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We show that the subset of high energy neutrino events detected by IceCube which correlate with the Galactic center (within uncertainties of their reconstructed arrival directions) could originate in the collisions of protons accelerated by the Sagittarius (Sgr) A* disk dynamo. Under very reasonable assumptions on source parameters we demonstrate that the supermassive black hole at the center of the Galaxy could launch protons and nuclei with multi PeV energies. Acceleration of these particles in a period of seconds up to Lorentz factors of $\sim 10^{7.5}$ is possible by means of the Blandford-Znajek mechanism, which wires the spinning magnetosphere of Sgr A* as a Faraday unipolar inductor. During the acceleration process the $\sim$ PeV progenitors of $\sim$ 50 TeV neutrinos radiate curvature photons in the keV energy range. We show that IceCube neutrino astronomy with photon tagging on the Chandra X-ray Observatory could provide a valuable probe for the Blandford-Znajek acceleration mechanism. We also argue that EeV neutrinos, which may be produced in a similar fashion during the merging of binary black holes, could become the smoking gun for particle acceleration in a one-shot boost.

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The IceCube high-energy starting event (HESE) search resulted in the discovery of astrophysical neutrinos [1]. In four years of data taking, 54 events with neutrino vertex contained in the detector volume have been observed [2]. The HESE sample rejects a purely atmospheric explanation at more than 5.7σ. The data are consistent with expectations for equal fluxes of all three neutrino flavors [3]. While the flux above 200 TeV can be accommodated by a power law with a spectral index $\gamma = 2.07 \pm 0.13$ [4], lowering the threshold revealed an excess of events in the $30 - 200$ TeV energy range [5], raising the possibility that the cosmic neutrino spectrum does not follow a single power law, and/or may be contaminated by additional charm background [6].

Quite recently, the IceCube Collaboration reported a combined analysis based on six different searches for astrophysical neutrinos (that included the HESE data sample) [7]. Assuming the neutrino flux to be isotropic and to consist of equal flavors at Earth, the all flavor spectrum with neutrino energies 25 TeV $\leq \varepsilon_\nu \leq$ 2.8 PeV is well described by an unbroken power law with best-fit spectral index -2.50 ± 0.09 and a flux at 100 TeV of $6.7^{+1.1}_{-1.2} \times 10^{-18}$ $(\mathrm{GeV\,s\,sr\,cm^2})^{-1}$. Splitting the data into two sets, one from the northern sky and one from the souther sky, allows for a satisfactory power law fit with a different spectral index for each hemisphere. The best-fit spectral index in the northern sky is $\gamma_N = 2.0^{+0.3}_{-0.4}$, whereas in the southern sky it is $\gamma_S = 2.56 \pm 0.12$. The discrepancy with respect to a single power law corresponds to 1.1σ [7] and may indicate that the neutrino flux is anisotropic [8].

The higher statistics data seem to reinforce earlier claims that a significant part of the flux contributing to the HESE sample originates in the Galaxy [9]. In particular, it has been noted that the largest HESE concentration is at or near the Galactic center, within uncertainties of their reconstructed arrival directions [10, 11]. The excess contains 7 shower-like events, including a PeV event (#14) and two sub-PeV events (#2 and #25) with arrival directions consistent with a Galactic center origin within their 1σ uncertainty. Interestingly, 2 of the 7 events occurred within one day of each other and there is a 1.6% probability that this would occur for a random distribution in time [11]. More compelling, event #25 has a time very close to (around three hours after) the brightest X-ray flare of Sagittarius (Sgr) A* observed by the Chandra X-ray Observatory [12], with a p-value of 0.9 [11]. In this paper we show that this intriguing correlation could provide the first experimental evidence favoring the Blandford-Znajek mechanism, which wires the spinning magnetosphere of Sgr A* as a Faraday unipolar inductor [13]. We first investigate whether the supermassive black hole at the center of the Galaxy could be the source of multi-PeV cosmic rays that would produce high-energy gamma rays and neutrinos upon interaction with the ambient gas. After that we further examine radiative processes which lead to energy losses during the acceleration. In particular, we study radiation of curvature photons on the black hole magnetosphere. Under reasonable assumptions on source parameters we show that protons accelerated by the spinning black hole dynamo could explain the IceCube-Chandra connection advanced in [11].

To develop some sense for the orders of magnitude involved, recall that the maximum luminosity of an accreting black hole is given by the Eddington limit,

$$L_{\rm Edd} \sim 1.3 \times 10^{44} M_6 \ {\rm erg\,s^{-1}}\,, \qquad (1)$$

where $M = 10^6 M_6 M_\odot$ is the black hole mass and $M_\odot$ is the solar mass. At any higher luminosity, ordinary matter is more likely to be driven off by radiation pressure than to accrete. The critical accretion rate required to sustain the Eddington luminosity, assuming a typical $\eta = 0.1$ efficiency of conversion of mass to radiant energy, is found to be

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{\eta c^2} \simeq 2.2 \times 10^{-2}\ M_6\ M_\odot\ {\rm yr}^{-1}\,. \qquad (2)$$

The accreting plasma is assumed to support an axisymmetric magnetic field configuration due to the generation of currents.

The characteristic strength of the $\vec{B}$-field can be obtained assuming pressure equilibrium between the magnetic field and the in-falling matter, whereby [14]

$$B_p \sim 6 \times 10^5 \; M_6^{-1/2} \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}} \right)^{1/2} \; {\rm G}. \tag{3}$$

Accretion from a thin disk would spin a black hole up to its near critical angular momentum

$$J = a \, J_{\rm max} = a \, \frac{GM^2}{c} \,, \tag{4}$$

where a is the dimensionless spin parameter. Now a point worth noting at this juncture is that for a Schwarzschild black hole, $a = 0$, whereas for a maximally spinning (extreme Kerr) black hole, $a = 1$. Actually, the increase of the spin parameter would stop at $a \approx 0.998$ due to the fact that photons emitted from the disk on retrograde paths are more likely to be captured by the hole than prograde ones, hence de-spinning the hole [15].

For static black holes, the scale characterizing the event horizon r_h coincides with the Schwarzschild radius

$$r_S = \frac{2GM}{c^2} \simeq 3 \times 10^{11} \; M_6 \; {\rm cm} \,. \tag{5}$$

For spinning black holes, the (spherical) event horizon surface has a radius

$$r_h = r_g \left(1 + \sqrt{1 - a^2} \right) , \tag{6}$$

where $r_g = r_S/2$ is the gravitational radius. Just *outside* the event horizon lies the ergoregion defined by

$$r_h < r < r_g \left(1 + \sqrt{1 - a^2 \cos^2 \theta} \right) , \tag{7}$$

where θ is the angle to the polar axis. The outer boundary of the ergoregion is the ergosphere, which is ellipsoidal in shape and meets the horizon at the poles $\theta = 0, \pi$. Inside the ergosphere, spacetime is dragged along in the direction of the black hole rotation (frame dragging), so that no static observer can exist and a particles must co-rotate with the hole. The angular velocity Ω of a black hole is defined as the angular velocity of the dragging of inertial frames at the horizon, and is found to be

$$\Omega = a \left(\frac{c}{2 r_h} \right) . \tag{8}$$

The supermassive spinning black hole endowed with the external poloidal field B_p induces an electric field of magnitude $E \sim \Omega r_h B_p / c$. This has associated a permanent voltage drop across the horizon of magnitude

$$\Phi \sim E r_h = \frac{a r_h B_p}{2} \sim 2 \times 10^{17} a \left(1 + \sqrt{1 - a^2} \right) M_6 B_4 \; {\rm V}, \tag{9}$$

where $B_p = 10^4 B_4$ G. In analogy with an electric circuit, the black hole can be thought as a disk dynamo with non-zero resistance, so that power can be extracted by currents flowing between its equator and poles [13]. If a cosmic ray nucleus of charge Z can fully tap this potential, acceleration up to $\varepsilon = Ze\Phi \sim 10^{2.5} Z M_6 B_4$ PeV may become possible, where we have taken $a \sim 1$. However, the charge density in the vicinity of accreting black holes could be so high that a significant fraction of this potential would be screened and so no longer available for particle acceleration. Therefore it seems more appropriate to define an effective potential where the available length scale, the gap height ζ, is explicitly taken into account [16]

$$\Phi_{\rm eff} \sim \left(\frac{\zeta}{r_h} \right)^2 \Phi = \frac{\Omega}{c} \left(\frac{\zeta}{r_h} \right)^2 r_h^2 B_p \,. \tag{10}$$

In the absence of energy losses the maximum Lorentz factor is given by

$$\gamma_{\rm max}^{\rm acc} \sim 10^{8.5} \frac{Z M_6 B_4}{A} \left(\frac{\zeta}{r_h} \right)^2 , \tag{11}$$

where A is the nucleus mass number. Accordingly, the characteristic rate of energy gain is found to be

$$\left. \frac{d\varepsilon}{dt} \right|_{\rm acc} = \frac{Ze \, c \, \Phi_{\rm eff}}{\zeta} \,. \tag{12}$$

Within the potential drop, the cosmic rays follow the curved magnetic field lines and so emit curvature-radiation photons. The energy loss rate or total power radiated away by a single cosmic ray is [17]

$$\left. \frac{d\varepsilon}{dt} \right|_{\rm loss} = \frac{2}{3} \frac{Z^2 e^2 c}{r_c^2} \gamma^4 \,, \tag{13}$$

where r_c is the curvature radius of the magnetic field lines, and γ is the Lorentz factor of the radiating particles. Acceleration gains are balanced by radiative losses. In the absence of other damping mechanisms, the radiation reaction limit is [18]

$$\gamma_{\rm max}^{\rm rad} \sim 10^9 \left(\frac{a B_4}{Z} \right)^{1/4} M_6^{1/2} \left(\frac{r_c}{r_h} \right)^{1/2} \left(\frac{\zeta}{r_h} \right)^{1/4} . \tag{14}$$

All in all, direct electric field acceleration on the black hole magnetosphere would allow Lorentz factors up to

$$\gamma_{\rm max} = \min \left\{ \gamma_{\rm max}^{\rm acc}, \; \gamma_{\rm max}^{\rm rad} \right\} . \tag{15}$$

The resulting cosmic ray spectrum would be sharply peaked at nearly the maximum energy, like spectra of high-energy particles produced in linear accelerators. This particular footprint may help distinguishing a Blandford-Znajek origin from conventional Fermi shock acceleration, which typically gives power law spectra $\propto \varepsilon^{-2}$ [19]. The curvature radiation spectrum emitted by mono-energetic particles has a peak at

$$\varepsilon_{\gamma,{\rm max}} = \frac{3}{2} \hbar c \, \frac{\gamma_{\rm max}^3}{r_c} \,. \tag{16}$$

For $\gamma \ll \gamma_{\rm max}$, the curvature spectrum radiated by single particle follows a power law, $\varepsilon_\gamma^{1/3}$, as in synchrotron emission, and then decreases exponentially for $\gamma \gg \gamma_{\rm max}$.

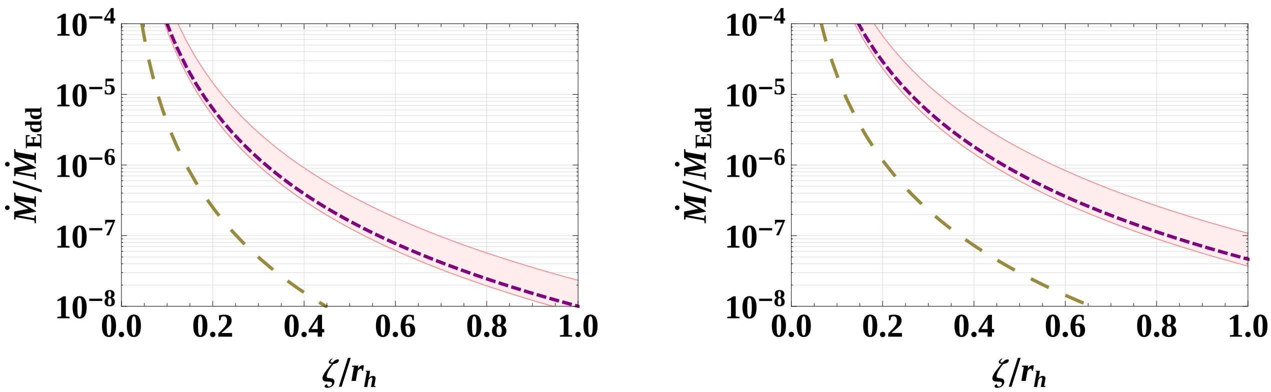

FIG. 1. The pink band indicates the region of the parameter space that can explain the Chandra flare in the keV energy range from curvature radiation of protons (left) and iron nuclei (right). The dashed lines (long $\varepsilon_\nu/\varepsilon = 10^{-1.3}$ and short $\varepsilon_\nu/\varepsilon = 10^{-2}$) are contours of constant Lorentz factors of protons (left) and nuclei (right), which could produce a $\sim$ 35 TeV neutrino after scattering on the ambient gas. We have taken $r_c \sim r_g$. We avoid reference to specific accretion models and present results for the generous range $10^{-9}~{\rm yr}^{-1} < \dot{M}/M_\odot < 10^{-4}~{\rm yr}^{-1}$, which can accommodate the X-ray luminosity observed by Chandra: $L_{\rm X} \sim 5 \times 10^{35}~{\rm erg\,s}^{-1}$.

At this point a reality check is in order. Sgr A* has a mass of $M \simeq 4.31 \times 10^6 M_\odot$ [20] and the accretion rate varies in the range $2 \times 10^{-9}~{\rm yr}^{-1} \lesssim \dot{M}/M_\odot \lesssim 2 \times 10^{-7}~{\rm yr}^{-1}$ [21] (see however [22]). Altogether this yields a peak on the photon spectrum at

$$\varepsilon_{\gamma,{\rm max}} = 2.8 \times 10^{12} \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{3/2} \left(\frac{Z}{A}\right)^3 \left(\frac{\zeta}{r_h}\right)^6 ~{\rm keV}\,. \qquad (17)$$

The highest peak flux and fluency flare ever observed from Sgr A* lasted for about 5.6 ks and had a decidedly asymmetric profile with a faster decline than rise [12]. The total $2 \lesssim \varepsilon_\gamma/{\rm keV} \lesssim 10$ emission of the event was approximately 10^{39} erg. Partially ordered magnetic fields with intrahour variability [23] could partially accommodate the duration of the flare. The $\sim \varepsilon_\gamma^{-2}$ spectrum observed by Chandra over less than a decade of energy [12] can be accommodated by tuning appropriate source parameters, but it is less naturally obtained than with Fermi mechanism [24]. The IceCube event #25 correlating with the Sgr A* flare has a shower topology, and therefore the deposited electromagnetic equivalent energy in the detector, $33.5^{+4.9}_{-5.0}$, is roughly equal to the neutrino energy $\varepsilon_\nu \approx 35$ TeV [2]. Backgrounds to astrophysical neutrinos originate in cosmic ray air showers. Muons produced in these showers, mainly from decay of charged pions and kaons, enter the detector from above. The total atmospheric muon background in four years of data is found to be 12.6 ± 5.1 [2]. The background from atmospheric neutrinos reported by the IceCube Collaboration is $9.0^{+8.0}_{-2.2}$ [2]. Note that neutrino background events are overwhelmingly ν_μ [25], which produce track topologies. For this reason, the chance that the HESE event #25 is atmospheric in origin is negligible. Sgr A* is radiatively inefficient, so the photon density will be low in its environment. The protons and/or nuclei accelerated by the radiatively inefficient accretion flow (RIAF) escape the engine and interact with the dense molecular gas surrounding Sgr A*. This gas concentration is known as the central molecular zone (CMZ), with a size of $R_{\rm CMZ} \sim 100$ pc and a mass of $M_{\rm CMZ} \sim 10^7 M_\odot$ [26]. Neutrino production proceeds dominantly through pp collisions within the CMZ [27]. Then, the neutrino energy is expected to scale with that of the parent protons according to $10^{-2} \lesssim \varepsilon_\nu/\varepsilon \lesssim 10^{-1.3}$ [28]. Substituting these figures in (11) and (16) we can study the required conditions to associate the IceCube neutrino event with the flare observed by Chandra. Our results are encapsulated in Fig. 1, where we show that the possible connection is valid for a large range of $\dot{M}$ and ζ. Note that for $\zeta \sim r_g$, $Z = A = 1$, and $\dot{M} \sim 5 \times 10^{-8} M_\odot$ yr, we find $\gamma_{\rm max} \sim 10^{7.5}$. Interaction of these energetic protons within the CMZ could lead to PeV neutrinos.

Thus far we have shown (under reasonable assumptions) that PeV and sub-PeV neutrinos could be produced in the vicinity of the Galactic center through pp collisions and that the parent protons could also radiate X-rays during the acceleration process. To explain the 2:38:29 hours delay of IceCube detection of event #25 with respect to the Chandra giant flare we require further assumptions. In particular, the pp collisions should take place before the ultra-relativistic protons undergo diffusion in the CMZ. The diffusion properties depend strongly on the magnetic field strength, which is quite uncertain [29, 30]. Early estimates inferred a large-scale milligauss magnetic field permeating throughout the Galactic center based on the apparent resistance of nonthermal filaments to distortion by molecular clouds [31]. More recent estimates are somewhat lower: a strength of $\sim 6~\mu$G was inferred from radio emission distributed over the inner $6^\circ \times 2^\circ$ [32], while a strength $\gtrsim 50~\mu$G was deduced from nonthermal radio emission in the inner $3^\circ \times 2^\circ$ of the Galaxy [33]. Herein we follow [29] and adopt a fiducial value on the extreme lower side, $B_{\rm CMZ} \sim 10~\mu$G. For $\varepsilon \sim 3.5$ PeV, this leads to a proton Larmor radius

$$r_L \simeq 1.1 \frac{(\varepsilon/{\rm PeV})}{(B_{\rm CMZ}/\mu{\rm G})}~{\rm pc} \sim 0.4~{\rm pc}\,. \qquad (18)$$

The average gas density of the CMZ is estimated to be $10^4~{\rm cm}^{-3}$ [34]. In CMZ clouds (which have a line-of-sight length of 1 pc) the gas density may increase up to about

10^6 cm^{-3} [35]. Accordingly, we assume pp interactions occur within the CMZ innermost region, where the gas density could be up to one [36] to two [37] orders of magnitude higher. We adopt the pp cooling time advocated in [37]

$$t_{pp} = \frac{1}{\sigma_{pp}\, n\, c} \sim 7 \times 10^6 \text{ s}, \tag{19}$$

where $n \sim 10^8$ cm^{-3} is the number density of the accretion plasma and $\sigma_{pp} \sim 50$ mb is the inelastic cross section. Note that for this particular choice of parameters the proton mean free path is $ct_{pp} < r_L$, and so the particles could interact before they diffuse in the CMZ. Needless to say, one may argue that to accommodate the data we have made very speculative considerations in regards to n and $B_{\rm CMZ}$. Whichever point of view one may find more convincing, it seems most conservative at this point to depend on experiment (if possible) to resolve the issue.

Electrons are also accelerated in the inner parts of Sgr A*. For such extremely low luminosity RIAF, the energy losses are dominated by synchrotron and curvature emission (inverse Compton scattering dominates in relatively high luminosity RIAFs) [38]. The radiative energy loss rate of electrons is much higher than that of protons, and so accelerated electrons provide more economic ways for production of high-energy gamma rays, with spectra extending into the 100 GeV energy range [37]. It seems then reasonable to associate the Chandra flare with proton curvature radiation, rather than with electron processes. Future correlation studies of new IceCube data and Chandra observations [39] would provide a definitive probe of this model.

Now, if the Blandford-Znajek mechanism operates at the center of our Galaxy it is very likely that it is also at play in most active galaxies. Hence, it is tempting to speculate that the putative association of high energy neutrinos with blazar flares [40] could also be indicative of acceleration in black hole disk dynamos. One more time, the emission spectra of high-energy gamma rays could provide complementary information in this context. Conspicuously, the diffuse neutrino intensity from RIAFs of low luminosity active galactic nuclei can be compatible with the observed IceCube data [41].

The landmark detection of the gravitational-wave source GW150914 [42] opens another door for testing the Blandford-Znajek mechanism. The GW150914 waveform indicates that the source of the gravitational waves is the coalescence of two black holes of rest-frame masses $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, at luminosity distance 410^{+160}_{-180} Mpc (i.e. redshift $0.09^{+0.03}_{-0.04}$). The mass and spin parameter of the newly formed black hole are

$$M = 62^{+4}_{-4} M_\odot \quad \text{and} \quad a = 0.67^{+0.05}_{-0.07}, \tag{20}$$

and the source is localized to a sky area of 600 deg^2.

The maximum magnetic field strength that could be steadily confined by the newly formed black hole can be estimated assuming that there is rough equipartition of the magnetic field energy density $B^2/(8\pi)$ with the radiation energy density, and consequently with the accretion energy density. The energy density of the radiation field at the Eddington limit is found to be

$$\rho_{\rm Edd} \sim \frac{L_{\rm Edd}}{4\pi r_g^2 c} \sim 2 \times 10^{14} \text{ erg cm}^{-3}, \tag{21}$$

and so the equipartition field strength is

$$B_{\rm Edd} \sim \left(\frac{2L_{\rm Edd}}{r_g^2 c}\right)^{1/2} \sim 8 \times 10^7 \text{ G}, \tag{22}$$

Substituting (20) and (22) into (11) assuming $\zeta \sim r_g$ for protons we obtain $\gamma^{\rm acc}_{\rm max} \sim 10^8$. This is comparable to $\gamma^{\rm rad}_{\rm max} \sim 10^{7.7}$. Collisions of the ultra-relativistic protons with the ambient gas and photon backgrounds surrounding the black hole would produce secondary neutrinos directly chasing the gravitational waves [43]. The IceCube and ANTARES collaborations conducted a combined search for neutrinos candidates in both temporal and spatial coincidence with GW150914, using a time window of ±500 s around the gravitational wave transient [44]. No neutrino candidates have been observed.

The remarkable power of GW150914 is open to more speculation. The total energy radiated in gravitational waves during GW150914 is found to be [42]

$$\varepsilon_{\rm GW} = (3.0 \pm 0.5)\, M_\odot\, c^2 \sim 5.4 \times 10^{54} \text{ erg}, \tag{23}$$

with a peak wave luminosity of

$$L_{\rm GW} = 3.6^{+0.5}_{-0.4} \times 10^{56} \text{ erg s}^{-1}. \tag{24}$$

Note that at the peak the luminosity in gravitational waves is more that 15 orders of magnitude above the Eddington limit. Equipartition arguments seem to indicate that rotationally-powered super-Eddington magnetic fields of $B_{\rm sEdd} \sim 10^{11}$ G might have existed for a limited period of time ~ 50 ms [45]. However, for such a large magnetic field strength, the maximum proton energy will be limited by radiative losses; namely,

$$\begin{aligned} \gamma^{\rm acc}_{\rm max} &\sim 10^8\, \frac{Z}{A}\, \frac{B_{\rm sEdd}}{B_{\rm Edd}} \left(\frac{\zeta}{r_h}\right)^2, \\ \gamma^{\rm rad}_{\rm max} &\sim 10^8 \left(\frac{a}{Z}\right) \left(\frac{B_{\rm sEdd}}{B_{\rm Edd}}\right)^{1/4} \left(\frac{r_c}{r_h}\right)^{1/2} \left(\frac{\zeta}{r_h}\right)^{1/4}. \end{aligned} \tag{25}$$

Now, assuming $\zeta \sim r_c \sim 150\, r_g$, we would expect to see a few protons reaching Lorentz factors of up to $\sim 10^{10.3}$, in a time scale $\zeta/c \sim 50$ ms. Should nature be so cooperative, since the proton spectrum is expected to be sharply peaked at nearly the maximum energy, the GW150914 neutrino emission would have been predominantly at EeV energies. Thus, the search for temporal and spatial coincidence of these onliest prompt EeV neutrinos with binary black hole mergers could provide direct evidence for cosmic ray acceleration to extreme energies in a one-shot boost.

In summary, the timing and approximate positional coincidences of one of the IceCube neutrino events with the observed photon flaring in X-rays at the Galactic center by Chandra represents the "first light" in the nascent field of multiwavelength–multimessenger astronomy [11]. Herein we have put forward a possible explanation for such intriguing association. Future X-ray observations confronted with high-energy neutrino data will test the IceCube-Chandra connection, providing the final verdict for the ideas discussed in this paper.

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