Primordial Magnetic Fields From Kerr-Newman PBH

Gordan Krnjaic

w/ Dan Hooper & Aurora Ireland

arXiv: 2206.04066

NEHOP Naples Italy, 5/21/23

Overview

Motivation for primordial B fields

Kerr-Newman PBH

Cosmological history

Model building

Overview

Motivation for primordial B fields

Kerr-Newman PBH

Cosmological history

Model building

Seeing into the past

Cosmological relics before BBN ($t \sim$ sec) are few and far between

- CMB photons
- CvB neutrinos
- Baryons/electrons

Not negotiable

Seeing into the past

Cosmological relics before BBN ($t \sim$ sec) are few and far between

- CMB photons
- CvB neutrinos
- Baryons/electrons

Not negotiable

If we're lucky, we may look farther back in time with others

- *Maybe* Dark matter (… but could have been made after BBN)
- *Maybe* Gravitational waves (… but model dependent)
- *Maybe* PBH … you know this already

Seeing into the past

Cosmological relics before BBN ($t \sim$ sec) are few and far between

- CMB photons
- CvB neutrinos
- Baryons/electrons

Not negotiable

If we're lucky, we may look farther back in time with others

- *Maybe* Dark matter (… but could have been made after BBN)
- *Maybe* Gravitational waves (… but model dependent)
- *Maybe* PBH … you know this already

What about *Magnetic Fields*?

Primordial Magnetic Fields

1. Opportunity to see further back into cosmic history pre-BBN

Primordial Magnetic Fields

1. Opportunity to see further back into cosmic history pre-BBN

2. Leading candidate to **seed galactic magnetic fields** via dynamo

Need seed large scale > 10 kpc fields $B_{\rm IGM} > 10^{-20}{\rm G}$

Kandus Kunze Tsagas 1007.3891

Primordial Magnetic Fields

1. Opportunity to see further back into cosmic history pre-BBN

2. Leading candidate to **seed galactic magnetic fields** via dynamo

Need seed large scale > 10 kpc fields $B_{\rm IGM} > 10^{-20}{\rm G}$

Kandus Kunze Tsagas 1007.3891

3. Observational consequences

Ultra high energy cosmic ray propagation

Modify blazar emission spectra Durrer and Neronov (2013)

Primordial Magnetic Fields

1. Opportunity to see further back into cosmic history pre-BBN

2. Leading candidate to **seed galactic magnetic fields** via dynamo

   Need seed large scale > 10 kpc fields $B_{\rm IGM} > 10^{-20}{\rm G}$

   Kandus Kunze Tsagas 1007.3891

3. Observational consequences

   Ultra high energy cosmic ray propagation

   Modify blazar emission spectra Durrer and Neronov (2013)

4. Known formation mechanisms

   1st order phase transitions Hogan 1983

   Inflationary long wavelength modes

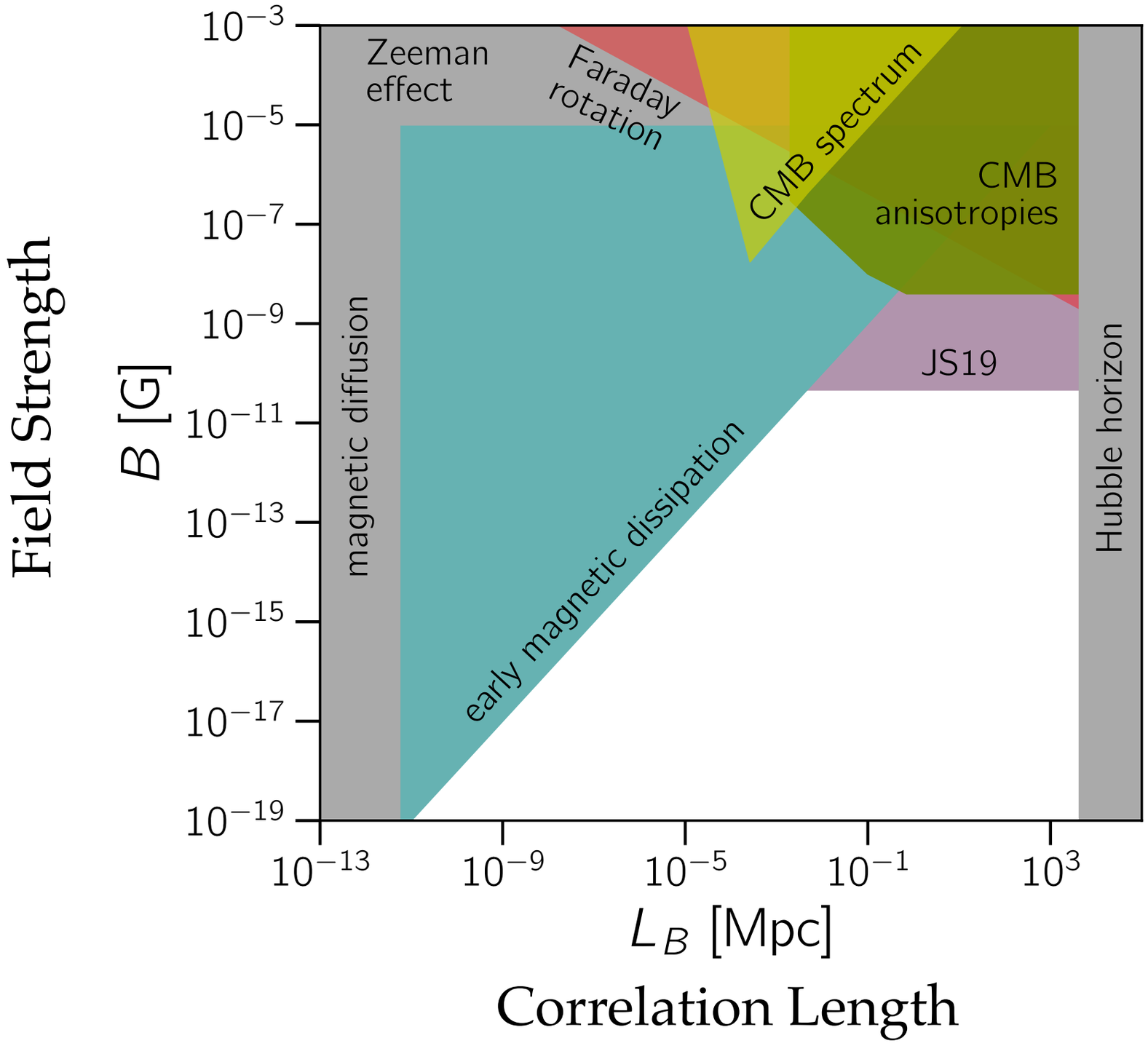
   Turner, Widrow (1988); Ratra (1992)

   Compensated isogurvature perturbations

   Flitter, Creque-Sarbinowski, Kamionkowsi, Dai 2304.03299

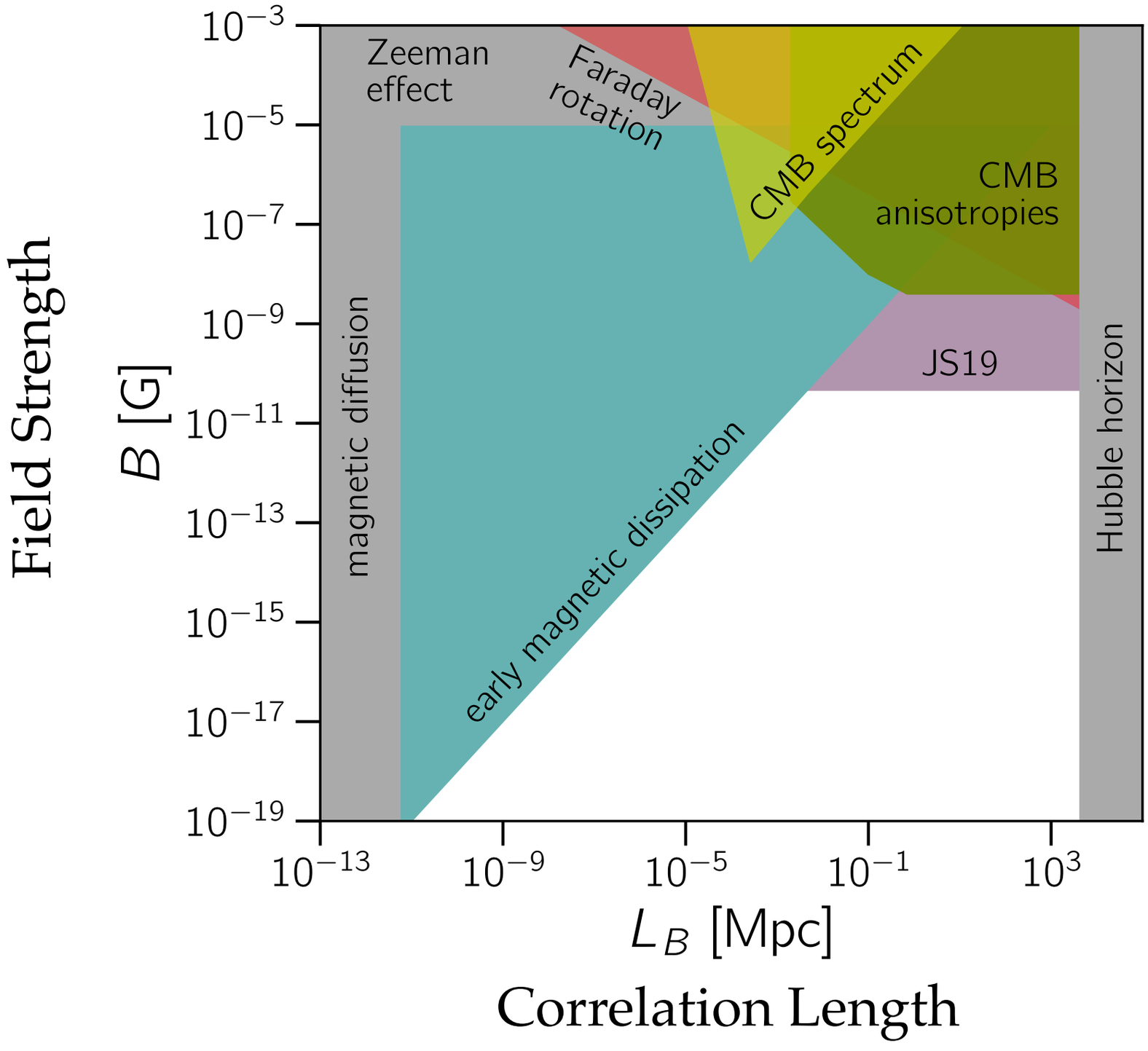
Primordial Magnetic Fields

Batista Saveliev 2105.12020



Primordial Magnetic Fields

Batista Saveliev 2105.12020



Propose new formation mechanism: **Kerr-Newman PBH**

Overview

Motivation for primordial B fields

Kerr-Newman PBH

Cosmological history

Model building

Kerr-Newman Metric

$$\alpha = J/M$$

Charged spinning black hole metric

$$ds^2 = -\frac{\Delta}{\rho^2}(dt - \alpha \sin^2\theta\, d\phi)^2 + \frac{\rho^2}{\Delta} dr^2$$
$$+\rho^2 d\theta^2 + \frac{\sin^2\theta}{\rho^2}\left[(r^2+\alpha^2)d\phi - \alpha dt\right]^2$$

Characteristic scales

$$\rho^2 = r^2 + \alpha^2 \cos^2\theta, \quad \Delta = r^2 + \alpha^2 - \frac{2Mr}{M_{\rm Pl}^2} + \frac{Q^2}{M_{\rm Pl}^2},$$

Extremal condition saturates inequality $\alpha^2 M_{\rm Pl}^2 + Q^2 \leq \frac{M^2}{M_{\rm Pl}^2}$

Newman; Couch; Chinnapared; Exton; Prakash; Torrence (1965)

Kerr-Newman B Field

Vector potential satisfies $$A_\mu dx^\mu = -\frac{Qr}{r^2 + \alpha^2 \cos^2\theta}\left(dt - \alpha \sin^2\theta \, d\phi\right)$$

Newman; Couch; Chinnapared; Exton; Prakash; Torrence (1965)

Kerr-Newman B Field

Vector potential satisfies $$A_\mu dx^\mu = -\frac{Qr}{r^2 + \alpha^2 \cos^2\theta}\left(dt - \alpha \sin^2\theta \, d\phi\right)$$

Build field strength tensor $$F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu$$

$$\vec{B} = \frac{Q\alpha}{r}\left[\frac{2(\alpha^2 + r^2)\cos\theta}{\rho^4}\,\hat{r} + \frac{(r^2 - \alpha^2\cos^2\theta)\sin\theta}{\rho^4}\,\hat{\theta}\right]$$

Newman; Couch; Chinnapared; Exton; Prakash; Torrence (1965)

Kerr-Newman B Field

Vector potential satisfies $$A_\mu dx^\mu = -\frac{Qr}{r^2 + \alpha^2 \cos^2\theta}\left(dt - \alpha \sin^2\theta \, d\phi\right)$$

Build field strength tensor $$F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu$$

$$\vec{B} = \frac{Q\alpha}{r}\left[\frac{2(\alpha^2 + r^2)\cos\theta}{\rho^4}\,\hat{r} + \frac{(r^2 - \alpha^2\cos^2\theta)\sin\theta}{\rho^4}\,\hat{\theta}\right]$$

Asymptotically recover classical charged spinning sphere

$$\lim_{r\to\infty} \vec{B} = \frac{Q\alpha}{r^3}\left(2\cos\theta\,\hat{r} + \sin\theta\,\hat{\theta}\right) + \mathcal{O}\left(\frac{1}{r^4}\right)$$

Newman; Couch; Chinnapared; Exton; Prakash; Torrence (1965)

Overview

Motivation for primordial B fields

Kerr-Newman PBH

Cosmological history

Model building

Step1: Form Schwarzschild PBH

PBH are easy to make with the right ingredients

- enhanced small scale power
- large non-gaussianities
- first order phase transitions
- ⋮

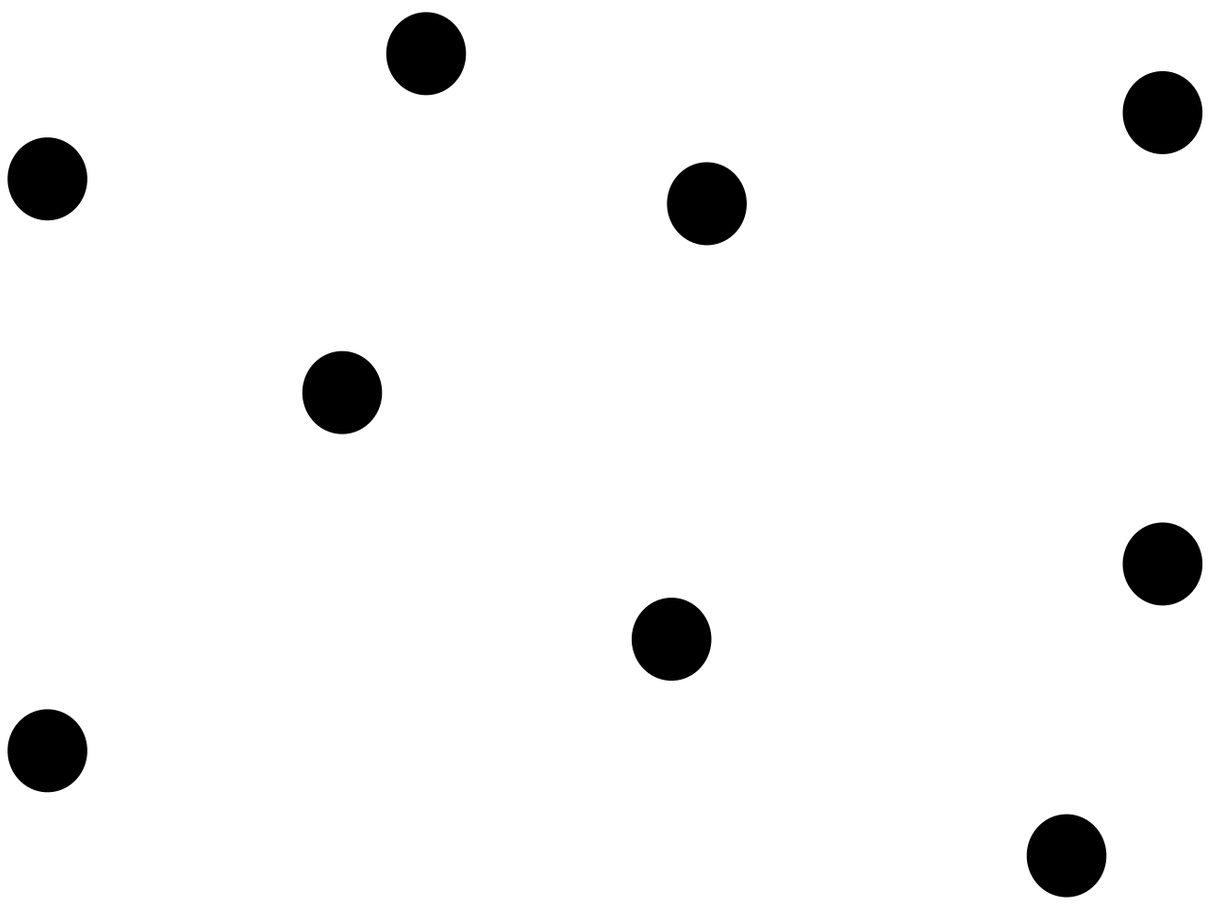
Lots of talks here!

Nearly all formation mechanisms form Schwarzschild PBH

Generically no quantum numbers at formation

How do we add features?

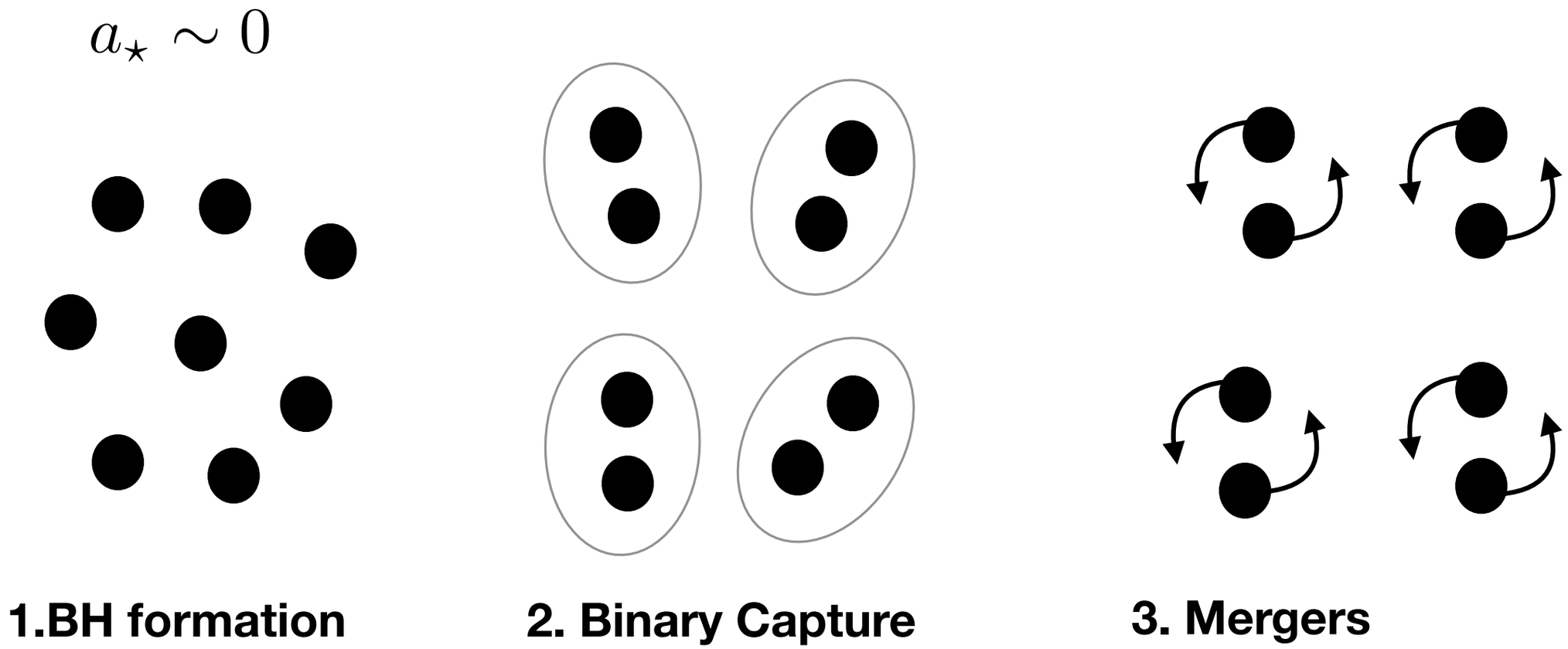
Step1: Form Schwarzschild PBH



$t < 1$ sec

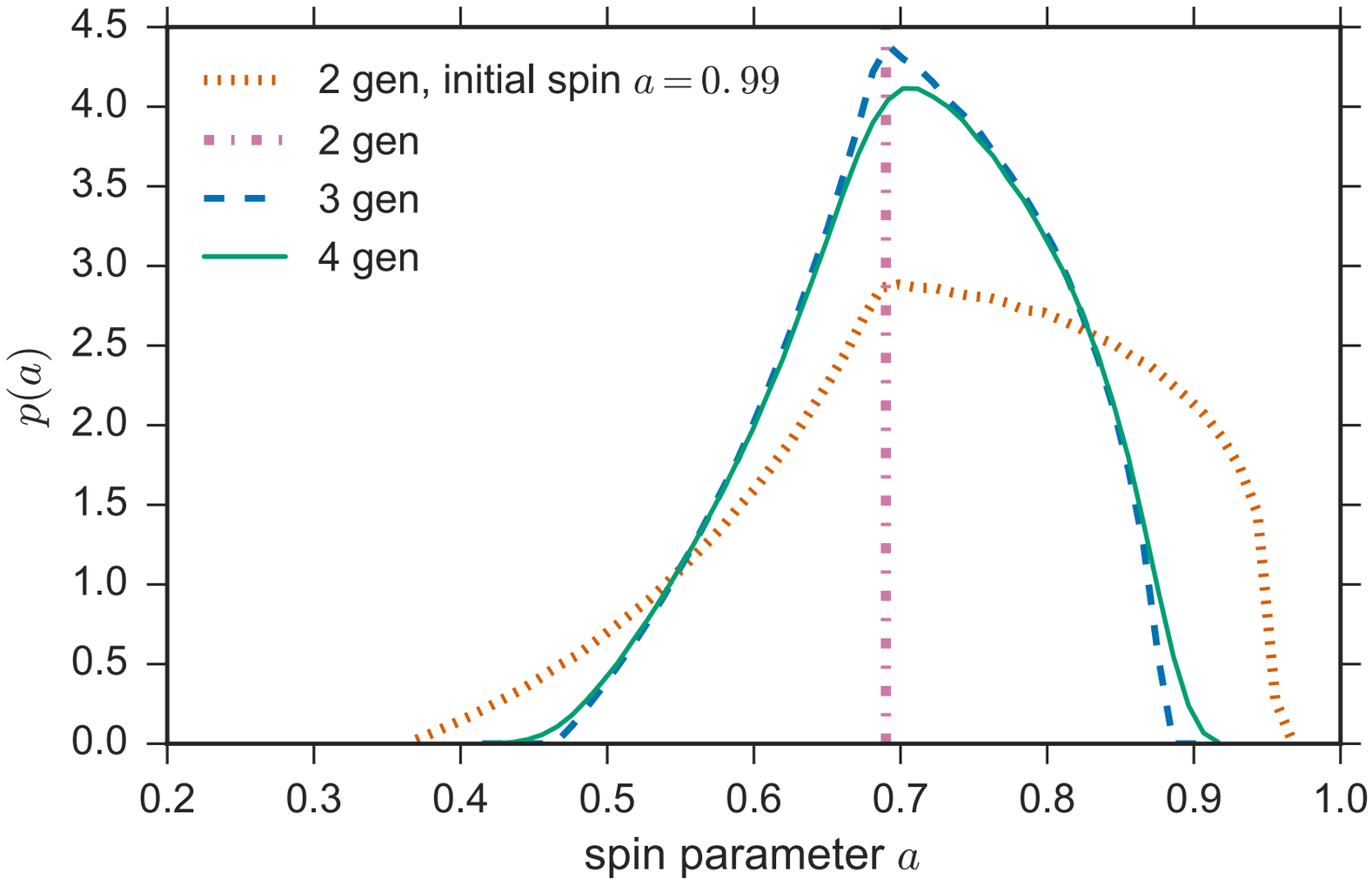
Step 2: Add Spin (Kerr)

Post formation, mergers can generate spin



Hooper, GK, March-Russell, McDermott, Petrossian-Byrne 2004.00618

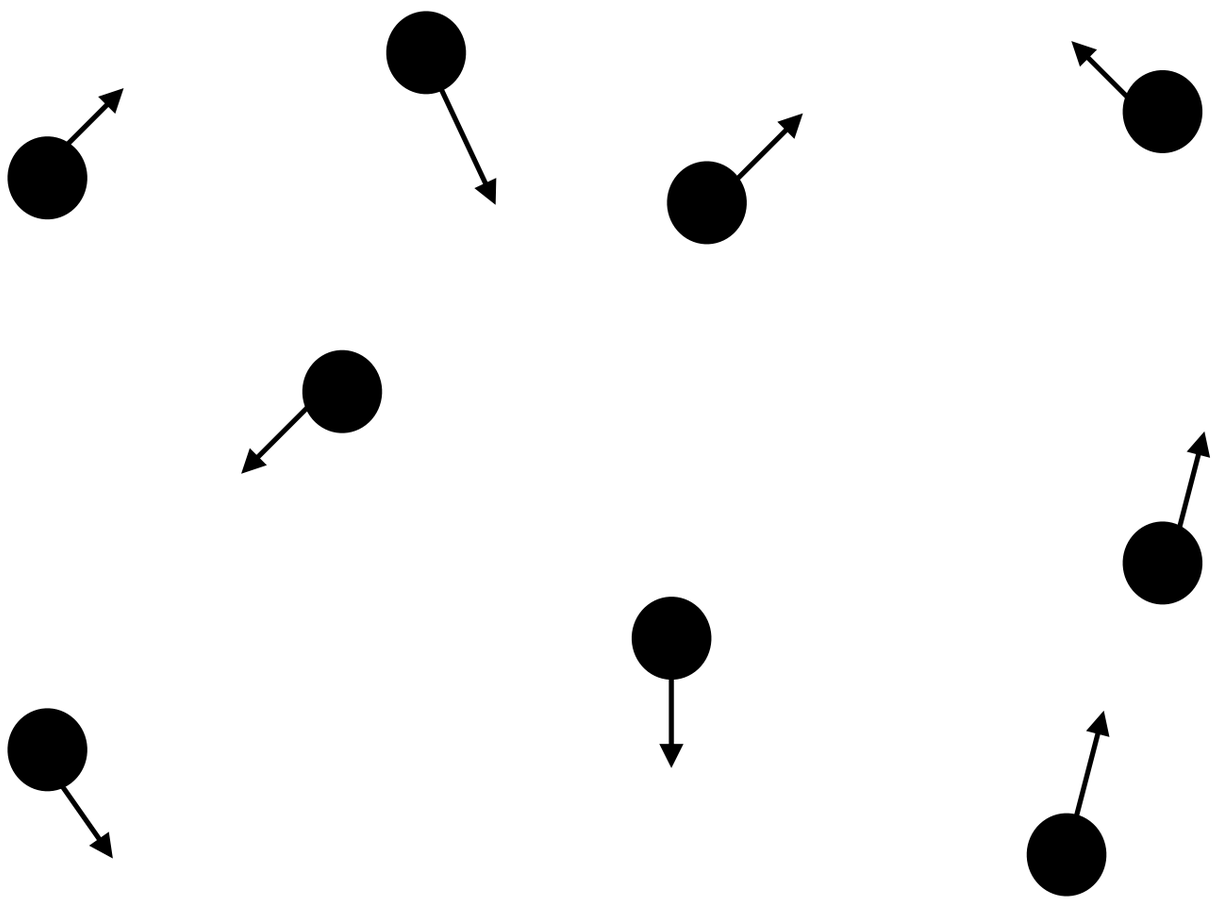
Step 2: Add Spin (Kerr)



Even one merger on average yields large spin $\langle a_\star \rangle \sim 0.7$

Feshbach, Holtz, Farr 1703.06869

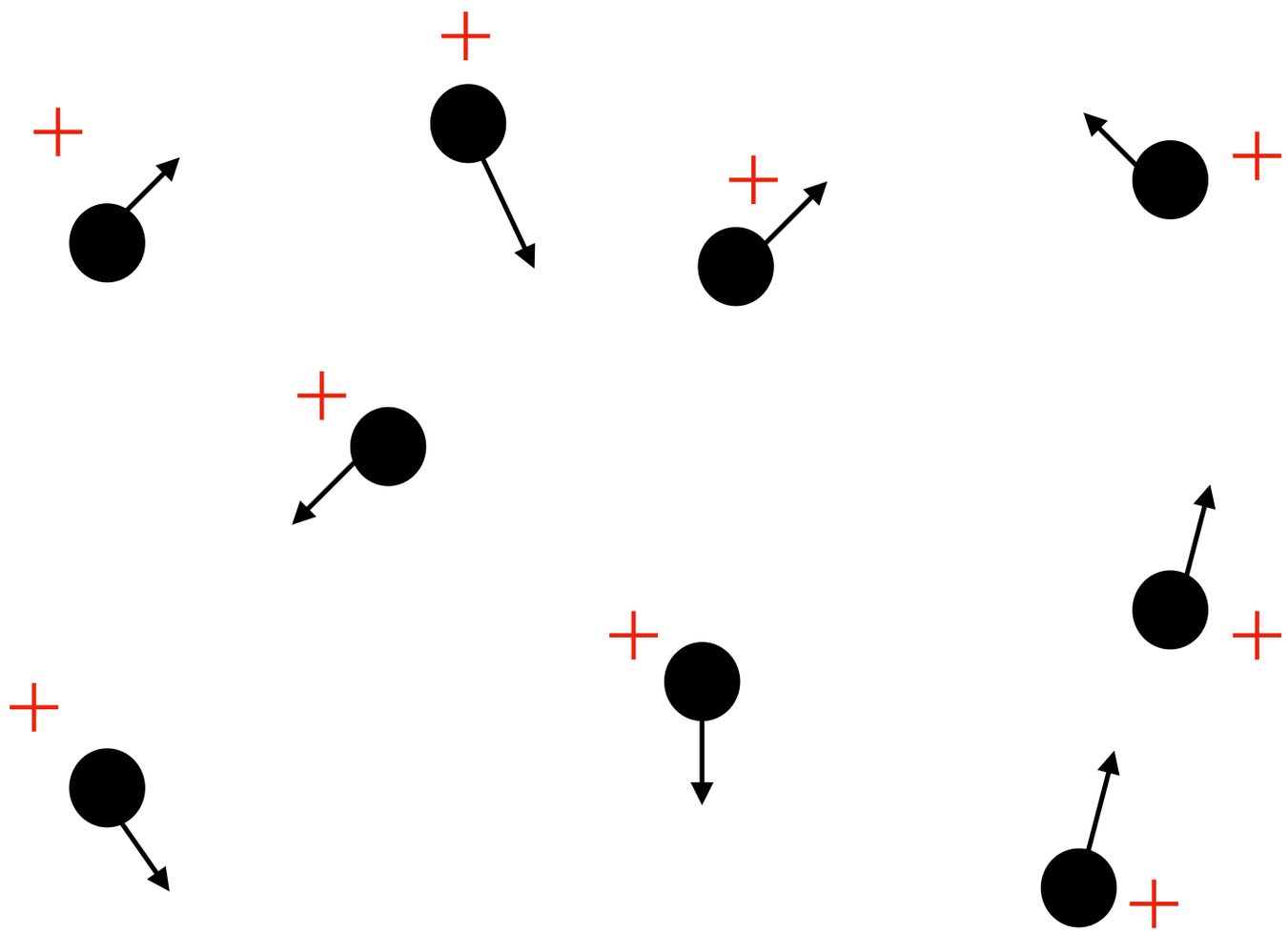
Step 2: Add Spin (Kerr)



$t < 1$ sec

Step 3: Turn On Chemical Potential (Kerr-Newman)

Chemical potential affects accretion and Hawking evaporation

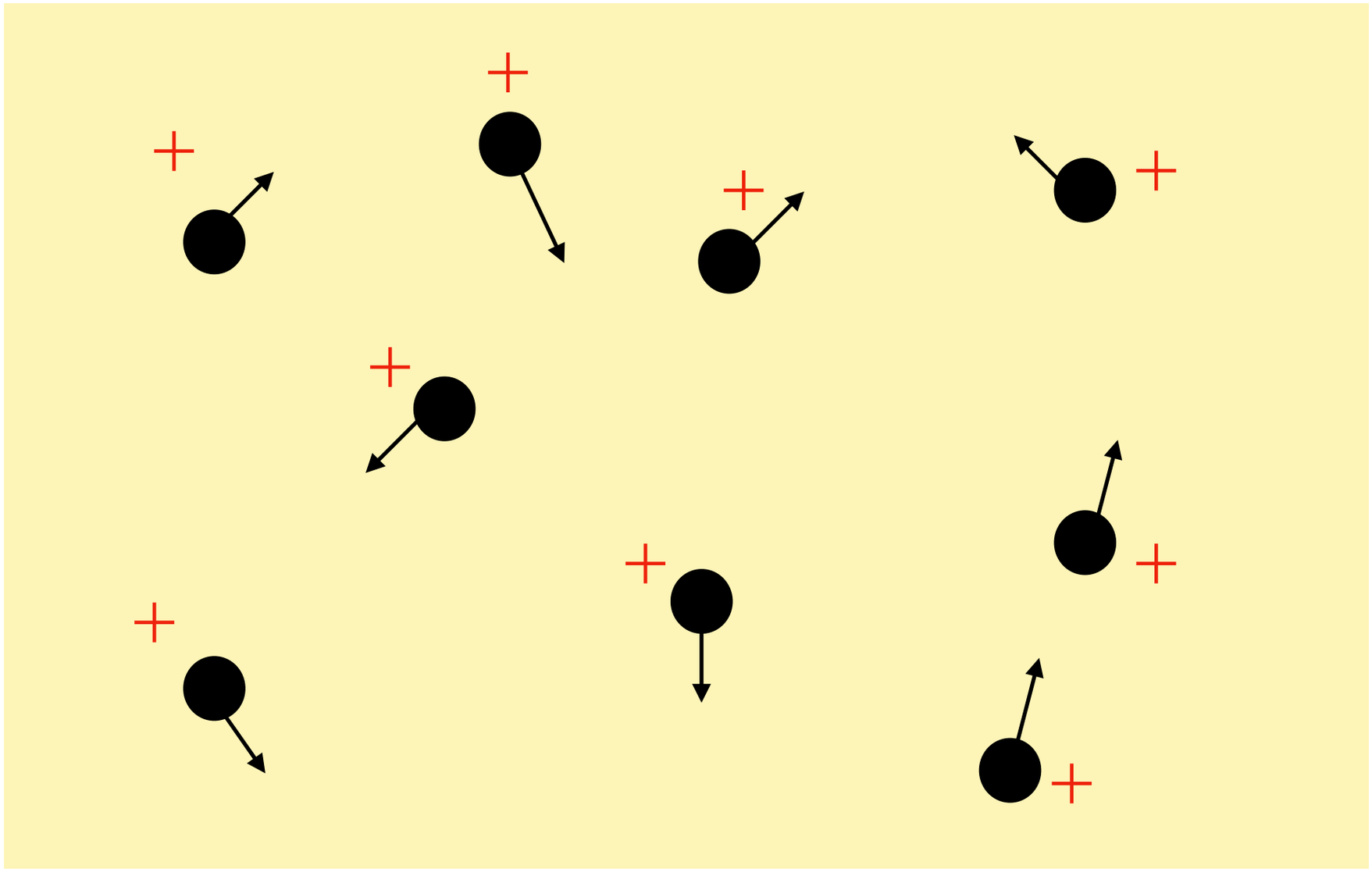


BH acquire net charge while potential is on

$t < 1$ sec

Step 3: Turn On Chemical Potential (Kerr-Newman)

Plasma carries compensating charge for net neutrality

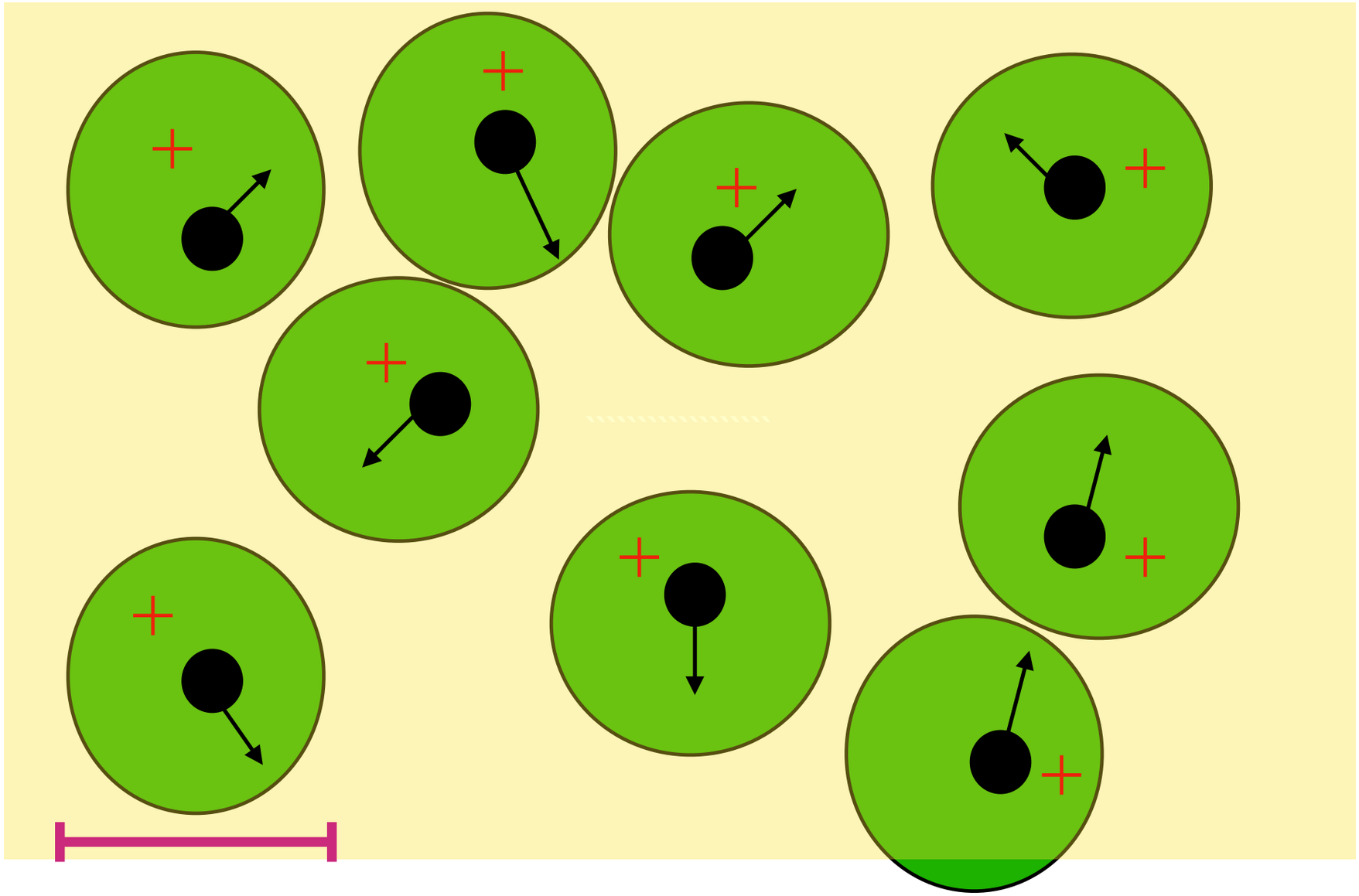


Screens E-fields, but allows B field domains

$t < 1$ sec

Step 3: Turn On Chemical Potential (Kerr-Newman)

Plasma carries compensating charge for net neutrality



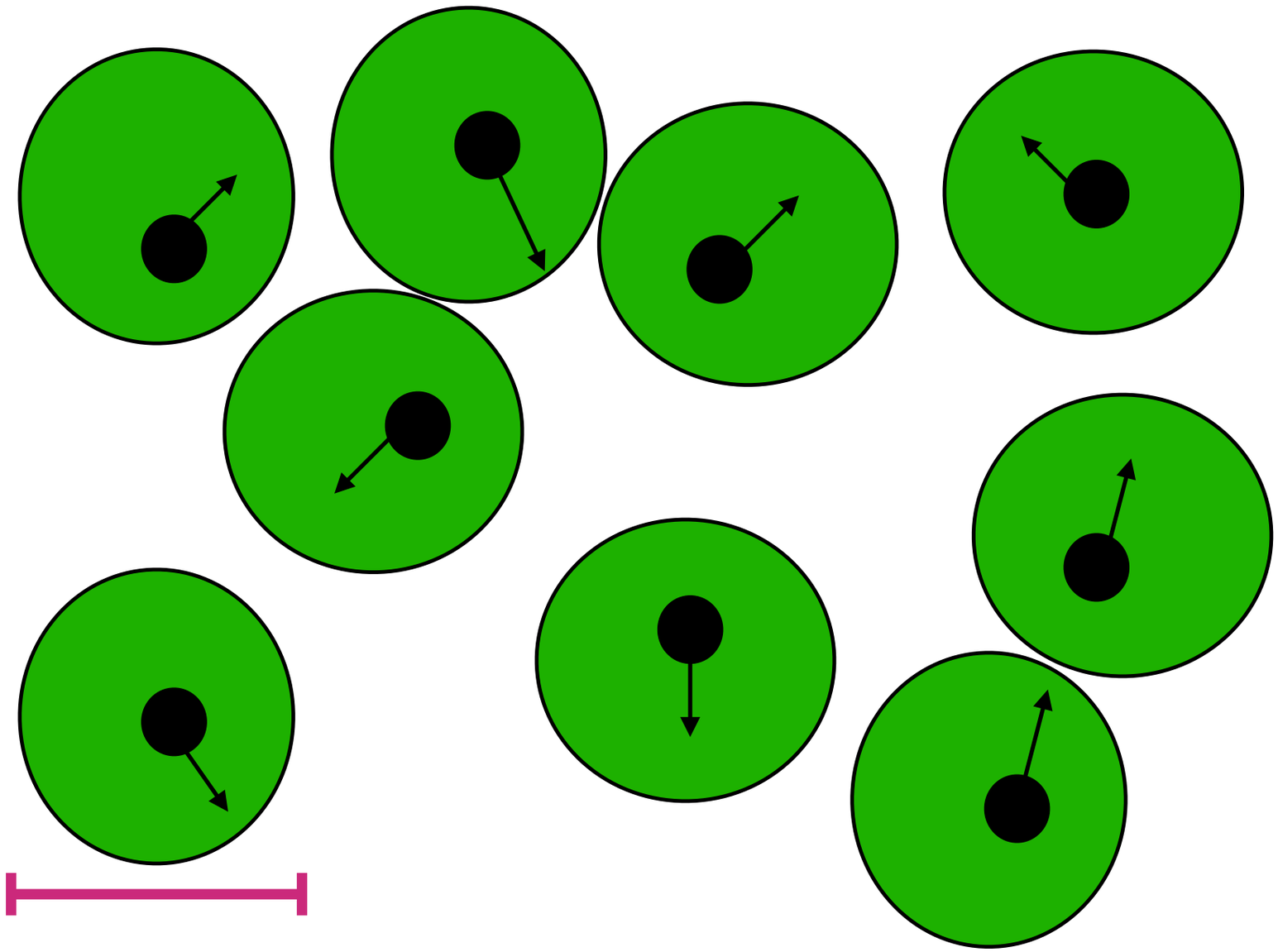
Correlation length ~ nearest neighbor distance

B-field ~ single BH B-field volume average

$t < 1$ sec

Step 4: Turn Off Chemical Potential

Eventually chemical potential shuts off, PBH are Kerr again



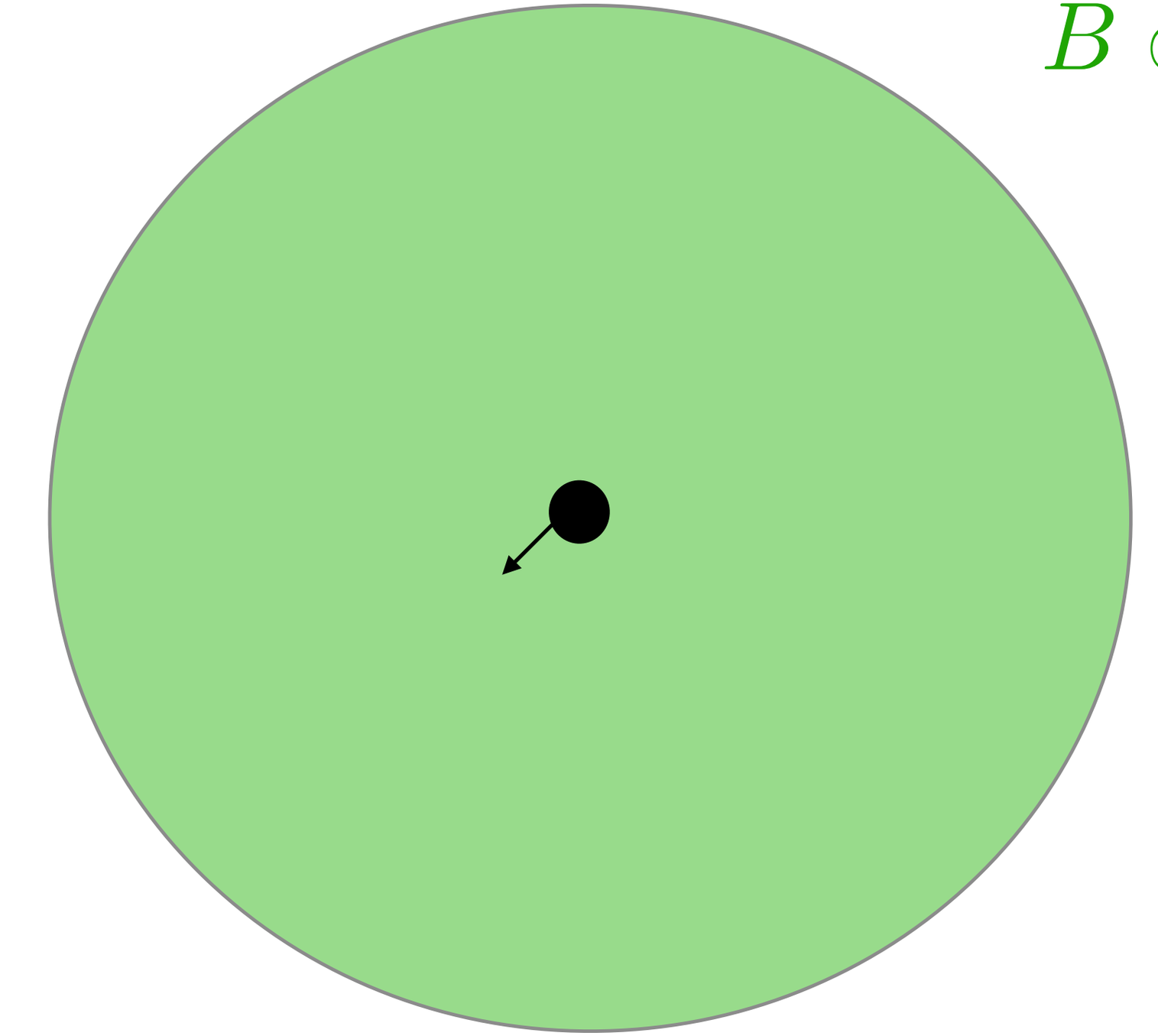
B-field domains persist after Kerr-Newman era

$t < 1$ sec

Step 5: Redshift to z = 0

Present day field

$$B \propto a^{-2}$$

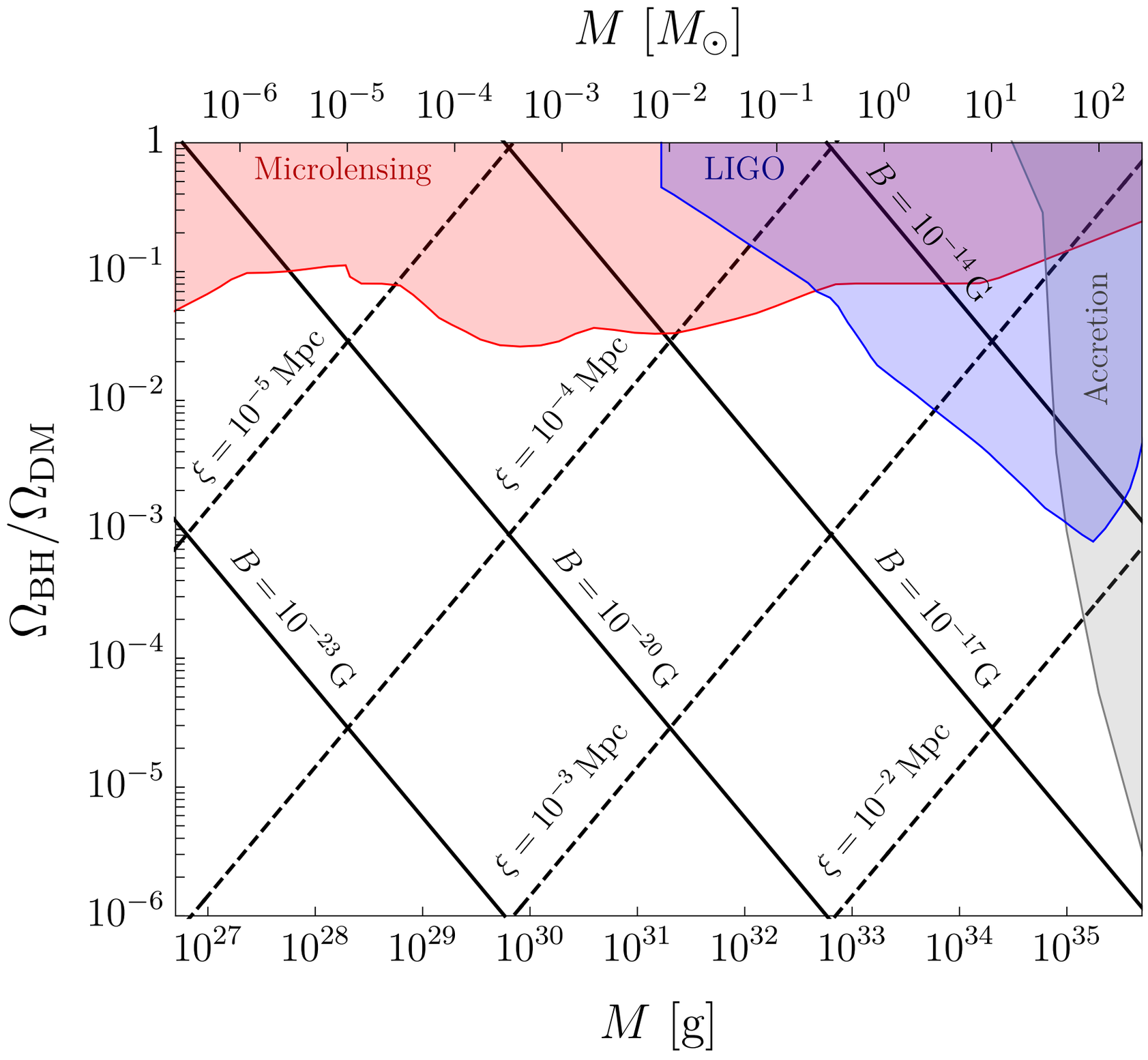


Correlation length $\lambda \propto a$

$t = 13.7$ Gyr

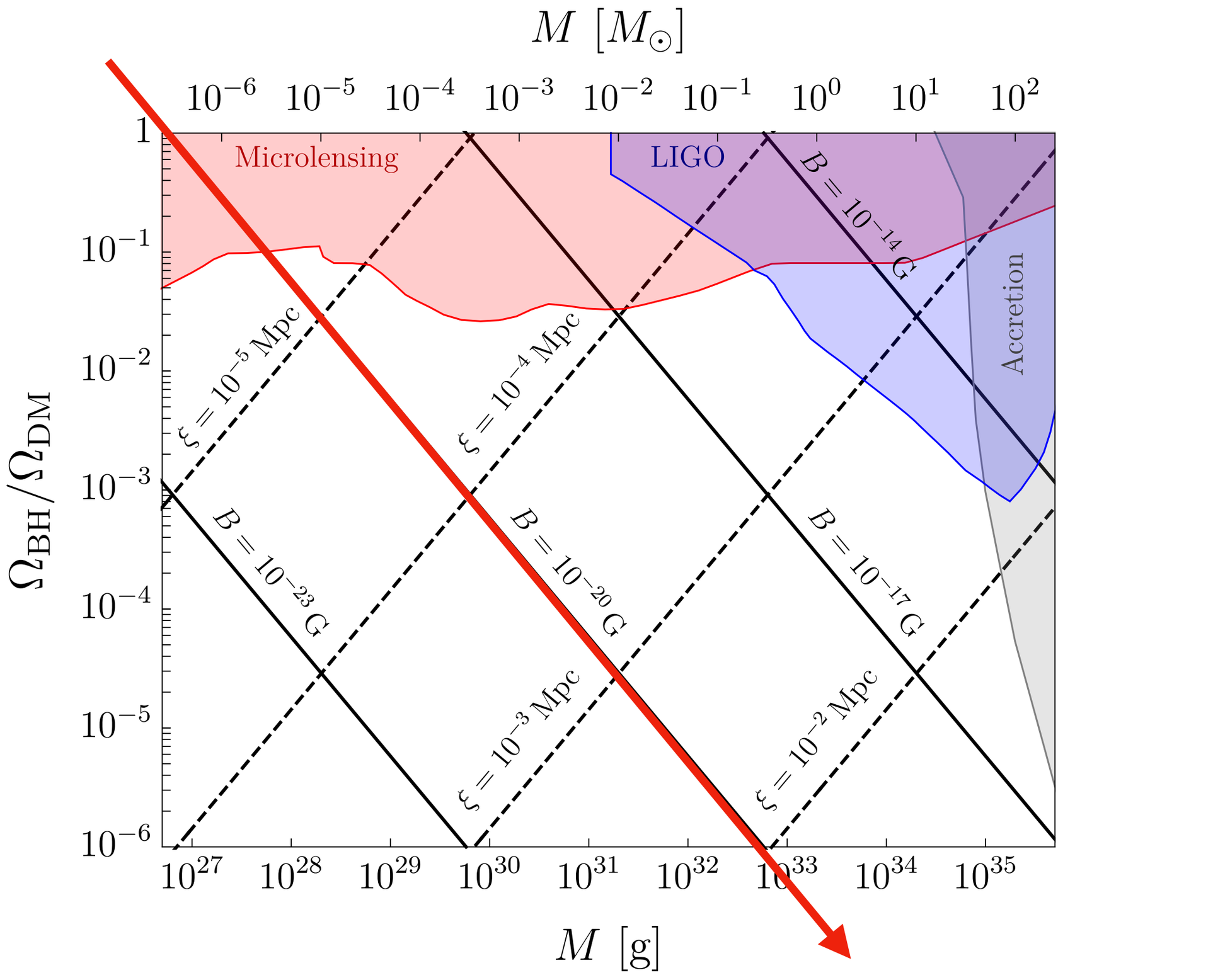
Parameter Space

$$Q_\star \alpha_\star = 0.5$$



Parameter Space

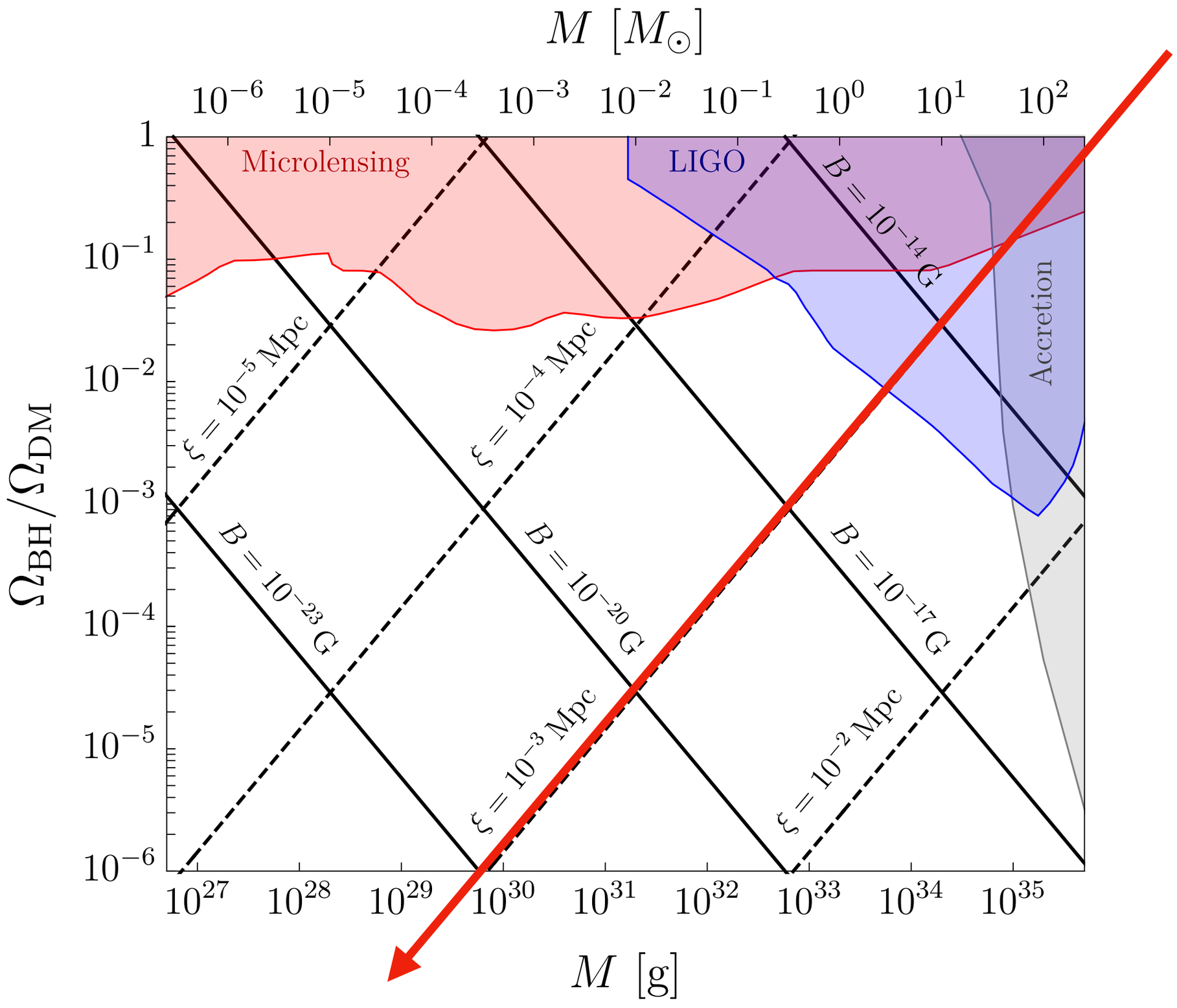
$$Q_\star \alpha_\star = 0.5$$



Constant B field

Parameter Space

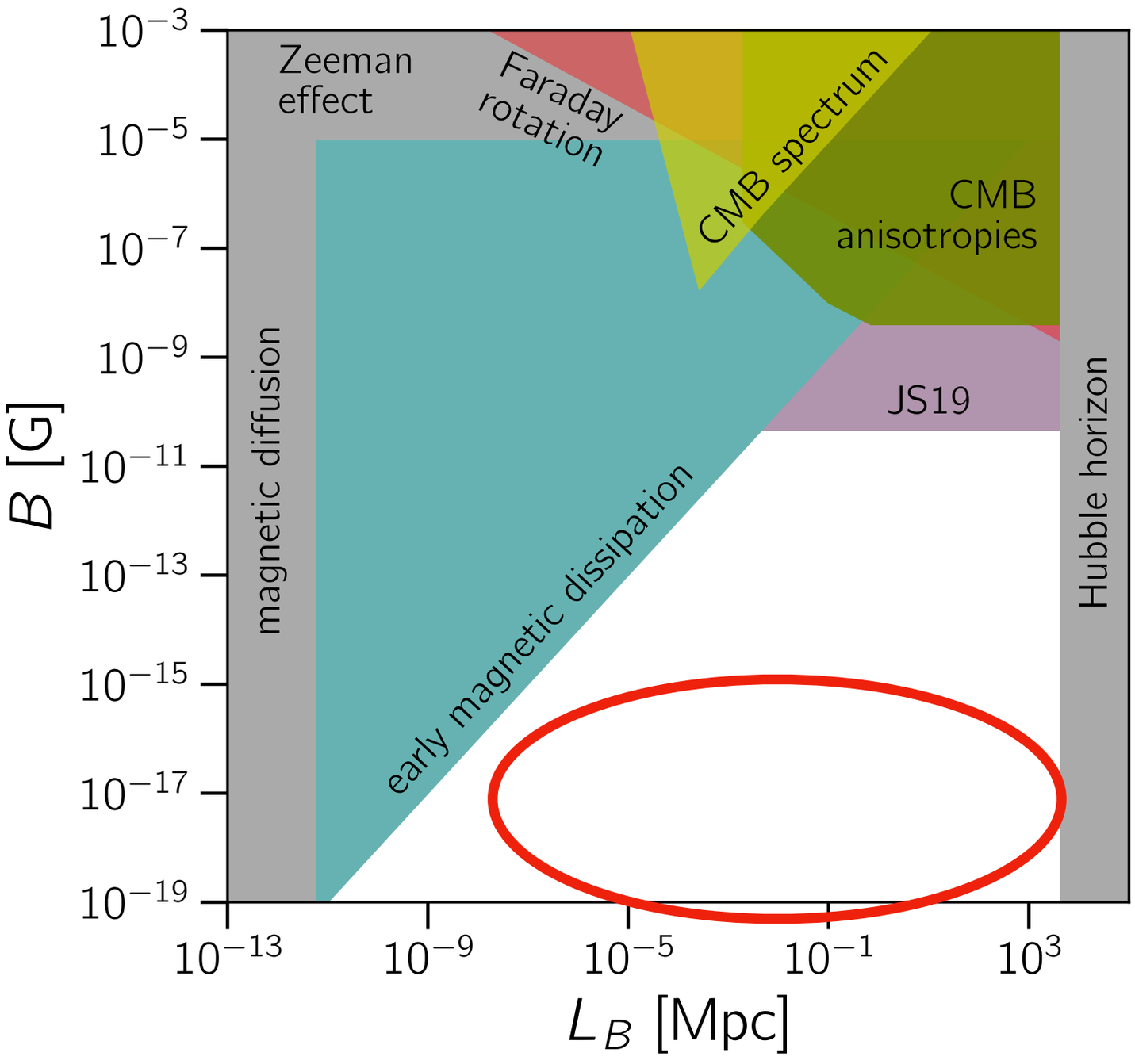
$$Q_\star \alpha_\star = 0.5$$



Constant correlation length

Parameter Space

Batista Saveliev 2105.12020



PBH seed galactic B fields

Overview

Motivation for primordial B fields

Kerr-Newman PBH

Cosmological history

Model building

Towards a Complete Model

Possible realization: add misaligned scalar coupled to charged ψ

$$\mathcal{L} \supset \hat{\mathcal{O}}_\mu(\phi)\bar{\psi}\gamma^\mu\psi + V(\phi)$$

In analogy with Affleck-Dine or spontaneous baryogengesis

Towards a Complete Model

Possible realization: add misaligned scalar coupled to charged ψ

$$\mathcal{L} \supset \hat{\mathcal{O}}_\mu(\phi)\bar{\psi}\gamma^\mu\psi + V(\phi)$$

By isotropy, only time component nonzero

$$\mathcal{O}_\mu(\phi)\bar{\psi}\gamma^\mu\psi \to \mathcal{O}_0(\phi)\bar{\psi}\gamma^0\psi \equiv \mu_\psi(t)n_\psi$$

Towards a Complete Model

Possible realization: add misaligned scalar coupled to charged ψ

$$\mathcal{L} \supset \hat{\mathcal{O}}_\mu(\phi)\bar{\psi}\gamma^\mu\psi + V(\phi)$$

By isotropy, only time component nonzero

$$\mathcal{O}_\mu(\phi)\bar{\psi}\gamma^\mu\psi \to \mathcal{O}_0(\phi)\bar{\psi}\gamma^0\psi \equiv \mu_\psi(t)n_\psi$$

As long as scalar evolves in time, chemical potential is on
It splits energy levels of +/- to bias accumulation of net charge

$$dN \sim \frac{d\omega}{\exp\left[(\omega - m\Omega - q\Phi)/T_{\rm BH}\right] \mp 1}\,,$$

Towards a Complete Model

Possible realization: add misaligned scalar coupled to charged ψ

$$\mathcal{L} \supset \hat{\mathcal{O}}_\mu(\phi)\bar{\psi}\gamma^\mu\psi + V(\phi)$$

By isotropy, only time component nonzero

$$\mathcal{O}_\mu(\phi)\bar{\psi}\gamma^\mu\psi \to \mathcal{O}_0(\phi)\bar{\psi}\gamma^0\psi \equiv \mu_\psi(t)n_\psi$$

As long as scalar evolves in time, chemical potential is on
It splits energy levels of +/- to bias accumulation of net charge

$$dN \sim \frac{d\omega}{\exp\left[(\omega - m\Omega - q\Phi)/T_{\rm BH}\right] \mp 1}\,,$$

Eventually $\mu_\psi \to 0$ and PBH quickly discharge

Conclusion

Primordial B-fields compelling cosmic relic

- Can seed galaxy fields during structure formation
- Can affect cosmic ray trajectories
- Window into pre-BBN universe

Conclusion

Primordial B-fields compelling cosmic relic

Can seed galaxy fields during structure formation

Can affect cosmic ray trajectories

Window into pre-BBN universe

First study of Kerr-Newman PBH and their *B*-fields

PBH get spin through mergers

Temporary chemical potential = PBH charge

Kerr-Newman BH = B-fields

Chemical potential shuts off, B-fields remain

Conclusion

Primordial B-fields compelling cosmic relic

- Can seed galaxy fields during structure formation
- Can affect cosmic ray trajectories
- Window into pre-BBN universe

First study of Kerr-Newman PBH and their *B*-fields

- PBH get spin through mergers
- Temporary chemical potential = PBH charge
- Kerr-Newman BH = B-fields
- Chemical potential shuts off, B-fields remain

Future directions

- Model building for chemical potential inducing field
- Relationship between B correlation length and LIGO merger rate?

Conclusion

Grazie!