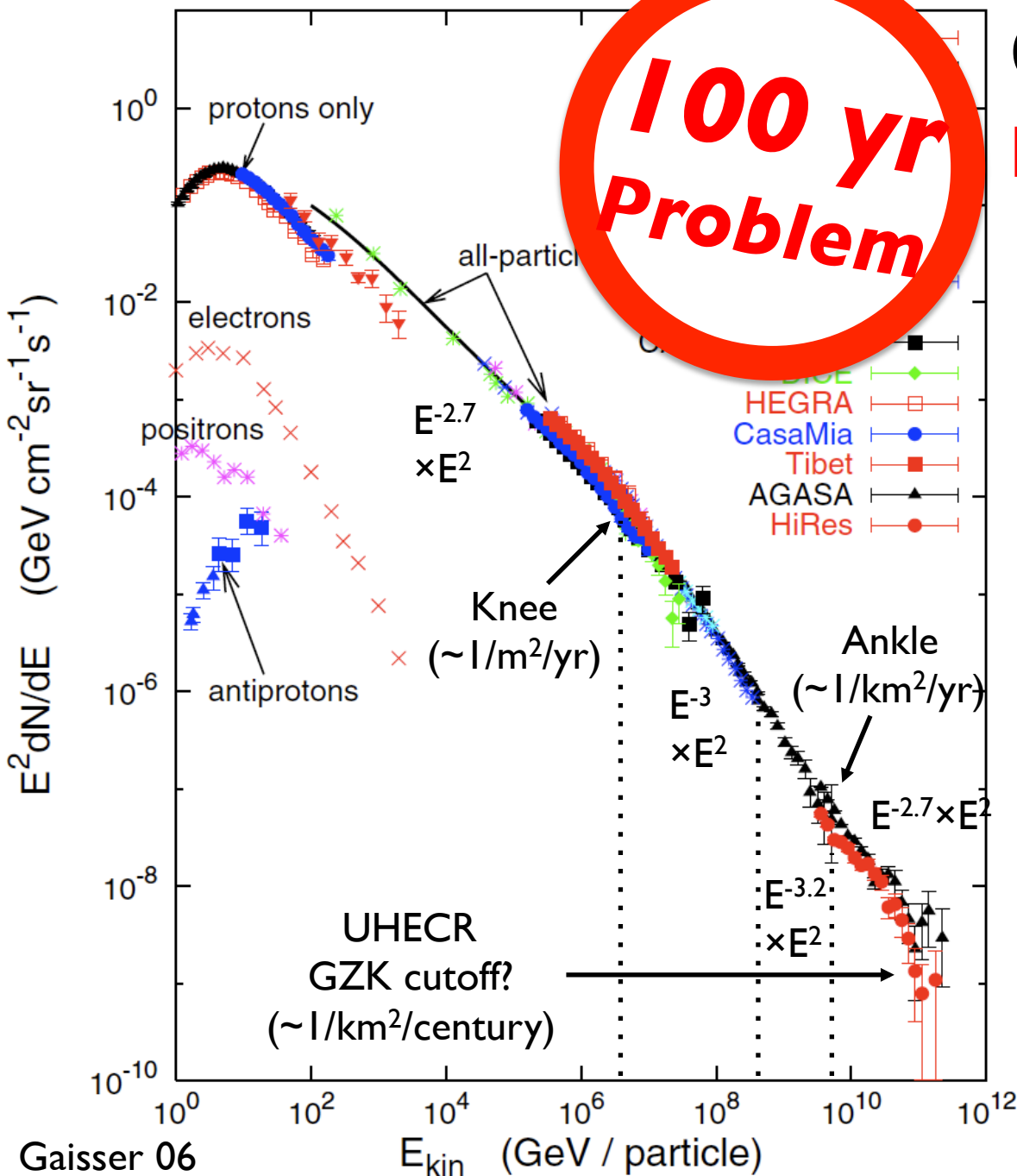
LSTs

MSTs

~ 1 mCrab
Deep Survey

SSTs

$\sim 10\text{ km}^2$
Cosmic Ray
Knee



Cosmic Ray

$E < 10^{15-16}$ eV (Knee)

$$F \propto E^{-2.7}$$

Supernova remnant(?)

$$L_{CR} \sim 10^{41} \text{ erg/s}$$

$$\sim 0.1 E_{SN} / t_{SN}$$

$10^{15-16} < E$

$< 10^{18}$ eV (Ankle)

$$F \propto E^{-3-3.2}$$

Galactic origin?

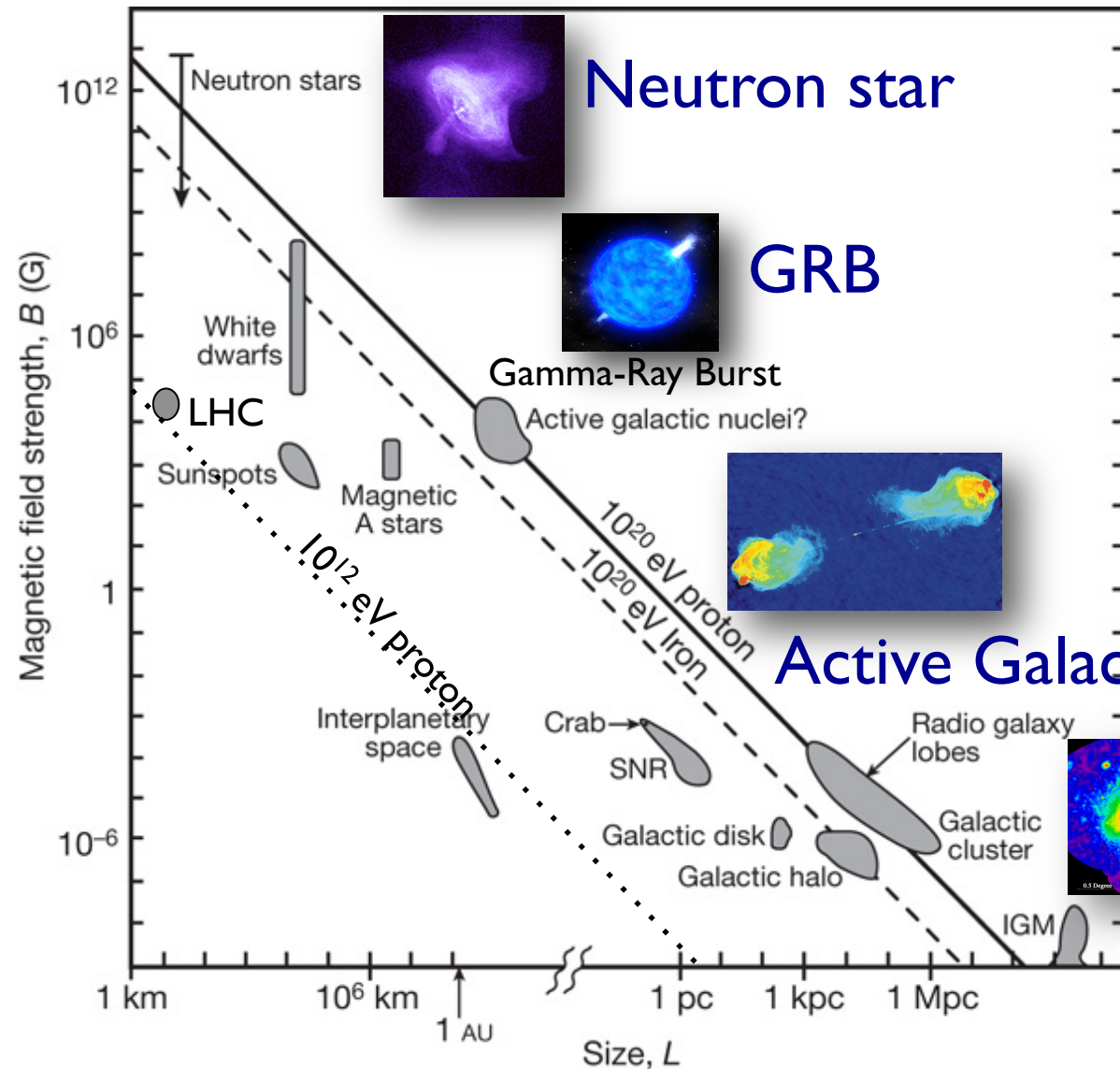
$< 10^{14-15}$ eV by SNR

$10^{18} \text{ eV} < E$

$$F \propto E^{-2.7}$$

Extra-Gal. AGN? GRB?

Cosmic Ray Sources



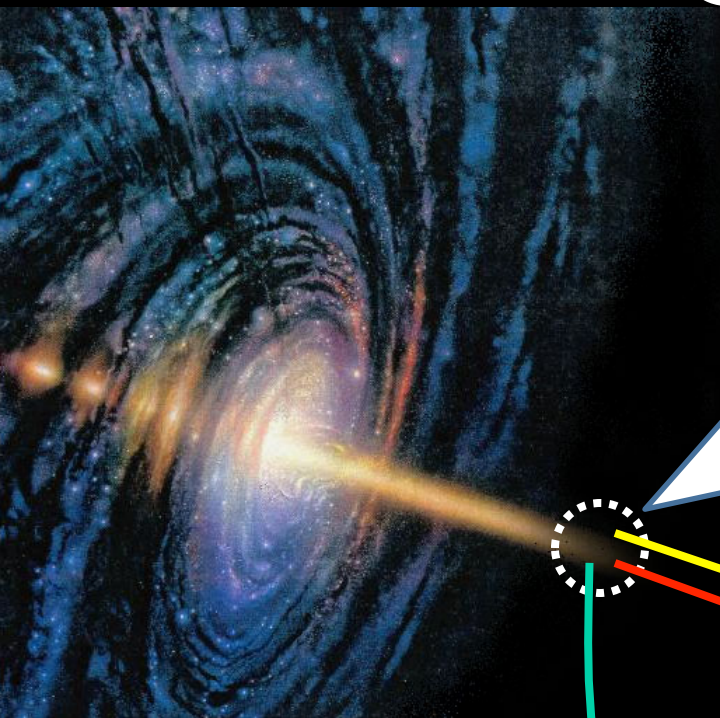
- Hillas condition
 $E < ZeBR (v/c)$
- $L_B \sim 4\pi R^2 (B^2/8\pi) c$
 $\propto (BR)^2$
- UHECR sources
 $\Rightarrow$ Bright sources

Active Galactic Nuclei

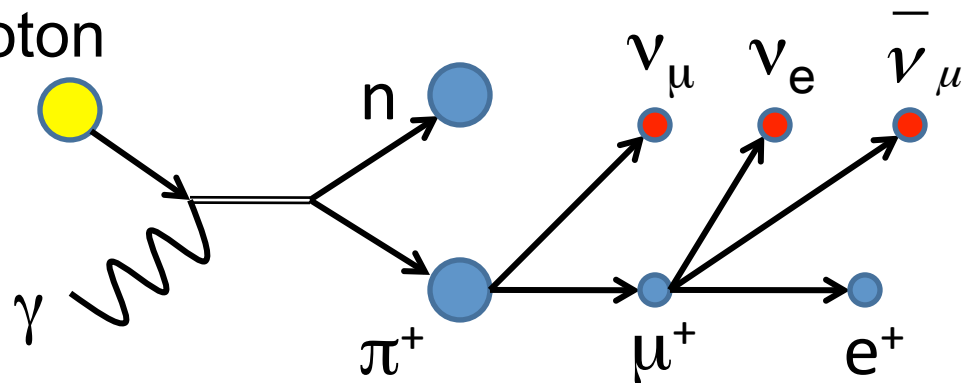
Galaxy Cluster

PeV
Dark
Matter?

Cosmic ν

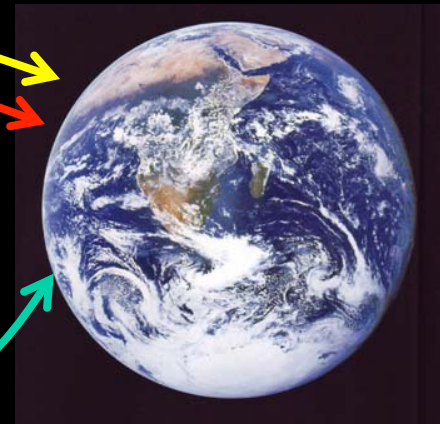


proton



Strong penetration
Not delayed

CR origin
 ν interaction @ $> \text{TeV}$
 τ appearance
Limiting ν speed
Equivalence principle



p

First 2 PeV ν s

PeV = 10^{15} eV

"Bert"

8 Aug 2011

3 Jan 2012

"Ernie"

**Breakthrough of
the year 2013**

1.04 ± 0.16 PeV

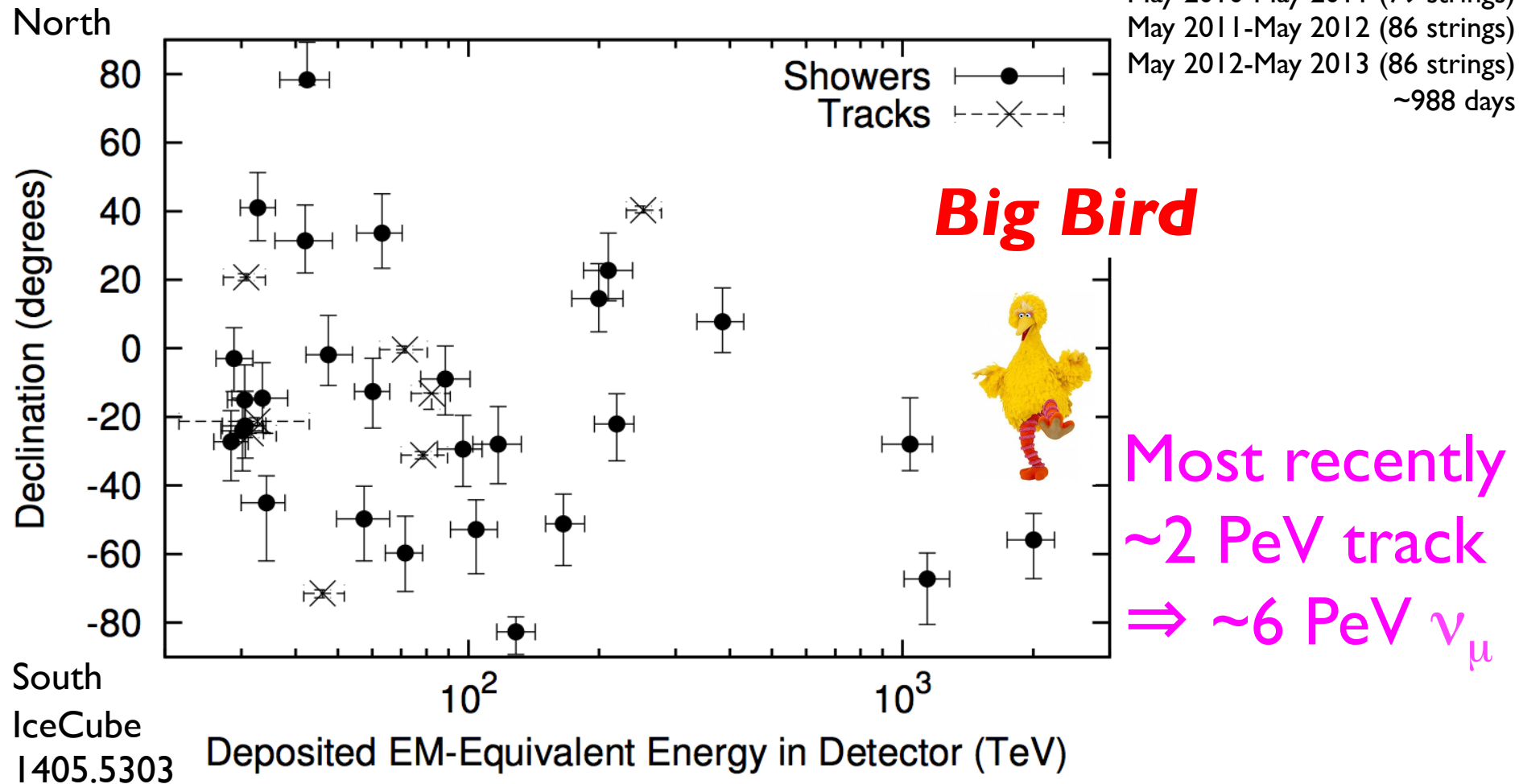
1.14 ± 0.17 PeV

Reported in Kyoto ν 2012

Aartsen+(IceCube), arXiv:1304.5356

Dawn of High-Energy ν Astronomy!!!

More Events

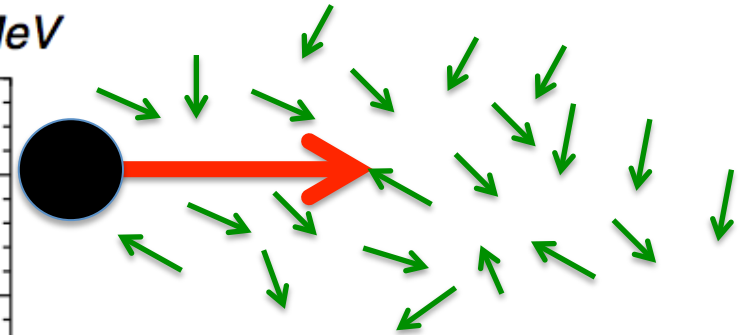
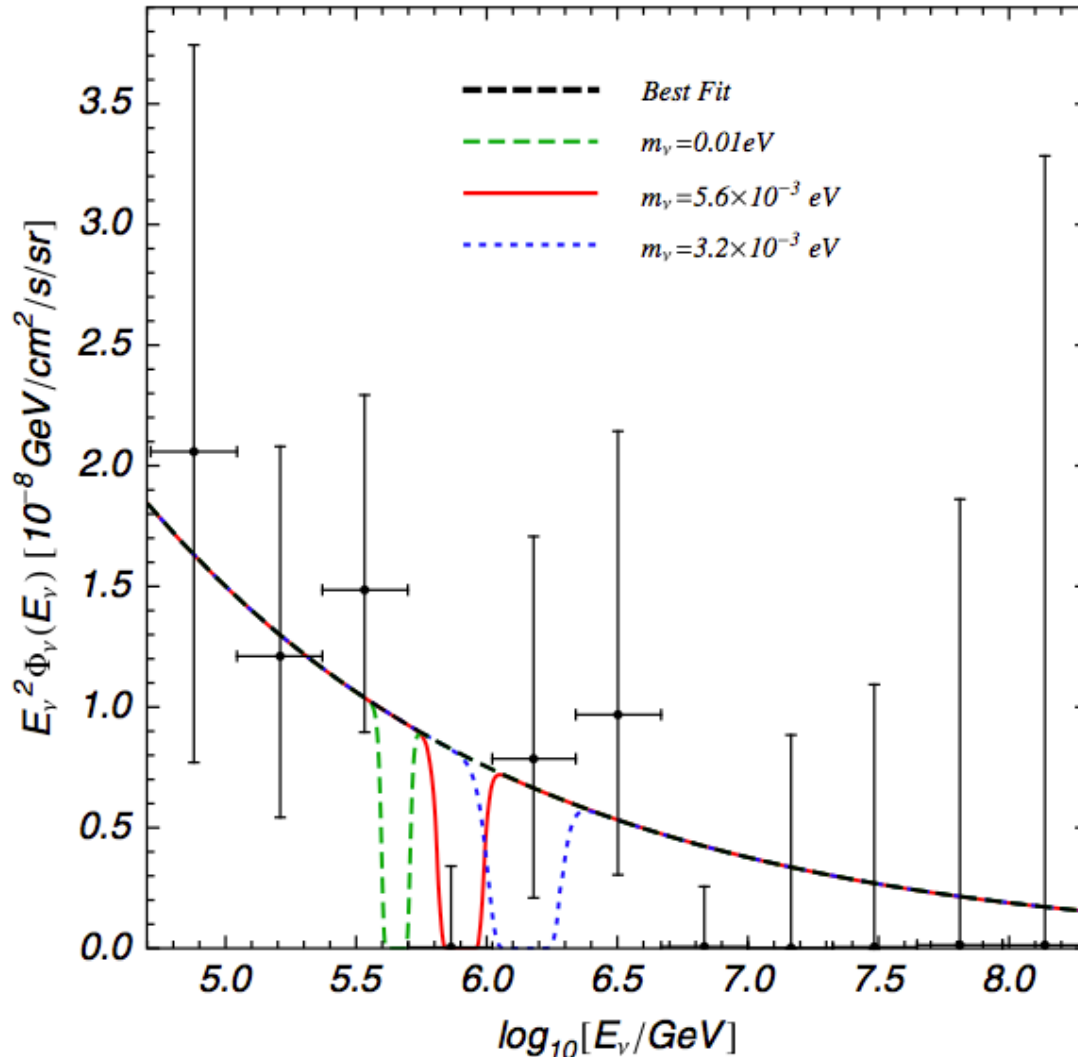


Reject a purely atmospheric explanation at **5.7σ**

37 (9 μ + 28 showers), Background $8.4 \pm 4.2 \mu$ & $6.6^{+5.9}_{-1.6} \nu$

BH & Particle Physics

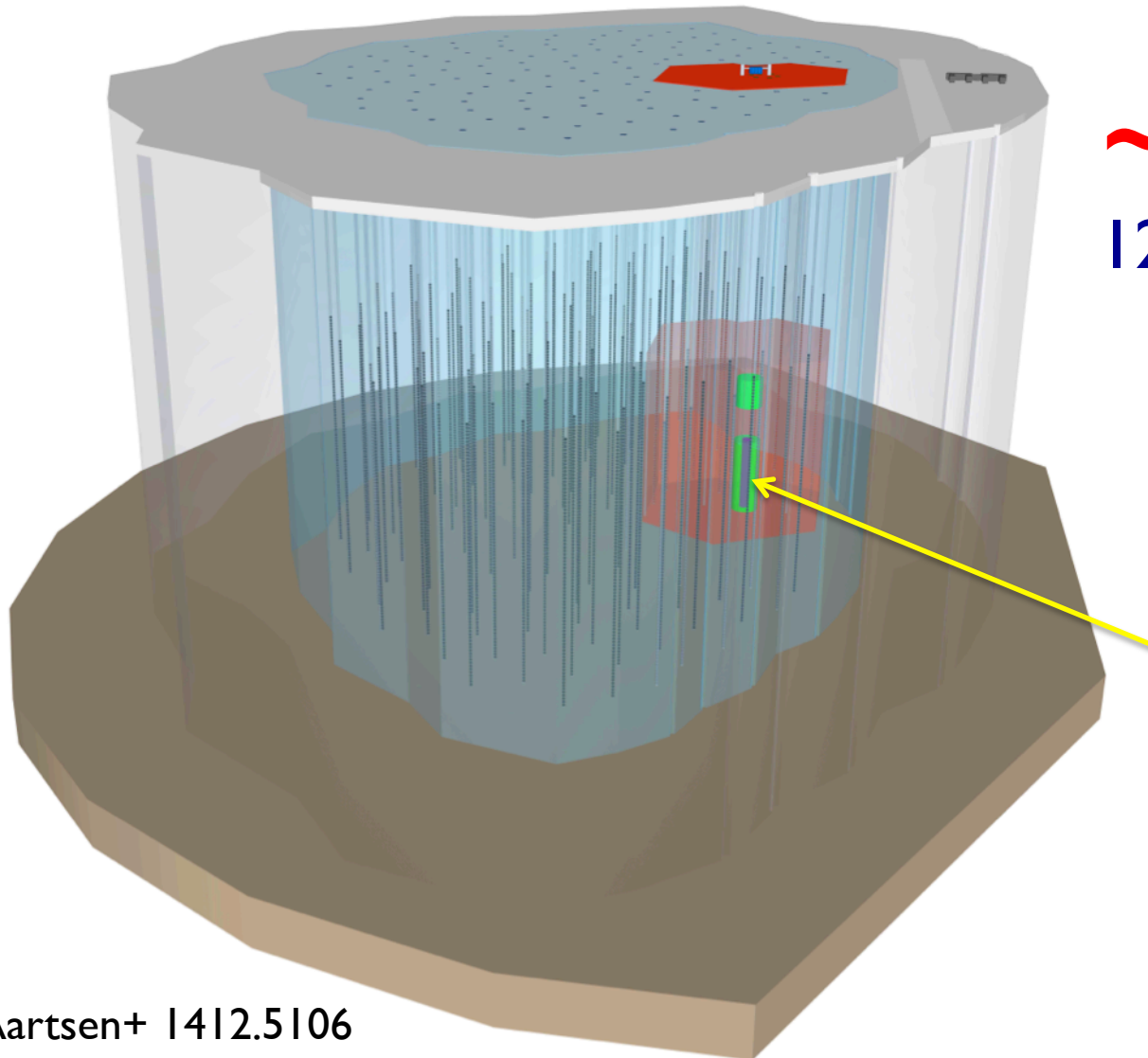
$g=10^{-3}$ with traveling distance 1Gpc and $M_s=3\text{MeV}$



$\nu\nu$ interactions
w/ cosmic ν BG
 $\text{meV} \times \text{PeV} \sim \text{MeV}^2$
 $\sim \text{MeV}$ mediator

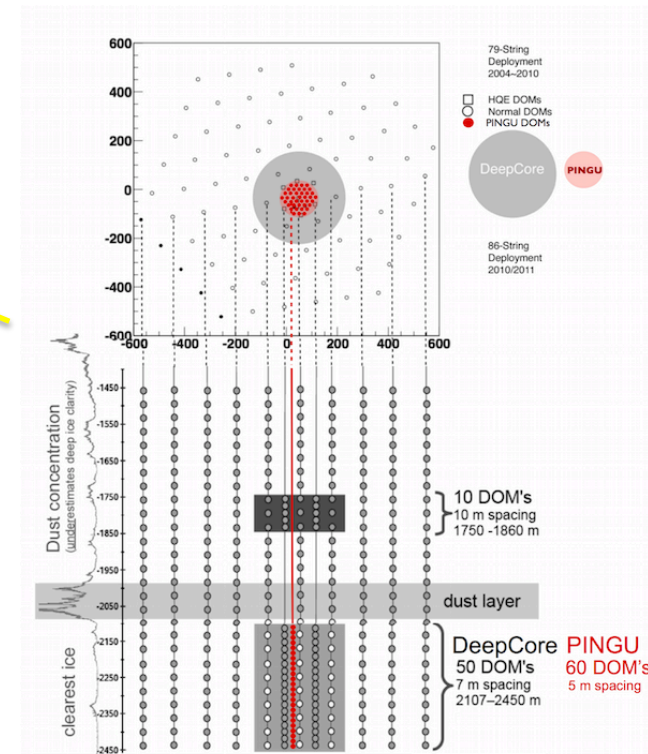
Ibe & Kaneta 14
Araki+ 15
KI & Murase 14

IceCube-Gen2



$\sim 10 \text{ km}^3$

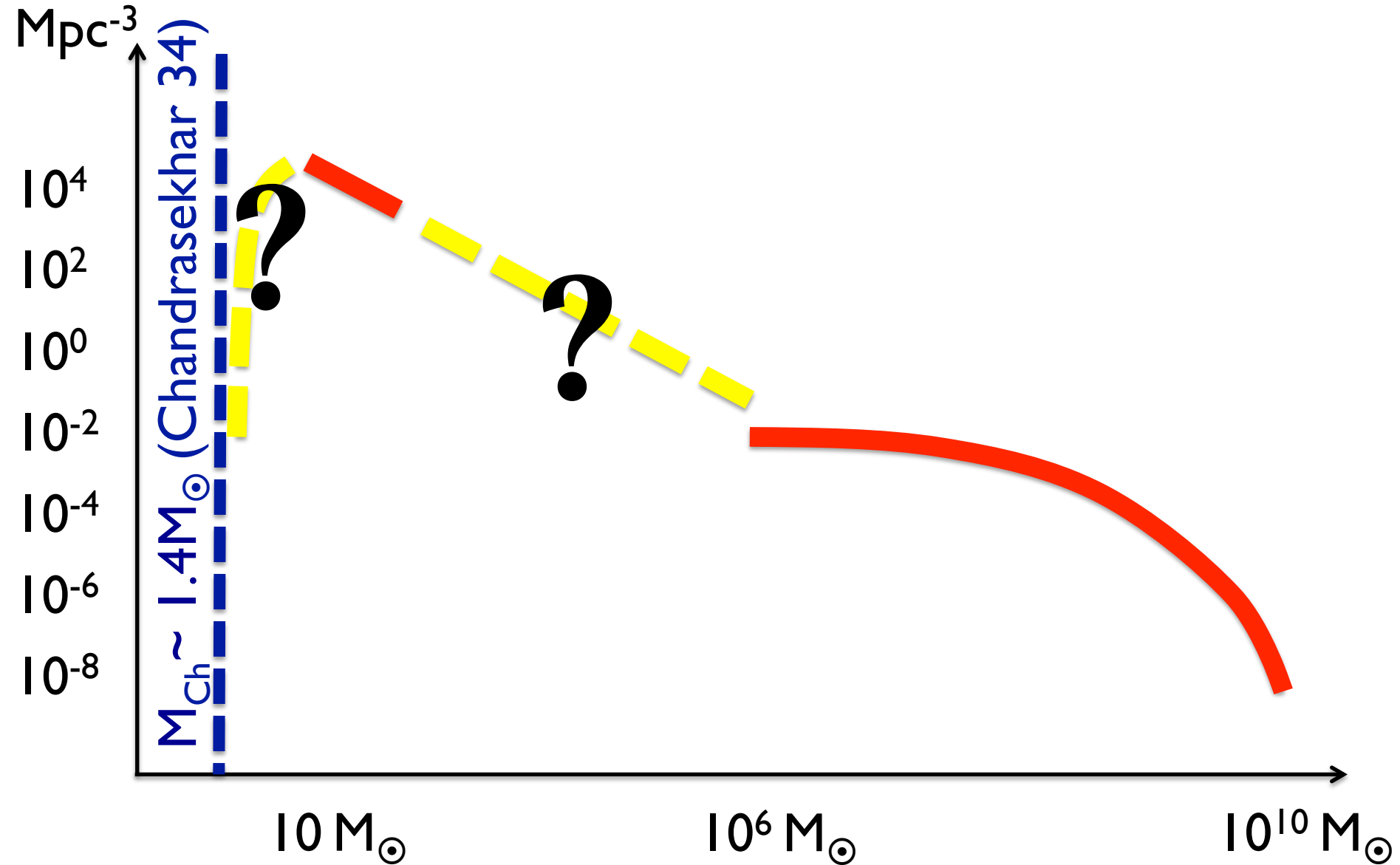
125m $\rightarrow$ 250m spacing



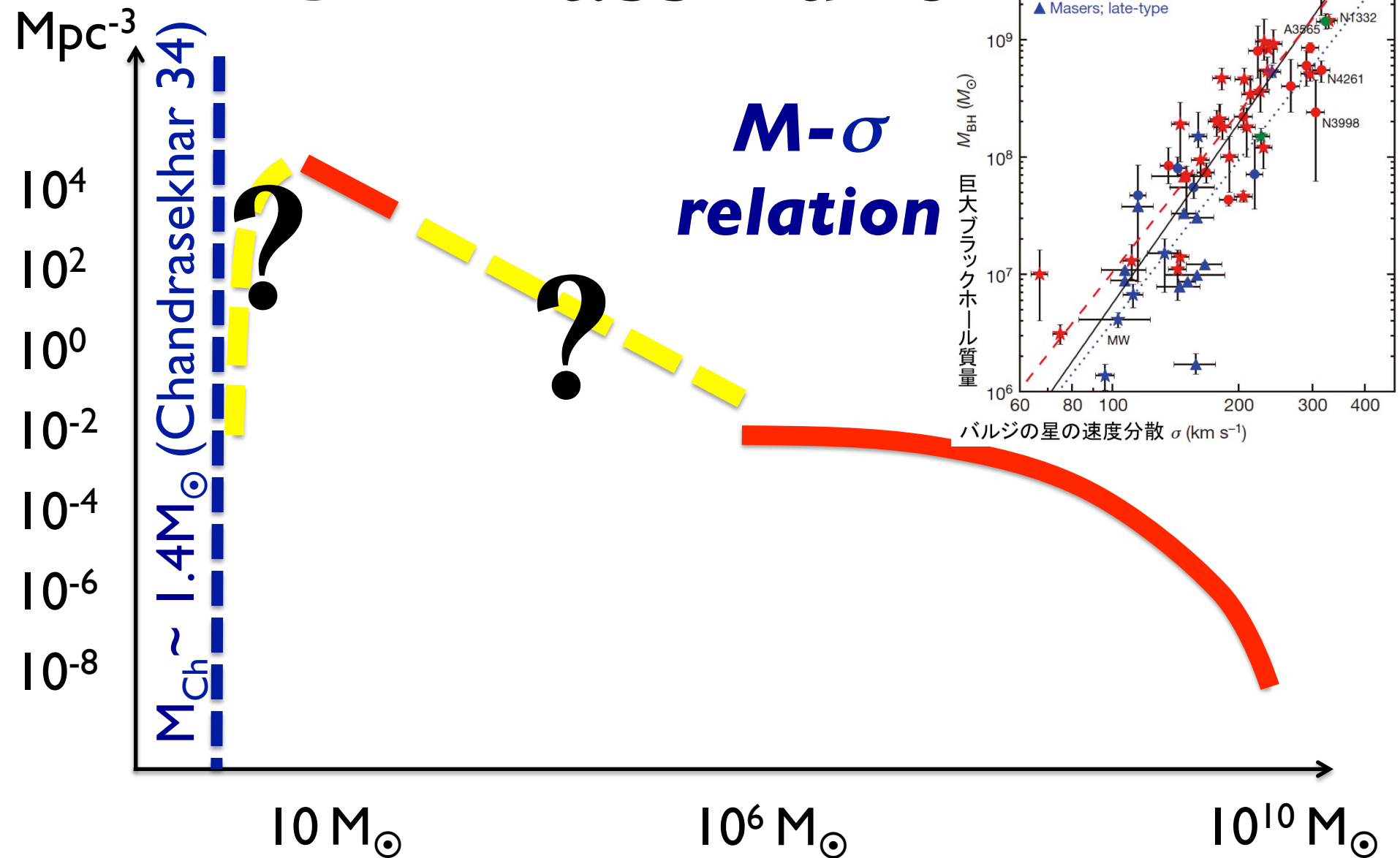
~20? Years from Now

- We will fully understand energy flows from BHs?
- We will make a complete census of BHs?
- We will witness multidisciplinary revolutions?

BH Mass Function



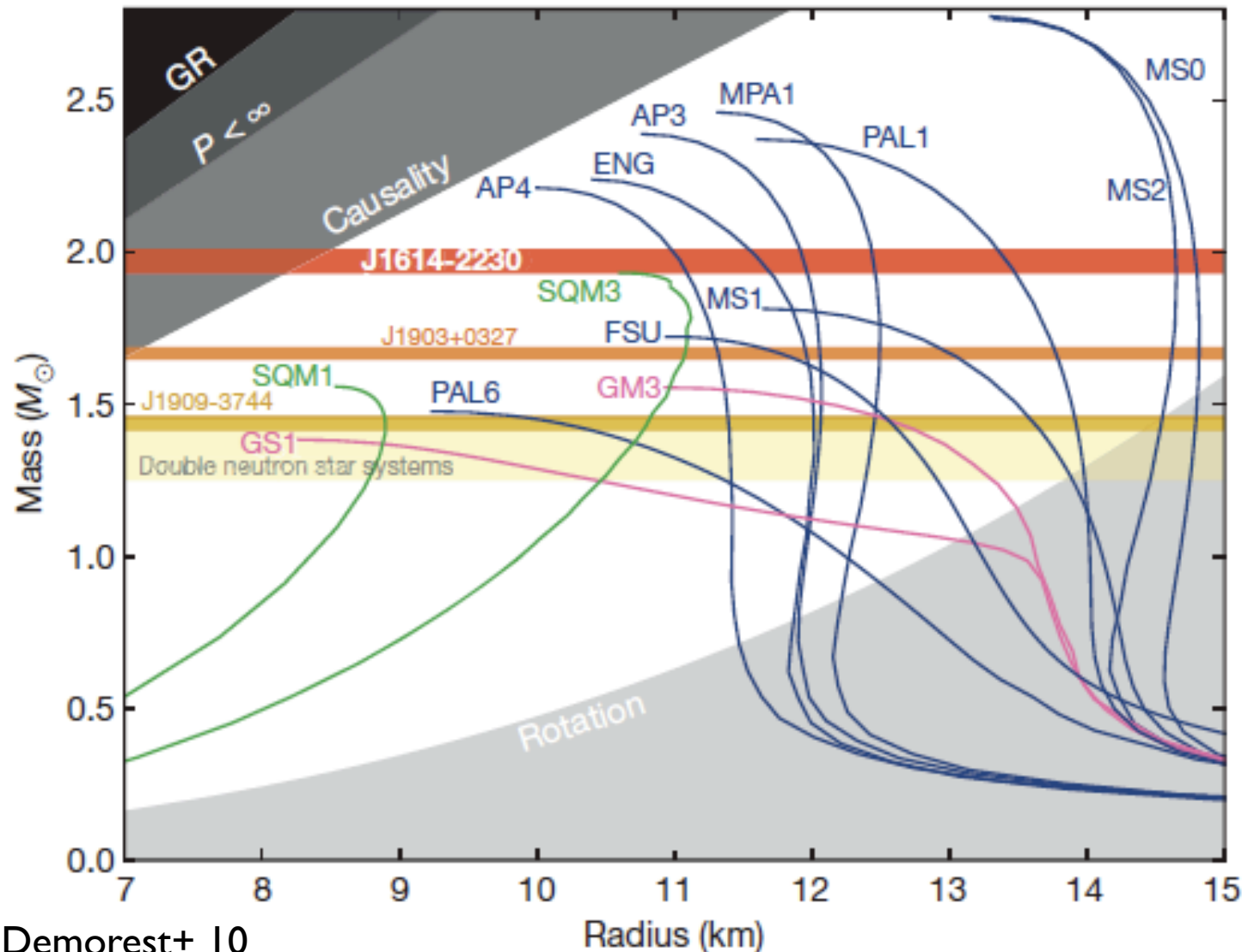
BH Mass Func



Max Mass of Neutron Star

- **$M < 1.4 M_{\odot} \Rightarrow \text{Neutron star}$**
- **$M > \sim 3 M_{\odot} \Rightarrow \text{Black hole}$**
 - General relativity
 - Causality $c_s < c$
 - EOS below nuclear density
 - Any EOS above nuclear density
- ***What is the exact boundary?***

Max Mass of Neutron Star



$2M_{\odot}$

msec NS +
 $0.5M_{\odot}$ WD

Shapiro delay
 $\sim (1.97 \pm 0.04) M_{\odot}$

Stiff EOS

(Hyperon?

3-body?

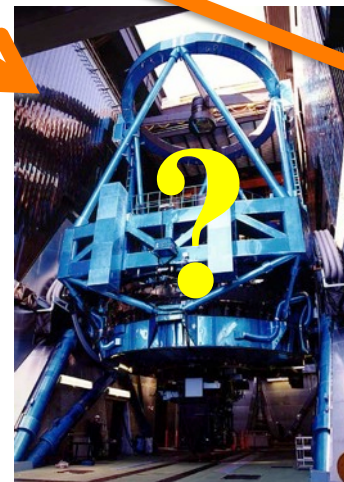
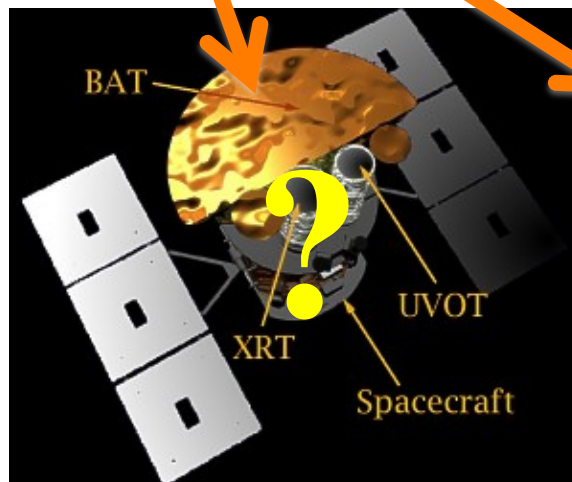
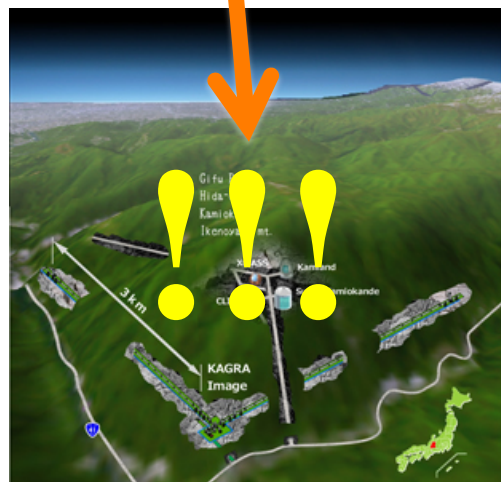
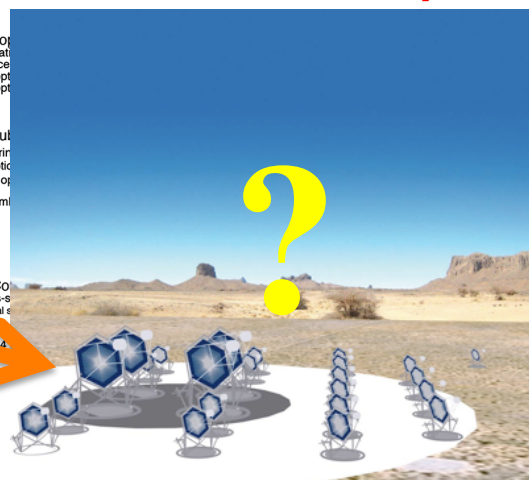
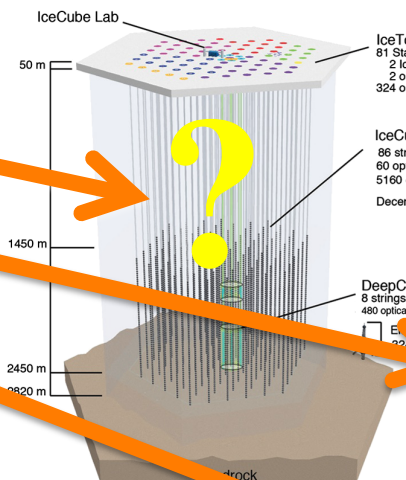
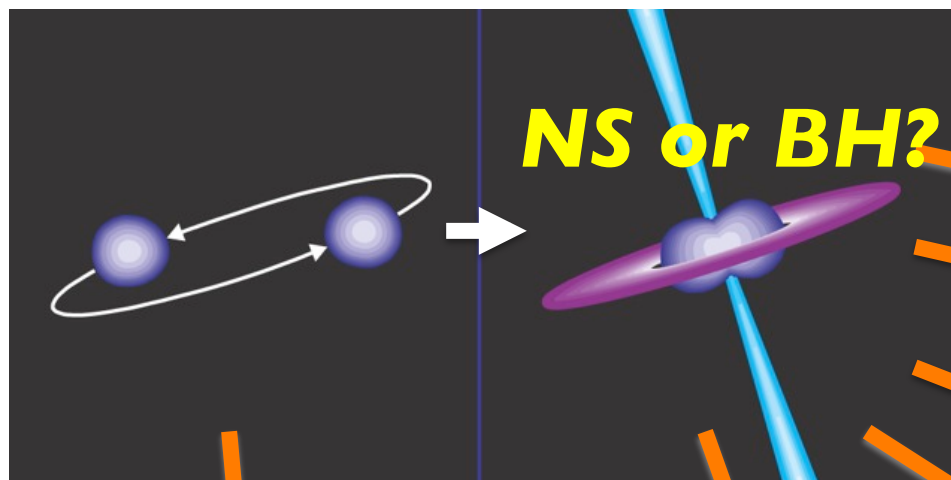
Vector force?)

Counterparts to GW

Gravitational Wave Sources

Neutrino

Gamma-ray



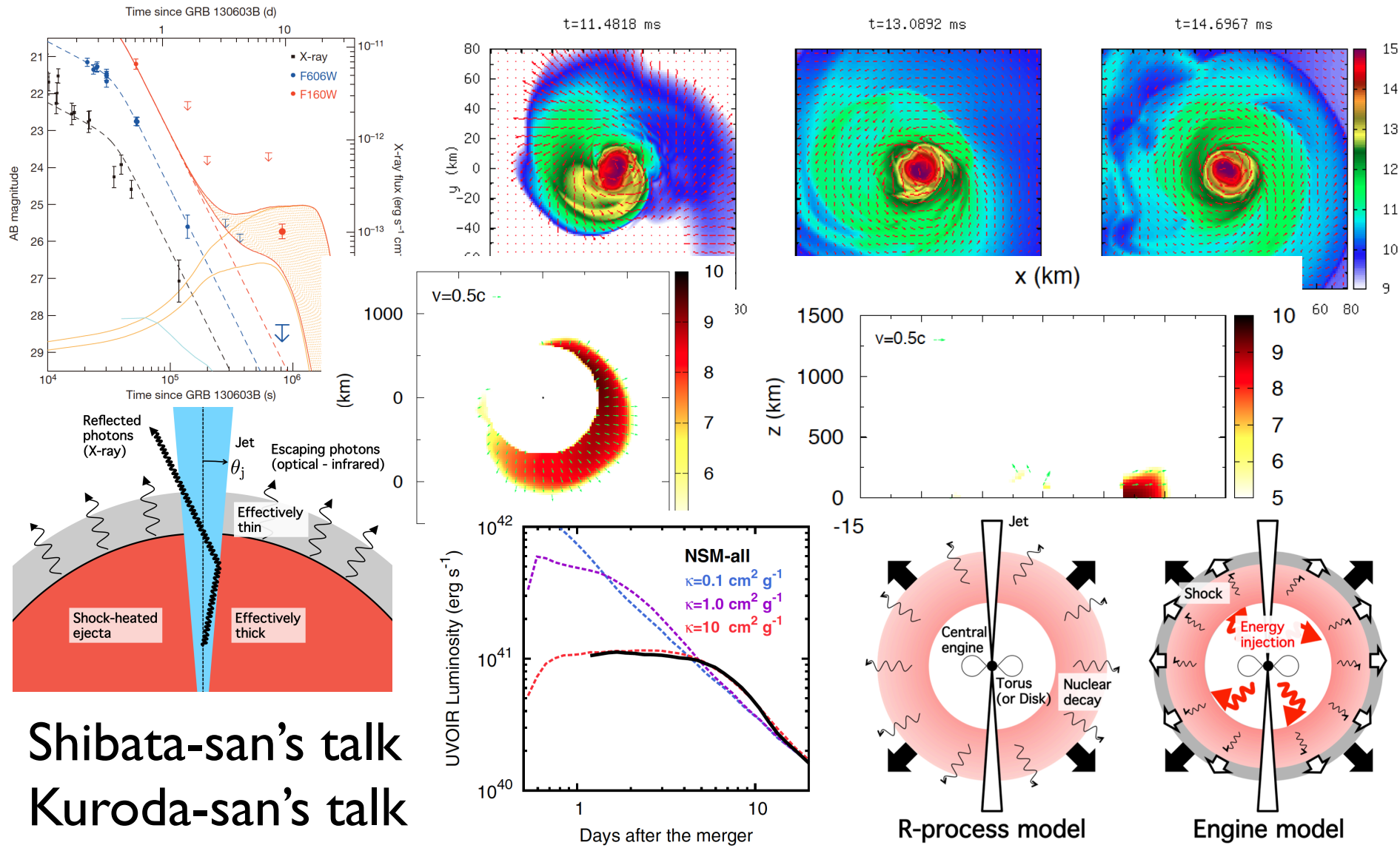
Gravitational wave

X-ray

IR-Opt

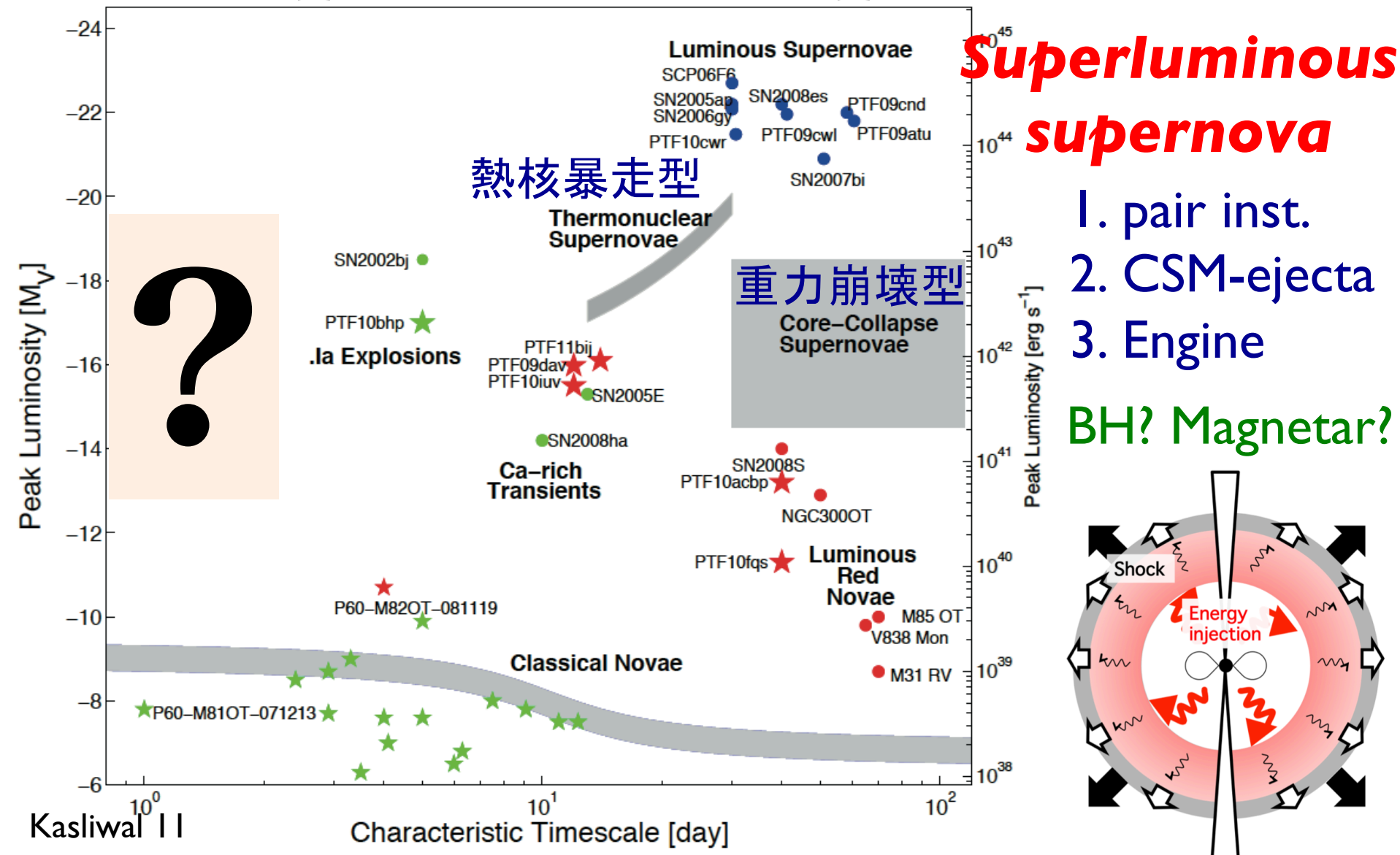
Radio

Rapid Developments

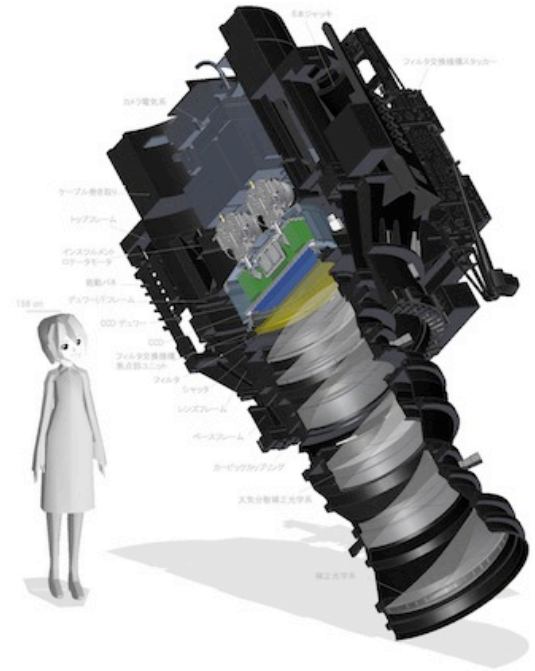
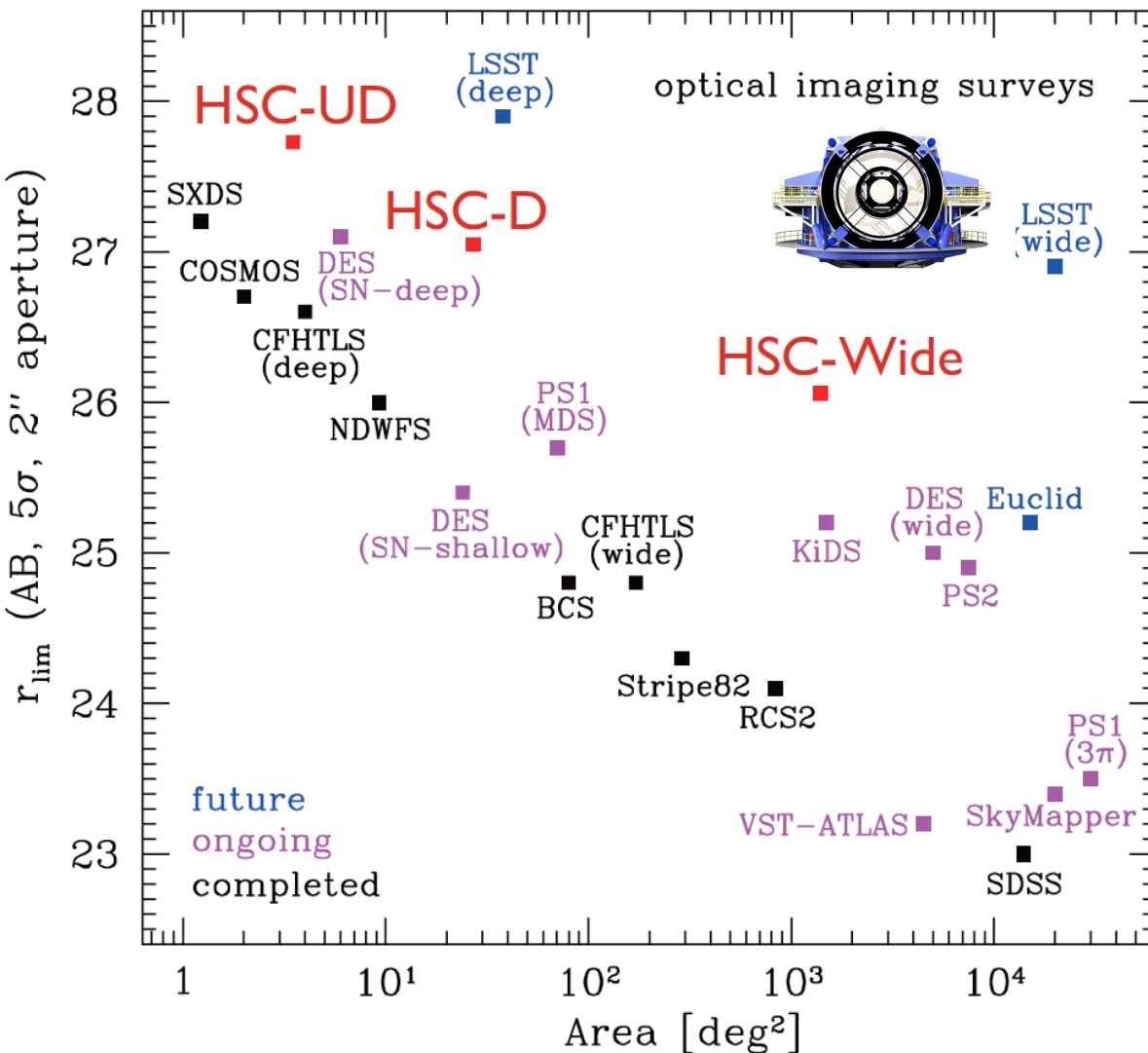


Shibata-san's talk
Kuroda-san's talk

BH-powered Supernovae?

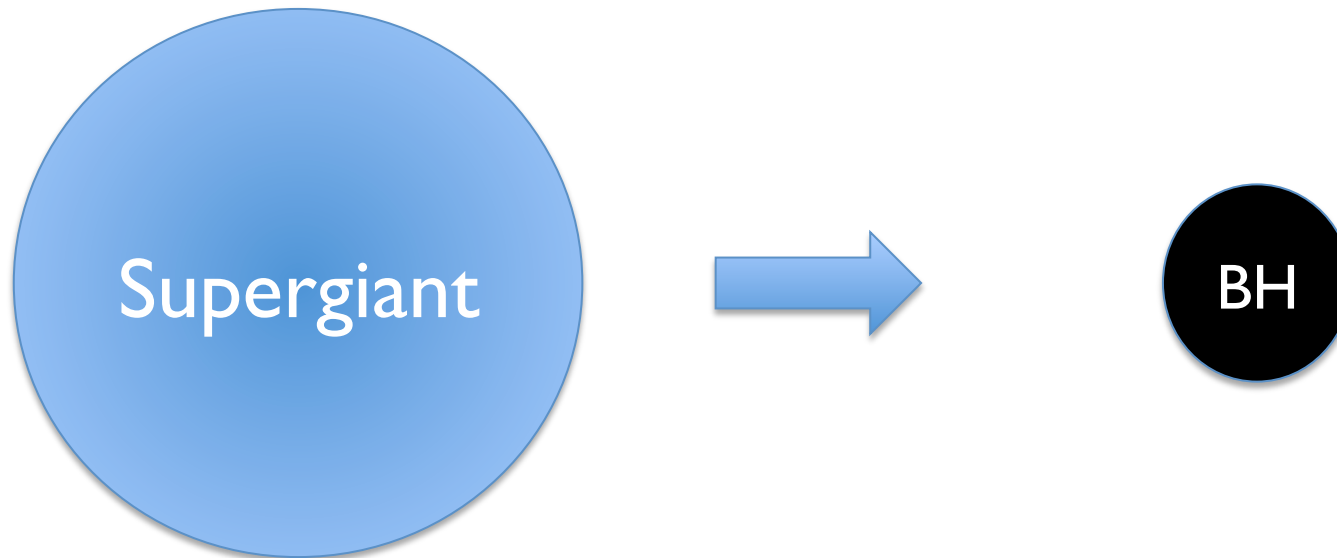


Deep-Wide-Fast Survey



Dark-energy-driven
optical survey
 $\Rightarrow$ BH transients

Survey about Nothing



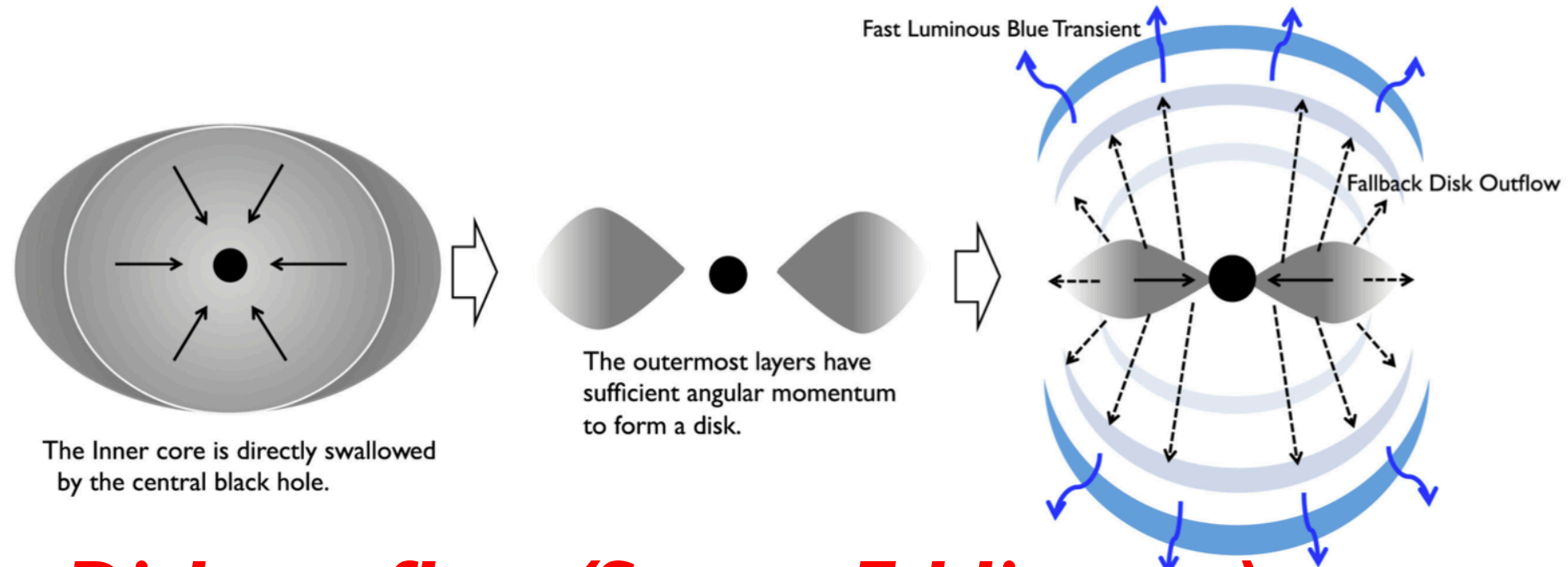
Kochanek+ 08

Disappearance of massive stars

$t_{\text{age}} \sim 10^6 \text{ yr}$

Watch $\sim 10^6$ supergiants $\Rightarrow$ 1 events/yr

New-born BH



Disk outflow (Super-Eddington)

UV-Optical transients

$t \sim$ a few days

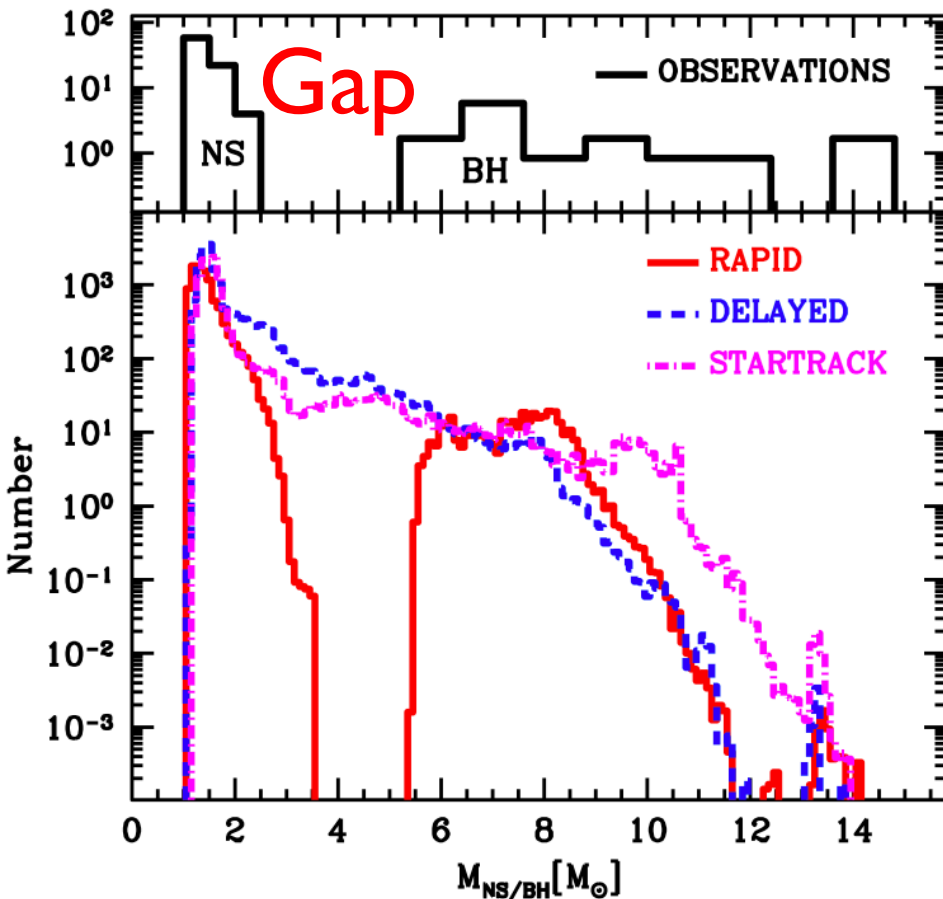
$L \sim 10^{42-44}$ erg/s $\sim$ supernova

Pan-STARRS may have already detected

Kashiyama & Quataert 15

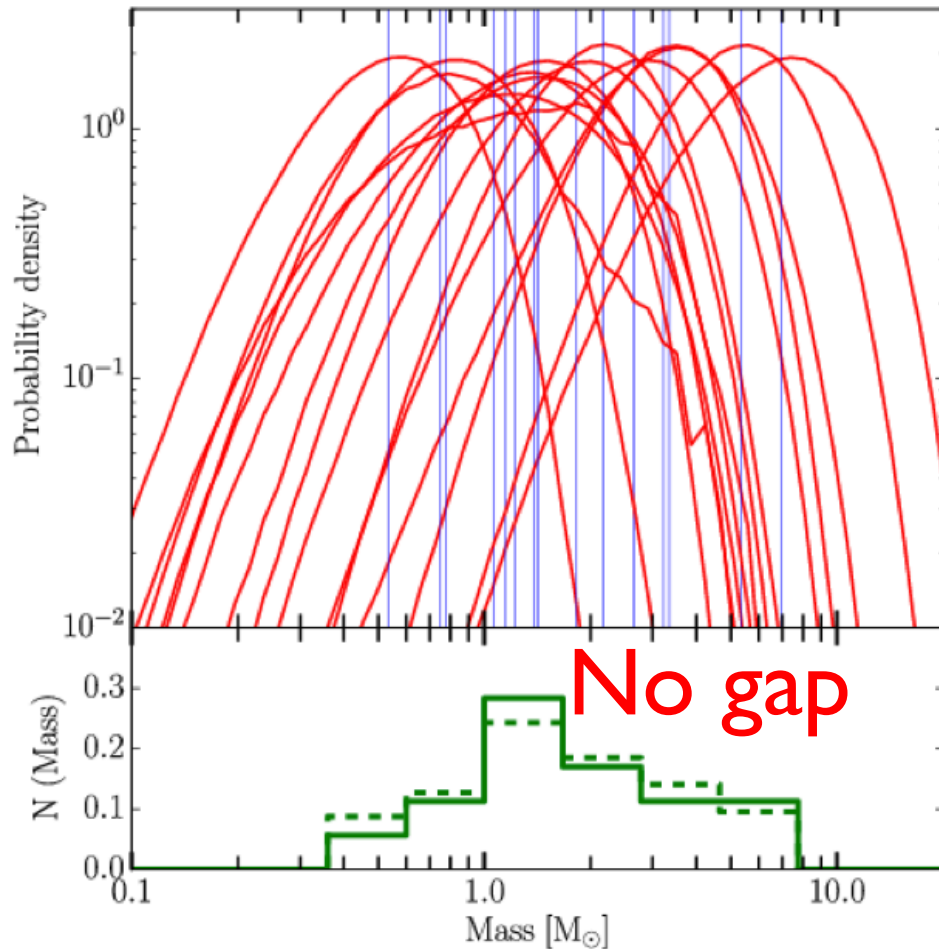
Mass Gap?

Galactic X-ray binaries



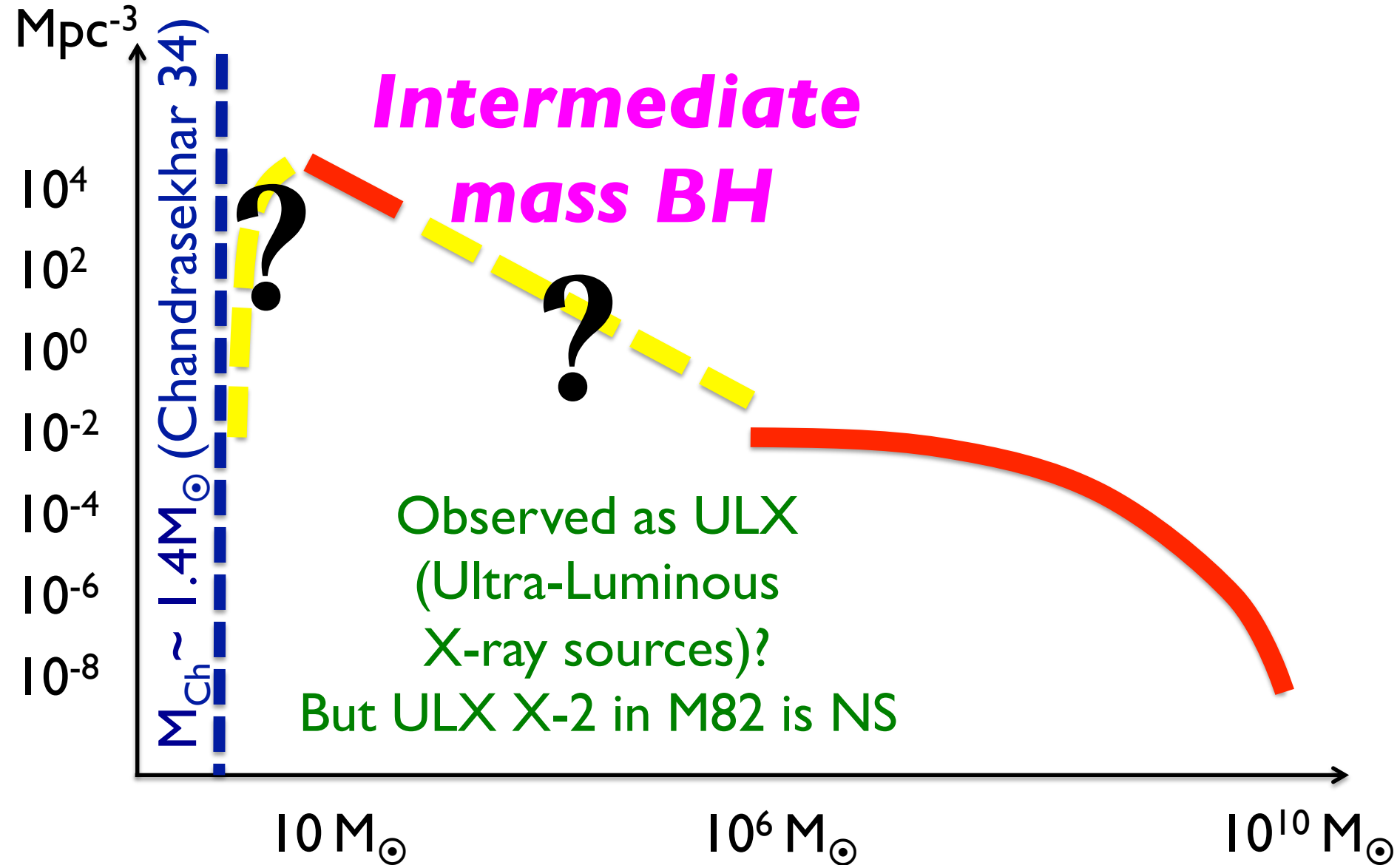
Bailyn+ 98; Belczynski+ 12

Microlensing

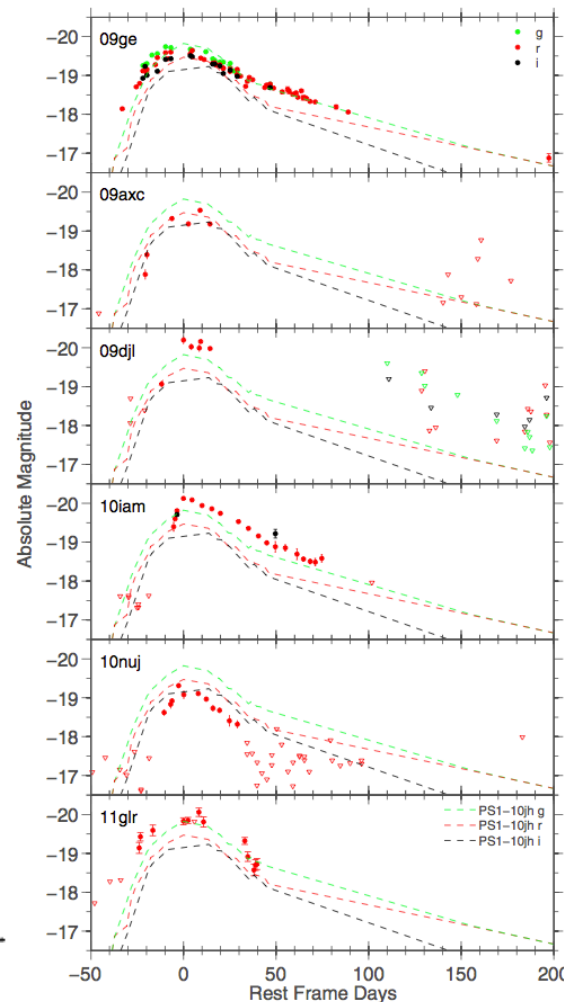
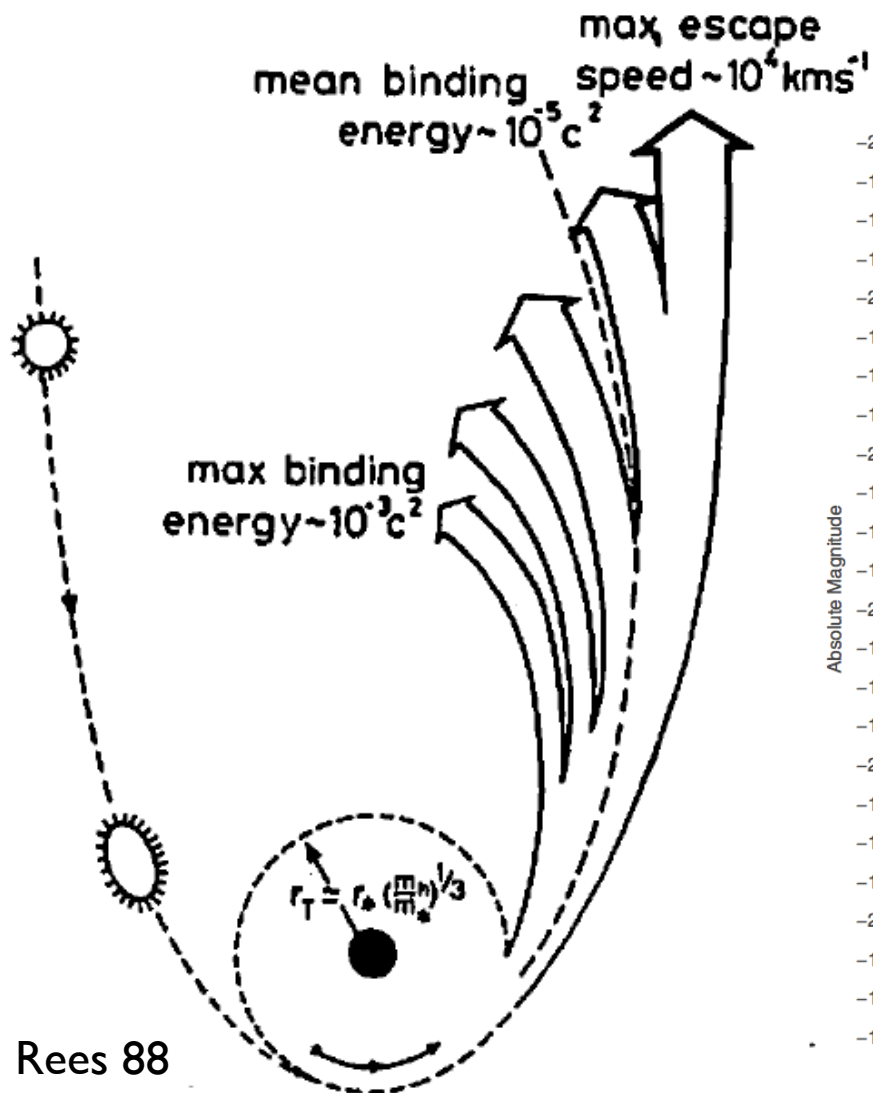


Wyrykowski+ 15

BH Mass Function



Tidal Disruption Event



Optical TDE
is discovered
 ~ 10 events

Dimmer than
expected

$$E_{\text{exp}} \sim 0.1 M c^2$$

$$E_{\text{obs}} \sim E_{\text{exp}} / 100$$

Arcavi+ 14

Piran+ 15

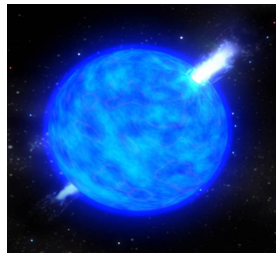
Miller 15

Metzger & Stone 15

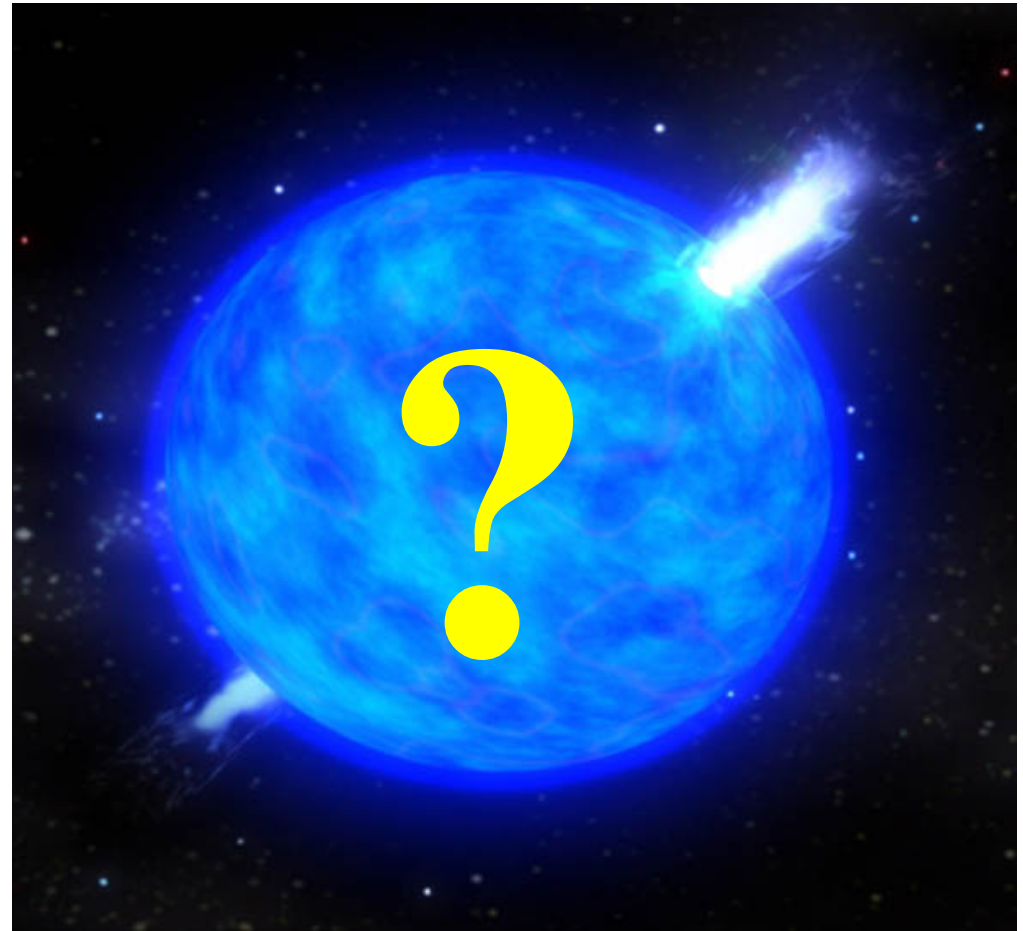
Gullochon+ 15

Pop III GRB?

Present Day GRB



Komissarov & Barkov 10
Meszaros & Rees 10
Suwa & KI 11
Nagakura, Suwa & KI 12
Matsumoto+ 15



Gigantic ($\times 10^2 - 10^5$) GRB @ $z > 10$???

Wide X-ray Survey

Sakamoto
Kawai YKISI3
Yonetoku

Lobster/ISS-Lobster



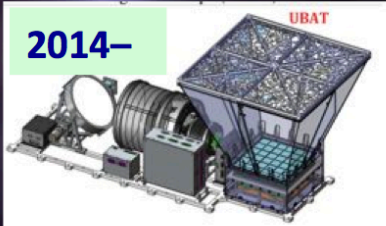
EXIST



Janus



UFFO Pathfinder



LOFT



SVOM

2018(20)-



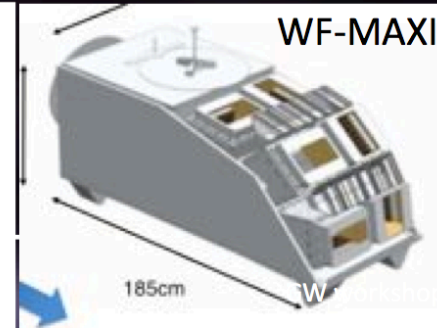
A-STAR



CALET



WF-MAXI



Astro-H/SGD shield



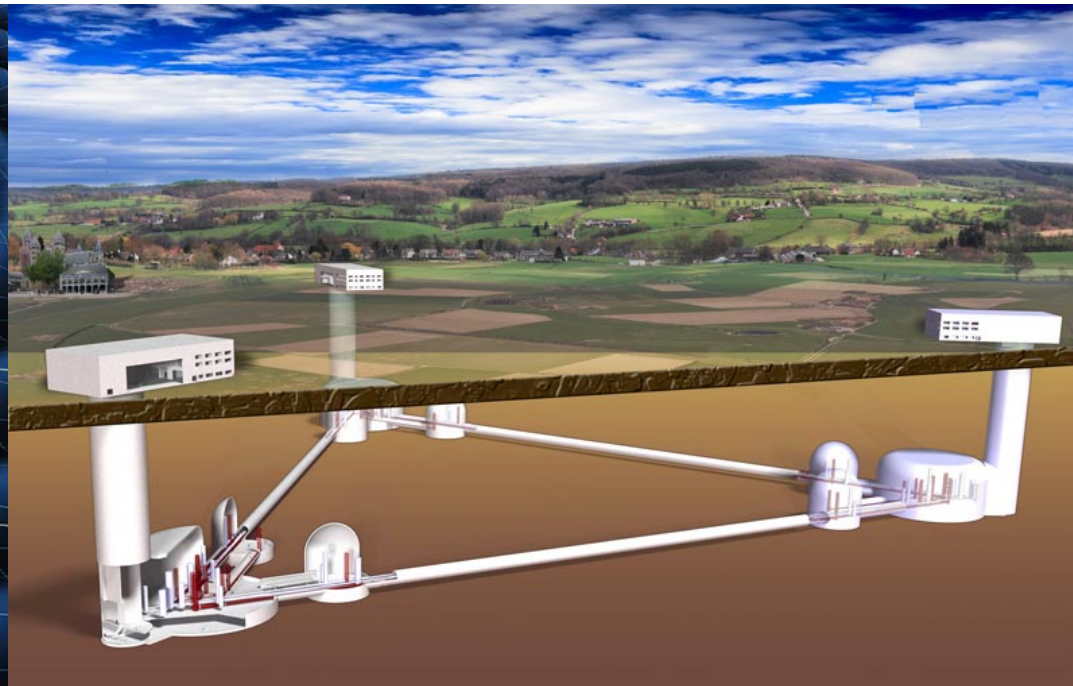
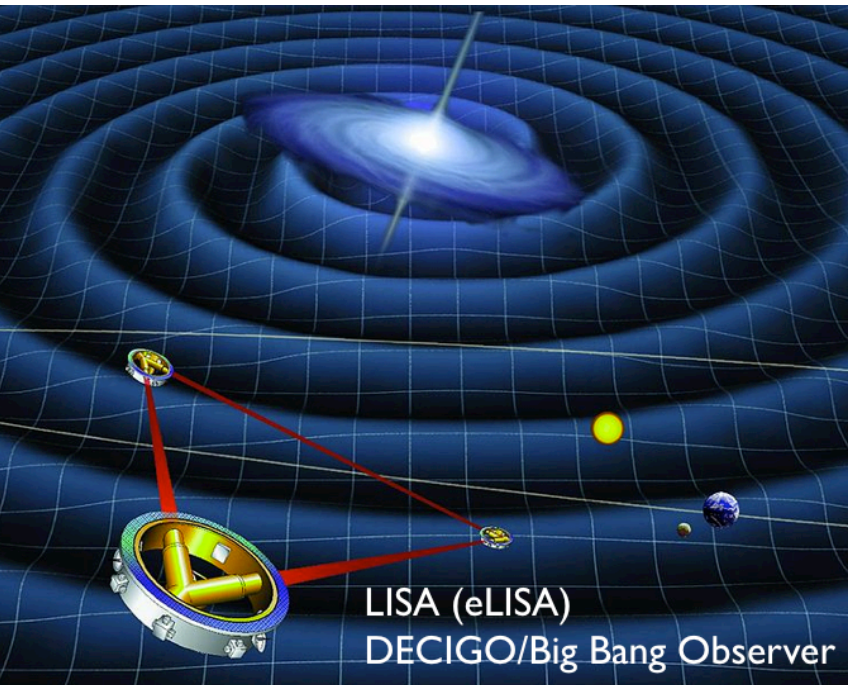
Hi-Z GUNDAM



Ultimate GW Observatory

eLISA, DECIGO

Einstein Telescope



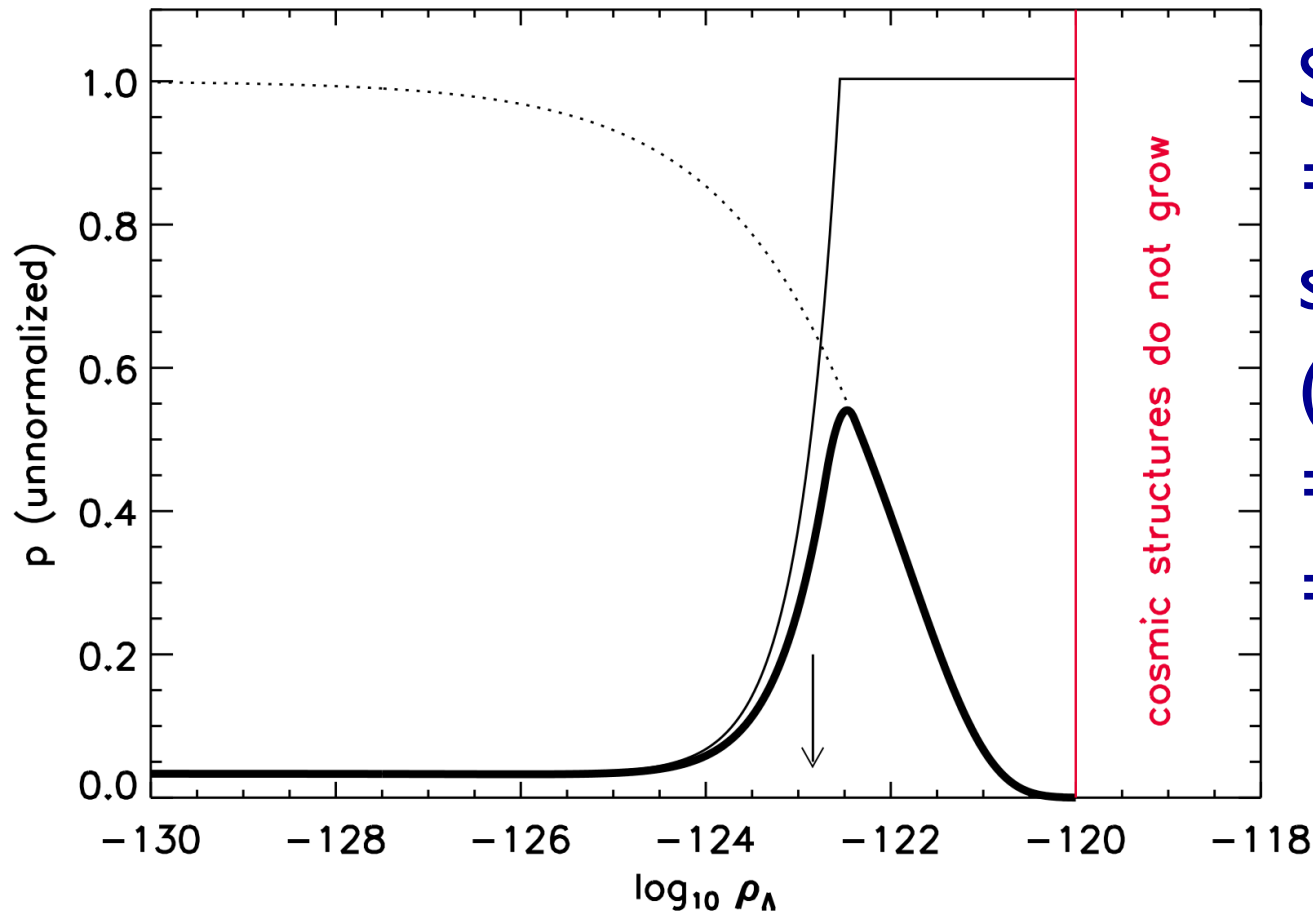
IMBH binary mergers upto high- z

~20? Years from Now

- We will fully understand energy flows from BHs?
- We will make a complete census of BHs?
- We will witness multidisciplinary revolutions?

BH & Life

PDF of cosmological constant Λ



Small Λ

$\Rightarrow$ Many nearby
small galaxies

(low metal)

$\Rightarrow$ GRB

$\Rightarrow$ Life extinction

***Anthropic
principle***

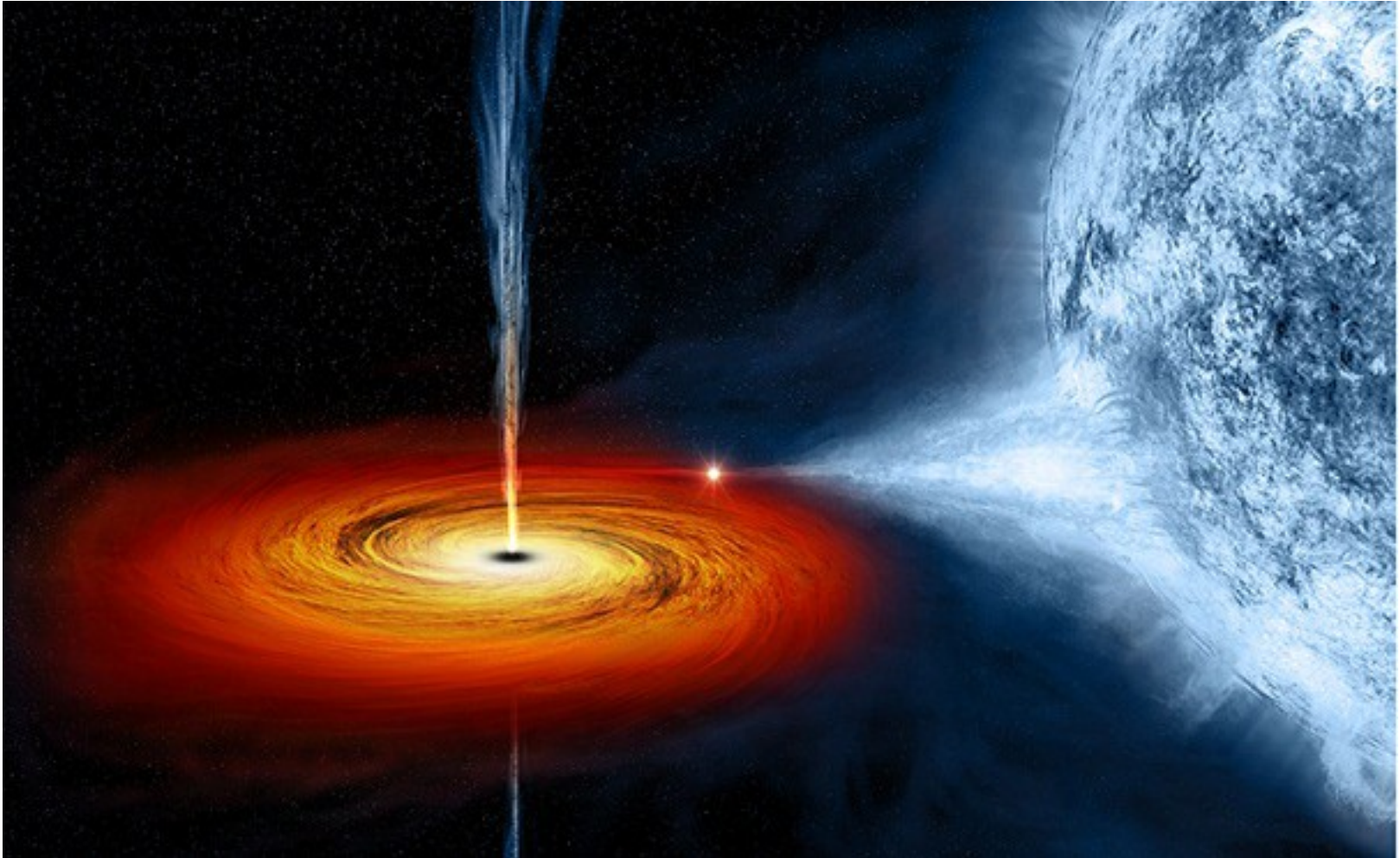
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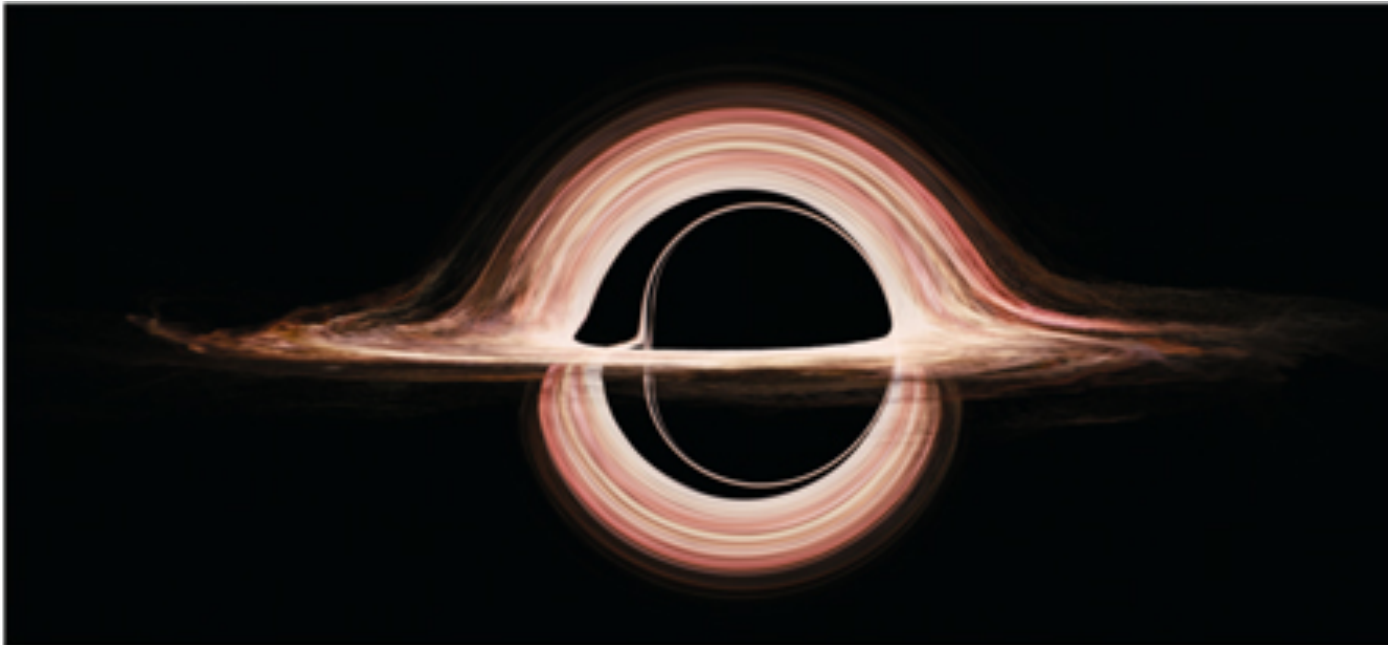
Thank

You

Pulsar Timing Array

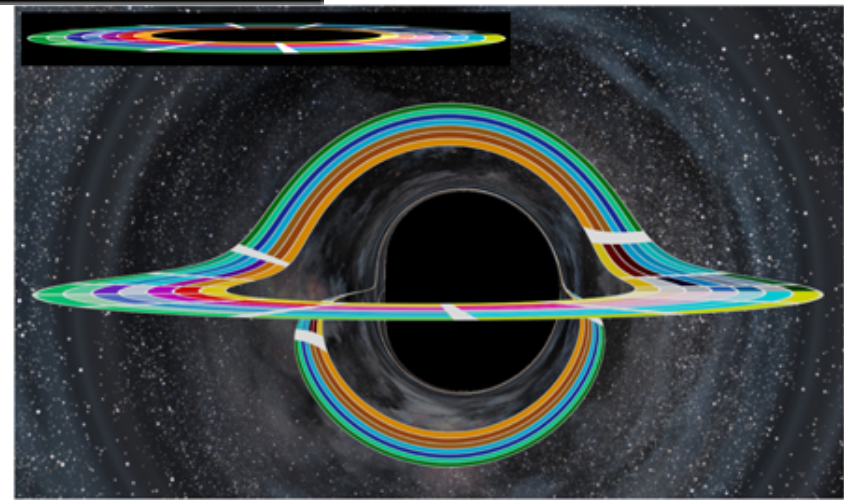


BH Shadow



Gargantua BH
in the movie
“Interstellar”

Oliver+ 15

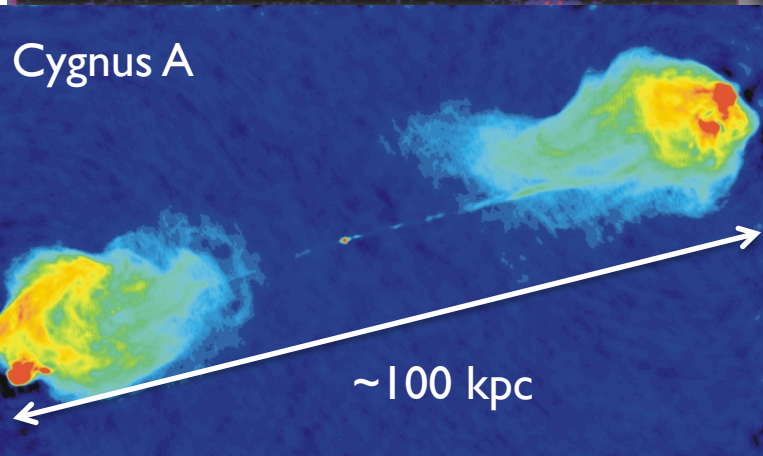
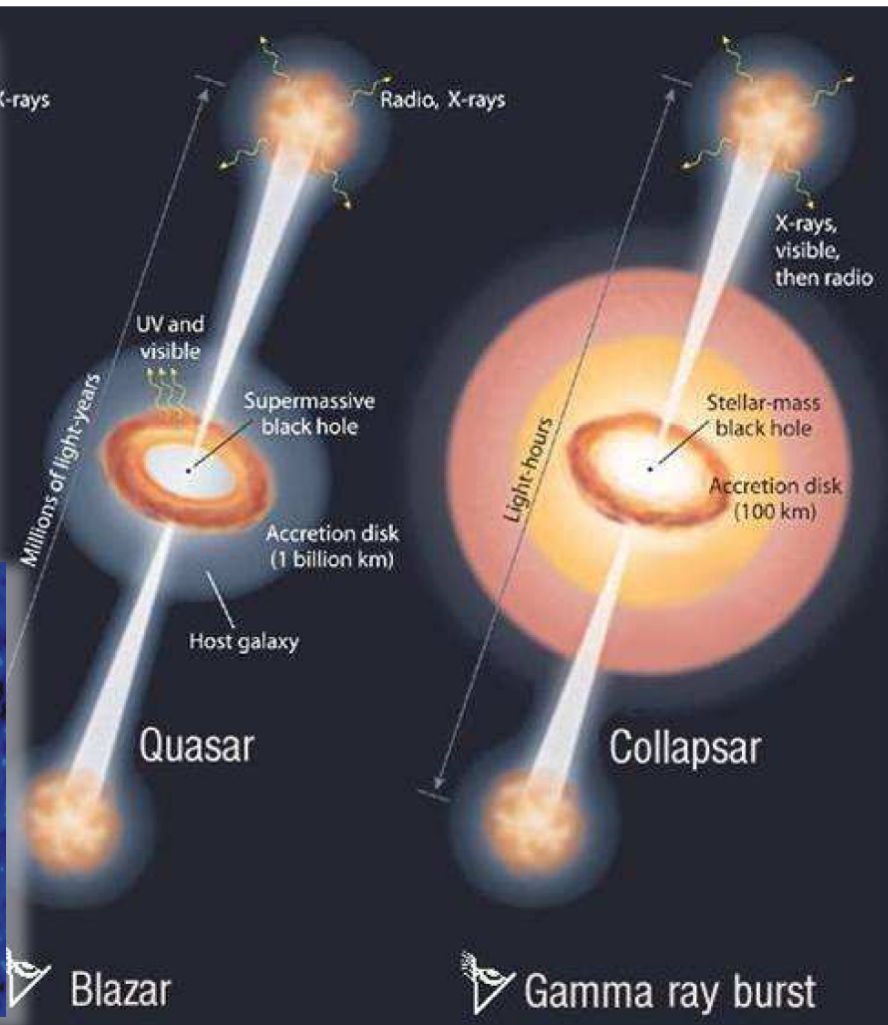
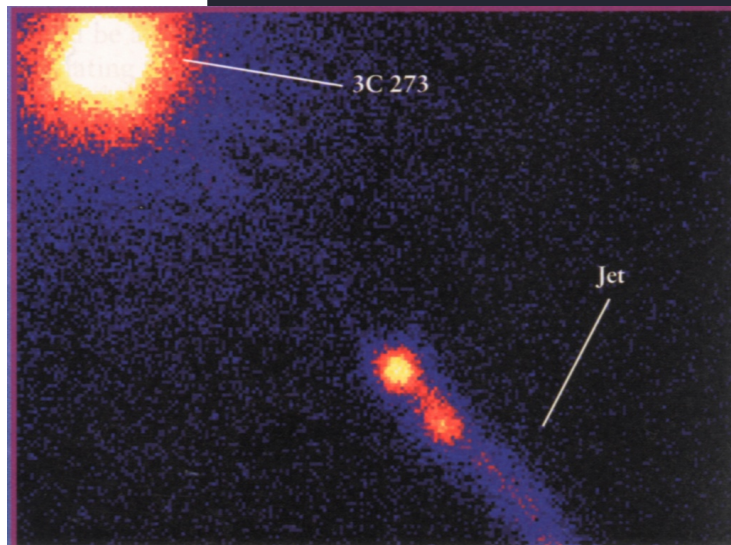


Observed BHs

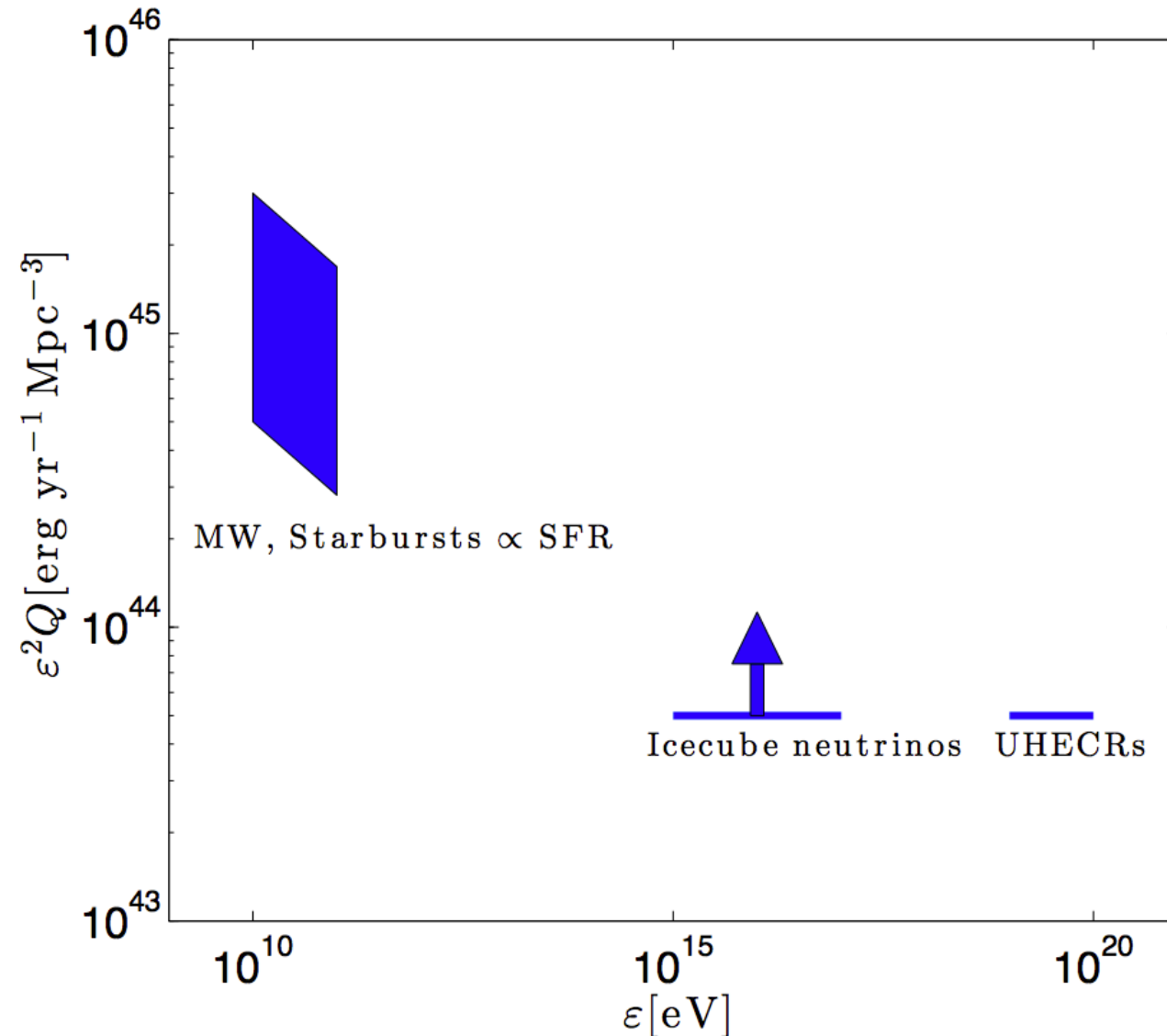
$\sim 10 M_{\odot}$

$\sim 10^6 - 10^9 M_{\odot}$

$\sim 10 M_{\odot}$



Energy Generation Rate



Single-type
sources
produce
all CRs?

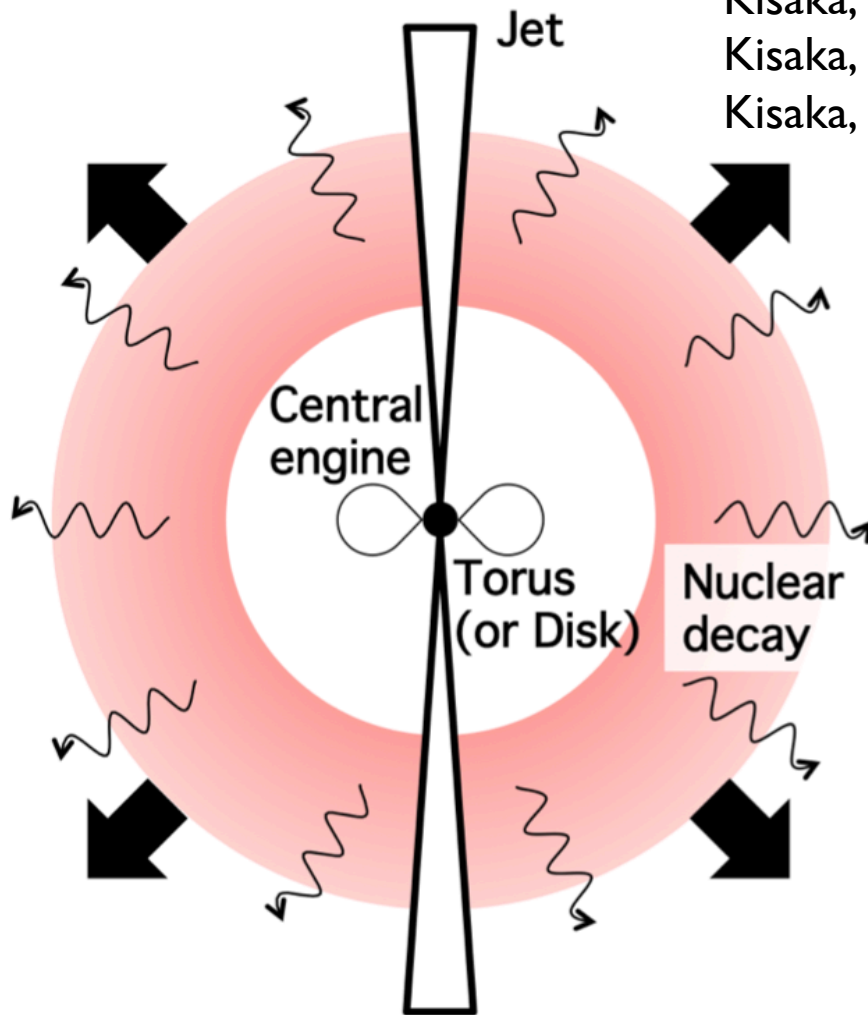
Katz+ 1311.0287

Engine-powered Macronovae?

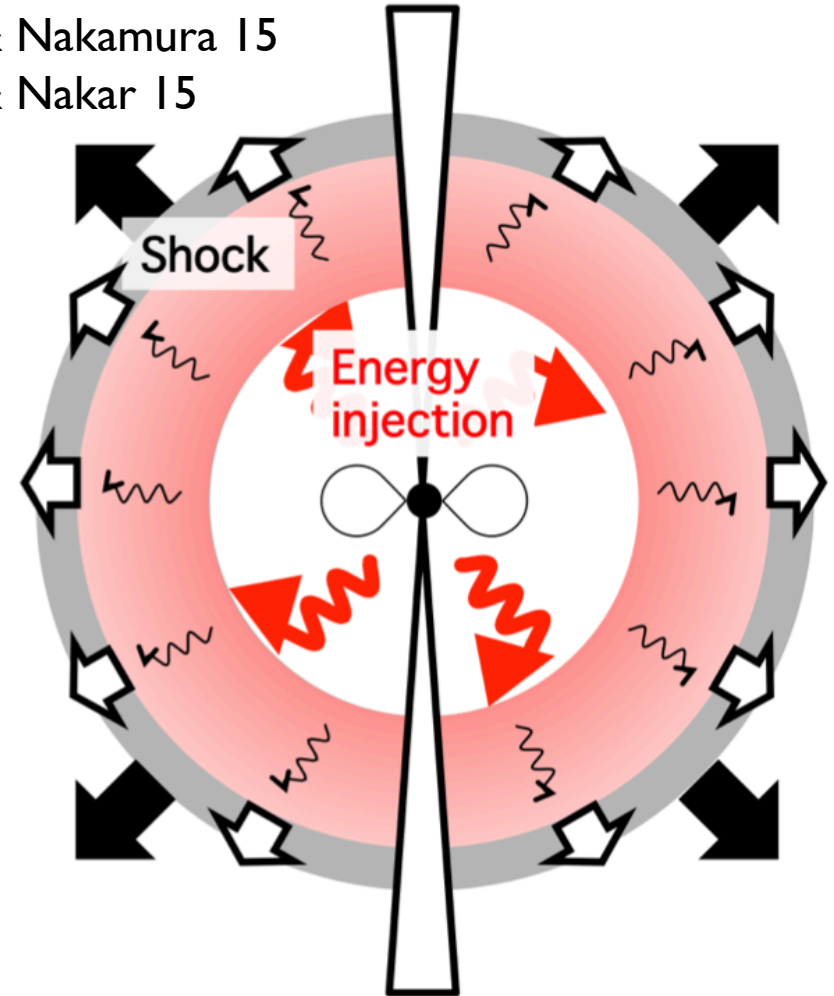
Kisaka, KI & Takami 14

Kisaka, KI & Nakamura 15

Kisaka, KI & Nakar 15



R-process model



Engine model